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# Joseph Black, carbon dioxide, latent heat, and the beginnings of the discovery of the respiratory gases

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**West JB.** Joseph Black, carbon dioxide, latent heat, and the beginnings of the discovery of the respiratory gases. *Am J Physiol Lung Cell Mol Physiol* 306: L1057–L1063, 2014. First published March 28, 2014; doi:10.1152/ajplung.00020.2014.—The discovery of carbon dioxide by Joseph Black (1728–1799) marked a new era of research on the respiratory gases. His initial interest was in alkalis such as limewater that were thought to be useful in the treatment of renal stone. When he studied magnesium carbonate, he found that when this was heated or exposed to acid, a gas was evolved that he called "fixed air" because it had been combined with a solid material. He showed that the new gas extinguished a flame, that it could not support life, and that it was present in gas exhaled from the lung. Within a few years of his discovery, hydrogen, nitrogen, and oxygen were also isolated. Thus arguably Black's work started the avalanche of research on the respiratory gases carried out by Priestley, Scheele, Lavoisier, and Cavendish. Black then turned his attention to heat and he was the first person to describe latent heat, that is the heat added or lost when a liquid changes its state, for example when water changes to ice or steam. Latent heat is a key concept in thermal physiology because of the heat lost when sweat evaporates. Black was a friend of the young James Watt (1736–1819) who was responsible for the development of early steam engines. Watt was puzzled why so much cooling was necessary to condense steam into water, and Black realized that the answer was the latent heat. The resulting improvements in steam engines ushered in the Industrial Revolution.

fixed air; alkalis; renal stone; specific heat; James Watt

JOSEPH BLACK (1728–1799) has a special place in the history of respiratory physiology because his research on the nature of carbon dioxide marked the beginning of the rapid advance in knowledge of the respiratory gases (Fig. 1). Carbon dioxide had actually been briefly described about 100 years before by van Helmont (1580–1644), but Black was responsible for first elucidating its properties. His work influenced subsequent investigators such as Cavendish (1731–1810), Priestley (1733–1804), Scheele (1742–1786), and Lavoisier (1743–1794), and over the ensuing 20 years after Black's publication all the respiratory gases including oxygen, hydrogen, nitrogen, and water were characterized.

Black's pioneering work on carbon dioxide assures him a major place in the history of physiology. However, he did much more. In fact historians of science sometimes ignore his work on carbon dioxide and instead emphasize his major advances in the area of heat. He was the first person to recognize latent heat, that is the heat added or lost in the change in state of a substance. An example is water when it is converted into steam or ice. He also described the specific heats of various substances. His work influenced his friend James Watt (1736–1819), who made critical advances in the design of the steam engine. This had been invented by Thomas Newcomen (1664–1729) but was inefficient. Watt's modification greatly improved its performance and was a major factor in the development of the Industrial Revolution, which had an enormous influence in history.

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### *Brief Biography*

Joseph Black was born in Bordeaux, France, where his father was a wine merchant who himself had been born in Belfast but was of Scottish origin. Joseph's mother was also from Scotland and it was she who taught her children to read English. At the age of 12 Joseph was sent to a private school in Belfast. There he was reported to have been an excellent scholar (7). Four years later in 1744 he entered the University of Glasgow where he took the arts curriculum. However, there is a note that in his fourth year he studied physics and was the favorite pupil of the professor of natural philosophy (7).

At the end of his arts course he studied medicine under Dr. William Cullen (1710–1790). This man was one of the most illustrious professors of medicine in the English-speaking world at the time and an important figure in the Scottish Enlightenment. When he moved to Edinburgh he was the physician of David Hume (1711–1776), the eminent philosopher, and had a wide circle of friends including Adam Smith (1723–1790), the economist. Cullen was a firm believer in the experimental method and he employed Joseph Black as his assistant in the laboratory who later reported that Cullen treated him "with the same confidence and friendship . . . as if I had been one of his own children" (13).

In 1752 Black moved to Edinburgh University to continue his medical studies. At the time, this institution had the finest medical education in the United Kingdom. It is not always appreciated that the Scottish universities at that time were far ahead of the better known English universities such as Oxford and Cambridge in the field of medicine.

Black was required to write a thesis for his M.D. degree in Edinburgh and he became interested in the properties of limewater, which was thought to be valuable in the cure of kidney stone, a common ailment at the time. However, it transpired that the action of limewater was a contentious subject between two of the major professors and Black therefore decided to work on a related topic, the properties of "magnesia alba" (magnesium carbonate). A feature of this research was Black's use of accurate balances and in fact Black is credited with inventing the first accurate analytical balance. His experimental work on magnesia alba and his subsequent elucidation of the properties carbon dioxide are described below.

