What Is Embedded Systems and How Should It Be Taught?—Results from a Didactic Analysis

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This paper provides an analysis of embedded systems education using a didactic approach. Didactics is a field of educational studies mostly referring to research aimed at investigating what's unique with a particular subject and how this subject ought to be taught. From the analysis we conclude that embedded systems has a thematic identity and a functional legitimacy. This implies that the subject would benefit from being taught with an exemplifying selection and using an interactive communication, meaning that the education should move from teaching "something of everything" toward "everything of something." The interactive communication aims at adapting the education toward the individual student, which is feasible if using educational methods inspired by project-organized and problem-based learning. This educational setting is also advantageous as it prepares the students for a future career as embedded system engineers. The conclusions drawn from the analysis correlate with our own experiences from education in mechatronics as well as with a recently published study of 21 companies in Sweden dealing with industrial software engineering.

Categories and Subject Descriptors: K.3.2 [**Computers and Education**]: Computer and Information Science Education

General Terms: Human Factors, Theory

Additional Key Words and Phrases: Didactic analysis, education

1. INTRODUCTION

Computer-based embedded systems have been designed for more than 30 years and the need for adequate education in embedded systems is deemed more important now than ever. From an academic perspective, the subject of embedded systems is a new, relatively undefined subject, mostly regarded as an interdisciplinary field combining areas such as computer science, automatic control, and electronic engineering.

The aim of this paper is to present results from a didactic analysis performed on the subject of embedded systems. Didactics is a field of educational studies

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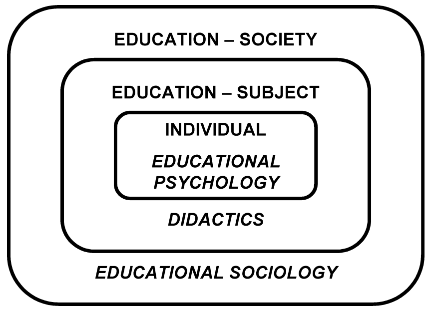

Fig. 1. Didactics is defined as subject matter education. From Dahlgren [1990].

mostly referring to research aimed at investigating what's unique with a particular subject and how the particular subject ought to be taught. In this paper, we apply a didactic approach to the analysis of embedded systems education [Dahlgren 1990]. The didactic analysis is used to identify and describe the identity and legitimacy of the subject (what is the subject of embedded systems and why should embedded systems be taught?). We also use this analysis to provide insight into the questions of selection and communication (which material should be taught and how?). To further fuel the discussion we bring up educational experiences and a model of the evolution of embedded systems.

The paper is structured as follows. Section 2 describes the context of this study, providing a background and perspectives from research on education, and describing the characteristics of embedded systems. Section 3 provides the didactic analysis, while Section 4 brings up, and places this analysis in the perspective of, educational experiences and feedback from industry. Section 5 discusses the results of the analysis and the experiences, and present some recommendations on how to teach embedded systems.

2. CONTEXT

2.1 The Educational Context

Educational studies are usually divided into three fields, depending on the scope and purpose of the studies. Educational studies performed on an individual level, where the learning process of an individual student is studied, are usually referred to as educational psychology. Studies of education on a society-level are usually referred to as educational sociology. Studies on the scale of a group of students, for example, a class, and the relation between the efforts undertaken by the teacher, university, and class are usually referred to as didactic studies, at least in central Europe and the Nordic countries. (In Anglo-Saxon countries the term subject matter education is preferred.) [Kansanen 1995], (see also Figure 1).

Most research in the field of didactics aims at describing what's unique with the particular subject and how the particular subject ought to be taught [Dahlgren 1990]. To analyze embedded systems according to the didactic approach, therefore, represents the same aim.

Several attempts to describe and model different levels of learning and understanding have been introduced in the literature. To illustrate the didactic aim, a few of these will be presented here.

When given an assignment, homework, or similar exercise, students approach the task differently. These differences in approaches were thoroughly researched in the 1970s and commonly described as the deep and surface approaches to learning [Marton et al. 1984]. Students were asked to read a text and were afterward asked questions related to what they read. The difference in results the students gave was explained with the notion that the students simply approached the task differently; the students created different intentions of the task. Students who approached the task with a "deep" intention learned more than the other students. The question, however, is how didactics can support the "deep" approach when most educational systems usually promote the "surface" approach, for example, by focusing on details instead of an overall picture [Marton and Säljö 1976a, 1976b]. A student who sees a meaning, a purpose, with the task, usually adopts a deeper approach. The meaning or purpose can be related to the larger picture of the education, to a future professional role or if the purpose of performing the task is explained more clearly.

