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Technological Breakthroughs, Energy, and Efficiency at the Beginning of the First Industrial Revolution: Spillovers from the Modernization of Science

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Spillovers from the Modernization of Science

Angelo Baracca[1]

Abstract

The take-off of the First Industrial Revolution in England around the mid-eighteenth century, which shifted manufacturing to the factory system, was due to the emergence of the new entrepreneurial class with highly skilled and culturally informed technicians who fully assimilated the values of capitalism and transferred them to their fundamental innovations. One could apply the Gramscian concept of "hegemony" to describe the spread of new literary and philosophical societies in which entrepreneurs, technicians, and intellectuals met to discuss solutions to newly emerging problems. Inventions that increased labor productivity flourished, and in the field of energy production, where water wheels and steam engines already existed, decisive advances were to streamline their use in capitalist production, which prevented future developments because science was still tied to old approaches. The contributions of John Smeaton to the development of water wheels, and of James Watt to the steam engine are analyzed here in detail, emphasizing how both led to the completion of Newtonian mechanics and the birth of thermodynamic science. The concept of efficiency that inspired their research was destined to inform all of modernity.

In those same years in France, the regime of absolutism prevented the nascent bourgeoise from establishing their hegemony. Through the Enlightenment movement, they sublimated their planning by studying and systematizing the achievements of British "practical mechanics" in a rational sense. In particular, Lazare Carnot, trained in the school of military genius, generalized the criteria that Smeaton had established for water wheels to all mechanical machines, introducing the first formalizations of energy concepts. Lazare's son, Sadi Carnot, inspired by the same criteria, formulated the first theory of "fire machines" in 1824, opening up the modern field of thermodynamics, which introjected from its inception the criterion of efficiency.

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Foreword

This work aims to be more than a mere essay on history of science and technology since there is already an abundance of excellent research on the First Industrial Revolution and the development of thermal engines, among other topics. My aim is rather to develop a comprehensive reconstruction of the connections between the formation of the new entrepreneurial class, the related radical social and cultural changes, and the consequent breakthroughs that were introduced in the fledgling industrial system. Such innovations needed to forge the concepts and criteria necessary to support them, at a time when the levels of scientific elaboration had not yet reached an adequate level. This happened for the basic concepts of work, energy, and efficiency. The innovations made in England by the highly trained and skilled technicians who actively interacted with the entrepreneurial circles introduced the necessary basic concepts of "practical mechanics" in an empirical manner. These key innovations were adopted and systematized within the Enlightenment culture that was dominant in France.

Incidentally, I begin with an annotation that I consider pertinent to clarify the reasoning behind my considerations. It is essential to my interpretation of what *science* is that in its historical analysis, the name of James Watt should not even appear—considering that he is a technician, not a scientist! I will instead discuss the fundamental role of his 1769 patent for the separate condenser in the initial formulation of the Second Law of Thermodynamics. Similarly, I attribute to the "engineer" John Smeaton (in reality a highly skilled technician), in his research on waterwheels in 1759, both the unambiguous definition of the concepts of mechanical work and power, as well as the clear—but certainly not formalized—distinction between the different concepts of kinetic, potential, and total mechanical energy.

One of the central points of this reconstruction is the reiteration that the concept of efficiency for mechanical and thermal engines became the underlying criterion that animated these improvements but also all the activities and innovations of the First Industrial Revolution in general.

Specifically, through an in-depth analysis of their papers, I will delineate the conceptual thread that links together John Smeaton's efficiency criteria for the ideal waterwheel, their generalization by Lazare Carnot for the concept of ideal mechanical machines, and (after James Watt's patent of the separate condenser) Sadi Carnot's theory of heat engines. These works laid down the conceptual foundations of both the First and the Second Laws of Thermodynamics.

A basic feature that links these contributions is that during the first phase of industrialization, technical innovation preceded—and paved the way for—the development of science. In the next phase of industrialization, in the second half of the nineteenth century, the formation of the middle class on the European continent prompted the reversal of the interrelationship between science and technology. In fact, the need to compete with the century-old British industrial power pushed the new entrepreneurial class, through the progressive scientific milieus homogeneous to these aims, to radically transform the scientific method: the systematic introduction of models (increasingly formalized) were a probe to explore new properties or phenomena and forged innovative scientific tools capable of guiding radically new technological innovations at the basis of the Second Industrial Revolution.

Introduction

In the second half of the eighteenth century in Great Britain, economic growth and technical innovation experienced a sharp acceleration, which gave rise to the First Industrial Revolution. It was a unique phenomenon in Europe (which at the time meant the world) due not only to the characteristics of the British entrepreneurial class and the particular economic conditions at the time, but also to the international location (colonies) of the country: in other European countries, the process of industrialization would take off many decades later and would have significantly different characteristics.

This industrialization process was marked by an increasing development and use of machines to intensify the production of goods or replace living labor. In Great Britain, peculiar social and economic conditions had been created: agricultural productivity had increased, moving away from self-consumption and towards a market for agricultural output, making labor available for other jobs. The level of consumption had increased: in the previous century, a bourgeois stratum had formed and free enterprise had arisen while the power of the monarchy had been limited;[2] merchant-entrepreneurs had accumulated capital to invest; the cultural level of the population had risen; communication routes had improved. There was also widespread expertise in the development of mechanical tools, including precision instruments, which placed the country at the forefront of Europe. The fact that Great Britain was rich in coal was of great importance for the subsequent development of the factory system.

Moreover, the country benefited from its position on the Atlantic Ocean, from the resources and riches provided by its colonies in North America (with the Seven Years War [1756–1763], France lost Canada and Louisiana to Great Britain;[3] the war also marked the decline of Holland), as well as from its predominance in maritime trade, in particular with India for the import of valuable cotton cloth and the monopoly of the tea trade, which allowed the country to collect considerable amounts of money. During the eighteenth century, the decline of the Mughal Empire allowed Great Britain to progressively extend its control over the Indian peninsula. Between 1750 and 1820, the English East India Company—originally a private association of merchants who traded in some coastal areas—extended its dominion over vast parts of the Indian territory, whereas in other

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[2] By the time constitutional charters and declarations of rights appeared in North America, France, and other countries, a regime of limited monarchy, parliamentary representation on a non-estates-basis, and a formalized legislative procedure had been present in England for over a century; therefore, the foundations of modern constitutionalism had already been laid. Moreover, there are important constitutional documents dating back to the Middle Ages, such as the Magna Carta of 1215, and to other struggles against the absolutist ambitions of English sovereigns, such as the Petition of Right of 1628.

[3] However, the interests of the English colonists in North America came into increasing conflict with those of the mother country, eventually leading to open revolt and the American Revolutionary War of 1775–1783.

territories the local sovereigns were left on the throne, provided they accepted British protection. The Company was subject to the supervision of the British government.

Colonial exploitation was a decisive factor contributing to the industrial take off of Great Britain. Cotton, increasingly sought after for fabric production and imported from India at bargain prices, constituted the backbone of the nascent industry (wool, the basis of the traditional English textile industry, was not suitable for mechanical spinning and weaving). India in particular was also something new in that it was neither a trading base nor a peopling colony, and for a long time it represented the prototype for a new settler colonialism, which transformed the savagery and genocide of New World conquest into brutal and inhuman exploitation.

In England, the process of enclosure played an important role in the development of primitive accumulation. Through this process, many common lands that were left to free grazing or the collection of wood were privatized and fenced, thus depriving the poorest peasants of the free right to pasture and forcing them to find new employment in factories, feeding the army of labor force at the disposal of the captains of industry.

The development of internal communication routes was fundamental to commercial and industrial growth. The condition of the roads left much to be desired, but a dense network of navigable canals was developed, which required an intense contribution of technicians (the training of engineers did not yet exist) who developed their knowledge of hydraulic technology and introduced innovative solutions (tunnels to overcome differences in height, bridges, etc.).

The English landscape changed radically. The Midlands—rich in water, necessary for the waterwheels and for the bleaching, dyeing, and printing of yarn—went from an agricultural and commercial region to a wildly industrialized one after the creation of thousands of factories. The cotton mills were dusty and dangerous places where workers worked from 12 to 14 hours under harsh discipline. Children, because of their short stature and nimble fingers, were required and abused to operate machinery and rewire threads. An urban proletariat was formed; it was to live through a social and moral degradation that was at first unknown. The poor workers' houses crowded into filthy streets and several families lived together in the same house. More than fifty percent of those born did not make it past their fifth day of life. Nevertheless, the population of England grew from 7.5 million in 1760 to 14 million in 1821.

Women were still invisible, except as an underpaid labor force, but reproductive and domestic labor were an essential factor in early accumulation. How can we fail to observe the absence of women among the entrepreneurial and scientific exponents of these processes? There were few, but notable, exceptions in the intellectual world, such as Madame de Staël (1766–1817), deeply involved in the events of the French Revolution; Jane Austen (1775–1817), author of *Pride and Prejudice* and other notable novels, who as a woman did not sign her works; the British Mary Wollstonecraft (1759–1797), one of the first to support the need to recognize greater rights for women; Anne Seymour Damer (1749–1828), famous English sculptor; and the historian Catharine Macaulay (1731–1791). But we will also see the people's revolutionary Olympe de Gouges, author of the Declaration of the Rights of Women and of the Female Citizen, who was condemned to the guillotine in 1793 because "she wanted to be a Statesman!"

Part 1 – Culture and Innovation in the Industrial Bourgeoisie

1. Machine Development: The Energy Bottleneck

The first technical innovations had occurred in the field of wool production but had failed to establish themselves. Cotton, on the other hand, proved to be much more suitable than wool when processed by the first machines: Kay's *flying shuttle* (1733) and Paul and Wyatt's *spinning wheel* (1738). The real turning point came due to three inventions for spinning cotton: the *spinning jenny* by James Hargreaves (1765), the *water-frame* by Richard Arkwright (1769), and the *mule* by Samuel Crompton (1779). Compared to manual processing, they greatly increased the production of yarn and made it possible to obtain a homogeneous yarn of much higher quality than that obtained by hand. Once spinning was mechanized, the definitive progress in textile processing was determined by the mechanical loom, invented by E. Cartwright in 1787 (initially moved by hydraulic energy): in 1825, a single boy using two looms could produce up to fifteen times more than a craftsman.

The growth and concentration of entrepreneurial and production activities, and the increasing use of machines, gave way to a bottleneck in the retrieval of energy sources: it could be considered the first energy crisis of the industrial era, which, however, was overcome with the introduction of radical innovations (primarily of technical nature) since the level of scientific knowledge was not yet sufficient to drive substantial innovations. Indeed, it was the technical innovations and inventions that spurred the introduction of new concepts and points of view, or the study of phenomena that, although they were already empirically known and had been used since ancient times (waterwheels, heat, electrical phenomena, chemical processes, metallurgy), now led to the development of innovative physical or chemical concepts, derived not from speculative considerations but from systematic experimental research.

Furthermore, it is worth noting how mining exploitation and the development of the factory system—as well as its increasingly sophisticated processes—generated and aggravated the modern phenomenon of increasing *environmental impact*.

It must be emphasized that the real novelty was not so much the introduction of machines, which had been developed since ancient times to perform or facilitate certain operations (such as the lever, or the pulley), but their purpose, namely to raise productivity levels in order to increase, improve, and standardize goods and commodities, in a word, the *logic of capitalistic profit*. It is not easy for us—who have introjected the capitalist and productivist mindset—to understand what revolution this new use of machines brought on a conceptual and methodological level, and finally even on scientific concepts. The structural transformation at the economic, productive, and social levels brought about a profound change in the intrinsic way of considering natural processes and conceiving their study, the choice of variables and correlations that must be considered in order to set up problems in these terms. *Throughout this first stage of industrialization, new concepts or phenomena emerged in the work of technicians who were in direct contact with the needs of the entrepreneurial world: scientific formalization was driven by the need to interpret these phenomena.*[4]

Throughout the second half of the eighteenth century, water power constituted the dominant motive force to power the machinery of the nascent British industry, but this was possible owing to the skills of a generation of technicians—many of them with a good scientific background–who were stimulated by the tasks on which they were called to perform a systematic and scientific study of waterwheels. In order to set up their work correctly, as we will see, these technicians were compelled to define those energy concepts that Newton, in the age of nascent manufacturing, had not included in his mechanics.[5] In essence, it was the emergence of the social category of labor, as opposed to capital, that *led to the consideration and formulation of the physical concepts of mechanical work and energy.*

England was nevertheless very rich in coal, and the development of mining activity had stimulated the invention of the steam engine. Initially, Newcomen's machine (1705)—more an *atmospheric* than an actual *steam* engine—remained a device that had many drawbacks for industrial use. The engineer James Watt was the inventor of a fundamental innovation (perhaps the most important technical innovation of at least the first phase of the Industrial Revolution) that not only made the steam engine suitable and reliable for any use, but also paved the way for an understanding of thermal phenomena and the specific laws that regulate them. This machine, however, did not firmly establish itself until the nineteenth century, partly because the use of heat actually broke the mechanistic horizon and the related culture dominant in the eighteenth century, but also because the great improvements in waterwheels delayed the adoption of this innovation.

2. New Tools and New Venues for the Elaboration of the Culture and the Tools of the Entrepreneurial Classes

Throughout the eighteenth century, universities were still not up to the task of elaborating tools or of creating a culture suitable to the productive innovations that were

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[4] Only after the mid-nineteenth century, under the impetus of the take-off of a second wave of industrialization and that of a renewed bourgeoisie, did the relationship between science and technology begin to overturn itself, due to the need for scientific concepts and methods capable of guiding the discovery of truly new phenomena or processes, and thus providing new technical innovations. See Section 12.

[5] In fact, it is significant that in the *Principia* (1687), Newton did not introduce or even consider concepts and laws related to energy, even when he had developed differential calculus and therefore had the mathematical tools to draw all possible implications from the laws of dynamics. He studied motion (the momentum mv), but not even Leibniz, who he opposed, gave an energetic meaning to vis viva (mv^2), which only at the end of the eighteenth century was actually "reinvented" as kinetic energy. However, it had a factor of ½, which is not a marginal accident but a fundamental factor in a radically new interpretation, as we shall see, obtaining $\frac{1}{2}mv^2$.

bursting onto the social scene. The academic culture was tied in substance to an Aristotelian tradition that was absolutely incapable of elaborating the new concepts that were becoming necessary (Scottish universities were partly an exception, see section 5.1). Even Newtonianism, which reflected the culture and mentality of the emerging commercial bourgeoisie, was not up to the needs of modern industry.

But during the eighteenth century in England, a large number of circles, which were often called "literary" circles—places of meeting, discussion, and comparison between a myriad of characters such as merchants, entrepreneurs, craftsmen, technicians, "engineers," and builders of machines and communication routes—flourished spontaneously. Many entrepreneurs had in some empirical way (but with ingenuity stemming from their resourcefulness) created a process or a new product, or perfected one already in existence. On this basis, they invested their savings to develop a factory. Quotation marks are here used to denote a change of meaning over time: The "literary" circles only occasionally dealt with literary matters (any relevant issue was called literary). They were instead meeting places of various types that periodically gathered wide audiences (often in the house of one of the participants) to discuss current issues, political events, philosophical issues, technical problems, new inventions, the solution of concrete problems, and so on. They did not use the term "science" but spoke of "natural philosophy." What we now call "techniques" were usually called "arts." There were no "engineers" in the modern sense of the term (the first academic school of engineering will be created by the French Revolution); the English "technicians" of that time had a practical training, even if they were often aware of the advanced scientific progress, and not infrequently brought original contributions of great importance (we will specifically see the cases of John Smeaton and James Watt): often the distinction between "technician" and "craftsman" was only a matter of skill or genius.

One must insist on the accumulation of new phenomena and processes, of new points of view, of different ways of considering phenomena, of brilliant intuitions, of new roads to be taken, of old roads abandoned, of fertile conceptions that were unthinkable before, which were born from the fruitful interaction of craftsmen, entrepreneurs, builders, and technicians within the world of production and economic initiative. In this context, not only the picture of natural phenomena was radically modified, but also the very way of conceiving, facing, and developing them.

