From the Steam Engine to DNA: Revolutions

Author(s): JAMES BURKE

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SUMMARY

- A dynamic web of change links us to one another and to the events of the past and future.
- James Watt's improvements to the steam engine are linked to the invention of the copier, carbon paper, and the safety match, as well as the discovery of DNA.

From the Steam Engine to DNA: Revolutions

JAMES BURKE

James Burke creates award-winning information packages in the form of television series, which then become award-winning audio-tapes, printed books, and multimedia games. Because his practice is primarily in multimedia, informing television audiences, the following chapter from Burke's recent book The pinball effect: How Renaissance water gardens made the carburetor possible, and other journeys through knowledge *conveys only a partial glimpse of the reasons he has been named STC Honorary Fellow this year.*

In addition to his effective practice in multiple media, James Burke is a role model to us for his ability to communicate with generalist audiences. Today we commonly address less-specialized, less technically literate audiences than we did even 10 years ago. The proliferation of technology into everyday life across cultures provides us with communication challenges we must deal with more frequently in our professional practices. Burke is an exemplar for effectively engaging a generalist audience on complex topics.

Historical myths die hard, don't they? In spite of the facts, they persist. Like the one which starts this story: James Watt sitting in his mother's kitchen, watching the kettle boil and dreaming up his great steam engine that would power the Industrial Revolution and change the world.

In fact, the idea came to him in 1765, in the repair shop at the University of Glasgow, for the very prosaic reason that an already-existing model steam engine (used for demonstrations by the Natural Philosophy Department's laboratory) had broken down. Watt fixed it with a minor modification, for which he got all the credit as inventor of the steam engine, totally eclipsing the reputation of Thomas Newcomen, a hardware salesman from Dartmouth and the engine's original designer.

The reason Watt then became famous so quickly was that Britain was going through an economic boom, which generated a growing need for raw materials, especially minerals. Miners were digging ever deeper and, as they did so, getting their feet increasingly wet. Mines were flooding, and Newcomen's engine (in fact, a pump) wouldn't drain them fast enough—until Watt improved the engine, after which everybody wanted one. Watt's career as a manufacturer of steam-driven mine-draining pumps was assured. This suited him fine, because that's all he wanted to be. Neither he nor anybody else had given much thought to other uses for the pump engine. Using it to drive factory machinery was out of the question because the gearing mechanism that would turn an up-and-down pump motion to a round-and-round driving motion—the "sun and planet" gear—would not be invented for another sixteen years, by one of Watts employees, William Murdock (who got the job because he came to the interview wearing a wooden hat he had made).

This gearing system worked simply enough. A fixed gearwheel was attached to a connecting rod hanging from the steam engine beam. As the beam end went up and down with the action of the pump piston attached to its other end, the wheel teeth meshed with those on another gearwheel, which was attached to the end of a driveshaft that was free to rotate. As the connecting rod went up and down, its fixed gearwheel rotated around the drivewheel, the action looking like a planet circling the sun.

With this rotary motion, Watt's steam engine could turn wheels carrying belts and so drive machines in cotton mills, corn mills, grinding mills, rolling mills, potteries, sawmills, iron foundries (where the steam engine worked the bellows in blast furnaces), breweries, starch makers, bleach makers, oil mills, and cloth mills. As for kicking off the Industrial Revolution, by 1795 Watt had introduced all the basic industrial work practices at his new engine-making factory in Birmingham. The plant was laid out so as to maximize the flow of production for standardized engines.

This article originally appeared as Chapter 2 in *The pinball effect: How Renaissance water gardens made the carburetor possible, and other journeys through knowledge* (Boston, MA: Little, Brown and Company, 1996). Reprinted with permission of the author.

Jobs were broken down into specified operations, with appropriate specialization of labor. Watt could then pay piece rates because he was able to establish how long it should take to make a standardized component.

