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Students' Misunderstandings and Misconceptions in Engineering Thinking*

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It is well established that students' misunderstandings and misconceptions frequently impede learning processes and frustrate their best efforts. Little is known about how they relate to engineering thinking. We claim that some learning difficulties are common to several engineering disciplines. The aim of the study presented in this paper is to answer the question: What engineering-thinking misunderstandings and misconceptions are typical of students in the areas of electronics, mechanical and software engineering? Based on analysis of interviews with experienced lecturers, this paper presents three levels of students' engineering-thinking misunderstandings, according to their generality. The first level relates to misunderstandings of specific content learned in a concrete engineering discipline; the second level deals with more general students' problems in interpreting and integrating knowledge, which they typically make in several engineering disciplines; and the third level describes misunderstandings characteristic of students in most engineering disciplines. In addition, we discuss the match between the misunderstandings of students studying engineering disciplines and the system of categories, which characterizes engineering thinking.

Keywords: engineering design; engineering thinking; misunderstandings, misconceptions

1. Introduction

Most young engineers working in high-tech industries 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." [1, p. 104]. Many experts view engineering design as a central engineering activity [e.g., 1, 2]. In our opinion, a specific kind of thinking fuels and shapes engineering design—i.e., engineering design thinking [3]. We believe that developing engineering design thinking among students in the course of undergraduate studies is very important because it can contribute to the maturation of novice engineers and assist them greatly in their future design work. Consequently, such development should be one of the central aims of engineering education.

Over the last two decades, the opening of engineering colleges in Israel has meant that more and more people have access to academic engineering education. As a result, today a very diverse population, from the point of view of knowledge base and cognitive capabilities, is studying for engineering degrees. It might increase the number of mistakes existing in students' thinking during their studies. This paper deals with a specific kind of mistakes: misunderstandings and misconceptions—namely, interpreting engineering concepts incorrectly. We, as educators, are in charge of helping our students arrive at the correct understanding. It is also extremely important to find pedagogical ways to avert future difficulties that novice engineers may face once they leave university or college, join the workforce and perform their first design projects. This situation encourages us to investigate students' engineering-thinking misunderstandings and misconceptions.

Despite the fact that the term students' misconceptions is widely used in educational research literature, we found no studies that investigate the connection between students' misunderstandings and misconceptions in engineering disciplines and the framework of engineering thinking. For example, between 1996 and 2011 the three main journals dealing with problems of academic engineering education, the *Journal of Engineering Education*,

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the *International Journal of Engineering Education*, and the *European Journal of Engineering Education*, published over thirty papers on various aspects of engineering or design thinking. These papers, however, mentioned only a few difficulties of students in design and project courses that investigated students' cognitive activities and misconceptions concerning concrete engineering disciplines.

The purpose of the current study is to reduce this research gap, at least partially, and to answer the following question: "What engineering-thinking misunderstandings and misconceptions are typical of students studying mechanical, software, electric and electronics engineering?"

In what follows, we describe the existing approaches toward the analysis of misunderstanding and misconceptions, especially in engineering disciplines. Then, we depict the characterization and categorization of engineering design thinking. Afterwards, we present our research method and the results: a classification of students' misunderstanding and misconceptions and the linkage between these difficulties and the categorization of engineering design thinking [3].

2. Students' misunderstandings and misconceptions

According to the classical approach to errors and misconceptions [4], students come to class with early theories based on their daily experience, that is, with intuitive perceptions. Systematic errors in thinking are the results of these perceptions [5]. There are many definitions for the term students' misconceptions. Cromley and Mislevy suggest that "There are ideas derived from daily experience that students bring to their learning experience and that contradict scientific understanding and [are] often resistant to change" [6].

The most common term for students' prior ideas—misconception—emphasizes the mistaken character of prior knowledge. Still, a misconception can also be defined differently—e.g., as alternative conceptions, preconceptions and naïve beliefs. Different definitions "reflect differences in how researchers have characterized the cognitive properties of student ideas and their relation to expert concepts" [7]. Researchers use other terms to describe similar phenomena of misunderstanding: phenomenological primitives or p-prims [7], naïve conceptions [8], intuitive [9] or naïve knowledge [10]. Regardless of which definition is the correct one, all these terms refer to students' prior knowledge, which is inconsistent with or contradicts the new scientific knowledge that they are learning. This situation can, therefore, cause a cognitive conflict for students.

In their classic study, Smith *et al.* [7] formulated central features about misconception research:

1. Students have misconceptions—this assertion rejects the view of a students' prior knowledge as a tabula rasa.
2. Misconceptions originate in prior learning—they may be the result of everyday experiences of physical phenomena or incorrect generalization of prior knowledge when grappling with new mathematics tasks.
3. Misconceptions can be stable and widespread among students. They can be strongly held and resistant to change—misconceptions consistently appear before and after lessons or instruction, in substantial numbers of students and adults, and coexist alongside correct ideas.
4. Misconceptions interfere with learning—they affect the learning process.
5. Misconceptions must be replaced—"Learning involves the acquisition of expert concepts and the dispelling of misconceptions" [7, p. 122].
6. Instruction should confront misconceptions—in order to surrender their misconceptions, students must see the disparity between them and the expert concepts and the advantages of the latter.
7. Research should identify misconceptions.

