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David Olive, who died in Barton, Cambridgeshire, on 7 November 2012, aged 75, was a theoretical physicist who made seminal contributions to the development of string theory and to our understanding of the structure of quantum field theory. In early work on S-matrix theory, he helped to provide the conceptual framework within which string theory was initially formulated. His work, with Gliozzi and Scherk, on supersymmetry in string theory made possible the whole idea of superstrings, now understood as the natural framework for string theory. Olive’s pioneering insights about the duality between electric and magnetic objects in gauge theories were way ahead of their time; it took two decades before his bold and courageous duality conjectures began to be understood. Although somewhat quiet and reserved, he took delight in the company of others, generously sharing his emerging understanding of new ideas with students and colleagues. He was widely influential, not only through the depth and vision of his original work, but also because the clarity, simplicity and elegance of his expositions of new and difficult ideas and theories provided routes into emerging areas of research, both for students and for the theoretical physics community more generally.

CHILDHOOD

David Olive was born on 16 April 1937, somewhat prematurely, in a nursing home in Staines, near the family home in Scotts Avenue, Sunbury-on-Thames, Surrey. He was the only child

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of Lilian Emma (née Chambers, 1907–1992) and Ernest Edward Olive (1904–1944). Ernest worked as a clerk for the Bank of Belgium in the City of London. David believed the Olive family to be of Huguenot origin, although he was unable to establish this definitely. However, the male line of the family could be traced back to the eighteenth century in the London area through his grandfather Thomas Henry Olive (1866–1948), an interior decorator, his great grandfather, William Henry Olive, a publican in Richmond, and William’s father, James John Olive (1797–1869), a brazier and gas fitter.

His maternal grandfather, Frederick McCall Chambers, was a music hall artist, who apparently disappeared mysteriously from the family scene. David had two cousins on his mother’s side and eight on his father’s, but only one of them received a university education and there seems to be no scientific, or particularly intellectual, background in his family.

By 1940, David’s family had moved to Walton-on-Thames, where he began his schooling at a local kindergarten. In 1941, to contribute to the war effort, Ernest resigned his post with the Bank of Belgium and volunteered for service in the Royal Air Force, which left the family in need of income. They moved to a bungalow in Govett Avenue, Shepperton, and Lilian took in a lodger and acquired a part-time job. David briefly attended Shepperton Grammar School before his mother decided in early 1943 that they should move to Edinburgh, partly to escape the bombing raids and partly to be near her mother. There, they lived in rented accommodation in Joppa, a suburb of Edinburgh, eventually taking rooms in the house of Mrs Susan Gage, the widow of the former steward of the Muirfield Golf Club. David struck up a friendship with Leslie, the younger of Mrs Gage’s two sons, even though he was five years older than David. He joined Leslie at the Royal High Preparatory School and their friendship lasted a lifetime.

Late in 1943, Mrs Gage invited the Olives to move with her temporarily into the Muirfield Club House, where she had been invited to stand in for the steward. Ernest joined them there on leave over Christmas. This happy occasion was the last time that David saw his father, because, on 25 February 1944, Ernest died when the Lancaster bomber, on which he was serving as a flight engineer, was shot down over Germany. Lilian, understandably distraught, could not bring herself to give the news that Ernest was missing in action to the six-year-old David and eventually she left a letter announcing his father’s death for David to read. Other disasters followed: the family furniture stored in London was destroyed in a fire, a loss not covered by insurance; a deposit that had been paid on a house being built was forfeited; and, in a particularly cruel stroke, no widow’s pension was forthcoming from the Bank of Belgium because Ernest had resigned his position there to volunteer for the Royal Air Force, rather than waiting to be conscripted.

Soon after the loss of her husband, Lilian decided to return to England, to Birchington in Kent, where David attended Woodford House School, but the move did not last. To get away from the V-1 and V-2 rocket bombs, and also because they found the education at Woodford House inferior to that provided by the Royal High School, David and his mother went back to Scotland in the spring of 1945. Lilian bought a bungalow in Newhailes Avenue, Musselburgh, near Edinburgh, next to friends, Jimmie and Mabel Weatherhead, parents of one of David’s classmates. Jimmie, a local bank manager, was in a position to help, at least with financial advice.

The Royal High School had the further advantage that no fees would be charged provided that David performed sufficiently well academically. This was a condition he had no difficulty in meeting, ending up top of his class every year from 1946 onwards (figure 1). He left the junior part of the Royal High School in 1949 and the senior part in 1955, as Dux (the
leading academic student). He remembered two of the women who taught him as really inspiring: Hilary Spurgeon, who gave David his first science courses, and Letitia Whiteside, who provided extra science classes after hours. But the others were, in his view, lacklustre: the man who taught physics just read from a text book, while the head of science was ‘awful’ (although, it seems he added some colour by standing on a stool at the end of the last lesson of the day and proclaiming, after Horace, *Odi profanum vulgus*). For all this, it was not at school that David found the direction of his future scientific career.

In David’s view, more important than anything he learned at school was the time he spent with his Meccano set, building its little metal ‘girders’, together with nuts, bolts, wheels and gears, into relatively complicated mechanical devices in the form of cranes, lorries, cars, etc., sometimes powered by electric motors. The more complicated, the longer was the time that might be taken for the construction, up to months in some cases. David felt that this
encouraged him later, in his research career, to conceptualize long-term programmes aimed at achieving complicated objectives.

As a teenager, David developed other interests that would stay with him throughout his life. Beginning in 1952, Lilian encouraged David to take an interest in golf. Perhaps the seed had also been sown by that last family Christmas with his father at Muirfield. He joined the local club as a junior member, had lessons with the club professional and became secretary of its junior section. In spite of his love of the game, in his own estimation, David was never very distinguished as a golfer, but a number of his contemporaries at the club became quite well known.

An even more consuming interest, music, which was to become a life-long passion, had its beginnings in these years. This was encouraged by his friend, Leslie Gage, who had a large radiogram. Starting with Beethoven, David soon progressed to Mozart, Berlioz, Delius and many others, both the widely familiar and others rarely heard. He became a great admirer of the conductor Sir Thomas Beecham, and at one Edinburgh Festival he and Leslie Gage managed to slip into the Usher Hall to sit in on some of the great man’s rehearsals.

David left the Royal High School laden with academic honours, including bursaries and scholarships for Edinburgh University. In his farewell speech as Dux of the school, foreshadowing his future intellectual path, he chose to talk about theoretical physics, a subject which already fascinated him.

**Undergraduate Years**

After matriculating at University of Edinburgh in September 1955, David continued to live at home. He began by taking the courses in mathematics, mathematical physics and natural philosophy (as physics was then known there). The mathematical physics lectures took place in the Tait Institute, newly opened in 1955, which had been established for Nicholas Kemmer (FRS 1956). Appointed as Tait Professor in 1953, initially within the natural philosophy (physics) department, Kemmer had found that Norman Feather (FRS 1945), the holder of the more ancient chair of natural philosophy, thought that there was no such thing as theoretical physics, because, in his view, physics was in essence experimental. So, Kemmer had secured an independent institute for theoretical physics. Against this background, when David had to choose two of the three courses he was studying to specialize in for his degree, he decided to drop physics, rather than mathematics or mathematical physics, even though he continued to attend physics lectures throughout his second year.

David found Kemmer’s lectures on hydrodynamics, given without reference to notes, wonderfully, indeed enviably, clear. He also attended lectures by John Polkinghorne (FRS 1974), whose first lecturing post (1956–58) was in the Tait Institute, and who was later to become David’s colleague and collaborator in Cambridge. He continued to excel academically, as he had at school, only held back at times by his nearly illegible handwriting, which caused at least one examiner to mark him down.

A large part of David’s social life centred on the Edinburgh University Physical Society, which organized hiking expeditions in addition to lectures on physics. Through the society and other activities, he met many of his future colleagues and friends, such as Keith Moffatt (FRS 1986), David Fairlie, Jim Mirrlees, Ian Drummond, Ian Halliday, Tom Kibble (FRS 1980) and Alan MacFarlane, all exact or near contemporaries. They were just part of a remarkable
succession of students in theoretical physics and mathematics at Edinburgh at that time, and Kemmer’s charismatic influence inspired many of them to follow research careers in fundamental physics.