So, in spite of his inventing the steam engine being a myth, Watt was indeed the originator of many of the manufacturing techniques that made possible the Industrial Revolution. But there was another, less well known invention by Watt that was to have as great an effect, in its way, as his steam engine. One day, in the twentieth century, it would trigger a revolution as fundamental as that of the industrial era because Watt's other invention would bring into common use a kind of soot. In the modern world this material would open the way to the investigation of the processes of life itself and trigger a second, biological revolution.

This second revolution will bring radical change to life in the twenty-first century, and the trail leading to it begins with Watt's steam engine business and the troublesome fact that he was too successful. It was while Watt was in Redruth, Cornwall (where many mines were interested in his steam pump because their galleries ran out under the sea, and flooding was particularly common) that he found himself overwhelmed with paperwork for a "multiplicity of orders." His greatest problem was, as he wrote to a friend, "excessive difficulty in finding intelligent managing clerks." In 1780 he came up with a way to solve the problem: an alternative way to make copies of technical drawings, invoices, letters and all the documents that needed duplicating. (He'd already tried and failed with a two-nibbed pen.) The patent for his idea referred to "A New Method of Copying Letters and Other Writings Expeditiously." Watt had invented the copier.

Documents were written or drawn on damp paper with a special ink that included gum arabic, which stayed moist for twenty-four hours, during which copies could be made by pressing another smooth white sheet against the original and transferring the ink marks to the new sheet. Initially, the copier was not a success. Banks were opposed because they thought it would encourage forgery. Countinghouses argued that it would be inconvenient when they were rushed, or "working by candlelight." But by the end of the first year, Watt had sold two hundred examples and had made a great impression with a demonstration at the houses of Parliament, causing such a stir that members had to be reminded they were in session. By 1785 the copier was in common use.

Then in 1823 Cyrus P. Dalkin of Concord, Massachusetts, improved on the technique by using two different materials whose effect on history was to be startling. By rolling a mixture of carbon black and hot paraffin wax onto the back of a sheet of paper, Dalkin invented carbon copies. The development lay relatively unnoticed until the 1868 balloon ascent by Lebbeus H. Rogers, the twenty-one-year-old partner in a biscuit-and-greengrocery firm. His aerial event was being covered by the Associated Press, and in the local newspaper office after the flight, Rogers was interviewed by a reporter who happened to be using Dalkin's carbon paper. Impressed by what he saw, Rogers quit ballooning and biscuits to set up a business producing carbon paper for use in order books, receipt books, invoices, etc. In 1873 he conducted a demonstration for the Remington typewriter company, and the new carbon paper became an instant success.

The paraffin wax Dalkin used, and which was therefore half-responsible (together with carbon black) for changing the world of business, had originally been produced from oil shale rocks. After the discovery of petroleum in Pennsylvania in 1857, paraffin oil was produced by distillation and was used primarily as an illuminant to make up for the dwindling supply of sperm-whale oil in a rapidly growing lamp market. Chilled-down paraffin solidified into paraffin wax. Apart from its use in lighting, the wax was also used to preserve the crumbling Cleopatra's Needle obelisk in New York's Central Park.

A more everyday use came with a new and exciting way to make fire. For centuries travelers had either carried glowing embers with them or found an already-made fire from which to take a light. But as transportation improved and people traveled farther and faster, these means became impractical. So by the mid-nineteenth century the new phosphorous match had become popular. By far the most successful type of match was the one invented by two Swedish brothers called Lundstrom. Their "safety" match was tipped with red phosphorus, instead of the previously common white version of the mineral, for the very good reason that white phosphorus tends to ignite spontaneously (and also poisoned the matchmakers). In order that their match would burn easily after the initial phosphorous flare, the Lundstroms injected a small amount of paraffin wax into the wooden splint, just below the match head.

