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Notes on Advanced Engineering Education.

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This article reviews history, analyses principles and presents a modern interpretation of advanced engineering education (AEE). AEE originated in France, was adapted in Germany and reached its zenith in the second half of the 20th century as part of technological efforts induced by the space race. AEE is an enhanced form of education aimed at producing inventors, thinkers and leaders capable of bringing new technological changes and scientific revolutions. AEE introduces a challenging educational environment that is generally addressed to the most enthusiastic and capable students; it is not necessarily suitable for the mainstream education. The role of AEE is projected to increase as the world becomes a global knowledge society.

Keywords: advanced engineering, engineering education, history of education, technological development

1. Introduction

While most articles on engineering education are dedicated to the problems and methodology of mainstream education, the focus of this paper is advanced engineering education (AEE)—education that is tailored for talented individuals with the aim of producing engineers, scientists and leaders with highly advanced abilities. AEE can be traced back to the times of the French Revolution and took its modern form after WW2.

AEE shares some principles with several modern approaches aimed at improving engineering education but remains different from these approaches in other respects. For example, both AEE and CDIO (the Conceive — Design — Implement — Operate approach, which is comprehensively presented in the book by Crawley et al. 2014) emphasise the need for integration of education with research or practice. The Conference of European Schools for Advanced Engineering Education and Research (CESAER 1990) is a European association that maintains and promotes advanced standards in engineering education and research. Practically, CESAER unifies many different approaches to engineering education under a single umbrella. Many educational approaches including AEE flexibly incorporate the elements of problem-based learning (PBL, see Edstrom and Kolmos 2014). AEE would also agree with Holistic Engineering Education (HEE, see Kellam, Peters, and Maher 2008; Grasso and Burkins 2010) that some exposure of engineering students to social sciences can stimulate their creativeness. At the same time, the level of fundamental education that is commonly designated for engineering students is seen as insufficient by AEE and as excessive by CDIO and HEE. AEE interprets PBL as being synonymous with enhancing, not reducing, the theoretical content of engineering courses.

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These differences are determined by differences in the goals pursued by these approaches: AEE is designed to produce graduates capable of achieving intellectual breakthroughs, technological transformations and organisational changes, while the other approaches are aimed at improving the mainstream education of professional engineers.

One of the most important features of engineering education is its unrelenting versatility, which is determined by rapid technological development and the multiplicity of roles played by modern engineers. While a large volume of literature is available for mainstream engineering education, the publications dedicated to advanced education are relatively scarce (Karlov and Kudriavtsev 2003; Chubik and Zamyatina 2013), although various issues related to advanced segments of engineering education were repeatedly discussed in the literature (Zamyatina and Mozgaleva 2014; Wedelin et al. 2015). This paper is written to explain that reaching the educational standards of an advanced engineer is not a trivial matter. Although it is not always easy to introduce AEE in practice, it represents a powerful form of education and, if implemented properly, can produce impressive results.

2. Three categories of engineering education

The following levels of education, which we shall call "categories", can be distinguished in engineering:

- **Associate engineer**
- **Professional engineer**
- **Advanced engineer**

The first category is typically linked to a corresponding diploma, an associate or junior degree with duration of no more than three years. The engineering graduates from this category are trained to perform a specific type of engineering job, possess a set of skills that is focused on the immediate requirements of the job, and need some supervision when the tasks become more general or complex. Specialists of this type are often called technologists or, in some countries, technik(er)s or technicians, although the exact meanings of these terms may differ from country to country and from workplace to workplace (for example the role of a technician may range from a skilled manual worker to an engineering associate). The first category of education is represented by Colleges of Further Education in UK, TAFE (technical and further education) Colleges in Australia, Fachschule in Germany, many of the American Colleges, Colleges of Technology in Japan, Technicums in the USSR, by other similar institutions, and by programs of associate or junior degree levels in some of Institutes and Universities. This category is often subdivided into engineering associates (e.g. technicians) and associate engineers (e.g. technologists).

By contrast, a professional engineer is expected to be competent in solving a wide range of problems from a selected branch of engineering. While a professional engineer should be able to perform specific technical tasks that are traditionally assigned to an associate engineer, professional engineering practice involves a range of more difficult and of more sophisticated problems bearing a greater responsibility. For example, a professional engineer can be expected to conduct appropriate research, suggest a solution to an engineering problem, and to use basic scientific tools to evaluate the soundness of the suggested solution. In most cases, these tasks lie outside the range of the abilities of both technicians and technologists. To qualify for the job, a professional engineer is expected to possess at least the Bachelor of Engineering (BE) degree with a typical duration of four (or more) years.

While continuing this consideration, one might conclude that an advanced engineer should possess at least a Master of Engineering (ME) degree. This seems to be correct: the time required to educate an advanced engineer cannot be any less than 5-6 years, which corresponds to the ME. However, we must admit that Master's level education does not guarantee that the graduate can perform any challenging tasks that are outside abilities of a professional engineer. In most cases, ME graduates may have additional knowledge or experience but, fundamentally, they do not stand above professional engineers in the same way that professional engineers stand above technicians in the extent of their professional abilities. AEE is more associated with implementing a certain set of educational principles than with attaining a particular level of academic qualification. Hence AEE can be interpreted not so much as a higher degree, but as an alternative educational route.

AEE is intended to be deployed as the primary tool for educating intellectuals who can lead technological/scientific changes or revolutions. AEE operates in the areas where close interactions of science, engineering and innovation result in rapid scientific and technological progress, eventually leading to a new spiral of economic growth. In this context, advanced engineers can perform different roles ranging from scientific research to managing technological change. AEE is much less concerned with maintaining the existing level of technology—this important task is entrusted to professional engineers.

2.1. *What do engineers do?*

The three categories of engineering education can be broadly related to the three types of roles expected to be performed by engineers. In modern society engineering specialists are needed for

- servicing existing technologies
- improving conventional technologies and
- introducing radical innovations and fundamental technological changes.

The correspondence between the categories and the roles is not exclusive (let alone the possibility of various intermediate roles and categories). An able technician or technologist can be innovative and may suggest significant technological improvements, while a talented professional engineer may conduct outstanding research and instigate a fundamental technological change. This, however, does not negate the fact that technicians should be trained to be familiar with equipment servicing requirements, while the education of professional engineers must be largely dedicated to working with existing technologies. This is what most engineers do in the real world and what is primarily expected from engineering graduates by industrial employers. In mainstream education, the necessary focus on existing technologies is moderated only at the Ph.D. level, where students are expected to acquire advanced research abilities but usually only in a very specialised field. AEE is relieved from these constraints: the whole educational process from year 1 to ME or Ph.D. is fully dedicated to preparation of the students for the third role. Associate engineers are preoccupied with day-to-day industrial practice, advanced engineers deal exclusively with engineering research, innovation and theory, while professional engineers have to balance both of these elements — this description is somewhat simplified but still points to key distinctions between the three categories.

2.2. *What is engineering?*

The categories of engineering education are related to alternative interpretations for the substance of engineering discipline, which were repeatedly debated in a new emerging field of philosophy of engineering (van de Poel and Goldberg 2010). The common interpretations of engineering can be categorised as illustrated in Figure 1 (Klimenko 2007). According to Figure 1A, engineering is primarily derived from practical experience — this perspective aligned with the style of engineering education aimed at educating engineering associates and focusing on practice and application. Figure 1B interprets engineering profession as being based on a balance of scientific knowledge with industrial application and practice, which is a commonly accepted premise in education of professional engineers. While discussion of this alternative (practice vs theory) persisted in engineering education for a long time (Fox and Guagnini 1993; Christensen et al. 2015), the philosophical thesis that correlates with AEE cannot be expressed in terms of this one-dimensional analysis without considering other dimensions. Indeed, Figure 1C, which interprets engineering as "applied science" (i.e. application of science to industrial problems), relates more to an occasional science perspective on engineering than to AEE. According to Figure 1C, engineering is not a field of knowledge or research but only an application of existing scientific knowledge to practical problems.

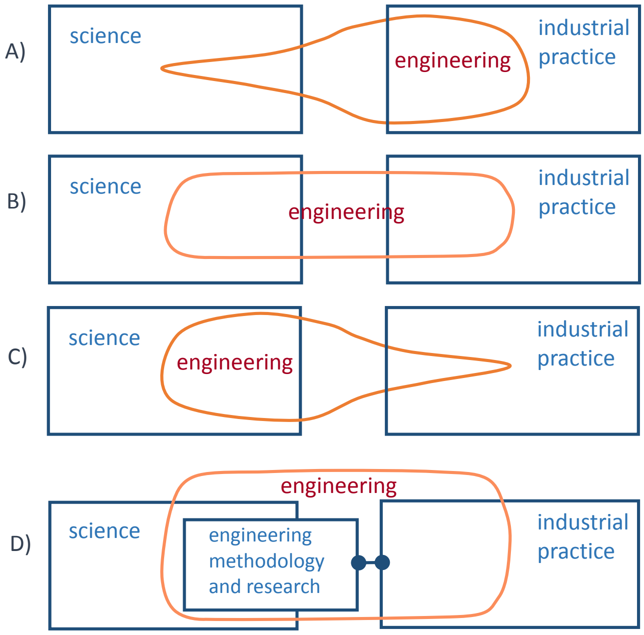

Figure 1. Different perspectives on role of engineering as the discipline connecting science and industrial practice.

AEE pertains to the interpretation of engineering illustrated in Figure 1D: engineering possesses a methodology of research and study on its own, which is related to but not identical with the corresponding methodologies of conventional science. Academic rigour is paramount in science while engineering is more concerned with effectiveness and efficiency. This leads us to conclusion that engineering research directly contributes to accumulation of scientific knowledge and reason. Engineering research, however, does not duplicate conventional science — this would be highly inefficient and contradictory to the key engineering principles. Engineering always accepts advice and guidance from science whenever such guidance is available but, at the same time, advanced engineering is prepared to lead and research when the needs of technological development require crossing the frontiers of our knowledge. The research segment of engineering is often called "engineering science" and seen as being a part of general science but, for the sake of clarity "science" is necessarily understood here as "science other than engineering" while the segment of engineering dedicated to research and innovation is referred to as "advanced engineering". While the engineering profession also has a strong involvement in day-to-day industrial practice, it is the research and innovation part of engineering that is of prime interest for AEE. Hence, AEE focuses on key issues and does not cover the whole spectrum of functions performed by the engineering profession. Since engineering problems can easily overlap with different scientific disciplines, advanced engineering plays an important role in integration of knowledge acquired by these different disciplines. Transdisciplinarity is one of the key features of AEE.

3. History of advanced engineering education

The history of AEE indicates that the principles of advanced forms of engineering education were not invented at a single place in a final form (Karlov and Kudriavtsev 2003). Rather these principles travelled from country to country and from institution to institution while being adapted and improved on the way. Education is an important part of the technological/social evolution of human society and tends to progress gradually. This section reviews the historical development of engineering education, focusing on facts and events that are relevant to advanced engineering and giving interpretations from the perspective of requirements and expectations of AEE.

