Carnot's contribution to thermodynamics

At first almost ignored and unread, Sadi Carnot's analysis of heat engines—published 150 years ago—contained ideas and methods that were to be developed later by Clausius and Thomson.

Martin J. Klein

Sadi Carnot's first and only scientific work was published just one hundred and fifty years ago. It initiated the development of the classical thermodynamics that James Clerk Maxwell characterized so well as "a science with secure foundations, clear definitions, and distinct boundaries."[1] The role Carnot's ideas played in developing that science is the subject of this article.

The little book that appeared in Paris in June 1824 dealt with a problem of great practical importance. Its full title makes that clear: *Reflections on the Motive Power of Fire and on Machines Fitted to Develop that Power.*[2] Sadi Carnot wanted to understand the production of power by the heat engines that were affecting more and more aspects of contemporary life and that seemed "destined to produce a great revolution in the civilized world." The first few pages of his book describe the "enormous importance" that the steam engine had already acquired in the economy of nations, and especially in the economy of France's recent and traditional enemy. England, the home of the steam engine, now depended upon it for the national prosperity and power. Despite the importance attached to such engines, despite the progress made in their design, their theory was "very little understood." And so Carnot set out to establish a rational basis for answering the much discussed question of how and to what extent heat engines could be improved. How could one decide, for example, on the merits of proposals being made to replace steam by some other working substance, perhaps air, in these engines? What was needed, Carnot wrote, was a new analysis undertaken "from a sufficiently general point of view," an analysis that would bring out the basic principles underlying the production of power from heat. Such an analysis would "establish principles applicable not only to steam engines but to any imaginable heat engine, whatever the working substance and whatever the method by which it is operated."

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Heat engines

Carnot undoubtedly had a model in mind when he proposed this general study of the principles of heat engines. He alluded to it when he wrote: "Machines which do not receive their motion from heat, those which have for a motor the force of men or of animals, a waterfall, an air current, etc., can be studied even to their smallest details by the mechanical theory. All cases are foreseen, all imaginable movements are referred to these general principles, firmly established, and applicable under all circumstances." Just such a general theory of strictly mechanical machines had been developed in 1783 by a remarkably independent, thoughtful, and critical engineer of the previous generation—Lazare Carnot, Sadi's father. Lazare Carnot discussed machines from a standpoint that emphasized the concepts of work and living force [*vis viva*] or kinetic energy. He presented a dynamical theory of machines whose goal was to establish the conditions for operation at maximum efficiency. The Principle at which he arrived was that "any impact or sudden change is to be avoided," since "whenever there is impact, there is simultaneously a loss of moment-of-activity [work] on the part of the impelling forces, a loss so real that their effect is necessarily diminished." Machines must therefore be operated so that their state of motion is changed only "by insensible degrees" in order to have them "produce the greatest possible effect."[3]

(I cannot pass by Lazare Carnot without pointing out that he is known in French history as "the great Carnot," and for good reason, quite apart from his scientific achievements. An army engineer before the revolution, he was responsible for organizing the armies that fought off attempts to reimpose the old regime. He served with Robespierre on the twelve-man Committee of Public Safety that ruled France for a year, was one of the five original members of the Directory, Minister of War during Napoleon's consulate, and Minister of the Interior during the Hundred Days before Waterloo. Exiled by Louis XVIII, Lazare Carnot died in Prussia in 1823.)

Sadi Carnot would have liked to construct the kind of "complete theory" for heat engines that his father had set forth for mechanically driven devices. That was not possible. Lazare Carnot could base his work on a well developed science of mechanics, writing, as he did, a century after the publication of Newton's *Principia*. Sadi Carnot had no such fixed starting point. "We shall have [a complete theory of heat engines]," he wrote, "only when the laws of physics shall be extended enough, generalized enough, to make known beforehand all the effects of heat acting in a determined manner on any body." Those laws of physics did not exist in 1824, and so Carnot had to follow another course.

