

Chapter 9

Flourishing



Keep on yearning, always learning, world is burning

West Gate Bridge

The only phrase I could think of was ‘There but for the grace of God go I’. It was 1971 and I was reading the specialist newspaper called ‘Construction News’. The article was an account of proceedings at a Royal Commission of Inquiry into the collapse of a span on the west side of the West Gate Bridge over the River Yarra in Melbourne Australia when 35 people were killed.¹ The inquiry panel was questioning Christopher Simpson—the engineer responsible for the construction of the bridge on the east side of the river and working for the designers of the bridge called Freeman Fox and Partners. I felt keenly that they might very well have been questioning me had circumstances been slightly different because Christopher and I graduated together in 1964. I read verbatim the difficult questions and answers put to Christopher. I felt keenly that I could have been him. I wondered how I would have coped.

Being part of, or witnessing, a terrible disaster is clearly very distressing. In this final chapter, we ask, ‘How do we minimize this kind of distress and continue to flourish in the future?’ How do we learn from past events? Are there patterns of unwanted events in past disasters that were lying hidden, unrecognised and unforeseen as the final failure incubated? Can we identify those patterns and use the understanding they give us to avoid future failures and to ameliorate the effects of climate change? What are the ‘grand challenges’—both natural and man-made? Are they global and/or local? How important is it to slow up, halt and reverse the fragmentation of the professions into ‘silos’? What is ‘joined-up’ thinking in ‘joined-up’ organisations and nation states and how important is it?

Becoming a professionally qualified engineer is not easy—it requires the kind of hard work and dedication that generates self-respect. Almost all engineers I know are modestly proud of what they have achieved. When you have been part of the designing and making of a challenging project you have great satisfaction when you see the finished product. To be working on a bridge as part of it collapses is devastating and something that stays with you for the rest of your life. Recovery depends on a strength of character that goes beyond the ordinary. But personal trauma need not stand in the way of success. Psychologists Feldman and Kravetz² have noted this in people who have an accident, receive a devastating medical diagnosis, lose a loved one or live in a country where war and famine are almost routine. They identified five factors that seem to help people: hope, personal control, social support, forgiveness and spirituality. They write *‘truly accepting the consequences of a trauma with realistic thinking rather than delusional positive thinking can open people up to true hope – something that enables setting and achieving goals that ultimately can improve one’s life....A realistic view of the situation + a strong view of one’s ability to control one’s destiny through one’s efforts = grounded hope’*.

Flourishing is about achieving your potential—individually and collectively despite obstacles and setbacks. The word stems from the Latin *florere* ‘to bloom, blossom, and flower’. Aristotle was the first to understand its importance. He saw that flourishing occurs when we want to do what we ought to do—take pleasure in moral action. He thought that earthly happiness is a by-product of using our individual capacities to realise our potential. In that sense what really matters is not what we believe but how we behave. Karen Armstrong³ calls the religious emphasis on belief as determining action, a metaphysical mistake and an accident of history. Acting by creating imparts feelings of achievement. As we noted in Chap. 2 personal hobbies like gardening, drawing, craftwork or simply just repair jobs around the home can be very satisfying. Throughout history we have built big cathedrals, mosques, churches and temples as expressions of communal faith. Experiencing those spaces often creates feelings of high spirituality. Sports stadia like Queen Elizabeth Olympic Park in London, exhibition halls and museums like the Guggenheim Museum in Bilbao, large-scale art works such as the i360 tower in Brighton opened in 2016 (Fig. 9.1) and the colossal Cornish Man Engine⁴ (Fig. 9.2) are all artistic expressions that embody the conscious use of the imagination.

Given the complex challenges we are facing in the twenty-first century, we can learn a lot about our collective future from the advice from Feldman and Kravetz and the experiences of those who live through personal trauma such as the West Gate Bridge collapse. In order to flourish together, we need to maintain hope, take collective control, support each other, live with a spirit of forgiveness that unites rather than divides us and develop a sense of spirituality that goes beyond conventional religion. The five principles of *Part*, *Unintended*, *Preparedness*, *Ingenuity* and *Learning* are key ingredients. When we truly understand ourselves as *Part* of the natural world then we have hope for a better future. When we admit our tendency for technical triumphalism—past arrogance in thinking that we are in total control of the natural world then we are ready to accept unforeseen and *Unintended* consequences and unknown unknowns. When we recognise that *Preparedness* for an uncertain future

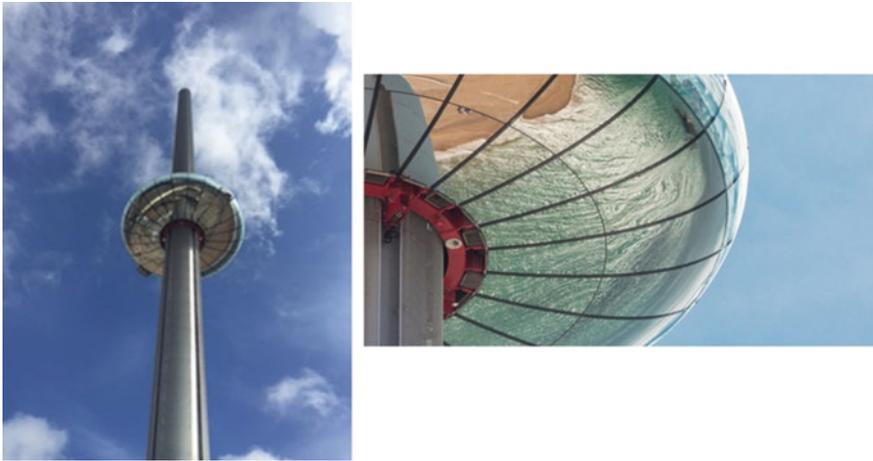


Fig. 9.1 British Airways i360 viewing tower, Brighton, England Conceived and designed by Marks Barfield Architects and John Roberts (Jacobs Engineering Group). By permission of Brighton i360 Limited

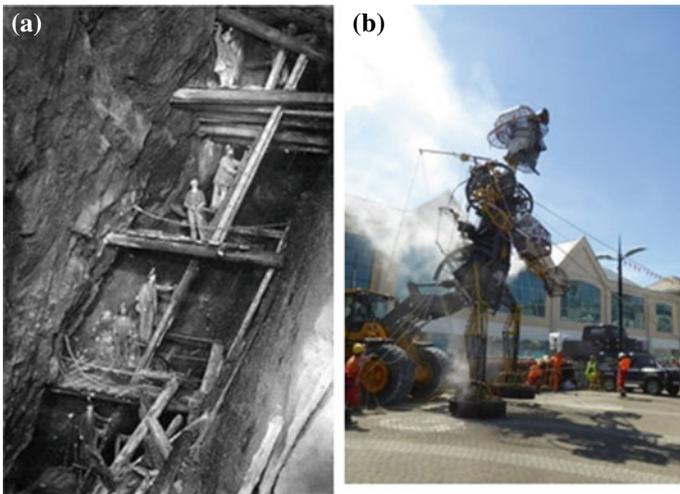


Fig. 9.2 **a** Mineworkers riding the man engine at the 234 fathom (428 m) level of Dolcoath Mine, Camborne, Cornwall in 1893. John Charles Burrow (1852–1914) by permission of the Steve Colwill Collection. **b** The mechanical giant puppet built to celebrate the Cornish man engine. Image by Rod Allday CC BY-SA-2.0 via [Wikipedia Commons](#)

is by developing communities that integrate rather than divide us with a sense of overall common purpose. When we accept that the golden rule of *all* religions is ‘Don’t do to others that you would not have them do to you’ then we have a key to spirituality. Again, this rule emphasises that the way we act leads to the way we believe rather than, as most religions now teach, belief determines how we should

behave. We should be using all of our considerable *ingenuity* to find new ways of living to *learn* how to be resilient when an unknown becomes a known—for example, an unforeseen consequence (an unknown) of climate change hits us (becomes known).

Christopher's story started with an offer to work in the company that Sir Ralph Freeman senior had created. Freeman had been one of the most eminent engineers of his day—for example, he designed the iconic Sydney Harbour Bridge (1932) in Australia. His son, also Ralph Freeman (and also knighted for his services to engineering) joined the business after the war and was made a partner in 1947. He had pre-war experience of bridge design and construction in Africa and worked on the 3.2 km steel girder road and rail Storstrøm Bridge in Denmark. He served with distinction in the war as chief engineer to 21 Army Group and was responsible for military bridges in France, Belgium, Holland and Germany. Freeman junior took over as senior partner at Freeman Fox in 1963, a position he held until he retired in 1979. Freeman Fox and Partners were in the early 1970s without doubt the top bridge designers in the world. They were responsible for the Forth Road Bridge, the Severn and Wye Bridges, the Erskine Bridge and both Bosphorus Bridges in Turkey. Freeman's other most notable partners were Sir Gilbert Roberts, Oleg Kerensky and Bill Brown. Roberts and Brown were responsible for the design of the West Gate Bridge. They had previously developed new design concepts including suspension and cable-stayed bridge decks with a stable aero-foil-shaped cross section, box girders with stiffened steel decks, new methods for spinning of cable wires and a new cable configuration.

As soon as he started work, Christopher began to gain some very valuable experience of bridge design and construction—including a two-year spell in Germany. He was then seconded in 1970 to the contractor Fairfield-Mabey working in Scotland on the Erskine Bridge, and responsible for the construction of the south side. One day he had an urgent phone call asking him to go straightaway to Australia to work on the West Gate Bridge in Melbourne. A new contractor, John Holland Pty, had been appointed by the Bridge Authority. Although the company had a high reputation, it had no experience of the construction of long-span steel bridges. The contractual position had become unclear with no definition of responsibilities of the respective parties. Christopher was given the responsibility for the construction of the bridge on the east side of the river.

