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Foreword

The need for a major change in the process of preparing engineers has become widely recognized in recent years. Since at least the end of World War II, academic engineering has been focused on mathematical rigor, applied physical sciences, and the analysis of useful technologies that address human needs, with a strong faculty focus on research and publication. As a result, it does a better job of producing applied scientists than engineers. The graduates are reasonably comfortable with applying equations to solve well-defined technical problems, but they have had minimal experience in problem finding, working across disciplines to conceive and design a system, fabricating a prototype, assessing customer acceptance, manufacturing, and distribution needs as well as cost, reliability, and ultimate lifecycle sustainability.

If our engineering education process were applied to the problem of producing musicians, we would produce much better musicologists than performing artists. We might spend the first year teaching them the theory of vibration of strings, focusing on mode shapes and natural frequencies, pitch, etc. The second year might be focused on the history and theory of music, including melody and harmony, point and counterpoint, tempo, etc. The third year might be focused on orchestration, including the blending of voices, woodwinds, strings, percussion, etc. And finally, in the fourth year—if you are still enrolled at that point—we might give them a real violin and teach them to play a scale. This would complete their education in music, and we would award them a degree in music. Of course, no talented musician would be willing to endure such a sterile learning process. As ridiculous as this example might seem, the traditional undergraduate engineering curriculum has many similarities.

In society today, an engineer is a person who envisions what has never been and does whatever it takes to make it real. (The science and math enter in the 'whatever it takes' portion of this process.) This concept of engineering does not begin with mathematical rigor; it begins with vision and creativity. And the need for a string quartet or an orchestra is much more common than that of an acapella soloist. An interdisciplinary and collaborative mindset is fundamental in the field today, yet it remains weakly addressed in the traditional learning process.

How to address this educational challenge? The problem of redesigning the educational process for engineers to achieve this major shift in outcomes is highly complex, culturally dependent, unique to each institution, and uncertain at best. The authors in this book approach this problem with a global perspective, identifying concepts that work on three continents, and focus on a systems thinking approach and problem-based learning pedagogy. The mindsets proposed and the examples provided from three very different institutions provide an illustrative guide to attacking this challenge at any institution. This book provides a major contribution to the challenge of substantial redesign of the learning paradigm in engineering.

May 2023

Richard K. Miller
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Preface

This book took off in the northern autumn of 2019, with authors from three different universities, three different countries, and three different cultures. At that time the authors from two of the institutions did not know each other, but all authors had the same idea that engineering education needed to be reshaped to respond to the contemporary challenges in the global society, the SDGs, the increasing complexity, the increasing digitalization and not the least, employability and its relevant competences. We agreed that there is no human system that is not complex; indeed, the presence of human beings creates the complexity.

As we were discussing and writing, then came COVID-19, which ensured that we could not meet. If Australia was not under lockdown, it was the US or Europe, so we kept our effort alive by zooming and communicating writing in the early morning, late evening and, for the lucky ones, in the middle of the day. Finally, we agreed to meet in May 2022, to finish the book.

During this period of almost three years, the structure of the book slowly emerged as a complex system itself, taking shape in four parts:

- Part I, explaining systems, design, and how we need to respond,
- Part II, addressing the learning processes for both students and for academics,
- Part III, containing cases from our three universities, illustrating different methods, directions, and outcomes, and
- Part IV, the key recommendations and an open invitation to make change.

Each part has its goals. In Part I, systems are a description of the complexity of the world we live in, and design is a process and methodology to engage in problem solving, encompassing problem definition, innovation, as well as the arts and aesthetics. Design humanizes the engineering tools and brings solutions to the realms of culture, ethics, and sustainability.

In Part II, the learning process is an interesting human journey that has been taking place over the years with the quest of finding effective pedagogies that bring knowledge and innovative practices to young learners to create better life for all.

In Part III, our personal experiences show up in the cases and indicate that this book is a work in progress. As we were finalizing the writing, we continue to realize that there is more to write, and engineering education will evolve further with the introduction of intelligent machines and closer interactions among people from all over the world. We humbly believe that this is a step forward towards clarifying what needs to be done, but not the last word.

In Part IV, we summarize our recommendations as 10 key steps in making change and we invite you to make these changes at your institution.

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Aalborg, Denmark — Anette Kolmos
Sydney, Australia — Roger G. Hadgraft
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Cambridge, MA, USA — Kamar Reda

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About the Authors

Dr. Fawwaz Habbal is a Senior Lecturer in Applied Physics at the Harvard School of Engineering and Applied Sciences (SEAS), USA. He currently conducts research in nanophotonics and takes an active interest in addressing open-ended human challenges.

At SEAS, he served in various administrative roles, including the Director of Graduate Engineering Studies and the Executive Dean for Education and Research. He has been a driving force behind numerous research and education initiatives. He co-founded the Harvard Learning Incubator program and served as co-director of the Master in Design Engineering (MDE) program. The MDE program equips students with the skills to tackle and mitigate open-ended human challenges effectively. He has devised unique pedagogical strategies emphasizing active learning, computational methods, and studio-based instruction. This approach helps students grapple with complex, open-ended human challenges. In acknowledgment of his substantial contributions to academia and his embrace of diverse cultural perspectives, the Ulsan National Institute of Science and Technology in the Republic of Korea awarded him an honorary doctorate in engineering.

Before joining SEAS, he established startups in the field of digital imaging. His corporate tenure includes a role as Corporate Vice President at Polaroid Corporation, overseeing research and product design. In addition, he served as a Senior Research and Engineering Fellow for the same corporation.

Prof. Anette Kolmos is Professor in Engineering Education and Problem- and Project-Based Learning (PBL), and Founding and Former Director for the UNESCO category 2 Centre: Aalborg Centre for Problem-Based Learning in Engineering Science and Sustainability. She was Chair holder for UNESCO in Problem-Based Learning in Engineering Education, Aalborg University, Denmark, from 2007 to 2014. Among other professional appointments, she was also President of SEFI 2009–2011 (European Society for Engineering Education), and Founding Chair of the SEFI-working group on Engineering Education Research. She was awarded the IFEES Global Award for Excellence in Engineering Education, 2013 and the

SEFI fellowship in 2015. During the last 20 years, her research focus within Engineering Education includes gender and technology, project-based and problem-based curricula, change from traditional to project organized and problem-based curricula, development of transferable skills in PBL and project work, and methods for staff development. She is Associate Editor for the *European Journal of Engineering Education* and was Associate Editor for *Journal of Engineering Education* (ASEE).

Prof. Roger G. Hadgraft is a civil engineer with more than 30 years of experience in improving engineering education. He has published many papers on problem- and project-based learning, and the use of online technology to support student-centered learning to meet the needs of engineering employers. He was instrumental in introducing a project-based curriculum in civil engineering at Monash University and in several disciplines at the Royal Melbourne Institute of Technology (RMIT) in Melbourne, Australia. He established the Master of Sustainable Practice and Bachelor of Sustainable Systems Engineering, both at RMIT. He was an Australian Learning and Teaching Council Discipline Scholar and has been a member of several national learning and teaching projects. He has consulted on problem- and project-based learning to universities both nationally and internationally. In his current role at the University of Technology Sydney, Australia, he is leading the transformation of the curricula using studios to embed the development of future workplace skills, with an emphasis on the integration of technical and social skills.

Jette Egelund Holgaard is Associate Professor within the field of PBL in Engineering Education. She has an M.Sc. in Environmental Planning and a Ph.D. in Environmental Communication. She is affiliated with the Aalborg Centre for Problem-based Learning in Engineering Science and Sustainability under the auspices of UNESCO (UCPBL). Her research in UCPBL is related to the Technical Faculty of IT and Design, the Faculty of Engineering and Science, and the Institute of Advanced Studies in PBL, Aalborg University. During her career, she has had several leading positions at Aalborg University. Her current research has a specific focus on the relation between PBL competences, interdisciplinarity, and societal challenges in the reshaping of engineering education. She builds on prior research in sustainability science to frame societal challenges for engineers in the context of the UN Sustainable Development Goals. She has more than 130 publications related to the before-mentioned research fields.

Kamar Reda is a bioengineer with a keen interest in studying complex human and natural systems. She has actively taught courses that delve into systems and design thinking, focusing on uncovering the underlying causes of human conflicts and environmental challenges. More recently, she has dedicated her efforts to exploring novel methods and processes for educating future engineers, specifically addressing the challenges presented by AI, environmental issues, and economic concerns. She has also developed strategies for remote education and problem solving, incorporating these approaches in practical settings to bring valuable insights. She is currently engaged in research towards obtaining a Ph.D. in Bioengineering at Harvard University. This research reflects her passion for integrating principles from engineering and biology to address complex challenges within the field of bioengineering. Her teaching experiences, research pursuits, and engagement with various educational topics enable her to offer practical solutions and a comprehensive understanding of education, learning, and interdisciplinary problem solving.

Chapter 1
Introduction

1.1 The Rise of Complexity and Urgency

The world is facing unprecedented challenges, which its inhabitants and governments are struggling to address. COVID-19 has been a standout example for such challenges since 2020, with huge impacts on the world and on national economies. However, lurking in the background is climate change, the greatest threat to human life on earth. We are already seeing its effects through the increased severity of cyclones, tornadoes, floods, droughts, bushfires, crop failures, dust storms, and so on.

Artificial intelligence and digitalization are additional layers on top of the sustainability goals (SDGs), and they provide new opportunities and challenges for reshaping societies as well as engineering institutions. The Fourth Industrial Revolution, involving an expected increase in the use of new technologies, like the Internet of things (IoT), big data and machine learning, and robotics, will saturate all corners of society from the daily life of citizens to industrial production and global collaboration. New technological opportunities (AI, robotics, the Fourth Industrial Revolution) have changed human interactions, leading to changes in the way students learn, especially with the emergence of digital learning culture.

Emerging trends in engineering education are responding to these challenges. Topics related to systems thinking, design thinking, interdisciplinarity, complexity, and the use of real problems and projects in education are becoming part of engineering education. Many schools have integrated these trends in their curriculum and others are yet to do so.

When the learning situations change overnight, as happened during the COVID-19 crisis, and both teachers and students suddenly are urged into a digital mode, it creates challenges for how to scaffold and support learning. Not only are the complexities of societal problems increasing, AI and big data are more and more commonly applied and become crucial parts of engineering knowledge, learning, and solving complex human challenges.

The complexity of dependencies, which cannot be overlooked, raises attention to more systemic approaches. We need systemic ways of analyzing and modeling these

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problems so that we can, at least, make a start at addressing them. Systems thinking is a critical skill for future engineers. Systems maps can help to articulate and define the nature of the problem in ways that all stakeholders can relate to and appreciate. A system diagram typically includes the significant components of a system and the interactions between them. The system boundary defines the system of interest, separating it from the larger system in which it is embedded. The definition of the boundary predetermines the solutions available. Redefining the boundary opens new solutions.

High-level modeling tools, such as system dynamics, using stocks and flows, can transform the systems diagram into a quantitative model. The work of Donella Meadows, and others, is a good example (Meadows, 2009). These simple quantitative models can help stakeholders quickly understand the consequence of high-level decision making, e.g., where to allocate funds to reduce poverty. Which is better, spending on health or education? As the understanding of a system deepens, there are more sophisticated tools to be applied at smaller scales. Artificial intelligence, data analytics, and machine learning are all promising, data-driven tools to better understand aspects of system behavior.

Furthermore, the range from the simple to the sophisticated, from overview to the detail, from the philosophical roots of doing to technical insights, clearly questions the ability of any individual to cope with the breadth and depth of these challenges. In other words, the multidimensional nature of engineering calls for increasing capabilities to handle interdisciplinarity. Engineers should not sprend their energy to *be* interdisciplinary as such, but they should learn how to *work* in collaborative and interdisciplinary settings, where the interdisciplinarity profiles change with the problem at hand.

1.2 The Vision—Sustainable Development of Sociotechnical Systems

Over the past century, we became aware that most challenges should be viewed within a systems context, and engineering is shifting from technical problem solving to society focused, holistic problem solving. The problem-solving ecosystem requires different curricula, methodologies, and learning processes.

In this book, we examine new educational approaches to address human challenges within multidisciplinary and systems lenses. A broad set of ‘complexity’ traits may better describe current human challenges that are not addressable by positivist analysis. Different learning modalities have emerged and continue to evolve. Many of these modalities are combinations of doing, thinking, and listening, and attempt to engage the working long-term memory. Informal settings, such as maker spaces and active learning areas, encourage more interactions and enable creativity and innovation.

Complexity cannot be addressed by individuals or by people from a single discipline. When collaborative approaches are required to address complexity, interactive learning environments, such as problem and project-based studio pedagogies, provide appropriate physical environments that enable problem solving and engage both intrinsic and extrinsic motivations.

More innovative approaches appeared recently. For example, borrowing from the Arts, learning at the studio is 'supervised' by critics, who are proxies for the public and other stakeholders, and they provide the broadest context.

Learning in a problem-based setting, and a project-based environment, employs real-life problems as starting points. They integrate context dependency from the challenges experienced in real-life practice with an overall transformative scope of societies.

Several other forums for learning modalities include *acting* as a method for engaging the emotions and creating collaborations, as a literary campaign, creating sociability and appreciation. In Chap. 2, we present examples of how systems thinking, and inquiry-based learning approaches are appropriate in considerably different institutional contexts.

A world threatened by global problems needs engineers with global perspectives to tackle complexity and to address everyday problems in the broadest perspective. Education has no single model, as it is embedded in societal context. The educational mindset conceptualized in this book provides a frame of reference to the reshaping of engineering education. The examples of how this framing can emancipate itself in different institutional settings illustrate learning as a social experience. The methods exemplified in this book demonstrate how this can be done in formal classrooms, in informal ones, and in person, as well as remotely.

These diverse ecosystems point the way towards curriculum redesign issues that must be addressed. The goal of the book is to bring a focus on reshaping educational mindsets, methods, and directions for better education that may serve the coming decade. We all want to create a better future for ourselves and for the next generations, and there is a general agreement that education and social connections are critical to create a better life on Earth. Education is a key for better understanding the world, which brings more harmony and prosperity.

1.3 Challenges and Mindset for Reshaping Engineering Education

Twenty-first-century challenges are multidimensional and cannot be addressed through one specific perspective. Understanding different aspects of complexity requires not only a diversity of people but it also requires a diversity of mindsets. Due to the increasing multidimensionality of engineering, technological systems are expanding in complexity, and embedded trade-offs in design are increasing.

As such, no single perspective is ever enough in engineering, but as the platform for contextual learning is becoming increasingly complex and dynamic, the more should the focus be on shifting and combining different perspectives. Furthermore, with the increasing complexity and pace of development, the societal risk of using reductionist approaches to engineering is as emergent as ever.

In this book, we argue that a proactive and critical use of newly calibrated mindsets on technological development are needed in alignment with the grand challenges of our time, with a deeply founded respect for contextual differences. We take, as our starting point, the following overall challenges:

- A **sociocultural-environmental** challenge to address and embrace the diversity of people in complex systems, including ethics. The sustainability challenge must be included to address the increasing urgency to manage complex and interactive resource flows and ensure quality of life for future generations.
- A **digital** challenge to transform the learning and the development of the disciplines. The digital age must be reflected in the young engineers' competency development.
- An **employability** challenge to address the learning outcomes for educating candidates who could relate to the ever-changing work and market conditions and are able to combine professional identity with citizenship as agents of societal change.

We argue that some of the core mindsets needed in engineering education to address these challenges are:

1. A **future mindset**, including systems and design, to systematically address the increasing complexity and unpredictability of sociotechnical systems as well as the digitalization challenge, and to assess the future impact of engineering work. This is discussed in Part I of the book (Chaps. 2, 3 and 4).
2. An **interdisciplinary-learning mindset** to facilitate active and reflective learning, individual and collaborative learning as well as contextual and transformative learning to develop the needed generic competencies required in a complex world. This is discussed further in Part II of the book (Chaps. 5, 6, 7 and 8).
3. A disciplinary and digitalization mindset to align engineering education to the emerging nature of engineering disciplines and the digital platforms as well as AI for new knowledge.

These challenges and mindsets are aggregated in Fig. 1.1, in an engineering education context, which puts the learner at the center of the system. The model has been inspired by (a) interacting competencies promulgated by international accreditation bodies, such as ABET and Engineers Australia, (b) interactions between disciplinary knowledge, design, and (c) interpersonal and professional skills, but we expand the views beyond these.

The future mindset has two dimensions. The first is self-centered—how do I develop myself as an engineer to achieve my career goals? This is commonly referred to as lifelong learning. The second dimension is a future mindset of professional practice, which embraces impact assessment—what are the consequences of my work? This includes an understanding of the lifecycle of engineering products. How will this product be operated, maintained, decommissioned, recycled, etc.? How

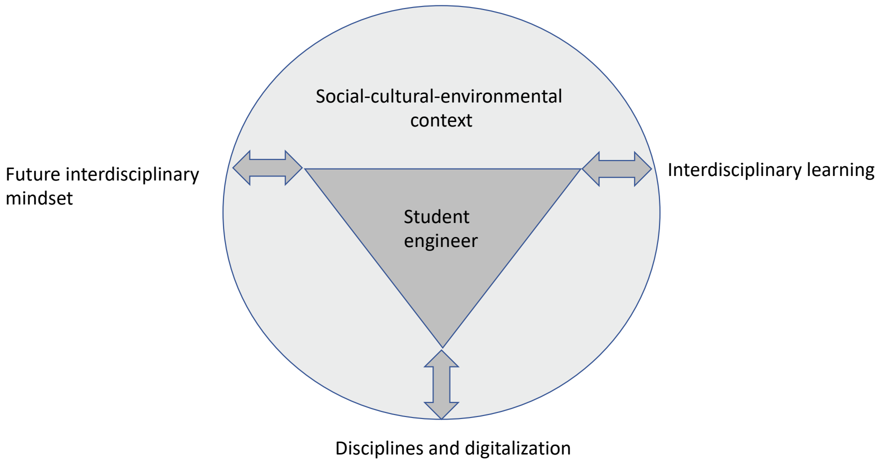

Fig. 1.1 Conceptual framework for mindsets

does the operational energy over its lifetime compare to the embodied energy in its construction or manufacture? And has this been optimized?

Furthermore, a lifelong learning perspective is needed in an ever-changing world. As we approach challenges as systems and argue for systems analysis, there is a need for even more flexibility. Elements and components can be combined in numerous ways, and through design competencies, relations among the engineering specifics, disciplinary knowledge, and the overall system dynamics need to be articulated within a sociocultural understanding.

The above-mentioned new mindsets provide the tools to integrate systems and complexity in engineering education in various ways—both for the content of the curriculum and the learning methodologies. Thus, the engineering curricula and pedagogy can promote an integrated understanding of complex problem identification and problem solving and enable engineering students to address not only technical requirements but also consider the overall challenges including sustainable and contextual constraints and potentials.

Figure 1.1 furthermore presents the relations between the disciplines, the design processes, and the student engineer, framed in a sociocultural-environmental context. The key aspects of each dimension include core mindsets as elaborated in the following. We, by no means, argue that this is a universal perspective on engineering education, but it is the perspective that we will use in this book to move beyond current requirements from accreditation and establish a new ground for reshaping engineering education.

In addition, these mindsets must be brought into action, and the main purpose with this book is to offer a framework for doing exactly that to exemplify actions in different institutional contexts. As the book relates to reshaping engineering education, a considerable emphasis has been put on the *learning* mindset in relation to the two other mindsets.

In the following, we will briefly introduce the challenges which have brought this reshaping process into action.

1.4 The Sociocultural-Environmental Challenge

A shift to solving complex human issues is the future of engineering. With that, people's culture and their interactions must be part of the problem definition, solution, and evaluation. The way people interact, shape, and reshape the cultural settings for technological developments are part of the problem-solving paradigm. In other words, we must consider not only how culture materializes itself, but also how culture is lived. Stressing the need for a sociocultural-environmental mindset on the reshaping of engineering education, to make synergy out of diversity, is needed to address complex and wicked problems. Key components of this sociotechnical mindset are ethical practice and sustainability.

Technology is developed for a purpose, and it is applied very differently in different cultural contexts. Different cultures have different framework conditions, and differences occur in terms of access to financial resources, demographics, market dynamics, political contexts, levels of literacy, among other factors. It is therefore challenging to transfer technology developments across cultural contexts, and this means that we also must include the way people interact, shape, and reshape the cultural settings for technological developments. In other words, we must consider how culture is institutionalized and materialized and embedded in discourses and practices. Thereby a sociocultural-environmental mindset on the reshaping of engineering education is needed to make synergy out of the diversity needed to address complex problems.

However, many of the complex problems that engineers are facing, are grounded in an unsustainable interaction between nature and human behavior, which ties the sociocultural context to the environmental context. The impacts from climate change underline the urgency of the sustainability challenges, but the concern for sustainable development is far from new.

In the 1980s, the report of the World Commission on Environment and Development pointed towards a threatened future and called for coordinated efforts for sustainable development (World Commission on Environment and Development, 1987). Governments and environmental agencies, throughout the world, initiated strategies in alignment with this future trajectory. Cleaner technologies were developed to limit the environmental impacts in the short run, and management systems and standards were developed to provide cleaner production, cleaner products, and cleaner ecosystems that all together could decouple economic growth from environmental impacts. The ambition embedded in the call for a circular economy captures the essence of such decoupling by extending the lifecycle of products and rejecting a linear take-make-consume-trash model.

During this development, increasing focus has been given to the social pillars of sustainability and, in 1999, the *United Nations Global Compact* was initiated. It was recognized that environmental and human impacts had to be considered alongside trade-offs, which made decision making for sustainability even more difficult.

The power of education has also been a part of the sustainability agenda for several decades. In 2005, UNESCO launched the *United Nations Decade of Education for Sustainable Development* and in the final stages of the decade, in 2012, The Higher Education Sustainability Initiative (HESI) took off (United Nations, 2022). During its first decade, HESI grew to a membership of almost 300 universities worldwide.

Education for Sustainable Development (ESD) furthermore institutionalized itself in the framing of different professions, and in 2002 the first conference on Engineering Education in Sustainable Development was held. What Stephen Sterling had called the BIG question became an important part of rethinking engineering education: How should—and how can—education and learning be rethought and reconfigured to make a significant and central contribution to achieving a more sustainable and just world? (Sterling, 2022).

What also became evident in this new century is that we needed to rethink the way we understand nature. As a reaction to the understanding of nature as something to be exploited for the benefit of the humankind, a preventive approach to nature developed during the last part of the twentieth century. Symptomatic was the famous act of Julia Butterfly Hill who sat in her treehouse for 738 days to prevent the tree from being cut down. There is no doubt that social movements striving for environmental protection have had crucial importance by raising attention to value of nature in itself.

In the twenty-first century, nature however started to communicate more clearly without the help of environmental protectionists—a language spoken in terms of cyclones, tornadoes, floods, droughts, bushfires, crop failures, dust storms, etc. For some, nature might still be an object of exploitation on one hand and a treasure to protect on the other, but most of all, nature has become one of the most important stakeholders to serve for long-term survival.

In 2015, the UN Sustainable Development Goals, the SDGs, provided a comprehensive framework for addressing the complexity of grand challenges which are excellent plans for engineering projects; in a similar way the US National Academy of Engineering provided similar guidelines (United Nations, 2021; US National Academy of Engineering, 2022). The SDGs related to clean water, energy, industry and infrastructure; cities and responsible production are directly targeted in engineering practice. However, engineering underpins every industry, which ultimately contributes to improving poverty, hunger, health, equality, work and economic growth, climate action, life on land and in water, peace, and partnerships.

Furthermore, besides providing a framework to handle the complexity of sustainability itself, the SDGs succeeded in addressing nature conservation and protection as well as the sociocultural context. Engineers of the twenty-first century must think in triple bottom lines (People, Profits, and the Planet) to act as agents for sustainable development and to identify themselves as global citizens and partners.

The engineering education community has responded in different ways to address this question. One response has been to create new branches of engineering with specific focus on sustainability, such as environmental engineering. Beyond such specializations in sustainability science, engineering, and management, efforts have been made to integrate sustainability in engineering programs at large. These approaches revealed challenges that are not easy to overcome. Many programs that have focused on development and teaching of solutions to standard problems had a tunnel vision approach that limited engagements of other areas of engineering disciplines.

Conceptual frameworks and methodologies from sustainability science can frame system thinking toward sustainable societies (e.g., lifecycle-thinking, ecodesign, and circular economy frameworks), but the increasing complexity of the sustainability challenge necessarily calls for collaboration across disciplines, sectors, and cultures. No single discipline, sector, or culture can manage this challenge alone; partnerships are needed to combine knowledge across interdisciplinary borders, and contextual learning is needed to point to the right partnerships to cope with the problem at hand.

In summary, complex problems must be solved in a larger sociocultural and environmental context to sustain nature and human beings and to create conditions for humanity beyond being. We all want to experience quality of life, whatever that means in different cultural settings. No doubt, engineering has had and will have a profound effect on humanity and on the planet. If we are to mitigate climate change, then engineering will need to play a larger part.

However, as nature has started to speak back in rather indisputable terms, the attention to the interdependencies and diversity in the societal and environmental context becomes ever more critical. Engineering, as a profession, therefore, must prepare graduates to work on the grand challenges of the twenty-first century, but in doing so, their ability to collaborate becomes crucial. Complex challenges have many interacting components and cannot be addressed by individuals or by groups of similar backgrounds. Broad collaborations by diverse teams are critical. Furthermore, no single society can afford finding solutions alone nor keep grand challenges outside their borders. Nature cannot be kept within borders.

1.5 The Digital Challenge

Over the past 15 years, digital technologies have expanded and invaded every aspect of our lives. The introduction of smartphones in 2007, enabled an unprecedented level of information exchange, and the ability to connect wirelessly to the Internet attracted younger and older generations. The introduction of social websites connected people and opened new doors for new commerce at unexpected volumes. In a short time, the world experienced the birth and growth of many small companies that became commercial giants by facilitating enquiries, sales, and purchases online, worldwide.

All these changes happened at an unprecedented speed; a digital quake overwhelmed us and made it necessary to navigate through fast and permanent changes to seek criteria for norms and regulations that would embody ethics and civility, enable free will, freedom, and democratic processes. Unfortunately, these goals remain elusive.

What is astonishing is that the digital quake covered every geographical area of the world, almost at the same time. This created unprecedented opportunities for people and countries. Although the utility of the digital technology is vastly available, innovation in digital technologies continues to be in the hands of a few countries that have dominated the digital markets and then gained from its related commerce. This might be viewed as an extension of the early innovation in semiconductors leading to amazing advancements in electronics, information storage technologies, and wireless circuitry.

In addition, software evolved into flexible platforms and enabled communications and constructing information. Although many of these technologies were initiated by US companies, the world at large participated and created supplementary technologies, without which the current advancements could not have happened. For example, a vast number of sensors of different types and purposes are now connected by the Internet of things (IoT) which enable further communications and generation of data that can be used for many social, medical, security, and educational purposes.

Although challenging, digitalization holds a huge potential in the reshaping of engineering education. Employing digital technologies in education continue to be layers within current content and pedagogy. We observe more and more digital learning and blended formats for engineering students. These will create even more possibilities for active learning methodologies and applied blended learning modes. However, learners will have to organize their own learning process virtually, and they will need ideas, imagination, peer-to-peer discussions, and structures for how they can organize, reflect, and improve these processes. Therefore, meta-cognitive skills for progressing learning become an important part of future skill sets.

Digital technologies are not only a matter of communicating and teaching online. Artificial intelligence will dominate the digital technology space. This is creating a need for massive shifts in content of many of the courses as well as in pedagogy.

Many of the current courses added computational aspects and simulations to their content and problem solving, but this is the tip of the iceberg. Machine learning will shift how and what we teach. Unfortunately, the instructors are not ready for this massive shift, and there is a resistance to moving forward with a fully digitized curriculum. How do we enable our students to be true citizen of the digital age? How are they going to learn to work with intelligent machines and learn along with them?

1.6 The Employability Challenge

The employability challenge is not a new one. It is the challenge of bridging the gap between education and the skills needed for productive work. Engineers, who match future societal needs, are in many countries a scarce resource, and matching students' talents to jobs that are evolving quickly is a complex matter.

Competencies for employability can, according to Yorke (2004), be viewed as '*a set of achievements – being skills, understandings and personal attributes – that make* *graduates more likely to gain employment and be successful in their chosen occupation, which benefits themselves, the workforce, the community, and the economy'* (Yorke, 2004, p. 3).

First, such description captures the complexity of moving from the individual micro-level to the societal value of graduates on a macrolevel. Graduates may be educated to address different contextual layers in the design of technological products and services, but to transfer this to a situation where they must put themselves in the center of development is another matter. The interaction between intrinsic and extrinsic motivation becomes important. Students need to reflect on how personal traits, personal interests, and attributes will shape their career track, on the one hand, and external requirements on the other.

Reflexivity about professional identity-making, thereby becomes an important competency for graduates in a lifelong learning perspective. It is about making sense of a new work-context and relating it to personal motivations. Graduates must be able to think critically about the context and be creative to do more than react to requirements; they should also be able to create changes in the new work environment. This is expected from an academically trained workforce. Some universities have responded to the employability challenge by requiring students to make a competency profile or a career plan of their own, but that is not enough.

Secondly, it can be noted that the descriptions presented above imply a rather individual focus on employability, as the single graduate is intended to meet these sets of requirements. For sure, individuals must be enabled to stand on their own when graduating as they cannot bring either professors or fellow students with them on their first day in a new job. However, professional requirements are seldom fully met by individuals alone, but collaboratively. This might be in peer-to-peer collaboration, in teams or by interacting in larger technological as well as national systems of innovation.

Thereby, each student must also reflect on how they position themselves within these social settings, critically consider the preconceptions they bring into a group, reflect on the relation between individual and collective values, and contribute to a healthy work environment. The accessibility and interplay of resources, the strategies reinforced by management as well as the administrative support might also interfere at the organizational level.

In that sense, the university must act as a playground for future professional work, for example by letting students work on real-life problems. It might be hard to solve complex problems in education—but the relation to the real-world problems should be part of students' learning processes to prepare them for their later careers. The transformation from the educational setting to the professional setting can be further reinforced by making room for students to have a part-time job related to their subject of study or supporting internships. The conditions for doing might however be considerable different in different national contexts. In research universities, working in research labs opens possibilities for understanding work on open-ended problems.

Third, the definition of employability includes complexity due to a high degree of diversity in stakeholder interests in both the workforces and communities. Therefore, students might find themselves in very different types of engagements dependent on how they are intertwined in the quadruple-helix ecosystem which involves the university, industry, government, and civil society. Work in business, academia, government, and non-governmental workforces will evidently include different practices, institutions, and discourses. As technological systems as well as the challenges of engineering are becoming more complex, graduates are expected to be able to cope with more interactions and partnerships in the quadruple-helix.

As the streams in the quadruple-helix get more closely intertwined, and the partnerships more mutually dependent, the boundaries become more blurred. What then becomes important is that graduates have a clear professional identity, and at the same time can connect in meaningful ways across boundaries. It also means that graduates should be able to decode organizational cultures and structures within their own discipline, department, section, or community. They must make sense of and reinvent different patterns of boundary crossing between organizational and interorganizational units to create synergy out of diversity.

The major boundary to cross for graduates, from education to work, not only calls for skills to cross different disciplinary borders, but also to cross borders between the academic and non-academic domains. How educational stakeholders shape 'what matters' from an academic point of view might not correspond to what other stakeholders would outline as a matter of importance (Kolmos & Holgaard, 2018). Thereby, interactions and communications among university faculty and future employers of graduates are crucial.

To sum up, employability challenges engineering education institutions to develop a set of professional attributes suited to the future of work and citizenship. This must include interdisciplinarity and a range of generic competencies. Following this complexity, conceptualizations of employability competencies overall call for boundary-crossing competencies in many difference shades. Learning about creating innovations and entrepreneurial skills is also critical. Some universities have courses and open spaces for innovations and startups.

1.7 Structure of the Book

The educational mindsets conceptualized in this book provide a frame of reference to the reshaping of engineering education. Some examples of how this framing can be applied are provided.

The book is structured in three parts, where the first two parts elaborate on the presented mindsets including the future-system-design mindset (Part 1—Chaps. 2, 3, and 4) and the interdisciplinary-learning mindset (Part 2—Chaps. 5, 6, 7, and 8). Part 3 exemplifies how these mindsets can act as a framing of educational activities as had been practiced in three different institutions, Harvard University, the University of Technology Sydney (UTS), and Aalborg University (AAU), Denmark (Chaps. 9, 10, and 11). Finally, Part 4, Chap. 12, summarizes the lessons learned and the lessons yet to be learned.

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Part I
Systems, Design, and New Competencies

Introduction to Chaps. 2, 3, and 4

Sociocultural systems, as creators and users of technology, are complex systems. They are ecosystems in constant evolution. While sociocultural systems are dynamic systems, which offer a path forward, they also carry the history of the past. The discrepancy between the present situation and the envisioned situation is crucial, and therefore, we must consider the dimension of time. Whereas the present might be difficult to grasp, the future holds challenges of even greater uncertainty.

The ability to take risks is crucial to make more radical innovations. Universities have a clear role of taking such risks as part of their research agenda, and every student should be able to master foresight to handle uncertainty and create sustainable solutions. Although expanded to include nonlinear trends, forecasting can be a risky exercise and may lead to misguided approaches or outcomes. Instead, foresight is an approach to envisioning different futures by taking into consideration sensitivity when creating solutions.

When predictability is low, some students might start to feel uncomfortable. Foresight methodologies provide a framework for navigating in chaos, and they reinforce decision making by limiting uncertainties through structured analysis. Methods within this area are important, as large infrastructure projects are not easily corrected. Furthermore, the dependency to other complex systems, like political systems, is high.

If the curriculum is not open for integrating foresight, students might miss out the possibility of learning how to take risks. If the students only consider one scenario, how can they respond to the 'what if questions' which will inevitably arise in a change process? A quick Internet search shows that academic researchers point out the connection between engineering and multiscenarios, even in product developments on the micro-level. As there is no single future, multiscenario building, e.g., of climate scenarios, is promising.

Resolving current challenges also requires further attention to the dynamics of ecosystems and accounts for future evolutions of culture and technology. For universities, it is not only a matter of integrating foresight into the curriculum. Innovative leadership is essential for the success of transforming future engineering education. Some universities have taken up this challenge by introducing mission-driven approaches on the strategic level. Mariana Mazzucato (2022) has introduced so-called moonshot programs, which integrate triple helix actors to solve problems on a massive scale. In this way, political agendas are broken down to targeted missions, which initiate interactions and partnerships across sectors to initiate a portfolio of projects. Not only university faculties should be involved, but also students, to reinforce changes.

Foresight is about using mental models to shape future scenarios, and mental models are grounded in experience as well as a solid knowledge base and ability to imagine future constructs. The American Sociologist, C. Wright Mills (1959) introduced the term of sociological imagination and the ability to 'think yourself away,' pull away from the situation and think from an alternative point of view. Without opening for alternative futures and being able to imagine sociocultural systems completely altered, it will be difficult to account for the urgency of sustainable development.

From a systems engineering point of view, design methodologies can act as an enabler to understand, develop, and interlink complex technological systems. Although design processes are iterative in nature, most of them involve activities similar to empathize with the user, define the problem, ideate solutions, prototype the most promising solution, and test against the requirements. These phases, however, cover a huge range of methods.

Furthermore, to act in complex systems it must be acknowledged that there is not only one creator and one receiver of technology. As complexity arises, multiple stakeholders must be taken into account, and it becomes a co-designing process that will intertwine the creator and user perspective. Design implies interdisciplinary collaboration and communication. Furthermore, it is not only a co-design by humans. It is a co-design with intelligent machines.

Design is fundamentally a creative process to address human challenges, and it starts out with real-life problems. The other side of design is to offer insights and qualities which people did not know of or have the sole purpose of creating pleasure. Design provides the opportunity to distinguish one product from another, one service from another, and one system from another. Design processes are taking care of the interlinkages in the system. In short, functionality does not work alone.

Although most design happens at a micro-level, design includes considerations to the user context as well as the sociocultural context. Design centers around developing new products and service systems that can support sustainable development and that are so flexible that they may be adjusted to the pace of change in society, while taking into consideration different sociocultural contexts. As previously mentioned, foresight is needed to take into consideration potential impacts of megaprojects, as early as possible; design thinking is needed to do the very same thing on a micro- or meso-level.

Systems thinking, foresight, and design are the fundamentals of future engineering, and they must play an important role in reshaping engineering education. It is, however, not a question of how to add to the curriculum; it is a question of how to rethink the curriculum. Engineering curricula must evolve to provide students with the required knowledge to be contributing citizens and to be able to participate in solving complex challenges. However, this requires systematic change on several fronts: curricula (obviously), academics (new skills and new attitudes), students (new skills and new attitudes), industry (new forms of engagement), and institutional support (through facilities, resources, etc.).

When the curriculum must be reshaped, a reshaping of the competencies is a part of the process. Complex systems cannot be addressed properly without sense making and initiative; foresight calls for leadership and decision making; design includes complex problem solving, critical thinking, creativity, and entrepreneurship to transform ideas to value, and so on. Furthermore, systems thinking is also about being able to distinguish between text and context, to question dualisms and create dialectic relationships, between human and machine, between nature and culture. Fulfilling this need will require a paradigm shift of engineering education to value an open and interdisciplinary curriculum.

Overall, Part I argues for such an interdisciplinary turn of pedagogy. Chapter 2 elaborates on systems and foresight, whereas Chap. 3 outlines the design approach to handle complex systems, taking into consideration the potentials of digitalization. In Chap. 4, we outline competencies that will enhance systems thinking and design, including digital literacy, creativity, entrepreneurship, and the ability to address social needs and user requirements.

Chapter 2
A Systems Approach to Addressing Human Challenges

In Chap. 2, this chapter discusses the nuances of complex systems, accentuating that human communications and technology are integral parts of our social systems. Whenever humans are positioned at the centre of any system, complexity emerges. Interventions in complex systems are very difficult, due to feedback loops and their associated time delays and the presence of many interacting components. Each element within a complex system intertwines with others, making any intervention a precarious act, where intervening in a part of the system invariably affects other parts. Engineering education is a complex system, and it is evolving under the new AI technologies. Interventions are required and the relational dynamics among students, as well as between students and educators, are critical axes around which educational experiences must revolve. The dynamic educational ecosystems, burgeoning with myriad informal and formal, verbal and non-verbal communications,shape the educational experience and outcomes in profound ways. Ensuring that interventions do not inadvertently disrupt or diminish these interactional ecosystems requires an adept understanding of the inherent complexity embedded within the educational systems.

2.1 Investigating Challenges as Systems

The twentieth century ushered in many social challenges, which continue to test our intelligence and creativity. The UN work on categorizing these challenges is perhaps the most comprehensive list of these challenges. The Strategic Development Goals list provides elaborate details of these challenges, which are mostly inherited from the past. Ubiquitous digital technologies enlarge this list and put humanity at an inflection point of unprecedented threats.

Innovation causes rapid changes and vast disruptions, which affect every aspect of our lives. New technologies empower us with more efficiency, capacity to manage large data, which can create transparency and facilitate integration among physical,

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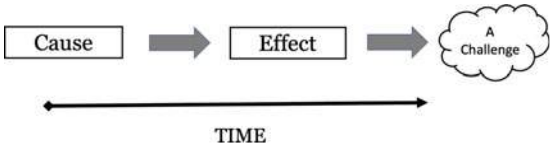
Fig. 2.1 Cause and effect—one event-oriented challenges



biological, and digital domains. But these advances are redefining what it means to be human.

Human challenges are multicomponents and multivariable functions and have many interactions. When we take a close examination of these components, we can create lists of their constituencies, but we rarely translate our lists to connections among them. If we did, we usually use a simple cause-and-effect logic. This approach simplifies the issues and may lead to actions that exaggerate, rather than reduce, the challenge. It is well recognized that a systems approach is needed to understand and mitigate these challenges.

Humans have an intuitive sense of systems, and over thousands of years, we built complicated physical systems with many components and connections, such as transport or water distributions. Seven thousand years ago, the Sumerians built dams and aqueducts on the Tigris and the Euphrates rivers (Helbaek, 1972) and they had a sense of their system. Their system boundary included roads and a network of irrigation spaces. Much later the Romans built amazing aqueducts (De Feo et al., 2011) and transportation networks (Hitchner, 2012). These early systems functioned very well and were sensitive to sustainability. They provide good insights into how early work considered human needs within nature and its limited resources.

Although there is a long history of systems thinking, there is a much shorter history of systems theory. Systems theory was formally defined by Von Bertalanffy in his *General Systems Theory* book (Von Bertalanffy, 1950). This work initiated the development of systems-oriented research in disciplines (Francois, 2004; International Institute for General Systems Studies, 2001; Midgley, 2002) and later work linked theories with implementation methods (Cabrera & Cabrera, 2015).

Systems theory invites a sophisticated level of classification and methods for addressing the different types of systems. In our childhood, we thought of events in cause-and-effect relationship, and we rarely challenge such assumptions. Most of us are linear thinkers, and our examination paradigm has limited tools. Interestingly, when we notice the connectivity among elements of an issue, we are not terribly surprised, but we brush their interactions aside focusing on some issues that we can solve quickly (Fig. 2.1). When we examine the SDGs, we cannot afford to do that, as every goal is part of the quest for a sustainable life, by staying within planetary boundaries (Costanza et al., 2016).

Paradigms are very powerful human constructs (Kuhn, 1970). They last for a long time and offer a sense of security and assurance. Often the human brain gets stuck in one of them with no place to escape. We need to shed the one cause-and-effect paradigm and move into a systems paradigm. The paradigm of interacting elements

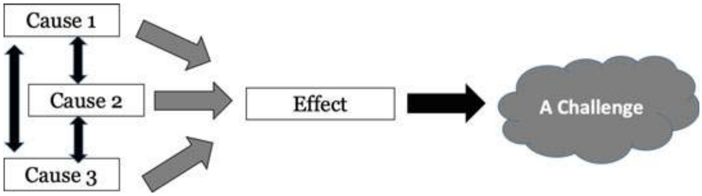


Fig. 2.2 Several interacting causes lead to an effect, which is part of the challenge

of nonlinear dependencies, requiring multiple tools to examine its elements, is the enabler to understand human challenges and finding mitigations. Indeed, our world is made up of many connections which create challenging *systems* (Fig. 2.2).

The number and types of these systems increased with the addition of the digital innovations that augmented our physical and mental capacities. Making decisions with the help of machines is relatively new to us, but it has been anticipated for a long time. Now we have additional tools to find mitigations and solutions for the plethora of systems issues that consist of older challenges inlaid with digital technologies.

Investigating systems requires using several tools or lenses. These lenses are part of our social-mental construct, and they represent different notions related to sustainability, socioeconomics, ethical, cultural, legal, business, health, and political issues, among many other lenses. This makes for a long list of interacting items and studying them requires a methodology, which we will discuss next.

2.2 Defining Systems

Systems are mental constructs, and some are nature-made. Every system is bounded by space and time, influenced by its environment, defined by its structure and purpose, and expressed through its function. Each system has a number of elements. These elements can be human-made, hardware and software artifacts, and nature made of physical and biological elements.

Systems can be organized hierarchically according to their type of interactions and may have categorical combinations like natural systems, man-nature systems, man–machine system, or machine-machine system. Typically, these systems are not isolated and there might be significant interactions between these hierarchies. These interactions lead to dynamics that may not be stationary and change in time.

Thus, system dynamics are manifestations of how the different components—being physical/chemical, virtual/symbolic, mental/cognitive, ecological, sociological, and biological—may exist, organized, and communicate within a system and with the outside environment.

2.3 Closed and Open Systems

Closed systems are perhaps the least interesting, and closed social systems are rare. A closed system does not exchange energy or communicate with the outside. There are some examples where the system is isolated and has only an internal flow. Most systems are open systems.

Open systems maintain their dynamic existence by continuously exchanging matter and energy with their environment. Von Bertalanffy studied systems that are maintained by '*the continuous flow of matter. Living forms are not in being, they are happening, they are the expression of a perpetual stream of matter and energy which passes through the organism and at the same time constitutes it*' (Von Bertalanffy, 1968).

The conceptual model that Von Bertalanffy gave for the living organism, as an open system, has revolutionary implications for behavioral and social sciences. In particular, the role of entropy in these systems is very different than in closed systems. In closed systems, entropy is a source of disruption and disorganization. The universe, as a closed system, obeys the normal rules of thermodynamics and entropy. However, in open systems, which exchange energy and matter, entropy leads to new system organization! As the open system interacts with the environment, the environment suffers the consequences of the disrupting entropy, and the open system creates a new order! Open systems do not have infinite interactions, and there are 'boundaries' that define their extent. As we are examining a challenge, we need to define the boundary of its system.

One of the mysteries of life is the presence of open systems and their negative entropy. In open systems, i.e., life on earth systems, steady states are maintained by a self-regulating balance of decay and synthesis, leading to emergence of increased order and organization. These characteristics are specific to open systems and form new rules. Since all systems, physical and biological, interact with some other systems, a system can have a 'negative entropy' while the entropy of another interacting one increases (Prigogine & Stengers, 1997).

Evolution is a good example for the presence of systems, which continue to improve themselves. For example, viruses are biological systems that are expected to move into disarray and randomness. But some virus systems continue to evolve into better organization. The COVID virus, as a living system, is an improbable non-equilibrium state, but it continues to evolve into more dangerous ones—better for its survival, but not for us. As the system evolves, mistakes on the DNA level can happen, which could lead to the demise of the virus or not!

Due to the interactions among the elements of the system, the totality is more than the sum of the parts. There is more than one meaning for the word 'more' here. More might refer to the functions, activities, creativity, interactions with the outside, and possibly more viability.

2.4 Ordered and Unordered Systems

Academicians classify systems according to the type of interactions among their parts and with their environment. Theory and mathematics contributed to the classifications of systems, with the goal of understanding organizations and managing them (Thelen & Smith, 1998). Other contributors, interested in biological systems, or systems engineering, used network theory for classifications too. Social challenges need classifications that place humans and their environments at the center of the classifications. These theories identify features and create methodologies to address the challenges. There are several books and articles that have been written on the classification of systems (Bushe & Marshak, 2016; Stacey, 2016). A quick Google search gives more book titles than anyone could ever read. Here, we provide a general overview of the system interactions and their implications for addressing pressing human challenges.

In each system, there are several *elements*. These elements interact within the system and with other elements of other systems that may be present in the same environment; see Fig. 2.3. These interactions define the nature of the system. If the interactions are limited and they exhibit time reversal then, most likely, the system belongs to the category of ordered systems. Time reversal is an interesting test. Not all systems can be brought back to their original state. For example, most electromechanical systems can be fixed when some elements break; cars are very complicated, but a broken car can be fixed. On the other hand, the state of a traffic on a given hour of a certain day cannot be brought back. In this case, there is a significant number of interactions, and thus the traffic system does not belong to the ordered category. Interactions that are time-dependent and nonlinear create dynamics that may be difficult to predict, calculate, or simulate. These interactions are encountered in complex systems.

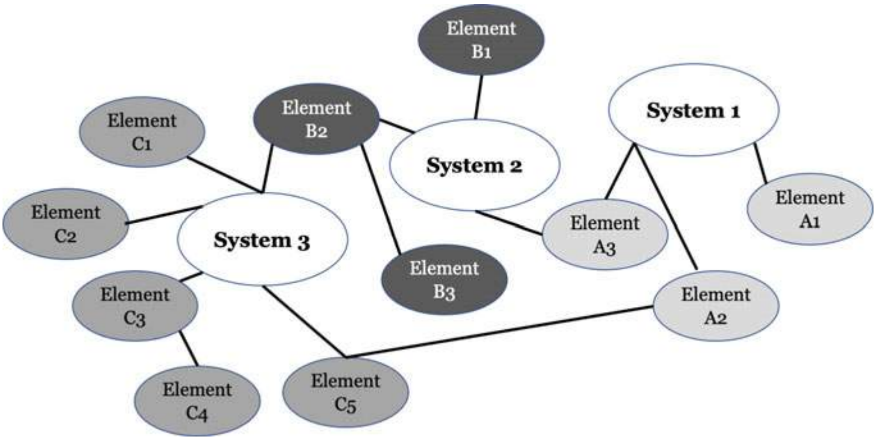


Fig. 2.3 An illustration of three interacting systems

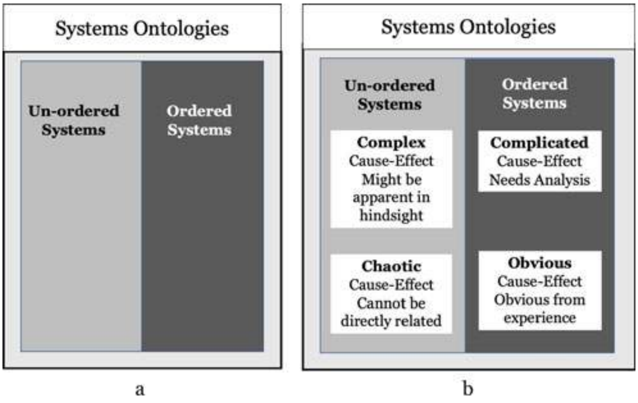


Fig. 2.4 **a** Two general ontologies of systems, **b** Cynefin framework

Most human systems are unordered systems, and they exhibit unpredictable dynamics. There are categories within the ordered and the unordered systems, which will be discussed next.

The framework of ordered and unordered systems (Fig. 2.4a) was extended to a descriptive model, called the Cynefin framework (Snowden & Boone, 2007), which provides a more detailed ontology of systems and provides a methodology for addressing them. The Cynefin model can be used to engage engineers in ways of thinking about systems problems (Berger & Johnston, 2015). This model presents four ontologies: obvious and complicated (ordered) systems, and complex, and chaotic (disordered) systems (Fig. 2.4b).

There are many simple systems. Some of them may become complicated. This happens when the number of elements increase as well as the interactions increase. These systems become more capable or intelligent. But the interactions stay time-reversable. This type of ordered system is mostly Newtonian and can be addressed by good engineering tools.

On the other hand, when the system has a large number of interacting elements, the system is complex. Complex systems may end up chaotic with some changes in initial conditions, nonlinear dynamics, or emergent behavior (Bertuglia & Vaio, 2005). Chaotic systems do not last for a long time, and most of the time, they revert to being complex systems. Chaotic behavior is a manifestation of nonlinear dynamics, and therefore not all chaotic systems are complex (Rickles et al., 2007). Also, not all nonlinear systems are chaotic; initial conditions play an important role.

The engineering profession has developed an enormous body of knowledge around *ordered* systems, resting largely on the physical sciences and mathematics.

This scientific knowledge defines the *obvious* or *clear* category and is constantly being refined, through scientific research. The best practice is an ongoing effort in every engineering discipline, and much of this knowledge is captured as codes of practice and international standards, e.g., ISO standards at https://www.iso.org.

2.5 Addressing Ordered and Unordered Systems

For ordered systems, the strategy for problem solving is to '*sense, categorize/analyze, and respond.*' When the problem is obvious or simple, categorizing the problem makes the solution clear, and by using best practices and engineering standards, a good solution can be obtained. For more complicated problems, an analysis step is required. This may not be easy to do, but the outcome is predictable. Recall that for ordered systems, even when there are interacting elements, Newtonian physics and engineering science apply, and by breaking the system into components, a solution can be constructed.

Unsurprisingly, most of the undergraduate programs are built around analysis of complicated systems. Appropriate complicated challenges are normally assigned for different disciplines or majors. These prepare students to sense, analyze, and respond with appropriate solutions. Computer simulations have added significant capacity to problem solving and reduced the time to find solutions. In addition, big data, machine learning, and different intelligent machines can open doors for creativity and invention.

When the system has many interacting elements, finding effective solutions is not straightforward. The strategy for problem solving is to '*probe-sense and respond*.' If the internal and external forces cause the system to reach a chaotic state, as in disasters and emergency situations, one has to act quickly, and the strategy becomes act-sense and then respond at a system level.

To probe a complex system, we need to map it and study its components and their interactions. Mapping provides a clear visualization of the components and their behavior. In addition, the map explains and communicates information on the challenge and is used to manage complexity and find root causes of the challenge.

To map a complex system, we start by identifying it. That is, we find its boundaries. Boundary identification is an important step since all systems exist within bigger systems, and one cannot try to find mitigations for a complex system in its broadest context. Next, we need to identify the system's elements and how they interact with each other. We need to identify the feedback loops and the systems pattern of behavior.

2.6 The Dynamics of Complex Systems

Some human challenges are nonlinear dynamic systems subject to forces of stability and instability. These forces are a result of significant direct and indirect interactions among the elements and the presence of feedback loops. Other forces that contribute to the overall systems dynamics result from the amplification of fluctuations and random events. The overall actions of these forces lead to collective behavior of the system and its ability to adapt to changes in its environment.

Complex systems are dynamic entities, whereas a system's map is a visual representation that is a snapshot in time and does not show the dynamics of the interactions among the elements of a system. It is possible to illustrate the feedback loops and give indications on the dynamics. Then, some may refer to the map as a causal map.

In general, systems have inputs and outputs and, in complex systems, the relationships among these components are nonlinear. Feedback loops, Fig. 2.5, are often present and create complexity as they drive some elements of the system.

Feedback loops are part of many physical and biological systems, as well as in economics. They are important in electronics, genetic regulation, and economic cycles, for example. There are two types of feedback loops called positive and negative loops. The positive ones increase or enhance a parameter or a process, and they tend to drive the system away from its equilibrium. The negative ones reduce a parameter or dampen a process and drive the system toward an equilibrium state. Thus, feedback loops may create a growth or the decline of the system. Figure 2.6 illustrates these points.

Delays in feedbacks create complexity. An example for systems with time delays is cloud-rain formation, depicted in Fig. 2.7. In this case, there are several nested loops and each may have a particular time delay and unpredictability. The feedback loops and interaction among the different elements illustrate a dynamic complex system.

In complex systems, there is no central command and control, nor planning and management. System elements act individually or collectively, under the influence of the feedback loops and their dynamics. These give rise to collective and unexpected behaviors.

Complex collective behavior can be a result of simple rules that control the interactions and communications among the individual agents. This can be observed as

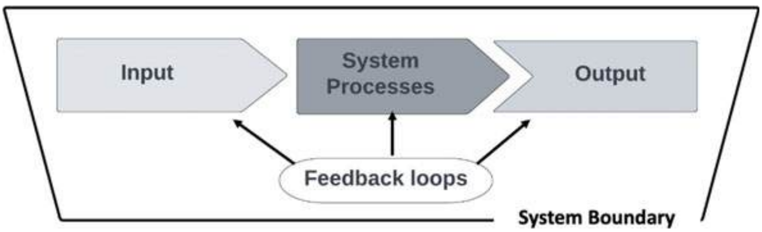


Fig. 2.5 A general diagram of a system of input/output and feedback loops

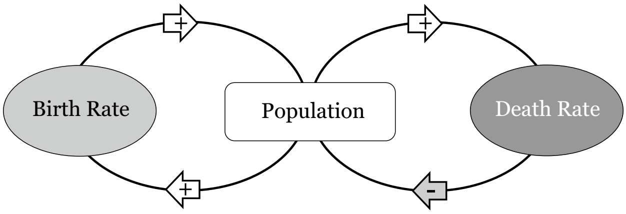


Fig. 2.6 A simple diagram of a population system—the balance between birth and death

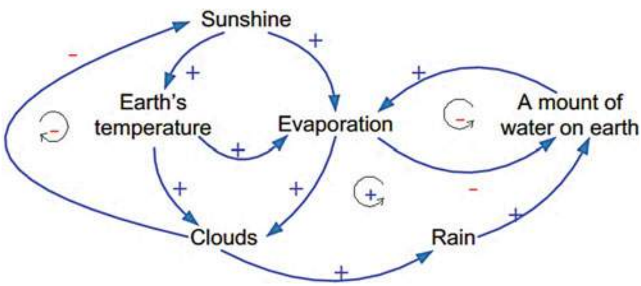


Fig. 2.7 Cloud-rain formation evaporation → clouds → rain → amount of water → evaporation

swarm intelligence in social insects such as ants, bees, birds, and fish. Collective behavior by fish and birds has three rules which create complexity and include separation or collision avoidance—i.e., short-range interactions; cohesion, or steering toward average position of neighbors—i.e., long-range attractions; and attempt to match velocity with nearby flock mates.

When the environment changes, or some parts of the system change, the overall system adapts to the new conditions and a new order emerges.

Emergent properties of complex systems are profound. New phenomena and behavior appear unexpectedly. Elements that were not interacting become part of new webs of interactions, and other interactions may disappear, and the system undergoes a paradigm shift.

For systems with several time-delay loops, and when a time delay becomes greater than the intrinsic response time of the system, periodic and even chaotic events, and solutions arise. Such complex adaptive systems live dynamically at the edge of chaos, where new possibilities emerge from the diversity of the elements (i.e., agents) and their creativity. These spontaneous responses give the system new life and sustain it.

On the other hand, a system might be in a state that is different from what we desire. This may promote some actions. Such actions may drive the feedback loops or change some interactions. Because of the nonlinearity of the system and its time delays, a thorough study of the system map is not enough. Some experimentation and observation will be needed. When the system is in a dynamic stability, chaotic states might appear. These states are very sensitive to initial conditions and our actions may create unexpected outcomes. The origin of these outcomes may not be known for a long time, during which the system may have fluctuating states and explosive instabilities.

Addressing complex nonlinear situations is not easy, but it may be urgent. As we mentioned before, the strategy for problem solving is to '*act, sense, and respond*.' Acting fast might be very important, as some situations require an immediate action plan since a system solution requires more time to study. Natural disasters are examples of these situations, and they put human beings at risk, and they need to be managed fast.

Introducing positive feedback might be appealing but should be monitored very carefully. Even small positive feedback steps that reinforce an initial change, can accumulate an exponential growth, and create an imbalance between the negative and positive feedback loops. When there is such an imbalance, unexpected chaotic outcomes may ensue (Radzicki, 1990).

After an intervention, a complex dynamic system may enter one of three states, albeit these states represent a continuum. The system can reach a stable equilibrium (point attractor) which is independent of time. Also, it is possible that the system periodically goes back to a previous stable state (periodic attractor). A more complex behavior can happen too. The system may be characterized by non-repetitive and non-predictable fluctuations that arise because of a concurrent interplay of negative and positive feedback loops (strange attractor). This interplay and the significant interactions create a new order.

The system can be in any of the above-mentioned states, depending on the dynamic combination of the forces, and on the relative strength of the interaction among the system's various elements. The system passes from a stable equilibrium to periodic behavior to chaos when the strength of the value of the parameters, i.e., linkages between the variables, changes (Feigenbaum, 1978), or when the number of variables with different periodicity increases (Thietart & Forgues, 1995).

In complex systems, every intervention is an experiment and a step forward to create mitigations. A new order might be a progressive one. On the other hand, we need to be aware that some solutions may create additional future challenges and bring the challenge to the realm of wicked problems (Rittel & Webber, 1973).

2.7 AI as a New Agent

Systems have several classifications and attributes. They mostly evolve around human needs, experiences, and challenges. More recently, we are experiencing the introduction of artificial intelligence, within many engineering spaces, in the thinking, making, and implementing. AI will augment our systems and provide exciting opportunities and new challenges. Students and educators need to engage these new agents and, as we map systems, a special care needs to be paid to their new type of interaction.

Table 2.1 Complex system classification, modified from (Magee & de Weck, 2004)

Some systems attributes	Some references
From simple to complex	Hubka and Eder (1988), Beitz et al. (1996)
Boundary: open versus closed	Von Bertalanffy (1968), Boulding (1953)
Origin: natural versus artificial	Von Bertalanffy (1968), Boulding (1953)
Time dependence: static versus dynamic	Von Bertalanffy (1968), Boulding (1953)
Control: autonomous/human in the loop	Ashby (1963)
Functional type	Beitz et al. (1996), Van Wyk (1988)

We may summarize some of the attributes of the systems, as shown in Table 2.1, and we note that most of the initial defining work was done a long time ago. But this is not a complete list, and more can be included when considering artificial intelligence systems.

2.8 SDGs as Complex Systems

Clearly, the Sustainable Development Goals (SDGs) belong to the class of open and unordered systems. Each SDG has several complex challenges. The SDGs illustrate what engineering students should learn to address, and what instructors should include in their courses to engage students with human challenges. There are several ways of grouping the SDGs; one is listed in Fig. 2.8. Obviously, some of the SDGs have more engineering challenges than others (the circled ones), yet these goals also include social aspects, with which engineers will need to grapple. Climate action is perhaps the standout example of this kind. There are several engineering solutions to mitigate climate change, but they cannot be implemented without political and social will.

The SDGs are giant problems and progress will only be made with each of them in a piecewise fashion, in every national and regional context. Engineers might reasonably be expected to address aspects of these problems, either in their own countries or in international contexts.

Although, in principle, engineering can contribute to problem solving in all aspects of the SDGs, there are some specific ones where engineers will need to provide basic services, such as in clean water and sanitation (SDG 6), infrastructure, in terms of buildings, transport, energy, telecommunications (SDGs 7, 9, 11) as more and more of the population live in cities. Engineers will also be involved in more efficient agriculture (SDG 2), better health services (SDG 3), education services (SDG 4), responsible production and recycling (SDG 12), and so on.

