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On the Nature of Mechanical Engineering Work—An Engineering Ethos*

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This paper suggests that day-to-day engineering work is energized by a unique belief system which forms an enduring and coherent engineering ethos. It proposes that the engineer's view of the world is at once formative, utilitarian and reductionist. Good engineering practice comes from the productive synergy of these three elements. The paper identifies the main sources of influence in the formation of a distinct engineering world view as engineers progress through their education and subsequent career as academe, work and heritage. These lead to separate but complementary aspects of an engineering ethos, namely seeing the world as essentially problematic, as a commercial challenge and as an opportunity for continuous, useful, material development. It is argued that, together, these three outlooks empower the practice of engineering. The paper concludes that while the work environment usually actively promotes an integrated set of outlooks, contemporary engineering academe does not. Students emerge from their university experience with a poorly developed sense of what it means to be an engineer.

INTRODUCTION

THE picture of the engineering professional that has been built up in this series on mechanical engineering work [1–4] is that of a practitioner deeply immersed in problematic real work issues. In seeking effective and cost-efficient outcomes to these issues, the engineer draws on, and further develops an extensive and specialized knowledge, a resource perhaps arcane to many clients. That knowledge is applied through a particular enabling process, engaging a range of competencies that goes far beyond special knowledge to include good judgement and wisdom. Adding to the picture, the engineer is also supposed to act in an altogether proper way, guided by a code of ethics which emphasizes high responsibility to the community, to the client and to the profession. Now all this sounds a bit formidable, suggesting that the practice of engineering is a very serious matter. And so it is; but engineering is also fun and I believe that what brings somebody to the practice of engineering, and keeps them happily engaged in it, is the immense satisfaction gained from following the 'heart'. Elms [5], captured something of the spirit of the engineering 'heart', writing 'an engineer must be technically competent, must in some sense render a public service, and must have a *certain style or outlook on the world*' [my italics]. To me it is this certain outlook on the world that conditions how practitioners approach engineering tasks, indeed maybe it is this special view of the world that defines what they do as engineering. In any case, I think it is our style and outlook that, at heart, energizes our day-to-day engagement with the world and it is the satisfaction of seeing how that view can effect useful change that keeps us coming back for more!

This paper aims to identify and describe the attitudes that go to make up that special outlook and thus to define something of the engineering ethos. Of course, my selection is a personal one and therefore there is no claim to completeness. The selection is also made in the context of mechanical engineering, influenced by its specific role of providing a wide range of marketable goods and services in a technological society. The selection is made, too, from the point of view of an academic, a participant observer of the great changes that have swept through engineering schools since the 1950s. Nevertheless, the elements I have chosen are, I hope, sufficiently characteristic of the engineering mind to at least provide some feel for its uniqueness, for there is no doubt that engineers see the world quite differently to other groups. They do operate on the basis of a special engineering ethos.

The paper begins with the major sources of influence in the formation of that ethos. Three elements that contribute to it, or three distinct ways in which engineers interpret their world are distinguished and described. It then turns to how well education and practice in engineering work in creating and maintaining a harmonious and productive synergy of these powerful motivating forces.

INFLUENCES ON OUTLOOK

Given the extensive educational programmes that feed into professional engineering practice, the origin of much of the mechanical engineer's

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Weltanschauung will be in academe. Indeed Bondeson [6] states that any educational process has three principal elements: knowledge, skills and values. For Bondeson, education is essentially a normative activity and there is no such thing as simply transmitting whatever facts are supposed to be basic. For example, the notion of value-free science is simply misguided. Furthermore, any time we attempt to decide what needs to be known, implicit in that decision is also a judgement about what does not need to be known. Any selection of facts is of necessity selective, as is any selection of skills to be taught. So the way in which faculty look upon the world, as well as other values they hold, will be implicit in course aims and structures, in course content and in the way in which individual subjects are approached. Even if only indirectly, such perceptions will be continually imparted to student engineers.

For most of the graduates of engineering schools the next most significant formative source of these sorts of values will be employment in the world of industry and commerce. The values underlying operating a business for profit can be expected to be vastly different from those in academe, particularly contemporary academe with its strong associations with the science world-view. They will nevertheless be genuine and legitimate engineering values, to be joined with those inherited from engineering education. Engineering in medium to large technology-based organizations typically has a strong hierarchical structure, so that these values will be disseminated through role models and the expectations of engineering supervisors. In smaller companies the sources of influence may be more diverse and uncertain.

