Kenneth Langstreth Johnson. 19 March 1925 — 21 September 2015

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K. L. Johnson

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Elected FRS 1982

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Kenneth Johnson, born in Barrow in 1925, studied mechanical engineering at Manchester during World War II. After some years in industry and an early appointment back in Manchester, he spent most of his academic career teaching and researching at the Engineering Department of Cambridge University. He was also a long-serving Fellow of Jesus College. He was renowned for the insightful analysis of meticulous experiments in contact mechanics. He was widely acknowledged as the doyen of this area, particularly after the publication of his seminal work of the same name. His major publications included topics in friction and wear, rheology and lubrication, rolling contact and adhesion. Important applications of his insights included the prediction of corrugations and cracks in railway lines. He was gratified when, after many years of dormancy, his ideas in adhesion were used by others to explain the climbing behaviours of insects and other small animals with soft feet. He was a devoted family man, characterized by warm personal qualities that won him many friends around the world.

Background and family life

The paternal grandfather of Kenneth Langstreth Johnson (hereafter KLJ or Ken), Richard Cuthbert Johnson, formerly of Leeds and later of Lancaster, had seven children, one of whom, Frank Herbert Johnson, was bright enough to attend Lancaster Royal Grammar School and to win an Exhibition to study history at Sidney Sussex College, Cambridge. He was appointed to a teaching post at Barrow Grammar School in 1922, rose to become Senior History Master, ran the school orchestra and remained there for the rest of his teaching career until 1956. KLJ's mother, Ellen Johnson (*née* Langstreth), was a school teacher; she was born in Todmorden in 1888 and married Frank in March 1923. KLJ was born on 19 March 1925.

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The young KLJ attended Victoria Infants' School in Barrow from 1930 to 1933. He recalled his main memory of this time as having to sit by a girl to help with his knitting, and commented that this perhaps accounted for his subsequent shyness with girls. The other memorable event at the time was the birth of his sister, Margaret Elizabeth, in August 1932. At seven years of age, he transferred to St Paul's Primary School, Abbey Road, Barrow, for a happy three-year period. He remembered the headmistress, Miss Fallows, as being 'brilliant', teaching scripture like a novel, and introducing her young charges to the novels of Charles Dickens.

This period culminated with the once dreaded (though possibly now much lamented) 11-plus examination in March, for entry to the grammar school. It comprised papers in arithmetic and English, and an intelligence test. Barrow, with a population of about 50000, had only one grammar school, so competition was stiff, but KLJ was placed third overall in town.

Thereafter KLJ, after what he described as a conventional happy childhood, set out on an academic trajectory aimed, after his father, for Cambridge; however, he also led an active outdoor life of rugby, athletics, swimming, Boy Scouting and, later, fell walking and climbing on the nearby Western Fells in Cumbria. He recalled, 'The Grammar School for Girls stood alongside, separated by a high spiked fence. This must have been just for show, since there was easy access round the back.' Clearly the shyness was wearing off.

In the sixth form, studying mathematics, applied mathematics and physics, he received high-quality teaching from teachers who held degrees in engineering and had been recruited during the Depression. He was appointed Head Prefect and was on the school teams for rugby, swimming and athletics. His second sixth-form year, 1941, coincided with the wartime bombing of Barrow, a strategic military target. In normal circumstances he would have stayed at school for a Cambridge Scholarship year. However, the wartime need for technically qualified staff was pressing, so on taking his Higher School Certificate he became what was known as a 'Snowflake': he was interviewed by C. P. Snow (later Lord Snow), then Director of Technical Personnel at the Ministry of Labour, and offered a State Bursary on an accelerated course to read mechanical engineering at Manchester College of Technology, attached to the Ministry of Aircraft Production. It is worth noting the origins of this scheme: soon after the outbreak of the World War I in 1915, most university students (including KLJ's father) volunteered for military service in France. Of the 40 or so freshmen in Frank's year of 1913, only two returned to complete their degree. During the German rearmament in the 1930s it was recognized that further war, when it came, would be long and very dependent on science and engineering. To avoid the mistakes of 1915, Snow, a chemistry lecturer at Cambridge, was recruited to Whitehall to increase the output of science and engineering graduates.

Forgoing his Cambridge ambitions, Ken therefore went to Manchester, where he was a resident of Dalton Hall, a Quaker foundation, which provided a rewarding student experience. After just two years and three months, including one day a week spent on military training, parades being rotated though the week to give minimum disruption of the lecture timetable, he graduated in December 1944 with the top first-class degree of his year and winning the accolade of the Isobel Stoney Prize.

Early career

After his graduation, an interview at the Ministry of Aircraft Production sent KLJ to a firm in Gloucester called Rotol, which was set up to design and manufacture aircraft propellers

for use with Rolls-Royce and Bristol aero engines. The plant was located halfway between Gloucester and Cheltenham, and Ken was found accommodation in a National Service hostel that took a wide variety of 'war workers'. The single-storey huts contained about 12 identical rooms on either side of a central corridor. Each room was about 8 feet square, containing a bed, cupboard, table, wash basin and toilet.