A lecturer who sometimes joined the physical society hikes was William Edge, whose specialty was projective geometry. Edge, who was perhaps not completely at home in the twentieth century, encouraged many of the more talented students, including David, to go to Cambridge after graduation from Edinburgh, to follow a path, well-trodden at least since the time of James Clerk Maxwell, of reading the Mathematical Tripos for a second undergraduate degree. In December 1957, before he finished his Edinburgh degree, which he completed in three years rather than the usual four, obtaining first class honours, David competed successfully for an open scholarship at St John’s College, Cambridge, on Edge’s advice.

After Edinburgh, David spent the summer working at Metropolitan Vickers, an electrical engineering company in Manchester, and it was from there he put his trunk on the train to go up to Cambridge in October 1958. As a scholar of St John’s, he was given rooms at C2 Chapel Court, in a part of the college with the relatively modern convenience of a toilet on each staircase, although it was still necessary to cross the court in order to get a bath. In his first year, he studied for Part II of the Mathematical Tripos, then taken by students coming to Cambridge directly from school in either their second or, more commonly, third year, and he again obtained first class honours. Having experienced the intensity of the Cambridge course, he came to feel that he had benefited from the somewhat slower pace of the Scottish system, and he said that this led him to think of himself as Scottish, in spite of having been teased at school for being a ‘sassenach’.

At some point during his first term, he attended a meeting of the Cambridge University Heretics Society, at which, perhaps appropriately enough, the speakers did not show up. David and some other members of the society decided to go out to a pub instead. In this way, David met Jenny Tutton, then in her second year reading mathematics at Girton College, whom he was to marry four and a half years later.

In his second year at St John’s, in order to complete the requirements for the BA degree, which Cambridge allows graduates of other universities to take in two years rather than three, David studied for Part III of the Mathematical Tripos, taking courses by John Ziman (FRS 1967) on solid state physics, Christopher Zeeman (FRS 1975) on algebraic topology, Fred Hoyle (FRS 1957) on general relativity and cosmology, among others. The courses David found most inspiring included one on quantum field theory by John Polkinghorne, who had returned to Cambridge from Edinburgh in 1958, and, especially, two courses on quantum mechanics by Paul Dirac (FRS 1930), whose expositions and contributions to physics were to have a very profound influence on David’s approach to research in theoretical physics. The Part III examinations at the end of the academic year took place at the height of the hay fever season and, perhaps because of this, although David passed, he failed to be awarded a distinction, the mark necessary for an assured place to remain in Cambridge to undertake research for a PhD. Nevertheless, his special talents had been recognized; the Science Research Council awarded him a research studentship and, notwithstanding his somewhat disappointing examination performance, he was allowed to stay on.

David spent his last summer before starting research in Austria. He had obtained a grant from the Austrian Institute to attend a German course at the University of Vienna, which lasted for most of July, but David stayed on until late September. His interest in music had not diminished at all during his undergraduate years and here he had the leisure to attend
many performances at the Vienna State Opera, including the whole Ring cycle and Tristan und Isolde, conducted by Herbert von Karajan, Der Rosenkavalier, Capriccio and (at the Redoutensaal) Cosi Fan Tutte, conducted by Karl Bohm, as well as Aida, conducted by Lovro Von Matacic, as he recorded in the very detailed notes that he kept on the concerts and opera performances he attended over the years.

BEGINNING RESEARCH AT CAMBRIDGE

David began research in October 1960, working within the Department of Applied Mathematics and Theoretical Physics (DAMTP) in Cambridge, which had been established just a year earlier (figure 2).

At first, he had lodgings in Park Parade, but his landlady objected to his habit of playing classical music loudly and he moved to Alpha Road at the end of the term. One term later, he joined D. H. J. (Ben) Garling and Johnson (Joe) Cann (FRS 1995), fellow graduate students at St John’s College, in a flat in Newnham Road. Both Ben and Joe found David to be very
undomesticated; his mother had looked after him so well that he had acquired no practical skills in cooking or housekeeping.

The particle theory research students in DAMTP were housed in the Austin Wing of the old Cavendish Laboratory off Free School Lane in the centre of Cambridge. His contemporaries then included David Bailin and Ian Drummond and, in the year ahead of him, Peter Landshoff. John C. Taylor (FRS 1981), who had just returned to Cambridge from Imperial College, was appointed as David’s research supervisor. Weekly seminars were attended by Paul Dirac, then Lucasian Professor of Mathematics, as well as the other faculty: Richard Eden, John Polkinghorne and John C. Taylor.

Taylor initially suggested to David that he try to find a renormalizable theory of the weak interactions based on Yang–Mills gauge theory. This was an extremely ambitious objective, eventually successfully attained through the work of Glashow, Salam (FRS 1959) and Weinberg (ForMemRS 1981), and of ‘t Hooft and Veltman (for which they received Nobel Prizes in 1979 and 1999, respectively). Convinced by an earlier paper by Salam and Komar (1960) that it was impossible to construct a renormalizable theory of massive gauge particles, David’s interest shifted to what was then the local speciality of studying the analytic properties of perturbative quantum field theory. His first paper (1), written in collaboration with Taylor, early in his second year as a research student, was a contribution to the understanding of the complicated singularity structures that can occur, in particular acnodes and cusps.

From this work, his interest developed towards the then current attempts to formulate an axiomatic theory of the scattering matrix, known as the $S$-matrix, and this was the first area in which David would make important contributions. The leading proponent internationally of this approach was Geoffrey Chew of the University of California at Berkeley, who fortuitously spent the academic year 1962–63 in Cambridge as a visiting fellow of Churchill College.

On 15 April 1963, David married Jenny Tutton at the Catholic church of Our Lady of Perpetual Succour, Belper, Derbyshire, with Joe Cann acting as best man. After a honeymoon in Paris, David and Jenny returned to an upstairs flat in Devonshire Road, near the railway station in Cambridge, convenient for Jenny’s daily journey to work as a mathematics teacher at the Hertfordshire and Essex County High School for Girls in Bishop’s Stortford. [Jenny’s two younger sisters, Rodie and Clare, were also to marry Cambridge theoretical physicists: Rodie married Tony Sudbery, who, after taking his PhD in Cambridge, spent his career in the University of York, and Clare married Ian Drummond, who was to be David’s faculty colleague in DAMTP.]

Just before his PhD examination, conducted by Gordon Screaton and (following the practice then usual in Cambridge) his supervisor, John Taylor, David was elected to a research (i.e. postdoctoral) fellowship at Churchill College, along with Ian Drummond, possibly (as David thought) thanks to the backing of Chew. His doctoral dissertation was entitled Unitarity and $S$-matrix theory.

On 7 September 1963, David and Jenny set sail on the Berlin from Southampton to New York. They travelled on to Pittsburgh to spend the academic year at Carnegie Tech (now Carnegie Mellon University) at the invitation of Dick Cutkosky. It was to be David’s only year away from Cambridge as a postdoctoral fellow. While he was there, David restructured the unpublished paper, ‘Towards an axiomatisation of $S$-matrix theory’, which he had written just before leaving Cambridge, and published it as ‘An exploration of $S$-matrix theory’ (2), an approach to a self-consistent determination of the singularity structure of the $S$-matrix. As well as research life in the physics department and social contacts with its members, the
Olives enjoyed the concerts available in Pittsburgh, and David took the opportunity to acquire new amplifiers, speakers and turntable for his audio system. However, when Jenny became pregnant with their first child, they decided to return to Cambridge, where David’s fellowship at Churchill College would provide accommodation and a secure salary for a few years.

Arriving back in Cambridge in August 1964, David and Jenny moved into a newly built flat at Churchill College. David took part in the social and intellectual life of the college, presided over by its founding Master, Sir John Cockroft (FRS 1936), until his death in 1967. Cockcroft attracted many distinguished physicists to the college as visitors, including Peter Kapitza (FRS 1929), Mark Oliphant (FRS 1937), George Gamow and Murray Gell-Mann (ForMemRS 1978).