Smith *et al.*'s study defined the main directions taken by educational research of misconceptions in the last twenty years. Most studies in this field aim to identify various misconceptions in numerous science and engineering disciplines. Thus, in mathematics and physics this type of research covers many topics. In physics, for example, misconceptions in the following areas were widely researched: classic mechanics [8, 11], quantum mechanics [12], light [13], magnetic induction [14], floating and sinking [15], and gas laws [16]. Even the University of Dallas has posted on its website a guide to enhancing conceptual understanding that includes a list of preconceptions and misconceptions in all areas of physics [17]. On the other hand, the research of misconceptions in engineering disciplines is less advanced and developed [18]. Usually, such research deals with identifying specific misconceptions in concrete topics; for example, in the application of both force and moment equilibrium in statics [10]; the rate and amount of heat transfer and impact of entropy on the efficiency of real systems in thermodynamics [19]; highlighting an individual's misconceptions on electrical circuits [20]; misunderstanding of the concepts of frequency response in signals and systems [21]; structural modeling in civil engineering [22]; and misconceptions about the flip-flop state in digital logic design

[23]. In [24] educational researchers try to describe the most difficult concepts in engineering science.

Nevertheless, the pedagogical implications, which are directed toward overcoming and replacing the misunderstandings by clear science and engineering concepts, are backed by a significantly smaller group of studies in the fields of science and engineering educational research. Smith *et al.*'s words, written in 1993, are still relevant today: "Much less emphasis was given to modeling the learning of successful students in those domains, to characterizing how misconceptions evolve, or to describing the nature of instruction that successfully promotes such learning" [7, p. 123]. Generally, researchers in the field of engineering education are satisfied with offering recommendations that can help overcome students' misunderstanding and misconceptions. They, for example, counsel instructors and educators:

- to take into consideration students' tendencies to make errors [10];
- to highlight individual misconceptions in order to help each one recognize his or her misconceptions and to support self-assessment [20];
- to rebuild curricula with emphasis on problem solving and real-world projecting [22];
- to agree on a standard definition of different terms that lecturers commonly use for the same specific concepts [23].

Some researchers distinguish between misunderstanding and misconceptions [18]. Acquisition of new knowledge may lead to misunderstanding. This happens when the student acquires an interpretation, which he or she believes is correct, but that conflicts with a purely scientific view. In contrast, misconceptions occur when students use prior or initial knowledge when absorbing new scientific ideas. Misunderstandings usually relate to the level of difficulty of the material students are studying, and are relatively easy to overcome by repeated in-depth explanations. When a person realizes that he or she has misunderstood, he or she can correct the mistake relatively quickly. Misconceptions, on the other hand, are stable thought tendencies and are very resistant to change. Additionally, misconceptions are robust, they appear in a large number of students, and overcoming them requires a fundamental change in the learners' concepts.

In engineering courses, lecturers and instructors usually teach concepts, ideas and approaches that are new to the learner. Because they do not have preliminary experience related to these engineering concepts, we propose to classify students' mistakes as misunderstandings. Still, while absorbing new ideas, the student may use his or her prior mistaken knowledge, and so misunderstandings and misconceptions can intertwine. In other words, sometimes it is difficult to identify the reason for a student's specific error clearly—was it a misunderstanding or was it a misconception? Our major concern is that if they are not handled properly, these misunderstandings will become misconceptions and entrenched in the thinking of the future engineers. In our first step toward identifying misconceptions, we refer to both misunderstandings and misconceptions as misunderstandings without distinguishing between them. Using the results presented in the current paper, we plan to conduct an additional study that will deal with identified misunderstandings and misconceptions in detail.

3. Engineering design thinking

The Accreditation Board for Engineering and Technology (ABET) defines a set of eleven abilities required of graduate engineers [25]. Several authors [26, 27] use this set as a base for the research of engineering students' cognitive activities. Other researchers identify effective engineer qualities and mental characteristics [28–30]. Another approach to analyzing engineering design thinking leans towards the development of theories, models, and schemes of cognitive processes in engineering design. As a result, a number of theories appear in the literature. De Bono [31] developed the theory of lateral and vertical design thinking that relates to the creative processes of new ideas and the sequential processes of their development. Eris [32] proposed the divergent–convergent inquiry-based design thinking model that links the phase of concept creation in the design process with convergent thinking, and the phase of decision-making and specification with divergent thinking. Lawson [33] and Kroll *et al.* [34] offered design process schemes that emphasize the iterative nature of design thinking.

The study by Waks *et al.* [3], which focused on the characterization and categorization of engineering design thinking in electronics engineering design, takes into consideration both attitudes—identification of cognitive skills and development of design thinking schemes. In the study, we identified five main engineering design-thinking categories and organized them in a schematic representation, presented in Fig. 1. We relate not only to pure cognitive factors, but also to additional aspects such as linkages to environment and motivation, which, as it turns out, can affect cognitive processes.

Category (1) comprises the aims towards which engineering thinking is directed. Category (2) is the knowledge and tools on which engineering thinking is based. Category (3), the central category, constitutes engineering thinking itself. Two additional

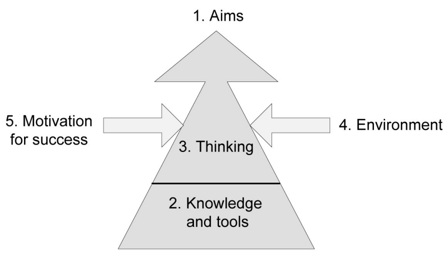

Fig. 1. Schematic representation of the research categorization system

categories are the environment (4) and motivation for success (5) (external and internal factors), which also affect cognitive processes. All the categories include several sub-categories, which describe different cognitive characteristics and processes.

