International Journal of Engineering Education Vol. 27, No. 4, pp. 838–851, 2011
Printed in Great Britain

0949-149X/91 $3.00+0.00

Engineering Thinking: The Experts' Perspective*

SHLOMO WAKS
Department of Education in Technology and Science, Technion—Israel Institute of Technology, Haifa 32000, Israel.
E-mail: waks@techunix.technion.ac.il

ELENA TROTSKOVSKY
Department of Electrical and Electronics Engineering, ORT Braude College, Karmiel 21982, Israel. E-mail: elenatro@braude.ac.il

NISSIM SABAG
Department of Electrical and Electronics Engineering, ORT Braude College, Karmiel 21982, Israel. E-mail: nsabag@braude.ac.il

ORIT HAZZAN
Department of Education in Technology and Science, Technion—Israel Institute of Technology, Haifa 32000, Israel.
E-mail: oritha@techunix.technion.ac.il

Most student graduates in engineering schools are involved in engineering design, that is, the development of new products for which engineering thinking is required. Our literature survey, however, did not yield material pertaining to engineering design thinking in the field of electrical and electronic engineering. Therefore, we propose to clarify the term 'engineering thinking'. Specifically, this paper presents a characterization of engineering thinking in general, and electric and electronic engineering thinking, in particular, from the point of view of experienced engineers. In addition, to highlight the uniqueness of engineering thinking, we compare engineering thinking in engineering design and research thinking in scientific research in the area of the exact sciences.

Keywords: engineering design; engineering design thinking; experts; characterization

1. Introduction

What is engineering thinking? Is it different from scientific thinking? In order to answer these questions, we should identify and clarify relevant types of thinking. This paper deals with the characterization of engineering thinking as compared with scientific thinking.

Engineers initiate and design technological components, devices and systems. In their work, they solve a wide range of practical problems. The ability to solve such problems is based on knowledge and experience acquired both in academic education and in practical work. Owing to a persistent process of the doubling in scientific knowledge every 10 years [1], in the next decade engineers will need to learn significantly more new information and be conversant with a whole realm of new technologies [2]. As a result of the time constraints of the existing learning frameworks for a B.Sc. degree, it is unrealistic to include all of the experience accumulated in high-tech industries within the engineering curriculum. Therefore, it may be impossible to acquire additional knowledge in the short period of undergraduate engineering studies [3]. The National Academy of Engineering in the US argues that in the 21st century 'the B.S. degree should be considered as a pre-engineering or 'engineer in training' degree' [2]. From this perspective, the development of cognitive engineering skills in the course of the first-degree study program is expected to help students to reduce the gap between the knowledge acquired in academia and the market demands, and to assist them in the transition from the learning environment to the field of work. The questions to be asked at this stage is what are the engineering thinking traits and what are the cognitive abilities involved in it?

In order to answer these questions, we refer to design as the central engineering activity [4]. Most novice engineers are involved in the design and development of new products, i.e. in engineering design, which 'is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.' [5, p. 104]. Therefore, understanding the nature of engineering design thinking is important for educators in all engineering areas.

In recent years, educational research has focused on a wide range of cognitive processes and design-related behaviors, such as creative thinking involved in the design process [6, 7], problem definition [7], primary mechanisms that enable systems thinking development [8], iterative design behavior [9, 10], and self-reflection [11]. Numerous studies have focused on comparing the design processes of fresh-

* Accepted 8 February 2011.

men and senior engineering students with those of practicing engineers [12, 13], development of students' cognitive activities in introductory design courses [14-18], and bridging educational research and teaching [19].

Analysis of 47 manuscripts (36 articles and 11 books) dealing with engineering design thinking revealed that the authors come from different areas. The majority, 21 authors, belong to mechanical and aerospace engineering, 15 to industrial engineering and management, 12 to the humanities (mainly philosophy and psychology), 9 to civil engineering and architecture, 7 to areas of computers, information and engineering education, and 8 to the field of electrical and electronic engineering. The papers could also be categorized by their focus. Ten articles and 5 books analyzed, in depth, general and specific cognitive processes in mechanical design while only 4 articles investigated student cognitive activities in introductory design courses. Electronics engineers wrote two of them and two were written by large groups of researchers, with only one author in each group being from the field of electrical engineering. Nevertheless, according to an analysis of 273 papers in 12 sources (10 journals and 2 proceedings of engineering conferences), 27.1% relate to design courses in EE (Electrical Engineering), and 26.4% relate to ME (Mechanical Engineering), and design is taught in the EE curriculum nearly to the same extent that it is taught in ME [20]. These data raise the following questions: What is the reason for this situation? Why are a relatively small number of papers dedicated to research of cognitive processes in electrical engineering education?

One possible explanation could be the fact that lecturers of electricity and electronics are constantly faced with a huge influx of new content. Electronics is one of the most rapidly developing scientific and technological areas, and as such, the efforts of the majority of the academic educators are directed towards mastering new knowledge. Thus, they seldom have the opportunity to pay attention to the pedagogical aspects of the learning process. An additional reason may relate to the academic promotion of most engineering educators, which is based on their contribution to the disciplinary research.

This paper seeks to contribute to the educational research concerning cognitive processes in electronic engineering design. In what follows, we further describe the existing approaches toward the analysis of engineering design thinking. Then, we present our research method and the characterization of engineering design thinking by elaborating on the thinking aspects of engineering design in comparison with scientific research in the exact sciences.

2. Engineering design thinking

There are currently two main approaches to the analysis of engineering design thinking. The first is directed toward the identification of cognitive activities, abilities, and skills of experienced engineers. Several authors [16, 17] used a set of 11 abilities required of graduate engineers as defined by the Accreditation Board for Engineering and Technology (ABET) [21], and research students' cognitive activities based on this definition. Other researchers observed engineering practice and connected it with cognitive skills [22], identified effective engineer qualities and mental characteristics [20, 23, 24]. The second approach advocates the development of theories, models, and schemes of cognitive processes in engineering design. Such models and schemes deal with the complexity of cognitive processes, which combine unconscious and semi-conscious (or extra-rational) thinking with rational thinking [25, 26] and emphasize the iterative nature of design thinking [10, 27, 28]. The theory of lateral and vertical design thinking relates to creative processes of new ideas and their sequential development processes [29]. The divergent–convergent inquiry based design thinking (DCIDT) model links the phase of concept creation in the design process with convergent thinking and generative design questioning, and the next phase of decision-making

Table 1

In science	**→In technology**
1. *Analysis* of existing phenomena	→ *Synthesis* of a new whole
2. *Abstract/* Theoretical	→*Concrete/* Practical
3. *Idea* initiation & development	→*Product/* Process dev. & implement.
4. *Research*	→*Design* for application
5. *Ideal* (perfectionism)	→*Optimum* (max. possible quality)
6. General *Problem treatment*	→Specific *Problem solution*
7. Curiosity as driving factor	→*Need* as main driving factor
8. *Assumption* (Reliance on)	→*Facts* (Reliance on)
9. *Accuracy* (demand for)	→*Tolerance* (with compromise)
10. *Linkage to any kind*	→ *Social/ Economic linkage*

and specification, with divergent thinking and deep reasoning questioning [30].

