Case Study 2 HIPST – FST

1. Title: Steam, Work, Energy

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3. Abstract

This case study concerns the formulation and production of a kit for high school physics teachers (students aged 14-19) to supplement their lessons on thermodynamics with elements offering an historical contextualisation of how several fundamental laws of physics were discovered, and how certain concepts have become structured in time. The case study will show how this project was born from the specific request of several teachers who had already approached energy and thermodynamics in their classes from a historical point of view, and will illustrate the decisions made in drafting educational material. The kit consists of a CD and printed materials for further study. The CD follows a development that begins by introducing the first steam engines (Savery, Newcomen and Watt), proposes a synthesis of the theories on the nature of heat up to the establishment, as of the mid-nineteenth century, of the kinetic theory of heat, and then illustrates how the bases of thermodynamics were developed, through the works of Carnot, Joule and many other scientists who contributed to forming this new sector of physics. The CD follows a course that evidences the connection between science, technology and society. On one hand, it shows how practical necessities and empirical-technical solutions gave rise to the premises for forming new theories and, in particular, of how the law of conservation of energy was one of the greatest generalisations of physics in the nineteenth century. On the other hand, it shows how the technological innovation of the steam engine and its successive improvements made possible also by new scientific acquisitions, profoundly transformed society and its organisation, starting from the first Industrial Revolution. An original element of the CD is that it contains videos showing instruments in operation from the historical collection of the Fondazione Scienza e Tecnica Physics Laboratory. In particular: the Tyndall apparatus, the fire piston, the Joule apparatus, the Puluj apparatus, Watt's steam engine and the horizontal cylinder steam engine, and Prony's dynamometric brake. The CD structure and the materials it contains have been created for use by teachers in class, while the printed materials for further study are intended to support teacher training on the subjects handled. Moreover, in the course of the year, the Fondazione Scienza e Tecnica will hold a series of courses expressly dedicated to teachers, and aimed at offering training in historical contents.

4. Case Study Description

The "Steam, Work, Energy" project has taken on concrete form in the production of a kit with learning tools for use by high school physics teachers (students aged 14-19) in illustrating the concepts at the basis of

thermodynamics, providing an historical outline of the relationships between science, technology and society. The kit contains a CD and a series of printed materials for further study. The CD is structured around 15 slides, accompanied by texts, images, animations and video, and subdivided as follows:
1. Savery's and Newcomen's steam engines
2. Watt's scientific approach to the construction of the steam engine
3. Watt's "atmospheric" engine, in the simple version, with the separate condenser, and with parallel motion
4. Watt's double-acting steam engine
5. The spreading of the steam engine and the Industrial Revolution
6. The state of studies on the nature of heat in the early nineteenth century: the caloric
7. First doubts on the caloric theory: the contributions of Rumford, Davy and Young
8. The fire piston and gas studies
9. The birth of thermodynamics with the work of Sadi Carnot, "*Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*"
10. Introduction to the principal concepts contained therein (cycle, efficiency) of the ideal engine, first version of the second principle of thermodynamics)
11. Measuring the efficiency of steam engines
12. Joule, the mechanical equivalent of heat, and the precise measurement of energy
13. The conservation of energy and the first principle of thermodynamics
14. Progress of steam engines, applications to transports
15. Progress of steam engines, other applications

The **content of the CD** is available at the link provided in **chapter 10**.

As already stated, the kit also includes printed supplements for more in-depth study or texts written ex novo by experts, which enrich the content of what the CD presents in synthesis. The most original aspect of the CD is that it contains **videos** showing several **historical instruments** in operation from the collection of the Fondazione Scienza e Tecnica Physics Laboratory. Indeed, one of the purposes in realising this project has been that of identifying a way to enable a direct contact of teachers and students with the **experimental and material dimension of science**, of which the objects in the collection are tokens.

The **Istituto Tecnico Toscano** was founded in 1850 by Grand Duke Leopold of Tuscany on the model of other European schools to provide professional technical training to workers in the nascent industry of Tuscany. The collection of its **Physics Laboratory** with its more than 3000 pieces is the most complete in Italy and one of the most important in Europe as far as physics instruction in the nineteenth century is concerned. It conserves the instruments in their original casings grouped in sections that refer to all of the **branches of classical physics**, just as they were divided in the **late nineteenth century**: mechanics, hydrostatics, pneumatics, thermology, acoustics, optics, electricity and magnetism, meteorology. As teaching was the Istituto's main activity, most of the instruments are of an educational type, but it also includes research and professional instruments, models and elements of machines and apparatuses of “physique amusante”.