Phosphorus had one other, very odd side effect. It gave the British the reputation of grave robbing in order to help solve the problem of feeding a rapidly rising urban population. Thanks to James Watt's steam power and industrialization, the English manufacturing towns were expanding at a breakneck pace. During the nineteenth century, population in the cities rose from one-third to four-fifths of the national total. The census of 1851 already showed that for the first time, anywhere in the world, there were more people in towns than in the countryside. One typical cotton town, Oldham in Lancashire, had 12,000 inhabitants in 1801, but by 1901 the number had risen to 147,000. In the same period the national population tripled.

While some of the reason for the population surge was a declining death rate, due to better hygiene and a general improvement in health, most of the increase was related to improvements in diet and plentiful food supplies. This became possible because of phosphorus and the work of a German chemist called Justus von Liebig, whose trick was to burn vegetation to discover its chemical constituents. Liebig thought that plants derived their nutrition from the soil and the air. Using his own money, he set up the world's first real chemical research laboratory at the University of Giessen in Germany. It proved so popular that his students came from all over the world. In his lab, Liebig discovered a law of crop growing that was to have an astonishing effect. The "law of the minimum" states that crop yield is determined by whichever one of a crop's natural nutritional elements is lowest in quantity.

But Liebig's key discovery was that phosphoric acid was necessary for all plants. The easiest way to produce phosphoric acid was to treat ground-up bones with sulfuric acid. The English led the way in this type of production and by 1870 were producing forty thousand tons a year. This output was what led Liebig to accuse them of grave robbing to feed their crowded city populations:

> *England is robbing all other countries of the condition of their fertility. Already in her eagerness, she has turned up the battlefields of Leipzig, of Waterloo, and of the Crimea; already from the catacombs of Sicily she has carried away the skeletons of many successive generations. Annually she removes from the shores of other countries to her own, the manurial equivalent of three millions and a half of men, whom she takes from us the means of supporting, and squanders down her sewers to the sea. Like a vampire, she hangs around the neck of Europe—nay, of the entire world—and sucks the heart blood from nations....*

If indeed this grave robbing really happened at all, it could well have been triggered by Liebig's *Organic chemistry and its applications to agriculture and physiology.* The book became an overnight international bestseller, running to seventeen editions in eight languages, and turned agriculture into a science. In the book he showed how ground-up mineral phosphates, treated with sulfuric acid, would produce better fertilizers that would be more easily absorbed by plants. Everywhere the search for phosphates intensified, and in America phosphate fertilizer production went into high gear after the discovery of enormous deposits in South Carolina, Georgia, and Florida. Most of the output from these sources went to tobacco growers.

Because of Liebig's work, all over Europe and America in the second half of the nineteenth century, crop yields provided the food so urgently needed for the growing industrial millions. All that remained was to find the means to distribute the food. Thanks again to James Watt, the way was already at hand in the form of the steam locomotive. Although the first steam-driven train (the *Rocket*) had been developed by George Stephenson in 1829 for service on the Manchester-to-Liverpool line, passenger trains had initially met with considerable opposition. Investors considered that the trains offered little hope of profit. Besides, it was said that at 40 mph, the passengers would asphyxiate.

This minor consideration did not, however, prevent the almost incredible expansion of railroads in the United States. By 1838 every eastern state but Vermont had them. By 1850 the network had spread to Kentucky and Ohio. Just after the Civil War, in which railroads played a key role, there were 35,000 miles of track; by 1890 the figure had risen to 164,000. Nothing like it had ever been seen before. From 1869, when the transcontinental line was completed, most railroad company names included the word "western."

Although railroad tracks were used to open up the country and to establish new centers of population, the most spectacular developments came in freight transportation. Mile-long trains rumbled through the night, their whistles echoing mournfully across the land, bringing America's seemingly inexhaustible natural resources and harvests to the manufacturing and population centers of the East. The various railroad companies cooperated to set up more than forty of these fast freight through-lines so that deliveries could go to their destinations nonstop. As a consequence, freight rates fell, and use of the freight services rose from ten billion ton-miles in 1865 to seventy-two billion in 1890. By 1876 over four-fifths of all grain shipments went by rail. Special stockcars were developed for the transportation of live animals. The first refrigeration cars were carrying fresh strawberries east from Illinois as early as the mid-1870s, and New Yorkers began to see fresh milk again for the first time in decades.