A similar analysis of approaches to learning, or rather of student understanding, was performed by Bloom, who identified three educational domains, or the three types of learning. The three domains are cognitive, affective, and psychomotoric, where the cognitive domain is related to mental skills, or knowledge. The affective domain is related to feelings and attitude, while the psychomotoric is related to manual and physical skills [Bloom et al. 1964]. Further, each domain is divided into a number of categories, where each category represents a level of understanding or knowledge and where each needs to be mastered before moving on to the next. The six categories of cognitive knowledge and intellectual skills are [Bloom et al. 1964]:

1. Knowledge: To recall data, recite text, quote figures etc.
2. Comprehension: To understand the meaning, to state a problem in one's own words.
3. Application: To use a concept in a new situation, apply knowledge into situations in workplace, etc.
4. Analysis: To separate material and concepts into parts to enable understanding of organizational structure, troubleshoot by use of logical deduction, etc.
5. Synthesis: To build a structure from separate and diverse components, to form a whole by creating new meaning and structure.
6. Evaluation: To make a judgment about the values of ideas and materials.

Variants of Bloom's taxonomy have been presented by various authors, for example, the seven levels of engagement presented by Biggs [2003], which models the variations in a student's engagement from memorizing to theorizing.

To summarize the educational context, when turning the focus to the subject of embedded systems, key words are used when (1) discussing what to teach and how to teach it (2) how to promote deep approaches to learning, and (3) how to climb the six steps of knowledge within the cognitive domain.

Taking an industrial perspective one can instead ask what type of engineers are needed. This question is further discussed in the following section and in Section 4.

2.2 The Industrial Context—Common Characteristics and Trends for Embedded Systems

The capabilities of electronics and software provide an extremely wide range of applicability. This is seen today where this technology is being used in applications from toys and sewing machines to space shuttles. This broad applicability is further mirrored by the use of terms such as ubiquitous computing and pervasive computing [see for example Ubicomp 2004].

The use of electronics and software within products has given rise to the term embedded systems, as opposed to mainly desk-top computers. Embedded systems are strongly characterized by their tight coupling to the environment. This coupling may be manifested in several ways and includes aspects related to physical integration, protection against a harsh environment, communication with peripherals, as well environment dependencies related to assumptions about the controlled process and/or the user/operator. This tight coupling gives rise to real-time constraints, for example, referring to required speeds of motion, required precision, and time durations, which can be used to derive timing requirements on the embedded system. The tight coupling and interactions with the environment also provides the need to describe and handle several parallel activities.

Embedded systems face a fast technological evolution, an increasing connectivity, and more demanding requirements. The evolution during the past 30 years has taken embedded systems from stand-alone microprocessor-based systems to distributed embedded systems, systems which today also are increasingly connected to the external world. For example, distributed control systems first appeared in process control, later in aerospace in the 1980s, and in the automotive industry in the 1990s. Diagnostic links through GSM and other means and telematic services are already in place in vehicles.

Examples of tougher demands include increased dependability requirements following from the increased usage and dependence on embedded systems: their use in mission-critical systems and the fact that embedded systems provide new vulnerabilities, e.g. through security violation. Since embedded systems also have to be cost-efficient, this clearly poses a huge challenge for industrial developers and researchers.

The use of embedded systems has paved the way for large improvements of existing devices including flexible tailoring of product variants and by enabling completely new functionality, for example, active safety functionality in cars.

However, as a consequence, product complexity is becoming a crucial issue in systems development. Indeed, integration problems are already a serious problem. As a further consequence, the processes and company organizations are becoming increasingly complex. Accordingly, the roles of engineers also tend to become more and more specialized. This becomes an issue since specialists tend to have difficulties in interacting with each other. Both in industry and research, a multitude of efforts are devoted to develop more "engineering" like methods for the development of embedded systems, such as the use of model-based development [Adamsson 2002; Törngren and Larses 2004; ARTIST 2004a].

The increased product complexity calls for a change in industrial practices and may motivate changes in educational systems. The broad applicability and spectrum of applications of embedded systems also complicates the treatment of embedded systems as a field of engineering. This topic is further elaborated in the didactic analysis.

2.3 History of Embedded Systems at the KTH Mechatronics Lab

This section provides a brief background of Mechatronics education and research at KTH, with the purpose of illustrating the context of the authors.

The history of embedded systems within mechanical engineering at KTH is said to have begun in 1976. The professor of Machine elements returned from a sabbatical at Stanford University, bringing back to KTH an Intel 8008 microcontroller. The professor declared that the microcontroller should be regarded as a machine element, to be compared with gears, bearings, etc, and should therefore be thoroughly analyzed for its possibilities and functionality from a mechanical engineering perspective. This soon led to the establishment of an education and research team called "Computer-controlled mechanics", established and managed within Mechanical Engineering at KTH. The education and research team soon developed into the Mechatronics Lab at KTH. Currently, the KTH Mechatronics Lab is organized in two research areas: robotics and motion control, and embedded control systems [see Wikander et al. 2001; MechatronicsLab 2004].

The need for education and research in this area was strongly driven by the possibilities of product development, opened up by utilizing software, electronics, sensors, and actuators. Using this technology it is possible to improve the functionality and performance of existing mechanical systems and also to develop entirely new functionality. One well-known example of an early embedded control system based on mechanical technology is fuel injection in combustion engines, where the camshaft, mechanisms, and the cylinder valves constitute an embedded controller with parts for sensing, processing, and actuation. In the late 1970s, microprocessors came to be used in such applications for improving the combustion process in the engine, primarily with the purpose of reducing emissions. Within machinery, software, electronics, and networks provide the added dimension of explicit and flexible information transfer and processing.

