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# Promoting Engineering Students' Learning: An Interdisciplinary Teaching Approach of Electronic Circuits*

BETO CATZ[1], AVINOAM KOLODNY[2] and AHARON GERO[1]
[1] Department of Education in Technology and Science, Technion – Israel Institute of Technology, Haifa 32000, Israel.
[2] The Andrew and Erna Viterbi Faculty of Electrical and Computer Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel. E-mail: betoc@campus.technion.ac.il, kolodny@ee.technion.ac.il, gero@technion.ac.il

Interdisciplinarity, namely, combining two or more fields of knowledge around a central theme, allows students to observe the topic from several viewpoints and may foster their cognitive skills. Therefore, the Faculty of Electrical and Computer Engineering (Technion – Israel Institute of Technology) developed and implemented an interdisciplinary teaching approach of electronic circuits. This approach integrates the two main branches of electronics, i.e., analog electronics and digital electronics, which are traditionally taught separately in academia. The research described here examined whether this interdisciplinary approach has advanced learning compared to the traditional disciplinary way. The study, which used quantitative and qualitative tools, involved 156 junior electrical and computer engineering students. According to the findings, the analytical skills of students taught via the interdisciplinary approach were significantly higher than those of their peers who studied in the disciplinary way. Students who experienced interdisciplinary learning argued that it was interesting and natural, improved comprehension and analytic capabilities, but was also characterized by a high cognitive load. The preference for interdisciplinary learning was significantly higher among students who experienced it compared to their peers who were exposed to traditional learning.

**Keywords:** interdisciplinary education; academic achievement; attitudes; electronic circuits

## 1. Introduction

The two main branches of electronics are analog electronics and digital electronics. Although both share the same underlying technology and physical devices, each topic is based on different assumptions, uses different models and has different purposes. Traditionally, analog electronics and digital electronics are taught separately in higher education, and it is common for students to specialize in one of these areas. As a result, students are accustomed to treating analog electronics and digital electronics as distinct fields [1]. However, the importance of mixed-signal design combining both analog and digital circuits has increased considerably [2]. Moreover, interdisciplinarity, i.e., integrating two or more areas of knowledge around a central theme, allows students to view a topic from several perspectives, may cultivate their cognitive skills and prepare them to work in complex environments [3, 4]. Thus, it might be preferable to teach electronic circuits in an interdisciplinary approach that integrates analog and digital electronics and underscores their interrelations [5].

In light of the above, the Faculty of Electrical and Computer Engineering (Technion – Israel Institute of Technology) combined two undergraduate courses, the first focusing on analog electronics and the second on digital electronics, into a single course "Electronic Circuits" integrating the two fields. This unique course, mandatory for junior electrical and computer engineering students, deals with analyzing electronic circuits from both the analog and digital viewpoints while taking system considerations into account. It is important to note that most universities teach electronic circuits via the traditional disciplinary approach. However, in a limited number of institutions (e.g., Massachusetts Institute of Technology) a similar interdisciplinary course is offered [6].

The study described here examined, using quantitative and qualitative instruments, whether the interdisciplinary approach mentioned above (i.e., combining analog and digital electronics) has advanced learning compared to the traditional disciplinary way. To the best of the authors' knowledge, such an analysis was conducted for the first time. The research findings and conclusions expand the body of knowledge on the subject and may improve the training of engineers. These contributions are validated in view of the considerable gap between the qualifications of engineering graduates and those needed in the industry [7].

The paper opens with a theoretical background that reviews relevant aspects of interdisciplinary education. Next, the "Electronic Circuits" course and the two separate courses that preceded it are described. Then, the research goal and methodology are presented. Finally, the findings are discussed.