3.1. *UK: the stronghold of professional engineering*

While military and civil engineering has been known for hundreds of years, the modern rise of the engineering profession is associated with the Industrial Revolution, led by the UK. The invention of steam engines, development of sophisticated machinery, and the growth of manufacturing in the 18th century created a need for qualified professionals—mechanical engineers—who could develop and maintain these new technologies. The class-based society of 19th century Britain quickly determined a proper place for engineers: above manual workers but below graduates of the top Universities; the latter formed the British intellectual elite and occupied top positions (Jorgensen 2014). Engineering education in the UK emphasised practical skills and was mainly based on apprenticeship, but later involved some fragmented schooling such as in Mechanics' Institutes (Gillard 2011). Emphasis on professional experience and professional registration is a part of the British tradition, which ensured good practical skills of professional engineers. Overall, the British account of professional engineering proved to be successful in creating space for the growing industrial and military might of the British Empire. Yet, in the second half of the 19th century, it became more and more obvious that British engineering education and, subsequently, British industrial development are lagging behind those of Germany. Repeated attempts of adopting more continental style of engineering education had only very limited success, despite being supported by Prince Albert and other progressive thinkers (Hennock 2006). Only 4 graduates per year from the Royal School of Mines — the first state engineering school established in 1851 in London — could find jobs in the mining industry. Many provincial engineering schools had to close soon after opening (Hennock 2006). One cannot avoid the impression that, at that time, the professional bodies of self-educated engineers and the University establishments did not have — and did not want to have — anything in common.

The technological innovations of the 20th century brought engineering education into most reputable British Universities, opening opportunities for advanced engineering education within these Universities while leaving professional engineering education to the polytechnic Institutes and technical Colleges (Grayson 1984; Jorgensen 2014). A viable alternative was to follow the continental model and establish advanced technical

University(-ies). Fully exploring these opportunities would be a natural evolution of engineering education in line with social changes in the UK, but this has not happened. The possibility of establishing an advanced technical University or Institute, similar to MIT in the US, was repeatedly discussed by the British government in the 1950s (Walsh 1998). Winston Churchill actively supported the idea after his retirement. The whole effort to establish an advanced technical Institute in the UK was finished with a rather modest success of creating a new residential college in Cambridge University — the Churchill College.

While derivatives of the British engineering degrees and the British tradition of professional accreditation are widely used in the modern world, British engineering degrees still tend to remain quite ordinary, even at UK's best institutions. Three years is generally considered to be sufficient to reach the BE level while a 4-year program would reward its students with the ME degree. It should not come as a surprise that Britain, which generally has a University system of exceptional strength and versatility (one can recall that the UK yields only to the USA in University rankings – see QS 2016), performs unremarkably in R&D (ranked 22nd according to Bloomberg 2016). While British mainstream engineering education is formidable and satisfies the immediate needs of the industry, the weak presence of AEE in the UK acts to sever the links between fundamental science and practical engineering, impeding transfer of research strength from academia to intellectually intensive sectors of industry. An impartial observer can only wonder why the country that possesses unrivalled educational and intellectual resources has consistently undervalued advanced forms of engineering and has largely failed to adopt and support AEE. Perhaps the strengths and weaknesses of the British education and innovation sectors are deeply embedded in British tradition, which makes these weaknesses difficult to see and difficult to change. It seems that inherently antagonistic view on the roles of fundamental and practical disciplines is the main source of the problem.

In 1992, the British government followed Australia's lead and made the radical step of upgrading all polytechnics to the University status and, therefore, merged different forms of tertiary engineering education into a unified model (Levy 2000). More than 20 years after, educational debates still continue and suggestions of bringing back polytechnics have reemerged in public discussions (Scott 2012; IPPR 2013). The arguments for and against reintroducing polytechnics tend to go in circles around the same problem of social justice often sidelining questions of quality and effectiveness of education. These arguments seem to miss the major point: the reforms have resulted in downscaling the more advanced forms of engineering education as much as they have reduced the polytechnic-style education. Universities and polytechnics have converged (Christensen et al. 2015). As observed by Scott (2012)—a prominent British educator and defender of the reform—"Universities have become as much like the former polytechnics as the other way round".

The British reform of 1992, its motivation and the subsequent developments, which have resulted in shrinking of the spectrum of engineering education in the UK, have many common points with the changes in engineering education that occurred in Australia at the same time. These changes are examined in the next subsection.

3.2. *Australia: punching above its weight*

Four of the oldest ("sandstone") Universities in Australia were established in state capitals in the second half of the19th century, while the remaining two "sandstones" appeared a bit later, just after the formation of the Australian Federation. These Universities generally followed the British model, although engineering education was part of these Universities from their early beginnings. The spectacular rise of Australian tertiary education is associated with the reforms conducted by the government of Robert Menzies. These reforms were carefully planned and implemented step by step in the 1950s and 1960s. These steps included introducing student scholarships and providing federal funding to support university growth, while implementing a number of measures aimed at lifting standards of university education and research. The educational principles of effort, performance and merit-based access for all social groups emerged during the Menzies era. Menzies (1961) had a vision for Australia's future based on strong, fundamental and diverse education and saw universities as places where deep fundamental studies and academic excellence meet practical goals. The attentive reader would not miss the point that the political ideas, which formed the basis of Menzies reforms, do have broad conceptual similarities with the specific educational principles discussed in the next section. Strengthening of the system of Australian engineering education was one of the major outcomes of the Menzies reforms. Although Australian education was largely replicated from the British system, the former colony seemed to easily avoid the problem of undervaluing the advanced side of engineering. The Martin et al. (1964) report, which was commissioned by the Menzies government 10 years after the beginning of the reforms, already indicated that, while numerous improvements were still needed in many areas of education, engineering education in Australian Universities had become impressively strong. Like in the US, Australian BE degrees were always based on extended programs (at least 4-year long), but Australian Universities capitalised on better secondary schooling and moved their undergraduate programs further ahead.

The last educational initiative of the Menzies government was introduction of Colleges of Advanced Education (CAE) a broad category of educational institutions that, jointly with Universities, formed a binary system of tertiary education but, unlike the Universities, were focused on practice-orientated models of education. In the middle of the 1970s, the newly elected federal government of Gough Whitlam abolished all tuition fees and took over funding of tertiary education from the states. While abolishing the fees had a positive impact on student quality and diversity, it can be argued that the burden of the tuition-free and federally funded system of tertiary education was financially unsustainable in the long run and that another reform of education was inevitable.

Of particular note there is the major reform of tertiary education implemented in the early 1990s by the Hawke-Keating government, which is named after the education minister of the day: the "Dawkins Revolution". While this reform was economically successful, it continues to receive conflicting assessments of its outcomes (Meyers 2012; Croucher et al. 2013; Stokes 2014; DET 2015). One of the implications of the reform was upgrading the status of a CAE to that of a University, which doubled the number of Universities in Australia. The declared goal of the reform was to give the opportunity for a University education to every Australian. The reform brought both positive and negative changes into Australian education.

Under the binary system, the combination of all three levels (categories) of engineering education — TAFE Colleges, CAEs and Institutes of Technology (which had the same status as CAEs), and, at the top of the list, the Universities — produced professionals with different sets of skills, meeting the requirements of industry and of other institutional employers (Meyers 2012). The Colleges being relatively small and flexible could quickly adjust to local needs and conditions. Many Colleges had direct educational arrangements with industry (Dawkins 1987). The Australian University sector provided undergraduate engineering education of high standards with depth and content not yielding to (and, in my observation and experience, exceeding) the depth and content of the corresponding top programs in the USA.

The upgrade to the University level reduced the practical segment of engineering graduates as the former Institutes and CAEs tried to emulate University-style education (some successfully, others not) which caused so called academic drift (Christensen et al. 2015). As a result of the reforms, the top segment of industry-orientated engineering programs has disappeared. The academic drift was eventually felt by industry, which complained about the lack of practical skills among engineering graduates. In the late 1990s – early 2000s, this was marked by a reduction in the fundamental content and sophistication of the courses. The changes stemming from the Dawkins reform have resulted in a narrowing the spectrum of engineering graduates due to abandoning more advanced forms of engineering education, while also reducing the number of engineering graduates with practical orientation (the details of these changes are to be discussed in further publications).

The "one size fits all" formula applied to education does not remove social stratification in the society but, instead, abolishes important social lifts. These lifts can reinforce social justice and propel talented and able individuals to top positions through education. As an effective tool of social mobility, AEE can be resented by the conservative establishment and, at the same time, objected to by radical equalists (although for different reasons). It seems, however, that the slogan "the same education for everyone" was instigated for selling the reforms (which were not popular due to the reintroduction of tuition fees) to the public, while scaling down the advanced forms of education was not the goal of the reform but its side effect. In simple terms, the reform decreased differentiation and increased the availability and cost of education, but off-loaded this additional cost on the students.

The old Australian University system, which appeared in the wake of the Menzies reforms, was tuned for pursuit of excellence in education of students selected for their abilities and involved segments of outstandingly high quality and international standing. After the Dawkins revolution, this system has been changed and adapted for mass production of graduates (Meyers 2012; Stokes 2014) with an emphasis on average needs and quality. As the educational institutions of the Asia-Pacific region continue to improve, the long-term attractiveness of the Australian education sector will depend on its ability to reinstate and pursue more advanced forms of education, which can augment and enhance the educational mainstream. This point is valid across disciplines but is especially relevant to engineering.

3.3. *India: potential for growth*

Engineering education in Indian Universities mostly follows the conventional British system but, as in the USA and Australia, is based on four-year-long BE programs. Indian experience in AEE began in the late 1950s and early 1960s after five original Indian Institutes of Technology (IIT) were established in Kharagpur, Bombay, Madras, Kanpur and Delhi, with competing assistance from the USSR, Germany, the USA and the UK (Bassett 2009). The IITs were recognised as the "Institutes of national importance" and placed under the direct patronage of the President of India (Indian Parliament 1961). The IIT contribution to education has been acknowledged by the US Congress (House of Representatives 2005). The number of the IITs has subsequently grown to 19, although these institutions still produce less than 1% of engineering graduates in India. The main feature of IITs is highly competitive entrance examinations and intensive education to high academic standards, comparable to the best European institutions. This case seems to be unique: while being a developing country, India became not only the world's largest democracy but has also joined an exclusive club of nations that possess AEE capabilities. The Indian experience demonstrates that is it possible to create and retain the pockets of a high-quality intensive education within a tertiary educational system, which inherently suffers from mass production and insufficient standards. It is arguable that the introduction of IITs had by far overtaken the overall socioeconomic development in the country: India's R&D sector could not possibly adequately accommodate most of the IIT graduates. This has created a bias in the IITs toward undergraduate-style education with insufficient presence of the research segment and insufficient integration of learning and research.

Education at IITs is primarily based on the BE degrees and lasts for 4 years. These degrees reach high standards but still are not fully immune from the long-term weak points of engineering education in India (mass-production and insufficient integration). For many decades, IITs graduated scores of high-quality BEs who continued their study and research in the USA, the UK and other countries. This problem was understood by Indian government, which in recent years has made significant investments to upgrade the breadth and quality of engineering research in IITs. If these measures are successful, they will increase the value and standing of the ME degrees and, prospectively, bring the full potential of AEE into IITs. Overall, Indian Institutes of Technology represent institutions of engineering education of a high quality, which are well-positioned to provide intellectual fuel for continuing economic growth in India.

3.4. *France: the alma mater of advanced engineering*

If any country can claim to be the birthplace of AEE, it must be France. Introduction of AEE in France is closely connected to ideas of freedom and equality brought by the French revolution. France's renowned system of Grandes Écoles was shaped during the reign of Napoleon, who sought to developed educational institutions fostering excellence and bringing up a new French elite based on meritocracy and advanced abilities (Grayson 1984; Karlov and Kudriavtsev 2003; Jorgensen 2014). The students of Grandes Écoles learn a broad range of technical and scientific subjects. These ideas of integrated learning of fundamental and applied disciplines strongly correlate with modern understanding of AEE. Grandes Écoles have taught many intellectuals and famous figures (engineers, scientists, businessmen and statesmen), who have left notable traces in the history of France and the world. Engineer Sadi Carnot, scientist, engineer and philosopher Henri Poincaré, engineer and architect Gustave Eiffel, engineer and industrialist André Citroën, and Valéry Giscard d'Estaing, former President of France, are all graduates of Grandes Écoles. Sadi Carnot (see Figure 2) proposed a thermodynamic cycle of maximal efficiency and, therefore, introduced a statement that is equivalent to the second law of thermodynamics long before it was re-discovered by famous scientists Rudolf Clausius and William Kelvin. Despite his tragically short career, Carnot's brilliant discovery is symbolic and indicative of the potential of AEE.