In Melbourne, life was challenging due to demands of the job as well as settling down in a new country. But people were very friendly and helpful, and Christopher built good relations with the contractor—for example, he played squash regularly with Bill Tracey who worked for John Holland. Unfortunately, Bill was one of the 40 people killed. The other engineers who lost their lives and had worked closely with Christopher were Jack Hindshaw and Peter Crossley. Jack was the Resident Engineer. His role was to represent the designer on site—on behalf of the client—and to make sure that the contractor carried out the work as required. Jack had only been in Australia for a relatively short time after replacing the previous resident engineer. Christopher recalls that Jack was small in stature but very likeable with a strong Lancastrian accent. Christopher had worked in the London Office with

Peter Crossley. Peter was Deputy Resident Engineer and an exceptionally intelligent engineer with a degree from Cambridge University and a very successful career ahead of him.

The building of the bridge had not been easy with political, industrial and engineering problems. The original contractor was called World Services and Construction Pty Ltd. They had many difficulties with the trades union and eventually the company was dismissed from the contract by the Bridge Authority. As well as the problems at West Gate, Freeman Fox also had to cope with the collapse of their Milford Haven Bridge in Pembroke in Wales in 1970. That bridge differed from West Gate in that it was an all steel structure and was being erected by cantilevering out from a pier. Lengths of the full cross section of the box were welded on the end of a growing cantilever until the total length reached and rested on the next pier. The collapse occurred just as they were near to the next pier. At that point, the cantilever was at its longest and hence most vulnerable stage. The forces in the bridge at the root of the cantilever were at their maximum. As a direct consequence, a steel diaphragm at the pier buckled, the bridge effectively broke its back, the end of the cantilever fell to the ground and the span ended up broken and leaning at a sharp angle on the first pier.

At West Gate, all of the long approach spans were constructed in concrete. The main span over the river and the two spans each side of the river were designed as a composite structure—a steel box girder topped by a concrete deck. This was quite unusual at the time for a bridge of this size but was used because of political pressure to have as much local content as possible. The problem was that the Australian steel mills could not produce enough steel of the required quality for a full steel design. Also, there had been problems with cracking in the steel beams of a bridge built earlier in Melbourne. Long-span bridges have to be made as light as possible because the effect of its own weight is large when compared to the effects of the traffic. The result was that the erection of the bridge was challenging. The method of erection of the first of the steel spans was quite different from that used at Milford Haven. Two full span lengths of half boxes were assembled on the ground directly alongside the span. So, if you imagine the bridge in cross section, the joint between the two halves was down the centre line of the bridge. Each half section was the length of the span. After assembly, each one was jacked on towers high into the air and moved across to the final position on top of the piers at either end. The adjacent steel plates along the centre line were then to be joined together to form the full cross section. The joint was to be made by inserting a series of friction grip bolts into pre-drilled holes on both sides of the centre line. The problem was that the half sections were asymmetrical, and the abutting plates were very flexible. Consequently, the plates buckled and distorted along their length. It was difficult to get the holes in the steel plates aligned so the bolts could be inserted and tightened. The spans on the east side of the river were constructed first—to learn lessons that could be used for the west side.

On the day of the collapse, the identical steel span on the east side had already been built. Indeed, the partly erected bridge was visited by a number of dignitaries. In Fig. 9.3, Christopher is shaking hands with the Governor of Victoria Major General

Fig. 9.3 Meeting on West Gate Bridge. Image by Ketlar Photographic—provided by Christopher Simpson



Sir Rohan Delacombe. Christopher remembers that on the fateful day Jack and Peter came to him on the east side of the river. They had received a message that there was a problem on the west side—advice was needed but there was no indication that it was critical. Jack asked Christopher to accompany him. As they prepared to take the ferry, Christopher saw something that concerned him with the jacking operation to enable the cantilevered span to land on the next pier on his side of the river and he felt he needed to attend to it. So, he asked Jack if he could sort that out first before joining them on the west bank. Jack agreed and with Peter boarded the ferry to cross to the other side of the river. Christopher went up and on to the deck of the eastern span. A little later he was briefing some of the men when they heard a horrendous crash coming from the west bank. Christopher told me that the noise, dust and smoke is something he and the others will never forget—the western span had collapsed killing 35 men on the bridge including Jack and Peter who had only just reached the top of the deck.

The Royal Commission of Enquiry uncovered all sorts of incubating issues and the trigger event. They concluded *‘There can be no doubt that the particular action which precipitated the collapse.... was the removal of a number of bolts from a transverse splice in the upper flange plating near to mid-span. The bolts were removed in an attempt to straighten out a buckle which had occurred in one of the eight panels which*

constitute the upper flange. The buckle in turn, had been caused by the application of kentledge (heavy weight) in an attempt to overcome difficulties caused by errors in camber. To attribute the failure of the bridge to this single action of removing bolts would be entirely misleading. In our opinion, the sources of the failure lie much further back; they arise from two main causes. Primarily the designers of this major bridge, FF & P (Freeman Fox and Partners) failed altogether to give a proper and careful regard to the process of structural design. They failed also to give a proper check to the safety of the erection proposals put forward by the original contractors, WSC (World Services and Construction Pty Ltd). In consequence, the margins of safety for the bridge were inadequate during erection; they would also have been inadequate in the service condition had the bridge been completed. A secondary cause leading to the disaster was the unusual method proposed by WSC for the erection.... This erection method, if it was to be successful, required more than usual care on the part of the contractor and a consequential responsibility on the consultants to ensure that such care was indeed exercised. Neither contractor, WSC nor later JHC (John Holland & Co), appears to have appreciated this need for great care, while the consultants FF & P, failed in their duty to prevent the contractor from using procedures liable to be dangerous’.

As I later read the Commissioner’s report, I began to realize that Christopher and his colleagues on site had to deal with a set of very complex technical issues—box girders were state of the art at the time. Freeman Fox were at the top of the game technically and pushing at the boundaries of what was possible. The whole episode was really about solving a hugely difficult technical problem very severely aggravated by the political and commercial pressures surrounding the project. The role of the Bridge Authority, the human and organisational factors especially in the London office of Freeman Fox, the inexperience of the contractor and the consequential difficulties on site, had not just been circumstantial to technical matters, but had been a central part of the reason for the collapse and loss of life. In the whole of my engineering education up to that moment I had never been asked to even think about human and organisational factors. I realised for the first time that engineering is not just a technical discipline. Above all, engineering is a risky activity done by people for people. As we have seen in earlier chapters when it is done well it contributes to the quality of life. But if the people involved make mistakes that are not just narrowly technical but also include poor management practice, then lives may well be lost. In retrospect, this now sounds all too obvious but at the time it began to help me make sense of all sorts of issues deriving from the narrow technical focus of my education. It also led directly to my later work with Barry Turner and his theory of ‘incubating’ accidents-waiting-to-happen’.⁵

Will This Never Happen Again?

How often do we hear people say after some unfortunate event, ‘We must ensure that this never happens again’? The feeling that someone close has suffered in vain is

very painful. We naturally want to learn the lessons. But how realistic is it to believe with absolute certainty it will never happen again. History does repeat itself—we can, and we do attempt to learn the lessons and reduce the risks down to acceptable levels—but they are never zero. We know that sloppy thinking, negligence, corruption and wrongdoing have to be rooted out. But failures incubate in many various guises and investigators may get so immersed in the details of specific events that they fail to spot the ‘big picture’ patterns that Barry Turner’s incubating accidents model suggests. Incubation, or accident waiting to happen, as used by Turner, is an emergent property of events. Likewise, so is the actual catastrophe as the incubating pre-conditions are triggered by a final event. People responsible for projects need to look for signs that the pressures in Turner’s balloon are growing and when necessary take action to reduce them. In other words, they have constantly to be prepared, vigilant and careful—actively looking for evidence of incubating issues and being ready to act—to spend money to save money—especially with low-chance high-consequence risks. Some of the detailed things we learn are common sense. West Gate tells us rather obviously ‘Don’t position site huts under the bridge you are building’. But what might be the cost-risk benefit on a future restricted site where positioning the huts somewhere else is an upfront immediate real cost? Other lessons are much less straightforward and more general. For example, being prepared to admit you don’t know when that is genuinely the case risks you being seen to be incompetent. Someone else may claim to know—when perhaps the fact that they don’t know only emerges later after they have gained the advantage.

People do get trapped inside their specialist groups, teams or pockets of knowledge when groups are not integrated and do not communicate well. Information or resources are not shared, and the bigger picture does not emerge—indeed sharing may threaten protection of personal information and expose vulnerabilities. Problems created by organisational silos seem to be a lesson that goes to the heart of many of the failures of the social services and criminal justice system as well as Australian bridges.⁶ Ultimately, learning and executing these lessons is a matter of culture—learning together has to be our collective purpose. But to do that we have to bridge some quite large cultural divides as we attempt to make sense of the patterns of behaviour that both lead to success and failure.

Revisiting Patterns

Patterns are at the heart of Turner’s incubating accident model as they are for the modern game-changing disciplines of IT, quantum physics, complexity theory and systems engineering. Systems engineering is becoming a major new way of thinking because, at heart, it is about reversing the effects of fragmentation—its central purpose is integration. The way this can happen is by matching patterns of the physical world with the human and social worlds of the various disciplines of engineering.

The stories of previous chapters illustrate graphically how physical systems such as ploughs, bicycles, engines and heart pacemakers have successfully evolved in

complex patterns of ingenuities entirely embedded in society and culture—notwithstanding some ‘dead ends’ and failures too. Unfortunately, the prevailing ‘western’ cultural view is that the physical and the human are distinct and disjoint. The word ‘hard’ is still frequently used to describe physical systems and the word ‘soft’ for people and social systems. Hard implies objective, impersonal, value free, cold and emotionless. Soft is subjective, personal, value laden, warm and emotional. But the notion of a hard system also suggests (especially to academic engineers and scientists) well-defined, difficult, rigorous and having optimum solutions that can be found using scientific methods. The notion of a soft system denotes ill-defined, complex, lacking rigour, with no possibility of clear solutions.

