An integrated four-year course in physics, chemistry, biology and geology based on and covering the Ordinary Level of the science syllabus approved by the New South Wales Secondary Schools Board

prepared

under the guidance of the N.S.W. Director-General of Education, Dr. H. S. WYNDHAM, C.B.E., M.A., Ed.D., Dip.Ed., F.A.C.E.

and

with the co-operation of the Department of Education

ABRIDGED SCIENCE FOR HIGH SCHOOL STUDENTS

by THE NUCLEAR RESEARCH FOUNDATION SCHOOL CERTIFICATE INTEGRATED SCIENCE TEXTBOOK GROUP OF AUTHORS AND EDITORS

under the chairmanship of PROFESSOR H. MESSEL, B.A., B.Sc., Ph.D.

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Heat a form of motion. As early as the seventeenth century an early English scientist, Robert Boyle, noticed that " when, for example, a smith hammers a nail it will grow hot, which shows the heat acquired by the piece of iron was produced in it by motion ". At that time scientists thought that heat was a kind of fluid—called *caloric fluid*—so we can understand how strange this observation appeared to Boyle.

Heat and work. Much later, towards the end of the eighteenth century, an American named Benjamin Thompson, who later moved to Germany and became known as Count Rumford, carried out some experiments which proved that when the supposed caloric fluid flowed into an object—that is, it became hotter—the mass of the object did not become greater. Rumford began to question whether there was, indeed, such a fluid. He was not so sure that the caloric theory provided the true explanation of heat. About 1800 Rumford was supervising the men who were boring the barrels of brass cannon to be used by the German Army. He noticed how very hot the lathe cutting-tool and the brass shavings became, especially when the tool became rather blunt. Rumford concluded that the *work being done* to overcome frictional resistance was providing the heat. Slowly, scientific thinking was making progress.

About the same time Humphry Davy, an English experimenter, devised experiments in which pieces of ice were rubbed together and caused to melt by the action of mechanical energy alone.

The idea of the identity of mechanical energy and heat was gaining popularity. Heat energy was now thought of as a kind of motion. The theory gained adherents when John Dalton in 1803 formulated his ideas on the particle theory of matter from which was developed the concepts of atoms and molecules. Now scientists could understand how motion might be taking place in a hot object which was apparently at rest as a whole: the atoms or molecules were moving *within* the object.

Joule's experiments. However, the greatest name in the development of heat theory was that of James Prescott Joule, an Englishman. He was tireless in carrying out experiments in order to determine the relationship between heat and energy. Lord Kelvin, a famous scientist of the period, even related a story of meeting Joule in France while the latter was on his honeymoon. Joule had neglected his young wife to lean dangerously over a waterfall with a giant thermometer. He was measuring whether there was any increase in temperature as the water lost potential energy in falling. Joule found, in fact, that the water at the base of the falls was very slightly warmer than that at the top.

In all great scientific advances, there is generally a point of break-through in understanding or discovery after which progress in scientific knowledge moves rapidly forward. This point was achieved by Joule in 1843 when he concluded that " energy is *indestructible* and whenever energy is expended an exact equivalence of heat is *always* obtained ".

This was the first statement of the great fundamental law of modern science, which is now called the *law of conservation of energy*—see Chapter 32—and may be stated as follows:—

> *Energy is indestructible. It may be transformed from one form into another but the total amount of energy remains constant.*

Major developments in all fields of science, since that time, have been based upon this law. Examples include the following:—

Electrical energy. As research into electricity was undertaken during the latter part of the nineteenth century, it became possible to devise units for measuring electrical energy which depended upon the fact that electrical energy is equivalent to other forms of energy as demonstrated in the following experiment.

Experiment 33.5. Conversion of mechanical energy to electrical energy.

Clamp a toy electric motor in a stand. Connect a 2-volt electric lamp—or an electric meter—to the terminals which would normally be connected to a battery when running the motor. Fix one end of a piece of thread to the driving pulley of the motor and then wind the thread as many times as possible round the pulley. Connect the free end of the thread to a mass of one or two kilogrammes.