Literary and philosophical societies arose almost everywhere in the most active and vital centers; they were attended by the most prominent figures of the time, the protagonists of cultural and technical events. The most famous was perhaps the *Lunar Society* founded in Birmingham in 1765, which met monthly in the home of one of its members (who offered dinner and libations) in the evening closest to the full moon (hence the name) in order to facilitate the return of the participants at night after the meeting. Among the most famous members were the entrepreneur Matthew Boulton (who was its soul and regular host), James Watt, Erasmus Darwin (grandfather of Charles Darwin), the entrepreneur Josiah Wedgwood (initiator of the famous English house of ceramics, and another grandfather of Charles Darwin), and the chemist Joseph Priestley. There were occasional attendees, including Americans Thomas Jefferson (who was later the third president of the United States), Benjamin Franklin, Sir Richard Arkwright, and John Smeaton.

The *Manchester Literary and Philosophical Society*, founded in 1781, began regularly publishing *Memoirs and Proceedings* in 1783. Being the first scientific journal after the *Proceedings of the Royal Society*, it was later joined in 1793 by the *College of Arts and Crafts*, and in 1786 by the *Manchester Academy*, along with others. Other circles sprang up at Leeds (1783), Rotherham, Newcastle, Derby (1783), Leicester, Northampton, Exeter, etc.

In the second half of the eighteenth century, London was teeming with meetings that took place in private homes and gathered the most prominent personalities and distinguished scholars, such as Cavendish, Priestley, and Wollaston. But the importance of London faded as societies sprang up in the provinces.

There were also other means of disseminating scientific culture and innovations, such as the *Itinerant lecturers*—itinerant "scientists" who held public courses on topics mainly of "natural philosophy" and chemistry. Their preparation varied greatly, from the self-taught to those with academic training; they brought with them considerable experimental equipment with which they illustrated their lectures. Special courses were organized for those who were employed in industry and production: industrialists such as the steelmaker John Wilkinson followed these lessons. Itinerant scientists did not contribute directly to scientific discoveries, but they played an incalculable role in the spread of science. The concept of "hegemony" formulated by Antonio Gramsci in his *Prison Notebooks* seems appropriate to summarize this situation:

> the supremacy of a social group manifests itself in two ways, as 'domination' and as 'intellectual and moral leadership' [and] the 'normal' exercise of hegemony on the now classical terrain of the parliamentary regime is characterized by the combination of force and consent, which balance each other reciprocally, without force predominating excessively over consent. (Gramsci 1971, p. 215; original publ. Gramsci 1948–1951, p. 70)

3. The Formulation of Scientific Concepts of Work and Energy in the Environment of Technicians Engaged in the Factory System

Before the takeoff of the Industrial Revolution, there had been attempts and proposals both by scientists and technicians to define energy concepts in face of the problems posed by machines, but they remained rather confusing. The specific terms used were many, and it was not easy to distinguish them: power, impetus, *vis viva*, energy, moment of activity, motive force, and others. The inconsistent ideas are also evidenced by the search for perpetual motion.

The transition from manufacturing to the factory system involved the systematic use of energy sources capable of driving not only a single machine but an entire factory, and this posed the need to unambiguously define (in order to measure it) the modern *concept of (productive) work*, and to introduce the first considerations relating to *energy efficiency* (term first used much later), which bypassed in practical terms the diatribes on perpetual motion.

Part 2 – Energetic and Conceptual Innovations of "Practical Mechanics" in England

4. The Figure and the Role of John Smeaton

The figure of John Smeaton (1724–1792) stands out among all the others: an "engineer" who at the time had no academic title but followed a solid scientific tradition and approach. He was also a member of the Royal Society, where he read numerous memoirs on mechanics, scientific instruments, and even astronomy, which testifies to the variety of his interests. (For the first work that I will discuss, Smeaton also received the prestigious medal Sir Godfrey Copley.) He was the main figure in the first society of civil engineers founded in 1771, which after his death changed its name to the Smeatonian Society of Civil Engineers. His studies on waterwheels not only led to improvements that the engineer Farey later considered so crucial as to have slowed down the development of the steam engine (to which, however, Smeaton also gave a significant contribution [Stewart 2017], preceding Watt's fundamental invention), but they laid the foundations of modern hydraulic technology (i.e., water turbines, which succeeded the water wheels) and extended the concepts of Newton's mechanics.

Smeaton was highly original and the ingenious builder of the most varied technical works, including canals (fundamental communication routes at that time), lighthouses,[6] bridges over rivers,[7] seaports, and machinery commissioned by the captains of industry

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[6] I deem it significant to mention the construction of the Eddystone Lighthouse that took place between 1756 and 1759 in the English Channel, built on top of a rock to signal its danger to navigation. The rock was small, so the work was carried out with great technical innovations from a moored boat, during a storm, with Smeaton risking his life (you can find illustrations by searching "Eddystone Lighthouse" on a search engine). Sometime in the period between 1807 and 1810, the Eddystone Lighthouse inspired the Scottish engineer Robert Stevenson to undertake the even more adventurous construction of the Bell Rock Lighthouse on a rock at the water's edge that emerged only at low tide, about eighteen kilometers from the mainland, and which for centuries had threatened the ships heading towards the inlet of Edinburgh, causing an unspeakable number of shipwrecks and victims. The Bell Rock Lighthouse included genuine technological innovations such as the then pioneering use of hydraulic cement and a system of mortises and dovetail tenons to connect the tower's granite blocks. Stevenson made a considerable number of technical improvements and devices, including the use of red and white flashing position lights. See (Strachan 2018): "Stevenson drew the inspiration for his lighthouse design from Eddystone Lighthouse ... Built 50 years earlier by John Smeaton, this was a milestone in lighthouse design. ... it was the only off-shore structure that had until then managed to survive for any length of time against the constant battering of the seas." For more interesting details, see Spencer, Christopher. 2011.*Who Built the Bell Rock Lighthouse*? History. Available at https://www.bbc.co.uk/history/british/empire_seapower/bell_rock_01.shtml.

[7] The technique for building pylons or bridge foundations over flowing water was not simple (yet the grandiose bridges built by the Romans still stand), but it had many improvements over time. One technique was to place wooden piles on the riverbed and then fill the interior volume with stones. Smeaton introduced the modern cement technique. In fact, in rudimentary forms, cement had been used since 3,000 B.C. by the Egyptians, the Chinese, and the Greeks. In the third century B.C., the Romans discovered that mixing volcanic ash with lime and sand produced a substance as hard as stone (*pozzolana*), similar to today's cement, and began using it in large buildings. But after the fall of the Roman Empire this knowledge was lost, and mainly stone buildings were built. Smeaton, in his search for a water-resistant building material, rediscovered a form

(Skempton 1971).[8] Around 1749, Roebuck—an entrepreneur of multiple pursuits who would also become the first partner and financier of Watt—commissioned to Smeaton hydraulic bellows, which were set in motion by a waterwheel. During those years, Smeaton performed rigorous experiments and quantitative measurements. Waterwheels had been in use since ancient times, but they were built with craftsmanship criteria and there were no precise ideas about how they worked. In fact, the most common and simple type was the *undershot* wheel, which was operated by a flow of running water under it that transmitted the motion to the blades. Only in cases where there was a natural waterfall were *overshot* wheels built, operated by falling water, or even by water flowing at a wheel's intermediate height (*breastshot* wheels). *In 1759, Smeaton's crucial experiments reached the extremely important conclusion that overshot wheels could produce an effect double of that produced by undershot wheels*. It is evident that this conclusion involved comparing different modes of action of mechanical energy.

4.1. Smeaton: The Modern Concepts of Work and Energy and their Social Significance

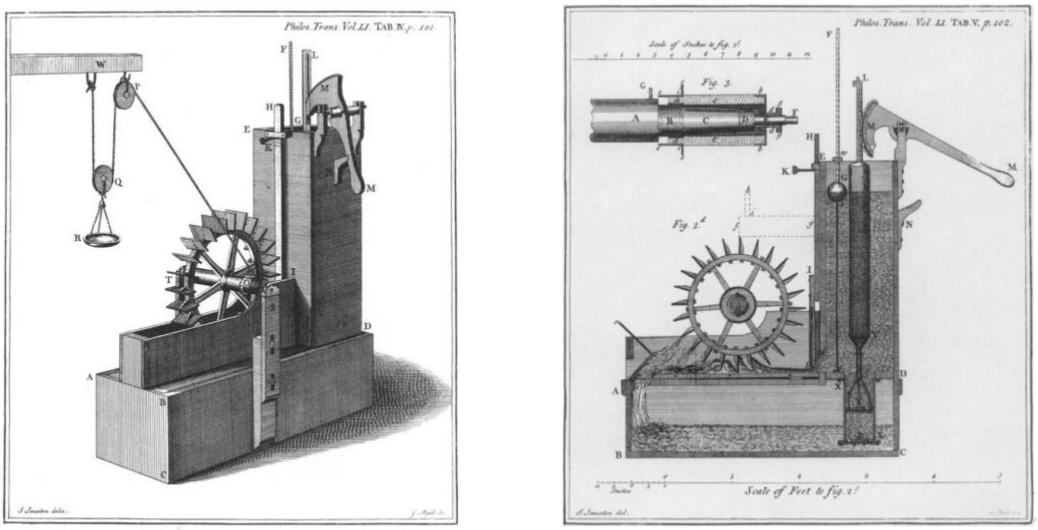

Fig. 1: Smeaton's waterwheel model (Smeaton 1759)

For his fundamental 1759 study of waterwheels (which includes a section on windmills that will not be addressed here), Smeaton built a scale model that was about one meter tall, on which he made rigorous measurements of the water flowing through it and the

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of cement in 1774, which he further improved (see for example "The History of Concrete" at http://www.concretecontractor.com/concrete-history/).

A recent article (Seymour et al. 2023) reveals that Roman concrete has "self-healing" properties that have helped it last for millennia. Researchers analyzed 2,000-year-old Roman concrete samples and found lime deposits in ancient Roman mortars: when the cement gets wet, these deposits can dissolve, filling cracks and strengthening the structure. The researchers produced their own version of Roman concrete and found that cracks in it "healed" within two weeks while those in modern concrete did not.

[8] To get an idea of the breadth and variety of Smeaton's interests and activities, see (Smeaton 2013).

effect it produced. I have used the term *effect* precisely to understand the problem that he was, in a sense, *induced* to solve by his work as a manufacturer of machines for use in industry. How was this *effect* to be precisely measured? I would say that it was natural for him (“*I shall be obliged*”) to connect weights by means of a rope through a pulley, and thus measure the *effect* of the wheel under different conditions. Here are Smeaton’s clear words, which would not be out of place in a modern physics textbook:

> as I shall be obliged to make use of a term which has hitheretofore been the cause of disputation, I think it necessary to assign the sense in which I would be understood to use it; and in which I apprehend it tis used by practical *Mechanicks*.
>
> The word *Power*, as used in practical mechanicks, I apprehend to signify the exertion of strength, gravitation, impulse, or pressure, so as to produce motion: and by means of force, gravitation, impulse, or pressure, compounded with motion, to be capable of producing an effect: and that no effect is properly mechanical, but what requires such a kind of power to produce it.
>
> The raising of a weight, relative to the height to which it can be raised in a given time, is the most proper measure of power; or, in other words, if the weight raised is multiplied by the height to which it can be raised in a given time, the product is the measure of the power raising it; and consequently, all those powers are equal, whose product, made by such multiplication, are equal: for if a power can raise twice the weight at the same height; or the same weight to twice the height, in the same time that another power can, the first power is double the second: and if a power can raise half the weight to double the height; or double the weight to a half the height, in the same time that another can, those two powers are equal. (Smeaton 1759, 105–6)

I will not dwell on all aspects that Smeaton discusses because here I would like to focus on the historical development of the concepts, with a purpose that I can define as didactic.[9] Two observations are relevant from my point of view: Smeaton’s precise definition is equivalent to a formula (which he clearly does not write down, as in all his works on “practical mechanics” there are no formal formulas)

$$\text{Power} = \text{weight lifted} \times \text{height} / \text{time} = \text{Work} / \text{time}$$

which is the modern formula found in physics textbooks. It must be noted that it is not enough that the force acts (like a weight resting on a surface), but that it produces a displacement, transforming matter. The combination of both factors produces something; it produces a good: if it does so in a shorter time, it produces a greater good. The mentality is new: force must produce something to be useful.

In fact, Smeaton, involved as he was in creating machines to increase the production of goods (or to put frames in motion), defines a specific type of work—***productive work***—as that which is suitable for producing goods or value to be exchanged. I find it significant that this definition is commonly adopted by physics textbooks, given that it excludes

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[9] See (Morris 2017) for a more specific discussion.

many other forms of energy consumption or of "fatigue," such as the so-called passive or physiological work. Every living being performs work and expends energy in all its activities (even when sleeping), but those that were (and remain) quantified in the era of capitalism are only those exercised to produce goods and value. It is only this "productive" work that is renumerated, certainly not the work (to give one of an infinity of examples) that women do in housekeeping or washing clothes, or the *reproductive work* that is essential for the sustenance and reproduction of the workforce. Here is a primitive expropriation, fundamental to the *original accumulation*, which recognized and remunerated only productive work! For Marx, "the so-called original accumulation is nothing more than the historical process of separation of the producer from the means of production." *The formulation of the scientific concept reflects this ideological choice. This selection, the concealment of all work that does not produce exchange value and is not remunerated, has stamped a class mark on the choices and concepts of modern science, concealing this origin in formalism.* Of course, a modern physics course later develops these aspects, as if they were abstract, in the thermodynamics part.

Smeaton unequivocally enunciates the aim of his research:

> In comparing the effects produced by waterwheels, with the powers producing them; or, in other words, to know what part of the original power is necessarily lost in the application, we must previously know how much of the power is spent in overcoming the friction of the machinery, and the resistance of the air; also what is the real velocity of the water at the instant that it strikes the wheel; and the real quantity of water expended in a given time.[10]
>
> the proportion of the two products[11] will be the proportion of the power to the effect[12]: so that by loading the wheel with different weights successively, we shall be able to determine at what particular load, and velocity of the wheel, the effect is a maximum (Smeaton 1759, 106–7).

For this purpose, he measures the *effect* produced by the wheel by varying all the parameters (i.e., water flow, load) and collects the results in a table. This method of experimenting on scale models later became a standard approach in the field of engineering. Smeaton, in his constant endeavors as a builder, took care to verify the applicability of his conclusions on real machines.

4.2. The First Substantial Distinction between the Different Forms of Energy[13]

In the third part of his work, Smeaton deals specifically with the study of overshot wheels. Here he is forced to compare the action of pressure by the flowing water on the

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[10] This corresponds to the modern concept of efficiency of a thermal engine: W/Q_{abs}.

[11] The weight of water and the weight raised by it, multiplied by the height to which it is raised in a given time.

[12] The modern concept of efficiency.