Table 1 shows the first three categories, which were revealed in previous research, including most of their sub-categories that are relevant for the present study as well. A short explanation of these categories and sub-categories appears below.

3.1 Aims

Engineering design is directed toward the creation of new technological components, devices and systems. The aim of engineering can, thus, be seen as the application of existing knowledge to meet human needs.

3.2 Knowledge and tools

One characterization of engineering process emphasizes three components of engineering: problem solving (consisting of the systematic processes that engineers use to define and solve problems), knowledge (consisting of the specialized knowledge that enables and fuels the problem solving process), and the integration of process and knowledge [35]. “Thus knowledge, including conceptual knowledge, is central to the practice of engineering” [24, p. 280].

3.2.1 Creation of a knowledge base

This sub-category illustrates the cognitive processes of knowledge acquisition, mainly in the sphere of academic education. In the course of education, the student gains new theoretical and practical knowledge and develops high thinking skills that he or she will use in future engineering practice. Undergoing these processes is inevitable for engineers.

3.2.2 Collecting and learning relevant knowledge

The engineer, while looking for a solution to a new problem, must first acquire missing knowledge by collecting and studying all possible relevant knowledge. The actual process of looking for relevant data in a wide scope of disciplines expands the individual’s knowledge base and may help, on the one hand, to find an optimal solution to an engineering problem (as presented in Section 3.3.5) and, on the other hand, to find new knowledge and tools. Ceaseless expansion of scientific knowledge and fast development of engineering tools stimulate the process of collecting and studying new relevant knowledge, which is an inherent part of engineering work throughout an engineer’s career.

3.2.3 Application of models and laws in engineering design

When creating new real systems, the engineer uses an engineering tool kit that includes a collection of new and well-known theoretical as well as practical methods and models. These engineering resources are based on scientific laws, but are mainly applicative in character. Thus, engineering models may differ from scientific models by their degree of accuracy.

3.2.4 Using heuristics

Engineering design is intended for concrete practical purposes. Accordingly, it can use heuristics. A heuristic is a practice rule that distills the essence of experience. In engineering design, one cannot always find a theoretical explanation for such rules. The high complexity of modern systems, the intricacy of engineering problems and, sometimes, the lack of tools to deal with them, can explain the approach of applying heuristics to engineering design.

Table 1. Thinking aspects of engineering design

Category	**Num.**	**Sub-category**
1. Aims	1.1	Knowledge application: Directed to a new product
2. Knowledge and tools	2.1	Creation of a knowledge base
	2.2	Collecting and learning relevant knowledge
	2.3	Application of models and laws
	2.4	Using heuristics
3. Thinking	3.1	Synthesis, aspiration to understand how
	3.2	Concrete thinking
	3.3	Systems thinking
	3.4	Advance toward the desirable
	3.5	Optimal solution

3.3 Thinking

Thinking is the central issue in our category system. It relates to the engineer's cognitive approaches and processes.

3.3.1 Synthesis, aspiration to understand 'how'

In the process of creating a new object or device, the engineer must understand how to build and assemble the elements of the new system that will meet the product's requirements. Therefore, 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" [38, p. 35]. Nevertheless, the engineer also applies an analytic process in the selection of appropriate solutions and alternatives and in decision-making processes. It seems that in engineering design the cognitive processes of analysis and synthesis are expressed as interwoven cognitive modes.

3.3.2 Concrete thinking

In the process of product development, the engineer translates the customer's demands into the technical requirements of the developed system. He or she chooses components that possess specific properties, defines their work modes, and uses materials with specific characteristics. In the last stages of the design process, the engineer performs tests and makes decision about the fitting of the developed systems' characteristics to the technical requirements. Moreover, the fact that the complexity of modern technological systems results in components having mutual influences on each other means that the engineer must be able to predict undesirable effects and determine how to neutralize them when they occur. It is evident that most of these mental actions are relatively concrete.

3.3.3 Systems thinking

The engineer, when 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" [37, p. 26]. In his characterization of engineering system thinking, Frank claims: "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" [38, p. 166].

3.3.4 Advance toward the desirable

The anticipated features of the developed product are defined in the first stages of the design process. In attempting to meet desired specifications, the engineer uses an end-backward method: looking at the desirable features of the product and planning appropriate actions. One engineering strategy is a means–end analysis in which the engineer continuously evaluates the status of the developed product and compares it with the desired goal in order to reduce the gap between them [35]. The engineer advances top-down, from the final system characteristics to its elements and processes, while persistently checking whether he or she has deviated from the predefined goals and making the necessary corrections if deviations appear. This is advancing toward the desirable.

3.3.5 Optimal solution

Reality constraints 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. Lawson [33] emphasizes that the need for an optimal solution appears when the engineer must meet contradictory goals—for example, achieving maximal acceleration and minimal fuel consumption. Therefore, an optimal solution can be found when one balances contradictory demands.

We considered all these characteristics when establishing the linkage between students' misconceptions and misunderstandings and engineering thinking.