Joining Grandes Écoles is more competitive and education there is more challenging than in France's traditional Universities (according to Grayson (1984), the latter educate around 80% of engineering graduates). It is not a surprise that the École graduates are highly sought-after by all kinds of prospective employers: research institutions, Universities, industry, government and military organisations. Most students of the leading Grandes Écoles possess impressive analytical abilities that, for engineering graduates of the British system, are difficult to match. While in the British system, educational strength belongs to the Universities, in France it is concentrated in the Institutes (Grandes Écoles). This difference, however, does not seem to be fundamental — in principle AEE can be effectively implemented both within and outside the University walls. The essential differences between the French and British systems of engineering education stem from differences in educational principles and the expected social roles of the engineering graduates (Jorgensen 2014). Compared to Britain, France has suffered

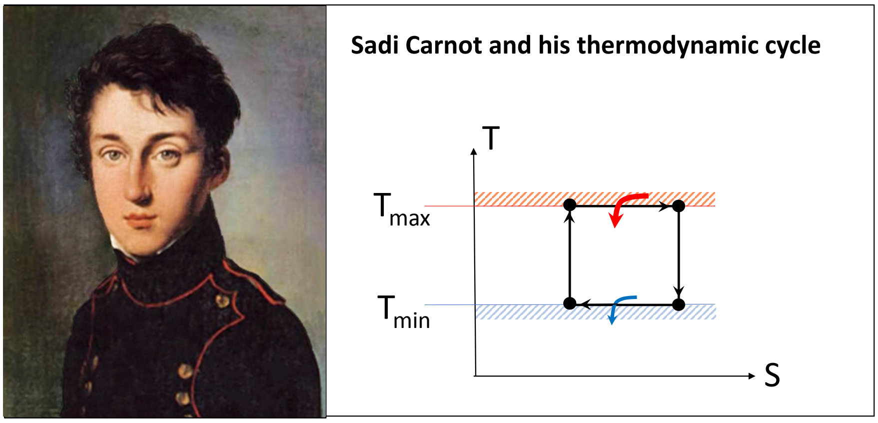

Figure 2. Sadi Carnot, French engineer and a graduate of École Polytechnique in Paris, and his thermodynamic cycle (portrait by Louis-Léopold Boilly)

from a lower presence of practically-orientated segments of engineering, which, perhaps, contributed to the slower pace of French industrialisation, but its traditional strength in AEE brings new opportunities in modern conditions.

The academic standards of the Grandes Écoles have strongly influenced AEE around the world. However, despite a remarkable history of academic excellence, the Grandes Écoles have their weaknesses too—students of Écoles are insufficiently exposed to challenging problems from the real world. Integration of academic learning with creativity and research is one of the key elements of AEE, while these great schools seem to lack this element. This weakness is systemic and goes back to 19 century when the Écoles became detached, both educationally and socially, from technical schools of the lower ranks (Kranakis 1989). The link connecting intellect with practice was interrupted. In the second half of the 19th century, the long-term investment into AEE should have given France a competitive advantage but the sector failed to innovate and the country resorted to importing the newest technologies. (Fox and Guagnini 1993).

The weaknesses of Grandes Écoles are now understood in France (Laporta 1988). This has opened debates whether traditional role of the Grandes Écoles needs to be preserved or adjusted for the realities of the modern world. It seems that the reformation view has finally prevailed and measures are being undertaken to address the weaknesses. A new grand institution — The University of Paris-Saclay — has been opened in 2015 by bringing together 19 France's most prestigious institutions including École Polytechnique, CentraleSupélec and southern fragments of old Sorbonne University (Thoenig 2015). The idea of integration of educational and research strengths, which is the main goal of this unification, is a key principle in AEE but the grand scale of the project and associated infrastructure issues threatens to overshadow the educational principles. With the right emphasis, the University of Paris-Saclay is posed to become one of the world's greatest centres of AEE in the future.

3.5. *Germany: long-standing engineering tradition*

Germany and most German-speaking and Nordic countries have common traditions of tertiary education, which in the beginning of 20th century had a profound influence on the world's engineering and science (Grayson 1984; Sato et al. 2008; Jorgensen 2014). Since Germany entered the age of industrial revolution after Britain and France, its engineering tradition was affected by both and French pursuit of AEE and British strength in practical engineering. As the result, engineering education in Germany excelled in academic studies, at the same time, retained segments with strong practical emphasis (Harwood 2006). Karlsruhe Institute of Technology (KIT) was established in 1825 as Polytechnische Schule, replicating French École Polytechnique and serving as a model for other German institutions (Hennock 2006). Political fragmentation of German states in the first half of the 19th century brought impressive diversity of forms and methods into German education. At the turn of the 20th century, Germany educated both more practical and more advanced engineers (the ratio can be estimated to be at least 4:1 in favour of practical engineers — see Fox and Guagnini 1993). During these years, the German system of engineering education proved to be effective in supporting industrial growth and innovation.

Unity of fundamental and applied sciences became the foundation of modern AEE not least due to ideas of Felix Klein, Dean of Mathematics at the Göttingen University. In a move, unusual for a traditional German University, Klein established an institute of applied mechanics and invited engineer Ludwig Prandtl to lead it. This institute was to give the world many prominent and fundamentally educated engineers (such as Theodore von Karman and Stephen Timoshenko). In the beginning of the 20th century, Klein's ideas and inspiration propelled Göttingen University to the leading position in the world.

The dual orientation of engineering education in Germany (Fox and Guagnini 1993; Jorgensen 2014) is reflected in two types of tertiary education: a practical and profession-centred education in Fachhochschulen (FH) and more academically advanced University-type education in Technische Hochschulen (Institutes of Technology or Technical Universities, TU). The former institutions should not be confused with Fachschule (Berufsfachschule or Berufs-Fachakademie), which graduate associate engineers or technicians. From the 20th century, the latter institutions have acquired the status of Universities, although some of them still refer to themselves as Institutes (RWTH Aachen and KIT are considered to be among the best in Germany; Swiss ETH Zurich is ranked highly and also belongs to the same tradition). The best Technical Universities in Germany are known as the "group of nine". In the end of 19th and the beginning of 20th century, German-style education in general and TU in particular demonstrated remarkable strength. The fact that Karl Benz, Ludwig Prandtl, Albert Einstein and many other famous figures are graduates of TUs is indicative of the role which these institutions play in the German system of education.

The traditional form of engineering education in Germany is a 4 to 5-year integrated program awarding the Dipl.-Ing. degree. The main feature of the binary TU/FH system is that the both versions of this degree, 4-year long Dipl.-Ing. (FH) and 5-year long Dipl.-Ing. (TU) would comply with educational standards for professional engineers and are well-accepted by industrial employers. In addition Dipl.-Ing. (TU) is a stepping stone for engineering doctorates. After the Bologna Process, German Universities are now completing the planned change to more conventional Bachelor's and Master's degrees. This issue has been hotly debated in Germany, but these debates seem to miss the main point since the change from Dipl.-Ing. to BE and ME alone does not affect the style and quality of education (Dipl.-Ing. (TU) can be interpreted as an analogue of the integrated BE/ME degrees). The historical strength of German engineering education is not in a particular degree but in its capacity to combine practical and advanced segments into a coherent stable system. The main question is whether the binary system of German education can remain stable after the change at the time when this change creates a pressure toward unification (Christensen et al. 2015).

German engineers are generally prepared to lead and can demonstrate both specific expertise and broad erudition (Croome (1991) noted that the profession of engineer-architect in Germany would correspond to six different engineering professions in the UK). The educational standards in Germany are generally high but, at present, fall behind the academic excellence of the French Grandes Écoles. Perhaps, it is the trend of the German Technical Universities to grow in size, put as many students into lecture theatres as possible and mass-produce TU graduates that inevitably placed educational constrains, which have gradually resulted in falling short of the AEE expectations. (In modern days, the both types of the tertiary institutions, FH and TU, produce similar numbers of engineering graduates—see DAAD (2012)). At the same time, it was more Germany than France that played a key role in influencing the advanced forms of education around the world — Germany's historical contribution to engineering education, which unified the French and the British approaches to engineering, is profound. Over the years, the German system of engineering education, which combined AEE with education of practical engineers and technicians, demonstrated the utility of this approach. This system, however, was eclipsed during in the second half of the 20th century when AEE was pushed to its limit by the technological effort of the Cold War. At present, the German education system is known for its conservatism, which on one hand still preserves high academic standards in engineering education (this reflects the outstanding strength of German education at the beginning of 20th century), but on the other hand makes any needed changes difficult and slow.

3.6. *USA: the way to the top*

In the 19th century, tertiary education in the USA developed around a very practical approach to education in general and engineering in particular. The early steps tended to follow the British university college model (Jorgensen 2014) but later developments are commonly seen by historians as combining British and continental European traditions (Akera and Seely 2015). One of the first prominent American scientists, Josiah Willard Gibbs, held his PhD in Engineering from Yale University (it was one of the first PhD degrees awarded in the USA). The influx of European migrants between the wars and after WW2 (Hungarian von Karman and Ukrainian Timoshenko can be mentioned as good examples) brought the first ideas of a more scientific curriculum in Engineering (Jorgensen 2014; Akera and Seely 2015). At that time, lectures given by German-educated immigrants became common in American Universities. Von Karman joined California Institute of Technology (Caltech) in 1930 and advocated a more fundamental, scientific curriculum in engineering schools (Von Karman and Edson 1967). He insisted that engineers should be taught a good deal of mathematics, but in a style that is different from the style of education in mathematics degrees: engineers should learn mathematics not by memorising theorems, but by actively using it. The concept of active and creative learning, learning and researching at the same time is very much in line with the modern understanding of advanced engineering. The educational principles advanced by von Karman in the 1930s, have shaped Caltech into America's prime technical University. Timoshenko had similar ideas and contributed to strengthening engineering programs in Stanford University (Timoshenko 1963).

After WW2, the arms and space race brought a new demand for more sophisticated technologies that required better-qualified engineers. It became clear that engineering education in the USA required major changes in curriculum. New standards for education of engineers, involving a substantial volume of mathematics and science, were promptly developed and implemented. Toward the end of 20th century, however, it was found that many engineering graduates lacked practical skills that are needed for employment in industry (Jorgensen 2014). The pendulum swung back, reintroducing traditional engineering subjects such as design, laboratory work, group projects, etc. at the expense of science and mathematics. These changes were echoed in many countries around the world. After the end of the Cold War, American engineering education became more relaxed and more related to day-to-day engineering practice (Akera and Seely 2015).

In the second half of the 20th century, it would have seemed natural for University engineering education in the USA to split into two streams: professional engineering and advanced engineering, with the former servicing basic industry needs and the latter preparing students for research and development in Universities, research labs and high-tech industry. This division has never formed, at least not in any explicit form. Most American Universities have similarly structured engineering degrees and differ mostly in the quality and prestige of the institutions. A typical undergraduate degree is 4 years long, starts with repeating some high school material and has plenty of flexibility in selection of the courses. The advanced part of engineering education has been moved to the postgraduate level (mostly to Ph.D) where students have to take advanced specialised courses. This, generally, is a good practice, but it also means that the best students have to wait for their postgraduate studies to experience more advanced forms of education. Practically, the high quality of the top American Universities and the possibility of attracting the best students from around the world into post-graduate programs conceal the low presence of undergraduate AEE in the USA Some Universities offer "Engineer's degrees", which represent an alternative to a Ph.D. for professional engineers, but again this division occurs only at the postgraduate level. While integrated BE/ME degrees are not common in the USA, integration of the College BLA (Bachelor of Liberal Arts) degree with University ME is more common. This integration has some conceptual similarities with integration in AEE but, from the perspective of advanced engineering, the College education is usually fragmented and insufficiently intensive, even if physics or mathematics is taken as the BLA specialisation. Some of the top institutions, e.g. Caltech and MIT, have strong elements of AEE in their curricula. Yet, the programs in these two institutions are quite different. MIT provides a flexible and modernised education incorporating elements of management and social sciences into their engineering degrees while Caltech is focused on integration of traditional science and engineering. Caltech offers the integrated BE/ME degree but only to outstanding students.