[13] See footnote 8.

blades of the wheel with the action water performs when it falls from above and hits the blades. These are actions that no general principle already established at the time made them possible to compare, so that Smeaton was led to base his work on considerations that opened the way to comparisons between different kinds of energy (kinetic or potential energy) and to the concept of the conservation of mechanical energy (which, it should be stressed, Newton denied[14]). I must be very clear, I do not claim that Smeaton introduced the modern notions of *(mechanical) potential, kinetic, and total energy*, least of all their formal expressions. I want to show that he conceptually and correctly clarified the distinction, and the equivalence, between them (Section 8 examines who formalized them and how). The following passage also seems an effective illustration of the *process of scientific abstraction* ("reasoning without experiment") and its power:

> In the former part of this essay, we have considered the impulse of a confined stream, acting on *Undershot Wheels*. We now proceed to examine the power and application of water, when acting by its *gravity* on *Overshot Wheels*.
>
> In reasoning without experiment, one might be led to imagine, that however different the mode of application is; yet that whenever the same quantity of water descends thro' the same perpendicular space, that *the natural effective power would be equal* [author's emphasis]; supposing the machinery free from friction, equally calculated to receive the full effect of the power, and to make the most of it: for if we suppose the height of a column of water to be 30 inches, and resting upon a base of aperture of one inch square; every cubic inch of water that departs therefrom will acquire the same velocity or *momentum*, from the uniform pressure of 30 cubic inches above it, that one cubic inch let fall from the top will acquire in falling down to the level of the aperture; *viz.* such a velocity as in contrary direction would carry it to the level from whence it fell; one would therefore suppose, that a cubic inch of water, let fall thro' a space of 30 inches, and there impinging upon another body, would be capable of producing an equal effect by collision, as if the same cubic inch had descended thro' the same space with slower motion, and produced its effects gradually: for in both cases gravity acts upon an equal quantity of matter, thro' an equal space; and consequently, that whatever was the ratio between the power and effect in undershot wheels, the same would obtain in overshot, and indeed in all others: yet, however conclusive this reasoning may seem, it will appear, in the course of the following deductions, that the effect of gravity of descending bodies is very

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[14] Newton even denied that any law of conservation of a mechanical quantity could apply; this law is instead a fundamental consequence of modern mechanics (and, I insist, Newton had all the mathematical tools to derive it, if he had conceived of it!):

> Bodies which are either absolutely hard, or so soft as to be void of Elasticity, will not rebound from one another. ... Seeing therefore the variety of Motion which we find in the World is always decreasing, there is a necessity of conserving and recruiting it by active Principles.
>
> For from the various Composition of two Motions, 'tis very certain that there is not always the same quantity of Motion in the World. (Newton 1718)

> different from the effect of the stroke of such as are *non-elastic*, tho' generated by an equal mechanical power. (Smeaton 1759, 124–125)

This is a clear recognition of the *equivalence of work, kinetic, and potential energy*. It should be noted that the superiority that Smeaton attributes to overshot wheels with respect to undershot ones is conceptually attributed to the fact that overshot wheels are driven by the weight of the water, by gravity; and that *the loss of "mechanical power" due to the deformation that the flow of water undergoes upon the inelastic impact with the blades can be reduced to a minimum*. In the following, we will see the decisive importance that this criterion will have (and will be explicitly stated) in Sadi Carnot's 1824 paper on the theory of heat engines (Section 10).

4.3. A Concept that Will Inform the Entire Development of Capitalism: Efficiency, the Symbol of Modernity

Thus, Smeaton comes to perhaps the most important conclusion of his research from a practical, conceptual, and methodological point of view (italics are of Smeaton):

> *the effect therefore of overshot wheels, under the same circumstances of quantity and fall, is at a medium double to that of the undershot*: and, as a consequence thereof, *that nonelastic bodies, when acting by their impulse of collision, communicate only a part of their original power*; the other part being spent in changing their figure in consequence of the stroke. (Smeaton 1759, 130)

This conclusion deserves several observations. First of all, on a practical level, Smeaton's conclusions and many technical improvements were fully acknowledged and adopted, making waterwheels an efficient and widely used motor in English industry,[15] which solved the first energy bottleneck in the development of capitalism. The technique introduced by Smeaton of using gravity to drive waterwheels led to the disappearance of undershot wheels in England, as hydraulic engineer Peter Ewart (1767–1842) noted in 1808:

> although undershot wheels were the most common about fifty years ago, they are now rarely encountered, and when economy of power is an objective, no new ones are built. (Reynolds 1983, 282; quote from Peter Ewart)

The efficiency of waterwheels increased to such an extent that it slowed down the spread of the new motor, the steam engine, which we will examine later.

A second important observation on Smeaton's former quote is that it contains a *fundamental prescription for maximizing the efficiency of waterwheels*. Since he correctly asserts that, due to inelastic impact, the falling water does not transfer all its power to the wheel, it follows that *to maximize the efficiency of the machine, the impact of the water on the blades must be avoided as much as possible, or at least minimized*: It is

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[15] See (Reynolds 1983). Quick information can be found in Wikipedia's "Water wheel" entry; it also contains extensive historical details.

therefore necessary to *minimize the vertical difference in height that the water travels in free fall* (namely, to minimize the impact, in order to ensure that *the water arrives on the blades with the smallest possible difference in speed with respect to them*). It is also required *that it leaves the blades with the smallest height difference with respect to the lower level*, which would be a fraction of unused potential energy. These criteria will become, appropriately formulated, the general basic principles of modern hydraulic technology (turbines, the successors of waterwheels).[16]

Here, a general remark is necessary: Smeaton introduces (even if he does not formalize it and does not give it the modern name) a concept, a criterion that will inform the whole development of capitalist society, and the very mentality and culture of Western society, that of ***efficiency.***[17] This concept has acquired increasingly broader meanings, becoming *the key concept of modernity*, informing all activities whether productive, economic, managerial, professional, or even personal: here lies its origin at the dawn of industrial society. In essence, *the contributions of engineers and scientists during the First Industrial Revolution introduced into science and technology the basic concept that has come to dominate the logic and substance of capitalist production. In concrete terms, not all the energy contained in a physical system is available for the process of valorization of goods: a part of energy must necessarily be "lost"— in reality "degraded" to a form that is no longer useful to be exploited in the process— if another higher "quality" part is to be made materially valorized in the process*. This basic criterion was introduced by John Smeaton in hydraulic technology, but strictly speaking it crossed the boundary of mechanics into thermodynamics. Smeaton's legacy would be continued by James Watt (directly using Smeaton's criterion) and pivoted towards heat engines. Later, Sadi Carnot—in developing the concept of entropy—would also continue Smeaton's legacy by inaugurating the integral adaptation of thermodynamics into the logic of capitalist valorization.

4.4. Smeaton's Further Experiments and Results on the Fundamental Laws of Mechanics

A study on Smeaton's work would not be complete without briefly mentioning his further conceptual contributions that in some way completed the formulation of the laws of mechanics, integrating the concepts introduced by Newton. They were two experimental research endeavors in fundamental physics, occurring in 1776 and 1782 respectively (both of which he communicated to the Royal Society). The two experiments were performed with the usual rigor, and even if they did not culminate in mathematical formalization, Smeaton's previous research and conclusions were innovative nonetheless.

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[16] In fact, the two fundamental aphorisms of modern water turbine technology are: water entering the turbine without shock, and water leaving at the lowest possible speed.

[17] See (Alexander 2008). This book extensively discusses the fundamental and ever more extensive role that the concept of efficiency has had in capitalist society. It starts precisely from Smeaton's work and discusses successive cases up to the present day, examining how efficiency has become the key concept of modernity.

As already mentioned, Newton had considered the physical quantity *mv*—which we nowadays call momentum or impulse—instead of the *vis viva*, denoted by mv^2. The contrast between the two concepts later generated fierce disputes and misunderstandings (Koyré 1968). With his experiments, Smeaton made it clear that both concepts of work and momentum could be used to study motion, provided that the "appropriate collateral circumstances" (space, or time) were taken into account. In fact, the two concepts respond to distinct physical problems:

> This then appears to be the foundation, not only of the disputes that have arisen, but of the mistakes that have been made, in the application of the different definitions of quantity of motion; that while those, that have adhered to the definition of Sir Isaac Newton, have complained on their adversaries, in not considering the time in which the effects are produced, they themselves have not always taken into the account the space that the impelling power is obliged to travel through, in producing the different degrees of velocity. It seems, therefore, that, without taking in the collateral circumstances both of time and space, the terms, quantity of motion, *momentum*, and force of bodies in motion, are absolutely indefinite; and that they cannot be so easily, definitely, and fundamentally compared, as by having recourse to the common measure, *viz.* mechanic power. (Smeaton 1776, 473)

In essence, Smeaton, with his simple but ingenious experimental apparatus and accurate measurements, demonstrated (if we express his results in modern terms) that the variation of the momentum *mv* (which Newton had considered) of a body is proportional to the interval of *time* in which the force acts, while the work $F{\cdot}s$ that the force performs in *displacing* the body is related to the square of the velocity that the body acquires.[18] (For kinetic energy, a concept not yet defined at the time, the factor ½ makes a substantial difference to the *vis viva* that Leibniz had assumed.) *Time and space are the two "collateral terms" that distinguish the respective effects of the action of force*.

In 1782, Smeaton carried out one further experiment, skillfully simulating the collision of non-elastic bodies in order to demonstrate that the "lost" power is stored in the deformation of the bodies, but he obviously did not possess the notion of energy dissipation, which was to be introduced by Joule in the 1740s (Section 11.a).

This discussion of John Smeaton's innovations during the take-off phase of the First Industrial Revolution should have clarified my interpretation of the entrenchment of scientific concepts—specifically of work-power and energy—in the social composition of England at that time. I would like to remark, in support of my interpretation, that Smeaton's name is not usually mentioned in treatises on the history of physics, thus obscuring the originality of his contributions even to fundamental science. James Watt, to whom I will now turn, is also at most mentioned as a "technician," an ingenuous machine

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[18] Formally, in the modern language of physics: $F{\cdot}\Delta t = m{\cdot}\Delta v$, while $F{\cdot}\Delta s = \frac{1}{2}m{\cdot}\Delta v^2$. Or, $F{\cdot}\Delta s = \Delta(\frac{1}{2}m{\cdot}v^2)$.

builder, whereas I will emphasize the originality and importance of his research and results for the foundations of the Second Law of Thermodynamics.

5. The Decisive Breakthrough for the Steam Engine: Watt's Separate Condenser. A Premise of the Second Law of Thermodynamics

One usually talks of "steam engines," but when it comes to its early iterations it would be more appropriate to speak of "atmospheric machines" because the active work was performed by atmospheric pressure, with the condensation of steam providing the vacuum (or better, the low pressure) that allowed the atmospheric pressure to act and generate the work. Schematically, the first invention that exploited the combustion of coal dates back to 1698, when Thomas Savery (1650–1715) patented a pump for draining water from the bottom of mines, a machine triggered by the condensation of steam. The name under which he patented it is significant: "The miner's friend." Incongruously, the use of Savery's engine could be dangerous due to the difficulty at that time of making vessels resistant to relatively high pressures (high-pressure machines would not be produced until the nineteenth century). Regardless, its main drawback was the need to alternate between heating and cooling the same vessel: this recognition was to eventually become James Watt's breakthrough.

The first machine to work with the reciprocating motion of a piston was built in 1712 by Thomas Newcomen (1664–1729), a blacksmith who was clearly not unfamiliar with the technical innovations of the time, as was the case for many craftsmen. Newcomen's machine was precisely more an "atmospheric machine" than a true steam engine since—after the steam had raised the piston in the cylinder—a jet of water was pumped into it to cool it down, generating a lowering of pressure that allowed the atmospheric pressure to lower the piston, thus activating a rocker arm that at the opposite end raised the rod pump and drained the mine shaft. Although its efficiency was derisory, the Newcomen's engine became popular, even when its operation was erratic and unsuitable for driving frames or production machinery: the problem was conceptually the same as Savery's machine.

5.1. The Exception of Scottish Universities: The Scottish Enlightenment

James Watt (1736–1819) found employment in 1756 at Glasgow University as a maker of precision scientific instruments. He became acquainted with many scientists, in particular the chemist Joseph Black (1728–1799), with whom he collaborated on various experiments in calorimetry and chemistry.

It must be said that Scottish universities (Glasgow, Edinburgh, St Andrews, and Aberdeen—whereas at that time the only universities in England were Oxford and Cambridge) experienced a peculiar intellectual flowering during the eighteenth century that is known as the "Scottish Enlightenment," characterized by a great cultural openness in all fields, which was a hotbed of innovative ideas. Key figures of the time include David Hume and Adam Smith.

Edinburgh and Glasgow also had philosophical and chemical societies and academies independent of the universities (Section 2), and the universities themselves were more rapidly transformed than those in England when comparing their levels of openness and modernity. Edinburgh saw the birth of the first edition of the prestigious *Encyclopaedia Britannica* in 1768, and from mid-century on, the Edinburgh Medical School was the leading center of medicine in Europe. At Glasgow University, many new chairs were established, including Medicine (1716), Anatomy (1718), Natural Philosophy (1727), and Astronomy (1760). Because of the newly-established Chair of Medicine—and through the work of William Cullen and Joseph Black—there was an increased interest in chemistry and its industrial applications. Some lecturers began to teach in English rather than in Latin, and evening classes were opened up to all. Adam Smith changed the teaching of Moral Philosophy to Political Economy. The creation of the Chair of Natural Philosophy led to the introduction of new tools into the university.

5.2. James Watt, the Inventor of the Separate Condenser

James Watt, like so many others we have discussed, was a refined technician with not only a wide range of interests related to the crucial problems of those decades, but also with scientific knowledge and experience. In 1768, he collaborated on the Forth and Clyde Canal project, which was a crucial project to link the Irish Sea with the North Sea. In Glasgow, he collaborated on chemistry research with Joseph Black, and he studied the composition of water at the same time as Cavendish and Priestley.

In 1763, Watt was commissioned by the University to repair a small model of Newcomen's engine, which was owned by the University and was used for demonstrations to students (note this aspect of modernity) but frequently jammed. Watt was prompted to study the workings of the engine in depth and perform quantitative measurements[19] (we could say that compared to Smeaton, he found the scale model already made).

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[19] To get an idea of how imprecise and confusing the ideas about steam engines were at the time, I provide the example of physicist John Theophilus Desaguliers, who in 1734 reported the empirical criterion adopted by Newcomen to assess the "strength" of and measure the machines he built:

> he removes the last digit from the square of the diameter [of the piston] and calls the digits remaining on the left quintals. Then writing a zero on the right, he calls the number on this side pounds. ... N.B. This gives between 11 and 12 pounds on each square inch of surface. Then he takes between ⅓ and ¼ for the loss which is occasioned by friction between the different peers and by other inconveniences. (Desaguliers, J. T. 1744. *Cours de physique experimentale*, Paris. Vol. 2, p. 565)

In 1721, the engineer Henry Beighton (1686–1754), an able builder of waterwheels and Newcomen machines, who was also published in the Transaction of the Royal Society, carried out experiments on Newcomen's engine, the results of which he collected in a table that correlated the size of the pump with the depth from which it drew in meters, in order to estimate the amount of water raised in a unit of time.

Watt attributed the malfunction of the model to the loss of heat through the walls of the cylinder, whose surface-to-volume ratio was much greater than in ordinary large machines. Through a series of tests, he realized that the main challenge was to keep the cylinder into which the steam expanded as hot as possible, so that the steam entering would not partly condense on the cold cylinder walls. By measuring the volume of steam obtained from a known quantity of water, Watt realized that the steam consumed by the machine was at each stroke about four times the volume of the cylinder, but that the amount of water after condensation was much less than the quantity of water required in practice: he discussed this problem with Black, who developed the concept of latent heat (Fleming 1952).

