

Science

Science and the Industrial Revolution

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Industrial Revolution were closely connected. It is difficult to show any direct effect of scientific discoveries upon the rise of the textile or even the metallurgical industry in Great Britain, the home of the Industrial Revolution, but there certainly was a similarity in attitude to be found in science and [nascent](#) industry. Close observation and careful generalization leading to practical utilization were characteristic of both industrialists and experimentalists alike in the 18th century. One point of direct contact is known: namely, [James Watt](#)'s interest in the [efficiency](#) of the Newcomen [steam engine](#), an interest that grew from his work as a scientific-instrument maker and that led to his development of the separate condenser that made the steam engine an effective industrial power source. But, in general, the Industrial Revolution proceeded without much direct scientific help. Yet the potential influence of science was to prove of fundamental importance.

What science offered in the 18th century was the hope that careful observation and experimentation might improve industrial production significantly. In some areas, it did. The potter [Josiah Wedgwood](#) built his successful business on the basis of careful study of clays and glazes and by the invention of instruments like the pyrometer with which to [gauge](#) and control the processes he employed. It was not, however, until the second half of the 19th century that science was able to provide truly significant help

to industry. It was then that the science of metallurgy permitted the tailoring of alloy steels to industrial specifications, that the science of [chemistry](#) permitted the creation of new substances, like the aniline dyes, of fundamental industrial importance, and that electricity and magnetism were harnessed in the electric dynamo and motor. Until that period science probably profited more from industry than the other way around. It was the steam engine that posed the problems that led, by way of a search for a theory of [steam power](#), to the creation of thermodynamics. Most importantly, as industry required ever more complicated and [intricate](#) machinery, the [machine tool](#) industry developed to provide it and, in the process, made possible the construction of ever more delicate and refined instruments for science. As science turned from the everyday world to the worlds of atoms and molecules, electric currents and magnetic fields, microbes and viruses, and nebulae and galaxies, instruments increasingly provided the sole contact with phenomena. A large refracting telescope driven by intricate clockwork to observe nebulae was as much a product of 19th-century heavy industry as were the steam locomotive and the steamship.

The Industrial Revolution had one further important effect on the development of modern science. The prospect of applying science to the problems of industry served to stimulate public support for science. The first great scientific school of the modern world, the [École Polytechnique](#) in Paris, was founded in 1794 to put the results of science in the service of France. The founding of scores more [technical](#) schools in the 19th and 20th centuries encouraged the widespread [diffusion](#) of scientific knowledge and provided further opportunity for scientific advance. Governments, in varying degrees and at different rates, began supporting science even more directly, by making financial grants to scientists, by founding research institutes, and by bestowing honours and official posts on great scientists. By the end of the 19th century the natural philosopher following his private interests had given way to the professional scientist with a public role.

The Romantic revolt

Perhaps inevitably, the triumph of Newtonian mechanics elicited a reaction, one that had important [implications](#) for the further development of science. Its origins are many and complex, and it is possible here to focus on only one, that associated with

the German philosopher [Immanuel Kant](#). Kant challenged the Newtonian confidence that the scientist can deal directly with subsensible entities such as atoms, the corpuscles of light, or electricity. Instead, Kant insisted, all that the human mind can know is [forces](#). This epistemological [axiom](#) freed Kantians from having to conceive of forces as embodied in specific and immutable particles. It also placed new emphasis on the space between particles; indeed, if one eliminated the particles entirely, there remained only space containing forces. From these two considerations were to come powerful arguments, first, for the transformations and conservation of forces and, second, for [field](#) theory as a representation of reality. What makes this point of view [Romantic](#) is that the idea of a network of forces in space tied the cosmos into a unity in which all forces were related to all others, so that the universe took on the aspect



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What [Romantics](#), or [nature](#) philosophers, as they called themselves, could see that was hidden from their Newtonian colleagues was demonstrated by [Hans Christian Ørsted](#). He found it impossible to believe that there was no connection between the forces of nature. Chemical [affinity](#), electricity, heat, magnetism, and light must, he argued, simply be different [manifestations](#) of the basic forces of attraction and repulsion. In 1820 he showed that electricity and magnetism were related, for the passage of an electrical current through a wire affected a nearby magnetic needle. This fundamental discovery was explored and exploited by [Michael Faraday](#), who spent his whole scientific life converting one force into another. By concentrating on the patterns of forces produced by electric currents and magnets, Faraday laid the foundations for [field theory](#), in which the energy of a system was held to be spread throughout the system and not localized in real or [hypothetical](#) particles.

