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CENTRE FOR REAL-WORLD LEARNING

Creativity and Engineering in Schools: A missed opportunity?

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About the Centre for Real-World Learning at the University of Winchester (CRL)
www.winchester.ac.uk/realworldlearning

CRL is an applied research centre focusing on the cultivation of learning dispositions. Its groundbreaking work in identifying creative habits of mind has been influential in the decision by the Organisation for Economic Co-operation and Development (OECD) to introduce the PISA 2022 Creative Thinking assessment and is used in more than 30 countries across the world. Since 2014 CRL has been undertaking research into engineering habits of mind (EHoM) on behalf of the Royal Academy of Engineering.

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Executive summary

This review explores the similarities (and differences) between the ways in which creativity and engineering can be systematically, intentionally and effectively incorporated into the curricula of all schools. It starts with the premise that engineering and creativity, though increasingly valued globally as the means by which some of the intractable and complex problems faced by humanity can be solved, are nevertheless often almost invisible in schools in England.

In addressing the multi- and inter-disciplinary nature of both engineering and creativity, it is argued that framing engineering as a set of engineering habits of mind (and body), just as the authors have done successfully in framing creativity, may help teachers to look beyond the traditional subjects of science and maths to incorporate a broader range of disciplines and create learning experiences that are closer to the real world of engineering.

By the same token it may be helpful to understand how, through the use of creative, engineering and especially design thinking processes, teachers may better be able to make choices about the use of effective pedagogies.

The review charts recent significant developments in teaching for creativity in English schools and suggests ways in which the engineering education community might learn from these and from recent international developments, especially the PISA (Programme for International Student Assessment) Creative Thinking results published in 2024.

The review makes three specific suggestions.

1. That an overview of the 'state of the nation' with regard to engineering in schools is undertaken, similar in scope to the Durham Commission on Creativity and Education (2019), a partnership between Arts Council England and Durham University.
2. That the Royal Academy of Engineering acts as a catalyst, drawing on existing international and national evidence, to develop a clear message about the importance of engineering in schools as a means of solving the world's challenges and (re)invigorating the experiences of young people and their teachers in schools.
3. That there is a concerted focus on teaching and assessment in embedding engineering in schools. This might include an explicit acknowledgement of the importance of understanding engineering habits and in the confident use of design thinking processes, all the while creating opportunity for pupils to learn through the process of solving authentic problems. There is work to be done in understanding how assessment practices can be developed to further improve teaching and learning in engineering.

Adopted thoughtfully, global priorities for education to develop a wide array of skills can be channelled into England's context and beliefs about the purpose of education. In light of the Department for Education's 2024 Review of Curriculum and Assessment, the Royal Academy of Engineering has a timely opportunity to advocate for embedding engineering principles within a broad curriculum. This aligns with the government's ambition to enhance skills-based education, but it is crucial that the right skills are prioritised – skills that resonate with both economic, personal and societal needs. Engineering competencies like adapting and creative problem-solving are essential for careers in engineering, but also valuable for all individuals, supporting active citizenship and personal development. By leveraging evidence from this report and partner research, the Academy can help ensure a broad curriculum equips young people with skills prized by employers and needed for meaningful engagement in society.


"Creativity is fundamental to effective engineering"
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Introduction

Creativity is fundamental to effective engineering, concerned as it is with the generation of novel solutions to problems. Engineering for its part, with its focus on finding and solving problems, is an inherently creative process.

Yet creativity, like engineering, is virtually absent from the national curriculum of schools in England. This could be because of uncertainty about how to harness creativity in classrooms or, perhaps, because creativity is often seen as the preserve of arts subjects and a rare commodity found only in the lone creative genius rather than being ubiquitous and teachable to all.

Like engineering, creativity frequently straddles different disciplines. It uses a broad design process that has much in common with the engineering design process. In the current educational discourse, both creativity and engineering are largely missing from policy conversations about what should be taught in schools in England.

The broad aim of this review is to explore how creativity and engineering might better be understood as mutually reinforcing disciplines with overlapping habits. Such an understanding, it is anticipated, might help to change the conversation in education, support schools to drive innovation in leadership and pedagogical practices and so inspire more young people to want to become engineers and develop their creativity.

More specifically, this review aims to:

1. Better understand the areas of common interest between engineering and creativity, for example, comparing creative and engineering habits, and design processes.
2. Suggest ways in which the engineering education community might learn from the evolution of creativity as a desirable outcome of education in jurisdictions across the world.

A version of this report was prepared as a stimulus for discussions at a workshop with policy-makers, researchers, school leaders and practitioners to explore our initial findings and consider potential recommendations for policy and practices in engineering and creative thinking in schools. The objective of this workshop was to explore and evaluate these ideas, with the intention of identifying potential new arguments, collaborations, and initiatives in policy and practice that may be energised by this interdisciplinary thinking. This current report concludes our findings.

Approach to the research

This research had three elements: an initial in-depth review and an expert workshop, culminating in this report.

Literature review

EBSCO databases, including Academic Search Complete, British Education Index, Education Source, and Educational Resources Information Centre, were searched using Boolean operators combining keywords into search strings, including wildcard to include variations of a word's stem, such as 'engineer', 'habits of mind', 'creative process', 'education', 'school', 'creative', 'thinking creatively', creative thinking skills', 'creative process'. Searches included all peer reviewed papers with dates between 2013 and 2023. To increase relevance, manual searching was conducted using expert author knowledge.

Expert group

The expert group attended a 1-day workshop at the Royal Academy of Engineering in London in May 2024. An early draft of this report was sent out prior to the workshop, and participants were asked for feedback. The group were invited to reflect on the reasons engineering and creativity are both invisible and undervalued in many schools in England, and what engineering might do to promote itself more effectively in schools and onto the national agenda for education. The purpose was to agree the direction of an overall argument, identifying promising practices, proposing additional ideas and refining recommendations.

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1. Engineering and creativity matter but are often invisible in schools

Engineering and creativity are at the heart of what has enabled homo sapiens to thrive. Together these two domains enable us to identify problems, generate new ideas and bring order to disorder. Expressing our creativity and thinking and acting like engineers to serve the greater good are at the heart of what it is to be human.

There is growing consensus among various sectors, including business and education, that we need to enhance creative capacities in the workforce and, therefore, that creativity needs to be explicitly included in school curricula. Similarly, there is a recognised demand for more engineers, which supports the argument for bolstering engineering education in academic settings. It is also increasingly noted, however, that both current and aspiring engineers often lack essential skills in creative and critical thinking; skills that are vital for innovative problem-solving in engineering contexts (Brent & Felder, 2014). Thus, the relationship between creativity and engineering extends beyond their shared status as critical competences that need to be fostered through formal education; it also includes the necessity of embedding creative thinking habits within the core skill set taught to engineers, ensuring they are equipped to tackle complex challenges effectively.

How engineering and creativity matter

From an economic perspective, industry in this country requires more participants in the workforce with technical skills and the ability to think 'creatively', and 'like an engineer'. While a great many ventures and problems require interdisciplinary skills (including many of those promoted by the Royal Academy of Engineering's 'This is Engineering' campaign), it could be argued that what is really needed is specialists who can work well at the boundaries of their sphere, collaborating with others to solve interdisciplinary problems.

The crossover between engineering and creativity lies in their mutual reliance on innovative problem-solving, design thinking, and the pursuit of novel solutions to complex challenges. Both domains are essential for advancing technology, improving society, and responding to the ever-evolving needs of humanity. They are complementary forces that drive human progress. This is not, therefore, purely about attracting more engineers to specific engineering jobs, but also about developing the habits of a creative thinker and an engineer in all young people, whether they become an engineer, or another equally important problem-solver.

Calls for the strategic importance of engineering, often labelled as STEM (Science, Technology, Engineering and Mathematics) come from a number of quarters with many different and overlapping motivations. Such voices include government, industry, education, non-governmental organisations (NGOs) and those focusing on the development of skills for life.

Governments and policymakers

Put simply, we need more engineers than we have. Demand for labour in the engineering industry outstrips supply by a significant margin (Department for Business Innovation and Skills, 2013; Joyce, 2018), with efforts to increase uptake of STEM subjects relatively unsuccessful (Adams et al., 2011), and an annual shortfall of 110,000 (Armitage et al., 2020). Much has been written about the need to encourage more young people into careers in engineering, and the general line of argument is that encouraging young people into engineering is vital for fostering a generation equipped with the problem-solving skills, innovative thinking, and technical knowledge needed to address the complex challenges of the modern world.

Recognising the critical role of STEM in driving economic growth, innovation, and national security, governments around the world have been proactive in promoting STEM education. Policies and initiatives may aim to increase STEM literacy, encourage pupils to pursue STEM careers, and ensure that the workforce is equipped with the necessary skills to meet future challenges.

In policy terms the value of engineering and engineers is often expressed in terms of a skills gap with 'the skills employers need' featuring as a "prominent phrase in the policy discourse" (Esmond, 2023; p. 360). Esmond highlights how a series of reforms over recent decades have been guided more by government imperative than shaped by independent landmark reviews. Decisions to re-shape education – particularly with regard to vocational and educational training – have had, if not unintended, certainly unexpected consequences: "ostensibly animated by craft-like engagement in meaningful practice, yet ending in routinisation and new inequalities" (Esmond, 2023; p. 361).

STEM and 'creative' industries

Companies and business leaders in technology, engineering, and related industries are significant proponents of STEM education, benefitting from a growth in the sector. They highlight the need for a skilled workforce to sustain innovation and competitiveness on a global scale. Industry partnerships with educational institutions often support STEM programmes through funding, resources, and mentorship.

The so-called 'creative industries' is a phrase used to describe a range of economic activities that are concerned with the generation and commercialisation of creativity. They include advertising, architecture, the art and antiques market, crafts, design, designer fashion, film and video, interactive leisure software, music, the performing arts, publishing, software and computer games, and television and radio. Unsurprisingly this group is vocal in its advocacy for the value of creativity. An unintended consequence of the title 'creative industries' is that, just as engineering can be unhelpfully exclusively associated with maths and science, so creativity can be located in a similarly narrow set of career pathways. It also unhelpfully implies that everything else people do for a living is not creative!

Higher and Further Education

Educational institutions, universities, and researchers in the field of education emphasise STEM for its role in fostering critical thinking, problem-solving, and creativity. They advocate for curriculum reforms and teaching methods that integrate STEM subjects more effectively and make them accessible to a diverse range of learners. A recent report from the Institution of Engineering and Technology and the Engineering Professors Councils, *New approaches to engineering higher education*, argued for the incorporation of creativity into engineering:

> **To reflect developing industrial needs and to attract a broad range of applicants, engineering programmes should enhance and emphasise the creative and innovative nature of the work of engineers; although acknowledging maths and science are important, they are a necessary but not sufficient part of the skill set required**
> (IET and EPC, 2019; p. 3).

Kazerounian and Foley (2007) identified 'blockers' to creativity in engineering education. The authors identified 'ten maxims of creativity in education, "a set of criteria that constitute an educational environment conducive to fostering creativity in students" and found that engineering students at the time were experiencing almost none of the ten. Kim (2020) identifies recent work highlighting the absence of programmes to develop creativity in engineers "asserting that creative performance was not encouraged at these schools" (p. 707).

In two studies, students were also sceptical about creativity, perceiving that there was little place for it in programmes requiring analytical, convergent thought. Further, while creativity is said to be essential for engineering, Kim found three studies showing lack of significant relation between creativity and academic performance in engineering schools. It is possible that, rather than not being important, creativity is being undervalued in assessments.

Cropley (2015; p. 161) argues that educational programmes "focus excessively on narrow and deep technical specifications, with little or no room in the curriculum for developing the ability to think and act creatively".

Non-Governmental Organisations (NGOs)

The lack of visibility of creativity on the curriculum is being increasingly challenged in a global context. The Global Institute of Creative Thinking reviewed the status of creative thinking within education systems internationally charting a growing global consensus on the importance of creative thinking (Lucas, 2022a). This consensus comes from a number of influential NGOs including organisations such as United Nations International Children's Emergency Fund (UNICEF) and United Nations Educational, Scientific and Cultural Organization (UNESCO), the Organization for Economic Cooperation and Development (OECD) and the World Economic Forum (WEF), and curriculum organisations like the International Baccalaureate and Center for Curriculum Redesign.

NGOs focused on education and development stress the importance of STEM education for achieving sustainable development goals arguing that STEM literacy is crucial for addressing global challenges such as climate change, health, and sustainable energy (for example UNESCO International Bureau of Education, 2019). A recent systematic review (Kayan-Fadlelmula et al., 2022) underlines these views. Yet organisations that seek to influence global agendas often adopt top-down approaches that reflect the interests and priorities of their primary stakeholders. These strategies may not always be in harmony with the policy contexts, economic structures, cultural identities, or democratic values of individual nations.

Skills for Life and Work

With the rapid pace of technological advancement, there is a clear need for continuous learning and adaptation in the workforce. Advocates for workforce development stress the importance of STEM education in providing foundational skills that enable lifelong learning and adaptability in a changing job market.

While engineering and creativity hold the promise of addressing many global challenges, school leaders must settle in their own minds the rationale with which they will exercise their leadership, developing a ‘theory of change’; the cause-and-effect model they adopt to explain to their stakeholders what they plan to change in their school, and why.

Beyond the direct benefits of advancing technology and improving societal infrastructure, and beyond the primary imperative behind campaigns to increase engineering and creative thinking that is often economic, the sorts of thinking that engineers do is inherently valuable as a mental discipline. Integrating engineering into children’s education can yield a wide range of positive outcomes beyond the development of technical skills.

In contrast with engineering, the impetus for schools to teach creativity is less motivated by employability needs – though employers have certainly called for it – and more overtly about inculcating learning habits thought to be more broadly beneficial. Creative thinking may benefit pupils in their ability to problem-solve, in their professional competence and their career development. The analytical, systematic, and creative approach that underpins engineering thinking cultivates a mindset that may also be beneficial across all areas of life and work. Specifically, engineering thinking has been claimed to be of benefit to children’s development in areas such as “math readiness, spatial thinking, literacy, and social skills” (Lippard et al., 2019; p. 462).

While engineering and creative thinking are potentially important for everyone, creative thinking is also beneficial to engineers. Engineers are not always prepared, though their education, for a world of increasing complexity (Mackechnie & Buchanan, 2012). There are also calls for innovative engineers, who need to be creative (Atwood & Pretz, 2016; Charyton et al., 2011; Charyton & Merrill, 2009; Cropley, 2015). The need for creative engineers is less obvious than it seems, which is why learners are not always on board with the idea. Cropley explains that well-defined problems can have routine solutions, but problem-solving must shift from routine to creative in a number of places:

- Where new problems arise
- Where a new solution satisfies an old problem but does so better, faster or cheaper
- Where a new solution opens up new possibilities and so satisfies a new problem
- Where a new problem can only be satisfied by a new solution.

If an engineering mindset encourages young people to break down problems, consider multiple solutions, and understand the implications of their decisions, it can be a powerful tool not only for those who pursue careers in engineering but also for anyone navigating the complexities of this part of the 21st century.

Why are engineering and creativity invisible in schools?

The absence of creativity and engineering as focal disciplines in school curricula can be attributed to several factors, each rooted in historical, institutional, and pedagogical contexts. Despite the growing recognition of their importance in the modern world, these subjects often face challenges in being fully integrated into educational systems for a number of reasons.

Traditional educational structures

Educational systems tend to be built on models that prioritise core subjects such as mathematics, language, arts, and science in their pure forms. These models aim to serve the primary educational goal of providing a broad base of knowledge, rather than fostering specific skills like creative thinking or engineering aptitude. As a result, subjects that encourage applied problem-solving and interdisciplinary thinking may not be adequately represented.

Engineering is not a compulsory subject within the English National Curriculum, for example, though many schools introduce engineering projects as vehicles for teaching design and technology, science, maths, and computing, or taking a cross-curricular perspective on these subjects (Lucas et al., 2014). Alternatively, engineering may be introduced through science or technology. In England, the Department for Education (DfE) encourages teachers to incorporate iterative design and engineering as a focus within design and technology (Hanson et al., 2021; p. 1,471). With the exception of some countries, engineering tends not to be covered within the formal curriculum but often appears as the vehicle through which science and maths content is taught (Hanson et al., 2021; p. 1,470). It most commonly manifests in primary schools through integrated STEM programmes (Hanson et al., 2021).

As a consequence of engineering not being on the curriculum, its greatest provision often comes from out-of-school sources. For example, there are a number of organisations dedicated to engineering that promote engineering as a career pathway and so dedicate aspects of their work to influencing school education. These organisations provide external events that schools may take part in, such as the 2021 Schools COP organised by Tomorrow's Engineers (2024), which focuses entirely on meeting the gap in the labour market. The Schools COP was part of 'Tomorrow's Engineers Week' (2024). Another event, 'Engineers Week' (National Society of Professional Engineers, 2024) began in the US in 1951 but is also promoted in the UK (Twinkl, 2024). Lucas et al. (2014) list several organisations providing careers fairs, visiting ambassadors, or signposts for teachers to ideas and resources to teach through lesson plans, projects, competitions, or after school activities.

Perception of relevance

There may be a perception among educators, parents, and policymakers that subjects requiring creativity and engineering are specialised disciplines relevant only to certain career paths. This overlooks the broader benefits of skills, including critical thinking, problem-solving, and the ability to innovate.

In term of opportunities for achieving recognised qualifications in engineering at school age, for example, there is a GCSE, but it is taken only by a tiny minority of pupils. There are no A-levels, but there are BTECs. In schools pupils tend to encounter engineering by getting involved in external initiatives such as engineering challenges, use of visiting STEM ambassadors, The Great Science Share (n.d.) or in after school engineering clubs. While these are important, they tend to have a lower status than the formal curriculum.

Putting creativity on the curriculum faces barriers in schools, mostly due to perceptions about what teaching for creativity might entail. The worry that creativity is difficult to define and assess may contribute to a view that pedagogies of creativity lack rigour, or that they disrupt progress through a knowledge rich curriculum. In England where the curriculum is narrowed as a result of accountability measures, teaching 'to the test', or focusing purely on knowledge content can be seen as the 'safe' option by school leaders.

The pace of technological change makes it challenging to develop curricula that remain relevant and up-to-date. Engineering and creative disciplines, in particular, evolve quickly, and educational systems can struggle to keep pace, leading to gaps in the curriculum.

Resource constraints

Implementing creativity and engineering programmes requires resources, including trained teachers, specialised equipment and updated curricula that many schools struggle to afford. Budget constraints can make it challenging to provide the hands-on learning experiences essential for these disciplines.

There is currently a shortage of educators who are specifically trained in engineering (Martin, 2024) or pedagogies for creativity (Durham Commission, 2019; Martin, 2024). The interdisciplinary nature of these fields requires teachers who are not only knowledgeable about the subjects but also skilled in facilitating creative problem-solving and project-based learning.

Assessment pressures

The emphasis on standardised testing and performance metrics in many educational systems can lead schools to concentrate on subjects that are directly assessed in these tests. Creativity and engineering, which thrive on open-ended exploration and innovation, may not fit neatly into the standardised testing frameworks, leading to their underrepresentation in curricula. Exams and tests which give marks for 'one right answer' are almost bound to disadvantage a pupil who is intent on generating multiple solutions.

Both engineering and creativity face challenges from assessment models that may not adequately capture the full breadth and impact of these disciplines. For assessment is almost entirely organised around individual subject disciplines and, except in vocational pathways, is much less adept at evidencing the development of practical skills.

Lack of confidence with pedagogy

Engineering in particular is a practical discipline. While experts can make good teachers, we know that expertise does not necessarily translate to an awareness of how to develop good pedagogy (Lucas et al., 2012). Supply and demand for qualified engineering is mismatched not due solely to underfunding, pay, or lack of public relations efforts, but to a lack of sound pedagogy for cultivating engineering minds (Lucas et al., 2014).

A study of undergraduates found that some engineering curricula did not properly teach or reward creativity, and that "those engineering students who view themselves as highly creative are less likely to graduate in engineering" (Atwood & Pretz, 2016; p. 540). **Table 1** compares how engineering and creativity currently fit into schools.

Table 1:
Summary comparison of how engineering and creativity fit into schools

	Engineering	Creativity
Integration	Engineering is often integrated into science, technology, engineering, and mathematics (STEM) education. Its presence may be more pronounced in specialised programmes or schools focusing on STEM fields.	Creativity is recognised as a cross-disciplinary skill, relevant across the arts, humanities, and sciences. It is often embedded informally within various subjects rather than taught as a standalone discipline.
Curricular presence	Explicit engineering curricula are less common in early education but may appear as elective courses or extracurricular activities in secondary schools. Some schools offer robotics, computer science, or applied science courses that include engineering principles.	Creativity is most visibly nurtured in arts education, including visual arts, music, drama, and creative writing. These subjects provide pupils with opportunities to express themselves, explore ideas, and develop creative thinking skills.
Constraints	Implementing engineering programmes can be resource-intensive, requiring specialised equipment, software, and trained instructors. This can limit its availability to schools with sufficient funding.	The emphasis on creativity can vary widely between schools, depending on the curriculum, teacher autonomy, and the school's educational philosophy. Standardised testing and rigid curricula can sometimes stifle creative teaching and learning practices.
Pedagogical approaches	When present, engineering education tends to emphasise project-based learning, encouraging pupils to apply mathematical and scientific concepts to solve real-world problems. This hands-on approach promotes critical thinking and collaborative skills.	Progressive educational models and some extracurricular programmes promote creativity through interdisciplinary projects, design thinking, and innovation challenges, allowing pupils to explore creative problem-solving in diverse contexts.

2. Engineering and creativity in education

In the last few decades there has been a global shift away from an exclusive focus on core subjects towards a focus on essential skills such as creative thinking, collaborative problem-solving and communication, alongside various habits of mind that equip learners to flourish at school and beyond (World Economic Forum, 2015). During this period our understanding of how best engineering and creative thinking can be embedded in school curricula has continued to evolve.

Engineering and engineering thinking in education

Using what we know about the world around us to make things and solve problems is an inherently human behaviour, practised long before the term 'engineering' came to be used. The 'engine' part of engineering has machine industrial connotations, but The Welding Institute's observation (2023) that the word 'engine' itself 'comes from the Latin word 'ingenium' (c. 1250), which means 'innate quality, especially mental power, hence a clever invention' reminds us of the importance of cognition in its broadest sense in engineering.