In engineering, as in life, these kinds of distinctions are often sincerely held, but are also deeply unhelpful. They tend to lead to stereotypes of technological triumphalism on the one side and badinage of ‘techy nerds’ high on the Asperger’s scale on the other.⁷ More seriously they have in the past encouraged a profound lack of interdisciplinary understanding, sometimes active hostility, and little active collaboration between engineering and other intellectual disciplines. The formidable challenges of the future will have interwoven hard and soft system issues. They will present us with unforeseen and presently unknowable physical and social consequences including surprises and opportunities. We are much more likely to succeed if we can collaborate across all kinds of boundaries whether professional, political, gender, ethnic or religious. Systems thinking is not just a new ‘management fad’, rather it is a genuine change in outlook.⁸

A system is a pattern of a collection of things, whether physical or human, arranged in layers of sub-systems as per the principle of *Part*. Systems are chosen and defined for a particular purpose. An important aspect of the principle of *Preparedness* is to engineer things so that the right information (*what*) gets to the right people (*who*) at the right time (*when*) for the right purpose (*why*) in the right form (*where*) and in the right way (*how*). Easy to say but very difficult to do. Some label this way of looking at things as ‘joined-up-thinking’ because an important purpose is to harmonise the detail of a system with the big picture and the physical with the human.

As a systems thinker, I start with three important ideas. First, I *model* my understanding of the world in levels or layers of dynamic patterns as per the principle of *Part*. We saw the importance of layered patterns for computers and the Internet in Chap. 6. Second, I see the components within the layers as parts and wholes at the same instance. Arthur Koestler⁹ captured this idea with the word *holon* from the Greek *holos* meaning whole and the suffix ‘on’ meaning a part as in proton and electron. Third I see holons as being interconnected and exchanging energy with other particular holons. In other words, holons are continuously interacting processes arranged in layers.

I find that a good way of thinking about layers of holons is this. In our own bodies groups of atoms are holons that combine to become various molecules (holons) which interact in cells (holons of skin, blood, neuron cells, etc.), groups of cells combine to become tissue (holons of skin, bone, etc.) which form organs (holons of kidney, heart, brain, etc.) and systems of organs (holons of skeletal, digestive, nervous systems, etc.) that together make us who we are—as holons. We are, in effect, a massive

collection of organised interacting atoms—interacting simpler things that lead, in successive layers, to more complex things. Unfortunately, the systems carry a bevy of uncertainties and unintended consequences from the interactions such as disease. Disease is the principle of the *unintended* in action at molecular levels although of course our molecules, cells and tissue have no intentionality—that is, ascribed by us as conscious human beings in ways we do not yet fully understand.

The layers do not stop with us as individuals of course. Each of us would not survive without being part of even higher level layers such as our family holons, and all sorts of social grouping holons from local societies to regional and national and international organisations. We see these layers of holons in everything. For example, a bridge is also made of atoms and molecules which form materials such as concrete, rock and steel (c.f. tissue) and we shape materials to form structural components like beams (c.f. organs) which interact to form parts of bridge-like foundations and superstructure (c.f. skeleton) which together make the bridge. But the bridge is part of a transport system such as highway (c.f. local society) which is essential to the life and economy of a region.

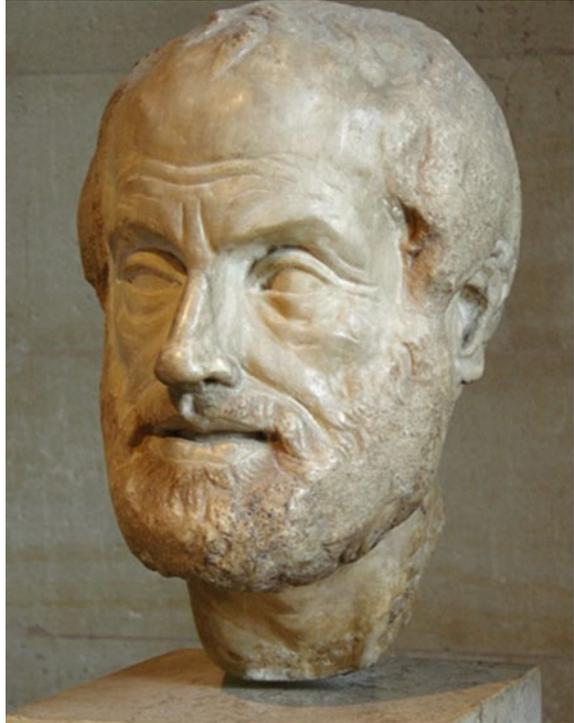
I think that the key to achieving joined-up thinking is threefold. Firstly, an organisational culture that works through active collaboration. Secondly, common consent to work with a particular model of the structure of the interactions between the holons. Thirdly, a common view of the structure of each holon based on a variant of the decision-making processes we looked at in Chap. 3.

So far, we have only covered the first two factors—collaboration and interactions between holons. The third key factor, the internal structure of the holons, can be usefully based on answers to common sets of question types required for *Preparedness*. Recall that the headings are *why*, *how*, *who*, *what*, *where* and *when*. The idea is that answers to *why* questions are the potential that drive the flow of changes in answers to questions, *who*, *what*, *where* and *when* by using methods and transformations from answers to questions *how*.

For example, asking *why* questions identifies the problem in terms of needs, wants, purposes and objectives for soft systems but voltage and acceleration for hard systems. Asking *who*, *what*, *where*, *when* questions identifies possible solutions and the criteria used, to select the best one, to carry flows of change. Within that grouping questions of type *who* identify the people and their capabilities for soft systems in which hard systems are embedded. Questions *what* identify the performance indicators and state variables. Questions *where* define place and context and *when* define timings for both hard and soft systems. Finally, questions *how* identify methods by which inputs (values of who, what, where, when) are turned to outputs. They might include method statements, recipes but also theoretical mathematical transfer functions and computer algorithms.

At the risk of being arcane, it is important to recognise that thinking of the world in this layered set of structured holons is not the reality—rather it is our way of *thinking about* the reality. It's helpful because it gives us a way of coping with the huge scope, size and extent of the world so that we can model, represent share and make decisions about it in a meaningful way. It integrates our thinking about hard and soft systems with one structure and follows Popper's three worlds in that we

Fig. 9.4 Sculpture of Aristotle at the Louvre Museum. Image by Eric Gaba, CC-BY-SA-2.5 via [Wikimedia Commons](#)



recognise that reality exists (world 1) but we can only access it through our human apparatus—our senses and our brains (worlds 2 and 3).

Finding patterns across whole systems requires individual and collective ingenuity. But above all it depends upon collaboration—and that needs rigorous practical wisdom (Fig. 9.4).

Practical Wisdom and Rigour

Practical wisdom is an expression of the principle of *Ingenuity*—being inventive, resourceful and skilful through direct practical experience. The loss of Aristotle’s idea of practical wisdom as *phronesis* (Chap. 3) in modern times means that we simply do not recognise, value or nurture it. Not only that, practical people are made to feel inferior compared to those with more theoretical knowledge. Of course, the roots of this loss are complex as Aristotle’s ideas have been interpreted and modified by many historical developments. For more on this see.¹⁰

Practice is often criticised as being ad hoc and lacking rigour because engineers use approximations and judgment. In fact, engineers must be, and are, rigorous in a different way for two compelling reasons. Firstly, engineering products will

inevitably be subject to the ultimate test—that of Mother Nature. If a bridge structure is inadequate to take the imposed forces, then it will collapse. This enforces a kind of ‘*natural honesty*’ and trustworthiness—a requirement that cannot be twisted by propaganda or ‘spin’. Secondly, engineers have a legal duty of care to society. Under this duty engineers must justify their decisions, if called upon to do so (e.g. when something goes wrong), in a society that questions expertise.

Rigour is the strict adherence to, and enforcement of, rules to an end. Mathematical logic is the ultimate form of absolute rigour with one value—truth. It is top-down reasoning, i.e. theorems (at the bottom) are deduced from axioms (including rules) which are true (at the top) by definition. The result is a self-consistent body of true statements—but only if the axioms correspond to reality. An example of where there are differences in the axioms is Euclidean plane geometry, (that we learnt at school with axioms that apply only to 2D plane surfaces) and spherical geometry (used by navigators, surveyors and astronomers with axioms that apply to a sphere). Science is rigorous in an opposite way to mathematics because it is reasoning from the bottom up. Put simply scientists’ construct theories (at the top) and use them to deduce propositions (at the bottom) that they can test with an experiment. If successful, then they have a truth or a fact (at the bottom). Unfortunately, one fact (at the bottom) does not prove that the theory (at the top) is true in all circumstances. That is because there could be lots of other propositions deducible from the theory in many different circumstances which haven’t been tested, or just haven’t been thought of, and which could turn out not to be true. We can never be sure because there are so many possibilities. Nevertheless, the more successful tests we conduct then the more we understand the context in which the theory works and the more dependable it is to make practical decisions. Such testing is part of the duty of care of all practitioners.

Practical rigour is more complex than either mathematical or scientific rigour and not well understood still less appreciated. It is the meeting of a need by setting clear objectives. Of overriding importance is the professional duty of care to deliver those objectives using all relevant and available information and expertise. Although we know that Newtonian physics may not be true throughout the cosmos, it is dependably true for most earth-bound engineering calculations, and we can responsibly and rigorously design big bridges using it. Practical rigour usually involves many values—some in direct conflict—and finding ways to reach the objectives in a demonstrably dependable and justifiable way that recognises all of our rational and emotional needs and desires.

The five principles are central to practical rigour. The principle of *Part* is required to consider the whole as well as the parts and hence to reduce the chances of missing something important. Scientific and mathematical rigour in the scientific method breaks a problem into parts, removes most of the difficult bits that we do not know how to solve and focuses on the bits we can solve. It is therefore a process of selective inattention. Practical rigour does not have that luxury—but requires a rigour that encompasses the bits of the problem that we do not always understand too well and understanding the totality of the ‘big picture’ as well as the detail.

