A Brief History of Science
Part 7: The Heydays of Mechanical Materialism

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THE GREAT UPHEAVAL of science in the 17th century after the millennia of slumber of the middle ages reached its pinnacle in the masterly work of Newton. For a long time Europeans had forgotten to look at the nature around them with eyes of curiosity, and had directed their interest to the divine. The success of Newtonian mechanics in explaining the motion around us, especially the motion of the heavenly bodies, caused a resurgence of materialist outlook. That, in turn, generated interest in understanding various aspects of nature, and led to a condition conducive to the development of various branches of science. People in larger numbers were taking part in scientific enquiry.

However, in the area in which Newton had maximum contribution, namely mathematical mechanics, we see relatively few new ideas added for a long time. His works on mechanics was so exhaustive and comprehensive that scientists in the period following Newton's lifetime found it difficult to add anything substantial to this body of knowledge. It was a period of digestion and assimilation of the ideas he created and their application in different domains. It was only in the second half of the 18th century that Leonhard Euler (1707–1783) and Joseph-Louis Lagrange (1736–1813) and much later William Rowan Hamilton (1805–1865) managed to enrich classical mechanics substantially beyond the Newtonian formulation.

Measuring the solar system

After Newton the heliocentric nature of the solar system and the laws governing its motion were established, but many important details about the solar system were not yet known. What is the weight of the Earth? How big is the solar system? What are the distances to the sun and the moon? What are the radii of the orbits of the other planets? The answers to these obvious questions were not known in Newton's time.

Using Kepler's laws, one can measure the ratios of the radii of the planetary orbits. But unless the true radius of the orbit of at least one planet is known, none of the radii is known in absolute terms. Thus the measurement of the Earth-to-sun distance became a matter of paramount importance. The distance to the moon could be measured using the method of parallax (the change in the moon's position in the background of distant stars when viewed from two different locations). But the same method cannot be applied to find the distance to the sun, because when the sun is glowing in the sky, the background stars are not visible.

Newton's friend Edmond Halley came up with a brilliant idea to measure the distance to the sun. He showed that this can be done only when the planet Venus comes

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Series Article

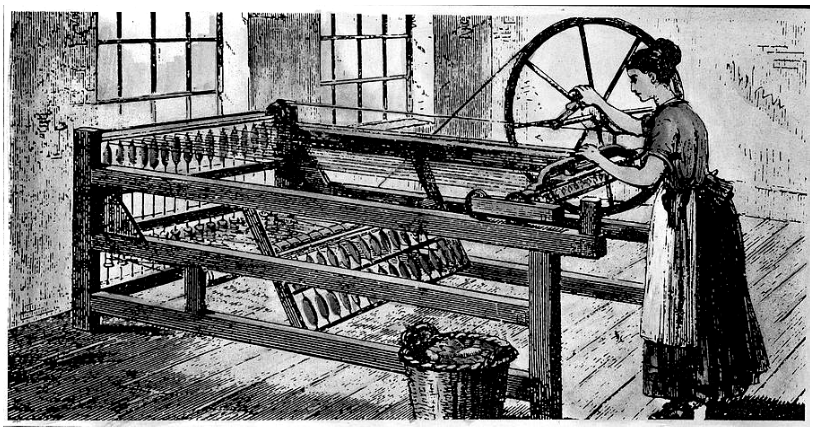


Figure 1: The Spinning Jenny.

between the sun and the Earth, which is a very rare incident. During a "transit of Venus," the planet is seen as a small black dot passing across the disc of the sun. The first recorded observation of a transit of Venus was made by the Englishmen Jeremiah Horrocks and William Crabtree in the year 1639. In a paper published in 1726 Halley showed that, if the path of Venus across the sun's disc is observed from distant locations on the Earth and the exact times of contacts with the sun's circumference are recorded, one can compute the distance to the sun from that information (for details, see Breakthrough, Vol.15, No.3, February 2012. The article is available in Breakthrough website).