In the present paper, both attitudes—identification of cognitive skills and development of organizing schemes of design thinking—were taken into the consideration. Further, a comparative study concerning researchers' thinking in the exact sciences and engineers' thinking in engineering design was carried out.

The Merriam-Webster Online Dictionary defines an exact science as 'a science (as physics, chemistry, or astronomy) whose laws are capable of accurate quantitative expression' [31]. Parallelism between scientific research in an exact science and engineering design is well known. Hill [32] compares scientific and design methods, points to five comparative stages of each, and emphasizes the uniqueness of engineering design. Waks [33] analyzes science–technology interrelationships in education and divides the differences between science and technology into ten dimensions. Each dimension is concerned with a different aspect of the issues.

The present study focused on the similarities and differences between the cognitive aspects of scientific research and engineering design.

3. Method

A comparative analysis framework was chosen for the study. Accordingly, the research participants belonged to two groups: lecturers from academia and expert engineers from industry. A qualitative research methodology was applied because it was assumed that interpretive research [34] would allow for interpretive analyses and a deeper understanding of the researched processes. This reasoning guided us to use open interviews as the main data collection tool. Twenty-one in-depth interviews were conducted: 18 of the interviewees were electronics engineers. In order to broaden the research scope and to find out the opinions of the specialists from additional fields, three experts from mechanical and software engineering were also interviewed.

Twenty of the 21 interviewees had significant scientific and practical experience: three experts had more than 25 years' experience in industry or academia, 11 specialists had been working for more than 30 years, and six of them had over 40 years experience. One interviewee was a young engineer with 3 years experience. Seven specialists had an M.Sc. degree and 13 were Ph.D.s. Moreover, 18 interviewees were experienced academic lecturers in engineering faculties.

The questions with which we started the interviews are as follows:

- What is common to research and engineering thinking?
- What are the differences between the thinking processes of researchers and engineers?
- How do engineers think in each stage of the design process?

Analytic induction strategy was applied for data analysis. 'Analytic induction, in contrast to grounded theory, begins with an analyst's deduced proposition or theory-derived hypothesis, and is a procedure for verifying' [35, p. 454]. The possibility of applying Waks's multidimensional approach [33] to the analyses of the similarities and differences between the cognitive aspects of scientific research and engineering design served as the deduced proposition of the research. The verification procedure had two stages. First, a sequence of interviews was conducted until the data collected did not add new traits to the gathered data. Second, inductive analysis of the collected information was performed until a stable structure of a system of categories of engineering and research thinking was obtained.

4. Results

Figure 1 shows the five main categories for engineering design thinking that were identified in our study. It is evident from the characterization of engineering and research thinking that not only pure cognitive factors appear, but also additional aspects, such as linkages to environment and motivation, which, as it turns out, can affect cognitive processes.

The first category indicates the aims (1) towards which the engineering and research thinking is directed. The second category is the knowledge and tools (2) on which the engineering and research thinking is based. The third and central category is the engineering and research thinking (3) itself. Two additional categories are the environment (4) and the motivation for success (5) (external and internal factors) that also affect cognitive processes.

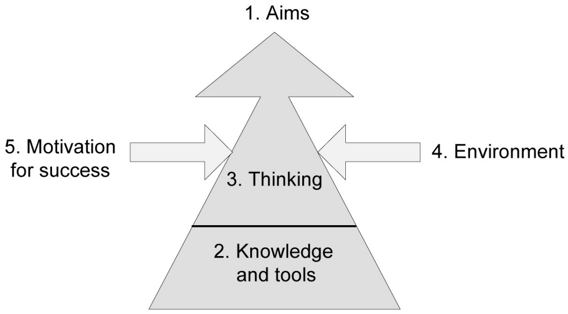

Fig. 1. Schematic representation of the research categorization system.

Table 2. Thinking aspects of scientific research in the exact sciences and engineering design

Category	Number	Scientific research	Engineering design
1. Aims	1.1	Knowledge broadening: directed to new knowledge	Knowledge application: directed to a new product
	1.2	Engineering research: knowledge broadening for knowledge application	
	1.3	Engineering for research: knowledge application for knowledge broadening	
2. Knowledge and tools	2.1	Creation of a knowledge base	
	2.2	Collecting and learning relevant knowledge	
	2.3	Identification of relevant basic scientific laws	Application of models and laws mainly
	2.4	Finding the theoretical foundation for a given research phenomenon	Using heuristics
3. Thinking	3.1	Analysis, aspiration to understand why	Synthesis, aspiration to understand how
	3.2	Abstract thinking mainly	Concrete thinking mainly
	3.3	Thinking focused on a theme	Systems thinking
	3.4	Advance toward the unknown	Advance toward the desirable
	3.5	Global solution	Optimal solution
	3.6	Creative thinking and algorithmic routine thinking	
4. Environment	4.1	Working mode: often individual activity	Working mode: usually team work
	4.2	Flexible working conditions	Firm working conditions
	4.3	Economic facet is less significant	Economic facet is very significant
5. Motivation for success	5.1	Motivation: scientific curiosity	Motivation: real need and individual responsibility
	5.2	Appreciation: global reputation and article publication	Appreciation: reputation in the firm and patent confirmation

A few sub-categories were also found for all categories. Table 2 shows the categories revealed in the research, including their sub-categories. It is clear that some of the sub-categories fit the dimensions of the science–technology interrelationships approach [33]; nevertheless, the emphasis on the cognitive aspects allowed one to distinguish between the sub-categories found in this study and the dimensions of Waks' approach.

Several sub-categories presented in Table 2 are divided into two columns. In this case, these sub-categories mainly belong to the area of scientific research or to engineering design. The other sub-categories are common to the two areas and are presented in the middle of the row. A detailed explanation of the categories will be given in the following paragraphs.

5. Aims

As Waks put it [33], 'Each dimension can be looked upon as a unique line or scale on which one edge represents subjects characterized by Pure Science while the other edge is related to Pure Technological Applicative attributes. Any scientific–technological topic has a unique location on the various dimension scales, depending on relative weights of science and technology.' Accordingly, the two components of sub-category 1.1, Knowledge broadening, as the aim of scientific research and Knowledge application as the aim of engineering design, are located on the opposite edges of the science–technology scale, while sub-categories 1.2 and 1.3, Engineering research and Engineering for research, represent an overlap between these two spheres. These similarities and differences are explained below.