It should be noted that a common definition of mechatronics emphasis synergism formed by an integration of mechanical, electronic, software, and control system components. Mechatronics is further traditionally associated with functionality involving motion, and motion control, of mechanical devices. Examples of such integrated systems include different types of vehicles, medical equipment, robotics, and manufacturing equipment. The concept of developing such systems, and achieving synergistic effects from their integration, is often referred to as a mechatronics approach to development. Such an approach conforms to traditional systems engineering and emphasizes codesign and systems optimization.

Some of these possibilities were seen at the time at the Mechatronics lab and it was deduced that there was a resulting need for education of engineers that had a broader knowledge than that provided by the typical disciplinary-oriented education. In addition, an increase in research efforts was taking place during the 1990s with the establishment, in 1996, of the first chair in mechatronics in Sweden, and, in 2002, with a chair in embedded control systems, both at the department of Machine Design. One driver for the research in mechatronics has been the insight that the traditional separation of disciplines has caused a shortage of theory that connects the more discipline-specific theories that were developing in isolation. One example of this is the earlier observation that research in automatic control did not consider computer system-induced faults and problems, such as, time-varying delays. Computer science/computer engineering, on the other hand, did not consider requirements posed by control applications; [see, for example, Wikander et al. 2001].

3. A DIDACTIC ANALYSIS TO EMBEDDED SYSTEMS

3.1 The Didactic Approach

Didactics is here defined as subject matter education and the didactic approach aims at analyzing the subject of embedded systems to define what's unique in this subject, thereby providing insight into how this subject should be taught. The didactic analysis of an academic subject, as defined by Dahlgren [1990], can be illustrated with a set of four questions that is applied to a subject (X).

- Identity (What is X?)
  The identity varies from disciplinary to thematic.
- Legitimacy (Why should X be taught?)
  The legitimacy varies from formal to functional.
- Selection (Which X should be taught?)
  The selection varies from a horizontal representation to a vertical exemplification.
- Communication (How should X be taught?)
  The communication varies from active to interactive.

These four questions, together with their extremes, are illustrated in Figure 2 and will be applied to the subject of embedded systems.

3.2 Legitimacy of Embedded Systems

The question of legitimacy is defined as the relation between the actual outcome of the educational efforts undertaken by the university and the actual demands that is put upon the students' abilities by the society and/or industry at the end of their education. This relation can be described according to two extremes—either formal legitimacy or functional legitimacy. In a simplified model, the formal legitimacy relates to formal knowledge, for example, knowledge gathered from textbooks that are read by the students. The functional legitimacy

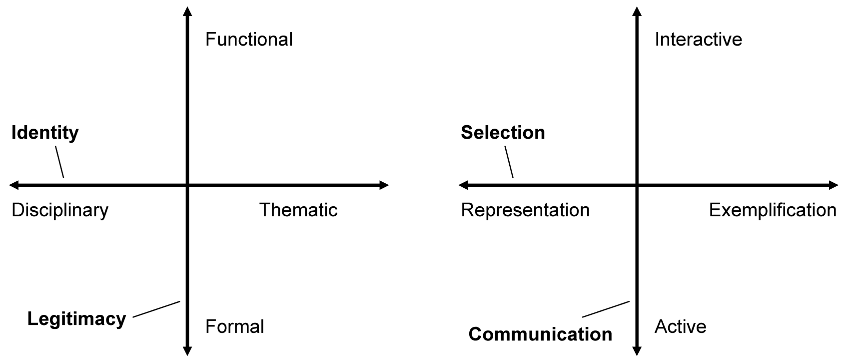

Fig. 2. The four questions representing the didactic analysis, together with their extremes.

relates to functional skills such as the ability to perform concrete work tasks as part of product development. The functional skills are usually not learned during traditional lectures or by reading textbooks, but rather are developed during hands-on exercises, laboratory experiments, trial and error, etc.

Examples of formal legitimacy in an embedded systems context could be when the society or industries require engineers with a certain amount of credits in a certain subject, for example, ten credits in automatic control, based on the reading of certain textbooks. The same companies would require a functional legitimacy if they instead specified the level of skills required within the subject of automatic control, for example, that the engineer should be able to analyze a system, to synthesize a state-space controller, to evaluate different controllers, etc. Note though, that the difference between a formal legitimacy and a functional legitimacy is not related to the depth of the understanding, or knowledge, but, in this example, to how this knowledge or understanding is specified by the company. In the example above, the formal legitimacy can also be characterized as knowledge and the functional knowledge as skills.

It is important to note the strong context dependency when discussing legitimacy. For example, a student specializing in theoretical mathematics might well fulfill functional needs related to solving certain analytical problems in industry; a competence that might well be regarded as formal in other contexts. In addition, educational methods do not necessarily imply either formal or functional knowledge or skills although certain educational methods are more often associated with either knowledge or skills [Grimheden and Hanson 2001].

The connection between knowledge and skills also makes it difficult to value the students' knowledge and skills. A hiring industry, for example, might search for a person with a specific set of skills to meet a particular need at the company. However, the same need might not exist a few years later. At this point, formal knowledge might be more important than functional skills: a high level of formal knowledge might facilitate the development of new functional skills, etc. When the hiring industry states the actual demands, that is the requirements of the education to the university, there is a great risk that the often shortsighted needs exaggerates the need for specific skills instead of more general knowledge.

