COMPLEXITY IN DESIGN OF DIGITAL SYSTEMS: ACTIVE LEARNING WITH PUZZLES

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ABSTRACT

In engineering education, puzzle solving has long been used to develop critical thinking skills. We here put forward the use of Jigsaw Puzzles in a degree program of electrical engineering for two main purposes: (1) Introduce the concept of complex systems, and (2) Justify the need for a methodological approach in a course of Digital Systems Design. This activity was carried out during the first week of the program course and it has been designed to be conducted in three progressive stages as the level of difficulty in puzzle solving increases. As a preliminary result, we have recognized the high impact in developing communication and teamwork skills, and the need of taking a methodological approach to solve problems.

KEYWORDS

Puzzle-based learning, Complexity, Engineering Design Methodology, Digital Systems Design.

INTRODUCTION

In general terms, complexity is defined as the quality of an object with many interconnected attributes and elements, fact which, in turn, makes the relevant object one difficult to understand as a whole. Complexity has been an item of study and research in areas such as computing, biology, information theory, and engineering [1]. Complexity, as far as engineering is concerned, has been mainly studied in the context of systems design. Design, in turn, is considered engineering's most important activity [2]. Furthermore, recent initiatives in education, such as CDIO (Conceive-Design-Implement-Operate Initiative), lead by MIT in conjunction with Boeing aerospace company (initiative in which Universidad Javeriana's Electronic Engineering Program takes part). CDIO established that «design in engineering constitutes the essential context vis-à-vis the training of an engineer ». According to the Accreditation Board for Engineering and Technology (ABET), design in engineering is generally an iterative decision making process whose main purpose is to conceive systems, components, or processes to satisfy some of society's specific needs by resorting to natural sciences, mathematics, and the basics of engineering and thus optimize the transformation of resources to achieve specific objectives thus, a complex system is defined as one with a great number of not easily interconnected parts. In order to ponder any product's design simplicity or complexity, the represented number of functions must be considered, its functioning principles assessed, and its symmetry and topology (among other factors) examined [1].

For this paper, we stick to Marashi and Davis' definition, i.e. that complex systems are those which contain multiple components and layers of subsystems with multiple non linear interconnections difficult to recognize, manipulate, and/or predict [5]. As a way to approach

complexity in engineering, given the lack of scientific principles in the processes behind any design, Nam Pyu Suh has pioneered a method which he has called axiomatic design, in which he proposes a set of axioms and corollaries based on (1) maintaining the autonomy of the functional requirements, and (2) minimizing the information content of (or in) the relevant design. In following with his proposal, a good design would be one that satisfies all the functional requirements with the least number of components and relations [3].

Yet, in spite of the efforts to maintain a minimum number of components in a system, there are areas of electronics, such as digital design for example, where a steep increase in the integration of functions has meant that the number of components on an integrated circuit has doubled every two years as, by the way, was established by Moore's Law. By 2010, the trend implied by this Law will be five years old since it was first predicted in 1965 by Gordon Moore [8], one of the founding members of Intel. This increase in complexity, inherent to the number of components, leads to the necessary introduction in electronic engineering, more specifically in digital design, of working methodologies to better cope with the complexity of these systems and we think that this concept should be approached from the word go with undergraduate education. In this paper, we show how puzzles are used to explain the concept of complexity. The paper is organized as follows: In Section II, "The Need of a Methodological Approach to Cope with Complexity in Digital Design Systems", an attempt is made in order to explain why the high level of components integrated in the design and manufacture of integrated circuits demands the introduction of methodologies, in both industry and academia, to cope with such complexity. Then, in Section III, "Incorporating Puzzle Solving in Learning Processes", we describe the context and background of several years work in understanding learning processes done by the Research Group MIMESIS, whereby technologies were presented together with innovative classroom experiences. In Section IV, "The Puzzle Solving Experience", we describe real activities with puzzles, and in Section V, "Preliminary Results", presents the result of the activity realized in 2010. Finally, this paper offers, in Section VI, some Conclusions in the proposed didactics.