If now you allow the mass to fall, causing the pulley to spin, you should see the lamp glow as the potential energy of the mass, changing to mechanical energy as the mass falls, is converted to electrical energy by the motor. We shall be reading more about electrical energy in the next chapter and there again shall see its equivalence to other forms of energy.

The mass-energy relationship. During the early part of the twentieth century Albert Einstein, one of the greatest of all physicists, extended the idea of conservation of energy even further. Einstein found that even *mass* and *energy* can be transformed into one another and are therefore equivalent, that is, that matter itself can be considered as one of the forms of energy—see Chapter 47. He expressed the mass-energy relationship in a mathematical form which can be used to calculate the amount of energy which can be made available from the conversion of a certain amount of matter. This

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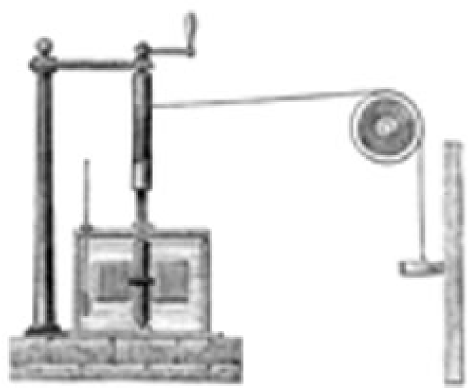
This Month Physics History

December 1840: Joule's abstract on converting mechanical power into heat



Calorimeter used by Joule in his 1876 determination of the mechanical equivalent of heat.

Scientists in the early 19th century adhered to caloric theory, first proposed by Antoine Lavoisier in 1783 and further bolstered by the work of Sadi Carnot in 1824. The work of a brewer and amateur scientist on the nature of heat and its relationship to mechanical work would give rise to the first law of thermodynamics.

Born in 1818, James Prescott Joule came from a long line of brewers, so chemistry was in his blood –as was scientific experimentation. Described as "delicate" in contemporary accounts, he and his brother experimented with electricity by giving each other electric shocks, as well as experimenting on the servants. The two boys were tutored at home until 1834, when their father sent them to study under John Dalton, one of the leading chemists of that time, at the Manchester Literary and Philosophical Society. Two years later, Dalton suffered a stroke and was forced to retire from teaching. The Joule brothers' education was entrusted to John Davies.

Eventually Joule took over as manager of the family brewery, but science remained an active hobby. Fascinated by the emerging field of thermodynamics, Joule jerry-rigged his own equipment at home–using salvaged materials–to conduct scientific experiments–initially to test the feasibility of replacing the brewery's steam engines with the newfangled electric motor that had just been invented. He found that burning a pound of coal in a steam engine produced five times as much work (then known

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as “duty”) as a pound of zinc consumed in an early electric battery. His brewery was better off with the steam engines. His standard of “economical duty” was the ability to raise one pound by one foot (the “foot-pound”).

His first experiments focused on electromagnetism and he quickly showed a gift for experimental apparatus; he built his first electromagnetic engine at 19, as well as improved galvanometers for measuring electrical current. Thanks to Dalton’s influence, Joule was a rare subscriber to atomic theory, and sought to explain electricity and magnetism in terms of atoms wrapped by a “calorific ether in a state of vibration.”

This did not match his experimental results, however, and in December 1840, Joule published a short abstract in the *Proceedings of the Royal Society* suggesting that the heat generated in a wire conveying an electrical current results from the heat generated by the chemical reactions in a voltaic cell. In other words, heat is generated, not merely transferred from some other source in an electromagnetic engine. Based on this work, he formulated “Joule’s Law,” which states that the heat produced in a wire by an electric current is proportional to the product of the resistance of the wire and the square of the current.

When Joule presented these findings in a paper read before the British Association meeting in Cambridge, he concluded, “[T]he mechanical power exerted in turning a magneto-electric machine is converted into the heat evolved by the passage of the currents of induction through its coils; and, on the other hand, that the motive power of the electro-magnetic engine is obtained at the expense of the heat due to the chemical reactions of the battery by which it is worked.”

