BIOGRAPHICAL
MEMOIRS

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Biogr. Mems Fell. R. Soc. 2015 **61**, 161-181, published 26 August 2015
originally published online August 26, 2015

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Elected FRS 1961

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Rodney Hill was born on 11 June 1921 in Leeds, and educated at Leeds Grammar School. He went up to Cambridge University in October 1939, with a Major Scholarship at Pembroke College. He graduated BA with first-class honours in 1942 in the Mathematical Tripos. Volunteering for war work immediately, he worked in full-time government service on ballistics in the Cambridge Mathematical Laboratory, and on the plasticity of metals in the Cavendish Laboratory. In 1943 he moved to the Armament Research Department at Fort Halstead in Kent, for three years. Here he was involved in, for example, the modelling of armour penetration by projectiles. This established his expertise in the Mathematical Theory of Plasticity, in which he became a world-recognized leader via the writing of a renowned book with that title (still in print after 60 years) and 170 research articles with eventually 26 collaborators. He had more than 10 research students. In 1963 he wrote a textbook, *Principles of dynamics*, based on his lectures to undergraduates. Subsequent appointments were at the British Iron and Steel Research Association in Sheffield, at Bristol University, and then as Professor of Applied Mathematics at Nottingham University (1953–62), and at Cambridge University. He retired in 1979 but continued with active research for more than another 20 years. Hill was elected a Fellow of the Royal Society in 1961, whose Royal Medal he received in 1993. He received the Honorary Degree of DSc from the Universities of Manchester (1976) and Bath (1978). He was awarded the von Karman Medal of the American Society of Civil Engineers in 1978, and the Panetti Medal of the Turin Academy in 1988. In 1982 The Rodney Hill 60th Anniversary Volume called *Mechanics of solids* was published, edited by H. G. Hopkins and M. J. Sewell. It contains 19 articles by 23 contributors in 693 pages. The Rodney Hill Prize in Solid Mechanics (US $25 000, at four-yearly intervals) has been established by Elsevier Ltd. It was awarded first in 2008 (Ortiz) and then in 2012 (Gao). A principal relaxation of Hill for 50 years was in extended botanical expeditions with his wife, Jeanne, in many parts of the English countryside, searching for, and identifying and recording, many

http://dx.doi.org/10.1098/rsbm.2014.0024

Published by the Royal Society

species of wild flowers and fungi; and in the cultivation of a garden at home. Rodney Hill married Jeanne Wickens in 1945. She died in 2003. They had one daughter, Caroline, who survives them. Rodney died in Cambridge on 2 February 2011.

Early life

Rodney Hill was born on 11 June 1921, at The Grange in Stourton, on the southeast edge of Leeds in Yorkshire. He came from a family with deep roots in the practical and cultural traditions of the West Riding, having no known mathematical abilities in earlier generations, but physically vigorous (for example grandparents living into their eighties and nineties). Rodney's father was Harold Harrison Hill (1894–1977), and his mother was Lena (*née* Clark) (1896–1969), the daughter of the headmaster of Rothwell Elementary School. Harold was an only child, the son of a railway signalman at Rothwell (between Leeds and Wakefield). From his grandfather's signal box Rodney often spent boyhood time watching trains. Harold had been educated at the University of Leeds, where he gained an MA for postgraduate work in history. Harold Hill also took an external London degree in economics. After serving in the Royal Navy in the World War I he became a schoolmaster, and he was eventually Senior History Master at Leeds Boys' Modern School. In retirement Harold was a prolific landscape watercolourist, and a golfer into his mid-70s. Rodney's mother had been a student at Leeds School of Art, and exhibited fashion design illustrations. Rodney himself was an only child, in a home background that encouraged scholarship and self-sufficiency. He attended Featherbank School in Horsforth, on the northwest edge of Leeds, from 1926 to 1932.

Rodney entered Leeds Grammar School with a scholarship in 1932. He gave regular prize-winning evidence there of all-round intellectual ability. This was not only in mathematics but also in art, English literature and other arts subjects. He obtained matriculation distinctions in mathematics, Latin and history, having obtained an English Literature prize in the previous year. The customary large-team games did not attract him at school (although he was an organizer of junior games), but Rodney enjoyed the one-to-one sports of squash, fencing and golf. He became head of his house (Clarell), and editor of the school magazine, thus acquiring early experience in an activity at which he later excelled professionally. In the Higher School Certificate of 1938 he obtained distinctions in pure mathematics, applied mathematics and physics.

His subsequent writing style proved to be economical. In this period he taught himself to play the piano, which he continued to do long into his adult years. (The long fingers of a pianist could later be recognized politely tapping on his desk while waiting for an answer to his question during a research supervision!) He also became proficient at chess, in which he was later to represent Cambridge University and town (at which time he also read widely in English literature, for example Trevelyan). He ran the school chess club. Thus were developing the powers of accurate observation and analysis that were brought to bear on the mathematics and physics that became his formal specialisms from the age of 15 years.

In December 1938, at the age of 17½ years, he was awarded an Open Major Scholarship of £100 at Pembroke College in Cambridge University. However, it also needed the State and County Scholarships gained in the preceding summer to make him a financially independent undergraduate.

A surviving 1938 letter from the Senior Mathematics Master at Leeds Grammar School to the Director of Studies in Mathematics at Pembroke College states, 'Hill is easily the best student of maths that I have had through my hands' and 'his tastes will, I believe, eventually be for the Pure side'(!).

Hill went up to Cambridge University to read mathematics in October 1939, at the age of 18 years, against a background of external events that must have seemed almost the least auspicious since the very founding of the University. Major Scholars were expected to take Part II of the Tripos in two years instead of three, by omitting all first-year courses of lectures. This imposed a heavy workload, to be carried under spartan conditions created by wartime restrictions such as blackout and rationing, and not improved by antique college plumbing. For example, there was no running hot water, the nearest bath was two courts away, and the winter allocation of one sack of coal per week fuelled a fire in one's room only in the evenings. Nevertheless, Hill was not deflected by this adverse general situation from his aim of a first-class honours degree. He won a college prize for a first-class mathematics result in a preliminary examination in 1940, and he became a Wrangler (that is, he achieved a first-class degree) in Part II of the Mathematical Tripos in June 1941. In that year he was awarded a Blackburne–Daniell College Prize 'for a second-year student who acquits himself most creditably in a University examination'. He graduated with a BA in 1942. His director of studies was Dr Robert Stoneley FRS. As remarked below, he later graduated with an MA in 1945, a PhD in 1948 and an ScD in 1959.