4. Method

The study applied a qualitative research methodology, i.e., interpretive research [40]. The open interview was chosen as the main data collection tool, and a series of twenty-two in-depth interviews with lecturers from academia was conducted. We preferred collecting information from lecturers rather than from their students for reasons of efficiency: one lecturer can report on many typical student mistakes. Our interviewees were five professors, sixteen senior lecturers and one young lecturer from an engineering university and a college. Both the university and the college offer mechanical, software, electrical and electronics engineering programs. In order to collect information on common difficulties among their students, our respondents answered questions related to misunderstandings and misconceptions that are representative of students studying engineering courses and performing design projects. These misunderstandings and misconceptions found expression in student errors. We looked for these kinds of mistakes and did not take into consideration mistakes deriving from incorrect mathematics methods or calculation errors. We divided all the errors into two groups: misconceiving of engineering principles and all the other mistakes, which were not our focus, and dealt with the first group of errors only. As mentioned above, in this study we did not aim to distinguish between misconceptions and misunderstandings. Therefore, we use the same term, misunderstanding, for the both phenomena.

The series of interviews continued up to the point when new interviews ceased to provide new data. We then analyzed the content of the interviews and systematized the collected material. This guided us in our construction of two kinds of classification.

5. Results

The majority of students' errors reoccur every year, and teachers expect them. Experienced lecturers enlighten students about such errors, and explain the meaning of misunderstanding in the course of learning. Despite many teachers' best efforts, students repeat these errors in exams. The quote below, from an interview with a lecturer who designed his own classification for such errors, affirms this claim:

Sh: [*Ph.D., senior lecturer, science and pedagogical experience of more than 30 years; course: Analog Electronics*]
I can predict their (students') mistakes in advance; they are so common that I developed a system of signs and list of abbreviations for almost all kinds of errors. I find and highlight them in exams every year and now I haven't expanded my list of errors.

This finding is compatible with the assertion that many questions remain difficult for students despite ample correct instructions, and "incorrect answers to these questions tend to cluster into small number of alternatives" [42, p. 128].

We classified all the misunderstandings we found in two ways. First, we classified the misunderstanding into one of three levels. Second, we linked students' misunderstandings to engineering thinking characterization. Figure 2 presents the three levels of misunderstandings of engineering thinking.

The first level relates to misunderstandings of specific content learned in a concrete engineering discipline such as misunderstanding the basic concepts of an open and closed loop in control theory or the concept of recursion in the introduction to programming. In what follows, we present several citations from interviews with the experts, who explain this kind of misunderstandings:

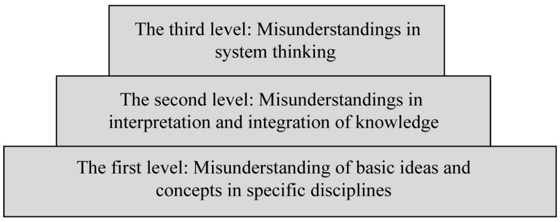

Fig. 2. Schematic representation of the three levels of engineering-thinking misunderstandings.

U: [*Ph.D., senior lecturer, pedagogical experience of 22 years; course: Introduction to Control Theory*]
We always talk about closed loop and open loop, and students get confused with the concepts. Something is always wrong. When we come to draw the Root Locus (a method for analyzing the stability of a control system), we must take the transfer function of the open loop and they take the closed loop, no matter how many times I explain that. Also, understanding what open loop and closed loop are: even here there is a problem. The same problem exists in Bode (a method for analysis stability of a closed loop system according to its open loop transfer function).

D: [*M.Sc., senior lecturer, industrial experience of 14 years and pedagogical experience of 20 years; course: Introduction to Programming*]
The other problem arises when it comes to recursion. Students who try to understand the recursive mechanism encounter problems because they do not do the next step and do not see behind the recursive mechanism, the mechanism of the stack. Implementation of recursion is done in such a way that C (a programming language) gives them the services of the stack: what calls what, parameters, local variables; everything is in the stack, so that it goes down to a recursion depth and returns.

Educational researchers emphasize that "understanding conceptual knowledge is critical to the development of competence in engineering students and in practicing professionals" [24, p. 280]; therefore, misunderstandings of basic concepts in engineering sciences comprise the first and fundamental level of engineering thinking misunderstandings.

The second level refers to more general misunderstandings in interpretation and integration of knowledge, which are typical of students in several engineering disciplines. Thus, in some electrical and mechanical engineering courses, students do not understand the importance of measurement units for a physical parameter, or the meaning and need for approximation and neglect part of the results in problem solving. An additional problem is that students lack of self-control, namely, they do not repeatedly check the operations they are performing and their ways of thinking in the course of problem solving. Many students lack the ability to interpret the calculated results and link them to real values of the required parameters. The next excerpts from the interviews reflect these attitudes:

R: [*Ph.D., senior lecturer, industrial experience of 23 years and pedagogical experience of 20 years; course: Theory of Semiconductors*]
They (students) do not pay attention to measurement units and do not write them down. They write something equals 12. It does not matter if it's volts, or amperes, or centimeters. There is always somebody in class who does that. The additional difficulty is that in the theory of semiconductors you must have an understanding of the approximations. In many places, we neglect something because it is really very small. They (students) do not know to do that, so they need to perform a huge amount of calculations during exams, and therefore, fail. Once I got an answer from one of my students that, the length of MOS transistor channel measured 18 cm whereas the realistic measure is in tens of nanometers.

N: [*Ph.D., senior lecturer, industrial experience of 16 years and pedagogical experience of 23 years; course: Electric Circuits Lab*]
In many cases during their studies students have no sense of how to approximate, what is a kilo, what is a mega, what is a milli. They can relate to a million as if it is a thousandth. Once I asked my students to run an experiment and calculate the power dissipation on a 0.25 watt-resistor (it means that this particular resistor cannot absorb more than a quarter of a watt unless it burns out). A student submitted her laboratory report where it was written that the power is something like 62,000 watts (it's about 250,000 times the maximum permitted power).

