additional cooling below -205° C. which it had gained by expansion. Thus the high-pressure gas which succeeds it reaches the expansion-valve at -215° C., and expanding from a lower temperature gains by free expansion a greater amount of cooling, say 15°, so that it now passes away over the coil at -230° C. and cools to this temperature the compressed gas by which it is succeeded. This intensification proceeds until the cooling reaches the boiling point of hydrogen at the pressure obtaining in P. That pressure is practically atmospheric, since the vessel communicates with the gasholder, which is sealed by a few inches of water. Liquid hydrogen then collects in the lower part of the vessel P.

One of the results of liquefying hydrogen has been to show that helium is a still more volatile gas. It is possible, therefore, to reach a lower temperature than that of liquid—probably even than that of solid—hydrogen by applying to helium the same process of free expansion with intensification by counter-current interchange which has succeeded in liquefying hydrogen. But helium is an exceedingly rare gas, so that the cost of further advances will be very great. Moreover, the most volatile gas probably becomes solid and loses practically all vapour-tension at a temperature above the absolute zero, so that for the attainment of that interesting point no combination of the three methods of cooling above described will suffice. Some fourth system of pumping energy will have to be devised before any portion of matter can be absolutely deprived of heat, and it is for the discovery of this fourth method that onlookers interested in low temperature research are now waiting.

PROFESSOR TAIT.

IN the month of February, Prof. Tait, owing to a lingering illness, resigned the chair of natural philosophy in the University of Edinburgh. Since then the graver symptoms of his illness had somewhat abated, and it was hoped that he might live to enjoy some years of rest and relaxation.

This hope was disappointed by his sudden death on July 4, at Challenger Lodge, Wardie, whither he had been removed for change of air on the invitation of his friend and former pupil, Sir John Murray.

The end of his blameless life and brilliant career brings to many an irreparable gap in their circle of friendship, and to the University of Edinburgh the loss of her chief ornament. Of late years Tait had confined himself more and more to his class work, to the management of the affairs of the Royal Society of Edinburgh, and to the pursuit of his manifold scientific investigations. But, although his direct participation in University affairs diminished, his colleagues never lost the impression that a great man dwelt among them, and not one of them would have dreamed of taking action in a matter likely to interest Tait without considering his opinion. To those who knew him intimately, and therefore loved him, the coming years will never fill his place, although they may alleviate the sense of loss by weaving around it happy memories of flashes of his keen and rapid intellect, of the merry geniality and quaint eccentricity of his singularly beautiful character, and of his staunch, almost quixotic, devotion to an approved cause or to a friend.

Tait was in most senses an Edinburgh man. He was born at Dalkeith on April 28, 1831. His early education was obtained at the Dalkeith Grammar School, and at the Circus Place School in Edinburgh. Like his namesake, the late Archbishop of Canterbury, Tait was a distinguished pupil of the Edinburgh Academy; and loved to tell amusing stories of his mathematical master, Dr. Gloag, whose stern, eccentric character was one of his favourite recollections. At the University he studied for a session under Kelland and Forbes. The former became his colleague and lifelong friend, and he cherished the memory of the latter even in such insignificant matters as the details of class-certificates and class-examinations; and, when the priority or credit of Forbes's work was called in question, he defended him with a ferocious knight-errantry that surprised those who knew Tait little and seemed so characteristic and charming to those who knew him well.

Some of Tait's Academy schoolfellows are still alive, and they speak of him with a mixture of love and respect which shows that he must have been a leading figure among them. Clerk-Maxwell was his most intimate school and college friend, and the friendship thus begun continued to the end of Maxwell's life, absolutely undisturbed by the fact that the two were rival competitors for the Edinburgh chair in 1860. The two men were in truth the Damon and Pythias of British science. Each in his special way was strong in mathematics, both had intense love for physical science, and both were men of wide and varied culture. Each understood perfectly both the strong and the weak points of the other, and both were men of playful disposition and of absolute frankness and sincerity. Those who have occasionally seen letters that passed between them will readily agree that their correspondence should be preserved with a view to ultimate publication; for it would undoubtedly prove one of the most interesting scientific documents of the nineteenth century.

The promise of the two illustrious Edinburgh friends was amply fulfilled in Cambridge. Tait was senior wrangler and first Smith's Prizeman in 1852, being then twenty-one years of age, and Maxwell was second wrangler and first Smith's Prizeman, equal with Routh, in 1854. They were happy in their private tutor, William Hopkins, of whom Tait always spoke with the highest appreciation, and to whose tuition he attributed with characteristic generosity much of the mathematical skill which doubtless came to him by the grace of God. He often contrasted the method and spirit of Hopkins' teaching with the work of the modern coach; but in his depreciation of the latter he perhaps scarcely allowed enough for the brilliancy of Hopkins' pupil and the altered circumstances of the tutor of to-day.

