Some significant South African contributions to engineering

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Significance:

To mark the centenary of the University of the Witwatersrand (Wits), we review several major engineering achievements made over the last century by South African citizens, or individuals educated in South Africa – several of these contributions were made by Wits graduates and academic staff members. Equally significant are some outstanding contributions to engineering education. There is no sense in which this review is exhaustive but is more a reflection of the authors' personal interests and expertise.

The University of the Witwatersrand (Wits) celebrates its centenary in 2022. As part of this celebration, we recall some of the contributions made by South Africans to the most significant engineering achievements of the last century. Space limitations have forced us to limit our selection to a handful of these many brilliant contributions – many of which have an association with Wits. The selection we have made is inevitably coloured by our personal knowledge, our experience and interests, but also our ignorance. We offer no ordering or prioritisation as to whom we think might have contributed most. On topics such as this, one is unlikely to ever reach consensus.

This leads us to another issue: what is engineering, and who should be categorised as an engineer? In recent times, a lot of research and development work is undertaken by large teams, with members drawn from a multiplicity of different disciplines. Examples are the ITER nuclear reactor and the Large Hadron Collider whose missions are to investigate, respectively, the viability of fusion power generation and the frontiers of particle physics. Are these physics projects? The answer is surely 'yes'. Are these projects undertaken predominantly by physicists? The answer is 'no'. Both projects involve mathematicians, chemists, computer scientists, and engineers of many varieties.

To further muddy the waters, one might ask the question: what type of engineer is so and so? As engineering educators, we find a diversity of opinions on this subject too. At one end of the spectrum, one finds institutions that offer courses that are arguably over-specialised such as engineering acoustics. After completing such a course, we suppose that one becomes an acoustics engineer. Towards the other end of the spectrum, Cambridge and Oxford, for example, offer courses in engineering science which are broadly based and focus on the fundamentals of mathematics, physics and chemistry. One also finds courses such as global engineering design that could encapsulate almost anything. Our theory of the case is that categorising engineering into electrical engineering, mechanical engineering and so on has clear administrative benefits, but one should be wary of letting this categorisation produce siloed thinking. Engineering is a broad discipline with porous and poorly defined boundaries.

In discussing the South African engineers that we believe have made outstanding contributions, the reader will notice that some start out as engineers of one variety and then metamorphose into what one could categorise as mathematicians, physicists, computer scientists, medical doctors and so on. These developmental changes can occur in the opposite direction too, when mathematicians, physicists and chemists become engineers. We believe that this adaptability of thinking is to be lauded, and for that reason we believe that a broad-based education that focuses on the fundamentals is the correct way to foster the engineers of the future. While it is surely right to recognise and celebrate our past achievements, it is arguably even more important to think about the things that are likely to facilitate the production of future generations of outstanding engineers.

We have grouped our selected outstanding engineering contributors into seven topic areas. In each case we provide an introductory overview, with person-specific contributions provided in the supplementary material.

Biomedical engineering

Reginald William James (1891–1964) was Professor of Physics at the University of Cape Town from 1937 to 1956. James was a Londoner who entered St John's College Cambridge in 1909 to study natural science. He recalls that his lectures on physical optics combined the best content with the worst of delivery.[1] This ambivalent experience did not appear to do any long-term damage to his development as a physicist. In the fullness of time, he made a world-wide reputation for himself in X-ray crystallography. He was a fine experimenter, neat, careful and thorough, and an excellent designer of apparatus. His book, *The Optical Diffraction of X-rays*, first published in 1948, has been reprinted four times, and is rightly regarded as a masterpiece. In 1937, James left a position at Manchester University to take up a professorship at the University of Cape Town. In 1955, he was recognised for his services to science and elected Fellow of the Royal Society. His professional career reached its culmination when he served as Vice-Chancellor of the University of Cape Town during the absence of T.B. Davie in 1953 and 1955, and after Davie's death, from 1956 to 1957.

