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DESIGNER'S DELIGHT AND DILEMMA*

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IT IS WITH pleasure that I take this opportunity of presenting the first Engineering Inaugural Lecture in this University. Almost exactly a year ago I took up my appointment to the Inaugural Chair of Engineering, and in a few months from now our first students will be completing Part I of their four-year course for the B.Sc (Engineering) Degree with Honours. My colleagues and I have been much encouraged by the help we have been given by many individuals and groups, without whose generosity we should not have raised the necessary capital to launch the new Faculty. I have been impressed particularly by the obvious goodwill towards this project from people in and out of the University, and it augurs well for the success we are all determined to achieve in the future.

I am happy to report that the basic organization of the courses has been completed, and the Regulations for the new degree have been drafted with the aid of the Engineering Curriculum Advisory Committee, a group of practising engineers whom I have invited to advise us on course content and related matters.

I am particularly glad to have with us the President of the Rhodesian Institution of Engineers and many fellow Members, for it was largely due to the initial efforts of the Institution that the project was launched. The Chairman of the Rhodesian Association of Consulting Engineers and several fellow Members are also with us tonight, and we want them to know that their support and encouragement are greatly valued. Several Ministries, Municipalities, and other organizations are also represented here, and we are encouraged by this, but time and space do not permit me to go into detail. I must, however, associate myself warmly with the Principal's tribute to the Fund Raising Committee and particularly to its Chairman, Mr Eddie Marsh. Their success in coming so close already to the target sum has been a vital link in the chain of events leading up to the successful launching of the new Faculty. We want them, and the generous donors they contacted, to know that they have a very real share in whatever good is achieved for the people of Rhodesia through the new Faculty.

I have thought it appropriate in this lecture to share with you some of the problems and outlook of engineers of any discipline, for our Faculty is one of broad base, covering, as it does, the disciplines of Civil, Electrical, and Mechanical Engineering. It may be that I shall be tempted to provide

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illustrations mainly from my own discipline, Electrical Engineering, but I shall try to resist this.

I have referred first in the title to the 'Designer', and I think this is correct, for engineers are concerned primarily with design. Not only are they concerned with design of structures, circuits, and machines, but they are also involved deeply in plans of operations, in maintenance schedules, and in production runs.

Society continues to require of the engineer that he keep on improving the manner in which he harnesses the resources of Nature, and Society never relaxes its demands that he make these resources available in forms that will not only sustain its life, but also continue to improve its standard of living and its health. The consciousness that Society urgently needs his services certainly helps to make our engineering designer's work a delight, but he is also often in a dilemma, for the two last-named demands are often mutually exclusive.

Let us trace some of these trends as they were developed over the centuries of recorded history.

Historical Outline. Engineering has certainly been practised for a very long time. Earliest records reveal that civilization has depended on engineering for its progress. In ancient Egypt and Mesopotamia they needed flood control of the Nile and the Euphrates; indeed Noah was deeply involved also in flood control and then, when the floods got out of hand, he found a way round the problem by turning his attention to naval engineering!

About 4 000 B.C. saw the construction of the Nile dam at Memphis (Roux, 1957), 3 000 B.C. the installation of a piped water supply, drainage, and sewerage works in the Indus valley, and 2 500 B.C. the Step Pyramid, oldest known building of hewn stone in the world (Kirby, 1956). What tremendous obstacles those ancient engineers overcame as they had the huge blocks manhandled up their inclined planes! But time was long in those days, and perhaps those due to occupy the tombs under construction did not press as hard as they do today to occupy the rectangular concrete ones we call flats! In 2 000 B.C. they designed and constructed bathroom facilities of high standard on Crete, and in the same epoch Semiramus built a large bridge across the Euphrates. Yes indeed: engineering has been practised for a very long time!

Modern engineering practice owes much to the Greeks and the Romans. The Greeks gave us the concept of regularity (Evans, 1964); indeed, Euclid's geometry (300 B.C.) is still the foundation of much of our drawing and surveying. The Romans had a genius for the development of organizational methods and skills, and for setting up well-disciplined projects; and today we can still see several of their strong, well-proportioned structures of impressive grandeur.