The main question to discuss is not whether functional skills are better than formal knowledge or vice versa. The issue, instead, is to find the balance of the identified demand of the hiring industry (a demand that for industries in the area of embedded systems usually leans towards functional skills) versus the more traditional formal knowledge that historically has been the preferred type of knowledge delivered by a university. To summarize, to meet the demand of functional skills required by the society and industry, the educating universities needs to move from traditional formal knowledge to a mix where functional skills are deemed more important. In a comparison with, for example, medical faculties and departments, this move was made a number of years ago, in many cases, coinciding with the implementation of PBL (for Problem-Based Learning). Many of these medical universities realized the need to educate physicians with skills instead of solely knowledge—the traditional theoretical subjects, such as, chemistry, had to stand back for hands-on practice in medicine; see Grimheden and Hanson [2003]. Even though PBL is not the only method of giving the university's education a functional legitimacy, several examples from universities points toward the adequacy of PBL for this purpose [Vernon and Blake 1993].

3.3 The Identity of Embedded Systems

According to the didactic analysis, the identity can be described according to the two extremes—either disciplinary or thematic. The question of identity is defined as "what distinguishes the particular field of knowledge?." Most traditional subjects, such as, mathematics, chemistry, and physics are viewed as disciplinary, meaning that there exists a strong consensus in the surrounding society regarding the contents of the subject, and the classification and organization of the contents, etc. In several cases, the knowledge is organized and developed systematically, and the created knowledge is easily classified into the existing structures.

In previous publications, didactic analyses of the subject of mechatronics have been presented [Grimheden and Hanson 2001]. This discussion is based on these experiences and, as we will see, embedded systems and mechatronics have many similarities from the viewpoint of didactics.

The identity of mechatronics is based on the notion of regarding mechatronics as the "synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes" [Comerford 1994]. That is, mechatronics should not solely be considered as the union between mechanical and electrical engineering, automatic control and computer science, or other combinations of traditional disciplines within an engineering sphere [Grimheden and Hanson 2001].

The keyword is synergistic and in the didactic analyses, the concept of synergy is used to describe the essence of mechatronics. Therefore, the identity is defined as thematic where the theme is related to the concept of synergy. A subject with a thematic identity is typically developed within disciplinary subjects where existing subject delimitations are replaced by new categories of knowledge. In some cases cross-disciplinary activities and research fields create new subjects and, in these cases, the common denominator is the theme that joins the respective groups or area together. One example of a thematic identity is automatic control—a subject that has developed from the subjects of electrical engineering and physics.

Similarly to mechatronics, the area of embedded systems is not very well defined and large resources are spent on unifying the field (see, for example, the ARTIST education guidelines, Section 1.1.1 [ARTIST 2004b]). In a follow-up in Section 2.2., it is straightforward to realize that embedded systems are found in applications with widely varying requirements and constraints such as

- Small to large series, implying very different cost constraints, thus different needs for optimization and reuse
- Relaxed to very strict requirements and combinations of different quality requirements, for example, with respect to safety, reliability, real-time, flexibility, and legislation
- Short to long life times
- Different environmental conditions in terms of, for example, radiation, vibrations, and humidity
- Different applications characteristics resulting in static versus dynamic loads, slow to fast speed, compute versus interface intensive tasks, and/or combinations thereof
- Different models of computation ranging from discrete-event systems to those involving continuous time dynamics (usually referred to as hybrid systems and typical in mechatronics)

There are, therefore, many perspectives that can be applied to embedded systems, including taking the viewpoints from applications, technology, theory, and processes. This means that many different specific areas of embedded systems can be identified related to, for example, different application requirements (e.g., safety or low power), specific technologies (e.g., communication protocols or specific hardware), or theories (e.g., scheduling theory or formal languages); and this is precisely what we see in the academic community. The variety of applications means that the components, developmental methods, and techniques will differ to a great extent [Törngren 2003].

One question that arises is what the identifiable core knowledge for embedded systems is. When mapped on the question of identity, we, therefore, see that embedded systems as a field, is best characterized by a thematic identity. The identity is difficult to characterize as disciplinary—the discipline of embedded systems is not yet established the core of the subject is hard to identify, and, in addition, the subject is facing rapid changes due to the technological evolution and the increasing complexity in application. The theme could, for example, be illustrated with the definition presented by IEEE: an embedded system "is part of a large system and performs some of the requirements of that system; for example, a computer system used in an aircraft or rapid transit system," [IEEE 1990]. From this definition, it follows that computer-based systems embedded into products like, for example, TVs, telephones, toys, and vehicles qualify as embedded systems and that the characteristics of these products include their interactions with the environment. Relevant aspects are dependability and cost, which implies key areas, such as, safety-critical systems, real-time systems, etc. Such aspects, areas, and applications can, therefore, be used to describe the subject of embedded systems as themes of the subject.