The caloric theory

The theory of heat generally accepted in the first part of the nineteenth century was the caloric theory, according to which heat is an imponderable fluid.[4] The quantity of heat, that is to say of the caloric fluid, is conserved; caloric can neither be created nor destroyed. The caloric theory accounted for the phenomena of latent and specific heats in a simple and natural way. Caloric was also an essential ingredient in the static molecular theory of gases developed by John Dalton and others. Laplace demonstrated the power of the caloric theory by using it to correct Newton's expression for the velocity of sound in a gas. There were difficulties with the caloric theory of heat, but it had no serious competition at the time Carnot was writing. The much older view that heat was a form of motion persisted, but it had never been developed into a real theory. It was often discussed in parallel with the caloric theory. What seemed inescapable was the conservation of heat, whatever the nature of heat might turn out to be.

Carnot accepted the caloric theory in this sense. He accepted it cautiously, with reservations, and even with second thoughts, as we shall see, but the conservation of caloric was essential to the reasoning of his book.

He began his analysis by pointing to the fact that "the production of motion in steam engines is always accompanied by . . . the re-establishing of equilibrium in the caloric," or in other words by the passage of heat from a hot body to a colder one. Not heat alone but "its transportation from a warm body to a cold body" is required to produce motive power. Carnot saw that this fact about steam engines exemplified a universal principle. He emphasized that heat, or caloric, was *not* consumed in the working of an engine. The same quantity of caloric that left the hot reservoir and produced the expansion of the working substance was ultimately absorbed in the cold reservoir. He compared the motive power of heat to that of a waterfall. Just as the descent of a given quantity of water through a certain height can produce work by turning a waterwheel without any water being lost, so the fall of a given quantity of heat through a certain temperature difference can produce work by the expansion and contraction of some substance, without any heat being lost.[5]

Motive power could be produced from steam because it expanded when heat was supplied to it. But this property was hardly peculiar to steam. "Wherever there exists a difference of temperature," wrote Carnot, "it is possible to have also the production of impelling power . . . All substances in nature can be employed for this purpose, all are susceptible of changes of volume, of successive contractions and dilatations, through the alternation of heat and cold. All are capable of overcoming in their changes of volume certain resistances, and of thus developing the impelling power." But if one could always take advantage of a temperature difference to produce work by having a body expand at the higher temperature and recompressing it at the lower with an accompanying indirect transfer of heat, it must follow that any direct flow of heat amounts to a loss of potential motive power. Carnot concluded that such direct heat transfers must be avoided. This was the "fundamental basis" for constructing heat engines.

The Carnot cycle

Carnot then carefully described a cycle of isothermal and adiabatic processes carried out on a gas, "atmospheric air, for example," in such a way as to produce a certain quantity of motive power W while transferring a quantity of heat Q from a hot reservoir at temperature t_1 to a cold one at temperature t_2. This cycle is exactly the Carnot cycle, which has been a familiar feature of thermodynamics texts for over a century. Carnot called attention to the reversibility of his cycle. Every step could be carried out in the opposite direction, so that the cycle would require the expenditure of the same amount of work W in order to accomplish the transfer of the heat Q from the cold reservoir at t_2 to the hot one at t_1.

He proceeded to prove that the work produced by this cycle was indeed the maximum possible amount of work that could be obtained from the given quantity of heat Q with fixed temperatures t_1 and t_2. Carnot's proof is worth looking at, for it shows how essential the conservation of caloric was to his argument.

Suppose there were a more effective cyclic heat engine, one which produced more work W' than the Carnot engine, for the same values of Q, t_1, and t_2. We could then use it to run a Carnot engine in reverse, thereby restoring the heat to its original location in the hot reservoir at the cost of motive power W. The working substances would also be in their original states after the two cycles were completed. The only result would be the production of a net amount of work $(W'-W)$ which, by assumption, is positive. By repeating the combined cycle one would have, in Carnot's words, "an unlimited creation of motive power without consumption either of caloric or of any other agent whatever." This was "inadmissible." "Such a creation," he went on, "is entirely contrary to ideas now accepted, to the laws of mechanics and sound physics." The maximal property of the Carnot cycle could then be safely concluded, since the contrary assumption had led to the absurdity of perpetual motion.