Wartime activity in Cambridge

Hill's undergraduate progress entitled him to take Part III of the Mathematical Tripos, in the mathematical part of which quantum mechanics figured prominently at that time. However, he felt obliged to volunteer for war work, and so he did not take up the opportunity for advanced training that Part III lecture courses would have provided. Instead, he worked on full-time government service in the Cambridge Mathematical Laboratory on external and internal ballistics, and later on plasticity in the Cavendish Laboratory. This immediate taking up of war work meant that, as stated above, it was not until 1948 that Hill obtained his Cambridge PhD.

The Mathematical Laboratory at Cambridge University had become established by the beginning of the war, with Professor J. E. Lennard-Jones FRS as the Director. It soon became closely allied to the External Ballistics Department of the Ordnance Board under the control of the Ministry of Supply. Hill was directed to work in the laboratory from 8 July 1941. He was assigned the 'soul-destroying' task of calculating the trajectories of shells for the compilation of range tables, by small-arc iteration on desk hand-machines, such as the Brunsviga. (In 1958 he introduced me to my first desk calculating machine, as part of my PhD education, and thus graduation from the slide rule that I had learned to use as an engineering student before my mathematics undergraduate course, and from logarithm tables used at school.) After some months in this routine activity Hill began helping to operate the Bush differential analyser for solving the internal ballistic equations ('internal' here indicates that the shell is still travelling down the gun barrel). In this context Hill was able to show the existence of connected families of solutions, so reducing the need for separate computations, thus leading to his first research paper.

Fort Halstead

The developing war effort in 1942 saw the appointment of Lennard-Jones as Chief Superintendent of Armament Research (with a staff of ultimately more than 3000 under his authority in various parts of the country), in an Armament Research Department reconstituted from the old Research Department at Woolwich Arsenal. Lennard-Jones made his headquarters at Fort Halstead, an isolated but attractive location on a spur of the North Downs near Sevenoaks in Kent. Among his innovations was the setting up of new research groups headed by various scientists of distinction, brought in for the purpose. Professor Nevill (later Sir Nevill) Mott FRS became the first superintendent of a group for theoretical research in armaments, which became a permanent feature at Fort Halstead. In the spring of 1943 Mott assembled a team of able young scientists from Cambridge, Woolwich and elsewhere. Many of them subsequently went on to influential and distinguished careers in university or government service. They included J. W. Maccoll (Mott's deputy), J. Corner, A. F. Devonshire, L. Howarth (FRS 1950), E. H. Lee, D. C. Pack, I. N. Sneddon (FRS 1983), C. K. Thornhill, S. J. Tupper and J. H. Wilkinson (FRS 1969). For example, among subsequent Fellows of the Royal Society, Howarth later became Professor at Bristol University, and he specialized in fluid mechanics; Sneddon went on to Glasgow University, specializing in solid mechanics; and Wilkinson joined the National Physical Laboratory, specializing in numerical analysis. Rodney Hill joined the team in May 1943, and he stayed for three years.

(In the spring of 1957, during my final undergraduate year at Nottingham University, I was interviewed for a job at Fort Halstead by Maccoll and H. G. Hopkins (who in 1968 succeeded Hill as Editor-in-Chief of *Journal of the Mechanics and Physics of Solids*). They advised me that my best bet by far was to embark on a PhD course for three years under Rodney Hill as supervisor. That is what happened, to my great benefit.)

It can be seen that this wartime period was a pivotal stage in the careers not only of Hill but also of many other subsequently well-known scientists. Their attention was brought, at a formative age, to a range of practical and urgent problems, and their contributions deserve to be widely recognized. The atmosphere in the Theoretical Research Branch was stimulating, with Mott frequently sketching the line of approach to a problem, almost on the back of a postcard, and expecting his recruits to fill in the details. The Branch was responsible for advising military designers about both basic theory and day-to-day practice concerning the performance of explosives, fragmentation bombs, internal and external and terminal ballistics, attack and defence by tanks and other armoured vehicles, and so on. In particular, they were responsible for modelling the reconstruction of the German V2 rocket from Intelligence reports, and estimating its range and performance. Leslie Howarth was one of those involved in this activity, as indicated by Stuart (2009).

The physical background to this activity was utterly different from Cambridge. Fort Halstead was a vast establishment, not only of civilians but also of military personnel, with war equipment everywhere much in evidence. A balloon barrage was strung out overhead along the North Downs. German V1 flying bombs and V2 rockets descended all around in 1944, and in the areas such as Petts Wood nearer London where staff were billeted in private houses. In fact Fort Halstead lay within what became known as 'flying bomb alley', and one flying bomb landed in the Establishment, blasting windows in the Theoretical Research Branch. Fortunately this was at night; otherwise the Branch could have suffered heavy casualties. The morning revealed the desks of the scientists at the Fort to be 'like glass pin-cushions'.

Rodney wrote to Geoffrey Hopkins and me in 1980 that

> no shelters were available at Fort Halstead; flying bombs came over at any time of the day or night, and no warnings were given, otherwise nobody in London or Kent would have done any work; if a bomb's engine could be heard it was OK, but if the sound suddenly cut out, everyone headed for any available cover (table, corridor, ditch) in the seconds left before the descent—this happened quite often; the balloon barrage on the Downs brought down bombs with their engines running, so we were even more at risk!

As is very well known, other people were much less fortunate.

Problems brought to the Theoretical Research Branch were distributed initially according to the specialisms of the more senior members, some of whom had acquired relevant experience at Woolwich Arsenal. Those problems that were quite new in context tended to go to the young inexperienced graduates newly arrived from university. This was indeed a baptism of fire for them (and not far from being literally so), but it was a test that was to reveal Hill's true *métier*. One of his initial assignments was the problem of deep penetration of very thick armour by so-called Munroe jets and by high-velocity shells with tungsten carbide cores. This required a mechanics of plastic deformation with unrestricted magnitude.

Thus was aroused Hill's interest in the field in which he later became perhaps the foremost world authority. At this stage, however, he had no prior knowledge of the physics and metallurgy associated with plasticity, and little of stress or strain or the tensors that the mathematics would eventually require. There was no useful fundamental textbook. But G. I. (later Sir Geoffrey) Taylor FRS had written one or two helpful reports on shaped charges and Munroe jets. Nevertheless, working at first with Mott and Pack, Hill was soon able to show, for example, that penetration of a shell with a tungsten-carbide core and with pure ogival head would be seriously degraded if too much of the tip was ground conical (which was the current British practice for manufacturing convenience) instead of continuously curving to the tip. The demonstration was achieved not only theoretically but also in field trials planned by Hill in collaboration with the experimental group of Dr Charles (later Sir Charles) Sykes FRS.