Overall, the system of Ph.D.-level engineering education in the USA is exceptionally strong —it endeavours to integrate advanced learning with advanced research, which is consistent with the AEE principles. Over the years, this strength has been translated into the world's leading positions in innovation, research and development. The mainstream undergraduate engineering programs in the USA are of solid quality and standing, while variations in quality of secondary schooling and low presence of AEE at undergraduate levels are systemic weaknesses of American education. These weaknesses do not seem to have caused any substantial problems so far, and this status quo is likely to continue into the future as long as America can attract the very top layer of engineering graduates from around the world into its Ph.D. programs.

3.7. *Japan: combining technology and tradition*

Technical education in Japan was established during the Meiji reforms in the second half of the 19th century and is currently represented by the impressive network of Colleges of Technology, Institutes of Technology (which have the same status as Universities) and Universities (McGuire 1996; Sato et al. 2008; Bevrani 2012). As in Germany, engineering profession in Japan is highly respected and traditionally accepted as an academic discipline (Croome 1991). There is around half a million engineering students in Japan's 778 Universities, including 86 national Universities, which are generally considered to be more prestigious. Engineering education in Japan has provided qualified engineers to fuel

Japan's spectacular industrial development and growth in the second half of the 20th century. High academic standards and traditional ethics are two pillars of engineering education in Japan. However, the difficulties encountered in the last decades indicate that engineering education in Japan needs reforms that would reflect realities of the modern globalised and knowledge-based society. These reforms are called upon to bring innovation and achievement into engineering education, encouraging students with advanced abilities to reach as much as they can through education and research. Some institutions have introduced engineering degrees with enhanced education in physics. Although the ideas of reforming engineering education have been supported by Japanese industry, they need to modify the Japanese tradition and have had mixed success thus far.

3.8. *China: educating engineers on a grand scale*

Educational meritocracy has been an inseparable part of Chinese culture for hundreds (if not thousands) of years. The present scale of tertiary education in China is impressive: the number of University students in this country is similar to the population of Australia and about a third of these students study engineering. The quality of education in Chinese Universities is not uniform and remains inadequate in many educational institutions. However, the grand effort undertaken by the Chinese government (project 211, project 985 and group C9) to improve the quality of University education has borne fruit: graduates of the best Chinese Universities are educated to an impressive academic standard, comparable to the highest standards existing in the Western countries. The prime goal of engineering education in China is fuelling industrial growth with well-qualified professional engineers. It seems that advanced engineering education has not been specifically targeted in China so far. While the best Universities foster academic excellence, lack of initiative and creative research experience remain the weak points of the education system in China.

3.9. *USSR: advanced engineering hidden behind the iron curtain*

While tertiary educational systems are commonly degraded in totalitarian countries, Soviet Union was clearly an exception. Despite its grossly inefficient state-controlled economy and paranoid secrecy, the USSR managed to compete rather well in some segments of space and military technology. The secret of this success lies in creating and maintaining reasonably high standards of engineering education through numerous specialised technical Institutes scattered over the USSR, producing in excess of 300 000 engineering graduates per year (Grayson 1984), and in achieving highly advanced standards in relatively few selected institutions pursuing AEE.

The old Russian and later Soviet approach to education was predominately branched from the German tradition and continued on its own path. French influence on Russian education was also strong but mostly before the middle of the 19th century, while the oldest forms of tertiary education in Russia were replicated from those in Ukraine. Two institutions — Imperial Moscow Technical School (IMTS, later Bauman University) and St.Petesburg Polytechnic Institute (PPI) — opened new chapters in engineering education of Imperial Russia (Karlov and Kudriavtsev 2003). The long-term success of IMTS is remarkable and indicative of the great utility of integration for engineering education (the IMTS program, which integrated high standards of professional engineering education with creative elements of the "hands on approach" practised in technicums, had some historical influence on MIT in the late 19th century). Despite the existence of some common features, IMTS-style education mostly focuses on sound education of professional engineers and thus should not be confused with AEE.

The Soviet version of AEE was proposed by Abram Ioffe and implemented in PPI during the troubled years of WW1 and the revolution (Karlov and Kudriavtsev 2003). In the late 1920s, the system was extended to Kharkiv, where it was greatly contributed by Lev Landau. While these first steps were extraordinary successful in many respects, the forerunners of the Phystech system suffered from the great purge of 1937 and then from WW2 (Karlov and Kudriavtsev 2003).

A typical term for Soviet engineering degrees was 5 years, although some advanced institutions had extended 6-year-long programs. Among these institutions, there was one—MIPT (Moscow Institute of Physics and Technology, or informally Phystech)—that played a very special role among Soviet Universities and Institutes, implementing all major elements of AEE and taking this method of education to a new level (Karlov, Simonova, and Skorovarova 1996). MIPT was founded only after WW2 in 1946, initially as a faculty of the Moscow University. The new faculty was disliked (and nearly closed) by the University conservatives and Soviet bureaucracy. As the result of a struggle of top Soviet scientists led by Peter Kapitza (a former student and colleague of Abram Ioffe and UK physicist Ernest Rutherford) against the conservative establishment, Phystech was not only recreated as a fully independent institution but also was granted extended freedoms unprecedented for a communist country (perhaps, it was the need to compete in the arms race that made this exception possible). The rivalry between the Moscow University and MIPT nevertheless continued into the future. While the education of mathematics and science in MIPT was replicated from the Moscow University programs, which are widely known for their remarkable strength, the educational styles in these institutions were very different. Within a decade, MIPT became one of the highest Soviet achievements and a host institution for the world's most comprehensive implementation of the AEE principles. In the 1950s and 1960s, several Faculties of Physics and Technology were formed in leading Universities in some industrial centres (e.g. Dnipro and Kharkiv, which became the centres of Phystech education in Ukraine) and proved to be highly successful.

The educational method formulated and implemented in MIPT became known as "the Phystech system" of AEE. The long-term Rector of MIPT Oleg Belotserkovsky (Karlov, Simonova, and Skorovarova 1996, p.66) characterised its role by stating:

> The system of Phystech has removed rifts and contradictions between fundamental, applied and industrial sciences. Science, by its nature, is a unified endeavour.

Despite being a relatively small institution graduating on average only half-a-thousand students per year (Karlov, Simonova, and Skorovarova 1996), MIPT had a significant impact on the science-intensive sector of the Soviet R&D effort. Phystech has produced engineers, scientists and leaders with highly advanced abilities, who eventually spread and occupied the foremost positions in key research institutions. In the Soviet system, all these institutions (irrespective of their formal affiliations) predominately serviced the military-industrial complex and were responsible for principal technological advances and concurrent development of the associated fundamental sciences.

It needs to be understood that MIPT was not a stand-alone institution, did not have its own research base and was embedded in the high-tech segment of the Soviet research and development complex. Unlike more conventional Universities, MIPT cannot exist as an advanced institution without this segment. Because of this, direct replication of the MIPT-style AEE is hardly possible. Predictably, MIPT went into decline after the collapse of the USSR. Nevertheless, MIPT represents the most extensive and complete known experiment in AEE and provides a lot of educational experience to learn from. Still, the system of Phystech and the other implementations of AEE need to evolve with the evolving and changing world to remain relevant.

3.10. *Advanced engineering and knowledge society*

This brief historical review of AEE would be incomplete without a note on most recent trends. While the British system of educating professional engineers proved to be effective during the age of industrial development and growth, the recent technological trends of moving toward knowledge society bring new demands for education. The countries that played key roles in the industrial development of the 20th century and achieved high standards in education of professional engineers must realise that, at present, these standards are being (or can be) reproduced in many different places around the world. As the result, conventional engineering jobs can be performed in these places more efficiently and at a lesser cost. Selling education is a good business as long as the seller still has the capacity of learning and moving forward. Those who are too slow in achieving higher standards will inevitably fall behind. Educational strength is one of the key elements that are needed for success in the knowledge society.

The industrial revolution has dramatically changed social organisation in most Western countries, converting old medieval hierarchies into complex, interconnected and flexible industrial societies. However, the structure of governance within industrial companies (especially those pertaining to old industries) tends to remain highly hierarchical and rather inflexible. The age of information and knowledge brings new principles of organisation into industrial companies that have to adjust and evolve to be competitive. While the rise of engineering profession was associated with the industrial revolution, the emerging revolution of knowledge and communications brings new trends and expectations. It seems that the new sectors of industry are becoming more and more similar to a well-organised version of the academic environment. In these sectors, modern engineers are not expected to perform the same tasks over many years; they need to be inventive and flexible, have a wide spectrum of knowledge and learn quickly when needed, as well as be prepared to lead and work in complex and research-intensive conditions. These expectations are well aligned with the principles of AEE.

4. Principles of advanced engineering education

The history of engineering education demonstrates a substantial diversity in teaching methods and approaches, and this is also applicable to the advanced segments of education. It seems, however, that modern understanding of key principles of AEE, which were developed in the best French, German, Soviet and, in a more fragmented form, American institutions, can be summarised as:

1. **Meritocracy:** selecting the very best students on the basis of merits
2. **Fundamental transdisciplinarity:** comprehensively teaching them the fundamentals of engineering and science
3. **Integration:** progressively involving students into cutting-edge research while exposing them to the complexity of real-world problems

These principles reflect the educational method formulated and implemented as the Phystech system in MIPT (Karlov, Simonova, and Skorovarova 1996), which represents a developed and tested version of educational ideas previously advanced by Ioffe (Karlov and Kudriavtsev 2003). Historically, these principles were also contributed first by French excellence and German tradition and then by American innovation, which perhaps is best reflected in shaping early Caltech (Von Karman and Biot 1940; Von Karman and Edson 1967). The educational method advocated by von Karman in the 1930s clearly has common features with the AEE principles listed above.

Existence of common features is not a coincidence: different versions of modern AEE are related and can be traced back to common roots in Göttingen University. Timoshenko (1963) mentioned that he worked with Ioffer in 1916 on a new AEE program for SPPI, while both Timoshenko and von Karman studied in Göttingen and were impressed by ideas of Felix Klein (Timoshenko 1963; Von Karman and Edson 1967). Paul Ehrenfest, who closely knew both Klein and Ioffer, was another link between Göttingen and St.Petersbug. Ioffer was also directly influenced by the German school of education while studying in Munich but his doctoral supervisor, famous engineer and physicist Wilhelm Roentgen, held rather traditional views on research and education, which were unlikely to contribute to conceptualisation of AEE.

Although the AEE principles are generally known, the devil, as always, is in the detail. AEE becomes effective only when all these three principles are applied synergistically — absence of one element can negate the others. While engineering students are to reach advanced standing in the fundamentals, which is commensurate with that in applied mathematics and science degrees, the style of engineering education is different. Engineering education places more emphasis on understanding and learning by doing (i.e. by researching and solving) than on formal presentation of the numerous facts. As students acquire knowledge and skills, they need to specialise and start their research programs in a selected field. AEE views student learning and student research as different sides of the same integrated process. By the time of graduation, most students are expected to reach the level that corresponds to advanced standing in the field. Research into real-world problems that have progressively increasing levels of complexity is an important part of AEE. The key principles of AEE are now considered in greater detail.