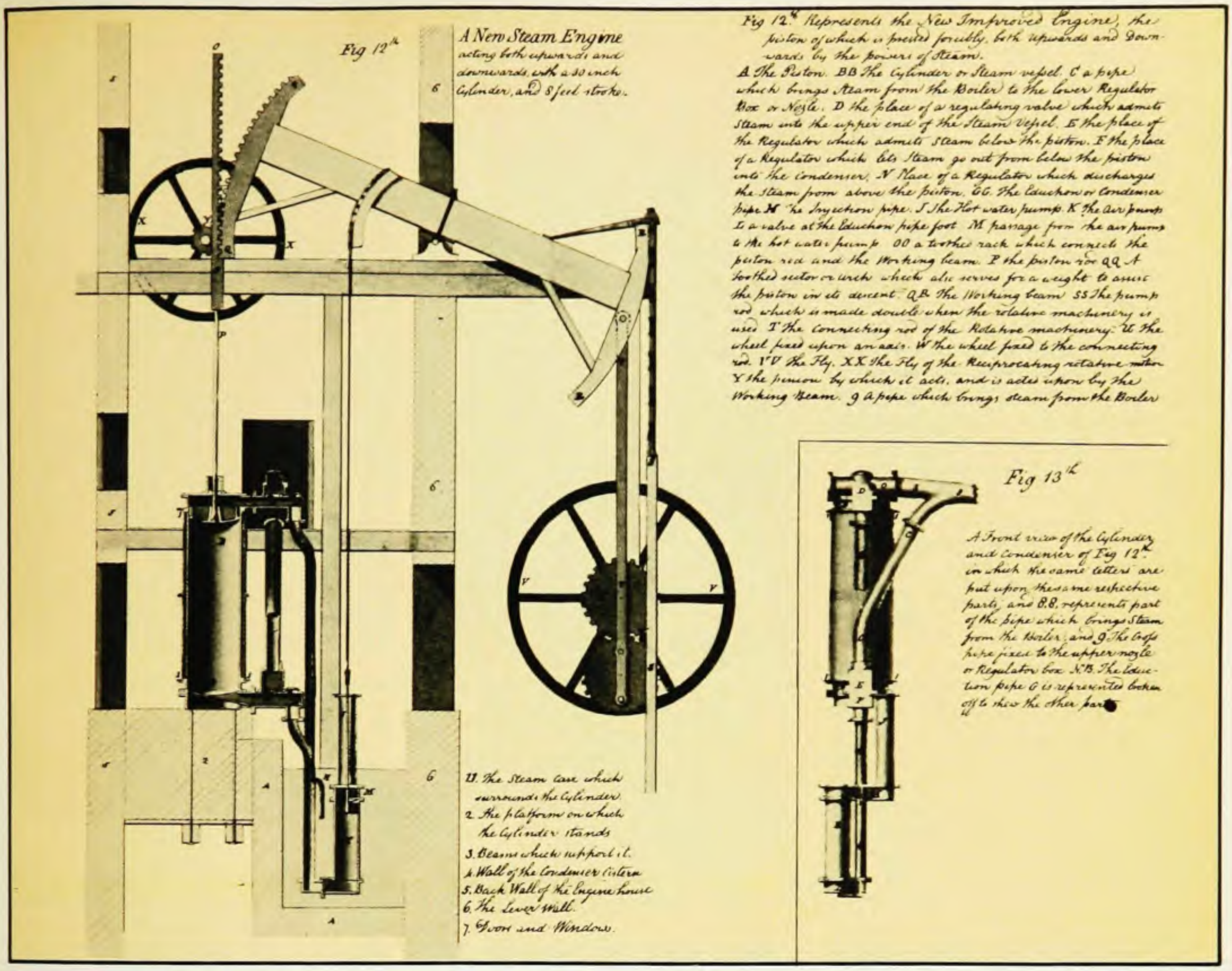
In a lengthy footnote Carnot commented on his appeal to the impossibility of perpetual motion. He realized that it might be claimed that perpetual motion, impossible in mechanics, could be achieved by electricity or heat. "But is it possible," he asked, "to conceive the phenomena of heat and electricity as due to anything else than some kind of motion of the body, and as such should they not be subjected to the general laws of mechanics?" In any event Carnot was willing to rest his case on the *a posteriori* argument that perpetual motion had never been observed, not even in the recently constructed Voltaic pile which had seemed at first to be a perpetual source of current.

