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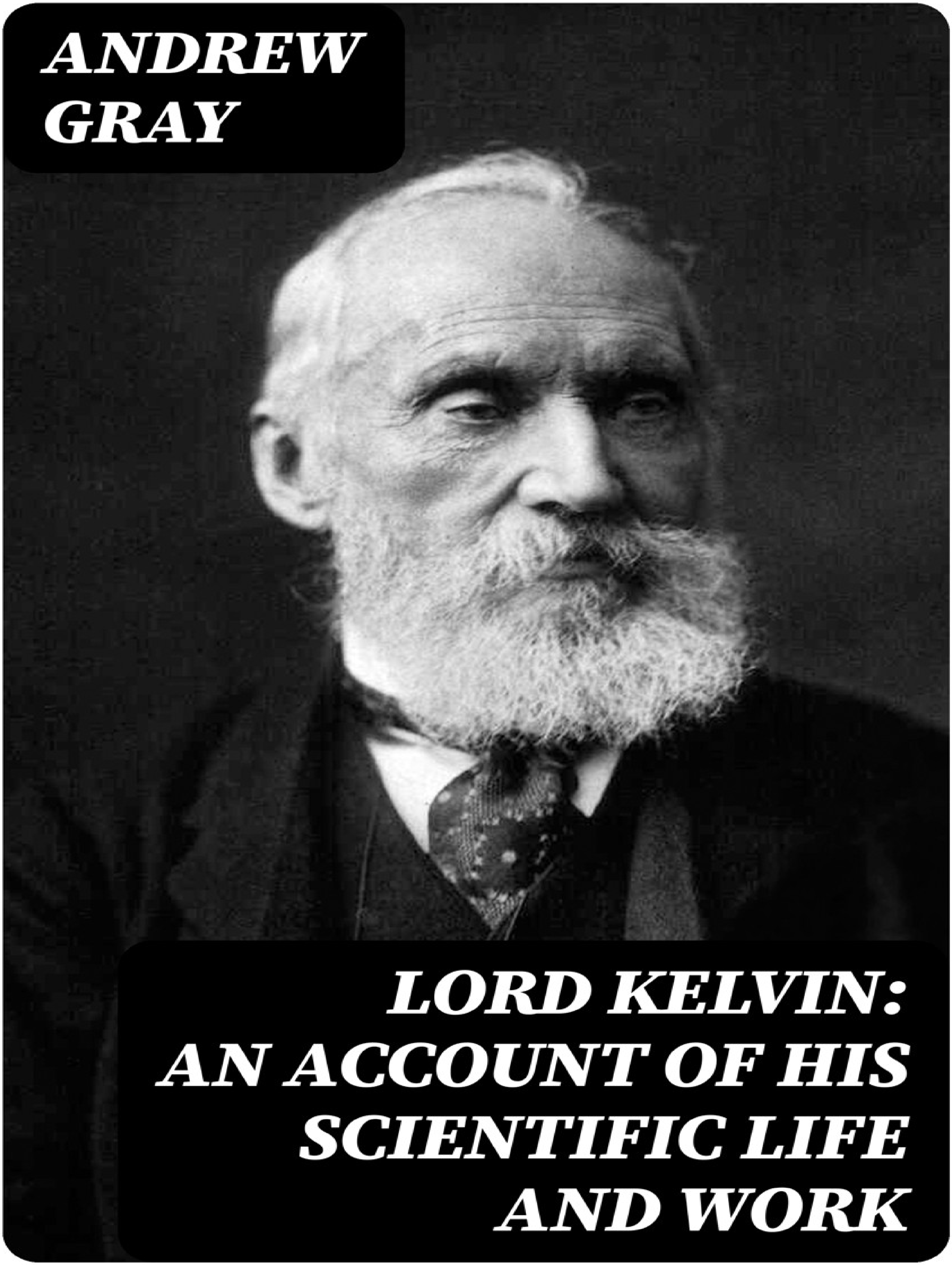
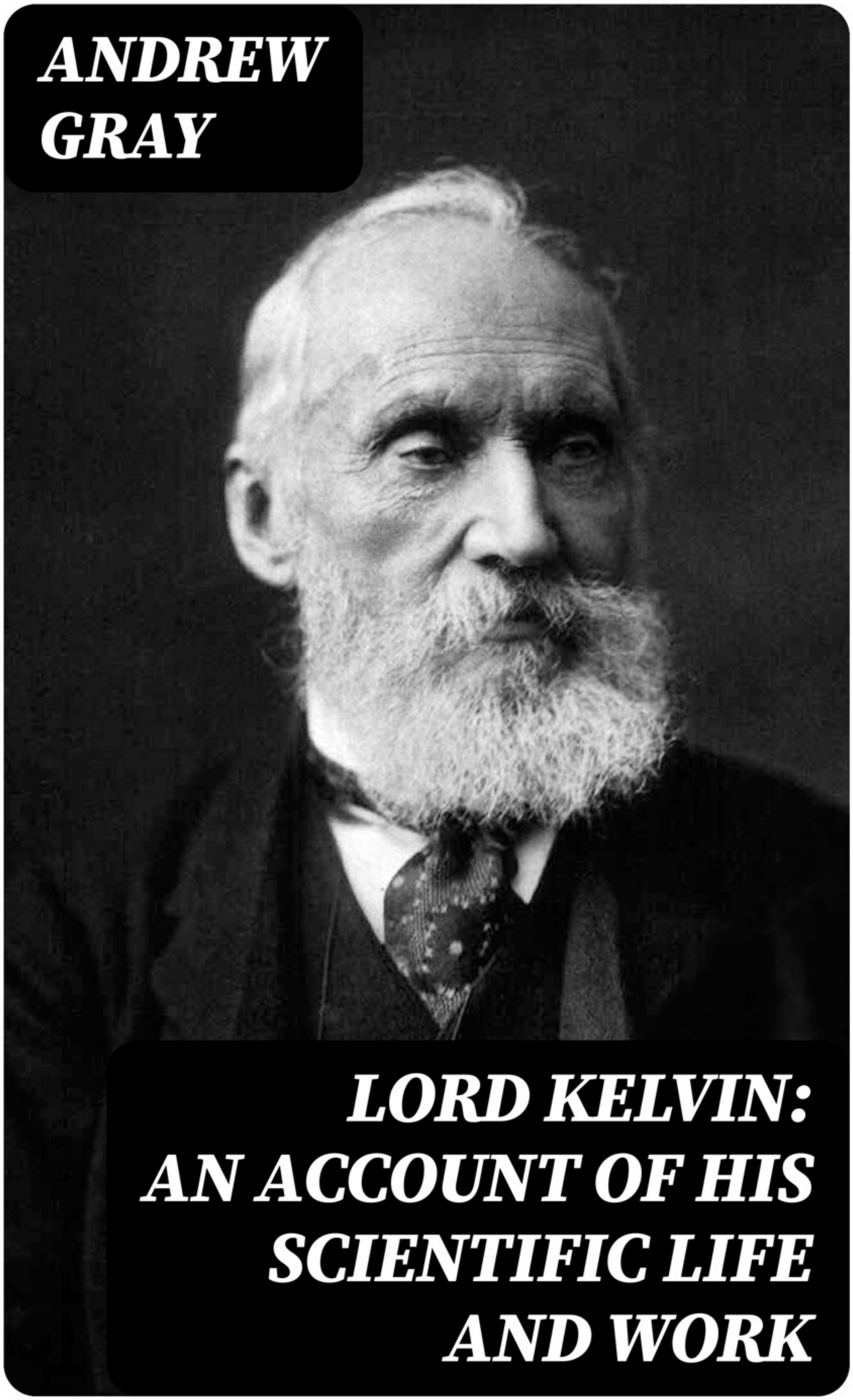