With further experiments, Watt realized that by condensing the steam in the cylinder with as little water as possible, the resulting condensed water retained a relatively high temperature, and therefore residual steam remained under the piston at a fairly high temperature, which impeded the piston's descent. He was therefore faced with two seemingly irreconcilable needs: having the cylinder as hot as possible to exploit the full expansive power of the steam, and having the cylinder as cold as possible to optimize condensation. It was clear to him that the malfunctioning of Newcomen's engine was due to the thermal inertia of the cylinder, which had to heat up and cool down in each cycle, in this way cooling the incoming steam (i.e., reducing its pressure) and then limiting the subsequent condensation (i.e., retaining a residual pressure). As Watt himself relates:

> I had gone to take a walk on a fine Sabbath afternoon. I had entered the Green by the gate at the foot of Charlotte street, and had passed the old washinghouse. I was thinking upon the engine at the time, and had gone as far as the herd's house, when the idea came into my mind that, as steam was an elastic body, it would rush into a vacuum, and, if a communication were made between the cylinder and an exhausted vessel, it would rush into it, and might be there condensed without cooling the cylinder. I then saw that I must get rid of the condensed steam and injection water if I used a jet, as in Newcomen's engine. Two ways of doing this occurred to me: First, the water might be run off by a descending pipe, if an offlet could be got at the depth of 35 or 36 feet, and any air might be extracted by a small pump. The second was, to make the pump large enough to extract both water and air. I had not walked farther than the Golf house, when the whole thing was arranged in my mind. (Hart, 1859)

This description clearly relates the early recognition of the need for two heat sources at different temperatures in a steam engine, which will play part in the future statement of the Second Law of Thermodynamics. This acknowledgment led Watt to the historic 1769 patent for the separate condenser, which laid the cornerstone for the steam engine to

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As already mentioned, in 1772 Smeaton also built a large Newcomen engine with technical improvements that gave it a performance that he considered exemplary (from his data an efficiency of only 1% is inferred), but without questioning its essential foundations, as Watt did.

become the modern engine for the Industrial Revolution. I quote the fundamental passages:[20]

> My method of lessening the consumption of steam, and consequently fuel, in fire engines, consists of the following principles:
>
> First, that vessell in which the powers of steam are to be employed to work the engine, which is called the cylinder in common fire engines, and which I call the steam vessell, must during the whole time the engine is at work be kept as hot as the steam that enters it, first, by enclosing it in a case of wood or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and, thirdly, by suffering neither water or any other substances colder than the steam to enter or touch it during that time.
>
> Secondly, in engines that are to be worked wholly or partially by condensation of steam, the steam is to be condensed in vessells distinct from the steam vessells or cylinder, although occasionally communicating with them. These vessells I call condensers, and whilst the engines are working, these condensers ought at least to be kept as cold as the air in the neighbourhood of the engines, by application of water or other cold bodies.
>
> Thirdly, whatever air or other elastic vapour is not condensed by the cold of the condenser, and may impede the working of the engine, is to be drawn out of the steam vessells or condensers by means of pumps wrought by the engines themselves, or otherwise.
>
> Fourthly, I intend in many cases to employ the expansive force of steam to press on the pistons, or whatever may be used instead of them, in the same manner as the pressure of the atmosphere is now employed in common fire engines. In cases where cold water cannot be had in plenty, the engines may be wrought by this force of steam only, by discharging the steam into the open air after it has done its office. (Watt 1769)

Similarly to what I have observed for the concept of productive work, the embryo of the Second Law of Thermodynamics emerged because of the problem posed by the Industrial Revolution of making the steam engine a reliable and efficient motor to move the looms and machinery of the nascent industry. It is also interesting to note that what we know as the “First” Law of Thermodynamics would not see the light of day until long after the “Second” Principle (Section 11), because its practical values were not so immediate.

A few comments on Watt’s patent will follow. The first two “principles” that it enunciates correspond to the recognition of the need to have two different temperatures to power the machine, one to be kept as high as possible and the other as low as possible (this will be the first part of Kelvin’s enunciation of the second law of thermodynamics of 1851). In

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[20] The full text of Watt’s patent can be found at: https://commons.wikimedia.org/wiki/File:James_Watt_Patent_1769_No_913.pdf.

1782, Watt’s fourth “principle” led him to create and patent the “double-acting” engine, in which the inside of the cylinder never came into contact with the outside air. The cylinder had two valves: one below and the other above the piston. The steam entered alternately at the bottom and at the top, expanding and compressing the piston with its pressure (therefore Watt’s engine was a true “steam” engine, while Newcomen’s was properly an “atmospheric engine”), and the steam also entered a jacket that wrapped around the outside of the cylinder to keep it at the same temperature as the steam.

Watt also introduced the “expansion principle” in order to save steam and therefore fuel (i.e., increase efficiency): this consisted in introducing steam only at the beginning of the stroke and then letting the piston act on its expansive force.

I will not enter into details about these developments, which are easily found in numerous articles, because the purpose of my reconstruction is to link the fundamental scientific and technical discoveries to the socioeconomic incentives that inspired them.

5.3. Watt’s Subsequent Work

Watt also represented the first truly significant historical case of combining technical skills with business acumen. Lacking the capital to build the engine on a commercial scale, he turned, with the aid of Black, to the industrialist John Roebuck—who became his partner and financier (it was Roebuck who advised him to apply for the 1769 patent). And when Roebuck went bankrupt in 1763, he was succeeded in the company by Matthew Boulton, another businessman who owned factories in Soho, near Birmingham. This prompted Watt to apply to Parliament for a patent extension until 1800. Watt then moved to Boulton’s factory, and set about developing his invention. The company of Boulton & Watt was astonishingly modern, Boulton provided the capital and Watt his technical skills: the factory included a laboratory (reconstructed in the Science Museum in London), where employees and other of Watt’s pupils and assistants worked together to study and produce new innovations, also taking care of the commercial aspects. This collaboration worked perfectly, stimulating inventiveness.

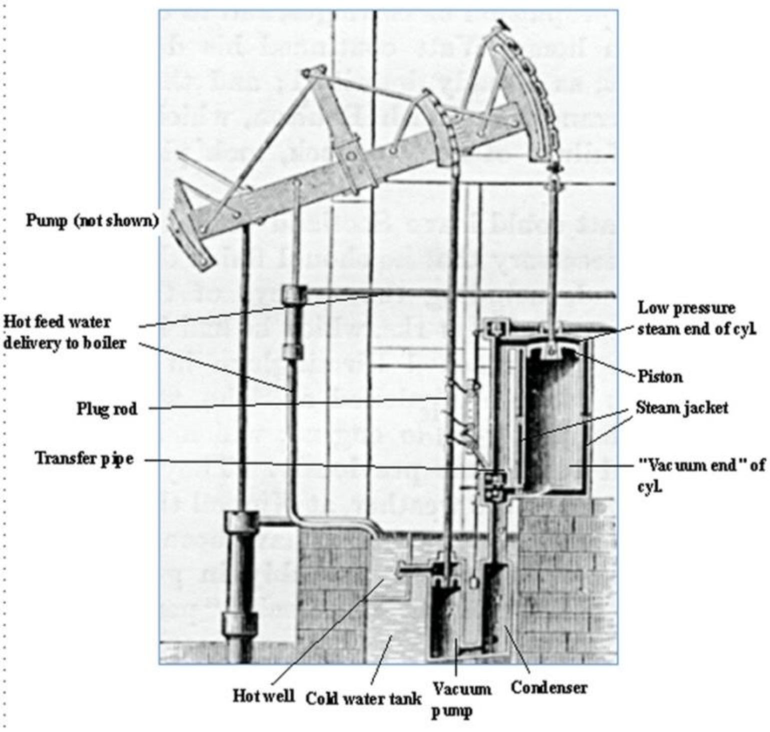

Fig. 2: A schematic of Watt’s steam engine printed in an 1878 book.

In fact, many other innovations and inventions were introduced by Watt and co-workers, which greatly improved the efficiency of steam engines. The first fundamental improvement was the double-acting steam engine. This made another technical innovation possible: Watt realized that if the machine was not used as a pump, but applied directly to move frames, the efficiency would be much higher. A technical problem arose in this respect, since in 1780 J. Pickard had already patented the modern rod-crank system, so Watt was forced to devise a different method of transforming the reciprocating motion of the piston into rotary motion. In 1881, he patented the so-called "sun and planet" system (suggested by his employee William Murdoch). Watt put it into practice in 1784 with his well-known "parallelogram," which he considered to be his inventive masterpiece.

In 1787, Watt introduced the centrifugal force regulator already used in windmills (known as Watt's governor), a device that automatically maintained the rotary speed of the engine within reasonably close limits regardless of the load (one of the early feedback mechanisms applied to energy technology). Two heavy balls were fixed to swing around an upright rod: when the engine ran fast, the upright rod turned fast, and the balls swung out and so acted as to admit less steam; when the engine ran slowly, the rod turned slowly, and the balls swung down and let in more steam.

The following year he added the flywheel, a heavy wheel attached to the rotating shaft so as to smooth out delivery of power from an engine: the inertia of the flywheel opposes and moderates fluctuations in the speed of the engine and stores the excess energy for intermittent use.

After all of Watt's improvements, it is estimated that Boulton & Watt's engines used 75% less fuel than an equivalent Newcomen engine, that is, for the same power produced it consumed a quarter of the coal. It is also noteworthy that, with the awareness of this superiority, Boulton & Watt's company charged customers a fee, or license fee, based on the fuel they saved over competing machines, especially in districts where the cost of coal was higher (this can be seen as a precursor to modern leasing).

By 1800, the year in which the separate condenser patent expired, Boulton & Watt had built 496 machines, 38% of which were pumps and 62% of the rotary type (Hills 1989, 70).

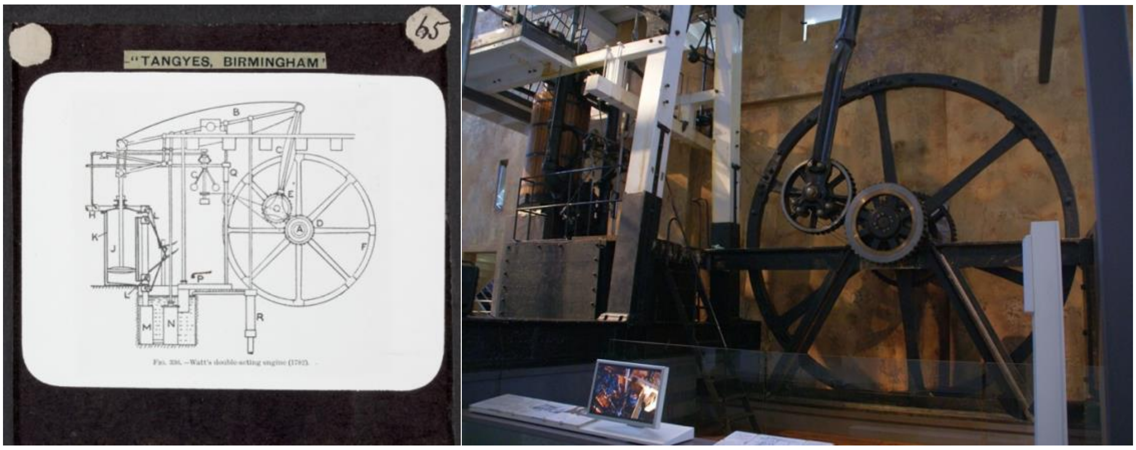

Fig. 3: Left: Cross-section diagram of Watt's rotative double-acting condensing steam engine. Birmingham, circa 1782: right: Boulton & Watt steam engine built in 1785 and decommissioned in 1887 - Powerhouse Museum. Wikimedia.

5.4. Watt's Engine Was Ahead of its Time!

Although Watt's engine was a great success—and its performance was undoubtedly much higher than that of Newcomen's engine—obstacles to its diffusion were considerable throughout the eighteenth century for a number of reasons, including conceptual ones. Ideas about heat, the performance of the various machines, their consumption, etc., were not agreed upon. On the one hand, Newcomen's engines continued to be used as pumps to lift water and run waterwheels. On the other hand, Boulton & Watt's machines were much more expensive and presented considerable technical and constructional difficulties: at that time, with mass production not yet established, the simplest components (which you might find in a hardware store today!) were manufactured specifically for these machines. Boulton & Watt found it difficult to find specialized technical staff in their various regions of operations and to organize the sale of their engines compared to some of their competitors.

The perfect fit of the piston with the cylinder, which was not so important in Newcomen's engines (although it was one of the causes of their irregular operation), was essential in Watt's engine: since there was no machine to ream cylinders of that exact diameter (the long, heavy reaming tool tended to tilt and slip during machining), the cylinder of the first engine was made of sheet metal hammered into a hardwood matrix and the gaps were filled with oil-soaked felt. Smeaton, who had built a simple machine in 1769, considered Watt's machine too difficult to build. In 1775, however, John Wilkinson (1728–1808)—perhaps one of the most celebrated metallurgists to be associated with the Industrial Revolution—built a new type of drill which allowed large cylinders to be reamed with reasonable accuracy.

Competition was also becoming fierce, developing both through adaptations of existing steam engines and the construction of "new" machines derived more or less directly from Watt's. Newcomen's engine, with relatively minor modifications, remained surprisingly popular.[21] Competing engines, even though they consumed more fuel, were much cheaper and could be erected more easily and safely. There were also many attempts to build different steam engines, sometimes with ingenious ideas, although in reality they were pirated machines that tried to use the principles of Watt's by circumventing his patent. Many other models of steam engines were proposed and often tested in different ways and shapes, including steam wheels (forerunners of the future turbines) which, however, could not operate with low-pressure steam. Watt himself patented a rotating model in 1782 but did not realize it (Cardwell 1971; Cardwell 1965).

5.5. A Short Account of Later Developments of the Steam Engine

Watt's separate condenser made the steam engine the key driving force behind the developments of the Industrial Revolution in the nineteenth century. Once Watt's patent expired in 1800 (and he gave up active work), other innovations hitherto blocked by the patent flowed abundantly (Selgin and Turner 2011). Watt's engines were immense devices which were suitable for operating industrial machinery but would never have permitted other modern applications.

The English engineer Richard Trevithick (1771–1833) devised and built an engine that could use high-pressure steam, thus it could be much smaller and more efficient (but he could not make them before Watt's patent expired). In 1801, he used it to build a steam wagon, which he called the "puffing devil," but it was immediately destroyed because of difficulties in driving it. In 1804, he built an 8km-long rail locomotive that he called "Catch Me Who Can" and later introduced other improvements which further increased the efficiency of his engines.

In 1825, George Stephenson (1781–1848) built the world's first steam-powered railway line: the Stockton and Darlington Railway. It was 13km-long and open to public transportation of passengers and goods; Stephenson inaugurated the line by driving his own locomotive. The first trains were pushed, not pulled, by the locomotive; furthermore, the locomotive was only used as an engine on flat or uphill stretches, while downhill stretches called for the use of inertial force.[22] This first locomotive was initially

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[21] J. Robison, in the entry "Steam engine" in the 3rd edition of the *Encyclopaedia Britannica* of 1797, pointed out the persistence of the use of even Savery's engine in various adaptations, thanks to the "few moving and rubbing parts." After 1780, Wrigley developed a particularly successful re-adaptation in which water was pumped over relatively small differences in height only by suction, thus not requiring high-pressure steam, and turning out to be simple and economical.

[22] In all vehicles kinetic energy is dissipated as heat when braking, but in electrically driven vehicles (trains, trams, subways) electric traction motors can be reused during braking as electric generators in what is commonly called electrodynamic braking. The advantages are especially significant in trains that have to make many close stops, with the consequent need for close acceleration and deceleration phases, or in downhill sections. On the London Underground, for example, the use of regenerative braking means that 20% of the energy used by the train can be returned to the grid. Today's rail vehicles are real power plants and as such have a high degree of energy recovery. On the downhill section from Bardonecchia to Turin, compared to a consumption for traction of about 600 kWh, 300 are recovered during braking and used by other passing trains, while 180 are dissipated in the form of heat by means of rheostats.

called *Active*, the final name was *Locomotion*. In the following decade, Stephenson participated in the construction of almost all English railway lines. In 1838 his son, Robert Stephenson (1803–1859), also participated in the *Leopolda* Railway project, requested by Leopold II of Lorraine to connect Florence to the port of Livorno.

6. The Transition to a New Horizon: From Mechanics to Thermodynamics: Watt, the Indicator Diagram, Precursor of Thermodynamic Work

The use of the steam engine to directly drive machinery posed a major problem. As long as the engine was used as a pump, the concept of mechanical power (as the product of the mass of water times the height in a unit of time) was sufficient to measure its effect. But if the engine was mounted directly on the looms, this concept was no longer applicable, and it was not known how to determine the frictional resistance of the drive shaft and the looms, especially with the constant innovations emerging in the textile industry. On the other hand, Watt relied on the fact that his engines were more economical in terms of coal than other machines but, since they were more expensive, he could not risk over- or under-dimensioning them and needed a rigorous method of determining the power output of his machine. As he wrote in a letter on March 19, 1790:

> We have built many machines for cotton mills, but the machines are so different in different places that we cannot give you instructions for power.

The very concept of "horsepower" (Hp) dates back to the early days of atmospheric machinery, attempting to express the power of machines in terms of the number of horses they could replace, although its determination was very uncertain (Cardwell 1971; Cardwell 1965). When the current use of the rotary machine made an unambiguous definition necessary, Watt set it at 33,000 pounds per foot per minute.