3.4 Selecting and Communicating Embedded Systems

The questions of selection and communication regard issues such as how the subject should be taught and what aspects of the subject that should be studied. The question of selection can be illustrated using two extremes—horizontal representation and vertical exemplification. Horizontal representation implies that the entire subject should be represented in the education, meaning that the education should consist of a shallow sample of each aspect of the entire subject. On the other hand, a vertical exemplification means that one or more examples from within the subject should be studied and, in contrast to the horizontal selection, these examples imply rather deep studies into the respective fields—depth instead of width.

An example of the question of selection could be the choice of how to plan an education in computer programming. A large number of programming languages exist; different companies and cultures use different languages. The university could teach something from every language (horizontal representation), which would lead to a good understanding of differences between languages, etc. If the university chooses to teach the students one single language, the level of understanding could be much deeper, but perhaps without the larger picture.

Also, in this case, it is not necessary to choose one of the extremes, but rather a question of how to find the best proportions between representation and exemplification. However, there is a link between this division and the question of identity; if the identity of a subject is regarded as thematic, a horizontal representation is difficult to achieve when teaching the subject. If the identity is disciplinary, there exists a consensus of the contents, definition, and structure, and it is not difficult to find an appropriate textbook in, for example, automatic control, further illustrated by the fact that introductory courses for engineering students are very similar. When searching for a textbook in embedded systems, this becomes more difficult. Every available textbook on embedded systems emphasizes different aspects. It is equally difficult to agree universally on curricula and courses in embedded systems, since each teaching team reflects the local interpretation of the subject of embedded systems (the same goes for mechatronics).

From this viewpoint, a thematic identity is, therefore, more easily taught using a vertical exemplification and, when turning focus to the question of legitimacy, a similar connection can be made. Embedded systems was identified as having a functional legitimacy, which further motivates vertical exemplification. To teach according to vertical exemplification promotes skills and applied knowledge, knowledge applied to the particular chosen example, while horizontal representation promotes broad and summary knowledge. The study of the legitimacy of embedded systems clearly identify functional skills instead of formal knowledge.

Therefore, the didactic analysis suggests that the education be organized more according to a vertical exemplification, where the examples are connected to the themes that act as a base for the thematic identity. A similar approach has been presented previously [Grimheden and Hanson 2003], where the subject of mechatronics is taught with examples, such as robotics (advocating that a course in robotics, in the right circumstance and context, can be turned into a course in mechatronics if robotics is seen as an appropriate example, or theme, of mechatronics).

The question of communication can also be viewed in the light of two extremes—either as active communication or as interactive communication. Active communication can be seen as a feedforward (open-loop) control system where the education is based on a prior understanding of how the material should be communicated, or other models of student learning behavior. The interactive communication can be seen more as a closed-loop control system where the action performed by the educator is based on the current status and knowledge level of the individual student or student team.

As described earlier, there is a direct connection between the identity of the subject and the selection of the subject—the thematic identity requires a vertical exemplification as selection. Equally, there is direct connection between the legitimacy of the subject, through the selection to the communication of the subject—the functional skills required by the hiring industry are supported by emphasizing examples, project work, team work, and cooperation with industry, etc. This is, in the end, facilitated by an appropriate educational form, where all education is based on an interactive communication, preferably with strong ingredients on project-based work.

4. EXPERIENCES FROM EDUCATION IN INDUSTRIAL SOFTWARE ENGINEERING AND EMBEDDED SYSTEMS

Industrial software engineering is not exactly the same as the engineering of embedded systems, but constitutes a large and important part of this. A study was performed in 2003 in Sweden involving 21 companies dealing with embedded systems [Josefsson 2003]. The study was initiated and financed by the association of Swedish engineering industries and the purpose was to develop a strategy for guaranteeing proper competence for the industry, mainly within the embedded systems industry.

The conclusions of the report are that the existing university programs teaching industrial software engineering are adequate, primarily regarding technical knowledge, but lack aspects such as preparation for work within industrial software engineering. Examples of aspects that need to be strengthened are [Josefsson 2003]:

- Business. The importance of the customer as an important actor, the importance of customer relations, and the importance of following a budget and time planning.

- Software engineering is reengineering and maintenance and the engineers should be taught accordingly.
- Teamwork. The engineers lack experience from working in and accepting various roles in teams.
- Components reuse. The engineers prefer to develop their own modules instead of using and modifying existing modules.
- Communication. The industry complains about the abilities to communicate (write and speak).
- Tests. The engineers are not capable of formulating test cases, perform and document tests, and debug complex systems.
- Development models. The engineers are not taught development models or how to adapt these according to need.

The study proposes the following changes to strengthen education:

- Practical skills: Internships, etc., in industry during the education. Project-organized education. Thesis projects in industry.
- Industrial connections: Guest lectures from industry, student visits, and industrial representatives in boards at universities.
- Job rotation: Job rotation for academic staff in industry, accepting students from industry at university.

When comparing the results of this study with the earlier described questions of legitimacy and identity, it is clear that a discrepancy exists between the industry demands on educated engineers and the actual outcome from the universities. This discrepancy relates to areas of software engineering other than the core of the subject—engineering software. The industrial report does not complain of lacking competences within the core technical subjects, such as skills in programming algorithms and languages, but mainly in the so-called soft skills, such as, team work and communication, as well as in broader areas such as development models, business, etc.