A more general problem related to the second level may be formulated as the problem of integrating theoretical knowledge and experience. This integration is essential for engineers, especially when designing complex systems. The next citations describe students' difficulties in knowledge integration in theoretical and lab courses:

E: [*Ph.D., senior lecturer, accumulated scientific and pedagogical experience of 40 years; course: Introduction to Electricity*]
In solving the electric circuit response to the entrance of an AC signal, we solve the steady state and the transient responses separately and then integrate them. Every time we practice it, I explain that we must integrate the partial results. Therefore, as long as my students solve the steady state and the transient responses separately, that's fine; a big problem arises when they need to integrate the responses and show the complete answer—they cannot find a connection between the two modes.

Et: [*M.Sc., senior lecturer, pedagogical experience of more than 30 years; course: Basic Electronics*]
In the course Basic Electronics, mechanical engineering students learn various components such as logic gates, operational amplifier, diodes and transistors. In the project, they need to operate an LED (Light Emitting Diode) from the output of a logic gate or operation amplifier. In this case, the driver—the component, which pushes the current, must be connected—this is the transistor—between the logic gate or amp to the LED. There are always students who do not understand—why? Why do I need it? Why can it not work without a transistor? And how do I connect it (transistor)? Probably they (students) cannot unite different parts into one circuit.

The third or the highest and general level relates to misunderstandings in systems thinking. Systems thinking are developed mainly through design practice, so freshman students have many problems when given design tasks. These difficulties are typical of most engineering disciplines. The first kind of systems thinking misunderstandings is not seeing a general problem; instead, students see only a narrow range. Here are quotes that reflect this idea:

S: [*M.Sc., senior lecturer, industrial and pedagogical experience more than 40 years; course: Advanced Programming*]
At first, it is very difficult for them to see the whole picture. They (students) get the task, what they are supposed to do, and right away, they jump to the computer and start to type, to write. They take half or a quarter of the picture, and start to carry out the task, only, of course, they can't achieve anything. They can carry out some part of the task, but not the whole one.

O: [*M.Sc., senior lecturer, pedagogical experience 33 years; course: Basic Electronics Lab*]
The student in lab must find out why the logical circuit that includes a number of gates does not work. He shows me the circuit and says: "I connected all the connectors in the right way and checked it a number of times, but it does not work". I explain that at the beginning, you must check the signal correctness in the inputs

and the outputs of the first gate, then check the next stage, and continue to the circuit output in the same way. Some students understand and succeed, but there are always students who cannot find their errors on their own, even after a number of demonstrations. It seems that they do not see the entire circuit and do not understand the connections between its parts.

The next kind of students' problems relates to the disassembling of a whole system into sub-systems and, conversely, the integration of sub-systems to form a complete system. The next citation describes the difficulties of disassembling:

D: [*M.Sc., senior lecturer, industrial experience of 14 years and pedagogical experience of 20 years; course: Introduction to Programming*]
There are three types of students. One will do it all in one program, without a partition. One will distribute it reasonably, by functionality. And there will be those that do over-division. Modules will be very, very small, and it is not good to make such small modules. This also happens in exams, in the laboratory, and in exercises.

Practical difficulties in integration of separated components into the whole system can appear in the laboratory and in the course of project development, as illustrated in the following quote:

U: [*Ph.D., senior lecturer, pedagogical experience of 22 years; course: Control Laboratory*]
You have to understand that you have sensors and you must supply the suitability between their signals. The sensor produces one scale of voltage; you must convert it to another scale of voltage—see how it all fits together, how the loop closes. Many of my freshman students fail in this task.

After demonstrating the classification of misunderstandings into three levels, we can assume that some first level problems, and all the second and third level problems relate to the process of engineering thinking development by students in academic education. Therefore, it is reasonable to match the system of categories characterized in our earlier engineering-thinking study [3] to the engineering-thinking misunderstandings discussed in the current study. Accordingly, we now return to our classification in Fig. 2 and Table 1 to demonstrate the linkage between them.

The first level refers to misunderstandings of basic scientific and engineering concepts in concrete disciplines, which are typical of freshman students. This kind of misunderstanding is associated with Section 2.2—Creation of a knowledge base (Table 1). Misunderstandings accompany the process of learning, as can be expected, but in the initial stages of engineering education, there are many and salient ones. None of the professors we interviewed for our study mentioned this kind of misunderstanding, yet almost all the senior lecturers brought examples that illustrate students' misinterpretations of fundamental ideas in concrete engineering courses. The next citation exemplifies misunderstanding of basic concept in dynamics:

V: [*Ph.D., senior lecturer, pedagogical experience of 37 years; course: Dynamics*]
Sometimes they (students) are confused and solve a dynamic problem as a problem relating to statics. In dynamics, there are motion equations, which are different from the equilibrium equations in statics. And they are locked into statics and do not think about other options.

The difference between the data obtained from professors and senior lecturers is explainable. Generally, senior lecturers teach introductory engineering courses. They are engaged in creating the initial levels of students' knowledge base; therefore, they encounter students' relatively poorly developed thinking and a large amount of misunderstandings. On the other hand, professors usually teach advanced engineering courses, which means that they meet students with comparatively well developed engineering thinking, therefore, misunderstanding of basic concepts is less typical of them. Hence, we can claim that the first level of misunderstandings relates to the creation of a knowledge base (Section 2.1, Table 1), which is one characteristic of engineering thinking.