A third source of values or outlooks for both the recruit and the practitioner in engineering might be found in the shared interests and attitudes of engineers as an identifiable group in society. In one sense, the way engineers think about themselves and their ideas about what it means to do engineering will be formed by overall perceptions of the community itself in a technological society. Just as individuals relate to the prevailing moral and ethical standards of their society, so too will individual engineers share in the way a community recognizes and reacts to the pervasive influence of technology in their lives. These communal perceptions may or may not derive from a good understanding of the part engineers play, but they are no doubt important, for example, to people deciding whether to choose engineering as a career. More directly, however, amongst engineers themselves there is always an interest in matters which extend across and beyond specific industry and academic boundaries. Engineers display a great enthusiasm for industrial site tours, visiting notable engineering works, for attending conferences and reading histories and biographies about famous feats and achievers. All of these recognize and promulgate elements of a unique heritage which projects not only a sense of belonging, but also a sense of what constitutes proper professional engineering practice. Together with professional education and the commercial reality of engineering jobs, a fairly diverse but enduring heritage creates a certain ethos which empowers and guides day-to-day engineering practice. And one outward sign of internalizing the spirit of this ethos is the demonstration of their special outlook when engineers approach a task.

It is certain that these three sources of influence will not be operating in equal measure at any one time during a career and, indeed, their effect seems to be cumulative. To follow career development then, but not to imply an order of importance, the paper moves to what I suggest is the dominant outlook in contemporary academe, viz. the world is full of problems to be solved and the engineer is thus properly primarily a problem solver.

A WORLD OF PROBLEMS

In an introduction to engineering aimed at answering students' questions about the profession, Krick [7] explained that engineering is the outgrowth of two historical developments. One of these was the gradual evolution of a problem-solving specialist concerned with the creating of things useful to society. The other development, for a long time essentially unrelated to the first, has been the rapid expansion of the scientific culture. According to Krick, the engineer is a technologist whose prime motive is to solve the problem at hand. The problems come from a particular class of mankind's problems, that of converting material and human resources into tangible artefacts, devices, structures and systems. Krick argued that the process by which such contrivances are created—design—is fundamental to and at the very core of engineering. He saw design and thus engineering itself as, essentially, problem solving. Nearly 30 years later, Ullman [8] wrote 'the mechanical (engineering) design process is a problem-solving process that transforms an ill defined problem into a final product'. The idea of problems 'out there' and engineering as problem solving is certainly enduring.

Krick's second historical development, the rise of a science culture, has had a particular impact on engineering academe, and some faculty like to describe themselves as engineering scientists. Of interest here, however, is that the confluence of engineering and science seems to have strengthened the interpretation of engineering as problem solving. Rubinstein [9], for example, discussed Descartes, Newton and Einstein as problem-solvers. He described how Descartes planned to derive a universal method for problem solving, trying to formalize certain rules for that process. Newton, focusing on both goal and process, originated a view of the world and of enquiries about it which has dominated scientific thought for 300 years. Within this framework of reductionism, Einstein arrived at a relation between space and time by 'reducing his problem to a metaphor involving a train and the observation of bolts of lightning striking at two different places' [9]. It should not be surprising, then, that engineers graduating from contemporary university courses have a great enthusiasm for the rhetoric of problem solving. The use of the word 'problem' to describe a state of affairs, and the belief that a solution to that problematic state of affairs ought to exist are, however, expressions of a particular view of the world.

To the problem solver, the things that an engineer has to deal with can be usefully isolated from a complex surrounding which is characterized by interconnectedness. In this special view, abstracting or isolating certain things from that surrounding with care does not change the essential nature of any forms or relationships that exist. The original state of affairs has merely been reduced (in the sense of Newtonian reductionism) to a simpler one by cutting the connections to things which are considered not centrally important. The new description, crucially, is now amenable to analysis whereas the complexity of the undifferentiated real world, in contrast, would make any useful interpretations or analysis of it either downright impossible or prohibitively (in an engineering sense!) time consuming. Defining the problem, that is selecting the things from the 'mess' to work on, thus becomes the means by which engineers impose order on their world.