4.1. *Selection and standards*

AEE is based on selecting motivated students with advanced abilities and on strict maintaining of educational standards. If education does not reach a sufficient depth, the transferred knowledge often becomes an intellectual “dead weight” unusable in practice. The selection is based on academic performance but can take into account other criteria such as interest, dedication, ingenuity, independent thinking, desire to learn, curiosity, intellectual leadership and common sense.

Many AE (advanced engineering) freshmen, who used to be at the very top in their high school classes and are now surrounded by people no less capable than themselves, may lose confidence and interest in their studies. AE students need to be treated with due care, encouraging cooperation and deep learning that go beyond formal requirements of the courses, although a higher than average attrition rate is normal for AEE programs. The students who have to leave the AEE program, can still be reasonably good students — giving them another chance in a mainstream engineering program is always a good idea.

4.2. *Transdisciplinarity and fundamentals*

Traditional engineering treats evaluation of a fluid flow around an aeroplane and around a skyscraper (or a suspension bridge) as belonging to different branches of engineering: aerospace and civil. Advanced engineering sees these cases as different applications of the same (or similar) methodologies of solving equations for fluid flows. This does not mean that the disciplinary boundary between these applications does not exist or that this boundary is insignificant. However, disciplinary boundaries are not seen as an obstacle for transporting useful ideas and methodologies between disciplines. This process is not always as simple and obvious as in the case mentioned above—transported ideas and methodologies often need adjustments or adaptations. For example, the flow around a skyscraper may be stratified but, again, treatment of this problem can be sourced from another discipline—atmospheric science. Important inventions are often adapted from different applications of similar ideas. Johannes Gutenberg, who was born in the wine-making regions of Germany, adapted the wine press to print books, starting one of the greatest revolutions in history—the revolution of knowledge. It is well known that significant innovations often lay at intersections of disciplines and cultures (Johansson 2004).

Transdisciplinarity, however, is not limited to occasional borrowing of ideas from different disciplines or to interdisciplinary studies, i.e. studies in areas that are placed between the traditional branches of engineering and science. It is based upon deep understanding of key issues in the context of similarities and differences between problems formulated in different disciplines. The concept of transdisciplinarity is linked to both education and research. Examples of transdisciplinary applications are numerous: the model of a compressible gas flow can be deployed to characterise the flow of traffic on a road (Orosz, Wilson, and Stepan 2010), thermodynamic considerations can be used to analyse income distributions in economics (Yakovenko and Rosser 2009) or predict the evolution of generic competitive systems (Klimenko 2013), and so on. The transdisciplinary use of concepts and models requires solid knowledge of major scientific and engineering methodologies and the ability to deploy these methodologies across different disciplines. This, in turn, needs a good combination of intuition and critical thinking.

Genuine transdisciplinarity is achieved through deep understanding of fundamentals (with strong emphasis on mathematics, physics and key engineering subjects, irrespective of research specialisation). Complex social and economic processes are understood, interpreted and, possibly, modelled in ways that are similar to the traditions of natural sciences and engineering. For some people who are concerned only with resolving specific problems in specific fields, such extensive study of fundamentals might seem excessive and unnecessary — this point of view is represented by the mainstream education of professional engineers but it is not shared in AEE. The AE students learn to understand strengths, possibilities and limitations of fundamental theories and be able to modify, adapt and progress these theories as needed by applications.

4.3. *Integration*

As a University teacher, I have observed a few students who succeeded in reaching the level of an associate engineer in a specialised technical College and then joined University after two or three years to upgrade their qualifications to a BE and become professional engineers. Many, far too many, of these students had difficulties adapting to a more general way of thinking adopted in the University (this, of course, does not preclude the existence of some very good students who could perform well in both the College and the University). The narrow education in a professional College did not form a good basis for continuing University education, and many students had to relearn and adapt.

In the same way, a student educated to the standard of a professional engineer would find it difficult to become an advanced engineer by merely taking a few additional courses. Some talented and motivated students might be able to do this, but many would not. To become an advanced engineer one should be educated as an advanced engineer from his/her first day in a University and, preferably, be prepared for this endeavour by enhanced education in high school. The stream of AEE must be integrated and continuous to be effective. While the absence of engineering specialisation in the first years saves time, which is used in AEE to enhance and strengthen the fundamental segments of the curriculum, gradually preparing students for more active learning and research. Broad but superficial education does not fit AEE.

AEE is addressed to talented and highly motivated students while AEE programs must combine breadth with depth, mixing transdisciplinarity with creative application of learnt knowledge to specific problems. This point can perhaps be illustrated by the old saying coming from the Confucian tradition:

> I hear and I forget. I see and I remember. I do and I understand.

While the goal of AEE is clear, implementations of AEE need understanding and integration. AEE programs should not be a mere superposition of conventional training collected from various fields — this would overload the study with excessive details, which is bad for any type of education at any level. The research and academic components of AEE must be linked by common goals and directions.

Integration, which is a key element of AEE, involves several directions of integration, which are conceptually related to each other:

Integration of academic learning and research experience. AEE sees creative research as an important element of learning, and effective learning as an important component of successful research. Academic learning and research are two sides of the same process. Unity of education and research implies that a good teacher must also excel in research. Practically, AEE often implies integration of the BE and ME degrees.

Integration of fundamental and engineering sciences. AEE pertains to holistic views on science and engineering, finding fundamental unity among diversity of disciplines. As educational method, AEE teaches fundamental and applied disciplines as interconnected components. Advanced engineers are expected be capable of both solving practical problems and, if needed, conducting fundamental research.

Integration of broad education with profound understanding and deep specialisation. Fundamental knowledge is not to remain a static storehouse of numerous facts, but should be deployed flexibly and efficiently to solve specific problems. Students should not be overloaded with countless details from various fields but must understand the basic principles and learn these details quickly as required by research and practice. The ability to demonstrate deep understanding through a creative application of general knowledge to a specific complex problem in a selected research field is an important requirement in AEE.

Integration of rigorous scientific methodologies and complexity of the real world. Students are to be exposed to problems of gradually increasing complexity and, by the time of graduation, reach advanced standing in a selected research field, which is expected to be intellectually intensive and, desirably, linked to innovative and growing sectors of the economy. While it is useful to teach engineering students some elements of social sciences, these elements should be adapted to engineering values and principles and incorporated into the program without compromising the other segments of AEE.

Integration of education with pre- and post-educational experiences. It is desirable that AE students develop interest in advanced mathematics, science and technology while studying in high school or even earlier. In University, AE students are taught to learn required details quickly and efficiently, upgrade their knowledge in line with technological and scientific progress, and become lifelong learners. AEE provides the fundamental basis for continuing learning.

Integration and unity of engineering profession. AEE graduates should be confident and capable of leadership but, at the same time, must proudly see themselves as engineers sharing a common tradition with their professional colleagues. This reflects the unity of the engineering profession and continuity of its best traditions. When dealing with a specific difficult problem advanced engineers often need to consult with and quickly learn from professional engineers who have experience in a particular area of interest.

5. Can AEE become the mainstream of engineering education?

While the presence of AEE should have a positive effect on education in general and some elements of AEE can be useful for upgrading the mainstream education, the answer to the question posed in the section header is generally negative. This chapter elaborates on this.

5.1. *Role of specialisation in science and engineering*

The following quote from "General systems theory" by Bertalanffy (1968) is very explicit about the trend of specialisation in modern science:

> Modern science is characterised by its ever-increasing specialisation, necessitated by the enormous amount of data, the complexity of techniques and of theoretical structures within each field. Each science is split into innumerable disciplines continually generating new sub-disciplines. In consequence, the physicist, the biologist, the psychologist and the social scientist are, so to speak, encapsulated in their private universes, and it is difficult to get word from one cocoon to the other.

This statement might seem to be an exaggeration. The fragmentation of modern science and engineering is, typically, visible neither to the general public, nor to specialists working in particular areas, but the reality of modern science and engineering is that they are divided into highly specialised and to some extent fragmented fields and subfields. In many cases, we notice fragmentation only by chance when come across these fragmented fields. While suggesting a framework that opens the possibility for analysis of some common features of tornadoes and hurricanes (which generally represent very different atmospheric phenomena), I found out that, surprisingly, there is no (or very little) overlap between numerous studies of hurricanes and tornadoes in atmospheric science (Klimenko 2014). In other cases, however, the gaps between different fields of science have been not only well-known but also hotly debated. A good example is the disparity between the time-symmetric theories of classical and quantum mechanics and particle physics on one end and the time-asymmetric nature of thermodynamics on the other end. This disparity has been debated from the times of Ludwig Boltzmann and is still not fully resolved in modern science (Price 2002). As noted previously, engineering is also divided into several traditional branches with noticeable differences in methodologies and applications.

Our sophisticated industrial society needs large quantities of various specialists and tertiary education is primarily designed to satisfy this need. It takes a great deal of learning to become a specialist in a field of modern science. Students and researchers of science have to work hard to reach the frontiers of known and only then can proceed to advance these frontiers. Even a small advance into the unknown is not an easy endeavour.

The conventional wisdom of contemporary tertiary education is based on specialisation: e.g. teaching nuclear physics is the best way of obtaining a graduate expert in nuclear physics and teaching civil engineering is the best way to graduate an expert in civil construction. A graduate selects an industrial or academic field and works in that field till his/her retirement. The nuclear physicist works in a nuclear lab and the civil engineer supervises a construction site. Good specialised education promotes critical thinking but, practically, only in the particular field of specialisation; bad education remains dogmatic.

While conventional specialised education reaches its goals and satisfies the mainstream educational needs of the society, it inevitably places constraints on the education of the smartest and most motivated students. Important discoveries are known to be at intersections of different disciplines (Johansson 2004).

5.2. *Recent integration trends*

The trends of fragmentation and integration reflect the dialectic of analysis and synthesis in the methodology of science and usually occur in a cyclic manner. Knowledge is fragmented at the beginning of the cycle to achieve deeper understanding of different parts and then reassembled, but at a higher level of sophistication. In this process of synthesis, the specific deep knowledge acquired in different fields remains important.

Trends toward integration in engineering and science became evident in the second half of the 20th century and are still increasing as the world moves toward knowledge society. The examples are numerous. A number of different approaches have been suggested to incorporate the influence of thermodynamics into quantum and particle physics (Zurek 2002; Beretta 2005; Goldstein et al. 2006; Abe 2011; Klimenko 2016). In engineering, integration trends can be illustrated by systems engineering, which began with the seminal work “A methodology for systems engineering” by Hall (1962). At present, systems engineering has become commonly accepted in the high-tech segments of industry and research. Modern Mechanical Engineering has also acquired transdisciplinary features — it has taken over some fields of science (e.g. mechanics of solids and fluids) and often crosses deeply into other branches of engineering. For example, methodologies and models used in Fluid Mechanics are not exclusive to Mechanical Engineering and can be effectively applied to various problems across many branches of engineering and science, despite existence of different traditions associated with these branches. While mainstream students can be easily confused by these differences and may need to stay within a specific branch, AE graduates are encouraged to develop conceptual understanding that allows for effective application of methodologies and ideas across different fields.

5.3. *AEE integration with science*

The integration trends are reflected in AEE programs by extensive study of fundamentals of science, with a strong emphasis on physics and mathematics. While advanced engineers can work as scientists (and are often highly successful in doing so), advanced engineering education is not a replacement for conventional science degrees. These degrees provide highly specialised knowledge that is needed for the very difficult task of reaching the frontiers of modern science and moving these frontiers just one little step forward. Long systematic study and incremental accumulation of relevant experience in a narrow field of knowledge form the basis of successful scientific research in modern conditions. Education that is tailored to fit advanced engineers is much broader in scope, focusing on major physical principles and ideas leaving the details to more specialised experts—the scientists. AEE follows the von Karman principle: advanced engineers do need to learn a broad segment of science and mathematics but they should to be taught differently, not in the same way as scientists and mathematicians. Complicated scientific problems can be explained to engineering students by invoking a suitable analogy or illustration (Klimenko 2012).