The principle of the *Unintended* is essential in creating appropriate theoretical and practical models of the problem. Practitioners make sensible approximations

that respect nature but provide useful insights into possible future behaviours as well as using creative foresight to imagine what could possibly happen. Practical rigour requires diligence and duty of care that leaves no stone unturned with no sloppy or slipshod thinking. Practical solutions must meet explicit needs and deliver a system valued in a variety of ways. Those ways are not just efficiency or cost but including such criteria as aesthetics, sustainability, practicability and resilience. Solutions have to be scanned for possible unintended consequences before being implemented, and able to be monitored to identify them during use.

Because a practical system has to work for a particular period of time then the principle of *Preparedness* is required to be ready to monitor, fine-tune, readjust and maintain performance. That requires finding and evaluating evidence that we can depend on. That evidence needs to be testable, if possible, in as many ways as seems appropriate—for example, data from measurements will allow judgements about performance such as the displacements of a retaining wall or length of cracks in an aeroplane wing. Judgements can differ between individuals with similar levels of competence—which is why calm critical discussion is so important. Good judgment is a critical part of practical rigour. Professional opinions are not arbitrary, rather they are based on practical wisdom. Engineers test their judgements by asking themselves this question. Could we justify our decisions in court?

All of this requires the principle of *Ingenuity*—perhaps most importantly of all for creative foresight to imagine possible unintended consequences. Practice requires the creativity to imagine what might happen—we might call it ‘imagineering’—how physical things will respond and how people might behave in future situations or scenarios. So, if we build a skyscraper how might it fail? If we write new social media software how might it be used? But engineers are human and therefore unable to foresee every possibility as 9/11 proved for skyscrapers and teenage self-harm, bullying and sexual abuse for social media.

But we can learn and adapt. So finally, since judgements are decisive then the principle of *Learning* is also key to practical rigour—learning to improve or self-renew. Without reflecting on and learning from experience practical problem solving does indeed become ad hoc.

Practical rigour implies practical intelligence, which in turn implies practical experience. In other words, experience is necessary but not sufficient for practical intelligence—a capacity to learn, reason and understand practical matters. And practical intelligence is necessary but not sufficient for practical rigour. That is because practical intelligence and rigour require reflective learning and development on that experience. Practical wisdom, based on trust, will be required to address the grand challenges of our common future.

Grand Challenges

Grand challenges are barriers that if removed would lead to important advances. In 2000, the UN established eight sweeping and ambitious Millennium Goals¹¹ ranging from eradicating extreme poverty and hunger to ensuring environmental sustainability. In 2015, these have morphed into 17 Sustainable Development Goals (SDG) and 169 targets including good health and well-being, reduced inequalities and peace and justice.¹² Clearly, such aspirational challenges require global partnerships involving everyone—again something easy to say but incredibly difficult to deliver. One of the first engineering organisations to ponder on more specific, yet still high level, engineering grand challenges was the USA National Academy of Engineering.¹³ In 2008, it issued a list of 14 grand challenges. The list largely concerns particular functions like solar power, but they are worth describing in a little detail before we consider some of the essential underlying generic engineering issues. In essence, they are contained within a more detailed expansion of the 17 UN SDGs. They are listed here in the order of the topics of previous chapters but in no particular order of precedence.

Challenge number one has been recognised by many western governments in principle but action is patchy. The need is to restore and improve our infrastructure—our built environment is critically important. Infrastructure includes many of the needs covered in earlier chapters. The UK National Infrastructure Plan 2014 recognises that *‘Improving... productivity is a vital element of... long term economic planning. High-quality infrastructure boosts productivity and competitiveness...’* U.S. policy states that *‘efforts shall address the security and resilience of critical infrastructure in an integrated, holistic manner to reflect this infrastructure’s interconnectedness and interdependency’*. Funding for infrastructure projects has been hopelessly inadequate. Too often we let infrastructure wear out before replacing it and simply exacerbate the problems—the lesson to be learned is not to neglect it through short-term thinking by moneymen.

The second in the NAE list of challenges is making solar energy economical. It is the subject of ongoing research. For example, present materials for solar cells have impurities that tend to hinder the flow of electricity. Newer purer materials could reduce that whilst at the same time reducing costs. Aeroplanes like Solar Impulse will see a direct benefit. In all solar applications, power fluctuates as the weather changes so has to be stored when plentiful. Possibilities include using large banks of batteries (as Solar Impulse), pumping water and recovering energy (as hydroelectricity), employing superconducting magnets or flywheels, and electrolysing water to generate hydrogen to power fuel cells. Fuel cells have the great advantage that they produce virtually no pollution, but hydrogen can embrittle metal, so the risks of fracture need to be managed carefully.

The third challenge is creating energy from fusion—the reaction in which two atoms of hydrogen combine together, or fuse, to form an atom of helium and some of the mass of the hydrogen is converted into energy. It is the process that powers the sun and the stars, and achieved in the laboratory but not, at present, practically

viable. The case for fusion is perhaps more speculative because currently it takes more energy to initiate and control the fusion than is produced. Fusion would be environmentally friendly with no combustion products or greenhouse gases—the actual products (helium and a neutron) are not radioactive.

The next challenge, number four, is to find ways to sequester carbon. This is capturing carbon dioxide produced by burning fossil fuels and storing it safely away from the atmosphere. Manufacturers of carbonated water can dissolve pressurised carbon dioxide in water. Makers of dry ice convert liquid carbon dioxide into compressed dry ice snow. Similar approaches could be developed for coal-burning electric power plants in which smokestacks become absorption towers. But once sequestered the gas how has to be stored. Suggestions include old gas and oil fields, but they aren't on their own large enough. Carbon dioxide with water can be severely corrosive as carbonic acid. In 2017, a number of researchers reported¹⁴ on 20 options for better stewardship of land. They identified and quantified 'natural climate solutions' to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands and agricultural lands. They argued that the actions could mitigate around 37% of the cost-effective carbon dioxide needed through to 2030 with a greater than 66% chance of holding warming to below 2 °C. The actions also offer water filtration, flood buffering, soil health, biodiversity habitat and enhanced climate resilience. Whilst more research is needed this seems to provide a robust basis for immediate global action to improve ecosystem stewardship as part of a major solution to climate change.

The fifth challenge is to reverse engineer the brain as part of improving communications and AI. Reverse engineering is the study of something to learn how it works in order to produce a copy—or an improved version. You will recall that I said that computers have been programmed to play chess rather well but are a long way from being creatively human. General-purpose artificial intelligence is a considerable challenge and not helped by media hype. Artificial brains have been designed without much attention to real ones. It's rather like the aeronautical engineering of flying without much learning from the flight of birds. Some experts believe that they can reverse-engineer the brain and open up enormous opportunities.

The security of communications in cyberspace is the next challenge. You would have to be a modern hermit not to be aware of the issues of personal privacy and national security in using social media through the electronic web of information sharing called cyberspace. These issues represent some of the most complex challenges engineers have ever faced. They range from protecting confidentiality and integrity to deterring identity theft. They are demands riddled with unintended consequences ranging from the 'dark web' to 'sexting' teenagers, self-harm and suicides. Encryption is a central issue—converting the syntax of meaningful patterns of sensitive information into code that is not meaningful unless you have a decoder. Sensitive information includes passwords, banking data, credit card numbers and other personal and private data. Unencrypted data is often called *plaintext*. Current methods use an encryption key to convert plaintext into *ciphertext*. Brute force is the crudest method to attack it—systematically trying each key until one that works is found—in that case, the strength of an encryption is directly related to the length of the

key. End-to-end encryption is more subtle because only the sender and receiver can decrypt it—no one else (including the Internet service or applications providers) or hacker can read it without some cryptanalysis—finding out weaknesses. Legitimate users benefit from secure encryption. Illegitimate use (for example, by terrorists or pornographers) is a threat because it is tricky for law enforcement agencies to get access. One suggestion that would be difficult to implement in practice is to divide a key into pieces so no one person or agency alone could decide to use it. Another suggestion is that a third party, such as a judge, could require a key be made available to law enforcement officers.

Challenge number seven is to enhance virtual reality (VR) in communications. The aim is computer simulation for all of the senses to create the impression of being somewhere else. Virtual reality can transport you to a football game, a concert, a ship on the ocean or to a space station. With the right skills you can ride a horse, fly a jet plane, perform surgery or control a nuclear reactor. Virtual reality is not just about depicting scenes but about creating an illusion of actually being there. It attempts to recreate the actual experience, combining vision, sound, touch and feelings of motion engineered to give the brain a realistic set of sensations. One potential unintended consequence could be an effect on the mental health of some people as their actual and virtual realities merge.

The eighth challenge is overwhelmingly serious—to prevent nuclear warfare and terror. We cannot assume that terrorists are not attempting to make nuclear weapons. The materials suitable for making a weapon have been accumulating around the world. Many countries have nuclear reactors—for producing power or just for doing research. Each one could potentially be used to produce the raw material for a nuclear bomb. The instructions for building devices are relatively easily attainable. If you have the materials, you could possibly make a bomb. Nuclear security is possibly one of the most acute policy issues of the twenty-first century—not just politically but also technically. The challenge is not just to locate dangerous nuclear material—but to find all of it in the world. Then to keep track of it, secure it and detect any diversion or transport that could fall into the hands of terrorists.

Perhaps one of the biggest issues of nuclear safety, terrorism and modern warfare is the difficulty our business, political leaders and opinion formers have in understanding the potential impacts of AI. Separating media hype, about equipment such as drones, from the reality is not straightforward—regardless of the possibilities of unintended consequences. Leaders tend, as do many of us, to think deterministically in terms of cause and effect. Typically, the argument is ‘We think this is the problem, this is what I’ll do about it, and this is what will happen’. The difficulty in managing terrorism and AI war machines is in the last stage—what will happen is unpredictable. Terrorism is not a finite game—with a start, middle and end. Some terrorists are in an infinite game that they will continue to play even when their colleagues die.