Referencing the Physics Laboratory collection as an integral part of the CD has the intrinsic value of illustrating the wealth of the **cultural heritage** held there, as well as another value of an **educational nature**. This consists in showing how the modern physics (and chemistry) laboratories were born and have developed especially since the mid-nineteenth century, often deriving from eighteenth-century scientific laboratories. A growing and increasingly **more rapid industrialisation**, the **spectacular progress of science and its applications**, the **enormous expansion of the educational system**, and the **need for new professionalisms**, indeed led to the **creation of a growing number of schools, universities and polytechnic institutes** where the presence of educational and research laboratories was fundamental. The importance of these laboratories was clear to the founders of the Istituto Tecnico of Florence. The ambitious programme of studies that had led to its institution meant attributing particular importance to the practical and applied activities, which therefore required a rich endowment of instruments and machines.
The **videos** on the **CD** concern the following objects:

1. A **model of Watt’s steam engine** whose makeup and operation is illustrated. We are reminded that in the nineteenth century, models of machines were common in the science laboratories of schools and universities, where they were used to show the practical applications of physics laws and phenomena. The model in question is a scale model of a double-acting fixed type of Watt steam engine, which was used for a good part of the nineteenth-century.

2. The **Tyndall apparatus**: widely diffused in nineteenth-century physics collections, it was used in a purely qualitative experiment to show how, by means of friction, mechanical work can be transformed into heat.

3. The **fire piston**, a curious instrument used as of the early nineteenth-century in Europe and until the invention of viable matches (in 1820 circa), which makes it possible to instantaneously light an easily inflammable substance, thanks to the rapid compression of air that is suddenly heated. This instrument’s use as a demonstrative physics apparatus survived for quite some time, as it permitted a spectacular demonstration of the transformation of mechanical work into heat by means of the adiabatic compression of a gas.

4. The **Joule apparatus** whose functioning is illustrated with a replica proposed for educational purposes of the one invented by James P. Joule in 1845 to measure the mechanical equivalent of the calorie.

5. The **horizontal cylinder steam engine**. This model shows a typical example of fixed steam engine widely used in industry. It is a machine that has reached technological maturity.

6. **Prony's dynamometric brake**, an apparatus proposed in 1821 by French engineer and mathematician Gaspard Clair François Marie Riche de Prony, the first example of a large series of dynamometric apparatuses which between the nineteenth and twentieth centuries were invented to measure the power delivered by steam engines and prime movers of various types.

7. The **Puluj apparatus** invented by Ukraine physicist and inventor Johann Puluj (1845-1918) makes it possible to determine (at least approximately) the mechanical equivalent of a calorie. More compact and easier to use than the Joule apparatus, it was essentially utilised in teaching.

The CD will be offered for a free use to teachers who will select the parts to use at school in accordance with their programme needs and interests. Training courses will be offered, in any event, so as to contribute to providing them solid background material.

5. Historical background, including the nature of science

This chapter presents four aspects that describe the picture where the contents of the work concerned by this case study will unfold, and that is: the technological innovation produced by the steam engine, the socio-economic transformations caused by the Industrial Revolution, knowledge of the nature of heat up till the mid-nineteenth century, the birth of thermodynamics.

The historical background illustrated hereinafter will also help show how the itinerary laid out by the "Steam, Work, Energy" kit offers teachers many cues to invite students to reflect on the nature of science. Take, for example, the fact that **practical necessities that have stimulated the production of new technological solutions have often been the motor to attain new scientific knowledge** (such as in the case in question, the necessity to improve the efficiency of heat engines led to more closely examining the nature of heat and the relations between heat and work). Or take the fact that **new knowledge is almost never the sudden contribution of an individual, but instead the result of a process of consolidation and refinement of many contributions, which do not necessarily follow a linear course**. Or take, on the contrary, how **certain results can be attained by different scientists separately and even via different routes** (such as in the case of the principle of energy conservation). Furthermore, the subjects proposed in this case study certainly offer many interdisciplinary suggestions that invite reflection on the complexity of relations between science, technology, society and their reciprocal influences.

The Steam Engine

When in the XVII century, England began to record a scarcity of wood – due to major deforestation processes – and coal, it became necessary to **dig increasingly deeper mines**. This also made it necessary to find efficient methods to extract the water that frequently flooded the shafts. Moreover, in the XVII century, several mining companies possessed the **economic**

means necessary to pay for the mechanisms which could have solved this problem with more efficient methods than mechanical and manual methods. Previously never considered to solve practical problems, also due to the abundance of manual labour furnished by slaves, the use of steam was conceived by **Thomas Savery** (1650?-1715), a versatile military engineer who was the first to build an effectively useful steam pump. The **principal patent was issued him in 1698** for a "new invention for raising of water and occasioning motion to all sorts of mill work by the impellent force of fire, which will be of great use and advantage for draining mines ... and for the working of all sorts of mills where they have not the benefit of water nor constant winds...". The great inconvenience of Savery's machine, however, was that of **using steam at a high pressure, which involved risks of explosion**; so it fell into disuse in the early 1700s.