James had another distinction of relevance – he had two Nobel laureates amongst his former students. Alan Cormack developed the theory that led to the invention of the CT (computerised tomography) scanner, which uses X-ray scanning to probe the human body. Using related techniques, Aaron Klug was able to determine the fine structure of viruses using electron microscopy. The personal contributions of A. M. Cormack and A. Klug are covered in more detail at ***Biomedical Engineering*** in the supplementary material.

Civil engineering

Here we celebrate the achievements of two of South Africa's most famous civil engineers: Jack Zunz and John Burland. One operated above ground level, while the other worked beneath it. Zunz is connected with the design and construction of some of the world's most famous structures, while Burland is credited with saving them.

Structural engineering, which is part of civil engineering, is the study of the 'skeletal properties' of constructed structures. The work of structural engineers includes the stability, strength, and rigidity of structures such as high-rise buildings, roads and bridges. This work must be integrated with that of architects and building services engineers – structural engineers also play an important role in the supervision of large-scale construction work.

Geotechnical engineering is another branch of civil engineering, and concerns the engineering behaviour of foundation materials such as soil, rock and clay. Computer modelling plays a major role in both structural engineering and geotechnical engineering. These calculations can be used to assess the strength and compliance properties of large buildings and structures. Computer modelling can also be used to determine the stability of slopes and cliffs, and establish the load-bearing capacity, settlement and deformation characteristics of foundational materials. The personal contributions of G. J. Zunz and J. Burland can be found at ***Civil Engineering*** in the supplementary material.

Engineering education

The provision of quality engineering education is a matter of prime importance in South Africa. One clear example, which nobody can realistically seek to replicate, was the training that R. W. James gave to Cormack and Klug. It is all about establishing a strong basis in the fundamentals, and revelling in the challenges of intellectual diversity.

Despite glowing examples such as this, it is regrettable that one still finds the viewpoint that teaching is where 'real academics' go to die. Good teaching must be valued, with fast-acting managerial feedback loops used to correct poor performance. In our experience, poor teaching is more to do with inadequate training than wilful negligence, or an unfortunate attitude.

It goes without saying that to teach well, one requires proficiency in the material one is teaching – this goes side-by-side with being active in research. Suffering, periodically, the slings and arrows of hostile reviews keeps one on one's toes. Most quality institutions put great emphasis on teaching mathematics, physics and chemistry to their undergraduate students. It is not uncommon to have formally trained mathematicians, chemists and physicists on the academic staff of engineering departments. They also encourage breadth – students from both Oxford and Cambridge graduate with an MA in engineering science, although the students have a large selection of subjects to choose from in their final year.

Displacement activities such as the appreciation of 18th-century French poetry in quality engineering courses is uncommon. While there is no harm in such interests, in our opinion they do not fit into an undergraduate engineering curriculum – there is just too much other material to cover. Another bugbear of ours are ratings tables that encourage universities to become 'popular' so that they can attract both students and government funding. This encourages the provision of lightweight courses that are directed more to entertainment than to learning. Establishing sound fundamentals is hard work, and staff and students alike should appreciate this. Great teachers are loved by their students. They teach, encourage and guide their students, but they do not indulge them.

We pay homage to two great intellects and outstanding teachers: Arthur Bleksley taught applied mathematics to physicists and engineers at Wits, while Seymour Papert was particularly interested in learning processes in young children. Their personal contributions appear at ***Engineering Education*** in the supplementary material.

Feedback control and circuit theory

In many ways, circuit theory and feedback control came together with the development of the telephone. Prior to the invention by Lee De Forest in 1906 of the 'grid Audion', propagation losses limited the distances over which telegraphy was viable. The Audion was the first successful three-element (triode) vacuum tube, and the first device which could amplify electrical signals. These devices are inherently nonlinear. Therefore, every time a signal was amplified in an early telecommunications network, noise and distortion would be amplified too. A second invention was required to tackle this problem. On 2 August 1927, a young Bell Labs engineer named Harold Black invented the feedback amplifier in a 'flash of insight' while riding the Lackawanna Ferry across the Hudson River on his way to work. Black recalled, 'I felt an urge to write, but I had nothing to write on and so I picked up my morning paper, which contained both a date and a blank page'.