KLJ was put to work in the Research Department, whose main concern was measuring with strain gauges the vibratory stresses in the propeller blades. For bending stresses the gauges were glued top and bottom parallel to the axis of the blade; for torsional stress the gauges were attached at 45°. The forward thrust developed by each blade of a propeller depends on its rotational speed and the length of the blade, but this is limited to keep the tip speed below the speed of sound. To convert the increasing power developed by the engine over the years it became necessary to increase the number of blades. The Spitfire fighter had started the war with three blades but had reached five when KLJ joined the firm in January 1945. The engine drove the propeller through a gear of non-simple ratio. Thus by measuring the frequency of any troublesome vibration it was possible to tell whether it originated in the engine or in the propeller. He later recalled that the introduction of a five-bladed propeller for the later versions of the Spitfire helped him to divide the pie equitably when his immediate family numbered five.

In addition to the bending vibrations, the blades were observed to vibrate torsionally if their aerofoil sections became stalled. This unstable vibration was known as 'stalled flutter'. To check whether a new design of propeller was subject to flutter it was driven on a spinning tower by a large electric motor located at Farnborough. Given the flutter problem to study, KLJ set about calculating the natural torsional frequencies of a blade, using the relaxation method of Southwell (1940).

During this period in industry he worked as a Manchester external candidate for an MSc, awarded in December 1948, on 'Stalled flutter of propeller blades'; from January 1949 he took up the post of Assistant Lecturer in Mechanical Engineering back in his old department at Manchester College of Technology and as Resident Tutor back in Dalton Hall. His experience of mechanical vibrations had led him to the conclusion that serious ignorance existed on issues related to damping, which was at that time rather vaguely attributed to hysteresis losses in the material. So in the somewhat limited time allowed by his teaching duties, he initiated a research programme into slip damping at interfaces in contact, thus beginning a lifetime study of many aspects of the contact problem. Experiments were conducted with a hard steel sphere pressed into contact with a flat steel surface and subjected to an oscillating shear force. In 1953 David Tabor, from Cambridge, who had recently published a major book with Philip Bowden, *The friction and lubrication of solids* (Bowden & Tabor 1950), visited Manchester and was impressed by Ken, particularly his careful experimental work; this proved to be the beginning of a long academic association and close friendship (Field 2008).

Teaching was always a great priority for Ken, and he took his responsibilities extremely seriously. In this period he became founding editor of the journal *Bulletin of Mechanical Engineering Education* (now *International Journal of Mechanical Engineering Education*); an early paper on laboratory teaching in the journal prompted an invitation to KLJ to speak at a conference in Cambridge, his first academic association with what became his natural home.

It is of interest that a much earlier (1908) researcher of the propeller at Manchester was the philosopher Ludwig Wittgenstein (Lemco 2007). His patent for an airscrew driven by blade-tip jets was inappropriate for use in aeroplanes but eventually found application in the Fairey

Rotodyne helicopter of the 1950s. Both KJL and Wittgenstein became Cambridge professors, but KLJ of course stayed with engineering.

Earlier, while at Rotol, Ken had met and courted Dorothy Watkins during healthy and wholesome pursuits such as walking, cycling, swimming, music and Youth Hostelling, activities that continued throughout the Manchester period. He passed auditions to become a member of the Hallé Choir and toured the country under the baton of John Barbirolli during the Festival of Britain in 1951, a tour that included Edinburgh, the new Festival Hall in London and the refurbished (from bombing) Free Trade Hall in Manchester.

In 1954 KLJ was appointed Demonstrator in Engineering at Cambridge. A short time before he began his appointment on 1 October 1954 he handed in his PhD thesis to Manchester. He and Dorothy were married on 11 September and had a brief honeymoon at Llangrannog on the Cardigan Bay coast (remembered by the smell of dead and dying rabbits struck down by myxomatosis). A final tidying-up of the Manchester work saw KLJ and Tabor, as External Examiner, travelling from Cambridge by train to Manchester, Tabor reading the thesis and Ken *The Guardian*, interrupted by questions from his interlocutor. In December 1954 KLJ was awarded a PhD for his thesis 'An experimental investigation of the effects of an oscillating tangential force at the interface between elastic bodies in contact'.

KLJ AT CAMBRIDGE, 1954–2015: RESEARCH

KLJ's academic career in the Cambridge University Engineering Department can be summarized thus: promoted to Lecturer in 1956 and Reader in 1970, elected *ad hominem* Professor in 1977, and served as Deputy Head of Department from 1983 to 1992, the year in which he formally retired on 30 September. He was elected to a Fellowship of Jesus College in 1957, where he served as Tutor for Graduate Students from 1963 to 1969. More will be said about the personal distinction he brought to these appointments later, but first we will consider his research activity.

A useful collection of KLJ's papers has been published (Kauzlarich & Williams 2005), and very recently a summary of his life and work has appeared (Hills *et al*. 2016). These have made the present task much easier: I have leaned rather heavily on these two publications. First, Hills *et al*. stated perceptively:

> The term 'contact mechanics' is not precisely defined, but we may sensibly think of it as the study of all the phenomena associated with the interaction between solid bodies pressed or held in contact: it includes a knowledge of the contact stress field, a characterisation of the material response both elastically and plastically, deduction of the effects of surface roughness, of lubrication, of friction, and an understanding of the physics of the interaction forces between the surfaces. Ken Johnson has contributed to all of these aspects of the problem, and in the last of these fields his efforts have been seminal.