The second level (Fig. 2) indicates more general misunderstandings that are typical of several engineering disciplines. These misunderstandings are linked to a number of characteristics of engineering thinking.

Thus, the problem of knowledge integration, which applies to integration of partial knowledge in different engineering courses, and integration of theoretical and experimental knowledge into the whole knowledge system, is closely related to Section 2.2—Collecting and learning relevant knowledge (Table 1). When the engineer collects all relevant knowledge related to a new project, he or she must integrate new facts, methods and approaches into his or her existing knowledge system. This is the optimal way of continually expanding personal engineering knowledge. The student in the course of learning must create interconnections between different aspects of several disciplines in the goal of integrating partial knowledge into his or her non-established knowledge system. This cognitive process is beset with many difficulties, and the next quote describes one of them:

Ar: [*M.Sc., senior lecturer, pedagogical experience of 13 years: course: Theory of Vibration*]
The students usually have a problem in transferring knowledge from one field to another, from one discipline to another. I always say that they put an iron curtain between subjects, and there is no diffusion of material from one side to the other. For example, in vibration theory we use many methods, which they learned in introduction to control and in signals and systems. When in tutorials I start to use these methods, I hear "We don't know, we don't understand". And I must explain again matters which must be well known.

We suggest that the lecturers' mission is to help students break down these "iron curtains" and "diffuse" knowledge between different subjects, namely, to facilitate the process of knowledge integration.

The next kind of misunderstandings, which belong to the second level (Fig. 2) and is common to some engineering disciplines, is linked to Section 2.3—Application of models and laws (Table 1). Many engineering disciplines use models of several phenomena, systems and components. The following comprehensive definition emphasizes an engineering view of model application: "Modeling, in the broadest sense, is the cost-effective use of something in place something else for some cognitive purpose. It allows us to use something that is simpler, safer or cheaper than reality instead of reality for some purpose. A model represents reality for the given purpose; the model is an abstraction of reality in the sense that it cannot represent all aspects of reality. This allows us to deal with the world in a simplified manner, avoiding the complexity, danger and irreversibility of reality" [41]. Simplification of reality causes limitation; therefore, engineering models in general are not universal. A concrete model can be used only inside its own boundaries, under specific conditions, and it provides a certain degree of accuracy. Students misunderstand these limitations; they do not see the area in which the concrete model acts and mix up different models. The next citation describes the problem:

N: [*Ph.D., senior lecturer, industrial experience of 16 years and pedagogical experience of 23 years; course: Digital Electronics*]
They (students) confuse the ideal diode model, the constant voltage diode model, and the constant voltage with resistor diode model. Additionally, they confuse the small signal and large signal model of bipolar transistors. Why is this type of model suitable, in which case? They do not understand.

Therefore, we can claim that students' misunderstandings of engineering models relate to development of engineering thinking, and in particular, the ability to apply models.

An additional general problem, which refers to the second level (Fig. 2), is misunderstanding of the need for approximation in problem solving. This problem can be linked to Section 3.2—Concrete thinking, in Table 1. Simplistic methods, which allow engineers to neglect a number of factors and calculate the result according to an easy formula, are typical in engineering practice. Nevertheless, students in theoretical courses generally try to implement all their new knowledge, use complicated methods, and endeavor to take into account all possible factors. They do not distinguish between more and less significant parameters and misunderstand the possibility of approximation. The next quote exemplifies this problem:

A: [*Ph.D., professor, industrial experience of 20 years and pedagogical experience of 10 years; course: Semiconductors*]
In electronics we use an approximation to an order of magnitude, we do not have to deal with small percentages. We should take into consideration the central phenomenon and ignore others. A frustrating situation is that many times, say in exams, the smartest students do not succeed because they think about a second-order effect and it prevents them from seeing the first-order effect.

The problem, which closely relates to students' misunderstanding regarding approximations, is misunderstanding heuristics, and this problem can be related to Section 2.4—Using heuristics (Table 1). Simplifying calculation methods can lead to development of practice rules and relationships, namely, heuristics. Here is an illustrative quote that reflects this idea:

M: [*M.Sc., senior lecturer, industrial experience of 15 years and pedagogical experience of 20 years; course: Introduction to Electronics Lab*]
I find differences in attitudes relating to the introduction to the electronics lab. Students try to solve problems through the theoretical model equation. I don't do that. I solve the problem based on a simple equation of the relationship between input and output. We both reach the same results—the students after two hours, and me after two minutes.

Heuristics are the quintessence of practice, so it is unlikely that students who lack an engineering practice will use heuristics widely. However, we think that the lecturers aiming to develop engineering thinking among their students might introduce practical calculation methods and useful heuristics mainly in labs and project consultations.

The next kind of student misunderstandings refers to Section 3.4—Advance toward the desirable, in Table 1. Sometimes students do not recognize the need for persistently checking the results of every stage of the project design. They want to achieve the main goal without constantly verifying intermediate outcomes and their own ways of thinking. The following citation reflects this idea:

T: [*Ph.D., senior lecturer, industrial experience of 16 years and pedagogical experience of 23 years; course: Project Design*]
The student offered his own non-standard idea in the project. The solution was not appropriate, but he was "locked" into his idea without thinking about alternative solutions. He tried to apply it and did not achieve the goal. When asked what problem he needs to solve, he replied: "I have to make my idea work".

