A Philosophy of Engineering Seminar:

SYSTEMS ENGINEERING AND ENGINEERING DESIGN

ENGINEERING AS SYNTHESIS – DOING RIGHT THINGS AND DOING THINGS RIGHT

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I have been a Visiting Professor of the Principles of Engineering Design at Bristol for about 15 years and have consistently argued that engineering *equals* design. Everything else done under the label of engineering is either applied science and technology, or it is craft – making things. The element that makes engineering different from science and craft is design. That is not popular with university departments, which are often made up either of physicists or of people who are actually trying to pursue the craft of making things. I have the greatest respect for both groups - my first degree was in natural sciences and I have done enough craft work in my life to appreciate those who can do it properly – but my thesis remains that engineering is design.

The notes in the flyer for this seminar say that '*engineering is primarily a social rather than a technological discipline*'; I cannot let that stand unchallenged. Take an aeronautical example: if you are halfway across the Atlantic, do you want to know that the diameter of the

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bolt that holds the engine on was calculated and the materials chosen so that it is strong enough? Or that it is there because that is the correct social context for it? Engineering is about making things that work and, if they do not work – not just in aeronautics but in many other fields, including the one in which I frequently work which is railways – people die.

On a lighter note, for almost every topic one can find insight from one of the leading 20th century philosophers of science, Douglas Adams. I have a line from *The Restaurant at the End of the Universe*, which is the second of the four books that make up the "*Hitch-hiker's Guide*" trilogy. It concerns a party of hairdressers and management consultants who are marooned on prehistoric Earth and have formed committees to invent things to make life better. They are having a review of their work.

'*What about this wheel thingy?*' said the captain. '*It sounds a terribly interesting project*.' '*Ah'*, said the marketing girl, '*we have a bit of difficulty there*.' '*Difficulty?*' exclaimed Ford, '*what do you mean, difficulty? It is the single simplest machine in the entire universe*.' The marketing girl soured him with a look. '*Alright, Mr Wise Guy*', she said, '*If you're so clever, you tell us what colour it should be*.' I like Douglas Adams, first because he is funny, but also because he makes many very perceptive remarks. Getting so obsessed with 'what colour should it be?', when you actually miss the point about whether it goes round and carries a load, seems to be a mistaken sense of priorities. Engineering, which I repeat is about making things that work, should never lose sight of the goal.

A popular rule is that "*form follows function*". Alas not always - a great example of where function followed form was the Millennium Dome. The first decision was how big it would be in square metres, followed by the choice of material to make the roof. Only then did somebody say, '*That's pretty good – now what shall we do with it?*' That is an archetypal example of letting the form dictate the function.

I once heard a speaker at an engineering dinner – and I cannot track down the source – say, '*a building designed by an engineer without the benefit of an architect is horrifying; a building designed by an architect without the benefit of an engineer is terrifying.*' Let us keep a sense of proportion in engineering as a social construct.

Everyone has their own definition of engineering and mine is, '*Changing the natural world to make it better meet the needs of mankind.*' Engineers are about re-forming this place from what it was originally, so that it works better to meet the needs of at least a sub-group of mankind. If you want to be biblical, this is a very complex world to design and build in six days so engineers have to finish off what God left undone. That of course invites the reaction that the history of mankind is one long snagging list.

That is getting to my central message. Engineering, in practice, is of no use unless it is sensitive to what society wants and will use. If you are stuck on prehistoric Earth, any sort of wheel is worth having. However, if you are trying to design a wheel for the next generation of expensive luxury car, it will not sell if it is the wrong colour. If it does not meet all the needs of customers for prestigious cars, it does not work. Engineering has to be sensitive to the social context of what it designs and how it will be built, addressing both the product and the process.

Let me move on to the design process. When I first started lecturing at Bristol, I tried to argue that design is the art of compromise. Since I had already argued that engineering equals design, it was not long before people asked whether I meant that engineering meant compromise – at which point I managed to offend the few people I had not already offended. However, I still defend that because there is rarely a right answer, a right design, because there are so many stakeholders who have conflicting objectives – performance, delivery time, cost, risk and many others. If the project becomes big enough to have a political dimension, you are talking about job security, national pride and international relations. There are many axes being ground in most engineering projects and the engineer has to take them all into account.