We move quickly through the Middle Ages and the Renaissance, and come now to the nineteenth century and the Industrial Revolution. Up to this period engineering had been progressing at a steady rate, but when iron gave way to steel, and when steam and electric power were pressed into the service of man, technology received an immense accelerative thrust (Finch, 1951). Appropriately it was during the nineteenth century that the first professional engineering institutions were formed, and professional engineering was born.

The first professionals were military engineers. They had to be ready, at short notice, with ingenious and workable methods of building bridges for the army, using whatever materials and labour were to hand. Their training was rigorous, and the demands made upon their skills were stringent. They soon earned high status, and tended to form themselves into societies to ensure that the high standards of their profession would be maintained by all members. Non-military structural work was undertaken by civilian engineers, and in time they too displayed a high level of competence. To distinguish them from their military counterparts they were called Civil (i.e., civilian) Engineers (Staub, 1964). To maintain high standards, promote discussion, and control entry to the profession, the civil engineers formed the Institution of Civil Engineers in 1818 (Norrie, 1956).

By 1847 industry and transportation were dominated by the steam engine, and there was thus an identifiable area of engineering practice in the field of mechanics. This was the year that saw the founding of the Institution of Mechanical Engineers (Burstall, 1963; Parsons, 1947).

Later the use of electricity in machines and communications had become of sufficient importance to warrant the formation in 1871 of the Institution of Telegraph Engineers, and this later became the Institution of Electrical Engineers (Dunsbeath, 1962).

Our own Rhodesian Institution of Engineers, which combines several disciplines, including the above three, is committed to the same standards of conduct, integrity, pursuit of excellence, and control of membership, as its illustrious forebearers.

Towards the close of the last century there came two turning-points in the technology that had begun to expand so rapidly during the earlier part of that century; first there was the advent of mass-production and automation, pioneered by men like Henry Ford; and secondly there was the demise of the back-yard inventor, and his replacement by the research team in the high-powered laboratory, pioneered by men like Thomas Edison. Both developments provided further acceleration of the rapid growth of technology at that time (Toffler, 1971).

Coming now to the twentieth century, and all the sophistication and intricacy of modern engineering, we may well wonder whether engineering is science or art; so let us now consider this question, for it will help us appreciate some of the delights and dilemmas of the designer.

Engineering: A Science or an Art? First, is it Science? Yes, engineering is, among other things, a Science. Society's insistent demands have forced our harrassed engineer to keep pushing the scientific theories and materials of his day to the limit in order to find solutions, often ingenious solutions, to the practical problems thrown up by that pressure. We find him accepting gladly the fundamental knowledge that flows from the work of that dedicated discoverer and analyser, the Pure Scientist. But the engineer's pursuit of this knowledge is motivated by his desire to apply it, to put it to work, in meeting the technological demands of a clamouring Society, and this approach is bound to be different from that of the Pure Scientist.

Look, for example, at Archimedes; he was sometimes a Pure Scientist, and sometimes an Engineer. See 'Archi', the Pure Scientist, lying on his back in his bath where he established one of the fundamental laws of Physics. His discovery so excited him that he caused a commotion in the street (Fig. I). But when it came to the practical business of lifting up the water from the well or flume, it was 'Medes', the engineer with his ingenious screw pump, that came to the fore.

Figure 1: ARCHIMEDES: MAIN STREET STREAKER, SHOUTING 'EUREKA!' (Drawn especially for this publication by Miss M. Phear).

Modern engineering is a rather special form of Science, for present-day design is often carried out at the frontier of that which can be achieved, and this is usually *beyond* the frontier of knowledge. But knowledge is always ahead of theory (for theory covers only those aspects of knowledge that have been formulated into a generally useful description). When a design is based only on theory it is necessary to use 'Factors of Safety' because physical theory can describe no more than what is usually a drastically-simplified version of physical behaviour, and the designer must protect against failure or malfunction that could be caused by those physical conditions that could not be taken into account by the theory.

Often knowledge is so scant, and theory so limited, that the designer has to resort to the use of a model. It may be a physical scale model or it may be a mathematical model. Sometimes the results can only be interpreted in terms of correlation coefficients, standard deviations, and regression lines. Always the engineer must check whether the theory holds good on which his calculations are based, and if his design will meet the requirements imposed by practical application.