In subsequent papers presented in 1841 and 1842, he quantified this heating effect, demonstrating that the total amount of heat produced in a circuit during “voltaic action” was proportional to the chemical reactions taking place inside the voltaic pile. By January 1843, he had concluded that his magneto-electric machine enabled him to convert mechanical power into heat. All of this led Joule to ultimately reject the caloric theory of heat. He also established that the various forms of energy are basically the same and can be changed from one into another, a discovery that formed the basis of the law of conservation of energy, the first law of thermodynamics.

In his most famous experiment. Joule attached some weights to strings and pulleys and connected them to a paddle wheel inside an insulated container of water. Then he raised the weights to an appropriate height and slowly dropped them. As they fell, the paddle wheel began to turn, stirring up the water. This friction generated heat, and the temperature of the water began to increase.

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It was the very precision of his measurements that caused some scientists to balk at accepting Joule's findings. He claimed to be able to measure temperatures to within 1/200 of a degree Fahrenheit, which would have been astonishing to a 19th century scientist. Some historians have speculated that Joule's experience in the art of brewing may have given him skills with experimental apparatus that his colleagues lacked. He also worked with John Benjamin Dancer, England's finest instrument maker, to build highly accurate thermometers. Among those inclined to accept Joule's work were Michael Faraday and William Thomson (Lord Kelvin), although they remained skeptical.

Thomson and Joule eventually became good friends and scientific collaborators. Thomson recalled in his memoir meeting Joule and his new wife, Amelia, during a tour of Mont Blanc in 1847. Joule was carrying a thermometer and claimed he would attempt to measure the thermal effects of fluid motion in local waterfalls. Thomson joined him a few days later at the Cascade de Sallanches, but they "found it much too broken into spray" to make a useful measurement. For several years, Joule conducted experiments and sent his results in letters to Thomson, who analyzed them from a theoretical standpoint and suggested further experiments Joule might try. Among the fruits of this partnership was the Joule-Thomson effect, in which an expanding gas, under certain conditions, is cooled by the expansion.

Joule lost his wife and daughter in 1854, and lived a fairly secluded life from then on. He died on October 11, 1889, and his gravestone is inscribed with the number 772.55–his most accurate 1878 measurement of the mechanical equivalent of heat. His work did not go unrecognized: the Queen of England granted him a pension in 1878 in recognition of his scientific achievements. The value of the mechanical equivalent of heat is represented by the letter J in his honor, and the standard unit of work is the joule.

Physics History

This Month in Physics History
APS News Archives

Historic Sites Initiative
Locations and details of historic physics events

Editor: Alan Chodos

LETTERS TO THE EDITOR

Letters are selected for their expected interest for our readers. Some letters are sent to reviewers for advice; some are accepted or declined by the editor without review. Letters must be brief and may be edited, subject to the author's approval of significant changes. Although some comments on published articles and notes may be appropriate as letters, most such comments are reviewed according to a special procedure and appear, if accepted, in the Notes and Discussions section. (See the "Statement of Editorial Policy" at http://www.kzoo.edu/ajp/docs/edpolicy.html.) Running controversies among letter writers will not be published.

ARE WE TEACHING SCIENCE AS PRACTICED BY SCIENTISTS?

Robert Millikan's[1] oil drop experiment to determine the charge of the electron has been the subject of considerable controversy.[2–4] Despite this, most general chemistry and physics textbooks consider it to be a beautiful and classical experiment in which data from the experiment unambiguously led to the formulation of the fundamental electrical charge (the electron). Millikan himself, despite the controversy with Felix Ehrenhaft, facilitated this impression, and a review of the literature shows that his handling of the data was controversial.[5] Most scholars would agree that Millikan's handling of the data was strongly influenced by his guiding assumption, namely, the existence of the electron and the magnitude of its charge.