This defect was eliminated by **Thomas Newcomen** (1663-1729) who invented a low-pressure machine which compared to the previous one had the advantage of being able to raise weights, as well as water. Newcomen's machine was incommensurably more successful than any previous machine. **Around 1725, the use of this type of machine also spread to the continent**, especially for pumping water from mines and for raising the water necessary to operate water wheels which, in turn, drove machinery. Newcomen's engine produced a considerable **economic advantage** for extracting water from mines, but it found little application in other fields due to its low efficiency and for the low power-weight ratio, and it could not be applied to produce a rotary motion. Despite its low efficiency and the enormous consumption of coal with respect to the work it accomplished, Newcomen's engine had no rivals for more than sixty years. It represented the main factor in exploiting the mining resources of Great Britain and was among the **driving forces of the country's industrial development**.

The first person after Newcomen to make important progress in the production of energy by means of steam was **James Watt** (1736-1819). Becoming interested in Newcomen's atmospheric steam engine and studying the properties of steam by means of various experiments, he realised the importance of **"latent heat"**, already studied by Scottish chemist, physicist and physician **Joseph Black** with whom he had occasion to discuss the matter. This though episodic collaboration marked a **first approach towards a scientific study of heat engines**, which until then had been built on purely empirical criteria. Towards 1765, Watt invented the **"separate condenser"**, which represented a fundamental stage in the evolution of the steam engine. With this solution, steam was no longer condensed in the cylinder where the piston moved, but in a separate condenser, thereby making it possible to keep the cylinder always hot (with a good heat insulation) and the condenser always cold. **Engine efficiency was thus considerably increased and fuel consumption diminished.** Watt's first engines with separate condenser were also of the **atmospheric type**.

Later, **Watt's double-acting steam engine** with the solutions described above and with other important technical considerations was capable not only of being coupled to pumps that could be driven by reciprocating motion but, with a **regular rotary motion**, it could also **drive machines of all types in workshops, textile and metallurgical industries**, etc. Forming a **partnership with the industrialist Boulton** in 1775, Watt created a successful commercial enterprise which in the last quarter of the century was able to build and install about 450 steam engines.

The Industrial Revolution
he introduction of the steam engine was one of the main movers of the **first Industrial Revolution**. This term summarily defines the period **between the mid-XVIII century and the mid-XIX century**, which witnessed a series of **radical transformations in the manufacturing, extraction and farming fields, and generated profound social, economic and cultural changes**.

The Industrial revolution **began towards the middle of the XVIII century in England** and then spread to Europe and North America. The causes which set it off were numerous and are still today object of debate among historians, but several essential factors in eighteenth-century England contributed to getting it started. Among these was the **availability of great natural and financial resources** owing, to a large extent, to the **exploitation of the colonies, the presence of raw materials on national soil, an economic liberalism that favoured exchanges and commerce, a stable situation both from the political and economic viewpoints, and the presence of a very powerful fleet**. Furthermore, **in England**, more so than in other parts of Europe, **society was more receptive to changes and transformations**, and there was an entrepreneurial class, often animated by a Protestant ethic, that believed in technological and social progress, and in the value of work.

From the **technological viewpoint**, several inventions were of capital importance:

the **introduction of the Newcomen steam engin**e made it possible initially to drain mines and better exploit mining resources. Successively, with the introduction of the improved and more effective **Watt engine**, it was possible to avail of a **prime mover capable of driving machines of various types**, and of **freeing manufacturing (textiles, metallurgy) or extraction activities from the necessity of the presence of waterways** capable of driving water wheels.

1. The **use of coal** (anthracite) instead of charcoal in founding iron, and **the introduction of new extraction techniques** made it possible to considerably increase metallurgical production and quality of products.
2. The **invention of new textile machines** (the spinning jenny, spinning mule, ...) capable of enormously increasing the production of yarns and fabrics led to **the creation of large textile complexes** that were almost entirely **mechanised**.

With the development of new inventions came large factories: textile and spinning mills, foundries, and ironworks, and all of previously unheard of dimensions. New technologies permitted the mining industry to **enormously increase production**, at the same time **diminishing mining costs**. New machines and procedures improved the agricultural exploitation of lands. The **first chemical industries** developed for the production of basic compounds such as sulphuric acid or soda. As of the beginning of the nineteenth century, the gas production industry developed, revolutionising public and private illumination. Parallel to these innovations, communications were improved with the construction of new roads, bridges, navigable canals, sluices. The first public railway was inaugurated in the 1820s, which marked the start of a radical transformation in land transports.

These technological and production advancements were accompanied by **profound and often dramatic transformations in society**. The nobility that founded its wealth on the products of the earth was displaced by an **entrepreneurial and often unscrupulous middle class** that founded its wealth on the new industries and the new financial activities. The creation of large factories and, later, of veritable industrial complexes accelerated **the growth of metropolises** which saw a great number of workers converge towards the production centres.