Let us take two examples of the above process in which the audience can participate:

(1) *The bouncing-ball postulation,* You are invited to postulate an answer (with reasons, of course!) to the problem posed in Figure 2. Your answer will be based on common sense or on learned theory. Some people will no doubt predict that, because of the spin, the ball will head in the direction D after bouncing at C; others will predict the opposite, i.e., that, again because of the spin, it will head towards B after bouncing at C; and yet others will say it does not matter anyway! But suppose the success or failure of, say, a space project could be affected by the accuracy of the prediction, it

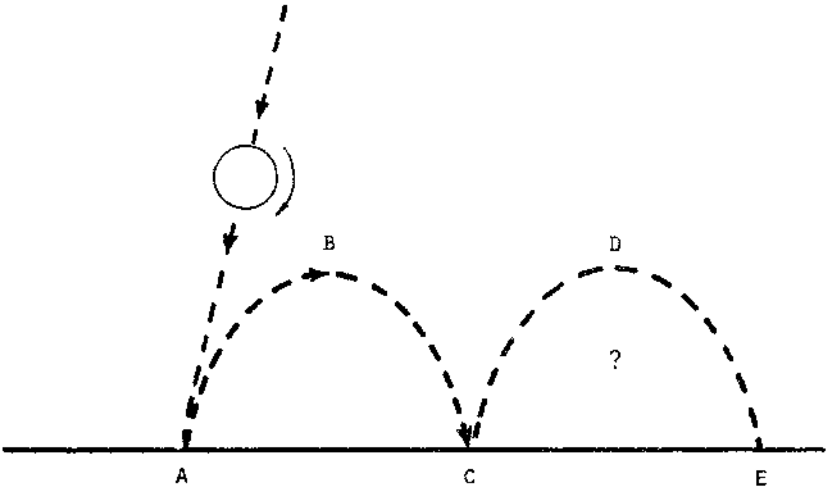

Figure 2: THE SPIN ON THE BALL CAUSES IT TO FOLLOW TRAJECTORY A B C AFTER BOUNCING AT A. WHAT WILL BE THE TRAJECTORY AFTER BOUNCING AT C: WILL IT BE C B A OR C D E?

would be imperative to 'get it right', and advisable that we try it out in practice by a controlled experiment. When we do precisely that, using a high-elasticity ball in our demonstration, we confirm, of course, that you were quite right; the spin reverses after each impact, causing the ball to follow trajectory A B C, C B A, A B C, and so on. Or were you one of those who predicted A B C, C D E?!

(2) *The ink-bottle postulation.* Here is another illustration. Suppose equal quantities of red and blue ink are contained in identical bottles, A and B. Transfer a small quantity of red ink from bottle A to bottle B. Mix thoroughly the red and blue ink in bottle B, and then transfer the same quantity as before of the mixture back from B to A. Next, mix thoroughly the contents of bottle A. Now both bottles have again the same quantity of ink in each. Which of the two bottles is the more contaminated by the colour of the other? (My wife's first response was to observe that it would be a disgraceful waste of good ink!)

Probably you will take a short cut by formulating a theory applicable to this situation, and possibly the reasoning will go something like this: 'Bearing in mind that a small quantity of *pure* red ink went from A to B, but that the same quantity of *mixture* went back from B to A, it follows that B is more contaminated with red ink than is A with blue ink.' Simple! Theory is so helpful. But good designers should test any new theory or supposition before they use it. (We remember the bridges that fell down, the transformers that blew up, the 'unsinkable' ships that went down on maiden voyages, to say nothing of the handle that fell off your pan the other day—all because design assumptions had not been thoroughly tested before incorporation.) So let us test whether or not the theoretical conclusion we came to concerning the ink bottles is correct, using numbers specially chosen to make the arithmetic easy. Suppose bottle A starts with 90 cc of red ink, and bottle B with 90 cc of blue. (a) Transfer 10 cc of red ink from A to B. Mix the 10 cc of red and the 90 cc of blue ink in B. (b) Now transfer 10 cc of the mixture back to A.

We calculate the respective volumes of red and blue ink in each container as follows: After operation (a) we have 80 cc of pure red ink in A, and we have 90 cc of blue, plus 10 cc of red ink, in B. The mixture in B is 90 per cent blue, and 10 per cent red. The 10 cc of mixture in operation (b) has, therefore, 9 cc of blue and 1 cc of red in it. After operation (b) we have 9 cc of blue and (80 + 1) cc of red in bottle A, and bottle B has (10—1) cc of red and (90—9) cc of blue. Our calculation has indicated that each bottle is equally contaminated! (If in doubt we should repeat the calculation using different quantities but being careful that they meet the requirements set out above.) Alas for our theory: the calculations show that it was wrong, plausible though it seemed!