LORD KELVIN: AN ACCOUNT OF HIS SCIENTIFIC LIFE AND WORK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LORD KELVIN:
AN ACCOUNT OF HIS
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AND WORK

Andrew Gray

Lord Kelvin: An account of his scientific life and work

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PREFACE

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This book makes no claim to be a biography of Lord Kelvin in the usual sense. It is an extension of an article which appeared in the *Glasgow Herald* for December 19, 1907, and has been written at the suggestion of various friends of Lord Kelvin, in the University of Glasgow and elsewhere, who had read that article. The aim of the volume is to give an account of Lord Kelvin's life of scientific activity, and to explain to the student, and to the general reader who takes an interest in physical science and its applications, the nature of his discoveries. Only such a statement of biographical facts as seems in harmony with this purpose is attempted. But I have ventured, as an old pupil and assistant of Lord Kelvin, to sketch here and there the scene in his class-room and laboratory, and to record some of the incidents of his teaching and work.

I am under obligations to the proprietors of the *Glasgow Herald* for their freely accorded permission to make use of their article, and to Messrs. Annan, photographers, Glasgow, and Messrs. James MacLehose & Sons, Glasgow, for the illustrations which are given, and which I hope may add to the interest of the book.

A. Gray.

The University, Glasgow,
May 20, 1908.

CORRIGENDUM

Page 105, line 9 from foot, for $\partial e+O$ read $\partial e+o$

LORD KELVIN

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CHAPTER I

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PARENTAGE AND EARLY EDUCATION

Lord Kelvin came of a stock which has helped to give to the north of Ireland its commercial and industrial supremacy over the rest of that distressful country. His ancestors were county Down agriculturists of Scottish extraction. His father was James Thomson, the well-known Glasgow Professor of Mathematics, and author of mathematical text-books which at one time were much valued, and are even now worth consulting. James Thomson was born on November 13, 1786, near Ballynahinch, county Down. Being the son of a small farmer he was probably unable to enter on university studies at the usual age, for he did not matriculate in Scotland until 1810. The class-lists of the time show that he distinguished himself highly in mathematics, natural philosophy, and classics.

