David Cropley & Arthur Cropley

Core Capabilities for Industry 4.0

Foundations of the Cyber-Psychology of 21st Century Engineering Education

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Overall production:
wbv Media GmbH & Co. KG, Bielefeld
wbv.de

Cover photo:
shutterstock/Willyam Bradberry

Ordner number: 6004780
ISBN (Print): 978-3-7639-6162-7
ISBN (E-Book): 978-3-7639-6163-4
Printed in Germany

Bibliographic Information of the Deutsche Nationalbibliothek (German National Library)
This publication is registered in the national bibliography of the Deutsche Nationalbibliothek; detailed information can be found on the Internet at http://dnb.d-nb.

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Introduction

The rise of Industry 4.0 has focused attention on the increasingly close interaction between human beings and technology, including artificial intelligence (AI). This interaction is playing an increasing role not just in industry but in a constantly widening range of life domains, in many of which a role for digital technologies such as AI would have been unimaginable just a few years ago: In fact, attention is broadening to encompass not just "Industry 4.0" but "Information Management 4.0," "Knowledge 4.0," "Education 4.0," "Thinking 4.0," and 94 other applications, according to one recent survey.[1] What is certain is that engineers will continue to be intimately involved in the rise of cyber-physical systems and this book is concerned with the psychological foundations of this interaction and what it will require of engineering education. What will Industry 4.0 mean for processes like acquiring information (learning), turning this information into knowledge (thinking), or coping with change in the emerging cyber-physical world, and how will engineering education need to react?

How broadly life will change and for how long it will continue to do so cannot be foreseen at present. However, the situation is becoming "open-ended." This means that we are faced with increasing uncertainty and dealing with uncertainty is itself an uncertain venture, to which human beings are largely averse. Thus, what is needed is *not* an attempt to predict concrete details of a specific, imagined future and define a set of "hard" skills that engineers will be able to acquire and then comfortably apply unchanged for a lifetime – in the world of 21st century engineering, skills acquired today may well be obsolete in a decade or two. What *is* needed is the promotion of *psychological* properties that will enable people to function effectively (and achieve personal satisfaction) under whatever circumstances emerge; regardless of where, how, and when they emerge. In psychological terms, this is a matter of what we call "capability" in this book: the *capability* to face novelty without fear, to adapt to change and become effective in new circumstances, or to acquire and discard well-loved knowledge and well-practised skills and techniques, as required by change. On the one hand, this capability will immunise people against the effects of factors like fear of challenge, unwillingness to change, or lack of self-belief (and the resulting inability to acquire new hard skills) and, on the other, it will foster their capability to acquire, organise and re-organise, integrate, and apply knowledge as and when it is needed – even if this contradicts what they already know and can do.

Of course, it will still be necessary for engineers to build structures that do not fall down and bridges that get traffic safely across rivers, or to ensure that the trains run on time (or indeed, run at all!) – assuming that such things continue to exist – even if the exact technology involved and the precise human skills required are not yet known. However, the proliferation of Industry 4.0 requires forms of engineering education

1 Bongomin, Yemane, Kembabazi, and Melanda (2020).

that promote not only acquisition of the technological skills needed to build the bridges (i. e., technology fluency – TF), but also the growth of appropriate personal capabilities (i. e., capability focus – CF): The combination of CF and TF involves a general "mindset" (not merely a toolbox of specific skills or a body of never-changing basic knowledge) that focuses on the "immunisation" described above. We refer to education that combines CF and TF as "dual-track," in a manner reminiscent of the World Economic Forum's "great reset" (Schwab & Malleret, 2020). Working out what CFTF involves psychologically and how to foster it through dual-track engineering education is the task of this book. At the end of our analysis, we come to the seemingly surprising or even perverse conclusion that what is needed – in psychological terms – is to pay much more attention to the *art* of engineering. In the uncertain and rapidly changing environment of Industry 4.0, it is no longer enough for engineers merely to replicate: they must *innovate* as well.

Although we will introduce a number of little-known or at least little-used concepts (e. g., the term "cyber-psychology" itself, the concept of "capability," the term "proactive lifelong learning," or the idea of "dual-track" education), our work is based on a re-examination and re-organisation of relevant aspects of existing psychological knowledge in order to form an educational cyber-psychology. Structurally, the contents of the book are organised into four blocks: The first two chapters introduce the basic issue with which the book is concerned: Industry 4.0 and the resulting "open-ended engineering." Chapters 3 and 4 focus on knowledge and knowledge acquisition (cognition) in such engineering (especially lifelong learning), and Chapters 5 and 6 draw on findings from creativity research to illuminate the personal properties Industry-4.0 capability requires, not only in individuals but also in the social environment in which they operate. Finally, Chapters 7 and 8 show how the psychological goals of engineering education need to change in order to encompass relatively neglected cognitive and personal properties that are now taking on new importance.

The contents of the book are organised in a twofold way: In the manner of an introductory textbook the basic theme has a beginning, a middle and an end, and unfolds in sequence as its overall line of thought is unfolded step by step in each successive chapter.[2] Nonetheless, in the manner of a handbook or reference book, each chapter deals with its own specific issue or issues and could stand alone. In the final two chapters we turn directly to the implications of the cyber-psychology of Industry 4.0 for engineering education. However, detailed, practical instructions on specific teaching practices would require a vastly more voluminous book than this one and we restrict ourselves to general principles. We hope that engineers and engineering educators will display their own openness for ideas, desire for novelty, divergent thinking, ability to tolerate uncertainty, and willingness to take risks – what might be called their "artfulness" – in turning these principles into practice.

