ROYAL ACADEMY OF ENGINEERING

Centre for Real-World Learning at the University of Winchester

Thinking like an engineer
Implications for the education system

Summary report, May 2014

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A report for the Royal Academy of Engineering Standing Committee for Education and Training
Summary report, May 2014

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About the Centre for Real-World Learning (CRL) at the University of Winchester

CRL is an innovative research centre working closely with practitioners in education and in a range of vocational contexts. It is especially interested in new thinking and innovative practices in two areas:

- The science of learnable intelligence and the implementation of expansive approaches to education
- The field of embodied cognition and its implications for practical learning and for vocational education.

Visit **www.winchester.ac.uk/realworldlearning** and **www.expansiveeducation.net**

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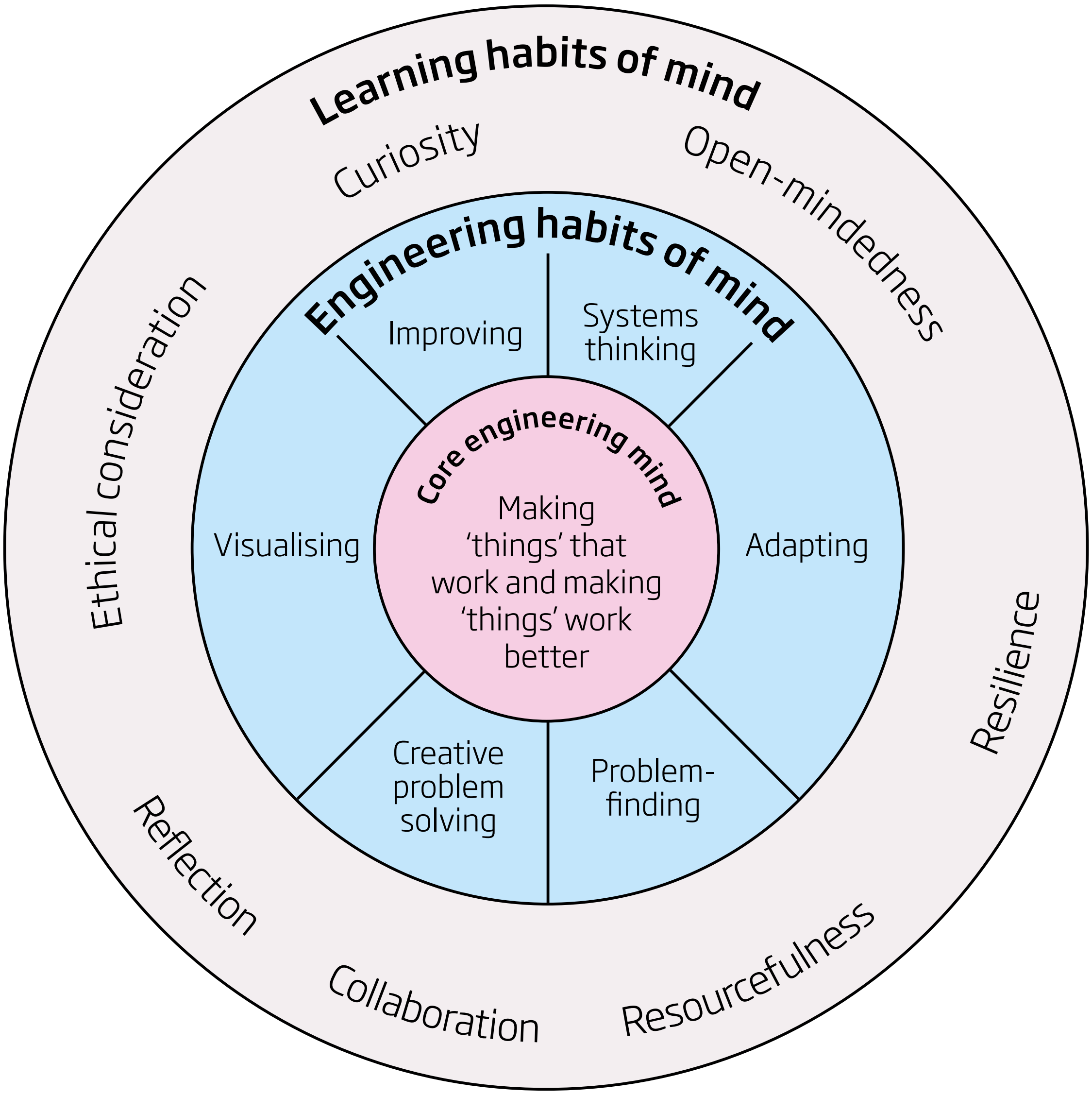

Learning habits of mind
Curiosity
Open-mindedness
Resilience
Resourcefulness
Collaboration
Reflection
Ethical consideration
Engineering habits of mind
Improving
Systems thinking
Adapting
Problem-finding
Creative problem solving
Visualising
Core engineering mind
Making 'things' that work and making 'things' work better

Executive summary

This report offers fresh insights into the ways engineers think. It suggests ways in which the education system might be redesigned to develop engineers more effectively and makes suggestions as to how the wider public might become engaged with these issues.

Engineers make 'things' that work or make 'things' work better. But they do this in quite particular ways. The report identifies six engineering habits of mind (EHoM) which, taken together, describe the ways engineers think and act:

1. **Systems thinking**
2. **Adapting**
3. **Problem-finding**
4. **Creative problem-solving**
5. **Visualising**
6. **Improving**

In selecting these six aspects of the engineering mind, the research team found strong consensus among a wide variety of engineers and engineer educators.

Thinking like an engineer makes a compelling case to suggest that, if the UK wants to produce more engineers, it needs to redesign the education system so that these EHoM become the desired outcomes of engineering education. It also needs to work closely with the teachers of, for example, science, design and technology, mathematics and computing.

