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FOSTERING HIGHER COGNITIVE SKILLS THROUGH DESIGN THINKING IN DIGITAL HARDWARE COURSE: A CASE STUDY

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Abstract. *Computer Science students are reportedly facing many issues in acquiring higher cognitive skills (e.g., analysis, and design). Digital hardware is one of the first courses in a typical Computer Science curriculum where students need to master these skills while analyzing and designing sequential circuits. This study investigates the pedagogical effectiveness of the Design Thinking methodology in improving students' higher-order cognitive skills in the digital hardware course. Design Thinking was embedded in the digital hardware course through a real-world design challenge where teams of students iteratively collaborated. The design problem was purposely set to necessitate knowledge and skills yet to be covered hence fostering in students' curiosity and eagerness to learn new topics, thus engaging students as active learners and meaning creators. The study demonstrates a significant gain in test scores. It also describes how to easily embed the Design Thinking process in the digital hardware curriculum.*
Keywords: Continuous quality improvement, Design Thinking, Digital Logic, Higher-order cognitive skills, Analysis, Design, Student learning outcomes

1. **Introduction.** Latest curriculum recommendations from the ACM/IEEE [1] highlight how imperative it is to develop higher cognitive skills in students through collaborative real-world practice-based learning activities. One of the first courses where design is introduced to students in a typical computer science curriculum is the Digital Logic course (also called digital hardware), which is identified as a core area of the Computer Science curriculum by the IEEE and ACM societies [1]. Indeed, Digital Logic forms the basis for computer architecture, which has a direct impact on many aspects (e.g., operating system, and compilers). Yet, teaching this subject comes with many challenges [2]. At the author's department, this challenge reflects itself as a systematic students' deficiency in higher-order cognitive skills (e.g., analysis, and design), preventing important course learning outcomes to be met. If not addressed properly, this problem may cause a higher rate of drop-out or even worse result in graduates lacking essential professional skills.

Design Thinking is a powerful methodology enabling innovative design [3]. It has been applied to various fields and can be used for different purposes: in the field of education, it can be applied by administrators to solving institutional problems (e.g., increasing retention rate) [4], or by instructors to address classroom issues (e.g., improving students' engagement in class) [5]. Design Thinking can also be incorporated in the curriculum, either as a stand-alone course or embedded into an existing course, to empower students with skills necessary for the job market of the 21st century [6]. Indeed, the Design Thinking framework develops several of the "seven survival skills that all students must master to get -and keep- a good job in today's global knowledge economy", namely "critical thinking and problem-solving, collaboration across networks and leading by influence, agility

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and adaptability, initiative and entrepreneurialism, effective oral and written communication, accessing and analyzing information, and curiosity and imagination" [7]. Acquiring these soft skills is even more important for Computer Science students, given the highly dynamic nature of the field.

Hence, the goal of this research is to investigate if students' higher cognitive skills and abilities are affected by their involvement in the various stages of Design Thinking. This study presents the results of an ongoing experience fostering Design Thinking in digital hardware education at the author's institution, a prestigious government university dedicated to undergraduate education. Design Thinking is increasingly incorporated in K-12 education policies as a general skill; however, no empirical studies to the best of authors' knowledge have been conducted to evaluate if Design Thinking can reliably improve higher cognitive skills in a Digital Logic course environment.

To assess the effectiveness of the proposed pedagogical approach, two assessment methods are used, namely exam results and Student Survey on Lecturing Skills. The former tests if using Design Thinking leads to measurable improvement in students' academic performance in topics demanding higher order cognitive skills such as analysis and design, and the latter investigates students' perceptions of the effectiveness of the method. Overall, the results of the proposed Design Thinking approach are encouraging. Students' increased satisfaction and improved exam grades present promising results, clearly demonstrating that embedding Design Thinking in the curriculum could increase students' academic performance, but also their engagement, and interest in the field.

2. Related Work and Background Information.

2.1. Recent innovations in digital hardware education.

Most Digital Logic courses consist of theory lectures complemented by practical laboratory experiments, as "learning by doing" enables a longer lasting body of knowledge [8]. The literature shows that the recent attempts to improve students learning in the Digital Logic course focused on innovating the labs, either by developing novel hardware solutions [2,9,10] or by proposing dedicated software strategies [11-13]. Both hardware and software tools are very valuable, but they will reach their maximum benefit only if lessons are designed following a sound pedagogical strategy. Literature shows that the most important teaching strategy used in the Digital Logic course is project-based learning, which has shown increased student's interest and learning motivation when applied in a digital hardware course [14,15], regardless of the project size [16].

However, all these strategies focus on design learning outcomes through the development of a specific product, predefined series of orderly steps. They are rigid in their approach, with a narrow scope of learning outcomes. Alternatively, the Design Thinking process focuses on the process instead of the product. Although structured in phases, it is flexible and enables multiple cycles of repetitive stages. These stages are explained in the next section.