We see from the above example that (i) even 'cast-iron' theories may lead to wrong conclusions; (ii) the more highly trained to theoretical reasoning, the more susceptible one may be to this kind of error; and (iii) it is immensely helpful to put in some practical values with the aim of trying out the validity of any unproved theory proposed as an aid to our design.

Yes, engineering is indeed Science. But it is also Art. We noted that Archimedes was both Pure Scientist and Engineer; we recall now that Leonardo da Vinci was not only a great painter but also an engineer. For example, he took the first faltering steps in aircraft design in addition to applying his mind to military engineering problems. But he had no research-and-development organization, and so it is for his other art forms that we remember him most (Kirby, 1956).

I am going to project now a picture that I took of Ashness Bridge above Derwent Water in the English Lake District, a place of rare beauty, loved by artists. But the focal point of this beautiful picture is, mark you, not the lake or the mountains, or the trees or the stream: it is the *bridge*, a bit of common engineering, serving the community in a practical, down to earth, manner. And no wonder this is so; that old stone bridge has form and line that makes it a fitting centre-piece of this beautiful scene.

But engineering design is also an art of a different form. I refer to the art of compromise in the decision-making process that is at the heart of engineering. Whereas the Pure Scientist can usually regard something as either right or wrong because it accords with or violates a fundamental law, the engineering designer is seldom allowed that privilege. For example: his urge to provide technical excellence on the one hand may be counter-balanced on the other hand by the equally compelling urge to conserve resources and to keep costs to a minimum, or suffer crushing defeat from his competitors. Although his will be the *delight* of the challenge met and the achievement of that which maybe seemed impossible, his will also be the *dilemma* of the cost-conscious decision, a process which is as much a part of art as 'the agony and the ecstasy' of a Michael Angelo.

We see then that the art practised by the engineer is mainly in the decision-making process, in which he weaves into one thread many strands of consideration representing science; technology; men and their organization, safety and health; timing; availability and properties of materials; accounting, economics; law; communication; pollution; and aesthetics — to name but a few. It is fitting therefore that at this University we have chosen to teach Engineering in its own Faculty, distinct from Arts, Education, Medicine, Science, or Social Studies, yet having strong links with them all.

Let us now seek to illustrate some of the twin principles set out above.

Some Examples of the Science and Art of Engineering. I shall confine myself to three examples: one illustrating the importance of the art of good communications; one illustrating, from the life of Marconi, the way in which engineering endeavour is sometimes carried out beyond the frontier of knowledge; and, finally, an illustration of the delights and dilemmas of those of us who design courses to prepare young engineers for their involvement in the 'technology explosion' of modern times.