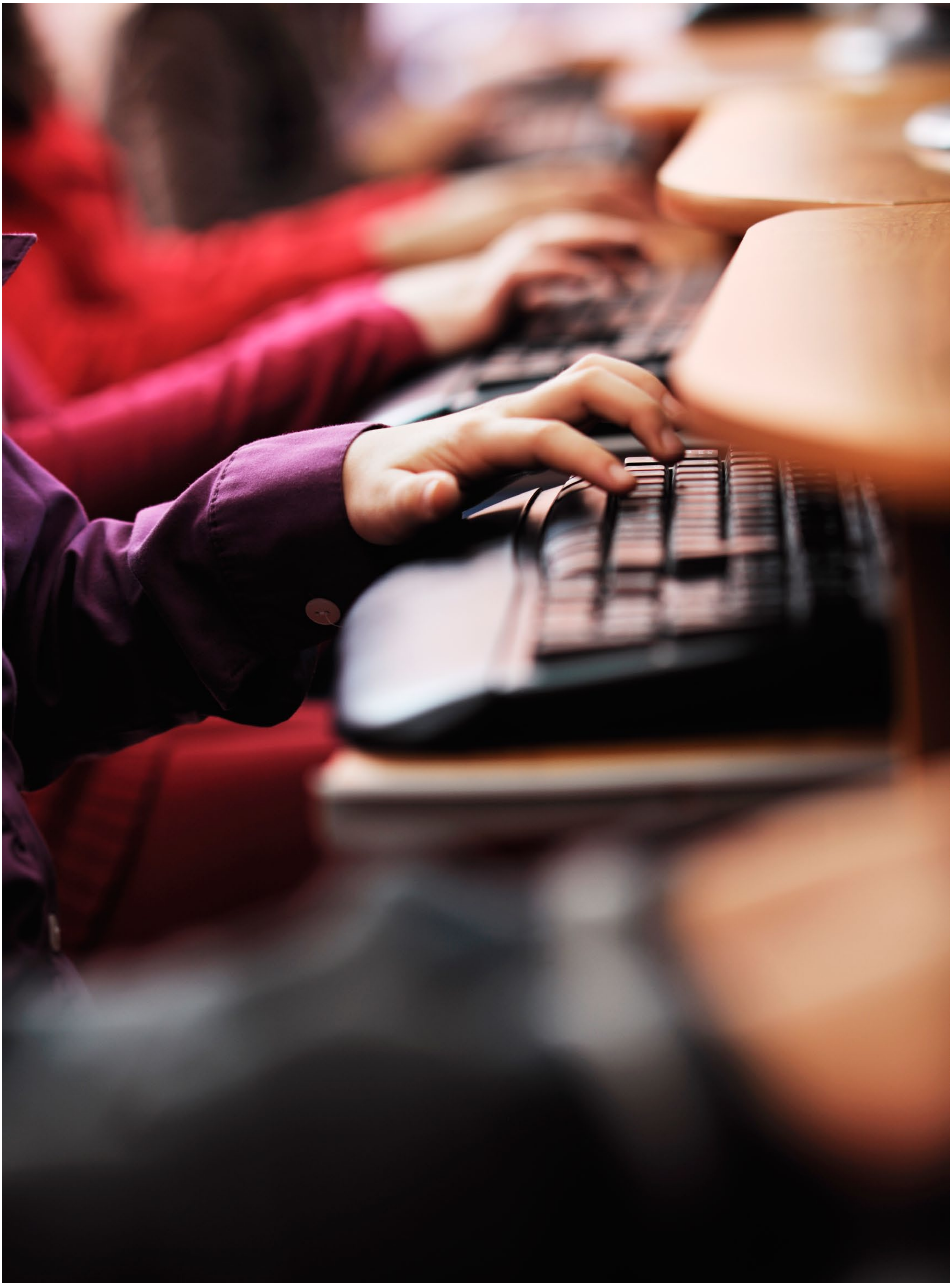
Young children are little engineers. Yet the primary school system almost extinguishes any opportunities for them to flourish as engineers and the teaching of engineering at secondary school is highly variable.

The report identifies those learning methods – problem-based and project-based learning, for example – which, when rigorously introduced, are highly effective at teaching learners to think like engineers.

Thinking like an engineer makes three broad recommendations:

1. The Royal Academy of Engineering to disseminate its findings to ensure wide engagement in the conversation about how engineering is taught.
2. The engineering teaching and learning community to seize the opportunity of the National Curriculum and the report's new thinking to bring about a mind-set shift in schools and redesign engineering education, especially at Primary level.
3. For employers, politicians and others to engage in a dialogue with schools and colleges about the EHoM they think are most important, suggesting practical ways in which they can help.

Given the continuing concerns about lack of STEM expertise in the UK and the recent publication of *Review of Engineering Skills* by Professor John Perkins[1], this report makes a timely addition to the debate with clear suggestions on the kinds of pedagogies which are likely to develop more and better engineers.



1. Introduction

1.1 The engineering context and two engineering challenges

'Shortage of engineers is hurting Britain' has been both an actual newspaper headline[3] and a more general national lament for too many years. Britain, we are told, does not have enough graduate and non-graduate engineers[4]. Furthermore, lamentably low numbers of women choose to study or practice engineering.

At first sight, this lack of engineers would seem to be a classic supply and demand problem as most recently described in the *Perkins' Review of Engineering Skills*.[5]

But what if at least part of the reason that we do not have enough engineers is because we just don't know enough about how great engineers actually think? Or at least if we do know this we do not make enough use of what we know. And what if schools, colleges and universities are actually teaching engineering in ways which do *not* cultivate the kinds of engineering minds we need?

This is precisely the approach the Centre for Real-World Learning (CRL) has chosen to adopt. We suggested that the Royal Academy of Engineering might like to approach the apparent supply-demand issue by asking two more fundamental questions:

1. **How do engineers think and act?**
2. **How best can the education system develop learners who think and act like engineers?**

Our first challenge was whether we could reach consensus as to how engineers think, considering the huge breadth of the engineering sector. Our second question is dependent on a successful result from the first. It is, in a sense a true engineering challenge. Can we redesign the education system in terms of its pedagogy so that it is more likely to produce more people who think and act like engineers?

1.2 Why the minds of engineers matter

What do engineers do? What, if you like, is the point of an engineer? How do they think? How do they approach problems? How is what they do similar to but different from how a scientist or a mathematician sees the world? What does an engineer have in common with an artist or a designer or a technologist or a politician or a team sports player? What, in short, goes on in the mind of an engineer when he or she is in full flow doing engineering?

Engineering is a broad field, typically being described as including four main traditions or disciplines – civil engineering, chemical engineering, electrical engineering and mechanical engineering and in recent years, the introduction of a fifth distinct but important discipline of digital or software engineering. There are also numerous subdivisions, many of which are represented by the professional engineering institutions (PEI)[6].

1.3 A challenge to the education system

With a few exceptions, engineering does not appear on the timetables of pupils of primary or lower secondary age in the UK. After age 14, engineering starts to be visible as, for example, in some academies, university technical colleges (UTCs)[7] and studio schools[8]. Students might encounter engineering at GCSE, A Level or Diploma (14–19) programmes in engineering.

Further education (FE) colleges provide a wide range of engineering qualifications, from level 2–5. Colleges also support employers in providing apprenticeships and other accredited work-based learning routes. Once at university there is a rich tradition of higher level study with more than 5% of the higher education (HE) sector involved in engineering.

> The real 'problem' of engineering education is the implicit acceptance of the notion that high-status analytic courses are superior to those that encourage the student to develop an intuitive 'feel' for the incalculable complexity of engineering practice in the real world.
>
> **Eugene Ferguson[2]**

Engineering is a broad field, typically being described as including four main traditions or disciplines – civil engineering, chemical engineering, electrical engineering and mechanical engineering and in recent years, the introduction of a fifth distinct but important discipline of digital or software engineering. There are also numerous subdivisions, many of which are represented by the professional engineering institutions (PEI).

But while society needs more engineers, there are plenty of people wishing to be doctors or lawyers or teachers. Why? Our response is to seek to reframe this challenge.

The argument goes like this:

Engineers think and act in certain distinctive ways. If we had a better understanding of this we could better specify the kinds of teaching and learning experiences which might develop engineer-learners. We refer to these specific ways of thinking and acting as 'habits of mind' and in this report we explore the engineering habits of mind (EHoM) which have emerged through an iterative process of study and conversations with engineers and educators.

But we do not present our EHoM simply as a different way of describing or packaging the engineering curriculum. At the very least we think that how people think and act as they learn is more likely to give us insights into their minds than what they know – their knowledge - or what they can do – their skills. We suggest that, without a good understanding of EHoM on which to ground choices about teaching and learning methods, we should not be surprised that too few pupils choose to study engineering.

2. Our approach

2.1 Research methods

We adopted a mixed methods approach for our analysis and its subsequent synthesis of opinions, experiences and theoretical approaches to teaching and learning to produce our model of engineering habits of mind (EHoM). The pragmatic philosophy underpinning mixed methods and its recognition of the value of using data gained from contrasting methods aligned well with the Royal Academy of Engineering's wish to incorporate multiple perspectives and explore real-world approaches to learning.[9]

Following a literature review through which we developed our initial list of potential EHoM, we carried out semi-structured interviews with twelve engineering educators, selected from a list of 28 names provided by the Royal Academy of Engineering. Our starting point was to undertake a review of the literature relating to habits of mind in engineering, mathematics and science. Our search for examples of case studies in which innovative pedagogies had been used to develop these habits of mind produced limited results, so we relied on citation indexing of a few seminal sources to generate further similar references. We also searched key journals including *Engineering Education*, *International Journal of Engineering Education* and *European Journal of Engineering Education*.