2 All translations from German in this book were made by us. Any emphases in translated passages were inserted by us.

CHAPTER 1
Engineering: The Open-Ended Profession

Cyber-physical systems are penetrating ever more deeply into an increasingly broad range of aspects of life and are bringing widespread and rapid change. As a result, engineering is becoming open-ended, so that a new kind of collaboration between engineers and technology is necessary. This will be based on "capability-focused technology fluency" (CFTF). Technology fluency (TF) requires domain-specific expertise; capability focus (CF), by contrast, involves a *general* (i. e., *not* engineering-specific) mindset based on two "meta-competencies": willingness and ability to update your own knowledge, on the one hand, and willingness and ability to use this knowledge to work effectively with rapid change, novelty and uncertainty, on the other. Developing understanding of the capability focus is the task of "cyber-psychology" and promoting "dual-track" pedagogy, which encompasses the growth of not only (technology fluency) TF but of (capability focus) CF as well, is the task of engineering education.

Key concepts[3]: cyber-psychology; CFTF mindset; half-life of knowledge; heterogenising schooling; Industry-4.0 capability; open-ended engineering; dual-track education

The Emerging Era of Industry 4.0

On October 4, 1957, the launch of Sputnik I – the first artificial earth satellite – took place. Although at the time the term "Industry 4.0" was unknown and what lay before the world was only vaguely glimpsed, the fact of the matter is that the age of Industry 4.0 had begun, whether we knew it or not. The effect of the launch should not be underestimated (Dickson, 2001). For the general public, who had no knowledge of the technological processes leading up to it, the launch came as a sudden, completely unexpected surprise, often referred to as the "Sputnik *shock*" (e. g., A. J. Cropley, 2001; A. J. Cropley & Cropley, 2009)[4], which Dickson compared with "the starting pistol in an exciting new race." Western newspapers greeted the event with spectacular headlines such as "Red moon over London!" or "Space age is here." The starting pistol set off a furious burst of activity in areas far removed from building and launching earth satel-

3 These key concepts identify terms introduced in the chapter that are not as yet widely used but are core elements of the present discussions. We ask readers to take special note of them.

4 A. J. Cropley still vividly recalls standing at a city street intersection with a knot of other people, staring at the sky and realising in amazement that the Space Age had begun.

lites, such as the passage of the National Defense Education Act by the US Congress in 1958. A few years later, Jerome Bruner (1962a) – a visionary pioneer in cognitive and educational *psychology* – began to explore the broader implications (beyond military applications) of what was happening. He offered the first glimpses of life in a new era, in which what he called "thinking machines" (p. 6)[5] would assume full responsibility for routine tasks.

As early as the 1970s, the engineer Joseph Harrington (1974, p. 178) specifically named the (at that time) future technological developments that would lead to the forecast new circumstances, at least in broad general terms: "digitization" and "robotization." In 2011, at the Hanover Trade Fair, the German Government announced "Industrie 4.0" as the key initiative in its high-tech strategy (Kagermann, Lukas & Wahlster, 2011; Kagermann, Wahlster & Helbig, 2013). This approach is marked by increasing digitalisation[6] and expanding communication networks and – paraphrasing the World Economic Forum's (2018) apt characterisation – it is bringing a *new division of labour* between humans and computers. Recently, thinkers from non-technological disciplines such as the sociologists Ruiner and Wilkesmann (2016) have discussed the rise of "Industry 4.0" in terms that are reminiscent of the forecasts just mentioned. In fact, Industry 4.0 is opening up new vistas in many domains (see, also, Apschner, 2017; Stengel, Van Looy & Wallaschkowski, 2017).

Thus, the vision of the thought leaders of 50–70 years ago is becoming reality: Reference to a fourth "revolution" within the Industrial Age in which technologically highly developed societies have been living for the approximately 300 years since Thomas Newcomen built the first commercially viable steam engine is now relatively commonplace in the relevant literature. The breadth of this revolution has recently been dramatically demonstrated by the success of information technology in providing almost immediate solutions to some non-medical aspects of the COVID-19 pandemic. Because of the absence of traditional medical remedies (e. g., vaccination, medication), it was necessary to turn to behavioural solutions such as "social distancing" in areas such as work organisation, education, merchandising, or socialising. With the support of AI, appropriate practical measures were available for implementation almost overnight (although they were not necessarily adopted at once). These included previously little-used, IT-based practices such as working from home, shopping online for mere everyday needs, or "virtual" birthday parties, anniversaries, and similar social gatherings. These changes have led to collateral benefits such as the achievement – at least in the short-term – of the substantial reductions in carbon emissions from motor vehicles that environmentalists have been seeking without success for at least 20 years.[7] In a press interview, the Australian sustainable futures researcher, Mathew Hounsell, referred with a certain irony to the emergence of "digital mobility."

5 Bruner may never have heard of AI.

6 The term "digitisation" is now used to mean "converting something to digital format," while "digitalisation" means "converting industrial or business processes to use digital technologies." We are referring here to the latter.

7 The apparently paradoxical ability of Industry 4.0 to provide answers to as yet unrecognised or apparently intractable problems is discussed in greater detail in Chapter 2.

Wheeler and Gunasekara (2020) reported that surveys in Australia indicated increasing, although far from overwhelming interest in measures such as working from home. In fact, these authors concluded that discussion of the relationship of work and life was showing some signs of a shift from "work-life *balance*" – where work and life are seen as separate, even rival domains, that need to be balanced against each other and coordinated so that they can co-exist, side by side but separate – to work-life "*integration*," where the two merge as partners in a single unified whole. An example of unexpected IT-activated effects of this integration was seen in the UK in August 2020. According to press reports, there were sudden large increases in the price of family-size houses. In the place of downsizing, *up*sizing was becoming the norm. This resulted from financially well-established people hastening to buy houses with an extra bedroom, which could be converted into a home office to permit working from home via IT. Further knock-on effects can be expected in areas like public transport, healthcare, commercial property, and retailing.[8]

Thus, engineering is expanding to encompass everyday life in a variety of settings with which it has not previously been regarded as intimately connected: "Engineering has evolved into an *open-ended* profession" (Zhou, 2012, p. 344). Although he preferred the term "Information Management 4.0," and focused on cyber-physical production systems, Ansari discussed conceptualisations of Industry 4.0 broadly (e. g., 2019, p. 1597) and called for examination of its "ontological and epistemological" aspects. The purpose of the present book is to conduct such an examination from the perspective of engineering, with particular emphasis on psychological "open-endedness," and to work out its implications for engineering education.