At the other end of the problem-solving schema lies the notion of solution, the second half of this particular outlook. Again, to the problem solver a properly defined problem must lead to the solution of that problem—there is an answer to the conundrum, it is believed. The path from problem definition to problem solution may be long and arduous, but an instrumental solution is obtainable. The confident expectation of a solution to a reduced and ordered representation of a hitherto intractably complex situation is at the heart of the engineering ethos. It is a powerful and empowering belief system.

A further dimension of this system emerges from the work of Simon and Newell [10] on human problem solving. They assert that problem solving can be explained by information processing theory. It is postulated that problem solving takes place by search in a problem space, and that the task environment determines the structure of that space. In turn, the structure of the problem space determines the possible programs that the solver can use and the function of a program is to search in the problem space by selecting operators and evaluating knowledge states. To Simon [11], 'human problem solving is basically a form of means–ends analysis that aims at discovering a process description of the path that leads to a desired goal'. For the engineer problem solver all the elements are there—definition (problem space), solution (desired goal) and a connecting path (search programs)—and engineers adopt both concept and strategy with great effect.

Despite wide familiarity with and enthusiasm for this approach, however, the practising engineer is frequently confronted with issues which do not lend themselves at all to the attractive rationalism of problem solving. Indeed, there are some harsh criticisms of its over-zealous adoption in situations where reductionism loses the sense of what is going on and in cases where creative opportunities rather than definable problems arise. And nowhere else does the necessity for other world views become more evident than in engineering work in its natural habitat of the world of commerce.

THE COMMERCIAL IMPERATIVE

Engineering work is but one of the many contributing functions in a commercial enterprise. Necessarily, then, the attitudes of mind that promote successful engineering in an integrated environment will be the most important. It is this element of the engineering ethos which becomes prominent in industry. The problem-solving mindset so dominant in academe may well, in fact, retain an important role but there are no prizes for problem solving as such. It is only in so far as that particular outlook contributes to the advancement of a project as a whole that it now has any special significance. Commercial realities direct the focus of attention, rather than academic challenge. However, this is not to suggest that the professional and intellectual demands on the engineer-in-industry will be any less than in academe. The demands are different, for now engineering work is essentially contextual rather than abstracted. Interconnectedness and complexity are characteristics of the normal environment, to be dealt with on a day-to-day basis. This requires the ability to recognize, understand and negotiate the myriad relationships that exist between the various stakeholders in any job, most of whom may not be engineers.

The key perspective on the commercial world that the engineer adopts is perhaps best captured in the phrase 'fitness for purpose'. The phrase is familiar, of course to engineering designers and it is a fundamental guiding principle for them. It means that it is the end purpose of the outcome that must direct the design process. Failure to observe this cardinal rule leads to the proverbial white elephant—a wonderful design that nobody wants or will pay for. But in a real sense it applies to all engineering work in industry. It is a hard lesson that all consulting engineers, for example, must learn. The time and effort that can be committed to a client's job is determined by what the client is prepared to pay. Any work undertaken outside of this constraint must be paid for by the consulting company itself and thereby becomes a direct loss. In other industries, in which engineering is an integral part of wider operations, the same principle applies. The time and effort that can be permitted in engineering a product, as distinct from costs raised in other functions, is limited by the absolute requirement that the business as a whole must pay its way. The fact is that while engineering is a technological and scientific profession, it is the marketplace which provides the true test of an engineer's work.

The professional in industry is very much aware of these realities and takes pride in managing engineering work to fit them. The commercial element sits comfortably in the engineering mind. Some particular dilemmas do, however, arise. Working to a restricted time and money budget can not be allowed to detract from the technical integrity of any recommendations or advice, nor put in doubt the efficacy of an engineered product or system. A fine balance has to be struck to be able to declare 'it's good enough; ship it' in closing off a job. To the engineer, closure is a great source of satisfaction, making all the effort worthwhile, but also opening up opportunities for a new, equally intriguing task. On the other hand, precipitate closure leaves the usefulness of the outcome to the vagaries of chance which, as every engineer knows, favour the unwelcome. The commercial imperative demands a sound judgement of what is the essential minimum of effort to ensure that an engineering output meets the clients' or company's expectations and specifications. The view of the world that sees such fitness for purpose as the powerful and motivating principle in engineering work comes from a heritage which judges success by utility.