Above all, perhaps, the new railroads (particularly in Europe) enabled people to move around as never before. People began to marry outside their own towns and villages, churning up the gene pool as they did so. The massive increase in the production of coal—to make iron to build locomotives, and then in turn to be used as fuel for the engines—also provided the raw material for the production of coal gas. The gas was a by-product of coalcoking, a technique first made commercially viable by James Watt's assistant, William Murdock (who had invented the "sun and planet" gearing system that allowed Watt's steam pump to drive rotary motion). The new gaslight stimulated more leisure-time reading in general and triggered the birth of the evening class (and unintentionally, perhaps, was the genesis of the educated, professional woman).

So now the economies of the West had well-fed, educated industrial and office workers, as well as efficient sources of raw materials supplying production lines that made goods to be sold by rail-traveling salesmen. In America the only thing that stood in the way of the nation's emergence as the first superpower was the country's lack of an effective way to draw all this together with a communications network. The railroads were to play a central role in solving this problem, though in an unforeseeable and indirect way. In 1851 the problem of running trains in different directions on the same single track (the cause of some spectacular head-on crashes) had been dealt with by the use of the telegraph to organize which train would wait and which would pass. It was only a matter of time until the transmission of Morse code would give way to that of speech, with the telephone, whose development took a major step forward thanks to Thomas Edison, who had spent his early career as a telegraph operator on the railroads.

When the phone went into general use, its chief drawback was that you could hardly hear what callers were shouting into the transmitter at their end of the line. Then Edison thought of using carbon black (the sooty material used earlier by Cyrus P. Dalkin to make his copy paper). There was nothing particularly new about carbon black. The black particles were the finest known particulate and had been used by the ancient Egyptians (and in India and China) as a black pigment, collected by scraping the residue formed by oil-lamp smoke, to make ink and eye makeup. By the nineteenth century the smoke was being produced first by coal gas and then from burning coal tar oils, including creosote.

Basically, the telephone worked when a voice vibrated a metal diaphragm in the transmitter mouthpiece. The vibrating diaphragm caused the current in an electromagnet to fluctuate. At the other end of the line, the varying current caused another electromagnet to vibrate, generating a changing magnetic field. This in turn made the metal diaphragm in the receiver fluctuate, reproducing the original sound. Edison and his backer, Western Union, were looking for a way to raise the sound levels produced by this system when, in 1877, somebody suggested that carbon black was supposed to be sensitive to an electric charge. When subjected to pressure, its electrical resistance changed. So Edison tried it, first of all separating Bell's receiver from the transmitter (placed in the same box, they caused interference) and then putting a small button of compressed carbon black between the vibrating diaphragm in the transmitter and its electromagnet. The first demonstration to the directors of Western Union caused a sensation. The carbon button worked so well that it was still in telephones fifty years later.

By 1880 the telephone was also bringing dramatic change to the shape of the city, by helping cause suburbs to come into existence. Horse trams had been available for years to take people out from the city center, but there was little incentive to move (especially for business owners) without an effective means of communicating with the downtown headquarters and factories. The telephone provided that means. Industrialization had also caused a boom in land values, substantially raising the cost of living in big houses in the city center. In any case, the newly affluent middle class wanted to get away from the workers, now crowded in tenements around the factories.

Increases in land values also triggered the building of skyscrapers, now that architects and construction bosses could talk by phone to their foremen up and down the building, instead of having to use whistles or messengers. Soon small retailers, feeling the pinch of rising downtown costs, began to move their businesses to the suburbs, using the phone to place orders with city center wholesalers. Thanks to all these changes, by the end of the nineteenth century there was a large and growing suburban market for a more individual form of transportation. Henry Ford answered the call with his Model T. The new cars were soon running on more durable tires, thanks again to carbon black. In 1904 it was found that the mechanical strength and endurance of rubber was powerfully increased by adding carbon black, because it greatly reduced the speed at which the rubber oxidized.