An interesting incident of these student days of his father was related by Lord Kelvin in his installation address as Chancellor of the University in 1904, and is noteworthy as indicating how comparatively recent are many of the characteristics of our present-day life and commerce. James Thomson and some companions, walking from Greenock to Glasgow, on their way to join the college classes at the commencement of the session, "saw a prodigy—a black chimney moving rapidly beyond a field on the left-hand side of their road. They jumped the fence, ran across the field, and saw, to their astonishment, Henry Bell's 'Comet' (then not a year old) travelling on the Clyde between Glasgow and Greenock."[1] Sometimes then the passage from Belfast to Greenock took a long time. Once James Thomson, crossing in an old lime-carrying smack, was three or four days on the way, in the course of which the vessel, becalmed, was carried three times by the tide round Ailsa Craig.

Mr. Thomson was elected in 1815 to the Professorship of Mathematics in the Royal Academical Institution of Belfast, and held the post for seventeen years, building up for himself an excellent reputation as a teacher, and as a clear and accurate writer. Just then analytical methods were beginning to supersede the processes of geometrical demonstration which the form adopted by Newton for the *Principia* had tended to perpetuate in this country. Laplace was at the height of his fame in France, and was writing the great analytical *Principia*, his *Mécanique Céleste*, applying the whole force of his genius, and all the resources of the differential and integral calculus invented by Newton and improved by the mathematicians of the intervening century, to the elucidation and extension of the "system of the world," which had been so boldly sketched by the founder of modern physical science.

In that period Fourier wrote his memoirs on the conduction of heat, and gave to the world his immortal book to be an inspiration to the physical philosophers of succeeding generations. Legendre had written memoirs which were to lead, in the hands of Jacobi and his successors, to a new province of mathematics, while, in Germany, Gauss had begun his stately march of discovery.

The methods and results of this period of mathematical activity were at first hardly known in this country: the slavish devotion of Cambridge to the geometrical processes and the fluxional notation of Newton, an exclusive partiality which Newton himself would have been the first to condemn, led analytical methods, equally Newtonian, to be stigmatised as innovations, because clothed in the unfamiliar garb of the continental notation. A revolt against this was led by Sir John Herschel, Woodhouse, Peacock, and some others at Cambridge, who wrote books which had a great effect in bringing about a change of methods. Sir John thus described the effect of the new movements: —"Students at our universities, fettered by no prejudices, entangled by no habits, and excited by the ardour and emulation of youth, had heard of the existence of masses of knowledge from which they were debarred by the mere accident of position. They required no more. The prestige which magnifies what is unknown, and the attractions inherent in what is forbidden, coincided in their impulse. The books were procured and read, and produced their natural effects. The brows of many a Cambridge examiner were elevated, half in ire, half in admiration, at the unusual answers which began to appear in examination papers. Even moderators are not made of impenetrable stuff, though fenced with sevenfold Jacquier, and tough bull-hide of Vince and Wood."

The memoirs and treatises of the continental analysts were eagerly procured and studied by James Thomson, and as he was bound by no examination traditions, he freely adopted their methods, so far as these came within the scope of his teaching, and made them known to the English reading public in his text-books. Hence when the chair of Mathematics at Glasgow became vacant in 1832 by the death of Mr. James Millar, Mr. Thomson was at once chosen by the Faculty, which at that time was the electing body.

The Faculty consisted of the Principal and the Professors of Divinity, Church History, Oriental Languages, Natural Philosophy, Moral Philosophy, Mathematics, Logic, Greek, Humanity, Civil Law, Practice of Medicine, Anatomy, and Practical Astronomy. It administered the whole revenues and property of the College, and possessed the patronage of the above-named chairs with the exception of Church History, Civil Law, Medicine, Anatomy, and Astronomy, so that Mr. Thomson became not only Professor of Mathematics, but also, in virtue of his office, a member of what was really the supreme governing body of the University. The members of the Faculty, with the exception of the Professor of Astronomy, who resided at the observatory, were provided with official residences in the College. This arrangement is still adhered to; though now the government is in the hands of a University Court, with the Senate (which formerly only met to confer degrees or to manage the library and some other matters) to regulate and superintend teaching and discipline.