On 5 December 1964, Jenny gave birth by Caesarean section to a daughter, Katie, who weighed less than three pounds and spent some weeks in an incubator. With the family growing, and David appointed to an assistant lectureship in the University of Cambridge from October 1965, he and Jenny purchased a house with a sizeable garden in the village of Barton, about five miles from Cambridge, which they continued to own for the rest of their lives and to which they returned in retirement.

In the first months of 1965 David gave his first lecture course, a graduate course on S-matrix theory, based on the paper he had written in Pittsburgh (2). These lectures in turn became the basis for his contribution to the book, *The analytic S-matrix* (3), written together with his Cambridge colleagues, Richard Eden, Peter Landshoff and John Polkinghorne. Completed against a tight timetable in July 1965, and published by Cambridge University Press the following year, the book’s four chapters were each assigned principally to one of the authors, with David contributing the final chapter, S-matrix theory. Exceptionally for a book on particle physics, *The analytic S-matrix*, known affectionately by the initials of its authors, ELOP, has remained in active use as the standard reference on the subject. The first three chapters comprise a general introduction, a discussion of the singularity structure of the Feynman graphs describing the perturbative treatment of quantum field theory, and an account of methods for analysing the high-energy behaviour of Feynman graphs, these two topics being ones to which their respective authors had made important contributions, as David had to S-matrix theory. Characteristically, rather than rely on the material of his co-authors, David’s treatment in the fourth chapter begins practically *de novo*, and so can be read independently of the rest of the book.

Throughout his career, nearly all of David’s research was done in collaboration, often working with a particular colleague periodically for over a decade or more, but he always sought to build up his own understanding of a topic from a set of basic principles or assumptions, which he would analyse and simplify, repeatedly going through the arguments to find the simplest, most elegant and rigorous discussion of the topic.

In 1966, David was promoted to a lectureship in the university, an effectively tenured position, and, on 25 October, Jenny gave birth to their second child, Rosalind. He continued to work on S-matrix theory and extended his interest to encompass the Regge theory of the high-energy behaviour of scattering amplitudes.

In August 1968, he travelled again to Vienna to attend the International Conference on High Energy Physics, the fourteenth in a series of conferences, then held every two years, which brought together leading experimentalists and theoreticians from around the world. As usual, he took full advantage of what was available musically while he was there, including a performance of *The Magic Flute*, with Dietrich Fischer-Dieskau, and a Franco Zeffirelli
production of *La Bohème*, with Renate Holm and Cesare Siepi. But, as he noted (44), it was an unexpected talk given in the marbled ballroom of the Hofburg Palace that was, despite the poor acoustics of the conference location, to change the direction of his research and, soon after, of his life.

The talk, by Gabriele Veneziano, then not quite 26 years old, introduced his soon-to-be famous formula for a two particle scattering amplitude. Veneziano’s objective was to illustrate how analytic properties could be combined with Regge asymptotic behaviour in an explicit mathematical function (Veneziano 1968), but it quickly stimulated attempts at generalization and eventually proved to be the seed that grew into string theory, one of the most influential developments in fundamental physics in the twentieth century, and one in which David was to play a leading role.

Back in Cambridge, David gave a general talk in DAMTP on Veneziano’s work, and remembered being taken aback by Dennis Sciama’s (FRS 1983) prescient suggestion that this might be the start of a new theory. He began collaborating with David Campbell and Wojtek Zakrzewski, then research students, on finding extensions of Veneziano’s formula to the scattering of particles with spin (4–6). While this work did not find a permanent place in the development of the subject, it served to focus David’s interest.

**Moving to CERN**

Early in 1969 David gave a seminar at CERN, Geneva, at the invitation of André Martin, and this motivated David to apply to spend his upcoming term of sabbatical leave there. In September, he and his family began a three-month stay, renting a CERN apartment in Rue du Livron, Meyrin, and taking the opportunity to get to know the Swiss countryside through visits to Chillon, Gruyères, Lauterbrunnen and, particularly, Annecy, nearby in France.

He soon met Daniele Amati, then a CERN staff member, who introduced him to Michel Le Bellac and suggested that the three of them collaborate. Amati was an Italian physicist, with great charisma, who had grown up in Argentina; he had a poster of Che Guevara on his office door and drove a Bentley, which he never locked and readily loaned to David and others in temporary need of a car. Amati had a great talent for stimulating lively research discussions and for encouraging younger physicists, a talent strangely lacking in some of the other staff members in the CERN Theory Division at the time. He was to have a major influence on David.

David wrote two papers (7, 8) with Amati and Le Bellac on the operator formalism for dual models, as the development of Veneziano’s breakthrough had become known. Amati arranged for David’s stay at CERN to be extended by a further three months at the beginning of 1970, for which David took unpaid leave from Cambridge. This time Jenny and their daughters stayed in Cambridge. David took a room in Chemin du Vieux Bureau, Meyrin, and devoted his leisure time to skiing and, as always, music. A recital of Beethoven sonatas by Wilhelm Kempff captivated him and he remained a devotee of the great German pianist for the rest of his life.

The collaboration with Amati and Le Bellac was joined by Victor Alessandrini, a younger Argentinian physicist, and the four agreed to give a series of six lectures on dual models, which then became the basis for an influential review article, ‘The operator approach to dual multiparticle theory’ (9). When he returned to Cambridge, David gave a version of these
lectures in DAMTP during May, which were attended by Ed Corrigan, Peter Goddard, Michael Green (FRS 1989) and, probably, Jeffrey Goldstone (FRS 1977), all of whom went on to make substantial contributions to the subject.

During David’s second term at CERN, Amati raised with him the possibility of his spending a longer time there as a staff member, for three years in the first instance. There was no possibility of obtaining leave from Cambridge for such an extended period under the university’s policies at the time. John Polkinghorne, the leader of the theoretical physics group within DAMTP, made it clear to David that it might be possible for him to return to a faculty position there, but that was by no means guaranteed. As David later put it, he was making an enormous gamble, because he would be giving up a tenured post in Cambridge for a fixed-term one at CERN, but he was prepared to make this sacrifice in order to be able to spend all his time on the theory of dual models, because he thought this might well be the theory of the future.

At the end of June 1971, David left Cambridge to take up what was eventually to be a six-year staff position at CERN. For the first month, he stayed in the hostel on the top floor of the building housing the CERN Theory Division. He quickly met other new arrivals with interests in physics similar to his own, including Lars Brink from Gothenburg, who was just beginning a postdoctoral fellowship and who was to become one of David’s collaborators and a life-long friend. He was joining the group of mainly young theoretical physicists working on dual models that had gathered around Daniele Amati, possibly the largest group in the world working on the subject. It was big enough to sustain a weekly seminar, meeting on Thursdays at 2 pm, with those attending regularly during David’s first year at CERN including Alessandrini, Amati, Brink, Corrigan, Di Vecchia, Frampton, Goddard, Rebbi, Scherk and Thorn.

The atmosphere was informal and collaborative, with a very free exchange of ideas. There was the feeling of participation in a shared enterprise to construct a new and radically different theory, as well as a camaraderie engendered by the active disapproval of many of the senior physicists at CERN and elsewhere. It seemed possible that a fully consistent theory of the strong interactions might be fashioned out of dual models, with the very requirement of consistency narrowing down the range of dual models that should be considered as physically relevant. There was the sense that the theory was thus defining itself, rather than being crafted by those working on it, and it was exciting to see its form, different from quantum field theory, emerge before one’s eyes from within itself. David’s background in S-matrix theory, which provided the conceptual context within which the theory could be defined, together with his ability to find precise, elegant and simple arguments, made it an ideal research area for him.

When David’s family arrived, they moved into a spacious, newly built apartment on the ninth floor at Le Lignon, with expansive views towards the Salève and the Alps beyond. David was to find living in Geneva somewhat of a culture shock for someone brought up in Edinburgh, though a shock that was not completely unwelcome. At a mundane level, he found it a relief not to have his Barton garden to tend and, without the teaching and administrative duties he had had in Cambridge, he was free to concentrate on research while also having time for his usual leisure pursuits. He joined the CERN golf club and purchased a season ticket for the opera and ballet season at the Grand Théâtre in Geneva.