The field of engineering encompasses various branches, each focusing on specific areas such as civil, mechanical, electrical, chemical, and many more. Engineers play a crucial role in advancing technology, innovation, and the overall development of society. The Royal Academy of Engineering's campaign to introduce more young people to a career in its field, called *This is Engineering* (Royal Academy of Engineering, n.d.-b) describes the huge diversity within the field, from sport to space, fitness to fashion, construction to computing, medicine to music.

In promoting this vocational area to a broader audience the Royal Academy of Engineering has avoided the sorts of definition used by the industry and higher education of engineering that have connotations of hard science and hard metal, such as

'the designing, testing and building of machines, structures and processes using maths and science'
(University of Bath, 2023)

'The application of science and maths to solve problems. While scientists and inventors come up with innovations, it is engineers who apply these discoveries to the real world.'
(The Welding Institute, 2023)

'about designing processes and making products to solve real-world problems.'
(University of Cambridge, 2023)

Engineering is a broad discipline that involves the application of scientific principles, mathematical methods, and empirical evidence to design, create, build, maintain, and improve structures, machines, devices, systems, materials, and processes. As such, engineering is a core component of STEM subjects (Science, Technology, Engineering, and Mathematics) in its application of scientific and mathematical principles to develop technological solutions.

A brief journey through engineering education

The journey of integrating engineering into UK schools has been part of a broad narrative of recognising the importance of technical and vocational education within a traditionally academically focused system. It has evolved through various phases, influenced by educational reforms, industrial changes, and a growing recognition of the importance of STEM (Science, Technology, Engineering, and Mathematics) education. While direct engineering education at the school level has evolved gradually, recent initiatives reflect a growing consensus on the need to equip pupils with the engineering skills and mindset necessary for the challenges of the 21st century.

The roots of technical and engineering education in the UK can be traced back to the Industrial Revolution, with the establishment of Mechanics' Institutes in the early 19th century. These were among the first efforts to provide adult education in technical subjects to meet the demands of industrialisation. However, these were not part of the formal school system.

Throughout the 20th century, technical education in the UK saw various reforms aimed at improving and expanding vocational training in response to industrial and technological advancements. The Education Act 1944 (Butler Act) marked a significant step in organising post-war education, which included technical schools as one of the streams alongside grammar and secondary modern schools, though the emphasis on engineering was not as pronounced in schools at this time.

The Education Reform Act of 1988 introduced the National Curriculum in England, Wales, and Northern Ireland. Design & Technology (D&T) became a mandatory subject for pupils aged 5 to 16 (Wakefield & Hardy, 2022). D&T courses included elements of engineering, such as problem-solving, design processes, and understanding materials and systems, laying the groundwork for engineering concepts in schools.

The late 20th and early 21st centuries saw a series of initiatives aimed at strengthening STEM education, driven by concerns over the UK's ability to compete in a global, technologically advanced economy. Efforts to integrate engineering more explicitly into the curriculum have been part of broader STEM education initiatives, including government (Harrison, 2011), industry, and educational bodies working together to promote STEM subjects and careers.

Policy discourse post-COVID recovery has increasingly focused on technology as a solution to societal problems, with 'fourth industrial revolution' becoming a key phrase for a world of work dominated by artificial intelligence (AI) (Esmond, 2023). Recent years have seen further emphasis on engineering and technology within the curriculum and extracurricular activities. Programmes and competitions, such as those organised by EngineeringUK and the Royal Academy of Engineering, aim to inspire young people and demonstrate the relevance of engineering to everyday life and society's challenges. The introduction of T-levels, a technical alternative to A-levels, in 2020 also reflects a commitment to providing clear pathways for pupils into engineering professions. 'T Levels', rolled out in 2020 (Armitage et al., 2020) were part of the English government's two-strand reforms to technical education. They are work-based placement learning for full-time pupils in upper secondary education, named to imitate the general 'A-level' pathway (Esmond, 2023).

Engineers use their knowledge and skills to find practical solutions to real-world problems and challenges. They do this through a unique way of thinking. In line with the National Academy of Engineering's description of engineering, Lippard et al., (2017; p. 455) define engineering thinking as "goal-oriented thinking that addresses problems and decisions within given constraints by drawing on available resources, both material resources and human capital."

Because engineering is about a way of thinking, there has been some movement towards embedding engineering thinking with other subjects in UK schools, reflecting a broader trend in education to integrate STEM principles across the curriculum. This interdisciplinary approach aims to foster an engineering mindset among pupils by applying engineering principles and problem-solving skills in a variety of contexts, not just in isolated engineering or technology classes. Several key initiatives and educational strategies highlight this trend:

The D&T element of the National Curriculum naturally integrates engineering principles with other areas of study. It is the largest contributor to the 'T' element in STEM (Harrison, 2011). D&T encourages pupils to apply creative thinking and problem-solving to design and make products that solve real and relevant problems within a variety of contexts. This subject embodies the application of engineering thinking across disciplines, including mathematics, science, art, and computing.

STEM initiatives and programmes have been developed to promote STEM education and incorporate engineering thinking across subjects. For example, STEM Learning provides resources, training, and support to schools to enhance the delivery of STEM subjects, often emphasising the interconnectedness of science, technology, engineering, and mathematics.

Schools are increasingly adopting project-based learning (PBL) approaches that encourage pupils to engage in interdisciplinary projects. These projects often require pupils to apply engineering thinking, such as designing solutions to real-world problems, conducting experiments, and working collaboratively, thereby integrating engineering concepts into a broader learning context (Lucas & Hanson, 2021).

Programmes such as the Engineering Education Scheme (Engineering Development Trust, 2024) provide opportunities for pupils to work on real engineering projects in partnership with professional engineers and companies. These schemes not only provide direct exposure to engineering but also allow pupils to apply their learning from other subjects in an engineering context.

Recent curriculum reforms and the introduction of new qualifications, such as T-levels, aim to better align education with the skills needed in the workforce, including engineering. While T-levels are more vocational, the emphasis on practical skills and industry placement reflects a broader educational philosophy to integrate real-world problem-solving and engineering thinking across subjects.

Through these and other efforts, the educational system in England is increasingly recognising the value of embedding engineering thinking across the curriculum, not only to enhance pupils' understanding of engineering concepts but also to develop critical thinking, creativity, and problem-solving skills that are valuable in a wide range of disciplines and careers.

Engineering creativity

Creativity research in engineering began to blossom in the 1950s, then faded (Charyton & Merrill, 2009). More recently, engineering education is beginning to draw on the concept of creativity to reflect the importance of engineering problem solving and design (Atwood & Pretz, 2016) as the need for creativity, problem solving, and innovation is a global imperative (Charyton & Merrill, 2009). Numerous research reports have shown the need for engineering curricula to enhance learners' creative skills (Daly et al., 2014).

Creativity in engineering is understood using the definition of 'functional creativity' (Cropley & Cropley, 2005).

Creativity and creative thinking in education

As a field of research, creativity has existed since the 1950s and the work of JP Guilford. It has been thought of as a type of novel thinking, or as the ability to connect ideas in new ways. One of the most widely accepted definitions of creativity is that it produces outcomes that are both novel and useful (Amabile, 1996): products that 'work'; ideas that have value. Whether practically, aesthetically, musically, organisationally, personally – they have merit in their own sphere. Cropley & Cropley's (2005) definition of 'functional creativity' closely resembles this idea.

In education, Ken Robinson's report (National Advisory Committee on Creative and Cultural Education, 1999) was a watershed moment for creativity, justifying its place in schools. Anna Craft and colleagues' (2001) research in the early 2000s significantly shaped the understanding and integration of creativity in education by emphasising the concept of 'possibility thinking' as a fundamental approach to fostering creativity in learners. She advocated for the idea that education should not only transfer knowledge but also cultivate an environment where pupils are encouraged to explore, question, and imagine alternatives and possibilities. Her contributions led to a broader acceptance and implementation of pedagogies and curricula that aim to develop creative skills and mindsets in pupils preparing them to navigate real-world complexity thoughtfully.

While many people are not keen to describe themselves as 'creative', creativity is something that all individuals can demonstrate, and it can be fostered through intentional practice just as other skills can (Daly et al., 2014). From 2009, Kaufman and Beghetto's work on concepts of 'little-c' creativity and 'mini-c' creativity highlighted the importance of recognising and nurturing everyday creative processes and personal insights within educational settings, reframing creativity as something children can be taught to do in everyday moments. They argued that fostering these forms of creativity in pupils promotes ongoing intellectual growth, personal development, and the ability to approach problems in innovative ways, underscoring the critical role of creativity in holistic education.

If we wish to teach children creativity, to develop their ability to have 'ideas that have value', we should see creativity not as a 'lightbulb moment' but as something learnable and malleable: a thought process or a set of habits.

In 2013 Creativity, Culture and Education commissioned the Centre for Real-World Learning (CRL) to develop one of the first frameworks for creativity specifically designed for and trialled in schools (Lucas et al., 2013). Identifying five distinct habits of creativity – being Inquisitive, Persistent, Imaginative, Collaborative, and Disciplined – CRL's model offers educators a concrete set of characteristics to develop in pupils to enhance their creative capacities. This framework has been influential in shaping educational practices and policies by emphasising the importance of creativity as a critical skill across the curriculum, encouraging a more holistic approach to student development that goes beyond traditional academic achievements to inculcate creativity in young people. CRL's model is now in use in more than thirty countries across the world.

In 2019, The Durham Commission on Creativity and Education, a collaboration between Durham

University and Arts Council England, made a significant contribution to the promotion of creativity in education by publishing a landmark report that offered a comprehensive analysis of the role and importance of creativity in the educational system. The Commission provided a set of recommendations aimed at embedding creativity across all levels of education, from primary through to higher education. Key contributions included advocating for a national plan for creativity in education, proposing changes to the curriculum to better support creative thinking, suggesting the establishment of Creativity Collaboratives to foster partnerships between schools and cultural organisations, and emphasising the importance of teacher training in creative approaches to teaching and learning. The report highlighted creativity as an essential skill for the 21st century, influencing policymakers, educators, and practitioners to prioritise and integrate creativity more systematically in educational practices and policies.

The Durham Commission Report on Creativity and Education (2019) has provided some helpful definitions:

Creativity: The capacity to imagine, conceive, express, or make something that was not there before.

Creative thinking: A process through which knowledge, intuition and skills are applied to imagine, express or make something novel or individual in its contexts. Creative thinking is present in all areas of life. It may appear spontaneous, but it can be underpinned by perseverance, experimentation, critical thinking and collaboration.

Teaching for creativity: Explicitly using pedagogies and practices that cultivate creativity in young people.

Arts Council England's (2021) Creativity Collaboratives research programme in schools is ongoing and is beginning to yield advances in pedagogy for creativity across the curriculum.

Challenges to teaching for creativity or engineering

How are teaching for creativity and teaching for engineering similar? Teaching in a creative way, or teaching in a technical way, does not necessarily translate to creative or engineering habits or to practical skills in students, although when teachers model their thinking there are powerful benefits. Both creativity and engineering can be taught (Royal Academy of Engineering, n.d.-a; Vincent-Lancrin et al., 2019).

Teaching engineering and creativity in schools presents several challenges, stemming from both the intrinsic nature of these subjects and the constraints of traditional educational systems.

Curriculum rigidity

Many school curricula are standardised and rigid, with timetables focusing on a set of traditional academic subjects. This rigidity can limit the flexibility needed to incorporate space for engineering and creativity, which often require a more hands-on, exploratory approach.

Lack of resources

Engineering and creative projects often require specific materials, tools, physical spaces and technologies, which can be expensive and difficult for schools to acquire and maintain. This limitation can hinder the ability to provide students with the hands-on experience that is crucial for learning in these areas.

Teacher expertise

Teachers tend to be confident in particular subject areas, reflecting their training and own schooling. Engineering has its own body of knowledge that spans a range of (STEM) subjects, applied to real-world problems. Creativity, while not limited to 'the creative subjects', also requires content knowledge. Teaching both requires not just knowledge, but also the ability to foster creativity, problem-solving, and innovation in learners. Designing curricula and selecting appropriate pedagogies require considerable teacher expertise.

Assessment models

Traditional assessment methods, such as standardised tests and written exams, may not accurately capture students' abilities and learning in engineering and creative endeavours. Developing alternative assessment strategies that can evaluate hands-on skills, creativity, and problem-solving abilities is challenging. It requires investment from teachers and learners, and other stakeholders who must be assured of its validity.

Pupil engagement

While engineering and creative projects can be highly engaging for some students, others may find them intimidating or frustrating. Balancing the curriculum to meet diverse interests and skill levels while still challenging students and promoting growth can be difficult.

Time constraints

The school day and academic year are already packed with subjects that schools are required to teach, leaving limited time for additional subjects or interdisciplinary projects that combine engineering and creativity with other areas of learning. Pupils and their families also place strong emphasis on core subjects where future learning pathways are dependent on them. For example, there are music technology courses that require A-Levels in maths, physics and music, and an instrumental performance level of Grade 8. While engineering and creativity are of obvious value to pupils following this route – indeed, one music technology course "focuses on creativity, innovation and research" – unless engineering and creative thinking are incorporated within these qualifications, time will not permit their pursuit elsewhere.

Cultural and societal attitudes

There may be cultural or societal attitudes that undervalue the importance of engineering and creative disciplines compared to traditional academic subjects. Overcoming these attitudes to gain support for integrating these areas into the school curriculum can be a challenge.

Innovation v. standardisation

The nature of creativity and engineering involves experimentation, failure, and innovation, which can conflict with the standardised approach to education that focuses on right answers and specific outcomes. Creating an educational environment that values and encourages innovation over rote learning can be difficult within the constraints of existing systems.

Specific challenges for engineering in schools

Engineering presents particular challenges to schools given its applied and practical nature (Hanson & Lucas, 2022). For example, the Office for Standards in Education, Children's Services and Skills's (Ofsted) accountability framework is a limiting influence. While Ofsted's revised education inspection framework recognises the important balance between knowledge and its application, other aspects of the accountability regime can pose a threat to many school leaders and the EBacc constraints and Progress 8 measure may stifle some opportunities.

The language of practical learning is not yet widely embedded and tends to provoke stereotypical, often binary responses. Knowledge can be pursued as a source of truth, beauty and wisdom – an end in itself, as well as the driver for applied solutions to real-world problems. Labels that are associated with postmodern and progressive views of education carry negative connotations for those of a different worldview. Leaders in the report cited spoke of 'interdisciplinary learning' and 'design thinking' being respectable labels. Rather than just changing the label, practical learning must ensure rigour and grounding within (and across) disciplines.

Participants in Hanson and Lucas's 2022 research spoke of upskilling teachers without former specialist knowledge. It is unclear whether the problem is that engineering is not taught well enough in schools, or that STEM subjects as separate entities are not inspiring sufficient pupils to pursue them at a higher level.

Open-ended design courses are inherently challenging, and teachers may be particularly sensitive to less confident pupils where 'learned helplessness' is an issue (Seligman, 1972). Learners are initially challenged and confused and may feel unable to progress. If the course goes well, they will have experienced doubts and anxious moments. Teachers need to be able to navigate them through the process without over hasty interventions, but swiftly mediating when problems arise through serious gaps in knowledge (Mackechnie & Buchanan, 2012).

3. Engineering and creative learning habits compared

In the last two decades there has been a move towards framing engineering and creativity not simply in relation to subject disciplines but also in terms of the habits that are required. How does an engineer think and act? What habits does someone exercising their creativity use to greatest effect? This reframing has been a central focus of research undertaken by the Centre for Real-World Learning.

The idea of habits of mind

In 1999 Lauren Resnick defined a person's intelligence as "...the sum of one's habits of mind"; when intelligent individuals are confronted by problems, she argued, they draw on internalised ways of thinking that guide their choices. Around this time Art Costa and Bena Kallick developed a set of general habits of mind which their research suggested were most important to cultivate in young people. Their 16 Habits of Mind model (2000) includes a number of 'critical thinking' habits such as 'thinking about thinking', 'questioning and posing problems', 'applying past knowledge to new situations', 'thinking and communicating with clarity and precision', 'creating, imagining, innovating', 'taking responsible risks', and 'thinking interdependently'.

In England the concept of Personal Learning and Thinking Skills (PLTS) was introduced in the early 2000s as part of a wider shift to preparing pupils for life beyond school. These were a set of six skill clusters – independent enquirers, effective participants, reflective learners, team workers, self-managers and creative thinkers. But they were always advisory and not mandatory and often got lost when set alongside subjects in which children were tested and examined. Stage-based models of the creative process fail to take into account certain factors of interest to teachers.

Habits models are useful as they go beyond IQ, or traits, and describe a person's *disposition* to use particular cognitive or practical tools, the difference between what one might be able to do, and what one actually does in practice.

Not fixed traits, these habits can be cultivated intentionally by

- Developing understanding of the habit
- Creating the climate for the habit to flourish
- Choosing teaching methods that facilitate the practice and transfer of the habit
- Building learner engagement and commitment to the habit (Lucas & Spencer, 2017).

Habits of mind can relate to the general intelligence level or learning, the subject level (such as science or maths), or to what Lucas et al. (2014) refer to as "broader concepts like 'practical learning' or 'creativity'" (p. 21). Engineering, as a more cross-disciplinary mode of thinking, would fit into this latter category. There will thus be a set of habits of mind that could be associated with development of engineering thinking.

We have always conceived the phrase 'habits of mind' as a holistic notion encompassing head, heart and hands working together in harmony (Hanson and Lucas, 2022). In this world view mind and body are not separated but integrated, (Claxton, 2015). But we recognise that in schools, which are dominated by 'headwork', it may be more helpful to refer to 'learning habits' rather than 'habits of mind.'

Across STEM subjects there is a growing emphasis on habits (Tytler et al., 2020). Anticipating the then future date of 2010, Australia's Taskforce on Educational Programmes (cited in Beder, 1999) recognised that engineers of the future would need more than technical skills, and that their education would need to develop additional skills and expertise beyond the "specific expertise utilizing the current technology with short-term horizons" (p. 17). Beder recognised that this approach would be "be more 'on learning how to learn' and less on filling the students with the requisite knowledge" (p. 17).

Creativity

When asked what it means to be creative, many people immediately think of using imagination. But creativity is much broader than imagination, and a more comprehensive view of the mental habits creativity utilises helps clarify thinking about what it means to think and act creatively.

With this idea of making creativity actionable, several frameworks have been developed to describe and cultivate the creative habits of mind. These frameworks aim to capture the cognitive and attitudinal aspects that contribute to creative thinking and problem-solving. Notable frameworks include:

- Torrance Tests of Creative Thinking by E. Paul Torrance (1966): This model identifies several key components of creativity, including fluency, flexibility, originality, and elaboration. It emphasises both cognitive and personality traits that contribute to creative thinking. The Torrance Model has been widely used in educational settings to assess and nurture creative potential.
- Creative Habits by choreographer Twyla Tharp (2009): *The Creative Habit* (Tharp, 2009) outlines a framework for developing and sustaining creativity. She emphasises the importance of rituals, routines, and discipline in fostering creative habits. Tharp's framework is applicable to various creative endeavours, not limited to a specific domain. The framework is a series of principles – advice to invest in yourself, set up a proper work station, link your creative practice with a ritual – rather than a set of cognitive habits.
- Six Thinking Hats by Edward de Bono (1995): While not explicitly a framework for creative habits, Edward de Bono's Six Thinking Hats method encourages individuals to adopt different thinking modes, fostering a more comprehensive and creative approach to problem-solving. The hats represent different perspectives, including creativity, and help individuals explore a problem from various angles.
- Growth Mindset by Carol Dweck (2006): While not exclusively focused on creativity, Dweck's research on mindset is relevant. In her work, she distinguishes between a "fixed mindset" and a "growth mindset." Cultivating a growth mindset, where individuals believe that their abilities can be developed through dedication and hard work, is seen as conducive to creative thinking and learning.
- Personal Creativity Characteristics by Treffinger et al. (2002). This is a framework of cognitive operations that underlie the creative process. Synthesised from over 100 definitions of creativity, its four primary categories are generating ideas (divergent thinking), digging deeper into ideas (convergent thinking), openness and courage to explore ideas (which involves specific personal characteristics), and listening to one's inner voice (reflection, or metacognition).

These frameworks provide valuable insights into the behaviours, routines, cognitive and attitudinal aspects that support creativity. Depending on the context and goals, educators and researchers may find these frameworks useful for understanding and fostering creative habits

In *Zig Zag* Sawyer (2013) approaches creativity ostensibly from a process view with his use of 8 steps: ask, learn, look, play, think, fuse, choose, make. But he acknowledges that:

> **The mental process associated with the eight steps can overlap, or cycle repeatedly, or sometimes appear in reverse order. This is why some creativity researchers prefer to describe them as "disciplines" or "habits of mind" that are associated with highly creative individuals.**

The 8 steps could be seen as an effort to inculcate habits.

Our own framework for creativity (Lucas & Spencer, 2017, see **Figure 1**) has five creative habits, each with three sub-habits.

This framework has significant buy-in from the OECD (Lucas et al., 2013), and was the initial starting point for an 11-country, four-year research project looking at how schools can teach and embed creativity (Vincent-Lancrin et al., 2019). A practical guide for teachers translates the framework into actionable ideas for teachers (Lucas & Spencer, 2017), and in 2021 it was influential in the development of a new PISA test of creative thinking that gives equal status creativity as to literacy, numeracy, and science, as a fourth 'pillar' of what it means to be intelligent. The CRL model is used in 6 of the 8 Creativity Collaboratives in England today.

Engineering

In 2014 CRL sought to address the gap in validated frameworks of engineering by exploring research into the development of habits of mind models and applying these to engineering (Lucas et al., 2014). The team found that interest in subject level (e.g. mathematical or scientific) habits of mind coincided with exploration of what it means to think intelligently more generally. For example, Costa and Kallick's 16 habits of mind, and Guy Claxton's

Figure 1:
The Centre for Real-World Learning's creative habits model (Lucas et al, 2013)

17 Building Learning Power habits (Claxton, 2002), developed on opposite sides of the Atlantic, were encouraging teachers to reflect on the thinking habits learners could adopt as they attempt their subject-based learning.