Professor Thomson was by no means the first or the only professor of the name in the University of Glasgow, as the following passage quoted from a letter of John Nichol, son of Dr. J. P. Nichol, and first Professor of English at Glasgow, amusingly testifies:—

"Niebuhr, after examining a portion of the *Fasti Consulares*, arrived at the conclusion that the *senatus populusque Romanus* had made a compact to elect every year a member of the Fabian house to one of the highest offices of state, so thickly are the records studded with the name of the Fabii. Some future Niebuhr of the New Zealand Macaulay imagines, turning his attention to the annals of Glasgow College, will undoubtedly arrive at the conclusion that the leaders of that illustrious corporation had, during the period of which I am writing, become bound in a similar manner to the name of Thomson. Members of that great *gens* filled one-half of the chairs in the University. I will not venture to say how many I have known. There was Tommy Thomson the chemist; William Thomson of Materia Medica; Allen Thomson of Anatomy, brother of the last; Dr. James Thomson of Mathematics; William, his son, etc., etc. Old Dr. James was one of the best of Irishmen, a good mathematician, an enthusiastic and successful teacher, the author of several valuable school-books, a friend of my father's, and himself the father of a large family, the members of which have been prosperous in the world. They lived near us in the court, and we made a pretty close acquaintanceship with them all."

A former Professor of Natural Philosophy, Dr. Anderson,[2] who appears to have lived the closing years of his life in almost constant warfare with his colleagues of the Faculty, and who established science classes for workmen in Glasgow, bequeathed a sum of money to set up a college in Glasgow in which such classes might be carried on. The result was the foundation of what used to be called the

"Andersonian University" in George Street, the precursor of the magnificent Technical College of the present day. This name, and the large number of Thomsons who had been and were still connected with the University of Glasgow, caused the more ancient institution to be not infrequently referred to as the "Thomsonian University"!

The Thomas Thomson (no relative of the Belfast Thomsons) affectionately, if a little irreverently, mentioned in the above quotation, was then the Professor of Chemistry. He was the first to establish a chemical laboratory for students in this country; indeed, his laboratory preceded that of Liebig at Giessen by some years, and it is probable that as regards experimental chemistry Glasgow was then in advance of the rest of the world. His pupil and life-long admirer was destined to establish the first physical laboratory for such students as were willing to spend some time in the experimental investigation and verification of physical principles, or to help the professor in his researches. The systematic instruction of students in methods of experimenting by practical exercises with apparatus was a much later idea, and this fact must be taken account of when the laboratories of the present time are contrasted with the much more meagre provision of those early days. The laboratory is now, as much as the lecture-room, the place where classes are held and instruction given in experimental science to crowds of students, and it is a change for the better.

The arrival of James Thomson and his family at Glasgow College, in 1832, was remarked at the time as an event which brought a large reinforcement to the *gens* already inseparably associated with the place: how great were to be its consequences not merely to the University but to the world at large nobody can then have imagined. His family consisted of four sons and two daughters: his wife, Margaret Gardner, daughter of William Gardner, a merchant in Glasgow, had died shortly before, and the care of the family was undertaken by her sister, Mrs. Gall. The eldest son, James Thomson, long after to be Rankine's successor in the Chair of Engineering, was ten years of age and even then an inveterate inventor; William, the future Lord Kelvin (born June 26, 1824), was a child of eight. Two younger sons were John (born in 1826)—who achieved distinction in Medicine, became Resident Assistant in the Glasgow Royal Infirmary, and died there of a fever caught in the discharge of his duty—and Robert, who was born in 1829, and died in Australia in 1905. Besides these four sons there were in all three daughters:—Elizabeth, afterwards wife of the Rev. David King, D.D.; Anna, who was married to Mr. William Bottomley of Belfast (these two were the eldest of the family), and Margaret, the youngest, who died in childhood. Thus began William Thomson's residence in and connection with the University of Glasgow, a connection only terminated by the funeral ceremony in Westminster Abbey on December 23, 1907.

Professor Thomson himself carefully superintended the education of his sons, which was carried out at home. They were well grounded in the old classical languages, and moreover received sound instruction in what even now are called, but in a somewhat disparaging sense, modern subjects. As John Nichol has said in his letters, "He was a stern disciplinarian, and did not relax his discipline when he applied it to his children, and yet the aim of his life was their advancement."

It would appear from John Nichol's recollections that even in childhood and youth, young James Thomson was an enthusiastic experimentalist and inventor, eager to describe his ideas and show his models to a sympathetic listener.[3] And both then and in later years his charming simplicity, his devouring passion for accuracy of verbal expression in all his scientific writing and teaching, and his unaffected and unconscious genius for the invention of mechanical appliances, all based on true and intuitively perceived physical principles, showed that if he had had the unrelenting power of ignoring accessories and unimportant details which was possessed by his younger brother, he might have accomplished far more than he did, considerable as that was. But William had more rapid decision, and though careful and exact in expressing his meaning, was less influenced by considerations of the errors that might arise from the various connotations of such scientific terms as are also words in common use; and he quickly completed work which his brother would have pondered over for a long time, and perhaps never finished.