Power is no longer about being capable of destroying another nation—rather it depends on what you value. Changing regimes, assassinating enemies or persecuting war crimes won’t make you more powerful. Unfortunately, we humans tend to judge our leaders on personal strength and steadiness, and we choose the one who makes us feel secure. Limited leaders make poor choices. Civilian drones, and other yet to

be imagined AI machines, armed with weapons will change the balance of power. Formal declarations of war will become relics of the past. Power will be about leading your foe into doing what you want without having to fight. Leaders should be thinking about systems of checks-and-balances because the future of war is not about the military but about sustainability, resilience and protecting our civil liberties, national preparedness and resolve.

Challenge nine is to manage the nitrogen cycle—processes central to producing food, controlling the impact of agriculture and sustainable development. Nitrogen is the main element in our air—nearly four-fifths of the atmosphere. We have altered the cycle in which nitrogen in the air is ‘fixed’, i.e. is converted from nitrogen gas into a form that can be used by living organisms as a nutrient. The widespread use of fertilisers and high-temperature industrial combustion has vastly increased the rate at which nitrogen is removed from the air. The resulting nitrogen oxides have caused air pollution and acid rain, polluted drinking water, eutrophication of watercourses (too many nutrients, decaying algae and depleting oxygen) and it has worsened global warming. We need to improve a range of engineering processes ranging from making fertiliser to recycling food wastes. Currently less than half of the fixed nitrogen generated by farming ends up in harvested crops. Less than half of the nitrogen in the crops ends up in our food. Fixed nitrogen leaks out of the system. Engineers need to identify the leakage points and devise systems to plug them.

‘Precision agriculture’ is one possibility—using sensors and algorithms to deliver nitrogen fertiliser as well as water and pesticides targeted to only the crops that need them. Sensors, powered with solar panels, collect data about moisture, temperature and acidity, nitrogen levels, crop yields and topography, using GPS and drones. The information is then used to manage and control resources more closely. A major difficulty is getting data from sensor to farmer in a form that is usable. This kind of approach may also be important in tackling crop failures that lead to famine.

The tenth challenge is perhaps the most scandalous in the sense it should already have been done—it is to provide access to clean water for everyone across the world—a disgraceful lack of well-being that is responsible for so many deaths—some say more than war. Estimates are that about 1 out of every 6 people living today do not have adequate drinking water and, in some countries, that proportion rises to a half of the population. Many more lack basic sanitation. Consequently, poor health results, by some estimates, in nearly 5,000 children worldwide dying each day from diarrhoea-related diseases.

The eleventh challenge is to advance health informatics. We have seen the contribution of engineers in medical engineering such as heart pacemakers. Health informatics is the broader use of digital electronics and computers. It ranges from the personal to the global, from keeping good medical records for individuals to sharing data internationally about outbreaks of disease. Engineers and medical doctors will need to work together to maintain healthy populations in the twenty-first century.

The twelfth challenge is to engineer better medicines and better methods of delivery of drugs as we saw through the pioneering work of Robert Langer. Improved ways are required to (a) assess quickly the genetic profile of a patient, (b) collect and manage massive amounts of data about an individual in a trustworthy way and (c)

create inexpensive and rapid diagnostic devices such as sensors able to detect minute amounts of significant changes in the blood.

Challenge number thirteen is to advance personalised learning through improved communications. Some learners are highly self-motivated and learn by exploring knowledge on their own with minimal guidance. Others might prefer a more structured approach or being motivated by external rewards or may need step-by-step instruction. Some even will resist learning altogether and show little motivation or interest. Systems have already been designed that store instructional content, deliver it to students and facilitate interaction between instructors and learners.

The fourteenth and last National Academy of Engineering challenge concerns the tools of scientific discovery. A theme of this book is that knowing and doing develop hand in hand. Engineers make the tools that scientists use, and the knowledge gained helps engineers make better tools and the process spirals as we have seen in earlier chapters. There is no reason to doubt that this will continue so perhaps this is one challenge that will never be met totally. The new bioengineering discipline of synthetic biology has exciting potential for the design of entirely novel biological chemicals and systems that could prove useful in applications ranging from fuels to medicines to environmental clean up and more.

The fourteen challenges of 2008 concerned specific areas of application. As if to demonstrate how opinions even amongst experts differ and how times move on, in 2013 The National Engineering Academies of USA, UK and China got together to discuss challenges under the six headings of sustainability, health, education, enriching life, technology and growth, and resilience.

Then, in 2014, the UK Engineering and Physical Science Research Council (EPSRC) produced a list of seven different generic challenges that cross-cut those of the NAE. Each of the EPSRC challenges applies to every NAE challenge to a degree.

The first one is about risk and resilience in a connected world. It concerns working with complex systems, recognising that the future is uncertain, and that our science is incomplete. Recognising the existence of unknown unknowns and adopting the principle of the *Unintended* will be decisive.

The second EPSRC challenge is controlling cellular behaviour—generic to all living things and central to medical engineering for well-being. Integrating novel engineering approaches with biology and medicine to design, create and control living systems throws up some difficult ethical issues. The key to this challenge is that new approaches are needed to design devices, molecules and surfaces which can guide cells to perform a specific target function, whilst allowing for other biological functions and mitigating against systemic effects.

The third EPSRC challenge is called ‘engineering from atoms to applications’—investing in the principle of *Part*. Again, it is cross-cutting and about understanding and working across the scales or levels of our understanding in ‘hard’ physical and in ‘soft’ human and organisational systems. It needs thinking based on holons—seeing systems as both a whole and a part at one and the same time.

The development of new materials, such as composites like carbon fibres and graphene, is important under this heading. Carbon comes in a number of forms, called allotropes such as diamond, graphite and fullerene, where the atoms are bonded

together differently. Diamond bonds are very strong crystal structures and so very hard and not easily contaminated. Graphite is not so rigid, but it is a three-dimensional crystal that cleaves into thin sheets. Researchers at the University of Manchester in 2004 have taken this to the limit and made layers as thin as one atom—graphene—the first two-dimensional material in the world. The layers are very strong but flexible, transparent and with high conductivity so that they can be used in transistors without any doping. Potential applications are just emerging. The material is multi-functional so can be used in many ways at the same time in electronic sensors, solar cells, membranes for purifying water, biomedical devices, sports equipment, aerospace and it can be combined with other materials for specific applications.

The fourth EPSRC challenge is the set of exciting opportunities set out by two of the NAE grand challenges for well-being. They are number twelve—engineering personally targeted delivery of drugs and number thirteen—advancing personalised learning. They are examples of bespoke engineering—engineering tailored to the individual. In the past century, mass production has given us good quality products from furniture and clothing to food and drugs to bicycles and cars. We have enjoyed things we might simply have not been able to afford if individually produced by a craftsman. But it has eroded our sense of individuality and identity. People look for and value highly individual creativity in art and design. Mass production can result in uniformity—sometimes drab like houses set out in box-like estates. Modern techniques such as 3-D printing create the possibility of much more individuality. The word printing is possibly misleading. Rather it is bespoke engineering by getting personal. We will be able to produce devices and products tailored to individual needs through computer-controlled manufacturing processes and robots. The idea has been used in regenerative medicine to create living tissue with stem cells and perhaps will even extend to the creation of new living organs.

The fifth EPSRC challenge is simply called ‘big data’ (Chap. 6). We produce, access, process and use more data than ever before in the history of humankind. As you will recall data is syntax and not semantic information. In other words, information is data that have been interpreted to give it meaning and that meaning can change with context. Some companies have been labelled as data rich and information poor where they collect and store large volumes of data, but they don’t interpret to make it useful. For example, companies that collect feedback from customers and then do not act on the results. A personal example is a friend whose flight was cancelled at short notice by an airline with no offer of alternative flights or accommodation and then within a few days sent an email asking for feedback about the service they provided.

One engineering challenge is to improve syntactical encryption to make data secure, robust, reliable and efficient whilst recognising the ways in which it is changing. The second derives from the semantics of how to interpret data to develop understanding—our ability to grasp the significance and importance of our data and build models to predict possible future scenarios—knowledge. Thirdly, using the data pragmatically or cognitively and further to be creative with it requires insight and inventiveness, making new connections between previously disparate ideas and being resourceful in developing them—the principle of *Ingenuity*. Choosing between them

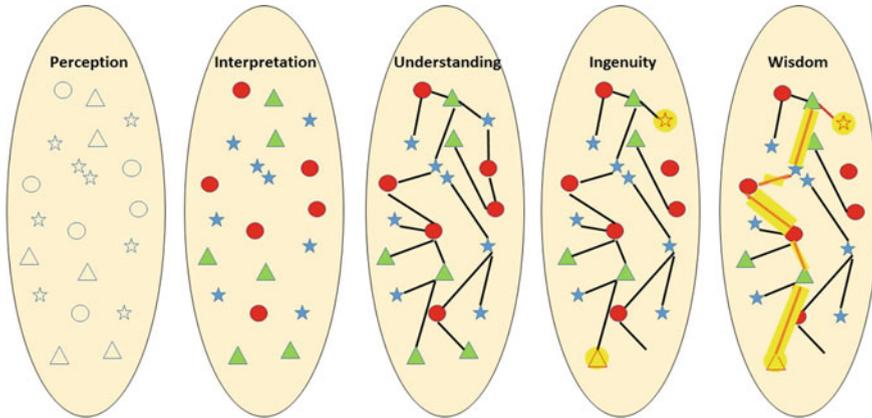


Fig. 9.5 Patterns

requires sagacity, soundness of judgement, foresight, being judicious and prudent—wisdom. Figure 9.5 diagrammatically illustrates these stages and is a development of original sketches by Hugh MacLeod and David Somerville.¹⁵ Perception is portrayed as identifying objects, interpretation gives them meaning (as colour in the diagram), understanding derives from joining them up to see connections and relationships, and ingenuity is spotting new and previously unlikely connections. Finally, wisdom is finding connecting pathways between previously unconnected objects.