5.1 Knowledge broadening in scientific research versus knowledge application in engineering design

Scientific research is directed to broadening knowledge by creating new knowledge, e.g., exposing new physical laws or a theoretical foundation of an unclear or unknown phenomenon. Engineering design is directed to the application of existing knowledge in new product development. This difference is reflected, for example, in the following quote from the Engineering Council for Undergraduate Education (E-CUE) [36]: 'While science and social science use many common strategies such as abstraction and modeling, the engineering method for problem solving uses these concepts in a unique way that is informed and constrained by the physical world on which it is based and the human world in which it is applied.' Further, while the development of a new product is designed according to market needs, and is intended to make an immediate profit, a new innovative theory or scientific discovery might not serve concrete practical purposes and might be unusable for a long period. For instance, in 1848, George Boole [37] formulated the laws of logic in algebra, but they were criticized or completely ignored by the majority of his peers. It was only 90 years later that Boole's theory was applied by

Claude E. Shannon [38] who demonstrated in 1938 how Boolean algebra could be used in the analysis and synthesis of switching circuits. This essential difference between the aims of scientific research and engineering design is encapsulated in the following phrase: 'science discovers, technology invents' [39].

Below, we present several citations from interviews with the experts that emphasize the distinction between the aims of scientific research and engineering design:

> P: My goal as an engineer is not to expand human knowledge, but rather to make use of that knowledge. This is the essential difference between a researcher and an engineer.
>
> K: It is my belief, that what best characterizes engineering thinking, is the fact that it is a way of thinking that sees a defined goal in front of it. It is a way of thinking, which was made for reaching that goal.

5.2 Engineering research: knowledge broadening for knowledge application

Engineering research aims to broaden existing knowledge for new applications. Both researchers and engineers are involved in this activity. The revolutionary work of Shannon [38] is a salient example of engineering research, as someone who obtained a master's degree in electrical engineering and a Ph.D. in mathematics, and his personality illustrates the combined attributes of both the engineer and the researcher.

A classical view of the development of science and technology assumes that a scientific discovery in 'pure science' precedes a practical application in engineering [39]. For example, the development of the theory of complex numbers began in the sixteenth century, and was continued through 1748 when Euler obtained his famous formula, until the early nineteenth century when graphical representation of complex numbers was described and popularized. It was only in 1893 that Steinmetz applied the theory of complex numbers to the calculation of alternative current in electrical circuits [40].

Nevertheless, as indicated above, engineering research is another kind of research. There are several historical examples in which the application of laws and new tools for engineering were discovered during the course of looking for the solution to concrete technical problems, and only later they were converted into universal methods that are currently used for a broader range of engineering problems. Fourier's transform is one such mathematical method that was originally developed for the theory of heat but is now used in a variety of topics, such as acoustics, optics, information transmission, and signal processing [41]. Additional examples are those of Karnaugh's maps, which have became a useful tool for the simplification of Boolean expressions; and finally, the stability analysis of electronic amplifiers developed by Bode [42], which became a universal method of control theory.

However, engineering research is aimed at the development of new technologies. This is a directed process for breakthroughs and finding new knowledge, which is a characteristic of scientific research. Yet this process is intended for use in immediate applications for concrete human needs—a characteristic of engineering design. The revolutionary development of LCD (Liquid Crystal Display) technology, which united efforts of leading international firms, their researchers and engineers, illustrates the overlap between science and technology [43, 44].

The following excerpts from the interviews reflect this attitude:

> A: So the question is, where is science, where is engineering? One can say that in engineering science, you are researching problems that eventually need to be the working tools of engineering.
>
> S: If an engineer reaches a very high level of thinking, so in some fuzzy cases someone may call him a scientist. The first case I remember about an engineer is Fourier. Because, by definition, he was an engineer, yet he was the first to use Fourier series. Looking at another example: people like Shannon and Nyquist who were apparently engineers, were the ones to discover the sampling theory.

5.3 Engineering for research

This kind of engineering deals with experiment design and development of complicated technology systems for scientific research, such as measurement equipment, automatic control systems of research processes, or robots that act in dangerous environments. Engineering for research is directed for knowledge application with the purpose of knowledge broadening. Here is an illustrative quote that reflects this idea:

> A: What makes a physicist–experimentalist? He builds up an experiment. When he builds that experiment, he is clearly doing an engineering job, and not a scientific job.

The two last sub-categories of engineering research and engineering for research can be viewed as the fusion of science and technology into a single entity, or scitech [45]. In our era, in scitech the distinctions between science and technology 'seem to fail' [39].

6. Knowledge and tools

In scientific research and engineering design, the researcher and the engineer base their work on existing knowledge and tools. Therefore, it is important to understand the role of the knowledge and tools in the cognitive processes of engineering. We first relate to two common aspects of these two areas.

6.1 Creation of a knowledge base

This sub-category illustrates the cognitive process of knowledge acquisition, which is typical for both scientific and engineering students. This base is constantly expanding. Thus, for example, courses in digital signal processing and digital communication did not exist in engineering programs twenty years ago, but now they are an integrative part of most electronics engineering curricula. The interviewees did not see any significant distinction between the demands of the academic education of these two groups, as illustrated in the following quote:

> Sh: At first, you need to get the tools, so both the engineer and the scientist are going through the same basic training courses. One may ask what the difference is. I think the difference is that a scientist's goal is to expand the general understanding of something without asking himself if that thing is useful or not.

Moreover, a new approach for science–engineering education advocates a common curriculum for science and engineering without any separation between them [45]. Therefore, a strong theoretical basis and a deep understanding of physical phenomena are necessary for the novice researcher and engineer.

6.2 Collecting and learning relevant knowledge

Both the researcher and the engineer, while looking for a solution to a new problem, must first complete missing data by collecting and learning the relevant knowledge. The actual process of looking for relevant data in a wide scope of disciplines may help, on the one hand, to find an optimal solution to an engineering problem (as discussed in sub-category 3.5), and on the other hand, to find new knowledge and tools.

Our interviewees emphasized the need to gain a wide perspective as one essential condition for success. Here is one example:

> G: To be a good engineer, you should have a good control of a wide variety of disciplines. It is essential in engineering. It is usually not enough to research in a small and narrow area, but if you want to start your way in industry, you need a wider perspective, which is one of the conditions for success. In this case, one will not see the whole picture, and therefore one will not necessarily choose the best solution for the problem.

In this regard, we mention Bonen's [46] methodology for estimating the time required for the development of a new product in an engineering design process based on a lack of knowledge. Bonen suggested a hierarchical structure that consists of four levels of firm or organization knowledge known as the 'knowledge gap'. The knowledge gap indicates the number of full-cycle design processes required for the development of a new product. Our interviewees used this methodology in practice explaining that:

> J: Organizational knowledge can be characterized by four levels of knowledge. It goes this way: The first level, called 'knowledge gap one', is when you already did something, and you and others know how to do it. 'Knowledge gap two' refers to knowledge about a product that someone else has developed in the organization but I haven't yet. A 'third knowledge gap' refers to a situation in which what we are going to design is very different from what the organization has developed in the past. The 'fourth knowledge gap' is obvious; it's the kind of knowledge about a product that no-one has ever designed before.