Exactly so.

Kauzlarich & Williams classified KLJ's research into five themes and invited experts in each area to nominate what they thought to be the six most influential of Ken's publications in each of these areas. A few of the nominations appeared in more than one topic. This has made my task of selecting key publications from a distinguished list considerably easier and I, too, follow these themes. The sections below are closely based, with acknowledgements, on the descriptions and nominations of the experts.

Friction and wear (T. H. C. Childs)

When KLJ came on the scene, Bowden & Tabor (1950) had established the junction growth theory of adhesive friction and Archard (1953) had just formulated his wear law. There was clear understanding that wear could be by the direct failure of metallic junctions or could proceed via oxidation and failure of the oxide. All these theories drew attention to the fact that real surfaces are rough, that frequently the areas of real contact between loaded surfaces, at the high spots or asperities, are much less than the apparent areas, and that it is the behaviour of these real areas that govern friction and wear.

Paradoxically, KLJ's earliest contributions (about 1955–65) to studies of friction and wear were not directly in the behaviours of these real contact areas in isolation, for example their deformation and failure under combined normal and tangential loading. Rather he studied the elastic subsurface deformations and relative motions of hard steel surfaces (for example a ball and a flat) loaded together in both static and rolling contact conditions, acted on by tangential forces and spin torques insufficient to cause sliding. In such conditions the apparent contact area consists of both locked and slipping regions. Johnson's studies (for example (1, 2)*) brought together the micro (real contact area) and macro (subsurface) views of surface interactions. The insights into and interests in contact mechanics that he developed underpinned a second period of friction and wear activity (about 1965–70 and 1985–95), one that was explicitly concerned with asperity deformation and failure (for example (7, 24)). From about 1995 (for example (25, 29)) he attacked a fundamental question relating to dry friction: how does slip occur at the real contact area between two elastic bodies—rather than assuming a sliding friction coefficient value as an input to a mechanical analysis, can it, or the limiting friction stress at sliding, be derived from the material properties of the sliding surfaces themselves?

The previous paragraph sets the scene, in terms of the technical areas to which KLJ has contributed. But his influence on others working in the fields of friction and wear has been, and still is, much greater than just through these particular achievements. His approach to problem solving combined rigorous analysis (with approximations, where necessary, guided by physical insight) with conceptually and sometimes physically simple experimentation. Clear and well-thought-out diagrams supported written descriptions of difficult concepts. His presentation of large collections of data, spanning ranges of physically diverse conditions, were routinely made digestible through the use of appropriate non-dimensional groups that enabled divergences between experiments and theory to be readily identified. And, as often as not, the divergences were as interesting for the insights they produced as the areas of agreement were for the satisfaction they gave. Of course these are points that apply generally beyond the areas of friction and wear, but they constitute a significant contribution that merits attention.

Rheology and lubrication (H. P. Evans)

KLJ's first reported effort of measuring traction in disk machines was in a paper co-authored with R. Cameron (6). (Disk testing is the experimental modelling of the contact conditions in many types of machine elements simulated by the study of two disks, driver and driven, of the same or different radii and materials pressed into contact, either under lubricated or dry conditions.) In these tests the contact pressures used increased to 1.8 GPa and the form of the traction curves was described: linear behaviour at low sliding, progress to a maximum value, and then a gentle reduction as the sliding speed became large—'viscoelastic behaviour is suggested

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

by the observed decrease in apparent viscosity as the time of transit of the oil through the contact zone was reduced by increasing the rolling speed'. In interpreting the measurements, attention was concentrated on evaluating hypotheses as to the cause of decreasing traction at high sliding rates. The paper came down on the side of the theory that the film shears like a plastic solid when a critical shear stress is reached, and found that the explanation of a Newtonian fluid whose viscosity is reduced by frictional heating was not supported by the high-pressure data.

A paper co-authored with Jim Greenwood, a long-time colleague in the Engineering Department at Cambridge, and S. Y. Poon (10) is one of two theoretical papers included in this section. This paper examined mixed lubrication in which the load was supported partly by an elastohydrodynamic film and partly by direct asperity contact. It introduced an ingenious treatment to conclude that 'the surface separation, upon which the asperity contact conditions depend, can be calculated directly from the elastohydrodynamic conditions, independently of surface finish'. Electrical contact resistance measurements were also presented and compared well with predictions emerging from the model.

A paper co-authored with J. L. Tevaarwerk (11) was an experimental *tour de force*. It provided a thorough demonstration of the nonlinear Maxwell model proposed by the authors. The experimental technique used disk tests operated in two different modes: rolling with spin, and rolling with sideslip. The two modes resulted in distinctly different strain rate histories. Essentially one mode was used to establish parameters for the nonlinear Maxwell model proposed. In a 'more discriminating test' the model was then shown to correspond to the experimental results of the other mode without any adjustment of the parameters. This has become probably the most referenced paper in the field, and justifiably so.