Much of the literature at primary and secondary education levels that we found originated from the US, and in recognition of the differing nature of schooling between the US and the UK, or even just England, these sources have been used sparingly throughout our report, mainly to illustrate how things might be.

In order to validate our findings from these interviews and gain further insight into EHoM and effective pedagogies, we established an expert group of engineers and engineer educators whom we brought together on two occasions for seminars held at the London offices of the Royal Academy of Engineering. A total of 23 individuals participated in the first session and 12 in the second. In the first session we discussed our revised EHoM model and invited participants to share examples of effective pedagogies. Since our aim was to value what is already working well in engineering education and build relationships with experienced professionals, we adopted an appreciative inquiry[10] approach to the discussions. In the second session we invited participants to discuss our draft report and help us formulate recommendations based on our findings.

We also developed a questionnaire survey that was circulated to a wider group of engineers and engineer educators by the Royal Academy of Engineering and completed online.

The final part of the research involved a matching of known learning and teaching methods used in a wide range of disciplines to our validated EHoM, allied to conceptual development by the research team of a broader pedagogical framework within which these might fit.

3. Engineering habits of mind

Engineering is often described in terms of its close relationship with the disciplines of mathematics and science. It may be particularly helpful, therefore, to learn from experiences in these subjects.

3.1 Mathematical and scientific habits of mind

In the 1980s and 1990s, concerns about the role of science and mathematics in society began to surface. Scientists, mathematicians and educationalists began openly to discuss issues such as the contribution of their subjects to solving important real-world problems and a mismatch between what scientists and mathematicians actually do and what gets taught in school.

One way of resolving such complex issues was suggested by Al Cuoco and colleagues in a seminal article, *Habits of mind: An Organising Principle for Mathematics Curricula*[12]. In the full report we explore Cuoco's arguments in some detail as they provide clear lines of thought for our later exploration of EHoM. He starts by distinguishing between real-world mathematics and what happens in schools and then explicitly refocuses on the teaching of mathematics as the cultivation of mathematical habits of mind (MHoM), rather than on precisely which mathematical content is taught. Cuoco identifies a generic set of MHoM along with more specific subsets for geometry and algebra. He imagines mathematicians as, for example, 'pattern-sniffers', 'experimenters', 'tinkerers', 'visualisers' and 'conjecturers'. Others have drawn on Cuoco's thinking to illustrate how it is possible to design learning experiences that enable students not only to become successful problem-solvers, but to think of themselves positively as such, thereby developing greater resilience for mathematics learning. In the hands of a skilled teacher MHoM are not simply an alternative way of presenting the mathematics curriculum. The MHoM *are* the curriculum!

Over a similar timeframe, there has been parallel thinking about scientific habits of mind (SHoM). In 2007, the Linnaeus Tercentenary Symposium lamented the fact that science education was not contributing to our understanding and solving of world problems such as how we feed the world's population, ensuring water resources for everyone on the planet, mitigating climate change and eradicating disease[13].

These issues prompted Muammer Çalik and Richard Coll to explore whether it was possible to teach science in a different way, with an explicit focus on SHoM. As part of their research they evaluated various approaches to the selection and definition of key SHoM, drawing extensively on the work of Colin Gauld[14]. Their selection of SHoM proved to be reliable and useful as a predictive tool in various areas and included notions such as 'open-mindedness', 'scepticism', objectivity' and 'curiosity'.

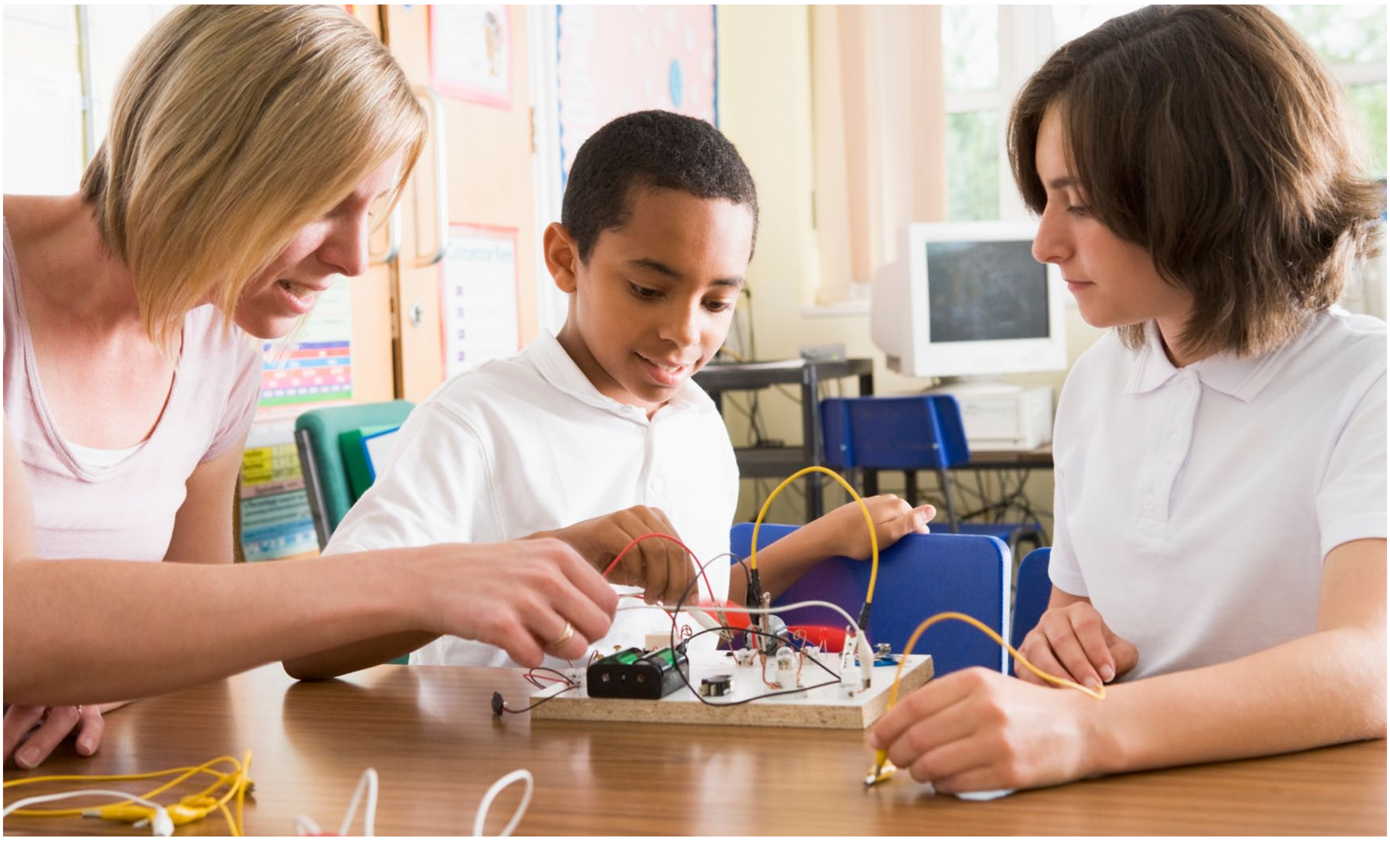
A powerful example of what SHoM look like in a young person is given by Craig Leager. Describing the beginning of a science lesson on a Monday morning he writes:

> 'Alondra bursts into her classroom with an exuberance and energy more typical of a toddler than for a fourth grader returning to school after a long weekend. Without hesitation she scurries over to her teacher and, in her limited English, begins a rapid-fire succession of questioning on every aspect of wetlands. For what seems like ten straight minutes Alondra peppers the teacher with her questions while barely taking time to take breaths between thoughts.'[15]

Alondra is, it would appear, a prototypical scientist demonstrating the SHoM of curiosity in huge measure. Leager writes thoughtfully about how: 'a judgment free classroom encourages students to pursue questions open-throttled.'