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## 2. Interdisciplinary Education

Most researchers define interdisciplinarity as an activity that combines two or more fields of knowledge in order to achieve a synergistic effect [8]. The literature offers different hierarchies for the degree of interaction between disciplines. Among the most common classifications is that of Piaget [9], distinguishing between multidisciplinarity, in which the integration between the fields is minimal (or non-existent), interdisciplinarity, where synthesis exists to some extent, and transdisciplinarity, in which the intense synthesis blurs the boundaries between the original disciplines. Other important hierarchies were developed by Jantsch [10] and Lattuca et al. [3].

A useful typology has been proposed by Ivanitskaya et al. [4] and is comprised of four stages:

- Unidisciplinarity (or Disciplinarity) – in which the student deals with a single area of knowledge;
- Multidisciplinarity – in which the learner deals with several fields of knowledge, but addresses them separately;
- Limited Interdisciplinarity – in which the learner combines a number of areas around a central theme, and identifies the strengths and weaknesses of the various viewpoints;
- Extended Interdisciplinarity – in which the student can transfer interdisciplinary knowledge.

In the present study, the combination of analog electronics and digital electronics around the subject of electronic circuits, corresponds to the third degree in the above model, i.e., Limited Interdisciplinarity.

Kelly and later Klein focused on the distance between the disciplines involved, emphasizing the difference between Narrow Interdisciplinarity and Wide (or Broad) Interdisciplinarity [11, 12]. In the first case, the fields of knowledge are close, namely, share similar epistemologies and methodologies. In the latter case, such compatibility does not exist. Here, the integration between analog electronics and digital electronics refers to Narrow Interdisciplinarity.

Over the years, interdisciplinary curricula have been developed at various levels, e.g., high schools [13, 14] and higher education [15, 16]. These programs cover a broad range of topics, such as robotics [17], nanotechnology [18] and aerospace [19]. Studies that characterized the above programs and others have identified strengths and weaknesses related to interdisciplinary education, as detailed below.

Affectively, interdisciplinary learning has a distinct advantage. Thanks to the interest it sparks, intrinsic motivation is often enhanced [3].

In the cognitive domain, interdisciplinary education has many benefits. The literature reports on interdisciplinary programs that have promoted students' comprehension [20, 21], analytical skills [3], critical thinking [22] and systems thinking [23, 24]. The theoretical explanation for these findings is based on Piaget's theory of cognitive development. Compared to a disciplinary course, an interdisciplinary course (either limited or extended, narrow or wide) provides more opportunities for learners in which they can link new knowledge with knowledge already exist. Therefore, learning is more meaningful in the latter case [25].

At the same time, interdisciplinary education may be perceived as superficial [26] or as unbalanced [27]. In the extreme case, the imbalance between the disciplinary and interdisciplinary components may cause the curriculum to be perceived by students as multidisciplinary rather than interdisciplinary [28]. In addition, interdisciplinary learning is often characterized by a heavy cognitive load. This load is usually due to the need to cover, in a relatively short time, a large number of concepts that are essential for understanding the relevant disciplines and the need to comprehend the interrelations among these concepts [29].

## 3. The Course "Electronic Circuits"

As mentioned, analog circuits and digital circuits are designed for different purposes and are characterized by different models. However, since both share the same underlying technology and physical devices, various parameters are interrelated. Moreover, the importance of mixed-signal design combining both analog and digital circuits has increased notably [2].

Therefore, and in view of the advantages of interdisciplinary education (Section 2), the Faculty of Electrical and Computer Engineering (Technion – Israel Institute of Technology), combined the course "Linear Electronic Circuits", focusing on analog electronics, and the course "Electronic Switching Circuits", dealing with digital electronics, into a single interdisciplinary course "Electronic Circuits". Similar to the two preceding courses, the new course is compulsory for junior electrical and computer engineering students. Prerequisites for the course are introductory courses in digital systems, electrical circuit theory, signals and systems and semiconductor devices.

At the end of the course "Electronic Circuits", the student should be able to:

- Analyze electronic circuits (analog and digital) based on mathematical, physical and engineering knowledge;
- Take system considerations (e.g., performance figures of merit) into account.