A pair of papers were co-authored with C. R. Evans and published in 1986 (16, 17). The first ('The rheological properties of elastohydrodynamic lubricants') chronicled the way in which the important parameters identified in describing the traction response of lubricating oils vary in terms of pressure and temperature. It explained the four regimes found to occur in the extensive disk machine testing that was performed. The key parameters of viscosity, Eyring stress and limiting shear stress were determined from disk testing for three lubricating oils of different types. The paper recognized that the fourth parameter, the lubricant's elastic shear modulus, cannot be established from disk testing because it is masked by the shear deflection of the disks themselves. This much-referenced paper presented a wealth of information, not least for analysts seeking to build detailed theoretical models of the shearing lubricant.

The other twin paper ('Regimes of traction in elastohydrodynamic lubrication') (17) presented the four traction regimes established by earlier experimental work in terms of two non-dimensional groups. These were based on the contact pressure, established as being the dominant influence on traction behaviour, and on a parameter influential in determining film thickness. The paper presented maps that partitioned this parameter space into regions where each of the traction regimes (Newtonian, Eyring, viscoelastic and elastic–plastic) were expected to occur. A map was proposed for each of three lubricants subject to extensive measurement in the experimental programmes that fed into this interpretative paper. The purpose of the maps was to 'assist in a prediction of traction forces in any particular application', and the process by which this prediction could be effected was detailed. Also included was a comparison of the maximum predicted traction coefficient with those determined from experimental traction curves over a range of temperatures and contact pressures.

The final paper of this selection of contributions to lubrication ('The behaviour of transverse roughness in sliding elastohydrodynamically lubricated contacts') (20) was also co-authored

with Greenwood. It sought to examine theoretically the influence of sinusoidal roughness in a sliding elastohydrodynamic contact. The paper typifies the approach seen in so many of the papers included in this collection: a simple theoretical treatment that is ingeniously developed to give a fundamental understanding of the essence of a tribological situation. This paper is particularly noteworthy for having identified the fundamental difference between elastohydrodynamic films that behave in a Newtonian way and those subject to significant non-Newtonian effects when surface roughness is included.

Contact stress analysis (D. A. Hills)

Chronologically, Johnson's first major contributions in contact mechanics began in Manchester, when he studied, both experimentally and theoretically, the problem of a fixed spherical contact subject to oscillatory shear. The results of that work, published in *Proceedings of the Royal Society* series A in 1955 (1), set the standard and pattern for the next half century: the careful devising of innovative experiments that pull out the essential physical features of the problem under consideration, the development of appropriate theory, drawing wherever possible on closed-form solutions whose interpretation and application to the experiment are clear, and, above all, the use of physical insight to explain phenomena previously obscure. The 1955 paper marked the start of Johnson's contribution to fretting (loaded contacts subjected to small oscillatory movements). The experiments he performed, developed by John O'Connor, Johnson's first research student at Cambridge and who himself went on to make major contributions to this field and later to develop the celebrated Oxford replacement knee, are still very widely quoted as demonstrations of physical evidence of partial slip in stationary contacts. An extension of the theory from spherical bodies to more general second order contacts was undertaken with P. J. Vermeulen (5). This included a deduction of the surface state of stress and this then led to the general question of the study of contacts between second-order bodies, each of which could be represented by a half-space—the Hertzian contact.

Hertz (1882) solved what we would now describe as the boundary value problem; he deduced the contact pressure between convex bodies in terms of the load and local curvature. One hundred years later, Johnson gave a seminal review lecture describing Hertz's original study, the intervening refinements and the practical application of the theory to engineering problems. Although a review, that paper (12), given at the Institution of Mechanical Engineers, provided the audience with a perfect picture of the classical study of the problem, its limitations and its extensions.

We turn now from elastic analysis to the problem of contacts involving plasticity. Finite-element (FE) methods have now given us a sledgehammer technique to investigate nonlinearities. I recall being told early in my career that engineering is the art of being exactly right rather than exactly wrong. Easy availability of FE methods that are now taken for granted came after KLJ's early work, so he turned to thinking, the application of physical insight, and dimensional argument; these processes provided real progress, in a way that contrasts with the unthinking use of commercial FE code giving additional obscurity. His insight was nowhere more acute than in his studies of the indentation test (8), and anyone wishing to learn about plasticity in general could do no better than to read KLJ's papers on indentation experiments. The paper in question, (8), makes quite clear to anyone the different possible responses that any elastic–plastic component makes to the application of load, and does so in a way that the reader can then generalize to a wide range of other problems. Of course, all elastic–plastic problems have to be solved by applying the Prandtl–Reuss equations, and KLJ's elegant

solution of them 'on-axis' beneath a hardness test is a model for how careful thought can say a great deal about a potentially intractable problem. In the paper Johnson argued how, from simple kinematic considerations, the strain state on-axis beneath a sphere can be specified, and from this how the stress state must follow. He proved unambiguously that, when an indenter is removed, there must be reversed plastic flow upon unloading. The use of simple kinematic simplifications to problems involving plasticity was then applied to contact problems involving more widespread plasticity, and it also formed the basis of his studies of shakedown under rolling contact, discussed below.