What is "Industry 4.0"?

Wilkesmann and Wilkesmann (2018) emphasised that although the term "Industry 4.0" is now widely used, its definition remains imprecise, partly because it is discussed from the perspective of markedly different disciplines: they specifically mentioned computer science and technology, economics, political science and sociology, to which we have just added psychology. Pfeiffer (2015) was of the opinion that "Industry 4.0" is a still diffuse term for a smorgasbord of suggestions related to technological development. Apschner (2017) analysed several thousand reports in Austrian print media and showed that the future of industry, work, and jobs was a dominant theme, citing Frey and Osborn's (2017) question: "How susceptible are jobs to computerisation?" In this book, we conceive of Industry 4.0 more broadly as a system for applying digitalisation and automation – especially, though not exclusively, through the full array of possibilities Artificial Intelligence (AI) offers – as well as a framework for a discussion and analysis of this application.

8 What remains to be seen is whether these and similar changes will endure, or whether people in the post-COVID-19 world will eagerly return to the tried and trusted old ways, such as spending hours travelling to and from work each day or emitting huge amounts of carbon from cars massed on arterial roads (and then re-opening the comfortingly familiar discussion of the apparently intractable problem of how to avoid pollution).

These applications involve more than just industrial production: As Botthof and Hartmann (2015, p. vi) put it, Industry 4.0 encompasses "a *socio-technical* system" in which "technological advances" interact with "social needs" to produce a "collaboration" (Bainbridge, 1983), an "integration" (Wheeler & Gunasekara, 2020), an "algorithmic pairing" (Parsons, 2020), or at the very least a new "division of labour" between humans and technology (World Economic Forum, 2018). Simply put, Industry 4.0 involves the "integration of cyber and physical worlds" (Sony & Naik, 2020). This involves not just new business models, production systems or economic sectors, but "new ways of *thinking* and *living*" and "new *social* models" (OECD, 2018). The need to understand the psychological aspects of this integration is the reason why a cyber-psychology is necessary. We want to move the discussion into the domain where technological advances and psycho-social factors overlap, with special emphasis on engineering and especially on engineering education.

Industry 4.0 in manufacturing and production

As D. H. Cropley and Cropley (2019, pp. 28–30) showed, in terms of industrial technology, the expression "Industry 4.0" refers to the application of cyber-physical systems (CPSs) in production processes (e. g., Rajkumar, Lee, Sha & Stankovic, 2010). These systems include machines that acquire and exchange information and trigger appropriate actions and control themselves using, among other things, sensors and actuators that interact with other "intelligent" machines (Kagermann, 2014). The interactions involve information from both the physical world (e. g., about the status of a feed magazine or open orders from customers) and the virtual one (e. g., electronic documents or mathematical simulations of the expected result of an ongoing process), and the use of so-called "digital twins" (Auer & Kalyan Ram, 2019). A related term is "smart systems."

In the industrial version of Industry 4.0, orders are managed independently through the entire value chain. CPSs book the necessary processing machines and corresponding materials and organise delivery to the customer, recognising impending delays, reporting such delays to the customer, or reorganising work sequences as required (Ganschar, Gerlach, Hämmerle, Krause & Schlund, 2013, pp. 22 ff). Keywords include "modularity," "interoperability" and "virtualization." Industry 4.0 also includes industrial automation, connectivity, industrial big data, intelligent robotics, semantic technologies, the Internet of Things, cloud and cognitive computing, cyber-security and product lifecycle management (see for example Kagermann, Wahlster & Helbig, 2013; Jasperneite, 2012).

Thus, Industry 4.0 will have profound consequences for work organisation. There will be a new production logic in the "smart factory" (cf. Bickelhaupt, 2018). Botthof and Hartmann (2015, p. 5) summed up the core of this new logic in a way that is easy to understand: "the computerisation of the world of work." Computerisation will bring new forms of work organisation and greater flexibility, for example in the working conditions of staff (e. g., teleworking, diversification of the workforce). From a psychological point of view, it will also have a strong impact on subjective aspects of work such as, for example, workers’ self-image, relationships with colleagues, and job satisfaction. Increasing use of AI will even have effects that extend to remote aspects of work organisation such as noise pollution legislation: Thus, its consequences will extend far beyond the technological and organisational domains.

Industry 4.0 in the broader sense

In its broader sense, however, Industry 4.0 involves the production, recording, processing and implementation of information about continuously changing environmental conditions: stated in a very generalised and simplified way, solving problems by means of *smart* data processing. For example, in addition to improved operational performance, Industry 4.0 also promises to develop new services that will require new business models (for an introductory discussion, see Drath & Koziolek, 2015). Intelligent value-creation systems are being networked, not only in factories and companies but also in value-creation networks in the broadest sense, in order to create horizontally distributed, but integrated, systems that can be managed in real time from start to finish. This in turn means that CPSs will enable end-to-end engineering encompassing the entire value chain and involving the complex management and further development of multidisciplinary systems. Bongomin, Yemane, Kembabazi and Melanda (2020) identified no fewer than 99 areas where Industry 4.0 is having disruptive effects: These go far beyond “merely” manufacturing and industry to include Education 4.0, Agriculture 4.0, Healthcare 4.0, Logistics 4.0, and Energy 4.0, to give a few concrete examples.

An example of the disruptive application of CPSs outside manufacturing is “precision agriculture” (i. e., Agriculture 4.0), in which, among other things, “smart” systems for “intelligent seeding” are being developed (Smart-AKIS, 2018). During sowing, a drone guided by a GPS satellite transmits data to a “smart” seed drill, which uses this information to sow each seed at exactly the right depth. This requires appropriate software and a mathematical model that can predict the effectiveness of the system, so that the seed drill can independently monitor its own performance and, if necessary, optimise its own behaviour, for example by temporarily changing speed, all without any consultation with a human operator.