These learning goals are identical to those formulated in the preceding courses (for analog or digital circuits). The curriculum of the new course includes most (but not all) of the topics taught in the separate courses and at a similar level. At the same time, a few new chapters were added. Thus, for example, bipolar transistor technology was excluded from the interdisciplinary course syllabus, but analog to digital and digital to analog conversion was added to it.

Digital electronics is covered in the first part of the course (four weeks). This section focuses on the implementation of logic gates (NMOS and CMOS technologies) and digital circuits analysis (e.g., noise margins, transition times and delays, speed optimization and logical effort). The next chapter (six weeks) deals with analog circuits analysis, and covers, among other things, gain stages, linearization, equivalent circuits, frequency response, feedback and stability. The concluding section (three weeks) addresses interdisciplinary topics, e.g., analog to digital and digital to analog conversion [30].

The course puts an emphasis on analyzing an electronic circuit from both the analog and digital viewpoints and demonstrates the interrelations between them. Thus, for instance, the concept of gain in analog circuits is related to noise immunity in digital circuits, and the bandwidth of an analog amplifier is related to delay in logic gates. The course is based on the textbooks *Foundations of Analog and Digital Circuits* [5], *Analysis and Design of Digital Integrated Circuits* [31], and *Analog Integrated Circuit Design* [32]. The main topics covered in the course are listed in Appendix A.

The course consists of four hours of lectures and two hours of tutorials per week. In addition, three two-hour workshops are held during the semester, the first on digital electronics and the others on analog electronics. Course faculty is comprised of a lecturer (PhD in electrical and computer engineering) and teaching assistants (graduate students in electrical and computer engineering). The teaching method in all of the sessions is front facing. The assessment is based on homework exercises (24%) and a final examination (76%). For comparison, each of the preceding disciplinary courses consisted of three hours of lectures and one hour of tutorial every week. The teaching method in these courses was front facing, and the assessment was similar to that of the new course.

## 4. Research Goal and Questions

The study examined whether an interdisciplinary teaching approach of electronic circuits (i.e., combining analog and digital electronics) has advanced learning compared to the traditional disciplinary way (i.e., teaching analog electronics and digital electronics separately).

The following research questions were formulated:

- Is there a difference between the achievements of students who studied electronic circuits in an interdisciplinary approach and those of their peers who experienced the traditional way?
- What are students' attitudes toward interdisciplinary learning of electronic circuits?

## 5. Methodology

### *5.1 Participants*

One hundred and fifty-six junior electrical and computer engineering students (Technion – Israel Institute of Technology) participated in the study. These students have not previously been exposed to interdisciplinary learning.

### *5.2 Method*

The study used quantitative and qualitative tools to increase the findings' trustworthiness and to enable the presentation of various aspects of the phenomenon under study [33].

One hundred and fourteen students took the interdisciplinary course "Electronic Circuits" (hereinafter: experimental group), and 42 students attended the two disciplinary courses "Linear Electronic Circuits" and "Electronic Switching Circuits" in the same semester (hereinafter: reference group). According to a *t*-test, at the beginning of the study no significant difference ($p > 0.05$) was found between the cohorts of the two groups in terms of GPA ($M_{exp} = 84.10$, $SD_{exp} = 6.18$; $M_{ref} = 84.54$, $SD_{ref} = 6.92$), where the mean values ($0 \leq M \leq 100$) indicated that the average study participant was a good student. The teaching staff of the three courses was considered highly-qualified.

At the end of each of the three courses, students took an achievement test. Students were tested on the type of circuits (analog and/or digital) learned in the course. Each test focused on two skills: electronic circuits analysis and systems thinking (hereinafter: dependent variables). The score of a member of the experimental group was the score obtained in the achievement test of the interdisciplinary course, and the score of a member of the reference group was the mean of the scores obtained in the achievement tests of the disciplinary courses.