The problem of determining the power of the engine was solved in two stages. Around 1790, "indicators" or pressure valves were inserted into the engine, which recorded the pressure in the cylinder at each stroke. In practice, an attempt was made to determine the maximum and minimum pressure in the cylinder, whose difference gave an indication of the average pressure developed.[23] These indicator measurements were inevitably inaccurate because the pressure on the piston of the engine was far from constant during a shot. In 1796 Southern, an assistant of Watt's, perfected this method to record the pressure in the cylinder continuously by replacing the indicator needle with a pen that drew a vertical line of height proportional to the pressure in the cylinder on a sheet of paper, which moved back and forth horizontally and in synchrony with the rise and fall of

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[23] In a typical series of experiments, one would start with the steam engine running at full load and gradually decrease the load by disengaging the machinery until only the drive shaft and gears were driven. Hills and Pacey in the works cited above, by very carefully examining the data of the time, show how thermal engines did not operate at full load: even when they were built of 1 Hp per 100 spindles, it turns out that they sometimes operated at only half of that.

the piston, indicating therefore the volume under it. Watt and Southern soon realized that *the area within the curve of this indicator diagram was proportional to the work performed by the engine in one cycle*. The "indicator diagram" was used to regulate the opening and closing of valves in new engines, thus achieving better operation, for example with the aforementioned expansion principle. This made it possible to adapt the machines to the load. A *Story of the Steam Engine Indicator* reports that:

> Bolton and Watt … realized the tremendous competitive value of owning such an instrument and consequently kept the existence of the invention so secret that they did not even attempt to get a patent on it. It appears that the secrecy surrounding Watt's indicator outlived Watt by nearly a hundred years. As late as 1900, Cecil Peabody, in his book *Manual of the Steam Engine Indicator*, stated that the exact form of the original indicator was not known. (Babcock 2001)

One does not need advanced knowledge of physics to understand that *the indicator diagram was the first realization of the pressure-volume diagram in which thermodynamic transformations are represented and studied in the field of thermodynamics*. Of the *thermodynamic cycle* of heat engines: it was undoubtedly the first recognition that the area within the cycle is precisely (with the appropriate units of measurement) the ***thermodynamic work*** performed in a cycle.

I believe that this reconstruction provides concrete substance to the formal reasoning in physics textbooks on the dimensional equivalence of thermodynamic and mechanical work.[24] In my view, it also confirms *the decisive link between the introduction of new modern concepts in physics and the material stimuli that came to the technicians of the time as part of their involvement in the Industrial Revolution*. In this sense, I speak of a marker of the turnover of social classes on the introduction of innovative concepts and laws.

I like to think that it was Watt's curiosity in investigating the dynamical properties of water that led him to investigate and discover its chemical composition in 1783, even though Cavendish had discovered it beforehand but did not publish it until later.

Part 3 – France: Enlightenment, Rational Approach, Institutionalization, and Formalization of Energy Concepts

7. French Enlightenment, and the *Encyclopédie* of D'Alembert and Diderot

Parallel to the hitherto discussed processes and innovations were the numerous renewals taking place in the Sun King's absolutist France, albeit with profoundly different but prospectively no less important characteristics.

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[24] In formulas, from the definition of mechanical (productive) work $W = F \cdot s$, since the pressure is the force on the surface, $P = F/S$, one can formally write $W = F \cdot s = P \cdot S \cdot s = P \cdot \Delta V$.

Since the seventeenth century, cultural approaches in England and France had been moving in profoundly different directions—the former empiricist, the latter rationalist—corresponding to the development and progressive predominance of the new bourgeois class across the Channel, and to the persistence of monarchical absolutism and the power of the aristocracy on the continent. However, even under the *Ancien Régime*, various ministers made use of the sciences and men of science for the service of the state (Gillispie 2004): the Minister Daniel Trudaine de Montigny established the *École des ponts et chaussées in 1747*, and the *École Royale du Génie de Mézières* in 1748. The selection of artillery officers, in addition to that of ingenious engineers, included an evaluation of mathematical skills. In 1774, finance minister Turgot promoted a vast program of reforms; it was he who employed chemist Lavoisier in the recently nationalized gunpowder industry.

During the *Ancien Régime*, bourgeois strata had also been formed in the administration, among the intellectuals, and in the technical cadres of the army, in what we now call the "military genius," engaged in the design and construction of bridges, roads, and other works. But faced with the domination of the absolute monarchy and the aristocracy, and the blocked economic and social situation, the French bourgeois and intellectual strata essentially sublimated the demands for change into projects of intellectual character: this was, in simple terms, the program of the Enlightenment.

Thus, the *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et métiers*—the first great encyclopedia of modern times, created between 1751 and 1780 by Diderot (1713–1784) and d'Alembert (1717–1783, who later abandoned the project)—aimed to collect all technical, scientific, and practical innovations (mostly from British sources), with an explicit systematic and pedagogical intent, free from any dogmatism, and aiming at an ideal of intellectual freedom. The ample space given to science, technology, and history was a significant novelty: by opening up to scientific knowledge, the *Encyclopédie* constituted, as d'Alembert himself wrote, a bridge connecting the past and the future.

Thus, while in Great Britain scientific and technical innovation gave rise to practical mechanics, in France it was developed as rational mechanics. The French physicists of this century made fundamental contributions to the conceptual arrangement of mechanics, not its practical applications and innovations, but its formal and mathematical formulation.

Despite attacks from Jesuits and Jansenists, the *Encyclopédie* was a huge success with the public (more than 4,000 subscribers): seventeen volumes and eleven volumes of plates were published between 1751 and 1775, followed by four more volumes of supplements and four volumes of plates (1775–1780). The *Encyclopédie* represents the synthesis of Enlightenment thought, as it expressed faith in reason, knowledge, and science, which were considered instruments of progress and the main road to triumph over error, obscurantism, and prejudice.

8. The First Formalization of Energy Concepts and General Principles of Machines in France: Lazare Carnot

Among the engineers of the French military genius was Lazare Carnot (1753–1823), who formulated the first general theory of (mechanical) machines. Lazare (we will only use his name so as not to cause confusion with his son Sadi Carnot, who, as we shall see, studied the laws of thermal machines) was not only a scientist and scholar but also one of the main protagonists of the political events of the French Revolution, with deep dedication but also loyalty to his republican but conservative convictions, and opposed the excesses of the Revolution.

Lazare trained at the military school of Mézière, where he also met Benjamin Franklin and developed an interest in machines. In 1778, he wrote an *Essai sur les machines en général* (which the *Academie des Sciences* in Paris rejected) for a competition held by the same *Academie des Sciences* in Paris, which we will discuss here, and after a rewrite in 1781, he printed it in 1783.

After the outbreak of the Revolution, Lazare was elected to the Legislative Assembly in 1791 and to the National Convention in 1792. He was a member of Robespierre's Committee of Public Health but came into conflict with him; he was the only one who was also a member of the Directory. In the Committee, he was in charge of military matters, in a spirit that can be considered an emblematic product of the Enlightenment: while the fortunes of the war against the European coalitions that intended to overthrow the Revolution and reinstall the monarchy were taking a turn for the worse, Lazare's organizational skills were responsible for the creation of the revolutionary army and its profound renewal, which made it possible to reverse the fortunes of the war between 1793 and 1794, to the extent that he was called the Organizer of Victory.[25] In 1795, it was Lazare who appointed Napoleon Bonaparte as commander of the army in Italy (he was the only member of the Directory who supported him). In 1800, Napoleon appointed him Minister of War, but in 1802 Lazare voted against Consular powers for life, because "if this power belongs to a hereditary family, it becomes despotic." When Napoleon crowned himself Emperor in 1804, Lazare's republican convictions prevented him from accepting any further posts, and he retired from public life. But in 1812 he returned to office during

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[25] Lazare proposed to the National Convention the *levée en masse,* which doubled the size of the army, introduced military training, renewed the conduct of war with a mass army composed of several mobile units, reversed military tactics from defensive to offensive, and had great success compared to existing tactics in European armies. He adopted the military use of balloons (before the Revolution, he had helped the Montgolfier brothers in their experiments), and a school was set up for this purpose; in 1793, a series of traffic light towers were built for communications between Paris and the north-eastern frontier. Once the troop problems had been solved, he moved on to organize the supplies needed for a mass army, mobilizing the brightest French scientists to direct the various sectors: he called in chemists Chaptal and Berthollet to solve the problem of gunpowder by organizing the revolutionary collection of saltpeter in Parisian cellars; he put mathematician Monge in charge of the Paris arms factory; and he commissioned new methods of tanning leather for boots that were in short supply (hence the name "organizer of victory").

Napoleon's disastrous Russian campaign, taking up the defense of Antwerp against the Sixth Coalition. During the Hundred Days, he served as Minister of the Interior but went into exile during the reign of Louis XVIII. He then lived in Warsaw and died in Magdeburg in Prussia.

During the Revolution, Lazare was also involved in the reform of teaching and scientific research, contributing to the creation of the *École Polytechnique*, which was the first school of academic training for engineers, the precursor of the modern Polytechnics. When the *Institut National* was created in 1795 to replace the suppressed Academy, this became his main commitment, carrying out various tasks related to technology, and in 1803 he drafted a second edition of the 1783 treatise on machines with the title *Principes fondamentaux de l'équilibre et du movemen*t, which actually set out the same content more clearly without adding substantial novelties. On the scientific side, Lazare also worked on geometry and differential calculus.

8.1. The General Theory of (Mechanical) Machines and the Substantive Distinction between Different Forms of Mechanical Energy

The aforementioned *Essai* of 1783 was *the first systematic treatise that treated (mechanical) machines in energetic terms*. Before Carnot, machine theory had mostly been restricted to elementary machines (such as levers and pulleys). Their operation was interpreted on the basis of the laws of statics (the "principle of virtual work")[26] and on the consideration of changes "by insensitive degrees," as Lazare put it, which did not take into account shocks and therefore ignored the dissipation of energy that Smeaton had emphasized for waterwheels, but there was no general theory.[27] During the Industrial Revolution, the increasing complexity of the new machines led to the idea that the great variety of machine geometry required separate treatments, considering them to be composed of mechanisms that could be classified according to the way in which they transformed motion.

Before proceeding to analyze Lazare's conclusions, which seem to me to be most relevant to my reconsideration, I would like to remark that the reading of Lazare's essay

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[26] The principle of virtual work dates back to the seventeenth and eighteenth centuries by many scholars, including Descartes, Bernoulli, Fourier, and Lagrange, who formulated it in different ways that are too complex to explain here. The principle is very formal in nature, and it is not easy to translate its conceptual substance into simple terms (any student of engineering knows this!). It takes into account the "virtual" (infinitesimal) movements and the "congruent" displacements of the parts of a system (i.e., allowed by the constraints, e.g., a beam fixed at one end and free at the other), and establishes formal relations based on the principles of mechanics assuming that each constraint is replaced by a congruent "virtual" (potential and not actual) displacement. It has become the fundamental principle of structural science that engineers study to set the behavior of beams and the resistance of engineering structures under the effect of stress.

[27] As stated before, in the eighteenth century the main problem of mechanics concerned the choice of whether the momentum (mv) or the *vis viva* (mv^2) was the quantity conserved when the motion was transferred: in the collision of bodies the momentum is conserved, while the *vis viva* is conserved only in the collision of perfectly elastic bodies but not in inelastic bodies. I have discussed how in 1776 Smeaton set up this exact problem, giving for the first time the correct answer on both aspects.

is rather complex, in part due to the formalism he uses. For example, he considers velocities as vectors, but since today's vector notation (with an arrow above the symbol of the quantity) had not yet been introduced, it is easy to confuse vector and scalar relations. Even the terms he uses are not the modern ones: for example, he also calls *vis viva* "moment of activity;" the modern concept of potential energy "latent living force;" sometimes he understands "force" as work. In line with D'Alembert, Lazare rejects the Newtonian concept of force, which he considers ill-defined, replacing it with the concept of moment, as in certain modern texts of mechanics.

Lazare's approach is based on energy considerations, or in very explicit terms, on the consideration of the *"productive" work* performed by the machines: from this point of view, the very clear specification he makes with respect to a kind of "work" that does not produce the desired effect becomes significant (in perfect consonance with the remarks I made in Section 4.1, but such clear considerations are not often found in physics textbooks):

> *When employing workers, it is more important to know how much work they are capable of doing of a kind similar to that which we have just discussed* [i.e., by machines] *than to know the weights they could carry without moving* [i.e., the so-called passive work]. (Carnot, Lazare 1803, 35)[28]

With these premises, Lazare develops a formal treatment that translates into mathematical formulas for the fundamental laws of the operation of (mechanical) machines. For example, he formally acknowledges that "the force [work] PH [weight times height] is resolved in the product of a mass by the square of a velocity. … This is the natural origin of the notion of live forces (in fact it is still often referred to as the theorem of live forces)."

When a body of mass M falls from a height H, it transforms its "latent live force" of MH into a "live force" of $\frac{1}{2}MV^2$, which is the mathematical formulation of the concepts of potential and kinetic energy (where the correct factor ½ finally appears, deriving from a correct deduction of the conservation of mechanical energy) and which Smeaton had acknowledged but not formalized. Thus, Lazare also concludes that the dispute over the use of mv or mv^2 "reduces to a matter of words, provided that one reasons consistently with the definitions adopted once and for all" (which Smeaton called the collateral conditions).

It is important here to insist on certain conclusions that Lazare draws on a rigorous basis, dispelling many widespread preconceptions or false conclusions:

> The advantage provided by the machines is not, therefore, that they produce great effects with small means, but that they make it possible to choose between different

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[28] Italics added. This and quotations from this publication were translated from French to English by the author.

> means that can be called equal, the one best suited to the present circumstance. … So what is the real purpose of machines in motion? ... it is to provide the faculty of varying at will the terms of the ... momentum of activity, which must be consumed by the moving forces. If time is precious, and the effect must be produced in a very short time, and if one has only a force capable of little speed but of great effort, one can find a machine to make up for the necessary speed by the intensity of the force; if, on the other hand, one has only a weak power at one's disposal, but capable of great speed, one can imagine a machine with which the agent will be in a position to compensate for the lack of force by its speed. Finally, if the power is capable of neither great effort nor great speed, it will still be possible, with a suitable machine, to make it produce the desired effect, but then one cannot dispense with using a great deal of time because, in the end, there is no way out of this circle, that it is absolutely necessary that the [momentum of activity] should always be equal to the effect one wishes to produce; and it is precisely in this that this principle, so famous and so important, consists, that in machines in motion, one always loses in time or in speed what one gains in force. … Machines are therefore very useful, not by increasing the effect of which the powers are naturally capable, but by modifying this effect. It is true that they will never succeed in diminishing the expenditure or consumption of the momentum of activity necessary to produce a proposed effect, but they can help to make of this quantity a distribution suitable for the object in view. ... it is finally through them that we shall give the moving forces the most convenient situations and directions, the least tiring, the most suitable for employing their faculties in the most advantageous manner. (Carnot, Lazare 1803, 235, 238–39, 240–41)

Note the further extension of the concept of *efficiency*.

Ultimately, Lazare takes the criteria established by Smeaton for waterwheels and generalizes them for all (mechanical) machines, stating them in a crystal-clear manner:

> This presupposes, however, that there is no shock or sudden change between the parts of the machine or the masses applied to it, or that the movement changes by insensible degrees, otherwise there would be a loss of living force all the greater, as the intensity of the shock would itself be greater; from which it obviously follows, that in order to obtain the greatest possible effect from machines, it is very important that they should be constructed in such a way that the movement never changes other than by insensible degrees.[29] … From this we can conclude, for example, that the way to make a hydraulic machine, driven by a current of water, produce the greatest possible effect is not to adapt an impeller whose wings receive the shock of the fluid. In fact, there are two reasons why the greatest effect cannot be produced in this way: the first is the one we have just mentioned, namely, that it is essential to avoid any percussion whatsoever; the second is that, after the shock of the fluid, it still has a speed which remains to it in pure loss, since one could use this remainder to produce a new effect which would be added to the first. To make the most perfect hydraulic machine, that is to say, one capable of producing the greatest possible effect, the real crux of the difficulty would therefore consist, 1o. in ensuring that the fluid loses all its movement by its action on the machine, or at least that only the quantity necessary for it to escape after its action remains; 2. that it lost all this movement by insensible degrees, and without there being any percussion, either on

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[29] To avoid inelastic shocks as much as possible.

> the part of the fluid, or on the part of the solid parts between them; but this problem is very difficult to solve in general, not to say impossible; perhaps even that in the physical state of things, and with regard to simplicity, there is nothing better than wheels driven by the shock. (Carnot, Lazare 1803, 247–48, 248–49)

I have already commented, in discussing Smeaton's work, that this formulation contains the fundamental principles of hydraulic technology and of future turbines.