It is difficult for a stranger to Glasgow, or even for a resident in Glasgow in these days of quick and frequent communication with England, and for that matter with all parts of the world, to form a true idea of life and work at the University of Glasgow seventy years ago. The University had then its home in the old "tounis colledge" in the High Street, where many could have wished it to remain, and, extending its buildings on College Green, retain the old and include the new. Its fine old gateway, and part of one of the courts, were still a quaint adornment of the somewhat squalid street in 1871, after the University had moved to its present situation on the windy top of Gilmorehill. Deserted as it was, its old walls told something of the history of the past, and reminded the passer-by that learning had flourished amid the shops and booths of the townspeople, and that students and professors had there lived and worked within sound of the shuttle and the forge. The old associations of a town or a street or a building, linked as they often are with the history of a nation, are a valuable possession, not always placed in the account when the advantages or disadvantages of proposed changes are discussed; but a University which for four hundred years has seen the tide of human life flow round it in a great city, is instinct with memories which even the demolition of its walls can only partially destroy. Poets and statesmen, men of thought and men of action, lords and commoners, rich men's sons and the children of farmers, craftsmen and labourers, had mingled in its classes and sat together on its benches; and so had been brought about a community of thought and feeling which the practice of our modern and wealthy cosmopolites, who affect to despise nationality, certainly does nothing to encourage. In the eighteenth century the Provosts and the Bailies of the time still dwelt among men and women in the High Street, and its continuation the Saltmarket, or not far off in Virginia Street, the home of the tobacco lords and the West India merchants. Their homely hospitality, their cautious and at the same time splendid generosity, their prudent courage, and their faithful and candid friendships are depicted in the pages of Scott; and though a change in men and manners, not altogether for the better, has been gradually brought about by sport and fashion, those peculiarly Scottish virtues are still to be found in the civic statesmen and merchant princes of the Glasgow of to-day. Seventy years ago the great migration of the well-to-do towards the west had commenced, but it had but little interfered with the life of the High Street or of the College. Now many old slums besides the Vennel and the Havannah have disappeared, much to the credit of the Corporation of Glasgow; and, alas, so has every vestige of the Old College, much to the regret of all who remember its quaint old courts. A railway company, it is to be supposed, dare not possess an artistic soul to be saved; and therefore, perhaps, it is that it builds huge and ugly caravanserais of which no one, except perhaps the shareholders, would keenly regret the disappearance. But both artists and antiquaries would have blessed the directors—and such a blessing would have done them no harm—if they had been ingenious and pious enough to leave some relic of the old buildings as a memorial of the old days and the old life of the High Street.

A picture of the College in the High Street has recently been drawn by one who lived and worked in it, though some thirty years after James Thomson brought his family to live in its courts. Professor G. G. Ramsay has thus portrayed some features of the place, which may interest those who would like to imagine the environment in which Lord Kelvin grew up from childhood, until, a youth of seventeen, he left Glasgow for Cambridge.[4] "There was something in the very disamenities of the old place that created a bond of fellowship among those who lived and worked there, and that makes all old students, to this day, look back to it with a sort of family pride and reverence. The grimy, dingy, low-roofed rooms; the narrow, picturesque courts, buzzing with student-life; the dismal, foggy mornings and the perpetual gas; the sudden passage from the brawling, huckstering High Street into the academic quietude, or the still more academic hubbub, of those quaint cloisters, into which the policeman, so busy outside, was never permitted to penetrate; the tinkling of the 'angry bell' that made the students hurry along to the door which was closed the moment that it stopped; the roar and the flare of the Saturday nights, with the cries of carouse or incipient murder which would rise into our quiet rooms from the Vennel or the Havannah; the exhausted lassitude of Sunday mornings, when poor slipshod creatures might be seen, as soon as the street was clear of churchgoers, sneaking over to the chemist's for a dose of laudanum to ease off the debauch of yesterday; the conversations one would have after breakfast with the old ladies on the other side of the Vennel, not twenty feet from one's breakfast-table, who divided the day between smoking short cutty pipes and drinking poisonous black tea—these sharp contrasts bound together the College folk and the College students, making them feel at once part of the veritable populace of the city, and also hedged off from it by separate pursuits and interests."

The university removed in 1871 to larger and more airily situated buildings in the western part of the city. Round these have grown up, in the intervening thirty-eight years, new buildings for most of the great departments of science, including a separate Institute of Natural Philosophy, which was opened in April 1907, by the Prince and Princess of Wales.

CHAPTER II

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CLASSES AT THE UNIVERSITY OF GLASGOW. FIRST SCIENTIFIC PAPERS

In 1834, that is at the age of ten, William Thomson entered the University classes. Though small in stature, and youthful even for a time when mere boys were University students, he soon made himself conspicuous by his readiness in answering questions, and by his general proficiency, especially in mathematical and physical studies. The classes met at that time twice a day—in mathematics once for lecture and once for oral examination and the working of unseen examples by students of the class. It is still matter of tradition how, in his father's class, William was conspicuous for the brilliancy of the work he did in this second hour. His elder brother James and he seem to have gone through their University course together. In 1834-5 they were bracketed third in Latin Prose Composition. In 1835-6 William received a prize for a vacation exercise—a translation of Lucian's *Dialogues of the Gods* "with full parsing of the first three Dialogues." In 1836-7 and 1837-8 the brothers were in the Junior and Senior Mathematical

Classes, and in each year the first and the second place in the prize-list fell to William and James respectively. In the second of these years, William appears as second prizeman in the Logic Class, while James was third, and John Caird (afterwards Principal of the University) was fifth. William and James Thomson took the first and second prizes in the Natural Philosophy Class at the close of session 1838-9; and in that year William gained the Class Prize in Astronomy, and a University Medal for an Essay on the Figure of the Earth. In 1840-1 he appears once more, this time as fifth prizeman in the Senior Humanity Class.