Carnot's Principle

Carnot's cycle could produce more work for the transfer of a fixed quantity of heat between assigned temperatures than any other, but there was even more to be said about it. Nothing in the argument depended on the choice of the working substance. It did not have to be the atmospheric air Carnot had used for illustrative purposes, it did not even have to be a gas. Any substance whose temperature could be changed by expansion or contraction would serve, which meant, in effect, any substance at all. The maximal property of the cycle was independent of the physical or chemical nature of the working substance. "The motive power of heat," as Carnot concluded, "is independent of the agents employed to realize it; its quantity is fixed solely by the temperatures of the bodies between which is effected, finally, the transfer of the caloric."

This is Carnot's Principle, the most significant result of his analysis. He had set out to "consider in the most general way the production of motion by heat"; he could hardly have suspected that he would be led to such a profound and far-reaching physical law. Once he had arrived at this law, however, Carnot did recognize that he had entered a new domain. He put aside the question of heat engines for a while and turned his attention to exploring the properties of matter with the help of his new principle.

In a lengthy discussion, amounting to about a quarter of the text of his brief book, Carnot derived a series of properties of gases. He could not deal, as he would have liked, with "the mo-



A steam engine designed by James Watt, reproduced from his patent specification of 1782. In this double-acting engine "the piston, . .is pressed forcibly both upwards and downwards by the powers of steam." Carnot was familiar with Watt's improvements, writing in his book that Watt had "brought these [steam] engines to a state of perfection difficult even now to surpass."

tive power developed by the action of heat on solids and liquids" because "physics as yet refuses us the necessary data." For gases he found, among other results, that the difference between the specific heats at constant pressure and at constant volume is the same for all gases, that the heat absorbed in an isothermal expansion is proportional to the logarithm of the ratio of final and initial volumes, and so on. I have deliberately expressed these results in words, without resorting to equations, just as in the earlier discussion I avoided graphical representation of the Carnot cycle. In doing so I am following Carnot himself. His text contains very little algebra and no geometric representations. Only in one extended footnote did he show how his somewhat cumbersome verbal expressions could be replaced by mathematical analysis. Hoping to reach a wide audience—all those who might be interested in technological improvements—he made a deliberate (if unsuccessful) effort to keep the book understandable to nonprofessionals.[6] Once he had formulated his general principle, however, he had to make greater demands on his readers, remarking in a note that he would now suppose them "to be *au courant* with the later progress of modern physics in regard to gaseous substances and heat." Whatever might be said about his readers—real or imaginary—Carnot himself was certainly thoroughly up to date on the many experiments on gases recently reported in the scientific journals.

Carnot posed one question which arose naturally from his general principle, but which he could not fully answer. He had shown that the maximum work that could be produced from a given quantity of heat depended only on the high and low temperatures between which that heat is transferred. But what was the functional form of this dependence? Carnot did not have enough experimental information to answer this question, but he knew how to go about answering it, as his mathematical footnote demonstrated.[7]

Carnot had hoped to reach a wide audience. When his little book appeared it did receive a long, thoughtful, and favorable review from Pierre-Simon Girard, a distinguished mining engineer, writing in a journal of general interest.[8] But Carnot failed to reach his intended audience. His work made no impression on engineering practice.[9] Even more striking is the way it was ignored by the scientific community, despite the fact that Girard also presented his favorable review to a meeting of the Académie des Sciences, a meeting attended by just about every luminary in the brilliant group of French scientists of the time: Fourier, Laplace, Ampère, Gay-Lussac, Dulong, Legendre—among many others.[10] Not one of them took up Carnot's ideas or even referred to his work.

Sadi Carnot did not move in these exalted circles. When he left the École Polytechnique, after already having taken part with honor in one military action in 1814, to his father's "extreme pleasure," he served in the Army Engineers doing dull work in the provinces for several years. He was glad to retire on half-pay in 1820 and to live quietly in Paris, pursuing his scientific interests as a private individual. Carnot never held a scientific appointment of any sort. Lazare Carnot's fame was hardly a help to his son under the restored monarchy. At the time Sadi's book appeared, he was sharing quarters with his younger brother Hippolyte, who had joined him after their father's death in 1823. Carnot could identify himself on the title page of his book only as S. Carnot, Former Student of the École Polytechnique. He had published nothing before and would publish nothing else during the few years remaining to him, though he never stopped working. After suffering several serious illnesses during the summer of 1832, Carnot succumbed to cholera during the epidemic in August that year. The one obituary notice that appeared, written by his close friend Robelin, could only regret that Carnot was so little known, that he had lived and died unrecognized and unread.[11] His notebooks and manuscripts were left to his brother, Hippolyte. It seemed most unlikely that anyone would ever be interested in them, despite the brave hope expressed by Robelin that the future would give Sadi Carnot the place he had never received during his lifetime.