Halley died in 1742, and the next couple of transits of Venus occurred in 1761 and 1769. In these two years a massive collaborative effort was undertaken by scientists, where they launched expeditions to distant lands across the globe, faced unforeseen hurdles, and recorded the event scientifically. When the data were brought back, the French astronomer Jerome Lalande calculated the distance to the sun to be 153 million kilometres. After this success the distances to the other planets could be calculated easily using Kepler's laws. Cavendish (1731–1810) figured out a way of measuring the weight of the Earth in 1798 using a sensitive torsional balance. Thus, by the turn of the eighteenth century, most of the important information about the solar system was known.

The Industrial Revolution

In the social sphere, capitalism was coming out of the initial phase where production was done in handicraft-oriented manufactories controlled by merchants into one of heavy industry controlled by financial houses. This transformation resulted from the industrial revolution (1760 to about 1830) which benefited from the development of science, and which, in turn, benefited science. The initial onset of the industrial revolution, however, did not depend on the scientific discoveries. Due to a short supply of firewood, use of coal in place of firewood as source of heat started in the manufactories. Technologies necessary for the mining and use of coal had to be developed, which paved the way for path-breaking inventions that changed the course of history. The initial inventions

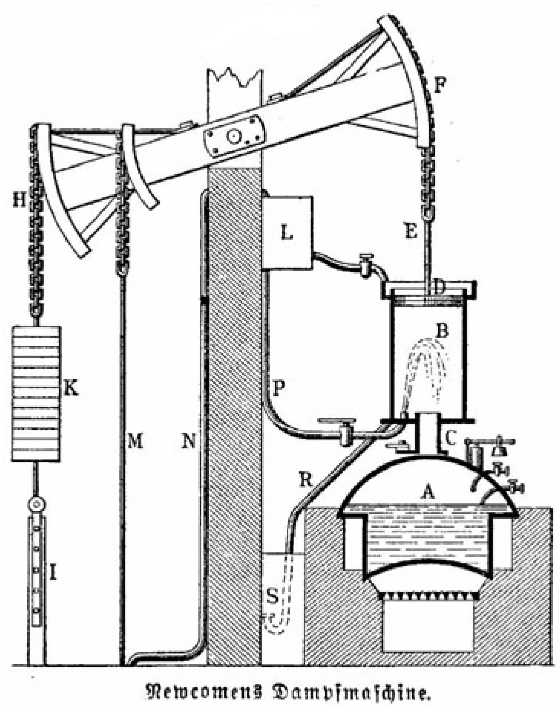


Figure 2: The Newcomen engine.

that multiplied productivity came from the working men. In the manufacture of textiles, Hargreaves' spinning jenny (1764), Arkwright's water frame (1769), Crompton's mule (1779), and Cartwright's power loom (1785) first increased the productivity of hand-operation, and then caused the transition from the old hand-operated technique to machines that ran on externally supplied power. In 1709, Darby developed the way of making iron from iron ore using coke obtained from coal (instead of charcoal), which increased the production of iron many folds.

Finally, with the invention of steam engine made the decisive break with the old production system. In 1711 a blacksmith called Thomas Newcomen (1664–1729) built the first machine working on steam power. It consisted of a cylinder in which steam was introduced through an inlet pipe, which pushed up a piston. When the piston reached the other end of the piston, the steam inlet would be closed and the cylinder would be cooled with a jet of cold water. This would condense the steam into water and the piston would return to the old position. Again steam would be introduced and the cycle would be repeated. The cycle was slow, but still the machine managed to replace muscle power in water pumping in mines and some other industrial operations. James Watt (1736–1819), the owner of a mechanics shop in Glasgow, improved the design by replacing the condensation inside the cylinder with condensation in a separate condenser chamber which was kept cold permanently by circulating cold water. At the end of the pushing phase an outlet valve would open, allowing the steam to exit to the condenser. He also devised the means for converting the reciprocating motion of the piston into the rotational motion of a wheel. The first working model was produced in 1765, and after a few refinements was released to the market in 1774.