What might a young engineer want to tell their teacher about as they

> If engineering students are to be prepared to meet the challenges of today and tomorrow, the centre of their education should be professional practice, integrating technical knowledge and skills of practice through a consistent focus on developing the identity and commitment of the professional engineer.
>
> **The Carnegie Foundation for the Advancement of Teaching**[11]



rush into a classroom after a holiday weekend? And how might a Year 4 teacher respond in such a way to encourage that student's engineering habits of mind to grow and for others in that classroom to see engineering activity as engaging and worthwhile?

3.2 A broader idea of habits of mind

At the same time as the idea of habits of mind (HoM) was being explored in science and mathematics, the expression was also being used to describe aspects of intelligence more generally. Psychologist Lauren Resnick memorably argued that:

'Intelligence is the habit of persistently trying to understand things and make them function better. Intelligence is working to figure things out, varying strategies until a workable solution is found… One's intelligence is the sum of one's habits of mind.'[16]

Also working in the US, Art Costa and Bena Kallick began to think about how the role of teachers might change if they were deliberately trying to encourage the kinds of HoM mentioned by Resnick. They came up with sixteen HoM[17] which, taken together, describe what smart people do as they go about their lives successfully dealing with whatever unexpected problems are thrown at them. In the USA, they have specifically been drawn on to consider which HoM might be at the core of engineering.

In the UK, Guy Claxton created an approach to teaching and learning called 'Building learning power' (BLP). BLP has seventeen HoM. Claxton, like Costa and Kallick, is also trying to describe intelligent thought and action but has specifically introduced a related concept, 'learning power'– the degree to which any learner can summon up the best learning strategies when learning, especially when meeting situations which are novel.

More recently, at the Centre for Real-World Learning (CRL) we have drawn from these three traditions to create and validate an extended model of practical learning which blends habits and frames of mind[18]. Our model tries to draw a distinction between more general frames of mind such as curiosity, wisdom, reflection, sociability, resourcefulness and determination and what we see as four main

Figure 1 – Centre for Real-World Learning engineering habits of mind	
Systems thinking	Seeing whole systems and parts and how they connect, pattern-sniffing, recognising interdependencies, synthesising
Problem-finding	Clarifying needs, checking existing solutions, investigating contexts, verifying
Visualising	Being able to move from abstract to concrete, manipulating materials, mental rehearsal of physical space and of practical design solutions
Improving	Relentlessly trying to make things better by experimenting, designing, sketching, guessing, conjecturing, thought-experimenting, prototyping
Creative problem-solving	Applying techniques from different traditions, generating ideas and solutions with others, generous but rigorous critiquing, seeing engineering as a 'team sport'
Adapting	Testing, analysing, reflecting, rethinking, changing both in a physical sense and mentally.

'compartments' of the learner's 'toolkit' – investigation, experimentation, imagination and reasoning. CRL has also focused specifically on the development of creative habits of mind in a piece of research published by the OECD[19]. The development of a set of creative HOM is, in a sense, a proof of concept for taking a broader concept such as engineering and seeking to identify its characteristic HOM.

3.3 Engineering habits of mind

For this part of the research we began by investigating American sources, in particular, a major review of engineering education within K-12 primary and secondary education[20] that called for the curriculum to be underpinned by six engineering habits of mind. These were 'systems thinking', 'creativity', 'optimism', 'collaboration', 'communication' and 'attention to ethical considerations'. Drawing on this report, on our review of the literature of EHoM, on others' work in the field of engineering[21] and the contributory disciplines of mathematics and science, we developed six engineering habits of mind in consultation with engineers and engineer educators through a number of seminars and workshops. These are presented with brief explanations in Figure 1.

We present our model of the engineering habits of mind as a series of concentric rings in Figure 2. At the heart of our model is the idea that we believe drives engineers of whatever kind – making 'things that work' or making things work better. We recognise that here we are referring principally to the traditional engineering disciplines. But as the *Universe of Engineering*[22] recognises, engineers engage in all sorts of activity which may not involve making things. However, even engineers such as chemical engineers or software engineers who do not 'make' physical products as such, are involved in the sub-elements of making such as designing and implementing. It is this extended and inclusive definition of making to which we attach central importance.

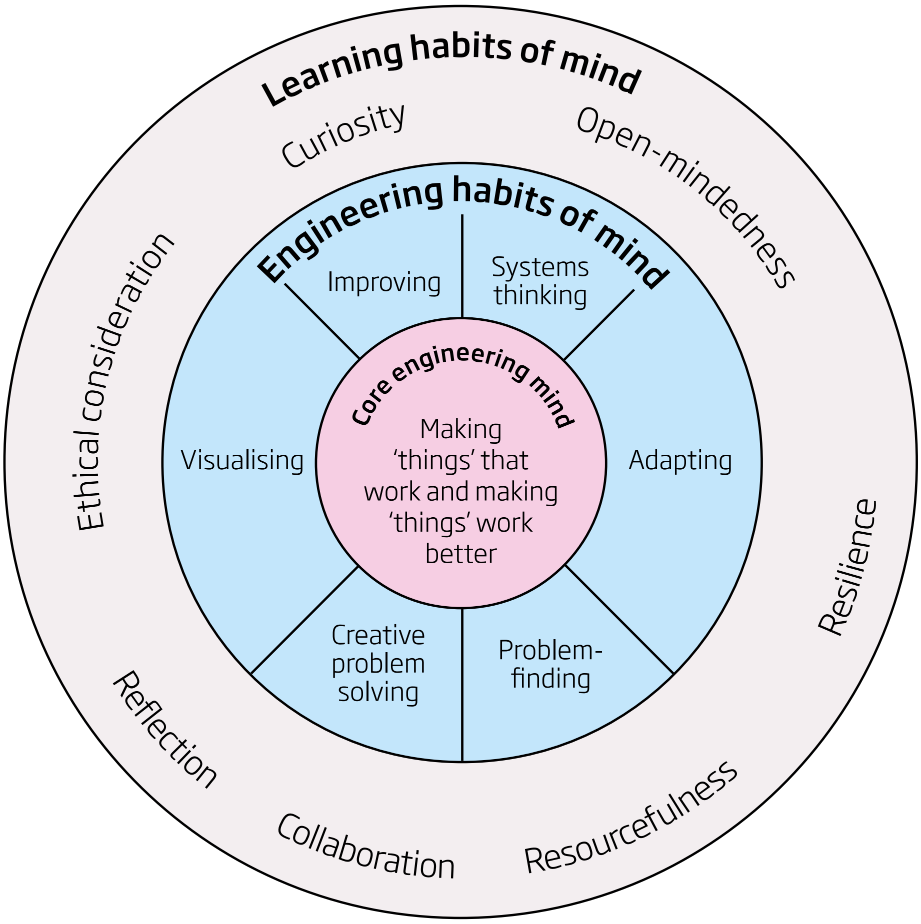
Our first finding from our research is that there was considerable consensus among all our respondents and from our expert reference group that the six EHoM we had identified for the middle ring in our model were appropriate descriptors for the characteristic ways in which engineers think and act when faced with challenging problems. The three EHoM ranked the most important by our respondents were:

- **Creative problem solving**
- **Visualising**
- **Improving**

In our longer report, we describe some of the specific suggestions made by respondents about each of the six candidate EHoM in detail.