The **tempos and ways of working changed**: the long hours of work in factories were increasingly more often marked by the speed and relentless rhythm of machines. **Child labour**, already very common in rural areas, spread to mines, spinning mills and factories where children were paid much less than adults and subjected to **gruelling rhythms, working in situations where accidents were the order of the day**. It was only in the course of the nineteenth century, slowly and often thanks to the support garnered by a part of the public opinion, that governments first limited and finally prohibited child labour, despite the great resistance of industrialists.

Manufacturing cities witnessed spectacular population increases. The sumptuous homes of the new bourgeoisie contrasted with poor districts where the nascent proletariat class was massed in unhealthy lodgings. These **densely populated quarters deprived of the most elementary standards of hygiene** were easily struck by the spreading of epidemic diseases such as cholera, typhus or tuberculosis. The sanitary and living conditions of the poorer classes slowly improved in the course of the nineteenth century.

The same period also witnessed the **development of a middle class** dedicated to trading and production activities, favoured both by industry as well as by the availability of new products, and a upper-middle class of professionals (engineers, physicians, etc). In addition to the revolution in production methods, the **formation of new social classes**, the **chaotic development of large cities**, the **accumulation of great wealth and the proletarianisation** of part of the population, the Industrial Revolution was also accompanied by

important social movements, such as the birth of **mutual aid societies** and the **first unions**, increasingly **greater schooling and literacy**, a considerable **increase in life expectancy**, and the **reduction of child mortality**. These transformations also bore considerable **influence on aesthetic taste, figurative arts and literature**.

As of the mid-nineteenth century, the first Industrial Revolution was followed by the so-called **Second Industrial Revolution** founded on the **cheap production of steel**, the **development of the large chemical industry** for the production of explosives and fertilisers, the **nascent electrical industry** and, finally, the **use of petroleum**.

The Nature of Heat

he necessity to improve steam engines, especially increasing their performance, was one of the principal motives which stimulated the study of the nature of heat. In modern terms, **heat is defined as energy transferred between two systems in different thermal states**. In the presence of a temperature gradient, heat always flows from the points of higher temperature to those of lesser temperature until a thermal equilibrium is reached.

Through time, **there have been a few theories concerning the nature of heat**: considered as a **form of internal microscopic motion of matter**, an **odourless and colourless material substance** – the **phlogiston** – released by bodies in combustion, transforming them into calcium – today's oxides. This theory, however, clashed with the fact that the combustion of some bodies produced oxides much heavier than the body itself – a fact that contradicts a loss of material substance. One theory concerning the nature of heat, quite diffused **towards the end of the XVIII century** was that of the **caloric**, a sort of elastic fluid that could enter bodies and impregnate them. It was held responsible for their temperatures: cooling was the same as a loss of caloric which spontaneously passed from a warmer body to a colder one. According to chemist Antoine Lavoisier, who saw the inconsistencies inherent to the theory of the phlogiston, the quantity of caloric remained constant in the universe.

The theory of the caloric considerably influenced the works of chemist **Joseph Black** who, **with various experiments on heating bodies** and their passage from one state of matter to another, showed the **existence of both latent heat** (at that time, latent caloric!) and **specific heat**. In modern terms, the former is the amount of energy that it is necessary to supply a body so that it undergoes a change of state (for example, in passing from a liquid to a gas). Specific heat is instead the energy necessary to raise the temperature of a mass unit by one degree. These two concepts not only played a fundamental role in the development of studies on heat, they were also at the basis of the improvements that James Watt made on the steam engine. To measure these magnitudes and the heat produced by chemical reactions, **Lavoisier** invented the ice-**calorimeter**.

While on one hand, the theory of the caloric proved effective, on the other hand, it was not the only one in circulation; it indeed coexisted with the theory Francis Bacon discussed in the XVII century that hypothesised that **heat was a form of motion**. In the XVIII century, Russian scientist **Mikhail Lomonosov** advanced the idea that it was precisely due to a motion of microscopic particles in matter. Several experiments and fundamental observations were made by the Anglo-American scientist and inventor **Benjamin Thompson** who became **Count Rumford** in 1791. His very eventful career saw him in the service of the Elector of Bavaria for whom, among other things, he reorganised the army. His experiments on weapons and explosives led him to take on problems concerned with heat. Thompson observed that the **boring of cannons**, which involved considerable **friction**, generated a large quantity of **heat**. His curiosity aroused by this observation, he conducted an experiment in which boring was performed with the cannon immersed in water. The water started boiling due to the heat generated, and boiling continued for hours, as though the heat source were apparently inexhaustible. Based on this and other similar observations, Thompson became convinced that the idea of the caloric passing from one body to another was indefensible – as it should have exhausted itself – and became convinced that the heat was instead due to a sort of motion. His experiments, though, were not very conclusive. Rumford's theory was vehemently attacked by the partisans of the caloric theory, but it was supported by experiments and considerations made by scientists like **Humphry Davy** and **Thomas Young**. Davy, for example, showed that by rubbing two pieces of ice in the vacuum of a pneumatic pump, it was possible to cause their partial melting despite the temperature at which the experiment was conducted was kept below zero. Nonetheless, in the first decades of the nineteenth century, few abandoned the theory of the caloric.