Is being wise the same as being smart? The word ‘smart’ is already finding its way into our vocabulary. We are hearing the words smart meters, smart infrastructure, smart homes, smart health and smart cities. Smart is having a quick, shrewd intelligence—usually implying common sense. A smart gas or electricity meter sends its readings to your supplier electronically. You may well already have one to keep track of your use of gas/electricity and how much it is costing. But your meter is only transmitting and informing you of your data. It is a long way from being smart in the sense of creating understanding, knowledge and is totally devoid of anything approaching wisdom. The future smart city is often quoted as having digital technology integrated across many services such as schools, libraries, entertainment, transportation, power and water supplies, waste management and law enforcement—but to be a really smart city the digital systems will need to be embedded in ingeniously wise human and social systems that are fully integrated by identifying cross-cutting processes.⁵ Smart buildings will be accessed by autonomous vehicles, incorporate solar walls and panels, have advanced computer-assisted energy management, with as much natural lighting and green space as possible, but at the same time must cherish our environmental and contextual heritage. There is a big risk here in that using a word like smart for these early applications is hype that will ultimately be self-defeating. The equipment may well do what it is designed to do but it will fail to live up to the expectations implied by the name. A better, more realistic phrase and not raising unrealistic expectations might have been ‘master meter’. Engineers would do well to

consider their language more carefully and exercise more restraint on the excesses of their marketing colleagues.

The sixth challenge that EPSRC called supra-structures is, like NAE challenge number six, the development and operation of better integrated interconnected infrastructures—both the physical and organisational structures/facilities—for a sustainable future.

Engineers at the Heart of Society

The seventh and final EPSRC challenge is to put engineers at the heart of public decision making—improving the use of technical expertise in democratic decision making, realising that the technical is embedded in the social, appreciating that technical and social boundaries hinder collaboration, learning together and inspiring more women. This is not a call for technocracy—government by an elite of technical experts. Technocracy means that leaders are chosen for their expertise and unelected. Technocracy is undemocratic. Of course, governments can and do consult experts of all kinds in making policy. However, there is often a lack of mutual understanding of the issues. For example, for many years, despite being advised to the contrary, governments in the UK did not seem to realise that lack of continuity of policy in providing and maintaining infrastructure created extra and avoidable costs. Partly, as a consequence, many engineers find the kind of decision making of politicians and civil servants rather baffling. If engineers are to be at the heart of public decision making there will have to be a change in the current culture of engineering education and professional development. There will need to be a much greater empathy, connection and integration with other disciplines especially the social sciences, law, medicine but also surprisingly perhaps with science and philosophy. James Crowden shows us that an engineering education can be a preparation for a life outside of the profession. Though usually conceived as a vocational subject, engineering, by its very nature, is an essential part of the human condition and needs to be taught in that way. Teachers of engineering should be aware that as well as *teaching to engineering* they can teach *through engineering*.

The American philosopher Carl Mitcham¹⁶ has laid down a similar challenge to engineers—he calls it the challenge of engineering self-knowledge. He relates it to C. P. Snow's assertion about a tension across the yawning gap between the two cultures of science and the humanities. In his 1959 Rede Lecture, at the University of Cambridge, Snow said that the split was a major hindrance to solving the world's problems. Mitcham's gap is not between two forms of knowledge production but rather between two forms that are practical action and consequences. He contrasts designing and constructing the world—by which he means engineering in its broadest sense—with reflecting on what it means—by which he means the humanities. At root, Mitcham wants a much wider debate across the gap between engineering work in changing our physical world and the broad social context with which it interacts.

In the spirit of a wider sense of engineering, some lawyers and economists have started to see their professional disciplines as a form of engineering rather than as a humanity, social or physical science. In his lucid account of law as engineering David Howarth, a distinguished academic lawyer and politician, has written about transactional and legislative law¹⁷: ‘...like engineers...lawyers want to make something useful that works for their clients. They are presented with problems to solve, an undesired current state of affairs, and a desired future state of affairs with obstacles and risks lying between the two’. The objects created by lawyers are not metal or concrete or plastic but relationships between people and designed in words rather than in drawings. The forces that lawyer’s harness are not natural physical laws but human and can include the coercive power of the state. Contracts, companies, conveyances, wills, trusts, regulations, statutes and constitutions are all useful objects designed and created by lawyers and in engineering terms are devices that produce change in the world outside of the device. Likewise, Harvard economics professor Alvin Roth pointed out in 2002 that whilst the economic environment evolves it is also designed. Entrepreneurs, managers, legislators, regulators, lawyers and judges all get involved in the design of economic institutions. Gregory Mankiw, also an economist at Harvard, agrees that economists should think of themselves as engineers rather than scientists. In April 2019, a major conference on economics as engineering was held in the USA.¹⁸

Meeting the Challenges

Discerning the relationships between law, economics and engineering widens our perspective of what engineering is and helps to bridge the gap between the social and the technical. This is important because that bridging is cardinal to meeting the SDGs and all of the grand challenges. It will facilitate the kind of integrated worldview needed to promote collaboration, value practical wisdom and nurture the ingenuity of creative resilience. For example, rethinking this way could be one key to finding the social ingenuity we need to address the scandalous corruption and lack of common humanity that prevents us collectively from providing clean water and prevent famine around the world. The reasons why this kind of scandal continues is not technical—it is entirely human. Rethinking could also help us to cope with the risks of the unexpected—to take advantage when the unexpected is good and to recover well when it is bad.

Risk is not well understood by almost everyone—it isn’t an easy idea. One of the largely unrecognised reasons is that it is as generic and as enigmatic as truth. Both are, at one level, straightforward. A true statement is one that corresponds with the facts. Risk is a bit like betting on the chance of some future event like having an accident as you drive your car. However, as we have seen in earlier chapters, at the deepest level truth is difficult to pin-down, and context dependent—as is risk.

Risk is to action as truth is to knowledge. In other words, just as truth is an attribute of what we think we know so is risk an attribute of how we think about how

we should act. Risk, perceived and interpreted in one context, doesn't easily transfer to other contexts. For example, many people accept higher risks when driving a car than when they are flying in an aeroplane because they feel in control driving a car but at the mercy of others in an aeroplane. Most experts agree on variations of a basic definition of risk as 'the chance that a particular set of conditions will happen in a stated context in the future' but interpretations differ. For example, statisticians emphasise probability as chance or degree of belief, psychologists see it in terms of how people think, feel and act and engineers see it in terms of safety and performance factors. When the risky set of conditions spell danger or harm then they are a hazard. The flip side when the conditions promise a benefit then they are an opportunity. A simple hazard is a trailing wire that someone may trip over. A complex hazard is the difficult to spot incubating conditions of an 'accident waiting to happen' as first articulated by Barry Turner. A chance, such as 1 in 1000, is the ratio of the number of times an event may occur to the number of possible future scenarios. So, for every 1000 possibilities 1 might occur. This kind of thinking is straightforward for a simple problem like the tossing of a dice or the spinning of a roulette wheel. Unfortunately, problems that involve the way people behave are often complex because people have the propensity to do the unexpected. In some instances, anything could happen. We have to admit the possibility of unknown unknowns and utter surprises like 9/11 and the 2008 banking collapse or the 2020 coronavirus in China. We now know that even simple physical systems can, under certain circumstances, be complex. Results from new theories of 'chaos' show that even quite simple deterministic processes, like the rotation of a hinged pendulum, can be unpredictable. In other words, in some situations, the number of possible futures is infinite. Therefore, a chance of one in infinity is zero and meaningless. Of course we can and do produce theories that project the past into the future, including risk analyses and predictions, but we should always remember that the theories depend on context and the principle of the unintended rules risk for any other than quite simple contexts (like a roulette wheel).

Paul Grundy, an Australian civil engineer, wrote of the six steps in reducing engineer risks. First, he says, know the hazards and risks. Then identify the weaknesses. Retrofit—replace, modify and upgrade systems—to plug the weaknesses and create resilience against all hazards. Plan emergency response procedures and educate the community to understand and implement the procedures. Finally, rehearse emergency responses regularly. Grundy's pragmatic suggestions are sensible if we target our thinking on what we think are the risks. But his scheme is also helpful in that it moves us away from a focus on trying to predict risk (predictions that are necessarily flawed and context dependent) to a focus on how we manage risk whilst avoiding telling people what to do and including and collaborating with them to build consensus about what needs doing. In other words, Grundy is helping us to recalibrate our thinking away from risk analysis towards engineering resilience.

Resilience is about recovery when things go wrong. One of the ways our natural world is resilient is through diversity. Systems that are not diverse, but rely on one thing, become vulnerable. When we optimise a system, we consider only a limited set of criteria—and we expose ourselves to being vulnerable to a surprise coming

from something outside of those criteria. Vulnerability is the opposite to resilience—a susceptibility to damage of the ‘weakest link’. The weakest link in a chain defines the total strength of the chain even if every other link is very strong. A really tough, strong boxer with a weak chin is only as strong as his chin. A vulnerable system is not robust, i.e. not strong, healthy, hardy and able ‘to take a knock’ or persist when subject to changes or perturbations and uncertain conditions. Lack of robustness through a vulnerability is especially important when dealing with high impact, low-chance surprises such as 9/11 and Grenfell Towers.

Physicists define ‘resilience’ as the ability of an elastic material to absorb energy. Ecologists define it as the ability of an ecosystem to return to an original state after being disturbed, while medical doctors refer to an ability to recover readily from illness, stress, depression or adversity. A general definition of resilience is an ability to withstand or recover quickly from difficult conditions or to adjust easily to misfortune or change. In the UK government’s critical infrastructure resilience programme (Cabinet Office, 2010), resilience is defined as ‘the ability of a system or organisation to withstand and recover from adversity’.