Martin Perl,[6] Nobel Laureate in Physics (1995), has been working on the isolation of quarks (fractional charges). Perl and his colleagues have used a Millikan style methodology with improvements based on modern technology and stretching the normal present experimental boundaries. Given the difficulties involved in cutting-edge experimental work, he has designed a philosophy of speculative experiments in which he outlines his research methodology that includes reason and speculations (guiding assumptions). Speculative experiments become important when the scientist is groping with difficulties, future of the research cannot be predicted, and stakes are high due to competing groups (peer pressure). Perl and Lee have summarized this as:

> Choices in the design of speculative experiments [cutting-edge] usually cannot be made simply on the basis of reason. The experimenter usually has to base her or his decision partly on what feels right, partly on what technology they like, and partly on what aspects of the speculations [presuppositions] they like.[7] (Note: Phrases in brackets are added for clarification)

In a recent study we asked Leon Cooper (Nobel Laureate in Physics, 1972) to comment on Perl and Lee's methodology cited above. Cooper endorsed this methodology:

> Of course Perl is right. Pure reason is great. Experimentalists base their decision of what experiments to do on what feels right, what technology they're capable of using and their intuition as to what can be done and what might really be an important result. Experimentalists sometimes say that the first thing they try to do in an experiment is to make it work. It is intuition guided by facts, conjectures, and thoughts about what really would be important.[8]

This makes interesting reading, as Cooper goes beyond Perl and Lee by emphasizing not only speculations but also intuition guided by facts and conjectures. It is remarkable that even physicists now recognize in public (as contrasted with Millikan's methodology) that progress in science is not merely based on the accumulation of experimental data but rather dependent on the creative imagination of the scientific community, that is, guiding assumptions, intuition, facts, and conjectures.

In contrast to the interpretations of Cooper and Perl, science textbooks and curricula in most parts of the world continue to present progress in science as a product of experimental data that unambiguously lead to the formulation of scientific theories.[5,9,10] Similarly, the importance of students' epistemological beliefs in learning science has been recognized by Heron and Meltzer.[11] This should be cause for concern for most science teachers and especially those interested in motivating students to study science. Such a state of our textbooks is even more troublesome if in retrospect we consider what physicist-philosopher Gerald Holton[12] had warned almost four decades ago with respect to what he called the myth of *experimenticism* (scientific research as the inexorable result of the pursuit of logically sound conclusions from experimentally indubitable premises).

Finally, a historical reconstruction of various episodes and experiments shows that interpretation of experimental data is difficult, which inevitably leads to alternative models/theories, conflicts, and controversies, thus facilitating the understanding of science as a human enterprise.[5] Another example is provided by the photoelectric effect,[13] where Millikan accepted the experimental data and still rejected the underlying theory (Einstein's), which he considered to be reckless. At this stage it would be appropriate to pause and reflect as to why textbook authors, curriculum developers, and even some scientists ignore the historical record and do not teach science as practiced by scientists. It would seem that teaching science as practiced by scientists would be more motivating for students and thus facilitate a better understanding of progress in science.

[1]R. Millikan, "The existence of a subelectron?," Phys. Rev. **8**, **595–625** (1916).

[2] G. Holton, "Subelectrons, presuppositions, and the Millikan–Ehrenhaft dispute," Hist. Stud. Phys. Sci. **9**, **161–224** (1978).
[3] M. Niaz, "The oil drop experiment: A rational reconstruction of the Millikan–Ehrenhaft controversy and its implications for chemistry textbooks," J. Res. Sci. Teach. **37**, **480–508** (2000); M. A. Rodríguez and M. Niaz, "The oil drop experiment: An illustration of scientific research methodology and its implications for general physics textbooks," Instr. Sci. **32**, **357–386** (2004).
[4] M. Niaz, "An appraisal of the controversial nature of the oil drop experiment: Is closure possible?," Br. J. Philos. Sci. **56**, **681–702** (2005).
[5] M. Niaz, *Critical Appraisal of Physical Science as a Human Enterprise: Dynamics of Scientific Progress* (Springer, Dordrecht, 2009).
[6] Perl has now abandoned his active quark research (SLAC-PUB-13512, Jan. 2009).
[7] M. Perl and E. R. Lee, "The search for elementary particles with fractional electric charge and the philosophy of speculative experiments," Am. J. Phys. **65**, **698–706** (1997).
[8] Reproduced in Ref. 5, p. 171.
[9] M. Niaz, "Do we need to write physical science textbooks within a history and philosophy of science perspective?" in *Science Education in Focus*, edited by M. V. Thomase (Nova Science, New York, 2008), pp. 15–65.
[10] F. Abd-El-Khalick, M. Waters, and A. Le, "Representations of nature of science in high school chemistry textbooks over the past four decades," J. Res. Sci. Teach. **45**, **835–855** (2008).
[11] P. R. L. Heron and D. E. Meltzer, "The future of physics education research: Intellectual challenges and practical concerns," Am. J. Phys. **73**, **390–394** (2005).
[12] G. Holton, "Einstein and 'crucial' experiments," Am. J. Phys. **37**, **968–982** (1969).
[13] Reference 5, Chap. 8.