At weekends the family frequently visited the mountains, hiking in summer and skiing in winter, often in the nearby Jura mountains. While Jenny and Katie preferred cross country skiing, David took Rosalind downhill skiing, where he struck a characteristically nice balance
between encouraging adventure and providing reassurance and caution when appropriate. David remained a keen skier past his years at CERN, taking advantage of the opportunities provided by conferences in Les Houches and other mountain resorts whenever he could.

Ed Corrigan, then David’s research student, came to CERN for two months in late 1971, and they worked together on building a consistent dual model that included fermions. At the beginning of the year, Pierre Ramond had introduced fermions into the theory in a way that looked extremely promising (Ramond 1971), and so it was to turn out, but many steps would be necessary to ensure that a full theory could be constructed that did not harbour inconsistencies. Most of David’s efforts in the first half of his six-year tenure at CERN were directed towards this end, working mainly with Lars Brink.

In 1972, through work at CERN and elsewhere, definitive progress was made on determining the physical states occurring in dual models, leading to an understanding of how the picture of dual models as describing the scattering of one-dimensional objects—referred to at the time as ‘rubber bands’, ‘threads’ or ‘strings’, as suggested earlier by Nambu (1969), Nielsen (1969) and Susskind (1970)—could be made precise in terms of the quantum theory of what was now termed a ‘relativistic string’ (Goddard et al. 1973). For some theoretical physicists, who had hoped that dual models would correspond to a more radically different sort of physical system, one that could not be given such a space–time interpretation, this was actually a disappointment, but for David, who had followed these developments closely, it was a stimulating breakthrough and he presented a brief account of it (10) at the sixteenth International Conference on High Energy Physics held at Fermilab, Batavia, Illinois, in the summer of 1972.

Having a detailed description of the physical states of the dual model enabled a precise formulation of the objective of constructing scattering amplitudes in the fermion theory as well as doing the same for the loop contributions that it was necessary to add into the original bosonic dual model of Veneziano. David and Lars Brink constructed the one-loop bosonic loop first (11, 12), realizing this would be a useful technical preparation for calculating fermion amplitudes as well as an important step in itself. After this, he and Lars began a series of papers (13–15) on the fermion theory and other aspects of the physical states in dual theory, with Joël Scherk, who had come to CERN from the École Normale Supérieure in Paris, joining the collaboration (figure 3). This led in October 1973 to David’s calculation, in collaboration with Corrigan, Goddard and Russell Smith, of fermion–anti-fermion scattering (16).

Even as this progress was being made, and while the fascination and promise of dual models, or string theory, as the subject was increasingly being described, remained compelling in the eyes of those working on it, the interests of most physicists was being captured by the ‘standard model’ of particle physics then being developed. In December, David wrote to Goddard: ‘Very few people are now interested in dual theories here in CERN. Amati and Fubini independently made statements to the effect that dual theory is now the most exciting theory that they have seen but that it is too difficult for them to work with. The main excitement [is] the renormalization group and asymptotic freedom, which are indeed interesting.’ It was becoming apparent that the gamble that David had taken in relinquishing tenure at Cambridge to take the staff position at CERN was a real one. As Paolo Di Vecchia has commented, ‘we were so attracted to the beautiful properties of string theory that it seemed a waste to abandon it, but it was clear that, if we had continued [to work on it] for much longer, we would not have been able to get a permanent job’. Indeed, David remembered Amati later warning him that ‘you are unemployable because you do string theory’.
Against this background, the months after the completion of the fermion calculation were a fallow period for David’s research, but he was invited to give a plenary session talk on progress on dual models at the seventeenth International Conference on High Energy Physics, held at Imperial College, London, at the beginning of July 1974. In his review (17), David sought not only to emphasize the conceptual formulation of dual models as a quantum theory of strings but also that dual (or string) theory contained within it electrodynamics, Yang–Mills gauge theory and Einstein gravity. Indeed, as he stressed at the beginning of his talk, consistency demanded that the theory contain massless spin 2, spin 1 and spin 1\(\frac{1}{2}\) particles, corresponding to the graviton, photon and neutrino, as seen in nature. Dual theory, conceived as a theory of strong interactions, ironically had produced from within itself the emerging theories of all the other fundamental interactions, offering the prospect of a unified theory.

### An apparent change of direction

The London conference of 1974 was a turning point in David’s research, not only because of the impact of his review talk, but even more as a result of a talk given by Gerard ’t Hooft on magnetic monopoles in gauge theories (’t Hooft 1974). David later said he did not really understand what ’t Hooft had done until he heard Murray Gell-Mann discuss it during a meeting at the Aspen Center for Physics, Colorado, which took place just after the London conference. This meeting, organized by John Schwarz, brought together many of those then working on string theory for what seemed in retrospect to be just about the last hurrah of the
early years of string theory, before it was eclipsed by the rise of quantum chromodynamics and the standard model. Although, outwardly, the focus of his interests moved on to other subjects, like a number of the early dual model devotees, David’s fascination with string theory never left him, and the major contributions that he made during the remainder of his career, even when they appeared unrelated to string theory, ended up playing a central role in its development down to the present day.

After David returned to Geneva in the autumn of 1974, he began trying to understand the ’t Hooft–Polyakov monopole, as it came to be known following a paper from Alexander Polyakov (1974), which appeared at roughly the same time and covered similar ground to that of ’t Hooft. Indeed, David spent most of his remaining three years at CERN elucidating the structure of monopoles in gauge theories, working initially with Ed Corrigan, who had come back to CERN as a postdoctoral fellow for two years, and with David Fairlie and Jean Nuyts, who joined the collaboration in 1975 (18, 19).

Nuyts had a familiarity with the theory of Lie algebras, and their roots and weights, and in the summer of 1976 he and David began to realize that this part of mathematics provided the appropriate mathematical language for describing magnetic monopoles in general non-abelian gauge theories. Peter Goddard came to CERN as a visitor for the summer of 1976, and their discussions led to the paper ‘Gauge theories and magnetic charge’ (22), which has had a long-term and continuing influence. The magnetic monopoles that David classified with Goddard and Nuyts became known as ‘GNO’ monopoles.

David later recalled how it was while driving with his family to spend some days in Wengen in the Bernese Oberland that the key idea came to him. Just as the electric charges were associated with points on the weight lattice of symmetry group, the magnetic charges were associated with another lattice, the lattice dual to the weight lattice. David realized that this dual lattice was itself the weight lattice of another Lie group, which GNO called the ‘dual group’. In the spring of 1977, Goddard met Michael Atiyah (FRS 1962) at a conference on mathematical education in Nottingham. Atiyah was becoming interested in theoretical physics, though he was not yet familiar with the then recent developments on monopoles in gauge theories. He immediately realized that the GNO dual group was the same as the dual group introduced by Robert Langlands (FRS 1981) within the context of what was known as the Langlands program (Langlands 1970), one of the major developments in pure mathematics in the second half of the twentieth century. However, it was nearly 30 years before the relationship between electric–magnetic duality in gauge theories and Langlands’ duality in the theory of automorphic forms began to be understood in depth.

The magnetic monopoles identified by ’t Hooft and Polyakov, and the generalizations studied by David and his collaborators, are extended objects in a gauge theory, and so have a different status a priori from the electrically charged particles, which are quanta of the fundamental fields in the theory. David formed the bold and prescient vision that there should be a dual formulation of the theory in which magnetic and electric charges and fields interchanged their roles.

When Claus Montonen, who had been David’s graduate student for a year before he left Cambridge, visited CERN in the spring and summer of 1977, David began working with him to find evidence for his duality conjecture. Together they considered the simplest theory containing ’t Hooft–Polyakov monopoles and showed that the spectrum of magnetic
charges of the monopoles was just like that of the electric charges of the fundamental quantum particles of the theory and, moreover, the mass of the monopoles was given in terms of the mass and electric charge of these fundamental particles by exactly the same expression as that relating the fundamental particle mass to the monopole mass and magnetic charge. All this provides evidence for a duality symmetry between electrically charged fundamental particles and magnetic monopoles, which are extended objects in the theory. The electrically charged particles are the massive gauge bosons produced by the Higgs mechanism in the spontaneously broken theory, so David and Montonen conjectured that there was a dual formulation of the theory in which the magnetic monopoles became fundamental particles, the massive gauge bosons associated with a spontaneously broken dual gauge symmetry.