Many of these problems will be improved incrementally. Clean water is provided to one village or town at a time, often in conjunction with renewable energy and wastewater processing. This simple example shows the interconnectedness of the SDGs; in this case, clean water will invariably require energy and it will also produce

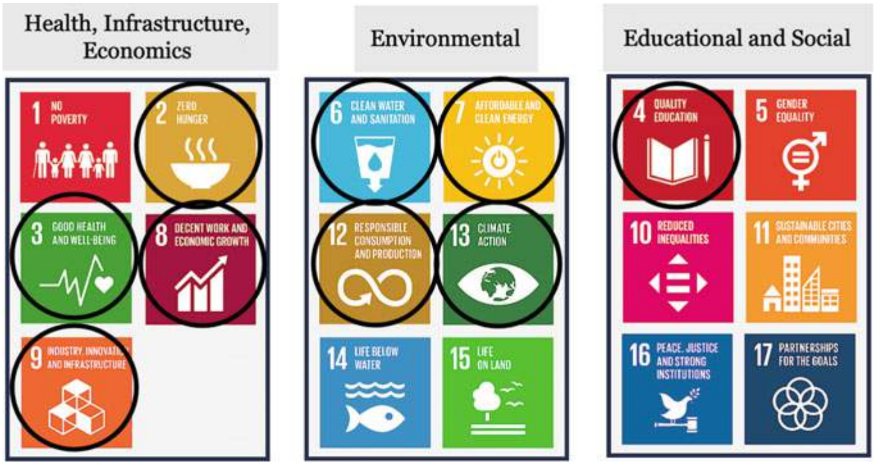


Fig. 2.8 Categories of the sustainable development goals, modified from (Kostoska & Kocarev, 2019)

waste, e.g., brine, which must be disposed safely for both humans and for the environment, an example of a water-energy-waste nexus. For example, see (Wang et al., 2018).

A close look at the SDGs brings forth the significant interactions among the strategic goals. Figure 2.9 shows how these goals are interdependent (Le Blanc, 2015). As we address one of the SDGs, we need to examine and address possible adverse effects on the others.

The mitigation strategy for complex challenges is to *probe, sense, and respond.* This fits neatly into a design thinking approach (Dym et al., 2005), where the first stage is to *empathize.* In the *probe* step, respondents must empathize with people

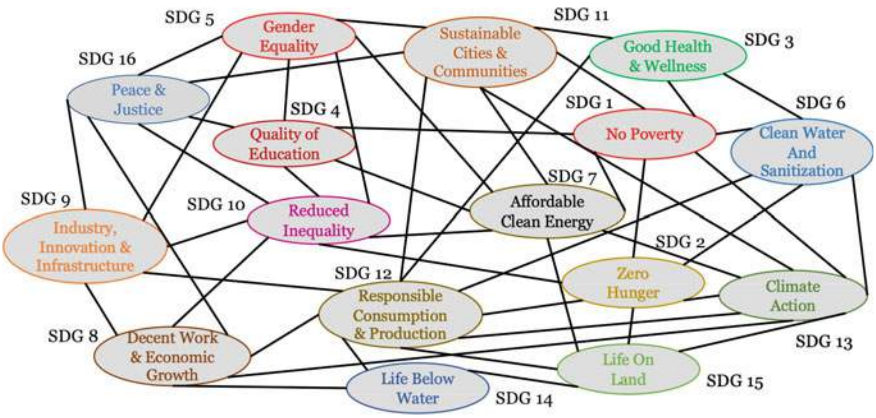


Fig. 2.9 Some of the interactions among the outcomes of the SDGs

experiencing the challenge and appreciate their situation. This requires involvement with the challenge and the people facing it. Empathy is not a simple matter to develop. Human senses and heuristics can interfere with getting the appropriate answers. Perhaps with appreciation and a direct involvement and understanding, the problem becomes defined enough for students to exercise their innovations.

Probing and sensing are part of the steps to define the problem to be solved. In addition, probing and sensing the system response informs creative solutions. Some critical questions should be asked such as: What is the nature of the problem? Is the system what we expected?

Responding is to develop appropriately scaled experiments to determine changes in system behavior, and to answer questions such as: What might we do about the system behavior? How do we know that the intervention works? Do we need to modify an implemented solution, e.g., in the case of transportation, reduce the toll to attract more customers?

When engineers work on complex human challenges, they need to develop this systems approach to problem management.

2.9 Systems Thinking

An important notion in human systems is the role of people in systems. Most systems are some combination of both engineered systems and social systems. A transport system, for example, is certainly made up of hardware such as roads, vehicles, and energy supply, but it serves human needs, and those users of the system will ultimately shape the hardware through their interactions, leading, for example, to a particular car size, height, new bus routes or new freeways or, indeed, reduction in the use of the transportation as people work from home. Understanding human transport behavior is critical to the design and operation of transport systems. This is an important lesson that is normally not discussed in technical courses.

To understand the interaction among the different components of the *Human-Artifact* system, different models had been proposed. Meadows proposed a model where 'system stock' is tracked (Meadows, 2009). Another model relies on establishing lenses and mapping by creating positive and negative interaction loops. Time delay is always noticed. These important factors of complex systems were discussed in the previous sections.

As we discussed earlier, the direct and indirect complex interactions among human beings, the human and the artifact, and machine-machine communications require several lenses and multidisciplinary people to study them. In the method of mapping complex systems, we created a visual study of a system and required that the relationships and the loops among its components to be indicated.

Broadly speaking, mapping allows us to provide an explanation of a system to better understand its complexity. Systems nest within larger systems. These systems interact and communicate. In addition, some elements that exist in a system may also exist within other systems.

In the example below, society is depicted as composed of several systems that have many interactions, Fig. 2.10. It is worth noting that the boundaries of these human systems are intertwined, and it is not reasonable to assume that each system has a clear boundary. For example, among education, medical, and financial systems there are several shared subsystems. When examining any of these systems, we need to identify these connecting elements yet focus on the main elements that attract the most connections. In addition, as we emphasized before, identifying feedback loops is critical.

Mapping the system with diverse groups and using multiple lenses, i.e., ways of viewing, ensure a broad view of the system. It is how we consider a system and its functions, as we define it.

As an example, let us create a simple map for an educational system. One may discuss this system from a financial point of view and consider budgets, faculty salaries, endowments, and financial aid. Equally, we could discuss it for infrastructure and link it to finances and pedagogy. A third view might be the curriculum and connections to jobs and the economic welfare of the graduating students as well as their contribution to society. As we use different lenses, we are connecting the educational system to the larger system that represents society.

This concept is illustrated in Fig. 2.11, where we limited the large number of interacting systems to one, e.g., the financial system and education.

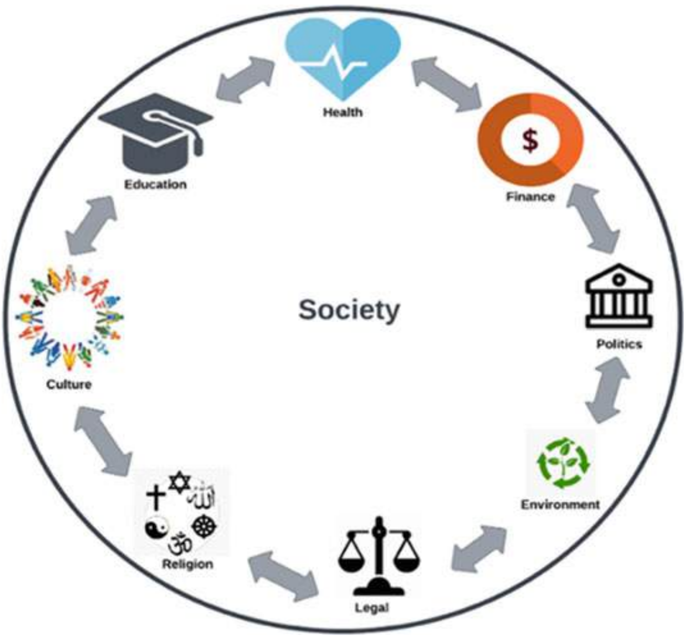


Fig. 2.10 Society as depicted by several human systems

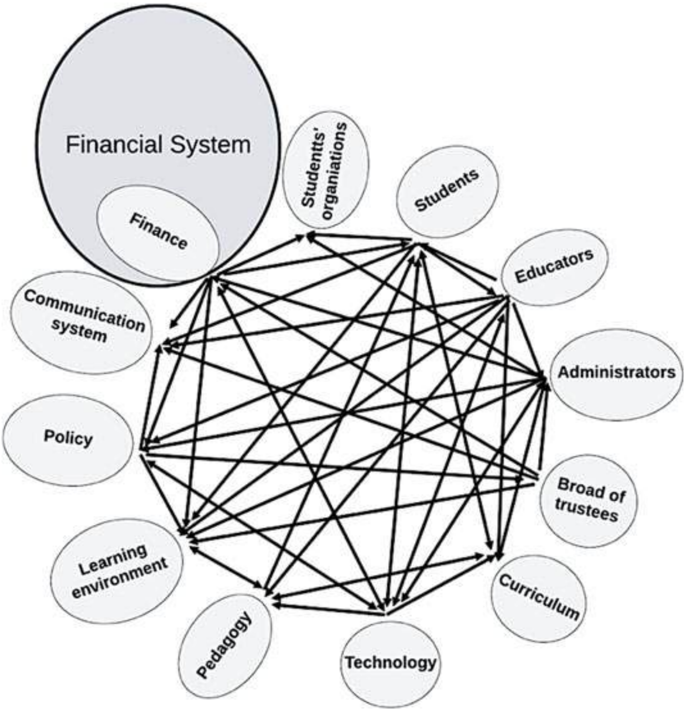


Fig. 2.11 Education as a system of interacting elements

Further, Fig. 2.11 needs to be considered within the broader social context. The system presented here shows relationships among several important elements, but these elements are not the same for all education systems, and the strength of their interactions can be very different. Educational systems change from one country to another and even from an institution to another within a country. Social contexts are critical, and they determine the relationships to other systems, as well as the different feedback loops.

In the example given here, the context is a US university where the educators constitute a main element in the system. Educators affect the curriculum, the pedagogy, and the learning environment. They drive policy and influence technology and the communication system. Of course, they have a significant influence on student learning and their careers. Each element in this example affects other elements and is affected by the totality. Many relationships are established, and many feedback loops are working. All of these create a unique complex system.

In a different model, the administrators might be the main element of an education system. Administrators make many decisions that can affect what and how students are educated. Similarly, the financial system with its banking and investment institutions significantly interacts with education in a social process that would vary in different sociopolitical systems.

As discussed earlier, mapping a system creates logical relationships among the system's elements and prioritizes these elements within a social context. Mapping is a study that is built on assumptions. One of the assumptions that might be built in the map is how the different elements evolve. But the map is a snapshot in time, and we need to be careful if we are using the map to consider how things will interact in the future. Time evolution can be very difficult to determine over a long time.

When we read a map, we may examine the purpose of a system. The purpose of the system asserts the values and determines the outcomes. If we wish to change the outcomes of a system, we need to examine all the main elements that affect the purpose and determine how the desired change might create feedback loops that may affect each element.

A good example to consider is a change in the outcome of an education system from being 'knowledge acquisition' to 'problem solving.' How would the change take place? and who would be creating the change, and who is affected by the new outcomes? In this example, the educators might be the prime element to create the change. But we cannot ignore the administrators, the technology, the learning environment, and the financial system. Moreover, we need to engage other stakeholders such as students' families and members of the political system, among others. The students are part of the system and will be heavily affected by this change, they need to be part of the process, but young people may be most ready for change. When such change takes place, what are the feedback loops? Are they from internal to the current system? Are they related to the infrastructure/finances? Are they related to employers? Is the accreditation affected? These are the types of questions that need to be addressed broadly.

Changes do not happen quickly, and their impact might be found several years after they take place. These time delays are important and difficult to track when a change propagates through several systems. Although interactions in human systems are based on communication (Luhmann, 1995), changes in one system do not necessarily cause changes in another interacting system. However, some changes might make a big difference across several interacting systems. For example, in the case of COVID-19, changes in health led to changes in the use of IT technology, which caused a significant change in the learning environment. Most of the curricula in different universities and countries adapted successfully to this change and offered interactive courses online. The value of this outcome will not be known for many years to come, and it might be that we are observing the beginning of a significant change.

2.10 System Mapping with Stakeholders

Enquiry for problem definition and understanding is critical, and it is important to engage end users and stakeholders in the change process. There are several tools that help the creation of an inclusive system map, which captures the views of the client, end users, the stakeholders, and the community at large. Some of these tools are qualitative and some are quantitative, and it is important to use both methods (Morgan, 2013). These tools include experience mapping (Kalbach, 2020), stakeholder mapping (Walker et al., 2008), fishbone diagrams, five whys (Romo et al., 2013), system mapping (Finegood, 2011), motivation mapping, the issues wheel, causal layered analysis, causal loop mapping (Inayatullah, 2005), generative dialogues (Proctor & Bonbright, 2021), assumption smashing, empathy mapping, analysis of feedback loops, system dynamics (stocks and flow) (Meadows, 2009).

System maps that include stakeholders give information on the persons and organizations that might be interacting in the presence of feedback loops. In Fig. 2.12, the map of an educational system shows causal loop diagrams from which a system dynamics model of stocks and flows can be built. This allows for an exploration of the system dynamics and its time lags.

Another framework for systems thinking (Cabrera and Cabrera, 2015) uses four concepts: *distinctions, systems, relationships, and perspectives,* cleverly implemented graphically with the Plectica software https://www.plectica.com. In this model, there are four steps to analyze systems. In distinctions, we separate *parts* of the system from other parts based on our purpose. Similarly, we separate the system from its surroundings. This process of *boundary making* is critical in the analysis. The next step is defining the components of the systems**.** Every component can be considered a whole, and made of parts, depending on the purpose. The degree to which we zoom in for more detail or zoom out for less detail depends on what is the purpose of the analysis. Similar to the above-mentioned method, using different lenses, we point out the *relationships* between the elements, the feedback loops and time delays. The analysis and solutions are done next and obtained within a *perspective* which is defined by the objective of the study.

The objective of the system may change in time and, in addition, the ecosystem within which the system is operating may undergo a significant shift. System mitigation must be sustained for a long time to create meaningful interventions. A long-term perspective is not easy to develop as it relies on speculating on the events of the future. In particular, unpredictable feedback loops and emergent behaviors create significant challenges. A method to investigate possible future directions is discussed in the next section.

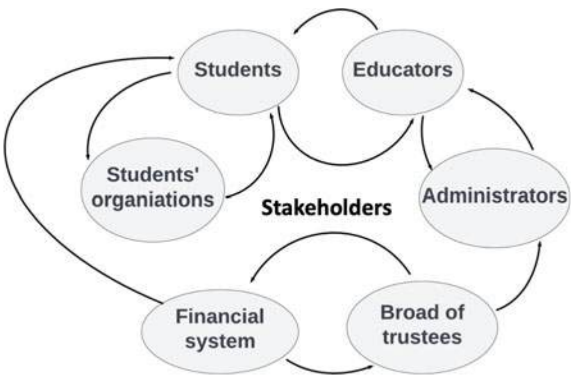


Fig. 2.12 Different interaction loops among stakeholders

2.11 The Power of Unpredictability

Life on earth continues to change. New generations of pupils and educators are learning and practicing many new disciplines. Pedagogy is evolving too and taking advantage of digital technologies. Such changes are normal, but the rate of change is unprecedented. The rate of change as well as the number of changes have created situations where the future directions and outcomes are very unpredictable. As research is creating new knowledge, the content of the disciplines is fast evolving too. This is an unprecedented and exciting time; predicting what will happen next is very difficult.

The need for understanding a particular phenomenon is creating a convergence between topics and disciplines that are normally at a distance. Students are interested in learning across different disciplines and researchers are applying new techniques borrowed from other disciplines. New names for these disciplines are invented like opto-genetics and quantum Internet and the like. We are in an exciting time with inventions and innovation bombarding our brains and changing our lives. But these bring a high degree of unpredictability too. Some of these changes could lead to new paradigms that affect society and our daily life.

Since 2020, COVID-19 and its mutations have had a dramatic effect on many aspects of our lives, including politics, economy, trade, transportation, medicine and public health, education, science and engineering, social relations, and the future of work. But as we are being harassed by the COVID-19 and its derivatives, there has been significant and rapid growth in technology, especially AI and biotech. In addition, the influence of COVID-19 has isolated and eliminated some technologies and created new ones. It is safe to say that the digital tsunami that has been hitting our lives, has not ended yet.

Could one have predicted these events and prepared for them? For example, could COVID-19 have been predicted? Maybe! People are obsessed by the future and many people spend significant energy trying to predict it. Could that be done? What prevents us from predicting the future?

The future is not a continuation of the present and is not necessarily a reflection of the past. It is something else. As in the past and present states, many elements and events interacted to form these states. These interactions and their nature cannot be reproduced. The events that are happening now can be an outcome of some events that happened in the past, but also due to some emergent events that are the outcome of complex interactions that are the nature of complex systems. In addition, human traits and interests may enhance some dynamics and dampen others.

Are there methods to analyze human traits and predict the time evolution of dynamic complex systems? Not really. But there are techniques of reducing the uncertainty and attempting to predict not a single future, but a wide range of futures. These are discussed in the following sections. We start by bringing attention to *human mental models* as they affect how we deal with unpredictability and then follow with a discussion of the *foresight technique*.

2.12 Mental Models and Biases

Learning is a social process, which relies on interactions and discussions. Learning strategies are personal and are affected by many factors, including experiences, culture, interests, and accessibility to knowledge. These factors may also create blind spots and hamper sociability, which is a cornerstone for creating constructive human interactions. Through sociability, conversation becomes productive, and disagreements are constructive.

Human interactions have been significantly changed by the digital tsunami that continues to hit our cognitive reality and behavior. These changes have altered our institutions and produced unexpected entanglements of our social traits. On the Internet, information is disseminated instantly. Social networks and instant messages create new sets of values that may be unacceptable to most people. For example, faced by the lack of options for accessing certain websites, people are coerced to accept new norms for privacy and security. New mental models are formed by such experiences.

Not only have digital technologies altered our mental models, but they also modified our heuristics. Human heuristics are the effective and ineffective strategies we apply when we face complex challenges. These strategies are based on previous experiences and tend to simplify the required complex cognitive strategies leading often to systematic errors. Heuristics are part of our mental models. They are representations of how the world works; they shape our thinking, connections, and opportunities. Education, on the other hand, makes us accept more models and gives us tools to better understand the world and make good decisions.

Our mental models are shaped by many things. An important one is our discipline. The call for interdisciplinary education is critical. Interdisciplinary education broadens our mental models and opens avenues for innovation and creative problem solving. It makes us able to appreciate the richness of diversity.

Disciplines have different mental models. In science, the model may describe a particular ecosystem. For example, in physics and chemistry, thermodynamics has laws that describe energy in a closed system and regard energy as something that cannot be created or destroyed. In biology, the ecosystems are in constant evolution, and the mental model describes groups of coexisting organisms, where some are cooperating, and others are competing for energy and resources and self-preservation. The model is governed by natural selection and adaptation. Thus, the system cannot be closed, as it requires energy to create adaptation.

Similarly, in economics, the concept of opportunity and opportunity cost and trade-offs dominate relations. Personal incentives lead to capitalistic competition, and creativity and innovation lead to the development of new technology and products that end up replacing the older ones. In free markets, the system is open to supply and demand forces, which are determined by customers that can be swayed by marketing forces and opinions. Like biology, there are limited supplies and competition through innovation (energy) and create evolution and diversity of products and services (species).

Similar to the above-mentioned scientific mental models, culture and human interactions and dynamics create mental models and human biases. An example of human biases is our tendency to stereotype from limited experiences. Often people miss nuances through such filters.

At schools and universities, we learn to curb our heuristics and tame them. Heuristics are useful shortcuts that may create helpful efficiency in urgent situations. But they also create biases. The combinations of different mental models and heuristics can drive wedges among people. Although engineers learned to use scientific models to create technologies, they are not immune to these biases.

One may consider curiosity as a bias. But that might be a positive one for those who are eager to create new value. Engineers need to be curious. Curiosity is an instinct that leads to unique behaviors. Since infancy, children test the boundaries and learn through a form of experimentation. Curiosity is not only a driver to knowing but relates to creative actions and active learning. It motivates student engagement to create solutions, and when it is combined with critical thinking (Moon, 2007), it can become a driver for innovation (Pusca & Northwood, 2018). In fact, human progress is built on creativity that is fueled by curiosity.

Trust is a required condition for most human interactions. Without it, markets and economies vanish (Zak & Knack, 2001), and countries go to war. Trust has a biological basis as well (Zak, 2017), because it is needed for socialization. It requires consistency, clear communication, and a willingness to tackle awkward questions (Galford & Drapeau, 2003). In organizations, building and maintaining trust is critical, and it requires skills, supporting processes, and unwavering attention. Trust plays a critical role when teams are formed. During active learning activities, trust becomes a key element for the success of the project.

Notions of curiosity and trust are critical for creating effective teams that can create important outcomes. Some students are natural leaders, and others can be taught to be effective leaders (Kozlowski et al., 1996). Creating teams with curious engineers, who trust each other, is a huge task for leaders.

While creating AI software and devices, engineers must feel responsibility for examining the consequences of biases that could be built in their algorithms. Embedding ethics training in the curriculum through case discussions is critical. This makes engineers aware of their social responsibilities (Fleischmann, 2004) and the need to act accordingly. Embedding ethical constraints within the development of AI algorithms is a huge challenge. AI is affected by our heuristics, *and* AI is altering them.

Some students can be self-motivated and have internal drives to learn and create, and one may consider that *incentives* are not too important in learning. But this is not correct. Most people respond to incentives, and their views can be affected by incentives. However, it is difficult to know what incentivizes people. Some incentives are related to physical and mental needs, others might support ideology, and create ambition. In general, incentives end up creating a bias for certain thoughts and actions. Grades, honorary mentions, and financial rewards all create incentives for learning. However, it may not last long. Encouraging intrinsic interests might be more effective. Further, faculty enthusiasm creates excitement and motivations for subject matters. Providing relevant examples and getting the students involved also incentivizes learning and enhances students' motivations (Buckmaster & Carroll, 2009). Here we find that students of different backgrounds, working in teams help each other to learn and solve problems. In such situation, excitement and enthusiasm enhance the chance to learn. Removing fear of making mistakes and failure is essential for innovation, and under such conditions, learning by trying and daring to expose new ideas are tremendous experiences that young people carry with them for future projects.

In general, human beings are not precise observers, and we make mistakes by omission and admission. We tend to *overgeneralize from small data*, which may affect an engineer's ability to make appropriate decisions. Using small data sets to infer overarching conclusions is common, and it might be a way to make quick decisions and reduce uncertainty but, unfortunately, it could also lead to poor conclusions and decision making (Tipton et al., 2017). The tendency to generalize from small samples is another aspect of heuristics that should be understood and avoided, especially for engineers and educators who are working on human challenges.

The above discussion brings out the importance of human conduct during the decision process. It is rather critical that we prepare students to become socially savvy. Heuristics and similar behaviors add complexity to the work environment and require careful examination of the structure and the norms of the team. While the team is defining the goals of an activity, serious dialogue needs to take place to limit biases. Such biases can be gender related as well as biases against some technical backgrounds.

Engaging diverse groups in defining and understanding the essence of a challenge is very worthwhile. Groups of broad interest discussing issues in open forums can reduce biases. Having stakeholders participate in guiding engineering students during the design process can uphold ethical conduct and avoid some biases.

2.13 Navigating the Futures

In the previous discussions, we encounter several situations where communications are critical to form a glue for human systems (Luhmann, 1995). We also pointed out that this glue led to fundamental changes. Communication is now instantaneous, and there are low barriers to disseminating information. In some sense that should create a more cohesive society with closer views. But there are enough indications to the opposite. A major issue is the difficulty of asserting factfulness to the transmitted information. How can we attest that heuristics and prejudices had not altered the information?

Is truth inaccessible? Or is it not important what is truthful but what people believe is true? (Ellerton, 2017). Should we not worry about the truthfulness, and treat it as an intellectual objective, but not a cultural value? Williams asserts that truth is an intrinsic value (Williams, 2010), and there is no doubt that truthfulness has political consequences and is an important element for trust and sociability.

Our fundamental values and mental models are affected by AI. Even the strict scientific methodologies have been altered by AI and that may have led to positive outcomes. Through machine learning, more discoveries are happening, and more unrealizable designs are made. But the interpretations of science and the translation of science into engineering and technologies, which can serve humanity, are under siege. Different interpretations may cause significant shifts in public opinion and confuse public health discussions and environmental debates (Koonin, 2021). These are not trivial matters. In media, we put our trust in reporters and editors. Nowadays, reporting is a matter of presenting points of views to support motives. Medicine is supported by scientific evidence and trusted scientific methods and reports. With these *assurances*, we accept treatments and subject our bodies to medical tests and synthesized drugs. Similarly, we put faith in our curriculum, but with questions on what a fact is, teaching becomes a challenging endeavor, not only from a pedagogical point of view, but also from a content view. If trust is at question, what do we dare teach?

If complexity is created by many interacting items, then complexity is alive and well in the current times. The interacting elements creating complexity are not only increasing, thanks to AI, but their dynamics are changing. The nature of the interactions is evolving unexpectedly. We know that complexity is not a static environment, but now its dynamic is fast moving, and far from an evolutionary process. Chaotic states are expected not to last for long. With the current speed of change, there is no time to understand the strange attractors or the consequences of the interactions. We must accept that we are swimming in a sea of unpredictable depths and unknown creatures.

In the past, people tried to make predictions to create decisions, but these predictions were mostly in error. The literature is full of predications by very knowledgeable people, yet many were proven wrong (Kappelman, 2001). Consider for example that by Albert Einstein (1932), or Thomas Watson, IBM Chairman in 1943, stating *'I think there is a world market for maybe five computers.'* And Robert Metcalfe, an inventor of the Ethernet in 1980, saying '*I predict the Internet will soon go spectacularly supernova and in 1996 catastrophically collapse.'* How could such knowledgeable people miss so much?

If the past and the present are consequences of many interacting events, issues, human interventions, as well as environmental changes, why should we expect these to persist into the future? (Fig. 2.13).

We know that the present is not a continuous function of the past. Thus, the future must not be a continuation of the present. Therefore, our views of the future cannot be distilled to one single future, and a different method for generating these future states must be used.

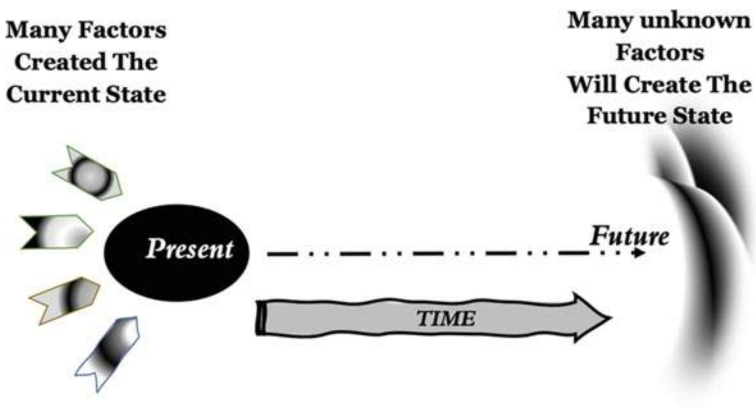


Fig. 2.13 Present is made up of many interacting elements—most of them do not persist into the future

2.14 Foresight

Understanding the parameters and possibilities of the future helps in making decisions in the present. In the past, progress took big steps over changing paradigms. A paradigm took many years to hold firm and establish new grounds. This is not the case in the twenty-first century. Shifts happen very quickly. Education must keep track of sociotechnical changes, economic trends, and related human factors. What could one do to prepare for new content and pedagogy? The evolution of education, like any complex system, requires a methodology to investigate.

An older method, forecasting, had been used over many years and was successful in some short-term situations to enable decision making. However, this method is not appropriate in the current fast-evolving events. The forecasting method (Armstrong, 2001; Slaughter, 1990) is based on two concepts:

(a) *Theory of cause and effect:* Investigated variables are put in a dependent relationship with their relevant determinants and are then predicted based on this knowledge.
(b) The use of *time series analyses*: a statistical tool determines trend and typical seasonal changes but may not fully consider the short-term fluctuations, business cycle, and irregular influences.

Although forecasting methodology had been expanded to include nonlinear trends (Fig. 2.14), the condition of direct cause and effect renders this method unsuccessful in addressing complex challenges, where there are several root causes, and these root causes interact nonlinearly.

A different approach relies on using probabilistic processes, some of which could be nonstationary and chaotic. This method is named *foresight* (Popper, 2008). Since most uncertainty comes from human behavior, foresight admits uncertainties through a concept for several futures and allows for human interests and behavior to be

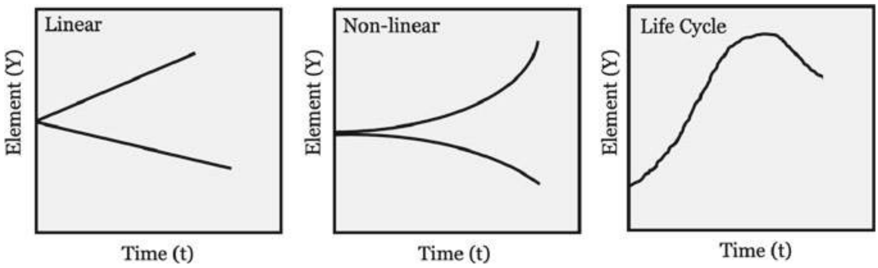


Fig. 2.14 Examples for forecasting—time series analyses and nonlinear trends

considered as parameters for exploring the possible futures. Multiple futures are an essential concept for reducing the long-term uncertainty (Battistella & De Toni, 2011).

Human behavior and culture, as well as technology, influence human futures through multiple complex and interdependent drivers. Futures built around critical uncertainties are the most useful to consider. But if insights gained from strategic foresight studies are not linked to today's decisions, they would be useless!

Methodologies for creating strategies consider different futures (Kosow & Gaßner, 2008). Such futures include desired, probable, plausible, and possible futures. Wild-cards are also part of the mix. Surprises happen, but most of the time, and in hindsight, we find that these surprises could have been foreseen.

The concept of several futures is illustrated in Fig. 2.15, where each one of these futures has drivers and interacting elements (Kosow & Gaßner, 2008). None of these futures is more likely to happen than the other, and one should not expect to get a single unique answer from the research that created each one of these futures. Through rigorous investigation, one can find different *scenarios* that lead to each of these futures.

In foresight work, the term 'scenario' is used for different activities such as summaries of ideas and foresight results. It is also used as an element of the process, such as visions or outcomes of some activities that the team wishes to communicate. Furthermore, a scenario might refer to exploratory information on what might happen in certain situations. Here, we use scenarios for visions of future possibilities and for visions that have been derived from quantifiable and non-quantifiable studies, which can be presented in narratives.

The objective is to make strategic plans for each of these scenarios and create decisions based on each one of them. The analysis may start by creating exploratory questions examining the futures that are possible (Börjeson et al., 2006). Questions like: 'what might happen?' and 'what would have led to what.' Probable futures answer 'what is most likely to happen?'. This category includes forecasting studies, which are characterized by a predictive nature and mainly focused on historical data and trend analysis. Another set of questions are normative, e.g., '*what future do we want?', and* starting from a point in the future, we may ask, *'how can this*

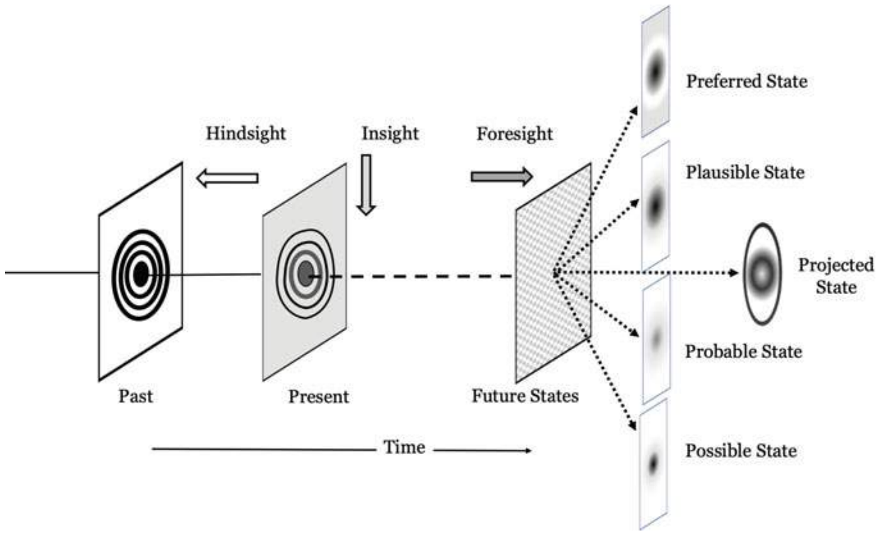


Fig. 2.15 Exploring multifutures, modified from (Kosow & Gaßner, 2008)

happen?' '*What does it take to reach a future where*….?', '*What would have led us to a situation*…?' Also, we can ask a predictive question *'what happens if* …?'.

When we examine the present, we obtain *insights*. These are reflections that can be used to feed information about the futures, but this does not mean that they are simple extrapolations. They should be deep linear or nonlinear time explorations. By examining the past, we gain hindsight. Hindsight is assumed to be 20–20, but not exactly. People have a bias that distorts the thinking about the past, and they have a tendency to perceive past events as more predictable than they were before the event took place.

Predictability is not the only bias. *Inevitability*—'it had to happen' and *memory distortion*—'I said it would happen,' are two other biases. In addition, any feed-back or corrected information a person may receive after they had given a judgment automatically updates the knowledge base underlying the initial judgment (Hoffrage et al., 2000). This situation of rewriting history happens often. It is true that when there are crises or poor consequences, we can look back and realize that a poor event could have been avoided. This could help when similar circumstances appear again. But that might be rare (Fig. 2.16).

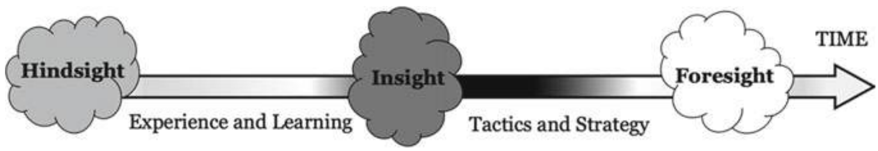


Fig. 2.16 Looking backward and forward (Kaivo-oja, 2006)

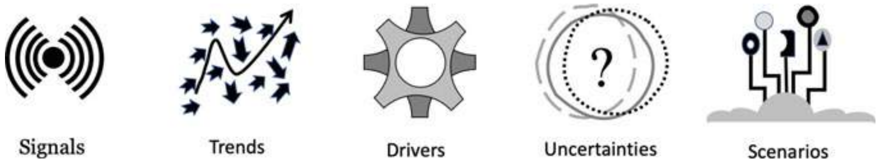


Fig. 2.17 Steps to create scenarios to study foresight

Similarly, foresight thinking has its biases: optimism and pessimism. Whereas optimism might be due to good data creating confidence, it is also possible that it is only wishful thinking. Pessimism might be a way to avoid making difficult decisions and taking a leadership position.

From research and investigations, different scenarios are generated using several methods. The challenge is selecting a small number of scenarios that can do a good job of explicating the range of alternatives that may be confronted—or of highlighting the paths of development of underlying drivers and other factors.

A general sequence to follow for creating scenarios is outlined in Fig. 2.17. These steps are listed here as a guideline, and other methods have been used too.

In this diagram, the first step is to find signals and trends. Signals provide tangible specific evidence of change and trends detect patterns and change direction in signals. Some of these signals might be weak, ambiguous, and complex. Finding them, and discerning their implications, is very difficult, but rewarding. Many times, these weak signals are the ones that create the new trends and the unexpected futures (Ilmola-Sheppard, 2014).

Drivers show possible structures behind the trends and point to root causes. Unpredictable directions or effects of drivers are the uncertainties. The important futures imagined with combinations of critical uncertainties are the desired outcomes, the scenarios.

There are several processes for creating scenarios. These may include individuals presenting their informed speculations about the future, using scenarios as a template for illustrating and enlivening their accounts. Surveys are used to obtain cluster views. These surveys could be digital and might be obtained through social media. In addition, expert panels may establish a framework of scenarios based on research reviews or conceptual analysis. Experts' judgements, as well as computer simulations or AI studies, may shed light on what is feasible. Workshops and open debates to enhance teamwork and hear broad views of different stakeholders and decision makers are required.

The different views are then clustered, from which scenarios emerge. Although there are no recipes for what is important, topics to study may include economic, cultural, educational, technical, and environmental. Quality of life, future of work, public attitudes to risks, strategic technical expertise, and evolution of technology and its rate of change are suitable topics to study. In addition, policies for public health, immigration, trade regulations, future of infrastructures and facilities, intellectual property, and treaties are additional topics for examination.

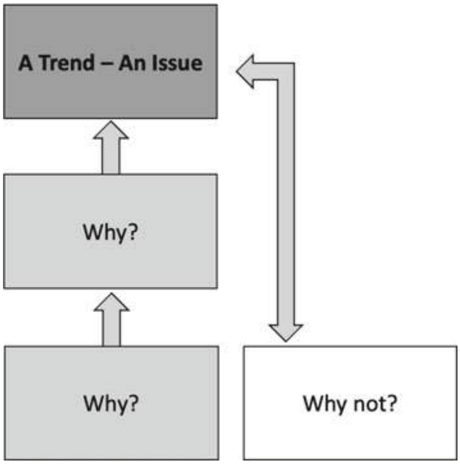


Fig. 2.18 Finding trends—"ask why and why not" as in Shaw (1989)

After collecting data, further work is needed to test the meaning of the data. Outcomes from group discussions become the important factors, and biases must be kept in check as well as demanding evidence when ambiguity or uncertainty are found. Questioning what we find and finding if there are some roots for a trend or an issue is part of the foresight mission. Figure 2.18 serves as a reminder that we should not only ask why, but also why not.

Several research methods to investigate different types of futures have been used, and here we cite some of them:

- **Delphi** is a basic method of foresight (Sossa et al., 2019). Experts submit anonymous feedback and ideas (e.g., using Post-It notes) to begin an open dialogue. This allows addressing complex and controversial issues through a structured debate.
- **Backcasting** starts with defining a desirable future (Tinker, 1996) and then works backwards to identify policies and programs that will connect that specified future to the present (Bibri, 2018; Dreborg, 1996).
- **SWOT** analysis (Gurel & Tat, 2017) systematically investigates strengths, weaknesses, opportunities, and threats.
- **Horizon Scanning** (Cuhls, 2020) seeks trends before they emerge into mainstream and assesses whether one is adequately prepared for future changes or threats. It also identifies key action points to proactively shape desirable futures (Cuhls et al., 2015).
- **Black swan** (Petersen, 1999; Taleb, 2007), events are characterized by their extreme rarity, severe impact, and the widespread insistence that they were obvious in hindsight.

2.15 Anticipation is the New Strategy

As had been discussed before, the fundamental step in obtaining information to create options for the *futures* is finding signals that inform possible future changes. Most of these signals are weak signals or silent signals; that is, they are not clear indicators of an important change. In fact, most of the ones that later were found to be very important were only emergent information, which can be easily missed. Yet they are about something beyond a current paradigm (van Veen & Ortt, 2021). Weak signals are the seed of change, and they do not come as an extension of our knowledge; nor do they fit our current thinking and expectations.

Weak signals have several manifestations. They inform us about a shift in something important, which may affect culture and society, and they could also be warning signals of events to happen, or of an impact that could lead to dramatic changes. In business, they may be announcing the future death of a technology and the birth of new companies (Lesca & Lesca, 2014). They may give indications for political unrest and uprisings or an environmental challenge. For individuals, weak signals may help creativity, create innovation, or inform about health, and what to learn and practice.

In a world obsessed by quantification, weak signals are immune to that; they are gathered qualitatively. They need to be collected from multiple sources and be explored across many events that might be happening in different locations (Taylor et al., 2015). Weak signals may emerge from many sources like science, arts, philosophy, political events, and from the work of creative people. They could be found through discussions, or by reading text and blogs, and they can be embedded in images. Paying attention to their appearance is difficult and requires focus and training.

People's observation and detection are affected by their mental models and openness to understanding what might appear as illogical ideas. Occasionally, weak signals are dug out of noise and recognized in camouflaged patterns, where they could hide within some current trends or concepts. Sometimes they are fragmented ideas, and the observer has the task of synthesizing them—vision becomes a necessity.

When a weak signal is suspected to be of importance, one must interpret it and attempt to consider its impact if it were to happen. Considering that these signals are part of complexity, their trajectories are not linear and can be random and on the fringes. Also, they are subject to feedback loops and their significance may take some time to be realized.

Identifying and interpreting weak signals is pivotal for initiating a foresight study and when such signals are revealed, they need to be taken seriously (Hiltunen, 2013). It takes efforts and concentration for many people to discuss and share ideas before they realize that they have stumbled on an important weak signal. Let us consider for an example, cryptocurrency.

Blockchains are 'tamper evident and tamper resistant digital ledgers implemented without a central repository nor a centralized authority' (Yaga et al., 2019). Weak signals for this technology came with the work of Leslie Lamport in the

1970s (Lamport, 1978) and later in 1980s (Lamport, 1981). In the 1981 paper, Lampert discussed password authentication with insecure communication, and later a consensus model for reaching an agreement under situations where the computers and networks are not reliable (Lamport, 2019). This seminal work led to another one by Satoshi Nakamoto and the creation of a peer-to-peer electronic cash system, i.e., Bitcoin (Nakamoto, 2008).

Although the science needed to be developed, we may ask whether Bitcoin could have been anticipated earlier than 2008? Could the weak signal for creating cryptocurrency revealed the possibility of creating this currency? Most people were surprised by the emergence of cryptocurrency and, most likely, had no clue that this type of currency is important, and it has special position in the commercial market. From an examination of Lamport's early work, one may conclude that cryptocurrency could become a reality. The peer-to-peer network technology that created Bitcoin is broader than finance, and Blockchain technology has a massive potential for disruption by providing good digital security.

With the help of the Internet, there are ample opportunities for discussions on the future. People today recognize that the future is embedded in technology and there are articles that attempt to cite many potential new technologies, such as quantum computing and soft robots that could make the future exciting. Unfortunately, these thoughts are descriptive of what we already know, and they are far from what we have termed here as weak signals.

2.16 Thoughts on the Future of Education

In the last section, we examined how a process, foresight, enables us to have information to help decision making in the face of the significant uncertainties posed by the complexity of modern life. In Fig. 2.19, we illustrate steps leading to the creation of the strategy to examine the future of a topic. Weak signals and megatrends are important parameters to scan first. Weak signals can be elusive, and megatrends can be more readily searched and studied. But the two topics are not independent. There could be some information from the megatrends that point to weak signal and thus can be explored. Data from both, megatrends and weak signals, must be collected and critically examined. With a visioning process, such as the one outlined above, scenarios are created. The scenarios facilitate creating the strategy map, which leads to create a strategy for today that anticipates several futures.

For education, the strategy is not universal. As we discussed, learning is a social process. Cultural values and practices must be considered as part of the strategy. Different schools in different countries may choose different paths. There is a general trend of using digital technologies, and this has affected education among many sectors. Digital learning and machine learning are megatrends. The general theme is that, faced with an abundance of digital information, we need to process information digitally to form new knowledge.

Fig. 2.19 A road map to create future strategy

Most students are highly exposed to images and screens and tend to consume less text. Teaching and learning must pay attention to create pedagogy and research that take advantage of visual information and its flow. Research and learning through the Internet is highly productive, and students at all ages in any country should be encouraged to pursue such style of learning. At the same time, one must keep in mind that incorrect heuristics can seep in if one is not mindful. Teachers must monitor and correct misinformation. They also should help learning online by creating visual modules and by creating online teams.

All in all, as the younger generation, that is accustomed to digital technologies, grows to participate in higher education, we must expect a significant change in attitudes and abilities. Education must be ready to satisfy and drive this trend. A distinction between formal and informal learning is no longer valid. Certification (degrees) might end up less important in the future. Higher education needs to provide series of workshops, short courses that educate students and enable them to learn using online resources. Creating communities of knowledge online must become a priority. These communities are not only for students but also for educators who could connect to different educational landscapes (Hopkins et al., 2020).

Creating a curriculum where students find it fun and interesting to search the Internet and interact, socially, on the Internet is a productive trend. This is a mega-trend, and it will continue for a long time. Related to that is learning through gaming and creating projects with ideas that can be shared and discussed online.

The digital wave with data and computation is creating a new paradigm that will force different curricula. Who will start making the change? In which topics? and when? These are questions that require foresight analysis. Most likely there will be a steady gradual change, but through the foresight process, educators can create the right plans for the future of education. In particular, engineering topics are more affected by changes brought by digital technologies. Simulations, computation, and machine learning are tools that will substitute a significant part of the current curricula.

Interaction and designing with machines are more than weak signals. Whether it is through big data, deep mining, or robotics, learning with machines is going to be a megatrend. It is also possible that some computer simulations progress and enable sophisticated problem solving with limited human intervention. Design becomes more sophisticated with creative options provided with intelligent machines. However, forming problem statements and choosing the needed constraints, i.e., the boundary conditions, will continue to be a human's work.

A related topic that may affect the future of education is student movement, as well as researchers, across countries. These movements will affect the future of education. Of course, this issue relates to political policies. Climate change may also force some unexpected movements. In addition, tools and financial means are obvious drivers for these movements and we could be surprised by the socioeconomic changes that may take place in areas of the globe that might be nascent now. These financial constraints could lead to alliances among colleges and universities and a degree of specialization to enable differentiation.

Environmental issues and stress on sustainability can also be a driver of change in education. These issues may end up affecting different regions and countries with different challenges and may lead to migrations across the globe. Research in this area should promote society's cultural development and not solely its socioeconomic development. Through reflection, analysis, and evaluation, students and their instructors can make a substantial contribution to a sustainable future (Hopkins et al., 2020).

As time passes, more cognitive activities will be required, and less physical work will be performed by people. Big data analysis shows considerable demand for online work (Stephany et al., 2021). For example, there are measurable changes in demands for different skills that are needed for projects related to robotics—how will these demands change the type of work that will be performed by people and how will education respond and prepare the appropriate workforce in time? (Stephany & Luckin, 2022).

The workforce requirements will change even more in time (Soto, 2020), and there is no question that the overall use of online work is a megatrend. Could education become mostly online events? How can we train engineers to learn online and work online?

Although a new vision of education must include digital technologies, broadly, it must gear learning toward building an equitable and inclusive society with sustainability as the main goal (Tawil & Locatelli, 2015). New literacies to enhance critical thinking in this information-intensive age, building up socioemotional and affective dimensions in learning are required to achieve an inclusive and equitable future society. Interdisciplinary learning and working on projects that are broad must become part of all aspects of engineering education.

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Chapter 3
Design for Complexity

3.1 Design Mindset

Design has traditionally been the process of transforming a problem statement, or need, into a solution. Design was originally the domain of the master craftsman, or architect, who translated the client's needs into an exquisite artifact. Design thinking is a recent attempt to make the design process more accessible to a wider audience, to solve a wider range of problems, in every discipline.

Much of traditional engineering education is the development and teaching of solutions to standard problems—design and build an electrical circuit, write a piece of software, analyze a beam. These might be components of larger systems, e.g., a mobile phone or a bridge. We can break down complicated engineering artifacts into major components and those components into smaller components until the whole artifact has been designed and brought together as a working system. This divide-and-conquer strategy has placed men on the moon and spacecraft beyond the solar system, which are remarkable achievements. Systems engineering describes the systematic design process that has delivered these remarkable outcomes.

As complexity increases, design must be seen, particularly at the conceptual design stage, as a collaborative process of engagement between the client, the designer, and a wide range of stakeholders to develop effective solutions for complex problems. No one of these individuals has all the perspectives required to develop appropriate solutions. Rather, the collective wisdom must be pooled to shape the final solution.

This is, of necessity, a collaborative process where the engineer must play the role of making appropriate technology available to the co-designers, demystifying what is possible. At a later stage, they can burrow down into the detailed design of the technology component of the solution. However, if the social dimension does not work, the technology will be of little assistance.

The Apple iPod is a wonderful example of technological success, solving the human need (play music anywhere, anytime), with a beautifully designed piece of hardware. Its success comes from a different systems view, which included, not just the person listening to their music, but also the music companies, and their contracted

F. Habbal et al., *Reshaping Engineering Education*,
https://doi.org/10.1007/978-981-99-5873-3_3

artists. For better or for worse, Apple reorganized the music industry. By contrast, the Microsoft Zune, attempting to solve the same problem, was an abject failure, which failed to identify with the whole system, instead concentrating only on the storage and playing of music, omitting the purchasing and browsing of new music. A different systems view led to an entirely different product and music ecosystem (iPod + iTunes store).

3.2 Design with Systems

In the previous chapter, we discussed the concept of visual representations (maps) of systems, which illustrate system behavior, causal loops, and information flow. These diagrams support problem-framing as well as diagnosis, identify possible mitigations and solutions, and motivate stakeholders to act on those proposed solutions.

The following is a discussion of the *design process* that engineers use to create effective solutions. The design process is an extension of systems analysis, enabling engineers and other practitioners to move from analysis to synthesis, to satisfy client needs. The chapter continues with a brief overview of systems engineering, as a formalized design process and finishes with a brief discussion of digitalization trends in engineering design.

3.2.1 A Significant Paradigm Shift with Entangled Components

There is a paradigm shift underway in engineering practice, made up of two different elements. The first element of the paradigm shift is an outcome of system challenges. Although cognitive development, as well as skill building, are critical components of learning curricula of the twenty-first century, the problem-solving methodologies of the twentieth century, concentrated mainly on the technical domain, are fading away, and a gradual implementation of design engineering initiatives have become more prevalent, with a focus on innovation.

Shifts in mindset are required to keep up with the challenges and the changes of the twenty-first century and its Fourth Industrial Revolution. We note that products are not only fostering innovation to facilitate physical labor, but also are creating devices and applications to augment our cognitive capacity. Such products are well accepted by society at large. These trends in creating digital system products will be a characteristic of the twenty-first century, and engineering education must shift to enable the younger generation to fully participate in this change. This calls for significant additions of systems and design engineering to the curriculum.

But this is not the only shift that engineering education must undergo. The second element of the paradigm shift is entangled with the first one. The second shift involves using big data and intelligent machines, with humans co-designing with these machines. The new machines, not only perform mathematical simulations and analysis for the problem at hand, but also provide options for different solutions and employ big data to optimize the performance of the solutions, to enable sustainability, and to create optimum human interfaces, among many other attributes. This trend can be seen as an extension of the exponential increase in the use of engineering software, since the 1970s.

Time and soaring computational capacity have reduced our dependency on analytical solutions and calculus approximations. The hard work to 'linearize' physical models and apply them as special cases, is augmented, if not replaced, by nonlinear models to address complexity and chaos in a systems context. Deterministic models can be replaced by stochastic ones, and with that we come closer to more realistic investigation of some of the challenges. Given the state of progress in AI, the above-mentioned direction should be taken seriously.

In short, we observe that the engineering curriculum is going into a new paradigm of two aspects: (a) systems analysis with engineering design and (b) co-designing with intelligent machines.

A new curriculum should provide engineering students with new content, processes, and training to establish competency in the following areas:

(a) *Systems Thinking*

- Knowing the foundations of systems thinking
- Understanding the functioning of systems dynamics: feedback loops and delays
- Being able to identify, explore, and map system relationships for interventions, while leveraging flexible and divergent thinking practices

(b) *Design Process*

- Knowing the basic elements of the design process
- Use design methodologies to understand critical design requirements and unexpressed needs, and to implement innovative and relevant solutions

(c) *Interdisciplinary Collaboration*

- Effectively participate and lead in multidisciplinary teams to accomplish significant objectives
- Understand team dynamics and apply tools to maintain optimum team performance
- Use planning tools to complete projects within time and other constraints
- Professionally documenting and communicating design outcomes

(d) *Communications*

- Provide constructive feedback
- Deliver crisp verbal presentations
- Create compelling visual presentations and representations.

These elements (a) through (d) are chosen based on the anticipated needs of future work and the expectations of employers. An example of those needs is listed in the World Economic Forum's '*Future of Jobs Survey*' (World Economic Forum, 2020).

Table 3.1 compares the learning outcomes with the top ten required skills from that survey.

Further, the World Economic Forum (WEF) presented a set of literacies, competencies and character quality that are critical for 21st-century successful persons. These are listed in Table 3.2. It should be noted that most of the qualities indicated by the WEF are consistent with the USA-ABET accreditation requirements (ABET, 2022).

Table 3.1 Top ten required skills and learning outcomes

Top ten required skills for 21st century	New emphasis systems and design engineering
Complex problem solving	Significant emphasis
Critical thinking	Significant emphasis
Creativity	Significant emphasis
People management	Emphasis through the multidisciplinary collaboration focus
Coordination with others	
Emotional intelligence	Through empathy embedded in the design process and applied by working on a human challenge
Judgment and decision making	Participating in collective decision making and team governance issues; creating problem statements. prioritizing activities and mitigations/solutions
Service orientation	Part of the goals of the initiative
Cognitive flexibility	Significant emphasis and goal of the initiative

Table 3.2 Literacies, competencies, and character quality needed to succeed in the twenty-first century

Foundation literacy	competencies	Character qualities
Literacy	Critical thinking	Curiosity
Numeracy	Creativity	Initiative
Scientific literacy	Communication	Persistence
IT literacy	Collaboration	Adaptability
Financial literacy		Leadership
Cultural and civic literacy		Social and cultural awareness

3.2.2 *Design as a Creative Process to Address Human Challenges*

If there is a word that integrates the essence of humanity, it is ‘design.’ Human beings have been designing their environment for thousands of years. The word design stands for several meanings in different contexts. As a noun, it may mean a plan to achieve a business, a chemical or a manufacturing process. It can stand for an architectural plan or an engineering drawing. It is also an action-oriented verb for creating or achieving a goal. It suggests the notion of a process through which a physical or a digital object is achieved. Some try to generalize the creation aspect of design by indicating that it is about technologies that are lifesaving; others state design must have an impact. But these are limiting notions too.

> Design is a process for problem definition and solving, that intentionally brings a human system from an inferior state to a higher performing state. (Simon, 1968)

Thus, design connects the artifacts to economics and to sociopolitical dimensions. It also connects to scientific discovery, and business innovation. Design connects to our cognition and emotions and allows integration to form implicit and explicit information.

Design, as an intellectual branch of knowledge, formally started almost 100 years ago, perhaps because of the complexity of the artifacts created beyond craftsmanship. In the 1920s, Theo Van Doesburg predicted a ‘new spirit’ that can construct new objects (designishistory.com, n. d.). This was followed by assertions that there is a need for methodologies and an ‘objective system’ to teach and assess the value of the artifact. In addition, there were attempts to create connections to science as a source of inspiration and discovery. For example, Cross (2018) pointed out that there was ’a desire to produce works of art and design based on objectivity and rationality, that is, on the values of science.’ This theme was developed during the 1960s (Baldwin, 1997) and voiced at the *Conference on Design Methods*, held in London in 1962.

The feeling was that ‘design’ should have solid epistemology that can be taught and developed through methodologies not too different from the scientific methods. Buckminster Fuller called for a ‘*design science* revolution’ based on science, technology, and rationalism, to overcome human and environmental problems (entreVersity, 2018).

Herbert Simon in ‘*The Sciences of the Artificial*’ argued for the development of ‘a *science of design*’ in universities; ‘a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process.’ Simon saw this *new science* as suitable for addressing human challenges, the sort that (Rittel & Webber, 1973) described as ‘wicked’ problems, a different class of human challenges of high complexity. Others, like Schön (1983), noted that science is analytical while *design is constructive*, that designers engage in reflective practice, and that the epistemology of this practice, implicit in the artistic and intuitive processes, brings insights to situations of uncertainty and instability. These notions make design methodologies especially well-suited for addressing large human challenges (Cross, 2001).

As Rittel and Webber articulated, most human challenges are open-ended, broad, ill-defined, and normally originate from conflicts within interdependent and interacting human systems. In general, linear techniques are not suited for addressing such problems. The design process approach has attractive attributes that are useful in addressing these challenges.

Interestingly, design has organic links to both the arts and engineering. The boundaries between art and design are blurred. For example, applied arts is a narrow example of the connectivity between arts and design. Perhaps more important is that design entails integrating aesthetics in addition to functionality.

Engineering as a problem-solving method uses scientific and mathematical principles, creating an inaccessible language for non-engineers. Design reaches out through the need for functionality and joins engineering with arts while humanizing the solution. Connection to products, industrial applications, and optimization are most successful when design interjects and is successful in creating gratification of the senses and sensuous delight.

When issues are complex such as in cases of open-ended human challenges, connections between design and engineering are critical. Design is forward looking and explores what can be, it joins with engineering, which translates design solutions into realities. Therefore, the concept of design engineering encompasses both imagining the future and building it.

An integral part of design engineering is innovation; without new syntheses and solutions, there are no transformative outcomes. Innovation is a mindset, a methodology, and a process, all in one. It derives new behaviors and outcomes and creates system transformations at scale. Thus, design creation is innovative; a repetition of a solution without new synthesis does not represent design. Through innovation, we can incorporate universal design and meet people's needs without stereotyping. The design process also manages the emotional challenges and logistical issues.

3.2.3 Design Connections

Design, along with the arts, sciences, and engineering, is a facet of human cognition and inquiry. Finding differences among the above-mentioned domains is easy; finding complementary parts is where opportunities arise. Science focuses on understanding natural phenomena and uncovering patterns and similarities among them, design deals with the artificial. Both science and design aim to solve problems and test solutions. However, there is a major difference between the philosophical underpinning of the 'hypotheses' of science and design. In science, the goal is to uncover what is, while in design the goal is to reveal what might be.

Modern engineering is analytical and uses mathematics as a language. It is founded on scientific principles, and illustrations and visualization are central to engineering methodologies. Through synthesis, and often through inspiration from nature, engineering improves human life.

The organic connections between design and engineering provide a holistic perspective. Through design, an examination and interpretation of systems leads to mitigations, if not solutions, which are sensitive to the overall human situation. The intuitive nature of design integrates well with the rigor of engineering. Engineering provides the rational, analytical, and theory-guided approach. The aesthetics and interpretation of the arts feed design and engineering with human compassion and humanistic interpretations.

3.3 The Design Process

In a previous chapter, we discussed the types of challenges that our graduates will encounter in the future practice, using the UN's SDGs as examples. Whether the problem is profoundly complex or lends itself to simple cause and effect, the design process encourages a systematic understanding of client needs plus a search and trial of suitable solutions. The design process has been popularized as the '*design thinking process*' (Brown, 2008).

3.3.1 Design Thinking

Over the years, the term design thinking has acquired multiple meanings and become trendy and is sometimes viewed as a new construct invented in Silicon Valley. Not only is 'design thinking' not new, it is also sometimes executed in a pedantic way, with little understanding of its limitations.

Nevertheless, it is encouraging that design thinking has been adopted by academics, as well as the public, and viewed as a method for solving any issue in industry, administration, and government. Under the banner of design thinking, some reduced design to a few steps done in a mechanical way, devoid of the creative process. The design thinking steps can be simple, and the systematic method is helpful for creating needed artifacts. However, the current simple approach needs to be carefully examined when addressing human challenges where significant innovation is required and which cannot be prescribed by 'users' or 'stakeholders.'

Expert guidance on design thinking has been provided by Rowe (1986) at the Harvard Graduate School of Design, and also von Hippel (1986) from the MIT Sloan School, who discussed 'user-driven innovation' and the steps for successful design. The design thinking approach starts by researching and defining the problem, first by empathizing with the client and stakeholders (Fig. 3.1). The simple process of customer interviews and the focus on end users to achieve a satisfactory design is important, leading to an agreed problem definition, acceptable to all stakeholders.

The next step is ideation, for which design thinking does not provide any explicit direction. Hence, expecting design thinking to be a process for innovation has limitations. However, there are many innovation techniques that can help at this stage,

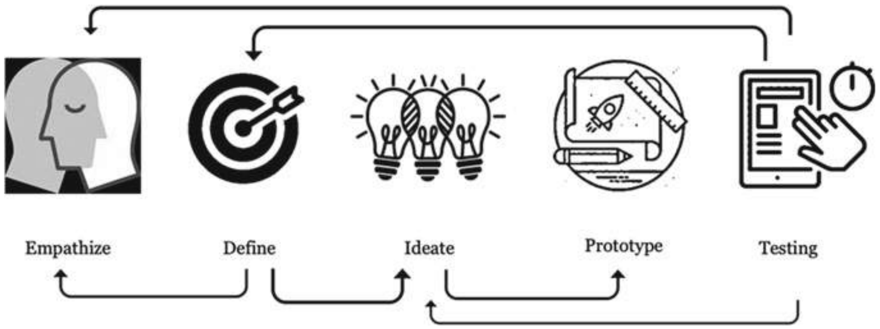

Fig. 3.1 Design thinking process (after interactive design foundation)

depending on the nature of the problem [e.g., TRIZ, the Theory of Inventive Problem Solving, Orloff (2006)] (Doblin, 2021). To achieve the radical innovation necessary to create ambitious solutions for wicked problems, the end user is the ultimate judge of success. Many innovative products have failed in the marketplace because they have failed to connect with genuine human needs (Destination Innovation, 2022).