In 1756 Black returned to Glasgow where he was appointed lecturer and later became professor. Remarkably, his research interests changed considerably. He became interested in the heat transfer that occurs particularly in a change of state, for

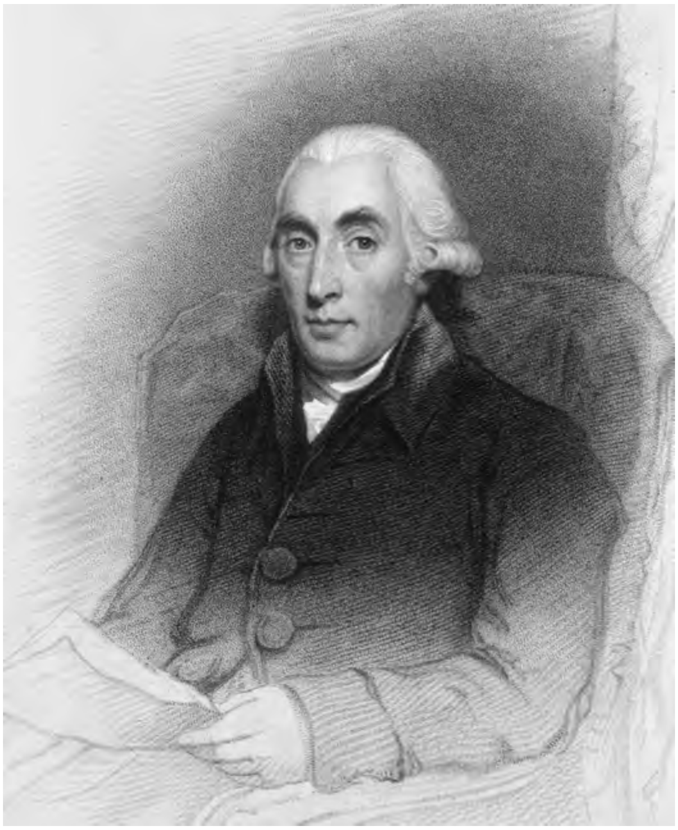


Fig. 1. Joseph Black (1728–1799). (From http://en.wikipedia.org/wiki/File:Joseph_Black_b1728.jpg).

example the transition from water to ice or water to steam. He had noticed that the change in state can occur over a prolonged period of time when a substance is heated or cooled without a change in temperature. For example, snow at near freezing point gradually melts to form water over a period of time without a change in temperature. He introduced the term "latent heat" to refer to this phenomenon. He also discovered that different liquids have different capacities to take up heat, and he introduced the concept of "specific heat."

James Watt (1736–1819), who was one of Scotland's most famous engineers, came to Glasgow at the age of 18 and became an instrument maker to Black. The latter remarked "I soon had occasion to employ him to make some things . . . and found him to be a young man possessing most uncommon talents for mechanical knowledge and practice . . . which often surprised and delighted me in our frequent conversations together" (4). Watt was influenced by Black's work on latent heat and applied this knowledge to improve the steam engine. This had been invented by Thomas Newcomen (1663–1729) and was extensively used to pump water from mines but was very inefficient. The improvements developed by Watt played a critical role in the Industrial Revolution that made Britain a leader in industry.

In 1766 Black returned to Edinburgh where he concentrated on teaching. His lectures became famous and were read for many years. Later in life he had episodes of hemoptysis, presumably caused by pulmonary tuberculosis, and he died in Edinburgh in 1799. To many people's surprise, his will indicated that he was quite wealthy.

For readers who want additional information, Ramsay wrote an early, readable biography of Black (13), and more extended accounts with corrections are by Guerlac (8, 9) and Donovan (7). A collection of Black's lectures was compiled by Robison (15) and an extensive series of letters between Black and Watt is available (14).

### *The Chemistry of Alkalis and Carbon Dioxide*

The circumstances leading to Black's work on alkaline chemicals were bizarre. Renal stones were apparently more common in the 18th century than they are now and they were a therapeutic challenge. "Cutting for stone," that is, operating to remove a renal stone or gravel from the bladder, was frequently described and in the period before anesthesia was a very painful and dangerous operation. As a result there was much interest in possible medical treatments. In 1739 a Mrs. Joanna Stephens invented a concoction that seemed to be helpful, and the English parliament voted her the sum of £5,000 (an enormous amount in those days) for the recipe. This turned out to be a strange mishmash of eggshells, snails, soap, and various other unlikely constituents, and as a result various medical people in the University of Edinburgh became interested in the properties of limewater, which was assumed to play a role. A dispute developed between two professors, and although limewater interested Black, he thought it best to stay out of the controversy. He explained in a letter to his father "I found it proper to lay aside limewater which I had chosen for the subject of my Thesis. It was difficult and would have appeared presumptuous in me to have attempted settling some points about which two of the Professors themselves are disputing" (8). He therefore chose to study a similar substance, magnesia alba (magnesium carbonate $MgCO_3$) and for his MD thesis he wrote a dissertation titled *De humore acido a cibis orto, et magnesia alba* (On the acid humour originating from food, and on magnesia alba). A year later he read a modified version of his dissertation as a paper titled "Experiments upon magnesia alba, quicklime, and some other alcaline substances" to the Philosophical Society of Edinburgh, and in 1756 this appeared in the second volume of the journal "Essays and Observations; Physical and Literary" of the Society (2), which later became the Royal Society of Edinburgh. The original paper is now very difficult to obtain but was reprinted by the Alembic Club in 1944 (3) (Fig. 2).