The highest fourth level—development of a new technology—is addressed in sub-category *1.2 Engineering research* in our study. From a pedagogical perspective, this methodology can be applied by engineering undergraduates and novice graduates for individual assessment of one's lack of knowledge.

The next two sub-categories emphasize distinctions between cognitive processes related to knowledge and tools in science research and engineering design.

6.3 Identification of relevant basic scientific laws in scientific research versus the application of models and laws in engineering design

The difference between knowledge used in scientific research and engineering design demonstrates the fact that the researcher relies mainly on theoretical laws for the discovery of new phenomena, while the engineer applies models mainly to create concrete systems. One of the interviewees, an engineer and researcher with more than 40 years of experience, explained:

A: A young engineer should build for himself a tool kit. Why? Because he needs a tool to do the work. For a researcher such a tool kit can interfere, because if he has it, he pulls it out quickly.

In other words, an engineering tool kit (a collection of useful methods and models) can interfere with the process of problem solving in scientific research. Nevertheless, such a dichotomy between the engineer and the researcher is not expressed in the high-tech industry, where science and technology converge, reinforce, and catalyze each other [45]. In this case, we can speak about overlapping and common tools for scientific research and engineering design.

The next two sub-categories emphasize the distinction between the cognitive processes linked with knowledge and tools in engineering design and in scientific research.

6.4 The need to find theoretical foundations of a given research phenomenon versus using heuristics

Scientific research looks for new natural laws, so it must find a theoretical foundation for the researched phenomenon; engineering design is intended for concrete practical purposes, so it can use heuristics. Heuristics is the essence of experience and, according to Lawson, when applied, 'a rough idea is quickly developed for the most significant elements of the solution which can then be checked by more precise methods and adjusted as necessary' [27, p. 189]. In engineering design, one cannot always find a theoretical explanation for concrete practical rules. The high complexity of modern systems, intricacy of engineering problems and, sometimes, lack of tools to deal with them, can explain the approach of heuristics application to engineering design. The additional reason may be the fixed time allocated for product development that does not always allow the engineer to investigate a problem in-depth and forces him or her to use heuristics. Here are several quotes that reflect this perspective:

A: How much of a theory do we have in the theory of electromagnetic compatibility? Very little. Suddenly, I have no tool kit. I have to start looking at the problem and try to make all the approximations by myself [*namely, a lack of theoretical tools causes the engineer to look for practical rules*].

K: When I obtain a product, a prototype that has just been made, I can still change it: to touch here, to change there, and such things. This is a part of your work when you're very dominant in the business, and then there are some practical rules that help you to decide what is better to check first, where to put your finger on, where it is preferable to look and this way you're accumulating knowledge, project by project, case by case.

7. Thinking

This is the central issue in our category system. It relates to cognitive approaches and processes of the researcher and the engineer.

7.1 Analysis, aspiration to understand 'why' in scientific research versus synthesis, aspiration to understand 'how' in engineering design

The researcher tries 'to figure out how the physical world operates' [47, p. 35]. He or she should identify essential factors of the investigated phenomenon and seek quantitative relationships between them. Therefore, the researcher deals mainly with analysis processes. According to Anderson and Krathwohl, the analysis process concentrates on 'breaking material or concepts into parts, determining how the parts relate or interrelate to one another or to an overall structure or purpose' [48, p. 67]. The engineer creates a new entity, so he or she must build and assemble the elements of the new system in order to meet the product's requirements. In other words, the engineer deals with synthesis or 'putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing. Creating requires users to put parts together in a new way or synthesize parts into something new and different a new form or product' [48, p. 35]. Nevertheless, the engineer also uses the analysis process in the selection of appropriate alternatives and in decision-making. Indeed, some models of engineering design also include phases of evaluating, verifying, and analysis [10, 26, 27]. Our experts also emphasize the distinction between the thinking modes of the researcher and the engineer:

F: In science, the scientist uses more questions; he always asks himself why this thing happens. Maybe this is the difference [*between an engineer and a scientist*]. An engineer usually doesn't bother himself with things that do not belong to his goal.

S.B.: The main question that a scientist asks is 'why'? 'Why is it so?' and the main question for an engineer is 'how can I make it happen?'

It seems that the cognitive modes of analysis and synthesis are expressed in engineering design not as different developmental stages, but rather as interwoven cognitive modes.

7.2 Abstract thinking mainly in scientific research versus concrete thinking mainly in engineering design

Scientific thinking can start from observing and analyzing concrete physical occurrences in order to find a cause–effect relationship, and afterwards to develop it into an abstract theory. Technology, however, must take into consideration human needs as perceived by human senses, and formulate them in more concrete terms than science [33]. In the process of product development, the engineer translates the customer's demands into the technical requirements of the developed system. Afterwards, he or she chooses components that possess specific properties, defines their work modes, and uses materials with specific characteristics. After the new system materializes, the engineer performs tests and, in the end, decides whether the product meets the technical requirements. It is evident that most of these mental actions are relatively concrete. Further, the complexity of modern technical systems yields mutual influences of their components; therefore, the engineer must predict undesirable effects and find how to neutralize them if they appear.

The following quote relates to the fact that the scientist relies on theoretical assumptions and, by doing so, he or she can neglect some real world factors and ignore the effects of the interaction with the environment. The researcher aims to achieve absolute precision:

> W: A scientist strives to reach the ideal conditions, but if they do not exist, the scientist's solution is based on the assumptions in any case. A scientist seeks for accuracy; we can even say absolute precision. As far as it can be reached.

At the same time, the engineer relies on facts and must take into account the wide range of external conditions:

> M: An engineer has to base his work on existing facts and to use whatever exists in development now: materials, parts, components, and existing knowledge.

Moreover, the engineer builds a set-up from components whose values spread over wide ranges (e.g., ± 5% of resistors values in electronic instruments). Therefore, as one of our experts said, tolerance is an essential characteristic of engineering thinking:

> A: Engineering is blamed for 'cutting corners'. Engineering approximations are measured by sensitivity to end performance and are justified in practice. Scientific approximations are justified by the model accuracy. Engineering is the science of approximations. This is the art of how to 'round corners'.

7.3 Thinking focuses on a theme in scientific research and systems thinking in engineering design

The researcher can focus on certain investigated effects: he or she can concentrate on specific parameters, and in order to make clear the essential factors, cast off some of the less significant factors. Thus, the scientist's thinking focuses on a particular theme. The engineer developing large and complex technological systems must 'look at the whole, and the parts, and the connections between the parts, studying the whole in order to understand the parts' [49, p. 26]. One of the specialists interviewed in our study explained this idea as follows:

> W: The emphasis on system thinking in science is smaller than in engineering. The engineer is dealing with nature itself and must see all the things that can cause a particular effect existing in nature.