Verganti (2009) challenged the notion of human-centric design, arguing that for true radical change, the designer must do more than translate user requirements. A truly innovative design, according to Verganti, must not only ask users about the 'product,' but inquire about the social, cultural, and environmental contexts of the challenge. It must consider not only the pragmatic need, but the reason(s) why people do things and how systems and their feedback loops interact. Designers with this orientation become interpreters in the discovery stage and more critical than the users.

Even in simple product design, Verganti asserts that people buy *meaning*, and the designer must understand, anticipate and influence how users will attach meaning to design. This discussion has been well extended by Eklund et al. (2021) and Sinek (2009). An example of a design-centric product is Swatch, which transformed the watch from being a commodity instrument indicating time, to a fashion statement. Currently, we observe a variety of digital wearable devices that have been created with a narrow application-based thinking and others, such as smart watches that cover broad contexts.

After the first step of the design process, designers continue to conduct their investigation but with an emphasis on creating their own vision and purpose, developing their particular language and new meaning (which ideally should be radical). In generating new meaning, designers must continue to explore and investigate their aim by working with users who define the sociocultural dimension. Ultimately, users need to actively participate in the creation of the product/solution. There is a *design push* approach that is complementary to the technology push and the market pull.

Innovation is one of the major sources of long-term competitive advantage (for individuals, organizations, and economies) and design is a tool for innovation to create economic value. Innovative design is broad and extends to business models as well as to human organizations. Human organizations are complex. Design helps translate visual and physical symbols and aesthetic experiences to an organization's values.

In the 1990s, Gagliardi (1990), Alvesson and Berg (1992) discussed organizational symbolism, and Strati (1999) wrote on aesthetics and organizations. This work suggests that organizations struggle while dealing with the ambiguity of knowledge work, and this struggle diminishes if employees perform their work as 'design practice.' That is, employees engage in finding the root cause of issues and being innovative in creating solutions that are sustainable and progressive.

Boland Jr. and Collopy (2004) in *Managing as Designing* suggested that since designers relish the lack of predetermined outcomes, managers as designers are better equipped to handle business uncertainties, and Dunne and Martin (2006) connected approaches for managerial problems to approaches of design, stating that 'we are on the cusp of a design revolution in business … today's business people don't need to understand designers better, they need to become designers.'

From the above discussion, we may conclude that design does not predetermine outcomes, and it is a mindset and an attitude that create opportunities for making the 'remarkable.' Design is a social endeavor and there are two social aspects that influence design through a cultural connection: vocabulary and functionality. Frank Gehry (philosophy-question.com, n. d.) warned about the influence of a certain 'vocabulary' while attempting to create high-impact design. Vocabulary creates the boundary, he stated. For example, words like cost–benefit analysis and discounted net present value, stifle innovation.

In addition to vocabulary, functionality is another aspect that needs to be understood. Functionality is normally viewed as 'how things work,' but some functionality evokes human and emotional dimensions of hopes and dreams of new possibilities. So, in its broadest sense, functionality connects to society and its aspirations. Thus, there is a dialectic dialogue between the outcomes of a design (the product) and culture. When the design is successful, a new language is adopted and, possibly, a new culture emerges leading to enhanced awareness. This is particularly true when a wicked problem is successfully addressed.

3.3.2 Systems Engineering—Beyond Design Thinking

Systems Engineering is a formalized and rigorous approach to engineering design, which is essential in complex industries such as the aerospace (INCOSE, n. d.). It can also be used in all engineering design tasks in a simplified manner, providing much more structure than design thinking offers, enabling students to deal with more complex design tasks. Typically, students need this simplified version to learn design over a range of tasks of different difficulties. Students may start designing smaller simpler tasks in their formative years, leading to larger, more complicated, and then complex tasks as they approach graduation.

Why is Systems Engineering necessary? Problem complexity is growing faster than our ability to manage it. Complexity is growing in terms of problem scope, the number of components, the number of interactions with adjacent systems, and the number of people involved in both the implementation team and in the number of stakeholders and customers. Systems engineering now needs to take account of the solution in context, including the business environment, the natural environment, and social and political aspects that may impact the solution's future uses and impacts.

Too often, the system engineering design emerges gradually, rather than from an overall system model, e.g., in transport and telecommunication networks, which tend to grow as one component is bolted onto the last. An overall system model is essential to guide these new additions. The overall system engineering model must also be regularly updated to recognize the changing requirements of the system, e.g., the introduction of 5G technology in telecommunications will lead to significant revisions in the communication protocols. Another example is the way Google Maps has transformed how people use transport systems, and the future impact of increasing use of artificial intelligence by system owners and system users.

A well-documented systems engineering approach counters some serious issues. For example, the loss of knowledge at project lifecycle phase boundaries, such as feasibility, conceptual, detailed design, construction, operations, maintenance, decommissioning stages, where there is regularly a significant turnover in team membership (Watson et al., 2020). Similarly, knowledge and investment are lost between projects, so a well-documented system enables new teams to learn from earlier projects. A systematic approach is required. This will be discussed next.

3.3.2.1 Lifecycle

Engineering projects move through a predictable lifecycle, from feasibility assessment, through conceptual design, detailed design, construction or manufacture, operations, and maintenance, to decommissioning. This is not necessarily a smooth pathway, usually requiring constant iteration and refinement, through conversations within the design team and back and forth with the client, to ensure that the right problem is being solved and to make sure that the final product will address all the client's requirements.

Most of what follows relate to the design stages of feasibility assessment, conceptual design, and detailed design, when the form and function of a product or service are being shaped. A model-based systems engineering approach (MBSE) then continues to support the product in operation, maintenance, and in its eventual decommissioning.

That does not mean that design does not occur at the other three stages. It is just that the nature of the products and services differ. For example, designing temporary formwork for construction, or a launch beam for a bridge, is also design. It may not use the same level of rigor as for the bridge itself.

3.3.2.2 The V-Model

In terms of systems engineering, the six lifecycle stages mentioned above are elaborated with some additional steps that pay attention to the key design stages and to the need for constant validation and verification (Fig. 3.2):

1. Concept of Operations (User view of the system intention)
2. System Requirements
3. Conceptual design
4. Detailed design
5. Implementation
6. Component testing (verification and validation)
7. Subsystem testing (verification and validation)
8. System testing (verification and validation)
9. Customer Acceptance testing (final verification and validation).

In traditional project management (often called the waterfall model), this is seen as a linear process, where action cascades from one step to the next until the project is complete. Unfortunately, this has led, at times, to the wrong product being delivered,

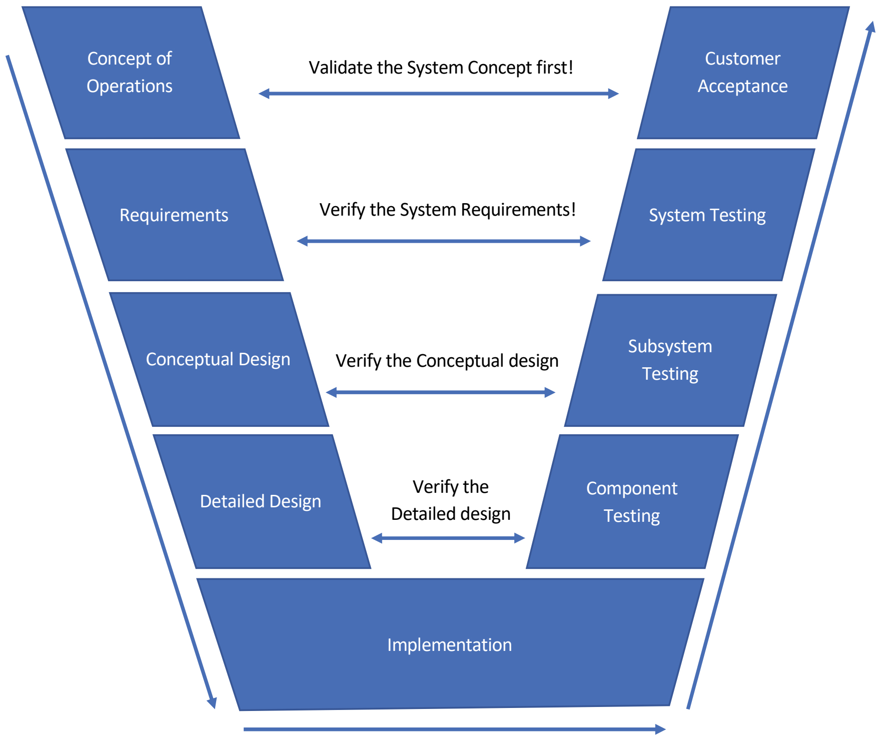

Fig. 3.2 V-diagram

since verification and validation, as a formal step, is left too late (de Bruijn et al., 2010).

At this stage, customers find themselves with a product that does not match what was requested or it contains obsolete technology, or it no longer matches business requirements. To counter this, verification and validation become part of every step, so that as the design proceeds, the design team is constantly checking with the client and stakeholders to ensure that what will be delivered is still in line with client expectations and requirements.

Consequently, systems engineering bends the process into a V, as shown in Fig. 3.2, introducing continuous checking processes across the V, to ensure constant alignment between user needs and the final delivery. Think of these steps as regular meetings with the client. The V-model was originally developed in Germany in the 1990s, with this focus on verification and validation, and was later adopted in the UK and US (Chapman, 2021). This iterative approach also aligns nicely with Agile Project Management, which has been widely adopted in technology companies (Atlassian, 2019).

The V-model begins with the Concept of Operations (ConOps), which is a high-level statement of what is to be delivered. It must address user needs and it may take quite some time for it to emerge. The clearer this statement is, the more likely that a successful project will be delivered. The Concept of Operations states the goals and objectives of the proposed system as well as the process to realize the system, including the stakeholders who must be involved in the process (ISO/IEC/IEEE, 2018).

What helps here is to be able to *validate* the Concept of Operations. This could mean building a rough prototype that can be tested in the field. Often, it's only when the end users see and touch a prototype that they can think clearly about what is required. Agile methodology has arisen from this build-test-build-test approach (Workfront, n. d.), where the intent is to co-develop the system with the end users, using a series of sprints and stand-ups to develop the system incrementally (Chapman, 2021).

A simple example is buying a home. Typically, we all go and view several homes before we get to the stage of signing a contract. As we proceed, we consciously or unconsciously change our specification of what we want. This is a process of convergence where certain needs may become more important in our minds and others less so. Ultimately, the problem becomes better understood through this process of successive refinement. Eventually, we have the confidence to sign a contract on our final choice.

This is true of large hardware and software projects as well. The sooner an end user can begin to interact with a system, the sooner they can tell whether it will do the job for which it is intended. Likewise, the user is more clearly able to articulate the nature of the problem to be solved.

Validating the system early helps to ensure that the next stage, system specification (requirements), is proceeding from a solid foundation.

3.3.2.3 Requirements Modeling

The next stage of the design process is to articulate the business requirements for the new system. Tools include naming the assumptions, defining design objectives, brainstorming, and in design, a technique that uses an easily constructed matrix to correlate objectives with proposed solutions, quickly highlighting those that are easily achieved and those that might also create the greatest long-term value (Fleming, 2021).

Requirements must then be documented and checked for completeness (AcqNotes, 2021; Koelsch, 2016). This may take several iterations. Requirements must be analyzed, refined, and decomposed, ready for validation. Again, this is an iterative process until everyone has agreed with the requirements.

3.3.2.4 Conceptual Design—Concept Generation and Selection

Deciding on which of the many solutions available is the most appropriate for a particular problem requires objective methods that enable stakeholders to have trust that the decision has been made fairly and honestly. Many tools are available, such as decision trees, multicriteria analysis, strategic risk analysis, investment logic mapping, business cases, cost–benefit analysis, cost-effectiveness analysis, and the choice of yeses (Fleming, 2021). The Theory of Inventive Problem Solving (TRIZ) also provides a broad set of heuristics to aid in concept generation (Belski & Belski, 2008; Orloff, 2006; Petrov, 2019).

3.3.2.5 Model-Based Systems Engineering (MBSE)

Systems engineering has evolved from a mostly paper-based process to a computer-based process, where the system under development becomes represented by a series of increasingly complex models. This has become known as model-based systems engineering. MBSE adds rigor and precision, enhances communication between team members, manages the complexity of systems, is in line with other engineering disciplines, which use models, and supports the entire product lifecycle.

The system model joins together a series of subsystem models and component models, in computer-readable as well as human-readable forms. Component models might include the structure, the thermal model, the elevator model, the cost model, the construction sequence model, and so on.

One emergent example is what has become known as digital twins, where a proposed system, e.g., a building, is represented as a series of three-dimensional objects, including all its services, enabling the client to take a virtual walk-through to examine each space (Koerner, 2021). The building could be furnished, walls painted, floors carpeted, and so on, providing the client with an authentic view of the final product. Similarly, all the mechanical, electrical, and telecommunication systems can be run as simulations.

Such a model enables the process of verification—are the spaces all as originally specified? It enables sightlines to be checked and, with the right simulation tools, congestion in corridors or elevators at various times of the day could be evaluated.

The model could also include construction sequence, so that every component of the building can be assembled in sequence, virtually, before the real artifact is constructed or manufactured (Constructible, 2022). Such a digital process can demystify complicated construction sequences, e.g., in major bridge projects, where launching of large bridge beams must be carefully rehearsed to ensure trouble-free completion.

At the heart of MBSE is a structured approach to storing the complete system description, which begins with *requirements*, including interfaces, components, etc. The other three major components of the system model include the system *structure* (usually a hierarchical breakdown of the system into subsystems and components), *behavior* (rules for how components behave and interact), and *parametrics* (the quantitative models of system behavior, including constraints).

These four key components are considered the 'four pillars of SysML,' the Systems Modeling Language (Hummell & Hause, 2015; SysML.org, 2021). SysML captures the complete system model and connects to subsidiary engineering models that are used to describe complex subsystem behavior (electrical, mechanical, structural, etc.). The future of systems engineering is an integrated set of digital models that describe both the form of the system and its complex behavior.

3.3.2.6 Digital Modeling

Digital modeling has been a part of engineering since at least the 1940s, when the finite element method was developed (Hrennikoff, 1941). Engineering computer software became readily accessible in the 1970s and accelerated through the 1980s as access to mainframe computers became readily available and affordable. The availability of cheap and powerful desktop computers has accelerated this trend in the last two decades.

In the early 70s and 80s, there was significant in-house program development, for specific purposes. However, it was not long before software houses emerged to service engineering applications in the major disciplines, e.g., mechanical, electrical, civil, chemical, etc. Many of these have evolved into comprehensive suites that address a wide range of engineering applications, e.g., Dassault, Siemens, and Bentley. Others are more specialized but also widely available, such as MATLAB, Ansys, Aspen, COMSOL, and others.

Engineering graduates need skills in using software relevant to their discipline. These should probably include one of the general systems software, plus one or more of specialized ones suited to their career path. Current progress on Python is facilitating designing and testing different software. The language is modular and flexible, and it is not difficult to master. In the next section, the history of computing tools is considered, including emerging trends such as AR and VR, and how these might be integrated into future engineering curricula.

3.3.2.7 Future Systems Engineering

The International Council for Systems Engineering has articulated a vision for the future of systems engineering (INCOSE, 2022). This vision recognizes that engineers operate within increasingly complex business, community, and natural environments. Engineering systems are evolving and are more sophisticated. Most of the engineering systems have systems nested inside them. Thus, systems engineering needs to be able to model these systems of systems, especially as they represent many social and economic systems that are the embedded within the challenges within the United Nations Sustainable Development Goals (United Nations, 2021). Systems engineering is then essential for addressing human goals.

Engineering is also using increasingly complex technologies, notably the rapid rise of artificial intelligence systems that are transforming formerly dumb infrastructure systems into smart systems that can respond to levels of demand, time of the day, and so on. These systems are increasingly transdisciplinary, turning traditional civil, electrical, mechanical, and chemical systems, into adaptive data engineered systems.

The INCOSE Vision statement maps out the skills that all engineers will need as they work on these increasingly complex and integrated systems. A summary of a typical project is contained in chapter three of the vision statement. It demonstrates how a socially integrated approach is used to develop a new product through several stages. These stages include (a) concept definition engaging all relevant stakeholders, (b) systems definition with the application of a range of digital tools, (c) systems realization of the hardware, software, and AI-ware, into systems production using digital twins, and (d) finally systems support, and utilization based on the digital systems tools and models that have been built during the development phase. This process will become fully integrated and become the standard for engineering design.

3.4 Digitalization Mindset

One of the amazing achievements of the digital age is the set of flexible and adaptable Internet protocols. Over the life of the Internet, there have been several major shifts in device connectivity as well as changes in hardware platforms and yet, the Internet continues to operate well regardless of the changes in the software, hardware, and network systems. The creativity of the engineering of the Internet protocols made the Internet a universal device (Internet Society, 2022). The Internet will probably continue to operate as is and serve humanity for many generations. Internet applications and its portals, the smartphones, are not the only transformations of the past 20 years. Advancements in renewable energy, medicine, public health, precision agriculture, aviation and space travel, robotics and AI made significant impact. We note that most of these advancements were achieved at a systems level and are outcomes of interdisciplinary engineering that took many iterations to reach its current stage. There is no question that the necessary conditions were provided by the ability to retrieve information over the Internet.

In fact, fast and easy access to the Internet facilitated the development and deployment of several search engines, with Google being the most popular search engine covering a worldwide market, followed by Microsoft's Bing, Yahoo, Baidu (China), Yandex (Russia), Duckduckgo, Contextual Web Search, and Yippy Search; a huge variety of searching engines are available to people across the globe.

These engines perform flawlessly on all browsers with easy-to-use interfaces, quality search results, and a personalized user experience. However, most of the platforms catalog the browsing habits of users and share information with advertisers. Such privacy issues have been a subject of discussion, but the practices of the companies that are providing the services free of charge, are tolerated; it is often said that if the service is free, we are the product!

In general, surveillance, tracking thoughts through searches, and communication, are now part of 21st-century practices. Citizens across the globe resent such practices, but so far there are no voices to support implementing legislation similar to the legislations used to control news media and similar agencies. These practices have implications on several aspects of human life including security and sociability, products and business practices, education, and the future of work, among several others.

With the numerous search engines and the massive number of websites that span research and education, data and information are readily available. Thus, these digital technologies present incredible opportunities for learning and creative entrepreneurship. With the stable Internet infrastructure, it was thought that online information will take away from the important role of the educational institutions and need for their teaching faculty and will render on-campus courses less critical. Such notions were rebutted by Herman (2020). Human beings are social animals; socialization and peer-to-peer learning must be part of the learning process. Group discussions and faculty-student interactions continue to be of prime importance.

In addition to the presence of knowledge online, there have been tremendous advancements in AI and robotics. These are facilitated by advancement in hardware and firmware which have been facilitated by miniaturizations in MEMS and CMOS electronics. In all digital fields, semiconductors continue to play a major role, and new silicon fabrication technologies led to great advancements that reached less than 8nm line definitions for electronic circuitry, which meant that nano-MEMS became useful for many applications. In addition, several software techniques are paving the way for new types of robotics, virtual reality, and augmented reality. Through apps residing and distributed using Cloud and Edge-computing, powerful applications will become available to various devices including autonomous cars and drones. Blockchain is becoming one of the popular techniques, and multiexperience, as well as others, delivers immersive experiences.

Machines are designing other machines, and such innovation is opening new dimensions. With that, great expectations are looming. How far can we advance AI and to what extend can it complement, if not substitute, human intellect? Such questions have been with us since Al-Jazari designed and built the first robots (Wikipedia, 2022). There is still a fundamental obstacle that we need to conquer, which is machines that understand context.

Human beings can understand their context quickly. In fact, a 2-year-old child knows a lot about themselves (Rochat, 2003) and by age of 4 they relate to the context of their environment and its rewards and risks (Moore & Corbit, 2019; Tummeltshammer & Amso, 2017). For machines, such as robots, as well as other artificial intelligence (AI), it is very difficult to train them to create solutions within context. This is a consequence of the fact that the human ecosystem has a very complex context. However, the effectiveness of an AI solution is highly influenced by its implementation in each human and social context. Such ability to recognize context as well as context integration within the social, biological, ecological, and organizational foci is a human trait, and it might be very difficult to create AI that can be successful in addressing broad complex interventions (Brézillon, 1999). Recently, Chat-GPT has shown significant progress in this direction. Context is acquired from people as they chat with AI.

In addition, there are notions that co-design is the way to integrate context within different AI modalities. Thus, human and machine would operate collaboratively, and each would perform the best they do in each domain. Previously, machines were expected to perform well under the supervision or the assistance of human beings. But can human beings be assisted by a machine or set of collaborating machines? And how much independence should such machines be given?

These proposals and questions might be viewed as part of the quest to create completely autonomous AI, or a general-purpose AI. An example of autonomous AI is driverless vehicles. Although great progress has been established, the driverless car is still far from being error-free and will require more sensors to provide data to enhance reliability and increase the ability of the AI to understand context and address complexity.

On the other hand, specific-purpose hardware–software systems show very promising outcomes. For example, recent advancements in robotics made it possible to create significant applications. Humanoid robots benefited from the advancements of machine learning, natural language processing, and imaging (Trend Max, 2020). There are many examples of such robots successfully performing specific goals such as interacting with toddlers and elderly persons and performing specific tasks in motor control and neurorehabilitation. Application areas include enhancing the mobility of healthy individuals, restoring the mobility of patients with gait deficits, and assisting those with upper extremity weakness to perform activities of daily living. In addition, wearable robotics for rehabilitation is a successful intervention.

There is a range of interesting devices; some are used to help persons with severe walking difficulties, a loss of balance with an increased risk of falling, as well as muscle fatigue that quickly sets in during exertions. Also, robotic exoskeletons have been used with significant success to help stroke survivors with hemiparesis of varying severities and types of impairments (Gagnon & Aissaoui, 2020). Soft programmable mechanisms with new flexible mechanical meta-materials, for example, can augment soft robots that can safely and effectively interact with humans and other delicate objects. In general, robotics can be viewed as part of the overall AI technologies that will have a role in education and learning.

Virtual reality (VR) is another technology that has started to hold traction in the last few years, and soon it will be part of the educational technologies that we need to engage with. VR provides simulated experience of a situation that can be similar to or different from a real-world one. These might include augmented reality or a mixture of realities and, in some situations, it may extend reality to create immersion experiences.

With such possibilities, using VR for learning[1] has limitless applications including training and experiencing and creating outcomes as part of active learning. These applications, of course, may cover different disciplines of different complexity. VR could create immersive experiences and benefit students by creating interesting experiences and deeper and lasting experiences. Applications of VR could spread as an extension of the human brain to encompass broad applications in business, games, and security.

Although we attempted to provide some insights of the technology that has been developed over the past 15 years, there are many undiscussed topics. Thus, the digital mindset should be viewed as orienting the readers to the important topics that are being invented and the speed at which inventions are made. Both the different inventions and their speed are important factors that are influencing education in general, and engineering in particular.

In the future, we will also see more and more digital learning and blended formats for engineering students, and this will create even more possibilities for active learning methodologies and applied blended learning modes. One way to respond to the situation of students sitting at a distance is by raising the awareness of how the students can improve their own learning. When learners must organize their own learning process virtually, they need ideas, imagination, peers, and structures for how they can organize, reflect, and improve these processes. Therefore, meta-cognitive skills for progress and learning become an important part of future skill sets.

3.5 Conclusion

The design process can reasonably be considered the engineer's universal problem-solving process. It begins with client request and proceeds through a process of problem definition, solution generation, prototyping, testing, and implementation. Effective engagement with stakeholders in the early stages is critical to ensure that the problem is properly defined in its full context. Systems engineering provides a structured approach to design, which ensures that what is finally constructed or manufactured also meets the client and customer needs, through a process of continual validation and verification. The future of design and systems engineering lies in digital tools and digital twins. This is a key area of competency required for all graduates.

[1] https://online.lsu.edu/newsroom/articles/how-virtual-reality-changing-education/, https://www.opencolleges.edu.au/informed/edtech-integration/10-ways-virtual-reality-already-used-education/

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Chapter 4
New Competencies for Systems Thinking

4.1 Introduction

The growing complexity of technological systems, which has been elaborated upon in previous chapters, has increased the focus on the sociotechnical dimension of engineering, which engineers must increasingly address.

First, the grand challenge of sustainable development has raised concerns about the nature-culture dualism, understanding 'culture' as related to what is human-made, while 'nature' is assigned to what is not human-made. Based on a review of literature that either constitutes or challenges this dualism in Western society, Haila (2000) has offered a more contextual and socioecological view on the spheres of human activity (Haila, 2000). With reference to Dewey (1958, p. 58), Haila (2000, p. 168) underlines that '*… thinking is no different in kind from the use of natural materials and energies, say fire and tools, to refine, re-order, and shape other natural materials, say ore'*. In this view, Haila (2000, p. 169) argues that '*action-dependence and context-specificity of the artificial is a fruitful starting point for decomposing the nature-culture dualism'*. Here, the interactions between human practices and natural processes, in particular cases, become the center of attention.

Many current conceptualizations to grasp the prospects of future societies have been developed in alignment with this understanding. Take, for example, the vision of a so-called circular economy. Geissdoerfer et al. (2017) carried out a comprehensive review of the concept of a circular economy and described how the concept has evolved from a rather descriptive approach to how natural resources influence the economy to a more intentional and design-based approach. This approach has gained traction with policymakers and matured to become institutionalized at the governmental level, e.g., in Europe and China. The resource flows are combined with an intensive focus on human practices involved with long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling of products and services. What makes sense in these processes is, as noted above, the interactions between human practices and natural processes, in particular design cases. Without

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action dependence and context specificity, the idea of a circular economy holds no prospects.

Likewise, and although previous dualistic approaches are still rather dominant in current institutionalizations, the interrelations between technology and science have drawn increasing attention. The notion of technoscience grew out of French postmodernist movements (Hottois, 2006, 2018) drawing attention to the interrelations between technological development and scientific discovery. So-called science technology studies (STS) created the foundation for understanding these interrelations (Sismondo, 2010). Authors within this STS area of research have emphasized how human practices frame the creation and use of technology and, likewise, how technology becomes an actant in framing human activity.

The STS methodology has offered opportunities to analyze and get inspired by overviews of how technology is socially constructed. For example, Bijker (2012) presented a theoretical framework for the Social Construction of Technological Systems (SCOT) and pointed to a system of relations between problems, artifacts, and social groups.

Another example is the actor-network theory (ANT) as developed by Latour (2005) and others, which stresses the opportunities for nonhumans (e.g., technological artifacts) to act or participate in systems or networks involving different types of exchanges (material) and translations (semiotic).

On the micro-level, and very aligned with the rejection of the rigid boundaries of the dualistic approach, Haraway (2000) wrote the so-called *Cyborg Manifesto* to question the separation of the human from the other—an animal, a machine, another human being of a different gender, etc. These types of conceptions are striking in the sense that, although they reject boundaries as a premise, they make use of boundaries as social constructs to analyze and develop existing understandings.

Although STS research communities typically present themselves as interdisciplinary research communities, it can be argued that their grounding in social science and humanities (SSH) has pushed for an unintended nature-culture dualism, with an overemphasis on cultural issues. Likewise, although research communities in the environmental and sustainable science domain are typically interdisciplinary, it can be argued that their grounding in natural sciences has also pushed for an unintended nature-culture dualism, with an overemphasis on natural resources. And, finally, as the nature-culture dualism has dominated in Western philosophy, it can be argued that there are considerable barriers in finding appropriate ways to deal with the interactions between *human practices and natural processes in particular cases*; nevertheless, societal development urgently needs this approach.

From an engineering education point of view, institutions have tried to cope with the challenge within the disciplinary discourse, e.g., by establishing new disciplines as hybrids of existing disciplines, such as environmental engineering. This strategy has resulted in professionals who have, as their core, the capacity to bridge between different disciplines, filling in the gaps in the workforce. However, as there must be severe gaps to initiate such a degree of institutionalization, the new hybrid disciplines are not sufficient to address the complexity of the current societal challenges. More must be done. There is a need for integration of multidisciplinary knowledge in engineering education *across* all engineering disciplines, and there is a need to let the particular cases and the particular context to determine what human practices and natural processes are of relevance in specific engineering domains.

The rise of hybrid education, however, adds even more complexity to what could be called a 'discursive battle' between the beholders of core knowledge of the future. Therefore, institutional top management has a serious responsibility in creating leadership to balance different types of disciplinary settings in a way that will match the needed systems approach. There must be a strategy to combine disciplines of specialized experts who can work in interdisciplinary settings (an integrated program approach) with those who have the interdisciplinary expertise to bridge between disciplinary experts (the hybrid program approach). The balance between the two is crucial as the different types of disciplines must coexist when students move beyond university borders.

Consider one example. If all engineering students are to integrate design in their engineering education, how would that affect the curriculum of industrial design? How would industrial engineers contribute to a multidisciplinary team. These may sound like simple questions, but the 'knowledge is power' discourse in academia might trigger potential conflicts. Furthermore, if we do not accept rigid boundaries between design and engineering, how should we then merge the thinking, the methods, and the practices among staff and students? The same questions could be asked about the increasing call to merge sustainability science and engineering in an engineering education for a sustainability approach. Our understanding of 'know-how' within a discipline is considerably challenged and, furthermore, it is constantly changing.

In line with the above, there is the question of how to integrate or, in other words, how can we make and create a curriculum that is so flexible that it can embrace the changing call for multidisciplinary approaches that real-life cases call for? How should we determine what is needed in the particular cases of our concern, and who is to decide what is relevant knowledge to combine with the knowledge we find to be necessary to uphold disciplinary identity? To answer such questions, no matter if we are institutional leaders, educational designers, students or professionals, critical thinking and sense making are key competencies.

4.2 Critical Thinking and Sense Making

Although definitions of *critical thinking* are diverse, some cornerstones have been defined, from Socrates and beyond, including processes of questioning, reasoning, and judging. Explicitly, critical thinking thereby also relies on a set of criteria and purposes, which are carried on by individuals, social groups, and even cultures. Therefore, it is a complex endeavor to study, to educate for, and not the least to effectively practice, critical thinking in diverse settings and situations.

Mogensen (1997) captures dimensions of complexity in critical thinking by outlining four perspectives of critical thinking being epistemological (underlining individual knowledge positions and acts), dialectical (including different views and social knowledge constructs), holistic (including emotional and social dimensions) and transformative (questioning wider structures e.g., related to political, environmental, and cultural spheres). Barnett (1994) has conceptualized the dialectics between individual and social knowledge constructs by distinguishing between critical thinking (as individual construct) and critical thought (collaboratively constructed).

Some scholars emphasize the context dependency of critical thinking. In a learning perspective, Schön (1987) has characterized critical thinking as a continuous process of reviewing models, theories, and ideas applied to a context at different levels (e.g., individual, community, and/or social levels). In an educational study, Guerra and Holgaard (2016) point out that arguments in a critical thinking process, besides being scientific and personal, are likewise grounded in contextual analysis. This underlines that even though critical thinking is a cognitive process of questioning, reasoning, and judging, it is informed by social and contextual interactions.

Other scholars have emphasized reflexivity considering the critical thinking process itself, which relates to meta-learning. Baron and Sternberg (1987) regard critical thinking as a thinking pattern that requires people to be reflective and pay attention to the decision-making process that guides beliefs and actions. King and Kitchener (2004) developed a model for reflective judgment including both people's different assumptions and range of knowledge, and the way people mobilize and use knowledge to justify their own judgments.

As we move on discussing the prospects of critical thinking for engineering education at a learning, as well as a meta-learning level, we will include both individual and collaborative processes of questioning, reasoning, and judging, related to different aspects of technological systems in context. To further stress the social, collaborative, and organizational aspects of critical thinking, the concept of *critical system thinking* offers a complementary framework.

Critical systems thinking derives from two sources—critical social theory and system thinking in itself (Jackson, 2001, 2010). Critical systems thinking recognizes that real-world problems do not correspond to traditional disciplinary boundaries and cannot be addressed in a reductionist fashion (Jackson, 2001). A move away from reductionism creates a need for overview, and the systems approach (with its focus on boundaries, elements, interrelations, feedback mechanisms, and transformation) provides exactly that.

The critical approach provides an attention toward what is at stake, what is problematic, what is valuable and, finally, what might be missing. Ulrich and Reynolds (2020) furthermore stressed the need for critical thinking about the boundaries and introduced 'boundary critique' as a process of defining, discussing, and negotiating what is relevant in an analysis. Critical systems thinking, furthermore, encourages a methodological, pluralistic, and emancipatory approach (Jackson, 2010), depending on the alignment between the system and the need for negotiation of values and interests.

Although a critical systems thinking approach has been criticized for being too much of an academic discourse and a concept in need of reframing (Midgley &

Rajagopalan, 2020), the approach more basically brings attention to the need for a critical dimension in systems thinking and the process becomes collective and interactive, besides being cognitive and mental. The approach is not only concerned with reflection on the chosen systems approach, but likewise reflecting upon the ethics of invention behind it as well as the type of problem addressed (Jackson, 2001, 2010). This means that the systems approach itself is questioned and, as the social part of a technological system typically involves different groups and organizations, critical thinking becomes an interactive and exposed process contributing to the *sense making* that informs shared decisions and actions.

Karl Weick introduced sense making to underline that complex problems do not make sense at the outset (Weick, 1995, p. 9):

> In real-world practice, problems do not present themselves to the practitioners as givens. They must be constructed from the materials of problematic situations which are puzzling, troubling, and uncertain. In order to convert a problematic situation to a problem, a practitioner must do a certain kind of work. [They] must make sense of an uncertain situation that initially makes no sense

Thereby follows that without a sense-making process to understand the problem in situ, decision making and action plans to follow will likely not make any sense either. Based on Weick (1995), sense making is:

- Grounded in identity—a consistent and positive self-conception that includes self-reflexivity.
- Retrospective—to reveal meaningful lived experiences. Retrospections express modifications of prior experiences.
- Social—sense making seldom happens in isolation. People enter dialogues and build narratives and activities, which are both individual and shared.
- Enactive—people enact with the environment and project themselves into an environment to observe the consequences.
- Ongoing—enactments create experiences, which feed the following retrospections, of which new enactments are based.
- Informed by extracted cues—people extract cues from the context to help them decide on what is relevant to make sense of.
- Based on virtues of relevance and plausibility rather than truth and accuracy.

Kurtz and Snowden (2003) especially relate sense making to complex adaptive systems and chaotic situations. When faced with extreme complex situations, cause and effect are only coherent in retrospect and do not repeat, whereas a Probe-Sense-Respond strategy is proposed (Kurtz & Snowden, 2003). However, retrospections are not of much use in chaotic situations, as no cause-and-effect relationships are perceivable. In these situations, an Act-Sense-Respond strategy is proposed, as there are no patterns to be analyzed; the strategy simply is to act quickly (Kurtz & Snowden, 2003). Thereby a stimulus is enacted to provoke a response that can be analyzed and makes sense in the given situation.

Van Wart and Kapucu (2011) relate such chaotic situations to crisis management, which is defined as unplanned situations with an urgency for fast change due to high criticality. In such situations, personal traits as self-confidence, willingness to assume responsibility, and resilience become important, to exhibit calm and strong leadership. In popular terms, there is less time for critical thinking as immediate action is needed, and intuitive aspects of sense making come into play, as well as to perform what Schön (1987) termed reflection-in-action.

These situations, complex and chaotic, are the ones underlining the need for human capacity. As expressed by Kurtz and Snowden (2003), there are at least three contextual differences between human organizations and ant colonies that make them more difficult to simulate using computer models: humans are not limited to one identity, they are not limited to acting in accordance with predetermined rules, and they are not limited to acting on local patterns. This being said, the complexity of systems and the urgency to act underlines the importance of having abilities to use digital technologies to handle as much of the information processing as possible, and as quickly as possible.

Back in 1990, Jerome Bruner raised attention to the act of meaning, and in his own words, he was decrying the Cognitive Revolution for abandoning 'meaning-making' as its central concern, opting for 'information processing' (Bruner, 1990, p. 137)—today we have reached so far in the digital age that the potential for a distributed workflow between human and machine becomes ever clearer. When actions are enforced, they must be analyzed; when extracted cues are pointed to, we must know more about how/why the domain unfolded.

When things make no sense, we must ensure that we are informed about the parts of the system that make sense at a given point of time. Even chaotic systems are loosely coupled with systems that we might have to know more about. In other words, the capacity to use digital technologies, as well as to develop digital technologies, to assist complex problem solving and handle chaotic situations, will most likely stand as one of the most important cross-cutting competencies, and cores, of engineering of the future.

4.3 Abilities to Use Digital Technologies Are Required

Digital literacy is highlighted as one of the fundamental literacies for most frameworks of 21st-century competencies (Pilco, 2013). Ryberg and Georgsen (2010) form group ideas of digital literacy into three overarching categories:

- *Retrieving and participating in information practices*, including the ability to search for, synthesize and disseminate information, follow the flow of stories and information, and move across multiple modalities and diverse communities.
- *Presentation, production, and performance:* to play/experiment with one's surroundings as a form of problem solving, adopt alternative identities for improvisation and discovery, provide dynamic models of real-word processes by simulation and be able to appropriate media content.

- *Collaboration and work skills*, including the ability to scan one's environment, pool knowledge toward a common goal, establish a collective intelligence, and interact with digital tools that expand mental capabilities in a meaningful and distributed way.

In an educational context, this definition of digital literacy underlines that digitalization expands our view of both information processing, problem solving, and collaborative learning.

In the European Framework for the Digital Competency of Educators (DigCompEdu), the following six competency areas are considered: professional engagement, digital resources, teaching and learning, assessment, empowering learnings, and facilitating learners' digital competency (Commission, 2017; Redecker, 2017). This framework is useful to underline the different areas of concern, as well as different response strategies from engineering institutions.

Area 1, Professional engagement focuses on engaging professional environments including organizational and professional communication and reflective digital practice as well as digital consumer data platforms (CDPs) (Commission, 2017). Area 1 thereby interlinks the digital and subject-specific competencies in professional practice and underlines the context dependency of digital competency. As an example related to engineering, the System Engineering Research Center has developed a Digital Engineering Competency Framework including five levels (SERC, 2022):

(1) Data Engineering, which covers data governance and data management,
(2) Modeling and Simulation, to predict real-life performance of potential technologies,
(3) Digital Engineering and Analysis, to optimize engineering systems,
(4) Systems Software, for systemic application of digital engineering approaches to develop software,
(5) Digital Enterprise Environment, to create digital engineering environments including software, hardware, and management aspects.

Whereas most engineering programs will most likely cover up to level three, levels 4 and 5 are typically addressed in specialized IT programs, which provide the foundation for new knowledge of computation and simulations as well as big data analysis and machine learning. As such, most engineering candidates are expected to have a high level of digital literacy but transferring this literacy from one engineering discipline to another is challenging. Unsurprisingly, it is also a challenge to transfer this digital literacy from technology development to human development—in this case development of the next generation of engineers.

Area 2, Digital resources, is related to sourcing, creating, and sharing digital resources and includes competency to select, create, modify, manage, protect, and share these resources (Commission, 2017). Area 2 thereby links the use of digital resources to educational practice. Examples of digital resources are scientific search engines, learning management systems (LMS), audio-visual productions (AV), and software designed for educational purposes, e.g., simulation programs.

The perceived importance of different digital resources however differs according to the educational context. Morais et al. (2015) even showed significant differences in the importance given to the use of digital educational resources between 1st and 2nd year students within the same program.

It is important to recognize that even though engineers, due to their technological focus, are expected to have a high contact with digital tools and a high degree of expertise in using digital tools, the resources needed for an educational session might differ. In other words, when the focus shifts from professional to pedagogical practice, faculty staff might lack an overview of digital resources for educational purposes. Without this overview, it becomes hard to understand which digital strategies might work best in particular educational contexts.

Some universities have responded by establishing technical support units with the obligation to create awareness of digital tools and support staff in selecting, creating, modifying, protecting, and sharing digital resources within the different fields of studies.

Area 3, Teaching and learning, relates to managing and orchestrating the use of digital tools in teaching and learning, including teaching, guidance, collaborative learning, and self-regulated learning activities (Commission, 2017). Area 3 thereby links to the use of digital means to improve educational activities.

An overarching example is the design of blended learning modes to offer a more inclusive, more flexible, or more diverse learning environments. In a systematic literature review, Boelens et al. (2017) underline the complexity of such blended learning environments as they point to challenges of incorporating flexibility, stimulating interaction, facilitating students' learning processes, and fostering an affective learning climate. Another example of the use of digital means to improve educational activities is gamification to engage learners (Faiella & Ricciardi, 2015).

These examples illustrate that an overview of digital resources and their applications for educational purposes is not sufficient. Faculty and staff must align the use of digital resources to the overall curriculum model, including consideration of the interplay between intended learning outcomes, design of educational activities, and assessment (whereas the latter is considered more specifically in area 4).

One response strategy is to reinforce the alignment of digitalization, teaching, and learning by specialized staff who can work as consultants in combining insights in pedagogical practice and digital literacy to support implementation incentives. More ambitiously, some engineering institutions have seen the strategic potential of establishing teaching and learning design units, which are targeted to the development of digital strategies that are aligned with the educational models, and who are able to develop the educational models of the institution through the power of digital technologies. Such design-based approaches to educational development must go hand in hand with staff-training, mentoring and peer-to-peer learning to benefit from the dialectics of educational research and practice.

Area 4, Assessment, points to digital tools and strategies to enhance assessment, including assessment strategies, the analysis of evidence, feedback, and planning (Commission, 2017). Area 4, like area 3, is likewise related to digital means to improve educational designs, in this case of assessments, and thereby the response strategies are similar. For this specific area of concern, an example is integrating quizzes for formative self-assessment into the learning management system and providing standard feedback for the user based on identified user typologies. For more summative assessments, digital exams are an option, now introduced in many engineering institutions. However, converting a paper-based engineering problem into a computer-based problem that can be automatically scored is challenging. For one thing, engineering exam questions are typically presented as cases related to a specific context and, furthermore, the partition problem-solving steps are also to be considered in the design (Keijzer-de Ruijter & Draaijer, 2019).

For **Areas 2–4**, the COVID-19 pandemic, and the urgency to plan and carry out remote teaching forced a growth in digital competency for educational faculties around the world. Whereas the instructional technology to deliver lectures was considered rather straightforward, it was less obvious how to use active learning approaches in an online environment (London et al., 2022) It can be argued that the acknowledgment of the challenges and limitations of transforming constructivist learning approaches to an online platform, is just as important a side-effect of the COVID-19 situation as the overall rise in digital competency.

This acknowledgment does not only include the importance of social presence and sense of belonging in a study environment; it also highlights the need for more systemic approaches to digital transformation of education, including general principles for what is considered the right blend for the next generation to respond to current societal challenges. When all teaching had to be distant, urgency became the main motivation and the technical tools available shaped the way teaching was carried out. After COVID-19, the lessons learned by doing now stand as a potential opportunity, but a lack of reflection on the why, what, and when of digital education, may not deliver the changes of practice that are possible. Similarly, a move to better digital tools, to empower the next generation of learners, may not occur soon enough.

Area 5, Empowering learners, focuses on the use of digital tools that can create more learning opportunities by accessibility and inclusion, differentiation and personalization, and active engagement of learners (Commission, 2017). Area 5 thereby underlines the potentials of digitalization to rethink educational systems. Whereas levels 2–4 used digital means to provide feedback to users based on typologies, area 5 includes personalized feedback and moves the benefits of blended learning beyond substituting what a teacher could act on in situ, to what the teacher could possibly act on given better data on each individual's performance.

With increasing ease of big data analysis, personal learning analytics have become within reach to inform students on their learning strategies, and machine learning makes intelligent big data management possible to guide students on their learning paths. Chen et al. (2020) concluded, based on a review of Artificial Intelligence in EDucation (AIED), that AI has extensively been adopted and used in education and, likewise, AIED has increased in modalities—from primarily computers and computer-related technologies to web-based online intelligent educational systems and a use of humanoid robots.

However, whereas such digital technologies can fill a gap in current scaffolding of learning and potentially can serve to increase retention of students, they also change the role of higher education in a way that unlocks dependencies from locations and questions the distribution of market shares. Whereas levels 2–4 have been heavily reinforced by a sense of urgency, due to the pandemic, level 5 has instead been strongly reinforced by a perceived risk of disruption of established educational institutions.

In the 1990s Clayton Christensen introduced disruptive innovations, where disruption describes a process where a company with fewer resources is able to successfully challenge established incumbent businesses by successfully targeting overlooked segments and gaining a foothold by delivering more suitable functionality for some customers (Christensen et al., 2018). Christensen et al. (2018) summarize different response strategies to prevent such processes of disruption, which includes extending current performance-improvement trajectories, proactively repositioning in new niches, using organizational dexterity by enacting dual structures, processes and subcultures; partnering with licensing start-ups or, more fundamentally, pursuing a re-emergence strategy by redefining the meanings and values associated with their legacy.

In an engineering education context, current strategies to counteract disruption include strategies for performance improvement by use of digital tools to enhance teaching activities, digital twins of on-campus educational activities, cross-institutional collaboration, combining educational and digital specialists, and partnering with companies, e.g., using AIED. Furthermore, more fundamental re-emerging strategies are getting established, by redefining the academic institution as a much more hybrid and open entity, with students and researchers as societal agents (Jamison et al., 2014). In such mission-driven approaches, accessibility and inclusiveness are not only a part of a fundamental democratic value of educational practice, but also, it is a necessary means to create the partnerships and outlook needed to cope with the grand challenges of our time, like the COVID-19 pandemic, or the concerning implications of climate change.

Areas 1–5 address the digital competencies of teachers, which are preconditions to scaffold students in developing digital competencies. However, this extensive focus on teacher's generic competency also highlights the extensive need for faculty development. The use of proficient professional levels, outlined in relation to the DigCompEdu framework, (Commission, 2017) summarizes the exact challenge facing engineering faculties. The first two levels picture the *newcomer*, having very little contact with digital tools and in need of guidance to expand their digital repertoire, as well as the *explorer* starting to use digital tools comprehensively and consistently. As mentioned, these first two levels might not be a problem for the technologically knowledgeable engineer, whereas the challenge arises at the third and fourth levels.

The third level outlines the *integrators* being able to experiment with digital tools for a range of purposes, and in specific contexts, whereas the fourth level pictures the *expert* being able to use a range of digital tools confidently, creatively, and critically to enhance their professional competency. The expert thereby needs a double if not triple qualification related to educational, digital, and subject-specific fields of study; they need capabilities in assessing digital technology in a user context, and abilities to do so while interfering with the field. Furthermore, the more systemic level introduced in area 5 challenges the level of progression from the expert to the *leader* who has such a broad repertoire of flexible, comprehensive, and effective digital strategies that they can serve as inspiration to others. At level 6, *pioneers* are set out to question the adequacy of contemporary digital and pedagogical practices, calling not only for a systemic but also reflective system thinking concerning digital transformation of engineering education.

Not surprisingly, progression on these levels can be overwhelming for any university teacher and, therefore, digital transformation of education is to be considered as a distributed, collaborative process. With this outset there is a need to clarify, at the institutional level, what competencies teachers should possess themselves and what competencies they should know who to consult. Depending on this clarification, the right organization and information flows can be designed to ensure coordinated action. In more popular terms, *strategy, not technology, drives digital transformation* (Kane et al., 2015).

Area 6, Facilitating learners' digital competency, stresses the facilitation of students' competencies in areas such as digital literacy, information and media literacy, communication, content creation, responsible use of information, and problem solving. Whereas areas 2–5 create the pedagogical core of the framework, area 6 links directly to students' competencies, including that students are educated to (Commission, 2017):

(1) Articulate information needs, to find information and resources in digital environments, to organize, process, analyze, and interpret information, and to evaluate the credibility and reliability of information and its sources, both comprehensively and critically.
(2) Effectively and responsibly use digital technologies for communication, collaboration, and civic participation.
(3) Modify and create digital content in different formats, and to consider how copyright and licenses apply to digital content, how to reference sources and attribute licenses.
(4) Manage risks and use digital technologies safely and responsibly.
(5) Identify and solve technical problems, and to transfer technological knowledge creatively to new situations.

These points relate very much to the developed European Digital Competency Framework for Citizens (Commission, 2016). Interestingly, one could ask whether these capabilities, which, besides number 5, are rather instrumental in nature, will in fact educate engineers to lead or even take an active part in digital transformation processes. This point is underlined by a systematic literature study of the digital competency of university students (Sánchez-Caballé et al., 2020), showing that most documents dealing with digital competency bring concern that authors do not believe that young people actually have the digital abilities that they are assumed to have.

The good news for engineering institutions is however that the focus on innovation—from incremental to radical innovations—provides a framing for technological change in general. We will argue that coupling the discourse of digital transformation with the one of technological innovation, creativity, and entrepreneurship, holds potential for a deeper understanding of digital literacy in an engineering context, as well as more targeted use and development of digital tools for educational purposes.

4.4 Creativity and Entrepreneurial Skills to Create Value

If we are to consider the art of creativity, we also must consider what we would characterize as a product of creativity. An example used in our own teaching is to show students a collection of three abstract paintings, which sold for over US$25,000 to an American art collector. We ask whether they consider these paintings a product of creativity. Due to the introduced storyline picturing a recognized and valued piece of art, students very seldom argue that this is not the case. When asked why, they typically respond in notions of originality and clear intention to provide the viewer with a new insight.

The next question is: Who is the creative one? The obvious answer is the painter—the artist. Students then get the information that the collection of pictures is painted by the chimpanzee Congo staged by the zoologist (and painter himself) Desmond Morris (Wikipedia, 2022, 2023). The introduction of Congo typically puzzles students' pre-assumptions of the intentional act of making something creative, and it puzzles their pre-assumption of the link between intelligence and creativity.

Then students are asked about the role of Desmond Morris and their perception of his creativity. From this discussion, students typically conclude that products of creativity might not only materialize in the tangible product presented. They also recognize that there are different types of actors in the process, which, although they have different incentives, are mutually interdependent on each other.

Desmond Morris is the entrepreneur, he is intelligent and original in the sense of being the one putting Congo, a chimp, behind a canvas to create paintings of value—he is knowledgeable about animals as well as art; he is choosing the materials; he is setting the stage; and he knows the target group and how to market his product by use of the storyline of its making. Congo, they guess, was just enjoying painting.

As there are differences in the types of products and incentives and roles of actors in the creative process, there are also differences in the epistemological view of creativity. (Sawyer, 2005, 2015) distinguishes between the rational and romantic approaches to creativity. Whereas the rational approach is generated by the conscious and deliberate mind, the romanticist approach bubbles up from the irrational unconscious.

Such approaches can be mirrored by different strategies to cultivate creativity. Whereas the rationalist approach implies a pedagogical practice that uses techniques to bring forward and combine a variety of cognitive schemes, the romanticist pedagogical approach is focused on creating a secure and undisturbed environment to explore possibilities, which at the time seems to be beyond reason underpinning current practices. In the rational approach, the ability to structure and combine mental maps is a key virtue, whereas in the romantic approach, the ability to free the thought from existing mental maps and open the mind for new perceptions are keys to develop new mental maps. Referring to the example above, Congo represents the romantic approach, whereas Desmond Morris might even address both.

In a constructivist view, as conceptualized by Piaget (2013), people construct knowledge and knowledge schemas based on external stimuli. Furthermore, people enter groups and what Sawyer (2015) calls group creativity, and groups are social systems which relate to symbolic rules and procedures (the domain) and social institutions (the field) by which ideas are included or excluded from the domain (Csikszentmihalyi, 1997).

In this respect, the idea of a free mind working independently of existing mental maps and starting out from a tabula rasa can be questioned (even in the case of Congo). On the other hand, if rational approaches to creativity build on the combination of already existing knowledge, the power of imagination, foresight, and radical innovation can likewise be questioned. In a pragmatic view of the two approaches, the combination, however, makes room for different ways to reach different types of innovations. The point is that engineers must build the capacity and the courage to master both approaches to creativity to foster the different types of innovations needed.

The interplay between convergent and divergent thinking (Guilford, 1957), which typically underlines design thinking frameworks emphasized furthermore the ability to shift between different cognitive modes and the embedded interplay between order and chaos. Whereas it can be argued that engineers traditionally have been more concerned with making order following a rather reductionist agenda, leaning toward convergence rather than divergence, complex systems call for the ability to handle chaos, think divergently, and create environments that challenge current mental maps. Turning back to our example in the beginning, distinguishing the creator (Congo) from the entrepreneur (Morris), entrepreneurial competency frameworks offer frames of reference to discuss the need for more specific competencies.

As an example, the European Entrepreneurship Competency Framework (EntreComp) distinguishes between three pillars of competencies in the following way (Bacigalupo et al., 2016):

(1) **Ideas and opportunities,** including the competencies related to spotting opportunities, creativity, vision, valuing ideas and ethical & sustainable thinking.
(2) **Resources,** including competencies related to motivation and perseverance, self-awareness and self-efficacy, financial and economic literacy, mobilizing others, and mobilizing resources.
(3) **Into action**, including learning through experience, working with others, planning and management, taking the initiative, and coping with ambiguity, uncertainty, and risk.

This example of a framework for entrepreneurial competencies expands the notion of creativity from the process of creating new ideas and opportunities to the whole process from idea to value creation. Thereby, other skills, highlighted by the World Economic Forum (World Economic Forum, 2020), such as leadership, social influence, and resilience come into play. Distinguishing between learning 'about', 'for', or 'through' entrepreneurship, Hannon (2005) and Thrane et al. (2016) argue for a learning 'through' strategy, where the learning experience is seen as a co-evolutionary process in which the individual *becomes* an entrepreneur as they transform disclosive spaces into opportunities. The term disclosive spaces is used by Charles Spinosa, Fernando Flores, and Hubert Dreyfus to refer to the socially inscribed contexts in which cultural innovation takes place (McLaughlin, 2006).

If the case of engineering education, the learning 'through' can be obtained by letting students experience and reflect on an entrepreneurial experience related to the development of new technology. With reference to the EntreComp framework, students have to go 'into-action' and the teacher's role is to frame the learning experience and facilitate students to mobilize the needed resources (and if possible, to provide easy access to resources) and the relevant actors (Bacigalupo et al., 2016).

The learning 'through' aspect of becoming also relates to the above EntreComp competency of self-awareness and self-efficacy. Besides the notion of learning 'about', 'for', and 'through' education, Mäkimurto-Koivumaa and Belt (2016) underline the importance of experiencing entrepreneurship by adding the preposition of learning 'in' entrepreneurship to stress the importance of a real-life experience.

The Entrecomp framework also touches upon the so-called life skills, as referred to by the Partnership for 21st Century Skills (P21) including personal qualities, such as taking initiative and coping with ambiguity, uncertainty, and risk (Bacigalupo et al., 2016). The focus on life skills presents a move toward affective learning outcomes including attitudes, motivation, and values. Life skills also relate to the industrial emphasis on resilience, as presented in the top ten list of skills needed by 2026 by the World Economic Forum. The focus on resilience can be seen as a recognition of the insecurity that follows complex technological systems as they unfold more and more wicked problems with higher urgency and complementing needs for quicker decision-making processes.

Resilience refers to a class of phenomena characterized by good outcomes in spite of serious threats to adaptation or development. In an educational context, resilience can be phrased as a matter of addressing, reflecting on, and coping with complex challenges in a way that results in good outcomes both in terms of personal and organizational long-term development and well-being. At the organizational level, resilience at least implies an appropriate capacity of qualified human resources with access to the resources necessary to succeed. Resources include both financial and natural resources, hardware as well as software, and finally, knowledge and supply networks. At the individual level, human resources are further elaborated in the Entrecomp framework, e.g., in terms of perseverance, self-awareness, and self-efficacy.

There can be different strategies to uphold resilience. In an educational setting, students build and maintain resilience in different ways and with different types of appreciation as a response (Fig. 4.1 provides an example of such). A traditional engineering curriculum leans toward appreciation of hard work and the ability to

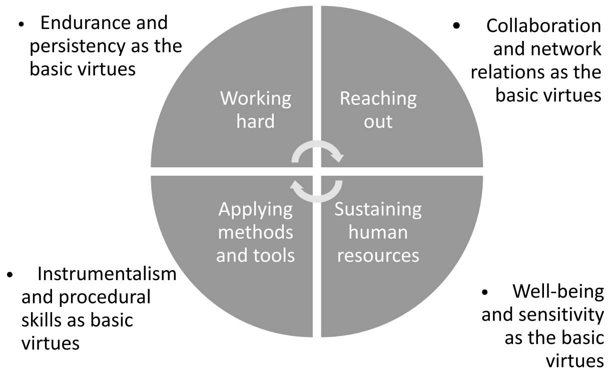

Fig. 4.1 Example of different strategies for students to foster and uphold resilience together with different types of appreciative responses (Holgaard, 2019)

apply and develop new theories, methods, and tools. These virtues are, as a plus, also more easily measured in the assessment of student learning outcomes than more affective and interpersonal learning outcomes, which are often tacit and harder to point to, measure, and appreciate.

Some institutions have tried to integrate intended learning outcomes pointing to students' ability to use and develop their knowledge networks across disciplinary borders or their ability to collaborate in a way that nurtures healthy work environments with higher performance levels. These capabilities are central in the 21st-century skills and in the future skills pointed out by industry partners, but there is a risk that the lack of assessment methods in higher education will limit students, and especially surface learners, who might lack the motivation to develop such skills specifically. This can result in lost potential to build resilience during education.

In the context of safety management and in alignment with the sociotechnical system perspective, Patriarca et al. (2018) present an extensive literature review of resilience engineering (RE). The findings show significant appearance of arguments for a new paradigm in terms of handling complexity across organizations due to increasing organizational flexibility, but at the same time, limitations occur in the 'knowledge for action' literature making it hard to operationalize RE. Consciousness on system dynamics was pointed out as playing a crucial role, and furthermore, it was stressed that resilience is not just about being able to adapt, it is also about being able to obtain stability after a transformation process. In more popular terms, adaptation and robustness go hand in hand.

In relation to an educational setting, a design-based study of challenges in entrepreneurship education points out that lacking resilience is one of the core challenges for students together with tunnel vision and a lack of boundary work (Holgaard et al., 2022). The iterative ability to move back and forth between stability and transformation, between the disciplinary and the interdisciplinary, seems to be as hard as it is necessary to address complex sociotechnical systems. However, as resilience is fundamentally important to transform ideas into value in engineering, more attention could be expected and recommended in the reshaping of engineering curricula.

Finally, it should be stressed that entrepreneurship is a matter of both individual and collaborative learning. In the entrepreneur paradigm, entrepreneurship is viewed as a creative act and an innovation in itself (Zhao, 2005). As we have introduced creativity as an individual as well as social act embedded in entrepreneurship, and as mobilizing and working with others is considered as a core competency in entrepreneurship, we view entrepreneurship as a social process relying on individual agency. Understanding entrepreneurship as a social process is evident—an engineer might become an entrepreneur, but they can never work in isolation. Their understanding of their interdependence with others is crucial to cope with the distributed innovation processes of complex technology systems.

4.5 Focusing on Societal Needs and End-User Requirements is a Priority

While user satisfaction has always been within scope for technological innovation, there are considerable changes occurring, to clarify user needs. A 'more-is-better' consumer-centered mass production perception of the user has gradually been undertaken through an increased focus on product differentiation, to offer products and services to satisfy specific user needs. User-centric design approaches have emerged and have provided methods to analyze 'user needs in context'. Later, user-driven approaches developed and emphasized users as important actors in co-design. Entering the Industry 5.0 era, this co-creation process seems to emerge even further in the use phase itself, whereas technology is seen as an answer to address personalized user behaviors.

Together with the increasing focus on personalization of technology, grand challenges on the societal level have called for urgent action. This means that the lead focus on user behavior is basically questioned and even regulated for the sake of the common good. The more complex and the more urgent the grand challenges have become; the more attention has been given to engineering to address more abstract societal needs. More reactive approaches to technology assessment (TA) have been supplemented by more proactive approaches like constructive technological assessment approaches (CTAs) interfering with user needs even in the design phase (Rip et al., 1995). Recently, CTA approaches have been even further elaborated, for example by suggesting ethical constructive technology assessments (eCTAs) (Kiran et al., 2015).

This development, which spans from the personalized to the societal level, challenges the engineering profession, as engineers of the future are expected to have the ability to address and connect different contextual layers. As noted by de Carvalho Guerra & Holgaard (2019), contextual layers in engineering and science studies include contexts of technology in materialized form (e.g., the context of use), contexts of technology in an institutionalized form (e.g., standardization), and contexts of technology in a discursive form (e.g., a public debate). As coordinated action is needed to address global challenges and as the impact of social media is increasing, a user-centric approach is too limited. For engineers, this means that more contextual layers must come into play and considerably more contextual knowledge is needed.