In addition, students from both groups filled out an open-ended questionnaire and some (11 students from the experimental group and 10 students from the reference group) were interviewed. The qualitative instruments were aimed to characterize respondents' attitudes toward interdisciplinary learning of electronic circuits (whether they have experienced it or not).

Achievement test results were statistically analyzed. Since some of the one-way MANOVA assumptions (e.g., homogeneity of variance-covariance matrices) were not met, independent $t$-tests (with Bonferroni correction) were conducted. Due to ethical considerations (access to the individual student's GPA was not allowed), ANCOVA was not performed.

The interviews were recorded and transcribed in full. The qualitative data were categorized through directed content analysis [34] performed by two experts in engineering education. The analysis relied on the tri-component attitude model [35], which was used in studies that investigated attitudes toward interdisciplinary learning [16]. Only information that has risen at least three times was included in the analysis. A possible difference between the experimental and reference groups regarding the behavioral component was statistically analyzed using a two-sample proportion test.

Ethical approval was obtained from the Institutional Review Board (permit #2018-062).

### *5.3 Instruments*

Each of the three achievement tests focused on electronic circuits (analog and/or digital) learned in the relevant course, and were similar in their level of difficulty. The few topics covered in the interdisciplinary course but not in the disciplinary courses (e.g., analog to digital and digital to analog conversion; see Section 3) or the limited number of subjects taught only in the disciplinary courses (e.g., bipolar transistor technology) were not included in any of the three examinations. Each test lasted one hour, and dealt with two skills (electronic circuits analysis and systems thinking). The use of a formula sheet and a calculator was allowed. Each test was written by the relevant teaching staff and validated by two experts in engineering education. The tests were graded by two independent reviewers using a rubric. A sample of the achievement test questions ("Electronic Circuits" course) is given in Appendix B.

In the open-ended questionnaires and interviews, respondents were asked, among other things, about their opinion on interdisciplinary learning of electronic circuits and their preference, i.e., the interdisciplinary approach or the traditional disciplinary way.

## 6. Findings

The main results of the study are presented below. First, the findings regarding student achievement are described, and then – those that relate to their attitudes toward interdisciplinary learning.

**Table 1.** Achievement Tests – Descriptive Statistics

| Group | Skill | M | SD |
|---|---|---|---|
| Experimental | Analysis | 68.96 | 21.32 |
| | Systems thinking | 59.62 | 21.77 |
| Reference | Analysis | 56.70 | 13.57 |
| | Systems thinking | 57.97 | 17.52 |

### *6.1 Academic Achievement*

Table 1 presents student scores ($0 \leq M \leq 100$) for the two dependent variables.

A $t$-test (with Bonferroni correction, $\alpha = 0.025$) revealed a significant difference ($p < 0.01$) between the experimental group and the reference group regarding electronic circuits analysis. This gap, in favor of the former, was characterized by a medium-large effect size ($d = 0.63$). As for systems thinking, no significance difference ($p > 0.05$) was found between the two groups.

### *6.2 Attitudes*

First, the attitudes of students who have experienced interdisciplinary learning of electronic circuits (experimental group) are presented. Then, the attitudes of their peers who have not been exposed to it (reference group) are described. Finally, the preference for interdisciplinary learning (behavioral component) is compared.

#### *6.2.1 Experimental Group*

Content analysis of the qualitative data identifies cognitive, affective and behavioral aspects of student attitudes.

In the cognitive domain, students claim that interdisciplinary learning has strengths as well as weaknesses. Regarding the former, about a quarter of the respondents (24%) argue that interdisciplinary learning constitutes a natural approach to electronic circuits analysis because the analog and digital perspectives are interrelated:

> "It [the combination of analog and digital electronics] feels natural and flows well." (questionnaire)
>
> "The connection between large signal [digital electronics] and small signal [analog electronics] cannot be ignored." (interview)

About a quarter of the respondents (23%) think that interdisciplinary learning contributes to the development of the professional career:

