

Gaspard monge

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RESUMEN Gaspard Monge (1746-1818), creador de la geometría descriptiva y fundador de la *École Polytechnique*, fue uno de los principales impulsores del despertar de las matemáticas superiores que tuvo lugar a fines del siglo 18. Desempeñó un importante papel en el gobierno Francés durante la Revolución y sufrió las consecuencias después de la caída de Napoleón. Entre sus muchas actividades, realizó investigaciones importantes en química y física, en particular, el estudio de la síntesis y determinación de la composición del agua, la metalurgia del hierro la capilaridad, y la fijación del metro como unidad de longitud.

ABSTRACT Gaspard Monge (1746-1818), creator of descriptive geometry and founder of the *École Polytechnique*, was one the main boosters of the awakening of higher mathematics that took place at the end of the 18th century. He played an important role in the French government during the Revolution and suffered the consequences after the fall of Napoleon. Among his many activities, he carried on important researches in Chemistry and Physics, particularly in the study of the synthesis and determination of the composition of water, iron metallurgy, capillarity, and the establishment of the meter as a unit of length.

LIFE AND CAREER¹⁻¹⁰

Gaspard Monge (Figure 1) was born on May 9, 1746, at Beaune (Côte d'Or), the eldest son of Jacques Monge (1718-1775), a small businessman, and Jeanne Rousseau (1711-1773), the daughter of a carrier. There were two other sons, Louis (1748-1827) and Jean (1751-1813). In spite of the hard economical conditions of the family, the children were sent to the *Oratorians Collège* in Beaune where they completed their primary and secondary education with brilliant results.^{8,9}

In 1762, at the age of 16, Gaspard completed his studies of Philosophy, Mathematics, and Physics at the college and continued them at the *Oratorian College de La Trinité* in Lyon. Within several months he showed such abilities that the fathers appointed him professor of Physics. The Oratorians of Lyon pressed Monge to become a member of their order but Monge declined the invitation and returned to Beaune in 1764, where was unemployed until he was engaged to draw a detailed plan of his native city. He did such a brilliant job that a colonel de Vigneaux, second in command at the *École Royale de Génie de Mézières*, that happened to see it, offered him to come to the work at the school as a cartographer, preparing plans of fortifications and making architectural models. Because of his social background, Monge could only enter Mézières as draftsman and technician, and not as student-officer.^{8,9} The school of Mézières, founded in 1748, was a prestigious institution, which recruited the best students by means of a very difficult entrance exam, followed by a high level of studies. Two famous French scientists, the Abbot Charles Bossut (1730-1814) and the Abbot Jean-Antoine Nollet (1700-1770), occupied the chairs of Mathematics and Physics.

Pretty soon Gaspard become noticed by developing a new geometrical method for solving the problem of projection, that is, to establish the relief map of the different parts of a ramparts in order to keep the defenders protected from the outside enemy, with the maximum construction economy. The procedures then in use allowed solving the problem only *in situ*; an initial solution was established and then enhanced using empirical corrections. His ability to judge bodies in three dimensions led him to suggest an improved procedure, based on representing a three dimensional body



Fig 1. Gaspard Monge (1746-1818).

by the orthogonal projection of its points on two mutually orthogonal planes. Putting this concept in practice was the first step in a new graphical technique, which would become known as *descriptive geometry*.^{11,12} This innovative procedure led Bossut to appoint him first as his *répétiteur* and then as *examineur des élèves* (student examiner). From here on his academic advance was meteoric: Succeeding Bossut in 1769 (although he did not hold the rank of professor) and, in 1790, Nollet as instructor of experimental physics. He devoted most of his time to solve complex difficult mathematical spatial problems in the theory of partial differential equations, calculus of variations, curvature of surfaces, equations of the families of corresponding surfaces, integrals of finite difference equations, the equation of vibrating strings, etc. etc. His first important original work was *Mémoire sur les Développées, les Rayons de Courbure et Différents Genres d'Inflexions des Courbes à Double Courbure*.¹³ Beyond that, his investigations extended to problems of Physics, Chemistry, and Technology, as described below.

In 1777, Monge married Marie-Catherine Huart (1747-1846), the widow of a *maître de forges* and consequently, he became interested in the operation of the small industry brought in a dowry by his wife, and on the physical and technical problems related to steel metallurgy. Three daughters were born: Émilie (1778-1827), Louise, (1779-1823), and Adélaïde (1780-1783).^{8,9}

In 1780, Monge was elected appointed *adjoint-geometre* to the *Académie des Sciences*, replacing Vandermonde, which had been appointed *associé*. This nomination forced him to stay for at least five months in Paris every year and have his brother Louis fill his place at Mézières while he was away. This arrangement brought him eventually into a serious conflict with the administration of the school. Afterwards, the Minister of the Navy, appointed him adjunct to the abbot Bossut, who was teaching hydrodynamics at the Louver. The death of Étienne Bézut (1730-1783), student examiner at the Navy, opened new horizons for Monge. Jean-Nicolas Pache (1746-1823), the secretary of the Ministry of the Navy, appointed him as the substitute (1783). Eventually, in 1784, Monge abandoned Mézières, after spending there the 20 most productive years of his existence. He was awarded an annual pension of 1,000 livres and replaced by his substitute, Claude-Joseph Ferry (1756-1845).^{8,9}

In 1785, the class adjuncts at the *Académie* was suppressed and Monge appointed associate member. In 1786 Monge was elected member of the *Société Hollandaise des Sciences du Haarlem*.

Monge supported the French Revolution and like many of his colleagues he joined the *Société Patriotique de 1789*, and when this seemed to moderate, he transferred to the *Société de Luxembourg* and finally to the *Club des Jacobins*. After the King Louis XVI had been replaced by an Executive Council elected by the Assembly, Monge was appointed Ministry of the Navy (1792); a position he occupied for less than one year. While being Minister, he signed

the act of the verbal process that condemned the King to death at the guillotine, an action that would lead, after the Restoration, to his downfall and humiliation.

His high office in the government brought him in contact and friendship with Napoleon Bonaparte (1769-1821), and consequently, participation on the Italian campaign and the Egyptian expedition. In Italy, he and Louis Alexander Bérthier (1753-1815), Napoleon's Chief of Staff, were charged with transmitting the text of the Treaty of Campoformio to the Directory in Paris. Monge was also appointed member of the *Commission des Sciences et des Arts en Italie* set up by the Directory to select all the Italian valuable art objects that the Treaty awarded to France. Once Egypt was conquered, Napoleon brought in a large number of engineers, mostly graduates of the *École Polytechnique* to reorganize the ports, the roads, the different public services, etc. as well as organize the logistics of maintaining a large army. In 1798, Napoleon created the *Institut d'Égypte* and put Monge as president. Napoleon and Monge returned to France in 1799.^{8,9}

In August, 1793 the Convention closed most of the French educational institutions, among them, the *Académie des Sciences*. The Convention, facing the impossibility to educate the young (the schools and convents had been transformed into prisons) realized the importance of reconstructing what had been destroyed. One of the important changes carried on was the reform of the *grandes écoles*. This led to the foundation of the *École Centrale des Travaux Publics* (which would afterward become the *École Polytechnique*), to educate engineers for Ponts et Chaussées, *Artillerie et de Génie*, the *École Normale*, and the *Institut National* (1795). Monge played a critical role in all the phases of creation of the *École Polytechnique* and was appointed its Director in 1797. Monge was appointed member resident of the *Section des Arts Mécaniques de la première class* of the Institute.^{8,9}