This change in legitimacy is related to the question of identity (software engineering is more thematic than disciplinary) and it is clear that the identity of software engineering is changing from the traditional knowledge-based identity toward a functional profession where other skills are as important. The theme of industrial software engineering (and, therefore, also embedded systems) is changing, and examples of new keywords are business (customer relations), teamwork, and communication. When comparing software engineering with computer science, we, therefore, believe that software engineering could be considered more thematic than computer science, as well as having a more functional legitimacy.

The difficulties of changing a curriculum and the teaching methods of any faculty can be illustrated by the recently published guidelines for a graduate curriculum on embedded software and systems by the ARTIST education group [ARTIST 2004b]. In these guidelines, the technical competencies required by an embedded software engineer are extremely well specified and, even if the need for practice is recognized as "an essential component for a well-rounded

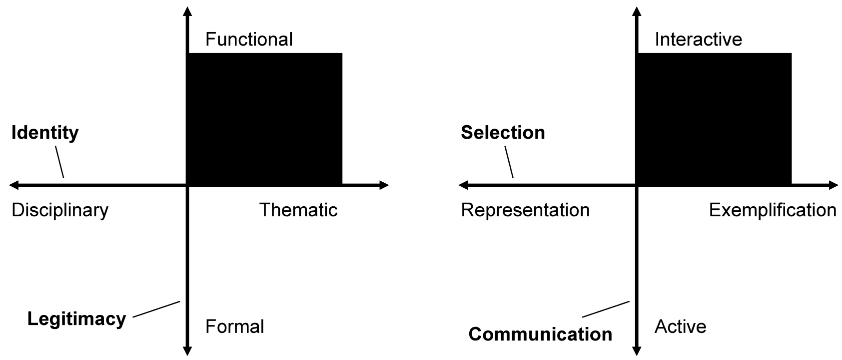

Fig. 3. Illustration of the didactic analysis applied to the subject of embedded systems.

education in embedded systems," practice is defined as "experimental laboratory work," and illustrated by the use of tools such as Matlab/Simulink, running code on real hardware platforms, etc. Nowhere is mentioned any of the complementary skills identified by the study presented above—teamwork, communication, and business, etc.

5. DISCUSSION

The previously presented didactical analysis can be summarized into the following: (see also Figure 3).

- Embedded systems have a thematic identity
  (Where most traditional academic subjects are defined as disciplinary)
- Embedded systems education should be focusing more on functional aspects
  (When most traditional academic subjects are taught formally)
- Embedded systems should be taught with more exemplifying selections.
  (When most traditional academic subjects are taught with a representation of the entire subject)
- Embedded systems should be taught with an interactive communication.
  (When higher education traditionally is taught in an active way, from the teachers' point of view)

5.1 What to Teach and How to Teach It?

As described previously, in the educational context, one aim of the education ought to be to promote deep approaches to learning and understanding, instead of memorizing facts, or surface-based approaches in general. A connection between the approach chosen by the student and the motivational factor is made. Also, when analyzing the question of selection, we identify a need to find a balance between representation and exemplification. This balance could be illustrated as the balance between teaching "something of everything" or "everything of something" (depth or width).

Relating to Bloom's taxonomy, we can identify industrial needs for engineers that can analyze systems and for engineers that also can synthesize systems. To be able to synthesize embedded systems according to Bloom, the students need to master analyses of embedded systems. Here we see a mismatch with the current situation in industry [Josefsson 2003]. When designing courses and curricula in embedded systems, we advise that not only the functional skills are put in focus, but also that the levels of knowledge, as proposed by Bloom, are approached in the correct order.

Two of the most important questions when designing an educational program for embedded systems would then be how to promote the deep approaches and how to find a balance between depth and width. To further fuel this discussion an outlook at education in medicine is presented:

PBL emanated from within education in medicine and was established as an accepted method of teaching medicine during the 1960s. Today, more than 80% of the medical schools use PBL as the preferred teaching method [Vernon and Blake 1993]. In a typical PBL setting, the work by the students and faculty is organized in projects where the project aims at working toward the solution of a particular problem. The environment is characterized by a larger amount of student responsibility and a coaching style instead of lecturing [Grimheden and Hanson 2003]. The PBL methods usually provide the motivational factors by delegating responsibility to the students. The balance between depth and width is, however, one of the most discussed issues within the PBL societies, with discussions and opinions in all directions.

A further motivational factor to consider is the previously presented report [Josefsson 2003] that states the need to enhance student skills in areas such as teamwork and communication, which is related to the question of legitimacy (the hiring companies require engineers capable of working in teams and communication). This strongly motivates a change in educational methods to encompass these skills.

The conclusions of the analysis presented here is that both the selection and communication of the subject (content and form) should move toward an exemplifying selection and interactive communication, to increase the focus on skills and depth instead of knowledge and width.