David and Montonen refined their ideas over the months preceding David’s departure from CERN in September 1977, but they felt that several problems remained. Characteristically, David was reluctant to write a paper before he felt that the arguments had reached their most elegant and succinct form. However, they were both convinced that they were on to something, and they drafted a paper, ‘Magnetic monopoles as gauge particles?’ (23), which became one of David’s most famous and influential research contributions; the proposal that it put forward, of the existence of a dual magnetic formulation of a gauge theory, became known as Montonen–Olive duality or the Montonen–Olive conjecture. The formulation of this conjecture exemplified very well David’s extraordinary ability to find precise, elegant and deep relations encapsulating the essence of a physical situation, and build on them a bold imaginative vision of what further structures might await discovery (figure 4).
Last Years at CERN

Although the study of monopoles dominated David’s last three years at CERN, his collaboration with Jöel Scherk drew him again to dual theory for a significant interlude in 1976. At the École Normale Supérieure, Scherk had begun collaborating with a visitor, Fernando Gliozzi, and they had noticed that after making a certain projection in the fermion dual model, which both removed something like half the states and solved one of the model’s problems by eliminating the unwanted tachyon (faster than light particle), the number of fermion states at any given mass equalled the number of boson states, which strongly suggested that the theory was space–time supersymmetric. This projection as a means of removing the tachyon had been discussed informally since 1974, but it had not been realized that it resulted in an equal number of fermion and bosons states. On a visit to CERN to give a talk, Scherk told David about their results. David, who had earlier studied the properties of the Dirac equation in various dimensions of space–time, pointed out to them that the consistency of their projection required this dimension to differ from 2 by a multiple of 8, which fortunately included the space–time dimension 10, which was needed for consistency of the theory for other reasons.

Building on their earlier work together, Scherk invited David to join the collaboration and together David, Gliozzi and Scherk wrote two papers on these ideas (20, 21). In essence, these papers defined what became, following the work of Michael Green and John Schwarz, superstring theory, and the projection has become known as the Gliozzi–Scherk–Olive, or GSO, projection, now one of the cornerstones of string theory.

By 1976 David had come to accept that there was no real prospect of a permanent appointment at CERN and also that no effort was being made in Cambridge to find a tenured post there to which he could return, positions which may seem very difficult to understand given the significance his work was to acquire. David was offered a permanent post at the Niels Bohr Institute in Copenhagen, and he made a number of visits there, but he eventually concluded, for family reasons, that he would prefer to go back to the UK. Then, in 1977, he was offered a lectureship at Imperial College, London, and at the end of September David and his family left Geneva to return to England.

When David later reflected on his time in the Theory Division at CERN, he viewed it as a particularly happy and fruitful period, despite the shadow thrown towards the end by the temporary eclipse of string theory, and the implications that had for his job prospects. It was an exciting time to be there, with inspiring colleagues and a very pleasant atmosphere that was highly conducive to research. He came to regard his last academic year there, 1976–77, with GNO monopoles, the GSO projection and Montonen–Olive duality, as the high point of his research career.

Imperial College

While his family returned to their house in Barton, near Cambridge, which they had let while at CERN, David at first lodged in a house near Kew Station in south-west London, convenient for travel to Imperial. He chose Kew because his father had lived there at one stage and nearby Richmond had family associations. Soon, however, he found a house to buy in Kew, into which he moved in mid March 1978. He spent the weekdays in London, returning to Cambridge at weekends, a pattern he was to follow for much of the next 15 years, except when on leave.
This gave him ample opportunity to follow his musical interests in the evenings, often visiting Covent Garden for the opera and ballet, and the Royal Festival Hall for concerts.

Soon after his arrival at Imperial College, David heard that his paper with Claus Montonen (23) had been accepted for publication. Although this paper was to become famous, David had been unhappy that they had not been able to find tighter arguments, and had worried that it might not be accepted by the journal. He wrote to his collaborator, ‘I am glad Physics Letters accepted our paper without any embarrassment, but further papers must be more solid.’ Later it seemed to Montonen that this raised the bar so high that, in spite of many future discussions, no further papers were ever written.

One day in April 1978, David answered a knock on his office door to find Edward Witten (ForMemRS 1999), then a junior fellow at Harvard, who was visiting Oxford at Michael Atiyah’s invitation. Atiyah had told Witten that he thought there might be something deep in David’s work on monopoles, and advised him to seek David out at Imperial. Witten, who had not come across these papers before, was inclined to be sceptical of very speculative conjectures like that of Montonen–Olive. The key observation supporting the duality conjecture was that the same formula gave both the masses of the elementary electric charged particles and those of the magnetic monopoles, which are extended objects, and Witten could not see how this could survive the renormalization procedure necessary to define the quantum field theory.

It occurred to them in discussion that there was some hope that supersymmetry might provide a rescue. By the end of the day of Witten’s visit, they had understood that the supersymmetry algebra in a supersymmetric quantum field containing monopole solutions is modified by the presence of central charges. They were then able to show that, in the context of certain supersymmetric gauge theories, the supersymmetry algebra actually implies the Montonen–Olive mass formula, so that the prime result motivating the duality conjectures necessarily holds in suitable theories with supersymmetry.

The joint paper (25) that they wrote was to become another of David’s most influential contributions. Witten much later remarked that, although he was very pleased with the result, with hindsight he could see that he drew the wrong conclusion from it. In effect using Occam’s razor, he took the fact that supersymmetry implies the Montonen–Olive mass formula to remove the need for any deeper explanation, such as duality. It was not until the work of Ashoke Sen (FRS 1998) showing the existence of certain two monopole states in $N=4$ supersymmetric gauge theories (Sen 1994), predicted by Montonen–Olive duality, that Witten became convinced of the depth and importance of the conjecture and, in large part through his influence, it made a seminal contribution to the reconceptualizing of string theory in the mid 1990s, in what has become known as ‘the second superstring revolution’.

During his time at Imperial, David would usually go back at weekends to the house he and Jenny had kept in Barton, near Cambridge, and on Saturday mornings he would often meet with Peter Goddard, by then a lecturer in DAMTP, to discuss physics in Goddard’s office. These discussions provided the basis for a continuing collaboration that lasted from the late 1970s to the early 1990s. Soon after David moved to Imperial, they completed a review on ‘Magnetic monopoles in gauge field theories’ (24), which provided a systematic account of the ideas David had been centrally involved in developing in the previous four years. For some years thereafter, David was much in demand as a review speaker on this subject at conferences and summer schools (figures 5 and 6).
In his first years at Imperial, David’s research mainly focused on studying magnetic monopole solutions to spontaneously broken gauge theories in greater detail, in particular the conditions on their charges for their stability, finding further circumstantial evidence for the Montonen–Olive duality conjectures (26, 27). In general, the nonlinear equations describing magnetic monopoles cannot be solved exactly in closed form, but it had been found that if attention is restricted to spherically symmetric solutions in an appropriate limit, the equations become integrable. Leznov and Saveliev (1980) had observed that where the gauge symmetry group is SU($N$), the equations are just those associated with the (finite) lattice of particles in a line interacting through suitable nonlinear springs introduced 15 years earlier by Morikazu Toda (1967). For a general (semisimple) gauge symmetry group, $G$, the equations can be characterized in terms of the Dynkin diagram of $G$, which encodes the group’s structure (28).

The way the study of spherically symmetric monopoles brought together solutions to gauge theories, the theory of Lie algebras and integrable systems struck David as deep and important. It was the initial motivation for his continuing interest in the Toda equations and their algebraic properties, a subject he returned to repeatedly over the next dozen years. At Imperial, David could easily attract and take on graduate students, in a way that had not been possible at CERN, and his work on Toda theories and other research was done in collaboration with a succession of current and former students, including Regina Arcuri, Luiz Ferreira, Andreas Fring, Frank Gomes, Marco Kneipp, Peter Johnson, Jonathan Underwood and, most notably, Neil Turok.
Turok, who was later to hold professorships in both Princeton and Cambridge before becoming the director of the Perimeter Institute in Waterloo, Ontario, started as David’s research student in 1980. Over the following 13 years he wrote a series of influential papers with David on Toda field theories (e.g. 29, 32, 39).