In early experiments Black added acid to magnesia alba and showed that it effervesced and lost weight. He used both distilled vinegar and oil of vitriol (sulfuric acid). In modern nomenclature the reaction was

$$MgCO_3 + H_2SO_4 = MgSO_4 + H_2O + CO_2$$

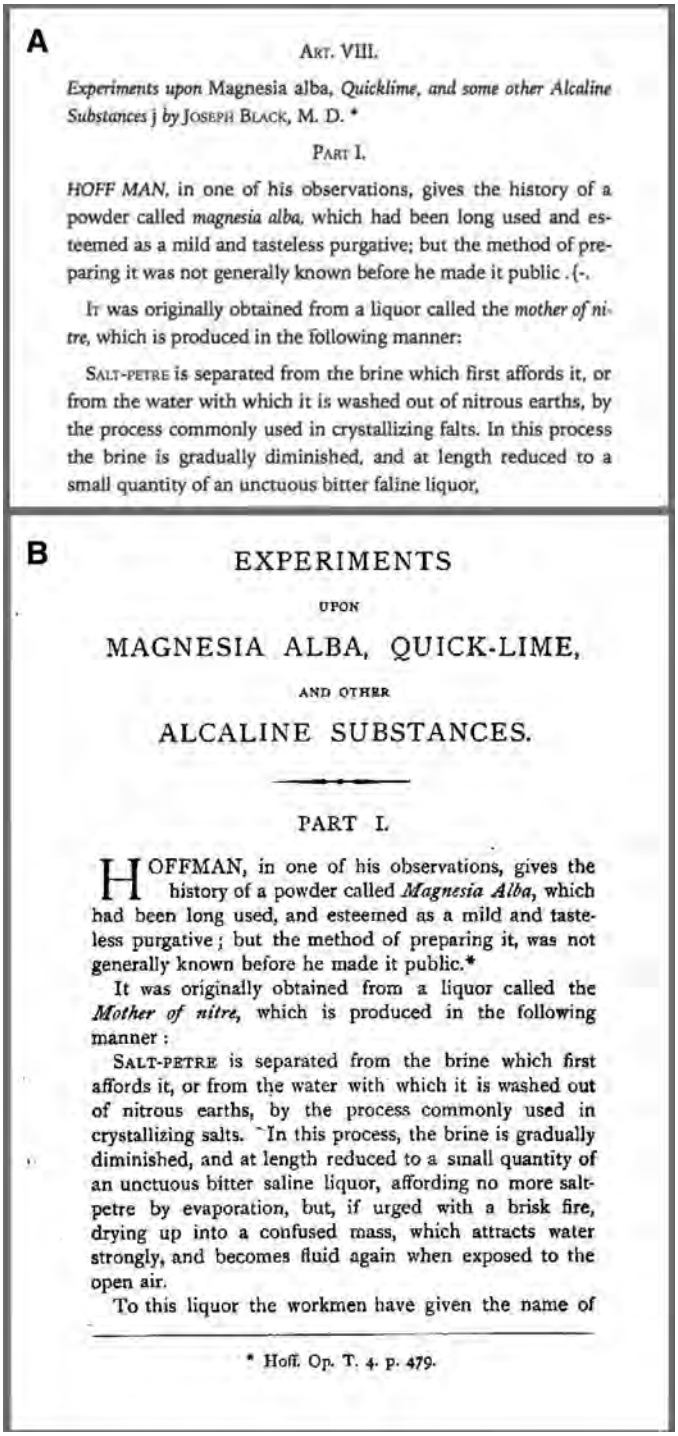
He also found that when magnesia alba was heated in a furnace, it also lost weight but the resulting material, which he called "magnesia usta," did not lose weight when acids were added. Here the reaction was

$$MgCO_3 \rightarrow MgO + CO_2$$

He realized that the action of heat on magnesia alba was the same as heating limestone, which is calcium carbonate $CaCO_3$. Again the reaction was

$$CaCO_3 \rightarrow CaO + CO_2$$

Black then looked at the properties of the "air" given off when magnesia alba was either treated with acid or heated. He found that it was not the same as atmospheric air. For example, he



A

ART. VIII.

*Experiments upon* Magnesia alba, *Quicklime, and some other Alcaline Substances* j *by* JOSEPH BLACK, M. D. *

PART I.

*HOFF MAN*, in one of his observations, gives the history of a powder called *magnesia alba*, which had been long used and esteemed as a mild and tasteless purgative; but the method of preparing it was not generally known before he made it public .(-.

IT was originally obtained from a liquor called the *mother of nitre*, which is produced in the following manner:

SALT-PETRE is separated from the brine which first affords it, or from the water with which it is washed out of nitrous earths, by the process commonly used in crystallizing falts. In this process the brine is gradually diminished, and at length reduced to a small quantity of an unctuous bitter faline liquor,

B

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PART I.