The parcel delivery service (i. e., Logistics 4.0) developed by United Parcel Service (UPS) reveals something of the psychological impact of Industry 4.0. UPS’s application of AI uses route-planning software called “ORION” (On-Road Integrated Optimization and Navigation) to calculate the best possible individual route for every delivery van for every order (BSR, 2016). The software takes into account not only factors such as the current traffic situation or the locations and settings of traffic lights, but also the influence of parking spaces, private access, variable speed limits and roads that are inaccessible to trucks. However, the urban road traffic system is so complex that individual human drivers are often unable to grasp the interactions among the factors involved and, as a result, some of the routing solutions calculated by ORION appear to humans to be longer in distance or time than they actually are. Thus, the benefits of ORION are only possible if the human beings involved are willing to trust the AI’s routing suggestions (i. e., to "collaborate" with it, or to divide up the work with it – see World Economic Forum, 2018, already mentioned).

Examples of Medicine 4.0 include "medibots" (see for example Srivastava, Medina-Sánchez, Koch & Schmidt, 2016) and artificial pancreases (e. g., Brown and many others, 2019). Although still in the development phase, the latter monitor blood sugar levels and adjust the insulin supply automatically if the level becomes too low or too high. They also have the ability to predict blood sugar levels using mathematical modelling and prophylactically change the insulin dose as required. In this way, hyper- and hypoglycemic episodes are proactively avoided instead of being treated reactively after the appearance of symptoms. In another application in "Medicine 4.0," i. e., far removed from Manufacturing 4.0, a smartphone app that is able to diagnose clinical conditions of the lungs, such as asthma, inflammation or respiratory infections immediately, without laboratory tests and with greater accuracy than human doctors is currently being clinically tested (see Abeyratne, 2013). The app analyses information contained in the coughing sound of the patient that is easy for AI to interpret but is not accessible to the human ear.

In a discussion of "technology infusion" van Doorn et al. (2017, pp. 43 ff.) discussed the rise of CPSs in consumer and office settings and estimated that even before COVID-19 such applications were actually growing much faster there than in manufacturing. Examples include robot waiters in restaurants and other hospitality settings, "social agents" in retailing, or on-line robot service providers. Van Doorn et al. (p. 46) pointed out that such CPSs are beginning to become capable of establishing "social and emotional connections with their human partners." Other non-industrial applications are also conceivable, such as "precision education" guided by AI (i. e., "Education 4.0"), in which lessons are adapted to the individual needs of individual learners using data, or in this application *learning* analytics (see Hart, 2016), or "intelligent justice" (i. e., "Justice 4.0") (see Re & Solow-Niederman, 2019).

Cyber-Psychology

The new and still developing "partnership" or "integration" of human beings with Industry 4.0 technology just described requires that engineers be prepared to make the best use of these tools (digitalisation, automation, AI), not simply through acquisition of appropriate technical knowledge and skills (technology fluency – TF), but also in terms of the way they think, their attitudes, their values and motives, and the way they interact with other people (capability focus – CF).[9] Daker, Cortes, Lyons and Green (2019, p. 1) emphasised that cyber-physical systems seem in some ways to be "surpassing" human cognition; however, as Parsons (2020) put it, humans and machines are now "algorithmically paired" (p. xvii). The issues thus go far beyond design, construction, and improvement of machines, tools and processes: As the concrete COVID-19 measures discussed above show in real-life practice, AI is seamlessly becoming part of

9 These two terms will be explained in greater detail below.

our entire “personhood” (Parsons, p. xvi). A purely economic-technological approach to the fourth revolution of the industrial age is therefore not enough: The topic needs to be tackled in a new way and in this book we begin such a re-examination. Perhaps surprisingly, we turn to psychology as the basis of our analysis: Perhaps even more surprisingly, to the psychology of creativity, which is as far removed from engineering as many people’s minds can imagine. Ultimately, we will go so far as to lay a foundation for the *art* of engineering (see Chapter 8).

Parsons (2020) called for a “cyber-psychology” and suggested neuropsychology as the foundation on which to build it. However, the cyber-psychology of engineering has further dimensions in addition to the neuropsychological aspects referred to by Parsons. These include *cognitive* cyber-psychology (How will Industry 4.0-capable people think?), *differential* cyber-psychology (What kind of person will be Industry 4.0-capable?), and *social* cyber-psychology (How will Industry 4.0 change social interactions among human beings, or itself be changed by such interactions?). Van Doorn et al. (2017) began an analysis of social cyber-psychology in their discussion of “automated social presence” (p. 44), emphasising social cognition and “psychological ownership” (maintaining people’s sense of control, expressing their personal identity, and promoting their sense of belongingness in interactions with AI). A *clinical* cyber-psychology is also emerging. For example, some people are experiencing mental health problems associated with the social and physical isolation, monotony and boredom, or even sensory deprivation associated with working from home (e. g., Rettie & Daniels, 2020). These researchers identified states such as depression and anxiety as key effects of cyber-psychology and linked them directly with the low levels of tolerance for uncertainty which we discuss in later sections.

Educational cyber-psychology

The cyber-psychology we outline in this book does not focus on framework issues such as the danger of handing over decision making to machines that are inherently incapable of weighing up the ethics of a situation, or the social justice/injustice of the disproportionately severe effects of restructuring work processes on low-skilled workers, but on the psychology of the individuals confronted with Industry 4.0 on a day-to-day basis, and, in particular, engineers.[10] We will apply this cyber-psychology to the understanding of education – in particular tertiary education – and will start laying out the basics of an *educational cyber-psychology* that goes beyond “cognitive enrichment” (Parsons, 2020, p. xvi) and also relates to affect, personal resources, and some aspects of social interactions. This will not involve developing previously unknown concepts, but reorganising and refocusing existing ways of understanding perception, organisation, and evaluation of information (cognition), motivation and emotion (affect), personal properties such as openness or self-image (personal resources), and social factors such as status and power, roles, or leadership. The *basic* knowledge for carrying out this task already exists, particularly in research on lifelong learning and on creativity: Our task in this book is to *apply* this knowledge to building a cyber-psychology.