THE NEED FOR A METHODOLOGICAL APPROACH TO COPE WITH COMPLEXITY IN DIGITAL DESIGN SYSTEMS

Our age's continuous and growing technological needs have meant that electronic systems have become more and more complex and that a greater diversity and number of functions are integrated into them. This is particularly true for digital systems which grow almost on a daily basis, fact which explains why both academia and industry are permanently in search of new ways to better approach this challenge [11], [10]. In order to understand the levels of complexity nowadays in use, we must take a look at the historical evolution of digital systems.

The first integrated circuits, which appeared by the end of the 1950's, had a few a transistors, but today's processors, which we find in all personal computers, can have over 2000 million transistors [6], fact which, when in the midst of the process of design, can be difficult to handle without clear guidelines. However, there is no unique standard methodological approach to develop this type of systems; on the contrary, different manufacturers and academic institutions have offered different proposals in an attempt to be more efficient vis-à-vis their particular concerns. Yet, many of those methodological approaches have points in common [11], [9], [12], which we can sum up as follows: Generating multiple perspectives and levels of abstraction; segmenting the process, and acknowledging the need for multiple work teams. The levels of abstraction start with the functional requirements of the system to be developed which, once examined, allow for the creation of input-output diagrams that define the most important functions. The next stage is to define the actual architectural construction, whereby the whole system is gradually broken down into simpler blocks which in turn carry out more specific functions. This description is very important and is carried out by iteration and increment. The level of the gradual break down is permanently modified until

the designers consider that the system has been properly described, at least in as far as static notions are concerned. Next, the dynamic behaviour of the system is defined to produce its time and state diagrams and even an HDL (hardware description language) in order to describe the systems' dynamics. With these descriptions at hand it is now possible to proceed to its physical installation, a process which can be done by means of multiple computational tools which in turn open the possibility to analyze and examine the system's physical behaviour. New perspectives and levels of abstraction will now be obtained, i.e., layout and distribution at semiconductor levels. The latter levels are of crucial importance because they have a deep and direct impact on performance, that is, even if the newly conceived system can accomplish all the functions for which it was created, we must bear in mind that it must accomplish them in the required time without resorting to a larger power load than the one that was previously established and it should be small enough to fit in a final product which looks attractive to the customer. Thus, of course, if by the time the installation stage is over and the product does not fulfil the desired characteristics, it would be necessary to review all the previous stages in order to finally satisfy all the requirements demanded by the client/user.

All of the above explains the need to develop new design technologies in order to interact with the complex systems that in turn need to be created. These new methodologies involve teamwork and rigorous documentation in order to achieve the coordinated interaction of the hundreds or thousands of persons who work on one same system. It is thus urgent and pressing that today's engineering students understand this complexity and be able to come out with tools to overcome the challenge and join other consolidated work teams.

INCORPORATING PUZZLE SOLVING IN LEARNING PROCESSES

Puzzle solving, as well as other related projects, are embedded in a teaching-learning model proposed by the research group MIMESIS. The model has two basic premises: first, the students must play an active role in their learning process; and second, hands-on process of learning, using several easy available didactic materials and incorporating activities in the classroom in order to understand and apply the main concepts to be used during the course.

The model has been basically implemented in courses under the area of Digital Techniques, which makes part of the Electronic Engineering degree course at Pontificia Universidad Javeriana of Bogotá, Colombia. The latter is a five (5) year undergraduate degree course whereby the subject Digital Systems Design is compulsory and is offered on the fourth year of studies. In it, team work and collaborative learning are encouraged via practical exercises which, nevertheless, still foster the students' autonomous training. Logic Circuits are a prerequisite and is followed by Architecture and Organization of Processors, subject in which the students design their own processor. As far as we know, it is one of the few proposals in which undergraduate students are exposed to the task of designing their own processor, similar to those they use in their conventional PCs, but with tailor-made functions defined by the student him/her-self. The subjects studied over the last years under the general umbrella of Digital Techniques, have undergone several changes due to two main basic factors: the advances in technology and the changes in the teaching methods. To begin with, advances in technology allow electronic designers to develop and produce, at competitive prices, very complex digital systems that in fact do work in the real world and perform with the same ease that many other high capacity devices offered in the marketplace; on the other hand, the tools from manufacturers now available for designers, make the possibility of closing the complete cycle of design a feasible one, that is, carry out the whole process: conception, verification, implementation, validation of specifications, and the systems operation. All these procedures now come across the subjects' contents, including the methodologies necessary to support the mentioned design stages.