Clapeyron

Four years after Carnot's death his book found its first attentive and active reader. This was Émile Clapeyron, a graduate of the Polytechnique several classes after Carnot, who was an engineer working on the design and construction of steam locomotives. He published a "Memoir on the Motive Power of Heat" in the *Journal* of the Polytechnique, in which he expounded the developed Carnot's ideas.[12] Clapeyron translated what he called Carnot's "chain of difficult and elusive arguments" into the language of mathematical analysis. It was in Clapeyron's paper that the Carnot cycle was first represented graphically on the pressure–volume diagram. (James Watt's indicator diagram had been kept a trade secret for many years.[13])

In addition to putting Carnot's discussions of gases and condensing vapors into mathematical form Clapeyron expressed Carnot's general principle as a single equation. If one considers an infinitesimal Carnot cycle for any substance, a cycle in which the temperatures are t and $t + dt$, this cycle can be represented adequately as a parallelogram in the P–V plane. The work done in such a cycle is $(dP)(dV)$ and the heat transferred from hot to cold reservoir is dQ. Clapeyron followed Carnot in treating heat as a conserved fluid, even though the caloric theory was largely discredited and in decline by the time he wrote. Carnot's principle then states that the ratio of work produced to heat transferred is a universal function of temperature. Clapeyron wrote this in the form

$$\frac{(dP)(dV)}{dQ} = \frac{dt}{C(t)}$$

where $C(t)$, let us call it the Carnot function, is the same for all substances. The equation expressing Carnot's principle can be rewritten as

$$\frac{dQ}{dV} = \frac{dP}{dt}C(t)$$

a form equivalent to one of the now familiar Maxwell relations. Clapeyron stressed even more heavily than had Carnot the "great importance" of $C(t)$ for the theory of heat. He was still unable to determine the functional form of the Carnot function, since the required experiments had not been done. He did, however, find its value at several different temperatures from data of several sorts: the heat released in isothermal compression of a gas at 0°C, and the latent heat together with the slope of the vapor-pressure curve of several different liquids at their boiling points. Clapeyron recommended further experiments that could help fix the function $C(t)$, "the common link between the phenomena caused by heat in solid bodies, liquids, and gases."

Clapeyron's paper should have had readers. Published in a major journal, it was also translated into English (in 1837) and then into German a few years later (1843), such translation being a rather common practice throughout much of the nineteenth century. Despite this trilingual exposition and development Carnot's theory was doomed to several more years of slumber.

Thomson's "thermometric scale"

In the spring of 1845 a young Scottish mathematician was in Paris working in Victor Regnault's laboratory. He was helping out with the precise measurements of properties of gases that made up Regnault's research program. It was William Thomson, born in the same year that saw the publication of Carnot's *Reflections*. Thomson had just graduated from Cambridge as Second Wrangler and First Smith's Prizeman, but he had already published sixteen papers on mathematics and mathematical physics, many of them based on the methods introduced in Fourier's *Analytic Theory of Heat*.

While Thomson was working in Regnault's laboratory he read Clapeyron's *Memoir* and decided to look up the work by Carnot on which it was based.

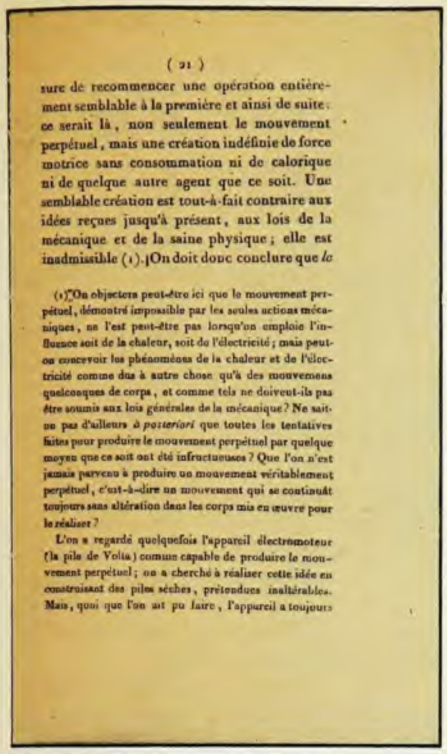

RÉFLEXIONS
SUR LA
PUISSANCE MOTRICE
DU FEU
ET
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.
PAR S. CARNOT,
ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