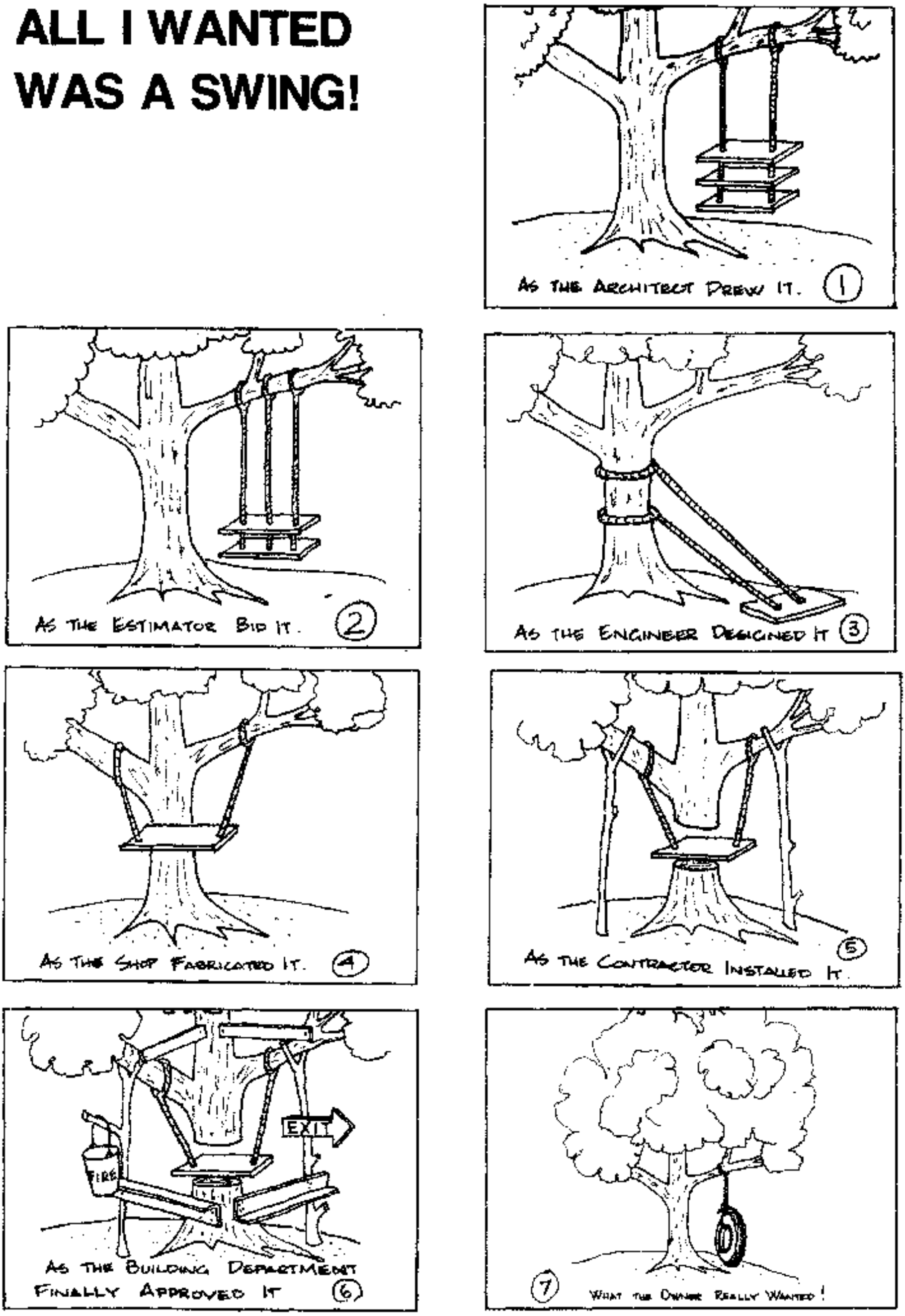

Figure 3: THE IMPORTANCE OF GOOD COMMUNICATION IN ENGINEERING PROJECTS. (With acknowledgments to Roberts Construction Co. (Rhodesia) Ltd. for their kind permission to reproduce these drawings from the Roberts Construction Bulletin.)

Good communication. The message of Figure 3 is obvious, and it must be confessed that the finger is pointed with some justification! The Science used in the engineering problem must be accompanied by the Art of good communications. It is important that the problem should be clearly defined so that the one who sets out to solve it, or to find a way around it, has a clear objective; and his solution in turn must be clearly transmitted to the technicians and others entrusted with the important tasks of detailing and of construction.

Radio Communications. This year (1974) marks the centenary of the birth of that great engineering pioneer, Guglielmo Marconi, the father of radio communications. Michael Faraday and Clerk Maxwell had propounded a remarkable theory which described possible propagation through space of electromagnetic waves they had never yet encountered. Theirs was one of the finest pieces of scientific reasoning recorded in history (Eastwood, 1974). In 1887 Hertz managed to generate electromagnetic waves, but it was Marconi who in 1894 first developed the use of these radio waves for communication purposes. Spurned by the Post Office in his native Italy he travelled to England where he secured the support of W. H. Preece, Chief Engineer of the British Post Office. In 1897 the Marconi Company was formed in England and, while demonstrating his radio transmitting and receiving equipment to the Fleet in 1899, he noticed a curious phenomenon: he found it possible to remain in radio contact with the ships even after they had sailed a considerable distance over the horizon (Jolly, 1974). Here he found himself in a situation not covered by the scientific theories of his day. He was out beyond the fringe of knowledge, and the engineer in him thrust him into the unknown with the postulation that his radio waves would reach great distances by a mechanism still to be discovered, even though theory insisted they would be limited severely by the same obstacles that obstruct light waves.