Lucas et al. cite earlier work with Creativity, Culture and Education developing a framework for creative thinking as "a proof of concept for taking a broader concept such as engineering and seeking to identify its characteristic [habits of mind]" (p. 20), because engineering, like creativity, involves what can be imagined as a 'toolbox' of different thinking habits.

Subsequently numerous works list the items in this toolbox although few cite their source. Ashbrook and Lowry (2019), for example, refer to a set of engineering habits of mind without citation: 'optimism', 'collaboration', 'paying attention to ethical considerations', and 'systems thinking'.

Underpinning one commonly listed set of engineering habits is a report by NAE & NRC (National Research Council, 2009) which lays out the principle that K-12 engineering education should promote engineering habits of mind. NAE & NRC takes the term 'habits of mind' (p. 152) from the American Association for the Advancement of Science (American Association for the Advancement of Science, 1990) report *Science for All Americans*. In this report, the phrase 'habits of mind' is defined as a set of values, attitudes and skills that can be thought of as habits "because they all relate directly to a person's outlook on knowledge and learning and ways of thinking and acting.". The report details a set of thinking skills "associated with science, mathematics, and technology" including curiosity, openness to new ideas, informed scepticism, computation and estimation skills, manipulation and observation skills, communication skills, and critical-response skills. Clear rationale is given for the importance of these values attitudes and skills (habits), although not for their inclusion as a definitive list, and there is no claim made that the list was developed in a research-led way.

Although NAE & NRC (National Research Council, 2009) did not appear to be the origin of the list because it did not lay out a rationale or any research, this document is the source of the widely used list, as this quote from the National Research Council (2010; p. 30) makes clear:

The Partnership for 21st Century Skills has developed an outcomes-based framework (P21, 2009) that suggests the skills, knowledge, and expertise students will need to succeed in the workplace and in their lives outside of work. Among the recommended skills are creativity and innovation, critical thinking and problem solving, and communication and collaboration, traits consistent with engineering habits of mind proposed by the Committee on K–12 Engineering Education (NAE and NRC, 2009)**.**

An Annex in NAE (National Research Council, 2010; p. 45) explains each of the six.

"The engineering design requires a different mind set from the mind set appropriate to science, mathematics, or any other academic field" (National Research Council, 2010; p. 140). NRC divides the habits of mind into 3 areas: systems thinking, teamwork, societal and environmental impacts of technology. It's unclear why there are suddenly 3 when there were 6, but this could be a list specific to 'design' rather than to engineering in general.

Loveland and Dunn (2014) also cite NAE's (National Research Council, 2010) 6 engineering habits of mind and compare them with national standards for engineering education to (presumably) show the crossover. Creativity is one of the six and relates to the importance of imagination in the design process.

Another example of work that lists the toolbox's content is Lippard et al.'s (2019) systematic literature review, where findings from 24 research studies were combined to conclude that children in preschool classrooms demonstrate "six engineering habits of mind" (p. 188) including:

- **Systems thinking** – "facilitates higher order thinking as children seek to identify and understand interconnectedness and how materials relate to each other and contribute to the system as a whole" (p. 189).
- **Creativity** – "the use of imagination in solving engineering problems" (p. 189).
- **Optimism** – "reflects the belief that problems can be viewed as opportunities… and helps children develop positive responses to new challenges. Optimism includes children's perseverance and motivation to learn." (p. 189).
- **Collaboration** – "allows for groups to incorporate strengths and abilities of each group member into the problem-solving process" (p. 189).
- **Communication** "includes understanding the needs and wants of others… Communication challenges children to clarify their thinking…" (p. 189).
- **Attention to ethical considerations** – "includes consideration that any given solution to a problem will impact others in the environment…" (p. 190).

Each of these habits is discussed under a heading (p.189), but the primary justification for each appears to be the 2009 NAE and NRE. Lippard's research used the 'Early Engineering Observation Tool' (p. 193) to spot use of the six engineering habits. The source of this Tool is not revealed in the study.

The authors cite an earlier paper (Lippard et al, 2017) that investigated engineering learning and thinking in young children. This paper fails to define what the habits that comprise 'engineering thinking' (which it does define) are, other than noting that "…we have relied on the idea of engineering habits of mind (NAE & NRC, 2009) [i.e. (National Research Council, 2009)]" (p. 465). In this paper the authors aim not to define the habits, but to define the sorts of interaction that help develop the habits. It recognises "the field lacks a unifying organisational framework" and proposes that valid, reliable measures of children's engineering thinking are needed.

In an attempt to provide clarity, Lucas et al (2014, see **Figure 2**) reviewed earlier literature to develop a model of engineering habits of mind and then worked with practising engineers to validate their selection.

The six EHoM six habits of mind evolved from the earlier NAE & NRC's six (National Research Council, 2009), see **Table 2**.

The framework of six engineering habits of mind developed by Lucas and Hanson has proved practical and useful to practitioners. It has been explored theoretically (Lucas et al., 2014), empirically (Lucas et al., 2017), and from a leadership perspective (Lucas & Hanson, 2018).

Lucas and Hanson are not the only authors to link creative thinking to engineering thinking, but the framework's inclusion of 'creative problem solving' as a habit may need further refining because creative problem solving can, itself, be broken down further into habits. Others refer to the importance of the habit 'creativity' for STEM in general (Hummell, 2014; Jones, 2014), for example. In Lippard et al. (2019), 'creativity' was one of the six engineering habits of mind and defined simply as "the use of imagination in solving engineering problems". It is the one habit out of the six that was not observed in the classroom in this research and no wonder, if it is being defined so narrowly.

Figure 2:
Engineering Habits of Mind (EHoM) (Lucas et al., 2014)

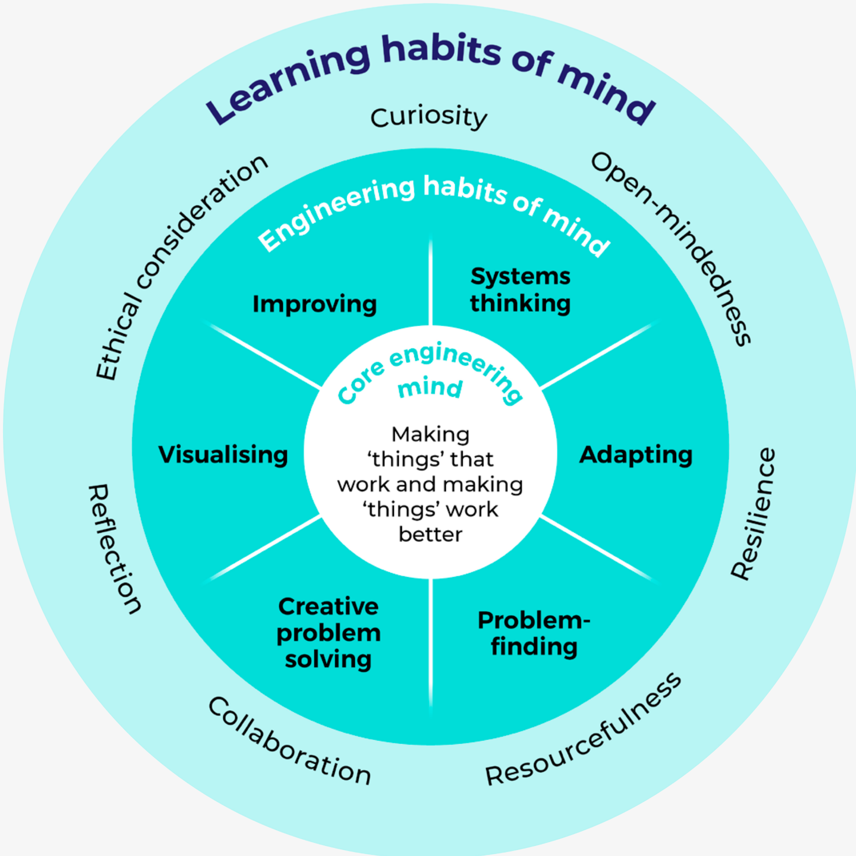


Table 2:
Comparison of Lucas et al. (2014) habits with National Research Council (2009) habits

NAE & NRC (National Research Council, 2009)	Lucas et al. (2014)
Systems thinking	Systems thinking
Creativity	Creative problem-solving
Optimism	Adapting
Collaboration	Problem-finding
Communication	Visualising
Attention to ethical considerations	Improving

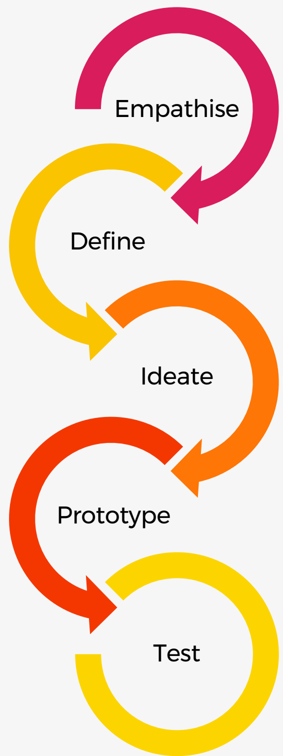
Design thinking

Engineering habits and creative habits are similar to another set of habits; those of 'design thinking'. Design thinking is a process of solving complex problems with real or imagined human clients that also emphasises collaboration and experimentation and iteratively generates creative solutions. Design thinking involves a mindset that is both inventive and analytical. Teaching design thinking to students could develop their ability to navigate complex problems and innovate within any field, including the arts and sciences, and to integrate creativity with technical precision.

Design thinking involves a number of steps (Hasso Plattner Institute of Design at Stanford University, 2010, see **Figure 3**)

As a concept, design thinking has evolved significantly over the years, transforming from a process used primarily in product and industrial design to a widely applied approach in solving complex problems across various disciplines. We lay out a brief overview of its evolutionary journey:

Figure 3:
Design thinking as a process of steps (Hasso Plattner Institute of Design at Stanford University, 2010)



In the 1950s and 1960s design thinking began to take shape in the fields of architecture and industrial design. John Arnold brought creative thinking to Stanford through his Creative Engineering seminars, and introduced the concept of design thinking (Von Thienen et al., 2018).

The 1970s saw the rise of the design methods movement, which aimed to apply scientific and systematic approaches to design problems (Langrish, 2016). Herbert Simon's seminal work, *The Sciences of the Artificial*, first published in 1969 (Simon, 2019), proposed that design could be seen as a way of thinking and his ideas influenced the conceptualisation of design thinking as a distinct cognitive process.

Design... is the core of all professional training; it is the principal mark that distinguishes the professions from the sciences. Schools of engineering, as well as schools of architecture, business, education, law, and medicine, are all centrally concerned with the process of design (Simon, 2019, p. 111)

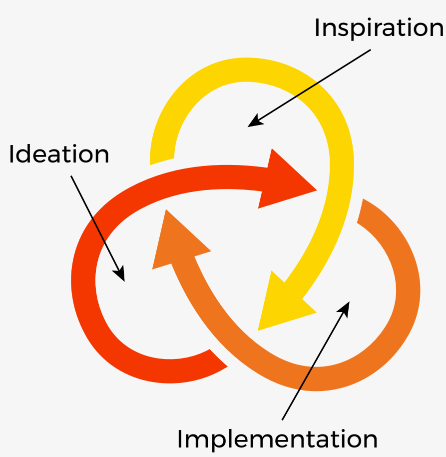
The term 'design thinking' began to be more formally recognised in the 1970s and 1980s. Peter Rowe's book *Design Thinking* (1998) examined the processes architects use. Around the same time, design consultancies like IDEO started to emerge, applying design thinking principles to product development and business innovation. This period marked the transition of design thinking from design and architecture into broader applications in business and innovation.

Tim Brown, CEO of IDEO, a design and innovation company, and author of its design thinking blog defines design thinking as "a human-centered approach to innovation that draws from the designer's toolkit to integrate the needs of people, the possibilities of technology, and the requirements for business success." (Brown, cited in IDEO, n.d.). It's "a way to solve problems through creativity". Thinking in this way involves adopting a designer's mindset with a characteristic "beginner's mind" that demonstrates "the intent to remain open and curious, to assume nothing, and to see ambiguity as an opportunity". Its three core activities are inspiration, ideation, and implementation, (IDEO, n.d., see **Figure 4**).

IDEO argues that the design mindset involves "dreaming up wild ideas, taking time to tinker and test, and being willing to fail early on". It "embraces empathy, optimism, iteration, creativity, and ambiguity [and] keeps people at the center of every process".

Design thinking gained mainstream popularity in the 2000s as organisations recognised its value in driving innovation and addressing complex challenges. The d.school at Stanford University (Hasso Plattner Institute of Design at Stanford University, 2023), founded in 2005, played a significant role in promoting design thinking

Figure 4:
Three activities of design thinking (IDEO, n.d.)



as an interdisciplinary approach that could be applied beyond traditional design disciplines. Business schools and universities worldwide began integrating design thinking into their curricula.

Design thinking has been applied to a wide range of sectors since the 2010s, including healthcare, education, technology, and social innovation. The rise of digital technology has further expanded its application, using design thinking to develop user-centric digital products and services. The concept has also been adapted for tackling societal and environmental challenges, promoting sustainable development and social innovation.

Throughout its evolution, design thinking has maintained its core principles of empathy, collaboration, iterative learning, and a human-centred focus. Its adaptability and applicability across different contexts and challenges have solidified its importance as a framework for innovation and problem-solving in the 21st century.

Similarities between the habits of mind for engineering, creativity, and design thinking

While there are distinctions among the habits of mind associated with engineering, creativity, and design thinking, there are also overlapping elements that reflect a shared emphasis on problem-solving, innovation, and a holistic approach to complex challenges. Creativity is "inherent in the engineering design process" (NAE, 2010; p. 45) and it is to be expected that there is crossover. Here are some commonalities that may be observed, **Table 3**.

While these commonalities exist, it's important to recognise that each domain – engineering, creativity, and design thinking – also has unique characteristics and learning habits specific to its context and goals. The synthesis of these shared elements contributes to a comprehensive approach to addressing complex challenges and fostering innovation.

Table 3:
Similarities between key habits of mind for engineering, creativity, and design thinking

	Engineering habits	Creative habits	Design thinking habits
Collaborative	Collaboration is crucial in engineering, with teams often comprised of individuals from diverse disciplines working together to solve complex problems.	Collaboration is a common theme in creative processes. Combining diverse perspectives often leads to more innovative solutions.	Interdisciplinary collaboration is a hallmark of design thinking. It encourages teams with diverse backgrounds to work together to address challenges from multiple angles.
Adaptable; flexible	Engineers need to be adaptable, as projects may encounter unexpected challenges that require adjustments to the design or implementation.	Creative individuals often demonstrate flexibility, embracing unexpected inspirations or modifications to their initial ideas.	The iterative nature of design thinking encourages adaptability. Teams can adjust their approach based on the insights gained during the process.
Open-minded	Engineers benefit from an open-minded approach that considers various solutions and perspectives.	Open-mindedness is a foundational aspect of creative thinking, allowing individuals to explore unconventional ideas.	Design thinking encourages an open-minded exploration of possibilities, valuing diverse viewpoints and creative solutions.
Inquisitive	Engineers seek to understand the fundamental aspects of a problem, explore potential solutions, and continuously ask questions to refine their understanding. Curiosity in engineering thinking extends to a desire to discover and innovate, driving technological advancements and improvements.	Creative thinkers are characterised by a natural curiosity and a willingness to explore the unknown. They are inquisitive about the world around them, seeking to understand, question, and challenge existing norms and ideas. Curiosity drives the generation of novel and imaginative concepts in the creative process.	Design thinking places a strong emphasis on empathy, which involves being curious about the experiences, needs, and perspectives of end-users. Design thinkers approach problems with a genuine interest in understanding the human context, fostering empathy through curiosity.
Imaginative	Loveland and Dunn (2014) discuss the use of creativity as a habit of mind in engineering in terms of use of imagination in the design process. Two ways it is said to be nurtured is through “using digital multimedia tools as a teaching strategy and making space for creativity in the class” (p. 14) through brainstorming, communication of ideas and designs, and open-ended problem solving.	Imagination is the engine fuelling the creative process. It’s important in generating ideas, in connecting unrelated concepts, envisioning futures, problem-solving, overcoming constraints, empathy, artistic expression, and innovation.	Imagination allows designers to put themselves in the shoes of users (empathise). It enables envisioning of the underlying issues that may not be immediately apparent (define). It is most apparent at the ideate stage as imagination fuels creative brainstorming. Imagination helps bring prototypes to life, and imagine potential user reactions during testing, enabling further iteration.

4. Engineering and creative design processes compared

There have been many attempts to develop and refine engineering and design processes over the years. At the heart of both are a set of steps, often iterative ones, that enable the development of ideas, thinking, solutions, processes and products. As neither process is yet widely and consistently acknowledged in schools and as each domain tends to emphasise its own models and language it may be helpful to understand the similarities (and differences) between the processes.

The creative process (and creative problem solving)

The creative process is less well researched than the concept of creativity itself (da Costa et al., 2020), yet the idea of a creative process, "individuals' engagement in behaviours and thought processes related to creativity" (Tolkamp et al., 2022; p. 1,329), has been around for many years and studied from different perspectives (Sternberg, 2020). For example, there are bodies of work looking at the creative process in specific domains such as music (Barbot & Webster, 2018) and advertising (Griffin, 2008), or organisations more broadly (Amabile, 1988).

As examples of the range of perspectives, Sternberg cites two different approaches. First, Wallas's four-stage model that conceives of the creative process as a series of steps. Second, unlike Wallas's clear steps in a temporally ordered chain of events, Koestler's view of *bisociation*, sees "two separate trains of thought become one [through various and separate processes such as] comparison, abstraction and categorization, analogies and metaphors" (Sternberg, 2020; p. 229).

Conceptual work on the creative process varies also by whether it focuses on what Kaufman and Beghetto (2009) call Pro-C and Big-C creativity, or by a more everyday variety, such as that which might happen in schools when children come up with an idea novel to them. Sternberg's (2020) 'Straight-A' creative process model proposes a different view from that offered by Wallas or Koestler, and focuses on Pro-C or Big-C creativity. His model, like Wallas's, concerns the processes involved in creativity from start to finish, but these processes do not describe cognitive activities. Instead, they develop in relation to the environment, **Table 4**.

Table 4:
Sternberg's Straight-A Creative Process

Phase	Variables most relevant at each phase	Comments
Phase 1	Activators (deactivators)	Internal or external Events promoting creative work
Phase 2	Abilities	Creative skills Analytical skills Practical skills
Phase 3	Amplifiers (attenuators)	Defying (acquiescing to) crowd Self Zeitgeist
Phase 4	Appeal to audience	Creator builds into ideas/products an appeal to audience to be judged as creative
Phase 5	Assessment by audience	Audience acts as arbiter of creative ideas/products

Such an approach is arguably less relevant to the classroom than Wallas's sequential model. Sadler-Smith (2015; p. 342) writes that Wallas's model, from his 1926 book *The Art of Thought*, "has the status of an in-house assumption among creativity researchers".

Preparation and verification are the two 'book-ends' of the process; both being under conscious control:

- 'Preparation' refers to the stage in the creative process where an individual actively gathers information, knowledge, and resources related to a problem or task. It involves consciously seeking out relevant information and engaging in activities that help build a foundation for generating creative ideas. This stage is focused on acquiring the necessary background knowledge and understanding of the problem at hand.
- During 'incubation' a person sets aside conscious effort and allows their mind to work on a problem unconsciously. It is a period of rest or detachment from actively thinking about the problem at hand. During incubation, ideas and information related to the problem are processed in the background of one's mind without direct awareness or deliberate focus. This stage often involves taking breaks, engaging in unrelated activities, or simply giving oneself time away from consciously trying to solve the problem. Incubation is believed to facilitate new connections and insights by allowing for subconscious processing and integration of information.
- 'Illumination' refers to the stage in the creative process where a sudden insight or breakthrough occurs. It is often described as a moment of clarity or inspiration when new connections are made and ideas come together. Illumination can happen after a period of incubation, where the mind has been unconsciously working on the problem. This stage is characterised by an "aha" moment or a burst of creativity that leads to novel solutions or perspectives.
- 'Verification' refers to the final stage of the creative process. It involves evaluating and testing the ideas or solutions that have emerged during the previous stages. This stage is focused on assessing whether a proposed solution is feasible, effective, and aligned with desired outcomes. Verification may involve conducting experiments, seeking feedback from others, or analysing potential risks and benefits before implementing or finalising a creative idea.

Sadler-Smith (2015) argues that, though widely understood to be a four-step model, a fifth step 'intimation' is more reflective of Wallas's original understanding. The fifth stage, occurring in the centre of the process refers to the stage in the creative process where ideas or insights begin to emerge into consciousness. It is a stage of becoming aware of potential solutions or connections that were previously unconscious or on the fringe of consciousness.

From a psychological view, Guilford (1950) found the four stages superficial, untestable, and telling next to nothing about the cognitive processes occurring at each step. Several authors called for the need to discern a problem finding phase, including Osborn, whose work led to what is referred to as creative problem solving, or CPS. This is a step-by-step process intended to spark creative thinking and the finding of innovative solutions. American advertising agency executive Alex Osborn published a seven-stage CPS process in 1952, refining it to 3 stages in 1967. In collaboration with Sidney Parnes, the Osborn-Parnes CPS model – used in a range of US education programmes – contained 5 stages:

1. Data finding
2. Problem finding
3. Idea finding
4. Solution finding
5. Acceptance finding.

Isaksen and Treffinger similarly honed in on the need for a problem finding phase, adding 'mess finding' to the front of the CPS model in 1985, refining the model through the 1980s and 1990s, with 'Version 6.1' comprising 4 components and 8 steps (Treffinger et al., 2003).