**Leave in Charlottesville**

When David went on leave to the University of Virginia in Charlottesville in 1982–83, he took Neil Turok with him, carrying on their work on Toda theories. In Charlottesville, David gave a course of graduate lectures on the theory of Lie algebras, the mathematics that had underlain his seminal work on magnetic monopoles, but otherwise he used the freedom of his visiting appointment to develop the ideas that he had been evolving over some years in collaboration with Peter Goddard, who joined him there for some months at the beginning of 1983. Through discussions with Graeme Segal (FRS 1982) in Oxford and others, they had become aware that evidence of deep connections had begun to emerge between string theory and the theory of Kac–Moody algebras, a mathematical theory that had been initiated in 1967 by Victor Kac (1967) and Robert Moody (1967), coincidentally just about when the seeds of string theory were being sown by Veneziano’s famous paper.

Around 1980, mathematicians realized that, in constructing representations of Kac–Moody algebras, they had rediscovered the vertex operators that physicists had been using to describe
the interactions of strings. The connection to the formalism of dual models was spelled out by Igor Frenkel and Victor Kac (Frenkel & Kac 1980) and by Segal (1981). The algebraic properties of these vertex operators had already featured prominently in work of both David and Goddard, and had been a central tool in understanding the structure of dual models and their detailed interpretation as string theory. Together in Charlottesville, and stimulated by what they had learned in the context of magnetic monopoles about the weight and root lattices of Lie algebras, David and Goddard studied how the vertex operator construction could be used to associate a Lie algebra to each integral lattice (i.e. a lattice such that the scalar product of any two lattice points is an integer). The nature of the Lie algebra so defined depended on whether the lattice is Euclidean or has some other signature. Although it seemed clear that these results should have some role to play in string theory, by producing symmetries of the spectrum, for example for strings moving in a space in which some of the dimensions have been compactified to form a torus formed by assuming periodicity under displacements corresponding to the lattice, at first sight there seemed to be obstacles to using this to incorporate symmetry into string theory in a realistic way.

David and Goddard paid particular attention to even self-dual lattices, in part because of their connection to modular invariance, which had already proved important in string theory. They noted that, in the Euclidean case, these lattices only existed in dimensions that were multiples of 8. In dimension 8, there was only one, the root lattice of the group $E_8$, while in dimension 16, there were two, the root lattice of $E_8 \times E_8$ and a sublattice of the weights of the Lie algebra of $SO(32)$. This observation proved prescient because just over a year later, in the autumn of 1984, the 16-dimensional even self-dual Euclidean lattices, and the associated vertex operator construction of Kac–Moody algebras, were to play a key role in the developments that led to the dramatic revival of interest in string theory.

When Igor Frenkel visited Charlottesville in March 1983, David and Goddard were able to discuss their results with him and they discovered a strong overlap with results he had recently obtained. Frenkel arranged for them to be invited to speak at the conference on Vertex Operators in Mathematics and Physics that was held the following November in Berkeley at the recently established Mathematical Sciences Research Institute. Afterwards they circulated the paper, ‘Algebras, lattices and strings’ (30), which they had prepared for the proceedings and which was then influential in introducing many physicists to Kac–Moody algebras and their construction in terms of the vertex operators of string theory.

**Coset construction and conformal field theory**

At the Berkeley conference David and Goddard also learned, from the talk of Daniel Friedan, about his work with Qiu and Shenker and about the then unpublished work of Belavin, Polyakov and Zamolodchikov on conformal field theory and the representations of the Virasoro algebra. The Virasoro algebra is the Lie algebra of the conformal symmetry group and plays a central role both in string theory and in conformal field theory; indeed, in a sense, conformal field theory describes the structure of string theory. Friedan, Qiu and Shenker (FQS) had established necessary conditions for a representation of the Virasoro algebra to be unitary, showing that there was a continuum and an infinite discrete series (Friedan *et al*. 1984), but, apart from the two representations corresponding to a free fermion and to a free boson, a construction, or even a proof of existence, of the rest of the discrete series was wanting.
In 1983 David returned to Imperial, after he and his family had spent some weeks in the summer at the Aspen Center for Physics, and he had resumed his Saturday meetings with Peter Goddard. The following spring their discussions focused on a recent paper of Edward Witten (1984), ‘Non-abelian bosonization in two dimensions’, which demonstrated an equivalence between certain boson theories associated with Lie groups, now called Wess–Zumino–Witten (WZW) theories, and certain free fermion theories, by exploiting the equivalence of representations of isomorphic Kac–Moody algebras contained in the two theories. Looking for general conditions under which Witten’s equivalence might hold, they sought to demonstrate that the energy-momentum tensors of the boson and fermion theories were the same. In such two-dimensional theories, the moments of energy-momentum tensor generate the conformal symmetry of the theory, and they provide a representation of the Virasoro algebra. The aim of David and Goddard was to determine when the representations of the Virasoro algebra in the two theories were equivalent because this would be a necessary condition for the complete equivalence of the theories.

They spent some weeks working together at the Aspen Center for Physics in the summer of 1984, and found many instances where the two energy-momentum tensors differed. However, they realized that the difference between them was often very interesting. The boson theory could always be imbedded within the fermion theory and the question of equivalence was whether it was, in effect, all of that theory: subtracting the boson energy-momentum tensor from the fermion one gave zero if the theories were equivalent but otherwise the difference was itself an energy-momentum tensor, and in a sense described what was needed to be added to the boson theory to yield the full free fermion theory. The difference provided a representation of the Virasoro algebra, one which commuted with the boson representation of the Virasoro algebra, such that their sum equalled the fermion representation. Further, explicit calculation showed that in many instances these ‘difference’ Virasoro representations provided missing representations from the discrete series of FQS, thus proving their existence and giving an explicit construction in these cases.

They (31) did not manage to construct the whole of the infinite discrete series while in Aspen, but on their return to England they explained what they had done to Goddard’s research student, Adrian Kent, and together they generalized the construction by replacing the fermion theory and considering instead a WZW theory associated with a Lie group, $G$, and the theory contained within it associated with a subgroup, $H$, of $G$. Any such pair, $H \subset G$, defines a Virasoro representation given by the difference of the Virasoro representations associated with the $G$ and $H$ theories. David, with Goddard and Kent, associated this representation with the coset $G/H$ and it has become known as the coset or GKO construction (33, 35). They were able to show that all the representations of the FQS discrete series could be obtained in this way, thus completing the classification of unitary representations of the Virasoro algebra. The WZW theory associated with a Lie group $G$ is a conformal field theory and, for $H \subset G$, the coset construction associates a conformal field theory associated with $G/H$ with the corresponding energy-momentum tensor. This coset construction has remained one of the main ways of constructing and characterizing conformal field theories.

The following year, 1985, in collaboration with Werner Nahm and Goddard, David succeeded in solving the original problem from which they had been fruitfully diverted by the coset construction, by showing that the condition for the fermion theory in Witten’s non-abelian bosonization to be equivalent to a WZW theory was that the fermions should transform
according to a representation of $G$ that could be used to extend it to form a larger group, $G'$, in such a way that the pair define what is called a symmetric space (34).

REVIVAL OF STRING THEORY

Also at Aspen in the summer of 1984 were Michael Green and John Schwarz, who were studying anomaly cancellations in supersymmetric gauge theories coupled to gravity in the hope of establishing that, under suitable conditions, string theory might satisfy this consistency requirement. They first found that the cancellation occurred for the gauge group with the Lie algebra of $\text{SO}(32)$, provided that its weights lay on the lattice which is even and self-dual, and then they realized that it also holds for $\text{E}_8 \times \text{E}_8$ (Green & Schwarz 1984). Aware that these two groups had been singled out by David and Goddard a year before in their paper ‘Algebras, lattices and strings’ (30), they sought to construct a string theory with $\text{E}_8 \times \text{E}_8$ symmetry, unknown at the time, based on ideas from that paper on the incorporation of symmetry into string theory using Kac–Moody algebras. But further ideas were necessary about treating left and right moving waves on closed strings very differently, which came with the construction by Gross, Harvey, Martinec and Rohm (Gross et al. 1985) of what they called the heterotic string.