Aspers (2006) points to three qualitatively different dimensions of context. While the first-dimensional concerns networking, the second stresses the aforementioned emphasis on the end user in terms of 'Knowing the Final Consumer market'. The third dimension stresses the importance of 'Knowing How to Interpret Provinces of Meaning' (Aspers, 2006, p. 755), whereas 'provinces of meaning' refer to information embedded in different sources of inspiration. Besides moving attention to other 'provinces' than those centered on users, this dimension also indicates that creativity and divergent 'out of the box' thinking are important for questioning established boundaries and dominant relations.

Heikkinen (2018) argue that what is needed is knowledge workers that have the skills to cross boundaries and, inspired by the T-shaped expertise (Conley et al., 2017), he argues that there is a need for these knowledge workers or so-called T-shaped professionals to possess deep disciplinary knowledge along with the ability to communicate across, for example, social, cultural, and economic boundaries. Working from knowledge depth in one discipline, the challenge is to create understanding of and communication with many disciplines and many systems using so-called boundary-crossing skills (Heikkinen, 2018).

The illustration of the T-shaped professional offers a frame of reference when considering how to further emphasize societal needs and end-user requirements in engineering education, but it also raises areas of concern. How should the boundary crossing between design and engineering be arranged when addressing user needs in technological innovation? How should the boundary crossing between engineering and social science and humanities be arranged when addressing societal needs in engineering education? What level of understanding is needed for the engineer to move horizontally in the T? What is needed for the engineer to stay deep in the analytical thinking and problem solving of their discipline? And, finally, which curriculum strategy is flexible enough to combine the horizontal and vertical dimensions of a T-shaped engineer?

A way to start is to relate the design process and the science, technology society perspective as a framing of the T-shaped engineer. How well it is performed depends on the interdisciplinary skills required at key stages, e.g., stakeholder engagement, leading to requirements, generation of solutions, choice of solutions, etc. It's the ability to grapple with the social and environmental elements, as well as the technical and economic, that showcases interdisciplinarity. The overlay on the above T-shaped profile in Fig. 4.2 illustrates how such things come together through design.

Jamison et al. (2014) argued that a curriculum strategy that embraces contextual and transformative processes, including complex mapping of the appropriation of

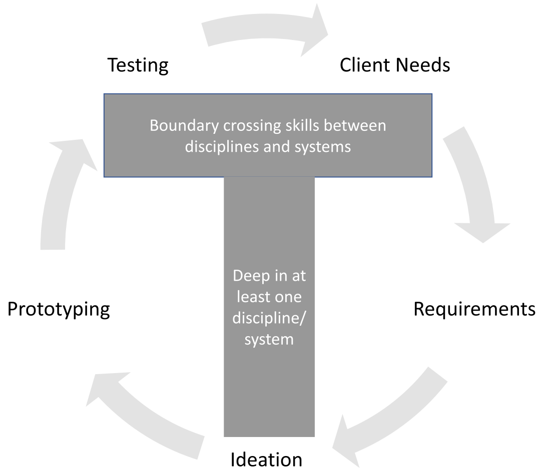

Fig. 4.2 Concept of a T-shaped professional. Reproduced from the adapted version from the T-Summit, 2017 presented in Heikkinen (2018) with the addition of the design process

technology into society, has to move beyond acquisition of knowledge and practical training. It is not only a matter of knowing about, and being able to use, specific methods for, as an example, collaborative design or technology assessment. It is an identity formation process taking into consideration the interplay between scientific, technological, social, and environmental dimensions of engineering, and it is a matter of being enabled to point to dynamics, synergies, trade-offs, and potential controversies of importance in this contextual landscape.

To avert an overcrowded curriculum, there is tremendous pressure on engineering education designers to select curriculum content in a way that creates the foundation for *exemplary* learning. Thereby students can acquire skills to situate content and methods (Klafki, 2007), and be able to ***transform*** learning experiences to other situations of relevance, meaning that exemplify relevant societal, material, and social constructs (Negt, 1974). For example, the way that we iterate, reframe, and co-create might be quite transferable across disciplines. Nevertheless, there is a risk that the attention toward such transferable processes is blinded by instrumentalism related to each of the theories and methods.

Furthermore, the shifting focus toward identity formation implies a new social role for engineering, which, according to Jamison et al. (2014), is that of the change agent, or social reformer, whose competency and professional identity consists of knowing how to adapt theory and professional practice to the specific sites in which technologies are to be used. It is an interplay between theory and practice, and an interplay between what is perceived to be and what is imagined to be. It is a *transformative* learning process, which is a process of examining, questioning, and revising our perceptions of our experiences (Taylor & Cranton, 2012, p. 6). Not surprisingly, a curriculum focused on transmission of mostly technical know-how runs short in this transformative turn of pedagogy.

4.6 Summary

In this chapter, we have presented diverse future engineering competencies which challenge current understandings of what it means to become an engineer. The new understanding leans toward a more dialectic and contextual approach to engineering requiring an ability to relate to and make synergy of a multitude of interests as well as epistemologies. We argued that the Science, Technology, and Society (STS) methodology offers opportunities to contextualize engineering practice. We also point out that independent of the chosen methodological framework an instrumental view to future engineering competencies will not be sufficient to capture the complexity of human systems. The interdependencies in these systems are too important to be seen as linear and a matter of use. Methods and tools generated in other knowledge domains cannot just be borrowed as the challenge is to reshape the dialectics of knowledge systems for changing contexts.

In this reshaping process, we have pointed to a set of overarching competencies. Critical thinking and sense making are needed to examine, assess, and make reason of and not the least develop the interference between technology and society, between constructing and co-constructing, between self-reflexivity and enactment. We must expand our knowledge above professional engagement.

One of the upcoming challenges is the rethinking of digital resources in engineering practice as well as in engineering education. Yet again the challenge is not as much to learn how to apply digital resources but knowing how to reshape our mindset and select the right strategies to frame digital competencies to their context of use. Another core area of future engineering competencies is related to creativity and entrepreneurial. This is a skill of shifting between different cognitive modes and social spheres to create whatever is perceived to be valuable.

We have stressed that a focus on end-users' requirements should be a priority, but as values of our time include grand challenges as sustainability the trade-offs moves beyond the user of technology as is, to also include the impact of the technology on current as well as future generations and natural environments. This means that the entrepreneurial competencies and the move from idea to value creation have increased in complexity to a point where cognitive modes of creativity are pillars to social modes of entrepreneurship.

Engineering students must be capable to cross boundaries among the many disciplines and the many systems as well as to keep up the depth of disciplinary knowledge. This is a matter of competency management and competency development across borders. The previously addressed frameworks for system and design thinking offer suitable outsets to rethink contextual integration in engineering, but still the competencies to handle the process of contextualization continue to change due to the rapid changes in the technological context. We cannot transfer from one comparable situation to another, as contextual complexity has increased. We must integrate and transform what we know, what we do, and how we perceive ourselves as engineers.

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Part II
Pedagogy, Strategies, Generic Competencies, and Transformation

Introduction to Chaps. 5–8

In the previous part, we have argued that societal complexity is the overall most dominant trend for technological development and for humans. In this Part II, we will investigate how we can reframe engineering education. The competency requirements from society have evolved to expect graduates with much more flexibility. We live in an era of uncertainty, complexity, risk, artificial intelligence, and high speed, as described in Part I. Big companies are looking for creative minds to build interdisciplinarity in their organizations. Diversity, in both thinking and minds, is becoming a requirement for any successful organization, academic, industrial, and government. Tight connections between working life and academic projects can be a necessary path toward fruitful engineering skills.

Students need to be equipped with appropriate skills, knowledge, values, and creativity to excel in their tasks as described in Part I. Knowledge acquisition should not be the only driver for education, rather, appreciation, experience, curiosity, and creativity. Students need to learn how to apply creativity and employ it in understanding the problem to put a solution together. They also need to learn how to work to create collaborative knowledge constructions in complex settings. All this will require both knowledge and generic competencies.

An important factor for the whole process is that many students actually desire to address social challenges, which originates from the fact that they live with and recognize these challenges. This creates motivation as they feel ownership of the problems and challenges. Therefore, working on solving challenges that students have experienced in any fashion normally yields better outcomes and motivates the students for a deeper understanding of the systems.

Thus, there is a need for reframing the engineering curriculum to address the contemporary challenges—both from a content point of view and a pedagogical point of view. With the emergence of more complex social and global challenges, we recommend thinking about adopting new ways of teaching by expanding the curriculum to offer students a more realistic education that serves them in both their social lives and careers.

In the following four chapters, we will address this reframing from four different angles. In Chap. 5, we are painting the picture of the learning landscapes and how these have evolved. The variation of the learning approaches gives us an understanding of the foundation of the teaching and learning strategies. One size does not fit all—and students learn in various ways. Likewise, teaching and learning are based on various learning approaches.

Chapter 6 follows this line by arguing that we see a trend of more active learning modes in engineering education. We argue that to apply more student-centered learning methods, we need to understand three principles: examplarity, variation, and reflection. When having these principles in mind, we can create curricula that are more flexible in facilitating students' learning and gaining competencies.

COVID-19 has pushed the flipped classroom to become mainstream, but this might still be in a lecture mode, although there is a huge variation in the way it is practiced. Projects and studios might be a solution for more student-initiated parts, but the way these have been applied at many institutions is basically as a uniformed learning method. But the variations in the learning outcomes and the practices are important to build into the curriculum system.

Chapter 7 is following on the argument of variation and reflection. It argues that one of the more beneficial aspects of a variation of student-centered curricula is that students get the chance to reflect and develop both generic competencies within and across disciplines as well as meta-competencies.

Chapter 8 is about the academics and ways to establish curriculum change. It is argued that academics stick to their beliefs, values, and worldviews and that the point of departure for transformation should be from that point. Furthermore, educational leadership, curriculum strategies, and new ways of peer learning among academics are important elements in planning any process leading to a change or a paradigm transformation.

Chapter 5
Toward a Comprehensive Pedagogy

5.1 Introduction

As we discussed in part 1, humanity is facing many critical challenges, most of which are open-ended and complex systems, and they require broad input and experiences to address. We expect students and educators to be engaged in such societal issues and form multidisciplinary teams to address them. The increased complexity of technical methodologies and know-how expected of future engineers, *challenges* existing curriculum strategies. The deep learning needed to dig into a discipline, to understand and apply it, must be combined with a learning strategy to increase the ability of students to relate to, and connect with, other disciplines in a meaningful way. It is not a matter of substituting students' learning of core technical competencies; it is a matter of creating synergy in the learning process so students will experience the inevitable interaction between technical and contextual learning.

As noted in the previous parts, the system is expanded beyond relations between technical and material constructs to include relations between people and the discourses, practices, and institutions they carry into the particular sociotechnical system. Together with the increase in complexity of both technology systems and value chains comes an increased need for perspective shifts to gain a comprehensive understanding of the system. Perspective shifts include a call for inclusiveness in the learning process, and this shift is based on a pragmatic approach to learning. Systems call for interdisciplinary views which basically are learned by formation of sets of actions to potentially change the system relations.

Because these challenges are complex with many interacting elements and of broad impact, learning achieved from pure disciplinary courses is not sufficient to teach students who address such challenges. There are several educational institutions that offer interdisciplinary courses to address human challenges. Whereas interdisciplinary education is necessary for addressing human challenges, this is not sufficient. In this section, we are not addressing the content of such courses, nor are we proposing new content, rather we are stressing the importance of pedagogy and ways to understand the learning processes beyond interdisciplinary learning.

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Unique pedagogy is needed to develop the appropriate skills and bridge the gaps between traditional academic fields and enable what is required to address large-scale challenges.

We start by a discussion of several general pedagogies in which skill development can be achieved within the context of systems thinking and design. Such skills combine computational, visual, experimental, and aesthetic methods. In addition, we advocate for those human-related skills, such as teamwork and collaboration, communication, and critical thinking, to be part of the skill building.

We stress that the cornerstone for all these pedagogies is the need to address open-ended challenges where answers are not fully known to even the educators. Many students are not familiar with working on problems that may have more than one acceptable answer and may require deeper studies, and also, students might not know how to conduct investigations or imagine that a problem may have more than one answer. For many years, students are immersed in attending lectures, reading textbooks, and solving problem sets, but the real world requires different training. Shifting out of a paradigm that is centered on teachers downloading information and requiring students to memorize this information is not an easy task for the students or for the educators.

Nevertheless, there are several educational methods that engage students and create an internal motivation that leads them to be well engaged with the content. These concepts belong to the general philosophical direction that appeared more than 100 years ago, when John Dewey advocated for educational progressiveness where authoritarianism is abolished (Dewey, 1897), and the emphasis is placed on delivering knowledge within students' interests and experiences.

Edward Lee Thorndike debated with John Dewey over this philosophical direction and methodologies, in the early part of the twentieth century (Goodenough, 1950; Tomlinson, 1997). The debate was intense, and different educators and psychologists took different sides and created modifications of Dewey's theories. In some sense, Thorndike won the debate, and it took many years for educators to realize the importance of giving the learners the ability to choose their own paths.

Being part of a social system and learning through social interactions is another advancement. In the past 25 years, major shifts took place. Digital technologies made a significant drive toward enabling learners to choose their paths. MOOCs helped in the shift from traditional learning methods but might have contributed to the creation of silo learners. Teaching online pushed the boundaries, with more progress in creating learning and assessing methods.

The historical perspective has integrative value. We start with an overview that illustrates the path toward the state we reached, and then we discuss some of the progress that is taking place in the early part of the twenty-first century in different universities. At the end of this chapter, we point out that our understanding of how people learn has improved a lot and the different theories bring different aspects, some of which can be integrated to generate wisdom upon which educators can use to deliver the best learning.

We end the discussions of this chapter with a short analysis of artificial intelligence and its impact. We introduce AI as a cognition augmenter with influence on learning content and methodologies. We keep the learner's agency and future in the center of this discussion and attempt to analyze AI relationship to society, ethics, and commercialization.

5.2 Learning Theories

Learning is a human practice. It is related to development, knowledge, and creating skills. Through learning, we adapt to changing environments and create a better life for ourselves and for others. Learning is complex as it involves several factors that are all related to humanity. In thinking about learning, we must introduce factors from our biology and psychology, the culture, and the environment and, more recently, technology and its implications.

All such factors influence learning in complex and interactive pathways. Factors related to human behavior, cognitive, emotions, political systems, culture, and prior experiences must be considered and integrated. Obviously, learning cannot be understood through a single theory, and several learning theories have evolved and many overlap. Over the years, different orientations were developed and emphasized different aspects of the above-mentioned factors. These learning frameworks bear importance to pedagogy, and we emphasize that none of them is always true and there is significant overlap among these theories. Learning theories can be traced into certain categories: behaviorism, cognitivism, and constructivism.

5.3 Behaviorism and Connectionism

Thorndike's pioneering work (Thorndike, 1898) on comparative psychology led to the emergence of educational psychology and that had impact on behavior analysis and reinforcement theory. Today, some of these concepts have bearing on AI and machine learning methodologies. Thorndike's *law of effect* established the basic framework for several empirical laws in behavior psychology and had a long-lasting impact on pedagogy (Thorndike, 1905). Through experiments on animals, like cats, Thorndike concluded that '*responses that produce a satisfying effect in a particular situation become more likely to occur again in that situation, and responses that produce a discomforting effect become less likely to occur again in that situation'.* (Gray, 2011, pp. 108–109).

This emphasized behavior conditioning and reinforcement of learning by repeating facts and *drilling* became known as the *law of exercise.* Thus, learning is directly related to the amount of repetition, or practice, i.e., the drill. In addition, Thorndike stated that learning is the result of associations forming between stimuli and responses, which was known as the *theory of connectionism* and was elaborated on by others like Pavlov (1927), Skinner (1938), and Hull (1935).

Although Dewey advocated that there are missing elements in the Thorndike model, the method of learning by memorizing became essential to pedagogy for many years and may have been encouraged by Bloom's taxonomy (Bloom & Krathwohl, 1969; Dewey, 1998). Bloom, however, put problem solving at a higher-order skill and his taxonomy puts remembering as a foundation for creating and recognizing elements and patterns. The taxonomy considers understanding, applying, analyzing, and evaluating as the steps between remembering, toward creative actions.

An important modification of the taxonomy created a set of verbs and products to illustrate how the different levels operate (Anderson et al., 2001). In addition, a consideration of the knowledge dimension was added. Different levels of knowledge, starting with factual, conceptual, procedural, and meta-cognitive knowledge were considered (Anderson et al., 2001). This results in 24 learning objectives, with the simplest being remembering facts, and the highest being innovative creation, which considers meta-cognitive creative actions (Heer, 2012). Bloom's taxonomy has been applied in formal curricula descriptions at many universities and taxonomies can give an understanding of progressing learning.

In general, behaviorism focuses on behavior patterns, and many parts of our educational system are based on these ideas, where we describe the patterns in lectures as input and require the students to replicate the patterns, e.g., through problem solving, as output, which we assess. The learner's inner world is not taken into consideration. A particular instruction, such as memorizing, is one of these patterns.

Appropriate feedback loops, such as praising and grading, reinforce these patterns. This area has developed over many years, and in some sense, we cannot ignore behavior as part of how we learn, and the importance of memorizing and repetition is often overlooked in the critical literature. Some parts were added, with educators modifying Bloom's taxonomy, and we found an additional space for independent human thinking and believing in the learner's intellectual capacity was further emphasized (Heer, 2012).

5.4 Cognitive Constructivism

Cognitive constructivism introduces the capacity of the human brain as a central element in the learning process and approximates the human as a computational machine with a processing capability, storage, and retrieval mechanism. Thus, one must follow the information flow into memory and consider previous experiences and how they interact with new knowledge. Further, knowledge comprises of mental representations with images, mental constructs, imaginations, and other human constructs, physical and mental, all of which interact in a complex way with the new knowledge.

The learner is not passive but is actively participating in the development of the knowledge by engaging in their interpretations and analysis. Furthermore, the learner's stage of cognitive development influences what new knowledge is assimilated and how it fits with older knowledge. Piaget introduced the *principle of equilibration* that states that all cognitive development progresses toward increasingly complex and stable levels of organization (Piaget & Elkind, 1967). Equilibration takes place through a process of adaption and assimilation of new information into existing cognitive structures. The accommodation of the new information forms the new cognitive structures. This process continues as more information is introduced, and the learner employs their previous knowledge and their engagements to assimilate further knowledge.

These concepts lead us to realizing that acquiring knowledge is *not a uniform process.* It is a *personal* activity that depends on many factors, including previous experiences, cultural background, and maturity. Repetition is less important and drilling information is, most of the time, irrelevant, but being able to recall information is critical. With today's digital search engines and machine learning, remembering lost its prime space, and more emphasis must be placed on the learner's ability to invest personal time and energy to assimilate and possibly modify what messages they are receiving (Perry, 1999). This is not to say that there are no items that we need to remember, but that the human brain can be less burden by many facts when they are accessible through digital methods. Obviously, a student or investigator must be able to recall information, and this lower-level cognition is still needed for analysis and reaching reasonable conclusions. Even if information is passively received, connections to prior knowledge will require personal involvement. Learning how to learn requires training, effort, and ability to interact well with different digital media.

5.5 Social Constructivism

A crucial role for learning is making sense of the world and the meaning of its events. Social constructivism emphasizes the collaborative process among people and their connections to culture and society. Thus, learning is considered as socially constructed, rather than innate, or passively absorbed. In fact, long ago, Dewey stated that '*Learning is a social activity—it is something we do together, in interaction with each other, rather than an abstract concept*' (Dewey, 1986) Since then, these concepts were refined with elaborations and details. Not only is it well recognized that learning is a social process, and it is influenced by cultural factors, but significant insights were obtained about the process of learning and related mental processes. In addition, the dynamics of the influence of culture were studied. Cultural evolution in time and space, and with technology, showed that learners are not copies of a certain construct and, in fact, learners participate in the construct of the culture they belong to.

This complex dynamic interaction makes acquiring knowledge a process built on symbolic mental constructs that are created by internal symbolic mental processes (Fox, 2001). The complex assimilation process for new knowledge that is accommodated and integrated within existing knowledge and mental structures was examined.

Several theories were constructed to explain this process. Here, we present some of these theories, and later, we connect them with new pedagogy that has been emerging by integrating digital technologies during the past ten years or so.

5.5.1 Learning Through Sensing

For Bruner, the purpose of education (Bruner, 1973, 1977) is not to impart knowledge, but to create autonomous learners, who become creators of innovations. In Bruner's theories, thinking is based on physical actions and the use of mental images as well as the five senses. Bruner believed that social interactions are essential in creating the learning.

Bruner proposed that learning involves encoding physical action-based information and storing it in memory. For example, infants learn by doing, rather than by internal representation or thinking. This mode of learning through physical activities develops to more complex ones later, for example, riding a bike or skating. Information is stored as sensory images, i.e., they are visual ones. This is an important notion which became part of our teaching as we commonly insert diagrams and illustrations in presentations and inherently believe that an image is worth a thousand words. Bruner believed that this encoded information continues to evolve as we grow older and later it gets stored primarily as words and symbols (Bruner, 1978). Some of the symbolic information becomes structured as in the case of mathematical equations, maps, and musical notes. These symbolic images end up enabling learning other topics (Bruner, 1966).

Symbols are very powerful**,** and we use them as shorthand in many domains, such as road signs and guidelines in hospitals and buildings. One may drive this even further by considering that numbers and alphabets are nothing but symbols. It is interesting to note that written words in Far-Eastern languages are modified images and they represent more complete meaning, whereas the invention of the alphabet by the Phoenicians attempted to create the sound used to articulate the words. For example, the written word of listening in Chinese has three elements: the ear to hear, the eye to watch the expressions of the speaker, and the mind or the heart to decipher the meaning, see Fig. 5.1. The learning symbol is written in two ways: hands and farming tools with off-spring child in a house, and the other symbolizes a bird practicing flying under the sun. These symbols are added to create meaning. Similarly, there are many signs that are universally recognized, like a stop sign or the exclamation mark for paying attention.

In addition, learning through images is well established and is facilitated by technology such as YouTube and other visual apps.

Fig. 5.1 Chinese symbol for to listen

5.5.2 Learning Through Social Interactions

Bruner constructed learning within social interactions and through a combination of cognitive and physical processes. Earlier, it was Vygotsky who placed much emphasis on culture and community in creating higher-order mental functions like learning (Vygotsky et al., 1978). His pioneering work was obscured by the lack of translations and the politics of the USSR. For Vygotsky, the environment is critical in creating the learning. Where learners grow up will influence how they think and what they think about. Social forces, such as values and beliefs, are part of human development as well as learning (Mcleod, 2008).

Therefore, communities play a very important role in the process of making meaning, and learning is a matter of sharing and negotiating socially constituted knowledge. With the advent of digital technologies, we observe changes in the formation of communities. There are now virtual communities, and these might be quasi-stable. They end up being formed quickly and dissolve fast too. Nevertheless, learning through such interactions is influential and must be considered, albeit not all their contributions are positive.

Social interactions affecting learning were also discussed by Piaget, who believed that regardless of culture, people pass through universal development stages. Young individuals construct their knowledge through early stages and culture is an indirect force in learning. Piaget also emphasized peer-to-peer learning from which the learner obtains deeper knowledge. Similarly, Vygotsky believed that early development is critical and will require support from adults.

From the above discussion, the emphasis on creating knowledge through a construct influenced by culture and social interactions does not give enough emphasis to the learner agency and self-direction. Of course, not all people are able to be self-guided. But it can be encouraged through the environment and the learning processes.

By the mid-1970s, Ernest von Glasersfeld introduced additional notions to what and how knowledge is constructed. Von Glasersfeld believed that all knowledge is constructed and not perceived by our senses (Cardellini, 2006). Active participation is required to acquire knowledge. With that, construction theory evolved to make knowledge a mental construct by individuals. Knowledge resides within our minds, and it may not match any reality (Driscoll, 2000). People are constantly developing their individual mental models of the real world from their perceptions of that world, and they update their models by new experiences and information. With Arends stating that meaning comes from experiences (Arends, 1998), constructivism made experiential learning essential.

Experiences integrate knowledge as well as disseminate knowledge, and individuals learn by interacting with each other, and this learning is both cultural and personal. Learning is filtered by the individual interpretations and their personal values. As the diversity of knowledge is shared through social interactions, knowledge and meaning emerge. These steps are critical for creating common knowledge, which is a step toward creating culture.

5.6 Educators as Enablers

Creating the appropriate environment for reflections and collaborative discussions, which lead to knowledge creation, is an immense task and noble responsibility. Thus, the most important responsibility for educators is not to instruct but to create environments where learners actively interact and co-create knowledge and meaning. Another aspect of the educator responsibility is to enable learners to fill in their knowledge gaps. As students may not come with similar backgrounds, scaffolding becomes a necessary enabler to create a participatory environment. Brooks and Brooks (1999) wrote on such environments, and Honebein (1996) summarized some pedagogical goals of constructivist learning environments, as:

(a) To provide experiences for knowledge construction processes where it is left up to the students to determine how they will learn.
(b) To provide experiences in which educators provide alternative solutions and students appreciate the presence of multiple perspectives.
(c) To create authentic tasks connected to realistic contexts.
(d) To provide agency for the students and make them the center of the learning process.
(e) To ensure collaborative effects and social experiences.
(f) To encourage using different modes of representation including imagery.
(g) To encourage meta-cognitive processes such as reflections.

Table 5.1 Classroom orientations

Traditional classroom	Constructivist classroom
Teachers-centered stage—teachers direct	Student-centered—teachers interact and support
Strict adherence to a fixed curriculum	Pursuit of student questions and interests
Learning is based on repetition	Learning is interactive, building on what the learners already know
Students work primarily alone—can be competitive	Students work in cooperative groups
Teachers disseminate information to passive learners	Students are active learners

In Table 5.1, we present contrasting views between traditional and constructivist classrooms. Clearly, the constructivist method puts the students as active learners at the center of the stage, and places emphasis on their interactions. The move from the traditional classroom, based on behaviorist thinking, to the constructivist classroom, is fundamental for developing learning environments for complex problem solving.

5.6.1 Students Are the Focal Point

Over the years, there were several moves to change the classroom from a lecturing place to a learning space, with different tools and mechanisms. In addition, the emphasis has been to change the classroom from being a formal platform for educators to be at the center of the stage to download their knowledge, to having the students as the focal point, ready to construct their own knowledge. This is a major shift in pedagogy.

Introducing such learning environments has been practiced over many years by many institutions. In particular, as early as the beginning of the twentieth century, Marie Montessori developed a theory and practice for educating children in which the child develops natural interests and activities within a supportive environment, which engages a variety of materials, including mathematics, natural science, culture, and the arts (Montessori et al., 2017). The learners develop a sense of self-responsibility and follow and develop their innate interests.

This educational style operates within a psychological self-construction that occurs through an environment plus interactions. The assumption is that all learners follow an innate path of psychological development and act freely when they are within an environment prepared according to the Montessori model. In addition, in this model, the role of the instructor is not to teach but to guide and counsel the learners by letting them create their own learning pathway and provide support when needed.

The Montessori schools are a special place, but the concept is broad and covers several other models. All of these models have a commonality, which is unification of three elements: First, the instructor is an advisor and supporter and does not download knowledge to a group of listeners; second, the learners have agency and interact with the environment, in the broadest sense, and with their peers, and third, the learning is taking place in an appropriate space, where interactions are facilitated by a lack of barriers and the presence of appropriate tools.

5.7 Learning by Doing

Concepts such as learning by doing, hands-on-projects, experiential learning, cooperative learning, and project-based learning belong to the superset of the ideal, which Dewey aspired to institute. These concepts differ on the execution side but have similar foundations and the objective of problem solving and critical thinking (Parker & Thomsen, 2019). The models favor group work and developing social skills, and they propose understanding and actions as the goals of learning as opposed to rote knowledge.

For example, cooperative learning (Johnson et al., 2014) and active learning create excitement when students develop their collaborative skills, build their self-confidence, and learn to take risks (Brame, 2016). Students may perform experiments that elucidate their learning and develop new ideas that test some theory. Active learning is not limited to hardware, and there are big opportunities in engaging students with computer simulations and modeling. We developed such modules for fluid mechanics and thermal transfer, as well as robotics. In addition, with Python as a platform, data analysis is accessible and may bring out important social findings.

Different methods put different emphasis on social responsibility. Project-based learning is another constructivist method in which the students learn by exposure to different problems using experiential learning and discovery (Guerra et al., 2017). In this method, emphasis is on big challenges and open-ended questions. Other social skills are also learned through these methods including critical thinking and communications.

In one variation in engineering, the context included four phases for creating comprehensive outcomes. These included conceiving, designing, implementing, and operating (CDIO) (Crawley et al., 2007). Within this context, there is flexibility to achieve each of these phases using different techniques. In general, the work that the learner is performing needs to be consistent with the cognitive capacity of the learner. Having a group of learners of different backgrounds enables creating comprehensive outcomes.

In general, in these methodologies, the instructors provide the theme of the projects. These projects could vary in scope and complexity, which will be discussed in the next chapter. Some might be related to a human challenge and do not have a single known answer. Although the instructor(s) choose the topic, they leave it up to the students to choose their problem statements and work on them. In choosing topics, attention should be paid to keep these topics broad enough to be useful as examples for future activities.

5.8 Connectivism in Online Learning

The importance of the social content in learning became a central pedagogy theme and practiced in many learning environments. In addition, this element made it in a model on its own, called connectivism. Different aspects of connection were practiced and known before this name was adopted. For example, the concept of peer-to-peer learning has been practiced at classrooms and outside them. But the advancements in digital technologies gave a new flavor for connectivism. In fact, technology created a very strong pedagogical shift in democratizing education, creating new environments, and allowing for fast experiments and measurable assessments. It enabled students to make choices in what to study and when. Initially, the concept of online learning, such as MOOCS (Baturay, 2015), allowed students to learn on their own pace and choose content from a large menu. This became popular enough that some universities taught online only, and some like MIT (Abelson, 2008) and Harvard (Brown & Adler, 2008) adopted the approach.

The concept of online learning was not only to provide economy of scale and freedom of choice of what to learn but also to create social connections among learners. This concept was presented by Oliver (2000) and then by Siemens (2005) as well as Downes (2005), who emphasized the connective model and advocated that the Internet is the medium for connective learning, or what is also termed as e-learning.

Learning online provides unprecedented learning opportunities. The ease of connecting, as well as the diversity of participants, which includes cultural experiences, provides tremendous opportunities for innovative outcomes. If we were to consider that every learner is a node and every node is a learner, the network becomes infinite, and no classroom can match the scale of the digital networks. And, since each individual learner has a distinctive point of view, cultural background, knowledge, and values, opportunities for creativity are enormous.

Learning as networks is a new realm, and interactions among learners can be viewed as interactions among diverse nodes in a network as in systems, described in Part I. These interactions give rise to complexity and unexpected outcomes such as emergence and even chaotic results. Self-organization has been observed in networked learning, and the diversity of the participants encourages interdisciplinary education and enables broad creative ideas.

Clearly, e-learning is a powerful platform, and it enables reflections and fast communication through blogging, email, and chat rooms. Although this platform is devoid of issues related to scale, different policies and the culture of different institutions can pose some obstacles for collaborations. As an example, a collaborative and flexible concept was envisioned in 2016–2017 and attempted to construct a new model for collaborative education by offering different courses online from different universities. In this model, learners decide which course to take from a menu of courses offered by more than one institution, and then graduate with a degree from one of them. The concept was discussed among UTEC, Harvard SEAS, Philadelphia

University, and OCAD, but differences in cultures among these institutions hindered the sustainability of the collaborations.

In addition to having people in nodes, machines can occupy the nodes allowing for a new dynamic of human–machine interactions to enable a new type of learning and creativity. Co-invention with machines will become an essential part of our learning and doing. In addition, some of the content will be abridged and more mathematical simulations will be readily available, leading to shorter time for design and manufacturing.

Learning on the Internet matured but, perhaps, the most profound change took place during the COVID-19 pandemic. Not being able to communicate face-to-face made teaching instructions move to online, communication. This forcing function created the needed impetus for a significant change toward online education, which integrated several of the progressive pedagogies outlined before.

5.9 A Third Dimension of Learning Theories

Learning theories have developed, and in our education systems, we find elements of all theories, also in the new digital platforms. But for student-centered learning, it is important to understand student motivation, and therefore, another dimension is needed, which is not present in the above theories, which mostly concern the content and the interaction. Student motivation is a whole field in itself, related to psychology and the affective domain.

Illeris (2015) has developed a landscape of learning theories (see Fig. 5.2) and has defined three dimensions of learning, related to content, incentive, and interaction in and with society. In relation to the previous, Illeris adds the affective dimension of learning, in terms of the learner's inner motivation and incentives of learning.

This discussion is an attempt to map the dimensions of learning theories and each theory will add a bridge to the understanding of how students learn. But it also reminds us that we cannot only form teaching and learning based on the content dimension grounded in cognitive or social cognitive learning theories, as the *emotional incentives* are important parts of learners' motivations and learning. In the same line of argumentation, interaction and collaboration are needed to combine societal challenges with academic content.

Furthermore, the different dimensions of learning offer different aspects of diversity and inclusivity. The content perspective relates to the individual and cognitive dimensions of learning. Piaget introduced the concept of schemas, which organize comparable impulses from the outside world. The dynamics in these schemas constitute learning in its cognitive sense through the before mentioned assimilations (adding to schemas) and accommodations (changing schemas). Divergent thinking is about moving across schemas and exploring new impulses, which we have not yet explored.

When rethinking engineering education, the schemas that we have traditionally used in our understanding of electrical engineering, software engineering, and so forth must be rethought as well. The schemas we have explored have to be expanded,

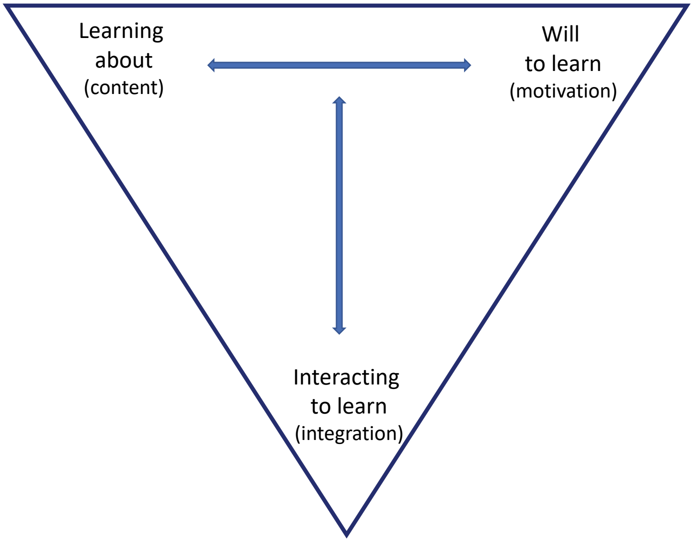

Fig. 5.2 Dimensions of learning (Illeris, 2015)

and in order not to overwhelm our cognitive capacity, we must find ways of selecting the relevant spheres to gain new impulses, and we must find other people who can complement our schemas in new ways.

Inclusivity in the cognitive domain relates to what we perceive as valuable knowledge constructs and, thereby, valuable sites to be explored and important schemas to (re)visit. In this sense, engineering educators have an important role in selecting core content but also in providing flexibility for students to select content themselves to complement their personal learning path.

The incentive perspective relates to the individual and emotional dimensions of learning. Diversity then relates to exploring different sources of motivation and inspiration for our engineering work—it is a diversity of feelings. This emphasis on affective learning outcomes has lately drawn attention to the role of emotions in engineering (Lönngren et al., 2020). In this respect, engineering students must be aware of, and consider, both intrinsic and extrinsic sources of motivation for students, peer, and self-motivation.

From an educational point of view and despite a rather limited focus on affective learning outcomes, different theories have shown attention to intrinsic sources of motivation for student learning. Positive psychology, e.g., person-centered teaching (Rogers, 1969), has had a tremendous influence on educational models. However, such models also create challenges for academic staff in motivating and empowering students to work with motivational aspects of their learning.

Without doubt, the problem determines the choice of applying relevant theories. This is a pragmatic view on learning and knowledge construction. If there are motivational issues, there is a need for looking into the corner of incentives, and even if there is research evidence that active learning increases student motivation, there might still be issues which can be understood and developed further by more psychological theories than cognitive or social cognitive theories.

5.10 Artificial Intelligence as a Cognitive Augmenter

Artificial intelligence has been in a steady development and improvement. AI has reached a level that its impact on learning is obvious. AI is related to e-learning, but it is far more impactful. Thus, it is critical to include this digital modality as part of our analysis.

5.10.1 Advancements and Concerns

AI is a sophisticated technology that provides augmentation to cognitive capacity. It should be considered as a tool that provides opportunities for learners and educators, and yet, it may present distortions and misleading information. AI consists of computer applications with very broad capabilities and objectives. It covers several areas of science, engineering, and automated techniques, as well as machine learning and deep learning. In general, AI systems algorithmic models perform cognitive and perceptual functions of the world. Such considerations were previously reserved for human thinking, judgment, and reasoning.

Now machines can augment human thinking and model observations using supervised and unsupervised learning and reinforcements. So, should we rejoice when we know that machines acquire data and perform structured and unstructured analysis and they process information and then create knowledge and recommendations to reach particular goals? Clearly, there are several science and engineering domains that can readily take advantage of the powerful AI. But will this technology be sensible enough and stay under the watch dog of humanity? Or will it stray fast and far and add an uncolorable new challenges?

AI augmentations may exist in physical and virtual dimensions and do not necessarily require acquisition of data. AI has functions that include rule-based analysis, e.g., expert systems, artificial neural network including vector machines, Bayesian networks, and decision trees. Also, symbolic AI has advanced to an impressive capability that flourished with the advancement of fast hardware. In addition, symbolic AI-enabled inverse design with very important implications to improved experimental research.

It should not be surprising that AI is not always guided by human objectives and sometimes it appears that it operates autonomously. This capacity for autonomous cognition raises a key issue of whether AI can independently operate within ethics, e.g., Boddington (2017); Whittaker et al. (2018); Winfield and Jirotka (2018). Ethical considerations are critical part of engineering and design. Being responsible and innovative, people can utilize AI for creating provocations and learning exercises. But ethics is a human trait, and it is a complex topic that is related to culture and time, and AI should not be bounded by only legal norms and laws. Jobin and colleagues (Jobin et al., 2019) identified 84 published sets of ethical principles for AI, which include transparency, justice and fairness, non-maleficence, responsibility, and privacy.

In addition, UNESCO (2021) describes draft recommendations on the ethics of artificial intelligence. AI is advancing continuously and has significant power and ability to integrate and synthesize and must be constrained by a code of ethics like the one used for medical practices.

More recently, AI language models based on an advanced version of the generative pretrained transformer (GPT) became available with a human chat interface and designed to generate human-like text. GPT-3 and 4 are pretrained over a series of language models which have been trained with a very large dataset of textual information and can be applied to deal with specific language-related tasks. The machine learned rules of grammar and syntax, the meaning of words and how they are used in many varying contexts. This learning enabled it to become a good writer of different text, including problem-driven reasoning and analogy-driven reasoning. As an example, design-by-analogy is the projection of existing reference in a source domain to address a comparable challenge in the target domain. With such capabilities, GPT-4 can perform interesting tasks, but they are not error free. Nevertheless, ChatGPT-4 will provide significant services including searches and supporting Microsoft Office suite, providing programming codes, and customer support. However, such AI will take some time to perfect these tasks, and it should be monitored for validity and accuracy. Meanwhile, engineering and design can use this technique and create effective learning exercises.

The design of the ChatGPT has an interesting element of involving the human in the decision making. When a chat did not satisfy the interacting human, the AI learns and shifts in attempt to satisfy the human. In doing so, the machine perfects the context of the request. This enable the AI to learn better and faster and deliver a closer contextual information.

More advanced GPTs are underway, and they are expected to appear with improved human-like capabilities. Here, we encounter a philosophical point on whether we can talk about learning in the context of machines as learning requires consciousness and agency. Neither one of them is attained by the current technology (Rehak, 2021).

5.10.2 Artificial Intelligence in Education (AIED)

AIED is an emerging field with several aspects. AI connections to education can be grouped under four headings: 'Learning about AI, Learning with AI, Using AI to learn about learning, and Preparing for AI' (Holmes et al., 2019). AI, as an intelligent tool, has unique contributions to education and should be considered with an eye to its strengths and weaknesses (Miao & Holmes, 2021). Each aspect of AIED needs to be considered independently.

(A) **Learning about AI**

Learning the AI tools and techniques is very important and there could be a process that is highly *mechanical* and *automated*. AI can then be effective contributor to teaching AI technologies. For example, it can provide instructions about machine learning and natural language processing together with the statistics and coding. This may also serve people who are interested in developing and contributing to the creation of AI applications.

There is a need to understand AI algorithms and how these algorithms find patterns and connections in the data and make this literacy accessible to learners and citizens of different backgrounds (Miao & Holmes, 2021). But this literacy should not be limited to the technical components. The human dimension must be an equal part of the learning. The impact of AI on human cognition and agency must be discussed at length (Holmes et al., 2019). For example, people must understand power and political motivations that are behind the adoption of automated decision making.

It should be clear that learning with AI is not complete and might be even defective, if it was not supervised by humans who introduce human thinking in this process, including ethics and understanding the limitations of AI.

(B) **Learning with AI**

As AI intelligence improves, one might be tempted to use AI as a substitute teacher. However, such an effort should be studied very carefully as the lack of human interaction and sociability may have grave effects on the students' mental health. Instructions from machines might be very different from the teaching and mentoring with a human touch. Young people are very impressionable, and it is possible that the absence of the human and the lack of the emotional content will adversely affect their learning. Young people need to have role models who provide motivations and excitement. Machines are void of the human elements and students may feel isolated causing them to drop from their educational paths.

(C) **Using AI to Learn About Learning**

Learning analytics and educational data mining are tools to gather data on how learners learn, their learning progression, and which learning designs are effective. The goals of such studies are to inform learners, teachers, and other stakeholders about students' practices. But there are other negative side effects to AI gathering such information. Such information may affect admission policies, retention of students, and education planning. This overlapping but nonetheless distinct issues cannot be left to algorithmic thinking.

(D) **Preparing for the impact of AI**

This involves ensuring that citizens understand the risks of AI and are prepared for its possible impacts. Therefore, preparing for AI should be integrated within learning about AI. The impact of AI on human dimensions needs to be emphasized despite the tension with economic gains. The purpose of education becomes a crucial point to consider. Education cannot imply only to transmit knowledge that is selected without regard to the learners' input and delivered in a process that does not focus on the learners. Transferred knowledge must help people to develop their individual potential, self-actualize, and promote understanding, tolerance, and sociability among all peoples.

As we advocated in this chapter and other chapters of this book, a shift to learner-centric learning where students have control over the learning processes, thereby maximizing their agency, is critical. Some thoughts about the role of AI in education embody a naive approach to teaching and learning. Most of the proposals consist of simple approach of providing direct instructions and informing of prespecified content, while adapting to the individual capacity, and then assessing the individual's performance using AI-driven e-grading and proctoring. Such an approach has many issues. First, this style of advising negates the importance of agency and innovation. Second, adapting to the capacity of the learner by using AI evaluation methods has many pit faults. Some commercial companies that deal with education sought to use AI-driven tools to create personalized recommendations for students to pick from and create their educational content. Thus, the AI algorithms become responsible for the individual educational pathway, which might be personalized but might not be focused on the learner's destination of interest. Third, e-proctoring was shown to fail in considering the human dimensions. This method was accused of 'intrusion (Barrett et al., 2019; Hager et al., 2019), racial discrimination, preventing learners taking their exams and exacerbating mental health problems, while having little impact on cheating or attainment' (Brown, 2020 and Conijn et al., 2022).

In short, there is tremendous need to carefully consider the impact of AI algorithms on the development of human cognition (Ilkka, 2018) and the education of a new generation. There is a tremendous commercial interest in AI and an incredible amount of investment in it, which approaches US$80 billion, of which US $2 billion were targeting education, one of which is championed by Google (Google, 2023). Among these excitements, voices must advocate the need for a significant pedagogical depth; and that unmanaged AI can pose significant risks to education (Holmes et al., 2019).

These concerns, however, should not discourage people from utilizing this technology, and while AI can provide insights and recommendations, it should not be allowed to make final decisions on its own. Humans must carefully evaluate the information provided by AI and consider all relevant factors before making conclusive decisions.

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Chapter 6
Teaching and Learning Strategies

In order to develop a curriculum, there is not one size that fits all institutions nor all students. The engineering programs are within various universities and various cultures and represent different learning ecosystems. Even at one institution, one size does not fit all. Students are diverse, with diverse backgrounds and diverse individual learning styles. Therefore, there is a need for emphasizing *exemplarity*, *variation,* and *reflection* in engineering education practice, and in the following, we argue for the importance, but also the challenge, of leaving a reductionist approach to learning and moving to a more open and dialectic approach, where societal needs and end-user requirements are intertwined with aspects of learning. To address these new challenges, we propose more active learning strategies for lectures, inquiry-based, problem-based, and project-based approaches to learning, and we emphasize teamwork and diversity of thinking as core elements to address complex socio-technical systems.

6.1 Exemplarity

One of the biggest concerns for moving to more active learning systems is that students do 'lose important technical scientific learning outcomes' when they are working on projects. It is a concern that should be addressed as there will be a change in learning outcomes when changing the teaching and learning methodologies. In the first chapters of the book, the argument for new learning outcomes, such as understanding complex problems and being able to participate in complex problem solving, will involve more active learning, inquiry-based learning, and team-based projects. That will involve new learning outcomes responding to the contemporary challenges.

In Chap. 5, new approaches to learning framed by social constructivism were presented together with new learning principles. One of these principles is exemplarity. Exemplarity is a well-known concept in German educational literature and

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there are several understandings. Negt used the concept to say that the problems students are working on should be exemplary to the societal problems (Negt, 1971; Servant-Miklos et al., 2019). This was a way to indicate that science should reflect the societal problems and that the general education should prepare students to become critical citizens. Another understanding is formulated by Wagenschein who emphasizes that the learning outcomes should be exemplary to the overall learning outcomes formulated in the curriculum (Korsgaard, 2019; Wagenschein, 2000). This is a question of selecting the content/scientific knowledge that is exemplary and aligned to overall learning outcomes. If students are working on problems, the methodologies they are using in analyzing the problem and solving the problem should be exemplary to the overall learning outcomes.

For example, problem and project based (PBL) curricula have variations in the intended learning outcomes. Lectures give an overview and a preliminary understanding, whereas projects mostly have learning outcomes at the level of analyses and syntheses, which are higher levels in the Bloom taxonomy (Bloom, 1956). This is an extremely important principle for PBL curriculum design, to allow space and freedom for the students' choice of problems, to practice a co-constructed curriculum. It will require that the learning outcomes are formulated in more general terms of methods and methodologies. This does not mean that students learn less, they learn methodologies and methods which they can apply on new problems.

However, many colleagues might question whether student learn particular learning outcomes from the textbook. There are many responses to this. One is to say that when students are more active, they use more time for learning and will not lose anything. Research indicates that the graduates from PBL curricula value the projects and cases more as they remember what they have learned (Kolmos et al., 2020b; Schmidt et al., 2009). Another response is that when students have learned the knowledge relevant to analyzing and solving one problem, they have the potential for transferring or transforming their knowledge to a new problem (Bertel et al., 2022).

There is no doubt that students remember the learning from the projects more than the learning they have from taught courses (Kolmos et al., 2020b). The reason is, of course, that the students are actively working with the content more than in the taught courses. So, the deep learning in the projects should, on the one side, be exemplary for the overall learning outcomes in the curriculum, and on the other side, students should have possibilities of influencing the direction of learning.

6.2 Variation in Learning

Variation is a core principle in evolution and an important force as it allows natural selection within specific species. As humans, we all belong to the same species; however, we all look different because of differences in genes. We talk about genetic variations which is an embedded understanding of development. But rarely do we talk about variation in students' learning, except for the different learning style tests that have been applied to a certain degree for creating awareness of individual preferences.

Variation in learning is a concept derived from phenomenography, which has added inspiration to many educational and instructional learning methods. Variation theory assumes that individuals *understand and reflect on the world from their own perspectives*. The learning takes place when students are '*capable of being simultaneously and focally aware of other aspects or more aspects of a phenomenon*' (Marton & Booth, 1997, p. 142).

The object of learning is important as learning is always about something. Learning is the capability to do something with specific content and in some contexts. Learning is interpreted as a change in the way something is done, seen, experienced or understood, and education is aimed at developing learners' abilities to handle various situations, to analyze and solve different problems, and to act effectively according to one's purposes and the conditions of the situation (Kullberg et al., 2017; Marton, 2006).

Variation influences learning in many ways. For the individual learner, it is important to be aware of ways to create a varied approach to given content. In teams, it will be important for individual learners to bring in their awareness of varied approaches and get into dialogues of understanding. For institutions, it is important to create a curriculum that allows students to experience and learn content knowledge in different ways. This will mean a variation in teaching and learning methods for students to experience different ways of learning and collaborating (Fraser et al., 2006; Linder & Fraser, 2006).

This is in line with the statement that there is not one correct way for engineering education to respond to the integration of complexity—there are multiple ways for the learner to form a comprehensive understanding of a phenomenon. With a variety of learning situations, the learner could challenge the understanding and learning from one situation to another and from applying one method to another. Variation in the teaching and learning methodologies is important as students experience learning of the disciplines in various ways.

Most curricula are organized as a series of courses (subjects, units) of which a certain percentage will be compulsory and the rest elective courses. The teaching within each of these course blocks is also very much alike, with textbooks, assignments, and perhaps some groupwork and assessment. Lately, the flipped classroom has swapped the lecturing part and the activity part so that the activity/assignment part takes place in the classroom instead of the lecturing part (Reidsema et al., 2017).

The variation in most curricula is to be found in the content more than the learning methodologies and we argue for more variation in learning methodologies within student-centered learning and even within the application of projects in education. Students learn from the way they are learning either at an aware or unaware level. If they have only experienced individual learning in education, they will have a harder time learning to collaborate in their work. If they have never tried to analyze problems, they will have a harder time identifying and dissecting a problem or a user need.

Even if academics are aware of the dynamics in learning, the norm of the curriculum is mostly organized in replicable stereotypes of taught courses, normally embracing oral lectures, individual assignments, tests, and assessments. We are, therefore, facing a discrepancy between how we think about learning and the curriculum systems, which are very much alike from one course/discipline to another and part of a cultural inheritance in academia transferred through experiences from one generation of teachers to the next. The way we have been taught and the way we have experienced learning form our basic beliefs in learning. These are difficult to disrupt.

However, if we want to educate engineers who can navigate and cope with complex socio-technological systems, there must be a disruption in a way that enables students to move outside the classroom and combine theory and practice.

6.3 Variation Goes with Reflection

Variation in learning goes hand in hand with reflection. If we just apply more variation without comparison and reflection, students might get more confused. Students need to learn to compare their learning experiences to make sense of it and develop their inner understanding. This counts for all knowledge and competencies. In the learning of theories, students might compare concepts. In the learning of methodologies for analyzing problems, students might compare various methodologies to choose the one that will be aligned with the problem. In learning generic or meta-competencies, the students might compare their experiences of, e.g., project management methods and knowledge sharing in the teams to learn how to contribute to efficient teamwork (see the next chapter).

The experiential learning process in which the learner has reflected on their own experiences will lead to a meaningful inner understanding—but the language, the concepts, and the articulation are dependent on already existing language. Therefore, engineering students also must gain a conceptual understanding of learning and be able to distinguish between different types of experiment and reflection processes. This is important as if we only let the students experience and compare experiences, they might stay as novices or take a very long time to learn core scientific concepts. It is a dialectic process between practice and theory and a type of experiential learning (Kolb, 1984).

Schön characterizes three different types of experiments and reflection processes (Schön, 1983):

(1) The *explorative* experiment, which is very much the trial-and-error process.
(2) The *move-testing* experiment, whose purpose is to test and compare experiences.
(3) The *hypothesis-testing* experiment, which is much more theoretically founded.

The explorative experiment implies a type of common-sense reflection, where the primary aim is to test for establishing awareness. Move-testing takes its point of departure in intended action and thus implies a comparative reflection. The hypothesis-testing experiment also implies generalization of experiences and conceptualization, because experiences must be analyzed before new actions are taken (Kolmos et al., 2004).

Taking the urgency of the grand challenges of our time into consideration, explorative experiments are not sufficient—but it is also important to stress that they cannot be left out of the decision-making process, to increase the pace of innovation. More likely, it is an iterative and agile process between different types of active experimentations that are needed, and therefore, students should not only be capable of conducting different experiments, but they should also be able to adapt the overall experimental design to the situation at hand.

But reflection before, in and on a situation raises the question of what students are meant to reflect on. Argyris and Schön distinguish between two types of reflection depending on the attention given to the reflection process: single- and double-loop learning (Argyris & Schön, 1997). Single-loop learning concerns reflection on activities in accordance with established rules and procedures, and the question is whether *we did things right* and what we need to do to correct our actions for better alignment with the rules and procedures. Double-loop learning considers a deeper reflection concerning the rules and procedures. The questions are much more about whether we are *doing the right things*, or whether they could be done in a better way. Do the rules and procedures need to be revised?

Inspired by Argyris and Schön, a conceptualization of 'triple-loop learning' has developed (Tosey et al., 2012). Triple-loop learning contains a critical reflection on the underlying assumptions leading to the governing values. More philosophical questions concerning *how we decide what is right* and whether other values would suggest more radical innovations come into play. If we accept the argument that critical thinking and sense-making are critical for future engineers, even double-loop learning is insufficient, and students must be assisted to reflect on more fundamental and inherited values.

Furthermore, the on-reflection processes can, by analyzing a longer series of similar experiences, be used for more strategic development of competencies. According to variation theory, there should be a sameness and difference in the situations from which learning is transferred from one situation to the next. The sameness makes it possible to recognize patterns in the contexts or methodologies and to allow for bringing experiences and knowledge from one situation to another. The difference gives the opportunity to advance learning and might guide the learner to alter understandings and combine different learning tracks; otherwise, learning will remain on the same track. For the individual learner, the ability to reflect and create transformation of, and progression in, learning is a crucial part of creating lifelong learning paths. We will come back to this transformation process and the generic competencies needed in this regard in the following chapter.

6.4 New Learning Environments

During the last 15 years, there has been a trend toward more flipped classrooms, meaning that students read/watch material before a class and are more active in the classroom when they meet with their classmates and during lectures. The tradition for university courses is a lecturing part combined with some exercises where students apply the concepts. There is no doubt that even if more active learning methodologies are applied, the role of the instructor is essential in framing, presenting, guiding, responding, and knowing in a new type of reflective and dialogue-based classroom.

Open spaces with appropriate tools have been advocated as enablers for such progressive pedagogies. In particular, the concept of using the classrooms for reflections, collaborative work, discussions, and activities opens the possibilities to ask the learners to study and review the content of their class ahead of the convening time of class (Reidsema et al., 2017). At the class, they devise questions and present their reflections. The instructor provides explanations and examples and generates further discussions. The instructor also gives opportunities for peers to comment and answer questions.

The class members become accustomed to teamwork and support each other. This pedagogy was well articulated by Nechkina (1984) who said '*…let pupils extract new things from autonomous reading of a textbook, which has been created accordingly. Allow them to consider it, then discuss it with their teacher at school and come to a united conclusion'*.

Thus, the concept of the *flipped classroom* was born. The study before the class time includes several forms of learning such as oral, visual, and listening (Mazur, 1997). This requires that the instructor makes detailed preparation for the work outside the classroom to make sure that there are well-defined steps to reach a common learning that can be used to execute projects and joint exercises at the class time. In addition, questions need to be designed to test the students' abilities to define and critique their hypothesis and find solutions in steps of gradual difficulty.

During COVID-19 times, online learning and working became popular and enabled flipped classrooms and made them more accessible. Students got used to learning and discussing topics on the screen. Students showed leadership and agency to learn through their own research and investigations. One may note that there are more courses that already built on discussions and reflections and thus flipped classrooms are readily practiced. Flipped classrooms and peer-to-peer learning have been practiced for different types of class levels and materials, including topics in science and engineering, and it has shown some good positive outcomes (Miller et al., 2018). One of these outcomes is breaking the separation between the learner and instructor and better sociability.

Some students prefer to pick topics that are new or that seem to be a combination of new and old topics. The probability of getting involved in a new topic is low, while picking a familiar topic seems to be much higher. Trying to understand and solve problems that students have never experienced before requires more than lecturing. Since social challenges are different among different societies, students tend to get involved in external activities through volunteering in local communities, for example, to satisfy their desire in addressing social challenges and help in improving the society.

COVID-19 is an example that students loved working on because they experienced it and lived the challenge in their everyday life. Experience is a very important factor in evolving students, and it offers them the mindset to weighing potential solutions to find the right one. By teaching students some theoretical concepts, they can learn how to solve problems and map challenges, but the solutions might not be realistic or a good fit. Fitting a solution in a system requires a solid understanding of the system and its relationship to other systems, which comes from experience and involvement.

6.5 Inquiry-Based Approaches to Learning

Accepting that an increased focus on end-user requirements and societal needs should be a priority in technological innovation, as argued in Chap. 4, also implies acceptance of the importance of contextual learning in engineering education. From a systems approach, the core of contextual learning is being able to point to the most *relevant* contextual aspects to consider as well as the most *relevant* relations in and across established boundaries. Furthermore, the ability to situate the knowing, acting, and being in the T-shaped graduate (Chap. 4) is also a competency of its own. The educational design might therefore be quite different from more traditional designs grounded in an academic disciplinary approach (the I-shaped graduate) (Heikkinen, 2018). In the following, we will argue that both inquiry, studio, and problem-based learning approaches can offer considerable support to change engineering education in a way that supports T-shaped professionals for the future.

Chinn et al. (2021) define inquiry as 'finding things out' under the following six conditions, stating that inquiry is an act where:

(1) One is, in fact, gaining new ideas or new knowledge.
(2) Active work is involved in thinking through and working conclusions out.
(3) Considerations (evidence) are made to reason through to a conclusion.
(4) Those involved have the authority to express their own interpretations, suggest new ways to approach areas of concern and reach their own conclusions (epistemic agency).
(5) There is some degree of complexity in the reasoning involved.
(6) Engagement moves beyond the individual or team to a broader community.

Therefore, inquiry implies a creative, collaborative, and active process that combines theory and practice for complex reasoning and epistemic agency. This approach to knowledge construction can be seen in scientific practices and that inquiry-based learning (IBL) is more often seen as practice within science education than within engineering education (Kolmos et al., 2021). In engineering education, IBL is more embedded in educational models that reflect professional practice (such as problem-based learning models) or parts of professional practice (such as design-based learning models).

In any case, inquiry-based approaches stand in contrast to approaches that are mostly concerned with corroborating dominant understandings or reconstructing what has previously been constructed. Inquiry can be seen a trajectory for transformative learning. Asking questions about a situation and seeking information as and when required becomes central, not only to knowing the why and what but also to creating new ideas of what could be (Holgaard et al., 2017). These ideas are evident in a situation where the dominant technological trajectory is far from reaching the ambition of a circular economy.

In engineering education, there is, however, no universal educational model to deal with the challenges of rethinking our society. It is really a question of how we can bring complexity into education in ways where students can learn to handle complexity, both in terms of analyzing and understanding the dynamics in complex problems, but also to find solutions. Learning can become a transformative process that moves beyond the individual, with an ambition to transform surrounding communities as well.

Transformations of society call for the part of inquiry focusing on new ideas and new knowledge, which underlines creativity as a central component in fostering change in technological systems in society. Csikszentmihalyi (1988) offers a systems approach to creativity and argues that dynamics in social institutions and cultural symbols must be in place in a system to foster creativity. Thereby, creativity builds on contextual knowledge. Cropley notes, it is a paradox that even though few would disagree that creativity is an essential component in technological innovation, '*many leaders, managers, professional practitioners, and educators are either apathetic to creativity or uncertain of how to exploit it in practice*' (Cropley, 2016, p. 156).

From a social-constructivist perspective, Sawyer argued that creativity is basically a collaborative process (Sawyer, 2008), which is aligned with the understanding of technological innovation as a distributed process that includes several actors. It is a dialectic process between individual agency and collaboration in the inquiry process, between constructing and co-constructing new knowledge, new technologies, and new systems that include different technological trajectories. The collaborative nature of inquiry is important, as complexity and system approaches require organizations and interdisciplinary teams of engineers to work together. It is, therefore, an ever-increasing requirement for engineering education to educate engineers who can work, collaboratively as well as individually, and to participate in dynamic and agile work processes. This dynamicity calls for active learning to capture the nature of technological systems—as noted above, inquiry requires active work.

In a (re)introduction of active learning in Engineering Education, Lima et al. (2017) propose that '*Active learning is learning which engages and challenges students using real-life and imaginary situations where students engage in such higher-order thinking tasks as analysis, synthesis, and evaluation. In active learning environments students are engaged in meaning-making inquiry, action, imagination, invention, interaction, hypothesizing and personal reflection' (page 3).*

In a study of the impact of active learning, Freeman et al. (2014) performed a meta-analysis of 225 studies, which reported data on examination scores or failure rates when comparing students' performances in undergraduate science, technology, engineering, and mathematics courses, under traditional lecturing versus active learning. The study showed that, on average, students' performances in examinations and concept inventories increased under active learning, whereas the odds ratio for failing decreased. Heterogeneity analysis indicated that these results hold across STEM disciplines. These results, together with the fact that international organizations like UNESCO stress the need for many more STEM experts in the decades to come, provide strong arguments for active learning methodologies in STEM education.