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SALT-PETRE is separated from the brine which first affords it, or from the water with which it is washed out of nitrous earths, by the process commonly used in crystallizing salts. In this process, the brine is gradually diminished, and at length reduced to a small quantity of an unctuous bitter saline liquor, affording no more salt-petre by evaporation, but, if urged with a brisk fire, drying up into a confused mass, which attracts water strongly, and becomes fluid again when exposed to the open air.

To this liquor the workmen have given the name of

* Hoff. Op. T. 4. p. 479.

Fig. 2. Black's publication on alkalis and the discovery of carbon dioxide. This was his only major publication in English. *A* shows the original article, which is now almost unobtainable. *B* shows a later reprint. *A* is from Ref. 2. *B* is from Ref. 3.

reported in a letter to Cullen "I mixed together some chalk [$CaCO_3$] and vitriolic acid. . . The strong effervescence produced an air or vapour, which, flowing out at the top of the glass, extinguished a candle that stood close to it; and a piece of burning paper immersed in it, was put out as effectually as if it had been dipped in water." He also showed that it was toxic to animals that breathed it. For example sparrows "died in it in ten or eleven seconds" although "they would live in it for three or four minutes when the nostrils were shut by melted suet" (15) (p. 231). He further found that when he bubbled his new gas through limewater it formed a white precipitate. This was calcium carbonate and the reaction was

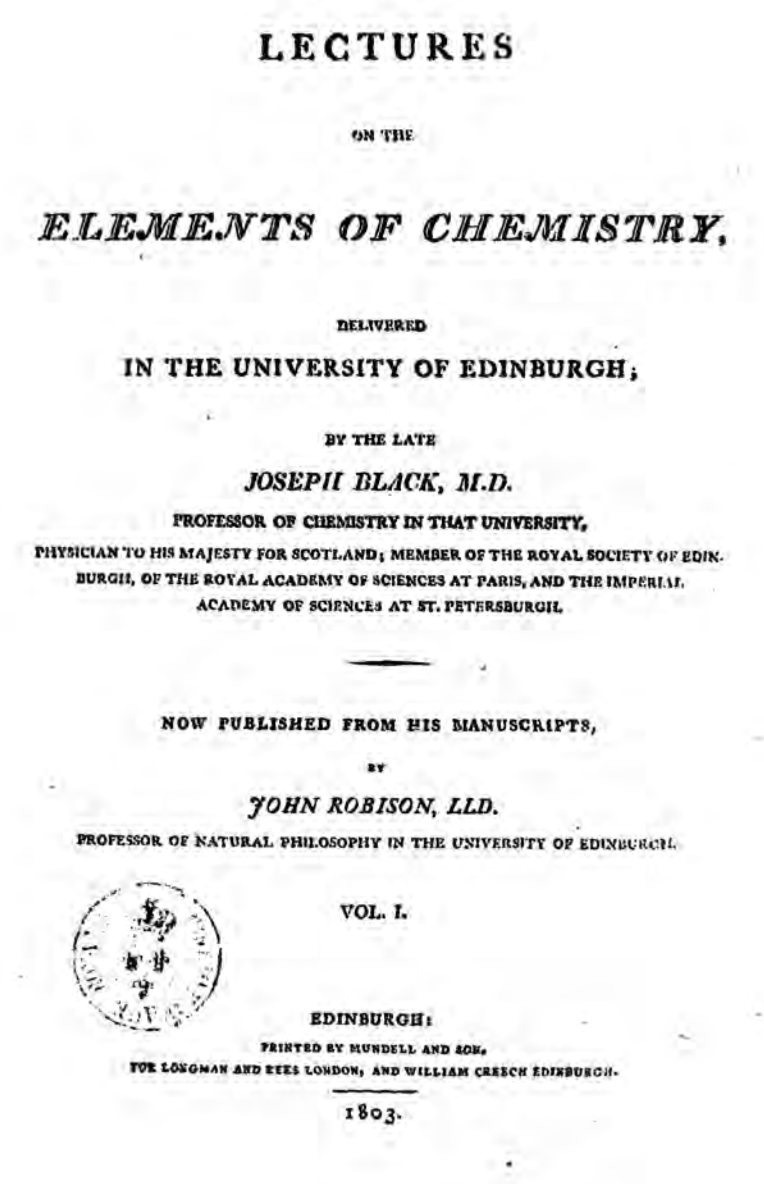
$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

When Black used this test in a brewery he found that the same gas was given off in the process of alcoholic fermentation. He called the gas "fixed air" because in his experiments on alkalis the gas had been combined with a solid material. This was the first demonstration that gas was a weighable constituent of a solid body. As noted earlier, Black had developed very accurate chemical balances and these enabled him to show that when magnesium carbonate was heated and "fixed air" was liberated, there was a loss of weight. He also realized that it was the same gas as that described about 100 years earlier by Jan Baptist van Helmont who called it "gas sylvestre" and who produced it by adding acid to limestone. He also recalled that Stephen Hales (1677–1761) had suggested that the loss of weight of sal tartar (potassium carbonate) on heating was due to the loss of "elastic fluid," which he called fixed air (10). Black also thought that it might be the same gas produced in the Grotto del Cano in Italy where it was known that people could survive if they were standing but dogs perished because the noxious gas, being heavy, remained close to the ground.