In his inaugural address as Chancellor of the University, already quoted above, Lord Kelvin refers to his teachers in Glasgow College in the following words:

"To this day I look back to William Ramsay's lectures on Roman Antiquities, and readings of Juvenal and Plautus, as more interesting than many a good stage play that I have seen in the theatre....

"Greek under Sir Daniel Sandford and Lushington, Logic under Robert Buchanan, Moral Philosophy under William Fleming, Natural Philosophy and Astronomy under John Pringle Nichol, Chemistry under Thomas Thomson, a very advanced teacher and investigator, Natural History under William Cowper, were, as I can testify by my experience, all made interesting and valuable to the students of Glasgow University in the thirties and forties of the nineteenth century....

"My predecessor in the Natural Philosophy chair, Dr. Meikleham, taught his students reverence for the great French mathematicians Legendre, Lagrange, and Laplace.

His immediate successor in the teaching of the Natural Philosophy Class,5 Dr. Nichol, added Fresnel and Fourier to this list of scientific nobles: and by his own inspiring enthusiasm for the great French school of mathematical physics, continually manifested in his experimental and theoretical teaching of the wave theory of light and of practical astronomy, he largely promoted scientific study and thorough appreciation of science in the University of Glasgow....

"As far back as 1818 to 1830 Thomas Thomson, the first Professor of Chemistry in the University of Glasgow, began the systematic teaching of practical chemistry to students, and, aided by the Faculty of Glasgow College, which gave the site and the money for the building, realised a well-equipped laboratory, which preceded, I believe, by some years Liebig's famous laboratory of Giessen, and was, I believe, the first established of all the laboratories in the world for chemical research and the practical instruction of University students in chemistry. *That* was at a time when an imperfectly informed public used to regard the University of Glasgow as a stagnant survival of mediævalism, and used to call its professors the 'Monks of the Molendinar'!

"The University of Adam Smith, James Watt, and Thomas Reid was never stagnant. For two centuries and a half it has been very progressive. Nearly two centuries ago it had a laboratory of human anatomy. Seventy-five years ago it had the first chemical students' laboratory. Sixty-five years ago it had the first Professorship of Engineering of the British Empire. Fifty years ago it had the first physical students' laboratory—a deserted wine-cellar of an old professorial house, enlarged a few years later by the annexation of a deserted examination-room. Thirty-four years ago, when it migrated from its four-hundred-years-old site off the High Street of Glasgow to this brighter and airier hill-top, it acquired laboratories of physiology and zoology; but too small and too meagrely equipped."

In the summer of 1840 Professor James Thomson and his two sons went for a tour in Germany. It was stipulated that German should be the chief, if not the only, subject of study during the holidays. But William had just begun to study Fourier's famous book, *La Théorie Analytique de la Chaleur*, and took it with him. He read that great work, full as it was of new theorems and processes of mathematics, with the greatest delight, and finished it in a fortnight. The result was his first original paper "On Fourier's Expansions of Functions in Trigonometrical Series," which is dated "Frankfort, July 1840, and Glasgow, April 1841," and was published in the *Cambridge Mathematical Journal* (vol. ii, May 1841). The object of the paper is to show in what cases a function $f(x)$, which is to have certain arbitrary values between certain values of x, can be expanded in a series of sines and when in a series of cosines. The conclusion come to is that, for assigned limits of x, between 0 and a, say, and for the assigned values of the function, $f(x)$ can be expressed either as a series of sines or as a series of cosines. If, however, the function is to be calculated for any value of x, which lies outside the limits of that variable between which the values of the function are assigned, the values of $f(x)$ there are to be found from the expansion adopted, by rules which are laid down in the paper.

Fourier used sine-expansions or cosine-expansions as it suited him for the function between the limits, and his results had been pronounced to be "nearly all erroneous." From this charge of error, which was brought by a distinguished and experienced mathematician, the young analyst of sixteen successfully vindicated Fourier's work. Fourier was incontestably right in holding, though he nowhere directly proved, that a function given for any value of x between certain limits, could be expressed either by a sine-series or by a cosine-series. The divergence of the values of the two expressions takes place outside these limits, as has been stated above.