After his return to Paris, from Egypt, Monge resumed his duties as director of the *École Polytechnique* but relinquished them two months later when, following the *coup d'état* of 18 Brumaire (November 9, 1799), Napoleon overthrew the French Directory and replaced it with the French Consulate. Bonaparte bestowed Monge with many titles, appointments, honors, and gifts: Senator for life, vice-president of the *Senate* and *senator of Liège*; *Grand Officier* of the *Legion d'Honneur*, *Comte de Péluse*, etc. etc. In 1806, Monge was elected president of the Senate. With the final exile of Napoleon in 1815 after the Hundred Days, the restoration of the Bourbons brought a terror wave to France. Monge was one of its victims: he was stripped of his honors, harassed politically, expelled from the *Institut de France*, and forced to hide (he returned to Paris in 1816). These sanctions that caused him much pain particularly because none of his friends and colleagues protested against what he considered an injustice. After illness, he passed away on July 28 1818 and was buried in the *Père Lachaise cemetery* (Fig 2).



Fig 2. Monge's tomb at the Père Lachaise cemetery

As told by Dupin, Brisson, and Barral^{1,2,5}, his students at the *École Polytechnique* were prohibited of assisting to his funerals; but did so in the first day out they had. No official homage was rendered. Claude-Louis Berthollet (1748-1822) pronounced a speech at his funeral. On December 12, 1989, within the celebrations of the bicentenary of the French Revolution, his ashes were transferred to the Pantheon (Taton, 1950a, 1951c).^{8,9}

As a suitable epilogue the author can remark that when Gustave Eiffel built his famous tower in 1889, he decided to honor 72 distinguished French scientists by putting their names in the structure. There are eighteen names per side of the tower, all positioned just below the first platform of the structure, on the outside. The letters in the names are 60 cm high. Monge's name is located on the third facade, opposite the Military Academy.

In 1781, Monge was selected to edit the volume *Dictionnaire de Physique* of the *Encyclopédie Méthodique*.¹⁴ Among his many publications in the area of advanced mathematics the can mention *Géométrie Descriptive*¹¹, *Géométrie Descriptive; Suivie d'un Théorie des Ombres et de la Perspective, Extraite des Papiers de l'Auteur*¹², *Feuilles d'Analyse Appliquée a la Géométrie*¹⁵, and *Application de l'Analyse a la Géométrie*.¹⁶

Monge's first physical observations correspond to a trip he made in the Pyrenees together with the commander of his school in the summer of 1774. Together with Jean Darcet (1725-1801), they carried on a set of detailed barometric experiences, with the purpose of determining the altitude of a mountain. Darcet published their findings the following year.¹⁷ Monge visited many locations of important mines and French industry, and eventually published in 1786, along with his friends Charles-Auguste Vandermonde (1735-1796) and Berthollet, a long memoir describing the physical and chemical modifications of iron, cast iron and steel during common metallurgical operations.^{8,9,18} His expertise in iron industry led to him being put in charge of the project to modernize the French steel industry, in order to accelerate the manufacture of weapons and provide all the technical directives to carry on this job. Together with Vandermonde and Berthollet, they were asked to publish a practical manual, with the pertinent drawings, to manufacture forged steel and cement steel.¹⁹ A following publication was related to the manufacture of cannons and consequently, together with Berthollet, they were assigned to research the methods for fabricating gunpowder.^{8,9,20}

Monge was initially a supporter of George Ernst Stahl's (1660-1734) phlogiston theory and used to explain the results of his most important chemical studies (iron metallurgy¹⁸ and the synthesis of water^{21,22}). Eventually he adopted the new chemistry of Lavoisier. In 1784, with Louis Clouet (1751-1801) he achieved, the first liquefaction of a pure gas (sulfur dioxide). Other subjects he investigated were the explosion of gunpowder, the composition of nitrous acid, the double refraction and the structure of Iceland spar²³, conversion of the coloring matter of Prussian blue into an elastic fluid, aerostatic studies, inflation of balloons with hydrogen and carbon monoxide, the action of electric sparks on carbon dioxide gas²⁴ acoustics, capillary phenomena²⁵ an explanation of certain meteorological phenomena²⁶ felting and fulling in the manufacture of clothing²⁷ optical phenomena^{8,9,28} and fabrication of cheese²⁹. In 1805 Chaptal and Monge were requested to judge a proposal by the chief engineer of the Paris guard of firefighters to fight fires of with a concentrated solution of sodium chloride, instead of tap water, as customary.³⁰ Chaptal and Monge made the pertinent experiences and found that the proposed change had several important advantages: (1) It allowed a longer life of water storage barrels, because they did not corrode and did not rupture when the temperature went under 0 °C (due to freezing), (2) the stored water did not decompose, (3) the saline solution did not affect the leather pipes feeding the pumps (they were washed after use), and (4) the proposed method did not require additional equipment.

SCIENTIFIC CONTRIBUTION

Taton publications^{8,9} contain a detailed list of the works written by Monge: books, memoirs, posthumous publications, unpublished papers, reports to different committees, etc. etc. Most of them are in the area of mathematics. The author will describe the ones carried on in the areas of Chemistry and Physics.

Together with Louis-Bernard Guyton de Morveau (1737-1816), Lavoisier, Laplace, Berthollet, and Antoine-François Fourcroy (1750-1809), he translated into French the Richard Kirwan's (1733-1812) book about phlogiston and the constitution of acids.³¹

Synthesis of water

Monge's most important chemical contribution was related to synthesis of water by ignition of a mixture of hydrogen and oxygen. In a paper read to the Académie in 1783²² he wrote that when a mixture of dephlogisticated air (oxygen) and inflammable gas (hydrogen) was inflamed by means of electrical sparks or by a sufficiently high temperature, the two fluids decomposed and released a large amount of the heat that "was contained in their composition". Monge believed that this fire, which was in a state of compression or maintained by adhesion by the constituent parts of the fluids, expanded, collided with the walls of the containing vessel and shattered them mechanically, when they were not resistant enough. If resistance was high enough, the fire lost its movement, passed through the pores of the walls as "temperature matter" and heated the surrounding objects. In spite of all the experiences that had been done using Volta's eudiometer, nothing was known about the nature of the remaining residue because they had been done on a very small scale, or because the inflammation had been carried on the water that masked this residue and prevented it from being seen. This experiment was important because it could give a new substance or provide light about the composition of a substance already known. Monge believed that it was better to carry it on a larger scale, in closed vessels, under dry conditions, and free of contact with any foreign substance.²²