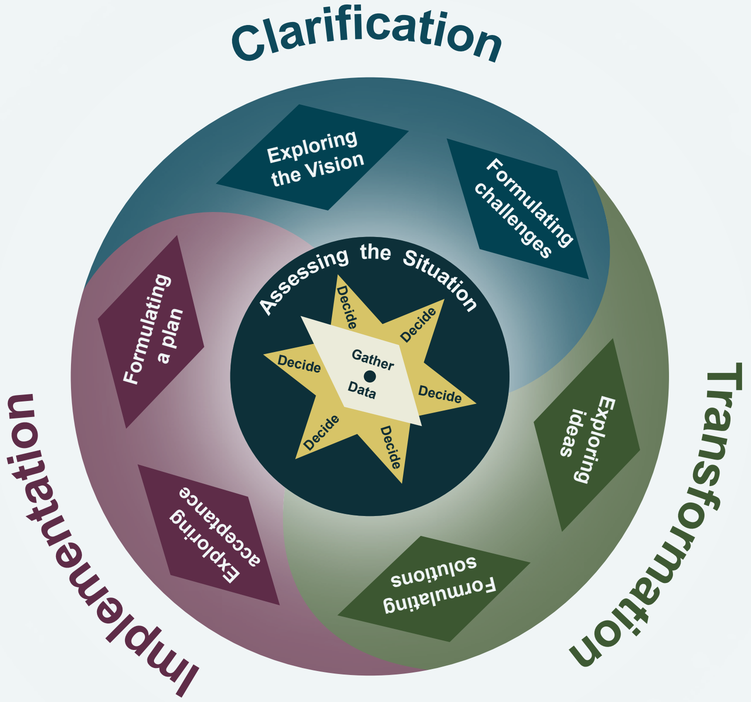
Puccio et al. produced the Creative Problem Solving Thinking Skills Model that has three key stages (clarification, transformation, implementation) and six specific steps (exploring the vision, formulating challenges, exploring ideas, formulating solutions, exploring acceptance, formulating a plan), (see **Figure 5**).

'Assessing the situation' is an executive step at the centre of the framework, aimed at guiding all steps.

In England, National Curriculum guidance recognises a design process, using the framework 'design, make, evaluate' (Department for Education, 2013), and teachers may use this in their planning. Hampshire Inspection and Advisory Service (HIAS) has a similar 3-phase 'explore, apprentice, apply' process for planning English units of work.

More recent thinking has reconceptualised these multi-step approaches as iterative. Sawyer (2021; p. 1) argues that while the creative process has been considered linear – using the above-mentioned descriptors such as preparation, incubation and execution – artists and designers teaching the creative process in fact use a "nonlinear, iterative, and

Figure 5:
Creative Problem Solving Thinking Skills Model (Puccio et al., 2010)



improvisational" creative process. Sawyer developed a framework of "eight characteristics of the pedagogy used and the creative process taught by these instructors" (ibid.). This eight-stage creative process framework includes: iteration, ambiguity, exploration, emergence, failure, deliberation, reflection, and constraint. For the general practitioner, *Zig Zag: The surprising path to greater creativity* (Sawyer, 2013) developed this as a zig zagging line metaphor incorporating eight steps: ask, learn, look, play, think, fuse, choose, and make. Verma and Punekar's work with designers (2023; p. 1030) similarly concluded that approach to form generation "is very individualistic and may involve some or all key factors in a random sequence".

Despite the numerous and varied frameworks of the creative process, there is much similarity in the elements they comprise. Tolkamp et al. (2022), collecting data from organisations including those in the engineering industry, argue that core elements include:

- **Problem construction:** typically considered the first step, and defined as 'the identification of goals, restrictions, procedures, and information required to solve a problem';
- **Information search and encoding:** 'the process of connecting, integrating, and encoding information'; and
- **Idea generation:** 'the production of alternative solutions or outcomes' which happens once information is available (p. 1,331)

Important elements of the creative process are metacognition, and creative self-beliefs (Anderson & Haney, 2021).

Creative process engagement

The creative process is relatively well understood as a series of steps. Other studies (da Costa et al., 2018; DaVia Rubenstein et al., 2018; Li et al., 2021; Ou et al., 2018) examine factors affecting creative process engagement – outside of this review's remit – but nevertheless shedding light on the definition. Creative process engagement is a field of research in its own right.

In attempting to understand the factors facilitating individuals to engage in a creative process, Ou et al. (2018) adopt the definition of creative process engagement as "individuals' involvement in creativity-relevant processes or methods, consisting of problem identification, information searching and encoding, and idea and alternative generation" (p. 101). Their study focuses on the facilitating factor of 'constructive controversy' (when people with different ideas and opinions work together to find a solution), which they posit is positively related to engaging in the creative process, because it encourages individuals to actively seek new information, consider different perspectives, and come up with creative solutions. Da Costa et al. (da Costa et al., 2018, 2020) similarly use problem identification, information searching and encoding, and idea generation to represent the creative process.

Li et al (2021) similarly look at factors that impact an individuals' participation in creative process engagement, focusing on examining how creative self-efficacy influences individual creativity rather than providing a specific definition or detailed explanation of the concept of 'creative process' itself. While the creative process itself is not defined in the paper, what is of interest is the paper's contention that higher creative self-efficacy makes an individual more likely to engage in creative process "subsequently leading to better individual creativity" (p. 66). What is the corresponding concept in engineering?

Learning to use the creative process

Rubenstein et al (2018) use Plucker at al.'s 2004 definition of the creative process: "how people approach and develop new and useful products or ideas within a sociocultural context". They argue that historically, research on the creative process has focused on examining the steps that creative people use but has overlooked how people learn these steps and the mechanisms behind them. They proposes to situate the creative process within a broader theoretical framework of self-regulated learning (SRL) (because, and it cites Sawyer 2012, research examining the creative process currently does so through various paradigms and models), which suggests that creativity can be learned and that strategies used in the creative process may inspire general learning strategies. Bringing together the idea of the creative process into the SRL framework "emphasises that the creative process can be learned and that creative process strategies may inspire general learning strategies" (p. 921).

As Rubenstein and colleagues develop their ideas about the 'how' part of the process (i.e. the cognitive steps people take), it is clear that the range and content of steps is up for debate. They note that Sawyer "synthesized across nine different stage models to describe the creative process through eight stages, the first of which was finding the problem" (p. 923). The authors settle on an understanding of creative process as reflecting "how people create, which is the combination of both internal, psychological conditions and external, behavioural manifestations during the development of a unique and useful products or idea." (p. 923).

They cite a number of strategies:

- Sawyer's Eight Stages – 2012
- Osborn's Creative Problem Solving Model – 1963
- Root-Bernstein and Root-Bernstein's 13 different process strategies – 2001
- Michalko's specific brainstorming techniques – 2006.

Similarities between the creative process and the creative design process

'The creative process' and 'the creative design process' share similarities, but they are not synonymous. The creative process is a broader concept that encompasses various activities and endeavours involving original thought, imagination, and innovation. On the other hand, the creative design process specifically refers to the systematic approach employed in designing or creating a product, system, or solution, **Table 5**.

In summary, the creative design process is a subset of the broader creative process. The creative process can refer to the act of generating ideas and creating across various domains, while the creative design process specifically pertains to the structured approach used in designing products or solutions within design-oriented disciplines. The former is a more encompassing term, and the latter is a specialised application of the creative process.

The engineering design process

Design is "a general activity for human progress, and particularly for the satisfaction of recognised needs" (p. 2). Hubka (1982) argues that in the past, experience and craft abilities were often sufficient to enable a person to design for problem solving. In a period of time characterised by rapid expansion of technology, however, experience and craft skill alone are insufficient. In this context, a growing body of literature is devoted to improving thinking processes to enable people to design solutions in any situation.

Also called the engineering method, the engineering design process – like the creative process – is a series of iterative steps. Just as with the creative process, it has numerous framings with a high degree of overlap. But there is also a lot of variation in engineers describe design actions and attributes (Dym et al., 2013; p. 7).

Engineering design is 'a thoughtful process for generating plans or schemes for devices, systems, or processes that attain given objectives while adhering to specified constraints.' (Dym et al., p. 7). Devices, systems or process are always 'artifacts';

Table 5:
Comparison of the creative process and the creative design process

	The Creative Process	The Creative Design Process
Definition	The creative process is a general term that describes the sequence of steps or stages individuals go through when generating new ideas, solving problems, or producing something novel. In the preceding section we have seen some of the names used for these stages.	The creative design process refers specifically to the systematic and structured approach used in designing products, systems, or solutions. It is often associated with fields such as graphic design, industrial design, architecture, and user experience design.
Scope	It is a broad concept applicable across diverse fields, including art, literature, science, business, and more. The creative process is not limited to a specific discipline or industry.	It is more focused and is typically associated with fields where design and problem-solving are integral. The creative design process involves translating creative ideas into tangible, functional, and aesthetically pleasing outcomes.
Key elements	Common elements of the creative process include inspiration, ideation, experimentation, and realisation. Habits of mind are required for these steps. This might be exploring possibilities, making connections, and thinking outside conventional boundaries.	The creative design process usually involves stages such as research, ideation, prototyping, testing, and implementation. It often follows a structured framework to ensure that the final product meets specified criteria and objectives. For Akoury (2020), drawing is "the language of creative design thinking" (p. 114). It allows "a mediation between intuition and understanding in order to… convert [objects of intuition] into images that can be processed by the understanding" (p. 124).

artificial and manmade things, which includes paper or electronic products.

The simplest frameworks have fewer, generalised, steps and may include steps such as: problem definition, conceptual design, preliminary design, detailed design, design communication (Dym et al., p. 7). Or, to use simple terms like Sawyer does for the creative process: NASA's engineering design process (National Aeronautics and Space Administration, 2018) identifies ask, imagine, plan, create, experiment, and improve.

Similarities between creative design process and engineering design processes

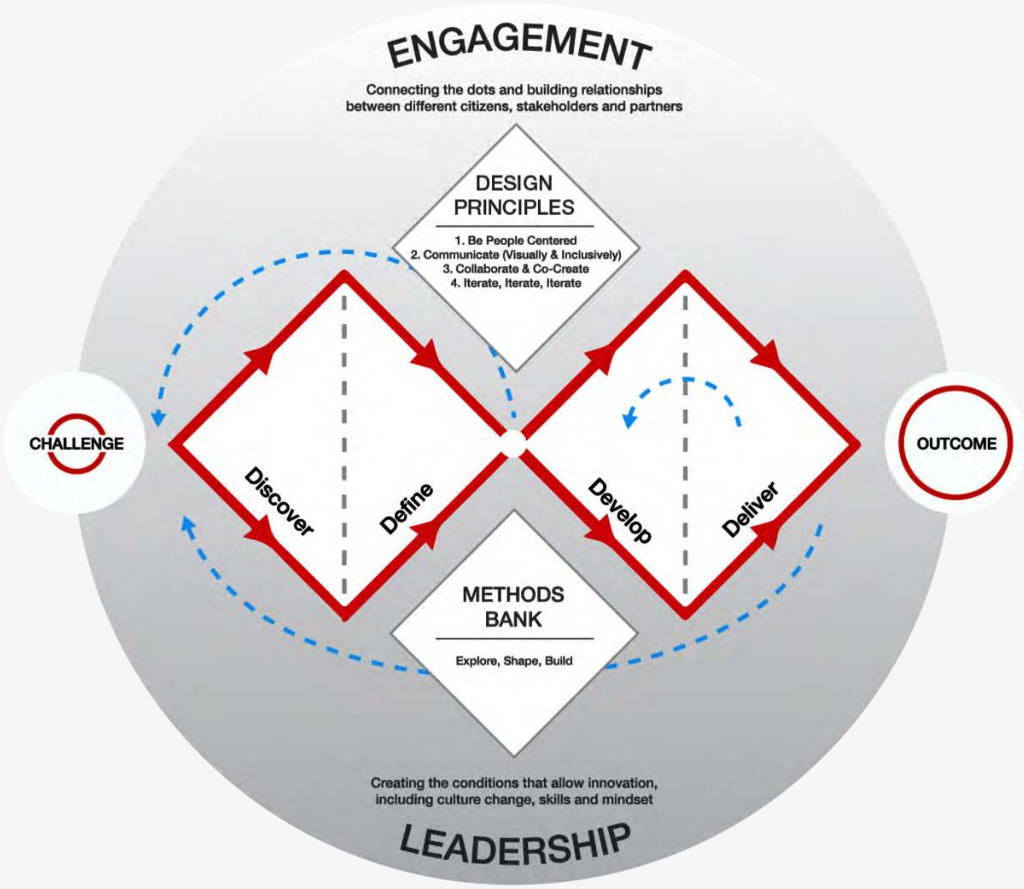
While the creative design process and the engineering design process may have distinct characteristics and priorities, there are commonalities between them, perhaps best expressed in light of the more generic 'design process' as developed by the Design Council. The Double Diamond framework (see **Figure 6**) describes the design process:

Both processes share fundamental principles related to problem-solving, innovation and –as expressed in the Double Diamond framework: "iterate, iterate, iterate"! **Table 6** compares the commonalities between the two processes in more detail:

While these commonalities exist, the emphasis and specific methodologies may vary between different creative design processes and engineering design approaches. Additionally, the context and goals of a project may influence how these processes are implemented. Both creative and engineering design processes contribute to the development of solutions that address real-world challenges and opportunities.

Imperial's Dyson School of Design Engineering emphasises the relationship between creativity and engineering as one that will enable students to "tackle the world's most pressing problems" (Kakar, 2023). The importance of creativity in engineering is evident, but in the real world, care must be taken that there is adequate reflection on existing solutions or iterations to problems. The 'creative' element of the creative problem-solving habit

Figure 6:
The Double Diamond framework (Design Council, n.d.)



of mind can be problematic to post-compulsory engineering educators (Lucas et al., 2014). While creativity was recognised as essential to engineering in general, in terms of the problem-solving habit of mind, creativity could "be in conflict with the requirements to consider previous solutions to problems and to adhere to recognised standards" (p. 45) because of the way creativity was seen by those engineers as requiring novelty, and not reflected in the fusion of ideas inherent in much engineering problem-solving.

Table 6:
Comparison of creative design process and engineering design process

	Creative design	Engineering design
Purpose	Development of solutions that address real-world challenges and opportunities.	As for creative design: the development of solutions that address real-world challenges and opportunities.
Problem definition	In both processes, there is a clear emphasis on understanding and defining the problem or challenge that needs to be addressed. This involves framing the problem in a way that inspires creative solutions.	Defining the problem statement is a critical first step in engineering design. Engineers seek to understand the requirements, constraints, and objectives of the project.
Iterative nature	Creativity often involves iteration, experimentation, and refinement of ideas. The creative design process embraces an iterative approach where concepts are tested, modified, and improved.	Engineering design is also iterative, involving prototyping, testing, and refining solutions based on feedback and performance evaluations.
User-Centered Focus	Many creative design processes, especially those influenced by design thinking, emphasise a user-centered approach. Understanding the needs and experiences of end-users is crucial for generating innovative and meaningful solutions.	User requirements and considerations are central to engineering design. Engineers strive to create products and systems that meet the needs of users and stakeholders.
Collaboration	Collaboration is often a key component of creative design processes. Cross-disciplinary teams work together to bring diverse perspectives and expertise to the problem-solving process.	Collaboration is also inherent in engineering design, with professionals from various disciplines working together to address complex challenges.
Prototyping and Testing	Prototyping and testing ideas are common practices in creative design processes. Creating tangible representations helps to evaluate concepts and gather valuable feedback.	Prototyping and testing are integral to the engineering design process. Engineers build prototypes to assess the functionality, performance, and feasibility of their designs.
Innovation and novelty	Both processes are focused on generating innovative and novel solutions. Creativity involves thinking beyond conventional boundaries to create something new and unique.	Engineers aim to develop innovative solutions to technical challenges. The engineering design process often involves seeking novel approaches and technologies.

5. Creativity's rise to prominence: High level and school level strategies

The emphasis on creativity as an essential skill has increasingly permeated educational systems globally. In over 20 educational jurisdictions, including Australia, Canada, Finland and South Korea, creative thinking is now considered a fundamental component of successful learning and has been integrated into various national curricula (Taylor et al., 2020). The case for intentionally teaching and assessing creativity has been well constructed, and the question about how to do it (rather than whether to do it) is now the greater focus in thinking about creativity. A hypothesis of this report is that engineering may be able to learn from policy and practice developments with regards to creativity in schools.

In this section, we outline some key drivers of creativity's achieved of this prominence in recent years. First, at the high-level though such means as advocacy and research. Then, at a more school-level through 'creative leadership'.

High level levers for curriculum change

A number of initiatives, globally and nationally, have contributed to the enhanced appearance of creativity and creative thinking as desirable outcomes of education in an increasing number of jurisdictions and schools. These can be categorised as: global advocacy, global curriculum and progression, global assessment, global research, national advocacy, and school-level innovation:

Global advocacy

For creativity, this has been a combination of influential bodies, whose prioritisation of creativity in frameworks and assessments is tilting the focus in educational jurisdictions globally. A growing number of international bodies are explicitly including creativity as part of the curriculum. The World Economic Forum (WEF, 2015, see **Figure 7**), is illustrative of this, including it as one of four competences (although really three in practice as creativity and critical thinking overlap considerably).

The Brookings Institution (Care et al., 2016, see **Figure 8**) has been tracking the spread of creativity in curricula across the world and shows how 21 educational jurisdictions have included it in their national or State curriculum.

Recently a new organisation, the Global Institute of Creative Thinking (GIoCT), is acting as a catalyst to bring together educators across the world. GIoCT (n.d.) imagines a world where 'creative thinking is not just an asset but a universal language, bridging cultural, educational, and professional gaps to solve humanity's greatest challenges'. Three specific initiatives are designed to heighten awareness of the importance of creativity in schools:

1. A global award scheme – recognising individuals and organisations at the forefront of embedding creative thinking in teaching and learning;
2. An annual awareness raising week promoting the importance of creativity in schools, held in the second week of October; and
3. A professional learning framework, commissioned from the Organisation for Economic Cooperation and Development (OECD, 2023b).

As part of its work, GIoCT commissioned an analysis of progress in embedding creative thinking/creativity in schools (Lucas, 2022a, see **Figure 9**).The research breaks down progress into five sub-headings which may contain the seeds of ideas for those interested in engineering – status, curricula, culture, curriculum design and pedagogies, assessment and professional learning.

GIoCT has also begun systematically to harvest case studies from which schools across the world could draw inspiration.

Similarly, the OECD (2023a) has also compared jurisdictions on their integration of creative thinking in education, based on a number of key activities, including the content of the jurisdiction's guidelines for initial teacher training, support mechanisms for schools, curriculum content, and system-level

Figure 7:
Creativity as one of four competencies. (World Economic Forum, 2015)

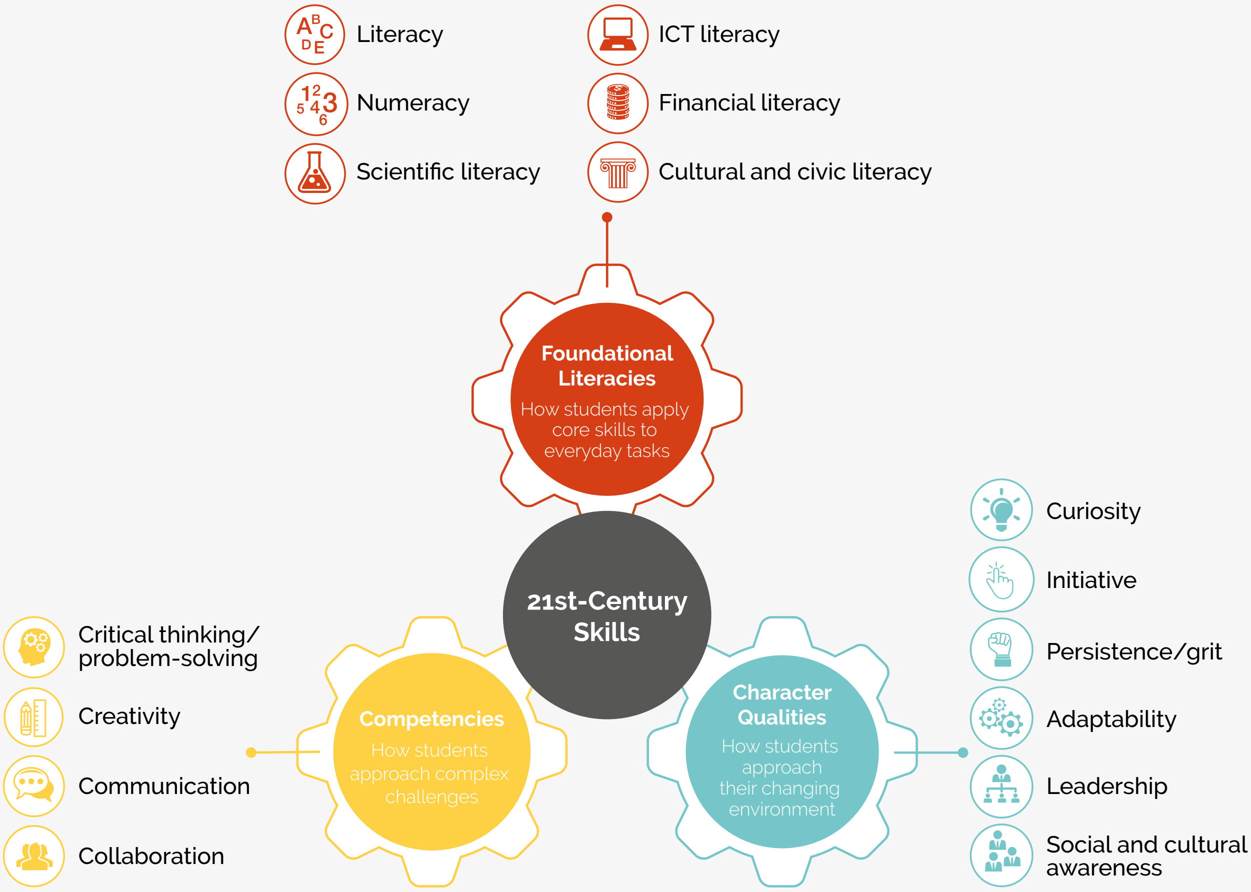
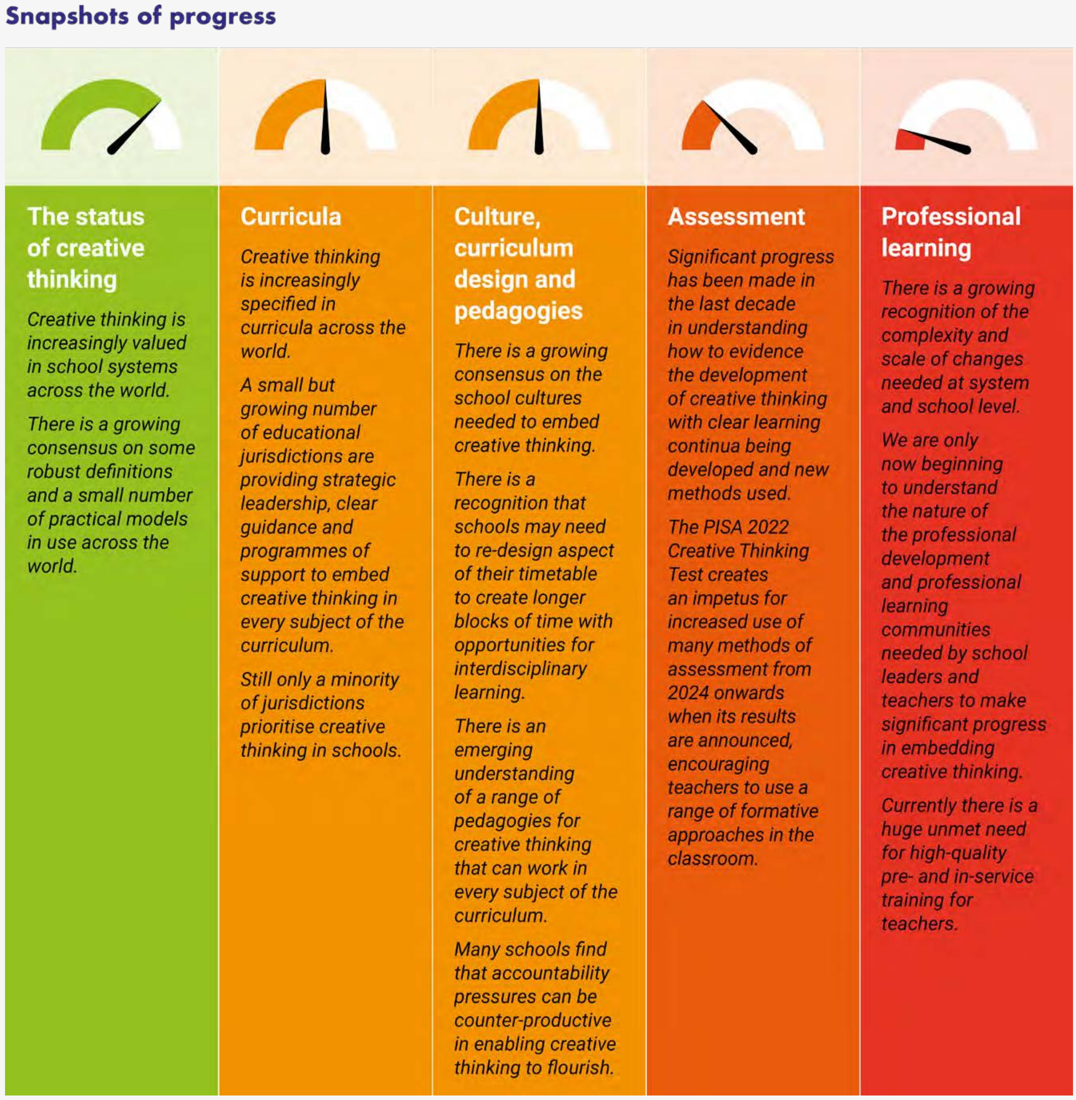