2.2. Design Thinking.

Design Thinking consists of five stages: empathize [20], define [4], ideate [20], prototype, and test. In a classroom environment, Design Thinking requires students to work on a problem or a project, where empathizing fosters emotional intelligence, prototyping enables flexibility, exploration, and investigation. Group work also develops important soft skills, transferable and applicable to many situations.

2.3. The digital hardware course at IAU.

Digital hardware is a one-semester (15-weeks) core course for all second-year students at the College of Computer Science & IT. It consists of weekly, two lecture sessions (50 min each), and one laboratory session (100 min). The lecture sessions introduce the theory, and the lab complements them enabling students to practice the covered topics. One-hour long midterm and three hours long final exam are administered in week 8 and week 16, along with several short (15 minutes) quizzes and bi-weekly lab assessments. The first part introduces Boolean algebra and other tools necessary for the following two parts. The second part focuses on combinational digital circuits, whereas the last part covers sequential circuits. Important student learning outcomes (SLOs) are:

1) Explain the fundamentals of digital systems, Boolean algebra, and logic expressions;
2) Use simplification methods for Boolean functions;
3) Analyze combinational and sequential digital circuits and predict their behavior;
4) Design combinational and sequential logic circuits. The poor performance of students in the past several semesters has been reported, especially in higher order cognitive skills (e.g., analysis and design), resulting in low rates of students meeting related course learning outcomes.

3. **Research Methodology.**

3.1. **Description of the experiment.**
A Design Thinking approach was adopted to teaching discipline-specific knowledge and skills in digital hardware course during the Fall semester of the academic year 2017-2018. Instead of teaching Design Thinking principles as stand-alone lessons, the authors decided to integrate its principles into the course content and used this method as leverage for learning. As stated in [6], Design Thinking "can thus provide rich experiences that encourage meaning-making without the imposition of a fixed set of knowledge and skills". The proposed approach consists of modifying the content of the lectures and labs by asking students to go through the first four stages of the Design Thinking process. After covering all the basic concepts during the first four weeks of the semester, a design challenge was given to the students. In order to "allow many teams to innovate in parallel and reach different conclusions", thus achieving an important property for an effective design challenge, students working in teams of two were asked to design a digital clock that may be used in different home appliances. However, since the necessary knowledge and skills (namely the design of combinational circuits, sequential circuits and counters) were not acquired yet at that time, the given problem can be considered as an ill-structured problem fulfilling the ambiguity and uncertainty properties associated with real-life design problems [17]. The given project was fostering the students' curiosity and eagerness to learn new topics, thus engaging students as active learners and meaning creators instead of the "why do I have to learn this" approach.

The instructor first related the problem with real life by using 'Empathy' which is the first stage of the Design Thinking approach. Once students identified the user's needs, then they defined the problem based on the information gathered from the empathize phase. One week was given by the instructor for the 'define' stage of Design Thinking. The course delivery was scheduled such that after learning each topic students move closer to the solution of the problem. So, step by step they moved towards the solution of the problem and following the 'ideate' step, they reached multiple ways to design a solution to the given problem. Thus, students started to learn and apply higher order cognitive skills. In the prototype phase, the students/designers selected the best solutions and created a prototype for it. In the end, students submitted the correct solution to the problem. The last stage test was done by the instructor. The instructor's feedback enabled students to learn from their mistakes. Consequently, the proposed experiment fulfilled the following suggestions from [18] on teaching Design Thinking:

i. Peer learning and teaching approach
ii. Student IP ownership of their stake in the projects undertaken
iii. Student interaction to attain educational goals
iv. Acquisition of knowledge through actions and practice, rather than traditional instructional learning

v. Willingness to try new things
vi. Involvement of a facilitator in the Design Thinking process and projects to inspire, motivate and act as a confidante
vii. Project work based on a problem-based approach
viii. A real-world problem to solve

3.2. **Evaluation methodology.** A total of 98 students were taught digital hardware, enrolled as four sections. Two sections made of a total of 50 students have been randomly designated to be the Control Group (CG), and the students followed a traditional schedule of classes and laboratory assignments. The other two sections (total of 48 students), designated to be the Experimental Group (EG). The EG of students were taught according to the pedagogical methodology described in the previous section.

The following research questions have been investigated to test the effectiveness of the proposed method:

- Q1: Embedding Design Thinking in digital hardware causes measurable improvements in students' academic performance in the relevant topics
- Q2: students have a positive perception of the effectiveness of the method

In order to be able to draw sound conclusions from the comparison of the two groups of students, it is essential to verify that these two groups are similar with respect to prior academic performances [19]. Since Electronics is the prerequisite course for digital hardware, class averages of both cohorts have been compared for Electronics, showing the same mean for both student populations confirming their comparability.