A further difficulty faced by students, which relates to the second level of misunderstandings (Fig. 2), is choosing optimal solution. The linkage to Section 3.5—Optimal solution (Table 1) can be observed. Engineers constantly face the problem of having to choose between wide ranges of different opportunities, with the goal of achieving an optimal solution. In most cases, there is no single solution to an engineering problem. Students are used to getting concrete values through problem solving and checking their answers by comparing them with the answers in the textbook. They often do not feel comfortable with high degree of freedom and want one result to be the only correct solution to their engineering problem. The following quote illustrates this phenomenon:

Et: [*M.Sc., senior lecturer, pedagogical experience of more than 30 years; course: Introduction to Control*]
When I say that it could be that the problem has more than one solution, it raises doubts. What do you mean? So, is my solution good or bad? It is different from yours, how can that be? Yes, it can be and that is good. When you compare alternatives, you choose parameters and criteria to compare. This way of thinking flusters them (students) because suddenly they have to make unambiguous decisions. This point is significant in engineering education and is missing in their previous education.

It is obvious that misunderstandings of the third level (Fig. 2) relate to Section 3.3—Systems thinking (Table 1). These misunderstandings were described above. Systems thinking develops in the process of engineering design and demands a broad range of knowledge, which makes freshman students' difficulties expected and explainable. We summarize this issue by quoting one of our interviewees:

Em: [*M.Sc., senior lecturer, industrial experience of 15 years and pedagogical experience of 20 years; course: FPGA Design*]
Students have difficulties in transition from a verbal task to a block diagram. To do this, they first need to distinguish between the parts that can be realized in a certain way, and then to build a functional chart connecting those blocks. It is difficult for them to see the connection between the blocks too. They aren't used to thinking this way.

6. Conclusions

It was found that engineering-thinking misunderstandings and misconceptions, which are typical of students studying mechanical, software, electric and electronics engineering, could be classified in one of two ways. First, students' misunderstandings in different engineering disciplines can be categorized as on one of three levels, according to the generality of the problems. Level one are misunderstandings of specific content learned in a concrete engineering discipline (most engineering education studies have found that these are the prevalent type of misunderstandings); Level 2 misunderstandings involve more general problems in interpreting and integrating knowledge, typical of students in several engineering disciplines; and Level 3 misunderstandings in systems thinking are characteristic of students in most engineering disciplines. The second classification relies on the match between misunderstandings of students studying engineering disciplines and the system of categories characterizing engineering design thinking. Several misunderstandings were classified by the two methods and the match between the classifications was demonstrated.

These two kinds of classification can be useful for teaching faculty in the process of self-analysis and reflection on their pedagogical practice. The first classification can help lecturers who teach basic engineering disciplines and ask themselves whether their pedagogical approaches in the early stages of academic education may lead to entrenched misunderstandings, which can appear in succeeding learning stages and even in postgraduate work. For example, they might ask the following questions: Should I require my students to write down the measurement units when solving problems? Should I emphasize the importance of analyzing the results from the practical point of view?

Lecturers who teach advanced engineering courses can perform self-reflection according to the following questions: Should I ask questions that require not only knowledge but also interpretation? Should I relate to other disciplines, and try to get my students to integrate knowledge from different areas? The second classification emphasizes specific difficulties that lecturers may come up against in developing students' engineering thinking and, therefore, can help them understand students' cognitive problems.

Engineering students may also find the two kinds of classification useful because they may help them understand what engineering thinking misunderstandings are possibly impeding their learning.

We propose to continue the research with the aim of focusing on and investigating the source of these misunderstandings and misconceptions, and finding pedagogical ways to help students overcome their difficulties. Furthermore, it will be useful to broaden the scope of the analysis and check the results of the study on additional engineering disciplines.