Figure 8:
Creativity's appearance in national or State curricula (Care et al., 2016)

	Competency	Inclusion	Identification	Progression	Pedagogy	Assessment
Skills	Creativity	21	12	5	0	0
	Critical thinking	21	11	6	0	0
	Communication	22	11	5	0	0
	Collaboration	21	10	6	0	0
Character	Mindfulness	17	10	5	0	0
	Curiosity	17	7	3	0	0
	Courage	9	5	5	0	0
	Resilience	15	8	6	0	0
	Ethics	18	10	4	0	0
	Leadership	10	7	4	0	0
Meta-learning	Metacognition	14	7	5	0	0
	Growth mindset	14	6	5	0	0

Figure 9:
Progress in embedding creative thinking in schools (Lucas, 2022a)



guidelines for assessing creativity (OECD, 2023, see **Figure 10**).

With these organisations highlighting the importance of creative thinking, governments are influenced, and even compelled, to consider how they can integrate this skill into their educational policies. This advocacy demonstrates the potential impact of influential bodies in shaping national curricula and underscores the importance of essential competencies for the future workforce. This approach can serve as a valuable model for engineering organisations aiming to promote engineering thinking, showcasing how strategic focus and international support can drive educational and policy reforms.

Global curriculum and progression

In Australia, the Australian Curriculum, Assessment and Reporting Authority (ACARA), the Victorian Curriculum and Assessment Authority (VCAA), and the Foundation for Rural and Regional Renewal (FORM) have undertaken significant initiatives to design creativity-led curricula and progression frameworks. ACARA has incorporated creative thinking into the national curriculum, emphasizing its importance as a general capability that should be developed across various subjects (ACARA, n.d.).

The VCAA has contributed by developing detailed guidelines and resources to support educators in integrating creative thinking into their teaching practices, ensuring that students can engage in creative problem-solving and innovative thinking (Victorian Curriculum and Assessment Authority, 2020).

Figure 10:
The OECD's criteria for comparing jurisdictions on their integration of creative thinking into education (OECD, 2023)

A	Do guidelines for initial teacher training for secondary education reference…
B	Does your jurisdiction provide the following support mechanisms to teachers and schools to help foster students' creativity?
C	Share of school subjects that reference creative thinking in secondary education curricula
D	Does your jurisdiction have system-level guidelines or evaluations to assess students' creativity?

Yes   No   Currently in development   Not applicable   Missing information

A		B			C	D
Developing students' creativity	Assessing students' creativity	Professional development for teachers on developing students creativity	Funding to run creative programmes/ projects	Organised visits to/from creative practitioners (e.g. designers, poets, performers, engineers)	(Subjects that reference creativity / subjects for which information is reported)	Assessment guidlines/ evaluations

FORM, a cultural organization dedicated to enhancing creativity and cultural development in regional areas, has collaborated with schools and communities to implement creativity-led programs and frameworks, fostering an environment where creative skills are nurtured and valued throughout students' educational journeys. They have paid particular attention to assessing creative thinking (Lucas, 2022b).

These efforts collectively aim to embed creativity deeply within the educational landscape of Western Australia, preparing students for the challenges and opportunities of the future.

The pioneering work of these Australian bodies in integrating creativity into curricula can serve as a valuable model for English engineering organisations aiming to promote engineering thinking. Their successful strategies in embedding creative skills across educational frameworks highlight effective approaches for incorporating engineering principles into learning environments. By studying these Australian examples, English organisations can gain insights into designing comprehensive programs that foster innovative problem-solving and critical thinking, essential for engineering education.

Global assessment

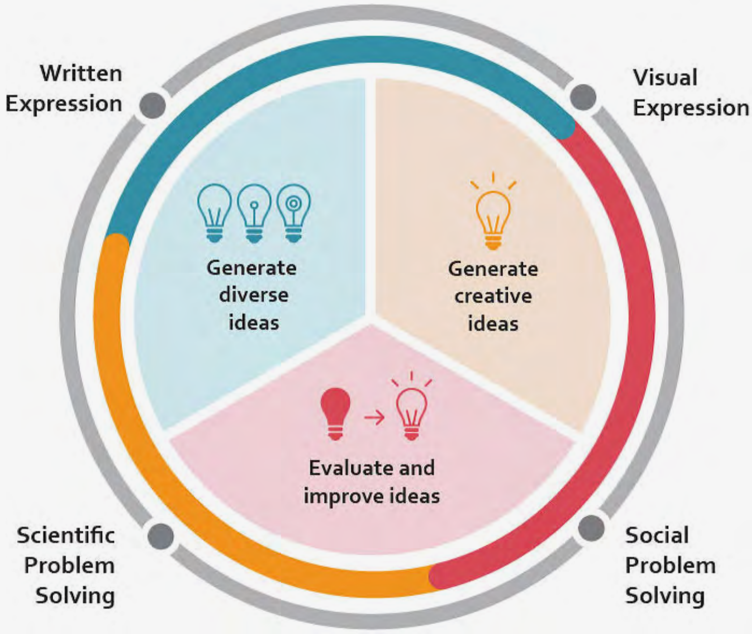
In 2022 the Programme for International Student Assessment (PISA) ran the first ever test of Creative Thinking (PISA, 2019; p. 23, see **Figure 11**). The Creative Thinking Test seeks to clarify not just the elements of creative thinking – generating diverse ideas, generating creative ideas and evaluating and improving ideas – but also to suggest two domains in which they might be embedded and two modes through which they might be expressed.

PISA's decision to select Creative Thinking as the focus of a new test signals to the educational world that creativity and creative thinking are important, and that the area is robust enough for it to be taught and assessed reliably.

This innovative trial has potential to influenced global education policies significantly by demonstrating that these skills are definable, desirable and measurable. By incorporating this assessment into PISA, the OECD has provided a robust framework that validates the importance of creative thinking alongside traditional academic subjects. This initiative has encouraged countries to recognise creative thinking as a critical competency, deserving of a prominent place in national curricula and worthy of systematic evaluation. The success of this innovative assessment has paved the way for educational systems worldwide to value and prioritize the development of creative and critical thinking skills in their students.

PISA has decided to use the occasion of the Test as an opportunity to highlight the benefits of creative thinking (OECD, 2022) and, at a system level, the barriers perceived by educational jurisdictions (OECD, 2023a). The ensuing country rank order from these tests, in descending order – Singapore, Korea, Canada, Australia, New Zealand, Estonia, Finland, Denmark, Latvia – (OECD, 2024) have immediately raised questions in schools minsters' minds across the world along the lines of 'how did we do so well?' and 'why did we not do as well as…?'. Such pressures can sometimes be helpful especially when, on closer examination, it turns out that those countries which have systematically highlighted the importance of

Figure 11:
PISA Creative Thinking Test
(PISA, 2019)



creativity and invested in its development in schools did very well.

English engineering bodies could leverage the OECD's pioneering idea of assessing creative and critical thinking to promote engineering thinking. By advocating for the inclusion of engineering problem-solving and critical thinking skills in national assessments, they can underscore the value of these competencies. This approach would not only elevate the status of engineering education but also ensure that pupils are equipped with the essential skills needed for the engineering challenges of the future.

Global research

In 2019 the OECD's Centre for Innovation and Research and Innovation (CERI) published the results of a four-year, eleven country study into the teaching and assessing of critical and creative thinking, (Vincent-Lancrin et al., 2019). It had worked with an international network of 319 schools over two years of fieldwork and data collection, and interventions within schools aimed to help teachers provide pupils with opportunities to develop their critical and creative thinking through lesson plans, pedagogical activities and assessment rubrics.

Initially stimulated by the CRL's model of five creative habits, the OECD's research showed how creativity can be embedded and assessed in a wide range of subjects and developed a large number of practical tools and resources which are freely available to teachers.

The Australian Council for Educational Research (ACER) has developed a model of Creative Thinking which has three strands – Generation of ideas, Experimentation and Quality of ideas (Ramalingam et al., 2020; p. 6, see **Figure 12**). Each strand has two or three more specific aspects.

National and State advocacy

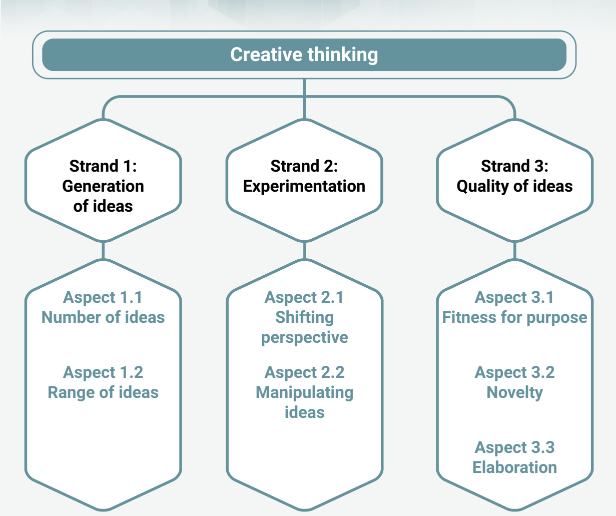
Creative Schools, Western Australia

In Western Australia, the Creative Schools (Creative Schools, n.d.) learning programme developed by FORM brings together teachers and creative professionals to use creative teaching and learning strategies that cultivate pupil agency, and engage them in deep learning of the Western Australian curriculum, the General Capabilities and the Five Habits of Learning (the five creative habits of Lucas and Spencer's (2017) *Teaching Creative Thinking*). Demand for the programme is growing, and has reached hundreds of schools across Perth.

Lead Creative Schools Scheme, Wales

In Wales, the Lead Creative Schools Scheme (Arts Council for Wales, n.d.) offers a similar opportunity for teachers to work with creative professionals (from sectors including the arts, creative industries, sciences, heritage, and others) to explore creative approaches to teaching and learning.

Figure 12:
ACER Creative Thinking Skills Framework (Ramalingam et al., 2020)



Creativity Collaboratives, England

Closer to home the Durham Commission on Creativity and Education has acted as a national focus for creativity in schools in England and the creativity agenda has benefitted greatly from the status and funding that has emerged since and due to the Durham Commission's series of reports and recommendations. The Commission was a joint research collaborative between a research university (Durham) and the national development agency for creativity and culture (Arts Council England). As publicly funded and academic organisations, the Commission's recommendations carried weight. The Commission took various actions through its reporting, including:

- Making a strong case for the value of creativity.
- Investigating where creativity sits in the education system currently.
- Summarising efforts that had gone before it.
- Making 10 actionable recommendations aimed at changing practice through:
    1. Establishment of collaborative school research networks, and their connection to higher education research partners, and the DfE.
    2. Considering the role of public examinations and qualifications frameworks in valuing creativity.
    3. Embedding creativity's recognition in the school inspection framework.
    4. Making England take part in international evaluations of pupil creativity.
    5. Connecting higher education institutions with collaborative school research networks comparisons.
    6. Funding digital training.
    7. Prioritising arts and culture in the curriculum.
    8. Teaching for creativity in the early years.
    9. Aligning external youth organisations with the agenda to ensure provision.
    10. Aligning qualifications frameworks with the needs of the workforce.

It has been a means of focusing political, educational attention, and led to evaluated, scalable interventions trialled at the school level. Its definitions of creativity, creative thinking, and teaching for creative thinking (Durham Commission, 2019), have enabled a new generation of teachers to act with greater confidence and precision. Most importantly the Commission's first recommendation – the establishment of a national network of Creativity Collaboratives, a model of research and professional development in which schools collaborate with research institutions in establishing and sustaining the conditions required for nurturing creativity in the classroom, across the curriculum – has been achieved. Eight Creativity Collaboratives in every region of England have been funded for three years to explore what works best. Externally evaluated by Durham University, the Creativity Collaboratives are already generating practically useful resources and know-how.

In the final stage of its first three years' funding, Collaboratives have been focusing on ensuring the sustainability of the work and have been awarded funding for two further years to ensure that momentum is continued. Through this research, the pursuit of a solid way to turn ideas into reality has led to development of approaches that focus on creative habits in combination with the creative process (Sowden et al, 2023). Effective teaching practice here involves using the creative process as a testbed in which to strengthen creative habits. In a similar vein, the work of Bianchi and Wiskow (2023) argue that schools "need to develop progression frameworks for the engineering or creative habits of mind they are seeking to cultivate". The authors' progression framework combines engineering habits and the engineering process (see Appendix 3.).

Leading for Creative Thinking, England

Part of transforming research into practice involves focusing school leadership on the task. In a parallel development Leading for Creative Thinking (n.d.), a new web community, has been developed specifically to support school leaders who wish to put creativity at the heart of their schools. *Leadingforcreativethinking.org* (n.d.) was developed to facilitate a global learning community for school, system, and teacher leaders. Its genesis was work carried out for The Mercers Company, and then with the support of Creativity, Culture and Education, to understand the key actions creative leaders undertake. The full set is:

1. Consider the change process
2. Develop leaders
3. Change the culture
4. Rethink structures
5. Develop a creative curriculum
6. Rethink pedagogy
7. Track progression in creativity
8. Ensure professional learning
9. Collaborate with external partners
10. Reflect and evaluate.

Engineering habits and the engineering process need to be brought into focus in each of these areas of school life.

For example, 'rethink pedagogy' will involve split screen teaching, where teachers plan for units of work, across the full range of subjects, that embed the design process or design thinking into units of work. Units are designed as opportunities to solve problems, where pupils find and use the knowledge and skills they need to work through a design to produce work and/or arrive at solutions that meet success criteria.

'Develop a creative curriculum' might involve mapping existing and potential opportunities for engineering thinking and habits onto the current curriculum. It might involve thinking about cross-curricular projects.

'Track progression in creativity' will certainly require experts in engineering to think through what progression in engineering looks like in all subjects.

Creativity Exchange, England

To support the Collaboratives and spread ideas more widely, a new website, Creativity Exchange (n.d.), was launched in 2022 as an online space where busy teachers can find ideas which have been successfully used by other teachers to adapt for their own contexts. Bolton School is just one of many examples of a school not in the Collaboratives which has nevertheless become a beacon of excellence in the North-West of England.

Rethinking Assessment, England

Meanwhile the Rethinking Assessment movement in England (Lucas, 2021; Rethinking Assessment, n.d.) has been gathering momentum. A specific recommendation is that all young people should leave school with a digital learner profile as a means of valuing their wider strengths, including dispositions such as creative thinking (Rethinking Assessment, n.d., see **Figure 13**). This is in line with the All-Party Parliamentary Group for Schools, Learning and Assessment's (APPG for Schools Learning and Assessment, 2023) recommendation, that a study of digital learning profiles be conducted to evaluate their use at primary and secondary levels of schooling.

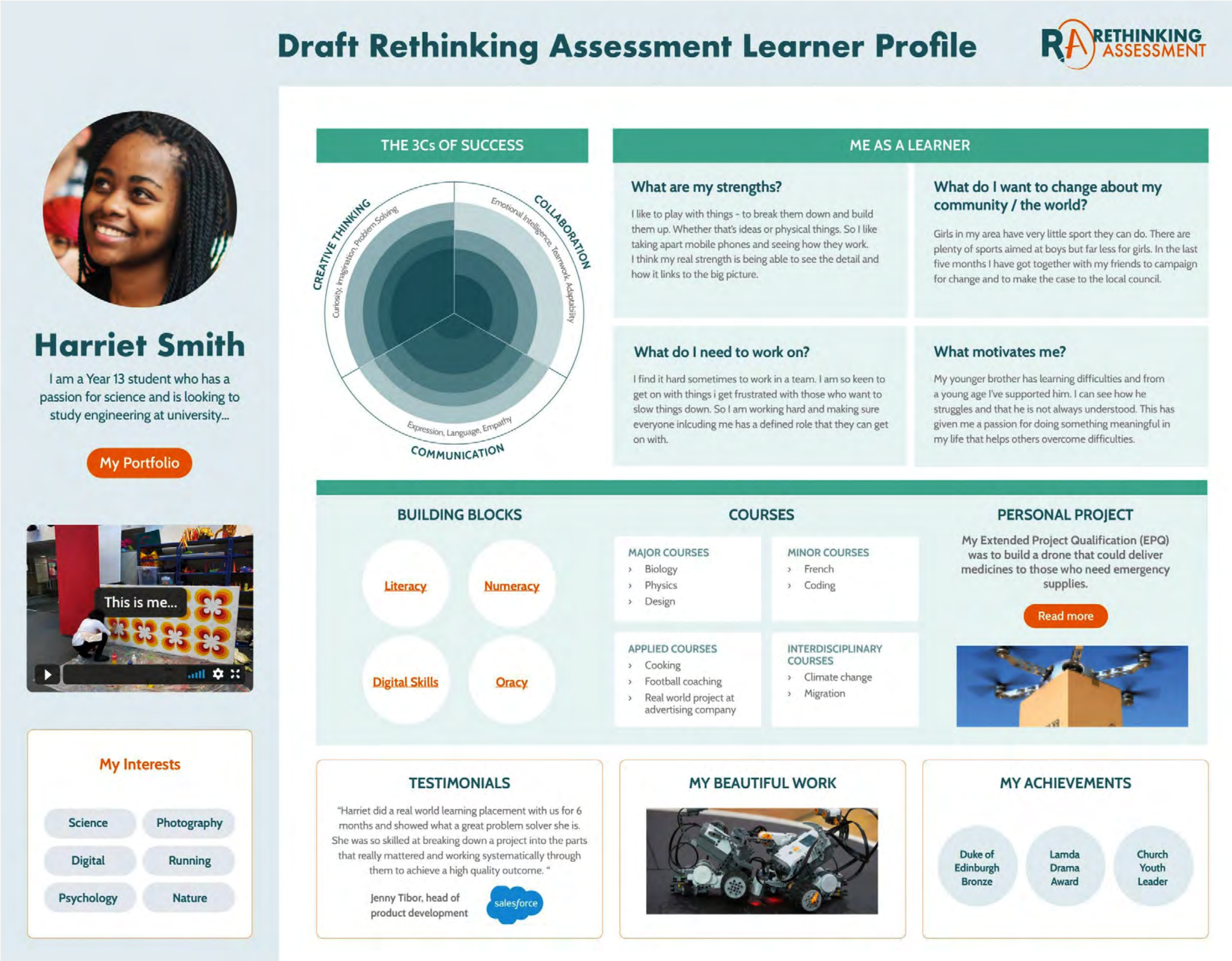
A specific element of the profile is designed to provide a space for showcasing young people's creative thinking as one of 3Cs (also including collaboration and communication). A small-scale exploratory study (Krstic, 2024) undertaken by Rethinking Assessment recently found that, despite the constraints of the English National Curriculum, with support from school leaders and professional development for teachers, it is possible to embed creative thinking in a number of subjects and evidence the progress made by young people.