Our engineering ethos is thus both utilitarian and reductionist. These two parts offer complementary but somewhat contrasting views of the world. The problem-solving reductionist outlook treats the world in its differentiated state, whereas the utilitarian view is essentially integrative. They both may be considered, however, as instrumental to the practical realization of an idea, held in the mind of an engineer, of some product, artefact or system of commercial use. This leads on to my selection of the third part of the special outlook of the engineer.

THE MIND'S EYE

The pages of a recent book by Eugene Ferguson, *Engineering and the Mind's Eye* [12], are alive with sketches, drawings, plans and photographs. In this fascinating book, Ferguson attempts to clarify the nature and significance of nonverbal thought in engineering and asserts that

> Pyramids, cathedrals, and rockets exist not because of geometry, theory of structures, or thermodynamics, but because they were first pictures—literally visions—in the minds of those who conceived them [12].

In developing the theme that the objects an engineer thinks about must be dealt with in the mind by a visual, nonverbal process, the author of course uses dozens of illustrations—his arguments are directed squarely at the 'mind's eye' of the reader. The book itself is an unequivocal statement of a special characteristic of engineering, particularly mechanical engineering with its historical and contemporary focus on useful machines and artefacts. That is, imagining the world as it might be by visual thinking—by creating pictures in the mind.

From the point of view of the development here, however, the book tells another story as well. The illustrations are of 15th- and 18th-century pumps, 18th-century fortresses, 19th-century axeheads, early 20th-century bridges, and dozens of references to examples of contemporary engineered products and systems, all of which were intended to change the world in some useful way. For the engineers, behind the visions of things that might be lies an enduring conviction that the built material world can and ought to be continually refreshed and refurbished by an ongoing flow of ideas for change put into practice. This is the third and, I think, the central plank of the engineering ethos—change of the material world is both within the human capacity and desirable. To the engineer of yesterday and today, change is good. Furthermore, there is no end to the possibility of change. Engineers as a group are often classified as politically conservative, but in terms of the material world they are unrelenting revolutionaries. Of course, engineering is not the only profession that is concerned with the built environment. Architecture and industrial design, for example, are too. But for the sheer range of goods and services provided by the profession, it is unrivalled.

Unlike the problem solvers view of the world, this third outlook has little or nothing to do with the science worldview. The process by which change is effected begins with design and as Ferguson quotes from the historian Layton [13]:

> From the point of view of modern science, design is nothing, but from the point of view of engineering, design is everything. It represents the purposive adaptation of means to reach a preconceived end, the very essence of engineering.

The distinctive nature of contemporary engineering continues to rest, as it has done for centuries, on the purposive employment of means to change the built world according to a vision in the mind, in the confidence that the outcome will change human life for the better. And while to a large extent engineering creates the form of the material world, it will do so at the right price, according to the engineer in the utilitarian mode, and with its physical integrity assured, as demonstrated by the engineer in reductionist mode. These, then, are the foundations of the engineering thought of that certain outlook and style. The engineering view of the world is at once formative, utilitarian and reductionist.

MAINTAINING A BALANCE

It is appropriate now to return to the main influences on the development of an emerging engineering outlook to consider their effectiveness in establishing a harmonious and productive synergy within a tripartite engineering ethos. It seems to me that good engineering depends on such a synergy. As Ferguson [12] concludes, engineering failures are more often than not errors of engineering judgement rather than errors in calculations. I suggest that errors of judgement stem from a failure to pay due respect to the rightness of one or other of the foundations of engineering thought. There are functional relationships between the three outlooks the engineer employs in any task, such that none is sufficient by itself to describe and explain the real world to an acceptable level of predictability. As an obvious example, deciding to go ahead with an exciting formative idea without regard to commercial appeal or without careful reductionist scrutiny is a road many inventors are tempted to follow in their enthusiasm for the new. The patent records are full of such plans that never see the light of day. The error in judgement is one of omission rather than of commission. The result is just as much an engineering failure as a decision, for instance, to use an inappropriate material in a corrosive environment, and in type probably much more common.