Into the boisterous joviality of Cambridge undergraduate life in his time Tait entered fully, and one often envied the boyish zest with which in middle age he would recall the part he had taken in many a college prank at Peterhouse in his youth. He was, indeed, all his days a sympathiser with the frolics and the foibles of ordinary men, and his stately figure and the genial smile on his rugged, manly face will be as much missed on the green at St. Andrews and in the smoking room of the "Royal and Ancient" as it will be in the quadrangle of the University. Tait was a keen golfer, and for forty years his invariable recreation was an annual holiday at St. Andrews, which he spent mainly on the links. He watched with great delight the triumphal progress to the championship of his amiable son Freddy, and it was said, probably with truth, that Freddy's fame was dearer to him than his own scientific renown. There is little doubt that Freddy's untimely death in the South African war and the agonising weeks of suspense that preceded the final news of his fate hastened the onset of his father's last illness, and it is certain that it darkened the close of a singularly placid and happy life.

In 1854 Tait was appointed professor of mathematics in the Queen's College, Belfast, and there he became acquainted with Andrews the chemist, and through him with Rowan Hamilton the mathematician. These two men exercised a decisive influence on his future life, and, as was his way, he repaid them both with the tenderest regard and reverence. Andrews stimulated his love for well-directed physical research, and helped him to cultivate that marvellous power of clearly apprehending and plainly

formulating both the facts and the theories of natural philosophy which was the greatest part of his genius as a physicist. Through the works and personal influence of Hamilton he was led to the study of quaternions—the source and inspiration of his most important contributions to pure mathematics.

In 1860 he was elected to the chair of natural philosophy in Edinburgh, which he was to hold for forty years with ever-increasing distinction. In that time a great army of students[1] has passed through his class room, and few have done so without carrying away with them the image of a great man and a notable teacher. A select number, not a few, have caught some of the original fire of their master and have gone abroad upon the earth to spread his ideas and practise his methods.

Of late years, mainly from want of funds, the laboratory equipment of Edinburgh University has been temporarily eclipsed by grander installations elsewhere; but it must never be forgotten that Tait was one of the first teachers in Great Britain to organise laboratory teaching for his students. Among his first "researchers" were a remarkable trio—Robert Louis Stevenson, William Robertson Smith and John Murray. No man but Tait could have drawn forth and brought together three men so highly distinguished, so utterly different. The popular estimates of the contributions of Murray and Stevenson to science would likely be correct; but it is probably not generally known that Robertson Smith made at least one important contribution to physical science, and was for a time Tait's assistant. He visited his old master regularly as long as he lived, and adored him, as everyone did, without exception, who had once come under his influence.

It appears to have been about the time of his appointment to the Edinburgh chair that Tait first became personally acquainted with Lord Kelvin. Kelvin (then William Thomson) was also a Peterhouse man, but had left Cambridge before Tait came up, and was already, independently and in conjunction with Joule, and concurrently with Rankine and Clausius, writing his classical memoirs on the theory of energy. The first edition of Tait and Steele's "Dynamics," published in 1856, does not, so far as a rapid examination could detect, contain either of the words *work* or *energy*. In its original form it was founded on Pratt's "Mechanical Philosophy," and written on the old-fashioned Cambridge lines, which knew not of Lagrange and Hamilton. Six years later it is on record[2] that in his introductory lecture Tait handled the notions of the "energetic" school with a freedom which bewildered his uninitiated hearers, and laid down the broad lines of a thoroughly modern course of natural philosophy. Probably, therefore, he had come under the influence of Joule and Kelvin before he became personally intimate with the latter. The conjunction with Kelvin produced the famous treatise on "Natural Philosophy," by Thomson and Tait, now familiarly known as T and T'. This wonderful book was published in 1867, and at once began to make a new era in mathematical physics. At first, owing to its highly condensed structure, its influence spread very slowly; but now it would be impossible to find an important treatise, or even a course of college lectures, on natural philosophy that does not show traces of its teaching. The work, it is true, is but a fragment, but the continuation is to be found in dozens of treatises written by men who have been nourished by the strong meat of its serried pages. The collaboration was so perfect that it is not easy to point out the parts due to Kelvin and to Tait.[3] During a somewhat intimate acquaintance, extending well over twenty years, the present writer never heard Tait drop a hint that would enable one to fix on any part of the great treatise as his special work. Its authors always spoke of it and quoted it in an oddly distant way, as if it had been the work of some third person. The two distinguished coadjutors were compelled, by diverging spheres of activity, to dissolve their partnership in T and T'; but, however divided their spheres, they were in scientific aim, as in friendship, undivided to the last.