> "It seems that the combination [of analog and digital electronics] is relevant to my future areas of practice." (questionnaire)
>
> "It [the combination of analog and digital electronics] is a kind of preview for what electrical engineers do in the industry." (questionnaire)

About one-fifth of the respondents (19%) claim that interdisciplinary learning is relevant to electrical and computer engineering students because it exposes them to various fields of knowledge:

> "It [the combination of analog and digital electronics] is very important for the things I will study later in the program." (questionnaire)
>
> "The combination [of analog and digital electronics] helped me choose which topics to focus on in my studies." (questionnaire)

According to 10% of the respondents, interdisciplinary learning promotes understanding and analytical skills thanks to the integration that makes it possible to analyze an electronic circuit from both the analog and digital perspectives:

> "The combination [of analog and digital electronics] provides a deeper understanding." (questionnaire)
>
> "We were given tools to analyze a circuit in two ways [analog and digital] simultaneously." (questionnaire)

Alongside these strengths, students also identify weaknesses that characterize interdisciplinary learning. Most respondents (81%) argue that interdisciplinary learning imposes a heavy cognitive load stemming from the very broad scope of content, namely, analog and digital electronics:

> "The scope of the material is enormous." (questionnaire)
>
> "The main problem is the unreasonable amount of material." (questionnaire)

About a third of them (30%) claim that interdisciplinary learning tends to be superficial because the time allotted to it does not allow for sufficient in-depth study:

> "Separate courses [in analog electronics and digital electronics] are better. . . so that there is time to study [in a more in-depth way]." (questionnaire)
>
> "The connection [between analog and digital electronics] is clear, but I prefer to delve [into each subject separately]." (questionnaire)