By tradition the academic practice is characterized by a narrow viewpoint and a systematic approach, while the industrial practice is characterized by a holistic viewpoint and a, more or less, ad hoc approach, as in Figure 4. The white arrows show the necessary path to fulfill a better balance in selection and communication (form and content). Industries are constantly struggling to move from an ad hoc toward a more systematic approach, and the universities are struggling to reach a holistic viewpoint.

One way to reach a more holistic viewpoint is to focus more on the communication, the form, and, for example, to teach in a more project-organized and problem oriented way—both to increase student motivation and also to move toward a "deeper" approach and, thereby, a higher level of understanding. A further motivational factor for the move toward these educational methods is that the project- and problem-based educational methods can be seen as preparations for a future professional role as an embedded systems engineer, which require skills such as teamwork, communication, etc.

Another example from our teaching indicates synergetic effects when giving courses with participants both from industry and university. Industrial

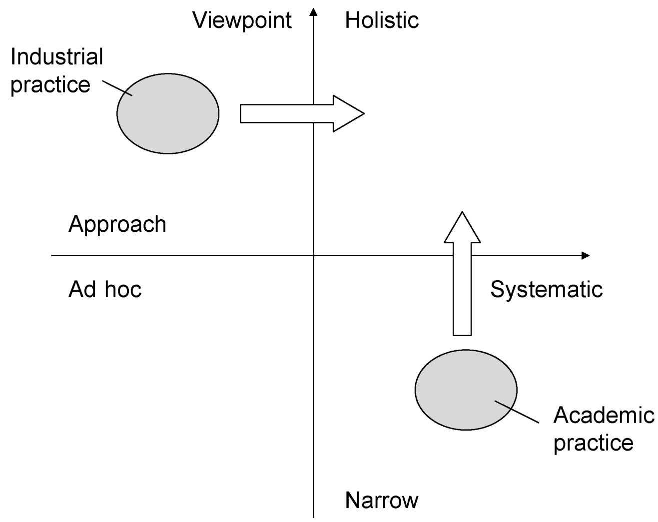

Fig. 4. Traditional differences in practice between industry and academy. The white arrows represent a desirable move to meet discrepancies in legitimacy of the education.

participants can contribute along the lines of Figure 4, with experiences that place theoretical pieces in a context, by reflections relating to tacit knowledge, and with real-world engineering constraints that are seldom touched upon in academic teaching.

5.2 Evolution of the Subject of Embedded Systems

To elaborate further, we discuss here the evolution of the subject of embedded systems. In earlier work, a model for the evolution of the subject of mechatronics has been developed (see Figure 5) [Grimheden and Hanson 2005]. Some evidence for this model can be observed when studying how newer academic subjects have emerged, based on certain needs and on existing disciplines. This is, for example, the case for the subjects of strength of materials, solid mechanics, or automatic control. To illustrate this model, consider the subject of automatic control where needs and, thus, a theme emerged in the early 20th century; in this case, the originating disciplines were electrical engineering and physics. Automic control has since developed into a well-established academic subject; thus the original theme has been further developed and a research discipline has emerged [Abramovitch and Franklin 2004].

The same model can be used on the subject of embedded systems and, therefore, used to describe the evolution of the subject.

The evolution of an academic subject is divided into six stages. In the first stage (1) no interaction between the original disciplines exists, disciplines such as computer science, electrical engineering, and mechanical engineering. The second stage (2) represents a situation where students combine courses from different disciplines to broaden their knowledge, that can be described as a multidisciplinary stage where the educational system is functioning in disciplines. This second stage thus represents the situation where a theme has been

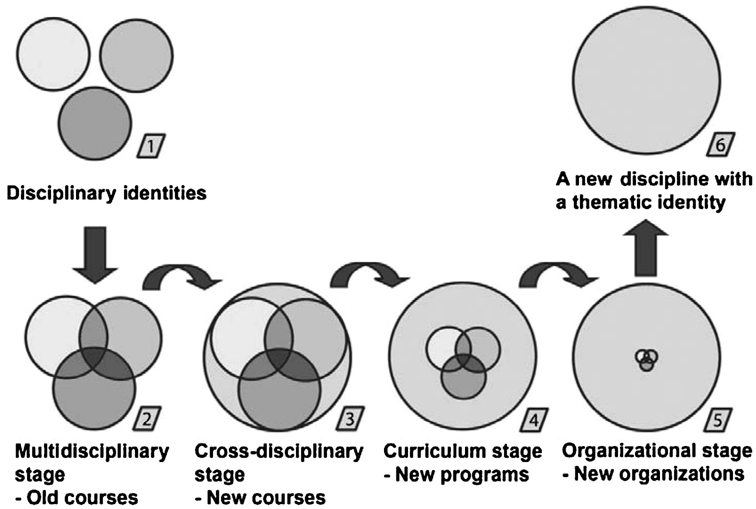

Fig. 5. A framework for discussing the evolution of academic subjects.

identified. In the third stage (3) efforts are put in place to organize and offer cross-disciplinary courses, efforts such as consciously giving courses in embedded systems by, for example, teaching electrical engineering, automatic control, and computer science to mechanical engineering students. In this stage, usually one discipline takes the initiative for the cross-disciplinary courses, which might play a major role in the future establishment of an embedded system program, for example. In the fourth stage (4) new curricula are created and the original disciplinary identities are diminishing in favor of the evolving thematic identity.