In 1822, French mathematician and physicist **Joseph Fourier** published a fundamental analytical study that led him to elaborate a **mathematical model** (thanks to a series of trigonometric series) on **heat propagation**. Just as Newton by means of a few laws and general concepts had been able to predict the movement of a body in space and time, Fourier was able to predict the thermal state of a body, once the initial conditions were known. Fourier did not express opinions on the nature of heat but assumed that when bodies change their thermal state, the total quantity of heat is always conserved. Fourier's mathematical tools not only brought a substantial contribution to the founding of modern thermodynamics but also proved to be very powerful calculation tools, fundamental in numerous branches of physics.

In the first decades of the nineteenth century, studies did not stop at heat transmission by conduction or convection. Italian scientist **Macedonio Melloni** conducted extensive research on what at the time was called **radiant heat** – today's infrared rays. Melloni studied the properties of numerous substances capable of differently transmitting, reflecting or refracting radiant heat which, capable of being transmitted even in a vacuum, was later recognised as an invisible portion of the electromagnetic spectrum, having a lower frequency compared to that of light.

The same period also saw **improvements in thermometers** that the accuracy and precision of all calorimetric studies depended on. The **dilation coefficients** of mercury, glass and many other substances were thus studied exactly. At the start of the century, the **properties of gases** and **their behaviours** were investigated in function of parameters such as **volume** and **temperature**. Fundamental researches were conducted by J**oseph Gay-Lussac** into how gassy substances combine and the relationship between pressure and temperature at a constant volume, by **John Dalton** one of the artificers of the atomic theory in chemistry and, especially, **Victor Regnault**, a great experimenter and inventor of numerous instruments, who among other things studied the **dilation of gases**, the **elastic force of steam**, the **latent heat of water** and its **pecific heat** at **various temperatures**.

Pierre Dulong and **Alexis Petit** studied the **specific heat of solid bodies**. The same decades also witnessed the appearance of the first studies on the **liquefaction of gases** of which **Michael Faraday** was a pioneer. All of this research made it possible to become better acquainted with the nature of gases, to formulate **rough laws** that described their behaviour in function of various parameters, and to begin understanding the mechanisms of **phase transitions between the state of liquid and gas**. These studies opened the doors to important **industrial applications** which would then be developed especially in the final decades of the century.

The Birth of Thermodynamics

In those very years of great scientific ferment, the transformations generated by the Industrial Revolution that had already developed in England since the middle of the 1740s were also spreading to the continent, first and foremost those owing to the introduction of the steam engine. It is legitimate to consider that the science of **thermodynamics**, which studies the **conversions of energy between heat and work and vice versa**, **originated in attempts to mathematically determine how much work could be drawn from a steam engine**.

The first impulse in this direction was given by French military engineer and physicist **Nicolas Léonard Sadi Carnot** who devoted himself to improving the steam engine whose construction was still essentially dictated by empirical considerations. There were vague intuitions but the scientific foundations of its functioning were still almost completely unknown. He was interested in understanding **how to design good steam engines**. In his time, steam power had indeed already been applied to pump water from mines, to drive forges, mills, textile machines, etc., but not very efficiently. English machines imported into France following the Napoleonic wars showed Carnot how backward French design had remained. Moreover, it disturbed him that the English had made such great advancements through the practical capabilities of a few engineers who did not possess a formal scientific education. Furthermore, the English engineers had gathered and published plausible data concerning the efficiency of many types of engines, and they revealed the merit of the construction of low and high-pressure engines with one or two cylinders. Believing his country's inadequate use of the steam engine to have been an important factor in her defeat in the Napoleonic wars, Carnot began to write a work on the efficiency of the steam engine. Others before him had dealt with the question, attempting to improve its performance by comparing steam expansion and compression with the production of work and fuel consumption.

In 1824, he published **"Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance"** ("Reflections on the motive power of fire and on machines fit to develop this power"), a work in which **he confronted the substance of the process without dealing with the technical and construction details**, as others had instead done. Carnot's heat engine is an ideal engine, just as the cycle he invented. To fully appreciate Carnot's work, we must bear in mind that concepts which for us today appear fundamental such as heat or energy, were at that time still extremely vague. Carnot introduced the idea of a **cycle** whereby following a series of transformations, a substance is taken back to its initial conditions. He also proposed the **principle of reversibility** in which heat could be extracted from the condenser and taken back to the source at the expense of an equal quantity of work. Assuming that **perpetual motion is impossible**, he concluded **that no engine can have a greater efficiency than a reversible engine**.