Monge prepared the dephlogisticated air (oxygen) by heating a red oxide of mercury in a tightly closed retort. The inflammable gas (hydrogen) was prepared by dissolved very clean iron filings with diluted sulfuric acid in a large enough vase, in order to obtain all the quantity needed, without introducing additional iron or acid, and avoiding the entrance of atmospheric air, which would have altered the results. The resulting pure gases were stored in an inverted glass cylinder, submerged in water and having a volume previously well calibrated with pure air. Combustion was carried out in a glass globe containing a small Volta eudiometer, which could be evacuated by means of a water pump. From the top of globe left three short pipes, one communicating with a water pump (to evacuate the balloon), and two communicating respectively with the stopcocks of the bell jars containing the two pure gases. This arrangement prevented mixture of the gases with atmospheric air until the experiment was concluded. Monge introduced a certain amount of dephlogisticated air into the eudiometer, followed by a larger amount of inflammable air, and then discharged an electrical spark in the mixture. Another small amount of oxygen was now added, and a second discharge induced. The procedure was repeated until all the hydrogen was consumed. Then added another portion of hydrogen and repeated the overall procedure for up to 137 times. At the end of these operations he observed that the glass bulb was clouded.²²

Monge recorded the following observations: (a) each explosion gave place to the sudden release of a large amount of heat, which he could feel in his face even at a distance of one meter. This forced him to cool the bulb after each explosion; (b) the cooling resulted in the formation of fog that disappeared during the following explosion because the heat released evaporated the drops; and (c) the noise of each following explosion become duller and eventually was accompanied by a luminous effect.²²

Afterwards, Monge emptied the bulb, weighed the liquid and gas phases, and noted that the total weight was slightly less than the one of the original gases. He attributed the difference to not having corrected for the different temperatures of the reservoirs, pressure changes during the initial steps of filling each gas, and to possible losses during operation of the vacuum pump. The final gas phase was found to contain a very small amount of fixed air (CO₂). Monge believed that the latter was not a product of the inflammation but originated from small impurities present in the original gases, or from the water used to dilute the sulfuric acid employed to clean the iron wire.²²

The most interesting results were those of the analysis of the resulting liquid. It was completely transparent, had an empyreumatic odor like that of distilled water, and it slightly reddened blue litmus paper (less than saliva). This acidity could not be attributed to CO₂, because the liquid did not form a precipitate with limewater. It rendered solutions of silver or mercury nitrate slightly opalescent (unfortunately Monge did not test for the presence of a chloride). Monge believed that the acidity most probable came from sulfuric acid carried over by hydrogen during its preparation, although he did not perform a simple test for this possibility. Only part of the water could come from the humidity of both original gases, because hydrogen and the oxygen were composed just of light and fire, substances which could be made permanent only by their combination with a substance unable to pass through the walls of the vessel.²²

The result of the experience was then that detonation of a mixture of hydrogen and oxygen yielded pure water, heat and light. Nevertheless, it was necessary to consider two possibilities: (a) the two gases being in solution with different substances in the fire fluid (caloric, considered as a common solvent), abandoned by inflammation the solvent and combined to produce water that would not be then a simple substance and (b) the two gases were dissolutions of water in distinct elastic fluids; these fluids abandoned the water that dissolved them, combined and formed the fire fluid and light that escaped through the walls of the vases. In this situation, fire would be a compound substance. Both consequences were equally extraordinary and additional experiences of a different nature would be required to decide between them. Admitting the first one, that is, regarding water as a compound of the bases of dephlogisticated air and inflammable air, it would explain the function of water in vegetation: vegetation would carry on the operation by which Nature decomposed water and removed the base of inflammable air in order to combine it with the vegetables (which were ready available), and the base of dephlogisticated air, with the aid of heat and light coming from the sun, returned to the aeriform (gas) state, and stay on as such. Water would not be then necessary to vegetation simply as a vehicle: it would be one of the materials. This explanation accounted at the same time for many other phenomena, such as moistening of cold surfaces by the flame of vegetable bodies, the condensation of water in the chimneys of stoves; and the violence of detonation of gunpowder, which Monge thought must be caused only by vaporization of the water produced by its combustion. Nevertheless, "*this hypothesis*" presented a serious difficulty, which he could not overcome: the mixture of inflammable gas and dephlogisticated gas needed only an increase in temperature to ignite; the pertinent temperature depended on the nature of the inflammable gas, on the amount of dephlogisticated gas, and on the density of both fluids. It was also well known that approaching a very cold body to the flame of a candle would turn it off, in the same manner that it could be lit again by approaching to a very hot body.²²

The author can see from the above that Monge did not seem fully aware of the consequences of his experiments or was weary of taking an audacious step forward. Heavy use of the old terms of caloric and phlogiston, excessive caution, hesitation, etc., caused him to forfeit the opportunity of playing a main role in solving one of the most important chemical questions at his time. Was water an indivisible material formed of hydrogen and oxygen or it

could be separated into its elements? The question of the composition of water and the priority of its discovery remains a subject of hot controversy and has been discussed in a previous paper.³²

Later on Monge would abandon the phlogiston theory to become an enthusiast defender of Lavoisier's new chemistry.

In a footnote to his paper, Monge remarked that the experiences described were carried on at Mézières during the months of June and July 1793 and repeated in October of the same year. He was not aware that Henry Cavendish (1731-1810) had carried similar experiences several months before and even less aware that Lavoisier and Laplace had also carried analogous experiences more or less at the same time like his, using an apparatus that was less precise than the one he had used [1]: *"I did not then know that Mr. Cavendish had [his experiences] several months before in England, though on a smaller scale; nor that MM. Lavoisier and Laplace had made them about the same time in Paris, with an apparatus, which did not admit as much precision as the one which I employed"*.²²

In his paper about the composition of water, Lavoisier recognized Monge's contribution to the problem, in these words: *"We were not aware that M. Monge was working on the same subject, we learned about it several days later after from a letter he sent to M. Vandermonde, which he read to the Académie, describing an experience of the same nature, giving similar results. Monge's apparatus was highly ingenious, he took extreme care to determine the specific gravity of both gases, he operated without losses, so that his experience is more conclusive than ours, leaving nothing to criticism. His result was pure water, weighing almost the same as the two gases used."*³³

Decomposition of CO₂

In a memory published in 1788, Monge reported his results on the effects of electrical sparks in fixed air (CO₂).²⁴ Other scientists, such as Joseph Priestley (1733-1804) and Martinus van Marum (1750-1837) had also performed this experiment. Priestley found that an electrical discharge in CO₂ increased volume from 20 to 30 % and changed its nature, at least partly, because about 25 % was not dissolved in water and did not gleam with nitrous air (showing that it did not contain oxygen). Monge thought as important to repeat the experience, in order to determine the nature of the gas present in the final elastic fluid, and if possible, the change that had taken place as the result of the electrical discharge. The CO₂ used in the experiments was prepared by reacting marble with diluted sulfuric acid, and stored in a glass bell submerged in mercury, taking care to avoid contamination with atmospheric air. The gas was then distributed into eight identical inverted bowls, sealed at the bottom by mercury, and each having two iron electrodes to produce the electrical sparks. These electrodes were communicated between them so that all bowls could be activated simultaneously.