It was these developments, initiated by the work of Green and Schwarz and promulgated through the unique influence of Edward Witten, that gave rise to the renaissance of interest in string theory beginning in 1984. In them, Kac–Moody algebras, and two-dimensional conformal field theory more generally, played a key role. As David continued working with Peter Goddard, Werner Nahm, Adam Schwimmer and others on conformal field theory and related infinite-dimensional algebras, the mushrooming interest in string theory meant that he was much in demand as a lecturer at conferences and summer schools. This prompted him to write a long pedagogical review, ‘Kac–Moody and Virasoro algebras in relation to quantum physics’ (36), in collaboration with Peter Goddard, which was widely read and has remained a standard reference. Alongside his work on conformal field theory, David continued to make contributions to Toda field theory with Turok and many of his other students. With a postdoctoral fellow, Michael Freeman, he also returned to the basic calculation of the one-loop contribution in bosonic string theory, using the Becchi–Rouet–Stora (BRS) formalism to simplify his earlier work with Lars Brink (37, 38).

From the mid 1980s, David began to receive long overdue formal recognition of his achievements. He had been made a reader at Imperial in 1980 at the age of 43, and four years later he was promoted to a professorship of theoretical physics. In 1987, he was elected a Fellow of the Royal Society in recognition of his contributions to $S$-matrix theory, dual models, the classification of magnetic monopoles in gauge field theories and on the concept of electric–magnetic duality.

David spent the academic year 1987–88 as a member of the Institute for Advanced Study in Princeton. When he returned to Imperial, he became head of the theoretical physics group, but the administrative duties of this post did not really suit his temperament. He discharged his responsibilities perhaps too meticulously, even down to counting out rations of photocopying paper for students when there was a funding crisis. The very qualities of mind, the almost obsessive need to resolve possibly tell-tale discrepancies in understanding, that led to David’s remarkably original and prescient research, nearly drove him and those
around him to distraction when he tried to reconcile, down to the last penny, the different financial systems Imperial deployed at the group, department and college levels. When a new administrator with some understanding of accounts arrived to support the group, it was not only David who was enormously relieved.

**Swansea and later years**

In 1991, when the University College of Wales Swansea was seeking to fill a chair in physics, Dean of Science Aubrey Truman, a mathematical physicist, argued in favour of appointing a theoretical physicist, particularly in view of the fertile cross connections with mathematics that had developed in the previous two decades. Truman had got to know David when David had served on the scientific advisory committee for the International Congress of Mathematical Physics that had taken place in Swansea in 1988. They had both been research students of J. C. Taylor, David in Cambridge and Truman later in Oxford, and, although they had not met, Truman had long admired David’s contributions to S-matrix theory as well as his later work. He approached David about the vacant chair and was delighted when he expressed an interest in moving from Imperial to Swansea.

It turned out that David’s colleague at Imperial, Ian Halliday, was also attracted by the idea of moving to Swansea. At the time, the future of the Swansea physics department had looked quite uncertain, and the vice chancellor, Brian Clarkson, became interested in the idea of recruiting David and Halliday as the nucleus of a theoretical particle physics group that might substantially raise the international standing of the department. The plan was formed to appoint David as a research professor in the Department of Mathematics and Halliday in the Department of Physics, with the group they were to lead linking the two departments. However, this initial arrangement did not last because there were tensions with some other members of the Department of Mathematics. David was not a political animal and he just got very agitated when he thought others were not behaving straightforwardly. As a result, the idea of linking the two departments was abandoned and the whole group moved to physics.

David demonstrated his characteristic carefulness in the negotiations with the university over the group’s move. Here, his meticulousness proved an asset because he ensured that every last promised provision was written out in exquisite detail in letters signed by the vice chancellor, which proved extremely useful to the group in ensuring that commitments were kept. David was very engaged in the whole development of the new group and his presence was a decisive factor in the recruitment of a number of outstanding young lecturers, Nick Dorey, Tim Hollowood, Warren Perkins and Graham Shore, soon followed by others. The new group brought highly valuable recognition to the physics department at a time when pure science was being cut in universities such as Swansea; the ranking of the Department of Physics improved dramatically. The group David and Halliday created, now with a strength of about 12 faculty members, has continued to thrive over the last 25 years as one of the leading theoretical particle physics groups in the UK.

David had spent the second half of 1992 participating in one of the first programmes at the Newton Institute in Cambridge. When the Olives moved to Swansea at the beginning of 1993, they retained their home in Barton, near Cambridge. Although Jenny may have made the move somewhat reluctantly, she continued to support David in his work, even helping with the production of diagrams for his public lectures (figure 7). She also helped new physics
students in the university who were having difficulties with basic mathematics. She shared the techniques she had developed for this with a wider audience in her book, *Maths: A Student’s Survival Guide* (Olive 1998).

David had had four Brazilian research students, Regina Arcuri, Luis Ferreira, Frank Gomes and Marco Kneipp. In these years he made a number of visits to Brazil, with Jenny sometimes accompanying him, to participate in workshops, research schools, etc., contributing to furthering the development of theoretical physics in the country. He developed a strong interest in Brazilian culture, particularly the food and the music. He loved to have lunch in the restaurants close to the Paulista Avenue in São Paulo, where one pays by the weight of the food taken from a generous buffet. Characteristically, David developed models for how to get best value for money. But it was Brazilian music that most engaged him, from Villa-Lobos to much less known composers such as Lorenzo Fernandez. He became extremely interested in a recording of Fernandez’s music by the Amazonia Quartet, but it seemed that it was sold out in São Paulo and had been discontinued. However, he tracked it down to a small shop in a distant part of the city and so acquired a rare CD, of which he was very proud.

Further public recognition of David’s achievements came with the award in 1997 of the Dirac Prize and Medal of the International Centre for Theoretical Physics (ICTP) in Trieste (see figure 8), shared with Peter Goddard, ‘in recognition of their far-sighted and
highly influential contributions to theoretical physics’. The announcement further cited their contribution of ‘many crucial insights that shaped our emerging understanding of string theory and have also had a far-reaching impact on our understanding of 4-dimensional field theory’, and went on to explain: ‘Olive’s work on space-time supersymmetry of the spinning string theory (with F. Gliozzi and J. Scherk) made possible the whole idea of superstrings, which we now understand as the most natural framework for supersymmetry and string theory. Goddard and Olive introduced key ideas about the use of current algebra in string theory which were very important in the subsequent discovery of attractive ways to incorporate space-time gauge symmetry in string theory, thus making it possible for string theory to incorporate the standard model of particle physics. These discoveries, made in the years 1973–83, were among the most crucial steps in making possible the “superstring revolution” of 1984–5. The “second superstring revolution” of the last few years has been equally dependent on pioneering insights about magnetic monopoles made in 1977 by Goddard, Olive, and J. Nuyts, and further extended by Olive and C. Montonen. Their ideas concerning a dual interpretation of magnetic charge, and then about electric-magnetic duality in non-abelian gauge theory, were way ahead of their time and have proved to have a far-reaching importance, which we are only now beginning to understand, in governing the dynamics of four-dimensional field theory and of superstring theory.’

The ‘second superstring revolution’, to which the Dirac Medal citation referred, was initiated by the work of Nathan Seiberg and Edward Witten (Seiberg & Witten 1984a, 1984b). Central to it was the generalization of Montonen–Olive duality to string theory, in the form...
David Ian Olive

of S-duality, and its extension to a modular group of dualities by the work of Ashoke Sen (1994). After 20 years, it had at last been realized widely how visionary David’s work on monopoles in the mid 1970s had been. These developments rekindled David’s own interest in electromagnetic duality. With Pierre Van Baal and Peter West (FRS 2006), David organized a programme at the Newton Institute on Non-Perturbative Aspects of Quantum Field Theory, centred on ideas of duality and supersymmetry, in the first six months of 1997 (40). His deep and beautifully clear expositions of electromagnetic duality and its generalizations became in demand at conferences and graduate schools. With Marco Alvarez, who had joined him as a postdoctoral fellow in Swansea, in some of his last work, David characteristically sought a deeper understanding of the quantization of magnetic flux, by considering gauge theories on smooth four-dimensional manifolds of arbitrary topology. They found that the quantization of fluxes in these theories provided a physical interpretation of some mathematical concepts, such as the Stiefel–Whitney classes (41–43).