4. Evaluation.

4.1. **Assessment data.** To answer the research question Q1, student scores from various assessments were collected and compared. Since the Design Thinking experiment started in week 5, students' performances in the assessments before and after week 5 were collected, that is to say, pre-experiment scores (midterm exam) and post-experiment scores (final exam). Note that quizzes were not included in the analysis as they were prepared to assess lower cognitive skills only. The midterm and final exams were constructed using multiple-choice and descriptive questions in alignment with the SLOs. The examinations in both groups were held simultaneously; hence the questions were identical. Papers were graded using the same rubrics. Statistical analysis of examination grades is available in Table 1, where all scores are normalized to 100. Better visualization of the gain in performance (defined as being the difference between post-Design Thinking and pre-Design Thinking scores) is available in Figure 1.

Midterm and final examinations covered all SLOs; thus they cover all skills from both lower and higher cognitive levels. To better evaluate the effectiveness of the proposed pedagogical strategy on specific cognitive skills, CG and EG were compared with respect to student learning outcomes (SLOs) in Table 2.

Table 1. Statistical analysis of examination grades

	Mean	Standard deviation	Minimum	Maximum
Control Group (CG): Midterm	77.80	12.00	45.00	97.00
Experimental Group (EG): Midterm	79.70	10.00	56.00	95.60
Control Group (CG): Final	78.80	12.87	45.16	97.50
Experimental Group (EG): Final	81.74	10.54	52.85	100.0
Control Group (CG): Overall	80.64	10.00	59.01	95.65
Experimental Group (EG): Overall	82.79	7.00	66.36	97.41

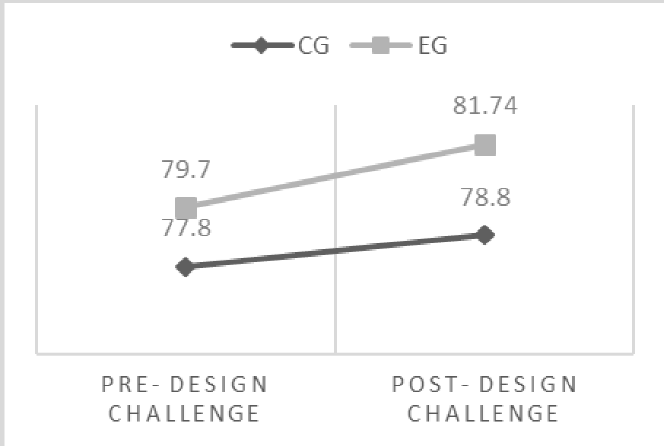

FIGURE 1. Student grade gain in CG and EG

TABLE 2. Comparison of scores grouped by SLOs (MT: midterm; F: final; O: overall)

SLOs	CG mean			EG mean		
	MT	F	O	MT	F	O
#1 & #2, lower cognitive skills	72.08	77.99	74.17	74.80	79.94	76.92
#3, analysis	81.17	80.21	81.29	83.79	82.30	83.37
#4, design	91.61	77.48	81.14	90.33	81.90	83.31

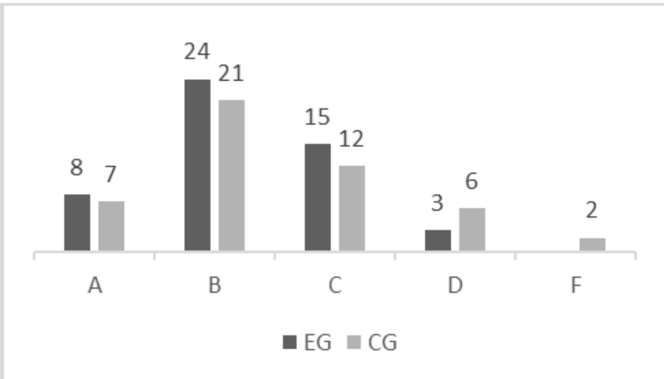

FIGURE 2. Student grade distribution in CG and EG

Finally, the overall grade distribution for both groups is displayed in Figure 2. The number of students who earned A's, B's and C's is larger in the EG, with fewer students earning D's and F's.