A PARIS,
CHEZ BACHELIER, LIBRAIRE,
QUAI DES AUGUSTINS, N°. 55.
1824

On the title page of his book, Carnot identified himself only as a "former student of the Ecole Polytechnique." This page and the two opposite are reproduced from the first edition by courtesy of the Science and Technology Division, The New York Public Library, Astor, Lenox and Tilden Foundations.

He searched libraries, bookstores, and the stalls on the quays along the Seine, but no success. Lazare Carnot on fortifications, Hippolyte Carnot on social reform—these could be found, but Sadi Carnot on heat was unknown.[14] Clapeyron's version proved to be enough for Thomson; Carnot's ideas had come back to life.

In 1848 Thomson published an article "On an Absolute Thermometric Scale Founded on Carnot's Theory of the Motive Power of Heat, and Calculated from Regnault's Observations." He pointed out that scientists had been "without any principle on which to found an absolute thermometric scale," and that as a result even the best existing temperature scale—Regnault's constant-pressure gas thermometer—provided only "an arbitrary series of numbered points of reference sufficiently close for the requirements of practical thermometry." Thomson had seen that Carnot's Principle offered a way out of this difficulty, and proposed an absolute scale based on this principle, a scale in which "all degrees have the same value." "A unit of heat descending from a body A at the temperature $T°$ of this scale, to a body B at the temperature $(T - 1)°$, would give out the same mechanical effect, whatever be the number T." He then showed how this scale could be constructed from Regnault's data,



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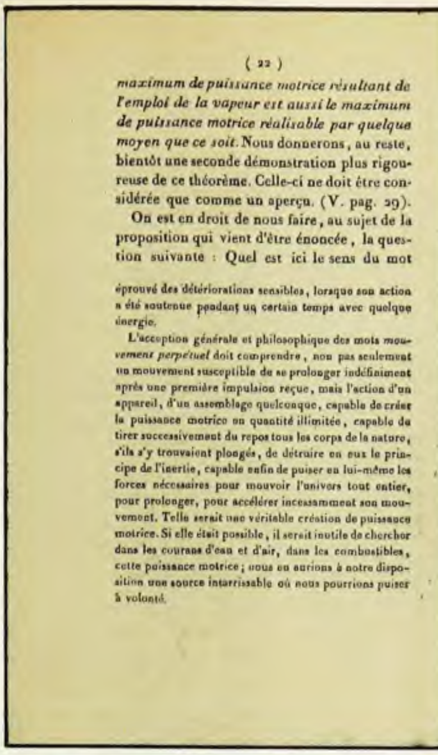
sure de recommencer une opération entièrement semblable à la première et ainsi de suite: ce serait là, non seulement le mouvement perpétuel, mais une création indéfinie de force motrice sans consommation ni de calorique ni de quelque autre agent que ce soit. Une semblable création est tout-à-fait contraire aux idées reçues jusqu'à présent, aux lois de la mécanique et de la saine physique; elle est inadmissible (1). On doit donc conclure que *le*

(1) On objectera peut-être ici que le mouvement perpétuel, démontré impossible par les seules actions mécaniques, ne l'est peut-être pas lorsqu'on emploie l'influence soit de la chaleur, soit de l'électricité; mais peut-on concevoir les phénomènes de la chaleur et de l'électricité comme dus à autre chose qu'à des mouvemens quelconques de corps, et comme tels ne doivent-ils pas être soumis aux lois générales de la mécanique? Ne sait-on pas d'ailleurs *à posteriori* que toutes les tentatives faites pour produire le mouvement perpétuel par quelque moyen que ce soit ont été infructueuses? Que l'on n'est jamais parvenu à produire un mouvement véritablement perpétuel, c'est-à-dire un mouvement qui se continuât toujours sans altération dans les corps mis en œuvre pour le réaliser?