Carnot was convinced of the validity of the caloric theory and of its conservation. He compared the motive power of heat with that of falling water that activates a water wheel. He affirmed that both have a maximum power independently, in the first case, of the machine on which the water works and, in the other case, of the nature of the substance receiving the heat. The motive power of water depends on the quantity of water and the height it falls from. The motive power of heat depends on the quantity of caloric and the difference in temperature between the reservoirs it operates between. A few years later, however, Carnot became convinced of the fallacy of the caloric theory, as shown by his late writings, for a long time left unpublished, which also show his "conversion to a dynamic theory of heat". Furthermore, he understood the law of the conservation of energy: "Motive power exists in an unalterable quantity in nature; it can be neither produced nor destroyed". Though the importance of Carnot's work of 1824 had been underlined by **Benoit Paul Emile Clapeyron**, it was not generally recognised until it was resumed by **William Thomson** (later **Lord Kelvin**) who underlined the necessity to modify Carnot's reasoning, so as to render it compatible with the new theory of heat. In 1848, Thomson indeed showed that Carnot's principle of cyclical transformations led to the conception of an **absolute scale of temperatures**. In 1849 he published "On an absolute thermometric scale founded on Carnot's theory of the motive power of heat, and calculated from Regnault's observations".

In 1850, **Rudolph Clausius** informed the Academy of Berlin of a work on the same topic which essentially contained the **second law** (or principle) **of thermodynamics**: **“Heat cannot spontaneously flow from a colder body to a hotter one”**. Clausius was not a great experimenter but he obtained remarkable results as a mathematical physicist. At the same time, professor of engineering and mechanics in Glasgow, **William John M. Rankine** presented a work to the Royal Society of Edinburgh in which he declared that **heat is generated by the motion of molecules**, and independently reached several of the results previously reached by Clausius. In March 1851, unawares of Clausius’ studies, **William Thomson published research containing a rigorous proof of the second law**. The law can be expressed in various ways, and another formulation is: **“In a cyclical process, it is impossible to convert all of the heat into work”**. This principle definitively shelved the possibility to realise a perpetual motion engine (though it did not discourage inventors and visionaries from pursuing this impossible dream).

Another fundamental point in the development of thermodynamics was that of **measuring the mechanical equivalent of heat**. The concept of the mechanical equivalent of heat played a fundamental role in establishing the principle of **conservation of energy**, which represents one of the **most important generalisations of nineteenth-century physics**. As has often occurred in the history of science, many reached the same conclusions at the same time. The principle of equivalence between work and heat was indeed formulated by numerous scientists whose ideas initially struggled somewhat to become established. Among them we must recall **Robert Mayer**, a physician from Heilbronn, **Ludwig August Colding** in Copenhagen, **James Prescott Joule** in England, and **Hermann von Helmholtz** in Germany.

Heir of a family of brewers, Joule developed an early interest in scientific matters and proved to be a very competent experimenter. For several decades, he sought to **measure the equivalence between work and heat, utilising various methods**. He confronted **electrical methods** (measuring the heat generated by the passage of a current in a conductor) and **purely mechanical methods**, obtaining results that tallied, at least for the order of magnitude. This strengthened his conviction that work could be converted into heat. In one of his most famous experiments, a mass of water is slightly heated by the friction produced in it by the rotation of a paddlewheel moved by weights. **Overcoming incredible technical difficulties**, succeeding in **measuring minimum temperature variations**, and constantly refining his methods, Joule succeeded in **determining the work necessary to raise the temperature of a gram of water by one degree with remarkable precision for the time**. The results of this experiment were presented in **1845.** In April **1847**, Joule held a conference in Manchester, proposing **“the first complete and clear exposition of the universal conservation of the principle now called energy”**. In June of that same year, the topic was again presented on the occasion of a meeting of the British Association held in Oxford. This might have passed practically unobserved if it hadn’t been for the presence of the then young Thomson whose attention Joule attracted. After the meeting, Joule and Thomson continued to talk on the subject. Thomson “drew ideas he had never had before”, while Joule had the opportunity to become acquainted with Carnot’s theory.

The same year Joule announced his vision of energy, **Helmholtz presented a paper on the same topic to the Physical Society of Berlin**, making a clearer formulation than what had already been presented by Mayer. His publication initially attracted little interest until it was attacked by Clausius in 1853. Others accused him of having dishonestly taken advantage of Mayer’s work, but in 1847 Helmholtz like Joule had never heard of Robert Mayer, but later recognised his priority. **The first principle of thermodynamics is simply a generalisation of the principle of the conservation of energy**. It can be neither created nor destroyed, but it can assume various forms. Every system contains a certain quantity of energy, which is defined as they system’s internal energy. In a gas, this is essentially the total kinetic energy of the molecules in movement. The internal energy of a gas can be modified either by supplying heat – for example by heating it – or by performing work on it – for example compressing it. The first principle thus states that the variation of internal energy of any thermodynamic system – a heat engine, or a chemical reactor, or another isolated system – corresponds to the difference of the quantities of heat and work supplied to the system.