Sustainability is a capacity to endure and implies resilience. That means a system is not sustainable when it is not resilient. But if it is resilient, it may or may not be sustainable because there are other factors, such as environmental management and consumption of resources that are needed for sustainability. In other words, resilience is necessary but not sufficient for sustainability, but sustainability is sufficient for resilience. Creating a sustainable world is a social challenge that requires developments across the whole of society—economic, societal and environmental. Sustainable living can take many forms including changing our individual lifestyles to conserving natural resources to the way we live in ecovillages and smart cities, to a greater use of permaculture, green buildings and renewable energy. What is for sure in an uncertain world is the central role of engineering—but in a less fragmented form.

Fragmentation

The engineering experience has been that specialisation leads inexorably to fragmentation with consequences that may be unforeseen, far reaching and enigmatic. They include a loss of cohesion across disciplines and organisations, professionals hunkering down into their professional ‘comfort zones’, bunkers or silos in which they hold their knowledge and power, and a focus on detail at the expense of overview and the ‘big picture’. They include difficulties in tackling issues that cross disciplinary boundaries and a lack of joined-up decision making across and between disciplines and silos. The likelihood of mistakes through poor communications, lack of shared information and issues falling ‘between the cracks’ can become serious. Furthermore, the inadequacies, often only realised in hindsight after an accident or failure investigation, can erode trust in expertise.

Fragmentation occurs in many guises. For example, economic globalisation, perhaps rather unexpectedly, is causing fragmentation between nation states and exposing the impotency of individual states within nation state blocs. The result is an understandable retrenchment by those who want to ‘take back control’ and a self-reinforcing loop where the politics of nationalism lead to more and more fragmentation and more extreme forms of nationalism.

One solution is to think differently about nation states by conceiving them as holons. By this thinking a nation state, considered as a whole, can create its own version of its politics as needed for internal cohesion. At the same time, a nation state, considered as a part, will recognise its interdependence with other states. It will understand the need for integrating policies at a number of higher levels of decision making to address complex issues that are commonly held. The key to success will be finding the political will to identify what is best decided at what level in the entire hierarchy of issues.

The principle of subsidiarity of the EU Treaty of Lisbon 2007 is a good starting point but not a good omen. The reason is that the principle has been lauded in the abstract but almost completely ignored in practice. In brief, the principle states that those closest to the issues know them best and are best placed to address them. In other words, we should never entrust to a bigger unit anything that is best done by a smaller one. Stated more formally subsidiarity says that models of systems should be created at the lowest practical level that is consistent with delivering their purpose. Unfortunately, because political subsidiarity in the EU has not been implemented sufficiently well, many people, especially in the UK, have felt that the EU is heading in a direction that they never signed up to. They resent the interference in our national life by what they see as unnecessary rules and regulation and they wonder what is the point? Of course, all political systems contain a diversity of views. But diversity for its own sake is not the point. Rather diversity creates different points of view that are key to the critical discussion that creates resilience and enables future success. But accommodating and managing diverse views bring challenges through the many conflicting complex issues at every level of decision making.

Learning Together Requires Leadership

Grundy’s schema is a typical engineer’s response, sensible, logical and efficient—it requires the principle of Preparedness, implies Ingenuity but makes no mention of Learning. Though perhaps not intentional Grundy’s scheme tends to give the mistaken impression that people who are not technically qualified have to be told what to do without consultation and discussion—reminiscent of ‘techy triumphalism’. Doing it differently just requires a slight change of emphasis. Work together in a spirit of goodwill. Argue honestly, see other people’s point of view and above all admit when you genuinely don’t know or don’t understand. I call it ‘honest disagreement amongst friends’. It is a recognition that we need to work together and not to fragment. It is a call for businesses to reconnect with society as Lord Browne, engineer and

one-time Chairman of BP, has written in his book *Connect*.¹⁹ He says that respect, authenticity and openness need to be embedded into the heart of business models. But change requires leadership. He writes *‘People tend to treat companies as they do other human beings. If we trust someone, we are likely to forgive them when they make a mistake. But if that person has a bad history, we might not even give them a chance to explain’*. He continues *‘Companies have to make friends before they need them....when firms increase their interactions with societal actors from a rare basis to often, they more than triple their chance of mutually beneficial outcomes. Top companies identify important stakeholders and work with them...using techniques to determine who to see and when...avoid outsiders being confused by multiple visits....with conflicting messages and...emissaries being played off against each other....Collaborating with others makes more sense when being the first mover might put the company at a competitive disadvantage...create gains that no single player can achieve individually....collaboration on standards and regulation provides the basis for industry wide reform’*.

Whilst systems thinking is necessary to meet those challenges it is by no mean sufficient. Politics also needs leaders who inspire consensus, encourage collaboration and recognise interdependence to find and deliver integrated levels of purpose. Politics does not need leaders who follow blind doctrinaire ‘policy red lines’. Greg Young has written²⁰ that leaders shape the culture of an organisation—a large factor controlling performance. He writes about companies, but his ideas also relate to the politics of nation states. He calls for a new kind of ‘transpersonal leader’ for the twenty-first century where companies (and countries) need to be nimble and agile in responding to rapid change. These leaders will embed authentic, ethical and emotionally intelligent behaviours into the DNA of the organisation (country). They will build strong, empathetic, collaborative trusting relationships and develop a sustainable performance enhancing culture.

That culture has to embody a respect for various views, enable work at developing common purposes identified at various levels and find resilient ways to dissolve the boundaries between those views. A resilient political and business culture embodies an integrity that has no place for corruption, collusion and fraud and values transparency and due diligence. By this view, nation states and companies need to move away from the sometimes-brutal competitiveness of the twentieth century to the kind of collaborative behaviour that Lord Browne identifies. As he says building trust is key.

Creativity, Problem Solving and Aesthetics—Turning Dreams into Reality

I set out to do three things in this book. First to show how engineers have made and still strive to make the quality of our lives better. Second to identify and explore some of the unintended consequences of the past and the ‘grand’ challenges ahead. Third

to suggest some ‘grounding’ principles that may help us to guide or steer our way through a risky future. In Chap. 1, I quoted Sir Neil Cossons challenge to engineers to ‘*spread the word to the rest of the world, get out of your professional bunkers and meet the people, ignite in them some of the **magic** of what it is that you do*’. Where does the ‘magic’ of engineering lie?

Cossons was not referring to magic as sleight of hand or deception or conjuring. Rather he was pointing to the allure and fascination through which engineering can be mysteriously enchanting. By that I mean pleasing, delightful and aesthetic—engineering as creating within us an emotional relationship with things—engineering as using our collective artfulness, *ingenuity* and inventiveness. If in doubt, just think of your mobile/cell phone and how only a generation ago that kind of performance and functionality was science fiction. Think of Ben’s pacemaker and how astonishing it is that a small gadget implanted in his chest can save his life. Think of a big bridge like the magnificent Millau Viaduct in France which certainly has a ‘wow’ factor. Think how people can talk, face to face, across oceans via satellite communications. Think of giant space rockets that have taken us to the moon and promise more space travel in the future.

The magic of all these things is in their making and the way we have collectively learned to elegantly coax the forces of nature to turn our dreams into reality.

This is why I have defined engineering very broadly as producing ‘*things*’ that we ‘*need*’ like quicker ways to travel and hip replacement joints and some things we don’t need, but may like to have, like a music streaming via the Internet or a holiday in a far off country.

But modern engineers specialise in one of the branches of engineering—and the result is often a lack of ‘joined-up’ thinking to address ‘big picture’ issues. As scientific knowledge grew after the Renaissance, so the professions fragmented into their ‘silos’. You will recall that the six main ‘horizontal’ branches are civil, mechanical, electrical, aerospace, computing and medical. The ‘vertical’ divisions include engineering workers, technicians, incorporated and chartered engineers. However, different countries use different terminologies—in North America, the roughly equivalent term for UK chartered engineer is professional engineer. We have traced the stories behind some of the important engineers of the past such as Michael Faraday, Joseph Bazalgette, William Armstrong, Thomas Edison and Frank Whittle as well as some of the less well-known engineers of the present—many of them women. These people are just as important to our national and international culture as politicians and celebrities because engineering is at the heart of society. We rely on it every day and it contributes to our well-being—from the roof over our heads, the food we eat, the water we drink, disposal of waste (including flushing toilets), the roads and railways we travel on through to media, communications, tv and radio, and medical equipment such as scanners. We have also seen that engineering is often taken for granted and hence undervalued—for example, lists of creative occupations rarely mention science or engineering and economic progress is rarely understood as depending on new technology. Design is often presumed to be *individual* emotional expression through form, appearance and symbolism whilst function is prosaic and

delivered by the precision of science. Consequently, engineering as applying those laws is dismissed as being relatively straightforward.

We have also seen that engineering has arisen out of, and is closely related to, other kinds of making, such as craft, fine art and invention. But largely unappreciated is the idea that aesthetics is more than just beauty but concerns our emotional relationship with things. To engineer is to solve problems as only we humans can but, historically, we have also underrated practical experience and overvalued academic ability to an extent that mars our educational systems. The Roman Vitruvius understood this when he articulated a set of objectives for practice as firmness (integrity or soundness of form), function (looking for simplicity in complexity) and delight (grace as elegance of form). Buckminster Fuller expressed the aesthetic of a structure as being '*where the stresses and strains are at ease*'. What he was saying is that the aesthetic of function is an elegance of flow of energy. For example, in the way the pressure, volume, velocity and temperature of gas are manipulated in a gas turbine engine to create the thrust that propels the aircraft. The way the complicated behaviour of the Internet *emerges* from the layers of interacting simplicity.

Modern engineered things did not suddenly appear 'fully formed'. They evolved over time as we have seen through the stories of the plough, bicycle, engines of various kinds, equipment that relies on electricity such as radios, computers, mobile/cell phones and heart pacemakers.