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"I first became personally acquainted with Tait a short time before he was elected professor in Edinburgh; but, I believe, not before he became a candidate for the chair. It must have been either before his election or very soon after it that we entered on the project of a joint treatise on natural philosophy. He was then strongly impressed with the fundamental importance of Joule's work, and was full of vivid interest in all that he had learned from, and worked at with, Andrews. We incessantly talked over the mode of dealing with energy which we adopted in the book, and we went most cordially together in the whole affair. He gave me a free hand in respect to new names, and warmly welcomed nearly all of them.

"We have had a thirty-eight years' war over quaternions. He had been captivated by the originality and extraordinary beauty of Hamilton's genius in this respect, and had accepted, I believe, definitely from Hamilton to take charge of quaternions after his death, which he has most loyally executed. Times without number I offered to let quaternions into Thomson and Tait, if he could only show that in any case our work would be helped by their use. You will see that from beginning to end they were never introduced."

Tait's contributions to our text-book literature began with Tait and Steele's "Dynamics," already mentioned. His friend Steele (second wrangler and second Smith's Prizeman in his own year) died early, and wrote but a few chapters of the book. It was so much altered in successive editions that the retention of his name on the title-page became simply a pious tribute to the memory of a friend. The "Elements of Quaternions," begun in 1859, but, in deference to Hamilton, not published till 1867, went through three editions, and along with the "Introduction to Quaternions," by Kelland and Tait (1873), formed, and still forms, the best approach to the science of S, T and ∇. The "Sketch of Thermodynamics" (1868), originating in articles in the *North British Review* (1864), and Balfour Stewart's "Heat" (1866), were for long the only readily available source of information for English readers on the theory of energy, and both contributed powerfully to the growth of the "energetic" school of natural philosophy. "Recent Advances in Physical Science" (1876), a series of popular lectures for professional men, is one of the raciest of his books, and the most useful for the general reader. "Light" (1884), "Heat" (1884) and "Dynamics" (1895), republications of articles written for the "Encyclopædia Britannica," are all models of their kind, clear, forcible and concise, like everything he wrote. Those who wish to have an idea of how Tait taught should read "Properties of Matter," which embodies a considerable part of the course he usually gave to his elementary class.

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subject of the Shorter Catechism. It was, therefore, no surprise to some when he and Balfour Stewart proved to be joint authors of "The Unseen Universe" (first printed privately in 1875). This remarkable book reflects the extraordinary width of Tait's knowledge and of his interest in things known and unknown; its success, so far as its immediate object was concerned, is best described by Tait himself in an obituary notice of Balfour Stewart.

"It has passed through many editions, and has experienced every variety of reception—from hearty welcome and approval in some quarters to the extremes of fierce denunciation, or of lofty scorn, in others. Whatever its merits or demerits, it has undoubtedly been successful in one of its main objects, viz. in showing how baseless is the common statement that 'Science is incompatible with Religion.' It calls attention to the simple fact, ignored by too many professed instructors of the public, that human science has its limits, and that there are realities with which it is altogether incompetent to deal."

Tait's scientific memoirs are being republished in three goodly volumes by the Pitt Press, two of which have already appeared. It is therefore unnecessary to do more than allude to the most important of them. The subjects range over pure and applied mathematics and experimental physics. The majority of the mathematical papers are written in the quaternion notation, and this has undoubtedly prevented some of them from becoming so well known as they deserve to be. We may mention specially two papers on Fresnel's wave surface (1859); a series of papers on the properties of "nabla" (∇), and on the linear and vector function, extending from 1867 to 1900; on the rotation of a rigid body about a fixed point (1868)—a paper of great power and elegance, which exhibits Tait's mathematical power at its best; on Green's and other allied theorems (1870), on orthogonal isothermal surfaces (1872); on knots (1877, 1884, 1885), a series of three papers suggested by the problem of the possible configurations of a Thomson vortex atom. In the three classical papers last named he virtually creates a new chapter in the geometria situs, and is brought into relation with the work of Listing, for whom he had the greatest respect. To this subject he returns again in two subsequent papers: a note on a theorem in geometry of position (1880), and on Listing's topologie (1884).