Black also showed that the gas exhaled from the lung contained fixed air. He did this by bubbling expired gas through limewater and noting the white precipitate of calcium carbonate. In his "Lectures on the Elements of Chemistry" (15), which were collected after his death (Fig. 3), he stated "And I convinced myself, that the change produced on wholesome air by breathing it, consisted chiefly, if not solely, in the conversion of part of it into fixed air. For I found that by blowing through a pipe into limewater, or a solution of caustic alkali, the lime was precipitated, and the alkali was rendered mild" (15) (p. 231). He carried out a particularly colorful experiment in Glasgow in the winter of 1764–65 when he placed a solution of limewater that dripped over rags in an air duct in the ceiling of a church, where it is said that 1,500 people remained at their devotions for 10 h. Apparently the result was the formation of a substantial amount of calcium carbonate, although further details of this study are not available (15) (p. 231).

Black's discovery of carbon dioxide was the first major advance in the discovery of the respiratory gases. At the time the topic was known as "pneumatic chemistry." Black's critical publication was in 1757 and it was only nine years after this that Henry Cavendish (1731–1810) reported the discovery of hydrogen. Six years after this in 1772, a pupil of Black, Daniel Rutherford (1749–1819), isolated nitrogen. Priestley produced oxygen in 1774 although Carl Wilhelm Scheele (1742–1786) had done this previously but reported it several years later. Finally, Lavoisier in 1777 in a memoir to the Académie des Sciences was able to make the dramatic statement "Eminently respirable air [oxygen] that enters the lung, leaves it in the form of chalky aeroform acids [carbon dioxide] . . . in almost equal volume. . . . Respiration acts only on the portion of pure air that is eminently respirable . . . The excess, that is the mephitic portion [nitrogen] is a purely passive medium which enters and leaves the lung . . . without change or alteration" (12).

Lavoisier's research was the coup de grâce of the erroneous phlogiston theory originally championed by George Ernst Stahl



LECTURES

ON THE

ELEMENTS OF CHEMISTRY,

DELIVERED

IN THE UNIVERSITY OF EDINBURGH;

BY THE LATE

JOSEPH BLACK, M.D.

PROFESSOR OF CHEMISTRY IN THAT UNIVERSITY,

PHYSICIAN TO HIS MAJESTY FOR SCOTLAND; MEMBER OF THE ROYAL SOCIETY OF EDINBURGH, OF THE ROYAL ACADEMY OF SCIENCES AT PARIS, AND THE IMPERIAL ACADEMY OF SCIENCES AT ST. PETERSBURGH.

NOW PUBLISHED FROM HIS MANUSCRIPTS,

BY

JOHN ROBISON, LLD.

PROFESSOR OF NATURAL PHILOSOPHY IN THE UNIVERSITY OF EDINBURGH.

VOL. I.

EDINBURGH:

PRINTED BY MUNDELL AND SON,

FOR LONGMAN AND REES LONDON, AND WILLIAM CREECH EDINBURGH.

1803.

Fig. 3. Title page of Black's *Lectures on the Elements of Chemistry*. These were very popular for many years. From Ref. 15.

(1659–1734). However, it has been pointed out that an early blow to the phlogiston theory was actually delivered by Black because his experiments with magnesium carbonate and limestone, in which carbon dioxide was released, were incompatible with the phlogiston theory. Later in his life in 1796 he admitted his change in belief when he was able to state "After having, for between 30 and 40 years, believed and taught the chemical doctrines of Stahl, I have become a converter to the new views of chemical action; and subscribe to almost all Lavoisier's doctrines. . ." (6).

Black's paper that appeared in the second volume of the "Essays and Observations: Physical and Literary" of the Philosophical Society of Edinburgh was one of only three in English that Black wrote (2). However, he had a reputation as an inspiring speaker, and his lectures attracted a large number of students. A compilation of his lectures was published in 1803 (15) and is available on the Internet.

After his move to Edinburgh in 1766 Black apparently did not pursue his work on alkalis and carbon dioxide. However, he continued to spend periods in his laboratory and was a consultant on various chemical problems mainly on industrial processes. For example he worked on methods of improving bleaching in the woolen industry, and he studied ways of converting seaweed into caustic potash. With others he also worked on the new design of furnaces for the production of iron and on material for coating ships' hulls to preserve them. He was also interested in sugar refining, brewing, and water analysis.

As indicated earlier, Black's interest in alkalis was stimulated by the medical problem of renal stone, and his two major publications, one in Latin and the other in English, stemmed from his work on this topic and earned him an MD degree. He practiced medicine although on a small scale in both Glasgow and Edinburgh. Although he submitted his work on alkalis in his MD thesis in 1754, he apparently saw his first patient in

1753. Among his patients was the famous philosopher David Hume (1711–1776), and he also advised the father of Walter Scott (1771–1832), the well-known author, that his son was in danger of developing tuberculosis because his nurse had the disease.