The common myths about engineering include the idea that engineers simply apply science. This derives from the caricature of science as the 'laying bare' of the inviolable nature rather than the creative result of individual inspiration to model what we experience. Science does not have all the answers we need—it is incomplete. We can expect our buildings to be 'as safe as houses' as long as we understand that does not imply perfection. There is always a risk that any engineered thing can fail. When things do fail because of negligence or evident lack of duty of care then those responsible should be brought to justice. But there will be many events where no one is to blame.

We have also seen that all is not rosy. We have made nuclear weapons, missiles, remotely controlled drones and created the potential for cyberattacks on our information systems by hostile powers—including terrorists. We have polluted our environment and altered our climate. The global 'grand challenges' are many but include risk and resilience, bioengineering, energy policy, new materials and bespoke engineering. If we are to meet these challenges, then it is imperative, therefore, that we learn from the ways engineered things fail. Engineers need to break down their professional silos by adopting 'joined-up' systems thinking. They need to more readily see the 'big picture', the context, as they contemplate the detail. Whilst we can never ensure that failures 'never happen again' we can reduce the risks to acceptable levels, and we can design our systems to be more resilient. To do that we need to spot the 'patterns' as they incubate. I have suggested five grounding principles that have been, in my view, implicit in the best engineering of the past and missing in the worst, and from which we would benefit if they should become explicit in the future. You will recollect that they are PUPIL, '*we are Part of a world of Unintended consequences for which we need to be Prepared through Ingenuity and Learning*'. PUPIL tells us

that we are *of* this world not just *in* the world and so we are both parts and wholes. It points out that everything we decide and act on has unintended consequences—some good and some bad. It helps us to recognise and hence deal with unknown unknowns through contingency planning. PUPIL cautions us to be prepared by developing resilient and agile systems that take us away from our current focus on prediction to thinking through how we manage outcomes, no matter how unlikely, that avoid misplaced ‘triumphalism’ of human technological progress. It advises us to revalue and nurture the lost art of practical wisdom to reduce the ‘ingenuity-gap’ between those who adapt well to complex changes and those that don’t and the chasm between academic and vocational education. PUPIL admonishes us if we are not pupils in life, i.e. we don’t ‘learn from our mistakes’—something we constantly avow to do but often fail to implement. It warns us that engineering education has placed little or no emphasis on the history of its disciplines—with the consequence that many of today’s engineers see little value in their heritage.

Engineering Is a People Profession

Most importantly of all PUPIL emphasises that engineering is not about things but is about people—making life better for us all. As I said in the Preface, the USA National Academy of Engineering has a campaign called ‘Changing the Conversation’. It has four messages: engineers make a world of difference, engineers are creative problem solvers, engineers help shape the future and engineering is essential to our health, happiness, and safety. Engineering is done by people for people to improve the human condition. Engineers are agents of change—they create technology by configuring patterns of flowing energy to achieve a desired outcome, a human purpose. There is a strong case for engineering to be conceived as a much wider discipline than it is currently the case. Politics, law and economics are forms of engineering—helping to engineer the flourishing of life on earth.

We need engineers as never before because unexpected and unforeseen surprises will become the new norm. We must prepare ourselves to face future challenges that we cannot yet anticipate. The UN Secretary-General António Guterres has pointed out that the Barry Turner incubation of the issues around climate change is well underway (although I have no way of knowing if he is aware of Turners work) when he said ‘*The world reached several dire milestones in 2017*’.²¹ He calls for us to ‘let some of the air out of the Turner balloon’ if we are to avoid some of the extreme events that threaten our futures when he says ‘*...we continue to see huge investments in unsustainable infrastructure that lock in bad practices for decades. As many have pointed out, the Stone Age did not end because the world ran out of stones. It ended because there were better alternatives. And the same applies today to fossil fuels. Our problem is not that we do not know what to do – it is how quickly we can do it*’.²¹ A new breed of engineers is required who can read and interpret the signs and change the conversation by initiating, discussing and debating with society at large the technical challenges and opportunities that lie ahead. A new

perspective on engineering by non-technically trained people could give greater value to the contribution that engineers make. The media should either appoint engineering correspondents or change their technology and their science correspondents to report on engineering as a whole (rather than their current tendency to focus on digital systems). Any form of triumphalism and hype is unhealthy—but it can only be countered by the better understanding of non-specialists. At root the message is that despite all the advances in science, we know less actually than we think we know. Contingency planning that expects surprises must be the new norm. Learn anew how to learn together is the new wisdom. Use the golden rule ‘do not do to others that you would not have them do to you’, whatever you are told to believe is the tenet we should always hold foremost in our thoughts. Behaviour is more important than belief—imperfect doing is better than uncertain knowing. But to do all of this collectively requires leadership that we can trust—perhaps the biggest challenge of all?

All this because engineering is really about people and their aspirations and not simply things and their functions.

End Notes

1. *Report of the Royal Commission into the failure of the West Gate Bridge*, (1971), Victoria, Australia.
2. Feldman, DB., Kravetz, LD (2014) *Supersurvivors: The surprising link between suffering and success*, Harper Wave, London.
3. Armstrong K (2009) A metaphysical mistake, <https://www.theguardian.com/commentisfree/belief/2009/jul/12/religion-christianity-belief-science>.
4. A man engine was a mechanism of reciprocating ladders and platforms for miners to travel up and down between working levels during the nineteenth century. It was invented in Germany but used in the tin and copper mines in Cornwall until the beginning of the twentieth century. The Cornish Man Engine puppet is a 10-metre-high giant mechanism built in 2016 to mark the 10th anniversary of the Cornwall and West Devon Mining Landscape becoming a World Heritage site. It toured from Tavistock to Geevor Tin Mine in July and August 2016.
5. Blockley D I (2020) *Building Bridges between theory & practice*, World Scientific Publishing, London.
6. The events at West Gate Bridge and failures in social services and criminal justice systems seem, at first sight, to have little in common. Closer examination reveals that lack of communication across organisational silos is common to all. The murder of Victoria Climbié shocked the nation in 2000. Harold Shipman was a family doctor who was found guilty in 2000 of murdering many of his patients. In 2002, Ian Huntley was found guilty of the Soham murders. A policy briefing by the UK Local Government Information Unit in 2003 said ‘*Despite all the initiatives for joint working and local partnerships, a silo mentality still appears to persist in government departments*’. In all of these cases, a lack in the joining-up of agencies led to disastrous consequences. Pieces of evidence,

considered in isolation, were pieces of a jigsaw. Had the pieces been put together, then a very different picture would have emerged.

7. Acker, F. (2005) Autism and Engineers—is there a connection? *Ingenia*, Issue 25, December 2005. See <http://www.ingenia.org.uk/Ingenia/Articles/343> (Last accessed February 2019).
8. Blockley, DI., Godfrey, PS. (2017), *Doing it Differently* (2nd Ed), ICE Publications, London. See also <http://myengineeringsystems.co.uk/> (Last accessed February 2019).
9. Koestler, A. (1967). *The ghost in the machine*. Picador, London.
10. See <https://blog.oup.com/2014/07/practical-wisdom-vs/> (last accessed February 2019) However, we should remember that Aristotle lived in very different times and we cannot simply apply his ideas directly—but there are observations that are worth considering in their own right as well as helping us to understand how present-day attitudes have arisen.
11. In 2000, world leaders adopted the UN Millennium Declaration and committed their nations to a new global partnership. They set 8 targets as follows: 1. Eradicate Extreme Hunger and Poverty. 2. Achieve Universal Primary Education. 3: Promote Gender Equality and Empower Women. 4: Reduce Child Mortality. 5: Improve Maternal Health. 6: Combat HIV/AIDS, Malaria and other diseases. 7: Ensure Environmental Sustainability. 8: Develop a Global Partnership for Development.
12. The Sustainable Development Goals (SDGs) were agreed in 2015 following on from the UN Millennium Goals with a deadline of 2030. They are 1. End poverty in all its forms everywhere. 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture. 3. Ensure healthy lives and promote well-being for all at all ages. 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. 5. Achieve gender equality and empower all women and girls. 6. Ensure availability and sustainable management of water and sanitation for all. 7. Ensure access to affordable, reliable, sustainable and modern energy for all. 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all. 9. Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation. 10. Reduce inequality within and among countries. 11. Make cities and human settlements inclusive, safe, resilient and sustainable. 12. Ensure sustainable consumption and production patterns. 13. Take urgent action to combat climate change and its impacts. 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development. 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels. 17. Strengthen the means of implementation and revitalise the global partnership for sustainable development.

13. National Academy of Engineering. *Grand challenges for engineering*. See <http://www.engineeringchallenges.org/> (Last accessed February 2019).
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15. Figure 9.5 was inspired by an illustration by David Somerville based on an original by Hugh McLeod—see <https://random-blather.com/2014/04/28/information-isnt-power/> (Last accessed February 2019).
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17. Howarth, D. (2013), *Law as Engineering*, Edward Elgar, Cheltenham, UK.
18. Duarte, P., Giraud, Y. (2019). *HOPE 2019: Economics and Engineering: Institutions, Practices, and Cultures*, April, The Center for the History of Political Economy, Duke University, USA.
19. Browne, J., Nuttall, R., Stadien T. (2015). *Connect: How companies succeed by engaging radically with society*. W H Allen, London.
20. Young G. (2016), *Women, naturally better leaders for the 21st century*, Transpersonal leadership series: White Paper 2, LeaderShape, Routledge, Taylor & Francis Group. See https://www.crcpress.com/rsc/downloads/WP-TL2-2016_Transpersonal_Leadership_WP2_FINAL.pdf (Last accessed February 2019).
21. The UN Secretary-General António Guterres continued ‘*The world reached several dire milestones in 2017. The economic costs of climate-related disasters hit a record: \$320 billion. Energy-related carbon dioxide emissions rose 1.4 per cent, to 32.5 gigatonnes—a historic high.... And I am beginning to wonder how many more alarm bells must go off before the world rises to the challenge*. See <https://www.un.org/sg/en/content/sg/press-encounter/2018-03-29/secretary-generals-press-encounter-climate-change-qa> (Last accessed February 2019).