According to Frank, 'The whole has to be seen as well as the interaction between the system's elements . . . A problem should not be solved by just dismantling it to parts but all its implications have to be taken into account. Each activity in a system's certain element affects the other elements and the whole' [48, p. 166]. In this spirit, we suggest that system thinking can be seen as a fundamental attribute of engineering thinking.

7.4 Advance toward the unknown in scientific research versus advance toward the desirable in engineering design

Hill [32] indicates that there is parallelism between the stages of generating an idea or hypothesis in science and finding a concept in design. The difference between the two processes stems from their different aims. The researcher is directed towards new knowledge, therefore he or she advances toward the unknown; the engineer is directed to a new product with well-defined features, therefore he or she advances towards the desirable. It is evident from what follows that these differences also appear in the prospective stages of these processes.

The researcher uses a forward-looking inductive method: he or she advances from observation to hypothesis, then checks the theoretical foundation and, finally, makes a decision whether to accept or reject it. The engineer uses a deductive end-backward method: he or she looks at the desirable features of the product and plans appropriate actions. This strategy is a means–end analysis, when the engineer continuously evaluates the current state of the developed product and compares it with the desired goal in order to reduce the gap between them [22]. The engineer advances top-down, from the final system characteristics to its elements and processes. The interviewees described this process as follows:

A: Engineering: i. Top—down. From the final system features down to the constituents and process. ii. End—backwards. Looking at the product/ deliverable features and tailoring the effort backwards. Research i. Forward- looking, using a set of observed rules. ii. Observations → model (Hypothesis) → tests/gedanken [*thought*] experiments → theory → back to further research.

K: Your assessment of the engineering performance is much more obligated. This is different from science where they say: 'Never mind, if we achieve it—O.K., if not—we will change something'. There is no real requirement that you should do it now. This is very, very different.

It seems that flexibility in requirements is a typical factor in scientific thinking, and hard requirement stability is a typical factor in engineering thinking.

In scientific research, the acceptance of a new theory, model or law is a desirable positive result of the investigation; the rejection of the hypothesis or getting a negative result is essential [51]. In engineering design, the final result must be positive. Moreover, each new developed machine, system, or device, is improved relative to its previous versions. That is, it can be claimed that scientific thinking accepts both positive and negative results, and that in engineering thinking a final positive result is required. Here is a quote from one of the interviewees that reflects this notion:

P: In research, you are going in a certain direction, and if you prove that this would not work, your research is successful. Meaning, it blocks others going this way . . . pay attention, here I'm showing you, there's nothing to do in this direction. In engineering, you must know how to do things better, whether it is an algorithm, or a process, or a construction. Anyway, you should do these things better.

In scientific thinking, the testing of a new theory, model or law is carried out by checking the suitability degree of a phenomenon with the theory that describes it. This checking can be done by logical analysis, so abstract thinking can be used. In engineering development, testing is one of the most important stages, and reflection is an inherent part of the thinking process:

N: After we figure out a solution, we have to implement it. After the implementation, we need to verify that it is indeed working. Well, it means that we're always doing something whose results we can show. It can be examined. In contrast to, for example, the solution of some mathematical problem.

Therefore, we claim that reflection is built-in within the engineering design process.

We summarize the differences between scientific and engineering cognitive activities by quoting one of our interviewees:

A: When climbing a tree, the scientist ever branches off until he meets the extreme leaf, and then goes to the next branch, to encapsulate the performance envelope. The engineer climbs to the top, shortcutting side branches *[namely, the engineer aims to achieve the goal in the shortest way].*

7.5 Global solution in scientific research versus optimal solution in engineering design

The researcher aspires to get a *global solution* for a given research problem that can represent the investigated effect in its entirety; the constraints of reality force the engineer to consider a wide range of particular factors. This leads him or her to strive to optimize the solution, i.e. to achieve the best possible solution under given conditions, as illustrated in the following quote:

N: What characterizes engineering thinking is the need to compare between different solutions. It means, it is not enough that I will offer one solution to the problem. I have to see if this is the optimal one. Maybe it is possible to suggest a better one, a cheaper, faster or more efficient solution.

The decision-making process about the optimal solution is based on specific criteria. Our interviewees indicated parameters such as effectiveness, minimal development time, development simplicity, cost, redundancy and their combinations as optimal solution criteria:

Ms: The main criteria were schedule and money. I have usually pushed to get the minimum risk in order to bring the product in time within the budget limitations.

M: The considerations are: easiness of implementation, timing, and performance compared to requirements. Here I have more tolerance, there I have less. Here I'm on the limit of some characteristic but the system works faster, there I'm in the middle of the range, but it works slower. Finally, you want to find the middle way, so you will not be on the limit of everything. It is not always possible but you try.

One of the specialists claimed that there is no optimal solution because, in general, only one solution, which meets all technical requirements, exists. Lawson [27] sees another reason for the lack of an optimal solution: the aims of engineering design can be in conflict, as, for example, in the case of maximal acceleration and minimal fuel consumption of an engine. So, an optimal solution can be found when one compromises while dealing with contradicting demands.

Based on the above descriptions, connections between the global solution in scientific research and the optimal solution in engineering design on the one hand, and abstract thinking in scientific research and concrete thinking in engineering design on the other hand, can be observed. Thus, abstract thinking and the intention for precision in scientific thinking lead to global solutions, and concrete thinking and tolerance in engineering thinking lead to optimal solutions.

7.6 Creative thinking and algorithmic routine thinking

This sub-category has been found both in scientific and engineering thinking. In these two areas, creative or 'lateral' thinking . . .pave the way for new ideas to evolve' [52, p. 246]. It leads to inventions in science and to innovations in engineering. In engineering design, this kind of thinking is typical for the very first stages of the development process. Algorithmic routine or vertical [29] thinking deals with the development of ideas. 'Vertical thinking is a sequential process in which every step has to be correct and justified before moving to subsequent stage—it is hierarchical ordered process' [52, p. 246]. This kind of thinking is very typical for the all next stages of product development in the engineering design process. Here are quotations that reflect this attitude:

R: It is like with artists, where does it come from? How does he create the picture or music? There is something unknown, some secret. He doesn't know for himself how it comes out. I think that here is something in common between the artist, the scientist and the engineer.

G: The first stage is really the creative stage, where one tries to break into new ways. There are the next stages when the creativity ends. There are people dealing only with how to do new things, others working more systematically. The two kinds are important and without both of them, we would not reach anything.

It is well established that the design process is iterative [10, 27]. Accordingly, it can be claimed that creative and algorithmic routine thinking are combined in the process of engineering design.

A relevant type of engineering thinking—integrative thinking [53]—has been found in our study as well. It refers to the fact that newly developed electronic systems include not only standard blocks and components, but also boards, sub-systems or, in short, shelf products, which have been developed for other needs, as described by one of the interviewees:

Ms: Digital electronics is like playing Lego . . . Company A has been a successful company for long time. They have one or two things of their own, which they developed by themselves. All the other products were what we call, as a joke, stitched products. Practically what they did, they combined things together—took from here and there, integrated it all together to form a system. It is pure Lego. Every firm here works that way. Not only digital electronics, also electro–optics, RF, radar and other sophisticated systems.