Mansoor Niaz
Department of Chemistry, Epistemology of Science Group, Universidad de Oriente, Cumaná, Estado Sucre, Venezuela
niazma@gmail.com

JOULE'S WATERFALL MEASUREMENTS: A GREAT STORY, BUT IS IT TRUE?

In a review of *Mere Thermodynamics* by Don S. Lemons,[1] Rex[2] passes on the story of how Joule supposedly measured, while on his honeymoon, the temperature difference between the top and bottom of a waterfall. This story is attributed to the young William Thomson (later Lord Kelvin) by Bent,[3] who notes that Joule "suggested that the water at the bottom of a waterfall should be warmer than at the top, for Niagara falls, 160 ft high, about one-fifth of a Fahrenheit degree." Lemons[4] is sufficiently skeptical to admit that this story is "possibly apocryphal." The temperature difference $\Delta T = 0.20\ ^\circ\mathrm{F} = 0.11\ ^\circ\mathrm{C}$ follows from setting $gh = c_w \Delta T$, where h is the height of the waterfall, c_w is the specific heat capacity of water per unit mass, and g is the acceleration due to gravity. I have searched Joule's writings in vain for any indication that he ever made these measurements. If he did, he seems not to have reported them, possibly for good reasons. The temperature increase because of conversion of gravitational potential energy into thermodynamic internal energy is smaller than the natural variation in air temperature with height (lapse rate[5]). If we take the average in the troposphere to be about $6.6\ ^\circ\mathrm{C/km}$, we expect the air temperature at the bottom of a waterfall 160 ft high to be about $0.32\ ^\circ\mathrm{C}$ higher than at the top. Lapse rates near the ground can be much greater (or of opposite sign). We also face knotty problems such as the extent to which water at the top and bottom is in equilibrium with the surrounding air, drag on falling water, temperature increases because of the roiling of viscous, turbulent water at the bottom of the falls, and evaporative cooling of spray. Niagara Falls is a very complicated system. $\Delta T = 0.11\ ^\circ\mathrm{C}$ is the *maximum* temperature increase assuming water falling in free space without evaporation and that the entire potential energy difference appears as an internal energy increase solely of the water. Joule faced the formidable task of extracting a small signal in the presence of considerable noise. Until someone can provide a solid reference to his measurements (or repeat them), I will continue to believe that he never made them or, if he did, he prudently set them aside because they markedly disagreed with his predictions.

[1] Don S. Lemons, *Mere Thermodynamics* (Johns Hopkins U. P., Baltimore, MD, 2009).
[2] Andrew Rex, Am. J. Phys. **77**, **862–863** (2009), book review of Ref. 1.
[3] Henry A. Bent, *The Second Law* (Oxford U. P., New York, 1965), pp. 14–15. Bent quotes Kelvin but gives no reference, and I did not find anything in the first two volumes of Kelvin's collected papers, one co-authored with Joule.
[4] Reference 1, p. 27.
[5] The dry adiabatic lapse rate is $g/c_a \approx 9.8\ ^\circ\mathrm{C/km}$, where c_a is the specific heat capacity of air per unit mass. This temperature profile corresponds to an atmosphere in neutral static equilibrium. Note the similarity with g/c_w used to obtain Joule's result. The average lapse rate often is taken as two-thirds of the dry adiabatic lapse rate.

Craig F. Bohren
Tŷ'n y Coed, 301 Lenape Lane, Oak Hall, Pennsylvania 16827
bohren@meteo.psu.edu