With the development of the steam engine, mankind saw a great leap in industrial productivity. Steam engines could effectively tackle the problem of water accumulation in mines using steam operated pumps. This hugely increased the production of coal to provide a cheap source of power. Cotton mills and other factories quickly adopted this source of power. Iron and steel making started in a big way. Transportation became much faster with the development of steamers and steamships. Railways powered by steam engines were developed in the early 1800s, which could carry much greater amount of goods. New industrial towns like Manchester, Birmingham, Newcastle, and Glasgow — with favourable political disposition

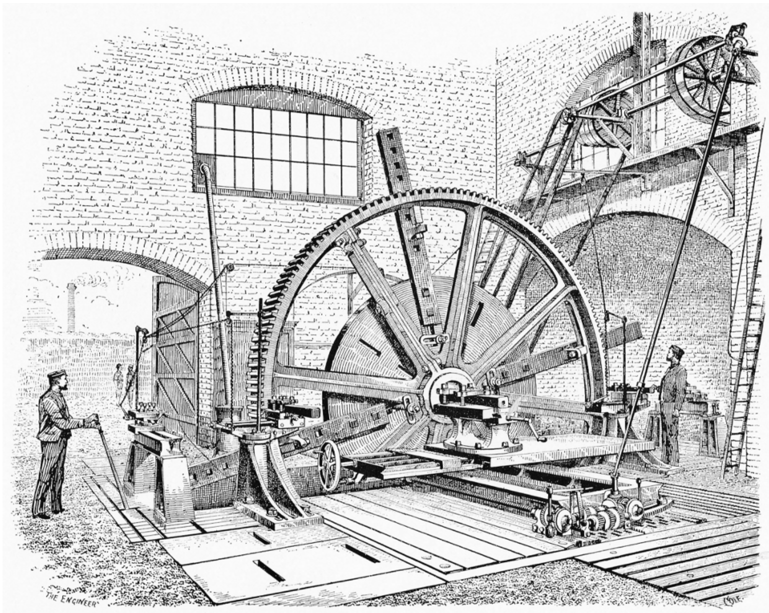
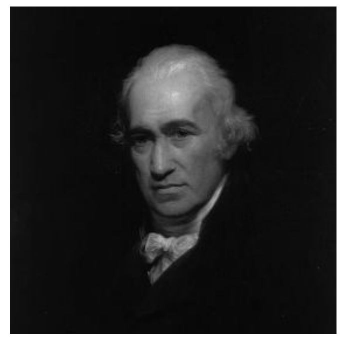



Figure 3: Left: The Watt engine in industry. Right: James Watt (1736–1819).

and access to water and coal — grew and assumed the centre-stage of industrial activity.

Science comes out of belief systems

We have seen how the development of science was impeded for a long time due to the beliefs in a geocentric picture of the universe and Aristotelian ideas in mechanics, which were overcome through the work of Copernicus, Galileo, Kepler, and Newton. After Newton, the fight with these unscientific notions was gaining victories one after the other. But in many fields the hangover of the medieval style of thinking persisted for quite some time. Imaginary "spirits" were thought to be responsible for many natural phenomena. Heat was thought to be due to the presence of a fluid-like substance called "caloric". Magnetism was explained in terms of a mysterious "essence" — the spirit of magnetism. Burning was thought to be caused by the presence of a substance called "phlogiston"; when a piece of wood burnt, this substance was believed to be coming out to form the flame. The distinction between living matter and nonliving matter was thought to be due to the presence of a "vital force" in the former. Nobody bothered to define what the nature of these mysterious spirits was, and how their presence or absence could be tested. One did not know whether these were material substances which could be isolated, or were particular states of matter. Still these ideas persisted even among capable scientists and impeded the development of science.

The nature of heat

The ideas about the nature of heat started developing only after its practical application was invented, first by Newcomen, and then by James Watt. The steam engine

Figure 4: Benjamin Thompson (1753–1814).

made it apparent that mechanical work could be obtained only by expending heat, and therefore they must be of a similar character. The first indication that "caloric" was not a material substance came from the experiments of Benjamin Thompson, later known as Count Rumford. He argued that if caloric was a material substance, its content must be different in water and ice. To test it, he weighed a piece of ice and the water obtained upon melting it, and found that they weigh exactly the same. This raised the first doubts about the caloric theory. Rumford further demonstrated that when a blunt borer is rubbed vigorously against a cannon barrel, it produced a large quantity of heat that could boil water. But in that process there was no reduction of the weight of the barrel. These ideas were slow in finding acceptance, but when it happened, people realized that heat was not a fluid-like material substance, and was really a form of energy that could be obtained only by expending another form of energy.