Several respondents suggested that it was unlikely that all the EHoM would be found in one person and stressed the overall importance of the team in successful engineering projects.

Figure 2 - Centre for Real-World Learning engineering habits of mind, final version



Some combinations of EHoM might potentially generate tension, for example, between using creativity to invent new ways of doing things and using logic to make things work. It was also suggested by some of our interviewees that some EHoM might be more relevant at different stages of an engineer's career, for example, both problem-finding and adapting may be habits refined through longer experience in the field. However, on testing this out through the survey, most respondents felt that all EHoM were important at each stage of an engineer's career, from recent graduate to experienced professional. The outer ring of the model includes more general characteristics of learning which are not exclusive to engineers.

Engineers, as Iain MacLeod puts it, rarely operate in one mode only, but are able to move between 'two modes of thinking'[23] including:

Creatively different v Reliably similar

Playing v Evaluating

Opening up v Closing down

Synthesis v Analysis[24]

Systems thinking v Analytical

Intuitive v Deductive

Idealistic v Pragmatic

4. The state of engineering education today

Engineering is about making real things that work and serve a purpose and which, for some but not all engineers, are elegant and aesthetically pleasing and interesting. It involves:

- perceiving and clarifying the need or problem, and/or negotiating a brief with other problem-holders
- carefully investigating contexts
- being a good member of a team which designs and constructs solutions
- generating and evaluating creative solutions in principle
- sketching, model-making, trialling
- designing specs, briefs and overseeing construction
- dealing with clients and costings
- an interest in lifelong enquiry, research, discussion, improvement
- and much more.

All of this can be done in 'junior form' in primary and secondary schools. The satisfaction of designing and building solutions must surely precede and accompany any hard brain-work there needs to be. Yet too often this is not the case. It appears that there is still no clear line of sight to engineering from pre-primary to the workplace.

4.1 Engineering in the curriculum

Engineering as a compulsory subject is not specifically included within the English National Curriculum, although a significant number of schools introduce engineering projects at some stage as vehicles for teaching design and technology, computing, science and mathematics, and for demonstrating the integration between these subjects. Projects focused on solving an engineering problem like designing a bridge, building a car or launching a rocket are used to demonstrate the applicability of these subjects to the real world. Bringing 'live' engineers into schools or visiting engineers in their workplace also provides opportunities for children to find out about engineering first-hand. We describe some of the umbrella organisations and some of the excellent resources and activities which exist, along with cases studies, in our full report.

4.2 Primary education

In January 2013, there were 4.3 million students in English state-funded primary schools[27]. They were most likely to have been introduced to engineering, if at all, through engineering projects in subjects such as D&T, science, mathematics or ICT/computing. In the full report we provide four examples of engineering topics being introduced into the primary curriculum in collaboration with the organisations Primary Engineer[28] and Joined-Up Science.

4.3 Secondary

Engineering becomes a little more obvious in the secondary curriculum. In English secondary schools, engineering provision includes qualifications such as GCSE engineering, D&T options in engineering, a 14–19 Diploma framework for engineering and A Level in engineering. There were 3.2 million students in English state-funded secondary schools in 2013[29], however, unless they attended an academy specialising in engineering or a UTC, the majority of them would have been unlikely to be offered these engineering qualifications, or experience much involvement in engineering, unless perhaps through the efforts of a committed teacher who introduces it into D&T, science or mathematics or runs an after-school club. In the full report we provide three examples of how engineering is taught at secondary level. We also report on ways in which the introduction of the National Curriculum 2014 in England could

> A significant body of research suggests that despite extensive long-term investments in engaging future engineers, the overall impact has been less than intended.
>
> **Robin Adams and colleagues[25]**

> The problems remain daunting, partially because they are so complex, surrounded by a lack of conceptual clarity, a general confusion about the nature of the engineering enterprise.
>
> **David Goldberg[26]**

offer opportunities for incorporating engineering into the core curriculum, particularly through computing at primary and secondary levels. Low cost resources for schools such as RoB-E are being developed by the Royal Academy of Engineering to introduce programming and hardware, and the low cost computer Rasberry Pi[30] is being bought by thousands of schools.

4.4 College

For those who progress beyond compulsory education, but who choose not to go to university, there are a wide range of engineering opportunities offered through FE colleges, apprenticeships or work-based learning.

4.5 University

There are many innovative approaches to engineering at university level and we describe these in our full report. Programmes to foster innovation in university engineering education, such as the National HE STEM Programme 2009–2012, which funded 60 projects in engineering, are beginning to show promise[31]. Some new curriculum approaches are already demonstrating how EHoM could be developed. The traditional approach to engineering education in universities, a transmission approach focusing on mastering the underpinning science and mathematics basics before attempting problem solving or projects, is slowly changing and in the full report we document examples of this occurring through the CDIO™ approach to pedagogy, active learning and real-world learning.

4.6 In brief

There are undoubtedly plenty of positive examples of innovative pedagogies that develop EHoM at all levels of engineering education. A Level results for 2013 show there has been a big rise in the number and proportion of young people taking A Levels in mathematics, physics, chemistry and biology and there are more students doing mathematics, further mathematics, physics, chemistry and biology at A Level than ever before[32].

Activities such as Rocket Factory 1[33] at primary level can encourage EHoM such as creativity and problem solving, along with more general HoM such as collaboration and resourcefulness. However, as many of the initiatives are single events, there is limited opportunity to explicitly and consistently develop EHoM through repetition and practice over an extended period of time. It is initiatives like Primary Engineer that take place over a longer timescale that offer greater potential for developing EHoM.

At secondary level, the UTCs specialising in engineering education are examples of excellent practice but their numbers are low and their geographical coverage is uneven[34]. So, for the majority of children in mainstream secondary education, access to engineering is again more likely to be through one-off events and competitions, with their inherent limitations.

In colleges and universities there are numerous examples of excellent teaching in engineering education[35][36], using, for example, problem/project-based learning with real-world projects supported by employers; active learning that fosters systems thinking and engineering design; peer learning fostering collaboration; or CDIO fostering integration across the engineering curriculum. Any of these approaches have the potential to develop the full range of EHoM. However, even at this level, students are not being systematically exposed to all six EHoM or encouraged to develop an 'engineering mindset'[37].

5. Education to cultivate engineering habits of mind

In the report so far we have suggested that:

- it *is* possible to describe a set of engineering habits of mind with which there is wide agreement
- notwithstanding some beacons of excellence, the teaching of engineering according to engineers, leading engineer educators and consumers does not routinely cultivate the kinds of EHoM we have identified
- engineering education is hugely variable according to the phase of education being considered, with very little, but, where it occurs, very innovative teaching going on at primary level and the bulk of engineering education concentrated at further and university level
- engineering education at school can easily give an impression of engineering which is misleading and unattractive
- the methods used to teach engineering where it does appear at school are rarely designed to cultivate the kinds of EHoM we have been discussing
- there is already a clear recognition of the value of authentic, practice-based, experiential learning in engineering courses, especially at further and higher levels.

5.1 The implications of EHoM

In this final section we explore the degree to which it might be possible to build on existing global trends in the teaching of engineering by focusing more precisely on the kinds of pedagogical approaches which seem most likely to cultivate learners who might really think and act like engineers.

By pedagogy we mean two things. Formally we have defined it in earlier research for City & Guilds (C&G):

> 'Pedagogy is the science, art and craft of teaching. Pedagogy also fundamentally includes the decisions which are taken in the creation of the broader learning culture in which the teaching takes place and the values which inform all interactions.'[39]

In practice, pedagogy highlights the fact that teachers need actively to take decisions to seek to deliver the desired outcomes of whatever they are teaching. This requires them to ensure that the best possible learning methods are selected according to their understanding of the subject matter, the experience of the learners and the resources available to them. Such decisions need to be taken at the strategic level – looking at the blend of methods over the whole course – and at the micro level – when thinking about each lesson or session. Often teachers will also take 'in-the-moment' decisions when learning progresses in ways which they had not expected.