These experiences, under evident pressure and with a crucial urgency, provided Hill with a training in pertinent science in the prime of his youth. He was still in his early twenties. The influence of these challenges may be recognized repeatedly in his later work. The urgent problems presented to Fort Halstead called for relatively simple but effective mathematics, guided by physical intuition. They also needed a willingness to communicate with others, including non-mathematicians and experimentalists. There was not time for complicated mathematics, nor were there any electronic computers to assist the work, and the experimental data were usually too crude to warrant over-sophistication anyway. Hill acquired a lasting taste for a pragmatic blend of rigour, elegance and simple realism in the application of mathematics. Additional indications of the urgent activities at Fort Halstead can be found in, for example, a biography of Ian Sneddon (Chadwick 2002).

Personal life

The sense of purpose evident at this time was noticed by colleagues as a cheerful and enthusiastic earnestness. Popular relaxations among the group at Cambridge (for example during tea breaks, or Oxo breaks when tea was short) had included music, books and lightning chess. At Fort Halstead ballroom dancing was added. It was a consuming passion for some,

and Rodney was not slow to find that he had medal-winning ability in this new enthusiasm. He met his future wife, Jeanne Kathlyn Wickens (born in 1923), in 1944. She had been transferred to work at Fort Halstead from the bombing range at Shoeburyness. Previously she had trained as a dancer and as a teacher of ballet, but the war had cut short a promising career. Rodney and Jeanne took part in Friday night dances at the Petts Wood Memorial Hall and the Daylight Inn. They were married on 1 June 1946 at St Botolph's Church in Cambridge, and they had one daughter, Caroline, born in Nottingham in 1955. The strength of Jeanne's support can be detected in the preface to Hill's first book, on plasticity (1)*. They were a devoted couple, and in later years they were to be seen walking arm-in-arm in Cambridge. Jeanne gave ballet classes for adults (1977–87) and became the Founding President and Director of the Capriol Society for Early Dance from 1979 to 1994. Jeanne's health gave cause for concern over some years, a fact that contributed to Rodney's reluctance to be away from home for long and to decline invitations to academic events not only abroad but also in England. She died in Cambridge on 9 June 2003.

Return to peacetime

In April 1946 Hill was seconded by the Ministry of Supply to work with a group of metal physicists under Dr Egon Orowan (FRS 1947) at the Cavendish Laboratory in Cambridge. By this time the applied mechanics of both solids and fluids was being forced to push the boat out onto a turbulent uncharted sea of exciting nonlinear problems, and away from the safer haven of linearity in which much prewar work had lingered. The trend was evident not only in England, of course, but also in other countries, especially the USA and the USSR. Hill found himself in demand as the leading adviser on continuum plasticity in England, not only concerning problems arising from the military interests (such as ballistics) at Fort Halstead but also for new theories of metal-working processes needed by engineering and technological workers in the steel industry. This included hardness testing (with Mott), and autofrettage and wedge indentation (with E. H. Lee). He obtained a Cambridge PhD in 1948 for a thesis entitled 'Theoretical studies of the plastic deformation of metals'.

Sheffield

In February 1949 he moved to Sheffield, after an invitation to be the head of a new Solid Mechanics Section in the Metal Flow Research Laboratory of the British Iron and Steel Research Association (BISRA). The post at BISRA produced new opportunities for collaboration with practical laboratory work in metal forming, for example on rolling and wire drawing. Once again the physical environment was very different from Cambridge. This was before the days of the Clean Air Acts, and the laboratory was situated in a smoky valley, in one of the grimiest and most derelict areas of the city. The theoreticians themselves were housed in a temporary hut while main buildings were being constructed. In compensation, however, Hill enjoyed walking with his wife on the moors outside the city at the weekends. At the suggestion of Professor H. W. Swift, Hill gave courses on slip-line field analysis as an

* Numbers in this form refer to the bibliography at the end of the text.

honorary lecturer in the Mechanical Engineering Department at Sheffield University. Swift was very helpful in promoting these new ideas within the Iron and Steel Institute and in the industry. Hill was joined in Sheffield by A. P. Green and J. F. W. Bishop, who thus became the first of a sequence of postgraduate students wishing to learn the new subject of mathematical plasticity from him at first hand. He also worked on rolling with R. B. Sims, and on wire-drawing with J. G. Wistreich.

(I had some experience of this grimy physical environment myself in 1953, when I was shown around a Sheffield colliery by a local National Coal Board Area Manager. This was preparatory to a first-year undergraduate course in mining engineering, which I commenced at Nottingham University, with a National Coal Board Scholarship, before transferring in 1954 to a mathematics degree course.)

A major book

From his PhD thesis Rodney developed a much more extensive monograph entitled *The mathematical theory of plasticity*, which was published by Oxford University Press in 1950 (1). It has 12 chapters occupying 356 pages. This book very rapidly established Hill as an international authority on the subject. The final draft was written in his spare time, in the evenings and weekends that were left to him after discharging his responsibilities at BISRA. He was then still only in his 28th year, and it is timely to recall a remark from a review of his book in *Engineering*: ‘The author has done his work so well that it is difficult to see how it could be bettered. The book should rank for many years as an authoritative source of reference’. It has. This prognostication was fully borne out. The book has been in print at Oxford for many years. Japanese and Russian translations have been made. Total sales by 1980 were about 13 000. It was reissued as a paperback (ISBN 970-0-19-850367-5) on 6 August 1998, and it is still in print (2015), currently priced at £36.99. More than 3000 paperback copies have been sold. Other reviewers’ comments include ‘The book is well-written … and a pleasure to read’ (J. F. Nye FRS) and it ‘should be in the possession of all those who wish to undertake study and research in the theory of plasticity’ (*Mathematical Gazette*). The book explains the physical basis of plasticity, and how the associated theory can be applied to the solution of a wide range of problems.

When Rodney accepted me as a new PhD student in July 1957, his answer to my question of what he would suggest that I do during the coming summer vacation was unhesitating: ‘Read my book’. I did. By early autumn I was embarked on a project arising from his more recent research papers, and this progress allowed him to say: ‘Now you won’t need to read more of the book’!