The work on rolling contact was aimed at explaining several things—rail corrugation, for example—but also at determining the steady-state residual stresses that, together with the passing contact loading, give the conditions for ensuing failure. In the mid 1970s Johnson was turning his mind to the various kinds of failure that can occur. Specifically, at that time the 'delamination' theory of wear had just been introduced, and there was a suggestion that both wear and rolling contact fatigue therefore involved the propagation of some kind of 'crack'. As ever, the nature of the contact stress field makes this rather difficult, and it was left to Johnson to make significant inroads into the problem and also to recognize that the amount of plasticity present was always very significant and could not simply be ignored. He successfully found the unifying theme between wear and rolling-contact fatigue, and published key papers on this with A. D. Hearle, Alan Bower and, later, A. Kapoor (14, 19, 21).

Rolling contact (A. Kapoor)

Steel wheels rolling on steel rails provide the low-friction rolling contact that gives railways an energy-efficient way of moving passengers and freight. Wheels roll or slide (or roll *and* slide) on rails, subjecting them to repeated loading. Before replacement, a typical rail may carry some 500 million tonnes, equivalent to 50 million repeated passes of a loaded wheel. The so-called permanent way is anything but permanent: each passage of each wheel is an irreversible event. What load can be supported safely on each tiny contact patch about the size of a small coin? Naturally, answers coming out of a single application of the load will not be correct. KLJ considered the effect of this relentless loading. The material can flow plastically, leading to the development of residual stresses and strain hardening. Wear can change the contact geometry to become more conformal, thus decreasing the stress. Simple concepts from the shakedown of civil structures were applied in the late 1950s and early 1960s to produce the very first shakedown limits in rolling contact. This is, in a sense, a safe contact pressure limit for the material to remain elastic in repeated rolling contact (4, 22). The intervening 40 years saw many research groups developing these ideas further; KLJ and his co-workers continued to produce various key publications investigating the shakedown of surfaces subjected to rolling contact, sliding contact, rough surfaces and oscillating loads, the key ones of which we will now consider.

After his first shakedown paper, KLJ started to model plastic flow and residual stresses. Work on measuring and predicting plastic flow continued throughout this period. In the 1980s the Cambridge group was working on modelling plastic flow in rolling contact, using a dislocation method and traditional plasticity theories modified to model the accumulation of plastic strain with time, a process termed ratchetting (18, 19, 23). Alan Bower used considerable computational resources to solve the plasticity equations to determine the extent of ratchetting in rolling contact (19). Alas, his experiments to mimic this behaviour in twist and tension–compression tests were met by the failure of the specimen by what we now know as

ratchetting failure. Ratchetting failure and ratchetting wear were next on the research agenda. All this research has found decent homes. Joe Kalousek in Canada applied 'pummelling' to design rail and wheel profiles, and ratchetting is currently being used to predict rolling contact fatigue in rails and wheels.

Rolling contact causes cracking and was dramatically brought to public attention in the UK by the catastrophic rail failure at Hatfield in October 2000. In the 1970s and 1980s KLJ had collaborated extensively with British Rail to work on squats and other fatigue cracks caused by rolling contact. Dislocations were used to model a crack parallel to the surface of a passing wheel; subsequently a research student, Bower, developed a model of rolling contact fatigue crack that is driven by Mode I (opening), Mode II (shear) and fluid pressure. These models are now being used increasingly by the railway industry to understand and control rail degradation.

The 1970s saw KLJ, with Cambridge colleagues Stuart Grassie and R. Wielie Gregory, developing dynamic analyses of wheel–rail interaction to address the formation of corrugations (longitudinal sinusoidal waviness on the rail surface, also manifested by longer wavelengths on dirt roads) leading to 'roaring rails' (13). Models incorporating vehicle, bogie, suspension, wheel, contact patch, rail, pad, sleeper, ballast and sub-base are extremely complex, and KLJ's simple semi-analytical approaches demonstrated the importance of pad resilience on dynamic loads at frequencies associated with this phenomenon, work that has led to the use of more resilient pads worldwide. Other models helped demonstrate the role of pinned–pinned response of rails between the two sleepers in developing corrugations. Much of this work has been applied subsequently to real problems by Grassie, who also collected considerable data on rail geometry and dynamic response in days when modern sophisticated equipment was not available.

Adhesion (J. A. Greenwood)

The Bowden–Tabor theory of friction suggests that friction is the force required to shear the junctions that form whenever two solids make contact. An obvious objection to the theory is that these junctions seem not to require a normal force to break them, so why do they require a tangential force? Do solids adhere, or do they not? One of KLJ's earliest publications (3) explained that elastically a circular contact must have infinite tensile stresses round its periphery if the contact area is any greater than the Hertz area for the current load, so any attempt to decrease the load without decreasing the contact radius will induce such stresses— so adhesion is not observed. Alan Roberts found (Roberts 1968) that rubber–glass contacts *were* larger than Hertz theory predicted and that significant normal forces were required to separate the two; his colleague Kevin Kendall suggested that this was perhaps due to the surface energy. An expert on elastic contact theory was brought in, and the Johnson–Kendall–Roberts (JKR) theory was born—and satisfyingly verified (9).