The utility of teaching some components of social sciences to engineers is commonly recognised in modern engineering education (Kellam, Peters, and Maher 2008; Grasso and Burkins 2010) but, in the context of AEE, this must be done in conjunction with deploying mathematics and enhancing (not watering down) core engineering and scientific subjects. While AE students can benefit from understanding the complexity of the real world and the multiplicity of perspectives that are reflected in social sciences, the von Karman principle is even more important for studying social sciences in AEE. One needs to appreciate that there is a large methodological gap between social sciences on the one hand and natural sciences and engineering on the other hand. The students of social sciences do not have comparable experience in quantification of knowledge and the numerous theoretico-modelling methodologies developed in natural sciences and engineering. The components of social sciences taught to advanced engineering students should focus on principal issues and not be excessive, must be adapted to engineering values and style, quantified when possible, and integrated into core engineering curriculum. For example, different perspectives can be shown from the point of view of an engineer, who needs to make a technical decision accommodating conflicting demands of different population groups, while a social theory can be presented as a working model for the behaviour of a complex socioeconomic system. AEE graduates are expected to be familiar with basic principles of economics, management and governance and, at the same time, have an engineering perspective that relates these principles to difficulties of controlling evolution of complex systems.

It can be argued that, to be truly educated people, engineers should be exposed to natural and social sciences in their original form, without any adaptation. These arguments have merits. However, if we approach this problem from engineering perspective, which sees effectiveness as being more important than any other valid considerations, learning science adapted to engineering style appears to be more effective for engineers.

5.4. *AEE and modern trends in mainstream engineering education*

The principles of AEE were broadly formulated at least a hundred years ago (Karlov and Kudriavtsev 2003). Since then these ideas were repeatedly discussed, used and reinvented in different, often fragmented forms and contexts affecting not only advanced but also mainstream education (Kellam, Peters, and Maher 2008; Grasso and Burkins 2010; Crawley et al. 2014). The attentive reader has probably noticed that AEE principles overlap to some extent with the modern approaches to engineering education that are discussed in the Introduction. Both AEE and PBL utilise “learning by doing”; both AEE and HEE advocate broad fundamental education; both AEE and CDIO imply integration of learning and practice. The existence of these overlaps is not merely coincident — good ideas tend to be reinvented or adapted but these ideas are used differently in AEE and in the mainstream education.

A typical AEE program involves learning the engineering fundamentals in conjunction with physics and chemistry, a stream of mathematical courses, lectures on engineering practice, economics, ethics and decision making, as well as a number of specialised and elective courses. Engineering fundamentals are learnt, understood and applied across all branches of engineering and relevant sections of science. The program culminates in an integrated and extended research project, where most of the learnt knowledge needs to be applied to a complex problem in a creative manner. This program is obviously different from conventional branch-based education of Mechanical, Chemical, Civil, and Electrical engineers, although the difference does not seem dramatic. In fact, as explained below, the gap between the advanced and mainstream forms of education is quite significant.

The meaning of the words “learning fundamentals” and “practical experience” in AEE is different from the same words used in mainstream education. In mainstream education, industrial practice implies a shift of the educational focus away from fundamental studies. It is not that professional engineers do not need to know basics of science but common day-to-day industrial operations and academic learning of fundamentals certainly have different focuses. Education of professional engineers is objectively torn between teaching fundamentals and preparing students for industrial practice. If academic education of professional engineers had the same focus as common industrial practice, these engineering graduates would be similar to technicians. In AEE, however, research practice and fundamental education are integrated and have the same direction of learning: one assists and stimulates the other. In mainstream education, industrial practice is aimed at training additional practical skills, which cannot be learnt in traditional lectures, while AEE practice reinforces, sharpens and extends knowledge obtained through academic study.

For example, while learning mathematics, a modern AE student is likely to study a wide spectrum of differential and integral equations, functional analysis, asymptotic, analytical and numerical methods, tensor algebra, theories of measure, stochastic processes and control. With this background, he/she is likely to be seen as a mathematician by non-mathematicians. This is not true — the AE student is not a mathematician and his/her main knowledge, abilities and expertise lie elsewhere. Mathematics is just a set of tools available at the student's disposal when his/her practical experience may require them. Many would see such extensive study of mathematics to be excessive for engineers. Indeed, for most mainstream graduates, advanced mathematics would not have a direct relevance to their thesis projects, industrial practice or future professional experience but, in AEE research projects, it has. An AE student does not need to wait for a Ph.D. program and is expected to start his/her research concurrently with his learning: these two key components of AEE should be well integrated. The student is not merely working in a lab, processing data or scheduling maintenance in an industrial plant but is solving a notable and complex previously unsolved engineering problem that involves a good deal of advanced mathematics. The problem comes from the real world and crosses boundaries between engineering and mathematics. This research experience represents both learning and advancing the frontier of our knowledge. "Undergraduate students cannot advance the frontier of our knowledge" — indeed, most cannot but some can, provided they are given a chance, have a suitable environment and supervision, and provided they are properly equipped with fundamental knowledge. Those who can are our AE students and these students will be pushed further to the limit of their abilities by AEE.

A good mainstream graduate may acquire research skills and developed creativity in a Ph.D. program. This program, however, is necessarily specialised and cannot compensate for any lack of the previous broad and fundamental education. Neither it can offer substantial integration of academic learning and research. Most Ph.D. graduates become experts only in a very narrow field. For AE students, a Ph.D. program is usually a natural continuation of their previous research.

5.5. *To teach or not to teach?*

If PBL, HEE and CDIO are good for mainstream education of engineers, then should AEE be recommended as an appropriate way of learning engineering for every student? (Here, we refer not to relabelling common engineering programs as advanced, which does not do any good or harm besides misleading the public, but to actually replacing conventional mainstream education with AEE.). Generally, I think that AEE is not suitable for mainstream education, but this statement needs further qualifications and explanations. First, AEE is not uniform and has noticeable variations across the globe. For example, the French-style AEE targets only the most capable and talented students, while modern German-style AEE is less intensive and less effective but addressed to a larger fraction of engineering students.

Interaction of different forms of engineering education should be productive and mutually enriching. Further transfer of some of the elements of AEE into mainstream engineering education can be very useful if done with proper care, understanding and adjustment. However, broadening of the mainstream education to the extent expected in AEE is likely either to overload average students with content that extends beyond their abilities or to make education superficial and impractical. Both cases are likely to have negative outcomes. Mainstream education, by definition, cannot afford to be excessively selective but removing one of the three pillars of AEE can render the other two ineffective.

Excessively broad but superficial education produces opinionated graduates who are nevertheless incapable of deploying their knowledge to resolve practical problems. A former student, who has heard about many different things but has superficial knowledge and cannot deploy his/her knowledge effectively, is not of interest to potential employers. NASA (which has played a key role in establishing practical systems engineering) suggests that every systems engineer has to have not only a good knowledge of physics and mathematics but also demonstrate effectiveness in and master at least one of the specific engineering disciplines (Ryschkewitsch, Schaible, and Larson 2009). Education of mainstream professional engineers needs to be primarily aligned with the immediate needs of industry.

Overloading students beyond their abilities damages students' self-esteem, motivation to learn, creativeness and independent thinking. AEE endeavours to broaden engineering education and, at the same time, achieve higher educational depth and sharpen ability of the graduates to deploy their knowledge. This type of education may be out of reach for weaker and less motivated students. At the same time, these students might still be able to perform at a reasonable level in conditions of a more specialised branch-based educational program. While being a slower learner, an average student can still progress gradually to become a high achiever in a more narrow and well-defined field of engineering. Specialisation is important in mainstream education and even an average person can achieve solid professional knowledge and standing in a specialised field. This can be assisted by PBL, HEE and CDIO as well as by some elements of AEE that are commensurate with the student abilities. While the integrative trends in science and engineering do require educating outstanding intellectuals that have transdisciplinary knowledge, abandoning branch-based engineering education on a large scale is likely to be impractical in the present conditions.

6. When do we need AEE?

The question of whether a particular country or a particular University needs AEE is not trivial and does not have a simple answer. This section attempts to discuss this question from different perspectives.

6.1. *Binary system of higher engineering education*

As outlined in Section 3, the binary system has appeared in the higher education systems of many countries in response to the technological development of the 20th century. This system involves two types of educational institutions that in this section are referred to as PI (professional institutions), where education is more directly related to day-to-day industrial practice, and AI (advanced institutions), which offer more knowledge-based education. The PIs offer degrees at the same level as AIs and should not be confused with TAFE Colleges and other programs at the associate or sub-professional levels. German Fachhochschulen and ordinary Polytechnics are good examples of PIs. German Technical Universities and French Grandes Écoles belong to the AI category. The names and exact roles of the institutions can vary significantly from country to country.

The binary system is natural for the modern industrial society where technological breakthroughs coexist with old industries. The system is a direct response to the needs of technological progress that require different types of engineering professionals. The binary system does not remain static: the best TAFE Colleges tend to become PIs while the best PIs become AIs. These trends are somewhat negatively viewed as “academic drift” (Harwood 2006), but this progression seems natural and even positive as long as it remains consistent with the needs of the society and achievements of the upgraded institutions. One of the roles of the binary system is in preventing excessive academic drift (Christensen et al. 2015). It is arguable that the Australian reform of 1989 and the British reform of 1992 were not consistent with institutional achievements and were largely justified by appealing to social justice.

While existence of the AI-type institutions is not synonymous to implementing AEE, it objectively acts to promote advanced education. Industry is primarily concerned with hiring practical engineering graduates at a reasonable cost to satisfy the immediate need for day-to-day operations. Hence, there is a pressure on tertiary education to graduate practical engineers in sufficient numbers. The binary system relives AIs from this pressure — industrial employers happily hire professional engineering graduates from PIs, who are prepared to perform day-to-day duties even better. At the same time, industry also keenly recruits AI graduates for more strategic and creative engineering tasks. In these conditions, AIs must continuously prove that their education is superior to the education in PIs whenever research, vision and innovation are at stake. This encourages AIs to progressively embrace the elements of AEE, move forward and excel. At the same time, presence of AEE constraints the academic drift: most PIs understand that they cannot compete with AIs on the AEE field and need to find an alternative niche in educating more practical engineers.

An abrupt transition from a binary system to a unified system by upgrading PIs to AIs has two major educational effects: 1) unsustainable academic drift in the new Universities, which is necessarily offset by 2) abandoning more advanced forms of education in the old Universities. These two effects result in mutual convergence of PIs and AIs (Christensen et al. 2015). In conditions of a unified system of tertiary education, the default direction of the system pressure is toward the mainstream. At the end, many institutions of the unified system may not be strong enough to reach the AEE standards and not practical enough to satisfy the basic industry need in practical engineers. These changes are generally irreversible: although PI can be easily recreated from TAFE Colleges, compensating for the lost positions in advanced engineering is more problematic — this requires focus and effort. While AEE is, to some extent, naturally present in good binary systems of engineering education, a unified system often needs an explicit action of the government. At the same time, lack of AEE in a unified system may, in fact, become an opportunity for visionary Universities to boost their standing by moving toward AEE.