It turned out that Black's feedback amplifier had a tendency to 'sing', or become unstable. Ringing caused by gain increases was expected, but ringing due to gain reductions required explanation. Feedback instability occurs in mechanical engineering systems too – an early example being Watt's flyball governor. These systems were designed so that as the speed of the engine increased (perhaps due to a load reduction), the flyballs spread apart, and the throttle on the steam supply was closed. As manufacturing processes improved, and the damping and friction in these systems reduced, they tended to 'hunt' – another form of oscillatory instability. In 1932, a Swedish engineer by the name of Harry Nyquist, wrote his famous paper 'Regeneration theory'[2], which explains how both gain increases and gain reductions might cause feedback instability. His so-called 'Nyquist diagrams' allowed one to design good systems using bad components. Nyquist's paper on regeneration theory is an important component of the connective tissue that binds mathematics, feedback control, and circuit and communications theory together. Nyquist made other important contributions to signal processing and communications theory.

Three South African theorists have made important contributions to the development of optimisation, control and circuit theory, illustrating their close connections. They are O. Brune, D. Q. Mayne and D. H. Jacobson. Their personal contributions are described at ***Feedback Control and Circuit Theory*** in the supplementary material.

Radar and communications technology

The Second Boer War was the first time that wireless communications had been deployed in a time of war. In years prior, the British military had some success with the development of early wireless communications systems, but under conditions very different to those found in the South African veld. At the time, Maxwell's equations were in place, but many facets of electromagnetic theory, antenna design, and circuit design were still poorly understood. There were no amplifying devices such as transistors or vacuum tubes, and any notion of 'selectivity' was laughable. The early 'Marconi' equipment probably operated in the low megahertz range depending on the length of the antennas used. Given that the first military testing of Marconi's equipment began in 1896, with the Boer war breaking out only three years later, it is remarkable that this early war time deployment achieved anything useful at all.[3] On the brighter side, the fields of applied electromagnetics and radio science were both evidently 'useful', and also wide open to the memorable contributions of another three great South African engineers – B. F. J. Schonland, G.R. Bozzoli and T. L. Wadley – whose personal contributions are described at ***Radar and Communications Technology*** in the supplementary material.

Spatial estimation and geostatistics

Electrical engineers are familiar with the notion of a 'filter' as a circuit with frequency-selective properties. These filters might block high frequencies, or extract signal components in a certain frequency range.

Further developments came with the application of statistical ideas to signal processing. One might have a signal that is distorted and corrupted by noise, and one might be tasked with extracting by some means or other the undistorted signal from its distorted noisy version – this is another form of 'filtering'. One can talk about an 'optimal filter' as one that provides an output that is closest, in some sense, to the original undistorted signal. This type of filter is required to attenuate noise and transmission distortion in long-distance telephony. Solutions to this type of problem go back to the work of Kolmogorov and Weiner in the 1940s. Weiner extended these ideas to cover 'prediction' problems, whereby the future value of a quantity is predicted from its noisy present and past values. A well-known application of prediction theory was anti-aircraft gun aiming, whereby a Weiner 'predictor' was used to estimate the future position on an aircraft so that anti-aircraft guns could be fired in front of it.

In the 1960s, these ideas were extended to cover signals and noise that had time-varying statistical properties. This new theory was named Kalman filtering after its originator R. E. Kalman. Kalman filtering also brought the so-called state-space modality into the picture. Kalman filters also play a central role in the solution of optimal control problems where they are used to 'estimate' the internal state of a system given access to the system's input and noisy output measurements. Estimation is also a term used to describe 'parameter estimation'. Parameter estimation is used to obtain estimate parameter values given noisy input and output measurements. In each of these problems the independent variable is 'time'.