In the **second half of the nineteenth century**, thermodynamics was gradually perfected, received an increasingly more sophisticated and complex mathematical structure, and began to have a fundamental role even outside of the field of physics. Thanks to the development of thermodynamics, the **design and building of heat engines** (steam engines, internal combustion engines, and turbines) **gradually became less empirical and more the fruit of calculations and applied theories**. We must remember, however, that the mathematical formalisms of thermodynamics had to be modified by engineers in order to be applied in the technical field. By the end of the nineteenth century, enormous steam engines drove transatlantic ships, power plants, and gigantic machinery in every kind of factory. Compared to their horsepower in the thousands, the horsepower of the early Newcomen engines seemed ridiculous.

6. Target group, curricular relevance and educational benefit

The idea of confronting the topic of thermodynamics emerged during the first HIPST national meeting held at the Fondazione Scienza e Tecnica, in a brainstorming phase aimed at collecting proposals from teachers to formulate new learning material. It was important for these proposals to have curricular relevance in the school ambit, on one hand, and to be inherent to the objects in the Physics Laboratory collection, on the other hand.
More specifically, the choice of thermodynamics emerged from the suggestion of two physics teachers – Paola Falsini, who teaches at the Liceo Scientifico Enriques Agnoletti in Sesto Fiorentino and Silvia Pirollo who teaches at the Liceo Artistico Alberti in Florence – who in their classes had previously and

autonomously developed the following projects: “From heat machines to the principles of thermodynamics”, and “Introduction to the concept of energy”.

The choice of the type of learning material and the structure of the “Steam, Work, Energy” kit was successively determined also by confronting the opinions of other teachers participating in the HIPST project work group, in particular Barbara Bellaccini and Ivan Casaglia from the Liceo Scientifico Castelnuovo, Firenze. This was done in the attempt to draw up material that could be effectively useful to integrate the teaching of a subject central to physics programmes and, at the same time, “difficult” for the risk of being very abstract, with an historical viewpoint that could also stimulate reflection on the nature of science.

The learning tool described in this case study is thus aimed at high school physics teachers (students aged 14-19), but it can also be utilised for interdisciplinary studies, in particular with history and philosophy teachers (immediate references are the Industrial Revolution in history, and the Enlightenment and Positivism in philosophy). Further routes can also be followed in literature and figurative art.

The work proposed has a particular curricular relevance in that it influences a fundamental topic in the physics courses of all high schools. Hopes are that it will have the educational benefit of being a tool that effectively encourages and assists teachers in introducing students to the history of science and technology and arousing their interest. This is not all, though. As we have often seen emerge from the evaluations expressed by HIPST work group teachers, it is also a matter of offering young people the possibility to enter into contact with a richer and much more articulated dimension of physics. One that does not stop as it does in most cases – at least in Italian schools – at a sterile mathematical formalism separated from the concreteness of facts, which often leaves students disappointed with a discipline that one supposes should explain natural phenomena and instead seems to end up as a mathematical abstraction.

The purpose of a task like the one presented in this case study is therefore to offer teachers and, through them, students, tools to approach the contents of physics from a very concrete perspective. This perspective should show the motivations and the complexity of research routes that have led to the acquisition of new knowledge about the laws of nature, that evidences the creativity of the scientific undertaking, presents the figures who were its protagonists, underlines the importance of the experimental dimension in science, and its profound interrelation with technology, the economy and society.

7. Activities, methods and “media” for learning

The “Steam, Work, Energy” kit is a flexible tool realised for teachers’ autonomous use in class. It offers reference material for the creation of one or more lessons or an entire course that can last several weeks. It is therefore left to teachers' creativity and specific interests to decide how to implement it: it can constitute the outline for one or more stand-up lectures; it can be the stimulus to create interdisciplinary projects with other teachers; it can be used as the point of departure to conduct laboratory activities; it can be the opportunity for extracurricular activity such as a visit to the Physics Laboratory of the Fondazione Scienza e Tecnica. A particularly significant added value is provided by the presence of the videos which offer teachers the possibility to very concretely illustrate how certain physics phenomena are produced, how certain measurements can be made, and the function of several machine models.

8. Obstacles to teaching and learning

The main obstacle to teaching, from what the teachers themselves underline, appears to consist in the lack of a historical dimension in the training of physics teachers who, unless they attend to their own training, may feel themselves in some difficulty to introduce the historical dimension into their lessons in a way that is not banal. For this reason, in addition to preparing supplements for further study on contents, already mentioned in paragraph 4, seminars will be held at the Fondazione Scienza e Tecnica for teachers and aimed at increasing familiarity with certain contents of history of science by means of a direct dialogue in small groups.