10 This is not because we regard such issues as trivial, but because we cannot deal with everything in a single book.

Engineers in the World of Industry 4.0

Technology, in particular augmented by AI, is becoming ever smarter and in order to make the best possible use of it engineers need to be smart too, not only in cognitive terms (their thinking) but also in terms of self-image, motivation, attitudes and values, and social interactions. From our pedagogical-psychological perspective, questions of the specific *kind* of qualifications engineers will need are of crucial interest. It is important to note that these reach beyond a purely cognitive cyber-psychology and also encompass the "differential" and "social" cyber-psychology of Industry 4.0 mentioned earlier. Such considerations almost inevitably lead to the question of the nature of the capability-development processes (i. e., education) associated with Industry 4.0 (see below). Later in this chapter, we will outline the special characteristics of Industry-4.0 capability-oriented education, which we refer to as "dual-track" education, and Chapters 7 and 8 are dedicated to this topic.

Apschner (2017) pointed out that one major theme in the media discussions she analysed was fear of human beings being replaced by AI: she referred to the "sorcerer's apprentice" phenomenon and the "Frankenstein syndrome" (p. 74).[11] However, despite the capabilities of cyber-physical systems, Kärcher (2015, p. 49) came to the conclusion that "humans will remain an integral and indispensable part of the production world of the future." The reason for this is easy to understand: People are "the most flexible and intelligent components of today's and future production systems." According to Kärcher, Industry 4.0 does not involve a competition or a struggle for survival: What is happening is merely that machines are becoming smart enough to be really useful to humans. Nevertheless, engineers need to be able to achieve an efficient division of labour and make the best possible use of the collaboration in order to get the best out of the machines. As the comments in the previous paragraph on drivers' willingness to use ORION argued, the ability of humans to collaborate is not just a matter of, for example, technology savvy (TF in the sense of the CFTF model; see below), but also involves attitudes, motivation, self-image, and the like. In short, engineering education must help technicians become "Industry 4.0-capable" in diverse psychological dimensions.

Industry 4.0 is bringing change with unprecedented speed and thus new problems that engineers have to solve. It is therefore no longer possible simply to adjust what already exists over and over. acatech (2013, p. 8) explicitly established the connection between Industry 4.0 and novelty when it defined the newly emerging core task of engineering science as "*innovation* in technology." In the sense of Hartmann and Tschiedel (2016, p. 13) "a management concept that constantly tries to adapt 'human capability' to the technical 'circumstances' (including those predicted for the future)" is not sufficient. Industry 4.0 requires more than specific, fixed skills that can be learned, perfected, and then applied again and again in a routinised manner: It involves constantly changing combinations of ideas that can be redesigned for new –

11 Frankenstein 4.0?

even unforeseen – situations. The capabilities that will be of greatest value in the emerging digital world are discussed below and later, but it is important to note here that they exceed specific knowledge and skills to encompass factors such as attitudes, motivation, self-image, openness, or courage, to name some examples.

The capability-focused, technology-fluent mindset (CFTF)

Our aim is to work out, for engineers, a psychological answer to the question of the knowledge and thought processes and no-less-important essential personal characteristics that define Industry-4.0 *capability*, and to use this as the basis for a discussion of engineering education. Henriksen, Mehta and Rosenberg (2019, p. 63) gave a compact psychological definition of what is needed: they referred to a "creatively focused, technology-fluent mindset" (CFTF). We will generalise their insight by expanding the "C" of CFTF to stand for not just "Creativity," as it does in Henriksen, Mehta and Rosenberg's seminal paper, but for "Capability," and thus call for an "Industry-4.0 *capability*-focused, technology-fluent" mindset.

In the context of Industry 4.0, the "C" for capability can be understood in terms of two meta-competencies, which we will discuss in more detail below and in later chapters: on the one hand, the ability and willingness to learn constantly and in many environments (in short: what is often referred to as "lifelong and life-wide learning" – LLL) and on the other hand, the willingness and the ability to constantly change in response to newly acquired knowledge (often referred to as "creativity"). For example, not only must new knowledge be acquired by means of LLL, but it must also be applied to facing and dealing capably with change, uncertainty, novelty, and the like. As a result, in addition to its cognitive aspects (e. g., knowledge, information processing) the CFTF mindset, as we conceptualise it here, encompasses what we will refer to from this point as *Industry 4.0-relevant* "capabilities": among such capabilities are openness to the new, willingness to speculate, or tolerance of uncertainty.

Capability vs. skill

According to A. J. Cropley (2018a), skills are clearly defined sequences of actions that make it possible to cope with specific situations; the more deftly the actions are carried out (i. e., the higher the level of skill), the more successful their application is likely to be. A simplified example of a skill would be dexterity in milking cows by hand. This skill was once highly developed in many agricultural workers, involved specialist knowledge, and was extremely useful on farms. Consequently, it cannot be dismissed out of hand. However, it was only applicable in highly specific situations (obtaining milk from female mammals) and with the passage of time became largely obsolete, due to the advance of machine milking and increasing commercial, industrialised dairy farming. The usefulness of this skill was not only limited to certain tasks at certain locations (it was not geographically open-ended), but was also highly specific to a particular era (it was not temporally open-ended), although the people practising the skill may have expected it go on forever: How else would it be possible to get milk out of a cow?