Monge reported that the electrical sparking not only produced the increase in volume observed by others, but also that the increase continued during a considerable time after the electrical excitation had been stopped (even for several days). The (average) greatest dilation was that about 1/24 of the original volume. In addition, the surface of the mercury became covered with a black powder that adhered to the walls, and was accompanied by corrosion of the electrodes. The resulting gas was found to be a mixture of two gases, one soluble in water and in caustic alkali, and the other one not soluble; the soluble part and the insoluble one being in the volumetric ratio 35.5 to 14. According to Monge, the insoluble fraction was inflammable air because it could to explode with dephlogisticated air (oxygen) by means of the electric spark produced with a gold exciter. In addition, no reaction was observed when this gas was contacted with sulfur liver (potassium carbonate heated with sulfur), proving that it did not contain dephlogisticated air (oxygen). In other words, the calcination (corrosion) of the metal produced two opposing effects. On one hand, it deprived the CO₂ of the water it contained (reduction in volume) and on the other hand it restituted the inflammable gas (capable of a substantial expansion) increasing the total volume of the gas. The same phenomena were observed when instead of iron, the conducting wires were made of platinum, hard to calcine. In this case, the decomposition of water was attributed to calcination of mercury, a part of which, Monge supposed, was dissolved by the fixed air. Another of Monge's important conclusions was that the calcination of certain metals by CO₂ did not provide support for the chemists still backing the phlogiston theory.²⁴

Gas liquefaction

In 1801, Monge and Clouet were able to liquefy sulfur dioxide by passing a stream of SO₂ through an U tube sunken in a refrigerant mixture of ice and salt. They were surprised to notice that the tube was filled up little by little with a colorless and high mobile liquid, similar to water. Unfortunately, they did not publish their results and their achievement was consequently ignored. Most historians have attributed to van Marum and Adriaan Paets van Troostwijk (1731-1795) were the first ones to achieve the liquefaction of a gas although they actually liquefied an aqueous mixture of ammonia. Monge and Clouet's priority for the liquefaction of a *pure gas* was clearly demonstrated by Ernst Cohen (1869-1943).³⁴

Iron metallurgy

In 1786, Vandermonde, Berthollet and Monge published an extensive memoir (68 pages) discussing the characteristics of iron in different metallic states.¹⁸ In their opening statement they remarked that their properties so different that for some time chemists were doubtful whether it was the same iron metal. Torbern Olof Bergman³⁶ (1735-1784) had found that cold fragile iron differed from ductile iron by a white precipitate formed when dissolved

in sulfuric acid. Meyer had found that this precipitate, which he named siderite, was an iron phosphate salt, a result that was confirmed by Clouet. According to Clouet, the property of cold iron being fragile was due to the presence of arsenic. Later, it was argued that the various substances with which iron is occasionally combined were the cause for its existence in four different forms: Brittle and fusible when coming out of the furnace, ductile and infusible when refined; by cementation it becomes capable of the hardest temper and cementation carried too far renders gaining fusible and intractable on the anvil. One of the purposes of Vandermonde, Berthollet, and Monge's works was to determine more precisely to which substances did iron owe these properties in the different states.

The first part of their memoir was a description of the current art of iron metallurgy. The first operation was the melting of the mineral in a blast furnace. If the mineral had been a carbonate, free of other combinations, the resulting regulus (metal) should have been iron in its metallic state. But in mineral, the metal was combined with many other slightly soluble materials, which protected it from the action of external chemical factors. Hence it was necessary to mix the mineral with a flux (normally carbon) in order to fuse it more easily and produce the variety called cast iron. It was found to be fragile and fusible, variable properties that depended on the nature and amount of the different impurities it contained. In this state it existed in various forms having different colors (white, gray, and black).¹⁸

The following state, forging, transformed cast iron into wrought iron. This operation was carried on by first heating cast iron with coal until softening and then working it with a hammer. The resulting metal was now ductile and infusible and could be worked into many different shapes. The properties of iron could be further changed by a process called cementation, where iron bars and charcoal were packed in alternating layers, with a top layer of charcoal and then refractory matter. The bed was heated from below and kept in this state for a variable period of time, with the bars almost in a state of fusion. The final product was blister steel (*acier poulé*), thus named because the process released a gas that erupted through the metal generating cavities and blisters. The bars were forged and the blisters closed, by hammering. The resulting iron was more fragile, hard, and fusible. Further heating and quenching in cold water resulted in additional hardness. Vandermonde, Berthollet, and Monge found that conducting the cementation for longer time or higher temperature, so that the steel fused, the following quenching produced bars more fragile and more fusible, which could not be forged by ordinary means. They mentioned that Sven Rinman (1720-1792) had reported that putting a drop of nitric acid on steel led to corrosion and formation of a dark spot, while with soft iron no spot was formed.¹⁸

The following section of the memoir was a summary of the findings of René-Antoine Ferchault de Réaumur³⁵ (1683-1757) and Torbern Olof Bergman³⁶ (1735-1784), on the art of manufacturing steel. According to Réaumur, the differences in properties between soft iron and steel were due to the sulfur and salts they contained; these could be eliminated by dissipation into air or by reabsorption of substances that had a larger affinity; cast iron was simply a steel more cemented by terreous substances not entirely eliminated in the furnace. Bergman had found by the wet procedure that the different varieties of iron contained manganese, silica, and plumbago (graphite). He assumed that plumbago was a compound of fixed air and phlogiston, a kind of "*sulfur, able to combine with iron as long as the latter lost part of its phlogiston*". Wrought iron did not contain plumbago but more phlogiston and the matter of heat than any other state of iron. Steel, on its part, contained more plumbago and less phlogiston and the matter of heat than iron, and cast iron contained more plumbago and less matter of heat than steel. Hence, to refine cast iron, it was necessary to eliminate or decrease the plumbago it contained and add more phlogiston.¹⁸

Afterwards, Vandermonde, Berthollet and Monge described the different researches, experiences, and detailed analyses they had performed in order to determine the composition and properties of casts, steels, and soft iron. They finished their review remarking that although Réaumur and Bergman disagreed in many of their conclusions, they agreed in steel was iron in a state intermediate between cast and wrought iron. They believed that the results of their experiences and those of the two researchers indicated that cast iron and steel were not composed of the same principles. Their arguments were as follows: Iron should be considered a regulus that had not been completely reduced; is still contained part of the basis of dephlogisticated air the original mineral, in the form of carbonate. Since the reduction could be carried further on, they considered it as the main factor leading to the different cast irons that could be obtained from the same source. Carbon had the power of combining with different substances without changing its nature, with many metals, iron in particular. Hence they believed that in the blast furnace, cast iron absorbed a relatively large amount of this fuel, leading to a wide variation in the properties of the cast iron. Well refined forged iron was the iron completely reduced and contained no foreign substances, including carbon. In cemented iron, the metal was perfectly reduced and was mostly combined with the absorbed carbon it from the cement, Carbon had to be in a certain proportion just to yield steel of the required properties. Hence, the substantial differences existing between cast iron and steel. Most important these conclusions proved that the phlogiston theory could not subsist with the latest discoveries about calcination of metals and decomposition of water. When metals are dissolved in HCl or sulfuric acid, they first decomposed the water that diluted the acid, withdrawing the dephlogisticated acid present in it. Then, they dissolved and the base of inflammable air was released, recovering the elastic (gas) state, as shown by the abundant effervescence accompanying the process. In other words, the inflammable air produced when iron is dissolved in these two acids was not a component of the metal; it originated completely from the decomposition of the water.¹⁸