9. Evaluation

The evaluation process is still at a very partial level. The teachers of the HIPST work group have found the prototype of "Steam, Work, Energy" CD to be well structured, rich and original. Some of them have also pointed out the difficulty – intrinsic to the question of trying to get physics teachers to impart contents of a historical nature – as referred in point 8. For this reason we decided to produce more material for further study. The same reason urges us to accompany the knowledge of the kit with follow-up courses aimed at teachers. This will be possible in a quite large scale, during the year 2010, thanks to the support of the Regional Administration in Tuscany, that, after an evaluation of the results obtained by the Fondazione Scienza e Tecnica within the HIPST project, has financed further activities to disseminate its products. An evaluation of the entire project will thus be possible in the course of this year.

10. Teaching resources

The full content of the CD can be downloaded here: ftp://79.34.91.73/.

11. Video Resources

Model of Watt's steam engine. In the nineteenth century, models of machines were common in the science laboratories of schools and universities, where they were used to show the practical applications of physics laws and phenomena.The model in question is a scale model of a double-acting fixed type of Watt steam engine, which was used for a good part of the nineteenth-century.

The fire piston is a curious instrument used as of the early nineteenth-century in Europe and until the invention of viable matches (in 1820 circa), which makes it possible to instantaneously light an easily inflammable substance, thanks to the rapid compression of air that is suddenly heated. This instrument's use as a demonstrative physics apparatus survived for quite some time, as it permitted a spectacular demonstration of the transformation of mechanical work into heat by means of the adiabatic compression of a gas.

The Tyndall apparatus. Widely diffused in nineteenth-century physics collections, it was used in a purely qualitative experiment to show how, by means of friction, mechanical work can be transformed into heat.

The Joule apparatus. Its functioning is illustrated with a replica proposed for educational purposes of the one invented by James P. Joule in 1845 to measure the mechanical equivalent of the calorie.

The Puluj apparatus invented by Ukraine physicist and inventor Johann Puluj (1845-1918) makes it possible to determine (at least approximately) the mechanical equivalent of a calorie. More compact and easier to use than the Joule apparatus, it was essentially utilised in teaching.

The horizontal cylinder steam engine. This model shows a typical example of fixed steam engine widely used in industry. It is a machine that has reached technological maturity.

12. Resources on the web

The following list refers some useful resources on the historical origins of thermodynamics, available on the web.

- About Thomas Savery:
  http://library.thinkquest.org/C006011/english/jsites/steam_thomas_savery.php3?f=2&b=50&j=1&fl=1&v=2
- About Newcomen:

  http://library.thinkquest.org/C006011/english/jsites/steam_thomas_savery.php3?f=2&b=50&j=1&fl=1&v=2
  http://www.animatedengines.com/newcomen.shtml ·

- About James Watt:

  http://www.kuhf.org/cdprojects/steam/track9.html
  http://www.egr.msu.edu/~lira/supp/steam/wattengine.htm

- About the Carnot's cycle: ·

http://www.cs.sbcc.cc.ca.us/~physics/flash/ http://www.educypedia.be/education/mechanicsjavamachine.htmAbout the Perpetual motion: http://www.hp-gramatke.net/perpetuum/index.htm

13. Essential bibliography

- Angelo Baracca, Ugo Besson, Introduzione storica al concetto di energia, Le Monnier, Firenze, 1990
- Paolo Brenni, Il Gabinetto di Fisica dell'Istituto Tecnico Toscano, Edizioni Polistampa, Firenze, 2009
- Floriano Cajori, Storia della fisica elementare con l'evoluzione dei laboratori fisici, Remo Sandron, Palermo, 1930
- David Knight, Le scienze fisiche nell'Ottocento, in R. Shea (a cura di), Storia delle Scienze, Banca Popolare di Milano, Milano, 1990
- Donald S. L. Cardwell, Tecnologia, scienza e storia, Il Mulino, Bologna, 1976
- Donald S. L. Cardwell, The development of science and technology in Nineteenth-Century Britain, Ashgate, Aldershot, 2003
- Anna Giatti e Stefania Lotti (a cura di), Le stanze della scienza. Le collezioni dell'Istituto Tecnico Toscano a Firenze – Fondazione Scienza e Tecnica, Artigraf, 2006
- Amédée Guillemin, Les applications de la physique aux sciences, a l'industrie et aux arts, Hachette, 1874
- Charles Singer, E.J. Holmyard, A. R. Hall, T. I. Williams (a cura di), Storia della tecnologia, Volume 4, La rivoluzione industriale, Boringhieri, Torino, 1964
- Gerard L'E. Turner (a cura di), Storia delle scienze, Gli strumenti, Einaudi, Torino, 1991