By contrast, as Apple and Ellis (2015, p. 23) pointed out, what we call "capability" is a complex system encompassing the cognitive, affective and social domain. As we use the term in this book, "capability" is a general *mental* disposition that – of central importance for the present discussion – is not restricted to specific problems in specific locations and specific eras[12] and is not made redundant by change. Capability enables people to work out appropriate measures in unstructured or previously poorly understood or completely new situations. It enables them to deal with change and the complex problems it brings. Of course, the acquisition of, for example, milking skill is facilitated by the possession of general manual dexterity, so that such dexterity could be regarded as an aspect of neuro-physical capability. However, in this book we are concerned with *mental* capability: a state of mind, a way of thinking or a mindset. The elements of such capability include tolerance of uncertainty, acceptance of risk, enjoyment of challenge, comfort with complexity, self-efficacy, or the courage to resist social pressure to conform. Capability does not directly make milking cows easier, but it does enhance acquisition of this specific competency (or others) because, among other things, capable people are not only good at acquiring knowledge in general (cognition), but are also interested by, among other things, the challenge of doing so (openness), willing to accept the challenge (motivation), confident that they can succeed (self-efficacy), and willing to risk their dignity (courage).[13]

Table 1.1: Fundamental psychological differences between skills and capabilities[a]

	Skills	Capability
Main Characteristics	Physical or mental Specific Concrete	Mental General Abstract
Key Process	Relating novel situations to the already known and selecting the appropriate (skilful) response	Grasping the essence of novel situations Identifying the need for change
Typical Sub-Processes	Classification of new situations into existing categories Identification of the most appropriate already-known behaviour for dealing with a situation	Identification of the key aspects of new situations and building of new categories if necessary Working out new behaviours for dealing with a situation
Pre-Requisites	High levels of deftness in carrying out well-practised behaviours	High level of willingness to replace well-practised behaviours with new ones

[a] This table does not provide a comprehensive definition of skill and capability but simply seeks to highlight some of the fundamental differences between the two concepts.

12 For a diverse range of examples of creative solutions, spanning the entirety of human history, see D. H. Cropley (2019a, 2020).

13 As A. J. Cropley (2020a) put it, capability is general and "transferable"; it can be applied to different kinds of content under varying conditions.

Although they did not use the term, over 20 years ago Burton, Horowitz and Abeles (1999, p. 43) were already discussing "capability" in the sense just described. Wilkens and Gröschke (2008, p. 44) were writing before the Industry-4.0 era began, but they began to create a psychological definition of what we call "capability" when they emphasised, for example, "coping with complexity," "self-reflection," "combination," and "cooperation." Hetland, Winner, Veenema and Sheridan (2007, p. 6, Fig. 2) gave greater emphasis to cognitive aspects of "mental habits" such as "seeing," "observing," "exploring," "engaging," "reflecting," "understanding," "persisting," and "expressing." Sternberg (2012, p. 3) also referred to "mental habits." Table 1.1 contrasts some key characteristics of skills and capability to make the difference more easily understandable.

Technology fluency (TF) alone is not enough

Recent discussion in German-speaking countries of the new – or newly significant – capability for Industry 4.0 was summarised by D. H. Cropley and Cropley (2019, pp. 27–28).[14] For example, Erol, Jäger, Hold, Ott and Sihn (2016, pp. 14–15) differentiated between "personal" capability (e. g., autonomy, flexibility), "interpersonal" capability (e. g., the ability to work in an interdisciplinary manner and form networks), and "action-oriented" capability (e. g., analytical thinking and problem-solving skills). They also discussed "domain-specific" capability (e. g., specialist knowledge, mastery of specialist tools); however, for our purposes, domain specific capability is not capability but skill. Hartmann and Tschiedel (2016, p. 11) differentiated between "people capability" and "machine capability." These comprise what D. H. Cropley and Cropley (2015, pp. 10–12) called "personal resources." Liedtka (1998, p. 120) encapsulated these resources in a more business-minded fashion as "*entrepreneurial spirit*." In the sense of this book, Liedtka's "entrepreneurial spirit" is a capability (it is abstract, general, transferable, and refers to psychological functioning).

As the fate of firms such as Nokia, Polaroid, Kodak, and Smith Corona has tellingly demonstrated, in the age of Industry 4.0, technology fluency (TF – see above) is highly desirable, but it is not enough: All the successful, well-established international corporations just mentioned collapsed or went bankrupt when they failed to adapt their products to modern demands, despite the fact that the products they kept on improving to the bitter end were of high quality and very effective – their only weakness was that nobody used them anymore. Kodak, for example, had a long history of success with innovative imaging techniques based on their mastery of photo-chemical film technology. When confronted with the rise of digital imaging, the firm persisted with film, despite the fact that it had invented the first megapixel camera. It focused its efforts on the Advantix film system but, unfortunately for the company, digital imaging had made photo-chemical imaging obsolete. Technology fluency alone could not protect these companies from the effects of change.

Returning to individual people, Daker, Cortes, Lyons and Green (2019, p. 1) reported that "even among people who are very technically skilled at what they do, it is

14 Germany was the first country to adopt Industrie 4.0 as official industrial policy at national government level, so that it seems appropriate to give particular emphasis to German scholarship in the area.

common to find individuals who *recoil when they are asked to generate a new idea.*" We would say that they lack the *capability* of working with novelty. Kirton (1989) had already introduced the contrast between "adapters," who solve problems by reapplying what they already know and can do, and "innovators," who restructure problems and seek novel solutions. Thus, having domain-specific knowledge (technology fluency) is one thing, possessing the capability to use it effectively in the Industry-4.0 sense (capability) is another. Industry 4.0-focused capability goes beyond technology fluency alone and encompasses a psychological bundle of attributes that facilitate productive collaboration with cyber-physical technologies in a wide variety of different situations and settings. These include knowledge, certainly, but also incorporate ways of thinking, attitudes, motivational states, and personal characteristics such as flexibility and openness, to give some examples. An overview of Industry 4.0-focused personal attributes is given in Table 6.2.

University Teaching and Industry 4.0

Ray (2019) gave a journalistic, but nevertheless vivid and well-founded, concrete example of the purposeful use of one of Industry 4.0's signature technologies – Artificial Intelligence – to build an effective learning platform for the teaching of engineering, and gave examples of its positive effects: for example, stronger motivation, better teamwork and improved ability to learn in different environments. At this point, however, it is important to emphasise that the present book is not about using AI to make the contents of conventional instruction easier to understand or more engaging – as worthwhile as this may be. Fostering Industry-4.0 capability goes beyond didactic techniques and involves the promotion of special psychological resources (which, as just explained, we now call "capabilities"): The challenge for engineering education is not to make lessons more engaging but to promote the development of the necessary cognitive, personal, motivational, and emotional capabilities that prepare engineers for working highly effectively in the framework of Industry 4.0 (CF) in addition to traditional knowledge and skills (TF). Such an educational goal surpasses merely *promoting* desirable capabilities to also encompass *reducing or avoiding* the build-up of psychological properties such as inability to tolerate cognitive dissonance, fear of uncertainty, or feelings of threat in the face of novelty. D. H. Cropley (2015a, pp. 240 ff.) discussed the role of "blockers" in some detail and we discuss these further in Chapter 8.