6.2. *The role of AEE*

AEE is more transdisciplinary than the conventional education of Mechanical, Chemical, Civil, Electrical and other engineers. This is a different form of education; it serves different purposes, and is not intended to become a replacement for conventional engineering degrees. An AEE graduate is not expected to dedicate his/her life exclusively to a specific narrow field (although some AEE graduates might choose to do this) but, instead, be effective in transferring ideas, inventions, methods and theories between the fields. An AEE graduate can quickly determine and effectively resolve the main outstanding problem while unifying theory and practice and bringing change and innovation. I would argue that many AEE graduates acquire a special way of thinking (which can be called AE thinking) that is somewhat different from both the methodology of traditional engineering and the conventional methodology of science (Klimenko 2007). Further elaboration on this goes beyond the scope of this paper and is intended to be discussed in future publications. It is true that some very talented people educated as professional engineers (or in some occasions even people without specialised education) may be able to reach advanced standing through experience and persistent self-education. The goal of AEE is to prepare graduates to reach this advanced standing in engineering research and innovation by offering them a special integrated and consistent educational program.

The history of engineering education presented in Section 3 demonstrates cyclic oscillations between industrial practice and fundamental studies in attempt to find an optimal point, while this optimal point might not exist (Harwood 2006). In fact, many engineering graduates are insufficiently prepared to work in the real-world industrial environment and, at the same time, are not versed in mathematics and science well enough to understand and use them as needed. This contradiction between teaching more engineering science and teaching more engineering practice is objective and is not likely to have a single optimal solution. AEE resolves this problem by leaving day-to-day industrial operations to professional engineers while focusing exclusively on engineering research and innovation. Advanced engineers are, nevertheless, still engineers and not scientists. They are exposed to key issues that engineering profession has to deal with, to history and traditions of engineering, to the principles of strategic engineering decision making and, possibly, to the common reasons for conceptual engineering mistakes. The principal role of AEE is in linking fundamental science to the areas of rapid technological development, research and innovation. AEE graduates are equally comfortable talking to or working with practical engineers and industrial managers on one side and scientists and mathematicians on the other side. They understand both the language of science and the language of industrial practice and focus not on gaps between these cultures but on resolving the actual problems quickly and efficiently. The cultural and organisational gaps between industrial practice and fundamental science, which can be very large in real life, are common obstacles for technological development in many countries.

AEE is less needed in environments dominated by traditional industries that are served well by sound education of professional engineers. At the same time, the emerging knowledge society brings new demands for engineers, who are not expected to have the same engineering job for the duration of their professional lives. New engineers must be innovative, flexible and confident to deal with various problems that may belong to different fields of engineering and science. Ideas need to be brought across these fields, evaluated and adapted to current demands. These expectations are in line with the goals of AEE. It is clear, however, that the knowledge society is to coexist with traditional industries and different categories of engineering professionals will be in demand for a long time to come. It seems that industrial employers are more and more often interested in hiring good people with top academic credentials and original thinking rather than finding a holder of a specific skill.

There is another aspect of AEE that must be understood clearly — the number of places in academia, industry and government that demand unique skills of AEE graduates is limited by the current level of technological development. It seems tempting to boost this development by graduating more AE students and this can work but only to some extent. If AEE graduates are employed to do routine jobs, where qualifications of a professional engineer or even of a technician are perfectly sufficient, this would undermine attractiveness and prestige of working in industry and force AEE graduates to move to other countries, stay in academia, or shift to another profession, severing the AEE link between academic originality and intellectual/high-tech segments of the industrial sector.

While flexibility is an important characteristic of AEE and its graduates, the areas of rapid growth and high intellectual content should stay within the reach of its graduates. As noted in Section 3, implementations of AEE in the 20th century brought notable successes in the USSR and the USA and only a partial success in India, where the overall socioeconomic development lagged behind.

6.3. *Effect of AEE on education*

Since most teachers are inclined to reproduce and improve the educational system that they were educated in, upgrading the quality of an educational system usually takes a long time: better and more knowledgeable teachers must be educated first, which in its turn needs an upgraded educational system. This chicken and egg problem can be resolved by a slow incremental evolution of the system or by inviting experts from the places where such expertise is already available. The existence of high-level expertise gives a point of support that forms a basis for rapid progress in educating the required specialists. Many countries have successfully upgraded their educational systems by sending their students (who are to become teachers in the future) to study abroad.

As noted in Section 5, converting all mainstream engineering education into AEE would be impractical and, most likely, impossible without compromising the AEE standards. At the same time, the presence of AEE graduates can be instrumental in upgrading mainstream engineering education, whenever such upgrades may be needed due to technological, economic or social changes. AEE grants the ability to move quickly into new areas and establish specialised education there. Hence, the role of AEE is not only in creating technological breakthroughs into new areas but also in providing teachers, who can educate a new generation of engineers to research and advance these new areas even further. Although AEE does not form the mainstream of engineering education, its influence on the mainstream at critical points can be profound. Practically, the two ways of developing more advanced expertise in engineering — introducing AEE or inviting specialists from the countries where such expertise is already available — are both viable options. AEE, however, is likely to become crucial for countries that wish to export (rather than import) engineering education.

6.4. *Implementing AEE*

As discussed by Chubik and Zamyatina (2013) and reviewed in Section 3, AEE (and AEE-like programs) can be implemented in several different forms: 1) independent Institute or technical University, 2) faculty or college incorporated into a University and 3) an AEE program within a University. There might be more fragmented and distributed implementations. Although useful, they generally do not form a consistent unified concept and are not discussed here. Creating an AEE Institute instantly resolves many problems as, from the beginning, all internal regulations are tuned to AEE needs. Although most genuine AEE Institutes are usually very small, establishment of a new Institute usually requires government intervention and a substantial investment to attract highly qualified staff and build (or provide an access to) top research facilities. This is a costly but effective way, and there are numerous examples where this first strategy has achieved great success. Over the years, some of these institutions tend to grow in size, relax educational standards and become more bureaucratic and more ordinary while exploiting their past achievements. The second option is intermediate between options 1 and 3, while the third option is discussed below.

In principle, an AEE program can be established at a relatively low cost within existing Universities. The world's top tier Universities would, of course, be the best places, although in principle AEE can be introduced in any institution that has solid educational expertise across all major fields of engineering and science and at least several relevant research strengths of highest international standing. A full-scale AEE program can be based on the integrated BE/ME degree with estimated duration of five and half years, which is integrated with an extended multi-year research program conducted in intellectually intensive areas where the parent University displays an internationally recognised research strength. AEE can also be a joint effort between a University and an institution with highly advanced research capabilities. The cost of the program is reduced through using available resources and expertise, as well as through concentrating strengths of the parent institution(s). Even if an AEE program can dramatically enhance reputation of any University, implementations of options 2 and 3 may become problematic due to lack of support (or even direct opposition) within the parent University or due to state or University regulations conflicting with the requirements of AEE.

7. Discussion and conclusions

Advanced engineering is a segment of engineering discipline that is dedicated to engineering research, innovation and development of new technologies and often serves as a link between fundamental sciences and engineering profession. Advanced engineering contributes to the knowledge base and, thus, can also be considered to be a part of science, assuming that science is interpreted in its most general sense. Advanced engineering has it own methodology, is inherently transdisciplinary and goes beyond application of conventional scientific methods to industrial practice. Advanced engineering education (AEE) is an advanced form of education aimed at educating advanced engineers — innovators, researchers and thinkers.

This work demonstrates that the best practices in educating advanced engineers, which have been developed and implemented in a number of countries over last 200 years, are in fact related; they have common roots and, to some extent, share common principles. AEE was born in France in the aftermath of the French revolution and then spilt into Germany, which managed to combine French excellence with British practicality into a versatile educational system that, over the years, has demonstrated its utility. This system educates practical engineers to the standards commonly expected in industry and delivers more advanced forms of engineering education for those who are motivated to research and innovate. AEE matured and reached its climax in the USSR and in the US during the technological competition of the Cold War, when AEE was seen as a major tool for achieving and retaining technological leadership. Overall, AEE proved to be an effective tool for research, progress and innovation. The historical evidence examined in this work indicates that successful development of advanced technologies requires dual orientation of higher engineering education: solid mainstream education of professional engineers and fostering originality through AEE.

The end of the Cold War brought new priorities into education, reducing interest in AEE and giving way to two educational paradigms, liberal and conservative, that still tend to dominate public debates. The liberal paradigm is based on the premise that the prime purpose of higher education is addressing social inequalities and correcting various injustices (perceived or real) that still exist in modern developed societies. The conservative paradigm sees higher education as a commercial service provided to students who ultimately have to pick up the bill and pay for the service. The public debate on education goes in circles and is marked by endless collisions of these two paradigms. While acknowledging the importance of social justice and financial viability, we should not forget that proper education is no less than the basis of existence of our sophisticated modern societies (in the same way that passing on genetic information is the basis of existence of life forms). In this context, education plays many different roles, and must be versatile giving every student the opportunity to develop to the maximum of his/her abilities. For some this might be learning school grammar and mathematics, for others the challenge is to become an engineer, some will learn to innovatively contribute to research effort and some will bring new paradigms, discoveries and solutions that can change our world. Education is for all of them and everyone of them can be successful in his/her own way. Yet the modern thinking that can be derived from the either paradigm (i.e. liberal or conservative) favours mass production on the basis of a simplistic (one size fits all) educational model — this approach has prevailed in the reforms of tertiary education conducted in Australia and the UK.

While the institutions of Western education still occupy the top places in ranking lists, the first signs of competitive degradation have become apparent in the educational systems of many countries: the recent model of mass education is accompanied by relaxed standards and a reduced effort. At the same time, education is rapidly improving in some of developing and newly developed countries. In these countries, high standards of school education are now being translated into intense fundamental programs at selected Universities. Colonial training of technicians is in the distant past. The two major components of AEE — selection of the best and deep learning of fundamentals — are already there. The third component — development of creativeness through integration with research — is not, but there is understanding of the problem and an ongoing and persistent effort to address it. Education in these countries, which is geared toward establishing pockets of high-quality education, based on merit, equal access and performance, objectively drifts toward AEE. Once all key components of AEE are in place and a critical educational mass is reached, this will start a chain reaction of impressive transformations. The Indian experience is a convincing demonstration that the segments of advanced education can be created and sustained over many years in a developing nation.

Tertiary education is evolving, following the demands of the 21st century and new opportunities offered by electronic communications. In coming decades, tertiary education is to become more versatile, servicing different needs of the students and the society. Combining mainstream and advanced education within the University walls is to become one of the major challenges. Existence of all three categories of engineering education (see Section 2) is natural in the present environment that combines conventional industrial practice with research and innovation. While associate engineers are educated with the sole focus in industrial applications and AEE is exclusively dedicated to preparing the graduates for engineering research and innovation, mainstream education of professional engineers is objectively torn between these competing goals. The educational debate about the optimal balance in education of professional engineers is now 200 years old and does not seem to get any closer to an ultimate conclusion. Recent artificial attempts to narrow the scope of engineering education to a single model fail to recognise important changes occurring in the society. Modern society is gradually evolving, with industrial practice being shifted from extensive production growth toward knowledge, innovation and integration. Engineering education needs to respond to these challenges, if in the future engineering is to retain its role in society. AEE is one the major tools for providing the intellectual basis for accelerated technological progress.

It seems, however, that practical recommendations that can be derived from the present consideration are, inevitably, country-dependent (and, most likely, also institution-dependent). For example, engineering education in France needs more effective integration, Germany must renew and invigorate engineering education while preserving its binary character, while Australia and the UK face the most difficult task of (re)introducing AEE. Success or failure in this endeavour would undoubtedly reflect on technological progress in these countries. AEE is not a specific teaching method or a fixed curriculum (although adequate teaching and a consistent advanced curriculum are important for AEE), but rather a set of principles derived from accumulated experience of teaching advanced engineering. To be effective, the working of these principles needs to be understood and adapted to local traditions and conditions. As long as unity and consistency of these principles are preserved, AEE may (and, in fact, should) take different forms under different conditions.