According to the theory, the pull-off force for a circular contact, as occurs between a sphere and a plane, will be

$$P_c = \tfrac{2}{3}\pi R \Delta \gamma,$$

where R is the radius of the sphere and $\Delta\gamma$ the surface energy, so that a direct mechanical measurement of the physical–chemical quantity $\Delta\gamma$ becomes possible. Unfortunately, the physical chemists already used a different formula, the Derjaguin equation:
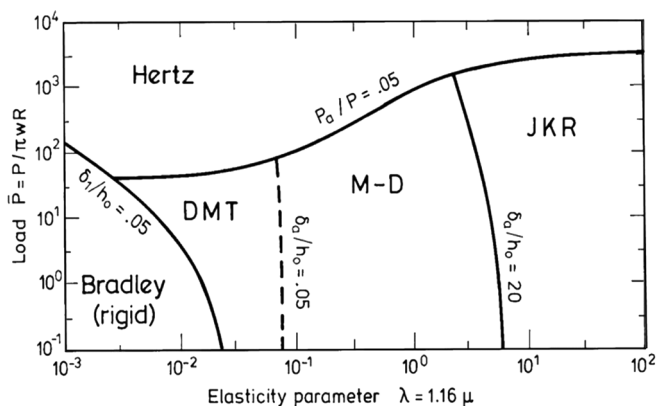
$$P_c = 2\pi R \Delta \gamma.$$

Figure 1. Adhesion map. (From (26).)

Both equations are apparently applicable to all elastic contacts even though neither contains an elastic constant. The difference lies in the contact geometry. In the JKR theory the infinite tensile stresses round the periphery mean that the contact has a neck: indeed, Maugis *et al.* (1976) reproduced the JKR equations by recognizing that this neck is the parabolic crack tip of fracture mechanics and, by applying the fracture mechanics equation, that the stress intensity factor, a measure of the stress singularity, will be

$$K = \tfrac{1}{2}(E^* \Delta\gamma/2)^{\frac{1}{2}}.$$

Tabor recognized that the height of the neck is critical because, of course, surface energy is merely an integral measure of the effect of surface forces, and these have a finite (rather small) range. The ratio of the neck height to the range of action of the surface forces gives the 'Tabor parameter',

$$\alpha = R^{\frac{1}{3}}\Delta\gamma^{\frac{2}{3}}/E^{*\frac{2}{3}},$$

and both equations are correct. The 'adhesion map' (figure 1) (26) details the behaviour of different contacts.

Origins and developments of the JKR theory (K. Kendall, A. D. Roberts and W. Federle)

KLJ's relationship with David Tabor has been mentioned above. The JKR theory was one of the most interesting fruits of their collaboration, specifically with Kendall and Roberts, two of Tabor's research students. Roberts was working to understand how windscreen wipers function. Kendall joined British Rail Research in 1969, trying to understand how rusting iron particles in the brake block stuck to carriage windows, giving them the familiar dirty brown colour. These nanoparticles stuck so hard to the glass windows that it was impossible to scrape them off. They both concluded that some kind of adhesion was taking place, giving 'greater than Hertz' contact patches. Ken was brought into the discussion and agreed to attempt the necessary modification of the Hertz theory; this he achieved the next day as his family were watching the Football Association Cup Final.

Adhesive contacts have a key role in many technological processes such as manufacturing, in which control over contaminant particles is essential, for example in wafer cleaning for semiconductors. Micromechanical devices demand better control over friction and

lubrication. Particle immobilization or release, controlled positioning in reproduction devices, and settling of bio-organisms on surfaces or biotechnologies all need to be better understood for continuing progress. The rising impact of the JKR equation, starting in the 1990s, reveals the steeply growing relevance of small-scale adhesive contact theories in physics and biology.

Ken showed that that the JKR theory is particularly accurate for the analysis of contacts at the micrometre and nanometre scale (28). The interest in adhesion and friction between contacts at this length scale had markedly increased with the introduction of new measurement techniques such as the atomic force microscope and the surface force apparatus (27), as well as with progress in silicon-based microfabrication technology.

A further area of application for Ken's contributions to contact mechanics emerged recently with the field of bio-adhesion. The adhesive structures on the feet of many climbing animals, such as geckos, tree frogs, spiders and insects, are small and soft, and therefore fall within the 'JKR regime' (26). These natural adhesives work well on rough substrates, allow rapid switching between firm attachment and detachment, and possess self-cleaning properties, so that many groups worldwide have started to mimic their properties and build synthetic bio-inspired adhesives.

One of Ken's friends and neighbours in New Square was Walter Federle, also a Fellow of Jesus College, a zoologist studying the function of adhesive organs in insects. Walter often took Ken to lunch in college during his later years, and they discussed bio-adhesion research. Despite his failing health, Ken enjoyed talking about science and he was always particularly interested to hear about his former students and colleagues.

Many important developments in the bio-adhesion field build on Ken's work, such as the understanding of how animals control adhesion via shear forces and how adhesive pads compensate for surface roughness. The JKR theory also forms the basis of the 'contact splitting' principle, which suggests that splitting of a single contact into multiple smaller contacts can lead to enhanced adhesion, providing an explanation for the independent evolution of dense arrays of microscopic adhesive hairs in geckos, spiders and insects (Arzt *et al*. 2003).