I describe the role of the engineering designer as finding the least bad compromise that all of the stakeholders can live with. Think of it as plotting their needs on a Venn diagram and trying to find that little blob where they overlap, which everyone can live with. Of course, in almost all real engineering design challenges there is no overlapping blob. There is no common ground; the engineer has the diplomatic task of persuading someone to move his position (that is, redefine his needs) or the project is abandoned.

This is not a new concept. Shakespeare wrote in Henry IV Part 2:

> "*….. When we mean to build,*
> *We first survey the plot, then draw the model;*
> *And when we see the figure of the house,*
> *Then must we rate the cost of the erection;*
> *Which if we find outweighs ability,*
> *What do we then but draw anew the model*
> *In fewer offices, or at last desist*
> *To build at all?"*

There is the principle of iteration – that you put up an idea and, if it does not fly or if the customer does not like it, you keep tweaking it and working with all of the stakeholders until you come up with something that can be done. If all else fails, you abandon it – and that is something which I suspect engineers, as a community, are very bad at. We persist, even when it does not make sense. The usual problem is that the customer wants a palace, until you tell him what it will cost, and then you start again.

It is especially true of institutional customers. Willy Messerschmitt once said, '*We can build any aircraft that the aviation ministry calls for, with any requirement satisfied. Of course, it will not fly*.' This is a global problem that often arises, with the customer requiring the impossible.

The designer is left with trading off a whole load of benefits and constraints, to arrive at a compromise that everyone can work with – speed, reliability, cost, timescale, mass, comfort, the list goes on. Then there are some less obvious features, such as ease of dismantling. I have included that because I once rebuilt an old Lotus 7. I think the Chapman approach to design was built around the pop-riveter. Having assembled the mechanical parts, you then pop rivet all the panels on. Of course, you then cannot take it apart to get at the mechanics – it was never designed to be maintained, which, if you have had an old Lotus, you will realise is quite a common activity. They were always known as collectors' cars – you drive 10 miles then go back to collect the pieces! If you can't design for reliability, at least design for maintenance by making it easy to dismantle; that is part of the context of the product.

Engineering design is a mass of disciplines, not all of which are purely technical. Most projects will involve a wide range of engineering disciplines – mechanics, electrics, electronics, computing, materials … Then there is project management, including planning, construction, testing, operating and disposing. To this we must add many subjective human issues, such as biomechanics, shape, colour and form.

Because I am both an engineer and a lawyer, I tend to become involved in legal issues and particularly in health and safety, both in construction and in use. Constructors are very good at thinking about the health and safety of their workers, and users are quite good at thinking about the health and safety of their customers, but the link between the two is often missed out. Safety in use has to be designed in from the start, not bolted on. Companies whose products are safe to build and safe to use are often the most profitable and successful, because safety is another one of the properties of a well-designed product that has its roots in exactly the same thinking as leads to efficiency, speed, economy and all the other desirable qualities. If the design is good, you get a whole load of consequences which – in systems engineering jargon – are called the 'ilities': sustainability, accessibility, usability, affordability and availability.

That leads into something I am very interested in, which is the ability of engineers to design something so that it still works when it does not work – what could be called partial failure or polite degradation. I work often with railways, which are extremely complex systems – it is only once you become involved that you realise how difficult they are. Experienced railway engineers often talk about '*degraded modes'*, where the railway must continue to operate safely, albeit at reduced speed, when something goes wrong. Designing for degraded modes is very difficult because you are asking, how will it work when bits are not working? Engineers rarely think like that because they think their babies are perfect.

Now we are moving closer to the concepts of system engineering and complexity. The definition of a system that I like is, '*A system is a set of parts which, when brought together, have qualities that are not present in any of the components themselves*.'

I have a little trick that I do in lectures – I will not do it here because this is an intelligent audience but I have used it in a House of Commons talk. I take a battery, two wires with clips on and a light bulb. I clip the wires onto the battery, put it all together, and the light bulb glows. Light is not a property of any of those pieces. Light is not a property of the battery, the wires or the bulb, but it is a property of the way you put them together. That is about as simple a system as you can get, but it has an emergent property – light – which is not there when you look at the pieces.