The next paper is of the same final date, but appeared in the *Cambridge Mathematical Journal* of the following November. In his treatment of the problem of the cooling of a sphere, given with an arbitrary initial distribution of temperature symmetrical about the centre, Fourier assumes that the arbitrary function $F(x)$, which expresses the temperature at distance x from the centre, can be expanded in an infinite series of the form

$$a_1 \sin n_1 x + a_2 \sin n_2 x + \ldots$$

where a_1, a_2, ... are multipliers to be determined and n_1, n_2, ... are the roots, infinite in number, of the transcendental equation $(\tan nX)/nX = 1 - hX$.

This equation expresses, according to a particular solution of the differential equation of the flow of heat in the sphere, the condition fulfilled at the surface, that the heat reaching the surface by conduction from the interior in any time is radiated in that time to the surroundings. Thomson dealt in this second paper with the possibility of the expansion. He showed that, inasmuch as the first of the roots of the transcendental equation lies between 0 and $\frac{1}{2}$, the second between 1 and $\frac{3}{2}$, the third between 2 and $\frac{5}{2}$, and so on, with very close approach to the upper limit as the roots become of high order, the series assumed as possible has between the given limits of x the same value as the series

$$A_1 \sin \tfrac{1}{2}x + A_2 \sin \tfrac{3}{2}x + \ldots$$

where A_1, A_2, ... are known in terms of a_1, a_2, ... Conversely, any series of this form is capable of being replaced by a series of the form assumed. Further, a series of the form just written can be made to represent any arbitrary system of values between the given limits, and so the possibility of the expansion is demonstrated.

The next ten papers, with two exceptions, are all on the motion of heat, and appeared in the *Cambridge Mathematical Journal* between 1841 and 1843, and deal with important topics suggested by Fourier's treatise. Of the ideas contained in one or two of them some account will be given presently.

Fourier's book was called by Clerk Maxwell, himself a man of much spirituality of feeling, and no mean poet, a great mathematical poem. Thomson often referred to it in similar terms. The idea of the mathematician as poet may seem strange to some; but the genius of the greatest mathematicians is akin to that of the true creative artist, who is veritably inspired. For such a book was a work of the imagination as well as of the reason. It contained a new method of analysis applied with sublime success to the solution of the equations of heat conduction, an analysis which has since been transferred to other branches of physical mathematics, and has illuminated them with just those rays which could reveal the texture and structure of the physical phenomena. That method and its applications came from Fourier's mind in full development; he trod unerringly in its use along an almost unknown path, with pitfalls on every side; and he reached results which have since been verified by a criticism searching and keen, and lasting from Fourier's day to ours. The criticism has been minute and logical: it has not, it is needless to say, been poetical.

Two other great works of his father's collection of mathematical books, Laplace's *Mécanique Céleste* and Lagrange's *Mécanique Analytique*, seem also to have been read about this time, and to have made a deep impression on the mind of the youthful philosopher. The effect of these books can be easily traced in Thomson and Tail's *Natural Philosophy*.

The study of Fourier had a profound influence on Thomson's future work, an influence which has extended to his latest writings on the theory of certain kinds of waves. His treatment is founded on a strikingly original use of a peculiar form of solution (given by Fourier) of a certain fundamental differential equation in the theory of the flow of heat. It is probable that William Thomson's earliest predilections as regards study were in the direction of mathematics rather than of physics. But the studies of the young mathematician, for such in a very real and high sense he had become, were widened and deepened by the interest in physical things and their explanation aroused by the lectures of Meikleham, then Professor of Natural Philosophy, and especially (as Lord Kelvin testified in his inaugural address as Chancellor) by the teaching of J. P. Nichol, the Professor of Astronomy, a man of poetical imagination and of great gifts of vivid and clear exposition.

The *Cyclopædia of Physical Science* which Dr. Nichol published is little known now; but the first edition, published in 1857, to which Thomson contributed several articles, including a sketch of thermodynamics, contained much that was new and stimulating to the student of natural philosophy, and some idea of the accomplishments of its compiler and author can be gathered from its perusal. De Morgan's *Differential and Integral Calculus* was a favourite book in Thomson's student days, and later when he was at Cambridge, and he delighted to pore over its pages before the fire when the work of the day was over. Long after, he paid a grateful tribute to De Morgan and his great work, in the Presidential Address to the British Association at its Edinburgh Meeting in 1870.