Risking financial disaster Marconi set up a trans-Atlantic radio link, with a transmitter at Poldhu on the Cornish coast, and a receiver on the Newfoundland coast, 3 500 km away. 'It can never work,' said the critics 'Why, there is between these two sites a wall of water rising 160 km above the straight line joining them, and whoever heard of a radio wave penetrating such a barrier?' But Marconi battled on, his confidence strengthened by the tentative tests carried out earlier with the Fleet. He crossed the Atlantic to the receiving site in Newfoundland and, at the appointed time on a wild day in December 1901 there, sure enough, was the letter 'S' coming faintly in Morse Code over his primitive receiver (Ratcliffe, 1974)! Reaction to the news varied from congratulations to downright disbelief!

Instead of arguing with his critics he conducted another test a month later. This time he crossed the Atlantic in an ocean liner taking his receiving apparatus with him, and noted that he could now receive signals from the Poldhu transmitter to a distance of 1 120 km by day and 2 500 km by night. The work of this engineer next stimulated physicists to find out by what mechanism the signal had travelled across the Atlantic. Oliver Heaviside was the first to suggest that the radio wave had propagated in a duct bounded below by the sea and above by conducting layers of charged particles in the atmosphere. That was the start of a scientific programme to discover the height and the electron-density of the upper conducting region, later called the 'ionosphere'. It extends from about 80 km to about 1 000 km above us (Ratcliffe, 1974).

Significant developments in ionospheric physics took place in the period between the two world wars, and it has been said of my late Principal, Sir Edward Appleton, of the University of Edinburgh, that up to 1965 no major step forward in that programme occurred without his personal involvement in its success. As the theory has become more sophisticated, the engineers have been encouraged to thrust further beyond its limits in their search for improved communications systems. This, in turn, has stimulated further scientific research to provide improved mathematical models of the medium, and so the process continues. Today, with the aid of computers, the author has developed a program to provide a sophisticated design of the short-wave communication path linking any two points on the earth's surface. And it is barely three-quarters of a century since Marconi sent those first faltering signals across the Atlantic! Meantime, in parallel with short-wave radio, man has developed systems to exploit the particular advantages of the long and medium-wave bands in addition to transmissions at very high frequencies (VHF/FM), microwaves, and even at optical frequencies.

The above illustration from the life of Marconi could be paralleled by others from many different branches of engineering where there has been similar cross-stimulation between Science, Art, and Engineering, resulting in an explosive rise in technical knowledge and ability. Each new advance feeds Society with more sophistication, and in turn it demands even greater advances, as manufacturers vie with one another for the market. In any engineering system the effects of positive feedback of this kind are known only too well: it cannot but lead to an unstable, runaway, situation. This is why technology is surging forward at an explosive rate (Toffler, 1970), and this brings us to our third example:

Engineering education in an exploding technology. Here again we have the *delight* of the challenge and virility of a dynamic situation on the one hand, and the *dilemma* on the other, as we tackle the problem of educating young engineers to master a runaway technology. Table I, based on information from Toffler (1970), demonstrates the rate of change of man's speed of travel over the years, and this in turn is a reflection of the exceedingly rapid rate at which technological skill has been building up, especially in recent years.

Boulding (1966) expressed the same idea when he asserted: 'The world of today . . . is as different from the world in which I was born as that world was from Julius Caesar's.' And, illustrating the same theme, Toffler (1970) has pointed out that of all the energy man has consumed in the past 2 000 years, about half was consumed during the past century.

Table I

THE CHANGE, OVER THE YEARS, IN THE SPEED OF TRAVEL ILLUSTRATES THE TECHNOLOGY EXPLOSION OF MODERN TIMES

Date	*Speed km/h*	*Mode of Transport*	*Rate of Change km/h/year*
1600 B.C.	32	Camel Caravan	+ 0,004
6000 B.C.	13	Chariot and Horses	
A.D. 1784	16	Mail Coach	− 0,005
A.D. 1825	21	Steam Locomotive	+ 0,12
A.D. 1887	161	Steam Locomotive	+ 2,3
A.D. 1958	644	Piston-engine Aircraft	+ 9,5
A.D. 1965	1 288	Jet-engine Aircraft	+ 32
A.D. 1938	7 725	Rocket Plane	+ 920
A.D. 1968	35 405	Space Vehicle	+9227

The foregoing are illustrations of a common theme; technology is expanding at an explosive rate, and the educator of today's engineer has a real problem on his hands!