Interestingly there are some little used examinations – the Higher Project Qualification (HPQ) (UCAS, n.d.) – which are already available to schools. These count as half a GCSE and are a potential entry point for schools wishing to assess projects with engineering or creativity at their heart.

Political changes in England, as well as potential changes to Ofsted and a move away from one word/phrase judgments, the possible freeing up of choice within EBacc and the plethora of recent reports advocating for creativity in schools offer practical ready-made possible solutions for policymakers.

Similar strategies could be adopted to advance the inclusion of engineering habits across compulsory education. For instance, a dedicated commission could be established to research and advocate for the integration of engineering principles into the curriculum, similar to the Durham Commission's work on creativity. Pilot programs, akin to the Creativity Collaboratives, could be implemented in clusters of schools to explore practical approaches for embedding engineering thinking in teaching practices. Additionally, organisations like Rethinking Assessment and exam boards could be approached to trial approaches to assessing or promote case studies on engineering skills, ensuring that these competencies are recognised and valued within educational assessment frameworks.

Figure 13:
Rethinking Assessment prototype learner profile (Lucas, 2021)



School-level innovation

Recognising the value of creativity to their pupils' lives, pioneering schools have taken the bold approach of experimenting with methods to promote and develop it. These schools have often been the home of promising practices, and are the ones who involve themselves in subsequent national initiatives and projects. For example, in 2012, when the Centre for Real-World Learning was commissioned by Creativity, Culture and Education to develop a progression framework for creativity, it was some of these schools (listed in Spencer et al., 2012) that provided a testbed for early iterations of the 5-habit creativity wheel.

This type of 'grassroots' change in practice happens as teachers experience the benefits of teaching for creativity, and mentor others to do the same. Brave leadership is essential, and these schools exemplify a proactive stance towards educational innovation.

Schools that serve as early adopters and pioneers in innovative educational practices present valuable opportunities for engineering bodies to collaborate and trial approaches to teaching for creativity. By partnering with these forward-thinking schools, engineering bodies can engage in collaborative efforts to develop and implement teaching methodologies that foster creative problem-solving and critical thinking skills among students. Furthermore, by leveraging the best practices identified in these institutions, engineering bodies can promote effective strategies for integrating engineering thinking into the educational landscape, ensuring that students are well-prepared to tackle the complex challenges of the future.

School level creative leadership

Advocates for creativity have recognised that curriculum, curriculum design, pedagogy, assessment and school accountability systems are all closely connected: change the assessment regime and pedagogies are likely to alter, too. Change accountability priorities and curricula will move to reflect this. But with concepts such as engineering and creativity the challenges are much greater than with single disciplines such as, say, science or music.

For many teachers, a first challenge is to understand what creative or engineering habits could involve. Then there will be the question of how habits should integrate within subjects. This leads to consideration of pedagogies, processes and assessment methods. And finally there will be the issue of continuous professional development and learning to develop the skills of teachers.

Change occurs when high-level advocacy is paired with practical efforts within schools. Leaders must consider the specific, detailed changes required for their particular school context.

The centrality of the curriculum

School timetables remain the clearest indicator of what counts within any individual school. How many lessons are allocated to each subject, how long such lessons last, where they are timetabled and who is selected to teach them says much about a school's priorities with regards to setting its curriculum.

But curriculum can all to easily become an abstract concept when in reality it is a much more organic and complex set of interactions between syllabus, teacher confidence and expertise, and pupils, with complex decisions to be made whenever new content or processes are introduced.

Cultivating habits of mind appropriate to creativity and engineering befits from a four-step process (see **Figure 14**):

- **Step 1** – This requires teachers to imagine both what the habit is and how it might manifest itself within subject disciplines
- **Step 2** – Strategies will include curriculum design, pedagogies and design processes, assessment and professional learning
- **Step 3** – Culture in schools exists at the school and classroom/workshop/lab level and is, arguably, the most important of these inter-connected steps. The key issue to explore is the degree to which the culture facilitates the cultivation of creativity and/or engineering and the required range of subject discipline knowledge and skills
- **Step 4** – Developing commitment will require consideration of the role of pupils in their learning, the kinds of feedback and assessment and the degree to which the school explicitly and intentionally prioritises the habits.

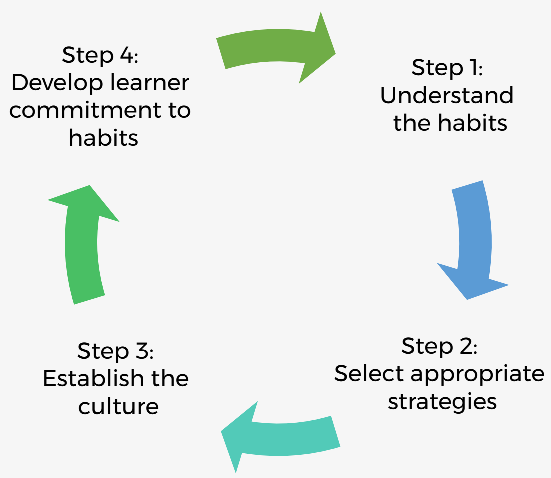
Step 1: Understand the habits

While teachers have a sound grasp of the content knowledge of their own subject, few may have stopped to consider the habits associated with these. How thinking like an engineer helps pupils to lift their gaze above individual subjects such as physics and maths and see the world through the eyes and ears of an engineer. Habits of mind (and body) for creative thinking and engineering thinking are both topics that will require specific in-service teacher development as well as, ideally, pre-service.

Teacher education for engineering

Engineering education needs to change to respond to new technologies, demands for more creative and problem-solving graduates, larger undergraduate classes, and a more complex relationship between engineering, society and the environment (Mackechnie & Buchanan, 2012). But the teaching of engineering is necessarily complex. The engineering design process, for example, needs to be understood clearly: it's not a hard science (controlled experimentation) but is iterative; the 'process' (not simply 'product') aspect is critical, and it is what requires the thinking habits such as problem solving and creative thinking.

Figure 14:
A four-step process of cultivating habits in engineering and creativity (based on Lucas & Spencer, 2017)



Best practice in teacher training from a systematic review (Hanson et al., 2022; p. 1,472) suggests several elements of professional development programmes:

- Provide real-world examples that develop understanding of engineering
- Promote interaction between teachers and professional engineers
- Emphasise learner-centred pedagogies that focus on asking questions not providing information
- Give teachers hands-on experience of designing lessons
- Have them teach a lesson in class to children.

Step 2: Select appropriate strategies

If teachers want to embed creativity or engineering into the curriculum, there are a number of areas they will need to consider. These can be categorised as

- broad principles, or concepts that influence decisions about what, when, and how to teach
- broad strategies or practices (which we also call 'signature pedagogies')
- tools and techniques that are used in the classroom.

It may be helpful to lay out these distinctions, because the reality is that the term 'pedagogy' is often used in different ways. Teachers typically plan lessons based on specific teaching strategies rather than broad educational philosophies like constructivism (which is one such use of the word 'pedagogy'). Strategies such as problem-based learning, modelling, and collaborative working offer concrete guidelines that teachers can easily visualise and implement.

More helpfully specific than 'pedagogy'; 'signature pedagogy', a term coined by Shulman (2005) refers to the set of distinctive teaching methods used in various professional disciplines. We think the term is a useful one to use specifically at the broad strategy level. We previously mapped five signature pedagogies onto the five creative habits, suggesting that these serve as umbrella terms representing a broad range of possible tools / techniques that could be employed to develop creative thinking (Lucas and Spencer, 2017). These five signature pedagogies are shown in **bold black** in **Table 7**.

This more tightly defined use of signature pedagogies is contrasted with the OECD's own list (Vincent-Lancrin et al., 2019), which collates examples that might be better described as anywhere from a pedagogy (Montessori education) to a broad principle (metacognitive pedagogy), to a broad strategy (creative partnerships, project-based learning, research-based learning, or studio thinking), to a tool or technique (dialogic teaching).

We discuss the concepts of 'principles', 'strategies' and 'tools' further in the section 'A joint framework for thinking about teaching engineering and creativity'.

Step 3: Establish the culture

To incorporate creative thinking and engineering habits into the curriculum successfully, school leaders play a pivotal role in establishing and nurturing the culture (Lucas et al., 2023). Their vision, commitment, and actions set the tone and direction for the adoption of values and practices that encourage creativity and innovation.

A supportive culture conducive to development of these habits should value and encourage innovation, experimentation, and the open exchange of ideas. It is essential for teachers to foster an environment where pupils feel safe to take risks, make mistakes, and learn from them, which are fundamental aspects of both creative and engineering processes. Teachers, in turn, need to benefit from this sort of environment themselves, which is the leaders' role.

In addition, schools should emphasise collaboration and interdisciplinary learning, as these approaches help pupils see connections between different subjects and apply their knowledge in holistic and innovative ways.

Several key changes and considerations are necessary to cultivate this kind of educational environment:

- **Professional development** Teachers themselves need ongoing training and resources to understand and implement signature pedagogies effectively. This includes workshops, seminars, and collaborative planning sessions focused on creative and engineering thinking.
- **Curriculum flexibility** The curriculum should allow for flexibility and creativity in teaching methods and assessment, enabling teachers to apply signature pedagogies according to the needs of their students and the specific challenges of their subject matter.
- **Resource allocation** Recognising that resources are scarce in state schools, there is a need for certain resources, such as materials for prototyping, access to technology, and spaces designed – or repurposed – for collaborative work, to support the active and hands-on learning experiences central to these pedagogies.
- **Community and industry partnerships** Establishing connections with local industries and

Table 7:
A joint framework for thinking about teaching engineering and creativity

Pedagogies	Learning elements highlighted by these philosophies	Broad principles / concepts educators may value	Broad strategies or practices ('signature pedagogies')	Tools and techniques
Constructivism Cognitivism Experiential learning theory Behaviourism Social learning theory Multiple intelligences theory Montessori education	*How the mind works*	Practical learning Developing metacognition Planning for 'split screen' thinking[1] Playing the 'whole game'[2] Pupil ownership Making thinking 'visible'[3] Challenging work Meaningful problems Opportunities for reworking Open ended tasks Time and space to reflect Habit-led culture Risk taking	Promoting a **growth mindset** **Deliberate practice** **Problem-based learning**[4] ***Interdisciplinary learning to integrate habits within subjects*** Extended projects STEAM education[5] Inquiry-based activities[6] Possibility thinking Research-based learning Discovery learning	Drafting Concept mapping[7] Posing good questions Dialogic teaching[8] Socratic questioning[9] Digital Art Tools[10] Coding Platforms[11] Math and science simulations[12] Research databases[13] Data collection tools[14] Interactive whiteboards[15]
	The role of social interactions	Socialising learners within communities of practice Developing communication Practising collaboration / sharing the product or idea Taking 'beautiful risks'	Modelling Collaborative working Authentic assessment ***Working with expert partners***[16] **Classroom as a learning community**[17]	Group discussions Peer-to-peer teaching Risk taking Peer mentoring Work experience Collaborative projects Collaborative tools such as digital platforms[18] Presentation software[19]
	The role of experience for learning	Hands-on learning as an important part of the learning process Real-world problems[20] to which to apply knowledge, and critical thinking about that knowledge Studio thinking[21] Planning for the unplanned	Project-based learning ***Design thinking*** ***The engineering design / creative process*** ***Playful experimentation*** **Playful experimentation**	Lab-based practicals Simulations Iterative design process Play / tinkering Drafting Re-thinking Manipulatives and hands-on prototyping materials[22]

1 ‘Split screen’ thinking aims to develop disciplinary knowledge while also developing critical capabilities and meta-cognitive skills essential to creative thinking or engineering thinking. The idea behind it is that the capabilities, or habits, developed are necessary both for engaging with the content and thriving in the world.

2 The ‘whole game’ is David Perkins’s concept used as a metaphor to describe the kinds of holistic learning we should provide pupils with in order to develop their thinking and ability to transfer learning to new contexts.

3 Visible thinking is Harvard University’s Project Zero’s (Harvard Graduate School of Education, n.d.) approach, which has identified a number of ‘thinking routines’ to help pupils develop creative thinking.

4 PBL is a dynamic classroom approach in which students actively explore real-world problems and challenges and acquire a deeper knowledge. By working on projects that cross subject boundaries, students can apply creative thinking and engineering skills to develop solutions for complex problems, thereby enhancing their understanding and abilities in both areas.

5 The combination of science, technology, engineering, arts, and maths into the concept of STEAM is an interdisciplinary educational approach to learning that uses these fields of knowledge as access points for guiding student inquiry, dialogue, and critical thinking. This pedagogy naturally integrates creative habits (through arts) and engineering habits (through technology and engineering) into all subjects.

6 Inquiry based activities involves teaching methods that are built around inquiring minds, which is the practice of posing questions, problems or scenarios—rather than simply presenting established facts or portraying a smooth path to knowledge. Students learn by doing, which nurtures both creative and engineering habits as they must design experiments, solve problems, and apply their learning in creative ways.

7 Visual representations that allow students to organise and structure their knowledge.

8 Dialogic teaching is an educational approach that emphasises dialogue and discussion as a fundamental component of the learning process. It involves interactive teaching strategies that encourage students to engage in dialogue, offering ideas, asking questions, and discussing various perspectives to deepen understanding and critical thinking. This method values the use of open-ended questions, collective problem-solving, and a shared inquiry among students and teachers, aiming to create a more dynamic and reflective learning environment. Jonathan Haidt’s Constructivedialogue.org Constructive Dialogue Institute. (n.d.). High Schools. constructivedialogue.org. Retrieved 1 May from https://constructivedialogue.org/high-school offers professional development to help teachers facilitate dialogue.

9 Socratic questioning is for form of dialogic teaching that is narrowly focused on leading students to uncover contradictions in their thinking and guiding them towards clearer, more refined thoughts through carefully crafted questioning by the teacher. In contrast, dialogic teaching involves a broader range of dialogue and interaction that is not solely led by the teacher but also involves significant contributions from students, fostering a more collaborative and less teacher-centered environment. Both approaches aim to enhance critical thinking and deeper understanding through dialogue.

10 Digital art tools might include software such as the Adobe Creative Suite or online platforms like Canva to integrate art and design.

11 Coding platforms include tools like Scratch or Tynker to integrate technology and engineering through coding projects.

12 Maths and science simulations, e.g. online resources like PhET Interactive Simulations or StarLogo Nova to explore scientific and mathematical concepts dynamically.

13 Research databases include access to online journals, books, and other scholarly materials to support inquiry.

14 Data collection tools such as sensors, lab equipment, or digital data logging tools to gather and analyse data.

15 Interactive whiteboards to facilitate dynamic discussions and sharing of ideas in real time.

16 The OECD (Vincent-Lancrin et al., 2019) identified some ‘signature pedagogies’ for developing creative thinking, including ‘Creative Partnerships’, which involves teachers working with expert practitioners to deliver lessons.

17 Classroom as a learning community is where the classroom is structured as a collaborative environment that promotes mutual learning among students and between students and teachers. For developing creative or engineering thinking, it would emphasise idea sharing, peer-to-peer teaching, and collective problem-solving. By treating the classroom as a community, students are encouraged to engage actively, take risks in their thinking, and support each other’s learning. This cooperative atmosphere fosters creativity and innovation, as students feel empowered to explore new ideas and approaches together, leveraging diverse perspectives to tackle complex engineering or creative challenges.

18 Collaborative tools such as Google Docs or project management tools to facilitate group work and project planning.

19 Presentation software such as PowerPoint, Prezi, or video editing software to help students prepare and share their project outcomes.

20 Real-world problems make the ‘game’ worth playing; an important principle in David Perkins’s concept of ‘playing the whole game’ of learning.

21 Studio thinking is an approach derived from the teaching methods used in art studios, which focuses on cultivating creative and critical thinking skills through hands-on, experiential learning. It emphasises the iterative process of creating, critiquing, and revising work, encouraging students to engage deeply with their projects and persist through challenges. It typically involves open-ended tasks, peer collaboration, and self-reflection, allowing learners to explore different solutions, receive feedback, and refine their ideas continuously. The studio environment fosters a culture of experimentation, risk-taking, and innovation, essential for both creative arts and engineering disciplines.

22 Prototyping materials such as building blocks, science kits, or art supplies help students explore concepts actively. Supplies for creating models or mock-ups of project ideas, such as clay, cardboard, or digital design software.

the broader community can enhance real-world learning opportunities and mentorship in both creative and engineering disciplines.

- **Encouragement of a growth mindset** Cultivating a school-wide culture that encourages perseverance, curiosity, and a growth mindset is crucial for pupils to thrive under these signature pedagogies.

Step 4: Develop learner commitment

The best and most satisfying way of developing learner commitment is, of course, to teach in such an engaging and authentic way that pupils are hungry to learn. But, if creative thinking and engineering habits are to be valued in the curriculum, experience suggests that they will need to be assessed in some way: "what gets assessed tends to get done in schools" (Lucas, 2022b; p. 4). For most schools this will require extension of the repertoire of assessment practices to support, and reflect accurately, their educational goals.

While it is easy to accuse standardised testing approaches of prioritising rote memorisation, it is important to recognise that traditional methods can and do assess more complex cognitive skills. Written exam papers can require pupils to 'explain', 'reason', 'argue', 'analyse', and 'compare'. Nevertheless, these assessments may still face challenges in fully capturing the breadth of skills associated with creativity and engineering, such as 'solve problems', 'innovate', or 'adapt'.

Schools can, in combination with traditional approaches, implement more dynamic and formative assessment methods that encourage ongoing learning and reflection. These might include project-based assessments, portfolios, and peer reviews, which allow pupils to demonstrate their understanding and application of concepts in real-world contexts. There are a range of approaches, including pupil-led, teacher-led, real-world, and online assessment (Lucas and Spencer, 2017). Many of these assessments not only evaluate the final product but, critically, the process pupils undertake, including their ability to think critically, iterate designs, and work collaboratively.

We know that it is possible to assess habits, including creativity, as shown by PISA's adoption of creative thinking as its 'innovative domain' test in 2022. Several key changes and considerations are necessary in schools to align assessment practices with the teaching of creative and engineering skills:

- **Development of rubrics** Create clear and comprehensive rubrics that capture the diverse aspects of creativity and engineering projects, such as originality, complexity, functionality, and the ability to integrate feedback.
- **Continuous feedback** Shift from solely summative assessments to more formative, ongoing feedback mechanisms that help pupils understand their progress and areas for improvement throughout the learning process.
- **Integration of self and peer assessments** Encourage pupils to engage in self-assessment and peer assessment to foster a deeper understanding of their own learning processes and to develop critical evaluative skills.
- **Use of (digital) portfolios** Implement digital portfolios that allow pupils to document and reflect on their learning journeys, showcasing a range of projects and their development over time.
- **Flexibility in assessment timing** Allow flexibility in when assessments are conducted to accommodate the iterative nature of creative and engineering projects, where timelines might need adjustment based on project demands and pupil learning needs.

Most importantly of all, schools will want to develop progression frameworks for the engineering or creative habits they are seeking to cultivate. Appendix 1 shows examples of frameworks developed by Rethinking Assessment in an exploratory study in schools (Krstic, 2024) based on a simplified version of the CRL model. Appendix 2 reframes the creative habits as a pupil self-report tool. Appendix 3 shows a progression in engineering framework (Bianchi, 2023).

Schools using progression frameworks like this report on the significant shift in tone when the conversation moves on from 'measuring or assessing pupils' skills/habits' to 'evidencing progression in the development of their creative skills'.

By considering these changes, schools can develop assessment practices that not only more accurately measure pupil outcomes in creative thinking and engineering but also promote a culture of continuous learning and improvement. This alignment between pedagogy and assessment is crucial for the effective integration of creative and engineering habits of mind into the curriculum.

A joint framework for thinking about teaching engineering and creativity

Table 7 presents a preliminary framework, categorising pedagogies, principles, strategies, and tools based on themes emerging from literature, practice, research, and experience. We believe these are the most suitable approaches for fostering creative and engineering thinking. While a more comprehensive review may expand this framework, it serves as a foundational guide for teaching methods that effectively develop these types of thinking.

Pedagogy in its broadest, overarching sense is an underlying philosophy, or learning theory, that guides all these types of educational choice. It shapes the organisation of knowledge content, teacher-pupil interactions, and the values emphasised in the educational environment.

A teaching tool, or technique, then refers to individual methods or resources in the classroom to achieve educational goals. This could include drafting, group discussions, or digital learning platforms, to name just three. These tools and techniques are practical components chosen for their effectiveness in facilitating the learning process as defined by the overarching pedagogy.