Black also had a number of administrative responsibilities in connection with medical institutions. He was a manager of the Royal Infirmary of Edinburgh, which is still a major hospital, and he was president of the Royal College of Physicians of Edinburgh. Among his honors were his appointment as physician to "his majesty for Scotland" (George III who actually never visited the country) and his election as a member of the Imperial Academy of St. Petersburg. In fact, Catherine the Great invited him to teach there at one time (1).

Black had some interesting friends in Edinburgh in 1766 to 1797. This 30 years was part of the period sometimes known as the Scottish Enlightenment, which was characterized by a ferment of intellectual and scientific accomplishments. Higher education was particularly strong in Scotland at the beginning of the 17th century when the country could boast five universities compared with England's two. Black's friends included the philosopher David Hume and the economist Adam Smith. Various clubs existed to facilitate the exchange of ideas.

One of the most colorful was the Poker Club, which derived its name not from the familiar card game but as a poker in a fireplace that stirs up a flame. Many of the liveliest minds in Edinburgh attended. Much of the discussion occurred over dinner, which began "soon after two o'clock, at one shilling a-head, the wine being confined to sherry and claret, and the reckoning to be called at six o'clock" (5). Adam Smith (1723–1790) was a member and his treatise on economics "The Wealth of Nations" (16) had an enormous influence. David Hume, the philosopher who wrote "A Treatise of Human Nature," found the Poker Club a way of dispelling the depression that apparently developed when he pondered human nature. He wrote "Most fortunately it happens that since reason is incapable of dispelling these clouds . . . I dine . . . I converse, and am merry with my friends" (11). Black was fortunate to be able to spend time with these inquiring minds.

*Latent Heat*

As indicated earlier, when Black returned to Glasgow in 1756 to be lecturer and later professor, his research interests changed to the topic of heat. Although this now seems to us as a major change in direction, he may not have seen it that way. After all, his previous work had been on the effects of heat on substances, and particularly on the subsequent elimination of fixed air with a corresponding loss of weight. His new interest in heat may have been prompted by observations of Cullen, who had been working in Glasgow. Cullen had noticed that when ordinary ether, a volatile liquid with a low boiling point, was exposed to a partial vacuum by means of an air pump, it began to boil, and the remaining liquid cooled markedly. Cullen published an account of this experiment in 1748, that is eight years before Black moved to Glasgow. However, as indicated before, Cullen had a high opinion of Black and they probably discussed these topics.

Black was aware of the well-known fact that snow is very slow to melt after the air temperature has risen above the freezing point of water. This suggested that heat was necessary for the change of state from ice to water because the water that was formed after thawing had a temperature only slightly above freezing. Black therefore carried out some experiments to investigate this. In one of these, two containers were set up in a large room where the temperature remained at 47°F. [Black used the scale described in 1724 by Daniel Fahrenheit (1686–1736) in all his work.] The containers were located 18 inches apart, and one of them contained five ounces of ice at 32°F while the other contained the same weight of water at 33°. Black found that the water warmed to 40° in half an hour. However, the ice took ten and a half hours to obtain the same temperature, or in other words 21 times as long as the water. Black therefore argued that the heat absorbed by the ice was $(40 - 33) \times 21$, or 147 units of heat. By contrast the water had only absorbed 8 units of heat. Therefore $147 - 8$ or 139 units of heat had been absorbed by the melting ice and were concealed, as it were, in the water (13).

In another experiment Black took a piece of ice at a temperature of 32°F, weighed it, and added it to a known weight of water of known temperature. This allowed him to calculate the amount of heat required to melt the ice, and this came out to be that which would have heated an equal quantity of water by 143°F. In a third experiment, a lump of ice at 32°F was placed in an equal volume of water that had been heated to 176°F and it was found that the water cooled to 32°F. Therefore the heat required to melt the ice was $176 - 32 = 44$°F of heat. This means that the latent heat of fusion came out to be about 144°F, which corresponds to 80°C. This is very near the