At Hill’s funeral in the chapel of Gonville and Caius College Cambridge on 25 February 2011, Dr Julian Allwood, who is the Director of Engineering Studies in that College, gave the address. During this he remarked that the rate of annual citations of Hill’s 1950 plasticity book had been two and a half times the number of years (60) that had elapsed since its publication. Allwood also quoted stories of Hill’s increasing reticence with all but a few collaborators. One such was of a professor on a one-year sabbatical in Cambridge, after Hill had returned there, and hoping to work with Hill but never actually meeting him. This was because Hill preferred to communicate by passing letters under the door late at night. And another delivered a requested paper by hand, instead of by second-class post as instructed,

for which early arrival he was berated. By contrast, John Hutchinson ForMemRS and Kerry Havner recall, at different times, walks with Hill in the countryside, or invitations to tea at his house, respectively.

Bristol

The next move was to Bristol University in September 1950. A three-year Research Fellowship was created for Hill, jointly in the Departments of Physics and (in the Engineering Faculty) Theoretical Mechanics. Joint papers were written here, from the standpoints both of physics (relating single-crystal behaviour to that of a polycrystalline aggregate, with Bishop, who had moved with him), and of engineering (bars and tubes under combined loading, with M. B. L. Siebel and B. (later Sir Bernard) Crossland (FRS 1979)). For the latter, advantage was taken of the laboratory facilities in the Mechanical Engineering Department, with the encouragement of Professor J. L. M. Morrison. There was also the opportunity for more teaching and related reading, and in due course Hill was promoted to the post of Reader in Plasticity.

A new family relaxation taken up at this time was the study of field botany and mycology. Thereafter, in many parts of the English countryside and in particular in East Anglia, this proved to be an absorbing diversion for the mind from the exigencies of a sustained research programme. He kept meticulous notes of his wildflower finds from 1953 onwards, as detailed below.

(Coincidentally, in 1963, when I was seeking a change from 10 years as an undergraduate and postgraduate student, and then lecturer, at Nottingham University, I saw advertised a post of Research Associate in Theoretical Mechanics at Bristol. When I asked Rodney to support my application, he gladly did so with the remark, ‘That was the job I had’. When I was appointed, he was also ready with suggestions of localities to look for a house to buy.)

Journal of the Mechanics and Physics of Solids

The advent of the *Journal of the Mechanics and Physics of Solids* (*JMPS*) proved to be a major event in the development of the title subject. It was launched in 1952 under the imprint of the infant Pergamon Press, whose chairman was Robert Maxwell. Hill suggested the title and the general aim of a forum for effective applied mathematics, linked with experimentation, in engineering science. Any such journal must begin energetically if it is to stamp out an identity for itself in the interested community. Hill took a strong lead by contributing 10 papers (some jointly) to a total of 55 that appeared in the first two volumes.

Hill served as Editor-in-Chief for 16 years (with a brief initial input from W. M. Baldwin) until handing over in 1968 to Professor H. G. Hopkins, of the University of Manchester Institute of Science and Technology. His editing style was such that he rarely needed to consult other authorities before deciding on the suitability of a submitted manuscript, which certainly expedited the decision process. He also chose to be a regular reviewer of books submitted to *JMPS* for review. Geoffrey Hopkins’s editorship advanced the journal for the next 14 years (1968–82), until he tragically died suddenly, on the way to a railway station. Hopkins’s death was particularly poignant because it was only weeks before the publication in 1982 of the volume of articles that he co-edited with me to honour Rodney’s 60th birthday (Hopkins

& Sewell 1982). Professor J. R. Willis (FRS 1992), of the University of Bath and later Cambridge University, bravely took over the editorship of *JMPS* at no notice, having to pick up the pieces without the advantage of advice from the immediately preceding editor. John Willis edited it from 1982 to 2006, acting jointly with L. B. Freund (1992–2003) of Illinois, and then K. Bhattacharya (California Institute of Technology) from 2003 to 2006. The journal has continued to be regarded as among the foremost in its field, and from 2006 to 2014 it has been edited jointly by Bhattacharya and Huajian Gao (Brown University, Providence, Rhode Island).

Nottingham

The University of Nottingham received its charter, and independence from London University, in 1948. It began to embark on two decades of substantial expansion under the vigorous Vice-Chancellorship, from 1948 to 1965, of Mr Bertrand L. Hallward (see Winterbottom 1995). He came from Clifton College in Bristol, where he had been Headmaster since 1939, during years that had included a period of 'adventurous evacuation' to Bude in Cornwall from 1941 to 1945, after the bombing of Bristol.

Professor H. R. (later Sir Harry) Pitt (FRS 1957; appointed Vice-Chancellor of Reading University in 1964) was appointed from his chair in Belfast University in 1950 to lead the existing Mathematics Department at Nottingham in succession to the retiring Professor H. T. H. Piaggio. (Pitt's career has been described by Sewell (2006) and by Bingham & Hayman (2008)). Pitt was soon instrumental in securing the creation of a new Chair of Applied Mathematics. Rodney Hill applied, and he accepted the post from 1 October 1953, when he was still only 32 years of age. I recall posters distributed around the university advertising Hill's Inaugural Lecture entitled 'The applied mathematician's world'. I attended it, on 19 November 1954, in a full Great Hall in the Trent Building, which occupies the primary position overlooking a lake in a large attractive park-like campus on the southwestern edge of Nottingham.

One of Hill's immediate responsibilities was to modernize the teaching of undergraduate applied mathematics. He gave second-year and third-year honours degree courses himself in dynamics of particles and rigid bodies, and also a new third-year course in elasticity. One of his objects, of course, was to encourage the advent of research students. One of these was Robin Knops, who was later appointed to a lectureship at Newcastle University under Professor A. E. Green FRS, and then to a professorship at Heriot-Watt University in Edinburgh. Two years later I began research under Rodney's supervision, on the buckling of columns loaded into the plastic range, which required application of the general theories in Rodney's most recent papers.

Hill's undergraduate lectures were characterized by conciseness and a tendency for brevity. He always came armed with his own chalk and board duster, which he took away with him. It was rare if he exceeded 40 minutes of a nominal 50. But those students who took the trouble to write down what he said, as well as what he wrote on the blackboard, found on reflection that they had a first-class and substantial set of notes.

The undergraduates ran an active Mathematical Society in those years, well supported by the academic staff, who helped with occasional visiting speakers for Society events. They also had an annual dinner, to which Hill brought C. A. Coulson FRS on one evening when he was visiting Nottingham.