The last two stages are characterized by a change in organization (5) where the faculty, to a lesser extent, relies on competencies in the various traditional areas but instead of competence in embedded systems, for example, by hiring staff with a degree in embedded systems rather than the traditional subjects. The final stage (6) also indicates the further evolution of academic subjects (connecting back to the first step). For example, when—and if—the discipline of embedded systems becomes fully established, it would be fruitful to discuss how this new discipline (however thematic) relates to neighboring subjects (either disciplinary or thematic). One example of this situation is given by the subject of automatic control, where themes relating to several other disciplines have been emerging, such as in the case of the ARTIST2 Network of Excellence [ARTIST2 2005], where a cluster has been defined to develop the connections between automatic control and computer science.

The increasing complexity of embedded system applications will require stronger interaction between, more or less, isolated disciplines. This will stimulate the identification of new themes and their evolution. As indicated by the framework, Figure 5, the required multidisciplinary interactions can either be resolved by broadening the scope of one discipline, e.g., corresponding to an evolution to stages 3 or 4, or by developing entirely new disciplines. For example, we can see the need to educate specialists in a theme of integrating software (computer science, software engineering), and hardware (electrical engineering), or in integrating controllers (automatic control) in their real-time implementation (computer science, software engineering, and electrical engineering).

For embedded systems there are several world wide efforts that can be classified into stages 2–4. The ARTIST guidelines [2004b] is one example aiming to define the scope of a curricula, i.e., level 4. The ARTIST guidelines, however, has a strong basis in computer science and, due to this, is slightly biased. One way to bridge the gap to the next level (stage 5) would be to increase the cooperation with other stakeholders, such as electrical and mechanical engineering disciplines.

5.3 Teaching Embedded Systems within Mechatronics at KTH

As a result of this analysis, the courses in embedded systems within mechatronics taught at KTH are problem-based and project-organized. The courses are taken primarily by students from mechanical engineering and vehicle engineering, but also by students from electrical engineering, physics, and computer science. The exemplifying selection is reached due to the problem-based setting; each course is built upon a project, the design of a product or a system, for example, a control system of an autonomous robot. The functional legitimacy is reached due to the project organization and problem-based setting as well. Each student is responsible for the design of a subsystem and will, during a number of projects, acquire a certain set of skills, such as, project work and administration, PCB design, implementation of control algorithms, etc. [Grimheden and Hanson 2003]. The motivational factor is increased by giving the students a high degree of economical responsibility in the projects and by giving projects in collaboration with industry. It is important to notice though that these exercises and skills are based on previous theoretical courses, for example, in automatic control and the courses in embedded systems are seen primarily as opportunities to apply and connect previous pieces of knowledge and develop knowledge into functional skills.

Courses and educational projects in embedded systems given by the KTH Mechatronics Lab have been presented previously [see for example Grimheden and Hanson 2003; Wikander et al. 2001].

6. CONCLUSIONS

The purpose of this paper is to provide an analysis of embedded systems education using a didactic approach. In this approach, a set of four questions are applied to the subject and mapping of the four questions, or dimensions, creates a characteristic representation of the subject. In relation to questions of identity and legitimacy, the subject of embedded systems is defined as having a thematic identity and functional legitimacy. The thematic identity (in contrast to a disciplinary identity) relates to the immaturity of the subject together with a rapidly changing technology, which makes it difficult to identify the knowledge-core of the subject. Instead, themes, aspects, and cross-disciplinary areas are used to describe the identity, themes, such as, distributed systems, autonomous systems, or different application domains.

The question of legitimacy is defined as the relation between the demands by society/industry and the outcome of the educational efforts. The area of embedded systems is characterized by a functional legitimacy (in contrast to a formal legitimacy). The functional legitimacy relates to functional skills rather than formal knowledge, even though most academic subjects traditionally represent mainly formal knowledge. The thematic identity of embedded systems means that the industries when hiring are requiring more of functional skills, such as the ability to synthesize an embedded system and to actively design control systems, etc.

The questions of identity and legitimacy are directly related to the second pair of questions—selection and communication—what to teach and how to teach it. As a direct result of the thematic subject with functional requirements the conclusion is that an exemplifying educational method is preferable, in an interactive setting. Instead of teaching "something of everything," more toward "everything of something" is advantageous. The interactive communication advocates more skills, such as, teamwork and communication, and is also seen as a preparation for a future career in embedded systems where these skills are deemed relevant. In addition, a focus on functional skills and project-oriented education, for many individuals promote their motivation for studying and gaining formal knowledge; thus the best of the two worlds meet.

Our conclusions are supported by experiences from the field of didactics and also by studies made in industry.

To conclude, the article presents a first attempt to define the subject of embedded systems according to the didactic approach; however, this has been mainly based on experiences from Sweden and from embedded systems within the scope of mechatronics. A preferred next step is to expand the study internationally to better capture the identity of embedded systems, investigate cultural differences, and also to further investigate industrial needs.

We hope that the context we have given, together with the presented model for the evolution of embedded systems as a discipline, can stimulate further investigations on the relevant basis for a new curriculum.

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