The nature of electricity

It was known for a long time that static electricity could be produced by rubbing various substances with silk. Its properties were extensively studied by Coulomb, Cavendish, Galvani, Volta, and Franklin. Big frictional machines were built that could produce very large quantities of charge. Playing with the strange properties of this "frictional" electricity almost became a hobby of many people. Through such investigations, Cavendish (1731–1810), and Coulomb (1736–1806) discovered that the charges were of two types, and that unlike charges attract each other and like charges repel.

Benjamin Franklin's famous experiment with lightning showed that this powerful atmospheric phenomenon that inspired awe and was linked with the rage of gods, was nothing but flowing electricity. Galvani's (1737–1798) serendipitous discovery that a dead frog's legs can twitch when touched with two dissimilar metals led to the idea of current electricity. Alessandro Volta (1745–1827) followed up the observation by exper-

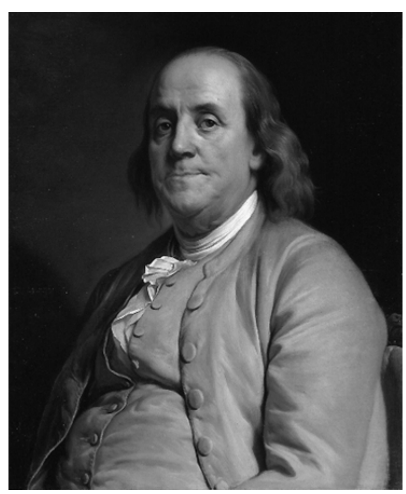


Figure 5: Benjamin Franklin (1705–1790).

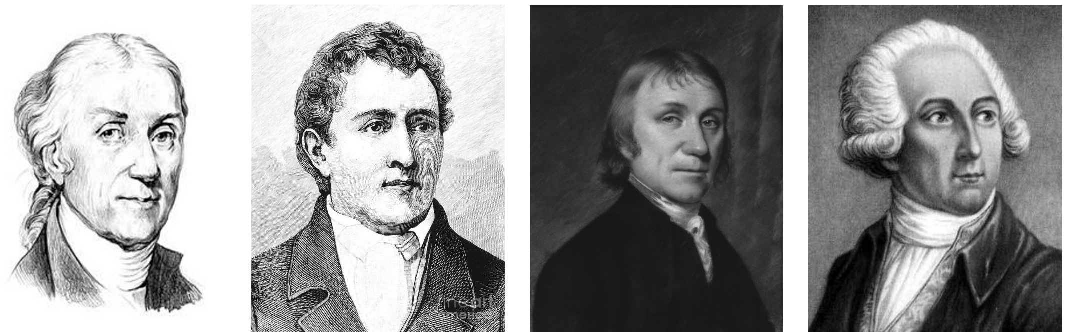


Figure 6: The players in the chemical revolution. L–R: Henry Cavendish (1731–1810), Carl Wilhelm Scheele (1742–1786), Joseph Priestley (1733–1804), and Antoine Lavoisier (1743–1794).

imenting with dissimilar metals dipped in acid or salt solutions, and came up with the idea of the first battery: a pile of zinc and copper plates arranged alternately, separated by cloth moistened with weak acid.

What is burning?

Chemistry was then just coming out of the cradle of alchemy. The alchemist's random experiments in search of a process that could transform different substances into gold yielded some knowledge about the experimental techniques. But there was little concrete knowledge about the processes of chemical transformation. In the early 18th century much of the chemists' curiosity centred on the process of burning, and the nature of air. But the progress on these questions was seriously hindered by the belief in phlogiston theory.