References

1. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, Engineering design thinking, teaching, and learning, *Journal of Engineering Education,* **94**(1), 2005, pp. 103–120.
2. H. A. Simon, 1997, *The Science of the Artificial,* 3rd edn, MIT Press, Cambridge, MA, 1996.
3. S. Waks, E. Trotskovsky, N. Sabag and O. Hazzan, Engineering thinking: The experts' perspective, *International Journal of Engineering Education,* **27**(4), 2011, pp. 838–851.
4. L. B. Resnick, Mathematics and science learning: A new conception. *Science*, **220**, 1983, pp. 477–478.
5. H. Radatz, Students' errors in mathematical learning process: A survey, *For the Learning of Mathematics*, **1**(1), 1980, pp. 16–20.
6. J. Cromley and R. J. Mislevy, Task templates based on misconception research *(PADI Technical Report 6)*. SRI International, Menlo Park, CA, 2005.
7. J. P. Smith, A. A. diSessa and J. Roschelle, Misconceptions reconceived: A constructivist analysis of knowledge in transition, *The Journal of the Learning and Sciences*, **3**(2), 1993, pp. 115–163.
8. M. Reiner, J. D. Slotta, M. T. H. Chi and L. B. Resnick, Naive physics reasoning: A commitment to substance-based conceptions, *Cognition and Instruction*, **18**(1), 2000, pp. 1–35.
9. B. Sherin, Common sense clarified: The role of intuitive knowledge in physics problem solving, *Journal of Research in Science Teaching*, **43**(6), 2006, pp. 535–555.
10. J. L. Newcomer and P. S. Steif, Student thinking about static equilibrium: Insights from written explanations to a concept question, *Journal of Engineering Education,* **97**(4), 2008, pp. 481–490.
11. T. Martín-Blas, L. Seidel and A. Serrano-Fernándeza, Enhancing Force Concept Inventory diagnostics to identify dominant misconceptions in first-year engineering physics, *European Journal of Engineering Education*, **35**(6), 2010, pp. 597–606.
12. D. F. Styer, Common misconceptions regarding quantum mechanics, *American Journal of Physics*, **64**, 1996, pp. 31–34.
13. M. Yalcin, S. Altun, U. Turgut and F. Aggul, First year Turkish science undergraduates' understandings and misconceptions of light, *Science & Education*, **18**, 2009, pp. 1083–1093.
14. L. D. Allen, An investigation into student understanding of magnetic induction, Doctoral dissertation, The Ontario State University, 2001. http://www.per-central.org/items/detail.cfm?ID=3794, Accessed 2 May 2009.
15. Y. Yin, M. K. Tomita and R. J. Shavelson, Diagnosing and dealing with student misconceptions: Floating and sinking, *Science Scope*, April–May 2008. http://www.stanford.edu/dept/SUSE/SEAL/Reports_Papers/k12_papers/Yin%20Tomita%20Shavelson%20Diagnosing%20Stu%20Misconcept.pdf, Accessed 12 October 2011.
16. H. Lin, H. Cheng and F. Lawrenz, The assessment of students and teachers' understanding of gas laws. *Journal of Chemical Education*, **77**(2), 2000, pp. 715–716.
17. Helping students learn physics better: Preconceptions and misconceptions, A guide to enhancing conceptual understanding, phys.udallas.edu/C3P/Preconceptions.pdf, Accessed 24 May 2009.
18. T. Goris and M. Dyrenfurth, Students' misconceptions in science, technology, and engineering, *ASEE Illinois/Indiana Section Conference*, Purdue University, West Lafayette, April 2010. http://ilin.asee.org/Conference2010/Papers2010.html[PS1], Accessed 10 October 2011.
19. M. J. Prince, M. A. S. Vigeant and K. E. K. Nottis, Assessing misconceptions of undergraduate engineering students in the thermal sciences, *International Journal of Engineering Education*, **26**(4), 2010, pp. 880–890.
20. S. Bull, T. J. Jackson and M. J. Lancaster, Students' interest in their misconceptions in first-year electrical circuits and mathematics courses, *International Journal of Electrical Engineering Education*, **47**(3), 2010, pp. 307–318.
21. K. E. Wage, J. R. Buck and M. A. Hjalmarson, Analyzing misconceptions using the signals and systems concept inventory and student interviews, *Proceedings of the 4th IEEE Digital Signal Processing Workshop,* 2006, pp. 123–128.
22. S. Yilmaz, Misconceptions of civil engineering students on structural modeling, *Scientific Research and Essays*, **5**(5), 2010, pp. 448–455. http://www.academicjournals.org/SRE. Accessed 18 July 2011.
23. G. L. Herman, C. Zilles and M. C. Loui, Flip-flops in students' conceptions of state, 39th *ASEE/IEEE Frontiers in Education Conference*, October 18–21 2009, San Antonio, TX.
24. R. A. Streveler, T. A. Litzinger, R. L. Miller and P. S. Steif, Learning conceptual knowledge in the engineering sciences: overview and future research directions, *Journal of Engineering Education*, **97**(3), 2008, pp. 279– 294.
25. 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.
26. 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.
27. 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.
28. 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 Journal of Engineering Education*, **22**(3), 2006, pp. 598–608.
29. C. L. Newport and D. G. Elms, Effective engineers, *International Journal of Engineering Education*, **13**(5), 1997, pp. 325–332.
30. C. L. Dym, Engineering design: So much to learn, *International J. of Engineering Education*, **22**(3), 2006, pp. 422–428.
31. E. De Bono, *Lateral Thinking for Management: A Handbook*, Penguin Books, Harmondsworth, UK, 1971.
32. O. Eris, Insisting on truth at the expense of conceptualization: Can engineering portfolios help? *International Journal of Engineering Education*, **22**(3), 2006, pp. 551–559.

33. B. Lawson, *How Designers Think: The Design Process Demystified*, Architectural Press, Oxford, 1997.
34. E. Kroll, S. Condoor and D. G. Jansson, *Innovative Conceptual Design: Theory and Application of Parameter Analysis*, Cambridge University Press, Cambridge, 2001.
35. S. Sheppard, A. Colby, K. Macatangay and W. Sullivan, What is engineering practice? *International Journal of Engineering Education*, **22**(3), 2006, pp. 429–438.
36. 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.
37. J. O'Connor and I. McDermott, *The Art of Systems Thinking: Essential Skills for Creativity and Problem Solving*, Thorsons, San Francisco, 1997.
38. M. Frank, Engineering systems thinking and systems thinking, *Systems Engineering*, **3**(3), 2000, pp. 163–168.
39. G. E. Dieter, *Engineering Design*, McGraw-Hill, Singapore, 1991.
40. N. K. Denzin and Y. S. Lincoln, *Handbook of Qualitative Research*, 2nd edn, Sage Publications, Thousand Oaks, London, 2000.
41. J. Rothenberg, The nature of modeling, in L. E. Widman, K. A. Loparo and N. R. Nielsen (Eds.), *Artificial Intelligence, Simulation, and Modeling*, John Wiley & Sons, NY, 1989, pp. 75–92.
42. D. E. Brown and D. Hammer, Conceptual change in physics, in S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change*, Taylor & Francis, NY, 2008, pp. 127–154.

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