Funds gradually became available for essential new staff in applied mathematics, and in 1959 J. E. Adkins was appointed Reader. He had just co-authored a substantial book, *Large elastic deformations and non-linear continuum mechanics* (Green & Adkins 1960). Adkins's role was to head a new Department of Theoretical Mechanics, the need for which had been proposed to the University by Hill. The role of this new Department was to teach and carry out research in applied mathematics within the Faculty of Engineering. The first lecturers to be appointed in 1960 under Adkins in this new Department were A. J. M. Spencer (FRS 1987) and W. A. Green (on the same morning that I was appointed Assistant Lecturer in Mathematics). It has become a very vigorous department. Spencer became Head of the Department when Adkins died prematurely in 1964.

Another type of innovation arose when Hill was consulted by the Mining Engineering Department on subsidence problems. These were evident in many parts of the city and the surrounding area, which is built over the Nottinghamshire coalfield. He proposed a theory of ground movement based on the idea that extracting a seam of coal by the longwall method results in an edge dislocation of the rock strata. This idea was developed by D. S. Berry, who led a stress analysis section recruited for the purpose in the Mining Engineering Department.

Externally, Hill was active in ways that brought credit to the University too. For example, he gave a general lecture entitled 'New horizons in the mechanics of solids' at the Ninth International Congress of Applied Mechanics in Brussels, in September 1956. When it was published in *JMPS*, which he edited at the time, this was the first of his papers that I read.

On the national scene at this time an important innovation was the advent of the annual British Theoretical Mechanics Colloquium. A (perhaps *the*) prime mover in this was Professor (later Sir) James Lighthill FRS, then of Manchester University, where the first meeting took place in April 1959. It is a four-day meeting (still continuing at varying locations around the universities) consisting of a few hour-long 'principal' lectures by invited speakers, and many shorter (often 20-minute) talks by any (usually academic) researcher, young or older, who wishes to describe their current research. Rodney Hill gave such a principal lecture in 1960, when the Colloquium was hosted by Imperial College in London. This was the first one that I attended.

During his nine-year tenure of the established Chair in Nottingham, Hill undertook the administrative tasks customarily associated with such an appointment. As well as assigning courses within his Department he was, of course, a member of Senate. He sat on appointment boards, and he became Vice-Dean of the Faculty of Pure Science. One of the tasks devolved to him in this role was the articulation of the Faculty response to the questionnaire sent out as part of a national survey of university teaching methods, by a committee chaired by Sir Edward Hale in the early 1960s. (Rodney was very ready to put this aside temporarily at no notice for a research discussion.) He welcomed distinguished visitors to the University. For example, he chaired a lecture by Clifford Truesdell. Truesdell had just co-authored, with R. A. Toupin, a landmark text of 573 pages, *The classical field theories* (Truesdell & Toupin 1960), which became widely influential.

This was the time when the emergence of interest in such so-called rational mechanics was taking place in some American and British universities. Hill's writings demonstrate an independent view of these developments, and it was clear that he had little taste for axiomatics *per se*, preferring a more pragmatic or practical approach.

Hill was beginning to lay down the basis of general studies of non-uniqueness and instability in elastic and plastic solids, which were to prove very influential over the

next two decades, and which in due course brought further research students and able collaborators. This was the topic in which I began my research training with him in 1957, and in which my PhD thesis about column buckling was written in 1960. I used to visit him in his office, at no notice, every three weeks or so to report progress or seek advice. He would put his papers aside immediately, for a discussion. In due course I saw what I needed to do, and his response was an encouraging 'That was a good idea.' When my thesis was being written in the spring of 1960, he asked to see the draft when it was well advanced, and announced that he was happy with it. Two years later I wrote a paper on fluid mechanics, prompted in part by some concepts of duality and variational principles that I had learnt from Rodney. But he did not care for this deviation from solid mechanics, and his clear advice was to 'drop it'. But I persevered, and George Temple accepted the paper within 48 hours by return of post. Then I returned to another application of my thesis topic.

In 1962 Hill resigned his Chair, and the title of Professorial Research Fellow was conferred on him for the year 1962–63. In that same year the Department moved, with others, from the top floor of the main Trent Building, 'down the hill' to a brand-new building on a developing campus. By then I was a Lecturer, and I recall Rodney coming to my adjoining office to ask me to help move his desk so that it would be 'in accordance with my feeling for symmetry'. In this period Rodney did some consulting work for BISRA on composite materials and on mechanical working processes.

Fellow of the Royal Society

The University of Cambridge conferred the degree of ScD on Rodney Hill in 1959. The highest honour to which any British scientist aspires followed in 1961, when he was elected a Fellow of the Royal Society. This gave much pleasure to his colleagues in Nottingham and to his friends elsewhere. I can recall knocking on his office door to congratulate him when the news was announced. Rodney had just opened the relevant post from The Royal Society, including a scroll within a cardboard cylinder. He immediately welcomed me in, and pushed all those papers to one side across his desk, to have a conversation.

A second book

Hill's undergraduate teaching during nine years at Nottingham were, as indicated above, centred on classical dynamics, and also on elasticity (leading to what was coming to be called continuum mechanics in the wider environment). The dynamics courses prompted him to use his sabbatical year to write a textbook called *Principles of Dynamics* (6), published by Pergamon Press in 1964. This book of 191 pages contains three chapters: 'Gravitational theory of planetary systems', 'Foundations of mechanics: general principles' and 'General motion of a rigid body'. His 'concern here is to present classical dynamics primarily as an exemplar of scientific theory and method', which is indispensable for scholars of structural engineering, applied mathematics and theoretical physics alike. It leads the reader to think hard about the subject, and to consider to what extent he or she might benefit from emulating such a style of thinking in his or her own writing. This book gave him 'more satisfaction than anything else I

have written'. A sequel on 'Lagrangian and Hamiltonian mechanics for arbitrary systems' was promised in the Preface, but did not appear.

Progress in solid mechanics

Progress in solid mechanics was the title of a sequence of volumes (2–5) published in the 1960s by North-Holland, containing articles invited by the joint editors, who were Ian Sneddon and Rodney Hill. Professor Ian Sneddon was Simson Professor of Mathematics in the University of Glasgow from 1957 to 1985. There were four volumes. Volume 1, published in 1960, contained articles by S. C. Hunter, K. Marguerre, H. G. Hopkins, W. T. Koiter, W. A. Green, P. Chadwick, B. A. Bilby and R. Muki. Volume 2 (1961) had contributions by J. E. Adkins, M. J. P. Musgrave, J. D. Eshelby, J. W. Craggs, K. W. Hillier, R. Hill himself and M. R. Horne. Volume 3 was devoted to a 268-page article by V. D. Kupradze on Dynamical Problems in Elasticity, in effect a free-standing book in itself. Volume 4 (1963) had major articles by P. M. Naghdi and by H. Zeigler. All this material provided substantial additions to the subject of solid mechanics.