In a recent MIT report, student-centered learning models like problem- and project-based learning (PBL) were identified as among the core responses to contemporary challenges, leading to engineering institutions like MIT, Stanford, Harvard, Purdue, Chalmers, Delft, Twente, Aalborg, and many more institutions implementing PBL in various ways in their existing curricula (Graham, 2012, 2018). A recent review of PBL in engineering education, however, indicates that the most common application of projects is within existing discipline courses rather than across courses, or at curriculum level (Chen et al., 2021).

It is a trend that more and more student-centered learning methodologies are applied in courses, and a few universities have also reorganized the curriculum to become more student-centered and project-based. Project-based learning has become popular, and there are design courses with project work as the main learning component. However, more systemic institutional changes to problem- and project-based learning imply a more fundamental change where real-life problems become the starting point and the navigator for learning. Such approaches recognize that understanding a problem and the way to approach different types of problems becomes of central concern in fostering transformative learning and learning for transformation of societies.

6.6 Variation in Problem-Based and Project-Based Approaches to Learning

Fundamentally, PBL implies that the problem is the starting point for the learning process, with emphasis on the multidisciplinary approaches. There are different approaches to conceptualizing the so-called problem.

The Cynefin framework (Snowden & Boone, 2007) provides a way of distinguishing various problems by characterizing problems as simple, complicated, complex, or chaotic. This classification was also discussed in Chap. 2 of this book. While simple problems can be handled with engineering fundamentals, complicated problems require expert behavior as there are multiple right answers.

For complex problems, the problem itself is not well defined. In fact, many of these types of problems relate to what Rittel and Webber called 'wicked problems', as there is no definitive formulation of the problem, and therefore, the solution space is totally open (Hadgraft & Kolmos, 2020; Rittel & Webber, 1974).

While complex problems call for a problem analysis, taking into consideration the context in which the problem exists, chaotic problems are characterized by being situated in a context that is so unstable that the boundaries between problem and context become blurred. Chaos management is a related concept as the context is highly unpredictable. Chaotic problems typically emerge from disasters in terms of human loss, as in the case of the COVID-19 pandemic.

Jonassen describes characteristics of problems depending on their structuredness, context, complexity, dynamicity, and the domain specificity of the problem (Jonassen, 2011). For each of the characteristics, there is a variation from the very structured to the ill-structured, from practical problems closely interrelated with real-life situations to abstract theoretical problems related to still unknown contexts, from simple to chaotic problems as in the Cynefin framework, from stable to fluctuating problems, and from disciplinary to interdisciplinary problems. The same problem can of course contain several of these characteristics, which furthermore increases the complexity of characterizing the problem.

It is an iterative process of identifying, analyzing, and formulating the problem which is consistent with the design process (Holgaard et al., 2017). This notion emphasizes that in a PBL environment, which includes real-life complex problems, students not only need to learn to *solve* problems, but they also need to learn how to *identify* them. A problem can take its starting point in an unsatisfactory situation—a *challenge*, a lack of attention to a yet unexplored *potential*, or an uncertainty about the actual challenges and potentials embedded in each situation. These three starting points form a so-called problem triangle (Fig. 6.1). The interrelations in Fig. 6.1 illustrate that regardless of the starting point in the triangle, a problem design process will at some point touch on all three dimensions.

Based on this work, Holgaard et al. (2020) presented a process of managing the problem design process in an entrepreneurial PBL environment. In an entrepreneurial setting, an initiating idea is the starting point for stating and initiating the problem as a discrepancy between an actual state and the vision embedded in the idea. The

Fig. 6.1 Problem triangle

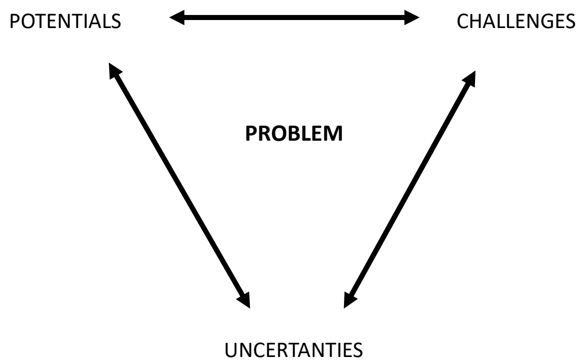
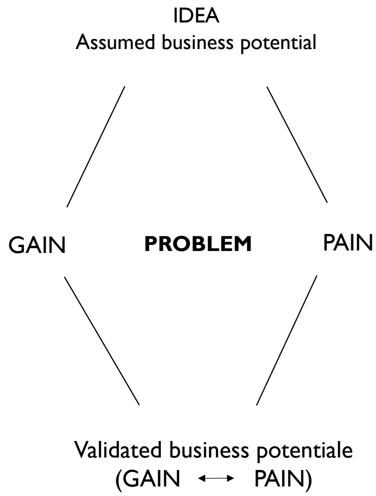


Fig. 6.2 Problem triangle in an entrepreneurial context



problem thereby is seen as the gap between the so-called pains in the actual state and the potential 'gains' if the idea is realized in the given context (see Fig. 6.2).

Understanding the problem as such is then seen as one dimension, whereas the validation of the idea to create value in a business context is seen as another. For other problems, which might move beyond a business context, the validated potential can be translated to other institutional framings, e.g., research or governmental institutions.

The overall idea, however, is that a problem is a discrepancy between what is and what could be, and the 'what could be' inevitably is related to a *value proposition.* Foresight, which is described in Chap. 2, is a way to reflect the past, the present and the future. A problem in this view is a social construction and, thereby, a carrier of the *values* embedded in the practices, institutions, and discourses of the co-constructors. This view underlines the importance of contextual knowledge as emphasized in the previous sections. It also explains the different perspectives expressed by stakeholders about the given situation or the proposed solutions.

In any case, bringing the *problem into the classroom* will be important—problems are the core of the learning process, and as students are the main players in solving these problems, it is important that they get the opportunity to identify, analyze, and solve problems. It might be hard to solve complex problems in education and the students might not be able to do this, but they will be able to learn how their narrower technical solution will relate to the complexity of real problems. We therefore argue that *problem design* should be an integral part of engineering education.

Real-life problems will not show themselves in forms that are easily accessible, and a systematic approach is therefore needed. There are different approaches to analyzing a problem, but three approaches seem repeatedly emphasized:

(1) Overview and structure: With increasing complexity of a problem, the need for an overview of the problem field increases and the same goes for the structure of

problem analysis. There are many ways to create an overview of a problem field (e.g., by mapping) and many ways to structure a problem analysis, e.g., using different models to make iterations. Furthermore, a selection of different theoretical lenses from quite different knowledge domains and different contextual layers is typically needed to focus the analysis (e.g., psychological, social, organizational, environmental, economic, political, and cultural lenses). Systems thinking, as described in Chap. 2, is a critical part of this step.

(2) Outlook and ownership: Complex problems cannot be defined from one perspective or from the view of one researcher, actor, or student. Therefore, it is crucial that students move away from their desks, out of the university, and get a sense of real-life problems, including the activities, actors, and resources, as well as the practices, institutions, and discourses, that constitute such problems. The question is also who 'owns' the problems? And among the owners, a critical question is how the students relate to the problems. The people dimension is central!

(3) Problem delimitation and decision making: Complex problems need complex decisions on unsecured ground—this means that students must be able to select and argue for different strategies and perspectives in the problem analysis, and considerations given to the formulation of criteria for this selection and decision-making process. While structure and overview represent potential paths in the inquiry process, the problem delimitation presents the chosen path. This also relates to ownership—students embrace problems with their professional identity, however mature that might be.

The most important reason for having such a systematic approach in the problem design process, besides making sure the 'right' problem is solved, is that attention to the process will prevent students from falling into a random solution mode too early in the process. In popular terms, if you do not know where you are going, any bus will do. For engineering students that have not yet experienced the joy of making a real-life impact as an added value of learning, the 'bus ride' might seem the main trigger of motivation.

With a variation in problems, there will also be variation in project types. By combining the dimensions of problems, interdisciplinarity, and team size, Kolmos et al. (2021) distinguished four basic project types: the *single-discipline project*, the *multiproject*, the *interdisciplinary project,* and the *megaproject* (see Fig. 6.3). These are ideal types as it is often difficult to draw the boundaries in real-life projects. As such, these ideal types are therefore developed for analytical and conceptual purposes only, and there might be many more variations in practice. The model in Fig. 6.3 is further developed for the case in Chap. 10.

A *single-discipline project*, carried out in a single project group, is the most widely used both at course and curriculum level (Chen et al., 2021). Students from the same course or educational program apply knowledge, theories, and concepts to a specific discipline problem. An example could be a group of students applying control theory while developing an anti-sway system for a ship-to-shore crane.

An *interdisciplinary* project can also be carried out in one project group of a small size. The team preferably includes students from different programs, whereas

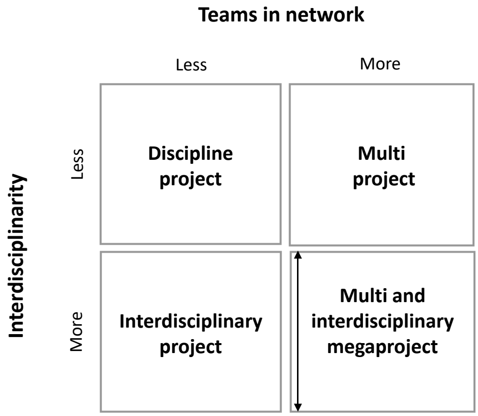


Fig. 6.3 Variation in project interdisciplinarity and complexity of teams (Kolmos et al., 2020a)

a more modest approach is to let students from the same program work on an interdisciplinary problem in a collaborative T-shaped approach. In engineering projects, the preliminary problem analyses are often interdisciplinary in terms of academic scope, as students use, for example, sociological methods or participatory action research to identify user needs, allowing interdisciplinary knowledge to be integrated into a project with students from the same educational program. An example could be students of media technology designing a sustainable city game for primary schools, for which they need to have knowledge of learning in primary schools, sustainable cities, and game design.

A *multiproject* is less common and occurs in bigger courses or clusters of subdisciplinary courses. It is characterized by several project groups working on the same or complementary elements (work packages) within the same or very similar disciplines, e.g., in larger software development projects, or when groups work in parallel on the optimization of prototypes. These types of projects require a lot of coordination among the participating project teams to ensure the quality of the common product.

The last category is the megaproject which has recently been introduced into engineering education as a new project type. The general term 'megaproject' covers large, long-term, and highly complex interdisciplinary projects, normally characterized by a large economic investment in, and commitment to, the development and implementation of infrastructure projects in cities, logistics such as high-speed trains, aircraft and airports, space technologies and renewable energy systems, etc. Of course, it will not be possible to mirror these very large projects in education, but it will be possible to design projects that address complex problems across disciplines. It is important that students learn to deal with complex problems in education.

For students to learn how to handle real-life complex problems, they must move beyond disciplinary teams. Multiprojects will help students learn to work across teams but not across disciplines. Collaborating within disciplinary settings will most likely be easier than in interdisciplinary teams—and collaborating to solve complicated problems in an interdisciplinary setting is most likely easier than solving complex problems in megaproject constellations. Therefore, there must be concern about progression in the development of competencies for team-based work, which, even in a disciplinary setting, is far from simple.

6.7 Studio Learning

The studio pedagogy originates from architecture, and during the last 30 years, several other disciplines have applied this way of organizing learning (Bull & Whittle, 2014; Kamalipour et al., 2014; Schön, 1984). The way it is applied in engineering education, students seek solutions for human challenges. They may work individually or as a group, but normally, they are interacting in open discussions with their colleagues, stakeholders, and clients in the studio and outside it. Constant feedback and critique are key elements of a studio.

Naturally, the physical environment facilitates the interactions and discussions. Students may work on their prototypes and designs in the studio and work is therefore viewed by all participants, instructors, and critics. The infrastructure of the studio can include engineering workshop tools as well as computer simulation tools, projectors, and whiteboards.

The studio is an environment where students learn through peer-to-peer learning, discussions, and critique, and their learning is encouraged and reinforced. When they find obstacles or devise unsuitable solutions, they are coached and critiqued by their educators, peers, and stakeholders. With these steps, knowledge is increased and tested. In the steps of 'reinforcement learning', students need to learn how to predict '*how good*' is their intermediate action. Thus, their work continues to be in the form of explorations. Feedback is used to update and improve the attained knowledge, so students learn to act and create to achieve a better design state while being critiqued by their peers and outside critics as shown in Fig. 6.4.

Fig. 6.4 Supervised learning states, with peers, critics, clients, stakeholders, and the public, participating in guiding the mitigation of a complex human challenge

We call this state a 'supervised learning' state. As the supervised learners receive their critiques and feedback, their 'rewards' are obtained without a delay. In a normal classroom structure, grades are received after several days, and sometimes weeks, from the time of their exams. Here the reward, i.e., the guidance, is immediate. Technically, the students are not receiving grades, rather, they receive advice or critique. This is a critical element of a studio, pun intended!

This process of supervised guidance encourages rapid iteration toward a solution and is useful when the 'environment' of the challenge is unknown. As the students are engaged in a complex challenge, and with clients, they become *active change agents*. Their function is to observe, empathize, and create solutions guided by the clients and other stakeholders, exploring, and innovating to create the best outcomes, through several iterations.

Knowing the environment of the challenge is a significant part of the challenge. The environment may not be in a *static state*, and it may have (almost certainly will have) *stochastic elements*. In fact, in these situations, *every* action the student undertakes may create a new state of the challenge. This is the nature of complex challenges. By replacing the teacher with a coach/critic and the grading process with critique and guidance, the burden of knowing is reduced, and the teacher also becomes a learner by engaging with the teams as they explore solutions.

There is a significant difference between the mental state of the teacher and the critic. A teacher tells the students what to do; they know the right answer. Whereas a critic tells the students how well they did, after they perform their actions. The critic never informs in advance what to do. The critic should not believe that they know the right answer; there is no right answer. A critic can provide rich feedback about the pros and cons of the proposed solution *from their point of view*, which should be clearly stated.

6.8 Team-Based Work is Critical to Produce Inclusive Designs

Applying projects in education also implies teamwork. A project is, by definition, an endeavor to meet or solve a specific task that is time limited and needs comprehensive resources. Very seldom do we think of projects as one-person efforts, but rather as work that is done collaboratively. Therefore, the team dimension is an important part of project approaches. Composition of teams can vary enormously and therefore students should also experience this variation.

There are many theoretical frameworks for understanding teams, and the point here is just to illustrate variables and conceptual understandings of teams, which the students should be allowed to experience. Students need some experiences before they understand the theoretical models and team variables, but the important part is that they are given the opportunity to experience the variations. The project organization not only depends on the type of problem addressed but also on the work

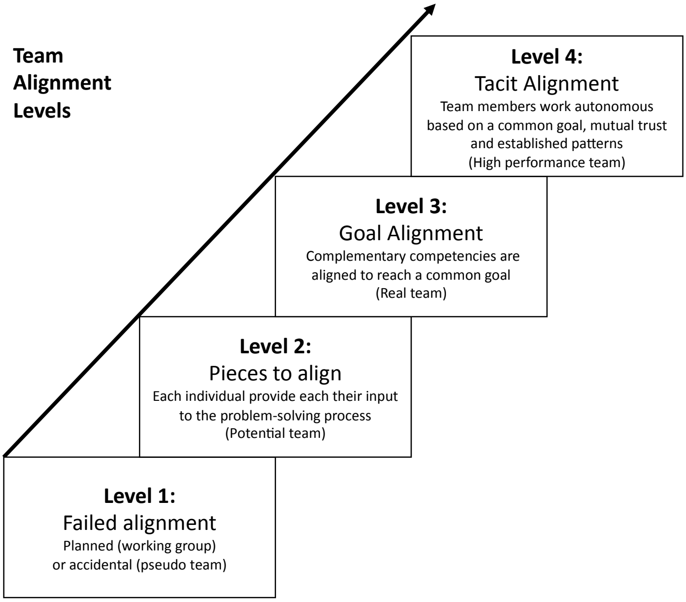


Fig. 6.5 Team alignment levels, based on Katzenbach and Smith (2015)

orientations of the team members involved, the accessibility of knowledge providers, available resources, etc. In any case, all project teams should aim to become high-performance teams, where the learning process and the project are experienced as an integrated and beneficial process.

Katzenbach and Smith defined five types of teams to be distinguished from a working group. A working group consists of individuals who do not share common goals with some common purpose but where the individual goals dominate, e.g., a study group of students, each with their own individual goals, but each is willing to share knowledge with each other (see Fig. 6.5).

Although working groups exist within the boundaries of a problem-based learning environment (e.g., when students work in parallel to learn a specific skill), working groups are not sufficient for problem-based project work, as the problem constitutes a shared concern, the solution to the problem is a shared goal and the project work is a shared practice.

One team type, defined by Katzenbach and Smith (2015), can have even less performance impact than a planned working group. This type is a so-called *pseudo-team*, where the members should be working on a common goal, but they do not manage to get there. They are stuck in a storming phase, without really being capable of creating norms or rules, and if they do, they do not obey them.

These types of pseudo-teams are highly damaging for students' motivation to work in teams and are, unfortunately, far too common. A typical pseudo-team practice is to let individuals work in a parallel mode without any interaction, where an important opportunity for peer learning is missed. Pseudo-teams can, unintentionally, be encouraged by choosing a problem that is too simple, which can easily be reduced to separate tasks that can easily be solved individually; consequently, students will miss an important opportunity for learning.

When team members have some shared experiences, they can start to align their knowledge and competencies. This is a kind of a potential team where team members try their best to norm and perform but without great success. The project report will reveal that the logic is missing and that they have not been able to build in a collective reflective process. Students will always believe that they are working in a real team, but as they fail to carry out formative evaluations along the way, the mistakes will most likely be revealed too late at the summative stage of the assessment. They have aligned parts of their project work, but still there are missing links.

One example is a student group trying to solve a rather complicated or complex problem through approaches used to solve simple problems—reducing the problem through questionable assumptions and independent work packages. Sometimes, students end up with missing pieces (as some group members did not do their part in the end) or pieces that do not fit together (as they have moved in different directions). But, in contrast to a pseudo-team, students might experience that they have, in fact, learned a lot from such mistakes. Disappointment with the solution provided will, however, most likely disturb the excitement of the learning outcome.

A next stage is when team members are aligning their expectations and have a common understanding and alignment of the goals. The team members collaborate with complementary competencies and are equally committed to the common goals and the project. This type of teamwork will most likely not be the students' first experience. On the contrary, many students will have to experience more than one 'potential team experience' before they are able to be as flexible as a real team requires. This is also because student groups are seldom matched together to complement competencies as in a real-life setting, as the primary concern is learning outcomes and not project deliveries. This type is also characterized by integration of reflection and adaptation in the collaborative process. Meta-competencies are needed to be in a position where you can set or develop real teams in the future as one has to be able to change perspectives.

Such teams are needed to solve complex problems, which need a synergy of different competencies and even disciplines. However, even though we might accept that real teams can only be imitated in an educational setting, the question is how we, as educational designers, can offer the best possible learning environment for creating competencies for establishing and working in a real team.

In Katzenbach and Smith's conceptualization, the highest level is the high-performing team. All the good qualities from the real team will be present plus tacit collaborative understanding and alignment. Team members build on each other's ideas; they are committed and enthusiastic and they reflect automatically before, in, and on the processes. They have created enough trust to dare formulate critical viewpoints and have enough faith to regard these as constructive elements in the common learning process instead of personal critique. The high-performance team also has a mutual commitment, and they can decode each other, so they can, in fact, exhibit the right degree of help to support mutual learning. The collaboration goes beyond the explicit verbal language, and tacit knowledge is an embedded and significant part of the flow in the team.

Working in teams also provides a new dimension to reflection before, in, and on action. What is special about a more team-based education is that there is the process of creating both a reflective practitioner and a reflective team. But how do we bring this into education—or at least provide students with the opportunity to experience a variation and progression of their teamwork? At least, two components in the curriculum will be necessary: (1) that the students will have the opportunity to experience more than one teamwork or project (variation criterion); (2) that the students will have the opportunity to reflect on their experiences (reflection criterion). Not many engineering programs offer these opportunities.

The above considerations of the learning processes complement a systems approach to engineering education and build on a social-constructivist view of learning as introduced in Chap. 5. This means that learning is seen as the process where knowledge is constructed collaboratively and in context. The dialectic relationship between the ones who are constructing, and the constructed, forms the basis of learning.

This social-constructivist view of learning offers an approach to complexity as it embraces diversity as well as inclusivity in the knowledge construction process. Knowledge is basically open for (re)construction by everyone, which raises critical concerns. There is a dialectic tension between diversity and convergence—in other words, between the complexities we experience in real life and the complexity we can cope with.

The degree of complexity seems overwhelming, and we introduced exemplarity, variation, and reflection as core concepts for coping with complexity in the curriculum. The learner's ability to handle various situations and solve different problems was highlighted, and inquiry-based, studio, and problem-based learning approaches have been proposed to facilitate the transformation needed for engineering education, to cope with complexity were discussed.

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Chapter 7
Generic Competencies

> A partner from one of the big international companies asked: how can we optimize human and social interaction? In our innovation projects, it is as though each time we start a new project, we start from scratch. Are there any tools or methods that I can use to optimize these processes? I think this is a new competition parameter.

This question is becoming more and more relevant. We have learned that technologies are becoming more complex both in terms of technical combinations and in terms of the societal problems that must be solved. But what is often forgotten is that behind the technologies, there are humans. As technology becomes more complex, more humans will have to collaborate and there will be many more boundaries to cross. These include academics with different disciplinary backgrounds and users with different levels of education and social position in society.

Engineering has traditionally been more product- than process-focused, which means that human interaction has received less attention and been valued less. The corporate world seeks optimization in every process to achieve more efficiency and better economy—and if the optimization for specific technologies might have reached its limit on the product side, the next step will be collaboration among human beings. Companies realize the need to cross boundaries between sales and innovation departments, between contractors and subcontractors. In any innovation process today, the number of actors involved is increasing.

Therefore, it is not enough for engineering students to learn to develop the content of technology and how technologies are combined and form systems. The students also need to learn how they, as humans and collaborators interact together in the design of systems, and here both cognitive and emotional aspects are at stake which are described in Chap. 5. As described in Chap. 5, reframing engineering education will involve rethinking the interaction between knowledge and competencies. We have several concepts for these types of competencies ranging from key skills, 21st-century skills, transversal skills, transferable skills, and generic competencies (Boelt et al., 2022; EU Commision, 2008; Kallioinen, 2010; Kearns, 2001).

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Generic competencies work across different contexts, in contrast to specific ones related to a subject or a disciplinary context. We are using the term generic competencies to indicate the character of the competencies, as general human competencies for work collaboration and life orientation. For many years, teamwork, communication, and project management have been added to the list of core generic competencies for engineers. Furthermore, we have chosen the competency concept to indicate the potential together with the qualification of application in practice (Fortuin et al.; Le Deist & Winterton, 2005).

Policies and regulation frameworks do exist to address both generic competencies in the engineering standards, SDGs, and accreditation. The transformation of engineering education from a teacher-centered approach toward student-centered learning, as described in Chap. 6, is also facilitated by the development of international standards and accreditation, and the mutual recognition of engineering qualifications and professional competencies (International Engineering Alliance, 2012). Accreditation can be seen as a transformative driver of change but, at the end of the day, it is the educational culture and the learning methodologies applied that will have a significant impact on students' learning. Accreditation can form the outside framework, but the inside life depends on academia and the culture. Engineering institutions have responded to this challenge with very different strategies, from adding on workshops to integrating competency development in the curriculum.

However, very often generic competencies have suffered from a 'lack of respect' in the engineering curricula and have not been highly valued among engineering academics but have been tolerated in the curriculum as something 'soft' and potentially relevant. On the other hand, the corporate world has emphasized this as a very important component in graduate competency profiles, along with technical knowledge and competencies.

It might be hard to solve complex problems in education, but the corporate world problems should be part of students' learning processes to prepare them for their later careers and their understanding of the diversity of problems. In the future, we will also see more and more digital learning and blended formats for engineering students, and this will create even more possibilities for active learning methodologies, to apply blended learning modes that may allow for the facilitation of university and corporate collaboration.

Teamwork, project management, communication, problem solving, etc. can all be covered under the concept of generic competencies, which are to be understood as cross-cutting competencies. Transferable skills, 21st-century skills, professional competencies, and transversal skills are other concepts for trying to conceptualize these competencies, which are related to codes for human interaction and behavior. The European Tuning project, which has been one of the research-based approaches for the process to a more student-centered learning model in higher education, defined generic competencies as a long list of competencies ranging from critical thinking, ethics, and language to problem solving and interpersonal and organizational competencies (González & Wagenaar, 2003). Scientific and technical competencies are not sufficient but have to be seen in light of society, context, human relations, and ethical purpose.

Therefore, the learning of generic competencies has to be an integrated part of the curriculum and the students' learning outcomes (Sánchez & Ruiz, 2008). But can we enhance students' awareness of their own learning practices, and can we bring that awareness into their education in such a way that we can formalize learning and assessment processes? Of course, there are tools that can structure—there are some quick fixes—but in the long run, this is not enough. It goes deeper, and the students need to learn to adapt, to participate in a complex collaboration. This cannot just be an external phenomenon; it must be integrated with the knowledge that one possesses, and it must be part of an entire culture and curriculum.

7.1 Generic and Meta-Competencies

Increased complexity at both the technical and societal levels will require collaboration, communication, and management. But it will also require competencies to continuously develop and learn how individual and collaborative competencies can be contextualized. In one situation, it will be communication by digital means; the next situation might be 24 h of face-to-face workshop. The collaborative contexts in which an engineer will have to work will differ enormously—and it is no longer enough to have experienced teamwork or to have participated in projects.

We must go above this level as the requirement today is to be able to participate in a variety of situations and to optimize the learning processes at work. It is no longer enough just to learn teamwork—the requirement is to develop teamwork skills to be efficient in various situations and to be able to choose the right collaboration strategy for the specific situation—in other words, *we need to move the competencies to a meta-level*.

Meta-competencies are defined, with reference to Brown (1993, p. 32) as 'the higher-order abilities, which have to do with being able to learn, adapt, anticipate, and create, rather than with being able to demonstrate that one has the ability to do so. Moving the competencies level to a meta-level does not only concern teamwork skills, project management and communication. A much broader concept is needed in order to understand what kind of problem we are aiming to solve and what kind of methods we have available to analyze and identify the core problem (Brown, 1993). A related concept is meta-cognition which is beyond factual, conceptual, and procedural knowledge and a question of strategy in combining knowledge, knowledge about cognitive tasks, and types of self-knowledge (Krathwohl, 2002). Whereas meta-competencies are about developing generic competencies, meta-cognition is the process of acquiring knowledge on how to acquire knowledge.

There is a distinction between the concepts of meta-cognition, competency, and meta-competency and yet they are closely related. For example, meta-cognition strategies to acquire knowledge within thermodynamics can be developed. Competencies go one step further, providing strategies to handle knowledge in action as thereby the field of thermodynamics is appropriated to a given context, e.g., the design of heating and cooling systems in different types of buildings, climates, or cultures. Meta-competencies on the other hand include strategies to handle competencies in action as competencies within a specific field is transformed in interaction with other competencies, e.g., competencies within the field of heating and cooling systems are combined with competency to design smart buildings or ensure business models for sustainable products.

There is a dialectic relationship between competency and meta-competency and it can have blurred boundaries. Meta-competencies can be defined by the development, adjustment and application of competencies and, therefore, at a higher reflection level (Brown, 1993). This links the meta-competencies to a notion of lifelong learning as students learn methods for how to develop their competencies (Cunningham et al., 2015).

The relation between generic competencies and meta-competencies is similar blurred. The generic competencies consist of three components: understanding of the societal problem including ethics, interpersonal collaboration, and organization of the process. The meta-competencies in this domain are to combine, adjust, apply, and develop the interaction among the specific generic competencies (see Fig. 7.1). Generic competencies are types of practice competencies, and learning takes place through both reflection on practice and conceptualization and analysis.

We have already described the importance of viewing problems in a societal context, and as the problem complexity increases, the complexity for interpersonal relations and organization will follow. The real-life problem, interpersonal collaboration, and organization act as a trinity that is fused together. As technology is a tightly woven system, the human side will likewise be tightly woven into the functions in the system. As the complexity increases, the interactions between knowledgeable people will increase.

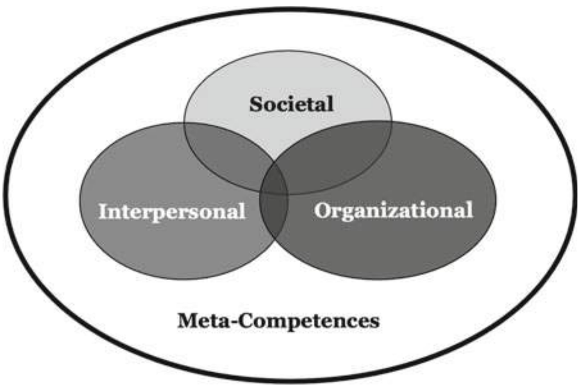

Fig. 7.1 Dimensions of generic and meta-competencies

We cannot increase the technological complexity without addressing the human interaction. Complex challenges, such as the SDGs and the integration and development of AI and IoT systems, all involve the competencies of being able to advance learning and set future goals. Thus, strategic leadership and anticipation are two other important future competencies in complex problem approaches, as system approaches will include both strategic leadership and anticipation embedded in a system perspective (Chap. 2).

There is nothing new in emphasizing generic competencies. As described earlier, this has been part of the accreditation for engineering education for a long time in terms of teamwork, collaboration, and project management. What is new is that more types of generic competencies are in play, such as entrepreneurial and digital competencies, and also that generic competencies are combined with a meta-level moving across generic competencies. Thereby, methodologies for developing lifelong competencies through the learning of meta-competencies are needed.

As complexity and the need for system thinking increase, engineers not only need to learn to solve problems in the right way, but indeed they need to analyze the problems and to devise new solutions. If there are recurring flooding situations and the decision is to build a new river crossing, a bridge may not be the best solution. In the first design phase, engineers will have to analyze the weather conditions, the traffic situation, the ground, possible ways of crossing the river, and many more elements, before deciding on the solution. In a complex problem analysis, engineers step backward to find new solutions and combine knowledge and expertise in a new way. The ability to step back, at the right time and use the right lenses to get an overview of the whole system, including the underlying rules and values, becomes an important competency.

The same is true for the collaboration among the involved actors and the engineers. If they have been used to collaborating on bridge projects, now there might be new expertise domains involved—and they not only have to analyze the knowledge domains and contextualize their expertise to a new innovation but also the way they collaborate has to be considered. This is a totally new element in engineering education.

7.1.1 Tacit Knowledge—Potentials and Risks

Development of meta-competencies is difficult, as the human interaction gets mixed in many ways with the inner world of the individual. One's way of interacting might depend on one's upbringing, personal identity, and personal life. But regardless of this, engineers need to learn to master collaboration, diverse contexts, and complicated communications and develop these capabilities as competencies to be applied in working life and life in general. Awareness and articulation of communication strategies and collaboration strategies can be learned. Most often, past social interactions form a body of tacit knowledge for the individual.

Dreyfus and Dreyfus emphasize that the expert has such a rich pool of knowledge and experiences, that the intuitive processes of knowledge creation will not necessarily be conscious, but tacit (Dreyfus, 2004). For the expert, this might be true, while for the novice, it is important to be much more aware of the rules and the process itself—hence the need for explicit reflection.

Tacit knowledge is the opposite of explicit knowledge and can be explained in two different ways, either as knowledge we cannot articulate or explain or as embodied knowledge that can only be expressed during practice. These two perspectives are not contradictory. Knowledge can become embodied; sometimes, it can reach a stage where it can be articulated and sometimes not. The concept derives from Polanyi, who argued that scientists should recognize that not all knowledge is propositional and in order, but that a lot of our ideas and learning comes from this messy and unordered embodied knowledge, which can hardly be communicated in words but rather in action (Polanyi & Sen, 2009).

Generic and meta-competencies will remain tacit, either as unarticulated or as practice competencies, if the learning is not facilitated by reflection. Nonaka and Konno worked with tacit culture and knowledge in organizations and the interaction between the explicit and the tacit level (Nonaka & Konno, 1998, Engeström, 2001). Baumard took this approach to another level as he distinguished between individual and collective knowledge (Baumard, 1999).

Baumard points out that there is a tacit element both for the individual and the team when there is a continuous interaction and complicated relations. Tacit and non-verbal communication might create both potentials and problems for learning from practice. The potential with tacit knowledge is that it is a source of intuition for the individual and for the team. In group creativity research, it is a well-known phenomenon that ideas can be developed in a process of smaller interactions and iterations. One member of the team can present an idea, which will create responses from the other members, building on the idea in a continuous brainstorm of associations. The process of interaction will form the team members' culture and might very often remain tacit and form tacit patterns of interactions.

The disadvantage of tacit knowledge for both the individual and the team is that it is difficult to transfer or transform knowledge and competencies from one area to the next without articulation. There is a need for both the individual and the team to be able to articulate, communicate and conceptualize. Furthermore, this creates difficulties for the development of the individual and for collective competency development, especially for the individual student in articulating and conceptualizing their own competencies when ending a project. Therefore, a process of creating attention and awareness by reflecting on these practice experiences will be an important element in learning generic competencies.

In a single team consisting of four to six students, the tacit element can lead to team creativity. Schön's reflective practitioners and their collaboration can be compared to a blues band doing a jam session. Each participant continues add-on to the contributions of the other participants and invites them to continue the development of the communication, which can be described as open, creative, uncritical, and reflective in relation to the theme and creative. Collaborative creativity and development might occur. In online teams, tacit knowledge also exists, although it is more difficult to create a common tacit culture as there are limitations when communicating through a screen (Sawyer, 2005).

However, the potential of tacit knowledge related to the team interactions often vanishes when there is a change in team members, team size, the length or credits of the projects, physical versus digital space, problem types, or diversity pattern. Then it becomes difficult to apply the knowledge and competencies the learner has obtained in a new situation.

As an example, students might articulate their reflections on teamwork experiences continually and state action points for change in a log-book format. To work collectively, teamwork experiences from the individuals must be articulated to align and negotiate understandings and perspectives for change. Furthermore, students must realize that if considerable changes in the team constellation happen, teamwork competencies have to be transformed. For example, a predescribed team culture might be beneficial in one team, while counteractive in another team setting. Likewise, project management systems, approaches to problem solving, etc. will change with the type of problem, the intended learning outcomes, and the actual team constellation. In other words, there is a need for meta-teamwork competencies to provide strategies for the interaction of diverse teamwork competencies, such as inclusiveness, collaboration, communication, project management, problem analysis, etc.

7.1.2 Reflection and Meta-Reflection

If practice experiences are not reflected, these will become trial and error, which can be beneficial but remain tacit knowledge. Reflection on practice learning from the education is not only crucial for the competency development of young engineers; it also influences how ready they feel for employment and their lifelong qualification and career strategies.

Reflection is essential for progressing learning of generic competencies. Regardless of the domain, the learning is framed by the learning methods and learning environments, which will create opportunities for students to experience collaboration among peers, knowledge management, creativity, and innovation. It can be argued that there is nothing new in reflecting in and on practice to attract attention to tacit knowledge. But it is new to think of the relation between generic and meta-competencies and that the learning of meta-competencies is based on a combination of reflection on practice and theory.

Back in the 90s, the learning of the Alverno College culture was known far beyond the US borders (Gibbs, 1999) for their integration of reflection as a cultural factor. Later came the Olin College culture, where ongoing reflections in teams and for individuals after class were also an impressive contribution to the learning culture and the education of the individual. Students need to learn to reflect and articulate their experiences from collaboration, managing projects, managing cultures, problem analysis methods, collaboration with external stakeholders, presentations, etc.

Kolb (1984) does not identify reflection as a method but as an element in a learning process consisting of concrete experience, reflective observation, abstract conceptualization, and active experimentation. This underlines reflection as a key to combine practice (active experimentation) and theory (abstract conceptualization) and can be the on-reflection which is looking backward as in Schön's conceptions on reflections (Kolb, 1984). Without abstract conceptualization, reflection-in-action can quickly become a tacit process mostly characterized by trial and error. What works and what does not work are concluded based on immediate responses in the process (see Fig. 7.2).

When reflection is brought into engineering education, engineering students may not be attracted by reflection, but rather much more by experimentation—they want to experiment; they want to design and build things. Therefore, it might be an advantage to ask students to set up experiments in their learning process and collaborative processes, and then ask them to reflect on these experiments (Kofoed et al., 2003). Especially in a team, discussions on how to set up new plans for knowledge management might also create awareness of the variety of possibilities that the students will face. For example, an experiment could be to ensure knowledge management by setting up team seminars, organized with presentations of the knowledge acquired from subgroups, opponents to discuss the application of knowledge, and inputs for further knowledge acquisition. If the action and future orientation drive the process, they increase the motivation to learn from the experiences gained from their experiments.

Reflection on practice might remain at a lower taxonomy level for learning if it is not combined and integrated with more general theories. For example, students need to be able to create attention to, and awareness of, their collaboration patterns and

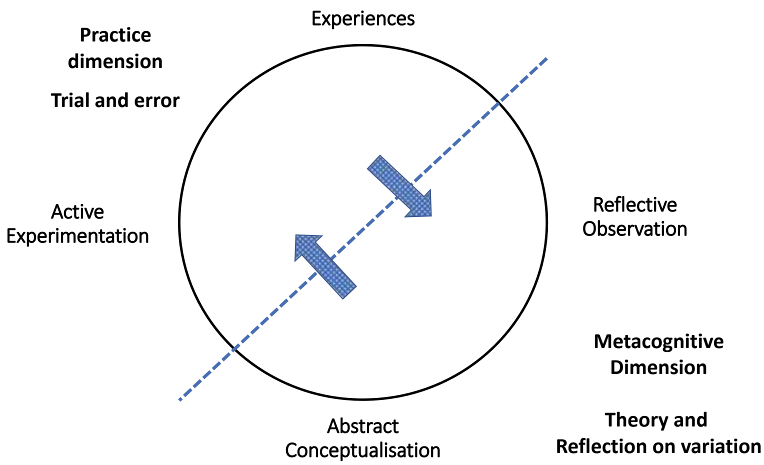

Fig. 7.2 Reflection relating practice and theory based on Kolb (1984)

their use of project management methods. That means that the student will become much better at reflecting on how well they are interacting in specific collaboration.

Reflection is an inner inductive process, which can be facilitated by oneself, by peers in a team, by comparing to previous similar experiences or facilitated by academic staff. Attention, awareness, and articulation enable understanding of existing practice but do not necessarily provide ideas for new innovative ways of collaborating. If reflection is not combined with theories and concepts, reflection might not contribute to learning. For example, if students state a team culture without considering theories of effective teamwork or fail to align their understandings of the team culture concept, the statement might be narrow-sided and open for diffuse interpretations.

We have to be careful that we are not teaching our students just to reflect on practice, but that they have to move around in the Kolbian learning circle and integrate the reflection of practice experiences into the learning and understanding of theories (see Fig. 7.2). Reflection on comparing several practice experiences will form the basis for understanding the variation and possible methods of project management or collaboration.

Engineering students should not only be able to apply and reflect on theory or methods in order to make constant improvements. They should also be able to question whether these are the right theories and methods or if other solutions are needed in relation to the given challenges. In integrating complex problems in engineering education, students will need to integrate values, analyze contexts, and question established norms and institutions. As an example, energy systems are highly dependent on the political climate, social movements and strong institutional dependencies. Complex problem solving is part of the new core in engineering to be able to deal with the societal as well as the human challenges and contribute to strategic leadership.

Thereby, there is a need to engage in meta-reflection as an integrated part of meta-cognition. Basically, meta-reflection happens when we reflect on how we reflect. Meta-reflection involves cross-cutting reflection on the appropriateness of the different interactions between theory and practice. Integration of meta-reflection in education is important, as it is not expected that students will develop these competencies by themselves. Rather, through guided reflections on varieties of learning experiences, students can gain a deeper insight into their problem, project, and collaborative and learning skills.

In a learning context, we characterize meta-reflection as a comprehensive reflection including different levels of reflection, see Chap. 6. In alignment with Argyris and Schön (1997) and their concepts of single- and double-loop learning, as well as the concept of triple-loop learning introduced by Tosey et al. (2012), we characterize three levels of reflection:

1. Single-loop reflection—that is reflection on activities (are we doing things in the right way).
2. Double-loop reflection—that is reflection on the governing variables (are we doing the right things).

Table 7.1 Variation in reflection

Type of reflection	Example
Single-loop reflection	Do I collaborate in the right way? Does the collaboration proceed as planned? Do I use the right methods to follow expected collaboration patterns?
Double-loop reflection	Do I choose the right way to collaborate? What possible collaboration strategies should I apply in this situation? Is there a need for developing new collaboration patterns—and what new ideas can I contribute with?
Triple-loop reflection	Which values are reflected in the way we collaborate? Are these values what we want? Which politics should we develop to aligned collaboration strategies with our values?

3. Triple-loop reflection—that is reflection on the underlying assumptions leading to the governing variables (how do we consider what is right).

Meta-reflection thereby includes reflection considering whether we are doing things right, whether we are doing the right things and more fundamentally, what we consider as being 'right' (see Table 7.1). For example, in designing human collaboration, we often forget to ask ourselves what possible collaboration strategies we can apply, and we forget to ask why we chose a specific one. We often forget to step backward and analyze the tasks ahead of us and form adequate organizations, and instead, we jump onto known pathways.

Furthermore, the complexity of doing things right, doing the right things and considering what is 'right' increases considerably when several interests are involved. Negotiations between actors are a well-known part of complex problem solving. A simple problem is solvable within the disciplines; a complicated problem connects to known collaboration among disciplines and subdisciplines, whereas a complex problem does not have a known solution and learners will have to step backward to understand the problem and to design solutions across traditional disciplinary boundaries. Thereby, meta-reflection also becomes a matter of reflecting on the boundary crossing between different disciplines in interdisciplinary projects. It becomes a meta-competency to handle interdisciplinary competencies in action, e.g., to foresee the limits of one's own discipline, knowing who to consult to interact with other disciplines, and ensure aligned interaction with mutual benefits.

7.2 Interdisciplinarity and Boundary Work

Interdisciplinarity is not a subject matter, it is a process that ends up building a format of thinking. Each student has their own contribution to understanding and solving a specific problem. When students from diverse disciplines work together, they build a level of trust, and they may start consulting each other or work together outside the classroom on different subjects. Interdisciplinary collaboration among students in the same course, brings together new ways of thinking, combined elements of solutions and more global fit of an outcome (Mausoom & Vengadeshwaran, 2021).

What the dimension of tacit knowledge reminds us of is that it is important to reflect not only at the individual level, but also among peers at the team level, and not least be aware of the diversity issues. Teams consist of individuals, and it can be very hard to look through what is happening in the team among the team members, but it is essential that the team members understand both their own and each other's perspectives. What can be beneficial to identify are many of the disciplinary and diversity factors that create boundaries. When boundaries are identified, it is much easier to establish common ground.

It is important to create a language and set of concepts in order to set common goals and be able to reflect on the process and the outcomes, and as mentioned in Chap. 5, language and linguistics acts include a multitude of symbols which is open for interpretation. That might be easier to say than do. But a language is part of the organization of the process and the application of structural competencies. What is much more complicated is overcoming the boundaries of disciplines and cultures.

The degree of interdisciplinarity is linked to the type of problem that the students are working on. As the problem becomes more complex, it will involve more actors and disciplines in both the identification and solving phases. Most of the research on interdisciplinarity is primarily focused on research, and the literature on how to deal with interdisciplinarity in education or in collaboration is limited (Everett, 2016). For research, the literature mentions three variations of interdisciplinarity: multi, inter, and transdisciplinarity (Keestra & Menken, 2016; Repko et al., 2019).

As illustrated in Fig. 7.3, a multidisciplinary approach ensures that the problems are looked at from different disciplinary angles and different discipline solutions are provided. There is an exchange of information and knowledge, but there is no real integration in the product. The interdisciplinary approach is an integrated approach and there will be a common solution in the end. The transdisciplinary approach is defined a bit differently in diverse literature, but there is general acceptance that boundaries of academia and the non-academic sector are crossed, and new knowledge will emerge. It is also a process involving new perspectives from the outside that will question own disciplinary origins and perspectives.

There are other conceptualizations of the variation in the interdisciplinary approach, e.g., Klein defines a narrow and a broad interdisciplinary approach, where the narrow is characterized by a shared knowledge paradigm, while the broad is characterized by different knowledge paradigms, e.g., engineering versus humanities (Klein, 2006, 2010). However, even if it might be possible to distinguish between

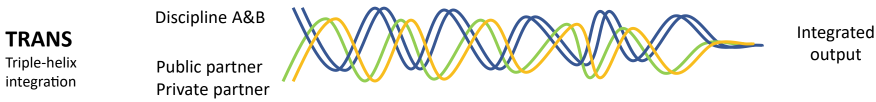

Fig. 7.3 Transdisciplinarity (based on Keestra & Menken, 2016)

multi, inter, and transdisciplinarity, in practice the concepts are used in abundance, and therefore, it is an advantage to regard interdisciplinarity as an overall concept embracing a scale from multi, narrow inter and broad inter to transdisciplinary approaches.

We have to be careful with the narrow disciplinary approach. Although engineers from, for example, electronics and mechanical engineering, might find it hard to work together in systems, they do share scientific and engineering practices and cross-cutting concepts. Scientific and engineering practices include, for example, defining problems, developing, and applying models, investigations, mathematical and computational thinking, etc., and there are cross-cutting examples like cause and effect, scales, systems, and system models, please see more in Chap. 2. There are also disciplinary-specific areas within the physical sciences, life sciences, earth and space sciences and engineering technologies (Council, 2012). The narrower interdisciplinary collaboration can be related to working on an innovation system, but we have to be careful that the technological systems are based on human and societal needs, which will involve a much broader interdisciplinary collaboration.

Interdisciplinary educational models will apply more attention to cross-cutting generic and meta-competencies to bridge the different disciplines. The generic competencies can be used across domains and disciplines, but these have to be combined with meta-competencies to capture the variation in the disciplinary approaches. There is a request, in particular, for interdisciplinary teamwork competencies in various types of projects, and as an example, learning generic competencies in an interdisciplinary team of law and engineering could also be applied in groups of social sciences, humanities, and engineering (Male, 2010; Male et al., 2011).

In education, there is a need for more attention to authentic problems to ensure that students learn methods for how to deal with complex, real-world problems, such as sustainability problems. Repko, Szostak, and Buchberger focus on interdisciplinary studies and emphasize that there are a series of characteristics or skills that we need to apply in interdisciplinary collaboration, such as an entrepreneurial mind (taking risks), a love of learning (excited to learn something new), self-reflection (self-awareness of strengths and weaknesses), intellectual courage (acceptance of, and respect for, other viewpoints), and patience and empathy (active listening) (Repko et al., 2019). All these characteristics are an extension of teamwork competencies in projects, but even more advanced, and they involve deep reflections and project skills as an extended part of the generic competencies.

The presence of these characteristics differs in different contexts. One moment, it is listening, and the next moment, it is having the courage to move across boundaries and take risks. The really difficult element is learning when we are doing the right thing, taking the context into account. Maybe it is not so difficult to learn to listen and to learn to act, but the hard part is decoding the situation and applying appropriate skills in a given moment. This is the art that experts can carry out, but which novices will have to learn in a more structured way (Dreyfus, 2004).

Similar abilities can be applied to intercultural collaboration as the individual will have to step outside their comfort zone to be able to understand another perspective like understanding variation of perceptions. Or it can be graduates going into work where they have boundaries to cross as they will meet new work cultures. Interdisciplinary collaboration is linked to academia, whereas the concept of boundary is a much broader concept and can be seen in relation to complexity, which is a philosophical concept, and to systems engineering, which is much more of an engineering and production approach. Regardless of the approach, there are knowledge domains and communities, organizations, and cultures, which are to work on common goals. Many scholars use the concept of boundaries to describe an increasingly heterogenic society, which has increased its focus on developing expertise (Akkerman & Bakker, 2011).

Boundaries of domains constitute what is regarded as expertise and what is not, as Lave and Wenger clearly describe in their concept of legitimate peripheral participation in communities (Lave & Wenger, 1991; Wenger, 1999). The technological development creates the need for more specializations, and thus, there will be an increased number of smaller expert communities but still with a need to reach out to other expert communities.

For all aspects, being able to work on boundaries seems to be a common competency—no matter whether we are talking about disciplines or cultures. Although it can be argued that boundaries will always represent analytical discourses for humans to be able to talk about, to negotiate and to create identities, boundaries will also be a connecting point. Boundaries do not mean that there is a strict black/white border, but that there is a sliding transition from one site to another or as a shared space (Leigh Star, 2010). Ecotones as a concept from biology could supplement the understanding of boundaries as an area with a mixed and merged zone in between two different domains. It could be the zone between a wood and a farmer's field, where the natural law for trees and woods is to spread the seeds to grow, while the grass field creates a counterpart by wanting to enlarge (Ryberg et al., 2021). Boundaries do not necessarily cause fights, but there might be tensions between different ways of understanding and contextualizing the same concept or action.

7.3 Transfer, Transformation, and Boundary Work

Boundary crossing, generic competencies, and interdisciplinary learning relate to the concept of transfer and/or transformation. Transfer is a complicated concept. The concept has multiple meanings, such as transfer from education to work or as a concept for learning. In many learning theories, learning transfer is a concept or metaphor meeting a lot of criticism from different angles. The concept signals that once things are learned, they can be transferred to other situations as replications. But if we only replicate, there will be no progress, so an understanding of transfer as replication is totally out of the question.

As introduced in Chap. 5, the social-constructivist theories emphasize that artifacts are created through the social interactions in a team. Each situation or context will be different depending on the individuals and the interactions in the group. Students can bring earlier experiences with them into a new situation, but they will never be able to replicate their learning in a new group; such a replication would have no meaning. But they can apply elements of their past experiences and knowledge and combine the learning elements to expand their learning and interaction with other group members. They can adjust and situate their knowledge and experiences together with the other members and learn how to apply their combined efforts in these new situations.

Compared to the understanding of replication, this is a significantly different approach as it is not enough to be aware of one's own competencies; it is also necessary to analyze and understand new situations. What are the purposes? What could be a beneficial organization? Who are the other group members? What are their expectations? Which of their experiences can the group benefit from?

Hager and Hodkinson (2009) argue against using the concept of '*"learning transfer" and think instead of learning as becoming within a transitional process of boundary crossing*' (p. 635) (Hager & Hodkinson, 2009). They argue that the concept of transfer itself signals a narrow and instrumental way of approaching learning, as has already been argued. But they also argue that the concept could misleadingly emphasize academic and educational knowledge in the transition from education to work without any considerations of the culture, interactions, organization, tasks, or visions applicable for work.

Meta-reflection and meta-competencies are necessary for the progression of learning and so that learners can apply knowledge from one area to the next. Learners can transfer some generic skills, e.g., how to handle phases in a project management process. This is a type of declarative knowledge. But each time learners are in a new situation; they will have to create a transformation process by appropriately adjusting experiences and knowledge to be recontextualized. They must learn to read the new project according to the new type of problem, the length of the project, and the composition of the team to go into a transformation process (see Fig. 7.4). The new team might be interdisciplinary or disciplinary, the collaboration with external partners might be new. Therefore, the way the students have learned to collaborate in project A will have to be reconstructed and transformed in the new project B.

For students to be able to transform their experiences into a new context, they need to learn to analyze the problem and the new situation. Reflection on previous experiences might not be enough as this very much concerns questions like: Did I collaborate right, or did I choose the right way to collaborate? What is needed to come from A to B and what have I learned? What possible collaboration strategies do I have? What possible methods do I know? To get to this level, there is a need not only to compare experiences from practice but also to compare and analyze experiences in relation to the theories.

Engeström points out that transfer and transformation take place from one activity system to another where transformation of meanings and activities takes place. The degree of variation and difference of these contexts or problems will influence the boundary crossing process and which competencies will be needed. Dohn et al. (2020) emphasize that from an activity system perspective, the goal of education (and of learning) is to facilitate students' capacities for transfer and transformation to support ill-structured and complex problems (Dohn et al., 2020).

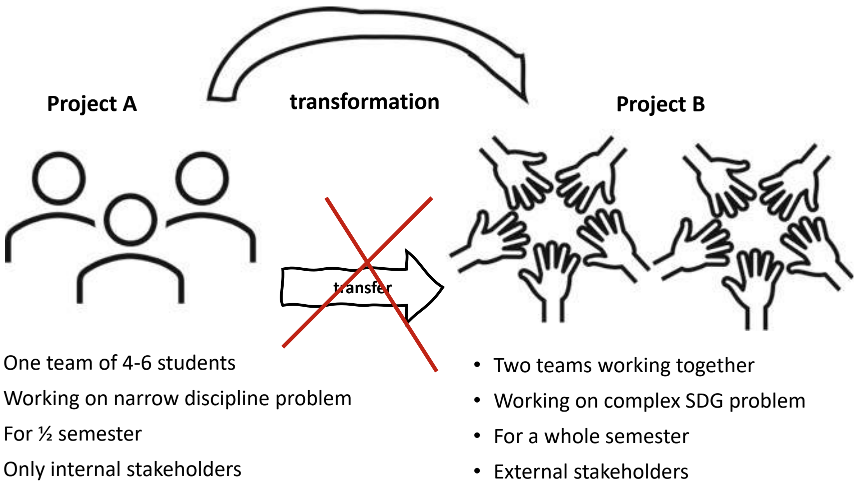

Fig. 7.4 Transfer and transformation

When learners reflect on their experiences and try to articulate these, they will never know when and where they will need these experiences again. Many different conditions will influence the need for prior experiences in new contexts: the need, the task, and the transition from idea to practice.

Carlile's work on boundaries in product development argues for three different ways of crossing boundaries: syntactic, semantic, and pragmatic, see Fig. 7.5 (Carlile, 2004).

The transfer level concerns the transfer of known and factual knowledge. When the problem and contexts are known, it will be relevant to apply transfer as a concept to understand the learning. It is types of declarative knowledge that can be memorized. For generic skills, it can be phases in specific management systems.

The translation level concerns translation between relatively new situations but still with recognizable elements for the problem and the context. Here, there is a focus on the language and understanding of the different team members. It makes a lot of sense to bring the translation level to generic competencies as students have to learn how to create dialogues of understanding instead of cheating oneself and each other by pretending they know.

The transformation level is a kind of pragmatic boundary crossing and concerns unknown problems and contexts in which knowledge is going to be developed. The concept of transformation indicates that it is not just to replicate existing knowledge but to adjust and understand how knowledge and experiences can be applied. Hager and Hodkinson (2009) are pointing out that transformation is a comprehensive process that includes not only awareness of what competencies the learning is bringing to a new situation but indeed the ability to understand new situations. This understanding of transformation aligns with the understanding of meta-competencies.

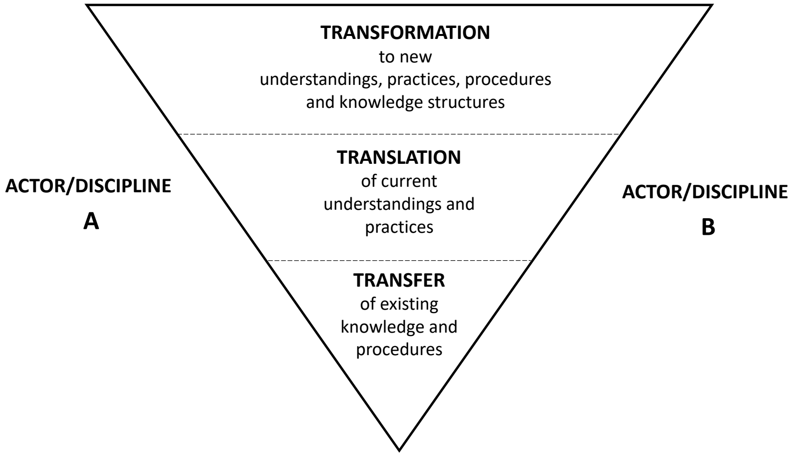

Fig. 7.5 Integrated/3-T framework for managing knowledge across boundaries, based on Carlile (2004)

Carlile also reminds us that boundaries are diverse and the competencies to work on boundaries will vary accordingly. With increased novelty and innovation, there will also be a need for increased interdisciplinary collaboration and a need not only learning to transfer, but to situate, construct, and innovate new technologies as well as human collaboration.

7.3.1 Boundary Objects and Brokers

Wenger defined boundary objects and boundary brokers (Wenger, 1999). A boundary object is the reification, the physical expression of common goals bridging diverse communities, and Leigh Star (2010) emphasizes that boundary objects can be characterized as being a material/organizational structure with scalability as a function that allows people from different communities to work together without it being necessary to have a consensus (Leigh Star, 2010). However, the work across communities must have a purpose or a problem as starting point; otherwise, it would make no sense to work together. Star also describes boundary objects as work arrangements that are at once material and processual, e.g., project management systems.

Brokers are the humans involved from various communities who are working on a common goal and making use of the boundary objects to communicate, see Fig. 7.6. But the function of brokers is to build relationships, facilitate knowledge sharing and progress in collaboration, and to bridge and link the communities (Long et al., 2013; Neal et al., 2021).

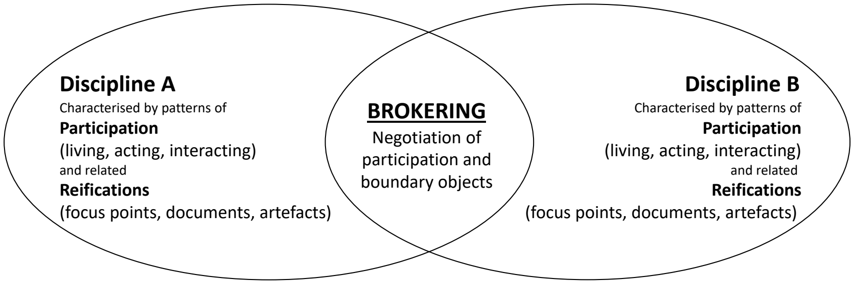

Fig. 7.6 Brokers and boundary objects in a community of practice (based on Wenger, 1999)

For example, for interdisciplinary teams, it will mean that the problem and project serve as a boundary object and the team members might need a period at the beginning where they create a common understanding of each other's perspectives. However, it is also the boundary object that will require negotiation among the team members. The negotiation concerns both the scientific approach and the structure of the process and the interpersonal aspects. For the brokers or the humans working on the boundaries, it is essential to be able to understand diverse perspectives. No matter whether the boundary is primary cultural or disciplinary, the openness and willingness to try to understand an opposite point of view will be essential. In this respect, meta-reflection is essential as it is not only a question of translation; it is a question of understanding other contexts to be able to grasp the meaning in a conversation.

This might not be an easy process, but students need to be exposed to the issues that they will most likely face later in their professional life and learn how to overcome diversity issues in the teams. Maybe the conflicts among team members are to be understood as disagreement in the problem-solving approach, but the individual learner might understand this as a personal conflict. If the latter is the situation, this learner will bring along a self-understanding of personal conflict strategies that might not be beneficial for scientific dispute. Therefore, reflection on, and articulation of, the experiences of both individuals and peers is required for progressing the development of generic competencies. Learning various strategies for negotiating and coping with disagreements is essential. Maybe we have to rethink the competencies the students need to learn along these lines to work as a negotiator and broker. For many years, we have talked about competencies for teamwork and collaboration, but when focusing on the process of becoming a negotiator, it becomes clearer that educators have to facilitate boundary work. Thereby, teachers can strengthen students' abilities to use and create boundary objects and work as brokers to connect to core stakeholders.

7.3.2 From Management to Leadership

In the same vein, learning project management in engineering education might not be enough, and it might be that we should move the bar to leadership. The principle of reformulating generic competencies to include meta-competencies also counts for leadership. During the last 20 years, there has been a trend of including both project management and leadership in the list of competency requirements (Boelt et al., 2022). Especially in light of the requirement of new competencies along with the increasing technological and societal complexity, engineers will face the need for more future-oriented and strategic thinking (see Chap. 2).

In the UNESCO report on SDGs in education, seven more general competencies are identified: systems thinking, anticipation, normative competencies, strategic competencies, collaboration, critical thinking, self-awareness, and integrated problem solving (UNESCO, 2017). The last four of these competencies have been highlighted for a long time and are all part of the formal accreditation systems in many countries. Also, systems thinking is mentioned in some of the accreditation criteria; however, anticipation as well as normative and strategic competencies are relatively new. For example, competencies of forecast and scenario building are often applied, e.g., in the environmental and sustainability fields. Scenarios for climate change are based on projection patterns relying on chosen variables and their relations.

Such general and generic competencies are also part of leadership and important for creating visions and strategic goals. Compared to management, leadership competencies are the competencies to align the organization, to set direction and to motivate employees, whereas management is the competency to plan, set up budgets, formulate subgoals, keep deadlines, organize the process and staff, and control the progression. The management part can be carried out primarily by competencies at the generic level, whereas leadership will primarily require meta-competencies in pointing out possibilities.