Numerous theories and educational philosophies have been put forward about how people learn that may complement one another or provide alternative perspectives from which teachers can draw. Examples include constructivism, cognitivism, experiential learning theory, behaviourism, social learning theory, multiple intelligences theory, and Montessori education. These appear in the left in **Table 7** and can be summarised as follows, citing individuals when predominantly associated with that person:

- **Constructivism** is an educational philosophy that views learning as an active, constructive process, where learners build new knowledge upon the foundation of previous understandings. As an overarching pedagogy for teaching creativity and engineering thinking, constructivism emphasises the importance of learners actively engaging with and manipulating their environment to solve problems and create new products or systems. This approach supports the use of tools and techniques such as problem-based learning, collaborative projects, and inquiry-based activities, which require pupils to hypothesise, experiment, and iterate, which can foster both creative and engineering skills. By encouraging pupils to explore, question, and discover, constructivism nurtures an environment where learners are not passive recipients of information but active creators of their knowledge.
- **Cognitivism**, as an overarching pedagogy, can also provide a framework for developing educational tools and techniques aimed at fostering creativity and engineering thinking. By emphasising the mental processes involved in learning, such as perception, memory, and problem-solving, cognitivism encourages the design of teaching strategies that enhance learners' ability to process information deeply, make connections, and apply knowledge in novel ways. Techniques derived from this approach, such as concept mapping, scaffolded learning, and the use of thought-provoking questions, support the development of higher-order thinking skills. These strategies help pupils not only to acquire knowledge but also to understand how to apply that knowledge creatively and critically in different contexts.
- **Experiential Learning Theory**, as articulated by David Kolb (1984), serves as an effective overarching pedagogy for cultivating creativity and engineering thinking through its emphasis on learning through direct experience and reflection. This theory proposes a cyclical model of learning that includes concrete experience, reflective observation, abstract conceptualisation, and active experimentation. By engaging pupils in hands-on activities that require them to design, build, and test solutions to real-world problems, teachers can use experiential learning to enhance both creative and engineering skills. Tools and techniques such as project-based learning, simulations, and iterative design processes encourage pupils to innovate, reflect on their learning experiences, adapt their strategies, and apply theoretical knowledge practically, thus deeply embedding both creative and analytical thinking skills.
- **Behaviourism** focuses on observable behaviours and posits that learning is a result of conditioning and environmental interactions. Although traditionally associated with repetitive learning and reinforcement, behaviourism has some utility in teaching elements of creativity and engineering thinking by using systematic training and reinforcement techniques. Tools and techniques derived from this approach might include the use of step-by-step training modules, rewards for innovative problem-solving, and structured feedback systems to reinforce desired behaviours such as creative thinking and precise engineering skills. While behaviourism might seem less intuitive for teaching inherently explorative skills like creativity, it can be effective in establishing foundational skills and behaviours that support development of creative habits and engineering processes, such as persistence, attention to detail, and methodical experimentation.
- **Social Learning Theory**, developed by Albert Bandura (1977), emphasises the importance of observing, modelling, and imitating others within a social context as a primary mechanism of learning. Its principles support the use of collaborative environments where pupils can witness and replicate creative problem-solving and engineering processes demonstrated by

peers or teachers. Tools and techniques that align with this theory include group projects, peer-review sessions, and mentoring, where learners can observe and discuss various approaches to creative and technical challenges. This exposure not only helps pupils acquire specific skills but also encourages them to adopt behavioural and cognitive strategies that foster innovation and technical proficiency, enhancing their ability to think creatively and apply engineering principles effectively in group settings.

- **Multiple Intelligences Theory**, proposed by Howard Gardner (1993), suggests that individuals possess different types of intelligences, such as spatial, logical-mathematical, linguistic, bodily-kinesthetic, musical, interpersonal, intrapersonal, and naturalistic. In the context of developing creativity and engineering thinking, this perspective suggests that teaching methods can benefit from incorporating diverse approaches. For example, using visual aids and models can support spatial thinking, problem-solving activities can foster logical-mathematical skills, collaborative projects can engage interpersonal dynamics, and hands-on experiments can encourage active learning. By incorporating a variety of instructional strategies, educators can create more engaging learning experiences that help pupils build creativity and engineering skills, while drawing on their diverse capabilities, leveraging their natural strengths, as well as developing those skills and methods of learning they could also benefit from.
- **Montessori education**, developed by Maria Montessori (1912), could be categorised as a pedagogy because it encompasses a comprehensive educational approach, which includes specific principles, practices, and educational strategies designed to foster learning. Unlike a broad principle such as growth mindset, which is a general belief about the nature of ability and learning, Montessori education provides a detailed framework for how education should be conducted. This framework includes a prepared environment tailored to children's needs, self-directed learning activities, and educational materials designed to support hands-on learning and discovery. Montessori education also emphasises respect for each child's individual pace of development, which aligns with its holistic approach to education. In contrast to a 'strategy' like problem-based learning, which can be applied within various educational theories and settings, Montessori education is a complete system of education with its own set of methods, materials, and philosophical underpinnings. It integrates multiple aspects of teaching and learning into a coherent whole, making it a distinct pedagogy rather than just a single strategy or principle.

These are some of the main the overarching pedagogies, but the demarcation between pedagogy and specific teaching techniques is often ambiguous, risking superficial comparisons between fundamentally disparate categories. Essentially, pedagogies provide theoretical foundations to inform the development of principles, strategies and tools to apply learning principles in educational settings.

To propose a framework for thinking about developing both engineering and creativity, we look first at how engineering is currently taught.

Teaching engineering today

Discussions about teaching methods for developing engineering habits often appear as lists, typically referred to as 'pedagogies' or their components. They are more accurately described as a mix of principles, strategies, and tools – as we use them in **Table 7** – however. One such example (Harrison, 2011; p. 24) claims "it may prove possible to identify something of 'an engineering pedagogy'…that might in turn include":

- Active learning
- Experiential learning
- Modelling
- Relating practice to theory (abstraction)
- And relating theory to practice (exemplification)
- Mathematical modelling
- 'Designerly behaviour'
- Business simulation / gaming
- Impact analysis (financial, environmental, social).

This set is no exception to the problem we mentioned earlier; that these lists usually consist of varied elements that do not directly compare, indicating a range of different teaching approaches rather than a unified teaching framework.

What is clear is that teaching for any engineering habit requires choice about teaching principles, strategies and tools. Teaching for any habit requires a logical set of considerations. Thus, the habit 'creativity' in engineering, for example, requires "aligning course content, instruction, assessments, and the environment towards creativity-focused learning goals" (Daly et al., 2014; p. 419) through the following steps:

1. Set clear learning goals – creativity is one; identify the other learning habits and their components.
2. Assess specific creativity skills and provide

feedback. These help both learners, by sending a clear message about the importance of creativity, and the teacher, by illuminating where additional support is needed.

3. Develop learners' understanding of what use of the creative habits looks like.
4. Plan specific desired results, learning, and assessment. (Daly et al., 2014).

Teachers thinking in this way avoid limiting their palette of strategies and tools to those that consider only single aspects of creativity, such as convergent thinking, found to be well represented in engineering courses at one particular university by Daly et al. (2014).

For example, a teacher wishing to develop engineering thinking might take the broad habit 'creative and critical thinking' and consider carefully what sort of activities might develop the creative thinking aspect, and which the critical thinking aspect. Breaking the habit down like this, teachers might identify a requirement for activities that help learners practice explaining unexpected results, formulating problems, selecting from among alternatives, analysing, critiquing, or grading, for example (Brent & Felder, 2014). The brief for an exercise practising grading, for instance, might read: "a student who took this course last year submitted the attached (project report, design, essay). Give it a grade and summarize your reasoning." (p. 114).

While all the examples Brent and Felder list involve short written activities, strategies for teaching engineering thinking will lean heavily on the practical because of the applied nature of the discipline. High-quality teaching for practical learning has six characteristics (Hanson & Lucas, 2022) and so strategies for engineering habits of mind will share these features:

- Learning covers the 'whole game' (Perkins, 2009).
- Learning (whether of knowledge or habits) is embedded in the curriculum.
- Learning takes a real-world perspective. Access to materials and time for children to generate their own problems of interest is said to be "crucial" in developing engineering habits of mind (Lippard et al., 2019).
- Learning uses a full range of teaching materials.
- Learning cultivates learner agency.
- Learning involves the tracking of learner progression.

Learning that is 'visible' (Hattie, 2009), such that teachers emphasise when children are using engineering habits of mind, could be added to this list. This is a particularly powerful approach when combined with modelling from practising engineers who demonstrate the habits in action (Hanson et al., 2021; p. 1,470) because good teaching tools alone are not sufficient:

> **...giving our students challenging, open-ended, hands-on, minds-on activities, projects, and problems that do not have one right answer is just the beginning. Finding our own creativity and modeling that type of ingenuity and love of learning are ways we as elementary STEM educators can guide our students in their own search for creativity in education.**
> (Hummell, 2014; p. 5)

For each of its six engineering habits of mind, Lucas et al. (2014) suggest some approaches that teachers tend to take, and relevant tools. They are many and varied, so not duplicated here. Again, they don't fit neatly into a single type of category such as 'principles', 'strategies,' or 'tools' either. Instead they are identified as "...thing[s]... that work well"; "kinds of approach"; "key tools"; things that learners might be required to do; things teachers tend to do; the job or role of the teacher; things teachers might offer; "specific methods and techniques"; or things the teacher "would want to" try. A framework is needed to think about how pedagogy, strategy, and tools/techniques relate to one another.

Pedagogic principles

Broad teaching strategies such as extended projects and inquiry-based activities (seen in **Table 7**) need to be carefully aligned with sound underlying principles. These could include principles like the importance of pupils taking ownership of their own learning and having choice about how they meet success criteria (open ended tasks). It could include the importance of presenting meaningful problems. It will certainly include practical learning, which is essential for developing the habits learners need to think and act within a domain. For example, in a science context, we know that practical science within science education supports the development of scientific and wider employment skills alongside building understanding of the norms and values of science; or to use our language – the development of scientific habits of mind and action (The Royal Society, n.d.).

Each of these principles (ownership, open ended tasks, meaningful problems, practical learning), and others, are shown in **Table 7**.

From their work with teachers in classrooms, Bianchi and Chippindall (2018) arrived at seven such principles for providing an environment where learners can 'tinker' as a way of learning . Broad strategies, and then techniques can then be chosen that align with these principles, which include:

1. Pupils are engaged in purposeful practical problem solving.
2. Pupils take ownership of the design and make process.
3. Pupils embrace and learn from failure.
4. Pupils' curiosity and creativity is responded to.
5. Pupils demonstrate mastery from other curriculum areas.
6. Pupils draw on a range of thinking skills and personal capabilities.
7. Pupils' learning experiences are guided by a whole-school approach.

For teaching strategies to be successful, we propose the broad principle of split-screen thinking is also imperative. Split-screen thinking implies that teaching strategies must be designed with the explicit intention of developing specific creative skills:

> **the opportunity to be creative through an open-ended project is not equivalent to careful planning of specific desired results, learning plans, and assessment evidence of the creative skills to be developed.** (Daly et al., 2014; p. 435)

It is necessary to find opportunities within the curriculum, and through teaching strategies, to develop creative skills.

In practice this might look like Daly et al.'s (2014) proposal – referencing Treffinger's framework of creative skills (although alternative sets of skills could also be used) – that teachers select specific creative skills for different tasks. For instance, a task might require learners to explore various methods for solving a technical problem, thereby practicing divergent thinking skills. This approach allows for flexibility in teaching creativity (or other engineering habits) within engineering by tailoring the skills to the demands of each task.

Signature pedagogies

Beyond these broad principles, the literature we have reviewed on engineering would suggest at least five key teaching strategies – or 'signature pedagogies' – although more could no doubt be added to this list: the engineering design process, playful experimentation, working with experts, interdisciplinary learning, and design thinking.

These are shown in ***bold blue italics*** in **Table 7** and described briefly:

1. The engineering design process

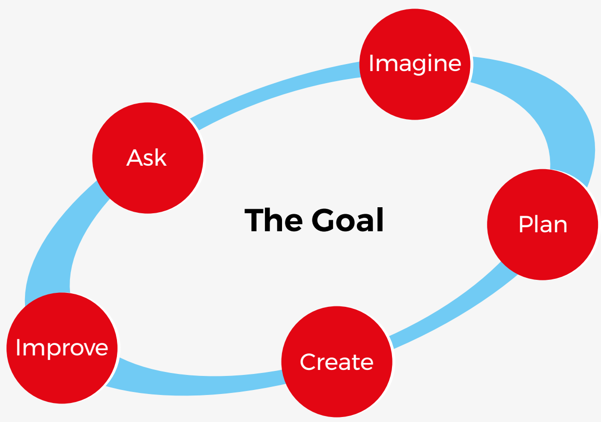
In addition to reframing engineering as a series of engineering habits of mind, Lucas et al. (2014) suggest two key signature pedagogies. The first is the engineering design process itself; an iterative process similar to the creative design process, and fundamental to engineering. Working through a complete iteration of the design process can involve an open-ended project where outcomes are not fixed so that learners must make real design decisions and use every thinking process required through the process.

Although the design process does not dictate educational implementation through real-world problems with genuine stakeholders, team working, and personal choice, the process does tend to lend itself to these sorts of teacher choices.

The engineering design process (NASA, 2018, see **Figure 15**) is an action-oriented framework for solving practical problems. It is described by NASA (2018) as:

- **Ask:** identify the problem, requirements that must be met; constraints that must be considered.
- **Imagine:** brainstorm solutions and research ideas. Identify what others have done.
- **Plan:** choose two or three of the best ideas from the brainstormed list and sketch possible designs, ultimately choosing a single design to prototype.
- **Create:** build a working model, or prototype, that aligns with the design requirements and that is within design constraints.
- **Experiment:** evaluate the solution through testing; collect and analyse data; summarise

Figure 15:
Engineering Design Process (NASA , 2018)



strengths and weaknesses of the design revealed during testing.

- **Improve:** based on test results; make improvements on the design. Identify changes to make and justify revisions.

Creativity involves bringing critical thought to bear, for example; evaluating the merits of an idea. This makes creativity a process; indeed, it is a "...disciplined process that requires skill, knowledge, and control" (Azzam, 2011). Jones (2014) proposes that teaching for creativity and innovation becomes easy when the engineering design process is applied in combination with technical knowledge.

Although Jones does not state how creativity arises, it could be proposed that each part of design process framework is supported by particular habits, and thus can be used to develop those same creative habits. We propose by extension, that the engineering habits of mind similarly support each step of the engineering design process, and thus can be developed through that process. It will be helpful to develop a framework linking the habits of engineering and the design process, just as the Creativity Collaboratives work in Winchester has helped teachers to do (Sowden et al., 2023, see page 49).

2. Playful experimentation, or tinkering for learning

Within the engineering design process itself is the second signature pedagogy. Creating, building, "making things that work" (Lucas et al., 2014; p. 45), they argue, is core, and mustn't be underestimated by being subsumed within the process. This could be described as 'playful experimentation' (Lucas, 2024) or 'tinkering for learning' (Bianchi & Chippindall, 2018; p. 1), and involves tinkering, prototyping, drafting, and re-thinking.

3. Working with experts

A third signature pedagogy includes the presence of, and contact with, practising engineers (Lucas, 2024). Engaging pupils with professionals or specialists who have extensive knowledge and experience in specific fields provides them with real-world insights, practical advice, and exposure to professional methods, which can enhance their problem-solving skills, inspire innovative ideas, and offer authentic contexts for applying their learning. By collaborating with experts, pupils gain a deeper understanding of the subject matter and are encouraged to think critically and creatively, mirroring expert practices in their own work.

4. Interdisciplinary learning

This type of learning integrates concepts, methods, and problem-solving techniques from multiple disciplines, encouraging learners to draw on diverse perspectives and knowledge bases to innovate and find holistic solutions to complex problems. Learners have the opportunity to think creatively as they apply engineering principles across various contexts and the potential to develop flexibility in thinking, adaptability, and a deeper understanding of how interconnected and multifaceted real-world issues are.

Specialist teachers at secondary level have an interest in their own subject, demonstrated by their pursuing it in-depth at HE level, however, and cross-curricular working can be intimidating. We mentioned real-world problems; these can be a gateway to interdisciplinary learning, allowing teachers keen on retaining focused attention on their own branch of science, for example, to develop interdisciplinary collaboration from the ground up, as they think about how they can set more real-world (and naturally interdisciplinary) projects while retaining a focus on their own subject.

Teachers wishing to inculcate engineering habits of mind could also consider pairing subjects, such as Drama and Maths, or Science and Geography for low-threat exploration of two disciplines, possibly with a topic or question.

Design & Technology is another curriculum area that has suffered from deprioritisation in many schools as a consequence of policy imperatives. The Design Council see design "as the jewel in the crown of a reimagined British education system – a core competency that develops creative problem-solving, technical knowledge, material intelligence, critical thinking and making ability, focused on the needs of our future economy and society." (Design Council, forthcoming).

5. Design thinking

Design thinking provides a structured but flexible process that guides problem-solving and innovation, including stages such as empathising, defining the problem, ideating, prototyping, and testing. Design thinking encourages a hands-on approach to learning, where learners engage deeply with problems, iterate on their ideas, and develop practical solutions. It emphasises empathy, collaboration and experimentation to generate creative solutions.

Stanford's d school (Hasso Plattner Institute of Design at Stanford University, 2023) is renowned for its innovative and human-centred approach to design thinking. It develops creative thinking in a number of ways and has potential for developing engineering habits:

- **Empathy and Human-Centered Design:** d.school places a strong emphasis on understanding the needs and perspectives of the end-users. This empathetic approach ensures that the design solutions are grounded in a deep understanding of the people for whom the product or service is intended.
- **Interdisciplinary Collaboration:** The d.school encourages collaboration among individuals from diverse backgrounds and disciplines. Teams often include designers, engineers, business professionals, and individuals with various expertise. This interdisciplinary approach fosters a rich exchange of ideas and perspectives.
- **Iterative Process:** Design thinking is an iterative process that involves prototyping, testing, and refining solutions based on feedback. This iterative approach allows for continuous learning and improvement, promoting a mindset of experimentation and adaptation.
- **User-Centered Design Workshops:** The d.school conducts a variety of workshops and courses focused on design thinking. These hands-on experiences immerse participants in real-world design challenges, allowing them to practice creative problem-solving in a supportive and collaborative environment.
- **Challenge-Based Learning:** Learners at the d.school engage in challenge-based learning, where they work on real-world projects and problems. This approach provides a practical context for applying design thinking principles and encourages students to develop innovative solutions to complex issues.
- **Mindset and Mindfulness:** Developing a creative mindset is an integral part of the d.school's approach. This involves fostering a culture of curiosity, openness to new ideas, and resilience in the face of failure. Mindfulness practices are often integrated to enhance self-awareness and creativity.
- **Design Thinking Bootcamps:** The d.school offers immersive design thinking bootcamps and executive education programmes. These intensive experiences provide participants with an opportunity to dive deep into the design thinking process and develop their creative and problem-solving skills.
- **Innovative Physical Space:** The d.school's physical space is intentionally designed to be open, flexible, and conducive to collaboration. The layout and environment are intended to inspire creativity and foster spontaneous interactions among students, faculty, and professionals.
- **Design Challenges and Projects:** Learners often engage in design challenges and projects that address real-world problems. These experiences help develop the ability to identify opportunities, frame problems, and generate creative solutions.
- **Leadership and Entrepreneurship:** In addition to design thinking, the d.school emphasises leadership and entrepreneurship skills. This holistic approach prepares individuals not only to generate creative ideas but also to implement and lead initiatives that drive positive change.

Through a combination of these elements, Stanford's d.school creates a dynamic and immersive learning environment that nurtures creative thinking, collaboration, and a human-centred approach to design challenges.

Principles from teaching creativity

In terms of broad principles that might also be relevant to engineering, a number of key ones have emerged from an Arts Council funded project aiming to develop creative thinking in children, including the importance of setting meaningful problems, opportunities for re-work, and 'beautiful risks' (Sowden, 2023, see **Figure 16**), and we also include these in **Table 7**.

Combine the habits and process

The University of Winchester Academy Trust (UWINAT) 'Creativity Collaborative' has been working with teachers over the course of the last three years to develop pedagogy for creative thinking. It has developed an approach that involves combining the creative process and habits (Sowden et al., 2023); a framework developed through literature review and the distillation of a range of creative cognition models, and put into practice by teachers.

The primary signature pedagogy used is the 'creative process' and its departure from our 2017 work on signature pedagogies for creativity is to suggest that any of the habits can be developed through this signature pedagogy, iteratively, and as appropriate.

The framework shows how development of an artifact should be an iterative process, such that the creative process of exploring, ideating, and evaluating can crop up numerous times as the artifact is developed, and different habits may be relevant at any time. Note the clouds around the outside: this shows some signature pedagogies and planning decisions teachers may tend to lean towards in planning creative opportunities. Clouds represent a set of general principles for the design of creative learning opportunities and could be similarly applied to the context of developing engineering habits.

In practice, teachers used their own preferred planning documents with added space to consider how to bring the creative process into their unit of work. They began by deciding on the specific (National Curriculum) content they must teach, which was often less than they had expected. Inherited plans can be useful time savers, but with fresh eyes, teachers often realised that a pared down version of what has been taught before would deliver the key content.

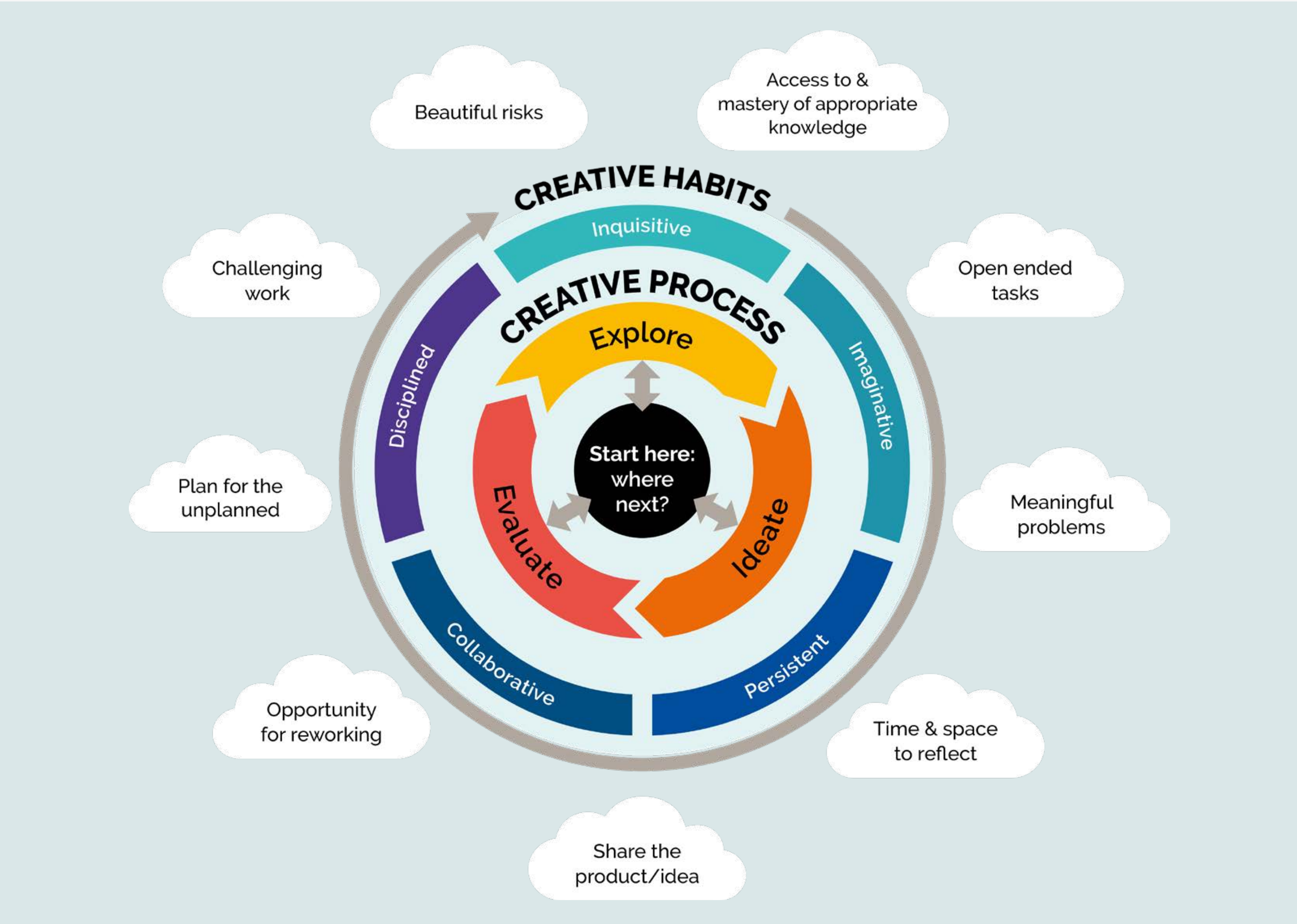
In thinking about designing lessons, we refer to the 'artifact' rather than outcome/product. The artifact is the visible product of learner activity; the visible outcome of a lesson or unit of work. This may be the solution, whether actualized or only designed, to a problem; it may be a recorded (written or drawn) or verbalised response to a question. Of course outcomes are always more than products – such as knowledge retained in the memory, habits practised. Talking about the artifact, or evidencing its development, should in some way evidence those intangible outcomes also.