With this in mind, the relevant subject matters have changed in such a way that the students can build their knowledge and acquire the necessary skills to produce reliable and easy to

maintain designs, always bearing in mind limitations such as costs both in time and money. On the other hand, the methodology used in the classroom has also undergone huge modifications when late magisterial expositions are compared to today's actual learning based on PBL that foster collective and collaborative work. Thus, the lecturer takes on the role of a guide of sorts, and actually guides a process in course with very few instances of cheer magisterial exposition. The physical arrangement of the classroom itself has changed. In order for the groups to better carry out their work, the classroom's furnishings allocated to these courses is now modular and flexible, so that they can be adjusted and reconfigured depending on the activities to be performed in each class. During the Digital Design course, for example, it is important that students become aware of the fact that a complex system is usually not developed by a single person and that, as is true in most industries, a product of this nature is developed by work groups with different functions and, at times, even groups and peoples working in different parts of the world and where, needless to say, the process of communication is essential.

THE PUZZLE-SOLVING EXPERIENCE

The experience with puzzles is introduced as soon as the Digital Design course starts, that is, during the first week. The idea is to use the puzzles to explain and show the need of a clear methodology when designing, to highlight the importance of team work and effective communication, plus introducing the concept of complexity. From Marashi and Davis' proposed definition for the concept of complexity, we took two elements and applied them to the design of systems. The first alludes to the notion of complexity as the number of elements that comprise a system and the second to the level of difficulty with which the parts that make up a system interconnect with each other. We set up an experience whereby puzzles are used in three progressive stages through which the two proposed elements are incorporated into one complex system. An even number of teams, each comprised by 3 to 4 people, are constituted and their members assigned a role: each team will choose a person to measure time and take notes. The teams must have at least two members.

Stage 1
Introducing a simple problem; by simple problem we understand one with a limited number of pieces easy to interconnect with each other. We chose a 6 piece puzzle which, framed together, made up a big figure. Each team will be given a sealed envelope with a problem to be solved. None of the members knows the nature of the problem. Instructions are explained to all teams, and then, each team will open the envelope and find the problem to be solved as fast as possible. The problem to be solved consists in a flat puzzle of 6 pieces. Once the activity ends, time is registered and the person in charge of taking notes will share his o her annotations in order to examine the strategies adopted by the members and discuss them in a short plenary. The differences of time among the different will be discussed as well.

Stage 2
The complexity of the problem is increased by augmenting its connecting parts. The more variables you introduce to a problem, the more complex their work will be, thus the need for a methodology. Once again, each team will receive a second sealed envelope with a second puzzle. This time, contrary to stage 1, directions are different for every pair of teams and this time round all teams will solve the same puzzle. In short:

Direction 1: Solve the problem as you please.
Direction 2: Solve the problem with some guidelines to solve puzzles.

The new problem is a puzzle of 35 pieces. Once the activity ends, time is registered and the person who takes notes will share his or her notes. The adoption of new strategies will be discussed in a short plenary, contrasting their performance against the one proposed in stage 1. The differences of time will be discussed as well as the benefits (if any) of using and

sticking to a methodology. Once the discussion is over, students are asked to articulate a general methodology to solve problems such as those found in stages 1 and 2, methodology which will then be applied in the third stage.

Stage 3

This time round the complexity is increased by changing the rules that govern the interconnecting parts. The more difficult the interconnecting parts are, more complex their work will be, thus the need to adjust a particular methodology.

To finish the experience, each team will receive a third sealed envelope with no directions at all. It is assumed that each team will use the methodology proposed by the end of stage 2. The new puzzle will consist of 60 pieces, but contrary to the puzzles proposed in stages 1 and 2, this new puzzle won't be flat but spherical (without borders).
This new interconnection rule will imply a paradigm shift vis-à-vis solving puzzles that the participants will have to sort out. The later discussion will be focused on the relationships that now have been established between methodology and complexity, between styles of solving problems and reasoning as well as the steps followed by a particular methodology, plus the relationship between the concept of methodology itself and the need for adjusting it when faced with a new problem. Students are encouraged to apply an instrument for evaluation purposes.