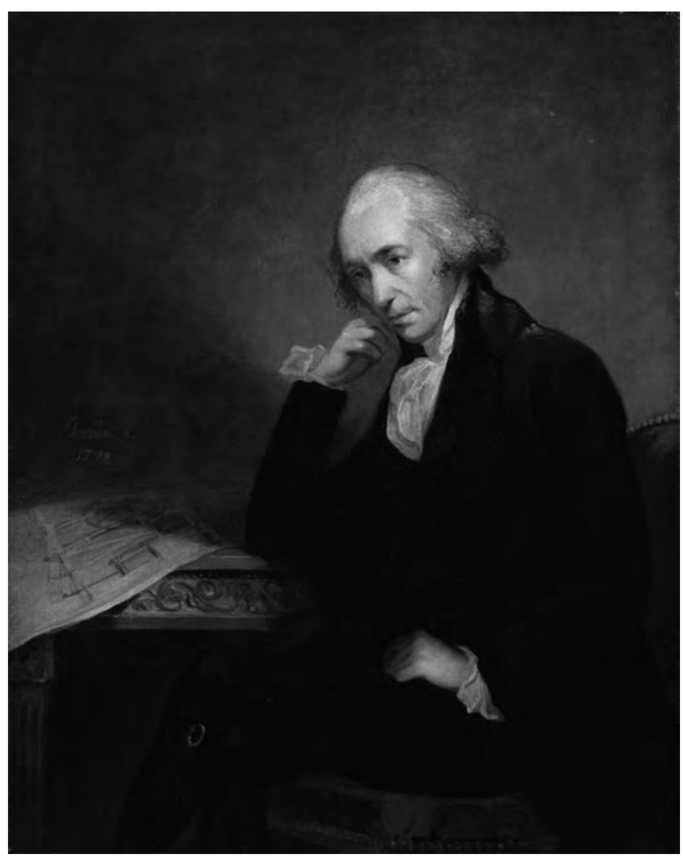


Fig. 4. James Watt (1736–1819). © National Portrait Gallery, London; reprinted by permission.

currently accepted value although the units for latent heat in the SI system are now kilojoules per kilogram.

Black's calculations cited above refer to the latent heat of freezing water. He also measured the latent heat required to turn water into steam. To do this he compared the time required for a known weight of water to rise from a given temperature to boiling point on the one hand, and the time required to convert the same weight of water into steam. The number he got was 830 units on the Fahrenheit scale and the accepted figure today is 967.

Curiously Black never published his work on latent heat. Instead it was communicated to a group of professors at the University of Glasgow in 1762, and it formed part of the lectures that were given to his students and that are now available (15).

Black also studied the specific heats of various liquids. This term refers to the amount of heat required to increase the temperature of a particular substance by a known amount. For example Black described an experiment in which a known weight of mercury at 150°F was mixed with an equal weight of water at a temperature of 100°F. He found that the temperature of the mixture at equilibrium was not 125° as might be expected, but 120°. In other words the mercury was cooled by 30° while the water was warmed by only 20° despite the fact that the quantity of heat gained by the water was the same as that lost by the mercury. Therefore, he said, the same quantity of heat has more effect in heating mercury than in heating an equal weight of water. Thus Black made a clear distinction between what we might call the intensity of heat on the one hand and the quantity of heat on the other. The intensity, or temperature, can be measured with a thermometer. However, the quantity of heat transferred to a substance requires both a measurement of the change in temperature and the duration of the heat transfer.

Incidentally it is interesting to note the great contrast in the number of publications between Black and his near contemporary, Joseph Priestley, who came from Leeds a couple of hundred miles to the south. The taciturn Scot published only three papers in English (13), whereas the ebullient Priestley is credited with some 150 publications including about 50 books.

*Joseph Black and James Watt*

As mentioned earlier, Black was friendly with the young James Watt (Fig. 4) whom he met in Glasgow, and their friendship was apparently partly responsible for one of the most important innovations in the Industrial Revolution.

Watt was born in Greenock on the Firth of Clyde not far from Glasgow. His father was a shipwright and Greenock had a long tradition of shipbuilding. James showed an interest in