The experiences performed by Vandermonde, Berthollet, and Monge to substantiate their claims, showed that (1) the dissolution of casts of iron in acids generated less inflammable air than that of sweet iron, proving that they were less reduced than forged iron; (2) white casts released less inflammable air than the grey ones; (3) the amount of inflammable air released by different forged airs were less variable; and (4) steel generated less inflammable air than forged iron. This result was due to the fact that steel contained carbon (consequently, a lesser proportion of iron). The main difference between forged iron and steel came from the carbon contained in the latter, originated during the cementation process. This observation explained Rinman's result on the action of acid over the surface of steel or forged iron. The black coloration resulting from the action of the acid was due to exposure of the carbon present in steel. In addition, it was found that strongly heating steel caused to burn in a different manner than forged iron. Steel threw far away burning tinkles, which exploded in the air since the contained carbon it burned more rapidly.¹⁸

The following section gave a detailed description of the operations carried in forging factories, just to transform the iron into different states (fusion of the metal in the blast furnace, refining of cast iron and cementation), and the different states of carbon combined with iron. Carbon had the property of combining with iron producing a true dissolution, as proved by the fact that both were uniformly distributed inside the mass, in of spite having very different specific gravities. All the different properties of the combination pointed out that the carbon was actually graphite.¹⁸

The last section of the memoir was a recapitulation of the results: (a) Cast iron should be considered as a partially reduced regulus since during dissolution in HCl and sulfuric acid; released less inflammable air, decomposed water, and absorbed less dephlogisticated air than sweet (forged) iron. In addition, heating cast iron, particularly the gray variety, transformed it into the white variety, without the need of contact with air; (2) gray and black cast iron contained absorbed carbon, as shown by the fact that it could be cemented and converted into steel, and the left residue when dissolved in sulfuric acid; (3) cemented steel was iron in the most reduced form, combined with a certain amount of carbon. The different varieties of steel differed only in the amount of carbon they contained, as shown by the larger amount of residue left after their dissolution in acids; (4) although iron perfectly forged was a regulus of the maximum purity, the one sold commercially contained little of carbon and little of dephlogisticated air; and (5) finally, coal, after being held in solution by melting steel up to the state of fusion and abandoned the metal on cooling, attracted always a certain proportion of the metal. This was the plumbago, which is separated from the metal; when cooling was slow, it swam on the as surface and could be collected in natural state. When cooling was fast, plumbago mixed with the metal and gave some of the properties of steel.¹⁸

Vandermonde, Berthollet, and Monge published the same information in a more "popular" language, with the purpose of communicating their findings to the manufacturers of the different varieties of iron. This second memoir contained more technical information than the previous one.¹⁹

An additional memoir by Monge alone²⁰ gave a detailed explanation of the art of manufacturing canons. It was written employing the nomenclature and the principles of the new chemistry, and included a large number of explanatory figures.

Capillarity

According to Monge, scientists were initially inclined to regard matter as an inactive substance, refusing for a long time to admit any activity between the molecules of a body. Afterwards they assumed that molecules were endowed with a force that varied with distance, very strong when the molecules could be assumed in contact and becoming insignificant as the distance became very large. This was the explanation given to the ascent of liquids inside wet capillaries, and the descent in the dry ones. In 1751, Johann Andreas Segner³⁷ (1704-1777) made a theoretical attempt to determine the shape of the surface of a drop of water, resting on a horizontal plane, assuming that the parts of a fluid attracted each other. He introduced the concept of surface tension of liquids and failed to give a mathematical description of the capillary action.

In a memoir published in 1789 Monge²⁵ tried to prove that the movement by which certain small bodies approach or move away were not the result of an immediate attraction or repulsion, but were produced by pressures or by foreign attractions not previously considered. Before explaining his ideas, he described the outcome of the following experiences: When over a standing liquid two small wettable bodies were put to float, without impelling them in any direction, the two bodies would remain in a state of rest. If they were put very close one to another from the other, they began to approach, very slowly at the beginning, then more rapidly, until they joined together and could be separated without overcoming a sensible resistance. In this situation, one body would advance towards the other, trying to keep in contact. In addition, if the walls of the vase where the experiment was carried out were also wettable by liquid, the surface of water ascended all around. If now a ball of cork were put on the liquid, it would remain at rest, but if were located very close to the wall, it would also move toward the wall with an accelerating movement. This phenomenon was usually explained by an attraction of the cork for the material of the vase. It was also possible to prove that the substances did not exert reciprocally any action when separated by a large distance. If the cork was now attached to the end of a filament, it could be brought very close to the walls of the vase without any effect. In the previous situation, if more water were added to the vase, the cork would ascend and remain attached to the wall until the surface of the water rose up to the border of the vase. When the surface of the water elevated slightly above the

border, it became convex towards the border. To approach the cork to the wall required overcoming a slight resistance; in addition, that the cork ascended, in spite of its weight. To attribute these results to an attraction and to a repulsion required accepting that the endearment of these two materials has changed and become opposite, without having observed any circumstance justifying it.²⁵

Repeating this experience with one of the bodies being non-wettable gave opposite results: the two bodies could not be brought into contact without overcoming a certain resistance. Upon release of the force, they would move one away from the other. When the vase was slightly overfilled, the cork remain attached to the walls of the vase. A third experience was conducted using two non-wettable bodies, for example floating two iron balls in mercury. The two balls would rush one towards the other; separating one would cause the second to follow it. If the mercury were contained in a glass vase, the surface of the mercury would descend along the border and become convex. If the balls were approached to the border, they would attach to the vase and resist their separation.²⁵

Monge, the mathematician, saw that the results of the three experiences (wettable-wettable, wettable-non wettable, non wettable-non wettable) were similar with the sign laws in algebraic multiplication, expressed as follows: (1) If two wettable floating bodies, +, +, (each surrounded by a depression of the fluid surface), are separated at first by a small interval, they will move toward one each other as mutually attracted; (2) When both are non-wettable, -, -, (the fluid rises up around them) they will also appear to be attracted when brought near one each other and (3) When one body is wettable, +, (surrounded by an elevation of the fluid) and the other non-wettable, -, (surrounded by a depression, they will appear to be mutually repelled, unless an obstacle opposes.²⁵