After the experience with the puzzles, starting on the second week, a digital design methodology is introduced. Now the question of methodology is approached from the system's perspective whereby the following stages of the process of design are introduced: 1) Understanding the problem, where the student is asked to draft a general description of the problem to be solved. 2) Top-down decomposition. Once the system can be explained in terms of inputs and outputs, the problem is segmented in simpler parts, a process also known as interface specification. 3) Once these simpler blocks have been pinpointed and their inputs and outputs identified, their interfaces need to be described via diagrams of blocks, their connectivity and times. 4) Describing the system's functionality. The students are encouraged to use an intermediate description level language, somewhere between structural and behavioral descriptions, which in digital systems is known as AHPL (A Hardware Programming Language). 5) Integrating the parts verifying that the system works as required. 6) Description in VHDL plus the subsequent configuration of the FPGA device.
The principles at the base of the proposed methodology and the strategies used by the students to solve their puzzles are related, so that to begin with, the problem to be solved is analyzed and broken down into simpler parts. Then the students deal with the problem of interconnecting the big pieces of the puzzle and the need to define as clearly as possible the relevant interfaces. Finally, they gradually learn how to integrate more complex problems. Along the course, at least three projects are presented to the students in order for them to implement the learned methodology when designing Digital Systems with different levels of complexity, that is, they will be exposed to systems with incremental levels of complexity in terms of the number of components which make them up as well as increments in the difficulty to integrate them.

PRELIMINARY RESULTS

As already said in the above section, the experience with the puzzles at the start of the course was divided in three stages, each one more complex than the one before. The puzzle's solution at the first stage is basically reached at intuitively and the time that the group takes to solve it depends on the particular skills of its members. Once this stage is over, an evaluation tool is implemented by each group in order to find the particular methodology used (even if unawares of such methodology) as well as the critical components which made the solution possible. Overall, collaboration among members and

drawing a plan to fulfil the task are always two very important elements for the design to succeed.

In the medium complexity stage, some groups work with a pre-established 'solution targeted' methodology while others work freely and follow no instructions at all. Overall, the shorter solution times come either from groups that follow a pre-established methodology or those that, before starting, establish their own particular strategy to solve the relevant task. Nevertheless, after carefully examining the work done by the different groups, we could see that for some of the puzzles the proposed methodology became in fact an obstacle which had to be modified and adapted in order to solve the group's particular problems.

When this moment arrives, it is time to ask all groups to put forward their own methodology and implement it for the final stage, whereby they will be given a spherical puzzle. At this level, the solution conditions change radically and the groups will have to adapt once more the methodology in accordance with the new context, point at which the methodological evolution should be not only obvious and necessary but iterative and incremental. As already said, the whole activity is attended with an assortment of tools to follow the connections that the participants make between the complexity of the device and the methodology used to solve the problem. Thus, to begin with, the students become aware of the importance of identifying the preliminary conditions and characteristics as soon as they start analyzing the problem, that is, at its first stage, step after which the problem can be broken down to simpler tasks with a sketch of fine granularity.

If we reflect on the aforementioned activity, we can identify five aspects which, in general terms, can be highlighted as critical elements relating the complexity of the problem and the methodology used to solve it: communication, teamwork, the ability to follow a methodical resolution strategy, the usefulness of a methodology, and the impact of all of the above on the process of reasoning. The first three befit the personal and interpersonal skills of an engineer; the last two are basically the students' perception of the skills themselves. Let's examine each aspect, one by one. The communication processes' main contribution to finding a proper solution is that it offers each member of the group the possibility to put forward his/her own ideas, learn from those of his/her peers, and thus put together the common task. In short, the students learn to listen, reach agreement, and evaluate. On the other hand, communication allows all members of the group to mediate among themselves, to keep track of the process' progress, put explicitly forward the norms and commitments assumed by the group, and work as simply and swiftly as possible.