The transformations of force necessarily raised the question of the conservation of force. Is anything lost when electrical energy is turned into magnetic energy, or into heat or light or chemical affinity or mechanical power? Faraday, again, provided one of the early answers in his two laws of electrolysis, based on experimental observations that quite specific amounts of electrical “force” decomposed quite specific amounts of chemical substances. This work was followed by that of [James Prescott Joule](#), Robert Mayer, and [Hermann von Helmholtz](#), each of whom arrived at

a generalization of basic importance to all science, the principle of the [conservation of energy](#).

The nature philosophers were primarily experimentalists who produced their transformations of forces by clever experimental manipulation. The exploration of the nature of elemental forces benefitted as well from the rapid development of mathematics. In the 19th century the study of heat was transformed into the science of thermodynamics, based firmly on mathematical analysis; the Newtonian corpuscular theory of light was replaced by [Augustin-Jean Fresnel's](#) mathematically sophisticated undulatory theory; and the phenomena of electricity and magnetism were distilled into [succinct](#) mathematical form by William Thomson ([Lord Kelvin](#)) and [James Clerk Maxwell](#). By the end of the century, thanks to the principle of the conservation of energy and the [second law of thermodynamics](#), the physical world appeared to be completely comprehensible in terms of complex but precise mathematical forms describing various mechanical transformations in some underlying [ether](#).

The submicroscopic world of material [atoms](#) became similarly comprehensible in the 19th century. Beginning with [John Dalton](#)'s fundamental assumption that atomic species differ from one another solely in their weights, chemists were able to identify an increasing number of elements and to establish the laws describing their interactions. Order was established by arranging elements according to their atomic weights and their reactions. The result was the [periodic table](#), devised by [Dmitry Mendeleyev](#), which implied that some kind of subatomic structure underlay elemental qualities. That structure could give rise to qualities, thus fulfilling the prophecy of the 17th-century mechanical philosophers, was shown in the 1870s by [Joseph-Achille Le Bel](#) and [Jacobus van 't Hoff](#), whose studies of organic chemicals showed the [correlation](#) between the arrangement of atoms or groups of atoms in space and specific chemical and physical properties.

The founding of modern biology

The study of living matter lagged far behind physics and [chemistry](#), largely because organisms are so much more complex than inanimate bodies or forces. Harvey had shown that living matter could be studied experimentally, but his achievement stood

alone for two centuries. For the time being, most students of living nature had to be content to classify living forms as best they could and to attempt to isolate and study aspects of living systems.

As has been seen, an avalanche of new specimens in both botany and zoology put severe pressure on [taxonomy](#). A giant step forward was taken in the 18th century by the Swedish naturalist [Carl von Linné](#)—known by his Latinized name, Linnaeus—who introduced a rational, if somewhat artificial, system of binomial [nomenclature](#). The very artificiality of Linnaeus's system, focusing as it did on only a few key structures, encouraged [criticism](#) and attempts at more natural systems. The attention thus called to the organism as a whole reinforced a growing [intuition](#) that species are linked in some kind of genetic relationship, an idea first made scientifically explicit by [Jean-Baptiste, chevalier de Lamarck](#).

Problems encountered in cataloging the vast collection of invertebrates at the Museum of Natural History in Paris led Lamarck to suggest that [species change](#) through time. This idea was not so revolutionary as it is usually painted, for, although it did upset some Christians who read the book of Genesis literally, naturalists who noted the shading of natural forms one into another had been toying with the notion for some time. Lamarck's system failed to gain general [assent](#) largely because it relied upon an antiquated chemistry for its causal agents and appeared to imply a conscious drive to perfection on the part of organisms. It was also opposed by one of the most powerful paleontologists and comparative anatomists of the day, [Georges Cuvier](#), who happened to take Genesis quite literally. In spite of Cuvier's opposition, however, the idea remained alive and was finally elevated to scientific status by the labours of [Charles Darwin](#). Darwin not only amassed a wealth of data supporting the notion of transformation of species, but he also was able to suggest a mechanism by which such evolution could occur without recourse to other than purely natural causes. The mechanism was [natural selection](#), according to which minute variations in offspring were either favoured or eliminated in the competition for survival, and it permitted the idea of evolution to be perceived with great clarity. Nature shuffled and sorted its own productions, through processes governed purely by chance, so that those organisms that survived were better adapted to a constantly changing [environment](#).