This new system building requires integrative thinking. Integrative thinking not only adapts known solutions for current problems and is used by algorithmic routine thinking, but also includes a creative component, which allows looking from original perspectives upon a known solution and observing new options. Therefore, in integrative thinking, creative and algorithmic routine thinking are merged.

8. Environment

This category relates to environmental factors, which can affect the cognitive processes of the researcher and the engineer.

8.1 Working mode: often individual activity in scientific research versus usually team work in engineering design

In most cases, the engineer works in a group, and it is unusual for a single individual to perform engineering design [54]. Hence, in engineering design great importance is attributed to teamwork, interpersonal communication, and the ability to act as part of the organization. Similar processes exist in large scientific research groups. However, in most cases, individual research work is intensified. The following quote from one of the interviews illustrates this difference:

> A: In the academic environment: i. Personal achievement and accrediting are fostered. ii. Loose interpersonal interaction. Team culture is rare. In the industrial environment: i. Objectives and constraints are derived top-down from organizational objectives/ strategy. ii. Team-work and culture are critical.

In an engineering environment, close contacts lead to permanent intellectual flow from one brain to another [54]. Engineers apply new knowledge in their work [22] and share it among team members, as is explained by one of our experts:

> A: There is a need to learn a lot in an unstructured way, the master's way, through the other's experience, through little notes of the others, which is less usual with scientists. The engineer must be a team animal.

Such conditions naturally enable young engineers to learn directly from colleagues.

In addition, engineering design deals with a flow of decision-making [54]. Design reviews, or a methodological process for important engineering decisions, exist in many firms. Therefore, due to the teamwork, the individual's solutions and decisions are checked too:

> S: Any respected engineering design in a distinguished firm, not just a two-man company, is controlled by an organized CDR, PDR, and SDR [*different forms of design reviews*].

Consequently, decision checking in a controlled and systematic manner can be seen as an essential capability of engineering thinking.

Finally, collective thinking in engineering practice leads to synergy. More than a dozen techniques for brainstorming and synergy creation are well known [54], and they are useful in engineering practice. Our specialists too emphasized the importance of collective thinking:

> S: If we need an idea, we do brainstorming. The content must come from people. When we want to build a system, we'll have some brainstorming, we will think. We will sit, a group of people arguing with each other, each one with his expertise.

8.2 Flexible working conditions in scientific research versus firm working conditions in engineering design

The message of this section is that working conditions can affect the cognitive process. For example, the researcher's individual work, in general, does not constitute a bottleneck in a sequence of stages of a whole group. As a result, the researcher himself or herself can set and change aims and timing. His or her working conditions are more flexible. In contrast, engineering teamwork demands conditions that are more firm.

Almost all the interviewees noted that time pressure is an obligatory factor in the engineering thinking process. The reason is not only a stressed time-schedule, but also the fact that the results of group activities depend on each of the participants. This leads to the need for individual responsibility. These urgent conditions can lead to mental carelessness, and an inclination to leave open misunderstood and unchecked questions in the problem-solving process. Nevertheless, several interviewees in our study claimed that such conditions could contribute to the development of the ability to think quickly and effectively.

In addition, the engineer acts in an industrial framework where the working processes are organized and specialized. He or she has to consider standards and instructions, and write standardized documentation on the product development:

> K: So, this is very tidy work—very pedantic; according to tough rules; at least in the hi-tech industry. The rules are very rigid and eventually a product, which is a required solution for a given problem, is developed.

Such a situation can affect cognitive processes and cause stagnation of thought. Our specialists realize this danger and call for the need for techniques that might enhance 'thinking out of the box'.

> A: For breakthrough, for innovation, you need technique, you need to know how to think out of the box.

8.3 The economic facet is less significant in scientific research in comparison to its importance in engineering design

Usually, the researcher does not look forward to immediate profit from his or her investigation. In contrast, the engineer works, in most cases, in an industrial enterprise and questions of cost and profit, risk and business success play an important role in his or her work [54]. Our specialists addressed this fact:

> G: Engineering thinking leads to some product

that can be sold and money gained from it; science does not.

S: Engineering design is compromising; so, an engineer who knows how to compromise and evaluate variables effectively is the one who reaches a less expensive product with more features at the same price.

So, thinking in economic terms can be seen as an integral part of engineering thinking.

9. Motivation for success

Understanding of the motivational factors in the engineering design process is necessary. Motivation should be built-in within the engineering education curriculum because it can accelerate cognitive processes. We will relate to internal or individual motivation factors and external or social motivation factors.

9.1 Motivation—scientific curiosity in scientific research versus real need and individual responsibility in engineering design

Scientific curiosity may be the main driving force behind scientific research. This factor acts in engineering design too, but the realization of necessity and real need of the treated problem seems to motivate the engineering process as well. Our interviewees noted that the use of their developed products in real life is the greatest satisfaction they gain from their engineering work:

N: The engineer has self-satisfaction that he got a problem to handle, a real problem. It is very flattering when he solves a real problem. He faces it and succeeds. This success builds self-confidence.

The sense of the personal responsibility of teamwork outcomes may also be considered as an essential motivation factor.

9.2 Appreciation: global reputation and article publication in scientific research versus reputation in firm and patent confirmation in engineering design

The researcher aims toward a global reputation in the scientific world. He or she writes articles and participates in conferences, and the number of his or her scientific publications and their citations in the world measures his or her success. The success of the common engineer is limited to the framework of his or her firm and can be measured by salary, promotion, and engineering authority. Patent recognition may be the only widely-acknowledged, public and social appreciation of engineering work, as is specified by the interviewees:

A: Engineering credit and appreciation are derived from team success. The appreciation sphere of the engineer is more local than that of the scientist.

B: It might be that he will receive a patent; this is the only place where the engineer gets personal credit.

10. Conclusions

The comparative characterization of engineering thinking in engineering design and research thinking in the exact sciences carried out in the article shows the similarities and differences between cognitive processes in these two areas. Creation of a knowledge base in the educational phase, collecting and learning relevant knowledge in the first stage of new problem-solving, and using creative and algorithmic routine thinking in the course of problem-solving, are common for both areas. Nevertheless, the difference in the aims of the two processes—knowledge broadening in scientific research versus knowledge application in engineering design—seems to be the reason for the difference between the tools, cognitive processes, environment, and motivation of the researcher and the engineer. Thus, for example, we identified that finding the theoretical foundation of a researched effect is obligatory for scientific research while using heuristics is accepted in engineering research; scientific research requires often abstract thinking while engineering research demands mainly concrete thinking; scientific research looks for global solutions while engineering research seeks optimal solutions.

We believe that our study may help engineering educators to observe the cognitive processes in these two professional fields, and in this way to aid in the design of engineering courses with concern for the development of engineering thinking. It is important to emphasize that the cultivation of engineering thinking during undergraduate studies is expected in order to assist the student in the transition process from academia to work in industry and to serve as a basis for the future success of graduate engineers.