Thus, a major issue in this book involves the aspects of Industry-4.0 capability young engineers should be helped to develop. Mehta, Creely and Henriksen (2020, p. 361) made a direct link between "21st century skills" and digital technologies, pointing out that the discussions "have been adopted … from *technology-focused* economic initiatives." They also emphasised that current discussions mainly see what should be taught as involving "meta-level skills such as critical thinking, creativity, and various other more *generalizable* or *transportable* skills" (emphasis added),[15] that are needed for "living in the contemporary digital world." However, they argued, on the one hand, that much of the discussion is "uncritical," and on the other, that it is greatly hampered by the fact that it is impossible to specify precisely what people will need to learn in the future, in view of the fact that (as we ourselves have emphasised) details of the future are not currently known. In fact, these authors' remarks summarise in a trenchant manner the psychological position we have adopted in the present book, so that their criticisms of existing work confronted us with a challenge that we could not ignore. Our purpose in the book is to commence a differentiated (i. e., not "uncritical") discussion (see for example the discussion of skills and capability in the previous section) and to build a psychological framework (a cyber-psychology) for understanding what is needed.

A vigorous discussion of this issue has been in progress for nearly 20 years. In 2007, the UK's Royal Academy of Engineering asked, "what kind of people can design integrated [engineering] systems?" (2007, p. 28), noting the importance of creativity and personal qualities such as openness. In Australia, the national accreditation body, Engineers Australia (2013), listed among the competencies that "must be demonstrated at the point of entry to practice" the personal attribute of a "creative, innovative, and pro-active demeanour". In 2004, the US National Academy of Engineering published its vision of "the engineer of 2020" (National Academy of Engineering, 2004). This document listed nine key capabilities (although it did not use that term), of which two are of particular relevance for this book: *creativity* and *lifelong learning*.

Lifelong learning and creativity may seem strange bedfellows. However, in a document prepared for UNESCO's International Bureau of Education, Marope, Griffin and Gallagher (2019, pp. 31–32) made a direct link in their discussion of the role of "macro-competences" in the future of curriculum. They saw lifelong learning as not only linked to learning, but as requiring "integrating … multiple domains of knowledge" (i. e., divergent thinking) and "using diverse tools and resources" (flexibility), which require "innovation and adaptability" (i. e., openness to novelty) and people "re-inventing themselves" (i. e., flexibility and self-efficacy). In the following we will focus on these two aspects of Industry-4.0 capability, in terms of both the knowledge and the personal properties they involve.

Lifelong learning has traditionally been regarded as having to do with mastery of conventional knowledge, especially "standard" knowledge and skills, such as literacy and numeracy, and as having the purpose of eliminating defects in these in people who did not have the opportunity of acquiring them earlier (e. g., Dave, 1973; Faure, 1972; Lengrand, 1970; Suchodolski, 1976). In other words, lifelong learning has traditionally been conceived of as a *homogenising* process: specifying the contents of a toolbox of necessary knowledge and skills and making it possible for everyone to possess these, even if they acquire them later in life than is typically the case (lifelong) and in settings other than conventional schools (life-wide). Creativity, on the other hand, is

15 When they are generalisable and transferable, we no longer use the term "skill" in this book, but refer instead to "capability."

concerned with *heterogeneity*: breaking away from standard forms and patterns, being different, overcoming the homogenising effects of school (e. g., A. J. Cropley, 2001; A. J. Cropley & Cropley, 2009). The element linking the apparently paradoxical partnership of these opposing processes (mental homogenisation versus mental heterogenisation) is the new perspective emerging from Industry 4.0: rapid disruptive change. What we will define in Chapter 4 as "proactive" lifelong learning can be understood as the process of acquiring knowledge about and understanding of how things are changing and are going to be, as against polishing or completing knowledge of how they are and will continue to be, while we see creativity as the psychological mechanism for participating in, shaping, and using change (i. e., collaborating with it). Together, these two define what we call the "meta-competencies" of CFTF.

The meta-competency "lifelong learning"

As already indicated above, the CFTF way of thinking in the sense of Industry 4.0 has two elements. One of these involves the application of knowledge to dealing with and implementing change; this is discussed in more detail below and in Chapters 2, 3, and 4. However, the first step in CFTF involves the acquisition of knowledge; after all, it is not possible to apply knowledge you do not possess. At a more formal level, the knowledge that will be needed in the future may not even exist at the time of school or university: Arbesman (2013) emphasised that the "half-life" of knowledge and skills (the period in which 50 % of what a person knows becomes incorrect or irrelevant) is continuing to decrease. This shortening of the period of usefulness of existing knowledge – the ever-faster obsolescence resulting from rapid change – represents a central aspect of Industry 4.0. For engineers, the period spent at school/university covers only a small part of their life, both temporally and spatially (i. e., it is not open-ended). It is thus essential that they continue to learn beyond the traditional school years (lifelong learning). In addition, however, even during that period, like everyone else, they also learn in many other settings: for example, at home, among their peers, in sporting clubs, etc, so that *life-wide* learning is also essential. Using the life and death metaphor that has become common in recent discussions (see D. H. Cropley & Cropley, 2015, p. 2), Vogel (2015, no pagination) made the link between lifelong/life-wide learning (LLL) and Industry 4.0 quite explicit when he discussed "why Industry 4.0 makes lifelong learning vital for *survival*."