I shall now see how Lazare's son, Sadi Carnot, translated these criteria and concepts (which he had evidently absorbed from his father) into the first theory of thermal machines (hence the dynamics of heat).

9. The Scientific Innovations of the French Revolution and the Napoleonic Period

The French Revolution of 1789 brought about the establishment of the power of the bourgeois class—which for decades had been elaborating its own culture and values through the Enlightenment—and pressed against the power of the parasitic aristocratic classes in the shadow of the absolute monarchy that was on the brink of bankruptcy.[30]

In the fields of science and education, the Revolution brought about the profound transformations that had been ideally anticipated by the *Encyclopédie* and Enlightenment thinkers. The statement "The Republic has no need of scientists" has become famous, but it needs to be put into context: why was the *Académie des Sciences* dissolved (1793) and why were eminent scientists such as Lavoisier guillotined? It was certainly not because the sciences were not useful, as we have seen in dealing with Lazare Carnot, but rather because certain institutions and certain people had been compromised by the *Ancien Régime*, and the Revolution was to sweep away all privileges: the *Académie* had been an elitist institution that had included honorary members of the aristocracy—Lavoisier had been among the royal tax collectors. But what is certain and of interest here is that the Revolution realized modern institutions: they were not adaptations to new

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[30] En passant, I would like to recall how the watchwords "Liberty, Equality, Fraternity" and the solemn *Declaration of the Rights of Man and the Citizen* of 1789 brought crucial aspects of capitalist exploitation to the fore, and also raised expectations beyond the wishes of the bourgeois class. On the one hand, the black slaves of Haiti took these declarations literally and in 1791 they carried out the first revolution for the abolition of slavery and against colonialism under the leadership of the former African American slave Toussaint L'Ouverture (1743–1803), who had joined the Jacobin movement. Toussaint was taken prisoner and died in France, but the army sent by Napoleon suffered a humiliating defeat, and in 1804 the Republic of Haiti became the first black state in modern history. On the other hand, the claim of women, what we now call the "reproductive labour" at the heart of capitalist accumulation, also emerged, but they too were far from gaining recognition: so much so that Olympe de Gouges, author of the Declaration of the Rights of Women and Citizens who wrote "Oh, women! Women! when will you stop being blind? What benefits have you derived from the revolution?", was condemned to the guillotine in 1793 because "born with an exalted imagination, she mistook her delirium for an inspiration of nature: she wanted to be a Statesman!"

needs, as in empiricist England, but a rational project that had been prepared by all the work of the *Encyclopédie*.

One of the lasting achievements of the Revolution, with implications for all fields of activity in modern societies, was the introduction of the metric system, which replaced and unified the myriad of measures that were used in every region and constituted a very serious obstacle to the spread of trade, industry, and all economic activity.[31]

An epoch-making innovation of the Revolution was that education, which had hitherto been in the hands of the Catholic Church, was secularized and nationalized. Teachers were paid by the state. This logic led to the creation of new institutions that still exist today: the *École Normale Supérieure*, the *Institut de France* (replacing the old *Académie des Sciences*), and the *École Polytechnique* (the forerunner of the modern polytechnic, where for the first time, engineers received university-level training).

It was officially recognized that the sciences were to become an important component of the new system of higher education. Scientists became professionals, paid by the state, an innovation that was destined to profoundly change the role of science. In contrast, the establishment of university degrees in Britain was more troubled: for a long time there were no degrees in the scientific disciplines, long combined under the name of "Natural Philosophy." Only a small percentage of those who published scientific research had paid employment in the field: the great Michael Faraday (1791–1867), a self-taught man with no formal education, began to do experiments in physics that impressed Sir Humphry Davy, who succeeded him as director of the Royal Institution and which he transformed from a salon institution in well-to-do London into a solid experimental laboratory. Likewise, there was James Joule, who followed the fundamental experiments on the equivalence of mechanical work and heat, without having a degree in physics (Section 11).

The *École Polytechnique* had physics and chemistry laboratories that were also used for students' practical exercises. Such an organized, centralized, and state-run education and research system was unique in Europe. It was in post-revolutionary France that a high-level alliance between academic research and political power was established.

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[31] The naturalistic approach is significant, based on the concept that units should be related to some natural phenomenon. With this logic in mind, in 1792 the Republic embarked on an impressive scientific enterprise that involved dozens of scientists and, amidst a thousand difficulties, lasted for six years. It aimed to measure the length of the arc of the terrestrial meridian between Dunkirk and Barcelona with triangulation on each leg, defining the meter as the ten millionth part of the quarter of the terrestrial meridian that passes through Paris (Paris meridian): on June 22, 1799, with a speech by Laplace, the platinum alloy samples of the meter and the kilogram were deposited. Today, any student of physics understands that this huge undertaking was useless, because the adoption of units of measurement is conventional (the English continue to use yards and pounds without any internal inconvenience). Moreover, the uncertainty of distance measurements led the *Bureau International des Poids et Mesures* to redefine the meter in 1889 as the distance between two lines engraved on a sample bar of platinum-iridium preserved at the Museum of Weights and Measures in Sèvres: all the samples of the various nations were calibrated on this sample meter. Today, of course, there are far more precise and refined measuring systems.

During the Napoleonic Empire, a great boost was given to the sciences. Bonaparte himself, who was very interested in science and technology, was a member of the *Institut* and therefore had direct control over its activities.

The system allowed a small group of scientists with a common approach to greatly increase their power at the expense of others. Berthollet and Laplace were generously financed by Bonaparte, of whom Laplace was a friend and even briefly a cabinet minister. For about ten or fifteen years, physics in France was essentially Laplacian.

10. Decisive Advances in the Theory of Thermal Machines and the Science of Heat: 1824, Sadi Carnot, The Efficiency of Thermal Machines

10.1. The Recognition of the Science of Heat as a Specific Discipline Independent of Mechanics

The professionalization of teaching and research activities in the institutions created by the Revolution led to the specialization of the various scientific fields: each field of phenomena began to structure itself autonomously, delimiting the type of phenomena studied, the specific criteria to be applied, its own autonomous method of investigation, and the body of laws that characterized it. Thus, to give just a few examples: mathematics presented its own self-consistent criteria and specific methods, rational mechanics experienced a process of formalization, and electrodynamics developed a statute independent of other fields. Thus, in the 1820s, Jean-Baptiste Fourier and Sadi Carnot, albeit with different approaches, recognized that thermal processes are distinct from mechanical processes and so must be studied using their own criteria.

The mathematician Jean-Baptiste Fourier (1768–1830) took an active role in politics during the Revolution, risking being guillotined, and was one of the scientists who followed Napoleon on his expedition to Egypt; on his return to France, he was appointed prefect of Isère and afterwards secretary of the *Académie des Sciences* for the mathematics section. Fourier made important mathematical contributions, and in 1822 he published his most famous work, *Théorie Analytique de la Chaleur*, in which he developed the mathematical theory of heat conduction. In it he introduced the development of trigonometric series, which was later called the “Fourier series” and became one of the most important computational tools, the “Fourier transform,” fundamental for the study of differential equations. In 1822, Fourier stated for the first time:

> whatever the extent of mechanical theories may be, they do not apply to the effects of heat. They compose a special order of phenomena which cannot be explained by the principles of motion and equilibrium. It is a fact that for a long time now we have possessed ingenious instruments capable of measuring many of these effects: we

> have collected valuable observations; but we know only partial results, and not the mathematical demonstration of the laws which comprise them all.[32]

10.2. Sadi's "Reflexions sur la Puissance Motrice du Feu"

This awareness was also expressed two years later by Sadi Carnot, albeit with a very different approach. Sadi Carnot (1796–1832) was the son of Lazare, and was also an officer in the Army Corps of Engineers and a student at the *École Polytechnique*. As an army officer, Sadi suffered from various frustrations. In 1819, he transferred to the newly formed General Staff but quickly retired on half pay while furthering his studies. His friends described him as reserved, almost taciturn, but insatiably curious about science and technical processes. He cultivated many cultural and artistic interests, frequenting the *Louvre*, the *Théâtre Italien*, the *Jardin du Plantes* and the *Conservatoire des Arts et Metiers*.[33] Music was another one of his passions, probably inherited from his mother who was an excellent pianist. Unfortunately, weakened by an inflammation of the lungs and later scarlet fever, he died prematurely on August, 24 1832 during a cholera epidemic.

By assimilating his father's conception of energy transformations and his approach to the systematic study of machines, Sadi extended his studies to "fire machines," resulting in the first theory of and approach to thermodynamics as a discipline independent of mechanics and based on its own specific concepts. His work of 1824 (when he was only 28 years old) was relevantly titled *Reflexions sur la Puissance Motrice*[34] *du Feu et sur les Machines propres à Developper Cette Puissance*, with 600 copies printed at his own expense, and was communicated to the *Académie des Sciences* at the session of June 14, 1824 by academician Pierre-Simon Girard. This work was written in a more accessible language for general circulation that was not purely academic, it contained only very rare and simple formulas, and it did not make use of mathematics since it discussed in words the intuitive reasoning of the transition to the limit of differential analysis. Yet, the *Réflections* can be considered one of the first treatises of modern thermodynamics.

In the style of the encyclopedists of the previous century, Sadi explicitly refers, almost as a tribute, to the progress of the Industrial Revolution in England and the enormous benefits it received from "fire" machines:

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[32] Fourier, J. B. 1822. *Discours préliminaire* in *Theorie Analytique de la Chaleur*, p. ii–iii.

[33] His posthumous manuscripts contain, in addition to relevant scientific contributions, fascinating notes on everyday life and aphorisms. I would like to quote a couple of them relating to his religious feelings:

> If human reason is incapable of discovering the mysteries of Divinity, why has not Divinity made human reason more clear-sighted ?
>
> God cannot punish man for not believing when he could so easily have enlightened and convinced him (Carnot 1897, 216).

[34] It should be remarked that although Smeaton had unambiguously defined the term work, this did not eliminate the different terms that were used. Sadi unequivocally specifies in a footnote:

> We use here the expression motive power to express the useful effect that a motor is capable of producing. This effect can always be likened to the elevation of a weight to a certain height. It has, as we know, as a measure, the product of the weight multiplied by the height to which it is raised (Carnot 1897, 42).

> The study of these engines is of the greatest interest, their importance is enormous, their use is continually increasing, and they seem destined to produce a great revolution in the civilized world.
>
> Already the steam-engine works our mines, impels our ships, excavates our ports and our rivers, forges iron, fashions wood, grinds grains, spins and weaves our cloths, transports the heaviest burdens, etc. It appears that it must some day serve as a universal motor, and be substituted for animal power, waterfalls, and air currents.
>
> Over the first of these motors it has the advantage of economy, over the two others the inestimable advantage that it can be used at all times and places without interruption.
>
> If, some day, the steam-engine shall be so perfected that it can be set up and supplied with fuel at small cost, it will combine all desirable qualities, and will afford to the industrial arts a range the extent of which can scarcely be predicted. (Carnot, Sadi 1897, 38–39)

Note his insistence on the peculiar advantage of heat engines of "being able to be used at any time and in any place," i.e., mobile, and he explicitly quotes "Trevithick and other English engineers" (Section 5.5).

10.3. Sadi Carnot and the Theory of Heat

Turning specifically to Sadi's innovative approach to the study of "fire" machines, I cannot afford to ignore an aspect which is by no means academic, but which I believe is indicative of the relationship between practical progress and theoretical elaboration in the Napoleonic period. Whoever reads any entry or article on the work of Sadi Carnot will find that he adopted, for the study of thermal machines, the model of heat as a fluid (which is conserved), the so-called "caloric fluid," which was then widely adopted (as were models of electric, magnetic, or luminous fluids) but would soon prove to be wrong. In fact, as early as the end of the eighteenth century, the ingenious and enterprising "adventurous scientist" Benjamin Thompson, Earl of Rumford—who, among his many other occupations, was employed by the Elector of Bavaria as an aide-de-camp—observed the process of boring cannon barrels and realized that friction, i.e., motion, produced heat (Brown 1981).

But if one carefully reads the terms that Sadi uses for "heat," one will not find an unambiguous reference to "caloric fluid": sometimes he speaks of caloric, sometimes of heat, or of fire[35]. My opinion is that he does not adopt a specific theory of heat because it is not strictly necessary for his considerations (as I will mention in Section 11, it was William Thomson, Lord Kelvin, in a lively interaction with James Prescott Joule who established in 1851 that Sadi's results are compatible and in agreement with the

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[35] The issue has been discussed in the historiography of science. See for example the notes to the English translation (Mendoza 1960, XVII).

mechanical theory of heat).[36] Moreover, from the very first lines of *Réflexions*, Sadi clearly expresses the concept of energy production from heat:

> To heat also are due the vast movements which take place on the earth. It causes the agitations of the atmosphere, the ascension of clouds, the fall of rain and of meteors, the currents of water which channel the surface of the globe, and of which man has thus far employed but a small portion. Even earthquakes and volcanic eruptions are the result of heat.
>
> From this immense reservoir we may draw the moving force necessary for our purposes. (Carnot, Sadi 1897, 37–38)

Additionally, in the last part of the note on p.67 of the *Réflexions* on the concept of the caloric, he expresses deep reservations about this theory:

> For the rest, we may say in passing, the main principles on which the theory of heat rests require the most careful examination. Many experimental facts appear almost inexplicable in the present state of this theory. (Carnot, Sadi 1897, 67–68)

Lord Kelvin would have been facilitated in his troubled considerations if he had known of a manuscript written by Sadi shortly after the *Réflexions* but which has come down to us posthumously[37], in which he unambiguously states that "*heat is nothing more than motive power or rather movement that has changed form, a movement of the particles of bodies*," and even goes as far as to calculate (although it is not clear how) a value for the mechanical equivalent of heat:

> Heat is simply motive power, or rather motion which has changed form. It is a movement among the particles of bodies. Wherever there is destruction of motive power there is, at the same time, production of heat in quantity exactly proportional to the quantity of motive power destroyed. Reciprocally, wherever there is destruction of heat, there is production of motive power.
>
> We can then establish the general proposition that motive power is, in quantity, invariable in nature; that it is, correctly speaking, never either produced or destroyed. It is true that it changes form, that is, it produces sometimes one sort of motion, sometimes another, but it is never annihilated.
>
> According to some ideas that I have formed on the theory of heat, the production of a unit of motive power necessitates the destruction of 2.70 units of heats. (Carnot, Sadi 1897, 225–226)

This value, converted into modern units, equals 3.7 J/cal, remarkably close to the current value of 4.186 J/cal!

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[36] Without resorting to demanding academic readings, refer to "William Thomson, 1st Baron Kelvin" on Wikipedia. https://en.wikipedia.org/wiki/William_Thomson,_1st_Baron_Kelvin#Thermodynamics.

[37] Sadi's manuscript dates back to 1823, even before the publication of the *Réflexions*, but it was never published and was only rediscovered in 1866.

This issue, however, is in my view highly relevant in order to trace the transition and evolution of Smeaton's legacy through Lazare Carnot to his son Sadi.

I have discussed how Smeaton had assumed that reducing jumps generated by water in free fall to a minimum was a criterion for the maximum efficiency of an overshot waterwheel. Moreover, we have seen how Lazare Carnot had generalized this criterion for any mechanical machine in terms of avoiding collision between parts, that is, transmitting movements "by insensible degrees": Sadi drew inspiration from these precedents to generalize this criterion for heat engines. *The only assumption he needs is the analogy between a "geometric difference in level" in the fall of water, and a "thermal difference in level" in heat transfer, without implying any assumptions about its nature*. With this "simple" analogy, the requirement to transfer water without differences in level ("by insensible degrees") translates into "transferring heat without differences (jumps) in temperature." It is obvious that if there is no temperature difference, heat is not transferred at all, just as water is not transferred if there is no geometric difference in height. While the notion of the "ideal waterwheel" (or mechanical machine) did not materialize, the theory of the "heat engine with maximum theoretical efficiency" developed by Sadi came into thermodynamics as Carnot's *ideal* (or perfect) heat engine. It is important to note that an ideal (mechanical or thermal) machine is not only not feasible in practice (because water as heat can only be transferred through a height difference, respectively geometric or thermal), but even if it were feasible, it would be of no use because it would generate energy at zero rate—that is, zero power! For all practical purposes, the term that counts is power (energy or work per unit time, see Smeaton, Section 4.1) and not work.