Our study mainly relates to electronic design. However, one of our interviewees, a professor of mechanical engineering, emphasized that he does not see significant differences between the cognitive processes of the engineer in the field of modern mechanics, such as micro-electromechanical systems design, and the engineer in the field of modern electronics. So, our wider purpose is to identify the global engineering thinking characteristics that might be common to different fields of engineering. In the future, we plan to carry out further research aimed at identifying similarities and distinctions in cognitive traits across various engineering disciplines, as well as to present the pedagogical implications derived from these identifications.

References

1. B. T. Wright, Knowledge management, *Presentation at meeting of Industry–University–Government Roundtable on Enhancing Engineering Education*, Iowa State University, Ames, 1999.
2. *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, National Academy of Engineering of the National Academies, National Academies Press, 2005, http://www.nap.edu/openbook.php?record_id=11338&page=R1, Accessed 23 June 2009.
3. S. Waks, Engineering Education—Prospective Research Issues, *Proceeding of the 9th Biennial ASME Conference on Engineering Systems Design and Analysis*, Haifa, Israel, 2008.
4. H. A. Simon, *The Science of the Artificial*, 3rd edn, MIT Press, Cambridge, MA, 1996.
5. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, Engineering design thinking, teaching, and learning, *J. of Engineering Education*, **94**(1), 2005, pp. 103–120.
6. J. J. Shah, S. M. Smith, N. Vargas-Hernandes, D. R. Gerkens and M. Wulan, Empirical studies of design ideation: alignment of design experiments with lab experiments, *Proceeding of DETC 2003: ASME 2003 International Conference on Design Theory and Methodology,* Chicago, IL, 2003.
7. R. Bailey, Comparative study of undergraduate and practicing engineer knowledge of the roles of problem definition and idea generation in design, *International J. of Engineering Education,* **24**(2), 2008, pp. 226–233.
8. H. L. Davidz and D. J. Nightingale, Enabling systems thinking to accelerate the development of senior systems engineers, *System Engineering*, **11**(1), 2008, pp. 1–14.
9. R. P. Smith and P. Tjandra, Experimental observation of iteration in engineering design, *Research in Engineering Design*, **10**(2), 1998, pp. 107–117.
10. R. S. Adams and C. J. Atman, Cognitive processes in iterative design behavior, *29th ASII/IEEE Frontiers in Education Conference*, **11**ab, 1999, pp. 13–18.
11. J. Hey, A. V. Pelt, A. Agogino and S. Beckman, Self-reflection: Lessons learned in a new product development class, *J. of Mechanical Design*, **129**(7), 2007, pp. 668–676.
12. C. J. Atman, R. S. Adams, M. E. Cardella, J. Turns, S. Mosborg and J. Saleem, Engineering design processes: A comparison of students and expert practitioners, *J. of Engineering Education*, **96**(4), 2007, pp. 359 –379.
13. C. J. Atman, K. Yasuhara, R. S. Adams, T. J. Barker, J. Turns and E. Rhone, Breadth of problem scoping: a comparison of freshman and senior engineering students, *International J. of Engineering Education*, **24**(2), 2008, pp. 234–245.
14. R. S. Adams, C. J. Atman, R. Nakamura, G. Kalonji and D. Denton, Assessment of an international freshmen research and design experience: A triangulation study, *International J. of Engineering Education,* **18**(2), 2002, pp. 180–192.
15. S. M. Nesbit, S. R. Hummel, P. R. Piergiovanni and J. P. Schaffer, A design and assessment-based introductory engineering course, *International J. of Engineering Education,* **21**(3), 2005, pp. 434–445.
16. M. L. Jacobson, R. A. Saidand and H. Rehman, Introducing design skills at the freshmen level: Structured design experience, *IEEE Transactions on Education*, **49**(2), 2006, pp. 247–253.
17. M. B. R. Vallim, J.-M. Farines and J. E. R. Cury, Practicing engineering in a freshmen introductory course, *IEEE Transactions on Education*, **49**(1), 2006, pp. 74–79.
18. C. A. Mullins, C. J. Atman and L. J. Shuman, Freshman engineers' performance when solving design problems, *IEEE Transactions on Education*, **42**(4), 1999, pp. 281–287.
19. J. Turns, R. Adams, A. Linse, J. Martin and C. Atman, Bridging from research to teaching in undergraduate engineering design, *International J. of Engineering Education,* **20**(3), 2004, pp. 379–390.
20. J. Turns, R. S. Adams, J. Martin, M. Cardella, J. Newman and C. J. Atman, Tackling the research-to-teaching challenge in engineering design education: Making the invisible visible, *International J. of Engineering Education,* **22**(3), 2006, pp. 598–608.
21. ABET (Accreditation Board for Engineering and Technology Engineering), *Engineering Criteria 2000*, 3rd edn, http://www.ele.uri.edu/faculty/daly/criteria.2000.html, Accessed 25 June 2009.
22. S. Sheppard, A. Colby, K. Macatangay and W. Sullivan, What is engineering practice? *International J. of Engineering Education*, **22**(3), 2006, pp. 429–438.
23. C. L. Newport and D. G. Elms, Effective engineers, *International J. of Engineering Education*, **13**(5), 1997, pp. 325–332.
24. C. L. Dym, Engineering design: So much to learn, *International J. of Engineering Education*, **22**(3), 2006, pp. 422–428.
25. T. Puk, Creating a quantum design schema: Integrating extra-rational and rational learning processes, *International J. of Technology and Design Education*, **5**, 1995, pp. 255–266.
26. K. Ehrlenspiel, On the importance of the unconscious and the cognitive economy in design. In U. Lindeman (ed.) *Human Behavior in Design. Individuals, Teams, Tools*, Springer, Berlin, 2003.
27. B. Lawson, *How designers think: the design process demystified*, Architectural Press, Oxford, 1997.
28. E. Kroll, S. Condoor and D. G. Jansson, *Innovative Conceptual Design: Theory and Application of Parameter Analysis,* Cambridge University Press, Cambridge, 2001.
29. E. De Bono, *Lateral Thinking for Managemen : A Handbook,* Penguin Books, Harmondsworth, UK, 1971.
30. O. Eris, Insisting on truth at the expense of conceptualization: Can engineering portfolios help? *International J. of Engineering Education*, **22**(3), 2006, pp. 551–559.
31. Merriam-Webster Online Dictionary, http://www.merriam-webster.com/dictionary/science. Accessed 2 August 2009.
32. P. H. Hill, *The Science of Engineering Design,* Holt, Rinehart and Winston, New York, 1970.
33. S. Waks, Science–technology dimensions in physics education: prospects and impact, *Physics Education*, **29**(2), 1994, pp. 64–72.
34. N. K. Denzin and Y. S. Lincoln, *Handbook of Qualitative Research*, 2nd edn, Sage Publications, Thousand Oaks, London, 2000.
35. M. Q. Patton, *Qualitative Research and Evaluation Methods,* 3rd edn, Sage Publications, Thousand Oaks, CA, 2002.
36. Engineering Council for Undergraduate Education (E-CUE), *From Useful Abstractions to Useful Design—Thoughts on the Foundations of the Engineering Method*, Part I. MIT School of Engineering, Engineering, 2005, http://web.mit.edu/engineering/ecue/core_abilities/From%20Useful%20-Abstractions%20to%20Useful%20Design-Pt%20I.doc, Accessed 11 November 2009.
37. G. Boole,The calculus of logic, *Cambridge and Dublin Mathematical Journal*, 1848, Vol. III, pp. 183–198, http://www.maths.tcd.ie/pub/HistMath/People/Boole/CalcLogic/CalcLogic.html, Accessed 2 December 2007.
38. C. E. Shannon, A symbolic analysis of relay and switching circuits, 1938. In N. Sloane and A. Wyner (eds), *Claude Shannon: Collected Papers*, Part 2, pp. 1–5. IEEE Press, NJ, 1993.
39. G. Dodig-Crnkovic, *Theory of Science*, MDH, 16/08/2001, http://www.mrtc.mdh.se/publications/0333.pdf , Accessed 2 April 2009.
40. P. J. Nahin, *An Imaginary Tale: The Story of* $\sqrt{-1}$, Princeton University Press, NJ, 1998.
41. Fourier Analysis, *Encyclopædia Britannica Online*, http://www.britannica.com/EBchecked/topic/22486/analysis/218290/Fourier-analysis#ref=ref732814, Accessed 12 December 2009.
42. H. W. Bode, *Method and Apparatus for Predicting Stability of a Closed Loop Apparatus*, patent number 2123178, 1938, http://www.google.com/patents?vid=2123178, Accessed 2 December 2009.
43. H. Kawamoto, The history of liquid crystal displays, *Proceedings of IEEE*, **90**(4), 2002, pp. 460–500.
44. J. A. Castellano, *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry*, World Scientific, 2005.