And then came one of those strange twists of history, bringing together the phosphates that had helped to feed the city populations, and the electricity that made possible the telephone which was now giving daily lives new shape. This time, the major change would come because of a scientist who couldn't find a job.

For some time it had been known that passing an electric charge through a piece of metal in a vacuum tube causes it to give off mysterious streams of particles called (after the electrified metal) cathode rays. These rays can be focused through an aperture, into a pencil-thin beam, and then magnetic fields can be used to direct the path of the beam. It was also known that if the rays are directed at a glass plate covered with a phosphorous material, the screen glows where the rays strike.

At the time scientists were principally interested in this phenomenon because they hoped it might reveal something about the behavior of electricity in a near vacuum. Nobody cared much what the cathode rays might be encouraged to do, so there were no plans to use the rays for any practical purpose. The end of the nineteenth century was the era of the amazing X-ray discovery, and everybody was keen to find other rays in the vacuum that might do similarly miraculous things.

At this point comes the twist in the tale. Ferdinand Braun, a German physicist, came to the reluctant conclusion that his field (radiation in vacuum tubes) was, to say the least, oversubscribed. Everything that could be done to tubes, electric currents, cathodes and screens had been done. So in 1896 Braun decided to look at the only thing left unresearched: the cathode rays themselves. Some years earlier Heinrich Hertz had shown that an electric current is made up of consecutive and repeating positive and negative cycles, and that the current can be defined by the frequency with which these cycles happen every second. However, nobody had ever actually seen this cycle occurring. Braun realized that cathode rays would make this sight possible and that such a development would allow engineers to monitor electric current in power generation, where it is essential to be sure that the power supply is at a constant, unvarying frequency. So far, there had been no way to do this.

Braun built a vacuum tube with a neck which opened out to a phosphorescent screen. When he set small electromagnets round the neck, he was able to use their fields to move the particle beam around. The field created by the electromagnets could also be made to affect the beam in reaction to the positive-negative changes in the current. In this way, Braun was able to get the beam to cause a spot to move across the phosphorescent screen while it moved up and down in response to the changes in the current, showing the current as a glowing sine wave. Braun's invention—which became known as an oscilloscope—could be used to reveal the characteristics of any current. It was a highly precise analytical tool, and the forerunner to the modern television tube, whose picture is built up by a beam of particles scanning back and forth, in a sequence of lines from top to bottom, on the screen.

But it was Braun's ability to measure electric current that takes the story to the next step and brings carbon black back into the picture, through Edward Acheson, a twenty-eight-year-old American who was working for Thomas Edison at Menlo Park. In 1880, after working for a period in Europe, Acheson returned to the States and began installing electric-light machinery. Since opportunities in the prime electricity-generating industry were pretty well exhausted, Acheson identified a niche market, in the generator-manufacturing business, for industrial abrasives.

His first idea was to make artificial diamonds for abrading tools; so he began to experiment by mixing clay and powdered coke, and fusing the mix at extremely high temperatures in an electric furnace. The result was a compound, silicon carbide, which Acheson named Carborundum and which turned out to be second in hardness only to diamonds. The abrasive characteristics of his new material won him a contract with Westinghouse, the firm supplying electric lights for the World's Columbian Exposition of 1893 in Chicago.

It was when Acheson accidentally overheated his mixture one day (to a temperature of 7,500°F) that he found that the silicon in the Carborundum had vaporized, leaving him with almost pure graphite. Graphite is a rare form of carbon black, in those days imported from Ceylon, and is extraordinarily resistant to wear and tear, or to extremes of temperature. Acheson promptly found patentable uses for it in electrodes, dynamo brushes, and batteries. However, a few decades later Hitler's rocket engineers would find another, more deadly use for graphite.