Darwin's [*On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*](#), published in 1859, brought order to the world of organisms. A similar unification at the microscopic level had been brought about by the [cell theory](#) announced by [Theodor Schwann](#) and [Matthias Schleiden](#) in 1838, whereby cells were held to be the basic units of all living tissues. Improvements in the microscope during the 19th century made it possible gradually to lay bare the basic structures of cells, and rapid progress in biochemistry permitted the [intimate](#) probing of cellular physiology. By the end of the century the general feeling was that physics and chemistry [sufficed](#) to describe all vital functions and that living matter, subject to the same laws as inanimate matter, would soon yield up its secrets. This reductionist view was triumphantly illustrated in the work of [Jacques Loeb](#), who showed that so-called instincts in lower animals are nothing more than physicochemical reactions, which he labelled [tropisms](#).

The most dramatic revolution in 19th-century biology was the one created by the [germ theory](#) of [disease](#), championed by [Louis Pasteur](#) in France and [Robert Koch](#) in Germany. Through their investigations, bacteria were shown to be the specific causes of many diseases. By means of immunological methods first [devised](#) by Pasteur, some of humankind's chief maladies were brought under control.

The 20th-century revolution

By the end of the 19th century, the dream of the mastery of nature for the benefit of humankind, first expressed in all its richness by [Sir Francis Bacon](#), seemed on the verge of realization. Science was moving ahead on all fronts, reducing ignorance and producing new tools for the amelioration of the human condition. A comprehensible, rational view of the world was gradually emerging from laboratories and universities. One [savant](#) went so far as to express pity for those who would follow him and his colleagues, for they, he thought, would have nothing more to do than to measure things to the next decimal place.

But this sunny confidence did not last long. One annoying problem was that the radiation emitted by atoms proved increasingly difficult to reduce to known mechanical principles. More importantly, [physics](#) found itself relying more and more upon the [hypothetical](#) properties of a substance, the [ether](#), that stubbornly eluded

detection. Within a span of 10 short years, roughly 1895–1905, these and related problems came to a head and wrecked the mechanistic system the 19th century had so laboriously built. The discovery of X rays and radioactivity revealed an unexpected new complexity in the structure of atoms. [Max Planck's](#) solution to the problem of [thermal radiation](#) introduced a discontinuity into the concept of energy that was inexplicable in terms of classical thermodynamics. Most disturbing of all, the enunciation of the [special theory](#) of [relativity](#) by [Albert Einstein](#) in 1905 not only destroyed the [ether](#) and all the physics that depended on it but also redefined physics as the study of relations between observers and events, rather than of the events themselves. What was observed, and therefore what happened, was now said to be a function of the observer's location and motion relative to other events. Absolute space was a fiction. The very foundations of physics threatened to crumble.

This modern revolution in physics has not yet been fully [assimilated](#) by historians of [science](#). [Suffice](#) it to say that scientists managed to come to terms with all of the upsetting results of early 20th-century physics but in ways that made the new physics utterly different from the old. Mechanical models were no longer acceptable, because there were processes (like light) for which no consistent model could be constructed. No longer could physicists speak with confidence of physical reality, but only of the probability of making certain measurements.

All this being said, there is still no doubt that science in the 20th century worked wonders. The new physics—relativity, [quantum mechanics](#), particle physics—may have outraged common sense, but it enabled physicists to [probe](#) to the very limits of physical reality. Their instruments and mathematics permitted modern scientists to manipulate subatomic particles with relative ease, to reconstruct the first moment of creation, and to dimly glimpse the grand structure and ultimate fate of the universe.

The 21st century

In the 21st century the revolution in physics spilled over into chemistry and biology and led to hitherto undreamed-of capabilities for the manipulation of atoms and molecules and of cells and their genetic structures. Chemists perform molecular tailoring today as a matter of course, cutting and shaping molecules at will. [Genetic engineering](#) and the subsequent development of [gene editing](#), a highly accurate and

efficient means of altering DNA, made possible active human intervention in the evolutionary process and held out the possibility of tailoring living organisms, including the human organism, to specific tasks. This second scientific revolution may prove to be, for good or ill, one of the most important events in the history of humankind.

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