David received national recognition at the beginning of 2002 in the UK New Year Honours with his appointment as Commander of the Order of the British Empire for services to theoretical physics, and in 2007 he was made a foreign member of the Royal Society of Arts and Sciences in Gothenburg, Sweden. In many ways, David enjoyed his time in Swansea more than his years at Imperial, which were made somewhat fraught by commuting on crowded trains and having to lecture to very large audiences of students. With his colleague, Colin Evans, David began to compile a history of the Swansea Department of Physics and he became an expert on the history of Welsh science, particularly in relation to the history of cosmic rays, operations research, radar, the atomic bomb and the Internet. He was a founding fellow of the Learned Society of Wales in 2010, and a strong supporter of it.

In the last six years of his life David suffered from increasingly poor health as a result of heart disease. He and Jenny first became aware of a problem when David became exceedingly tired when they were walking in the Lauterbrunnen Valley. Later, his golfing partner, a physician, advised him to consult his doctor because of the difficulties he was experiencing while they were playing. His deteriorating heart condition led eventually to kidney failure, but the weakness of his heart meant that dialysis was not possible. Through his last years, David remained mentally engaged and, in spite of his difficulty in walking any distance, he continued to travel for special occasions and conferences up to a few months before his death.

In late October 2012, David’s health suddenly deteriorated further and he and Jenny realized that he was gravely ill. One kidney had failed and efforts to keep the other kidney working were proving ineffective. His doctors concluded that nothing more could be done. David, then in hospital, phoned Jenny and told her in a rather matter of fact way that he was finally being allowed to come home for palliative care, because no further treatment would be effective. As was then expected, he only had a week to live, during which he showed grace and courage as he received many greatly appreciated telephone calls and emails from physicists and mathematicians around the world who had heard about his condition.

David died on 7 November in the house in King’s Grove, Barton, that he and Jenny had owned since 1965. At his funeral service 12 days later, the village’s fourteenth-century parish church, St Peter’s, was full with David’s friends, colleagues and relatives. David did not have a religious belief, but the kindly vicar told the congregation that we could be sure that David was now in a place where there were no more physics problems to worry about, not aware that that would have been no paradise at all for David. Following his wishes, he was buried in the village churchyard.
INTERESTS, PERSONALITY AND INFLUENCE

David had a wide range of interests, but his life-long love of music was exceptional. From his youth, he built up an outstanding collection of long playing (LP) records, which were gradually replaced from the mid 1980s onwards by an even more extensive collection of over 4000 CDs, housed in nine cabinets that he had constructed personally with great care and skill. He carried over from his LP collection his practice of meticulously making a note on the sleeve of each time he played a recording, in part to assess wear.

He had an encyclopedic knowledge of music, and of his collection of recordings in particular, which often astonished his friends and colleagues. Adam Schwimmer, who grew up in the little-known town of Grosswardein-Oradea in Transylvania, recalled a characteristic incident illustrating both the depth of David’s musical knowledge and his particular sense of humour: one evening David produced from one of his CD cabinets a recording of symphonies by Michael Haydn, Joseph’s much less famous younger brother, played by the Oradea Philharmonic in what Schwimmer described as an awful performance. David knew that Michael Haydn had been the court composer of the Bishop of Grosswardein, Schwimmer’s home town, and he had in his collection the only available recording of his works.

David’s notes on and knowledge of the concerts and opera performances he had attended over the years paralleled, even rivalled, the notes he made setting out his evolving understanding of his investigations in theoretical physics. Filed in numerous loose leaf folders, and annotated with underlinings in various colours and styles, which he did not even attempt to explain to others, these notes were written and rewritten as he sought an ever deeper and clearer understanding of the topic at hand, whether this was an established branch of mathematics or a new physical theory. In either case, he would strive to gain his own understanding, one that met his own exacting standards of concision and clarity, often producing novel insights into existing theories.

David’s frequent comment was ‘I think we can understand this better’, but, even when sceptical of an idea, he would not simply dismiss it but rather look for ways in which it might make sense. He was always seeking mathematically deep, elegant equations that encapsulated physical ideas. It was quite evident that his approach emulated naturally that of his great intellectual hero, Paul Dirac, whose lectures he had attended as a student at Cambridge.

The many files of handwritten notes that he amassed seemed an end in themselves for him, a record and reference for what he had understood. They would form the basis for his research publications, his lecture notes and his reviews, and their honing underpinned David’s exceptionally clear expository style, but he would be very reluctant to publish a result before he was convinced that the argument was sufficiently clear, sometimes to the frustration of his colleagues. He was justifiably proud of the seminal contributions that he had made to theoretical physics, but he never had a desire to rush into print to seek priority on an idea that had not yet been elucidated to his own personal satisfaction. Although he was determined to understand everything himself de novo, he readily shared the results of his endeavours with others.

The openness and generosity with which David would share his new ideas and insights with his collaborators, colleagues and students was in amusing contrast to the minute care with which he would dissect the bill for a meal shared with a colleague, for example in one of the Indian restaurants he loved in London, evoking the cultural stereotype of a Scotsman.
The leather briefcase, acquired as a schoolboy at the Royal High School, Edinburgh, was retained until nearly the end of his career. Progressively disintegrating, but kept in service by David’s own highly imaginative repairs performed with characteristic economy (e.g. by use of bits from an old Fairy Liquid bottle to mend the handle), it provided an outward symbol of David’s ingenuity and endearing frugality and it was only abandoned with the greatest reluctance in his later years (figure 8).

For some years, his entry in Who’s Who seemed to contain a perhaps Freudian reference to his concern to conserve financial resources: his interests were listed there as ‘music and gold’, the latter a misprint occasioned by his at times almost illegible handwriting; eventually it was corrected to ‘golf’, the other passion, together with music, that he carried throughout his life from his teenage years onwards. In Swansea, he was able to find the opportunities to play the game to an extent that he had not enjoyed since his youth in Scotland. He and Ian Halliday joined Pennard Golf Club, and for many years they played together every Saturday morning. Halliday found David’s golf style to be the antithesis of his careful, though inspirational, approach to physics: he would occasionally hit enormous drives but with very little control, and on one memorable occasion his drive hit the ladies’ tee marker 30 yards ahead and, following a trajectory reminiscent of Rutherford scattering, the ball whistled back past their ears to come to rest behind them, a drive of minus 150 yards.

He was in many ways a quiet and reserved person but David enjoyed the company of his friends and colleagues and he loved the process of collaboration, as the papers containing his major contributions to physics make clear. These were ahead of their time and helped to shape the understanding of the structures of string theory and quantum field theory gained in the last 40 years. His relentless and uncompromising search for rigour and clarity permanently influenced all those he taught or worked with.

ACKNOWLEDGEMENTS

In addition to his account of his work on string theory (44), David Olive left detailed notes on his early life and much of his scientific career, which have been immensely valuable to us. We are very grateful to many of David’s friends and colleagues for much information and helpful correspondence and, most particularly, to David’s widow, Jenny Olive, and younger daughter, Rosalind Shufflebotham, who also carefully read drafts of this memoir and provided the frontispiece and other photographs. Jenny died on 1 September 2018. The portrait photograph is from the Imperial College Archives and is used with permission. All other photographs were kindly provided by the Olive family unless otherwise indicated.

SUPPLEMENTARY MATERIAL

More detailed accounts of David Olive’s contributions to: A. $S$-matrix theory; B. fermions and the GSO projection; C. monopoles and duality; D. Toda theories; and E. algebras, lattices and strings, together with the full bibliography, are available at http://dx.doi.org/10.1098/rsbm.2020.0024.

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