In October 1942 came the first launch of the Nazi terror weapon, the V-2, whose full name in German meant "Vengeance Weapon 2." The rocket, launched from the pad at Peenemünde on the Baltic Sea, was over forty-seven feet long and nearly five feet across. Lifting off with a thrust of twenty-eight tons, its propellant burn lasted just over a minute and its speed at burnout exceeded 3,600 mph, at a height of 300,000 feet. The V-2 had an initial range of two hundred miles, and from 1944 to the end of the war, over a thousand were launched against England. Hitler's dream was to develop an upgraded version that would reach New York; for this reason above all, graphite was essential—because the burn time for such a rocket would be lengthy. Graphite was the only material that could be used on the aerodynamic control-vanes mounted in the rocket exhaust, because it could take extremely high temperatures over long periods without deforming.

This chapter began with Watt's first revolution. Graphite is now to be key to another. Back in 1895 the excitement over X-rays that had affected Braun's decision to analyze cathode rays also got people interested in what X-rays actually were. Wilhelm Röntgen, their discoverer, thought they might be extremely high-frequency light waves. Unfortunately, the only way to prove this was to see whether X-rays could be made to create interference patterns in the same way that light did. Interference occurs when light bounces simultaneously off a series of surfaces. As the reflected light waves spread out, in a process called diffraction, they interfere with one another, building up or canceling one another and producing characteristic light-and-dark interference patterns. The question is, what would be small enough to act as a series of separate targets off which to bounce the extremely small-wavelength X-rays?

Not many years earlier René Haüy, a French geologist, had noticed that rock crystals tended to break into regular shapes. When the pieces were further broken, they continued to make smaller and smaller regular shapes. Haüy theorized that in order to do this, crystals had to have regular atomic structures, called lattices. In 1912 it occurred to the German physicist Max von Laue that if crystals did indeed have regular atomic arrangements, the atomic lattice should be able to act as the infinitesimally small, regularly spaced targets off which X-ray waves could be bounced, so as to create interference patterns. Laue's theory presupposed that the X-rays hitting the crystal would cause their electrons to give off "secondary" X-rays which would then interfere with one another (if they were, as Röntgen had believed, light waves). The best crystal for this purpose turned out to be graphite, because its electrons are less tightly bound to the atoms and thus more likely to react to the energy from the incoming X-rays.

The very first experiment showed Laue that he was right. The scattered secondary X-rays fanned out around the central beam, exposing photographic paper when they hit it. Gradually, all round the axis of the main X-ray beam there appeared the familiar light-and-dark interference pattern caused by diffraction. So X-rays *were* a form of light. But there was something immensely more exciting. It became clear from the experiments that diffraction patterns vary depending on the atomic structure of different crystals. So for the first time it was possible to identify a solid material by nondestructive means. X-ray crystallography had been invented.

It was through the use of this technique that in 1952 Francis Crick and James Watson were able to confirm the three-dimensional structure of a molecule of protein. They saw that it took the form of a double helix, which agreed with what they had already deduced chemically. Their X-ray diffraction pattern confirmed the existence of the DNA molecule.

Because of the discovery of DNA, science is already well on the way to the Biological Revolution: developing forms of gene therapy to cure or prevent disorders, and manipulating genes to produce hybrid organisms like tomatoes that have more taste, strawberries that are not damaged by frost, or perhaps new forms of animal life. Above all, work is proceeding on deciphering the human genome, the DNA library all humans contain, that makes them who they are: sick or well, black or white, perhaps even intelligent or stupid. The world was not ready for the far-reaching social effects of the Industrial Revolution, triggered in the first place by Watt's steam pump. Is it ready for the Biological Revolution, triggered in the second place by his copier?

The first X-ray diffraction pattern of DNA was visible because of the way X-rays, bouncing off atoms, were made visible in a photograph. . . .