Contact mechanics: the book

KLJ's *magnum opus*, his monograph, *Contact mechanics* (15), was a fitting culmination of his studies on the modelling of contact mechanics. Universally regarded as the bible of the subject, it is a source to which one returns over and over again. It is very unlikely to be surpassed or outdated. It has been translated into many languages and has pride of place on many academics' bookshelves worldwide. It will be a long-lasting memorial to KLJ's deep understanding of the topics that formed his life's research.

KLJ AT CAMBRIDGE, 1954–2015: LIFE AND FAMILY

Ken and Dorothy had three children, Marian (born in 1957), Hilary (1958) and Andrew (1962), the last of these when KLJ was enjoying a sabbatical at Brown University. At that time one crossed the Atlantic by ship; Andrew has now been an air traffic controller in the USA for many years, avoiding the sea sickness that affected the family en route to Providence, Rhode Island, on the old *Queen Mary*.

In Cambridge KLJ continued choral singing, initially with the Cambridge University Musical Society under David Willcocks, and later with Collegium Laureatum. He was
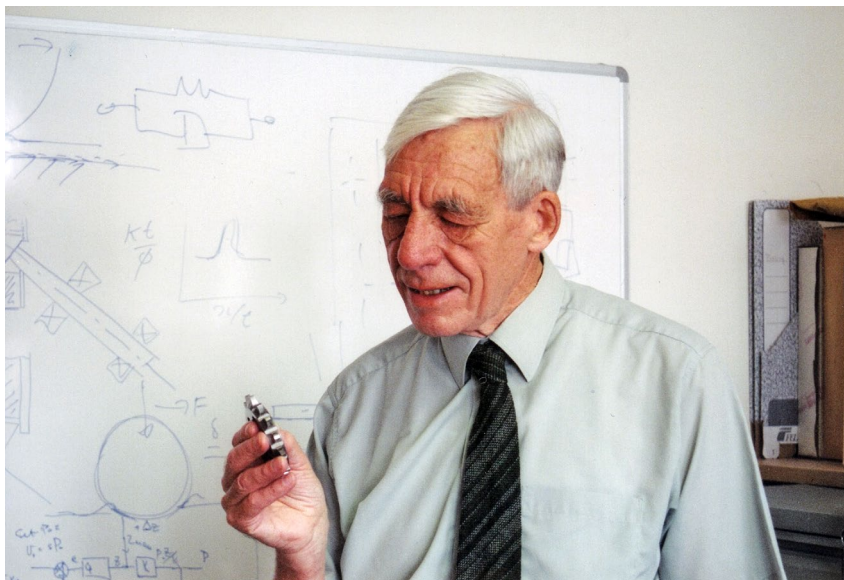
Figure 2. KLJ, an inspiring and dedicated teacher. (Online version in colour.)

President of Cambridge University Swimming Club and encouraged his family to swim, and to swim well. He was much valued as a consummate college man, and is fondly remembered by his many pupils for his well-informed supervisions and by students in the Engineering Department for inspiring and insightful lectures (figure 2). His behind-the-scenes advice was much respected, in for example introducing Sir Alan Cottrell FRS to the Jesus College election, which led to his highly successful Mastership. KLJ was unstinting in his wise advice to younger colleagues, of whom I was one. A close bond developed: I always regarded Ken as a father figure on whom I could rely. We enjoyed many family walking and climbing holidays in the Lake District (figure 3). It was my pleasure to lead Ken up C Buttress on Coniston Dow Crag, a climb he had achieved years previously in his Barrow days. Somewhat less of a pleasure was enabling him to climb Broadstand on Scafell by having him stand on my head to reach some high holds—not, I am now informed by Dorothy, because of an unsteadiness for heights on his part but because of a stiff shoulder, originally injured by a fall at Scout Camp years previously and much later replaced by some mechanical parts.

Ken and Dorothy hosted legions of students, researchers and visitors in their home at Park Terrace and latterly at New Square. Their generous entertainment almost always began with a sherry and included a delicious meal served with large helpings of convivial conversation. Most of the people I have contacted in the preparation of this memoir have extremely happy memories of their kind hospitality. All have commented on how much they valued Ken's innate good sense and stability. The people involved with his research have repeated their admiration of Ken's clever and careful experimental work and the brilliance of his analysis of the results, leading to deep insights into the physical nature of the phenomena he studied. The citation for the Royal Medal in 2003 stated: 'In recognition of his outstanding work in the field of contact mechanics. His work is characterized by elegant experiments, skilful analyses and insightful explanations of observed phenomena.'

Figure 3. KLJ and the author, together with their respective wives, Dorothy and Yayoi, walking in the Lake District in 1990. (Online version in colour.)

If a poor idea or theory was offered, his reply was 'I would be surprised if that were true.' An outrageously silly idea might provoke the reponse 'I would be extremely surprised if that were true.' Mrs Thatcher managed to render him speechless, when she introduced a conversation with him by saying 'We scientists …'.

After retirement in 1992 his life continued rather unchanged: research, college, family and friends. Many holidays were spent in Ravenglass in a cottage from which KLJ enjoyed the Western Lakes. We shared his 70th birthday on top of Bowfell, drinking champagne in the snow. Ken remained as sharp as ever and produced several publications. In the decade after his 80th birthday, mobility started to become a problem with increasing severity. Dorothy was ever supportive. In the last couple of years, life was beginning to be an effort. He welcomed visits to his book-lined home in New Square, but eventually even the short walk down to the Cam was too much (figure 4). On what proved to be his last visit to Wasdale Head in the summer of 2013, as we loaded KLJ back into the car, he said, with a small tear, 'This is the last time I shall see these hills.' Sadly, this proved to be true.