With that artifact in mind, teachers brainstormed all the elements that might be relevant to the 'explore', 'ideate' and 'evaluate'. How could they explore key ideas, practise key concepts? How could they come up with ideas? How could they justify their plans / designs; address flaws; self-assess learned knowledge and creative thinking?

Consideration of the creative habits came next. In exploration: might this be a good opportunity to practise good questioning; sharing of ideas? In ideating: could this be a chance for pupils to play with possibilities? In evaluating: could pupils reflect critically, but also learn to receive and use feedback better?

At primary level, teachers could focus on teaching the knowledge content of the STEM curriculum, as well as other subjects, using a creative process model for planning their units of work. At secondary level, specialist teachers could benefit from the same approach, teaching the specialist curriculum

Figure 16:
Creativity navigator – for mapping out creative learning journeys (Sowden et al., 2023)



content using a creative process model to plan topic delivery. It becomes less necessary to speak of 'project-based learning' when a unit is planned in this way.

Consider both visibility and value of knowledge and habits

A focus on teaching engineering and creative habits of mind requires adjustments to the way teachers think about planning a lesson. Big changes are not required, but if both knowledge, and habits, are to be cultivated, teachers will aim to balance both in terms of visibility and value.

Although some knowledge is simply received and memorized, and doing so requires certain habits, much knowledge lends itself to lesson design that considers how pupils can work their way through the creative process of exploring, coming up with ideas and producing their 'artifact', and evaluating both artifact and use of habits.

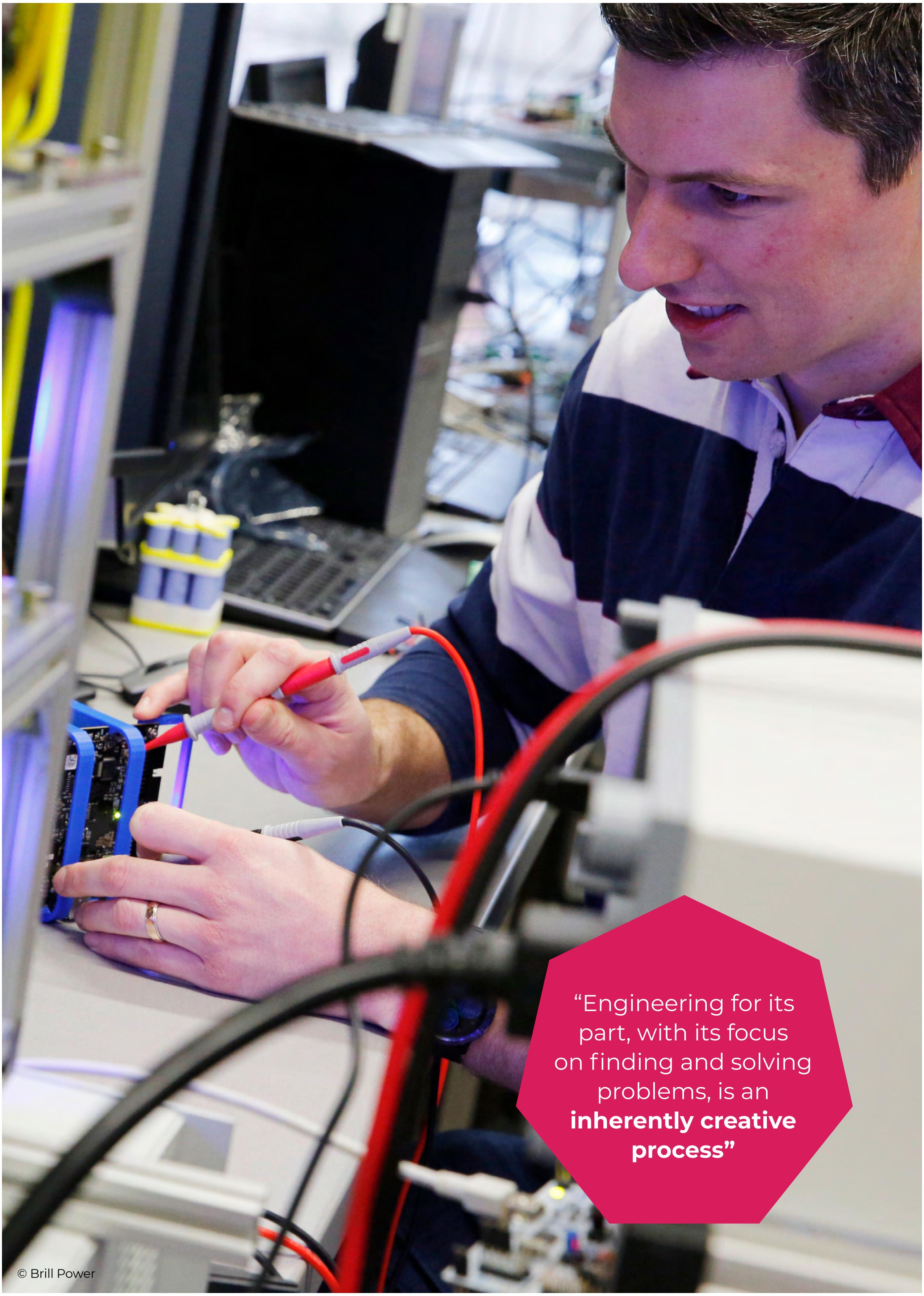
Table 8 shows how we think that teachers might consider visibility and value of knowledge and habits in the planning, teaching, and assessment of a unit of work. The key principle is that if something is valued, it should be made visible; when it is 'visible' (whether visually or aurally), then pupils recognise it as being of value.

Bringing together engineering and creativity 'signature pedagogies'

Table 7 draws together the signature pedagogies identified for ***engineering*** and **creativity**, along with others from literature and practice that may hold promise for effective integration into engineering or creativity teaching. It shows how these concepts fit together conceptually.

Table 8:
Visibility and value of habits and knowledge in a unit of work

Value		Visibility
Decide essential knowledge: Deciding on what pupils need to know. Deciding on a lesson / theme that will enable pupils to explore, develop ideas and craft their own artifact, and evaluate. Deciding on the habits that will support this. Consider learning outcomes: Framing in terms of both knowledge and habits. Consider opportunities to develop: Checking lesson / theme provides opportunities for learning knowledge and practising chosen habits.	**Planning**	Communicate learning outcomes: Producing material that pupils will see that draws attention to both knowledge and habits.
Keep the plan in mind: Value the process and not just the artifact	**Delivery**	Pupils explore: Researching, listening, asking questions to understand key concepts. Practising key skills. Pupils develop ideas and craft artifact: Developing ideas. Working on an artifact.
Notice learning: Attending to development in both knowledge and habits	**Assessing**	Pupils evaluate: Evidencing development of knowledge through the artifact. Noticing and recording use of the habits through self- and peer-evaluating. Consider language: Drawing attention to (opportunities for) use of habits



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“Engineering for its part, with its focus on finding and solving problems, is an **inherently creative process”**

6. Conclusions

As this review has shown, there is an increasing emphasis on creativity in educational policy and encouraging signs from various regions worldwide where it has become prominent. In addition to the many existing initiatives in engineering education, engineering might derive some important insights from this parallel evolution in creativity.

Both domains, as we suggested at the outset of this report, share some characteristics: they are undervalued and sometimes invisible in schools; they straddle individual subject disciplines; they require teachers to reframe the way they think about their teaching; they do not fit easily within current assessment paradigms. We offer three observations as to how engineering might be developed further in England:

- **Both creativity and engineering can be framed as a set of habits.**
  This enables us to focus on the thinking and making processes connected with both, to see beyond the associations of those subject disciplines traditionally associated with each and puts the focus on how best such habits and be learned and taught.
- **Both creativity and engineering share design processes.**
  Exploring the similarities and differences between the various creative and engineering design processes has the potential to offer fresh thinking about how engineering can be taught and learned.
- **There is a growing understanding of promising practices in terms of advocacy, curriculum design, the deployment of pedagogies and assessment practices and approaches to professional development and external evaluation of creativity in schools.**
  From such practices those interested in further developing teaching for engineering in schools may be able to derive helpful insights (as well as sharing their own experiences with those developing creativity).


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In more intentionally and systematically developing engineering habits in children and young people we propose four key steps:

1. Assess the state of the nation with regard to engineering in schools

Just as the Durham Commission (2019) did for creativity, so we suggest that an authoritative report on the state of engineering in England's education system, and particularly in comparison with other countries would highlight opportunities.

Real impact tends to be seen when schools and teachers put principles into practice and see the benefits for themselves. Impact assessment of the Creativity Collaboratives instigated by the Durham Commission is ongoing, but it is likely that the success and focus of the creativity movement will come from the systematic development of understanding in terms of curriculum design, the deployment of pedagogies and assessment practices and approaches to professional development and external evaluation of creativity in schools.

The same may well be true of engineering. Given the number of well-regarded Professional Engineering Institutions, research may need to be championed by a high-profile university. It is interesting that the authoritative Education Endowment Foundation (n.d) contains no research on engineering in schools.

2. Find a clear voice

In the same way that creativity is benefitting from the international leverage of organisations with a clear message about its importance, engineering needs a clear voice, such as PISA, and the Global Institute of Creative Thinking, or united voices, championing the value of engineering in solving the world's challenges and (re)invigorating school.

There are numerous Professional Engineering Institutions within the UK that all align with Engineering UK's mission to inspire and enable young people into engineering careers (Engineering UK, n.d.).

3. Focus on teaching and assessment

A lesson from creativity's rise to prominence is one of prioritising its teaching in schools across all disciplines. Some in the engineering field would wish to see an increase in both the volume and quality of specialist engineering education in schools. While not incompatible with our approach, we recommend schools maintain a broad focus on diverse subject knowledge. This approach should also foster the development of pupils' engineering habits, encourage the confident use of design thinking processes, and provide opportunities for pupils to learn through problem solving. We recommend such lessons are developed across the full range of subject disciplines, as appropriate, allowing readiness for specialisation to come later.

While understanding of effective pedagogies is growing, there is some work to be done in understanding how best assessment can be used to raise the status of engineering and, through a range of formative assessment practices, continue to improve teaching and learning in engineering.

4. Synthesise what is known already about how engineering can be systematically developed in schools

The Department for Education recently announced a Review of Curriculum and Assessment (2024) presenting a timely opportunity for the Royal Academy of Engineering and its partners to contribute a submission informed by a wide range of evidence and best practices. This submission could include a rapid analysis of how engineering is currently integrated across various subjects in the English National Curriculum, as well as an exploration of how it could be more prominently featured. Additionally, it would address effective implementation strategies, drawing on the approaches outlined in this report.

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Appendix 1:
Creative Thinking Progression

1. Imaginative	Starting point	Emerging	Developing	Deepening	Key indicators
1.1 Generating ideas	Learners provide one or two simple/ obvious ideas with strong support	Learners provide a small number of relatively obvious ideas with some support	Learners provide many ideas, some well-developed, largely working on their own	Learners generate a large number of ideas, relevant to the context and working independently	**Number/ agency**
1.2 Playing with possibilities	Learners provide a very limited range of ideas all focusing on the same theme	Learners' ideas represent a small range of themes and show some exploration of the theme	Learners provide a range of ideas that are distinct from one another and which show genuine exploration of the theme	Learners generate a wide range of alternative ideas and solutions, sometimes adapting existing ideas, sometimes integrating other perspectives	**Range/ complexity**
1.3 Making connections	Learners present ideas that are very obvious or conventional only containing concepts with which they are already familiar	Learners present ideas that are mostly obvious or conventional containing a few concepts with which they are not already familiar	Learners present ideas which show some flexibility and willingness to go beyond their existing experiences, combining elements of a task to explore new combinations of ideas	Learners present ideas which show that they can think flexibly going beyond their existing experience or social context, combining elements of a task to allow for novel combinations of ideas	**Novel connections**

2. Inquisitive	Starting point	Emerging	Developing	Deepening	Key indicators
2.1 Posing questions	Learners use a very narrow range of questions focusing mainly on basic understanding	Learners use a growing range of questions to suit circumstances and go beyond basic understanding	Learners use a range of questions to suit circumstances increasingly being able to explore, challenge and consider possibilities beyond the relatively obvious	Learners use a wide range of questions to suit circumstances and intentions and are able to clarify, probe, explore, infer, deduce, challenge and consider hypothetical situations	**Range of questioning techniques**
2.2 Exploring and investigating	Learners view the task through a single perspective without consideration of what task elements can be changed	Learners mainly view the task through a single perspective with little consideration of what task elements can be changed, or which alternative perspectives or pathways can be considered	Learners can shift perspective, thinking about the task/problem in a different way, considering the task/problem from a range of perspectives and being willing to test out alternative pathways	Learners are able to see more than one side of an argument, experimenting beyond conventional perspectives, questioning the boundaries of the task to navigate around possible constraints and testing out multiple pathways, even those that seem unlikely	**Range of perspectives adopted**
2.3 Challenging assumptions	Learners' explorations of the task elements are very limited and they do not challenge others' opinions	Learners' explorations are mainly routine, limiting exploration to obvious elements of the task, and revisiting the same ideas, rather than generating new ones, only occasionally challenging others' views	Learners demonstrate some evidence of experimentation, developing some of the task elements, or synthesising existing ideas, increasingly able to avoid jumping to conclusions and offer opinions which differ from others'	Learners think flexibly to develop elements of the task, effectively combining elements of a task to allow new possibilities, noticing the unusual, avoiding jumping to conclusions, recognising others' feelings and clearly articulating their own ideas	**Willingness to question status quo**

3. Persistent	Starting point	Emerging	Developing	Deepening	Key indicators
3.1 Sticking with difficulty	Learners develop their ideas in a limited way without elaboration, typically seeing mistakes as failure	Learners elaborate their ideas, but without an evaluation of effectiveness, or justification in relation to fitness for purpose but beginning to see the value of producing different versions of their work	Learners elaborate their ideas to evaluate their effectiveness, and/or justify fitness for purpose, increasingly seeing mistakes as opportunities, beginning to produce several versions of their work and inviting feedback on these	Learners think flexibly to manipulate elements of the task, effectively combine elements of a task to allow new possibilities, see mistakes as opportunities, enjoy producing several versions of their work and can act on feedback to improve their thinking	**Degree of elaboration**
3.2 Tolerating uncertainty	Learners are easily confused when faced with multiple perspectives and seek one right answer	Learners are prepared to consider alternative perspectives when considering a problem and are able to come up with more than one possible solution	Learners embrace multiple perspectives when considering a problem, are willing to use their intuition to explore challenges and are not put off by questions which do not have one right answer	Learners actively embrace multiple perspectives when considering a problem, find 'not knowing' an interesting place to be, enjoy using their intuition and relish questions which do not have one right answer	**Willingness to see multiple perspectives**
3.3 Daring to be different	Learners prefer safe solutions and are unwilling to take risks or disagree with others	Learners are prepared to take limited risks, try out alternative positions and offer their opinions to others	Learners are increasingly prepared to take risks, to adopt alternative positions, offer their opinions and disagree with others	Learners are prepared to take risks, to adopt alternative positions and to disagree with others as they develop their creative thinking, recognising that thinking creatively often requires disagreement along the way	**Willingness to take risks in thinking**

Appendix 2:
Pupil Self-Report Questionnaire

Creative Thinking Questionnaire				
Pupil name Test			**Date** 01/21/2025	
Imaginative	Not at all like me	A little like me	Quite a bit like me	Very much like me
1 I enjoy seeing connections between different ideas/things	☒	☐	☐	☐
2 I find it's helpful to play with different ideas before deciding what to do	☐	☐	☒	☐
3 I find it helpful to go with my gut-feel about what I am working on	☐	☒	☐	☐
Inquisitive	Not at all like me	A little like me	Quite a bit like me	Very much like me
4 I am not afraid to challenge other people's thinking	☐	☐	☒	☐
5 I enjoy exploring things I have not learned before	☐	☒	☐	☐
6 When I am learning something new I can normally come up with good questions	☐	☐	☒	☐
Persistent	Not at all like me	A little like me	Quite a bit like me	Very much like me
7 I am able to share views which are clearly different from other people's	☐	☐	☒	☐
8 I don't mind dealing with issues where there is no one right answer	☒	☐	☐	☐
9 I can stick with things even when they are difficult	☐	☐	☒	☐

Appendix 3: Progressing to be an Engineer (PEng) Framework

Purpose	Making 'things' that work and making 'things' work better				
Engineering design process	**Ask**		**Imagine and plan**		
Engineering Habit of Mind	**Problem-finding**	**Systems thinking**	**Systems thinking**	**Creative problem-solving**	**Visualising**
5–7 years	Make observations to inspire the asking of simple questions, finding out more information about how things work.	Explain how simple systems work.	Draw and label a design with different parts, showing how they connect together.	Come up with and describe how different ideas can solve a problem.	Communicate ideas in words and simple sketches.
7–11 years	Identify problems and ask questions to better understand their cause.	Explain how simple systems work, identifying how each part depends on another and predicting what would happen if there is a missing piece or link.	Draw and label a design that uses a system, explaining the role of each part.	Generate multiple ideas, effectively communicating their fitness for purpose and why certain ideas are better than others.	Use simple annotated sketches to turn ideas into words and drawings.
11–14 years	Critically examine problems, asking questions to understand their cause and how they impact different users.	Explain complex systems, including subsystems, describing how they depend on each other and predicting what can happen if there is a missing piece or link.	Draw and label a design that includes a system, justifying why each part is there, and how it best suits a user.	Use research and experience to come up with designs to solve a problem, justifying choices by applying scientific knowledge and evidence.	Use detailed annotated sketches to turn ideas into words and drawings to create a design specification.

Figure 17:
Bianchi and Wiskow (2017) Progressing to be an Engineer

Purpose	Making 'things' that work and making 'things' work better					
Engineering design process	**Imagine and plan**	**Create**			**Improve**	
Engineering Habit of Mind	**Adapting**	**Systems thinking**	**Adapting**	**Creative problem-solving**	**Problem-finding**	**Improving**
5–7 years	Observe a range of mechanisms (how things are made to work), suggesting ideas for how they could be used for a different purpose.	Use components to create a product with multiple parts.	Take an existing product and repurpose it by using it in a different way.	Create a prototype by taking a 2D design into 3D.	Check things work by testing.	Identify areas for improvement in a product and suggest changes to make it work better.
7–11 years	Plan a design that aims to solve a problem or task for a specific user, by transforming an existing mechanism (natural or man-made).	Use knowledge of how components work and interact to create a product that achieves a specific purpose.	Repurpose an existing product so that it can be used it in a different way, tailored to the needs of a specific user or purpose. Evaluate its fitness for purpose.	Create and evaluate a series of prototypes, taking 2D designs into 3D, making improvements based on observations and feedback.	Test that things work using a logical approach, gathering evidence to make an informed decision.	Evaluate how the product is working, identifying areas for improvement in a product and describing possible changes that can enhance the design.
11–14 years	Plan and evaluate designs that aim to solve a problem or tasks by transforming existing mechanisms (natural or man-made), suggesting alternatives and trade-offs with due regard for criteria such as cost and safety.	Create a product for a specific purpose, justifying the suitability of choices based on local and global issues – e.g. sustainability, energy, circular economy.	Repurpose an existing product, tailored to the needs of a specific user or purpose. Evaluate based on ethical, social and economic aspects.	Create a series of prototypes, taking 2D designs into 3D. Use cycles of self and peer-evaluation to identify and make improvements based on testing, observations and feedback.	Test and evaluate products against a specification reacting to the views of intended or specific user groups.	Identify areas for improvement in a product and describe changes to enhance the design, recognising the ideas that are most feasible and desirable.

Notes

Royal Academy of Engineering

The Royal Academy of Engineering is harnessing the power of engineering to build a sustainable society and an inclusive economy that works for everyone.

In collaboration with our Fellows and partners, we're growing talent and developing skills for the future, driving innovation and building global partnerships, and influencing policy and engaging the public.

Together we're working to tackle the greatest challenges of our age.

What we do

Talent & diversity

We're growing talent by training, supporting, mentoring and funding the most talented and creative researchers, innovators and leaders from across the engineering profession.

We're developing skills for the future by identifying the challenges of an ever-changing world and developing the skills and approaches we need to build a resilient and diverse engineering profession.

Innovation

We're driving innovation by investing in some of the country's most creative and exciting engineering ideas and businesses.

We're building global partnerships that bring the world's best engineers from industry, entrepreneurship and academia together to collaborate on creative innovations that address the greatest global challenges of our age.

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We're influencing policy through the National Engineering Policy Centre – providing independent expert support to policymakers on issues of importance.

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