With respect to pedagogy, one of the best explorations of the concept we encountered in our research was an article by John Bowden. In its opening paragraph, Bowden offers some deceptively simple questions with respect to the design of education curricula which are so clear and so strongly indicating an approach which he describes as 'capabilities-driven' which is very close to the 'habits of mind' phrase which we have used throughout this report. We quote them in full here:

1. What should the learner be capable of doing at the end?
2. What kinds of learning experiences and in what combination would best assist the learner to achieve these outcomes?

> I am assuming that useful habits of mind are acquired through repeated exposure to experiences in which they pay dividends. Hence it should be possible to draw up a list of experiences that are suited to repetition without becoming tedious and lead to success in what might be termed engineering-related endeavours.
>
> **David Barlex**[38]

3. How can the learning environment be best arranged to provide access to these optimal experiences?
4. How can the learning of differing students be catered for?
5. What specifically is the role of teachers in supporting such learning by students?
6. What kinds of assessment of student learning will motivate learning of the kind desired and authentically measure the levels of achievement of the intended learning outcomes?[40]

We have begun to answer 1 from the perspective of an EHoM approach. We now focus on 2 and 5 specifically, with some brief attention to 3 and 4, both of which require a level of exploration which is beyond the focus of this research. The issue of assessment, 6, is hugely important but is completely out of scope. While we have some suggestions to make about the role of formative assessment in general and aspects of this such as feedback, the broader topic needs careful investigation as part of any broader re-appraisal of engineering education.

If you want to educate children to think and act like engineers then it is clear from the line of argument in this report that you might want to start a lot earlier that at age 16 or 19. Specifically, you might want to change the way you teach to adopt pedagogies which explicitly seek to cultivate the kinds of EHoM we have been describing in the last section.

Such a shift in teaching and learning might take three different forms. You could:

1. stand back and contemplate the overall sense of what engineers do and adopt pedagogies which seem, on balance, likely to 'make' engineers
2. look more closely at the six EHoM we have identified and see what educators have found to be most helpful in cultivating each of these in turn
3. approach the challenge from a different perspective by looking at teaching methods which, in other disciplines or subjects or vocational pathways, seem likely to be transferable or useful to teachers wanting to grow engineers.

Let's look at each in turn briefly. (There is a more detailed appraisal in our full report).

5.2 Signature pedagogies for engineering

There is a concept which may be useful here, 'signature pedagogy'. First coined by Lee Shulman in 2005, it refers to 'the types of teaching that organize the fundamental ways in which future practitioners are educated for their new professions'.[41]

'Signature pedagogies make a difference. They form habits of the mind, habits of the heart and habits of the hand. As Erikson observed in the context of nurseries, signature pedagogies prefigure the culture of professional work and provide the early socialisation into the practices and values of a field. Whether in a lecture hall or a lab, in a design studio or a clinical setting, the way we teach will shape how professionals behave…'[42]

If there were a candidate pedagogical approach it would the engineering design process itself as an organising pedagogical principle. While there are many variations and degrees of complexity inherent in this process, it can nevertheless be easily grasped at all phases of education. In Figure 3 overleaf, we share NASA's elementary school standards-based engineering design process as an exemplar.

5.3 Methods likely to cultivate specific EHoM

A second way of looking at this would be to think specifically about which methods might best cultivate our target EHoM and in our full report we explore these in considerable detail. To give just one example, to develop the EHOM '*Improving*'– 'Relentlessly trying to make things better by experimenting, designing, sketching, guessing, conjecturing, thought-experimenting, prototyping' – a powerful method is a process of continuous improvement which fits engineering and engineering

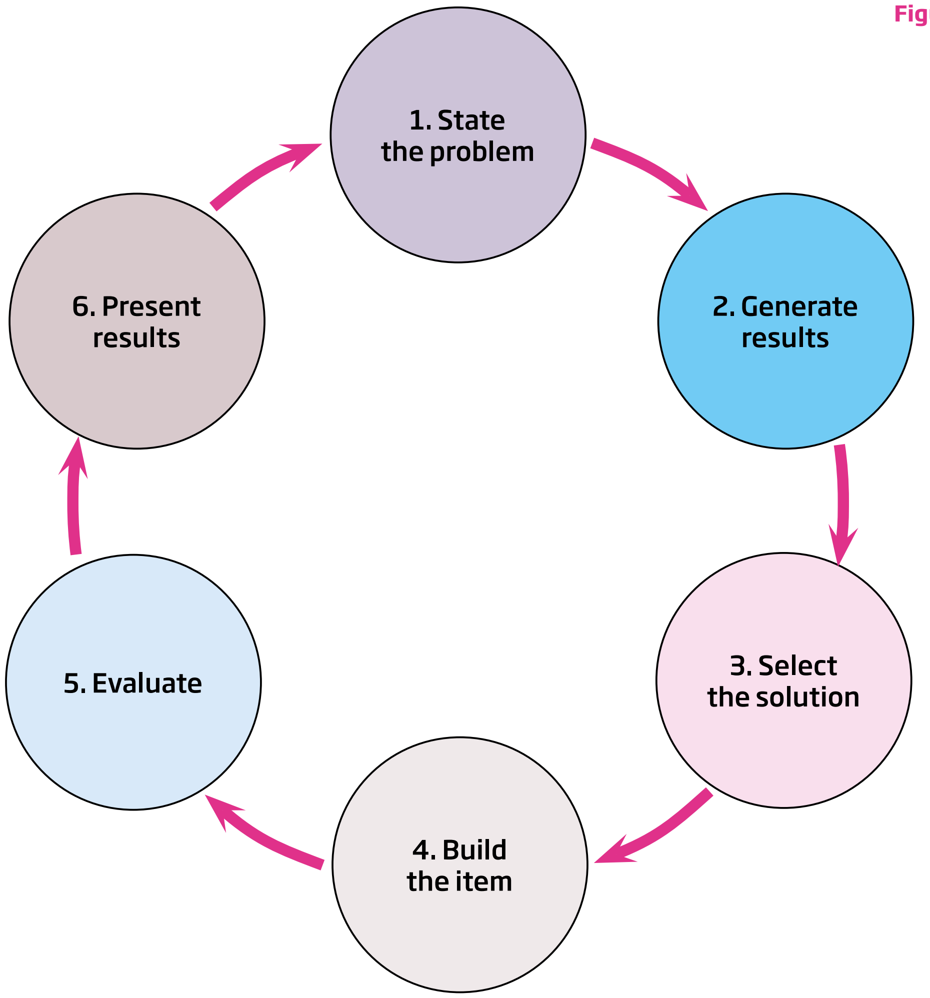


Figure 3 - The engineering design process

Source - NASA[43]

temperaments well known either as the PDSA cycle plan-do-study-act or PDCA plan-do-check-act developed by W. Edwards Deming and Walter A. Shewhart during the second half of the last century[44].

5.4 Vocational learning methods that work

Thus far we have looked at some signature pedagogies for engineering and explored some of the methods which seem suited to develop each of our six EHoM. Now we look at teaching methods which, in other disciplines or subjects or vocational pathways, seem likely to be useful to teachers wanting to grow engineers.