KLJ was extremely modest, a trait that has made collecting this information unusually difficult. So I shall let his modesty and dry, gentle humour speak for themselves by quoting from his acceptance speech for the 2006 Timoshenko Medal, given at the Applied Mechanics Dinner of the 2006 Winter Annual Meeting of the American Society of Mechanical Engineers (ASME), held at the Hilton Chicago Hotel on 9 November 2006 (see http://imechanica.org/node/462).

I must belong to a shrinking number of Timoshenko medallists who actually met the great man himself, that is if 'met' is the right word. It was at the 1956 IUTAM Congress in Brussels. He was always surrounded by KGB men in long black coats. It was impossible to get near enough to see the white of his beard.

However, I can claim to be a good friend of his side-kick: Norman Goodier, Timoshenko medallist in 1963 and co-author of his famous book on *The Theory of Elasticity*. Goodier graduated

Figure 4. Watercolour painted by KLJ shortly before his death.

in Engineering from Cambridge (England, that is!) and came to the United States on a scholarship to the University of Michigan, where he met Timoshenko. Interestingly for me, Goodier's Cambridge PhD Dissertation contained a report of an investigation into corrugation of railway rails. It showed rather more progress on that problem than I managed to make 50 years later.

When Timoshenko emigrated from Russia to the US, he found it an undeveloped country as far as mechanics was concerned, which led to the foundation in 1927 of the Applied Mechanics Division of ASME, with Timoshenko as first chairman. No doubt he was pleased to find an acolyte with a sound Cambridge training in mechanics. Goodier capitalized on the situation in the time honoured way, by 'marrying the boss'[s] daughter'.

[…]

In common with vibration analysts then and since, I worried about assessing the damping. I became convinced that in most practical cases of structural vibration the damping arose principally by slip at clamped joints. On returning to the university I made this the subject of my PhD. This topic brought me into close contact with R. D. Mindlin and his group at Columbia University, who were studying Hertz contact under the action of tangential friction forces. That was the start.

During my time as a Graduate Student I was profoundly influenced by three books: Timoshenko and Goodier's *Theory of Elasticity;* Den Hartog's *Mechanical Vibrations* and Bowden and Tabor's *Friction and Lubrication of Solids*. I tried to copy the simple and direct style of all three when I came to write my own book on *Contact Mechanics*. I have been fortunate that contact mechanics has become an expanding field. In the early days I had a visit from Don Conway of Cornell, who expressed surprise that anyone could fill their time with contact problems!

[…]

I must also take this opportunity to acknowledge my debt to David Tabor, who died last year aged 92. He not only invented the word 'tribology'*, but along with F. P. Bowden in the Cavendish Laboratory in Cambridge, he established the subject as a respected scientific discipline. Many members of ASME look back with pleasure and satisfaction to time spent in that laboratory.

[…]

About the time I formally retired from teaching in '92, microprobe instruments such as the Atomic Force Microscope and the Surface Force Apparatus were being developed mainly in physics departments, and used to study friction on the atomic scale. Irwin Singer of the Naval Research lab, in Washington, observed that this activity was going on in complete isolation from the traditional world of engineering tribology. He organized a NATO ISA [Advanced Study Institute] in Braunlager [Braunlage] to bring the two communities together. It was an eye opener for both sides. My activities changed quite dramatically from wheel/rail contacts, whose diameters are about 10 mm, to contacts of a few micrometres or less. At this scale molecular adhesion between the surfaces becomes a major effect. This meant that I had to make friends with physicists, for whom friction has suddenly become a fashionable subject. Maybe they will be able to explain the question that so exercised Bowden and Tabor 60 years ago: the relation between adhesion and friction. They picked up [a] paper of mine on adhesion in Hertz contacts, written in 1971 with two graduate students: Kevin Kendall and Alan Roberts which suddenly became famous as the 'JKR theory'. To bask in this celebrity, my co-author Alan Roberts recently entered JKR into Google and was rewarded by pages and pages of citations … to J. K. Rowling, the author of Harry Potter.

Honours

1982   Fellow of the Royal Society
1983   Honorary Fellow, American Society of Tribologists
1987   Fellow of the Royal Academy of Engineering
1995   Honorary Fellow, University of Manchester Institute of Science and Technology

Awards

1961   James Clayton Prize, Institution of Mechanical Engineers (also in 1969)
1983   National Award, American Society of Lubrication Engineers
1985   Tribology Trust Gold Medal, Institution of Mechanical Engineers
1998   George Stevenson Medal, Institution of Mechanical Engineers
1999   William Prager Medal, Society of Engineering Science
2003   Queen's Medal, Royal Society
2006   Timoshenko Medal, Applied Mechanics Division of the American Society of Mechanical Engineers

* Tabor actually used the term 'tribotechnology'; Peter Jost, who died in June 2016, is usually credited with the term 'tribology' in his eponymous report written 50 years ago (Jost 1968).

ACKNOWLEDGEMENTS

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