The paper has earlier identified three sources of influences, academe, work and heritage. Particularly in the early stages of a career, the influence of heritage will perhaps be transmitted mainly by role models in education or practice and so be somewhat subsumed by the other two. For that reason this commentary will focus first on work, then academe.

The practice of engineering has never been a solitary occupation. Engineering projects by their very nature involve collaboration between artisans, technicians, engineers and managers to put into practical effect a plan for action. Within the scope of the engineers' role, which usually overlaps that of manager, the work is rarely the responsibility of one person. Engineers tend to work in groups wherein different skills and responsibilities are acknowledged in a hierarchical structure. It is a significant characteristic of the profession that positions of authority and influence carry with them the clear responsibility for the personal and professional development of more junior engineers. This requirement does not stem merely from altruism, although such a motive is often present, but more from the recognition that only by promoting the potential of every contributor in an engineering enterprise can the task be undertaken at all. Most engineering projects are of such scale and complexity that independent thought and action is demanded of all professionals involved. The main drive and direction may come from the most senior positions, but without individual motivation and competence throughout the group, such initiatives quickly falter. The duty of care exercised by the engineering supervisor to ensure the development of other professionals thus has its roots in pragmatism, but from that need has grown the respected role of the mentor.

By and large, the engineering neophyte appears to be well served by the mentor system which operates in industry, at least where there is a defined engineering group. Many companies have graduate training or induction programmes which, among other things, clarify group structure and responsibility. This sets the scene for a continuing mentor relationship which provides guidance, encouragement, support and, from the point of view of this paper, role models of an engineering outlook. The new engineer will possess problem-solving skills which will be respected and utilized almost from the first day, reinforcing that particular part of the ethos. New engineers will be quickly apprised of the commercial realities of the company's operations too, and this will be a constant theme drummed into them. Of lesser immediate impact, but with a persistent regularity, the graduate will also be expected to demonstrate an ability to come up with innovative ideas for improvements to parts, machines or systems at increasing levels of economic importance. A good work environment insistently exposes the new employees to an integrated ethos, and this exposure endures as careers progress until, in turn, the individuals themselves become responsible for a new generation of graduates. The engineering mentor system is thus a powerful impetus towards internalizing a unique engineering ethos.

The situation is nowhere near as positive in academe. There, a number of developments antithetical to that ethos have changed the nature of engineering education. From the early 1960s onwards, an engineering curriculum based mainly on practice, and taught by faculty whose qualifications to do so rested on industrial experience, became increasingly science-based. While change was essential and in the broader scheme of things inevitable, much that was good and worthwhile made way for an apparently inexhaustible demand for engineering science content. As the content changed, the qualifications of teachers also changed from practice to academic. The PhD degree obtained through scientific research became the basic requirement, a qualification then quite foreign to industrial practice. Subjects such as descriptive geometry, perspective and engineering drawing were among the first casualties, so the value of nonverbal thinking, so important in visualizing a practical outcome to an idea to create something new, was downgraded. Design itself, resisting many attempts to reduce it to a science, was relegated to a peripheral place in many institutions, although there has been a growing rediscovery of its central role in engineering in recent years. The culture within teaching institutions changed too. The emphasis on research, and a promotion scheme that rewards research achievements above all else, has created an individual rather than a corporate spirit, where self-indulgence and personal advancement are actively encouraged. There is no room in such an environment for the mentor system that is so effective in most industries. Senior and junior faculty are in reality in competition for the scarce research dollar and the status that goes with it. Faced with this background to their studies, and immersed in the predominantly reductionist view of the world associated with scientific work, even senior engineering students are often unaware of the commercial realities that drive engineering work in their community. Furthermore, they typically do not relate to a heritage that has had, and continues to have, such a profound influence on society. This unintended outcome of the great changes in engineering education and engineering educators can be sheeted home to a collective error of judgement. Our failure to imbue the graduating students of our institutions with a coherent, internally consistent and empowering engineering ethos is an engineering failure of that kind.

In Australia, engineering education is now the subject of a nation-wide review. There is a general feeling that something has gone wrong with the way engineering students are being prepared for work. The review is to be wide-ranging, drawing on industry, academe and professional codes. It is a marvellous opportunity to define in contemporary terms what it means to be an engineer. Our students surely deserve the guidance such a formulation would offer.

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