In the following sections of his memoir, Monge explained his laws as follows: (a) Second law. When a non-wettable globule A is put to float on the surface of a liquid, the surface of the liquid around the globule is depressed and convex up. The globule remains in equilibrium because depression has the same depth everywhere and presses the globule uniformly. Then, if at a certain distance of A , a second globule A' is put, it will also remain in equilibrium and the bottom of both depressions are at the same horizontal plane. No change is observed when globules are approached until the summit of their curvatures of the liquid merge; the common summit of the two curvatures is at the same level as the rest of the liquid and the distance that separates them is the minimum distance at where they can remain in equilibrium. The latter is also the limit of capillarity for the given situation. If a globules are now brought closer, the liquid in between becomes depressed and its summit does not elevate to the same level as the rest of the liquid. Each of the two globules becomes subject to a pressure difference and consequently they move one towards the other. When two non-wettable globules are placed at a short distance, they approach one each other, not because attraction or other affection occurs between them, but as result of a pressure difference that is foreign to them. This result is also valid the two globules were submerged in the liquid. Scientists working with mercury observed this phenomenon frequently. When they tried to separate one finger from another, they felt a resistance that was not due to the difficulty in moving the liquid. (b) Third law. Placing over the surface a liquid two globules, one non-wettable (A) and the other wettable (A'), the surface becomes depressed around A and elevated around A' . The distance between the opposite curvatures varies as a function of the nature of the liquids, the nature of the globule and the temperature. If the two globules are approached until the summit of concavity and that one of the convexity merge, the two bodies remain in equilibrium because nothing has changed in their respect. This is the minimum distance where they can remain in equilibrium and is also the limit of the capillarity under the given circumstances. If they are brought closer, the depression of the liquid around A becomes smaller on the side of the other body because of the ascent that the latter produces around it, and leads to a non-symmetrical recess about A . The resulting pressure difference causes in a separation of the two bodies. In other words, when a wettable body is near a non-wettable one, the separation and movement that takes place is not caused by a possible repulsion between them but by the pressure difference that originates from their being wettable and not wettable. This result is equally applicable if the two bodies are submerged, instead of floating. (c) First law. Suspending from the end of a hanging filament a glass strip in such a way that it submerges in a water surface, water is seen to rise on both faces of the strip; the surface of this water is curve and concave up. This elevation is the result of the action that the glass molecules exert upon those one of the water as well as the action that the water molecules exert one each other. Since at present, there is no knowledge regarding the nature of these forces, we only know that the origin of the curvature depends on the nature of the strip, and temperature. Now, assume that two glass strips are suspended vertically, with their extremes submerged in water. The two strips are then approached until the origins of the masses of water are confounded in a same straight line. In this situation, both strips are in equilibrium because nothing has changed in their respect; the distance between both strips will be the limit of the capillarity of the space that separates them. This limit will depend on the same factors mentioned before. If the two strips are then approached in such a way that the two masses of water penetrate one another, the equilibrium is broken and the surface of the water between the strips will rise. The interesting fact is that the two strips will not remain vertical; they will become closer as one each other. It should be clear that what has been said regarding two plane strips is also valid for two floating bodies of any shape.²⁵

From the above experiments it resulted that when in a capillary a liquid rose above the level, the contained liquid attracted the walls of this space one towards the other. If walls were mobile, they approached each another and the capillary space decreased. The process continued until the liquid became too compressed. Hence, if a large number of

wettable plates were held in a parallel position inside a liquid and moved to approach one each other, eventually the movement would become autonomous and all the plates would join together into a large body.²⁵

The demonstration of the causes of capillary phenomenon provided Monge with a very intriguing explanation of the formation of large crystals from micro crystals (nuclei) originating close to each other in the bulk of a solution, or at the bottom of the vase. The “plates” (nuclei) being free to move, attached one to the other by the maximum number of points possible, following a mathematical law that expressed itself by the regularity of crystallization as long as a foreign cause does not disturb the order of an operation of this nature.

Although Monge did not derive the equations that describe capillarity phenomena, he understood that it was possible to achieve an analytical solution. His last comment was that *“by supposing the adherence of the molecules of a liquid to have a sensible effect only at the surface itself and in the direction of the latter, (then) it would be easy to determine the curvature of the surfaces of a liquid near the walls that contained it. These surfaces would be linear, with a tension constant in every direction and everywhere equal to the adherence between two molecules. Capillary phenomenon could be then easily determined by analysis.”*

A few years later, Laplace would provide the mathematical analysis of the phenomenon.³⁸

Optical phenomena

Monge studied in particular the causes and effects of coloration of objects due to atmospheric reflection and published two papers on the subject, the first one about certain vision phenomena and the second about the phenomenon of mirage.

Color perception

In his first paper,²⁸ Monge tried to discover the reasons why white and red objects observed through a red glass, or white and green objects observed through a green glass, instead of looking all red or all green, they actually appeared as white. According to Monge, it was known that colored transparent substances had the property of letting through rays of light of certain colors, while intercepting the others. For example, red glass allowed passage of most of red rays that stroke its surface and stopped the vast majority of rays of all other colors. It seemed then, that knowing the species of homogeneous rays that one particular colored transparent substance could transmit we could predict the changes that would take place in vision, when looking at objects through this particular substance. Monge assumed that by observation of a series of objects of different colors through a red glass, it was possible to predict that in relation to white bodies, the rays of all colors originating from their surfaces would reduce only to the red one passing through the glass. The images of these bodies would be the same as if their surfaces were red and the alterations that originated from the interposition of a red glass, resulted in a diminution of clarity caused by the suppression of the intercepted rays, and a change of the white color to red.

Regarding red bodies having the same hue as the rays that the glass allowed to pass, the vision would detect no other effect than a slight weakening of clarity caused by the flaw of transparency of the glass. Their color would seem to be the same, intercalating or not the red glass. For bodies of other colors, that is, those that did not reflect white or red rays, none of the rays they sent to the glass would go through, hence they would seem to be in total darkness and appear black.²⁸

Surprisingly, for the same two cases, the experimental results turned out to be exactly the opposite: When observing a series of objects of different colors through a red glass, red and white objects seemed to have the same color, but did not appear as red, they looked white. The same phenomenon was expected to take place when the objects were observed with a glass colored different from red. Bodies that reflected rays of the same color would appear as white. Monge demonstrated his conclusions by looking through a yellow glass at a piece of paper tinted yellow with karaya gum and showing that it looked white. He remarked that the same results were not obtained when using glasses tinted blue, green and violet, because these colors could be produced by different procedures (homogeneous rays or a mixture of different rays).²⁸

Monge concluded that when passing judgment on the color of a body, we were not determined only by the absolute nature of the light rays that the bodies reflected, since the impression given by a given ray produced not only the sensation of a red color but also a white one, according to the circumstances. He illustrated these effects by describing a phenomenon known by almost everyone: *“A little before sunrise on a fine day, when the clarity is enough to see the sky beautifully, one lets its light enter a room through an open window and illuminate a sheet of white object, for example a sheet of paper, that is simultaneously illuminated by a candle and the light reflected by the atmosphere. A small object placed on the paper, will cast a blue shadow on it, of the same hue as that of the sky...If the candle is now extinguished... the entire sheet of paper is then illuminated purely by skylight, as previously was the shadowed area...Its image on the back of the eye is composed of blue rays only, it should look blue as the shadowed part, however, it looks white”*. Monge wrote that this phenomenon had already been reported by the Abbé Pierre-Augustin Boissier de Sauvages (1710-1795), who had informed George-Louis Leclerc Buffon (1707-1788) about it.²⁸

Another important observation was related to the difference when observing a group of objects or only one of them: *“When we cast our eyes over a range of objects of different colors, there is no visible part of the surface of these objects, because at the same time as it sends to the eye rays of the characteristic color of the corresponding object it*

also sends rays of white light. It is by means of these rays of white light that we judge, not the contour of the objects, since this contour is established by the shape of the image painted on the retina, but rather the recesses, the breaks, and, in general, the degree of obliquity of different parts of the surface of the objects...So, even when amongst the objects of our gaze there be none that are white, we always have the awareness, not of white strictly speaking, but of white light, as a result of the brilliance that in general it gives to colors, and by the differences that it produces among tints, according to the obliquity of the surfaces". These results are contrasted with the one obtained when observing a single object: "... (Now) if (a) red glass is placed at the end of an opaque viewing tube and a single red or white object is observed through the tube, then none of it will appear to be white, they will appear red in both cases".²⁸

At this point, Monge remarked there was no definite knowledge regarding the nature of the light rays and no explanation for the different impressions they produced in the organs. Some attributed it to an intrinsic difference in the nature of the rays; others thought that it reflected the different speeds of light particles. He believed that this property was not absolute; it actually depended on the ratio of some properties of the rays to the corresponding properties of other rays. For example, if rays of light differed only on their speed, then to excite in us the experience of red, the light did not need to have a specific speed. Rather its speed would have to be in a certain ratio to the speed of other rays that are present.²⁸