Our focus here is spatial (rather than temporal) estimation. Let us consider, as an example, a Christmas pudding with coins buried in it. Let us suppose that we had a playful sister who helped make the pudding and distribute the coins in it. It so happens that she is also a trained statistician who is prepared to provide us with a list of locations where coins are either buried or not buried. She also provides us with statistical information about the spatial distribution of the coins (*the variogram*).

Accepting the challenge, we set ourselves the task of estimating the locations of the undisclosed coins using the information provided. We may well have thought that some data points were more significant than others, and that some form of weighting scheme was required. Upon further contemplation, we may have thought that particular emphasis should be placed on data that happened to be near a particular investigation point; this is *data proximity*. We may have also thought that we should discount data points that are close to points that we had already considered – *data redundancy*. If we already know about one point in space, there is arguably little new information to be gained from additional data points in the immediate neighbourhood. A third thing we might want to think about is *spatial continuity*. Suppose there are lines in space, that pass through our test point, that are equally likely to contain a coin. From this brief discussion we get the idea that spatial estimation is about finding an optimal weighted average of given spatial data in order to estimate the probability of finding a coin at an arbitrary location in the pudding.

The spatial estimation problem is the field pioneered by the South African geologist and engineer D.G. Krige. He conducted this work primarily in the context of gold mining, with the Christmas pudding acting as a surrogate for the gold-rich Witwatersrand. Krige's contributions are described at ***Spatial Estimation and Geostatistics*** in the supplementary material.

Vehicle dynamics

Vehicle dynamics is a multi-faceted topic involving predominantly mechanical and electrical engineering, but chemistry and materials science become important in fuel and tyre design. In modern cars there are multiple motor-driven sub-systems that fall under the catch-all umbrella title 'mechatronics'.

Erasmus Darwin, grandfather of Charles Darwin, was a physician, philosopher, slave-trade abolitionist, and poet. As a physician, he had to visit patients in nearby villages using a horse-drawn carriage as transport. At the time, vehicular steering was achieved by rotating the front-wheel beam-axle assembly about its centre. This meant that the front wheels had to be small (so they could fit under the carriage during steering) – while steering the carriage took on the geometry of a three-legged stool. The small front wheels also led to a rough and uncomfortable ride (the front wheels tended to fall into ruts and potholes in the road) – a problem not entirely unfamiliar 200 years later in present-day South Africa! This 'unfortunate' steering geometry also meant that the carriage tended to capsize under cornering.

Erasmus Darwin, although a medical man, set about re-designing the steering system for horse-drawn carriages. In his new design, the front-wheel radius could be increased by mounting the wheels on short steerable stub axles near the front corners of the vehicle. Provided the steering linkage was designed correctly, the front wheel would run tangent to the track centre line, thereby eliminating scuffing between the wheels and the road. This new design meant that the carriage was easier for the horses to pull, it was less likely to overturn, it provided a more comfortable ride, and there was significantly less 'tyre' wear. As vehicle speeds increase, handling and stability issues become important.[4]

In the 1970s, Dr Herbert Scheffel, inspired by Darwin's work, set about solving stability and tyre-wear related issues that were plaguing the narrow-gauge South African railways. His ground-breaking work led to what is now known as the 'Scheffel Bogie', which was introduced to the South African Railway fleet of ore-carrying wagons in 1975. Scheffel's breakthrough enabled speeds of 245 kph (152 mph) to be achieved on narrow Cape Gauge railway lines. A little later, another South African 'speed freak', by the name of Dr Rory Byrne, emerged to become one of the world's top Formula One race car designers. The contributions of both men are discussed in more detail at ***Vehicle Dynamics*** in the supplementary material.

Acknowledgements

While writing a wide-ranging historical review such as this, one is constantly aware that: (1) there are likely to be differences of opinion as to 'balance' and who should be included, and (2) that there are numerous people 'out there' who know a lot more about specific topics than we do. In order to mitigate both of these concerns we have benefitted from the guidance of several colleagues.

Competing interests

We have no competing interests to declare.

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