This paper endeavours to explain the major principles of AEE, its benefits and its limitations. The paper focuses on conceptual issues and accumulated historical experience. Although AEE may not be useful in every country, appropriate for every University and suitable for every individual, those who graduate successfully from AEE programs tend to develop outstanding abilities. Advanced engineers are problem solvers, theory builders, inventors and original thinkers, who can be successful in a wide spectrum of disciplines ranging from engineering to science, management or military service.

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References

Abe, S. 2011. "Maximum-power quantum-mechanical Carnot engine." *Phys. Rev. E* 83: 041117.

Akera, Atsushi, and Bruce Seely. 2015. "A Historical Survey of the Structural Changes in the American System of Engineering Education." In *International Perspectives on Engineering Education,* Vol. 1 edited by S. H. Christensen, C. Didier, A. Jamison, M. Meganck, M. Mitcham, and B. Newberry. 7–32. New York: Springer.

Bassett, R. 2009. "Aligning India in the cold war era: Indian technical elites, the Indian Institute of Technology at Kanpur, and computing in India and the United States." *Technology and Culture* 50 (4): 783–810.

Beretta, G.P. 2005. "On the general equation of motion of quantum thermodynamics and the distinction between quantal and nonquantal uncertainties (MIT, 1981)." arXiv: quant-ph/0509116.

Bertalanffy, Ludwig v. 1968. *General system theory: foundations, development, applications.* New York: G. Braziller.

Bevrani, H. 2012. "Engineering education system in Japan: Observations in Study, Teaching, and Research." In *First Engineering Education Conference,* Iraq: University of Duhok.

Bloomberg. 2016. "Bloomberg innovation index." http://www.bloomberg.com/. Accessed: 2016-09-19.

CESAER. 1990. "Conference of European Schools for Advanced Engineering Education and Research." http://www.cesaer.org/.

Christensen, S. H., C. Didier, A. Jamison, M. Meganck, M. Mitcham, and B. Newberry. 2015. *International Perspectives on Engineering Education.* Vol. 1. New York: Springer.

Chubik, P. S., and O.M. Zamyatina. 2013. "Traning elite specialists in engineering and technologies." In *Proceedings of the 9th International CDIO Conference,* 114–118. MIT.

Crawley, E.F., J. Malmqvist, S. stlund, and D.R. Brodeur, eds . 2014. *Rethinking engineering education: the CDIO approach.* New York: Springer.

Croome, D. J. 1991. "Educational Futures for the Construction Industry." *Industry and Higher Education* 5 (1): 35–46.

Croucher, G., S. Marginson, A. Norton, and J. Wells. 2013. *The Dawkins revolution 25 years on.* Melbourne Univ. Press.

DAAD, (German Academic Exchange Service). 2012. "Germany a Great Place for Knowledge / Engineering." .

Dawkins, J. S. 1987. "Higher education." Government policy discussion paper.

DET, (Dept. of Education and Training). 2015. "Higher Education in Australia: a review of reviews from Dawkins to today." Canberra.

Edstrom, K., and A. Kolmos. 2014. "PBL and CDIO: complementary models for engineering education development." *European Journal of Engineering Education* 39 (5): 539–555.

Fox, R., and A. Guagnini. 1993. *Education technology and industrial performance in Europe, 1850-1939.* Cambridge Univ. Press.

Gillard, D. 2011. "Education in England: a brief history." www.educationengland.org.uk/history.

Goldstein, S., J. L. Lebowitz, R. Tumulka, and N. Zanghi. 2006. "Canonical typicality." *Phys. Rev. Lett.* 96: 050403.

Grasso, D., and M.B. Burkins. 2010. *Holistic engineering education: beyond technology.* New York: Springer.

Grayson, L. 1984. "EE education around the world." *IEEE Spectrum* 21 (11): 65–71.

Hall, Arthur D. 1962. *A methodology for systems engineering.* Princeton, N.J. : Van Nostrand.

Harwood, J. 2006. "Engineering Education between Science and Practice: Rethinking the Historiography." *History and Technology* 22 (1): 53–79.

Hennock, E. P. 2006. "Technological education in England, 18501926: the uses of a German model." *History of Education* 19 (4): 299–331.

House of Representatives. 2005. "Resolution No 227." USA.

Indian Parliament. 1961. "The Institutes of Technology Act No 59." .

IPPR, Commission on the Future of Higher Education. 2013. "A Critical Path: Securing the Future of Higher Education in England." IPPR report, London.

Johansson, F. 2004. *The Medici effect: breakthrough insights at the intersection of ideas, concepts, and cultures.* Boston, Mass: Harvard Business School Press.

Jorgensen, U. 2014. "Rethinking engineering education: the CDIO approach." In *Rethinking engineering education: the CDIO approach,* edited by E.F. Crawley, J. Malmqvist, S. stlund, and D.R. Brodeur. New York: Springer.

Karlov, N.V., N.F. Simonova, and L.P. Skorovarova, eds . 1996. *I am Phystech.* Moscow: CenterKom.

Karlov, N. V., and N. N. Kudriavtsev. 2003. "On history of elite engineering education." *Researched in Russia* 6 (124): 1473–1480.

Kellam, N., W. Peters, and M. Maher. 2008. "The faculty perspective on holistic and systems thinking in American and Australian mechanical engineering programmes." *European Journal of Engineering Education* 33 (1): 45–57.

Klimenko, A.Y. 2007. "Why does one need to be taught engineering logic?." In *International Conference on Engineering Education,* 114–118. Univ. of Coimbra.

Klimenko, A.Y. 2013. "Complex competitive systems and competitive thermodynamics." *Phil. Trans. R. Soc. A* 20120244.

Klimenko, A. Y. 2012. "Teaching the third law of thermodynamics." *Open Thermodynamic Journal* 6: 1–14 (arXiv:1208.4189 [physics.class–ph]).

Klimenko, A. Y. 2014. "Strong swirl approximation and intensive vortices in the atmosphere." *Journal of Fluid Mechanics* 738: 268–298.

Klimenko, A. Y. 2016. "Symmetric and antisymmetric forms of the Pauli master equation." *Nature.com – Scientific Reports* 6: 29942.

Kranakis, E. 1989. "Social Determinants of Engineering Practice: A Comparative View of France and America in the Nineteenth Century." *Social Studies of Science* 19 (1): 5–70.

Laporta, J. 1988. “Systems Thinking: when engineering education calls itself into question.” *European Journal of Engineering Education* 13 (3): 293–306.

Levy, J. 2000. “Engineering education in the United Kingdom: Standards, quality assurance and accreditation.” *The International Journal of Engineering Education* 16 (2): 136–145.

Martin, L. H., N. S. Bayliss, K. B. Myer, S. Sunderland, A. D. Trendall, J. Vernon, and K. A. Wills. 1964. “Tertiary education in Australia.” Government Report.

McGuire, J.R. 1996. “Engineering education in Japan: my experience.” In *IEEE Frontiers in Education Conference (FIE),* 368–371. Salt Lake City, USA.

Menzies, R. G. 1961. “The Challenge to Education.” In *The Challenge to Australian Education,* Melbourne: Cheshire.

Meyers, D. 2012. *Australian universities : A portrait of decline.* Australia: AUPOD.

Orosz, G., R.E. Wilson, and G. Stepan. 2010. “Traffic jams: dynamics and control.” *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 368 (1928): 4455–4479.

Price, Huw. 2002. “Boltzmann’s Time Bomb.” *The British Journal for the Philosophy of Science* 53 (1): 83–119.

QS, Top Universities. 2016. “QS Higher Education System Strength Rankings.” http://www.topuniversities.com/. Accessed: 2016-09-19.

Ryschkewitsch, M., D. Schaible, and W. Larson. 2009. “The art and science of systems engineering.” *Systems Research Forum* 3 (2): 81–100.

Sato, Takashi, Christine Sobczyk, Shuichi Sakamoto, Nozomu Ishii, Yuji Tanabe, Masaki Goda, Takeo Maruyama, Tomiichi Hasegawa, Hideo Ohkawa, and Lutz Wisweh. 2008. “Differences of engineering education systems between Japan and Germany – consideration about before and after graduation.” In *IACEE 11th World Conference on Continuing Engineering Education,* Atlanta.

Scott, Peter. 2012. “It’s 20 years since polytechnics became universities and there’s no going back.” *The Guardian* Tue., Sep.,4.

Stokes, T. 2014. “The Dawkins revolution 25 years on (review).” *Journal of Higher Education Policy and Management* 36 (3): 357–365.

Thoenig, J.-C. 2015. “Why France is building a mega-university at Paris-Saclay to rival Silicon Valley.” http://theconversation.com/. May,27; Accessed: 2016-10-01.

Timoshenko, S. P. 1963. *Memoir.* ”Naukova Dumka”, Kyiv.

van de Poel, I., and D. E. Goldberg. 2010. *Philosophy and Engineering An Emerging Agenda.* Springer.

Von Karman, T., and M. Biot. 1940. *Mathematical methods in engineering : An introduction to the mathematical treatment of engineering problems.* N.Y.: McGraw-Hill.

Von Karman, T., and L. Edson. 1967. *The Wind and Beyond.* N.Y.: Little Brown and Company.

Walsh, James Jackson. 1998. “Postgraduate Technological Education in Britain: Events Leading to the Establishment of Churchill College, Cambridge, 1950-1958.” *Minerva* 36 (2): 147–177.

Wedelin, D., T. Adawi, T. Jahan, and S. Andersson. 2015. “Investigating and developing engineering students mathematical modelling and problem-solving skills.” *European Journal of Engineering Education* 40 (5): 557–572.

Yakovenko, Victor M., and J. B. Rosser. 2009. “Colloquium: Statistical mechanics of money, wealth, and income.” *Reviews of Modern Physics* 81 (4): 1703–1725.

Zamyatina, O. M., and P.I. Mozgaleva. 2014. “Competence component of the project-oriented training of elite engineering specialists.” In *Global Engineering Education Conference (EDUCON),* 114–118. IEEE.

Zurek, W. H. 2002. “Decoherence and the Transition from Quantum to Classical – Revisited.” *Los Alamos Science* (27): 1–26.

Appendix A. List of common abbreviations

AE – advanced engineering
AEE – advanced engineering education
AI – Advanced Institutions (institutions providing or expected to provide AEE, e.g. Grandes Écoles, TU, IIT)
BE – Bachelor of Engineering
BLA – Bachelor of Liberal Arts
CAE – College of Advanced Education (PI in Australia before the 1990s)
CDIO – conceive — design — implement — operate (MIT-initiated approach to engineering education)
CESAER – Conference of European Schools for Advanced Engineering Education and Research
Dipl.-Ing. – Diplom-Ingenieur is the traditional engineer's degree in Germany (ME equivalent)
FH – Fachhochschulen (PI of higher education in Germany)
HEE – holistic engineering education
IIT – Indian Institutes of Technology
ME – Master of Engineering
PBL – problem-based learning
PI – Professional Institution (industry-focused degree-granting educational institutions of higher education, e.g. FH, CAE)
R&D – research and development
TAFE – Technical and Further Education (colleges of vocational education in Australia)
TU – Technical Universities and Institutes (Technische Hochschule in Germany)

Appendix B. Abbreviations used for specific institutions

Caltech – California Institute of Technology
ETH Zurich – Swiss Federal TU in Zurich
IMTS – Imperial Moscow Technical School (current: Bauman University)
KIT – Karlsruhe Institute of Technology
MIPT – Moscow Institute of Physics and Technology (Phystech)
MIT – Massachusetts Institute of Technology
NASA – National Aeronautics and Space Administration (USA)
RWTH Aachen – Rhine-Westphalia TU in Aachen
SPPI – St.Petesburg Polytechnic Institute