A fascinating paper by Mollon gives a more detailed analysis of Monge's observations about color perception.³⁹

Mirage

It was common knowledge that sometimes at sea a ship seen far away seemed to be drawn in the sky, without being supported by the water.⁴⁰ The French soldiers had observed a similar effect during a march from Alexandria to Cairo. Villages, looked from the distance, seemed to be built on an island in the middle of a lake. When coming closer, the apparent surface of the water diminished until it disappeared when the observer was near enough. The illusion started again for the next village. Monge attributed this effect to the decrease in the density of the lower layer of the atmosphere, caused in the desert by the increase in temperature resulting from the heat transferred from the sun to the sand and then to the air layer in its immediate contact. In the sea, the effect was caused by particular circumstances, such as the action of the wind: the lower layer of the atmosphere maintained in solution a larger amount of water than the other layers. In this situation, the light rays originating from the lowest part of the sky, arrived at the surface that separated the less dense layer from the others above it and did not penetrate it. They were reflected and painted in the eyes of the observer an image of the sky. To the observer, part of the sky seemed to be under the horizon. This was the role it played when the phenomenon took place on the earth. At sea, we believed to see in the sky all the objects, which were floating on the part of the surface occupied by the image of the sky.⁴⁰

According to Monge, the country of Lower Egypt is nearly a level plain, extending itself like the sea, in the clouds at the edge of the horizon. When the surface of the earth was sufficiently heated by the sun, the land no longer seemed to have the same extension, but to be terminated by a general inundation. Villages appeared to be stationed in the midst of a large lake, from which the spectator was separated by an extent of land. Monge explained this phenomenon (mirage) on the base of optical principles: A ray of light traversed a transparent and uniform medium in the direction of a straight line. When it passed from a transparent medium into a denser one, if its direction was first perpendicular to the surface that separated it from the two media, then this direction would not change, it would simply be a prolongation of the original one. But if the direction of the incidental ray made an angle with the perpendicular at the force, then the ray would divide in its passage in such a manner that the angle that it formed with the perpendicular to the second medium would be smaller (refraction). In addition, with respect to the two media, independently of the size of the angle, which the incidental ray formed with the perpendicular one, the sine of this angle and that of the refracted ray were always in a correspondent ratio.⁴⁰

Then the sine of a large angle does not increase as rapidly as that of a smaller one. Hence, if the angle formed by the incidental ray and the perpendicular one happened to increase, then the sine of the angle formed by the broken ray increased in the ratio of the sine of the former, and the increase of the angle itself was less than the angle of the incidental ray. When the angle of incidence had reached its largest dimension (almost 90°), the angle formed by the broken ray was less than 90° . This was a maximum, or, in other words, no ray of light was able to pass from the first medium into the second, under a greater angle. When a ray of light passed from a denser medium into a lesser one, it followed the same line as in the first case, but in the opposite direction.⁴⁰

The final conclusions were: (a) If the ray of light was enclosed between the perpendicular and the direction of the diverging ray, which constituted the maximum angle, this ray would project into the less dense medium, (b) If the ray of light had the same direction as the diverging ray, the angle of which was the maximum, it would again issue forth by making an angle of 90° with the perpendicular, or by remaining on the plane which served as a tangent to the surface. But, if the angle which the ray of light formed with the perpendicular was greater than the maximum of the angle of reflection, or if the ray was compressed between the surface and the diverging ray, the angle of which was the maximum, it would not leave the dense medium; it would reflect itself to the surface and reenter the same medium, by making an angle of reflection equal to the angle of incidence, these two angles being in the same plane, perpendicular to the surface. This last proposition was the main reason for the occurrence of a mirage.⁴⁰

According to Monge, it was easy to understand why the phenomenon of mirage could not occur when the horizon was terminated by an elevated chain of mountains: These mountains intercepted all the rays of light transmitted by the lower part of the sky and only allowed to pass those above them which formed sufficiently large angles with the dilated surface, to prevent the reflection from taking place.

Iceland spar

In a memoir of 1786 (unpublished), Monge described the phenomenon of double refraction presented by Iceland spar,²³ discovered by Erasmus Bartholin (1625-1698) in 1670 and described in detail by Christiaan Huygens (1629-1695) and Isaac Newton (1642-1727). Monge described first the work done by others, particularly, Alexis Marie Rochon (1741-1817), and then his experiments to determine what in the crystalline structure and composition of Iceland spar (calcium carbonate crystallized in a rhomboid form) allowed explaining this double refraction. Rochon had explained the phenomenon by assuming that the crystal of the spar was built of dissimilar layers of a different density. According to Monge this was incorrect, it was more appropriate to assume instead that the faces of the crystal were built of two species of elements, "*one of them directed according to the faces of a rhomboid and the others are perpendicular to it*".²³ Using the principles developed by the crystallographer René Just Haüy (1743-1822), he exposed his ideas regarding the probable mechanism of crystal formation and experiments, which gave credibility to his explanation of the phenomenon. Over cautious, as usual, he remarked that "*it was necessary to wait until the form of the elements of these crystals has been determined as Haüy has done for calspar and many other mineral substances*".^{9,23}

METEOROLOGY²⁶

At Monge's time, it was believed that air had the capacity to dissolve water and convert it into an elastic fluid, and that the dissolved water air did not affect the transparency of the atmosphere. In addition, the capacity of the air for dissolving water decreased as its humidity increased and eventually reached a saturated state. The point of saturation increased as the temperature went up. Cooling saturated air resulted in condensation and reduction in humidity. Although this information did not suffice to explain the main meteorological phenomena, it was enough for many daily life observations, for example, the formation of water drops on the surface of a cold body in contact with saturated air. To these principles, Monge added another (mistaken) one that the amount of water dissolved in air *increased* as the pressure was increased. Monge wrote that the latter effect could be easily demonstrated by connecting a flask containing saturated air to a pneumatic vacuum engine. The initial air, initially transparent, became cloudy, more or less intensively according to the size of the vessel. Horace Bénédicte de Saussure (1740-1799) had suggested that a simple way to observe this phenomenon was to make the experiment in a dark chamber and illuminate it with a light source. The light would make the water drops clearly visible. According to Monge, this result explained what happened when the reading of the barometer decreased. The lower atmospheric layers, being less compressed, approached and exceeded their saturation state; the excess of water abandoned the air and formed a cloud that eventually fell as rain. The opposite phenomenon occurred with an elevation of the mercury column. Thus, the atmosphere could become supersaturated for two reasons, a decrease in temperature or a decrease in pressure. Each variable operated in a different manner, a decrease in temperature lead to formation of water drops on the top of a surface, a decrease in pressure to a uniform formation of drops in the air layer.²⁶ Monge proceed to describe an additional experience made by Saussure, which seemed to contradict his theory. Saussure had found that when making vacuum over a bell positioned on the plate of pneumatic engine, the air hydrometer located inside the bell instead of indicating an increasing humidity (as should have done if rarified air had a lower capacity for water), it showed at first a variation towards higher humidity and then, after each knock of the piston, increasing dryness (a table of the results is given). Monge believed that these results did not negate his hypothesis; they could be easily explained by the manner in which elastic fluids (gases) behaved when changing their density. The hairs of the hydrometer could not be in hydrometric equilibrium with the humidity unless the water molecules on its surface were in equilibrium with all the forces applied on them. Some of these forces tried to force penetration of water inside the substance of the hair, while the others opposed this intromission. In the particular case under consideration, only one force opposed penetration: the adherence between the constituent molecules of the hair. This adherence had to be overcome, in order to separate the hair molecules and allow penetration of new molecules of water. This force was not a simple resistance, since in trying to separate hair molecules it also tried to expel water molecules. There were two forces trying to introduce water inside hair material. One was the excess affinity of water for hair and the other the compression applied by the external fluid on the surface of hair. Any alteration in these three forces resulted in penetration of the water or its expression. Monge attributed the advance of the hygrometer towards dryness as the result of the decrease in pressure of the air over the hair. He failed to consider the thermal effects (vaporization/condensation) and did not attribute to rarefaction that part of the water in the air of the hygrometer served to replace the part of the water withdrawn from the bell by the pump.²⁶