45. Z. Tadmor, Redefining engineering disciplines for the twenty-first century, *The Bridge—The Journal of US National Academy of Engineering,* **36**(2), 2006, http://www.nae.edu/nae/bridgecom.nsf/Multi+Database+Search/862570B60074BA9085257181006C4F94?OpenDocument#Author, Accessed 9 February 2009.
46. Z. Bonen, *Rafael—From the Laboratory to the Battle* (in Hebrew), N.D.D. Media, Israel, 2003.
47. R. W. Paul and L. Elder, *Analytic Thinking*, Foundation for Critical Thinking, Sonoma, CA, 2006.
48. L. W. Anderson and D. R. Krathwohl (eds), *A Taxonomy for Learning, Teaching and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives.* Complete edition, Longman, NY, 2001.
49. J. O'Connor and I. McDermott, *The Art of Systems Thinking: Essential Skills for Creativity and Problem Solving*, Thorsons, San Francisco, 1997.
50. M. Frank, Engineering systems thinking and systems thinking, *Systems Engineering*, **3**(3), 2000, pp. 163–168.
51. K. Popper, *Conjectures and Refutations: The Growth of Scientific Knowledge*, 5th edn,, Taylor & Francis Group, NY, 2000.
52. S. Waks, Lateral thinking and technology education, *J. of Science Education and Technology,* **6**(4), 1997, pp. 245–255.
53. R. L. Martin, *Opposable Mind: Winning Through Integrative Thinking,* Harvard Business School Publishing, MA, 2009.
54. G. E. Dieter, *Engineering Design,* McGraw–Hill, Singapore, 1991.

Shlomo Waks is Professor Emeritus at the Technion—Israel Institute of Technology. He is Head of the National Center for Technology Teachers (Moretech). He obtained his B.Sc. in 1962, followed by his M.Sc. in Electrical Engineering; 2nd M.Sc. in Science Education and Ph.D. (1973) in Curriculum Development. His main academic activities are: Head of Departmental Graduate Studies (Technion); Consultant to the USAID on curriculum development in engineering/technology education. He has published about 100 papers in refereed journals and international conference proceedings, and tens of research reports and textbooks (as author or co-author) He is author of the book *Curriculum Design—From an Art Towards a Science*. He has mentored more than 40 Master and Doctoral students who have completed their graduate studies in Science, Technology and Engineering Education.

Elena Trotskovsky is a senior teacher in the Department of Electric and Electronics Engineering at ORT Braude College in Karmiel, Israel. Her interests include aspects of electronics engineering sciences, such as the theory of control and digital electronics, and educational problems, such as the development of engineering thinking among undergraduate students. She completed her first M.Sc. degree in 1978 in industrial electronics at Ufa Aviation University, Russia, and her second M.Sc. degree in 2009 in the Department of Education in Technology and Science at the Technion, Haifa.

Nissim Sabag is a senior lecturer in the Department of Electronics and Electrical Engineering and Chair of the Collegial Committee of Academic Affairs at Ort Braude College, Karmiel Israel. He was Head of the project for improving the learning and teaching of electronics involving eight high schools (1998–2002), Program Manager of various interdisciplinary programs (over $20 000 000) and was with ELBIT Computers Ltd. Haifa, Israel (1983–1989). His academic activities include electrical and electronic engineering as well as technology and engineering education, particularly, Project Based Learning. He published his first book (with M. Mudrik and M. Kalartg) in 1993: *Digital Electronics*, Open University & ORT Israel Pub. (in Hebrew). His recent publications are 'Chronology of Change Assimilation in Technology Education–Case Study' (with Y. Dupelt) *MoreTech. Journal of National Center of Technology Teachers* (2009) (in Hebrew). 'Internship in Electrical and Electronics Engineering' (with E. Trotskovsky) *MoreTech. Journal of National Center of Technology Teachers* (2009) (in Hebrew). He has aB.Sc. in Electrical engineering (1982); second B.Sc. (1995), M.Sc. (1998) and Ph.D. (2002) in Technology and Science Education from the Technion—Israel Institute of Technology.

Orit Hazzan is an associate professor in the Department of Education in Technology and Science at the Technion—Israel Institute of Technology. Her research focuses on computer science and software engineering education. In May 2004, she published her first book, *Human Aspects of Software Engineering*, co-authored with the late Jim Tomayko. Her second book, *Agile Software Engineering*, co-authored with Yael Dubinsky, was published by Springer in 2008. Dr. Hazzan has published about 100 papers in refereed journals and conference proceedings. She chairs the high school computer science curriculum committee assigned by the Israeli Ministry of Education, and in 2007 and 2010 she co-chaired, together with Jeff Kramer, the program committee of The IEEE International Conference on Software—Science, Technology and Engineering. In 2006–2008 she served as the Technion's Associate Dean of the Technion Undergraduate Studies.