L'on a regardé quelquefois l'appareil électromoteur (la pile de Volta) comme capable de produire le mouvement perpétuel; on a cherché à réaliser cette idée en construisant des piles sèches, prétendues inaltérables. Mais, quoi que l'on ait pu faire, l'appareil a toujours



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maximum de puissance motrice résultant de l'emploi de la vapeur est aussi le maximum de puissance motrice réalisable par quelque moyen que ce soit. Nous donnerons, au reste, bientôt une seconde démonstration plus rigoureuse de ce théorème. Celle-ci ne doit être considérée que comme un aperçu. (V. pag. 29).

On est en droit de nous faire, au sujet de la proposition qui vient d'être énoncée, la question suivante: Quel est ici le sens du mot

éprouvé des détériorations sensibles, lorsque son action a été soutenue pendant un certain temps avec quelque énergie.

L'acception générale et philosophique des mots *mouvement perpétuel* doit comprendre, non pas seulement un mouvement susceptible de se prolonger indéfiniment après une première impulsion reçue, mais l'action d'un appareil, d'un assemblage quelconque, capable de créer la puissance motrice en quantité illimitée, capable de tirer successivement du repos tous les corps de la nature, s'ils s'y trouvaient plongés, de détruire en eux le principe de l'inertie, capable enfin de puiser en lui-même les forces nécessaires pour mouvoir l'univers tout entier, pour prolonger, pour accélérer incessamment son mouvement. Telle serait une véritable création de puissance motrice. Si elle était possible, il serait inutile de chercher dans les courans d'eau et d'air, dans les combustibles, cette puissance motrice; nous en aurions à notre disposition une source intarrissable où nous pourrions puiser à volonté.

These two pages contain the seeds that later germinated into the Second Law of Thermodynamics. The last sentence on page 21, running onto page 22 in italics, reads: "One should then conclude that the maximum motive force resulting from the use of steam is also the maximum motive force realizable by any means at all." The footnote on these two pages comments on the impossibility of perpetual motion; it includes the suggestion that the phenomena of heat and electricity are due to some kind of motion of bodies, obeying the general laws of mechanics. Carnot writes the Second Law in more familiar form later on.

and presented tables in which the Carnot function *C(t)* was calculated over a range of 230° on the Centigrade scale.[15] (This first absolute temperature scale differs from the familiar scale he introduced a few years later. The temperature T on the earlier absolute scale is a linear function of log θ, where θ is the corresponding temperature on the later absolute scale.)

Mechanical equivalent

In describing the ideas on which Carnot's Principle was based, Thomson remarked on the conservation of heat, adding that "the conversion of heat (or caloric) into mechanical effect is probably impossible, certainly undiscovered." To this remark he appended a footnote saying that this opinion seemed to be "nearly universally held," although "a contrary opinion has been advocated by Mr. Joule of Manchester." Joule's experiments "seemed to indicate an actual conversion of mechanical effect into caloric," although the converse operation had not been demonstrated. "It must be confessed," Thomson concluded the note, "that as yet much is involved in mystery with reference to these fundamental questions of natural philosophy."

Joule was not the first to argue for the interconvertibility of heat and work at a fixed ratio,[16] but Joule's experiments were much more convincing to William Thomson than anything else he might have read or heard along this line.

A few months later, Thomson finally saw a copy of the long-sought-for book by Carnot. He proceeded to write "An Account of Carnot's Theory," which he presented to the Royal Society of Edinburgh on 2 January 1849.[17] By this time Thomson was even more puzzled and disturbed by the conflicting claims of Carnot's theory, which rested on the outmoded caloric theory, and Joule's experiments, which demonstrated the generation of heat from mechanical or electrical work. Thomson's growing concern over this fundamental difficulty had several causes.

When he read Carnot, Thomson must have been surprised to find a much more cautious and even skeptical discussion of the foundations of the theory than he had seen in Clapeyron's article. Carnot had written that the heat in a body must be considered a function of its state, but immediately added: "To deny it would be to overthrow the whole theory of heat to which it serves as a basis. For the rest, we may say in passing, the main principle on which the theory of heat rests requires the most careful examination. Many experimental facts appear almost inexplicable in the present state of this theory." Even more striking was a passage in which Carnot discussed the consequences of his general principle: "It [Carnot's Principle] is based upon the theory of heat as it is understood today, and it should be said that this foundation does not appear to be of unquestionable solidity. New experiments alone can decide the question."