The second part of Monge's memoir was devoted to a discussion of meteorological phenomena related to a lack of transparency of the atmosphere (smoke, fog, cloudiness, snow, rain, frost, hailstorm, and waterspouts), and the resulting atmospheric agitations (such as thunder). The critical situation occurred when the air became supersaturated.

The excess of water went from the gas to the liquid state (as massive small globules) and substantially modified the atmospheric transparency. The change in phase was the result of a temperature drop or a pressure diminution. As mentioned before, each of these two factors affected the transparency in a different manner.²⁶

Monge not only explained these phenomena in a very simplified manner, it also gave an exaggerated weight to local geographical factors. For example, when temperature decreased, hydrostatic laws forced the resulting mixture to ascend as a plume if achieved a temperature higher than that of the surrounding layers. If the temperature of the mixture was not substantially different from the adjacent layers, then it remained in the same position and produced cloudiness. Rain was simply a secondary effect to these situations. Larger temperature drops could result in snow; the water globules froze and crystallized as regular hexagons, which fell when the atmosphere was rather calm. When the atmosphere was agitated and the snow fell from higher altitudes, the hexagons collided and broke into irregular pieces.²⁶

The explanation of the origin of a thunder was even more curious. Lightning was always accompanied by the sudden formation of a large cloud, either as a cause or an effect. Hence, according to Monge, the noise of the thunder was not due to lightning but to the formation of the cloud. When a great volume of air became supersaturated and generated a cloud, the large amount of water withdrawn reduced its volume by about 90 %, causing a sort of vacuum, in the atmosphere. The upper layers by their weight, and the lateral by their elasticity, rushed in to fill this vacuum colliding violently and producing the accompanying noise.²⁶

A year later, the Swiss meteorologist Jean De Luc (1727-1817) sent to the publishers of *Annales de Chimie* a memoir, harshly criticizing Monge's theories and explanation of meteorological phenomena, and accusing him of little knowledge about the subject and the allied physical branches. De Luc requested that his paper be published in the same journal "to avoid Monge putting us thirty years back on the knowledge and understanding of the subject".⁴¹

CALORIC

In his contribution to the *Encyclopédie Méthodique*,¹⁴ Monge gave a detailed description of the hypotheses that served as the bases of the caloric theory. By definition, caloric was an impenetrable fluid, compressible, extremely elastic, of an extreme slenderness, and whose weight was not manifested by any phenomena. Caloric was the common cause of all phenomena related to heat. It had the property of being attracted by the molecules of all natural bodies, with forces that decreased as the distance increased, and according to laws that varied according to the nature of these bodies. It acted through the molecules according to the laws of Nature, by reason of its own mass and by consequence of the compression it caused. The general properties of bodies in relation to caloric were being formed by molecules that acted one on the other, with forces decreasing as the distance increased and with laws depending on their nature, and that did not touch one another, a fact demonstrated by their volume decrease when cooled down. These molecules were separated by layers of caloric, which were compressed by their trend toward the molecules, and by the pressure of these layers on the external one. The compression decreased as the layers became further away from the molecules to which they adhered.

UNIT OF LENGTH

According to Taton⁹, in 1790 the Assembly charged the Académie des Sciences with the task of establishing the bases of a decimal system of measures. The complexity and the diversity of units used by the different provinces had been a significant embarrassment for science and commerce, and the many attempts of the monarchy to solve the problem had been unsuccessful. The Académie decided that in order to facilitate its universalization, the projected system would be based on natural units such that the 10-millionth part of one quart of the terrestrial meridian, going from Dunkerque to Barcelona, to give a definition of the new unit of measure, the meter. The Académie distributed the task among many committees, with Monge and Jean-Baptiste Meusnier (1754-1793) charged with the measurement of the depart of the projected triangulation. Eventually Monge, Jean-Charles de Borda (1733-1799), and Lagrange were among the signatories of the thick report made to the Académie regarding the general system of measures and weights of May 29, 1793.^{8,9,42,43}

In the opening part of their report they wrote that the idea of relating all measurements to a unit taken from nature was born as soon as mathematicians realized the existence of such a unit and the possibility of establishing it. They understood that this was the only way to exclude all arbitrariness of a system of measurements, providing the option of keeping it forever, without any revolution in the world order putting it in doubt, avoiding its belonging to a particular nation, and having the satisfaction of seeing it adopted by everyone. Then they went into a discussion of the three different possibilities for defining a natural length unit: the length of a pendulum, a quarter of the equatorial circle, or a quarter of the terrestrial meridian. The length of a pendulum seemed, in general, to be preferred because it was easy to determine and, consequently, to verify. The laws that governed the movement of the pendulum were well known and had been confirmed by multiple experiences. Within this context, it seemed natural to prefer the length of a simple pendulum that beat the seconds at 45°. The law being followed was that from the equator up to the poles, the length of simple pendulum making equal oscillations was such as that one of the pendulum at 45° was precisely the average length of all these lengths. It was also the average between the two extreme lengths, one at the pole and the other at the equator, and also between two arbitrary lengths corresponding to equal distances, one at the north and the

other at the middle of the same parallel. Unfortunately, the unit thus determined contained in itself an arbitrary choice. The second of time was the 864 hundredths part of a day, and consequently, was an arbitrary division of this natural measure. Thus, using a pendulum to fix the length of the unit of longitude required the use of not only a heterogeneous element (the time), but also of an arbitrary element.⁴³

Hence, the best choice to define a unit of length that did not depend on another quantity was to take it on the earth itself. Thus, unit would have the additional advantage of being totally analog to all real measurements taken daily on the earth, for example, measuring the distance between two points. Consequently, it was more appropriate to relate the distance between two points to a quart of one of the terrestrial circles. Borda *et al.* chose the quart of the terrestrial meridian as the true unit of length, and the 10 millionth part of this length, to be the common length unit (the meter). Although the immediate measurement of one quarter of a terrestrial meridian was impracticable, it could be ascertained by measuring the arch of a certain stretch to calculate the value of the total arch. For this purpose, they proposed to measure a meridian arch from Dunkerque up to Barcelona, corresponding to a little more than 9.5⁰. One important advantage of this arch was that its two extreme points were at the sea level.^{42,43}

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