Return to Cambridge

In 1963 Hill was elected to a Comyns Berkeley Bye-Fellowship (for research) at Gonville and Caius College (where Mott was now Master), in Cambridge University. Associated with this was a grant from the Science Research Council, which augmented his salary to Readership level. The grant was for research into elastic and plastic macro-properties of heterogeneous materials such as fibre composites, which were just coming into vogue. This he held for six years, after which the University conferred on him a Personal Readership in the Mechanics of Solids. Thus he became a member of the teaching staff of the Department of Applied Mathematics and Theoretical Physics (DAMTP), where he gave courses on classical dynamics and solid mechanics, as well as serving on committees and examining duties. He was consulted by experimentalists in other departments, such as Engineering, Metallurgy and Tribophysics, and in the Polar Institute. In 1972 a Personal Professorship was conferred upon him, which he held until retirement in 1979; he was subsequently Emeritus. During this period in Cambridge, where he was now Professorial Fellow at Caius, the foundations laid at Nottingham for the unambiguous formulation of incremental boundary value problems were built upon in various directions. Properties of heterogeneous media (including fibre composites), single crystals, continuum plasticity and an independent reformulation of rubber elasticity were explored.

A sequence of new research students found fruitful employment in these or older fields. They included I. F. Collins, D. J. F. Ewing, J. P. Miles, R. W. Ogden (FRS 2006), G. P. Parry, L. J. Walpole and N. J. B. Young.

Collins, for example, recalls that as a supervisor Hill was always quietly encouraging, commenting 'that's rather nice' about a suggestion that turned out to be fruitful for metal-forming processes; and that he emphasized the need for a good understanding of 'the fundamentals'.

In October 1969 Rodney's mother was tragically killed when struck by a car. This called for sustained subsequent support to be given to his father until Harold's death in 1977. Jeanne's

mother died in 1971, and her father needed support in his Cambridge flat until his death in 1976. That was plainly a difficult period.

In 1979, prompted by health considerations, Rodney Hill resigned his chair, at the age of 58 years, and he was elected to another Fellowship at Gonville and Caius College. By this time he had also established new working contacts with distinguished scientists from abroad, who came to Cambridge to work with him at various times. These included Kerry Havner, John Hutchinson ForMemRS, Fred Milstein, Jim Rice ForMemRS and Bertil Storåkers. After this early retirement his research output continued for more than another 20 years and, as deliberate policy, in some variety of novel topics, as the record shows.

Rodney's preference was to work at home, often in an armchair with classical music playing in the background. And the foreign stamps from his substantial international mail became an impressive collection for his daughter, with whom he also solved crosswords in *The Times*.

Botany

When Rodney moved to Cambridge in 1963, Jeanne and he bought a house at 42 Gough Way, just off the Barton Road in the southwest suburb of the city. It is within walking distance of his then DAMTP office in Silver Street, in an 'old printing press' as he described it to me when I visited him there. (The Department now has modern purpose-built premises in Wilberforce Road.) The house had a garden that suited his interests, and which he kept meticulously neat, but ultimately it became 'overly large', as he told me when they decided to sell up about 30 years later and move to a smaller property closer to the town, where he and Jeanne established a wildflower garden. Later they moved to another house on Huntingdon Road. Rodney was an interested gardener, botanist and, in later years, mycologist.

He gave monetary support to several ongoing botanical projects. These included the West Cambridgeshire Hundreds Project, for which he helped to put together an initial report; the recording of ancient trees; the creation of the Heartwood Forest, which is the largest native woodland to be planted in England; a new wood at Elmstead Market to buffer two ancient bluebell woods; and the restoration of ancient broadleaf woodland at Wentwood Forest near Newport. He left a substantial legacy to the Woodland Trust for the purchase and management of ancient woodland.

Dr Julian Allwood published an obituary article in *Mathematics Today* in April 2011 (Allwood 2011). This remarks, in particular, on how Rodney liked to go on the fungal forays in the surrounding countryside, as mentioned above. Michael Pritchard of Caius recalled Hill's interests as a naturalist, expressed in practical terms by his donation to the Woodland Trust. Allwood also quotes Professor Kerry Havner (North Carolina State University) as having learnt that when Professor William Prager of Brown University visited Hill at Nottingham in the later 1950s, Hill would take Prager for drives out to the Peak District in Derbyshire. A different story cited by Allwood in the funeral oration was the fact that 'several leading professors of metal forming have visited the College—and all have wanted to visit his door in Caius College, often to have their photograph taken by it' even though Hill was not there. Evidently such a photograph became some kind of Cambridge qualification.

Professor John Hutchinson (Harvard University) recalls a six-month sabbatical in Cambridge in 1974, at DAMTP and in the Engineering Department. Rodney invited him

to join in woodland walks. They hired a taxi, which dropped them at one place in northeast Cambridgeshire or Norfolk and picked them up four hours later at another specified place. Doubtless applied mechanics as well as botany derived benefit from these excursions. Their driver, Terry Barker, recalls the trips. Rodney was always on the lookout for interesting plants, grasses and flowers. He and Jeanne certainly found ones previously unknown in the locality. For example, in 1974 their find of elecampane (*Inula helenium*) at Madingley, not far from home, and previously recorded at only one location (Hardwick) in Cambridgeshire, helped initiate the designation of Madingley Wood as a reserve.

Rodney and Jeanne's botanical outings were very varied in location and type, with long walks in the English countryside. They explored many paths in Exmoor, the Malverns, Herefordshire, the Sussex Downs, Savernake Forest and the Marlborough Downs, the Peak District of Derbyshire, Wharfedale, Swaledale and Ribblesdale, Tunstall and Rendlesham Forests near Woodbridge in Essex, and more. Of course, East Anglia was their nearest 'patch', and they visited numerous woodland and fenland areas there, which contain many 'hunting grounds' for naturalists. They kept precise records of their finds for 40 years, including '446 species of wild flowers (never pick!) in one year (1989), and 389 species of fungi in another year (2001)'. His collection of botanical records has been given to the Cambridgeshire and Peterborough Environmental Records Centre.