His first experimental work was on ozone, in collaboration with Andrews (from 1856 to 1860). He also began to work with the same distinguished investigator on the compression of gases, but this was interrupted by his removal to Edinburgh in 1860. His memoir on thermal and electric conductivity contains the result of an elaborate series of experiments extending over ten years. The original idea of the method was due to Forbes, but the complete theory and the difficult details are the work of Tait and his pupils. The memoir on mirage is a remarkably elegant and effective combination of experimental and mathematical methods, and is, perhaps, the best example of Tait's work as a natural philosopher. His investigation of the pressure errors of the *Challenger* thermometers was an intricate piece of experimental work extending over several years. It led him into the discussion of the compressibility of liquids, to which are devoted five memoirs (1893-1898). This investigation brought him into close relations with the French physicist Amagat, for whom he had a great regard. Much work is embodied in five papers (1886-1892) on the foundations of the kinetic theory of gases, in which he endeavours to analyse into their logically simplest elements the first principles of a difficult and much-debated subject. His interest in the game of golf produced three important papers on impact (1888-1892), and two on the path of a rotating spherical projectile. On this subject he also wrote a series of popular articles which were widely read and appreciated.

Besides his text-books and original memoirs, Tait contributed assiduously to the current scientific literature of his day. We may mention in particular his article "On Energy" in *Good Words* (1863); his memoirs of Hamilton (*North British Review*, 1866) and of Andrews (along with Crum Brown, 1888); his famous lecture "On Force" (British Association, 1876), so cleverly parodied in Maxwell's poem—

> "Ye British asses who expect to hear
> Ever some new thing, &c.";

his article "On the Teaching of Natural Philosophy" (*Contemporary Review*, 1878); his fine appreciation of Maxwell's scientific work (NATURE, vol. xxi. p. 317, February 5, 1880), and his various contributions to the ninth edition of the "Encyclopædia Britannica."

Limitations of time and space, and others besides, make it impossible to attempt here any appreciation of the relative importance of Tait's original contributions to the science of the Victorian age. For one thing, the sense of bereavement is too near to us to permit of the necessary historical abstraction. Nor is this the time to enlarge on the polemical discussions in which Tait took part. Ready to take a blow, he did not always spare his strength in giving one, and his opponents did not always relish his rough play. It may be doubted whether many of them carried for long any resulting bitterness; but undoubtedly some of them were led, temporarily at least, greatly to mistake his character. Personal contact with him at once dissipated any such misconception. To feel the magic of his personality to the full it was necessary to visit him in the little room at the back of his house, No. 38 George Square, Edinburgh, the Spartan simplicity of whose plain deal furniture and book-shelves, unpainted, unvarnished, ink-spotted, littered with books and pamphlets and with piles of manuscript bristling with quaternion symbols, was so finely in tune with the tall, rugged figure, the loud, hearty greeting and the radiant, welcoming smile of the kindly host. Ten minutes in that sanctum would have made a friend of his bitterest foe, and the conquest would have been mutual and permanent, for it seemed to be an axiom of Tait's that a man who had become his friend could sin no more. Thither came at various times Joule, Andrews, Kelvin, Stokes, v. Helmholtz, Rankine, Clerk-Maxwell, Balfour Stewart, Rowland, the Wiedemanns (father and son), Adams, Newcomb, Huggins, Newton, Lockyer, Hamilton (at least in the spirit), Cayley, Sylvester, Hermite, Cremona, Clifford, Klein, Bierens de Haan and many more, the majority, alas! now departed like their common friend. It has been the main part of our endeavour to indicate, faintly at least, some of the qualities that attracted and retained such a galaxy of friends; the most potent of all was doubtless the oldest, the simplest ground of liking—he was loved so well because he loved so much.

G. CHRYSTAL.

NOTES.

THE Hughes Bennett laboratory of experimental physiology, which has been added to the University of Edinburgh by Mrs. Cox as a memorial of the work of her father, Prof. J. Hughes Bennett, in connection with medical education, was formally handed over to the University on Saturday last. The addition comprises a large laboratory equipped with appliances for practical work in experimental physiology by individual students, and a small lecture theatre for class demonstrations. The memorial character of the new laboratory is indicated by a bronze bas relief representing Hughes Bennett, which has been executed by Mr. MacGillivray. This is fixed to one of the walls of the laboratory, with an inscription below it commemorating the fact that Hughes Bennett was the first teacher in