Since the burning of wood involved very complicated chemical processes, with many different substances taking part, little progress was made so long as people tried to understand the process of burning by studying burning of wood. But when people started studying the burning of metals, it was found that the product of combustion weighed *more* that the metal that burned. By burning substances in a jar with its mouth in water, John Mayow (1649–1679) showed that the volume of air decreases when something is burnt. He also showed that the volume decreases by the same amount when a mouse is left to breathe in air confined in a jar until it dies. These were the knowledge available when people like Scheele, Priestley, Cavendish and Lavoisier confronted the problem.

Scheele was a very competent Swedish chemist who discovered chemical elements such as barium (1774), manganese (1774), molybdenum (1778), and tungsten (1781), as well as several chemical compounds, including citric acid, lactic acid, glycerol, hydrogen cyanide, hydrogen fluoride, and hydrogen sulfide. It was probably he who first isolated oxygen. But he failed to understand its role in burning, because of his belief in the phlogiston theory. Henry Cavendish discovered hydrogen, and showed that it burns completely producing only water. But he thought he had succeeded in isolating phlogiston. Joseph Priestley made an arrangement of heating substances by focusing sunlight using a large lens, and used it on a substance called "red powder of mercury" (basically mercuric oxide). He found that a colourless gas emerged from the powder. He experimented with the gas and found that it aids burning. Yet, because of his adherence to the phlogiston theory he failed to identify it as oxygen that forms part of air.

Lavoisier, the French chemist, was free of such preconceived notions. He replicated these experiments, and managed to see what others failed to see: that this gas, oxygen, formed part of air. It is this gas that combines with substances in the process of burning, thus increasing the weight of the product. It is this gas that aids breathing — a process in which it gets converted into carbon dioxide. Because of this insight he is credited with the discovery of oxygen, even though others preceded him in isolating the gas. It was he who categorized substances as oxides, salts, acids, alkalis, etc., and founded modern chemistry as we know it today.

After this decisive break with the past, chemistry advanced unhindered, and within a century all the naturally occurring chemical elements and most common compounds were discovered.

The rise of empiricism

It is to be noticed that in all these advancements the essential inputs came from experiment. Incorrect fanciful ideas were slowly being dispelled by conducting careful experiments. Mankind was taking successful steps in understanding Nature, by following the demands of objectivity.

In this background, in the realm of philosophy the idea of empiricism was developed by Locke, Hume, and Mill, which demanded that one should rely only on experience as the source of ideas and knowledge. John Locke, in his book "An Essay Concerning Human Understanding" (1689) proposed a very influential view that genuine information about the world must be acquired by *a posteriori* means, because nothing can be thought without first being sensed. According to him, the human mind is a "white paper," on which the experiences derived from sense impressions as a person's life proceeds are written.

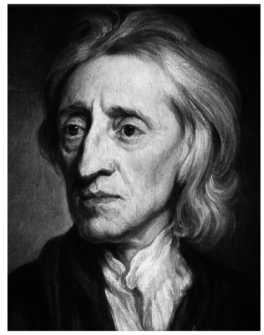



Figure 7: The early empiricists: John Locke (1632–1704), and David Hume (1711–1776)

The idea however did not go unopposed. The Irish Anglican bishop, George Berkeley (1685–1753), realized that Locke's view was in essence materialistic in nature, and hence challenged the Church propagated beliefs. In his "Treatise Concerning the Principles of Human Knowledge" (1710) he proposed the view that things only exist either as a result of their being perceived, or by virtue of the fact that they are an entity doing the perceiving. Berkeley maintained that any order humans may see in nature is the language or handwriting of God. Berkeley's philosophy later came to be called subjective idealism. This philosophy did not attract much attention during his lifetime, as in the post-Newton era mechanical materialistic views held sway. But later this view was adopted as the main philosophical plank for those who wanted to oppose materialism. Even today we see Berkeley's shadow in many current writings.