From the affective aspect, almost half of the respon-

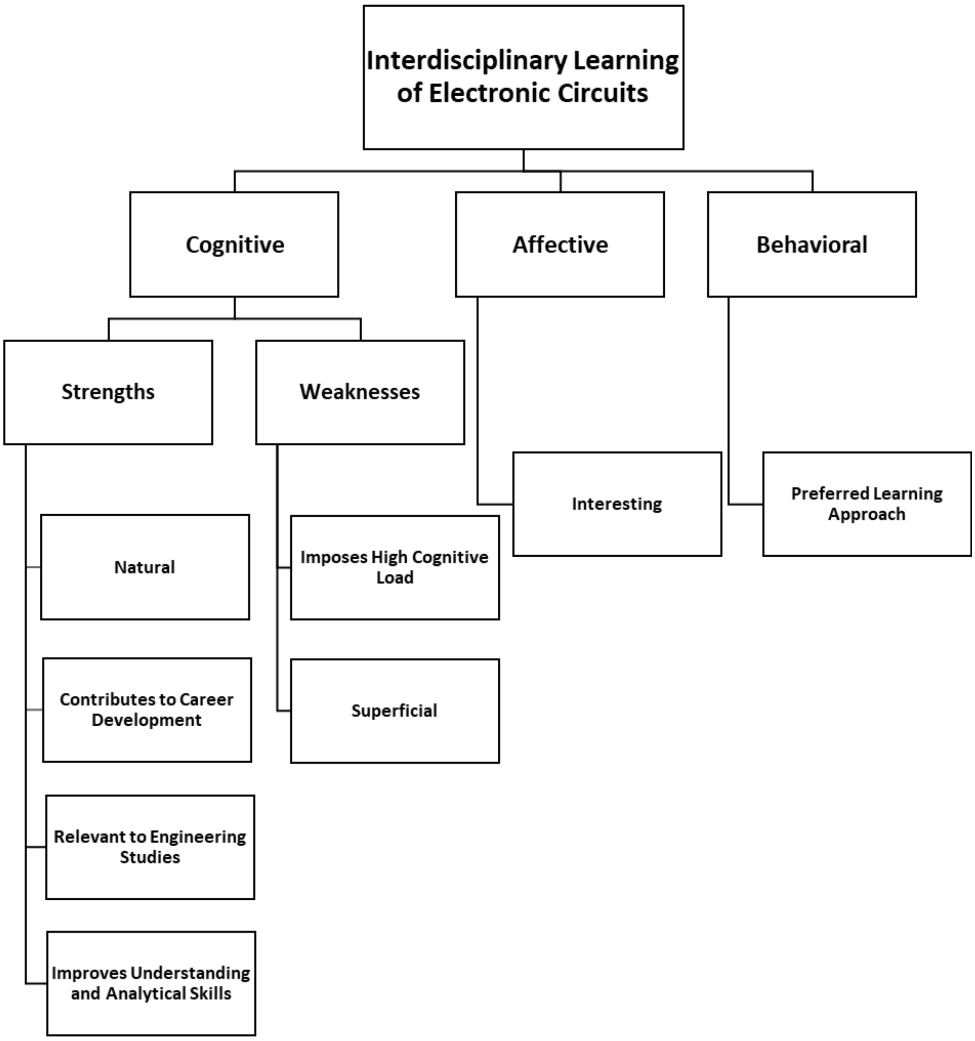


**Fig. 1.** Students' attitudes toward interdisciplinary learning of electronic circuits (experimental group).

dents (45%) think that interdisciplinary learning is interesting:

> "Interesting material." (questionnaire)
>
> "Everything was interesting." (interview)

In the behavioral domain, about one-third of the respondents (38%) prefer to learn electronic circuits in the interdisciplinary approach rather than the traditional disciplinary way. Fig. 1 displays students' attitudes toward interdisciplinary learning of electronic circuits.

### *6.2.2 Reference Group*

Content analysis of the qualitative data reveals cognitive and behavioral components of student attitudes.

In the cognitive domain, students think that interdisciplinary learning of electronic circuits has only weaknesses. About a quarter of the respondents (28%) believe that interdisciplinary learning impairs understanding since analog electronics and digital electronics are distinct fields based on different assumptions:

> "A combination of the two [branches] will be confusing and will hurt understanding." (questionnaire)
>
> "The assumptions [in each area] are different, and that can create confusion." (questionnaire)

Fifteen percent of them believe that interdisciplinary learning is unnatural because there is no connection between analog electronics and digital electronics as they have different uses:

> "In my opinion, there is no connection between the two [branches] because they [analog and digital] are two different uses of transistors." (interview)
>
> "I do not see how they [analog electronics and digital electronics] are related to each other." (questionnaire)

Fifteen percent of the respondents believe that interdisciplinary learning places a high cognitive load due to the wide scope of content:

> "Combining the content of the [two] courses [in analog electronics and digital electronics] into a single course will result in a very high load." (questionnaire)
>
> "The two separate courses [in analog electronics and digital electronics] are already busy. . . it seems crazy to me to combine them." (questionnaire)

And that it is superficial because of the inability to delve adequately:

> "Combining [analog electronics and digital electronics together] will result in a loss of knowledge." (questionnaire)
>
> "[In interdisciplinary learning] we will not be able to delve into the material." (questionnaire)

From the behavioral viewpoint, 14% of the respondents prefer to learn electronic circuits in the interdisciplinary approach rather than the traditional one. Fig. 2 shows students' attitudes toward interdisciplinary learning of electronic circuits.