The next paper which Thomson published, after the two of which a sketch has been given above, was entitled "The Uniform Motion of Heat in Homogeneous Solid Bodies, and its Connection with the Mathematical Theory of Electricity." It is dated "Lamlash, August 1841," so that it followed the first two at an interval of only four months. It appeared in the *Cambridge Mathematical Journal* in February 1842, and is republished in the "Reprint of Papers on Electrostatics and Magnetism." It will always be a noteworthy paper in the history of physical mathematics. For although, for the most part, only known theorems regarding the conduction of heat were discussed, an analogy was pointed out between the distribution of lines of flow and surfaces of equal temperature in a solid and unequally heated body, with sources of heat in its interior, and the arrangement of lines of forces and equipotential surfaces in an insulating medium surrounding electrified bodies, which correspond to the sources of heat in the thermal case. The distribution of lines of force in a space filled with insulating media of different inductive qualities was shown to be precisely analogous to that of lines of flow of heat in a corresponding arrangement of media of different heat-conducting powers. So the whole analysis and system of solutions in the thermal case could be at once transferred to the electrical one. The idea of the "conduction of lines of force," as Faraday first and Thomson afterwards called it, was further developed in subsequent papers, and threw light on the whole subject of electrostatic force in the "field" surrounding an electric distribution. Moreover, it made the subject definite and quantitative, and not only gave a guide to the interpretation of unexplained facts, but opened a way to new theorems and to further investigation.

This paper contains the extremely important theorem of the equivalence, so far as external field is concerned, of any distribution of electricity and a certain definite distribution, over any equipotential surface, of a quantity equal to that contained within the surface. But this general theorem and others contained in the paper had been anticipated in Green's "Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism," in memoirs by Chasles in Liouville's *Journal* (vols. iii and v), and in the celebrated memoir by Gauss "On General Theorems relating to Attractive and Repulsive Forces varying inversely as the Square of the Distance," published in German in Leipzig in 1840, and in English in Taylor's *Scientific Memoirs* in 1842. These anticipations are again referred to below.

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UNIVERSITY OF CAMBRIDGE. SCIENTIFIC WORK AS UNDERGRADUATE

Thomson entered at St. Peter's College, Cambridge, in October 1841, and began the course of study then in vogue for mathematical honours. At that time, as always down almost to the present day, everything depended on the choice of a private tutor or "coach," and the devotion of the pupil to his directions, and on adherence to the subjects of the programme. His private tutor was William Hopkins, "best of all private tutors," one of the most eminent of his pupils called him, a man of great attainment and of distinction as an original investigator in a subject which had always deeply interested Thomson—the internal rigidity of the earth. But the curriculum for the tripos did not exhaust Thomson's energy, nor was it possible to keep him entirely to the groove of mastering and writing out book-work, and to the solution of problems of the kind dear to the heart of the mathematical examiner. He wrote original articles for the *Cambridge Mathematical Journal*, on points in pure and in applied mathematics, and read mathematical books altogether outside the scope of the tripos. Nor did he neglect athletic exercises and amusements; he won the Colquhoun Sculls as an oarsman, and was an active member, and later, during his residence at Cambridge, president of the C.U.M.S., the Cambridge University Musical Society.[6] The musical instruments he favoured were the cornet and especially the French horn—he was second horn in the original Peterhouse band—but nothing seems to be on record as to the difficulties or incidents of his practice! Long afterwards, in a few extremely interesting lectures which he gave annually on sound, he discoursed on the vibrations of columns of air in wind instruments, and sometimes illustrated his remarks by showing how notes were varied in pitch on the old-fashioned French horn, played with the hand in the bell, a performance which always intensely delighted the Natural Philosophy Class.

At the Jubilee commemoration of the society, 1893, Lord Kelvin recalled that Mendelssohn, Weber and Beethoven were the "gods" of the infant association. Those of his pupils who came more intimately in contact with him will remember his keen admiration for these and other great composers, especially Bach, Mozart, and Beethoven, and his delight in hearing their works. The Waldstein sonata was a special favourite. It has been remarked before now, and it seems to be true, that the music of Bach and Beethoven has had special attractions for many great mathematicians.

At Cambridge Thomson made the acquaintance of George Gabriel Stokes, who graduated as Senior Wrangler and First Smith's Prizeman in 1841, and eight years later became Lucasian Professor of Mathematics in the University of Cambridge. Their acquaintance soon ripened into a close friendship, which lasted until the death of Stokes in 1903. The Senior Wrangler and the Peterhouse Undergraduate undertook the composition of a series of notes and papers on points in pure and physical mathematics which required clearing up, or putting in a new point of view; and so began a life-long intercourse and correspondence which was of great value to science.

Thomson's papers of this period are on a considerable variety of subjects, including his favourite subject of the flux of heat. There are sixteen in all that seem to have been written and published during his undergraduate residence at Cambridge. Most of them appeared in the *Cambridge Mathematical Journal* between 1842 and 1845; but three appeared in 1845 in Liouville's *Journal de Mathématiques*. Four are on subjects of pure mathematics, such as Dupin's theorem regarding lines of curvature of orthogonally intersecting surfaces, the reduction of the general equation of surfaces of the second order (now called second degree), six are on various subjects of the theory of heat, one is on attractions, five are on electrical theory, and one is on the law of gravity at the surface of a revolving homogeneous fluid. It is impossible to give an account of all these papers here. Some of them are new presentations or new proofs of known theorems, one or two are fresh and clear statements of fundamental principles to be used later as the foundation of more complete statements of mathematical theory; but all are marked by clearness and vigour of treatment.