4.2. **Students survey result.** To answer the research question Q2, the author evaluated students' perceptions of the effectiveness of Design Thinking. Instead of imposing yet another survey to students and overwhelming them during their final exam period, the authors decided to utilize students' feedback to relevant questions from the Student Survey on Lecturing Skills (SSLS). This survey is opened for students answers before the final exams start and ask 15 questions to students about various factors affecting their learning experience. This is an online anonymous survey. As an incentive to take it, students who do not answer it experience some delay in the announcement of their course grades. Hence, all 98 students (100% of the total enrolment) took the survey and provided valuable feedback. The items relevant to our research question are listed in Table 3, as compared

Table 3. Relevant items from the SSLS

Questions	CG	EG
	Year 16-17	Year 17-18
Improve my ability to think and solve problems rather than memorize facts.	3.9	4.4
Overall, I was satisfied with the quality of this course	3.9	4.5
The course outline including the knowledge and skills	4	4.5
Inspired me to do my best work	4.2	4.6
Encouraged me to ask questions, and, develop my own ideas	4.1	4.5

Table 4. Relevant open answers from the SSLS

Feedback	CG	EG
Positives	NA	This course was very fun and interesting! I enjoyed every class. For the first time, I looked forward to even going to a class! I hope to have a similar course to this in my upcoming semesters.
Negatives	NA	NA

to responses from the previous year (note that the survey is using a Likert scale with 1 corresponding to strongly disagree, and 5 to strongly agree).

In the SSLS, students also responded to open-ended questions where they could voice any positive/negatives, and feedback is provided in Table 4.

5. **Discussion and Recommendation.** Looking at Table 1 and Figure 1, one can observe that EG demonstrated not only a higher increase in the mean from midterm to the final exam but also a smaller increase in the standard deviation. Furthermore, in Figure 2 the number of students who earned A's, B's and C's is larger in the EG, with fewer students earning D's and F's. This clearly demonstrates the promising impact of Design Thinking.

Looking at Table 2, students in both groups performed better for SLO#4 in the midterm exam. This can be explained by the fact that SLO#4 is about the design of both combinational and sequential circuits, and the midterm covered only combinational circuits, the real challenge for students is in the analysis and design of sequential circuits. One can also observe that the grade gain is similar in both groups for SLO#1, and SLO#2, approximately +5. Indeed, SLO#1 and SLO#2 are covering lower-order cognitive skills and were introduced at the beginning of the semester. By the end of the term, these topics were well mastered by students. Surprisingly, for SLO#3, there is a slight drop in grade (approximately -1) after the design challenge both in CG and in EG. Even more, grades deteriorated for SLO#4 in both groups in the final exam. This unexpected phenomenon can be explained by several factors: the overall state of fatigue that students reached by the end of the semester, combined with the many project deadlines and end of semester assessments that accumulated, and finally the fact that the related topics were the last topics to be covered and did not get the opportunity to mature in students' mind. However, as depicted in Figure 3, the grade loss was significantly less in EG as opposed to the CG. The authors believe that the design challenge given to students in EG combined with peer-learning, learning by doing, and the prompt feedback from the facilitator contributed to lessening the performance drop that students usually experience in the final exam. A lessened performance drop can certainly be considered as a measurable improvement in students' academic performance, thus answering the research question Q1.

Regarding the research question Q2, Table 3 shows a significant increase in students' satisfaction in the EG. Especially the first question, "this course improved my ability

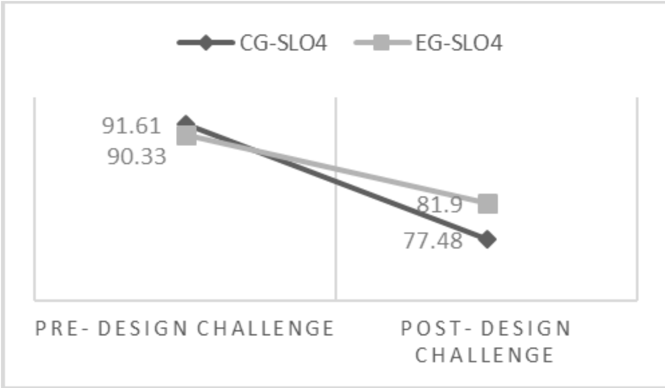

Figure 3. Student grade gain in CG and EG for SLO#4

to think and solve problems rather than memorize facts", very well reflects the students' perceptions of the effectiveness of the Design Thinking approach in improving their higher order skills. While the feedback in Table 4 does not directly answer Q2, it clearly shows student's eagerness to take another course following a similar format.

6. **Conclusion.** This study shows the results of the educational efforts of the authors to address a reported low performance of students in past years in achieving higher-order cognitive skills in an undergraduate digital hardware course. The authors proposed a pedagogical approach based on Design Thinking principles. The developed solution asks students early in the semester to solve a design challenge, which necessitates using uncovered course topics, the purpose being to initiate in them curiosity and a need for the new topics, thus keeping them motivated and eager to learn. This approach has helped students experience deep learning moments. Overall, the results of the proposed Design Thinking approach are encouraging. Students' increased satisfaction and improved exam grades present promising results, clearly demonstrating that embedding Design Thinking in the curriculum could increase students' academic performance, but also their engagement, and interest in the field. It would be interesting in future research to design a digital hardware course using only Design Thinking-based problem solving as a teaching mean, thus eliminating all aspects of classical lectures, and investigate its impacts on students learning.

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