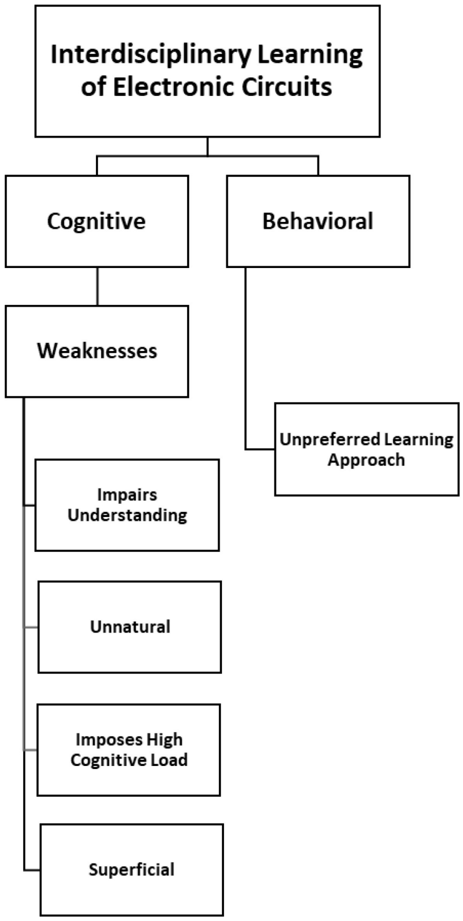


**Fig. 2.** Students' attitudes toward interdisciplinary learning of electronic circuits (reference group).

### *6.2.3 Preference for Interdisciplinary Learning*

A two-sample proportion test revealed a significant difference ($p < 0.01$) between the experimental and reference groups in the preference for interdisciplinary learning (38% vs. 14%, respectively). This gap was accompanied by a medium effect size ($h = 0.56$).

## 7. Discussion

The study described here examined whether an interdisciplinary teaching approach of electronic circuits (i.e., combining analog and digital electronics) has advanced learning compared to the traditional disciplinary way (i.e., teaching analog electronics and digital electronics separately). According to the findings, the achievements (analytical skills) of students taught via the interdisciplinary approach were significantly higher than those of their peers who studied in the disciplinary way. The gap was accompanied by a medium-large effect size. This result is congruent with findings showing that interdisciplinary learning often improves academic achievement. Thus, for example, achievements in STEM disciplines of students who attended a camp on robotics and GIS technologies were significantly higher than those of their peers who did not take part in the activities [36].

The improvement achieved in the present research is in line with the claim of study participants who were exposed to the interdisciplinary approach. According to them, comprehension and analytic capabilities are promoted due to the combination that makes it possible to analyze an electronic circuit from both the analog and digital viewpoints. The result is also consistent with reporting regarding high-school [19] and university students [20] who experienced interdisciplinary learning and noted that their understanding improved. These findings can be explained by the claim that compared to disciplinary learning, interdisciplinary learning further develops students' cognitive skills [21]. As mentioned in Section 2, the latter provides more opportunities for learners in which they can link new knowledge with knowledge already exist. Therefore, learning is more meaningful [3, 25].

In this study no significant difference was observed between the two approaches regarding students' systems thinking skills. This result could be explained by the findings that systems thinking is often promoted in active learning environments (e.g., project-based learning) [37, 38], which was not the case studied here.

The study identified various aspects in the attitudes of students who have experienced interdisciplinary learning of electronic circuits. From the cognitive point of view, students argue that interdisciplinary learning constitutes a natural approach to electronic circuits analysis (because the analog and digital perspectives are interrelated), contributes to the development of their professional career, and as mentioned above, advances understanding and analytic capabilities. Similar claims have been found in studies that characterized interdisciplinary engineering programs [19, 23]. Alongside these strengths, students argue that interdisciplinary learning involves a high cognitive load and tends to be superficial. These two weaknesses are often recognized in the literature as characteristics of interdisciplinary education. The heavy load is usually due to the need to cover, in a limited time, a relatively large number of topics that are essential for understanding the relevant fields of knowledge and the need to comprehend the interrelations among these topics [29]. The superficiality may be caused by the reason mentioned above [26] and/or by an imbalance between the disciplinary and interdisciplinary components [27].

In the affective domain, students who have been exposed to interdisciplinary learning find interest in it. This finding is consistent with the results of other studies that have characterized interdisciplinary learning at the high-school [39] and higher education levels [40]. In view of self-determination theory, the interest shown by students indicates a high level of autonomous motivation [41]. This is especially important in engineering programs, given the heavy load that characterizes them [42].