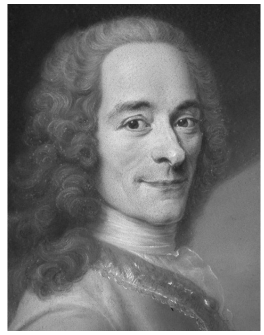
The Scottish philosopher David Hume responded to Berkeley's criticisms of Locke, and moved empiricism to a new level of scepticism. He urged people to have a questioning attitude towards ideas, opinions, and beliefs that are stated as facts and are taken for granted. Hume argued in keeping with the empiricist view that all knowledge derives from sense experience; that even the most basic ideas about the natural world cannot be conclusively established by reason. Rather, he maintained that these are more a result of accumulated habits, developed in response to accumulated sense experiences.

Thus we see that empiricism emphasized evidence, especially as discovered in experiments (and in case of astronomy, in observations). It demanded that all hypotheses and theories must be tested against observations of the natural world rather than resting solely on *a priori* reasoning, intuition, or revelation. The nineteenth century philosopher John Stuart Mill (1806–1873) later argued that all human knowledge, including even mathematics and logic, is derived by generalization from sensory experience.

The development of science in the eighteenth century was occurring in the intellectual atmosphere of empiricism. It helped dispel the unfounded beliefs that blocked the advancement of science. But, as we shall see later, the further development of this philosophical trend gave birth to positivism in the nineteenth century, which also misled scientific investigation for quite a long time.

Wave of Enlightenment Reaches France

The above developments occurred mainly in Britain. In France the intellectual atmosphere was dominated for a longer time by the dry scholasticism of the seminaries, where people argued endlessly about the meaning of each passage of the Bible, and Aristotle's writings. But around the middle of the eighteenth century enlightenment reached France like a wave. Dis-



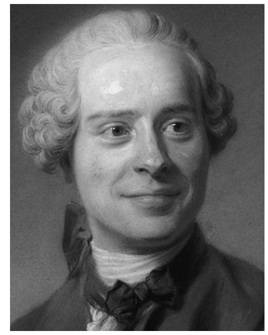


Figure 8: The encyclopedists: Denis Diderot (1713–1784), and Jean-Baptiste le Rond d'Alembert (1717–1783)

cussion groups or "salons" sprang up that discussed topics ranging from science to ethics, morality, politics, and aesthetics on the basis of the spirit of enlightenment. Voltaire (1694–1778) was instrumental in disseminating Newton's philosophy in France. Finally a group of prominent intellectuals led by Diderot (1713–1784) and d'Alembert (1717–1783) decided to compile the entire knowledge accumulated till that time in the form of a massive "Encyclopedie".

It became a rallying point of free-minded intellectuals and scientists who contributed to it over a long period from 1751 to 1772. It was published in 35 volumes and became immensely influential in spreading the message of enlightenment in the European countries as well as in America.

Most historians think that the Encyclopedia played a major role in creating the intellectual backdrop of the American revolution (1781) and the French revolution (1789) as the political ideals of the enlightenment, as embodied in the Encyclopedia, were incorporated in the American Declaration of Independence, the United States Bill of Rights, the French Declaration of the Rights of Man and of the Citizen, etc.

The mood of the time can be aptly seen in the life of a front-ranking French scientist of that time, Pierre Simon Laplace (1749–1827). He was a mathematical physicist after whom the famous Laplace transform (one of the basic mathematical tools in an engineer's kitty today) and the Laplacian operator (the basic mathematical tool for understanding electromagnetism and waves) are named. His prime contributions were in the area of celestial mechanics, especially in proposing the first scientific theory of the origin of the solar system. For some time he was a minister in the cabinet of Napoleon after the French revolution. After his book on celestial mechanics "Exposition du systeme du monde" was published, Laplace went to Napoleon to present a copy of his work. Someone had told Napoleon that the book contained no mention of God. Napoleon received the book with the remark, "Mr. Laplace, they tell me you have written this large book on the system of the universe, and have never even mentioned its Creator." Laplace answered bluntly: "I had no need of that hypothesis."[1]

One of the major conceptual developments in the 18th century and the early 19th century was the development of the concepts of causality and determinism, which set the agenda for science for years to come. We shall delve upon these issues in the next instalment. □

[1]According to another account, Napoleon's question related to the belief among some scientists that God's intervention is necessary for maintaining stability of the solar system. But Laplace's answer remains the same: "I had no need of that hypothesis."