Leadership and project management are far more comprehensive than described here, but the point is that engineering students do need to experience these types of competencies in education in order to be prepared for work.

The scaling of projects from discipline projects to interdisciplinary projects in the curriculum (see Chap. 6) will allow students to experience the variation in project processes and project management. A single project in a course will not develop leadership competencies as this really requires a complex situation involving several disciplines and possible stakeholders.

7.4 Creating Learning Trajectories as a Lifelong Learning Strategy

Lifelong learning has been on the agenda for the last 30–40 years. In Europe, first it was a question of getting the formal education system to offer professional master educations part-time for employees. During the last ten years, this approach has to some degree changed to offering micro-credentials, which employees or learners can apply in different ways for their own competency development. Therefore, the focus has changed from getting institutions to offer educations to adults, to letting the responsibility for lifelong learning be an individual matter. Educational institutions then support individual learning pathways by making minor educational course credentials available.

Being able to create and handle individual learning trajectories can be seen as a new concept of lifelong learning. Learning trajectories are a much broader concept that is based on the concept of personal learning and have individual flexibilities in the creation of one's own competency development. Learning takes place in many situations and the individual learner must be able to advance learning based on work in different networks and groups in both formal and informal settings. The individual must be able to develop their own professional and organizational competencies, both to assimilate knowledge to existing frameworks and to accumulate, transfer or transform learning from one context to another, and from one conceptual understanding to a new one. Accumulating, transferring, and transforming knowledge and practices are also about being able to choose strategies, methods, and techniques for specific situations.

Therefore, the awareness of learning and of the progression and combination of generic competencies—both individually and in teams—will be a core in future engineering competencies, and it should be addressed in education. Besides, this is also what companies are asking for.

Both the variation theory and Vygotsky's zone of proximal development theory point to the fact that the learner remains within prior developed schema's for learning, if there is nothing new in the learning situations (Vygotsky, 1978). There needs to be a balance between what is known and the challenge of the unknown. If the learner only meets totally new unknown challenges and has no experiences, it will be too difficult to solve the task and then frustration arises, and motivation might decrease proportionally. It would be like asking an English language student to develop a piece of software or write an essay in French. Both tasks would present totally unknown languages to the student, although there might be more transferable knowledge in the French language case than in the software case.

The same applies to the transfer and transformation of generic competencies. If an engineering student has never applied or gained knowledge of methods for user involvement, there is nothing they can transform to a new situation. But as soon as the learner has had their first experience with how to interview actors and methods of user involvement, there is a potential for developing these competencies by transformation from one project to another. Similarly, there is potential for the development of, for example, team skills and project management skills.

However, it is not only a matter of ensuring progression of practice experiences. The new trend of offering digital micro-credentials is in line with the digitalization agenda and the notion that university degree programs should become more flexible. Perhaps in this policy shift, the learner has been forgotten. Perhaps there has been too much focus on developing knowledge resources without considering their integration in various learning paths. It is however the individual learner, who participates in different communities or projects, who are to select and combine available micro-credentials to create his or her own learning trajectory.

Also, in cases in companies where engineers participate in project after project, there is a requirement to create progress in capacity building. But if the learner or the team has had a tacit or non-articulated collaboration, how can the individual then develop his or her understanding and competencies based on this collaboration?

It is a core aspect of learning to create individual transfer or transformation of individual competencies achieved in a team by understanding the task, understanding the individuals and their competencies, having the knowledge of how to design work processes aligned to the task, and being able to reflect and negotiate during the process.

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Chapter 8
Educational Transformation

8.1 Introduction

What we have been addressing in the previous chapters is more fundamental change in engineering education from a disciplinary to an interdisciplinary learning discourse by applying a series of boundary objects for students to learn to cross-disciplinary boundaries. We have also argued that boundary crossing embraces sets of generic and meta-competencies, which can be learned in one context but transformed into a new context. We have illustrated via concepts and will supplement by examples (see part 3) what this could look like in engineering education.

But what we have not touched upon is the following question: What does it take to transform existing practices to meet these new ideas? This question is especially relevant, as this is not about adding an extra course to an already heterogeneous and overloaded curriculum, and this is a not a question of faculties learning some extra tools. It is much more fundamental, as we need faculty to facilitate students' learning processes both within and across boundaries, and we therefore need a cultural transformation among academic staff.

Most educational researchers or educational change agents who really have visions and ambitions to drive engineering education into a new era have experienced barriers and mistrust among engineering colleagues. *Is this really necessary? Is this not what we are already doing? How can engineers learn fundamentals in projects? Would digital learning result in a superficial learning?* These are just some of the questions asked and statements formulated.

The previous chapters argue for more student-centered and active learning approaches combined with a broader contextualized and sustainable approach to student competencies. The student-centered approach has been on the agenda for several decades, and experience clearly indicates how difficult academic change is. Reviews of the implementation of problem- and project-based learning (PBL) in engineering education clearly show that PBL is applied within the discipline/course structure and less in interdisciplinary relations across disciplines or courses (Chen et al., 2021). Experiences also indicate that this has not been a process of speedy

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change; on the contrary, the need for more student-centered learning has been on the agenda for the last 25 years, supported by accreditation criteria for more outcome-based education and the need for professional competencies, such as teamwork and project management. (Hadgraft & Kolmos, 2020).

Comparing the change process of student-centered learning to the recent application of digitalization in teaching and learning, there is a significant difference. Kotter (1995) defined eight phases of organizational change, of which the first was the lack of urgency for change. Following that reasoning, the COVID-19 situation has created urgency, and what had not been possible to accomplish with respect to the use of digital means before was now implemented overnight. The education system was in shock, and very soon, both Teams, Zoom, and other systems were developed further to support classroom learning.

This fast change gave some experience; however, the experience of spring 2020 really needed to be reflected upon and developed further, and number of studies has grown rapidly in the last two years (Adedoyin & Soykan, 2020). For many teachers without experience in applying digital means in teaching, the most natural thing to do was to lecture in Teams or Zoom, which is not the optimal use of these systems. It takes time to identify the advantages in a blended learning system; however, there are experiences to build on. With respect to how this will impact education systems in the future, we still have to wait and see, but it will never go back to what it was before COVID-19, as there will be the footprints of COVID-19 at all levels, from the individual university teacher to the political level.

The political level has responded to the digital change in lifelong learning. Micro-credentials, as shorter digitalized units offering formal credits, are emphasized as part of a flexibility strategy and focus on lifelong learning, and this represents a shift in view of lifelong learning to a personal learning track, replacing or enhancing more formal education (Resei et al., 2019). During the pandemic, this has been further enforced, but it will not be without consequences for curricular coherence (Wheelahan & Moodie, 2021). However, there is still a need for offering minor units in formats as micro-credentials, which, as digital learning, also has the advantage of being able to reach out to a much broader group of people across national and cultural borders. Thus, higher education has new ways for both reaching out to companies and their continuing learning but also internally in applying online courses from other universities.

Digital transformation has changed the landscape of engineering education and is having a profound impact on engineering methodologies and how engineering is taught and learned. Some of the ways digital transformation is impacting engineering technologies, such as simulations, and others are related to methods and processes.

Simulations: Digital simulations are becoming increasingly common in engineering education, enabling students to conduct experiments and simulations in a virtual environment. This allows students to gain hands-on experience in a safe and controlled environment, without the need for expensive equipment or specialized facilities.

Online Learning: This method had been well discussed. Digital transformation had enabled the growth of online learning. Online learning allows students to access course materials and lectures at their own pace and on their own schedule, making it easier for students to balance their studies with other commitments.

Collaborative Tools: Digital tools are making it easier for students to collaborate on engineering projects, both with their peers and with professionals in the industry. This enables students to gain a deeper understanding of engineering practices and to develop real-world skills.

Access to Resources: Digital transformation has made it easier for students to access a wide range of resources, including online journals, databases, and research papers. This enables students to stay up to date with the latest developments in engineering and to conduct research on their own.

Digital technologies in content and methods became foundational for several aspects of education and created mindsets. When we include AI to the mix of digital technologies, we realize that the digital transformation is not complete yet, and more changes are heading our way. The importance of AI and its impact had been discussed in Chap. 5.

From practice point of view, we find that different universities have different approaches to utilizing digital technologies and examples of these will be discussed in Part III of this book.

Digitalization raises new needs and offers new opportunities. The new needs are to activate students behind their screens and create supportive learning environments to overcome the lack of a physical learning environment. For this, PBL and other forms of active learning can be of great value, and new opportunities are given to develop engineering education to embrace complex problem analysis and problem solving in an international and blended mode.

Urgency is one of the significant differences between student-centered learning and digitalization. Even if it can be argued that PBL and other active learning methodologies are needed, there has been no explicit urgency related to PBL. There has been a societal call for more employability, relevant competencies and, in particular, for students to learn to apply their academic knowledge. It has never felt as dramatic as during the life-threatening pandemic situation, which hopefully the world will not experience again, but we need to look into how to motivate faculty and lead educational change. Climate change is life-threatening, but it is not experienced as being as dangerous as the pandemic situation in daily life; however, there is an urgency to find ways to motivate educational change in order to embrace complexity and the development of competencies and knowledge to deal with the SDGs.

In this chapter, we present new viewpoints on faculty motivation and educational leadership. We take three university modes embracing ideal types of academic knowledge perspectives and societal values as the point of departure (Jamison et al., 2014). These modes frame types of curriculum changes, the necessity of educational leadership, and pedagogical development among faculty as shown in Table 8.1.

Table 8.1 Three university modes and strategies

University modes and mindset	Academic mode theory driven	Market-driven mode Innovation driven	Hybrid mode broader society driven
Curriculum changes	Add-on strategy Small changes to existing curriculum structure, e.g., new electives	Integration strategy Integration into existing courses and high degree of coordination	Rebuilding strategy Crossing disciplines with a high degree of coordination and involvement of external stakeholders
Educational leadership	Protection and response to external requirements	Network and facilitation of company–university interaction	Vision and strategic development required Facilitation of boundary crossing for internal disciplines and for university-companies-societies
Educational development	Focus on the individual, aiming to educate an effective teacher	Focus on the individual and institutional level, aiming to educate a skilled and collegial teacher	Focus on the individual and institutional levels beyond existing disciplines and aiming to create collaborative communities

8.2 University Modes and Faculty Motivation

The driver for becoming academic staff/faculty at a university is mostly the urge to dig deep into a problem or subject. It is the knowledge-driven desire which is basic. However, there is not one category of academic knowledge which can cover a content-based motivation; this will depend on the knowledge mode, values, the embedded mindset, and the perception of what engineering is. Faculty development has focused on the learning and teaching methodologies and has hardly addressed the content, which might be one of the reasons for hesitation among faculty (Fig. 8.1).

Jamison et al. (2014) defined three knowledge modes: the academic, the market-driven, and the hybrid learning mode. These modes frame the SDGs, system, and design approaches combined with societal and human values. The academic mode is oriented to theory and to learning the fundamentals—the basic sciences—like mathematics and physics. In the European tradition, the first years of study are dominated by theoretical courses.

Of course, an engineer needs to know mathematics and physics, but there is still the question of scope and its relation to other disciplines, which will suggest to students that engineering is more than the application of scientific theory, which is the widespread assumption reflected broadly in the literature (Arthur, 2009). The consequence for the engineering curriculum is most often that students need to learn basic science and to understand the theoretical foundation of engineering before

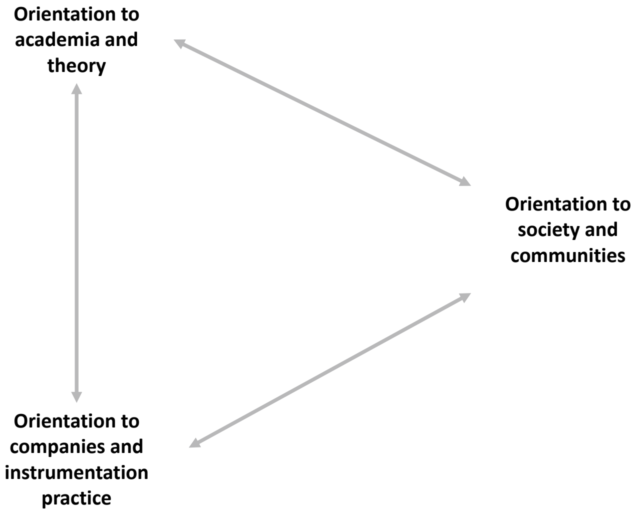

Fig. 8.1 University views

going into any application or problem-solving process. This is a sequential or hierarchical organization of knowledge—it is necessary to first understand theory before understanding context or practice.

In the book *Nature of Technology*, Brian Arthur gives new perspectives on technology and thereby engineering (Arthur, 2009). He finds that much of technology's evolution is based on a new combination of already-known technologies. Arthur argues that it is not only technology that uses science to evolve; the development of science is also dependent on technology, e.g., the steam engine came before thermodynamics. This approach determines the interdependence of science and technology and also that there exists an interactive process between science and engineering—you need to understand the underlying principles and also the problems with the existing technology practices. This is a much more interactive learning process, in which practice can lead to understanding the need for theory and vice versa.

The market-driven mode takes problems and issues in companies as its point of departure and is a much more a pragmatic mode oriented toward industry and a systems approach. Whereas the academic mode can settle for knowledge, industry aims for products and combinations of technology and knowledge. It involves systems and design processes, and graduates should be ready for working in industry and be able to understand business models as systems and boundaries for their work. There are expectations regarding collaboration in various teams and the ability to communicate with various groups, from laymen to experts. Contrary to the academic paradigm, the underlying value is much more that it should work and that there is a sufficient economic bottom line. It can be argued from an academic point of view that this approach is too instrumental, as it only tries to satisfy current needs; however, it comes as no surprise that this is the condition for companies.

In engineering education, there are tensions between the two approaches within programs and among disciplines. Some engineering programs seem to be more oriented to companies, like mechanical engineering, civil engineering, and production, whereas other programs like biotechnology and energy, are typically more oriented to theoretical knowledge (Routhe et al., 2021). There are, however, a few disciplines which do not develop quickly, but most engineering disciplines are continuously developing, e.g., with energy, the thermodynamics is the same, but the construction of the wind turbines will change, and the implementation of wind turbines will require a systems approach. If we look at biotechnology, the foundation will be there, but now big data can lead to new insights.

Engineering can be understood as being bound to two poles: On the one side, there is the theoretical scientific understanding, and on the other side, the more pragmatic approach. Engineering is not a case of either/or but both/and, and engineering education will have to embrace both dimensions. Engineering students should learn to be in both modes; it does not make sense to run academic and theoretical programs exclusively or, on the other hand, only programs on the application of technology. It is critical to understand both the technology and the underlying mechanism in, e.g., software algorithms, design methods, or complex problem identification and solving.

The hybrid learning mode is the third mode with an orientation toward society, emphasizing competencies, cultural awareness, sustainability, professional identities, and citizenship, which are very much the same as the ideal formulated in the first parts of this book and which are facilitated by student-centered, collaborative, and situated learning in a variety of projects. This book points in this direction where engineers have diverse understandings of engineering and can move between academic and market-driven modes and bring this to a societal and community context, with an understanding of variation and hybridization.

The hybrid learning mode is based on a combination of the academic and the market-driven modes and represents a much more value-driven and critical approach. It involves a perception of engineering as system and design processes involving a stakeholder perspective and the process of bridging theory and practice. In engineering education, students will need to learn how to design using problem identification, identification of needed disciplines, and technology development frameworks. It is also a value-driven mode in the sense that the sustainability and the SDG agenda will constitute the underlying values. The SDGs comprehend the north/south dimension, which addresses the unequal distribution of wealth in the world along with a lot of other dimensions. The development and application of technology are therefore seen in a much broader societal perspective, creating a vision and an ideal of a better world, to which engineers can contribute. Taking the great powers into consideration, and all the conflicts and potential wars, this might seem like a naive mindset; however, even the most powerful actors need strategies for climate change and stable markets. No matter the political standpoint, there is a common interest in addressing the SDGs for future global development. The sustainability mindset does exist among most academics and the academic development should focus on ways to address sustainability in the teaching and learning practices.

8.3 Curriculum Change Strategies

Curriculum strategies will depend on national policies, and there are systems in which the curriculum is coordinated at a central government level, even for higher education (Kolmos et al., 2016). This leaves minimal space for any change, and this is not what we are thinking of; on the contrary, we think of curricula which are run by institutions under consideration of accreditation criteria. Most institutions do have elements of all modes in their curricula, but they might not be integrated, or a strategy might not be implemented as a result of the academic staff's influence on the curriculum from a bottom-up perspective. At the ideal level, however, the various curriculum strategies would include a balanced mix of modes.

In recent years, more and more universities have declared themselves as mission-driven universities. This can be an institutional response to the SDG challenges and other grand challenges. In Europe, it is also a response to the EU research programs, which are mission driven (Mazzucato, 2018) and in line with notions of an ecological university, which has a north/south collaboration based on sustainability values (Barnett, 2011). This provides a direction for change for universities, a path on which many institutions already have taken the initial steps. However, the declared mission-driven universities will be facing ethical dilemmas with a new period of cold war. Arguments such as defending democratic values together with equity in society might be added to the pamphlet of sustainability actions.

Most universities are chiefly in the academic mode, where the curriculum normally consists of several courses or modules. Some of these courses are obligatory, and some are electives, which give the students the chance to create their own specialization throughout the curriculum. For the academic mode, as an ideal category, the *add-on strategy* is the most widespread. If there are new requirements for the curriculum, such as team skills, the normal procedure will be to establish a new course elective, so the students have the possibility to participate. This is an individual approach, as different kinds of electives can be combined according to how the individual learner creates their learning trajectory. The disadvantage is that it will also be the learner who must create the coherence among the curriculum modules, which is not always so easy. There might be design courses with interdisciplinary collaboration, but these are more single glue elements in a predominantly modular system.

For the teaching and learning methodologies, there has been significant incorporation of active learning methodologies. But, again, these changes mostly happen within the modules or courses and not normally as a comprehensive institutional strategy. This is reflected in the extensive reporting on PBL and active learning experiments in the literature at the course level (Chen et al., 2021). As the learning activities do not cross existing subject boundaries, the problems that students face are most often academic problems within disciplines. These will be predesigned by the faculty. This strategy will work for individual academics, as it necessitates only small changes to the curriculum. If there is a requirement for interdisciplinary competencies, it will be captured by establishing some interdisciplinary courses.

The two other strategies require a systemic approach with a high level of coordination at the system level and educational leadership. The *integration strategy* can be exemplified by the conceive-design-implement-operate (CDIO) community. CDIO contains a long list of standards covering the system level, including quality assurance and academic development, the integration of skills and competencies into the curriculum and, at a minimum, the integration of real-life projects—mostly company projects—where students learn to conceive, design, implement, and operate within the framing of the engineering profession (Crawley et al., 2014; Edström & Kolmos, 2014).

The *rebuilding of curricula* concerns a restructuring of the entire institution by establishing a new program. The rebuilding strategy emphasizes the societal context and involves restructuring courses, allowing for all types of active learning, including more open-ended projects. Progression through an entire program involves an emphasis on both technical knowledge and competencies and professional or employability competencies. Such a change will require strong institutional support from the highest level of the university and educational leadership that is able to facilitate a collective institutional vision and motivation for change. Academic development will concern not only the individual but also a high degree of collaboration across disciplinary boundaries. There will be a need for scholarly teachers who can think outside of traditional boundaries and facilitate transformation processes.

Both the integration and the rebuilding strategy will require strong educational leadership, which will have to be adapted to the actual curriculum. There will be differences in the specific activities depending on the characteristics of the performing curriculum. Basically, there are three different starting points for transformation in curricula:

- No or minor experience with cross-disciplinary curricula and generic competencies, meaning that a few teachers may have experimented with new teaching and learning methods. These activities are under the radar of top management.
- Sporadic experience with cross-disciplinary curricula and generic competencies at the course level and with positive feedback from top management.
- Systemic experience with cross-disciplinary curricula at a department, program, or institutional level and, of course, with support from top management but still with the need for further development.

These three types of experiences with more student-centered learning require different types of activities. In the first, institutions will need to create experiences and trust for these new ways of teaching and learning, and there is a need for educating the faculty. The education or 'training' needs to be contextualized and rooted in a broad disciplinary domain, with possibilities to plan and run experiments in practice. Academics need to experience and trust new ways of teaching and learning. If it is a first meeting with, for example, team-based project work, it takes time to understand that these new practices can lead to both deep disciplinary learning as well as to a broad understanding of societal problems.

For the second category with some experience, institutions will have some academic staff with experience and possibly an understanding of how to create variation in the student-centered learning methodologies; there will, however, also be a group without experience. This stage is normally a result of a longer period in which the management has encouraged academic staff to experiment with their teaching, and it is has slowly spread to more and more courses. However, there is no overview of what kind of learning methodologies are used, and thus there is no clear progression throughout the curriculum. The need for these types of institutions is much more to map existing practices and create an overview of possible progression both for generic competencies and for disciplinary knowledge. Institutional strategies can then be created to support new cross-disciplinary competencies within the curriculum.

For the third category, institutions do practice PBL at a systemic level, involving both an overview of learning methodologies and progression. However, no matter the degree of implementation at a systemic level, there is always the danger that institutions are stiffening the boundaries. For these types of institutions, there is a need for exchanging, evaluating, and proceeding. It might seem hard to initiate further change in this type of institution compared to those with less experience. On the other hand, it is extremely important that institutions do continuous development of all educations, not only in terms of minor adjustments, but indeed to facilitate more basic paradigm shifts.

No matter the curriculum strategy, there is a need for educational leadership which is more than the management of daily operations and facilitation of both top-down and bottom-up approaches, which are most efficient in combination.

8.4 Educational Leadership

In a conversation on educational leadership with a colleague, the following was said: '*Things have changed. When I was head of the department 15 years ago, I was seen as the voice of the employees, my colleagues. But now I am seen as an instrument and mediator for the top management. That makes me sad, as this does not align with my idea of leadership.*'

There is no doubt that in a change process, there is a need for both top-down and bottom-up processes, and to achieve educational change, there is a need for leadership. However, this quotation shows that it is a question of balance and being able to navigate on the edge of two directions, especially concerning educational change. There might be limited motivation among academic staff if they are told what to do. On the other hand, there might be lack of direction if there is no overall vision and plan. Visions and missions might create motivation.

Educational change must take place at the institutional level and will involve a shift in culture and understanding of learning among academic staff. Change in engineering education is often slow, and strategies should be applied to foster more rapid change. As culture plays an important role in the change process, a more experimental approach to teaching and learning is needed to create new, innovative learning environments. For that purpose, recognition of educational leadership, educational development, and academic staff development is needed, but it needs to be seen as leadership allowing bottom-up changes. Academics are, for the most part, demotivated by being told what to do and the 'art' of leadership involves both facilitating and supporting these experiments as well as engaging academics in creating a common vision (Drew, 2010).

Ruth Graham has pointed to the need for educational leadership as one of the essential elements in educational change (Graham, 2012, 2018b). National initiatives to reform engineering education have been seen in many countries, which frame the institutions' directions for developing higher education. One example of national initiatives is a case from Chile, with a national top-down-driven change. Engineering education reform in Chile during the last ten years represents a change in the educational landscape, which has been transformed almost entirely from a lecture-based engineering curriculum to widespread university engagement with educational change. There have been two government interventions in higher education—*MECESUP* and *Engineering 2030,* from the Ministries of Education and Finance—for ambitious, systemic educational change across the country. The reform has argued for a national investment in technology innovation as a vehicle for economic growth, strong leadership from influential engineering schools across the country, and best practices from across the world. Strong leadership from both the government and key university leaders has motivated change; however, it remains to create a higher level of academic staff motivation for change, essential for change in the engineering classroom. With this reform, Chile has positioned itself as a leading nation for engineering education in the decades to come. The elements in the change cover the emergence of systemic change, problem- and project-based learning, technology-driven entrepreneurship and innovation, collaboration with industry, service learning, engineering design, and new working spaces for entrepreneurship and innovation. This government initiative is described in the report '*Snapshot review of engineering education reform in Chile*' (Graham, 2017).

At the institutional level, elements such as vision, skills, incentives, resources, and action plans are necessary to create cultural change in higher education (Knoster et al., 2000). All these elements will require leadership, management, and the learning of new curriculum possibilities among academic staff. These organizational functions are present in most universities in the form of top management pointing out directions, program leaders managing daily activities, and an educational development unit offering courses to young academic staff. Nonetheless, there might not be a will or wish to change, maybe there is a lack of resources to change or there is a missing sense of urgency to move academia toward more mission- and challenge-driven universities.

A lot of curriculum changes have occurred because of existing academic staff who try out new teaching and learning methodologies that prove successful. The reporting on cases of active learning in the classroom is overwhelming in the conference literature and has also dominated the engineering education journals since the 1990s. These are the bottom-up initiatives, and research also indicates that successful leaders, who have managed to change a curriculum, normally have experimented several times in the classroom either before becoming a leader or as leader.

In the literature, we rarely hear about the failures, which is a shame, as it would make a space for sharing and conceptualizing the risks in any educational change process. It might be risky to change, and there is a lot at stake, as students need a guarantee that they will get a qualified degree. Many private universities are hesitant, as students and their parents are consumers. At many public universities, the funding is limited. Furthermore, accreditation systems can be both a barrier and a facilitator of change depending on national criteria and cultures. There is no recipe for reshaping and changing engineering education, and there is not one method which can be used everywhere. But what is common is that there is a need for leadership and an educational leadership system.

International university governance systems are quite different, as there are systems with government-appointed leaders, institutional-appointed leaders, and systems with elected leaders. There are advantages and disadvantages for all of these governance systems; however, educational leadership is mostly appointed at a lower level in the organization, and it is rare to see—if it exists at all—formal qualification criteria by virtue of formal education other than the disciplinary knowledge in the field. The most normal pattern is that the roles of educational leaders, such as vice-deans, department leaders, and study program leaders, are carried out by academics who have an interest in the field and might be interested in new innovations in education.

The mindset embedded in the three modes can therefore also characterize how leaders are thinking and what kind of visions and ideas they will have. For example, educational leadership within the academic mode will be to keep the changes within the existing structures, and the most dominant task will be to respond to external requirements, like accreditation, external boards, and managing the budget. All these activities are essentially management tasks related to running the daily operations of education. Pedagogical training will be seen more as an individual endeavor than as a collective responsibility, as each professor will be running their own courses, and there will be a need for training the most efficient teachers.

Educational leadership for the market-driven mode will involve more than the management of daily operations. There will be a need for networking with companies or other external stakeholders, facilitating faculty running student projects with companies, cross-course activities among academic staff, etc.

The same is the case for the integrated hybrid mode but with the very fundamental difference that visions and goals are focal points in terms of setting direction and motivating cross-disciplinary or cross-course activities. This is basically a leader who can facilitate bottom-up processes, recognize existing competencies, motivate collaboration among colleagues, reaching out to different communities and strategically create an overview of the curriculum. Faculty development will focus on both the individual courses and coherence in the curriculum and will aim to train a skilled and collaborative teacher.

There is therefore a need to develop educational leadership to create and sustain the required educational changes, combined with development of academic staff to apply more student-centered and innovative teaching and learning methods. There is also a need to establish both top-down and bottom-up strategies. This means that teachers should be actively involved in experimenting with their teaching and should make changes from the bottom of the organization while leaders support the changes from the top. Just practicing a top-down approach by telling academics what to do will typically not work; on the other hand, leaving staff to develop their teaching will result in a lack of coordination in the system. It is therefore advisable to implement strategies to coordinate and at the same time make room for experimentation.

An interesting review of educational leadership in higher education from 1985 to 2005 illustrates the important qualities for effective educational leaders. Even if the reporting is based on 20–35 years old data, these qualities are general competencies which will count no matter when and they add a personal dimension to the acknowledgment of university leaders, as shown in Table 8.2 (Bryman, 2007, 2013).

The vision and directions are basics in the qualifications along with ability to influence, communicate and recognize employees' efforts. The vision and direction together with the external recognition are embedded in the leadership role, and the same can partly be valid for influence and communication, which can be learned by using techniques. However, the personal qualifications as integrity and respect

Table 8.2 Educational leadership competencies (Bryman, 2007, 2013)

Vision and direction	• Clear sense of direction/strategic vision • Preparing departmental arrangements to facilitate the direction set
Integrity and respect	• Being considerate • Treating academic staff fairly and with integrity • Being trustworthy and having personal integrity • Acting as a role model/having credibility
Influence and communication	• Allowing the opportunity to participate in key decisions/encouraging open communication • Communicating well about the direction in which the department is going • Creating a positive/collegial work atmosphere in the department
Recognition	• Advancing the department's cause with respect to constituencies internal and external to the university and being proactive in doing so • Providing resources for and adjusting workloads to stimulate scholarship and research • Making academic appointments that enhance the department's reputation

go beyond how leaders fulfill their role and these qualifications might be hard to learn in any course on leadership. Integrity and respect are to be earned in a culture. Often successful leaders, who are acting as change agents and initiating change, have tried several times to create change and they might have background experience with failing or creating partial successes.

Educational leadership also includes the promotion systems of universities. Internal promotion systems at universities focus predominantly on research evaluated by the number of journal articles, impact factors, and the amount of external funding. Teaching qualifications come second (Graham, 2015). In Scandinavian countries, academic staff development in university pedagogy is mandatory, and pedagogical qualifications are a prerequisite to obtain promotion. However, mandatory pedagogy training does not impact or change the fact that the promotion system is oriented toward research criteria. Different initiatives have emerged worldwide to apply a new framework for promotion that acknowledges teaching qualifications at various levels, ranging from being an active teacher to becoming a national and global leader of education.

Pedagogical training, voluntary as well as mandatory, the formulation and integration of a framework for the development of teacher qualifications, and the development of reward/award systems are some of the instruments employed for motivating academic staff to change; they are thus also important tools in educational leadership (Graham, 2018a). Training for academic staff development can be organized in many ways, including as compulsory and voluntary courses offered by institutions or national organizations.

In many countries, there has been both a shift in phrasing the related activities, ranging from academic staff development to educational development and a shift in the foci of the activities (Gibbs, 2013). However, no matter which concepts are used, training is an important part of educational transition as we teach as we have been taught, and there is a need for creating new experiences, such as student-centered learning and education for sustainable development (Barth & Rieckmann, 2012).

8.5 Educational Development

No matter which mode or modes institutions represent, there is an overarching trend toward digitalization and internationalization. International collaboration concerning curricula has been enhanced by the realized possibilities via digital and blended learning, as there is the possibility to establish cross-institutional courses or projects. In Europe, the EU facilitates the establishment of cross-national and institutional consortia, where the future of higher education is seen as a combination of elements from different universities. This can be developed in various modes but foremost as new digital educational courses across institutions. The logic is obvious: Why should each institution run their own courses, e.g., in thermodynamics, when the same learning objectives exist?

These trends, which regard the ‘universities as partners,’ will set a new scene for pedagogical training and teaching. The individual ‘ownership’ of courses might in the future be a much more cross-institutional matter than a national and institutional one. We are looking into the future landscape of engineering education, which will be very different from what we have known during the last 40 years, where change has taken place at the institutional or single course level. No matter which mode institutions compare themselves to, these changes will happen. In an academic mode, it will be within the academic disciplines, there will be cross-institutional collaboration, and in the market-driven mode, cross-national, cross-institutional, and cross-sector collaboration will be added. To the integrative mode, sustainability and a north/south collaboration will be emphasized.

Pedagogical training might be framed in new ways. The individual pedagogical dimension based on knowledge and development experiences from practice will still exist, but it will no longer be sufficient, as there is also an increasing need for collaboration across boundaries, such as cultures, languages, disciplines, systems, formats. Furthermore, a more student-centered learning approach will include new ways of teaching as lecturing will decrease along with an increase in facilitation and supervision skills.

Therefore, pedagogical training has to address these new formats and be exemplary in the way we are teaching students. The collaborative element, which characterizes many new learning innovations, ought to characterize the training in terms of collaboration within the disciplines, across the disciplines, and not least across institutions and national boundaries. Even the organizers of pedagogical development should team up and create learning communities which represent the teaching environments.

Change will include a change of cultural behavior if it involves cross-disciplinary teaching or cross-institutional development of new programs and courses. Furthermore, it will involve not only a change in teaching and learning practices but indeed in the organizational development of the universities. Stensaker (2018) makes the point that with organizational development at universities, academic development should be seen as cultural work, which will both develop and disrupt the organization and create new emerging practices and knowledge. Over the last 20 years, the balance between academic researchers and administration has reached a new distribution at the universities, and a third space has developed with the increase in administrative personnel. Therefore, the internal organizational tensions between different university actors not only concern tensions between disciplines but indeed also tensions between academics and administrative staff in a third space (Whitchurch, 2012). The combination of academics and administrative staff contributes to establishing new local cultures for teaching and learning, e.g., for areas such as career development or professional competencies, like communication with companies or teamwork skills. This has been a trend for the last two decades and creates tensions in the organization concerning research-based teaching along with the learning of professional competencies as an integrated part of the discipline or as an add-on, which the students have to relate to and integrate by themselves.

Academic development in both content and form is challenging and will have to meet new trends. It will operate in a landscape of internal tensions at the universities and the emerging internationalization of education, which adds to the complexity of the future development of engineering programs. Of course, it raises the question if academic development in the future will be a question of supporting strategic leadership more than supporting academic teachers? If academic development tips over to the side of management and administration, it might be even harder to motivate academics to drive or to participate in educational change processes. Thereby, there is a need for visible leadership to furnish the overall directions for competency development.

Educational development is a cultural process, as it concerns the teaching practices and students' learning practices (Bali & Caines, 2018). Teachers are principally influenced by the way they have been taught. That is an embedded cultural behavior that we know how we learned, and we act accordingly even if this is not always with a level of awareness. Teaching together with a teacher from India will imply knowledge of the different systems; if the teaching involves lecturing, this might not be very different as regards the structure of the content, but in terms of facilitating students' learning, it might be very different depending on the teaching and learning culture.

The development of teaching and learning cultures is a core element in educational development and facilitating the development of culture is part of leadership. Bali and Caines (2018) call for ownership, equity, and agency via connected learning in academic development, as dialogue and reflection on beliefs and values with others is a core element in transformative learning. This can be facilitated by professional learning communities (PLCs) consisting of a group of practitioners with the purpose of reflecting on and developing educational practices. PLCs will be most efficient when there are shared values and visions, collective responsibility, reflective professional inquiry, collaboration, and when collaborative as well as individual learning is promoted (Stoll et al., 2006). This type of organization can be cross-disciplinary, cross-institutional, or within single disciplines—all as long as there is a shared purpose and practice and that it can be facilitated by social media (Luo et al., 2020). There are other methods of creating collaborative educational cultures, such as peer tutoring and peer teaching, co-construction of curricula, interdisciplinary programs. (Falchikov, 2003).

Educational development can be regarded as transformative learning with a focus on how academic staff are understanding themselves as teachers and researchers, how they have learned, how they value learning, and how they practice in the classroom. An important part of learning is to critically reflect on the frame of reference, which consists of the basic values and beliefs of the practice and trying out alternatives (Mezirow & Taylor, 2009). As we initially stated in this chapter, beliefs and values might be very diverse, and the three university modes might be one way of capturing the variation. Academics are, by education, raised with the embedded logics within their disciplines, which also impact their identity and values. If an acoustic engineer enters a room, she or he will automatically look at the ceiling first just as a psychologist will be watching the people first of all. If you have knowledge of the application of sustainable materials, you will see them in buildings and the environment. Therefore, the educational change is complicated as it involves the values and identities among academics.

In the coming chapters, there are cases from the authors' three universities. In the case from UTS, it is obvious how it started out with resistance and although slowly the studio thinking has merged into the curriculum as a natural part. This process has taken years, and part of this process is to build up academics' trust in new learning systems. But no matter all the difficulties, resistance, and systemic barriers, it can be done in iterations like at UTS and Harvard or in founding new programs or institutions with new mindsets from the outset like in the Aalborg University case.

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Part III
Case Studies

Introduction to Chaps. 9, 10, and 11

Three Cases—Three Different Ways of Responding to the Challenges to Develop New Mindsets

The authors of this book come from quite different experiences in three different universities, in three parts of the world, with three different educational policy systems, and three different learning cultures. Indeed, these institutions should be understood as ecosystems, with multiple factors, which are infused into each other, together forming special patterns of interaction.

For each university ecosystem, there is uniqueness, such as enrollment processes for students, learning traditions, or possibilities for interactions with companies. An ecosystem and its relations are constructed by involved factors, and there will always be developments, as the factors will not remain stable but will develop over time. To change a university ecosystem deliberately, several factors need to be redesigned and altered into the required contexts. Therefore, these cases can give inspiration for single factors, but it will not be possible to copy and paste the entire learning ecosystem from any one of the cases. Nevertheless, we believe there are many good ideas here that can be tried at your institution.

Development of global accreditation criteria has influenced the development of engineering education to become more transparent, concerning structures and learning outcomes. Similarly, technology and science are global phenomena which also influence educational institutional cultures. But this is not the same as saying engineering education has become more alike as culture and especially microcultures dominate practices.

In practice, student projects run in mechanical engineering at the University of Technology Sydney (UTS) might be organized quite differently from projects at Harvard or Aalborg. Specific elements will influence the students' learning experiences and how academics are facilitating the learning is often tacit and non-articulated by words. An example is how to frame the projects. How broad are the project proposals formulated? How much freedom do students have in influencing the direction of the projects? This can be described in principle, but in practice it will be hard to capture and, eventually, practice and the students' learning experiences will form their competencies. That detailed level will not be possible to describe in this book; it must be experienced. But we can describe the philosophies, the self-understandings, and possible evidence for what we are doing.

The writing of the book has been a journey which started in June 2019 and the communication was virtual for three years. All three universities have responded to many of the challenges described in the previous chapters, but the ways in which complexity and systems, together with sustainability and readiness, are addressed in the three institutions, are very different. What can be done at Harvard will, under the present situation at Aalborg University, not be possible but might be emerging at UTS.

What has become evident for us in this process is the diversity in each institution's foundational educational mindsets. It is in the process of comparison, we became aware of these underlying values and when we finally met physically in May 2022, we started to realize the importance of the educational philosophies saturating our thinking. We are on the same track concerning the overall aims and the challenges we need to address in engineering education, but the ways it will be developed will depend on our educational mindsets.

The practices at the three universities are very different concerning educational mindset and the organization of the curriculum. Harvard has the highest flexibility for students to select courses in the curriculum, whereas both UTS and Aalborg University have less flexibility. With a very flexible curriculum, the individual student can create their own competency profile; however, it is more difficult from the curriculum side to provide progression in generic competencies or interdisciplinary competencies. The progression of learning in an elective system is primarily the responsibility of the individual student.

On the other hand, if the highly selective curricula are working for the individual students, it provides a more solid platform for getting students to create their own learning trajectories and they can then become very strong in their personal competency profiles. But you need students who are mature enough to be able to create their own learning pathway.

Aalborg University has a mindset that is focused on becoming able to analyze and solve societal problems by collaborative learning and the development of collaborative competencies within the disciplines and potentially across the disciplines. The individual student is basically immersed in the collaborative projects and assessed for their individual knowledge, their team skills, and their ability for knowledge construction.

UTS has, to a much greater extent, targeted the professional attributes for engineers to serve society and to be able to work in companies, but with an individual approach, which now is under transformation to become individually focused and collaborative.

We need to have in mind that the student populations are very different—both Aalborg University and UTS recruit directly from high school and serve as public universities. Both institutions will have an intake of 1200–1600 students every year whereas Harvard's intake for engineering will be much less.

There are variations in the curriculum structures. At Harvard, there is a freshman year with general subjects followed by a few compulsory subjects and plenty of electives. The path through the electives will be individual. The UTS system is much more sequential for both the technical, disciplinary subjects, the professional engineering core, and the studio track. Furthermore, there are two internships. For many of the technical courses, there will be some type of project, but this will be dependent on the individual lecturer.

Finally, there is a totally different structure for Aalborg University, which has a system where the students are working half of their time in the taught courses and the other half on their projects. Most of the projects are types of ‘electives’ in the sense that students can choose their own problem within the frame of the learning outcomes. For some semesters these learning outcomes have a narrow focus, and in other semesters there is more opportunity for students to choose a project of interest to the project team.

There is no right and wrong in the three different university ecosystems, but no matter which system we have, there is an urgent call for development to solve the global challenges civilization has created. All three universities are addressing this in their own way and this diversity gives richness and inspiration for the readers to recognize potential strategies for their own practices to respond to the challenges and to develop new mindsets for teaching and learning.

Chapter 9
Teaching Practices at Harvard Engineering

9.1 Introduction

In the previous chapters, we discussed critical components of effective learning curriculum. We pointed out that problem-solving skills are critical for engineers of this century. In particular, we pointed out the importance of *systems thinking* as a core learning methodology, and the *design process* as the tool for addressing open-ended human challenges.

Connectivity among disciplines and people is critical to success in the systems-design model. On the one hand, people become isolated with the use of electronic gadgets and social networks, while on the other hand, work continues to be a social process requiring ever advancing technical tools. That work is happening within a new culture fueled by AI and machine learning, IoT devices, and digitally connected communities in smart cities. So, students should realize that seeking other perspectives, collaborating in research, and engaging others in problem solving, as they investigate the elements of the project, are critical to achieving success.

Since most human challenges are multivariable and made up of heterogeneous and interacting elements, with significant time evolutions, the problem-solving paradigm must shift to address these challenges as systems, thus examining them holistically and avoiding reductionism. Whenever possible, part of this paradigm shift is to move from analysis for empirical understanding to design through computation. In some situations, equations-based investigations should be replaced by simulations and statistical analysis.

9.2 Educational Structure at Harvard Engineering

Cognitive development and skill building are critical components of a 21st-century learning curriculum. Systems thinking and design engineering are ideal vehicles for introducing and developing these skill sets of the future. Beyond an emphasis

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on interdisciplinary learning, we focus on the complexity that arises in systems, as well as the philosophical and mathematical platforms for understanding complex challenges.

A new problem-solving paradigm is needed to address 21st-century challenges that are multivariable, made up of non-deterministic, heterogeneous, interacting elements with nonlinear dynamics. Such challenges must be examined holistically to avoid reductionism. A paradigm shift is needed from analysis for empirical understanding, to iterative design incorporating computation as well as physical making. We need to introduce elements of complexity and dynamic systems through courses and real-life experiences and should use data and computation to analyze different situations. Critical thinking, innovation, and design should be explicit cornerstones of the engineering design curriculum. We find that different courses have different emphases on the above-mentioned points. The overall key elements that are related to the discussions in Chaps. 5 and 7 include:

- *An interdisciplinary approach* by integrating concepts and practices from a wide range of fields including different areas of engineering, materials, applied physics, applied mathematics and design. The goal is to provide Harvard College students with a broad learning and enable them to become good citizens by working and collaborating to solve open-ended problems.
- Some of the courses emphasize *project-based learning*, giving students hands-on experience on real-world engineering problems. This approach encourages students to be creative and innovative and prepares them to be productive in the rapidly changing job market.

Design, as an intellectual branch of knowledge, formally started almost 100 years ago. The word design has different meanings in different contexts. We define design as the process and actions for defining and solving problems, to bring a human system from an inferior state to a higher performing state. Design connects artifacts to economic and socio-political dimensions. It also connects to business innovation and scientific discovery. Design connects to our cognition and emotions and allows us to form implicit and explicit integration of information.

When issues are complex, such as in cases of open-ended human challenges, the connection between design and engineering is even more critical. Through design and working on open-ended problems, the program emphasizes the ethical and social responsibility of engineers. Study cases are used to present ethics as a topic for discussions. Students are encouraged to consider the broader implications of their work and to use their skills to make a positive impact on society. These topics are discussed in Chap. 3 and emphasize an overall *design mindset*.

Design is forward looking and explores what can be. Engineering translates design solutions into realities. The concept of design engineering encompasses both imagining the future and building it. Design has organic links to both the arts and engineering. The boundaries between art and design are porous. Applied arts is a narrow example of connectivity between art and design. Design integrates aesthetics and functionality.

Designers make aesthetic design decisions, largely based on their intuitive judgments. What is pleasurable to the senses can be key to a successful design, whether in fashion, hardware, or a website. On the other hand, design necessitates integrating aesthetics with functionality and thus it connects artistic considerations to the artifact.

Engineering, as a problem-solving method, uses scientific and mathematical principles. Design, through the need for functionality, joins engineering with the arts. An integral part of design engineering is innovation; achieving transformative outcomes requires new syntheses and solutions.

Innovation is a mindset, a methodology, and a process, all in one. It leads to new behaviors and outcomes and creates system transformations at scale. The design engineering process enables innovative outcomes that are integrated, functional, sustainable, and aesthetic. The school provides activities to encourage an entrepreneurial mindset and provide courses that teach students how to create new businesses and bring innovative products to the market. In addition, Harvard established the i-Lab as resource for students to work together and obtain mentorship for their business venture including legal and IP.

In the twenty-first century, we need design engineering to emphasize creating technologies for society using observation and creativity. This is the spirit presented in Chap. 3 with a particular emphasis on systems thinking. We attempted to include a subject like 'Arts, Technology and Society' and a curriculum combining the humanities, social sciences, business, design, engineering, law, and policy. The integration of commerce and technology and the connections to liberal arts might become the underpinning of this curriculum.

New courses should attempt to address a particular human challenge, and thus they will be fertile grounds to create syllabi for new interdisciplinary courses, which support future dialogues among disciplines. In particular, the inclusion of the centrality of liberal arts and humanities in the development of technologies and commerce is an example of a such a syllabus, and it could be tailored to create future general education courses. The collaborative Master of Design Engineering (MDE) degree between the School of Engineering and Applied Sciences (SEAS) and the Graduate School of Design (GSD), and the combined MS/MBA program between SEAS and the Harvard Business School (HBS) are two examples among several that will enrich and be enriched by interdisciplinarity.

9.3 Social Experience is an Important Factor in Solving Challenging Problems

Life experiences are enriching means when addressing social challenges. With these experiences, heuristics and related biases become familiar and are better understood. In addition, with different experiences students develop skills, and appreciation for what it takes to make something work and develop habits of thinking deeply to understand the social context of the challenge.

These are some of the factors that are gained from working for a living and engaging in topics of consequence. In the Harvard MDE program, enduring life experience is part of the selection criterion for admission to the program. Applicants write about their experiences and reflect on their career passion.

The MDE program provides students with design-engineering toolkits that are used in the first-year design studio. This toolkit encompasses networked objects and environments, soft and hard infrastructures, and strategic plans, all of which can be applied to address grand challenges and mitigate threats to our built and natural environments. Students are expected to collaborate and communicate with each other and with stakeholders, to successfully analyze a specific problem. With their special life experience, students are expected to bring new ways of understanding the problem, predicting its complications, and evaluating some possible solutions.

An important aspect in learning is to appreciate the problem, give it full attention, and have a passion to solve it. If the student has a social experience related to the problem being solved, they will do all it takes to solve the problem, because it has a meaning and it is related to their own life, either in the past or in the present. A student, for example, who is an immigrant in a country might look at challenging problems of immigration from a different point of view than a student who is a native resident of that country. Another example, a student who studies problems related to hunger and poverty might appreciate it differently from a student who already lived the situation and survived it.

Social experience is a golden key in knowledge acquisition because it creates different thinking avenues in one's head, as the thinking is powered up by experience. In most cases, students who are not familiar with a problem they are assigned to solve, are asked to appreciate the problem by empathizing with the situation, interacting with the stakeholders, and diving deeper into the root causes.

9.4 Digital Transformation in Practice

For several years, Harvard University has been exploring and implementing digital transformation in its education curriculum. Harvard has leveraged digital transformation in its education curriculum including:

- *Online learning*: Harvard has developed many online courses and programs that can be accessed from anywhere in the world. These include courses offered through HarvardX and classes offered by the Harvard Extension School for students and professionals who are interested in obtaining training or degrees in particular subjects. Many HarvardX courses are free (Harvard University, 2023) and allow students to learn at their own pace and provide access to a wider range of resources and expertise.

- *Feedback and data analytics*: Harvard has been using student feedback to better understand student learning patterns and to tailor instruction to individual needs. This has helped to improve student outcomes and to identify areas where additional support may be needed.
- *Technology-enabled pedagogy*: Harvard has been exploring innovative teaching methods that leverage technology, such as simulations and Perusal, an online social annotation platform, where students read and annotate together, while taking the same course (https://www.perusall.com/). These approaches made learning more engaging and interactive, while also providing students with practical skills and experiences. This resonates with the ideas presented in Chaps. 4 and 7.

9.5 New Learning Methods for Undergraduates

At Harvard Engineering, we realize that the above-mentioned paradigm changes are not easy to digest and incorporate into a single course. In time, we wish that future curricula move in the directions outlined above. For now, we take small incremental steps and implement as much as possible of new learning within some courses.

The most important steps for a successful design are (a) defining the problem in a systems context, (b) approaching it as a system with creative thoughts and without biases. Therefore, it is important to spend significant time framing the problem and also digging deeply into determining the root cause.

The following are some examples of engineering courses aimed at training students to work together as a team to address real-world problems.

9.5.1 Science and Cooking

Harvard Engineering offers a range of general education courses that incorporate the peer-to-peer learning concept into engineering curricula. An interesting course that emphasizes peer-to-peer learning is *Science and Cooking—From Haute Cuisine to Soft Matter Science* (General Education), which became a favorite among students. Students from across the university departments and schools, such as business, chemistry, humanities, biological sciences, music, and social sciences, come to one classroom to attend lectures and work together on science projects. The class teaches scientific principles of chemistry, physics, and soft matter in conjunction with culinary skills. It also offers students the chance to apply the science concepts they learnt into the kitchen lab under the supervision of scientists and food specialists to observe and create new sciences in food.

Students have the opportunity to interact with scientists and chefs from around the world to learn the science behind each dish and engineer a science-based recipe. At the end of the class, students are expected to create a recipe to solve a specific problem in a dish or to simply create a better recipe. Each student is expected to apply the science laws they learned to create the recipe, which is the final project that they work on for several weeks. Experimentation and data analysis are part of the final project. The class teaches problem solving in a fun way that everyone loves! In addition, students get the opportunity to share their results with their peers and the public in a science fair.

Students were asked to evaluate the course in the middle of the semesters, and most of them expressed excitement about learning science by doing experiments. The question here is, what makes food science more interesting than plain chemistry science? One would think that both food and chemistry stem from one science which is chemistry, but what is it that makes students more interested in doing experiments on food to learn chemistry rather than just using chemicals to learn chemistry?

In the Science and Cooking course, students reported that they enjoyed the environment, which they described as the 'diverse fun' environment. One would think about the word 'diverse' as learning different things, but it was described by students as 'learning new aspects from our peers about cooking that were explained in class scientifically.' This indicates that students strive for 'new' ways to acquire knowledge, which comes from the 'new' disciplines that each student brought with them to the class. This could be interpreted as a transdisciplinary education coming from the domain knowledge and the general knowledge, which integration of system thinking. Although the course does not explicitly teach systems thinking, students naturally apply it as they analyze problems and devise solutions. Students were analyzing problems and fitting solutions without their knowledge of system thinking. One would think about employing interdisciplinarity in engineering education where sciences meet society and interact with arts and creativity (Fig. 9.1).

But how do we make it 'fun'? In the Science and Cooking course, students found the class 'fun' because they were visualizing the outcome and rewarded with a delicious taste! In the lab portion, students had the chance to eat their final outcomes,

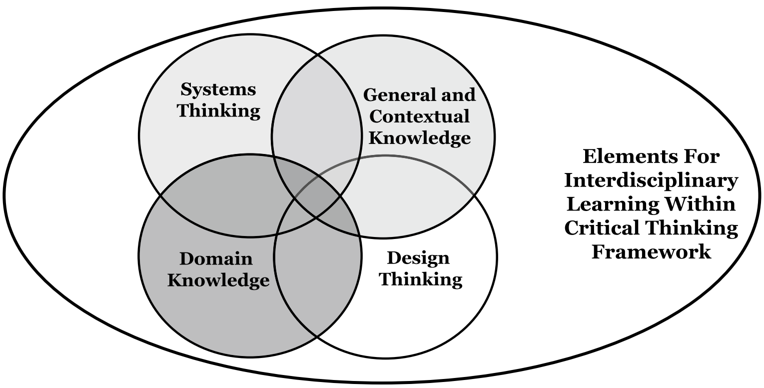

Fig. 9.1 Interdisciplinary education is a combination of accumulated systems thinking, domain knowledge, and general knowledge

and who doesn't like food?! The science was taught in the kitchen. Experiments were taking place in the kitchen, which is an unusual lab-setting, not a classroom, not a studio; it is a kitchen! Most people enjoy cooking in their free time, so in this course, both entertainment and science were mixed to make a 'fun' learning experience. One important thing in the cooking entertainment is trying new things, knowing that cooking is part of the culture, so learning through cooking is bringing different cultures to the same table to create a recipe.

9.5.2 Humanity and Its Futures: Systems Thinking Approaches

As citizens in a rapidly changing world facing increasingly complex challenges, the skills that tomorrow's leaders need are increasingly crossing disciplinary silos. Humanity's most pressing problems are interconnected, involve competing interests, and defy simplification into single disciplines. Reductionist approaches focused on linear understanding must be balanced against the integrative logic of systems-oriented thinking. Depth must be balanced with breadth.

This course gives students an appreciation for the complexities of today's most intractable problems and, in so doing, helps students develop a methodology for navigating the world they face. After an overview of systems thinking and its emphasis on interconnections and feedback loops, the course explores several issues and the complications they generate. Over the course of the semester, several topics, including epidemics, inequality, human displacement, and food systems are addressed.

The course employs multiple methods of learning, with course preparation varying from reading novels to watching videos to reviewing academic papers. Each case includes an overview of the issue and why it matters, before exploring existing disciplinary approaches to address the challenge. Prior thinking is evaluated both in terms of its rigor and effectiveness. What worked and didn't work? and Why?

Students learn to employ systems thinking using an interdisciplinary method to evaluate possible solutions. This future-oriented analysis emphasizes the necessity to zoom out and paint a mosaic of possible unintended consequences and roadblocks that may impede progress. By the end of the course, students would have developed a robust framework for integrating economic, political, technical, ethical, and social lenses into an analysis of complex problems and their potential solutions.

9.5.3 Aesthetic Pleasure and Smart Design: Janus Faces the Future

Engineers today can make almost anything they think of. Do we ask why we pursue one innovation over another? This course considers the personal and social drivers of innovation, including beauty and sustainable value. Complex or 'wicked' problems today demand interdisciplinary approaches that bring the humanities in dialogue with technology. Along with predicting the success of new products through existing needs and desires, innovation in its most spectacular cases comes close to art, making new and unpredictable things that generate new desires, markets, and behaviors. How will engineers today respond to the opportunities and obligations that accompany technological advances?

9.5.4 Engineering Problem Solving and Design Project

This team-based project provides an experience working with clients on complex multistakeholders, real problems. The course provides exposure to problem definition, problem framing, qualitative and quantitative research methods, modeling, generation and co-design of creative solutions, engineering design trade-offs, and documentation/communication skills. Ordinarily, the course is taken in the junior year.

9.6 Course Design Principles

The above mentioned courses (subjects) are designed to engage students, perhaps for the first time, in a unique learning experience designed to address large, complex human challenges. Students work on a problem that does not have an obvious solution, and that will likely have more than a single solution or mitigation. With that in mind, faculty attempt to provide students with helpful learning environments to perform their work. They will offer guidance as well as some ‘scaffolding’ and tools and techniques that might help the students to engage in the problem solving.

Students work as part of a project team, with a project manager that they nominate, and faculty approve. Students may decide to divide their team into task forces and address different aspects of the challenge at once. Faculty may guide the students and orient them toward fruitful answers for the most important issues, but it is expected that the students have significant independence in pursuing their problem solving. Once every week, the team presents their findings, and the faculty constructively critiques their work in an open forum.

9.6.1 Performance and Expectations

Students are required to attend and participate in all contact sessions and field trips and, in addition, there is significant work with their team outside the contact hours. Most students will work an additional 15 hours per week on average.

Each student's performance depends on their work as well as the team achievements. So, team members must testify to the value of the individual's work, and their contributions to the team. Faculty ask each of the team members for self-evaluation and peer evaluations periodically.

Students are informed that each individual's creativity is essential for the success of the project and their working with others translates their creativity into useful outcomes.

Students are required to present in front of their peers and other members of the faculty, and on some occasions, students are asked to give a short summary or explanation on the spot. Students learn to perfect their presentations to become concise, clear, and effective. They learn to 'visualize data' and use statistical methods as well as qualitative research methods to obtain new information. Engineering skills are critical; students use them for creating designs and prototyping when needed.

Every project has a 'client' with whom the students work to obtain guidance for addressing their solution. The client is a source of information and a sounding board for ideas and solutions.

The outcome of the teamwork is a combination of prototypes, analysis, solutions, proposals, and recommendations. These will be presented jointly as a collective outcome by the team. By the end of the semester, the students present their ideas in writing. There will also be a description, instructions, and documentation for the overall output. During the semester, students are expected to use their notebook to keep detailed documentation of the work. All data, analysis, and comments are recorded in their notebook. Faculty may examine the students' notebooks on a periodic basis.

At the end of the course, the students participate in a public oral presentation, at which the client assesses the work.

In the past few years, projects covered broad scopes that ranged from Renewable Energy at Harvard, Waste in Harvard Kitchens, Rodents at Harvard Residence Hall, Crime Mitigations in Springfield, MA, homelessness at Harvard Square, and mitigations of the Fukushima Nuclear Disaster in Japan.

9.6.2 Key Learning Outcome

For each course, each student must become proficient in integrating science and engineering concepts, to address problems of profound societal and environmental impact. Specifically, each student should have a very good understanding and demonstrated capability in the following areas:

(a) Systems thinking

- Knowing the foundations of systems thinking.
- Understanding the functioning of systems dynamics, feedback loops and delays.

- Being able to identify, explore, and map system relationships for interventions, while leveraging flexible and divergent thinking practices.

(b) Design process

- Knowing the basic elements of the design process.
- Using the design process to identify areas of opportunity.
- Using the design process to understand critical design requirements and implement innovative and relevant solutions.

(c) Project management

- Collaborating effectively in interdisciplinary teams to accomplish significant objectives.
- Delivering solutions within time boundaries to manage a project and use planning tools.
- Professionally documenting and communicating design outcomes.

(d) Communications

- Providing effective feedback to others, as well as offering self-assessment.
- Creating compelling presentations and representations.

9.6.3 Assessment of Learning Outcomes

The learning outcomes can be compared to the needs of future real work projects and the expectations of the hiring agencies. A report by the World Economic Forum on the 'Future of Jobs Survey' presented a set of literacies, competencies and character quality that are critical for 21st-century successful persons (World Economic Forum, 2020). The curriculum and learning outcomes, for the four courses described above, match many of these requirements (Table 9.1). Most of what is indicated by the World Economic Forum is also consistent with the ABET accreditation requirements (ABET, 2022), which SEAS degrees have obtained (Table 9.2).

9.7 Design Engineering at Harvard

We hope to infuse critical thinking and design into a variety of intellectual experiences for Harvard students. The goal is to train future leaders in creative systems thinking and to provide experiences that develop and test innovative ideas for solving real-world challenges in a variety of human domains. The program expands students' horizons by offering opportunities to explore uncharted territories in critical thinking and design. Students learn how to search for root causes beyond the linear Newtonian cause and effect, to express ideas through visualization, to obtain insights from descriptive, prescriptive, and predictive information using large data sets, to build physical and virtual prototypes, and to test the validity and impact of their solutions.

Table 9.1 Learning outcomes and required skills

Top 10 required skills for twenty-first century (World Economic Forum, 2020)	Harvard learning outcomes
Complex problem solving	Significant emphasis
Critical thinking	Significant emphasis
Creativity	Significant emphasis
People management	Some, through project management and teamwork
Coordination with others	
Emotional intelligence	Through working with client and teamwork
Judgment and decision making	Creating problem statements. Choosing mitigations/solutions
Service orientation	Some; working with client
Negotiation	Some; working with client
Cognitive flexibility	Significant emphasis

Table 9.2 ABET learning skills

Foundation literacy	Competencies	Character qualities
Literacy	Critical thinking	Curiosity
Numeracy	Creativity	Initiative
Scientific literacy	Communication	Persistence
IT literacy	Collaboration	Adaptability
Financial literacy		Leadership
Cultural and civic literacy		Social and cultural awareness

One, however, should not over emphasize the physical aspects of these productions. In time, different types of productions would include new technologies to empower us and make us more efficient and capable. Such technologies will be built on integration among physical, biological, and digital domains and will create new knowledge in cognition and health, as well as in commerce.

The main goal is to employ interdisciplinary engineering education to address broad aspects of design, engineering, and the arts, and their relation to society. The program utilizes a variety of pedagogies for systems analysis and leadership, including the use of the studio teaching format and experiential learning. In some courses and experiences, students work as a cohort, create networks, and share knowledge. Courses from across the Faculty of Arts and Sciences (FAS), SEAS, GSD, and HBS, as well as other schools, provide background support and scaffolding for problem solving.