Thomson, who quoted the first of these passages in his *Account*, would have been astonished had he seen those manuscript notes left by Sadi Carnot at his death.[18] Hippolyte Carnot did not arrange for publication of his brother's notes until 1878, so they had no effect whatsoever on the history of physics, but they are extraordinarily interesting all the same. Some time before 1832 Sadi Carnot had decided that his fundamental assumption on the conservation of heat was false. "Heat is simply motive power, or rather motion which has changed its form," he wrote. "Wherever there is destruction of motive power, there is at the same time production of heat in quantity exactly proportional to the quantity of motive power destroyed"—and reciprocally. "Motive power," he went on, "is, in quantity, invariable in nature; . . . it changes its form . . . but it is never annihilated." Carnot was not merely speculating on the nature of heat. He estimated the mechanical equivalent, and arrived at a figure that translates to about 3.7 joules per calorie. He saw that an experiment showing that the adiabatic free expansion of a gas leaves its temperature unchanged would be clearly incompatible with the caloric theory. "When a hypothesis no longer suffices to explain phenomena, it should be abandoned," Carnot wrote, adding: "This is the case with the hypothesis which regards caloric as matter, as a subtle fluid."

Joule or Carnot?

Thomson, who did not know Carnot's unpublished notes, was not prepared to give up Carnot's theory in 1849. One reason was to be found in a remarkable argument that his brother, James Thomson, an engineer with whom William often discussed scientific issues, had made on the basis of Carnot's Principle. By considering a Carnot cycle using liquid water at its freezing point, James had deduced that the freezing point must be lowered when pressure is applied. From the value of the Carnot function at 0°C he calculated an expected lowering of 7.5×10^{-3} centigrade degrees per atmosphere increase in the pressure. This phenomenon had never been observed and was, indeed, totally unexpected. Yet before the year 1849 was out William had confirmed its existence by careful experiments and verified the quantitative prediction within a few percent.[19] This striking success of

Carnot's theory could not be ignored, no matter what Joule's results indicated in the opposite direction.

William Thomson thought that "the fundamental axiom adopted by Carnot may be considered as still the most probable basis for an investigation of the motive power of heat; although this, and with it every other branch of the theory of heat, may ultimately require to be reconstructed upon another foundation, when our experimental data are more complete." He hoped that this "very perplexing question" might soon be cleared up, but he was not prepared to follow Joule's urging and abandon Carnot's axiom. "If we do so," he wrote, "we meet with innumerable other difficulties—insuperable without further experimental investigation and an entire reconstruction of the theory of heat from its foundation." Thomson thought that experiment alone could settle the issue, either verifying Carnot's axiom or providing "an entirely new basis of the theory of heat."[20]

The "either–or" choice that Thomson anticipated, between Joule's equivalence of heat and work and Carnot's Principle of the universal motive power of heat, never had to be made. The solution to the difficulty came, not from experiment as Thomson expected, but from a new analysis given early in 1850 by Rudolf Clausius.[21] Clausius, believing "that we should not be daunted by these difficulties," showed that *two* laws were needed for the theory of heat, that Carnot's Principle was not incompatible with the first of these laws, the equivalence of heat and work. By giving up the conservation of heat one did lose the basis for Carnot's own proof of that Principle, but a new basis could be found. That basis was Clausius's Second Law of Thermodynamics, which expressed the universal tendency of heat "to equalize temperature differences and therefore to pass from *hotter* to *colder* bodies." With Clausius's paper "the science of thermodynamics came into existence," as Josiah Willard Gibbs wrote.[22]

The new science of thermodynamics incorporated Carnot's Principle as one of its major theorems. It also incorporated the spirit of Carnot's approach, arriving at its results "independently of any mechanism or any particular agent," in Carnot's phrase.

What William Thomson wrote in 1849 about Carnot's argument applies just as precisely today to the thermodynamics to which it led: "Nothing in the whole range of Natural Philosophy is more remarkable than the establishment of general laws by such a process of reasoning."

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