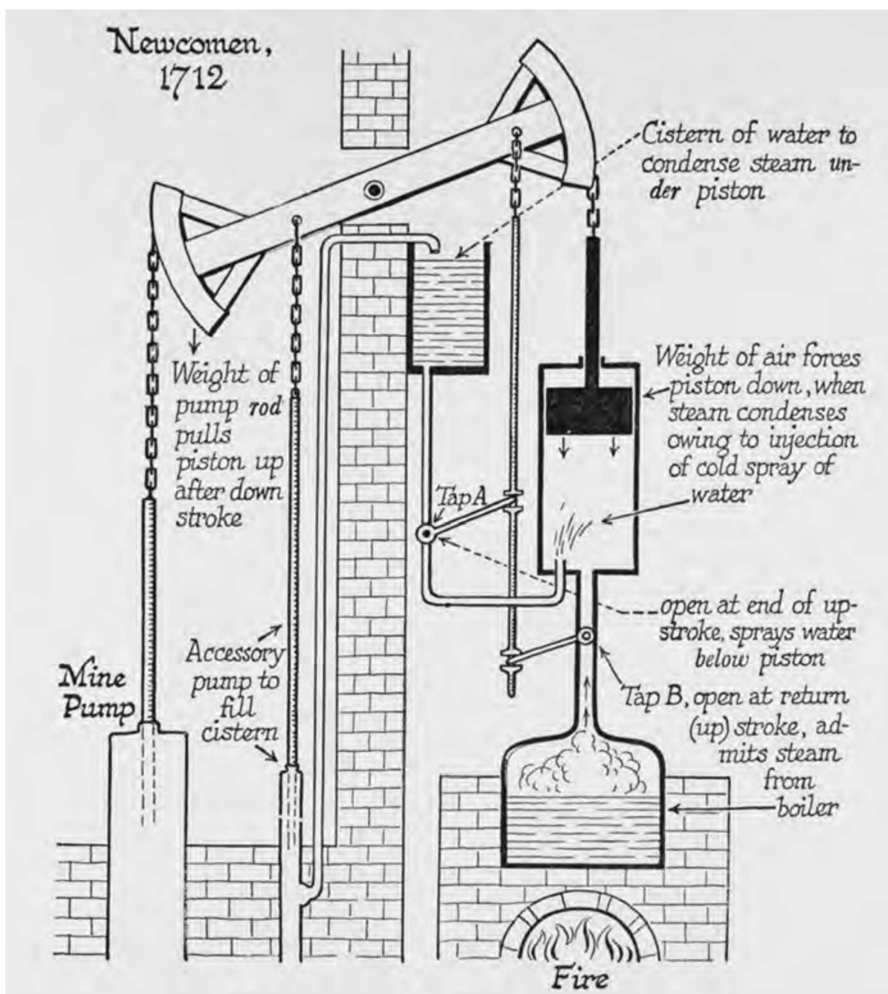



Fig. 5. Diagram of the Newcomen steam engine, which was the workhorse in the early 18th century. It was later modified by James Watt with help from Joseph Black with a resulting great increase in efficiency. (From L. Hogben. *Science for the Citizen*. London: Allen & Unwin, 1938. Illustrated by J. F. Horrabin.)

engineering from an early age and when he was 18 went to London for a year to study instrument making. When he returned to Glasgow, he found a place in the University where he called himself a mathematical instrument maker. There he met John Robison, who had an interest in astronomy, and the two enjoyed working on engineering problems. Robison was later to publish a collection of Black's lectures (15). When Black returned to Glasgow from Edinburgh in 1756 he met both Watt and Robison and the three became firm friends with an interest in engineering.

Apparently it was Robison who first interested Watt in early steam engines. These had been used for many years to pump water for mines but were inefficient. The most important was the Newcomen engine shown in Fig. 5. At bottom right there is a furnace that heats water in a boiler to make steam. Above this is a cylinder with a piston. The beam at the top is balanced in such a way that the weight of the mine pump (bottom left) pulls the piston up, filling the cylinder with steam. Then a valve is opened, allowing cold water from the cistern to enter the cylinder as a spray, thus condensing the steam. The result is a partial vacuum in the cylinder and the piston moves down because of the atmospheric pressure acting on it from above. When the piston is near the bottom of the cylinder the injection of water is stopped and the piston rises again, filling the cylinder with steam. Note that the power stroke is the descent of the piston because of the partial vacuum, not the rise of the piston as a result of the injection of steam as might be expected. Since the downward movement of the piston that activates the pump is caused by atmospheric pressure, this was often called an atmospheric engine. This design had been used for a period of over 50 years with almost no change since it was first proposed by Thomas Newcomen to pump water from mines. Watt's interest was sharpened when he was asked to repair a Newcomen engine owned by the University and he realized that it was very inefficient.

On investigating the pump, Watt recognized that one of the problems was that the cylinder was cooled during each down stroke of the piston as the steam was condensed. Therefore its temperature changed greatly with each cycle, with a consequent waste of heat. In addition he was surprised at the amount of water that was necessary to condense the steam. He then asked Black whether the amount of heat required to make steam was much greater than the heat required to raise water to its boiling point. Black realized that the key to this question was the latent heat of vaporization, which he had shown to be very large. The upshot was that Watt decided to choose another design that did not involve heating and cooling the power cylinder. Watt later wrote that Black "told me that [the doctrine of latent heat] had long been a tenet of his and [he] explained to me his thoughts on the subject" (14).

The solution devised by Watt was to have a separate chamber apart from the piston in which the steam could be condensed. The result was that the temperature of the main cylinder was maintained and this was assisted by surrounding it with a steam jacket. Readers of today may wonder why steam from the boiler was not used for the power stroke as was the case in later designs. The reason was that at that time it was impossible to fabricate a cylinder with the close tolerances required by the piston, and that could tolerate the high pressures without being damaged. Later Watt joined Matthew Boulton (1728–1809) in Birmingham, where precision engineering was available, and "expansive" steam engines (that is, powered by steam above atmospheric pressure) were developed.

Watt's modified engine became extremely popular and was used for many years. It was one of the inventions responsible for the Industrial Revolution, with a corresponding prodigious increase in industry in England and ultimately throughout the rest of the world. So it could be argued that Black's early work on latent heat had an important influence on the development of manufacturing and the resulting increase in the wealth of many countries.

In conclusion, Black clearly merits an important place in the history of respiratory physiology. His discovery, or more strictly rediscovery, of carbon dioxide started an avalanche of investigations of other gases of respiratory importance. Curiously some historians ignore his work on carbon dioxide but give much emphasis to his discovery of latent heat and specific heat. Arguably this influenced his friend James Watt and ultimately was a factor in the development of the steam engine that ushered in the Industrial Revolution and had an enormous effect on the wealth of Britain and other nations. Yet in some ways Black is an enigma. He only published one major paper in English, and although his published lectures were read for many years, they soon became outdated. He later became a consultant on a series of projects in industrial chemistry and was surprisingly wealthy when he died (13). He forms a striking contrast to his near contemporary, Joseph Priestley, who published prodigiously and discovered oxygen, the other major respiratory gas.

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