In an earlier piece of research for C&G, *How to teach vocational education: a theory of vocational pedagogy*[45], we identified a list of vocational methods which work in a number of different contexts and which are part of an engineering repertoire:

Learning by…. watching and imitating, by practising, through feedback, by being coached, through conversation, by teaching and helping, by real-world problem-solving and enquiry, by thinking critically, by listening, transcribing and remembering, by drafting and sketching, by reflecting on the fly, by competing, through virtual environments, through simulation and role play, and through games.

In the process of our research we encountered five additional methods widely used in engineering education. While these can also be used in other vocational areas we found them to have a specific engineering 'spin' on them which makes them noteworthy. The methods, which we describe in more detail in our full report are:

- Modelling and virtual modelling
- Using case studies
- Industry mentoring

- Using capstones
- Flipped classroom.

Of course any kind of vocational teaching, and especially teaching and learning that is trying to cultivate our proposed EHoM, is likely to involve a complex blend of approaches suited to student needs and available resources. Nancy Hoffman puts this well:

'[The challenge for vocational teaching and learning professionals is] to build curriculum and assessments that replicate the uncertain, messy, problem-based, people-intense, and time-limited world of work.'[46]

Of all the approaches to pedagogy we have encountered, the one created by David Perkins seems both thoroughly grounded in the literature and accessible. In a metaphor which could have been chosen with engineers in mind, Perkins explores the ways in which educators can make learning whole[47]. He offers seven principles which seem well suited to both learners and teachers in the real world of engineering education. These include ideas such as 'using extended projects and authentic contexts', working on the hard parts' and 'uncovering the hidden game to make the processes of learning to become an engineer as visible as possible. In our full report we explore all seven of Perkins' ideas in more detail.

5.5 Challenging the system

When all is said and done, there is a growing consensus about good practices in engineering pedagogy and these are alive and well in many universities and some colleges. These methods by and large are well-suited to the cultivation of EHoM. But sadly they hardly exist at all at secondary level and are virtually invisible at primary.

Each educational phase provides different challenges. But it is the two school phases on which we believe the focus needs to be. For when young people do encounter engineering or engineering-like experiences in mathematics, science and design and technology, it too often fails to present a view of engineering which is true to our EHoM.

The Royal Academy of Engineering's own review of change management of engineering education recently concluded that:

'The evidence in the engineering education literature suggests that successful educational reform is often associated with a combination of top-down and bottom-up change.'[48]

In terms of opportunities in England there are two areas which may be helpful:

1. The revision of the National Curriculum for primary and secondary education.
2. The support from all the main political parties for some kind of technical baccalaureate (TechBac) which might provide useful opportunities at secondary level for engineering.

In our conclusions and recommendations which will follow we seek to provide both, as well as some from the middle.

6. Conclusions and recommendations

6.1 Conclusions

We draw three main conclusions:

1. The most important finding from this research is that teachers of engineering really engaged with the question: 'how do engineers think?'. Our work has highlighted a core idea that engineers make 'things' that work or make 'things' work better. The report identifies six engineering habits of mind (EHoM) which taken together describe the ways engineers think and act:

Systems thinking
Adapting
Problem-finding
Creative problem-solving
Visualising
Improving

Our model of engineering habits of mind (EHoM) on page 10 provides a fresh way of exploring the teaching of engineers.

2. At various different levels the engineering teaching and learning community – school, college and university – agrees that understanding more about how engineers think could help teachers of engineering when they are constructing curricula, selecting teaching and learning methods and assessing learner progress on a course.

3. We also conclude that understanding more about how engineers think may also offer some clues as to how engineering careers can be more effectively presented to young people.

We found a high degree of consensus in answer to our first research question:

'How do engineers think and act?'

and were able to articulate a set of EHoM for exploration by the engineering community in the UK.

We conclude that the answer to our other main research question:

'How best can the education system develop learners who think and act like engineers?'

is essentially best dealt with as an engineering design problem!

The *problem* is that, although there is considerable innovation at HE where there is more of a tradition of experimentation and exploration in pedagogy, there is:

- virtually no engineering at primary level, notwithstanding some highly innovative and oversubscribed engineering education initiatives
- very patchy delivery of engineering opportunities at secondary, although with a few strong examples in UTCs and a few specialist schools
- varied provision at FE, often in under-resourced settings
- little or no explicit acknowledgement that pedagogical methods might be chosen which would cultivate the EHoM engineers told us they valued.

Our *idea* for solving this problem requires the engineering teaching and learning community to consider redesigning engineering curricula which *start* from the premise that they are trying to cultivate learners who think like engineers.

In terms of the teaching and learning methods most likely to cultivate EHoM we have identified:

a) some signature pedagogies, in the main related to the engineering design process, which are centrally important,

b) a number of core learning methods relevant to specific EHoM, and

c) a range of proven and underutilised vocational teaching and learning methods.

We also offer some more general messages from this research which may have relevance both for the engineering teaching and learning community *and* for use with the general public:

- **a)** how some aspects of thinking and acting like an engineer – making and fixing stuff – are core to what makes us 'homo practicus'
- **b)** how too many primary and secondary schools almost manage to extinguish the prototype engineers latent in young children
- **c)** the value of thinking and acting like an engineer for work and for the rest of life
- **d)** the close relationship between engineering habits of mind and wider employability skills
- **e)** how participation in well-designed project-based learning is an excellent preparation for the kinds of wider life skills that we all need in order to be able to thrive
- **f)** the advisability of having better methods of helping young people to think like engineers at school, college and at university, and
- **g)** how the model of engineering habits of mind may provide a framework for developing a better understanding of engineering among the general public.

If young people, ideally very young children, were exposed to styles of teaching and learning which related more closely to the real world of engineering, we conclude that it is much more likely that engineering might be seen as a subject worthy of studying and as a career of choice

The current lack of engineers in the UK is normally presented as an issue of supply and demand. But we believe it can be reframed as a lack of clarity, and possibly of understanding, as to how engineers think and act in the real world, their characteristic engineering habits of mind (EHoM). There is no such clarity about EHoM in the UK and this means that the development of pedagogies most suited to the cultivation of EHoM is necessarily limited. For many young learners, engineering, if it is encountered at all, is so far removed from its core interest in making and fixing things that it can all too easily sink under the weight of irrelevant theory.

6.2 Recommendations

The findings in this report are of potential interest to a number of key audiences – for the Royal Academy of Engineering, those in the engineering teaching and learning community more broadly, schools, employers and the wider public.

6.2.1 Continuing the conversation

The Royal Academy of Engineering might like to:

- Continue the conversation on 'how engineers think' through a variety of events, seminars, lectures, blogs, films etc.
- Consider whether more could be done to promote excellence in the teaching of engineering, for example through the process of accrediting degree programmes.
- Develop a language of talking about engineering pedagogy that is clear, simple but precise.

As a starting point these conversations might be held with CDIO, Engineering Council and professional engineering institutions, European Society for Engineering Education, HEA, QAA and RSA. The Design and Technology Association[49], the British Science Association[50] and the Mathematical Association[51] are also natural allies and Royal Academy of Engineering may wish to seek to consult with them. Charitable bodies, for example some of the Sainsbury Family Charitable Trusts[52], the Comino Foundation[53], the Dyson Foundation[54], or the Ellen MacCarthur Foundation[55], might be interested in supporting a wider dissemination strategy.