If you are going to start designing systems that have much more complex emergent properties like safety, you really have to think very deeply about all those pieces interacting, and how they interact with the people. The only way you can set about that is with an integrated approach. Every one of those myriad decisions that make up a system design have to be seen not just in the narrow context of how strong this bolt has to be, or how much current that wire has to carry, but in the much bigger context of, what is the emergent property I am trying to get and, more seriously, what is the emergent property that I am trying to avoid, like a crash?

That leads to thinking in terms of integrated system design as an overarching discipline for engineering. The Academy supports Visiting Professors of integrated system design at a growing number of universities, to help the universities to prepare graduates for the real world. They should not come out saying, '*I am a mechanical engineer and that is all I do'*, but '*I will do the mechanical parts of a bigger system*.' This means kicking people out of their comfort zone. Whenever I have tried teaching this, there is a great deal of resistance from undergraduates. '*I came here to study computing'*, or '*I came here to study structural engineering – why are you boring me with all this electrical stuff?*' Because that is how you are going to earn a living!

Future leaders in engineering will be the people who can work in a multidisciplinary team, with many branches of engineering but also all the other disciplines – and not just technical disciplines. Quite a lot of my work is with public affairs companies working with clients with scientific or engineering products who have to understand and influence the political system because, otherwise – as one of them has – they find that they have been put out of business. Those issues come up for engineers and the Academy's scheme is at least trying to expose undergraduate engineers to that way of thinking. That scheme is not dogmatic, and it does not say that you must do it this way – it is more like Mao's thousand flowers. We have produced a guidance paper, a sort of hymn sheet that the universities can tailor. It includes a little proselytising because the challenge to get some of the more dyed-in-the-wool academics to admit that there is more to engineering than a single discipline is often quite difficult. It's called '*Creating Systems that Work – Principles of Engineering Systems for the 21st Century*.' Let me quote from the Preface: '*Customers rarely want a system. What they want is a capability to fulfil a business objective. A system, be it a building, vehicle, computer, weapon or generator, is only the means to deliver the capability – housing, transport, calculations, defence or electricity. Engineers are responsible for defining, with the customer, the capability that he or she really needs, and expressing it as a system that can be built and is affordable*.'

The paper emphasises the importance of education. '*We must produce and employ effectively engineers who have the qualities of creativity, analysis, judgment and leadership*.' Those four have emerged from a good deal of debate. Creativity is not a passive process and you do not just follow the rules. Analysis: going back to my bolt holding the engine – this is based on hard calculation and not hand-waving. Judgment: you cannot look up answers for everything and, eventually, you have to make a value judgment. Leadership is important: if the engineer is not going to lead the project, who is? You're left with the management consultants on prehistoric Earth, and you would not want them leading it.

That sets the scene for what we were trying to do and we have boiled it down to six principles.

1. Debate, define, revise and pursue the purpose
2. Think holistic
3. Be creative
4. Follow a disciplined procedure
5. Take account of the people
6. Manage the project and the relationships

The big message is that good design is as much about human issues as technical issues – there are three principles for each.

Finally to return to the qualities of the engineers themselves. People are often held to fall into one of two types, described as foxes and hedgehogs. Hedgehogs have one trick and they do it well – they have spikes. Foxes have many little tricks and they are cunning. The popular view is that engineers are hedgehogs and they are very good at something, while project managers are foxes, being quite good at a number of things. But designers of engineering systems have to be both; their CV is T-shaped: it has a lot of breadth and at least one deep piece – '*there is at least part of this project for which I am the expert'*. If you cannot say that, then apart from anything else, you will not have any credibility with the others.

Those engineers have to be able to do one part of the project in detail and all of it in outline, which sets the agenda for their education. They have to know a lot of basic science and engineering – physics, chemistry and mathematics, the science on which engineering is based. They also have to have an analytical spirit – one that tries to model problems, rather than just brainstorm them. They need an awareness of the many disciplines that contribute. Finally, they need to be able to communicate with everybody – from the customer to the technician who assembles their design.

The message we are trying to convey to engineering education is, please can you think about how you form engineers who fit that pattern. This is hard to do, and it is uncomfortable for traditional engineering thinking, but it is crucial if we are to be able to engineer systems that work.

That is where I come back to my title. I started by exploring doing things right – you do not want the engine to be held on by goodwill – but, actually, doing right things is the much wider context of engineering systems.