In second place we have teamwork, an element which makes possible breaking down the problem into simpler tasks as well as encouraging a larger input of ideas for the benefit of the solution via the assignment of roles and responsibilities. Thus, a social configuration emerges whereby hierarchical structures are formed and leaders and followers identified. The groups' formation process is a natural one and they develop via the intercourse of feedback among peers and effective communication. The participants' teamwork efficiency will be manifest in things such as the time taken to solve the problem, the levels of harmony among members, the autonomous participation of each individual and their commitment to the group, all elements which contribute to a wider scope of learning than the one which would have been achieved individually. Students should become aware of the fact that teamwork adds to the strengths of all members and helps in overcoming each member's weaknesses. Still, in order to obtain the expected best results, they must also be aware that, to do so, processes such as planning the work ahead, coordinating the team vis-à-vis a clear shared objective, and each member's awareness of why, how and what he/she did are all essential.

The third aspect brought forward by the participants was that of setting out and then following a methodology, the latter working as a guiding sketch to get to solve the problem, but aware

of the fact that such sketch and methodology can be changed and modified in different contexts, that is, knowing that methodologies aren't unique and must therefore be flexible and dynamic; it is precisely these changes during the development of the problem, the element that alerts us to the need of methodological modifications and therefore becomes relevant when both identifying and understanding the problem and its particular characteristics. The methodological aspect is complemented by the fourth element, whereby the usefulness of the former comes to the fore. More complex problems demand more formal and rigorous solution methods, since a very simple methodology will be found lacking when dealing with a problem of greater difficulty. Posing an adequate methodology allows for solving the problem more efficiently, in less time, and thus makes optimal use of the available resources. Finally, the participants stressed that the activity they went through was like a simile of real life, whereby aspects such as communication, teamwork, and methodology are essential for a proper professional development as engineers, particularly when dealing with processes of reasoning and thought. The context of the experiment or activity, being as it is real, implies that the methodological processes used to solve such problem should not be mechanized, since each particular situation must be specifically analyzed and, furthermore, different solutions to the same problem must be confronted or pondered, meaning that each individual must be capable of evaluating and choosing the best possible option. Solving a particular problem offers knowledge that will be handy in future situations via the appropriation of clear methodological outlines which are flexible enough to be adapted the midst of particular future situations with new requirements.

CONCLUSIONS

Studies at University of Adelaide and Carnegie Mellon University have shown that there is a strong connection between the ability to solve puzzles and the ability to solve industry and business problems [4]. Puzzles are a fascinating way to learn problem-solving rules, among other things, because they are engaging and not directly related to textbook problems [7]. Puzzle-solving tasks develop skills needed in real engineering contexts and they reproduce effectively difficulties and conditions found in real workplace environments. The students agreed to the fact that the experience described in this paper did emphasize communication and teamwork skills although they were not mainly designed to develop these basic skills.

After the experience described in this paper is over, that is, once the students have solved the puzzles proposed and put into their own words their findings, it is easier for them to go into the concepts of complexity and methodology through papers and textbooks than it would have been without the previous experience. As far as the learning process is concerned, after years of research by the MIMESIS group, it has been found that giving more importance to the discovery of knowledge, from the students' perspective, can bring better results than using other approaches such as magisterial lectures from a professor's point of view. Jigsaw puzzle solving is a good metaphor for an engineering design process and the discovery of knowledge. It encourages inductive reasoning and fosters the ability to identify patterns in a large amount of data. This type of reasoning is essential for engineers and scientists. They are used here to introduce complexity and stress the need of using a methodology when solving problems. Furthermore, other topics related to the discovery of insight and knowledge and to engineering design can be explored to be used, for example, in the verification of processes in design, in following instructions, and in organizing and leading a group. We really think that such experiences can be replicated in the starting years of engineering programs to enable highly motivated students to succeed and to improve the students' continuity in the career in times when registration for engineering programs is declining. These activities can also be introduced also among school students interested in engineering programs, since they describe more effectively the type of work that engineers do on a real professional context. Quite often counsellors in high school scare students to panic because of the apparent difficulty in the study of mathematics and physics, leading to their choosing other disciplines.

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