When I found that, as Inaugural Professor of Engineering, it fell to my lot to lay down the broad plans on which the new Faculty would be based, I reasoned that if we were to set about teaching engineering techniques (even the most modern techniques) as our primary aim, our students would be hopelessly out of date within a few years of graduating. Rather, I decided, we should concentrate on fundamentals, and merely illustrate these with examples of modern technological practice in each of the three engineering disciplines; then the graduate will be well equipped to keep pace with new developments, even if these change with bewildering rapidity.

On the other hand, Rhodesia needs engineers so urgently to overcome present shortages that our graduates will carry heavy responsibility (and, incidentally, enjoy wonderful prospects) almost as soon as they graduate. They therefore need to have had practical experience before graduating. These considerations impose an influence on course planning diametrically opposite to the one stated in the preceding paragraph. We are thus again 'on the horns of a dilemma'!

Our approach to the above problem has been (a) to concentrate on the teaching of fundamentals of the type learned better at University than on the job, and (b) to build into the course a strong emphasis on industrially-linked projects, and practical industrial training during the vacations. And our lecturers are encouraged to be involved in consultancies that require innovation and modern methods.

Looking to the future, it is hoped that employers will realize that, owing to the rapid advance of technology, they would be wise to embark upon a definite programme of overseas visits for their graduate engineers. After all, these are the men they look to for the ideas that will keep the firm ahead in a competitive world; and, as such a programme will also remove the engineer's personal fear of 'getting out of touch' with modern trends, it will also help the firm to retain his services for a long time.

Yes, indeed, we have our *dilemmas* when designing courses for the young engineers who are taking up the challenge of an exploding technology, but there is also the *delight* of being involved in that challenge!

Let us conclude by looking at another open-ended question which is becoming more important year by year.

The Engineer in Society. One sometimes hears the question: 'Admittedly there have been remarkable advances in technology in recent years, but are these good for Society?' There are those who blame the engineer for the energy crisis, the pollution crisis, and the discomfort of life in a world shrunk a thousand-fold by jet travel and instant telecommunications. Well, this is about as fair as it is to blame the medical profession for the population explosion because their efforts reduce infant mortality and extend the average expectancy of life!

Society needs to accept that its increasing demands on the engineer to go on raising its standard of living have to be tempered with responsibility because those increases in the 'standard of living' tend to be accompanied by a fall in the 'quality of life'. As a key figure in the drama, the engineer has a heavy responsibility to Society, and sometimes this call of duty may lead to personal financial disadvantage. Often he is in a dilemma over these conflicting demands, and needs great moral courage, a level head, and clear perception of the issues involved.

It is in these issues that we perceive how valuable it is for our new Faculty to have been established on a multi-discipline campus instead of being set up as a Technical Institute in some other part of the country, as was once urged by some of our friends. The dining halls, the Students' Union, the campus societies — all of these provide opportunities to become aware of viewpoints the student may never otherwise have known, and they help to form in him a balanced outlook. For example, our engineering student may learn from his friends in Medicine to have a deep desire for the safety and health of the population in general and of his clients and employees in particular; from his friends in Science an appreciation of his country's foundations, fauna and flora, and a desire to preserve them; from those in Arts a feel for language and communication, a respect for the past and an awareness of the present. Those in Education may remind him of the continuing need to go on learning, for the thrill and health of discovery is available not only to infants but also to the mature, if they will but persevere; and those in Social Studies may give him an appreciation of the basic needs of man, his ways of organizing himself ethnically and culturally in communal and business life, and the predictable trends in his behaviour. Then his technological decisions may be not only clever: they may even be wise. Above all, if his friends in Theology point him to the One who is the Way, the Truth, and the Life, with a reminder that without Him even the best of us 'can do nothing', our student may even achieve sufficient all-round balance to cap wisdom with moral courage and the inner power to see the most difficult project through to a successful conclusion.

So shall the designer's *dilemma* give way to the *delight* of a job well done, and the world be a better place for his having laboured there.

POSTCRIPT

During the Inaugural Lecture additional practical illustrations were given, particularly in the field of telecommunications engineering, but it has not been feasible to include these in this written version of the Lecture.

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