They did not own a car after the Nottingham years (Austin Cambridge, 811 BAU, as I once noticed when using a pedestrian crossing!). Instead they used what other people spend on foreign holidays to hire taxis (frequently driven by Terry Barker as already mentioned) for all their botanical explorations. I am pleased to meet Rodney's request in the biographical notes that he deposited with the Royal Society that 'I hope that my biographer will find room for these details about "life outside mathematics". Their *cumulative* effect is necessary, in my opinion, for an adequate portrayal of my personality and life in the round.'

These trips could be very precise. If 3 hours 15 minutes was specified, Rodney and Jeanne would appear at the designated pick-up point by Terry exactly then, and not after only 3 hours 14 minutes. Professor Ian Collins (Auckland University) remarks that they had been known to explore the ground very systematically, for example on a north–south line, and then on a southwest–northeast line, and so on. This was how Rodney approached research problems, from different standpoints until a balanced view was evident, and preferring to work things out for himself from fundamentals—'you can know too much, you know, Ian'; but then not publishing until he knew he had a 'complete' solution.

Kerry Havner also tells me appreciatively of a 40-year long acquaintance with Hill, for example of being invited (with his wife) to tea with Jeanne and Rodney at home at 198 Huntingdon Road, and of being shown on a local walk the house in Huntingdon Road that had been occupied by G. I. Taylor.

Around the time of Jeanne's death in 2003, and later when Rodney's mobility began to decline, John Willis and Terry Barker, with others, were able to provide practical support. Eventually, in the summer of 2007, Rodney was obliged to move into a nursing home at Cottenham Court, a little further out of Cambridge from his house, where he spent his last four years.

External honours

In addition to his Fellowship of the Royal Society, the honorary degree of Doctor of Science was conferred on Rodney Hill by the University of Manchester in 1976, and by the University of Bath in 1978. At the Manchester ceremony on 12 May 1976, the Presenter remarked that Hill's work on 'the principles of plastic deformation involved in twisting and pulling and pushing, pressing, forging, coining, hammering' is 'marked by penetrating elucidation of the essential physics of the problem'. Also in 1978 he was awarded the Theodore von Kármán Medal, which was instituted in 1960 by the American Society of Civil Engineers for 'distinguished achievement in engineering mechanics' and is awarded annually. (Hill received it in London, at the British Institute of Civil Engineers.) The only previous British recipient of this medal was Sir Geoffrey Taylor. Rodney was also awarded the Modesto Panetti International Prize and Gold Medal for Applied Mechanics by the Turin Academy of Sciences, in 1988. (He received it at the Italian Embassy in London.) This was awarded at three-yearly intervals, starting with Sir Geoffrey Taylor in 1958.

Royal Medal

The Royal Society awards three Royal Medals annually, for 'the most important discoveries in the physical, biological and applied sciences'. They are also known as Queen's Medals. They are awarded by the Sovereign on the recommendation of the Council of the Royal Society. They were founded by King George IV in 1825. From 1826 to 1964 two were awarded annually, and a third annual medal was added in 1965 for the applied sciences. Each award is a silver gilt medal, with a prize of £5000.

One of the recipients in 1993 was Rodney Hill 'for his outstanding contribution to the theoretical mechanics of solids, and especially the plasticity of solids'. He received it in Cambridge.

The Rodney Hill Prize in Solid Mechanics

This prize was established in 2008 by Elsevier Limited. It consists of a plaque and a cheque for US $25 000. The prize is to be awarded every four years, to coincide with the International Congress of Theoretical and Applied Mechanics. It is to be awarded to a single individual, and only once to that person, 'in recognition of outstanding research in the field of solid mechanics'. The recipient is required to deliver a Prize Lecture at the ICTAM meeting.

The first such prize was awarded at the Adelaide Congress in 2008 to Professor Michael Ortiz, of the California Institute of Technology, for his contribution to non-convex plasticity and to deformation micro-structures. This was before Rodney's death in 2011.

The prize was awarded for the second time at the Beijing Congress in 2012 to Professor Huajian Gao, who is the Walter H. Annenberg Professor of Engineering at Brown University, for his contributions to materials science, nanotechnology and bioengineering. He is also the current co-editor, with Kaushik Bhattacharya, of *JMPS*.

Scholarship

Hill's list of scientific work speaks for itself, as everyone knows, and I shall not labour that point here. Suffice to say that his standing has been recognized in several ways, just one of which was in the *Festschrift* of 1982, edited by Geoffrey Hopkins and myself, containing articles by a total of 23 contributors. His appreciation was shown to me in two letters written in February 1982, expressing the view that 'I take especial pleasure in the knowledge that, rather like a speck of grit, I have nucleated a pearl of great price!'

Rodney Hill wrote the two books already mentioned, and edited four more with Ian Sneddon. He also wrote 170 articles (listed in the electronic supplementary material at http://dx.doi.org/10.1098/rsbm.2014.0024), 53 of them being co-authored with 26 collaborators in all. He contributed to *Festschriften* for G. I. Taylor, N. I. Mushkelishvili, W. Prager, F. K. Odqvist, V. V. Novoshilov and A. A. Ilyushin.

His style of writing is spare and concise. Every word is weighed, and must be weighed again by the reader. Mathematics has frequently to be read with paper and pencil to hand. They are essential when reading Hill. A comment to him that this or that paper was not easy to read would draw the swift reply that it was not easy to write. But the reader who perseveres may find a rich vein of understanding, with fresh thinking at every turn.

As his notes deposited with the Royal Society remark, it was his regular practice to write several drafts of an intended paper, with short sentences, seeking to be 'crisp, succinct and transparent'. Robin Knops echoes this when he accurately observes that Hill's publications were succinctly written and were informed by a powerful and original intuition, which was largely free from involved or technical mathematical detail, so that he was able to 'travel lightly'. His intuition was subtly argued, so that his publications demand prolonged and exacting study for their full appreciation. This deep intuitive insight is comparable to, if different from, that of other outstanding researchers in solid mechanics such as G. I. Taylor, J. D. Eshelby FRS, R. S. Rivlin and J. L. Ericksen.

The overall effect has been a pervading, beneficial and indelible influence on the international solid mechanics community, and as such has contributed to the scientific reputation of the UK.

With his students he was always looking to provide a balanced level of encouragement, waiting at first for the student to display an initiative or idea appropriate to the task in hand, but encouraging if and when it came. It was a learning experience worth having.