This is how the science of capitalism needs to resort to abstraction: it resorts to the theory of the ideal engine in order to be able to make the best real engines. In this way, Smeaton had proceeded to establish the superiority of wheels driven from above over those driven from below. Indirectly, Watt had acquired this theory to overcome the use of the steam engine as a pump; and now Sadi adopts it, in the wake of his father Lazare, to transfer the criterion to thermal engines and obtain the prescription for the maximum theoretical efficiency, of the ideal machine, which no real machine project can exceed. In the history of technology, there have been a succession of imaginative proposals for thermal machines with an efficiency higher than the theoretical "Carnot machine" (as it is now called in thermodynamics), which obviously had some conceptual "bugs."

Regarding the fruitfulness of Sadi's conception, it is significant that at the end of the nineteenth century Rudolf Diesel (1858–1913) "devised" his internal combustion engine trying to as faithfully as possible reproduce the transformations of the cycle of Carnot's engine,[38] even if the laborious practical realization in the following years presented very

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[38] The rational process followed by Diesel in 1892 is reconstructed in very clear terms in (Bryant 1969). The development of the diesel engine, after the original patent, was rather troubled and had aspects that would

complex problems due to the novelty of this engine and also required modifications to the original project.

10.4. The Principle of Producing Motive Power from Heat: The Specificity of Heat Engines

Sadi's work starts from a very clear premise of his reasoning:

> Notwithstanding the work of all kinds done by steam-engines, notwithstanding the satisfactory condition to which they have been brought to-day, their theory is very little understood, and the attempts to improve them are still directed almost by chance.
>
> The question has often been raised whether the motive power of heat is unbounded, whether the possible improvements in steam-engines have an assignable limit,—a limit which the nature of things will not allow to be passed by any means whatever; or whether, on the contrary, these improvements may be carried on indefinitely. We have long sought, and are seeking to-day, to ascertain whether there are in existence agents preferable to the vapor of water for developing the motive power of heat; whether atmospheric air, for example, would not present in this respect great advantages. We propose now to submit these questions to a deliberate examination. (Carnot, Sadi 1897, 42–43)[39]

At this point, Sadi recognizes in definitive terms the independence of the science of thermal machines from that of mechanical machines:

> In order to consider in the most general way the principle of the production of motion by heat, it must be considered independently of any mechanism or any particular agent. It is necessary to establish principles applicable not only to steam engines but to all imaginable heat-engines, whatever the working substance and whatever the method by which it is operated.

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be relevant for the general theme in this article because the realization of this engine, whose conception was truly innovative, also required in-depth theoretical studies and the solution of complex technical problems (among which are the complex search for a suitable fuel since the high temperature had to be generated by compression in the cylinder alone, which had to cause the ignition of the fuel without the need for a spark). These aspects are well covered in (Bryant 1976). Diesel's fortunes were tormented, it is perhaps not widely known that he suffered from psychological problems; after a bankruptcy in August 1913 due to debts contracted with various banks, on September 29, 1913 his corpse was found floating in the Eastern Scheldt during a crossing of the English Channel. The circumstances of his death have never been clarified. Theories range from suicide to murder at the hand of the German secret service to prevent him from attending an appointment in London with Rover emissaries for the construction of engines for English and French military vehicles and ships (and perhaps submarines). It is also noteworthy that Diesel was also driven by social motives (which he expressed in his book *Solidarismus, natürliche wirtschaftliche Erlösung der Menschen*), in that he wanted the engine to be simple and easily adaptable to different sizes so that it could be built by independent craftsmen in competition with the large industries that monopolized the construction of large steam engines. See (Gandolfi, n.d.)

[39] It is worth noting how the centuries-old diatribe on perpetual motion took on much more concrete connotations with the Industrial Revolution, the limits to the performance (interpreted as *efficiency*) of motors, which Smeaton had found in energy terms for water wheels, and now Sadi studied for the specific case of heat, establishing for the first time that heat (in intuitive terms) cannot be fully transformed into mechanical work.

> Machines which do not receive their motion from heat, those which have for a motor the force of men or of animals, a waterfall, an air-current, etc., can be studied even to their smallest details by the mechanical theory. All cases are foreseen, all imaginable movements are referred to these general principles, firmly established, and applicable under all circumstances. This is the character of a complete theory. A similar theory is evidently needed for heat-engines. We shall have it only when the laws of Physics shall be extended enough, generalized enough, to make known beforehand all the effects of heat acting in a determined manner on anybody. (Carnot, Sadi 1897, 43–44)

Sadi's program to establish a theory of heat "independent of any mechanism" confirms what I discussed in Section 10.1, obviously considering the cultural heritage and the specific conditions of his time.

Sadi summarizes the operating principle of a heat engine, reformulating the formulation by James Watt:

> The production of motion in steam-engines is always accompanied by a circumstance on which we should fix our attention. This circumstance is the re-establishing of equilibrium in the caloric; that is, its passage from a body in which the temperature is more or less elevated, to another in which it is lower. … The production of motive power is then due in steam-engines not to an actual consumption of caloric, but *to its transportation from a warm body to a cold body*, … the production of heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; …[40] Wherever there exists a difference of temperature, wherever it has been possible for the equilibrium of the caloric to be re-established, it is possible to have also the production of impelling power. Steam is a means of realizing this power, but it is not the only one. (Carnot, Sadi 1897, 44–48)

In general:

> It is necessary to establish principles applicable not only to steam-engines but to all imaginable heat-engines, whatever the working substance and whatever the method by which it is operated. (Carnot, Sadi 1897, 43–44)

10.5. The "Carnot Engine" with Maximum Efficiency

The detailed description of the "fire" engine with maximum efficiency to which Sadi refers to (and which would later become the "Carnot cycle") may well be overlooked by the reader interested in the conclusions (Section 10.7), but I argue it remains nonetheless significant when one thinks of the readers of his time:

> The necessary condition of the maximum[41] is, then, *that in the bodies employed to realize the motive power of heat there should not occur any change of temperature*

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[40] How can one forget Watt's patent?

[41] Of the motive power resulting from the use of steam.

> *which may not be due to a change of volume.*[42] Reciprocally, every time that this condition is fulfilled the maximum will be attained. This principle should never be lost sight of in the construction of heat-engines; it is its fundamental basis. If it cannot be strictly observed, it should at least be departed from as little as possible.
>
> Every change of temperature which is not due to a change of volume or to chemical action (an action that we provisionally suppose not to occur here[43]) is necessarily due to the direct passage of the caloric from a more or less heated body to a colder body. This passage occurs mainly by the contact of bodies of different temperatures; hence such contact should be avoided as much as possible.[44] It cannot probably be avoided entirely, but it should at least be so managed that the bodies brought in contact with each other differ as little as possible in temperature. … In reality the operation cannot proceed exactly as we have assumed. To determine the passage of caloric from one body to another, it is necessary that there should be an excess of temperature in the first, but this excess may be supposed as slight as we please. We can regard it as insensible in theory, without thereby destroying the exactness of the arguments. (Carnot, Sadi 1897, 56–58)

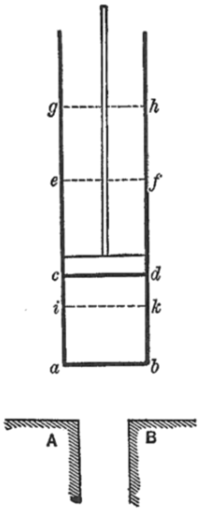

Fig. 4: Axial cross section of Carnot's heat engine (Carnot, Sadi 1897).

The reference to the concept of "insensitive" that his father Lazare had introduced is evident: *the Smeaton-Lazare-Sadi chain is complete*. For those not versed in thermodynamics, this concept has become that of *ideal reversible transformation*, consisting of a succession of equilibrium states, or, conceptually, states that deviate infinitely little from equilibrium states.

It should therefore be clear why Sadi does not need to adopt a precise heat theory: all his considerations and conclusions depend solely on the analogy between a geometric jump of the water falling on a waterwheel and a difference (jump) in temperature in a heat engine.

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[42] It should be clear from the discussion of Watt's "indicator diagram" that work is performed by the change in volume (Section 6, footnote 24). In contrast, in a transformation with constant volume, the change in internal energy is equal to the heat exchanged in the transformation.

[43] This is what happens in the Diesel engine, footnote 38.

[44] Think again of Rudolf Diesel's complex research.

10.6. The Limits of Motive Power Production in a Heat Engine

We thus come to the fundamental core of Sadi's work, where he poses the answer to the problem from the very first pages:

> whether the motive power of heat is unbounded, whether the possible improvements in steam-engines have an assignable limit. (Carnot, Sadi 1897, 42)

The fundamental results of his tightly woven reasoning, which is still largely accessible even to those with no specific knowledge of thermodynamics, can be summarized in the following conclusion:[45]

> *the maximum of motive power resulting from the employment of steam is also the maximum of motive power realizable by any means whatever.* (Carnot, Sadi 1897, 55)

This intuitive, not formal demonstration is followed by a second, much more articulate demonstration (Carnot, Sadi 1897, 61–68) which—with reference to the figures at the end of the book representing the scheme of the machine and the succession of transformations now familiar from thermodynamics textbooks (the *Carnot's cycle*)—reinforces the conclusion (obviously referring to the ideal engine):

> *The motive power of heat is independent of the agents employed to realize it; its quantity is fixed solely by the temperatures of the bodies between which is effected, finally, the transfer of the caloric.*
>
> This condition is found to be fulfilled if, as we remarked above, there is produced in the body no other change of temperature than that due to change of volume, or, what is the same thing in other words, if there is no contact between bodies of sensibly different temperatures. (Carnot, Sadi 1897, 68)

The specification "solely" confirms that Sadi does not need to adopt a specific heat theory.

These conclusions are the first result of this new domain of the science of heat. On the other hand, Sadi did not at that time have more data or results that would allow him to go further and quantitatively determine the efficiency of the ideal engine, namely the upper

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[45] In order not to make the reading more difficult, I would like to add in a footnote an observation that is important in denoting the modernity of the *Réflexions*. The reasoning followed by Sadi is an anticipation of the proofs by absurdity that characterize the demonstrations of the Second Principle:

> Now if there existed any means of using heat preferable to those which we have employed, that is, if it were possible by any method whatever to make the caloric produce a quantity of motive power greater than we have made it produce by our first series of operations, it would suffice to divert a portion of this power in order by the method just indicated to make the caloric ... from the refrigerator to the furnace, to restore the initial conditions, and thus to be ready to commence again an operation precisely similar to the former, and so on : this would be not only perpetual motion, but an unlimited creation of motive power without consumption either of caloric or of any other agent whatever. Such a creation is entirely contrary to ideas now accepted, to the laws of mechanics and of sound physics. It is inadmissible. (Carnot, Sadi 1897, 55)

limit of efficiency for any heat engine. In the final part of his *Réflexions*, he made some partial evaluations. (Incidentally, the reading of Sadi's essay is complicated by the fact that the pages follow one another without a division into paragraphs marking the passage from one argument to another.)

10.7. Sadi's Further Considerations and Deductions on Heat Engines

Sadi was well-aware of the scope of his results and, throughout a long central part of the *Réflexions,* he used them to study and derive the properties of matter. (I will try to shortly summarize them because they are extremely significant to scientific progress in this era, in which technical innovations were still introducing the most important novelties, opening up new fields, and preceding and inspiring further scientific elaboration.)

In the last part of the *Réflexions*, Sadi takes up the considerations on the best conditions for using caloric drops (i.e., the transfer of heat from one body to one at a lower temperature) and the most suitable substances to use to drive heat engines.

A very relevant conclusion is that:

> *The fall of caloric produces more motive power at inferior than at superior temperatures.*
>
> Thus a given quantity of heat will develop more motive power in passing from a body kept at 1 degree to another maintained at zero, than if these two bodies were at the temperature of 101° and 100°. (Carnot, Sadi 1897, 97)

This is a very important requirement in practice because it emphasizes the importance of keeping the coolant temperature low.

> It is easy to see the advantages possessed by high-pressure machines over those of lower pressure. *This superiority lies essentially in the power of utilizing a greater fall of caloric.* (Carnot, Sadi 1897, 114–115)

He then deals with some absolute calculations of the motive power of steam in cases where the fluid operating the engine is either atmospheric air, water vapor, or alcohol, in order to further verify how, in these concrete cases, efficiency is independent of the agent used. Such calculations were evidently subject to the uncertainties of the data and the precision that could be obtained. (It is important to state the fact that, at the time, error statistics for experimental measurements did not yet exist; this was mathematically developed mainly by the great German mathematician Carl Friedrich Gauss, 1777–1855.)[46]

Sadi also qualitatively examines the superiority of gases over liquids and solids in driving heat engines, since "Physics as yet refuses us the necessary data" (Carnot, Sadi 1897, 108–111).

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[46] For a historical perspective of the historical process towards precision, see (Koyré 1948).

It is also worth mentioning an interesting observation on the inherent limitations of external combustion engines:

> We are obliged to limit ourselves to the use of a slight fall of caloric, while the combustion of the coal furnishes the means of procuring a very great one. (Carnot, Sadi 1897, 113)

The discussion on the advantages of using elastic fluids is very interesting; I deem remarkable the accuracy of the observations concerning the applications, as well as the acute technical and practical considerations (the upper limit of temperature is that of combustion, see also below; the lower limit is given by "the temperature of the coldest body of which we can easily and freely make use; this body is usually the water of the locality"):

> The elastic fluids, gases or vapors, are the means really adapted to the development of the motive power of heat. They combine all the conditions necessary to fulfill this office. They are easy to compress; they can be almost infinitely expanded; variations of volume occasion in them great changes of temperature; and, lastly, they are very mobile, easy to heat and to cool, easy to transport from one place to another, which enables them to produce rapidly the desired effects. We can easily conceive a multitude of machines fitted to develop the motive power of heat through the use of elastic fluids; but in whatever way we look at it, we should not lose sight of the following principles:
>
> (1) The temperature of the fluid should be made as high as possible, in order to obtain a great fall of caloric, and consequently a large production of motive power.
>
> (2) For the same reason the cooling should be carried as far as possible. (Carnot, Sadi 1897, 111–112)

A third condition, namely that the transition from the highest to the lowest temperature of the elastic fluid should be due to the change in volume (Section 10.5), entails difficulties of realization in the case of large caloric drops because it requires solid vessels to withstand high pressures, large dimensions, and large volume and density changes that are difficult to realize.