Students have mentors from the faculty of any Harvard school and receive feedback on their work and achievements from both teachers and mentors. In addition, students participate in exhibits and forums and benefit from direct feedback from the public at large. Students cannot develop a deep sense of value without reflection, and mentors could enforce and participate in this process. Since mentors are most effective when they can discuss students' achievements among each other, a mentorship event twice per year allows mentors to share experiences and reflections and discuss how to provide the best support for their mentees. The program creates cross-school, collaborative workshops on topical issues such as arts as informing tool, visual thinking, augmenting data, thinking in philosophical, and quantitative, and speculative modes.

The interdisciplinary emphasis on design engineering has the potential to be an innovative and distinguishing characteristic of Harvard education. The courses offered in design engineering are created with greater emphasis on bridging the gap between arts and humanity, solving human systems challenges, the impact of the Fourth Industrial Revolution, and data-driven innovation. These topics could evolve over time through periodic updates and provocations, some virtual and other physical, with the goal of lifting humanity to a higher collective and moral consciousness and engage students in the uncertainty of creating mitigations.

9.7.1 The Master in Design Engineering

In 2016, Harvard School of Engineering and Applied Science in collaboration with Harvard Graduate School of Design created a new graduate program, the Master in Design Engineering, with the objective of bridging the gaps between technical specialization and practical, real-world solutions and enable broad understanding between technology and people (Harvard University, 2022b).

Students engage in addressing and solving major challenges facing society with transformative, interdisciplinary innovations. Some unique aspects of the curriculum of this program are an Integrative Framework for Technology, Environment and Society, and Independent Design Engineering Projects, and Collaborative Design Engineering Studio (Harvard University, 2022a). These courses focus on problem definition, diagnostic techniques, and the challenges of translating ideas into action.

In the spirit of Simon (1996), 'everyone designs who devises courses of action aimed at changing existing situations into preferred ones…it is the principal mark that distinguishes the professions from the sciences,' frameworks engage diverse but complementary disciplines, perspectives, and techniques to help identify, diagnose, and constructively address consequential social challenges, sometimes referred to as 'wicked problems.' The disciplines or 'frameworks' explored include systems analysis, industrial design, scientific methods, behavioral and organizational dynamics, law, economics, manufacturing, culture, aesthetics, health sciences, anthropology, public policy, ecology, and the like. While individual frameworks are presented, the teaching goal overall is to help students identify problems that are both consequential and tractable, and select and apply the suite of frameworks best suited to addressing the problem at hand.

9.7.2 Collaborative Design Engineering Studio

The *Collaborative Design Engineering Studio* is a unique experience that features a project-based introduction to a range of ideas, methods, and techniques essential for the design engineer. In the studio, students learn through making. The overall objective of the design studio is to teach methods, techniques and strategies geared toward describing, characterizing, and addressing complex, multiscalar, interdisciplinary real-world problems. Pedagogy and design engineering methods include *data visualization, system theory, modeling and simulation, group brainstorming, prototyping, multimedia communication, and presentation.*

The nature of the MDE studio problems solving includes:

- Relevance to society, but intricate to break down and address.
- Data from multiple sources, which is often not immediately accessible.
- Inherent conflicts or dilemmas that prevent 'simple' solutions from succeeding.
- Tradeoffs that are difficult to understand.
- A complex network of stakeholders.
- Issues that are multiscalar, with direct impact on individuals as well as on organizations.
- Issues that are systemic in nature, involving complex networks of factors that influence outcomes. No systemic solutions have been proposed or successfully tested.

9.8 Summary

In this section, we discussed some of the courses and related experiences that manifest the spirit of design at Harvard School of Engineering and Applied Sciences (SEAS). SEAS has progressive design content as well as innovative learning processes. The mission of the school is to create educated citizens who can productively engage in society and become creators of mitigations for human challenges.

Content development is an ongoing activity and is enriched by the scholarly research in the different areas of engineering and applied sciences at SEAS. The educational processes have several elements that were developed over the past 10 years. Interdisciplinarity is viewed as a cornerstone, and several active learning courses were modified to include topics that are normally taught in different areas. Similarly, design and systems are considered critical for addressing social challenges.

Creativity is essential for creating system solutions that encompass technical and social innovations. The environments under which engagements take place are important enablers. Creativity can be driven by curiosity as well as exposure to challenges that are important enough to excite students and make them invest in new solutions. This was illustrated in the discussion of Science and Cooking.

Creativity is an essential part of design. Students are taught design principles as they are engaged in addressing human challenges as well as in their technical projects. In such engagements, students work to apply engineering principles and come up with interventions that may move the system to a more progressive state. This is the focus of the Engineering Design course (ES 96).

In general, significant attention is paid to the learning environment. Creating and designing are important elements to cement theoretical knowledge. Teaching labs were constructed to enable activity-based learning as well as teamwork. With scaffolding from experienced staff, students work together and build prototypes that address complex open-ended problems. Scaffolding is critical to enhance students' confidence and move the projects forward at appropriate speeds.

Studios are an effective environment for engaging students in complex human challenges. This was part of our discussion where we pointed out the importance of peer-to-peer learning. In addition, implications of interdisciplinary learning with teams of students of different backgrounds were discussed too. Learning in open environments provides the needed informality that makes learners open to different perspectives and is willing to take risks to propose new ideas and ask questions without fear. Not feeling the risk of being critiqued or the pressure of seeking high grades, students accept the challenge and trying different solutions and enjoy reflections and new directions.

The MDE program provides many examples of these features. We pointed out that in the studio environment, the instructors are advisors and enablers of new learning. The 'sage on the stage' is transformed to become a critic and a friend. The learners are the ones at the focal point for creating new knowledge. At the same time, peer-to-peer learning creates comradery, team spirit and fun. With such conditions, student engagement is at a high level.

Many of these educational experiences are in an experimental stage. Issues related to accepting some of these models continue to come up, and some of the faculty reminisce about the old model and claim lack of rigor, but they are left to reconsider when they realize the significant retention the students have made under the new pedagogy. Further, not all students enjoy the flexibility, and some of them wish for a more structured curriculum. This is not surprising considering that most of the students grew up competing for grades and solving exercises in preparation for exams. However, the new pedagogy requires more time to cover all the required content. In fact, in most courses, students do not iterate on their solutions, leaving their innovations incomplete. It is not clear when this will be remedied. Unless most of the courses follow active learning paths, these deficiencies may continue to exist.

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Chapter 10
Problem and Project-Based Learning at Aalborg

10.1 Educational Mindset

Aalborg University has grown out of a certain educational mindset based on reform pedagogy and the German critical theory back in the 1970s. It was in the period where several new universities were established around the world, such as Maastricht University, McMaster University, Bremen University, Linköping University, Twente University, and many more (Kolmos & de Graaff, 2014).

In Denmark, Roskilde University in 1972 and Aalborg University in 1974 were founded as part of a critical political discourse carried by a strong student movement which wanted to relate the academic knowledge to society and at time especially for a more socially oriented society. In particular, the universities strove to have a closer relationship with the surrounding society by including societal problems in the curriculum.

Although the Danish tradition of a problem- and project-based (PBL) philosophy might have started out with the intention of societal transition, it has been embedded and transformed into a much more market-oriented agenda. Already from the very beginning of Aalborg University's history, there was strong support from surrounding society, and in particular from companies. Since the beginning, the university has grown from about 300 students in 1974 to more than 20,000 students. The PBL model is systematically practiced at all engineering and science programs and most of the humanities and social science programs. In medicine, the PBL model is very different from the rest of the university, as a case-based PBL model is applied.

In every curriculum, the three core factors will always be the academic teachers, the learning outcomes in the curriculum and the students, as outlined in Fig. 10.1, together with the AAU way of connecting those.

The original philosophy beyond the Danish PBL universities added five sets of learning principles which can be summarized as.

- Societal relevance meaning that the problem-orientation should relate to societal problems.

F. Habbal et al., *Reshaping Engineering Education*,
https://doi.org/10.1007/978-981-99-5873-3_10

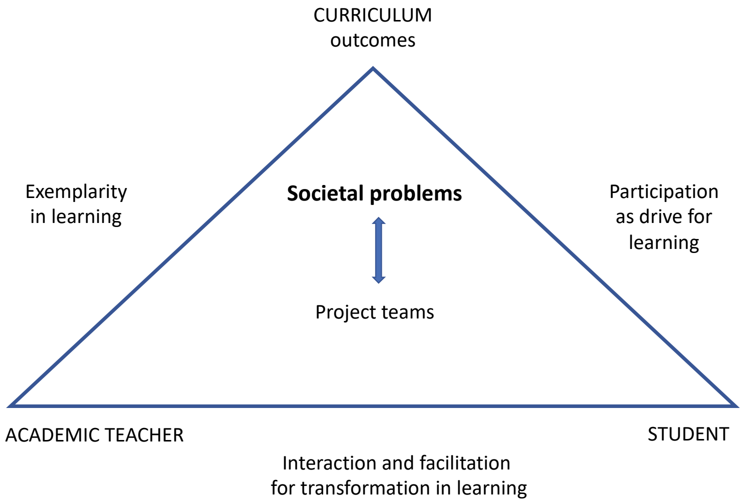

Fig. 10.1 Learning triangle in a PBL perspective

- Participant directed learning indicating that students should be decision makers in their own learning process within the given framework of study regulations.
- Project-organized teams where students collaborate and work on projects.
- Exemplarity in the sense that the projects should be exemplary for overall learning goals which also embed a social imagination of transforming the society.
- New roles for academic staff from lecturing to facilitation of students' learning.

These five principles are interrelated; however, the starting points for the PBL principles at Aalborg University are societal problems, which are analyzed and solved in project teams (Kolmos et al., 2004).

10.1.1 Societal Problems

To bring societal relevance and problems into a theoretical-oriented academia has been one of the core elements in the transformation of higher education during the last 50 years and it actually involves all the other principles. The societal problems will require a different way of approaching knowledge as it has to be related to reality, and learning is organized in analyzing and solving problems. Although problems can range from complex problems to narrower classroom and disciplinary problems, it will give a context for the learning and creates the starting point for the learning processes. This can create meaningfulness for the learner. The learning of control theory will become more meaningful if the students are to reduce a crane sway to improve safety in the working environment—or it is an optimization of a production line in order to save energy.

Societal problems can often be characterized as belonging to one of the SDGs and PBL can be seen as a pedagogy for mission-driven education. Identifying societal problems involves critical thinking which is described also in Chap. 4 and belongs to a critical discourse. Students get trained in analyzing why this is a problem and what is the problem?

In engineering, there might be too much distance between the technical knowledge (and the competencies expected to be learned) and the societal problems. The trick used is to narrow down the problem in an argued and explicit way, so that it can serve as a framework for continually revisiting the societal scope in the problem-solving process (Holgaard et al., 2017). Together with the intended learning outcomes of the educational program, the argued relevance for society also has implications for the problem-type addressed. The societal problem fields will include a lot of different problem types calling for different levels of abstraction and different academic lenses. Narrowing down the problem and the choice of problem type is a part of a negotiation and sense-making process for the teams of students.

10.1.2 Project Teams

It is project organized and team based as most of the authentic problems cannot be solved by the effort of only one person. The team-based and project organized aspect involves learning relevant competencies for collaboration and project management in diverse team formations (Spliid, 2011). These are often the competencies which are required by industry and society in general and have been embedded into most accreditation criteria for engineering education. Therefore, it has also been the most outspoken argument for applying PBL at both course and institutional level.

The project organization approach also adds both a focus on a co-constructed product in terms of an innovation, a project report, a device, or similar products which can be assessed. The product is to be understood as the analyses and the solving of the problem. The combination of learning process and the learning outcome in terms of the project can be seen in light of motivation as many students are driven by creation and the fact that they can be contributing with their project product to solve relevant problems.

Furthermore, the team-based aspect adds for the formation of individual and collective learning cultures. Most students find it difficult to collaborate. It can be difficulties in the social interaction and in the interpersonal cognitive understanding. For first year students, it is often challenging to collaborate and learn to manage the art of collaboration, and questions arise such as when do you say no and when do you add in to progressing the process. Students should also be able to position themselves within the group and point out how they can contribute to team efforts including both group performance and individual learning goals. This will create an identity formed by both the inner individual interests and the collaborative learning environment. This identity moves from what is good for me to how can I contribute to a common solution (Chen et al., 2020).

10.1.3 Exemplarity

Exemplarity is one of the principles explained in the Chap. 6 for selection of problems, methods, and content which have to be exemplary to the overall learning outcomes. There is no doubt that the students remember the learnings from projects more than the learnings they have gained from lectures (Kolmos & Holgaard, 2017). They are also using more time on the projects as the projects are most often chosen by the students, which creates ownership. The reason is of course that the students are actively working with the content more than passively receiving information through lectures. In a PBL curriculum, the learning outcomes in the projects are normally at a higher taxonomy level than the learning outcomes in the taught courses. Students are expected to gain deeper understanding and knowledge from their projects, and they have to learn how to search for knowledge themselves. Many courses at AAU are faculty-directed designed to integrate more narrow problems but also have integrated activities for active learning, and lecturing is more used to create overview and relate more stable knowledge constructs (Kolmos et al., 2004).

10.1.4 Participation

The principles of participant directed learning are an embedded part of working in project teams. The participant directed learning corresponds to a more recent concept of co-construction. If the students go to a company and have been asked to investigate a regulation problem at the end of the production line where products are packed, they will start by an analysis. When they start to analyze a system, they figure out that the problem cannot be solved by regulation as the problem in fact originates from the materials used. They learn to identify the relevant problems in their learning process. An example of the participant directed implications can also be that students working with acoustics bring in problems that they are aware of, like noise level in schools after removal of asbestos ceilings. With a personal relation to the problem, the students get even more motivated for learning and working with solutions (Zhou & Kolmos, 2013). Furthermore, critical thinking is enhanced as students have to consider the different interests related to the problem (Guerra & Holgaard, 2016).

10.1.5 Academic Staff

Learning to transform knowledge and competencies is a condition to train students in transforming their knowledge and competencies from one project to the next project. The project organization to address problems and situations will be different, and the project teams will vary in number of members, the scope of the problems, and the project management process. Therefore, the transformation of knowledge, skills, and competencies, as defined by the European Qualification Framework, are important to address. Transformation processes are not one to one processes and not linear or necessarily logical. It is part of the learning that takes place but is hard to articulate (Servant-Miklos & Spliid, 2017).

Therefore, the role of the teacher gets important as this is not just to communicate scientific knowledge, but indeed to facilitate learning of both scientific knowledge, the application of knowledge for analyses and problem solving and, the learning of how students transform their generic competencies from one project to another project situation. It does not really matter which concept is used to name the role, e.g., if the term used is a facilitator, advisor, or supervisor as the wording basically is defined by the cultural practice. What is important is the function which is to guide students and open up their mind to different scenarios in relation to both the product in terms of scientific content, the approach to analyzing and solving problems, and the process of which the students organize the learning individually and collaboratively.

This is a challenging part for academic staff who are used to be in a content mode. However, product and process are interweaved and one way to approach this function is also by facilitating transformation and activate exemplary learning by asking the 'what if' questions to the students to get the students to think in alternatives and to apply theories and methods learned in one case on another case.

Students need to learn the scientific knowledge in combination with analyses of and solutions to problems which to some extent will require a pragmatic approach and out of the box thinking before making decisions. It is basically to get the students to shift between convergent and divergent thinking and processing. That will also influence how the students learn to organize their collaboration and their project processes.

The functions and roles will depend very much on the type of project. Basically, there are narrow discipline projects, which are more faculty driven, and there are the more open problem projects which are more student driven and interdisciplinary oriented. In the first type of projects, teachers know the problem, the methodologies, and the results beforehand. In the last type of projects, there might be a lack of knowledge of both the problem and the results, but knowledge of the methodologies might be known, see Table 10.1.

The interaction with the students will be very different. In the teacher-driven projects, teachers do have an overview, know the directions, the tentative solutions and can facilitate the process of training the students' transformation competencies with confidence but maybe also within more limited scopes. However, although the most of the methodologies and results might be known, the students might still come

Table 10.1 Faculty- and student-driven projects

	Problem	Methodologies	Result
Faculty driven	+	+	+
Student driven	–	(+)	–

with new solutions. In the learner-driven processes, the teachers also participate in the inquiry processes. This is a process where the teacher helps out with methodologies and facilitates the transformation competencies much more in an interactive dialogue about what the students can do. These types of projects are increasingly important as there is an increase in the need for solving complex problems. Engineering students do have both types of projects, and the academics are trained in both types of interactions (Bertel et al., 2022).

This approach to teaching is based on the assumption that students are able to become responsible for their own learning. This might set high expectations as becoming drivers for your own learning is challenging. Research has indicated that when students are given the opportunities to decide on the problem, then they create ownership which increase the motivation for learning (Ghaemi & Potvin, 2020). However, even though the motivation factor might not be so easily handled, it is important to give students possibilities for directing their learning. Students might have been used to more spoon-feeding in high school. Therefore, there is a function in facilitating the students to make their own choices as part of their identity and personal growth. Often students just want one answer and act on that—please just tell us what to do and then we will. But the trick is to give them two or three possibilities to force them to think, argue, negotiate in the team, and make decisions. Which direction should they choose? In participant directed learning, it is about getting the students to decide (Kolmos et al., 2008).

10.2 Institutional PBL Approach

What is unique for the reform of two universities in Denmark, Roskilde, and Aalborg University, is that they were established as a new institutional and systemic approach more or less from scratch. Therefore, it was possible to create new interrelations among all the curriculum components. At Aalborg University, a semester approach was created contrary to a course approach with a high degree of flexibility qua the curriculum system with electives. In the Aalborg curriculum, the electives are primarily integrated in the students' projects and one of the reasons why the participatory approach not only serve as a motivation for learning purpose, but indeed also has a specialization purpose.

The Aalborg PBL model for engineering education is well described in many publications analyzing the history and early PBL principles and how these have been unfolded in the curriculum, see for example (Kolmos et al., 2004). Furthermore, another institutional framing has been the emphasis on a research and evidence-based approach to PBL using the university as a living lab. At the institutional level, it has had crucial importance with this research-based approach to PBL, as this has been established as a dominant discourse grounded in both experience (practice) and conceptual frameworks (theory). The research environment also created a vision of change inspired, not only from the problems and potential solutions within the institution, but also the developments in various other engineering education institutions around the world (Bertel et al., 2021a).

10.2.1 Curriculum Structure

Originally, the curriculum was born with a coherent semester of 30 ECTS, where 1 ECTS corresponds to approx. 28 h of student work in the European Credit Transfer System. The 30 ECTS is composed of 15 ECTS project work, 7,5 ECTS project unit courses which were assessed through the project assessment, and 7,5 ECTS basic science courses with separate assessment. At the Faculty for Engineering and Science, this was changed in 2006 to three single courses of each 5 ECTS and with separate assessment, see Fig. 10.2.

The reason for the change was a pressure from the subdisciplines in the taught courses as students had a tendency only to pay interest to the content if they were to apply it in their projects, and some students found that they were not accredited in the project exam for the knowledge they had gained in the project courses. The curriculum would be far too narrow and limited if the courses only have to correspond to the projects. The learning outcomes from the 15 ECTS projects are expected to be deep, whereas the taught courses are expected to give a more general educational foundation and overview of the subject. This also gives the project a solid knowledge based to be expanded in the projects and relates deep learning in the projects to a broader scientific understanding and approach.

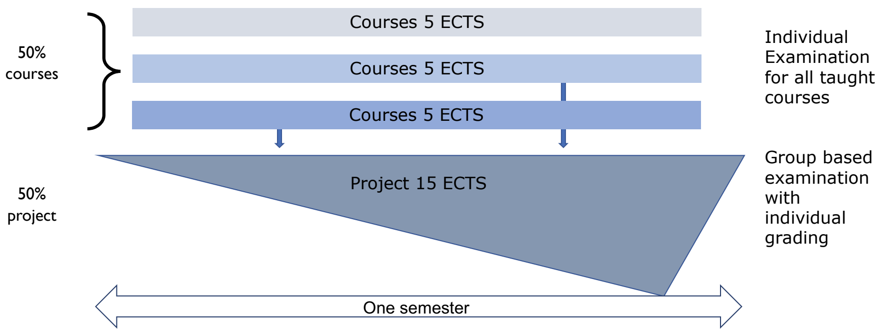

Fig. 10.2 Semester structure at AAU

10.2.2 AAU PBL Learning Principles

Around 2009, the Rector established an expertise group consisting of international and internal experts to development the core AAU PBL principles. International experts interviewed PBL researchers, staff, and students at Aalborg University to get a comprehensive view on the practices (Barge, 2010). At that time, the intention with this exercise was to become more explicit on the overall guiding PBL principles, across science and engineering, health science, humanities, and social science, that could serve as internal and external guidelines for PBL curriculum (Kolmos, 2013). Internally, this slowly became guiding principles for all curricula at Aalborg University. The principles came to serve as a framework in the accreditation of university programs, and later on, as the university was allowed to apply for institutional accreditation, the overall principles became even more important. In that sense, the degree of formal institutionalization has increased during the years from the establishment in 1974.

The AAU PBL principles have had a slightly change over the years, and in the current version, these have been structured under four headlines: principles, framework, practice, and support functions (University, 2015b) see Fig. 10.3.

Integrating the PBL principles into the accreditation system the university furthermore institutionalized the principles by presenting an educational profile. This profile outlines problem-based project work, research-based education, collaboration, student-centered learning as core values. Furthermore, it targets the programs by presenting core attributes of the graduates from the university by stating that educational programs have to foster graduates who can work problem based, have a

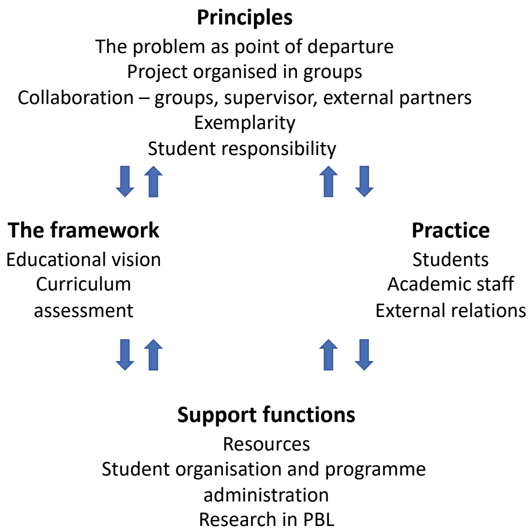

Fig. 10.3 PBL principles at AAU

solid scientific knowledge platform, can collaborate, and work interdisciplinary. By this close relation to the accreditation process on the institutional level, all programs must provide evidence that the PBL principles are met and relate to the educational profile of the university.

10.2.3 Aalborg University Principles for Digitalization

As part of the Aalborg University strategy 2016–2021 ‘Knowledge for the world’ (University, 2015a), the use of IT in PBL was a set theme, and first steps were taken to integrate IT directly in the PBL model. To support this strategy, a cross-faculty center for digitally supported learning was established to contribute to the ongoing development of digitally supported forms of learning, especially in PBL, and assist lecturers and tutors in implementing these forms with inspiration from the flipped classroom. PBL researchers at Aalborg University have studied and explored different types of digital PBL environments as a part of a comprehensive study on PBL for the future (Bertel et al., 2021b). Several projects have been initiated since, among those a project to provide overall principles for digitalization in a PBL context.

Like other universities, staff and students at Aalborg University experienced a steep learning curve under the COVID-19 epidemic, and experiences showed both strengths and weaknesses of digitalization in a PBL environment. First of all, the flexibility of project work and students’ acquaintance with agile project management, combined with applications like Microsoft Teams, provided a solid ground for students to adapt new learning strategies (Lyngdorf et al., 2021). Students are used to adapting to new situations due to the PBL learning environment. We learned that students were creating digital project management systems by combining various software possibilities and unfortunately Facebook was the most often applied system for communication as this was what students were used to. However, the team communication and collaboration patterns were challenged by an increasing individualization of the project work, and there were a tendency to more conflicts among team members (Lyngdorf et al., 2021). Students are comfortable with the digitalization of the taught courses, but they prefer to have the opportunities to work face-to-face in the project teams. Digitalization in the context of problem-based project work is a specific focus in the Aalborg University strategy ‘Knowledge for the world II’ (2022–2026).

10.3 Variation in Disciplinary and Interdisciplinary Projects

During the history of Aalborg University, several versions of interdisciplinary projects have been practiced, but most of the projects with primarily disciplinary learning outcomes. Recently, new reform for integration of STEM and social science and humanities (SSH) has been initiated. The educational programs are to include learning outcomes within a multi, inter, and transdisciplinary domain. This reform builds on a longer tradition at Aalborg University with a variation in interdisciplinary projects which are combining two dimensions: partly the team dimension covering size and number of teams working together on a problem, partly the knowledge dimension ranging from disciplinary to inter and transdisciplinary approaches.

Figure 10.4 outlines the different project types. It should be noted that the most widespread projects are the discipline projects. The five other project types are more randomly applied in different programs. It should also be noted that different concepts might be used to characterize the different types of projects. The point is not really to argue for a particular name for the project type, but to use a framing that makes sense within the institution, and to create a common language and overview of possibilities.

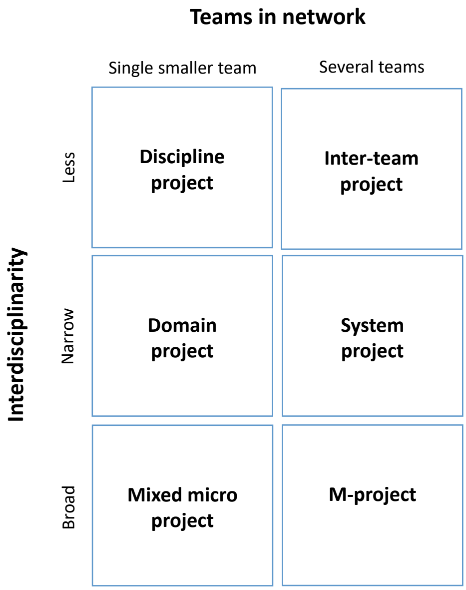

Fig. 10.4 Different types of projects

If we look at the dimension of single teams versus several teams, the project management and steering processes will be very different. It is much easier to organize the work for a team of 4–8 students in one team than for 4–8 student teams working on the same project. For the latter, the students learn coordination at different levels—both coordination within the single team and coordination with the other teams. It can be within a discipline, but also across several disciplines either in a narrow or a broad sense of interdisciplinarity. For mission-driven educations as some universities, among them Aalborg University, claim to be aiming at, it is necessary to educate candidates who have learned to work in a variation of working modes. This is not either/or—it is both/and.

At Aalborg University, the disciplinary project is the most widespread and the easiest to manage from a faculty point of view. For the rest of the project types, there are examples of these projects**,** but it is not compulsory that all students in engineering and science programs participate in such projects. The future requirement learning outcomes within multi, inter, and transdisciplinary domains can be addressed by other teaching and learning strategies. However, as team-based projects are a dominant learning philosophy it will be most natural to include and expand the problem-based projects. Therefore, Aalborg University is—in 2023—in a phase of experimenting with the rest of the project types to figure out what it takes to run these project types as an embedded part of curriculum offered to 20,000 students.

10.3.1 Disciplinary Projects

Disciplinary projects are the basic part of the curriculum at Aalborg University. These are designed to target specific learning objectives to enable students to become socialized into the discipline. If students, for example, must learn graph theory, the faculty must make sure that they tackle a problem in a field where it makes sense to use graph theory. This has traditionally been done by providing students with project catalogues that outline already existing problems that are suitable for the intended learning outcomes.

Following the PBL approach, disciplinary projects are contextualized and to do so students ‘borrow’ knowledge and methods from other disciplines. The degree of contextual focus depends on the learning objectives. During the first year of engineering programs at AAU, there is a specific focus on students learning to analyze and identify a problem from a societal point of view that can be narrowed down to a contribution from within the discipline. AAU has plenty of examples, e.g., of how students from various technical disciplines are applying sociological methods in their problem analysis or performing overall impact assessments of both current and potential solutions (Jamison et al., 2015).

Another way to characterize disciplinary projects relates to the flexibility of the curriculum. At undergraduate level students are building fundamental skills related to their discipline and thereby the intended learning outcomes can be rather detailed, and the students can be steered toward a specific solution space designed to obtain specific technical skills. It is at times more a solution in search of problems than a problem in search of a solution. However, in the later semesters, the students become much more active in moving their mindset from a potential solution to a problem field with different applications, different user groups, different cultures, etc. In this sense, students learn how to make their own project catalogues.

10.3.2 Domain Projects

Domain projects bring together students from different educational programs working within the same epistemological field and drawing on the same sphere of knowledge. In engineering education, this means that the team brings together students from different, yet similar, engineering disciplines. In the engineering program, this can take the form of an elective or a compulsory project related to general engineering, e.g., an engineering design project. It might be a stand-alone mini-project integrated in the curriculum or a more extended part of the program, e.g., a common curriculum at the first year across disciplines.

At AAU, these types of projects have moved from being institutionalized by a domain specific study board at the first year to a more collaborative mode across different engineering programs related to study boards within departments. As an example, graduating engineers within urban, energy, or environmental planning from Aalborg University build upon a corresponding Bachelor with a shared curriculum focusing on the engineering planning domain. An example of a domain specific program is sustainable cities integrating energy and urban planning.

As such, domain projects are rather narrow in their interdisciplinary approach as the engineering domain is typically divided into subdomains with even more epistemological similarities. However, the domain projects have an important role in letting students form their own professional identity. In the above example related to engineering in the field of planning, students might start their bachelor with the intent of becoming and urban planner but end up choosing a specialization within energy planning due to their engagement with different subdomains.

10.3.3 Mixed Micro-Projects

Mixed micro-projects are projects that brings individual students from different disciplines together to co-construct a product in a short period of time. The overarching learning outcome is not as much to validate or qualify a product; it is more about getting students to experience close interdisciplinary collaboration and learning in a co-construction process. Today, there are very few mixed micro approaches in projects as well as in courses. The issue with this project type is the fact that Aalborg University does not have a widespread elective curriculum, and it has been hard to get it formally acknowledge in the formal curriculum.

If students should learn to collaborate at a deeper level, then this project type is needed, and it occurs in periodical experiments. One example is an event where students worked in two groups at a large Danish company to address authentic complex problems outline by the company. The event was structured as a Hackathon where the students from engineering and social science for three days worked with problem identification, problem analysis, and finalizing with a pitch competition presenting their findings (Routhe et al., 2022).

10.3.4 Interteam Projects

The interteam project is still a project type within the program, but in contrast to the disciplinary project students collaborate across groups. Interteam projects occur in bigger courses or clusters of subdisciplinary courses. The interteam project is characterized by a number of project teams working on the same or complementary elements (work packages) within the same discipline, e.g., software engineering.

Interteam projects are and have always been less common at Aalborg University than disciplinary projects. Thereby, there is not an established tradition for such projects, and the integration into the formal curricula is rare. This project type has thereby developed by initiatives from below, seeing the opportunity in groups working together to address the same problem by different problem-solving strategies, or combine teams to cover different roles in a product development project.

The GIRAF project is one example of such project type at Aalborg University where student groups are working on development of an APP for kids with autism, and they need to understand the how autism will affect cognitive functions and especially how they can develop the app (Graham, 2022). At production and mechanical engineering, there are other examples such as projects centered around production development, where student groups are working together to optimize prototypes.

10.3.5 System Projects

In spring 2021, the Engineering Faculty at AAU launched a new project concept called *leadENG*. The aim was to let first-year students experience and work together in a narrower interdisciplinary setting to prepare them for working across engineering, humanities, and social science. The *leadENG* projects start at the second semester, and during spring 2021, several student groups were working on development of an electric car. They have a device to work collaboratively on and organize the development as work packages for system development.

During the spring 22 semester, they have expanded the number of projects and students are working on system projects comparable to the electric car, which means that the starting point is a wish to create a particular technology or a solution to a more or less well-defined problem. The second round of *leadENG* furthermore offered students the opportunity to work on the prototype from the first round to develop a small electric car (version 2). Challenges with version-1 from spring 21 include weight and driving comfort. Furthermore, it is desired that the version will be made modular. Seven groups participated: two from Energy, five from Material and Production.

Another project from the second round of *leadENG* is the Floating Vertical Axis Windmill. The project deals with the design/development of a prototype of a floating vertical turbine. The location of the mill could be the Limfjorden or one of the lakes at the campus. Nine teams were participating: two from Material and Production, five from Energy, one from general engineering, and one from civil engineering. Another project was high temperature stone bearing with a Stirling Engine connected. Two teams were working on this project: 1 from Material and Production and 1 from Energy.

By introducing a narrower interdisciplinary project structure, the intention is to offer students the opportunity to develop their collaborative, problem-oriented and project management skills, and competencies further in a network of teams. The coordination across the project teams provides added value to the project management competencies that moves beyond a single team (Winther et al., 2022).

10.3.6 Interdisciplinary M-Projects

The M-projects relates to at least two types of projects, the megaproject being of large scale, and the mission-driven project being broad in scope.

At Aalborg University, the megaproject was introduced into engineering education in 2019. The term 'megaproject' covers large, long term, and highly complex interdisciplinary projects. Megaprojects are normally characterized by large investments, a high degree of commitment in the development and implementation phase, and a considerable number of economic resources, mostly provided by public funds. Infrastructure projects in cities, logistics related to high-speed trains, aircraft and airports, space technologies, and renewable energy systems are typical examples of megaprojects. Furthermore, megaprojects have a longitude that calls for foresight. With complex problems, duration and risks of a megaproject follow collaborative complexity especially on an organizational level, and a long-lasting impact on the economy, the environment, and society (Priemus et al., 2008).

The mission-driven education including the SDGs in education requires new teaching and learning methodologies and megaprojects was seen to be an answer in an educational setting, to frame the interaction of students from humanities, social science, health, engineering, and science to work together in a meaningful way. One example of megaprojects is to work on handling waste. More specifically, it can be waste in private households, or it can be waste at the university, or at a more general level in the municipality. Student teams from environmental management, biotechnology, communication, and architecture can be working on the same problem from each their angle. Environmental management will investigate the environmental impacts of the waste management system, biotechnology on handling biomass waste in big cities, student from communication might focus on cognitive understandings and visuals information for the citizens and architecture students might consider the design of waste boxes. Many more disciplines could be working with the same challenge. During spring 22, there is a megaproject on Blue Denmark at Aalborg University, where student project groups are working on biodiversity in the Limfjord and Energy Islands.

There is huge potential in megaprojects, but also some barriers in the introduction of such (Bertel et al., 2022). First and foremost, as students feel insecure about entering this new type of projects. What could be more meaningful than analyzing and solving the complex challenges we are facing and will face in the future, one could ask. For some students, it is however still considered safest to stay within the comfort zone of the discipline, and in this disciplinary view they might even argue that contextualization will be enough.

There are many constrains in the megaprojects—first, the curricula still have disciplinary foci. Consequently, the problem design approach is closest to the disciplinary project view. Students want a 'catalogue' to be sure of what they are buying into by choosing this elective, as they still must comply with the study regulation within their program. Furthermore, like the *leadENG* project, the starting point is typically more a solution in search of problems than the other way around. Following the example from above—why are we handling waste instead of trying to avoid waste?

Waste is the problem, and we must consider what is considered as waste and also why, when, where it is a problem and for whom. However, this cross-cutting problem analysis becomes even more complex as fundamentally different world views of a problem are in play and the decision-making process thereby becomes hard to carry out and coordinate across group. In the first iteration of megaprojects at Aalborg University, the choice has therefore been to accept that the boundary object between the groups is more of a theme.

The analysis of the how different problems and different solutions come together and are mutually dependent on each other likewise is difficult to fit into a curriculum with a rather fixed semester structure. In one semester, it is hard to live up to such ambitions. After the first iteration of megaprojects, it has therefore been chosen to lower the ambition as students are only expected to gain insight in multiple perspectives of solving a similar problem. Furthermore, as megaprojects are electives it is hard to predict which kind of disciplines will be represented; thereby, it is hard to use complex real-life problems as the starting point as the most obvious solution might point to considerably other disciplinary interactions than available among those who signed up. It is a question of how 'mega' it can become in an educational context. Teams of students cannot call a private consultant when in-house competencies are lacking.

Whereas the ambition of a large-scale impact in a megaproject might be questionable in an educational setting, the mission-driven approach taken in the Aalborg University strategy from 2022 to 2016 inspired by (Mazzucato, 2018) offers a framework for relating different projects to a common mission. In doing so, interdisciplinary collaboration between groups addressing the same mission will be enhanced.

The actual implementation and implication of the mission-driven approach to projects is however to be further explored at the institutional level.

In sum, as Aalborg University is practicing a semester approach and not an elective course system, it is more difficult to build in electives where students from different programs are working together in one project. Therefore, we rarely see the interdisciplinary projects with students from a broad range of disciplines working together in one single team. However, specific activities are established with companies as problem owners and end users, e.g., by the use of hackathons pedagogy or other types of workshops. The new initiative has been taken at the institutional level for linking STEM and SSH. This initiative is part of the future mission-driven education where students learn to work across boundaries between disciplines and cultures.

10.4 Fostering Generic PBL Competencies in the Curriculum

PBL embraces new ways of learning and the cores is to let students work on authentic problems in project teams, and experience the process of identifying, analyzing and formulating problems, collaborating with other team members, faculty staff and external stakeholders, organize the work and structure the project from beginning to its end (Graham, 2012, 2018; Kolmos & de Graaff, 2014; Kolmos et al., 2020).

At the two engineering faculties (ENG and TECH) at Aalborg University, intended learning outcomes for PBL competencies have been formulated explicitly in the curriculum and there has been a process of facilitating the study boards and program leaders in how they could define the PBL competencies. The initiative was organized by the PBL Academy with help from the UNESCO Aalborg PBL Centre. Four types of competencies were identified partly by research and partly by practitioner experiences from curriculum development which is further described in Chap. 7. These are (1) problem oriented, (2) interpersonal, (3) structural, and (4) meta-cognitive (Holgaard et al., 2019).

The first three competencies are within PBL, as they all represent relations within a problem-based project including students' interactions with the problem, the people, and the structures of the problem. The problem covers the ability to identify and analyze complex problems like the SDGs with a sociocultural and environmental mindset. The problem is narrowed down to a problem which can be solved within the semester and within the educational setting, which can be disciplinary or interdisciplinary. The interpersonal domain is characterized by the collaborative aspects, which can be influenced by digital, cultural, and personal communication patterns, and where students need to learn how to handle these dimensions in a constructive way. The structural aspects cover project management, knowledge management, leadership, and establishment of partnerships.

Figure 10.5 presents the frame of reference used to inspire and structure the dialogue of PBL competencies. With this starting point, staff and students create their own list of PBL competencies. For staff this has been done in a curriculum development perspective, for students this is done to clarify personal PBL competencies.

As illustrated in Fig. 10.5, there the meta-competencies are a process of observing, reflecting, conceptualizing and develop the above mentioned first-order competencies. It is about creating attention and awareness to the mental maps navigating our relations and interactions in the problem-based project. Meta-competencies are needed, and it is about developing and changing through types of reflection as well as being aware of one's own learning and competency development.

The reflection on the domain specific PBL competencies starts by the observation of practice. This part is facilitated by linking and comparing experiences from practice together with theoretical framing. There is a constant iteration between the practice and the meta-cognitive dimension.

What is new at Aalborg University is the progression of the PBL competencies to improve and continuously develop generic competencies (Holgaard & Kolmos, 2019). Progression can be understood as continuity and interaction or sameness and difference. Continuity or sameness refers to the way past experiences will influence current experiences and learning happens in a continuum of circles. Progression appears when students build on past experiences in addressing new and different situations and interaction adds another perspective referring to the context of learning.

Thereby, students should not only be provided with possibilities to experience a variation of problems, project types and collaborative settings, they should also be facilitated to reflect on the experiences and critically question the relations between actions and situations, to develop the practices based on these observations together with theoretical inputs and be able to transfer these experiences and improvements to personal as well as professional attributes. These attributes however should not stay implicit, they should be made explicit and communicated to align expectations and optimize collaboration patterns in future work relations. Studies of PBL progression at Aalborg University (Holgaard & Kolmos, 2019) have shown that students after the first semester have difficulties conceptualizing and articulating their PBL competencies when these are not continuously reflected in theories.

At Aalborg University, the students have to submit a PBL competency profile based their experiences and theoretical reflection. In this way, students are supported in understanding and practicing the cross-cutting PBL principles from the very beginning at a 5 ECTS course in the first semester of their bachelor. During the study the experience from project work is complemented with workshops (at least 3 during the bachelor program) to support specific intended learning outcomes related to PBL and keep up the momentum and attention to the importance of ongoing reflection on the profession of PBL competencies.

At the second semester of the master study, all students have to hand in a PBL competency profile. Conceptualization of PBL competencies enables a conscious and qualified development of individual PBL competencies, and it promotes visibility and synergy in professional collaborative relationships. Competency profiles can supplement a CV, give a richer picture of a person's competencies, and highlight special positions of strength. Students are facilitated to make their PBL profile based

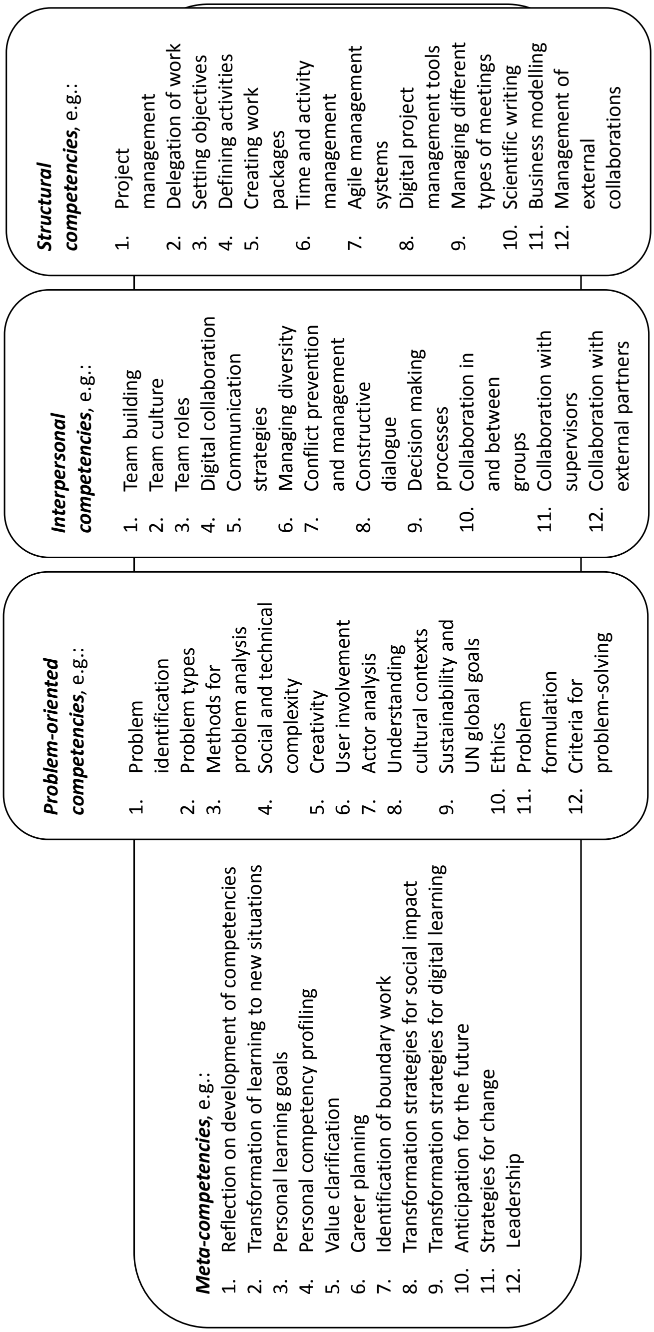

Fig. 10.5 PBL domains and meta-competency

on a guide to make a PBL competency profile (Holgaard & Kolmos, 2019) and a 3-h workshop presenting complementing competency frameworks. Each student gets feedback on their PBL competency profile with the core purpose of initiating further development in PBL competencies in the last part of the study. The guide as well as the workshops is carried out by use of inquiry-based learning techniques, e.g., providing a list of questions to facilitating reflection and transfer (Table 10.2). The most important transfer to facilitate is from personal experiences, of being in a PBL environment, to explicit personal and professional attributes outlining generic PBL.

10.5 Faculty and Staff Development

Faculty and staff development at Aalborg University is organized in a cross-faculty learning lab having a mandatory academic course for assistant professors as its primary activity. Other activities are open for faculty and staff, including introductory courses, brush-up courses and ad hoc activities. Besides, the activities organized by the faculty development unit Learning Lab which is an umbrella organization for all faculties. The engineering faculties at Aalborg University are supported by the Aalborg PBL Centre for Engineering Science and Sustainability under the auspices of UNESCO (UCPBL). The point is to ensure close relation between educational research and practice on the one hand and ensure cross-faculty development of the overall educational profile and PBL principles at a systemic level.

The pedagogical model for educating faculty and staff follows the same PBL format as the ordinary educational activities at the university. As an example, the pedagogical development for assistant professors combines courses and project work. The program includes five obligatory courses and three electives. The obligatory courses are provided in a flipped format with online resources and readings to be synthesized and discussed among peers at a following seminar/workshop (1/2-1 day). Assistant professors in the course are assigned with a peer-group for ongoing discussion, peer-observations, and peer-feedback. Furthermore, each assistant profession is assigned two supervisors, where one supervisor is from the UCPBL, and the one supervisor represents the academic field of the discipline. Thereby, the participants are acquainted with pedagogy at different levels of abstraction, across faculties and practice in direct relation to the programs they are teaching. This unifies three perspectives grounded in fundamental educational research, engineering education research, and teaching practice.

The assistant professors are challenged by applying the project phases and are to make a problem analysis addressing their potential improvement areas and in this problem field they argue for the choice of a problem. They formulate the problem, use course content and supplementing resources to outline a potential solution; they set up a pedagogical experiment and point out the criteria for success and invite peers and supervisors to formatively assess the outcome. In some cases, such experiments have even formed the basis for publishing. Although most participants choose to

Table 10.2 Facilitating questions to activate personal reflections and structured peer-interviews (in the workshop) to clarify personal PBL competencies

	Problem	Structure/ project management	Interpersonal	Meta-reflection
Experience	What types of problems have you worked with in the problem-based project work (concrete/ abstract, practical/ theoretical, stable/dynamic, etc.)? How have you worked with problem solving (specialized vs distributed, sequential vs iterative, operational vs entrepreneurial, etc.)	How have you organized project work in the teams, which you have been a part of? What tools, including digital tools, have you used to plan your project work? What competencies did you gain from working with these tools?	What competencies has the initiating phases of the projects given you in relation to establishing and defining your team (team building, team culture, team roles) Think about your experiences with communication and collaboration in your project work. What competencies has this collaboration given you in terms of working in teams, across teams and with external partners?	Think about your experiences from preparation a process analysis. Which concepts/ sets of concepts were brought into play to analyze problem design, open problem solving, project design, collaboration and learning? What competencies have you gained in this concern to optimize your own learning as well as organizational learning? Have you incorporated reflection on learning styles into your work to balance your own learning style as well as to make synergy of learning styles in teams? What competencies has this given you?

(continued)

Table 10.2 (continued)

	Problem	Structure/ project management	Interpersonal	Meta-reflection
Variation	Are your skills primarily aimed at one type of problem (which one, provide examples) or are your skills broadly aimed at several different problem types (provide examples of the variation)?	Have different problem types prompted different project designs? If so, what competencies has this given you in terms of situating your project design?	Which competencies have you gained in working with people from different backgrounds—disciplines, professions, cultures and which intercultural competencies have you gained from this?	What competencies have you gained in using different reflection approaches to reveal opportunities for change?
Your contribution (strengths/ role/ facilitate others)	What are your strengths in terms of identifying, analyzing, formulating, and solving a problem, and what have been your contributions in this process?	What has been your role in project management in the teams you have been in, and what competencies have this given you?	What has been your primary role in team collaboration?	How have you worked to develop your problem-based competencies through your studies (e.g., personal learning goals, strategies, use of theory and method, experiments, evaluations, new goals), and what competencies has this given you to facilitate your own and others' competency development?

(continued)

Table 10.2 (continued)

	Problem	Structure/ project management	Interpersonal	Meta-reflection
Potentials	How do you think your way of approaching and working with a problem empower you in your future work life?	What experiences has your project work given you in terms of the project manager role, and how will you transfer these experiences to further projects?	Think about your collaboration with external parties during your studies. What competencies has this given you when interacting with, and perhaps even being part of, another organization? How will this affect your skills in future business-to-business relations?	What competencies do you have in transfer learning outcomes from one situation to another, and do you expect to you use these competencies in your future educational and professional practice?

carry out their project alone, there are also examples of participants going together to compare and combine experiences in a gathered report.

10.6 Conclusion

Problem and project-based learning (PBL) offers a framework to enhance student agency as well as a mission-driven approach to learning. Students analyze, formulate, and propose solutions to real-life problems in the context of a larger societal mission such as sustainable development. PBL is a pedagogical approach with emphasis on societal relevance, exemplarity, participant directed learning, and project organized teams. Students go beyond collaboration; they co-construct and learn to handle the mutual interdependence in a team by aligning their project management approach to the problem at hand and the people involved.

Staff facilitate students to work with different types of problems and project types to prepare them for the variation of challenges they will face as future professionals. Students learn how to reflect on the problem-based learning process as a platform for developing the way they critically approach a problem, the way they collaborate and the way they develop themselves as professionals in a lifelong learning perspective. Along the same line, university leaders increasingly direct attention to students' development of generic competencies to work across disciplinary boundaries and address the increasing complexity of real-life problems.

The Aalborg University case also shows that even for a well-established PBL university, offering a systemic framework for complex problem solving, it is a considerable challenge to create a curriculum that emphasizes the increasing variations in engineering practice and makes room for interdisciplinary collaboration across programs. But each system will stiffen and become more instrumental if not there is a continuous development and the development of a systemic PBL institution is as hard as at any other institution. Due to the increasing complexity of the educational systems in their own sense, cross-institutional collaborations thereby become ever more important for learning how we can improve our responses to the urgent challenges we have in the international society.

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Chapter 11
Studios Reshape Engineering Curricula at UTS

As identified earlier, engineering curricula must develop three categories of skills and knowledge—(i) design and problem solving in complex, sociotechnical situations, (ii) the technical knowledge to support the design process, and (iii) the interpersonal skills to support engineering team processes. Traditional curricula, based on teaching the technical knowledge and skills, under-deliver developing the design and interpersonal skill sets.

Since at least 1974, several universities worldwide have implemented various forms of project-based learning (PBL), although PBL has not become the norm in engineering curricula as it has in medicine (Kolmos et al., 2004). The University of Technology Sydney (UTS) has embarked on a bold move to implement design studios in each of its engineering programs, extending the approaches originally developed in the Software Development Studio.

This chapter traces the development of the ideas and approaches and documents the several pivots in our thinking, through the development and rollout of the studio approach since 2016.

The chapter highlights the ways in which we have approached the big ideas in this book, namely the need for interdisciplinary, complex problem solving, the need to create active learning environments, supported by digital tools, in which reflection is a key part of the process, where students see their learning as part of their lifelong career trajectory, and where social, cultural, and environmental issues can be explored, and innovative solutions sought.

However, moving a faculty of 12,000 students and 1000 academic and professional staff in a new direction takes time. This chapter focuses on our implementation efforts from several perspectives—the curriculum restructuring required, the process of bringing academics along on the journey, switching their basic teaching habits, and the engagement of students as partners, which has been the source of considerable inspiration and delight. Hopefully, exposing our processes will provide some ideas for your own change journey.

Perhaps the big idea from all this work is to see **curriculum change as a social process**, in the same way that the learning process has already been emphasized

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as a social process. There is a wonderful indigenous word, **yindyamarra**, from the Wiradjuri people of what is now central New South Wales in Australia (Wikipedia, 2023). Loosely translated, it means to show respect, to give honor, to go slow, and to take responsibility (Sullivan et al. 2016; Wikipedia, 2023). This is a neat summary of our approach.

11.1 Acknowledgement

This chapter is adapted from several contributions from UTS teams and individuals: Hadgraft et al. (2016, 2017, 2018, 2019, 2020).

11.2 Pivot 1—Why Studios?

11.2.1 The Context

We live in a world of constant change and students will likely experience several distinct careers during their lifetimes. There is increasing evidence that graduates will need to be innovative, with creative and critical thinking skills as well as the ability to engage others with their ideas (World Economic Forum, 2020). At a time of significant global challenges, we need to graduate engineering and information technology professionals who are future oriented, with an interdisciplinary approach to innovative problem solving.

UTS is committed to produce graduates who are equipped for **ongoing learning and inquiry** in their personal development and professional practice, who operate effectively with the **body of knowledge** that underpins professional practice, and who are committed to the actions and responsibilities of a professional and **global citizen** (UTS, 2015a).

To formalize these ideas, in late 2014, the university articulated the Learning.Futures model of learning (UTS, 2014) comprised of an integrated exposure to **professional practice** through dynamic and multifaceted modes of practice-oriented education professional practice, situated in a global workplace, with international mobility and **international and cultural engagement** as centerpiece, and learning that is **research inspired and integrated**, providing academic rigor with cutting edge technology to equip graduates for lifelong learning.

Many universities have similar commitments through their learning and teaching strategies. Learning.Futures, however, has mandated key shifts in classroom practice, toward **flipped** learning using the best of online materials (not necessarily creating them ourselves), **collaborative** learning activities, e.g., inquiry-based activities, labs, studios, projects, **real-life** experiences, e.g., internships, community projects, competitions, **authentic** assessment based on authentic tasks, and diagnostic **feedback** (UTS, 2015b).

This university-wide initiative ticks many of the requirements for new learning environments set out in this book, namely student centered, active learning with online support, learning as a social process, brought to life through a practice-oriented curriculum that connects students to their profession.

The initiative has been further supported by a huge investment in campus buildings over the last 10+ years, of the order of AU$1.5B, including a new Engineering and IT building opened in 2014, replete with team-oriented pod classrooms, in which each group table has a large screen monitor to support collaborative work. The building also contains a learning commons where students can study and collaborate between classes.

11.2.2 The Faculty of Engineering and IT Strategic Plan

The Faculty of Engineering and IT has interpreted these intended outcomes as.

> *To create, develop and disseminate world class technological knowledge, equip engineering and IT graduates to contribute in a global environment, and co-create value with industry and the community.*

Within learning and teaching, our intent is to consolidate a **flexible, practice-oriented, and inclusive learning environment** that creates graduates who are sought after and globally competitive, integrate and encourage **innovation and entrepreneurship** into our courses and research, **integrate teaching and research**, focus on key areas where we can make a difference to the world through **interdisciplinary approaches** and the science of engineering.

We have interpreted the above needs to create a set of key **requirements**. Our learning environment shall be based on **personalized learning** as the heart of the **student experience, practice-oriented learning** based on **inquiry** (question asking is a key skill), development of **global** citizens with global perspectives, and access to the professional body of **knowledge**, which is linked to **research**.

11.2.3 Implementation—Studios, Online Learning and Assessment, E-Portfolios

There are **three key ingredients** to building a twenty-first century learning environment to deliver these requirements: first and foremost, it must be personalized. **E-portfolios** have emerged as a high impact practice in which students can co-create (and document) their emerging futures as global citizens (AAC&U, n.d.). Think of it as a continually evolving CV. Whereas a CV is backwards looking—this is what I have achieved in my previous roles—an e-portfolio is also forwards looking—what do I now need to achieve? Where are the opportunities (work placement, studios) where I can build those skills?

This step is all about **personalization** through reflection. Each student continually reflects on their activity to identify learning achieved and learning yet to be achieved. Helpful and unhelpful behaviors are identified. Students consider and adapt these new experiences to their intended career trajectory.

Second, **studios**, projects, and work placements are all *experiential* learning opportunities to develop skills and knowledge. Research from Prince and Felder (2006) supports active, experiential learning. Whereas traditional teaching and learning is often used in teaching engineering fundamentals, the complexity of modern design challenges, e.g., designing and building a National Broadband Network, are not amenable to lectures and tutorials as if there is a right answer. This step is all about **professional practice**.

Finally, we need to recognize that if you can ask the right question, you can find the answer (or answers). **Online learning** is increasingly the norm (see Lynda.com, Khan Academy, Codecademy, Udacity, …) and we can expect that all fundamentals will soon be available online with appropriate assessment tools. Students will be expected to demonstrate mastery of certain modules (beyond a 50% pass) before they can complete certain studios where that knowledge will be required (Lindsay & Morgan, 2016). This is all about flexible **knowledge and skill acquisition** and creation.

If online learning itself hasn't been challenging enough for most academics, **ChatGPT** has now completely upended our educational system—the next giant step in online tools and online learning. If we can ask an AI agent to solve simple engineering problems, why do we spend so much time teaching the fundamentals? Our basic curriculum assumptions are suddenly challenged. The next few years must see radical change in how we think about teaching engineering.

11.2.4 Some History and Context

UTS Engineering has a long history of engagement with practice-based learning (Parr et al., 1997). The revised 1998 curriculum emphasized professional formation, personal development, and academic development. The curriculum became practice oriented and learner centered, embodying environmental and social sustainability:

> *The course components [would] be mutually informing and synergistic, in order that the students experience their development as professional engineers, citizens, and lifelong learners in a holistic and supportive environment*. (Parr et al., 1997)

Many of the elements of the **core subjects** remain: Mathematics 1 and 2, Physical Modelling, Engineering Communication, Engineering Computation, Economics and Finance, Engineering Management (now two subjects: Project Management, and Commercialization and Entrepreneurship). Sadly, 'Engineering through History and Toward Sustainable Futures' has gone and Technology Assessment is an option rather than core (now known as Interrogating Technology). 'Uncertainties and Risk in Engineering' has been replaced by 'Design and Innovation Fundamentals'.

Almost 20 years on we are still grappling with the issue of what is the core of engineering practice.

11.2.4.1 The Professional Practice (Internship) Program

UTS also operates the largest internship program in Australia, now almost 50 years old. More than 1000 students complete an internship each year. Internship is mandatory for all local students. For these students, two six-month placements stretch their four-year degree to five years. Internships are usually taken in second and fourth years, and many students are already employed by the end of their second internship.

11.2.4.2 Software Development Studio (SDS)

Our Faculty's Software Development Studio was designed to emulate a real software development practice, where student teams work on industry-initiated projects. Team members are not peers, but come from different subjects, years of study and degree courses. This mixed team approach mirrors the diverse experience in a real workplace and encourages peer learning and peer mentoring. The teams also have half-a-dozen industry mentors who spend one to two hours weekly, working face-to-face collaborating with the teams. The students learn how to use sophisticated software development tools, such as GitHub, which they may encounter in the workplace, to share code and assets, and HipChat, Jira, and Confluence for communication and project management. Students can get credit toward their degrees through partner subjects or special project subjects.

A recent Grattan report into Australian higher education states that 'IT graduate skills and attributes are mismatched with the labor market' (Norton & Cakitaki, 2016). The report goes on to state that IT graduates often lack the necessary communication and interpersonal skills, which puts them 'at a disadvantage.' One of the SDS's purposes is to address just this issue. Strong emphasis is placed on the deliberate development and formative assessment of teamwork skills, particularly communication and collaboration—learning and working as a social process.

Key characteristics of studio learning environments are real projects, industry mentors, and reflective practice. There is a long tradition in the use of this approach in the creative arts disciplines, which is firmly based in Schön (1983)'s work on the reflective practitioner.

The faculty's definition of a studio is shaped by these Software Development Studios and adapted from the Australian Learning and Teaching Council's Studio Teaching Project Team (2015): '*The studio is a learning community of students, teachers and others such as industry mentors and practitioners, interacting in a creative, reflective process to develop some kind of product, in a physical space that enables collaboration.*'

The key ingredients here are real projects leading to real products, with industry mentors, using collaborative and reflective practice. Whereas Project-Based Learning (PBL) aims to **integrate complex learning** through deep involvement in a **team-based project**, involving design/construction of some object or system, a studio is a **learning community** of students, teachers, and others such as industry mentors and practitioners. PBL is mostly about completing the **product or project**, with some focus on the development of **capabilities**, which are usually technical. Studios are **mostly** about achieving capabilities, which go beyond the technical, with some focus on the final **product.** The development of the product is the journey; it is not the destination.

11.2.5 How Do Academic Staff See Studios?

Two workshops were organized during 2016 to grapple with the introduction of studios in Engineering and IT. The first workshop was mostly aimed at Deputy Heads of School for Learning and Teaching, together with some other key teaching staff. The second workshop cast the net more widely for those who had an interest in exploring the issue.

At the first workshop, staff were asked to identify **key issues** that they felt needed to be addressed. They then worked on some of these issues in small groups, with results as follows:

Purpose is a key issue. What are we trying to achieve? Some of the ideas presented include the getting of wisdom (by both staff and students); learning through doing, to enable the development of professional practice skills; allowing and supporting excellence—students can/will exceed scope and expectations; exploring (and stretching) boundaries—institutional structures and systems currently constrain our understanding of teaching, learning and assessment; integrating a number of existing subjects, e.g., across a semester, or longitudinally across several semesters.