Opus

Memoirs in these volumes sometimes describe, even in quite detailed technical language, the scientific work accomplished by their subject. Rodney Hill was writing pioneering papers about the mechanics of solids for 60 years, and I have been obliged to ask myself whether it would be reasonable to try to represent all that material from 170 papers and two books within a few pages. What would Rodney have thought about such a venture? I have chosen to make some selected points here, and otherwise to let his list of writings speak for itself.

The wartime studies of penetration of armour have already been mentioned in this memoir; sequels to this were developed, with several collaborators, in the later 1940s. Mathematical consequences of this work were refined into what became mature three-dimensional theories

of plastic distortion of metals beyond the time-honoured yield point, which is known as the limit of linearity and reversibility as expressed in Hooke's Law. That was the subject of the book that he wrote at the age of 28 years, and which became, as Geoffrey Hopkins remarked to me, a 'book for all time'. He included the basic foundations of the theory, and the solution of particular problems such as bending and torsion, the theory of the slip-line field, a description of steady industrial processes such as sheet-extrusion, strip-rolling and machining, and unsteady problems such as plastic yielding round a cavity, and indentation and hardness tests. Plastic anisotropy was also developed, such as the earing of deep-drawn cups.

The 1950s saw the application of these theories, with several collaborators, to industrial processes for which theories had previously been lacking. These included bending and twisting of thin tubes, cold rolling of strip, and necking in thin sheets. In 1952 alone he published 16 papers, 9 of them co-authored.

By 1956 Rodney was beginning to develop theories about the failure of uniqueness and consequent instabilities in rigid–plastic and elastic–plastic solids. These provided a rational basis for the calculation of, for example, buckling loads in compressed struts and plates (which I was able to exploit in my PhD thesis in 1960 and subsequently). Such lack of uniqueness is also associated with 'necking' in tension specimens. His interests also turned towards fibre-reinforced and composite materials, which were coming into vogue in the 1960s, and by 1970 into studies of elastic–plastic crystals at large strain. Some of this work was carried out with distinguished collaborators from abroad, as indicated elsewhere in this memoir.

Professor Jim Rice ForMemRS (Harvard University) tells me that he was a Professor of Engineering at Brown University when Rodney Hill agreed to host his visit to Churchill College in Cambridge for the year 1971–72, via a National Science Foundation Senior Postdoctoral Fellowship. Their agenda included particularly the proper formulation of constitutive and field equations for finite elastic–plastic deformation in ductile crystalline and polycrystalline media, and the connection of those macroscopic constitutive equations to a physical understanding of plasticity, at both the crystal dislocation level and the continuum descriptions of single-crystal shear within the individual grains of a polycrystal. Their collaboration was pursued not only by face-to-face conversations but also via frequent communication by the leaving of notes for each other. Jim told me that this mechanism was not at all an unsuitable format for the precise and very complex mathematical formulations that they were discussing. (With research students, however, certainly in my case more than 10 years before, the communication was always by face-to-face meetings, and never by the leaving of notes.)

The 1970s included the initiation of a fruitful collaboration with Fred Milstein on the properties of crystals at arbitrary pressure, who made several visits to Cambridge, and who has kindly provided information for the following brief summary of this work. Hill also continued long-standing collaboration with Bertil Storåkers and Kerry Havner, who also visited Cambridge as stated above.

Crystal properties

The seed of the Hill–Milstein collaboration was planted in June 1974 when Hill wrote to Milstein requesting 'exact references' to two of Milstein's publications, about atomistic and computational crystal mechanics, in which Milstein was unaware of Hill's work. Hill realized that Milstein's observations on crystallographic phenomena were directly

relevant to his own 'objectives of constructing work functions'. This contact resulted in an invitation from Hill for Milstein to visit Cambridge (which he did three times in subsequent years), and they eventually wrote six joint papers. These established the principles of elastic stability of crystals under load, and elucidated these principles by means of atomistic computations.

A consequence was the basis for numerous successive publications, authored by many workers, including more than 30 such papers by Milstein and co-workers.

This Hill–Milstein collaboration was carried out almost exclusively by exchanges of notes, either via Milstein's desk at DAMTP while he was in Cambridge or by post. In Cambridge, when 'things warmed up', as Milstein puts it, notes were exchanged on a daily or semi-daily basis. Milstein remembers that Hill's notes 'were always succinct, precise and insightful'. They were often typed but sometimes written with a fountain pen that must have had a 'well-worn point'! Hill and Milstein met face-to-face only about a dozen times spread over three visits to Cambridge spanning almost a year.

Shortly after arriving in Cambridge, Milstein was invited to Hill's house in Gough Way, where Jeanne served tea from a silver setting in the garden, of which 'Hill was clearly and rightfully very proud'. On another occasion Hill invited Milstein to lunch in Caius, which was a rare event as Milstein later learned.

Milstein told me that Hill clearly enjoyed the intricacies of crystal elasticity. One joint investigation was the description of infinitesimal changes of crystal load and geometry at the branch point leading from a primary tetragonal path to a secondary orthorhombic path under load that remains uniaxial after branching (this reminds me of my own 1960 PhD investigation, under Rodney's guidance, of the buckling load for an axially loaded strut in the plastic range). The infinitesimal changes on the primary path are described via second-order Taylor expansions of energy.

It was initially assumed that, at the branch point on the orthorhombic path, third-order expansions of moduli would be sufficient. Their first results were 'not even close', which caused Hill to 'dig deeper and come up with exact results'. These required fourth-order moduli owing to the highly singular nature of the branching (the load remains 'dead' while the lattice parameters orthogonal to the load vary inversely). A particular reference is Hill's 1982 paper on constitutive branching (7).

Acknowledgements

I am especially grateful to a number of people, some of them long-time friends and others whom I have not met, who have very willingly responded to my request for recollections of their contacts with Rodney, or for information about him: Mr Terry Barker, Professor C. R. Calladine FRS, Professor P. Chadwick FRS, Professor I. F. Collins, Mr John Davies (Leeds Grammar School Archivist), Sir Richard Dearlove (Master, Pembroke College, Cambridge), Professor K. S. Havner, Ms Caroline Hill, Professor J. W. Hutchinson ForMemRS, Professor R. J. Knops FRSE, Professor F. Milstein, Mr K. Moore (Head of Library and Information Services at the Royal Society), Professor R. W. Ogden FRSE FRS, Professor S. R. Reid FREng FRSE, Miss Jayne Ringrose (Pembroke College Honorary Archivist), Professor J. R. Rice ForMemRS, Professor B. Storåkers, Professor J. T. Stuart FRS, Professor J. M. T. Thompson FRS and Professor J. R. Willis FRS.

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