6.2.2 The engineering teaching and learning community

There is a growing consensus about what constitutes the engineering mindset and a strong evidence base

for the kinds of teaching and learning methods which might develop it.

a) Dissemination of core messages
We recommend that these core messages should be disseminated within the engineering teaching and learning community through a programme of engagement, further enquiry, via exemplar video clips and case studies of promising practices.

b) Signature pedagogies for engineering
We suggest that, in terms of teaching and learning, 'messy' approaches such as project-based and problem-based learning are actively promoted as methods for building engineering habits of mind. These are 'signature' engineering pedagogies.

c) Establishing a national hub or centre for engineering pedagogy
We recommend that the Royal Academy of Engineering considers supporting the establishment of a national hub for excellence in engineering pedagogy – perhaps involving a small number of applied academic centres – bringing together those who are expert in teaching and learning with engineers and employers.

d) Developing teacher capacities
The Royal Academy of Engineering might also like to support the development of teacher expertise by helping teachers to undertake small scale professional enquiries using initiatives such as the Expansive Education Network[56], possibly in partnership with Primary Engineer[57].

e) Improving transitions
CDIO might be invited to investigate the role of engineering habits of mind in supporting transitions between education sectors for student engineers.

6.2.3 Changing mindsets in schools and colleges

A radical change of attitude is required among teachers and, most, importantly, among headteachers, principals and senior leaders.

a) Seizing the opportunity of the new National Curriculum
From September 2014, the introduction of the new National Curriculum for England is a chance for senior leaders, especially curriculum planners, to create more opportunities for engineering through the new programmes of study for computing, mathematics, and science, as well as in design and technology.

b) Taking opportunities to extend teaching and learning
Increasing numbers of schools are providing extended teaching time –

whole days, whole weeks – rather than a diet of short lessons and engineering projects are ideal for this, as is the extended project at A Level.

c) Making school a foundation for lifelong learning
There is another important argument. Given the widely accepted view that schools have a key role in developing wider skills – for example, problem-solving, thinking, creativity – engineering is ideally placed as a means of doing this.

d) Taking stock of innovations that work
It might be a good time to review the approaches by UTCs and studio schools to the teaching and learning of engineering and share these more widely.

e) Putting the E in STEM
The UK continues to lack expertise in STEM subjects and this report provides fresh thinking for the engineering teaching and learning community to use with the Department for Business, Innovation and Skills and the Department for Education.

f) Working with others with overlapping agendas
There are specific opportunities for collaboration with:

SSAT – whose Redesigning Schooling[58] initiative has already stressed the need for better vocational pathways.

ASCL – whose Great Education Debate[59] provides a forum for the Royal Academy of Engineering to share the arguments in this report more broadly with school leaders.

Teach First[60], now the largest supplier of initially trained teachers and with a high proportion of talented STEM graduates, might wish to make use of the EHoM approach and is a potential source of ambassadors for engineering education.

Gazelle Group[61] – This group of FE colleges is actively promoting the development of STEM centres and is a natural ally for exploring EHoM.

City & Guilds has committed to including engineering in the early development of its TechBac® and might be interested in incorporating ideas in its thinking.

6.2.4 Employers and the wider public

Engaging with employers is critically important and there is some evidence that engineering graduates are sought after by many non-engineering companies. But, perhaps more importantly to the broader engineering community, it is vital that engineers engage in discussions about the EHoM they value and want. Beyond formal education, family learning activities will be important ways of showing informally how the kinds of engineering habits of mind described in the report can be developed.

a) Building a political consensus
In the run up to the next General Election in 2015 there is a useful window of opportunity to engage with policy-makers from the main political parties. There are also other potential partners:

CBI[62] – which is developing various educational initiatives around STEM, the articulation of wider skills of employability and better engagement of parents.

Royal Society – There is a chance to influence the Royal Society's Vision for the future of Science and Mathematics Education report and future activities[63].

RSA[64] – It might be possible to collaborate with its Great Recovery project and emerging interest in promoting maker movement ideas.

b) Engaging employers
We recommend that employers engage in a conversation about the usefulness of focusing on 'how engineers think'; that they encourages staff to share their knowledge with schools, colleges and universities to develop EHoM.

c) Collaborating with providers of family and extra-curricular learning
There are many including the U3A[65], The Maker Movement[66], Fix It clubs, after-school clubs and the many local bodies offering opportunities to experience engineering at first hand.

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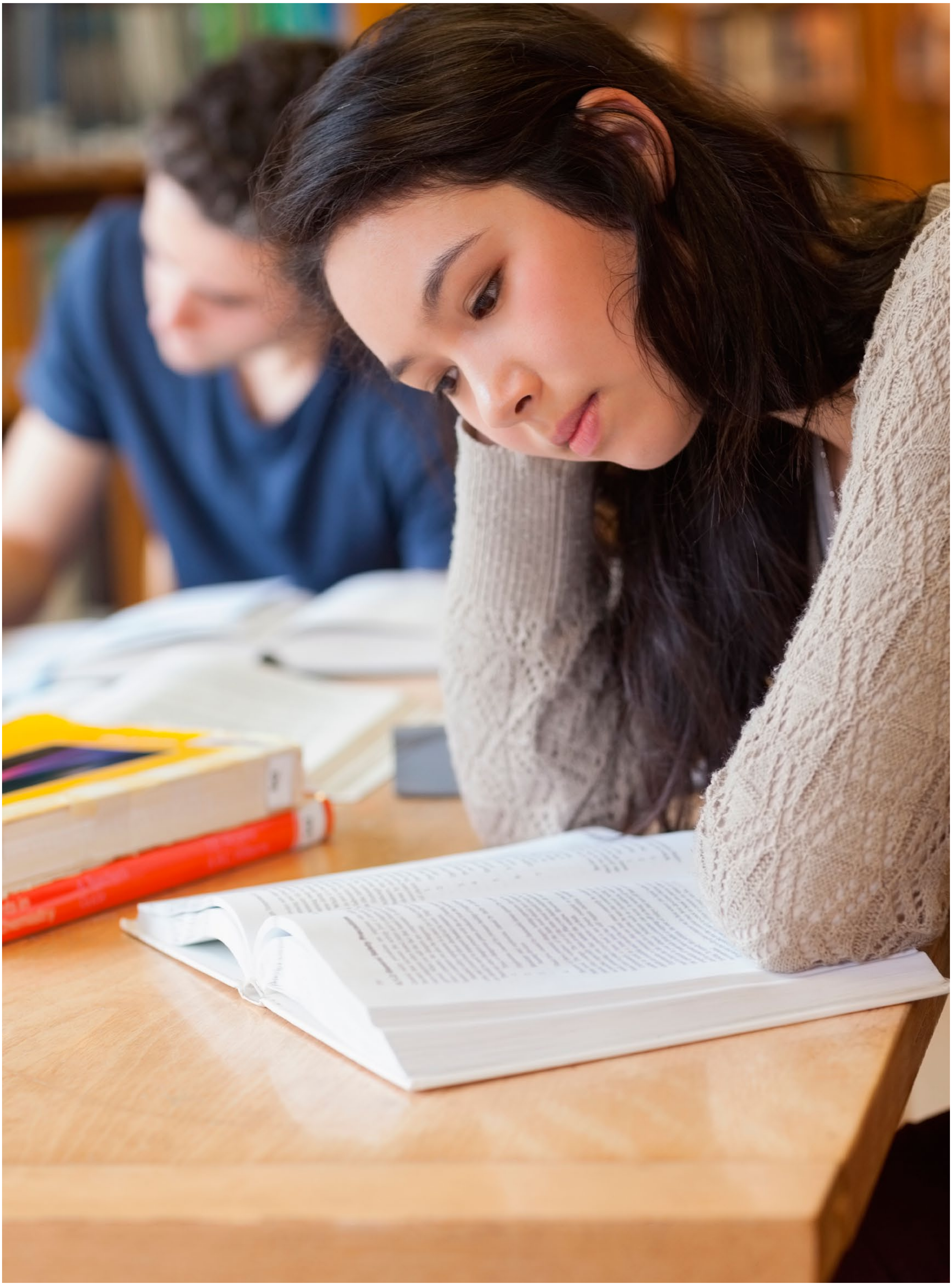

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