Real projects are seen as vital for studios, including design and build an artifact for a competition, e.g., the Warman competition (Warman Design & Build Competition 2022); cross-disciplinary projects versus subject specific or discipline specific projects; open source (software) projects; research-based projects; Engineers Without Borders (EWB) and other NGOs; greater engagement with industry.

The **student experience** is a key ingredient in the UTS learning model (above). Studios can improve the student experience through **flexibility** for student (career) directions; students need to investigate on their own; they need to move **outside of their comfort zones**; we need to define student roles and support them to achieve the intended capabilities and attributes.

Students should be able to **communicate** in several modalities and work in teams, including across multiple year levels. No two students will have the same experience and mapping diverse student **achievement** will be a challenge, particularly around technical skills. Studios should support in-depth technical learning in threshold subjects.

Student success is a necessary motivator: exciting projects lead to infectious motivation, as many have experienced. The value proposition is that students build a **portfolio** to get a job, with valuable artifacts to show at a job interview. They demonstrate their interdisciplinary skills, their technical knowledge, their client focus, their ability to work well with others, and their self-awareness through reflection.

Failure needs to be reconsidered. Would we be better to speak instead of 'not achieved yet'? Nevertheless, we will need to help students deal with freeloaders in teams or dysfunctional team members and with students with differing levels of commitment.

Reflective practice is not well understood by engineering educators; this and other aspects of studio approaches make it difficult to understand 'studio.'

There are some key **curriculum design** issues: Studios should be supported by online modules to develop knowledge and skills. We will likely need a limited number of non-studio subjects to build core technical capabilities in each discipline. We need a good supply of projects, including bigger picture, world/societal problems and issues—industry backed, mentored, open ended. We want to support different ways of learning—guided, not taught; learning on demand (and sometimes teaching on demand); shorter, high intensity, rather than spread over the semester; collaborative; rule breaking; pull, rather than push learning; enduring projects may work best; lots of learning paths; teacher (and students) negotiate objectives. We want to cross-fertilize from studios to other subjects.

Assessment is a key issue. Assessment should be authentic and contribute to the student's portfolio. Assessment should also be holistic and not based on the sum of a series of assessment marks. There should be credibility (both validity and reliability) in demonstration of learning outcomes. Students will need to negotiate intended learning outcomes, particularly when multiple disciplines are involved.

Grading is an issue that we need to consider or, more to the point, ungraded passes may be a better way forward. Grading leads to teachers' values being imposed on student learning. That may not sit well with a true, student-directed environment built around individual portfolios.

Workload for staff must be accounted for, both academic and professional staff. One concern is **scalability** for large numbers of students. Is there an ideal number for a studio? Space demands will be significant, particularly by encouraging more students to spend more time on campus. Where will they all sit, stand, and work?

Staff skills will need to be enhanced. Tutor training will be required for large classes. These include facilitation skills—students are guided, advised, taught on demand (pull learning); professional skills, e.g., resolving team conflicts; and IT skills.

Engagement of others is essential, e.g., industry, as guests and mentors. **Motivation** will be generated by bringing the faculty together, across disciplines, teaching, research, etc. We need to determine whether we will get buy-in from research-only academics. We will also create a learning environment that is broadly inclusive—team focused: staff and students, young and old; academic, professional, industry mentors working collaboratively—team learning and team teaching.

Timetabling/scheduling faces several challenges—formal classes versus informal team meetings (and space for both); open access to laboratories and equipment—we need a booking system and a certification system for laboratory and equipment access. Fortunately, there is development already happening on this front to allow students access equipment using certification based on their student card.

Space includes the physical, metaphysical as well as tools and resources. Spaces include creative spaces; laboratory space for design, build, test; open access, easily configurable; setup for human interaction rather than overloaded with technology—ambience and atmosphere are important. How specifically does a space need to be furnished and configured? What are the key attributes (group addressable TV screens, large writeable walls)?

Space is also **metaphysical** or logical; after all, it includes many other spaces, e.g., students' homes, as well as transport, cafes, etc. Tools and resources should provide seamless integration of the physical and virtual worlds, e.g., provide a range of computing tools to support team projects, e.g., Trello, Confluence, etc.

It is clear then, that there is much to think about as we introduce studios to our programs.

11.2.6 Reimagining Curricula with Studios

The initial studios were introduced into data engineering (a new program replacing ICT Engineering) and biomedical engineering, each with a different story.

Biomedical Engineering offered distinct challenges. It had already been decided that students would complete two out of four specialties: medical and assistive devices; biomaterials; genomics and bioinformatics; health economics, and innovation. Each of these sequences would be made up of three standard subjects. An easy approach to studios in this case was to combine two of the three subjects into a studio, with the third subject serving to develop necessary skills and knowledge in readiness for the studio.

Students also have four free electives that allow them to undertake a third specialty if that is of interest. Alternatively, they can broaden their knowledge in areas of business management and entrepreneurship, or they may deepen their knowledge in a technical domain such as mechatronics or data science.

These long studios (half the semester's work), of course, come late in the program (third and fourth years). We wanted to include an introductory studio, which would help students to understand why they were studying a broad range of subjects such as cell biology, genetics, physiology, anatomy, healthcare systems, biomedical regulation, and ethics, as well as circuits, signals, programming, and chemistry.

A *Fundamentals of Biomedical Engineering* studio was proposed to run across semesters 2 and 3 (actually two studios), with the intention of students engaging in simple problems from each of the four specialties listed above. This studio introduces the four key areas of biomedical work and creates the reason to learn the medical, engineering, and data sciences needed for work in the specialty studios in years 3 and 4.

The new **Data Engineering** program was introduced in 2017. It represents a rethink from a focus on the tools (ICT) to a focus on *data*, which underpins our business systems, such as the World Wide Web, Google, Facebook, banking, electronic ticketing, accommodation booking, and e-government.

Each of these data engineered systems must satisfy a set of business *requirements*, and it must be built in a user-centered way. The engineered system itself is represented in four parts: data gathering (the user interface); data preprocessing, transmission, and storage; data analysis and decision making; and data presentation and action.

Like biomedical engineering, data engineering is interdisciplinary. Students must learn from several disciplines to create the complex systems required by our modern society. Similarly, both new disciplines have a strong focus on the social context—what is the problem to be solved? How will people use this system or product—the social and cultural aspects? Innovation is critical in these relatively new fields, where new products and systems are being created constantly.

Within this interdisciplinary context, *specializations* include advanced data analytics, real-time systems, image processing and computer vision, Internet science, and cybersecurity. There are three studio pairs (six individual subjects), called Fundamentals, Applications, and Professional, which run across semesters two to eight.

The *fundamentals* stage is the first three semesters, which develop fundamental skills—design, technical, and professional. As well as the usual mathematics and physics, this stage includes Engineering Communication and Introduction to Data Engineering to develop basic design and professional skills such as teamwork and communication skills. Technical subjects included are C programming; information and signals; sensing, actuation, and control; network fundamentals; and introduction to data analytics.

The *fundamentals studio*, which stretches across semesters two and three, gives students an early chance to integrate the various aspects of data engineering. They might design a 4G network for a sports stadium, analyze data from the public transport ticketing system to streamline bus services, or design an app for a new online service.

In the *applications* stage (semesters 4–6), students dive deeply into one or more of the technical specializations above. They may work in a group across the specializations, for example, on an image processing application with aspects of data analytics and cybersecurity.

At the *professional* stage (semesters 7 and 8), students undertake two further studios, this time concentrating on the total problem, carefully investigating organizational and user requirements. This stage is supported by the core subjects in Design and Innovation; Project Management; Economics and Finance; Entrepreneurship; and Interrogating Technology.

11.2.7 Discussion and Conclusions

Engineering education is on the cusp of major change. Fundamental knowledge will soon be learned and assessed online. The free availability of such knowledge from websites such as Lynda.com, Khan Academy, Udacity, and now ChatGPT, is ample proof that the price of such materials is approaching zero.

This fundamental knowledge is also already captured in complex and sophisticated software, which means that students do not need to know how to solve the governing equations, though they do need to know how such analytical tools work, at least in principle, and be able to check that the answers that they have received are reasonable. Miscalculation leading to poor design can be fatal.

Studios are intended to give students the opportunity to apply the basics and use the sophisticated tools to solve reasonably complex, real problems. Students will work with industry mentors, in collaborative teams, using reflective practice as a key ingredient to draw out, for themselves, and with guidance, what has been their key learning during the semester. The learning, not the project, is the central activity.

Finally, the big challenge is to redesign our curricula for these trends. Will curricula eventually be only studios, with online learning supporting each one? Some of them would build basic competencies, such as structural design or design of circuits. Others would extend these skills into more complex applications using advanced computing tools. Other studios would immerse students in even more complex situations, such as resolving transport issues in any of our large capital cities. Other studios would be entrepreneurial, or humanitarian or research oriented. Many or most of the studios would be conducted with an industry sponsor.

Whatever we do, we need to move away from thinking that teaching standard solutions to standard problems is any kind of preparation for the complex future our graduates will face.

11.3 Pivot 2—Students as Partners

In 2017, a new imperative forced the teaching and learning design team to reconsider our approach to studios. The faculty had received unfavorable student evaluations of teaching, which forced us to rethink many of our teaching activities, to ensure high quality student outcomes (QILT, 2018). We decided to aspire to a gold standard, and, from that idea, MIDAS was born—More Innovative Design Able Students. (You'll remember that Midas was the king that turned objects into gold.)

Through MIDAS, we intended to engage students and staff in *authentic learning*, focused on design-rich curricula with a studio spine. Through MIDAS, we wanted students and teachers to be their authentic selves in a true teaching and learning partnership. MIDAS doesn't see students as numbers, but as partners, as people who can learn, contribute, inspire, teach, and create, and it sees teachers as people who also learn, contribute, inspire, teach, and create.

So, MIDAS became a particular focus on learning as a social process, as discussed earlier in this book, to create learning environments that are student centered, active, collaborative, experiential, and reflective. It built on our emerging studio experience and on the UTS model of learning discussed earlier.

11.3.1 MIDAS—More Innovative Design Able Students

MIDAS became a 5-year cultural transformation project that is reinventing curricula, learning and teaching practices, through student and stakeholder engagement, to prepare graduates for the new world of work in the twenty-first century, requiring a focus on innovative design practices.

Many reviews of engineering education in the last 20 years have urged transformation of engineering education (National Academy of Engineering, 2004, 2005; Spinks et al., 2006; King, 2008; Sheppard et al., 2008; Carnegie Foundation for the Advancement of Teaching 2009; Beanland & Hadgraft, 2014; Institute for the Future, 2015).

These international reviews recommended several issues to be addressed such as: complex challenges, interdisciplinarity, creativity and invention, leadership, sustainability, global ethics, and lifelong learning, all of which have been elaborated in this book (Hadgraft, 2017). Curriculum changes suggested included a professional spine, teaching for connection between topics, approximate engineering practice, use case studies, and situate problems in the world. The Henley Report (Spinks et al., 2006) recommended three different kinds of engineers: the technical specialist, the integrator, and the change agent.

Through the MIDAS project, staff and students are engaged as partners in activities and conversations to build capacity for a better learning experience, one that prepares students and staff for these challenges in the future workforce. The Learning Design Team in FEIT is building a sense of urgency to improve the student experience. How might staff create shared values—to discover, engage, empower, deliver, and sustain? The team aims for heightened awareness and traction—traction for transformation of mindset, beliefs, values, and behaviors.

In every conversation we have, in every action we take and in all our endeavors, we aim to create a place where students are at the center of these transformative conversations. Together we aim to graduate students as successful engineers and information technologists of the future, who are more innovative in their approaches, who use design thinking at the core of their practices.

11.3.1.1 Studios and MIDAS

Engineers and Information Technologists use design processes to solve complex problems and to develop new product opportunities (Koen, 2003). The Faculty's

Graduate Attributes, adapted from Cameron and Hadgraft (2010), embody the capabilities necessary for professional practice. A graduate is expected to be able to.

A. Investigate the client's *needs* (with social responsibility),
B. Use a systematic *design* process,
C. Apply disciplinary *technical* skills,
D. *Communicate* and *coordinate* tasks with co-workers and stakeholders, and
E. *Self-manage* tasks, projects, and career development.

Studios provide students with open-ended project opportunities to develop the full range of these professional capabilities. Each student defines a set of intended outcomes in a learning contract and then works to satisfy them, which they then document in a personal, reflective *e-portfolio*. Studios require graduate attribute E in action—self-management and self-learning.

A challenging task requires first an understanding of its *context*, the system in which it is embedded; the client *needs* must be identified, and formally recorded as the *requirements* to be delivered (point A above). These authentic project tasks will usually be developed with industry partners and develop students' social, cultural, and environmental awareness, usually in an interdisciplinary context.

Students use the *design* process (point B), empathizing with the stakeholders to understand the problem as deeply as possible. The initial focus is on problem definition. Is the problem clear? Are the requirements clear and deliverable? (Brown, 2008; IDEO, 2017; Stanford University d.school, 2017). In the process of developing a set of potential solutions and in evaluating them against the requirements, various kinds of technical (abstraction and modeling) skills will be required (point C).

Engineering and IT rarely happens as individual activity—*teams* are required almost always. *Communication* and *coordination* are key skills (point D), likely the most important skills across a career (Trevelyan, 2014). Technology professionals spend around 60% of their time communicating both within the team and across team boundaries.

Self-management (point E) is the key ingredient. Engineers and IT professionals must be able to manage their work, learning, and time to become reliable and productive team members. The studios require students to maintain a reflective journal that will help them to identify strengths and weaknesses, to shape their learning across technical and non-technical capabilities.

Finally, studios help students to see the global nature of engineering and IT practice, both in the context of problems and design opportunities but also in the nature of the teams in which they will work, blending cultural and disciplinary perspectives.

The studio is the vehicle for each individual's learning, as part of their overall career development at the university. Their personal e-portfolio will be a record of their achievement of the graduate capabilities and of their readiness to step into the world of work. It will contain many examples that might be discussed at a job interview, demonstrating the graduate is work ready. Importantly, development of an e-portfolio requires self-reflection, a key professional capability already discussed.

11.3.2 Student Involvement

The key part of the MIDAS project is involving students as partners in their own education. Things get done *to* students in the current university environment. We wanted to change that.

The core MIDAS team is working with the University Innovation Fellows (UIFs), four students from third, fourth, and fifth years across different engineering disciplines. They are the students selected as part of a Stanford University program empowering students to become agents of entrepreneurial change at their universities using *design thinking* as a tool (d.School, 2017). Each of these students undertake online training, followed by a week of immersion in design thinking at Stanford, though COVID disrupted the overseas component in 2021–2022.

The MIDAS team invited the UIFs and friends of UIFs to participate in conversations pertaining to Curriculum Renewal Projects, including a new Mechanical and Mechatronics Program, a new civil engineering program and related submajors, a new Master of Engineering (Robotics), Renewed Core subjects, Innovation studios, and a Student Communication package.

In the next section, students tell their side of this partnership in more detail.

11.3.2.1 Student Run Workshops Using Design Thinking

To uncover the hidden pains and unfulfilled desires of students within our current education system, an adaptation of the *design thinking* process (Empathize, Define, Ideate, Prototype, and Test) has been used in student-led forums and workshops. These forums are developed and run by student leaders to engage their peers and allow them to pinpoint key elements of the current university experience that need improvement. By allowing students to manage these workshops, a friendly and casual environment is established, allowing honest thoughts and ideas to be uncovered and discussed—a crucial element to the success of the workshops thus far.

The data gathered from these workshops has been invaluable in uncovering some true desires of the students. It also allows students to take ownership of problems they are facing and gives them the power to generate solutions, resulting in a sense of pride, satisfaction, and productivity.

This design process can be viewed on a much larger scale and forms a core process within the MIDAS project. By working with students as partners, a very deep level of empathy has been achieved as the students themselves are creating solutions to problems they are facing. In essence, it can turn the university experience into an open resource platform where students are provided with the resources they need to conduct their studios and projects. Students can develop a greater understanding of their own thoughts to allow for reflection on the situations that they face.

11.3.2.2 Outcomes from Student Run Workshops

Student run workshops have uncovered numerous problems which students consider of high importance at UTS: the need for **increased study spaces** on campus for both quiet study and for (noisier) group activities, desire for a **greater university-social balance**, **greater support for student entrepreneurs**, and more **project-based learning**.

Overall, one of the biggest insights into the current student mindset is that students are eager to learn and have a large desire to be challenged and to do well in their studies, but they feel as though they are sometimes lacking the resources and necessary support.

With this comes some surprises, however, as many students are also unaware of some of the opportunities and resources already available to them. It is possible that one of the key outcomes from these workshops is that resources need to be more visible and actively promoted to students to give them the greatest opportunity to make use of what is available.

The second biggest insight from these workshops is the interest that students take once they are exposed to the design process. Once they have gone through a few iterations of the process, many have been very eager to participate in following sessions and are open about their desire to continue shaping the university to suit their needs. This again comes back to the core principle of students as partners.

A university is much more than a business selling education, although some of the same principles apply. When developing any product or selling any service, the business will flourish if its customers are satisfied, and they feel as though they are the company's number one priority. If students can see that they are being put first and that the university is there to benefit them and grow with their needs, the success of those students and the reputation of the institution will follow.

11.3.3 Summer Studios

Summer studios emerged in our conversations with students to simultaneously address student dissatisfaction at having few subject offerings over the summer term, and as a high profile means to launch the MIDAS project. 360 students expressed an interest in participating in a summer studio experience. The summer studio experience is discussed in full in the next section, Pivot 3.

11.3.4 Conclusions to Pivot 2, Students as Partners

MIDAS is about the future state of engineering education at UTS. We believe education strategies and practices need to continuously adapt to a rapidly changing world. Our new curricula will be based on transformative, collaborative, and continuous renewal. Our studio-based curricula embody the key ideas from the international reviews: a professional spine of projects modeled on engineering practice, using real scenarios from industry and community partners.

In MIDAS, students and academics will get to be their true and authentic selves. Our students and academics will engage in genuine, mutual, and authentic partnerships. MIDAS respects that students and academics are on a journey together, both seeking meaning and both teaching and both learning. This is a process of continuous and transformative change for everyone.

MIDAS aims to build the support system required to enable the drivers of our future education. It has a positive vibe that harnesses and attracts staff and students and the wider community. Together, we rely on the design thinking process to help us achieve remarkable feats.

11.4 Pivot 3—Summer Studios

As explained above, summer studios developed out of our MIDAS strategy to create the next generation engineering and IT programs at UTS, using a sequence of studios in every program. More Innovative Design Able Students (MIDAS) is a response to industry demands for graduates who can respond more innovatively to the complex challenges in our world.

The 2016 national Quality Indicators for Learning and Teaching (QILT, 2018) also highlighted the need for summer offerings; it was decided to test our studio concept across a range of disciplines. Summer studios were born. The Associate Dean for Teaching and Learning's vision was that 'students will be transformed by the summer studio experience and will want that learning to continue all year long.' This intention came to fruition, as demonstrated by the data.

11.4.1 Learning Intent

Summer studios are designed to be high energy, high collaboration, project-based subjects where students can engage in real-world design challenges. The studios enable students to negotiate the ways in which they will demonstrate achievement of professional skills while working on real-world projects. Facilitated by a mixture of academic experts, industry and community partners, students work in teams to define problems and develop and implement projects.

Using a design thinking framework, students regularly engage in pitching and critiquing work among peers. Assessment is pass/fail and comprises a mixture of reflective writing and portfolio compilation and discussions.

The subject learning outcomes were modeled on FEIT's graduate attributes (UTS, 2018):

1. Engage with stakeholders to identify a problem.
2. Apply design thinking to respond to a defined or newly identified problem.
3. Apply technical skills to develop, model and/or evaluate a design.
4. Demonstrate effective collaboration and communication skills.
5. Conduct critical self and peer review and performance evaluation.

11.4.1.1 Student Response

18 teams of academics volunteered to conduct a studio in a range of topic areas (Fig. 11.1). Four of the topics were proposed by students and three of them were ultimately led by students, with academic assistance. 168 students subsequently enrolled and completed (20% women and 16% international), across 13 final topic areas. 5 topics did not attract enough enrolments.

Students were able to choose any topic that interested them, creating multidisciplinary classrooms for the first time in our studios. There were no prerequisites for any studio.

Fig. 11.1 Studio topics

1. Activating the Smart City
2. Humanitarian Engineering
3. Challenges and Opportunities of Landfill Design and Reusing closed Landfills
4. Data Science
5. Deep neural networks learning for AI
6. Quantum Computing by Example
7. Brain Computer Interface
8. Control and Automation studio
9. IOT Project using Python
10. DIY medical diagnostic device
11. Robotics rehabilitation studio
12. Vivid 2018 – designing a light display for a festival
13. 3D Printing and Assistive Technology
14. Global Aerospace Challenge
15. Numerical solutions for problems in Structural Engineering
16. Innovation & Entrepreneurship
17. Genome sequencing
18. Natural Language Processing

11.4.1.2 Facilitator Training

Thirteen studio leaders and 21 tutors attended four facilitator training workshops:

Workshop 1—The focus was on transformative experience and how to facilitate beauty in subjects. Three powerful ideas: we learn better by experiencing things; we learn better when we connect new experiences to our past experiences; the experience of art can produce profound shifts in perspective; how might you notice or inject beauty in your studio? This workshop was run by Dave Goldberg as part of his ongoing engagement with our team (Goldberg et al., 2014).

Workshop 2—What does success look like in a summer studio? 3 big ideas: The importance of NLQ—Noticing, Listening, Questioning (and the power of 'what' questions); what is the 'sticky story' of your studio? Why might a student give up their summer to do it? Defining studios. What are they? What are they not?

Workshop 3—Logistics of the Subject—Matters of Assessment. 3 big ideas: Being clear about subject learning objectives (SLOs); understanding the portfolio assessment—how will the SLOs be expressed in your studio? Backward mapping—What will students be doing each week?

Workshop 4—Timing and Mapping out sessions: Structure learning sessions around design thinking stages as inspiration; facilitation from very structured to a large single project with guidance; documenting the interplay between knowledge and skill acquisition and engagement through the project.

The common thread throughout the workshops was to offer practical language and steps to unleash behaviors where it is safe for the studio leader not to know everything about the project. Students would need to become active learners.

There's a new language around design that academics need to acquire to complement the technical knowledge. This impacted the first 2 weeks, where students felt a bit rudderless, not knowing quite what they needed to be doing to understand the problem they had been set.

11.4.2 Key Learning Activities

The summer studios were run intensively, from 22 January to 1 March, with 3-hour workshop sessions on Monday and Thursday afternoons, and informal, group-oriented work in the mornings of those days. The first Monday was an all-day launch activity, including a design thinking workshop conducted by our University Innovation Fellows (UIFs).

11.4.2.1 Sprints and Scrums

The 6-week period was divided into three, two-week sprints: (i) explore the problem, (ii) explore the solutions, and (iii) develop and test a prototype solution.

Students were initially apprehensive about working in the studios with a '*mixed bag*' of students of different ages, degree majors, as well as overall background. Their only prior experience was working in 'groups' to complete an assignment in a traditional class. After the studio learning experience, students asked for more opportunities during the year, to integrate with others in pursuit of a common goal, because they realized that the 'differences within a group allowed us to bring more to our diverse skill sets to complete a project at a higher degree.'

The design thinking approach was a new concept for most students because they realized they had always tried (and been trained) to think of a single, perfect solution when completing coursework; however, they were challenged 'to gather information and study the real causes of the problem [which] helps solve it in a more appropriate way.'

Bringing in this approach to class projects was overwhelmingly promoted by this cohort of students. 'Small teams working together is very powerful and we can be inspired by other people's creativity.' One student put it very neatly: 'Being in a creative environment that promotes and nurtures a design thinking framework has led to an increase in creativity in other parts of my life: creativity breeds creativity.'

Students also want the delivery mode of 'traditional' subjects to include the *narrative* of how the technical knowledge will help in the future engineering subjects as well as future jobs. Students said that 'being able to get a good contextual background of the capabilities and higher-level structure of the topic enabled them to find a wide range of resources to investigate and thus find their own path to become proficient at an otherwise very technical and difficult-to-understand area.' They want lecturers to invite industry speakers as guests into the teaching space because 'that helps to improve thinking and change strategies to get a solution.'

Each week, staff also met in a Studio Scrum, to debrief what was working and not working and what needed to improve. Data were collected every week from staff and students and used as feedback in the next classes, through iterative conversations. The final day included both formal presentations within each studio as well as an Expo of all student work on the final afternoon.

11.4.3 Student Feedback

The following statements from the Student Feedback Survey summarize some of the key student reactions:

> *The subject provided a whole new unique perspective to* **collaborate** *and come up with a solution, which really helped me a lot to step outside my comfort zone and just have a go at it. I would really encourage students to undertake this subject.*
>
> *Open ended scope, **freedom, and creativity**. I liked how I had freedom to learn using my own practical experiences instead of a regimented assessment schedule.*
>
> *[Specific studio leaders] should both be commended on their teaching and mentoring styles. They were very **approachable and always eager** to steer us in the right direction whenever we encountered difficulty.*

*This is the **standard** that should be set for all the engineering faculty's teaching staff. … we [will] have … better learners and ultimately top-class engineers.*

*I really enjoyed the opportunity to work as a **multidisciplinary** team on a large problem.*

*[Specific studio leaders] made the processes of learning really **fun and effective**. Both offered really inspiring ways to enhance my learning. I found the subject rewarding as it enabled me to work with a stakeholder in Nepal and to help communities to improve crop production on their farms.*

*The humanitarian studio gave me a lot of opportunities to develop my **innovation** and **human centered design** thinking as well as expand my network.*

11.4.4 Staff Reflections

For most of the academics involved in summer studios, this was the first time that they had conducted a project-oriented class where there were no prerequisites and where there was a mixture of students from different disciplines and different years, which meant quite a range of background knowledge in each studio cohort.

11.4.4.1 About Students

There were mostly positive comments about the students' engagement in the projects: students were highly motivated and open to new ways of thinking; they were interested in the learning materials and transformed their knowledge; they mastered practical problems and enjoyed the hands-on experiences; they asked many questions (most of the time) though some students became quite frustrated in a couple of studios where they felt they were overwhelmed by new concepts. We hypothesized that many students are not used to asking questions in class. Students grew in confidence, excitement, and courage.

11.4.4.2 The Teaching and Learning Process

Many aspects of project-based learning were identified: There was a steep learning curve in most studios at the beginning; design thinking was key in most of the studios, but this needs greater emphasis; many student groups developed genuine collaboration and group identity through solving the complex problems. They became supportive of each other and made decisions for the benefit of the group. Some students were reluctant to explore alternative solutions, tending to fixate on their first idea.

There were some negative aspects: In some studios, there was a big learning step to get started. However, proper scaffolding of the early stages of the design process is essential.

11.4.4.3 Assessment

The portfolio form of assessment was not well understood by students and some studio leaders. The intention was that students would add to their portfolio each week, including evidence of attainment of each of the learning outcomes as they proceeded through the design thinking process. Portfolios are a measure of progress. Most academics and students need training in understanding assessment as a measure of growth as opposed to evaluation. Assessment should be formative using constructive feedback and not just summative with grading.

11.4.4.4 Facilitators

The workshop sessions run in the months prior to the commencement of the summer studios were described earlier. Despite the workshops, some studio leaders seemed unprepared for some of the challenges, particularly the need to help students get started from their existing knowledge base.

Four of the 13 studios had significant involvement by students as facilitators. The Space, Humanitarian, and Vivid studios were effectively led by senior students, with academics providing overall coordination. The smart cities studio was initiated by a senior student who then provided the industry partner for the project as well as some student facilitation in the sessions. The student-led studios had very high levels of engagement and satisfaction.

11.4.4.5 Outcomes

At the end of the 6-week session, we asked our studio leaders what they should stop and start with their normal teaching, based on their summer studio experience. They said they wanted to 'stop strictly following the topics in a syllabus while putting more effort into integration with other subjects and other disciplines; stop giving too much structure; stop lecturing; and start facilitating.'

Other things leaders wanted to 'start' were 'more curiosity; multidisciplinary learning opportunities; collaborate with peers more; give students more independent work such as projects; start giving students more structure around design thinking and systems engineering; start getting engineers to communicate better; start co-designing studios with students and academics.'

Overall, it was clear that the studio leaders favor providing students with a *transformative learning experience*. They realized that not every subject must teach students to master the fundamentals before they have the chance to solve real problems in that area. Why wait? They observed that students have the 'capability to master a practical problem from their perspective in terms of the fundamentals, the hands-on skills, the research and development, while contributing as an individual member to a collective project': 'Observing this capability and the pleasant feelings from the students in their acquisition of knowledge through studio learning remains the best and unique reward for me as an educator.'

11.4.4.6 Final Comments

Our first aspiration for summer studios was to create a community of practice. We believed we were entering the very first stages of cultural change to achieve curriculum renewal. We all know that it takes much longer than one long hot Aussie summer to change teaching and learning practices. Nonetheless, in a small way, we have introduced new *language* into the faculty through the summer studio experience.

Moreover, we know the quickest way to change a system or build a new system is to use this new language. The new language encourages academics to embrace this idea of active learning, turning up authentically, and working together to try to improve something. Once we use *sticky* language to tell a new story and be prepared to change the story as people react to it, we teach people that it is okay to bring about change.

People will have their own stories. In every case, the new language will be rehearsed and communicated repeatedly. This process creates transparency, that we are working on things together to make things better, and that we are listening to students. There is a partnership.

Our second aspiration is to create a studio where academics can enroll and get the 'experience of the experience' while training how to be an effective studio facilitator. The biggest learning outcome is that studio leaders need to be better trained and certified. Once they themselves qualified as a studio leader, they earned the opportunity to run a studio in summer 2019. We might frame the chosen as an elite team of advanced facilitators of the future. They will design and facilitate the learning experiences of the future.

11.5 Pivot 4—Mechanical and Mechatronics Engineering

11.5.1 Introduction

Summer studios became a great introduction to studios for both students and academics. In 2018, we began the work of transforming the mechanical and mechatronics programs to include a studio spine, to embed complex problem solving and emerging educational technologies and pedagogies.

This section serves as a roadmap for similar transformations elsewhere. In many ways, curriculum design is not the major issue. Curriculum *change* is the major issue, first for our academic staff who are used to teaching in a particular way, and second for our students, who are often comfortable with an exam-driven system that does not serve them well in the long term. Learning the standard solutions of the past does not prepare a graduate to invent new solutions for a changing, complex future.

11.5.2 Consultation

11.5.2.1 Step 1: Industry

At the November 2016 Program Advisory Board meeting, we laid the foundation for revising the mechanical and mechatronics engineering programs. Four key questions were addressed: *global trends*, the changing *nature of work* and *projects*, the kinds of *capabilities* required in this changing environment, and the kinds of *graduates* for the future. Among the 18 industry representatives at the meeting, there was collective agreement that skills that the university should provide included ‘hard’ competencies such as costing; contracts; commercial/legal/regulatory; designing to specification; hands-on, prototyping skills and ‘soft’ skills such as confidence; critical thinking; arguing your case; persistence; remote communication; customer centricity; teamwork and leadership; interpersonal skills.

11.5.2.2 Step 2: Students

A small group of student representatives also provided input during 2017. They saw positives in the old, more traditional approach as one that’s familiar, coming from high school. They recognized that the current design and build subjects were helpful (Introduction to Mechanical Engineering, Mechanical Design) with a hands-on approach in some other subjects (e.g., Manufacturing Engineering, Advanced Manufacturing).

They saw negatives in the old curriculum, which they saw as not as hands-on as students are led to believe. Hands-on workshop time is lacking. Design philosophy is not well implemented in most subjects. The degree as it is, is not a realistic representation of real-world engineering.

They saw the positives of a new project-based, studio-based curriculum as modeling real-world mindset for engineering: learn the fundamentals first and develop advanced skills when necessary for completion of projects, maybe with the assistance of online modules. Academics should mentor students in the projects as required. This mentorship is what happens in engineering workplaces; why not start at university?

11.5.2.3 Step 3: Staff Input

A subsequent staff meeting sought to gather input from as many of the staff (academic, technical, administrative) as possible, using the themes of: Trends, Strengths, Methods, Concerns, and Opportunities.

The discussion of **Trends** affecting mechanical and mechatronics engineering quickly opened the breadth of the challenges and opportunities for these disciplines—safety, robotics, energy systems, autonomous vehicles, data-driven systems, Internet of Things, and environmental sustainability. The breadth of these challenges highlights the difficulty of designing mechanical and mechatronics programs to enable graduates to move into any of these fields.

Our teaching **Strengths** were seen to be well aligned with the proposed direction for more studio-based programs. It was felt that student interaction is already structured to provide a reason to come to campus/class/lab (with room for improvement). There are small group, face-to-face learning activities, supported by blended learning in a friendly environment. This is the essence of learning futures (discussed earlier in this chapter). Academics endeavor to provide constructive feedback and offer many teamwork activities in which time management skills, critical thinking, and independent learning are encouraged.

Graduate employability is at the forefront of curriculum intentions across the university. (This Faculty has an internship program that gives all single degree students 2 × 6-month industry placements during their degree). Industrially relevant projects and hands-on practical, active learning joins theory and practice.

11.5.3 Curriculum Design

The current mechanical engineering program runs over 10 semesters, including two, 24-week work placements (Fig. 11.2). A key insight has been to divide the curriculum renewal into **five main themes**: structural design; machines and mechanisms; system dynamics, vibration, and control; thermofluids; and manufacturing. This reduces the complexity of the task, with each theme assigned two subjects that prepare students with the basic knowledge in that theme.

Consequently, Fig. 11.2 has been color-coded to indicate the themes (groups of subjects) that make up the curriculum: mathematics/computation (pink), thermofluids (green), materials and structures (blue), core management (brown), machines (gray), design and project subjects (yellow), and electives (white).

Some other engineering programs in our Faculty have used three pairs of studios: fundamentals, applications, and professional stages (data, electronics, electrical disciplines, discussed earlier). This model was adopted during the development of the final version (Fig. 11.3). There is now a continuous 'spine' of projects and studios (the yellow subjects in Fig. 11.3) through all eight taught semesters.

Note that the theme-based subjects and studio sequence have absorbed former 'silo' subjects such as Chemistry and Materials Science and Fundamentals of

First Year			Second Year			Third Year			Fourth Year			Fifth Year	
Stage 1	Stage 2	Summer	Stage 3	Stage 4	Summer	Stage 5	Stage 6	Summer	Stage 7	Stage 8	Summer	Stage 9	Stage 10
Mathematical modelling 1	Mathematical Modelling 2		Engineering Commuptations	24 week Internship		Fluid Mechanics	Thermodynamics		Heat Transfer	Engineering Research Preparation	24 week Internship		Engineering Capstone
Physical modelling	Chemistry and Materials Science		Mechanics of Solids			Strength of Engineering Materials	Engineering Economics and Finance		Engineering Project Management	Entrepreneur-ship and Commercial-isation			Sub-Major/Elective
Engineering Communications	Introduction to Electrical and Electronic Engineering		Manufacturing Engineering			Machine Dynamics	Dynamics and Control		Mechanical Vibration and Measurement	Sub-Major/Elective			Sub-Major/Elective
Introduction to Mechanical and Mechatronic Engineering	Fundamentals of Mechanical Engineering		Design and Innovation Fundamentals			Mechanical Design 1	Mechanical Design 2		Advanced Manufacturing	Mechanical and Mechatronic Design			Sub-Major/Elective
			Engineering Practice Preparation 1			Engineering Practice Reflection 1				Engineering Practice Preparation 2			Engineering Practice Reflection 2

Fig. 11.2 Current mechanical engineering program

Proposed Mechanical Eng (from 2022)											
First Year			Second Year		Third Year			Fourth Year			Fifth Year
Autumn	Spring	Summer	Autumn	Spring / Summer	Autumn	Spring	Summer	Autumn	Spring	Summer / Autumn	Spring
Stage 1	Stage 2	Free	Stage 3	Stage 4	Stage 5	Stage 6	Free	Stage 7	Stage 8	Stage 9	Stage 10
Mathematical modelling 1	Engineering computations		Mathematical Modelling 2	24 week Internship	Design and Innovation Fundamentals	Engineering Economics and Finance		Engineering Project Management	Entrepreneurship and Commercialisation	24 week Internship	Sub-Major/Elective or Mech Choice Studio
Physical modelling	Applied Mechanics and Design A		Thermofluids A		Applied Mechanics and Design B	Materials and Manufacturing B		Dynamics, Systems and Control A	Dynamics, Systems and Control B		Sub-Major/Elective or Mech Choice Studio
Introduction to Engineering Projects	Materials and Manufacturing Engineering A		Machines and Mechanisms A (kinematics)		Thermofluids B	Machines and Mechanisms B		Sub-Major/Elective or Mech Choice Studio	Engineering Research Preparation		Sub-Major/Elective or Mech Choice Studio
Introduction to Mechanical Engineering	Introduction to Mechatronics Engineering		Mechanical Design Fundamentals Studio 1		Mechanical Design Fundamentals Studio 1	Mechanical Design Fundamentals Studio 2		Application Studio B	Design in Mechanical and Mechatronic Systems		Engineering Capstone
			Engineering Practice Preparation 1		Engineering Practice Reflection 1				Engineering Practice Preparation 2		Engineering Practice Reflection 2

Fig. 11.3 Proposed studio model for mechanical engineering

Mechanical Engineering and the former Design subjects. There are now two *Introduction* subjects, for Mechanical and for Mechatronics. These are project-based subjects that introduce basic design and build concepts and skills alongside fundamental knowledge and competency development in mechanical and mechatronics engineering.

The new program is made up of the five technical themes: structural design; machines and mechanisms; system dynamics, vibration, and control; thermofluids; and manufacturing. Each theme has two subjects (A and B) to cover basic theoretical concepts, in practice-based contexts. There are small projects in each of the A and B subjects.

The school is currently engaged in a process of collaborative design whereby teams of academics associated with each theme propose names, topics, design/practice projects and references to relevant standards for each subject and studio within a theme. Providing students with increased and more authentic exposure to and familiarity with engineering standards has been a recurring recommendation from our industry partners. This aligns well with the overall framework from the university and the Faculty, as described earlier.

Two introductory studios (Mech Studio A & B) then immerse students in basic design around machines and thermofluids systems. In the Application and Professional studios across stages 6–10, students choose from several topic/project options within the studios. These topics/projects could be from one of the five themes or from a related theme, e.g., robotics or acoustics. The open nature of the studios provides the opportunity to engage with industry and have students working directly on industry-based projects with industry mentors or to work in a similar way with research groups in the faculty.

11.5.4 Summary

Curriculum transformation is difficult. We have applied design thinking to the process and engaged our key stakeholders—industry friends, students, and staff. Key questions for our industry supporters have included: what are the big trends affecting your company? How is the nature of work changing? What capabilities will graduates need in your new workplace? Our studio-based curricula provide students with the complex challenges typical of the twenty-first century. Students begin their studies in their discipline and broaden themselves as they progress through the studio spine. This approach has transformed student learning and also academic teaching.

Through these curriculum changes and staff development, we have moved toward more multidisciplinary, complex problem solving that embraces the human-social-environmental aspects of engineering and IT. The new learning environment is more student centered, requiring active engagement with problems requiring sophisticated solutions. Students use a range of online tools to support their learning, their analysis, and their team processes. Learning in this environment is very much a social process. Reflection, for each student, and each team, is critical to students developing self-awareness of their strengths and weaknesses and areas for improvement. Students have become much more aware of the importance of the full range of skills, particularly collaboration and communication skills.

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Part IV
Invitation to Change

We now present a 10-point summary of the key actions that we need to adopt as engineering educators, linking the action items to the three mindsets we established earlier. Each point is expanded in the final chapter of the book.

Future Interdisciplinary Mindset

1. Engineering curricula should be design-oriented and interdisciplinary, with a focus on solving open-ended, complex, human challenges.
2. Engineers must adopt socio-cultural-environmental and innovation mindsets.
3. Interdisciplinary knowledge is the cornerstone for solving these complex human challenges—excellence in a single discipline must not be the only focus.

Interdisciplinary Learning Mindset

4. Learning environments must facilitate learning as a social process.
5. Experiences, variation and reflection should be practiced throughout the curricula.
6. Students and teachers need generic and meta-competencies to work across interdisciplinary boundaries.
7. Students must be encouraged to create their own lifelong learning trajectories.

Disciplines and Digitalization

8. Disciplines must embrace interdisciplinarity.
9. Digitalization is changing our earning environments and the engineering profession!

A call to action

10. Each institution must find its own way.

Chapter 12
Invitation to Change

12.1 Introduction

We invite you to make changes in your engineering programs.

We acknowledge the many challenges facing humanity and believe that engineers have a particular responsibility to act and create mitigations, if not solutions. In our writing, we have emphasized the importance of broader education and providing agency for students, and we recognize that implementing such changes can be difficult when the root causes of the problem are not clearly identified. In addition, we live in paradigms that make it hard to make and accept changes. Thus, incentives or, in some cases, dramatic losses may motivate people to make the change. We are really in need of a paradigm shift. We urge you to participate in creating this shift.

We hope that this book will serve as a wake-up call, highlighting the urgent need for change. To that end, we have summarized the key changes required, which are elaborated on in the preceding chapters. These chapters contain in-depth discussions and examples. The ten points listed here are not independent but rather form a network of intellectual tasks that are complementary and urgent.

In Chapter 1, we identified four key challenges that must be addressed in the future development of engineering education. The challenges are.

- *A **sociocultural-environmental** challenge, which requires us to embrace diversity and ethics.*
- *The **sustainability** challenge, which necessitates managing resource flows and ensures quality of life for future generations.*
- *A **digital** challenge, which involves aligning engineering education with emerging engineering disciplines and digital platforms, including AI.*
- *An **employability** challenge, which entails educating candidates who can adapt to changing the work and market conditions and serve as agents of social change.*

In addition, we summarize three essential mindset shifts that must be integrated into engineering education to address these challenges. These mindsets include (a) an interdisciplinary future mindset that emphasizes design, systems, and complexity,

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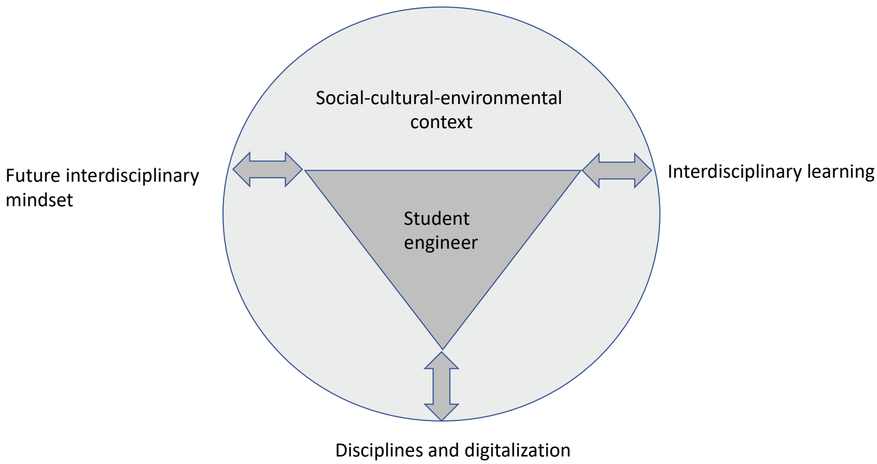

Fig. 12.1 Conceptual framework for mindsets

(b) an innovative interdisciplinary learning mindset that matches evolving workplace needs, and (c) a recognition that disciplines are being transformed through digital engineering, which we must embrace.

We expand on each of these themes below (Fig. 12.1).

Future Interdisciplinary Mindset

12.2 Engineering Curricula Should Be Design Oriented and Interdisciplinary, with a Focus on Solving Open-Ended, Complex, Human Challenges

All human systems are open ended, complex systems. There are no single answers that we know of, but different solutions, many of which are required. In addition, there is a danger of reducing complex issues into complicated ones and attempting to take on parts of the issue through disconnected solutions. Reductionism is tempting and is successful in science. But this is the wrong approach when dealing with human challenges. Students learn to solve exercises, each of which might be addressing a small piece of a big puzzle. This creates a methodology that is difficult to unlearn or even to question.

Most science is built on the Newtonian approach of cause and effect and assume time reversal for many of their observed phenomena. Unfortunately, complexity defies time reversal and what happens in human societies does not occur again, although sometimes it feels like déjà vu. Realizing that makes our hindsight interesting but not necessarily useful. Students need to understand and classify the different human systems and not confuse our ability to fix complicated systems, like electromechanical ones, with trying to fix a complex traffic snarl on a bridge using similar approaches. Students must keep in mind that most human challenges cannot be reduced to complicated systems challenges.

Addressing human challenges requires systems thinking and students should learn systems mapping and analysis. Design is the method to define and create innovative solutions. Design methodologies must be embedded in all courses. Thus, the design process becomes second nature. The technique of foresight should also be part of all engineering curricula. Both design and foresight are easy to introduce in engineering courses and can create enjoyable interchanges that facilitate learning and sociability.

Our mindsets live in paradigms which stick around for a long time. To be innovative, we need to tame these paradigms and question their validity. Students must be taught to be critical thinkers, open for diverse opinions and ideas. Our heuristics are entrenched in our mental models and, nowadays, they are extended by social networks and artificial intelligence. To be productive and social, we need to keep heuristics in check, and students, working in teams, need to call on each other when a heuristic seeps in.

12.3 Engineers Must Adopt Sociocultural-Environmental and Innovation Mindsets

Design is a problem-solving mindset. Students must be very good at applying the design process and implementing innovation. Design also serves as a process to identify the problem and the stakeholders. We have argued that engineers need to learn to become holistic problem solvers and achieve understanding of the impact of technology on humans and on nature. Ethics and sustainability need to be integrated within human needs as part of the engineering design process.

Engineering education needs to use science as a foundation but must move beyond the theoretical mode and include real-world challenges and their contexts. This requires deep understanding of the problem and interdisciplinary knowledge. The curricula need to include generic and meta-competencies to help students to cross the disciplinary boundaries and to participate on interdisciplinary teams.

We also need to be cautious not to consider markets and jobs as the main drivers of knowledge. Knowledge and pedagogy must not be squeezed to fit the cast of economics. Education should not be reduced to a business model. Do we educate students to obtain the best salaries or to make them better citizens? Do we want them to make the best gadgets or the best solutions?

Engineering pedagogy must shift to incorporate not only technical skills, and the design of well-defined technical problems, but also to give the students challenges that require them to grapple with complex problems. Learning how to design and implement complicated devices or artifacts is not enough for the twenty-first century engineer. The human context is critical for every design. A water purification plant needs to be understood in its social context, whether it is in a developing country or a technology-rich country. How to maintain such a plant must be part of the design process. Context is not easy to design for and interactions across cultures will be required.

Consequently, we need interdisciplinary learning, a second mindset shift.

12.4 Interdisciplinary Knowledge is the Cornerstone for Solving These Complex Human Challenges—Excellence in a Single Discipline Must not Be the Only Focus

There is tension between the importance of disciplines and their boundaries. Keeping the institutional cultures intact seems to be desired. In addition, there is tension between theory and practice as well as the degree to which students should incorporate human needs in their analysis. Things have shifted enough, and we cannot teach the content we learned many years ago, and with similar pedagogy.

Basically, there is tension in creating the new direction of engineering education. Should we hold to the content that built most of our civilization, or should we look into the future for insights. Changes are here, and we need to cope with some undesired outcomes of the digital technologies and integrate artificial intelligence wisely. AI will enable different skills and may render some skills obsolete.

We need to keep the essence of the critical liberal arts education and uphold societal values that are aligned with sustainability and human thinking. Design, systems thinking, and priority on problems might enable strategies and content for new directions for higher education. These will also engage the universities with society and create content that is aligned with the realities of interdisciplinary knowledge and competencies.

Interdisciplinary Learning Mindset

12.5 Learning Environments Must Facilitate Learning as a Social Process

In this book, we advocated that learning is a social process that enables engineering students to become effective citizens.

Learning as a social process involves culture and systems. The learning system and the pedagogies create social values by using different learning strategies, including digital ones. The curriculum contains content knowledge as well as pedagogy, which form a rich intellectual environment that influences students' knowledge and competencies.

Throughout the book, we emphasized active learning, inquiry learning, project, and problem-based learning and design-based learning. These learning strategies are team-based and collaborative methodologies. As engineers work in and on systems, the individual engineer needs to work, collaborate, and communicate within teams. A significant part of these new learning approaches will happen beyond the classroom.

From learning theories, different active learning methodologies, and different institutional practices, it is clear that there is no single successful method for educating students, nor in how to structure the curriculum or how to organize or frame students' learning processes. Variation is a key concept in terms of the basic learning approaches. Pedagogies and curriculum constructions vary as they should. With these variations we pay attention to transparency and reflection.

By transparency we mean that students are informed about the expectations of the new teaching and the type of learning experiments or methodologies to be used. Reflection is the opportunity for students to indicate their preference to a particular learning and how it was achieved. This feedback loop is essential to understand the effectiveness of the new designs and the appropriateness of the methodologies. We must keep the learner at the center of our attention.

12.6 Experiences, Variation, and Reflection Should Be Practiced Throughout the Curricula

The sociocultural experience is a fundamental platform for building knowledge. The role of these experiences is to influence students' values, which influence their capacity to learn. In general, students base their knowledge on their already existing conceptual frameworks and their experiences. A learner's previous experiences with the world and life, physical, social, or imaginary, represent a conceptual frame reference for giving meaning to new information.

The way we learn and the experiences form our identities, values, and, of course, create our learned competencies. More student-centered curricula in engineering education should apply a variation in the learning methodologies ranging from lectures to projects, taught exercises, and self-guided ones. In addition, these variations include different levels of design projects, starting from more narrow problems to open-ended complex problems. Also, different student interactions would include small teams to large ones, and even a team of teams working on the same problem. Such experiences create a wealth of learning opportunities, which the student will carry with them throughout their career. **So, variation and reflection are critical components of future learning environments.**

Variations go together with reflections and comparisons of gained experiences. However, such reflections need facilitated processes. With such processes, students can achieve an understanding of the skills and competencies they have learned in the various projects and other learning environments. Without comparing and reflecting, variation may cause confusion and negatively affect competency development.

It is important to note that with facilitated reflection, students can learn generic competencies such as collaboration, communication, organization, leadership, and management. These generic competencies are transferrable to different settings and students need to learn how to make such transfers. But transferring knowledge is not enough. We seek transformational knowledge. As the systems are becoming more complex, the commonality of similarity decreases. Transformation demands more than transfer, as knowledge is to be embedded and invested in practice and implies the ability to select, adapt and develop one's competencies. In other words, meta-competencies are needed.

The learning of transformation of generic competencies implies the learning of meta-competencies, and the learning of how to develop generic competencies, for both students and academics. Guided learning is a must to achieve these goals.

12.7 Students and Teachers Need Generic and Meta-Competencies to Work Across Interdisciplinary Boundaries

Interdisciplinarity is a must for complex problem solving and joining an interdisciplinary collaboration is not an easy path. Depending on the degree of interdisciplinarity, from a narrow one, sharing different knowledge paradigms, to a broad one across engineering and humanities or social sciences, the collaboration will face different and sometimes significant challenges.

In narrower interdisciplinary approaches, in which systems approaches can be used, the collaboration might face manageable challenges. But in a broad interdisciplinary collaboration, challenges might be severe, and participants from different disciplines might have different terms and jargons causing huge difficulties in understanding each other.

Having clear and transparent boundary objects and facilitating the learning by using generic and meta-competencies are good measures to crossing the interdisciplinary boundaries. For example, generic competencies such as collaboration learned in disciplinary context can be transformed into an interdisciplinary context by analyzing the problems, the context, the needs, and the difficulties in understanding the specific languages belonging to the different disciplines. These, of course, require significant planning and guidance.

The facilitation of generic and meta-competencies needs brokers who have an interest in transcending disciplinary boundaries and have the ability and conditions to do so. Brokering is hard work. It is not at all easy to enter a new field of epistemological understandings and create as much common ground to ensure a platform for collaboration and at the same time maintain the needed diversity to address the complex problems. It is not a question of merging disciplines, but instead to create an environment for constructive collaboration across boundaries.

Nevertheless, we also need to remember that each student's learning journey is unique and we need learning environments that encourage students to build their own learning and career trajectory.

12.8 Students Must Be Encouraged to Create Their Own Lifelong Learning Trajectories

Nurturing students' motivations and giving the students agency to create their own career directions is of utmost importance. In some universities, students learn how to co-create a course or a learning path in collaboration with others and on their own. But this might be easier said than done, as some disciplines have a significant number of required courses. In addition, students often have significant course options to choose from. Furthermore, students need to learn how to direct their own learning, both individually as well as within the collaborative teams.

When placing students in the center of the learning process, there is also a need for the faculty to learn to orchestrate students' learning, both in formulating the curriculum through learning outcomes that have broad methodological terms, and in managing the students' abilities to perform.

Facilitating or advising learning for an individual or a team is very different from lecturing or downloading information. Academics need to learn different skills. Practicing facilitation of learning does not come easily. Most teachers perfect lecturing and providing homework. These skills need to be modified to the new system of asking questions that guide learners. Questions like 'what-if' and 'what happens if,' and 'why,' and give parallel examples to work on, need to be practiced.

This becomes even harder when guiding students working on complex problems where it is not possible to know all the elements of the system nor to understand their relationships. Practicing such interactions between the instructor and the group may take some time, but it is doable, especially when the instructor encourages peer-to-peer learning.

This will also require that curricula have touch points where students from different disciplines and instructors, who have different backgrounds, work together. Co-teaching can be fun and exciting when some faculty confess that they 'do not know'. This brings a level of humility and closeness between the members of the working team.

Fortunately, this is the right time to practice such notions. In fact, there has never been a better time to undertake the task to integrate student-centered activities with active learning methodologies. In engineering education, variations of project-based learning are one of the answers to the challenges of changing the curriculum. Today, students have access to the world's knowledge at their fingertips. Now, what they need to learn are the process skills of complex problem solving and how to realize that these are open ended, with no unique solution.

Disciplines and Digitalization

12.9 Disciplines Must Embrace Interdisciplinarity

We have argued earlier that deep learning, by digging into a particular discipline, must be combined with a learning strategy to increase the ability of students to relate to, and connect with, other disciplines in a meaningful way. This is not a question of reducing students' learning of core technical competencies; rather, it is to create synergy in the learning process, so that students will experience the inevitable interaction between technical skills and contextual application.

Therefore, a dialogue between what is disciplinary and what is interdisciplinary is needed. To foster this dialogue, it is important that potential tensions are acknowledged and brought up front. Along the same line, already existing strategies to handle the T-shape of the future engineer have to be revisited. Is interdisciplinarity seen as a matter to integrate into the discipline from other disciplines? Is interdisciplinarity seen as an incentive to design new disciplines by merging components from different disciplines? In this book we have suggested a more collaborative and flexible approach to face the complex and ever-changing problems ahead.

Therefore, we do not believe that there is a contradiction in the specialization versus the generalization. We believe that they are complementary parts working to address complex systems. We do not argue in favor of replacing or reducing the core of each discipline, but we recommend a restructuring and recontextualizing of the disciplines through design-oriented curricula focused on creating an understanding of complex problems through systems analysis.

12.10 Digitalization is Changing Our Earning Environments and the Engineering Profession!

Digitalization is changing learning and the practice of the disciplines, through several shifts:

1. Digital tools are transforming learning.
2. Digital engineering is transforming engineering practice, e.g., digital twins.
3. Artificial intelligence, and other technologies, are transforming everything!

On the learning dimension, we need to merge the digital communication tools with active learning. Distance learning is not the norm at most campus-based universities, but the use of blended modes and flipped classrooms will become dominant. Thus, the learner is met with new challenges of organizing learning individually, as well as collaboratively with others by face-to-face interactions, as well as digitally, as in the workplace.

The pandemic has hastened the adoption of online learning in most universities. Students are seeing the advantages of moving through the learning materials at their own pace, rather than at a pace set by lectures. This flexibility is yet to be taken advantage of; it fits neatly in a project-based curriculum where students learn as required, rather than just in case. It also hastens the adoption of flexible learning in the workplace, supporting an apprenticeship approach where students work and learn simultaneously.

Digital engineering is also transforming engineering practice. Digital twins are a prime example, enabling large engineering projects to be modeled in space and time dimensions. Both designers and constructors can use such models to observe system behavior, including the sequence of construction—build once digitally and a second time materially. Such models can then be used for long-term operations and maintenance of complex engineering artifacts (infrastructure, aircraft, transport systems, telecommunication systems, electricity grid, etc.).

These models are the culmination of engineering software developments that started in the 1950s. These early models were analysis focused and simulations of various kinds. As time has progressed, models have become data-integrated, using geographical information systems (GIS) and other data sources. Consider all the various ways in which analysis tools are now integrated with Google Maps, for instance.

The challenge for engineering educators is to balance the time spent on learning the fundamental engineering principles versus the time spent on applying the principles using powerful software tools. This also requires educators to keep their computing skills up to date. In addition, educators need to design effective learning activities (interdisciplinary projects) where students use the tools as well to verify that the answers are meaningful, based on fundamental principles as well as societal needs.

It is important to discuss how to address complex problems and system thinking in a blended engineering curriculum that utilizes digital tools. As we face a large number of unsolved challenges, it is urgent that higher education create strategies to educate students who can contribute to the future solutions.

The interaction between society and academia is one of the core elements in terms of letting students identify societal problems or interact with society in other ways. Students learn how to identify relevant problems and propose different path to address them. Through such challenges, students develop capacity to determine what kind of scientific knowledge they need to learn. Students' voices should be taken seriously to modify the content of the curriculum.

Critical thinking becomes a necessary element embedded in both the process of analyzing and solving problems. With a focus on problems or challenges, students will need to learn to ask questions and seek paths to define the core of the problem (i.e., the root cause), determine the stakeholders and how they affect the process of creating solutions.

With AI and its encroachment on our lives, learning to critically endorse it and utilize it become critical skills. Group work with AI can be beneficial. Integrating AI with the curriculum is an urgent task and it is essential to include ethical and cultural considerations.

The *OpenAI* platform interacts in a conversational way with people, which makes it important, as it has easy-to-use, advanced technologies such as *ChatGPT*. This *chat.openai* application offers answers that might simplify issues and attempt to reduce complex issues into complicated or even simple ones. But it also creates quick and interesting answers, which could be compelling. This is the beginning of a significant change where AI takes the helm in creating information that, on the surface, looks useful and true. Through human chatting and directing the AI, the machine obtains context and possibly takes thoughtful directions. Students should be encouraged to work with the machines but at the same time they need to be taught to be critical thinkers and use discussions and reflections to harvest the AI products in ethical and productive means.

Context is not to be taken lightly, AI is not good, yet, in integrating context. Students need to understand their ecosystems and learn how their disciplinary knowledge relates to the broader context, and to the overall systems. But we must work in directions of embracing AI as it is there to be developed further. Connections among parts of the systems, their feedback loops and time delays must be part of the analysis and students must become critical learners and question what AI can do.

The intrusion of AI adds new layers of complexity and makes the future harder to analyze. Although unraveling the future is a hopeless pursuit, AI can help in such searches, but it must be used with caution and be tested against human ethics and cultural norms. For a given challenge, students must decipher multiple futures to navigate complexity and co-work with the machines to obtain insights and weak signals that help in creating scenarios for different futures.

In a longer perspective, there is no doubt that the disciplines and the learning will change, and we will look into new knowledge patterns based on big data and AI.

A logical consequence is that digitalization will be integrated into the curriculum already at early stages. For the learning and communication technologies, this already exist in blended learning forms. For the emergent technologies such as big data and AI, we need strategies and not at least faculty who can help facilitating a critical discourse.

And in these more complex learning environments, we need effective change leaders who can be instrumental in facilitating the paradigm shift.

12.11 A Call to Action—Each Institution Must Find Its Own Way

Each of us must address these lessons at our own institutions in a way that matches the unique culture and objectives of that institution. There are lessons that we learn from each other, but their application at our own institution is a unique journey. Institutions do have various curricula practices; however, each institution needs to have strategies and plans for how they most efficiently respond to these challenges.

The lessons in this book can be applied as a framework. We must combine the future mindset, which is a more holistic approach to learning of knowledge and competencies, with interdisciplinary learning and with the change of the disciplines by digitalization of various kinds.

But we need change leaders and early adopters. Most change has taken place in certain courses, but we need a systemic approach with appropriate planning. How do we scale up from the changes made in a few courses to curriculum restructure on a program scale? Chaps. 9, 10, 11 provide examples of changes made at our institutions.

Educational leadership is essential if we want to change curricula as a whole. We need explicit visions and direction, and we need to recognize educational leadership and development in the same way we recognize research. We need to be willing to take risks as we are in the middle of the climate battle, and we need knowledge and competencies to win that battle.

No matter which practices and strategies you might have, we want to stress that it is the faculty who should drive the change and you need to identify the faculty who can lead these changes and work collaboratively with other faculty. We have also emphasized that faculty are driven by values and identities and change needs to take the point of departure from the current paradigm. If there is no belief or no trust in new learning systems, you need to first plan to create trust.

We hope that this book has inspired you to make changes at your institution to address the challenges of the twenty-first century. We would be delighted to hear about your approaches and adventures.