As Knapper and Cropley (2000) emphasised, the LLL discussion has a very long history going back many hundreds, if not thousands of years, although it has only become prominent in modern educational theory (e. g., Faure, 1972) and only "officially" recognised since the 1970s (e. g., the 1976 Lifelong Learning Act in the US). The "lifelong" label makes it clear that LLL takes place throughout life. Some authors (e. g., Dauber et al., 1975) even warned against school as a life sentence stretching from the cradle to the grave. However, this fear reveals a fundamental misunderstanding of the core of LLL: it is not just a new term for extended schooling in the sense simply of, for example, adult, further and advanced education and training. Following A. J. Cropley and Dave (1978), Knapper and Cropley (2000, pp. 35–39) spoke of both "vertically integrated" learning (here: "life*long*" learning) and "horizontally integrated" learning (here: "life-*wide*" learning). Thus, LLL is also not just a matter of updating knowledge from time to time in order to keep up with the latest events, but involves the motives, values, self-image, learning skills, and the like, that collaboration with constant and rapid change involves.

However, as we will explain explicitly later, although learning extends beyond schooling and also occurs outside formal educational settings, formal education can make an important contribution. This involves not only promoting the acquisition of specific knowledge and skills that are useful in the short term, but which have shorter and shorter lives in the age of Industry 4.0, but also the development of lifelong learning capabilities in the sense outlined above. Examples of such LLL capabilities include: identification of personal learning needs, confidence in your own ability to learn (self-efficacy), recognition of relevant learning opportunities wherever they are encountered (i.e., in school or outside it), self-monitoring of learning progress, mastery of learning media, ability to work with others, good communication, and acceptance of feedback. It is this contribution we deal with in this book, largely under the heading "learning to learn" (see Chapter 7). Basically, a great deal of LLL takes place well beyond university and mostly outside university and requires special capabilities: Chapters 5 and 7 take up the question of how LLL can promote CFTF-capability and what engineering education can do to promote it.

The meta-competency "creativity"

Industry 4.0 opens up an age of previously unimaginable applications of knowledge and skills, but it presents new challenges in these areas: From a psychological point of view, it requires a new way of thinking. It is no longer possible to simply adjust what already exists. acatech (2013, p. 18) explicitly established the connection between Industry 4.0 and the creation of novelty when it defined the task of engineering science in the context of Industry 4.0 as "*innovation* in technology." Several papers summarised by D. H. Cropley and Cropley (2015, p. 6) differentiated between two types of innovation: "incremental" versus "discontinuous" or "disruptive." From the point of view of this book, the crucial difference is that incremental changes deal with the "utilization of existing technologies," whereas disruptive changes involve "turning away from what already exists" (Luecke & Katz, 2003, p. 2). The most striking thing about the age of Industry 4.0 is precisely this discontinuous or disruptive novelty or turning away from the customary.

In the last half century, turning away from the customary and interacting with novelty has typically been discussed under the heading "creativity" and the present book will draw heavily on understandings derived from this research. D. H. Cropley and Cropley (2019, p. 28) summarised thinking about the link between creativity and Industry 4.0: For instance, Mokyr (1990, p. 8) called for "technological" creativity and Rosenstock and Riordan (2017, p. 4) spoke of creativity as the decisive "psychological disposition" that is indispensable for people in modern societies which are marked by pervasive and rapid change. Bakhshi, Downing, Osborne and Schneider (2017) concluded that processes such as creative problem solving will soon be among the most sought-after job qualifications in industrialised societies and Frey and Osborne (2017) emphasised that professions based on *creative* intelligence are the least likely to disappear in the 21st century.

A representative survey carried out in German companies (acatech, 2016) showed that innovative ability, critical thinking and independent decision making were regarded by industry as essential for working in the context of Industry 4.0. However, in a survey of more than 500 German companies, the Fraunhofer Institute for Industrial Engineering and Organization found that in 2014 only 29 % of the companies had developed an "Industry-4.0 strategy" (Schlund, Hämmerle & Strölin, 2014, p. 6). In fact, as A. J. Cropley (2012) emphasised, many people – not least in the field of technology – are indifferent to creativity or are unsure how it can be promoted and used in practice. D. H. Cropley (2015b) described this confusion and uncertainty with particular clarity and with specific reference to engineering education (STEM education).

Dual-track teaching

Our emphasis on Industry-4.0 capabilities does not mean that technology fluency is becoming superfluous. A plumber hired to unclog your toilet might be open to new ideas, enthusiastic about challenges, and good at dealing with uncertainty: Unfortunately, none of these capabilities will make the toilet work properly unless the plumber possesses the necessary skills for doing the job, especially the appropriate manual skills. Even in the world of Industry 4.0, technological products must be capable of effectively performing the physical tasks to which they are applied: For example, the bridge that is built to get traffic across a river must be able to do just that. Indeed, it is important to remember that, for example, expertise, precise and rapid handiwork, and the skilled use of tools continue to be of great practical value. A. J. Cropley and Gribov (2005) argued that Industry-4.0 didactics do not involve purely Industry-4.0 capabilities, but should also support development of manual and technical expertise. They called for "two-dimensional" teaching (p. 65) – what we call "dual-track" pedagogy – which emphasises the systematic development of Industry-4.0 capabilities, not however, to *replace* traditional knowledge and skills, but to *supplement* them. Examples of such capabilities include recognising the similarity of ideas from distant fields, openness to and positive appreciation of uncertainty, or willingness to accept criticism.

How this could come about has long been the subject of much discussion. Over 40 years ago, A. J. Cropley (1977, 1980) discussed the psychological foundations of LLL and the key features of a system of lifelong learning. More recently, the European Union (e. g., European Council, 2008) supported the promotion of innovation and creativity in "education and training." A report from the Australian Curriculum Assessment and Reporting Authority (ACARA, 2016) made this even clearer. The agency recommended that critical and creative thinking be embedded in all areas of learning: in particular, the report called for "reason, logic, *imagination* and *innovation*" to be integrated into the *entire* curriculum. Our interest here is in the engineering curriculum.