Sadi then goes on to consider the general advantages of high-pressure steam engines and discusses the practical difficulties:

> It is easy to see the advantages possessed by high-pressure machines over those of lower pressure. *This superiority lies essentially in the power of utilizing a greater fall of caloric*. The steam produced under a higher pressure is found also at a higher temperature, and as, further, the temperature of condensation remains always about the same, it is evident that the fall of caloric is more considerable. (Carnot, Sadi 1897, 114–115)

Specifically for Trevithick's high-pressure engines (Section 5.5), Sadi notes that *they do not have a condenser*, the steam retains a higher pressure than the atmospheric one, and is discharged into the atmosphere, some useful motive power is wasted, but the construction is simplified and costs are lower, a very important consideration because:

> [they] can be used in places where there is not sufficient water for condensation. In such places they are of inestimable advantage, since no others could take their place. These engines are principally employed in England to move coal-wagons on railroads laid either in the interior of mines or outside of them. (Carnot, Sadi 1897, 119)

On the advantages and disadvantages of atmospheric air over water vapor, *there are passages in which Sadi seems to foreshadow an advantage of future internal combustion engines*[47]:

> atmospheric air could be heated directly by combustion carried on within its own mass. Considerable loss could thus be prevented, not only in the quantity of heat, but also in its temperature. This advantage belongs exclusively to atmospheric air. … Air, then, would seem more suitable than steam to realize the motive power of falls of caloric from high temperatures. … The use of atmospheric air for the development of the motive power of heat presents in practice very great, but perhaps not insurmountable, difficulties. If we should succeed in overcoming them, it would doubtless offer a notable advantage over vapor of water. … It is thus upon the use of atmospheric air and vapor of water that subsequent attempts to perfect heat-

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[47] The history of the internal combustion engine is beyond the scope of this paper, but I think a brief mention is interesting because it shows how in the history of technology, genius is not enough, while a country's level of development can be more decisive. The first regularly functioning internal combustion engine was invented between 1851 and 1853 by two Italians, father Nicolò Barsanti (better known as Eugenio, 1821–1864) and hydraulic engineer Felice Matteucci (1808–1887). Lacking a national patent office in Italy, they filed a Memoir at the *Accademia dei Georgofili* in Florence, and subsequently succeeded in patenting it in various countries, as divided Italy did not offer sufficient guarantees for international protection. Between 1851 and 1864 they built several prototypes. The advantage of Barsanti and Matteucci's engine over others that were proposed later, in competition, at the same time, was that it exploited the return motion of the piston due to the cooling of the gas rather than the thrust of the burst. Despite making several prototypes, the backward level of Italian industry did not allow their engine to be built and marketed. They then turned to a company in Belgium, but here Barsanti contracted typhus, and Matteucci returned to his work as a hydraulic engineer. In 1867, the Germans Nikolaus Otto and Eugen Langen proposed and patented an engine model similar to that of Barsanti and Matteucci. The latter claimed priority for the invention: the accumulated failures and frustrations fed the illness that led him to death.
A not dissimilar fate, *mutatis mutandis*, occurred to Antonio Pacinotti (1841–1912) who, at only 17 years of age, designed a reversible magneto-electric machine, the Pacinotti's ring, which functioned both as a direct current generator and as an electric motor. It was a true technological leap, which he unfortunately neglected to patent. As Italian industry was unable to produce it, he travelled to Paris in 1865, where he was swindled by the workshop foreman, the Belgian Zenobe Gramme, who patented it in 1871 and began industrial production.
History repeated itself, albeit in a different way, for Galileo Ferraris's (1847–1897) invention of the alternating current electric motor in the 1880s: According to the prevailing attitude in Italian academic circles at the time, Ferraris disdained "getting his hands dirty with technology" and did not patent his invention. But in the United States, Nikola Tesla claimed the property of the invention. The matter ended up in the courts, which this time proved Ferraris right, but Tesla obtained five patents that were bought by Westinghouse, who then offered them to Ferraris for a fee of $1,000, a ridiculous sum compared to the profits the company made. In short, there was no shortage of genius in Italy in the 19th century, but the country's backwardness prevented them from taking advantage of it.

> engines should be based. It is to utilize by means of these agents the greatest possible falls of caloric that all efforts should be directed. (Carnot, Sadi 1897, 120–123)

Sadi prefaces his final remarks with the following consideration:

> Finally, we will show how far we are from having realized, by any means at present known, all the motive power of combustibles. (Carnot, Sadi 1897, 123)

But one cannot fail to be struck by the consideration that concludes Sadi's essay, which sounds especially today as a warning against the reckless use of technology:

> The economy of the combustible is only one of the conditions to be fulfilled in heat-engines. In many cases it is only secondary. It should often give precedence to safety, to strength, to the durability of the engine, to the small space which it must occupy, to small cost of installation, etc. To know how to appreciate in each case, at their true value, the considerations of convenience and economy which may present themselves; to know how to discern the more important of those which are only accessories; to balance them properly against each other, in order to attain the best results by the simplest means: such should be the leading characteristics of the man called to direct, to co-ordinate among themselves the labors of his comrades, to make them co-operate towards one useful end, of whatsoever sort it may be. (Carnot, Sadi 1897, 126)

10.8. Sadi's Deduction of the Fundamental Laws of Gases

Finally, without going into details, it is important to point out that, in his *Réflexions*, Sadi derived the main thermodynamic laws of gases and their transformations from his conclusions about thermal machines:[48]

> *When a gas passes without change of temperature from one definite volume and pressure to another volume and another pressure equally definite, the quantity of caloric absorbed or relinquished is always the same, whatever may be the nature of the gas chosen as the subject of the experiment. … When a gas varies in volume without change of temperature, the quantities of heat absorbed or liberated by this gas are in arithmetical progression, if the increments or the decrements of volume are found to be in geometrical progression. … The difference between specific heat at constant pressure and specific heat at constant volume is always the same, whatever may be the density of the gas, provided the weight remains the same.* (Carnot, Sadi 1897, 72, 81, 87)

11. A Look at Developments in Heat Science up to Mid-Century: The Threshold of a Major Scientific Breakthrough

11.1. The Troubled Legacy of the Réflexions and the Establishment of Thermodynamics as an Autonomous Discipline

In reality, the *Réflexions* did not immediately receive the attention that Sadi expected, and which it certainly deserved. Over time, many historians have questioned the reasons

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[48] All italics by Carnot.

for the indifference of steam engine engineers to Carnot's work in particular (Kerker 1960; Redondi 1980; Salvi and Schettino 2019).

Ten years later, in 1834, the civil engineer Émile Clapeyron, a pupil like Sadi of the *École Polytechnique* (and a fervent supporter of the caloric theory), published a paper titled *Memoir on the Motive Power of Heat* in which he essentially translated the descriptive analysis of the *Réflexions* into mathematical formulas using mathematical analysis, and graphically represented the cycle of the engine by means of the Watt indicator diagram, familiar to engineers: all strictly in the key of caloric theory.

But 25 years had to pass before the *Réflexions* received substantial recognition from William Thomson (future Lord Kelvin, 1824–1907) and Rudolf Clausius (1822–1888) with the explicit formulation of the Second Law of Thermodynamics. Let me briefly review the decisive research between 1840 and 1850, with a premise which I deem necessary: several commentators of the *Réflexions* have already interpreted them as the introduction of entropy. In fact, everything would work properly in Sadi's reasoning if one interprets his term caloric as "entropy" (Callendar 1911; La Mer 1954; Lunn 1919). (Remember also his anticipatory remarks in the posthumous manuscripts on the transformation of heat into work, Section 10.3.)

Thomson recounts that when he was 21 years old and a recent Cambridge graduate spending the summer of 1845 in Paris in Regnault's workshop, he came across Clapeyron's work and searched in vain for the *Réflexions* at all the booksellers in Paris, who did not even know his name (they showed him at most books by Hippolyte Carnot, Sadi's brother and a politician). Thomson's interest in these problems was revived when, in 1847, he met James Prescott-Joule (1818–1889) at a meeting of the *British Association*.

In fact, the results of Joule's research in the early 1840s were, albeit indirectly, crucial in bringing Sadi's 1824 memoir back to the forefront of physics. Joule, in fact, did not accept the theory of the caloric fluid, and carried out the fundamental experiments on the transformation of mechanical work into heat (integrating with quantitative data the research of the German physician Robert von Mayer that had led him between 1842 and 1845 to formulate the principle of equivalence between the different forms of energy, which later became the First Law of Thermodynamics). Like Faraday and other English scientists of the first half of the nineteenth century, Joule had no formal education, let alone a degree (by chance he was tutored by John Dalton, who passed on to him his non-conformist ideas), and struggled to publish his results until he met Thomson. Joule's long series of experiments were decisive in proving the equivalence and mutual transformability of heat and mechanical energy. Although Joule was a skillful experimenter, he overestimated the sensitivity of his instruments, claiming to estimate 1/200 of a degree Fahrenheit (three thousandths of a K degree). Moreover, his varied experiments (heat production in the passage of an electric current through a resistance; in the passage of a viscous liquid through a capillary tube; in the compression of a gas;

and the famous "Joule's whirlwind") obviously gave different values of the mechanical equivalent of the calory: 4.290, 4.1868, 4.140, and 4.150 J/cal respectively. However, at those times there was no evaluation of measurement errors available to study the compatibility of the different measurements. Joule's presentations to the *British Association* did not fail to arouse skepticism. The academic community was reluctant to accept the reciprocal transformation of work and heat; several papers by Joule were rejected by the authoritative *Philosophical Transactions* but published in the *Philosophical Magazine*, a more liberal journal.[49]

As for Thomson, he was initially a firm believer in the caloric theory under which he interpreted Sadi Carnot's *Réflexions*, and even in 1848 in the work in which he introduced absolute temperature he wrote that "the conversion of heat (or caloric) into a mechanical effect is probably impossible, certainly not discovered."50 Still, a footnote highlighted his first doubts by referring to "Joule's remarkable discoveries." Over the next two years, Thomson converted to the mechanical theory of heat and began a fruitful collaboration with Joule (resulting in the Joule-Thomson effect in 1852).

The formulation of the Second Law of Thermodynamics resulted from a fruitful controversy between Thomson (by then Baron Kelvin) and Rudolf Clausius. Starting from the observation that the then acknowledged basis of Sadi Carnot's *Réflexions* appeared to be in contrast with Joule's experiments, they recognized that the contrast was only apparent because Carnot's theory was in fact independent of the caloric theory. Thus, in 1850 Clausius recognized that they were dealing with two independent and therefore compatible principles, and the following year Kelvin himself recognized the validity of this solution. They arrived in 1851 to the two different classical formulations of the Second Law, later proved to be equivalent.

11.2. The Methodological Synthesis of Nineteenth Century Positivism

There have been plenty of essays and books written on positivism, to which I would not add anything sensible or new. The aspect that I would like to emphasize at the end of this paper is that, in my opinion, the scientific methodology of *positivism* represents the culmination of the paradigm that assumed empirical evidence (experimental data) as the only legitimate basis for the certainty of scientific elaboration, excluding the assumption

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[49] See (Young 2015). Joule's 1850 work with the whirlwind experiment was accepted by *The Philosophical Transactions* on the condition of accepting the referee's suggestion to eliminate a fundamental conclusion on the equivalence of heat and work: This judgment is remarkably preserved in the archives and shows Faraday's handwriting. This says a lot about the resistance in academic circles to accept the equivalence of heat and work. When in 1883 the work was reprinted with another of Joule's works, he added a note: "A third conclusion, suppressed in accordance with the committee to which the work was referred, stated that friction consists in the conversion of mechanical work into heat."

[50] See (Thomson 1848). In 1813, the English engineer Peter Ewart published a paper in the *Manchester Memoirs* urging his readers to accept the principle of conservation of *vis viva*, writing: "If we could avoid all imperfections in our steam engines, we might find that a certain amount of heat always provides a fixed equivalent of heat." Interestingly, John Dalton helped Ewart write this paper, so it may have been through Dalton that Joule learned of the original idea to investigate this problem.

of hypotheses or models that did not derive from experience. In fact, the general term of *positivism* incudes a wide range of individual choices across different fields. Furthermore, implicit assumptions inspired at a minimum, as it is logical, all scientific elaboration, such as those that seemed natural at the time: those of the imponderable caloric, or luminiferous, electric, and magnetic fluids.

It is known that this methodology was explicitly formulated by Auguste Comte (1798–1857, with the publication of the *Course of Positive Philosophy* between 1830 and 1842) who—noting that the French Revolution had given rise to a new moral, social, and political order—proposed a philosophical synthesis that would prepare the advent of an "organic epoch" founded not on Hegelian speculative reason, but rather on the empirical paradigm of modern science. Comte thus legitimized the inheritance of the knowledge acquired by the science of his time and the approach that had made it possible in order to make it the basis of the future epoch (positive knowledge) by renouncing the knowledge of intimate causes and setting the limit to factual data: *The search for laws, aside the search for causes*. In essence, Comte brought the scientific approach and procedures that had been established at the turn of the nineteenth century to a methodological synthesis. Witnessing the crisis of growth of an era, Comte set out to define an organic vision, the ideal of a rational policy, the need for a scientific conception of man, and the function of knowledge in society. On this basis, he also proposed to address issues relating to man and society by adopting the rigorous method of the natural sciences, meaning he is now regarded as the founder of sociology.

However, as with all general definitions and categories, the term "positivism" should also be understood as a schematization: the constantly changing historical situation was far more complex, articulated, and rich. Indeed, not all positivist scientists could be lumped together in a single, uniform methodological approach; each of them interpreted the empirical approach in their own personal way (and it even changed in the course of their work). Moreover, adherence to experimental data could not be reduced to mere empirical observation, and at a certain level of elaboration it presupposed the adoption of an interpretative framework, like the fluid models. But the Avogadro-Ampère "hypothesis" on the distinction between the atom and the molecule was not accepted until the second half of the nineteenth century, leaving many problems in chemistry unresolved. Jean-Baptiste Lamarck formulated a theory of evolution of living species based on the principle that physical changes in organisms during their lifetime—such as greater development of an organ or a part through increased use—could be transmitted to their offspring. In addition, there were other different currents of thought in Europe, such as the romantic conception of nature, which undoubtedly inspired scientists and intellectuals from the German-speaking area in particular, such as Hans Christian Ørsted, who was stimulated by the idea of the unity of forces in nature to embark on the study of the links between electricity and magnetism, but whose philosophy then inspired the research of Michael Faraday.

With regard to positivism, I would observe, according to my interpretation of the social history of science, that it represented the early phase of development of industrial society, in which the rejection of hypotheses—or entities that were not directly observable and measurable—reflected the need to establish a verifiable and reliably applicable science. It was therefore also a reaction to the speculative hypotheses and models, sometimes elevated into world systems, that had dominated science (or natural philosophy) in the previous centuries.

12. The End of an Era and the Beginning of the Second Industrial Revolution

The conclusion of this work cannot but concern the end of an epoch, that of the First Industrial Revolution in England, with its reflections in the French Enlightenment and the inauguration of a new phase in the development of capitalism.

Actually, the assumption of a science based on purely empirical facts and experimental data would be literally overturned in the second half of the nineteenth century, when a second wave of capitalist development and industrialization led to overcoming the prevalence of technical achievements as the basis of new processes. The revolutions of 1848 definitively altered the social balances in Europe. Although after the shake-up practically all former rulers returned to power, in reality, the bourgeois strata gained a decisive role compared to the aristocratic classes, and in the following decades they influenced a decisive turn to industrial development.

How to overcome the challenge of surpassing the might of British industry? The solution was through a radical renewal of science. (Obviously, I do not argue that it was the conscious choice of every scientist or group of scientists, but the intellectual classes shared and reflected the ideals and purposes of the new bourgeoisie that was establishing itself on the continent.) The assumption of the rejection of hypotheses and models was reversed. The adoption and development of rigorous *mathematical models*—the possibility to refine and generalize them to cope with the gaps in reproducing the phenomena—became a probe to explore and discover completely new fields of phenomena, which could disclose innovative technical applications and open new industrial sectors. One of the most striking cases was when Maxwell's mathematical theory of electromagnetic phenomena predicted the existence of electromagnetic waves, but theoretical chemistry also recorded radically innovative discoveries.

The adoption of models based on rigorous mathematical methods overturned the relationship between science and technology that had characterized the first phase of industrialization. Maxwell's theory of electromagnetic phenomena made it possible to predict electromagnetic waves; organic chemistry opened a Pandora's box of innovations; statistical mechanics and the subsequent investigations into atomic structure revolutionized physics. In terms of energy devices and resources, internal combustion engines came to the fore, and the age of oil began.

The enormous industrial gap with the British colossus was bridged by radically transforming the technological basis. Around 1870, the ranking of European industrial powers was still England–France–Germany, within the next 30 years alone it was overturned into: Germany–England–France. The development of the advanced chemical and electrical industries became the driving sectors of German industry.

This turn in the last decades of the nineteenth century determined the take-off of the Second Industrial Revolution.

My analysis of these developments was set out, with other collaborators, in the essay *Scienza e Industria 1848–1915* (Baracca, Ruffo, and Russo 1979)[51], of which the present work is the logical and historical premise. I must stress that my entire research on these subjects was inspired by the work of David Landes (1924–2013), whose *Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present* (1969) is a fundamental essay on the subject.[52]

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[51] Also available as a preprint of the Max Planck Institute for the History of Science, with an extensive overview in English (Baracca, Ruffo, and Russo 2021).

[52] An accomplished Italian sociologist, Sergio Bologna, compared Landes, “author of one of the most beautiful history books ever written,” almost to a bourgeois Marx (S. Bologna, "Quando un borghese 'puro' è meglio di un comunista", Il Manifesto, 5 dicembre 1978).

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