The results of the present study reveal that students who have not been exposed to interdisciplinary learning of electronic circuits find only weaknesses. They believe it is unnatural because there is no connection between analog electronics and digital electronics. Moreover, they think that interdisciplinary learning impairs understanding since analog electronics and digital electronics are distinct fields based on different assumptions. This position is the opposite of that of students who have experienced interdisciplinary learning, and contradicts the findings obtained from the achievement tests. This fundamental difference between the two groups underscores the need to expose students to interdisciplinary learning. The latter can demonstrate that despite their different assumptions and purposes, analog electronics and digital electronics are interrelated. At the same time, students from both the experimental and reference groups agree that interdisciplinary learning places a high cognitive load and tends to be superficial.

The findings described above are in line with the behavioral component in students' attitudes. It was shown that the preference for interdisciplinary learning was significantly higher among students who experienced it compared to their peers who were exposed to traditional disciplinary learning. This gap was characterized by a medium effect size.

The study faced one major limitation: the number of participants in the reference group was relatively small. The limitation was due to the low number of students who took the two disciplinary courses simultaneously in the semester in which the research took place. To reduce the impact of this limitation, both qualitative and quantitative tools were used [33].

The theoretical contribution of this research is in showing that the integration of *close* fields of knowledge based on *different* assumptions (e.g., analog electronics and digital electronics) promotes students' analytical skills (given the interrelations between these areas are discussed). The practical contribution of the study is in the application of its findings to advance the training of engineers. In this context, the authors recommend teaching electronic circuits in an interdisciplinary approach that emphasizes the interrelations between analog and digital electronics. It is advisable to reduce the number of topics taught and allocate sufficient time for in-depth study. It is also suggested to schedule the course when the study load is not high. These contributions are validated in light of the notable gap between the qualifications of engineering graduates and those needed in the industry [7] and in view of the few studies examining interdisciplinarity in engineering education [43].

In a further study, the authors intend to characterize faculty attitudes toward interdisciplinary teaching of electronic circuits.

## 8. Conclusions

The study examined whether an interdisciplinary teaching approach of electronic circuits has advanced learning compared to the traditional disciplinary way. The analytical skills of students taught via the interdisciplinary approach were significantly higher than those of their peers taught via the traditional way. The students who experienced interdisciplinary learning claimed that while it improved comprehension and analytic capabilities, it was characterized by a high cognitive load. The preference for interdisciplinary learning was significantly higher among students who experienced it compared to their peers who were exposed to traditional disciplinary learning.

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## Appendix A: "Electronic Circuits" Course – Syllabus

The following are the main topics taught in the "Electronic Circuits" course (Section 3):

Logic circuits, noise margins, transition times and delays, ideal logic gates, transmission gates, dynamic logic, static and dynamic power, speed optimization and logical effort, timing requirements, regeneration, synchronization, latch registers, sequential circuits, meta-stability, memory circuits.

Analog signal processing, gain stages, large vs. small signal, linearization, equivalent circuits, frequency response, differential amplifier, feedback and stability, noise analysis.

Analog to digital and digital to analog conversion [30].

## Appendix B: "Electronic Circuits" Course – Achievement Test

The following is a sample of the achievement test questions given at the end of the course "Electronic Circuits" (Section 5.3). Questions 1–4 focus on electronic circuits analysis and Questions 5–7 deal with systems thinking.

*Part I*

The following buffer circuit (Fig. B1) consists of two NMOS inverters. Each inverter drives a capacitive load equal to three times its input capacitance. Parasitic capacitors should be neglected; only input capacitances shown in Fig. B1 should be taken into account.

| | |
|---|---|
| $V_{DD} = 5V$ | $\mu_n^* = 200\ cm^2/Vsec$ |
| $V_{TN} = 0.5V$ | $\mu_p^* = 100\ cm^2/Vsec$ |
| $V_{TP} = -0.5V$ | $C_{OX} = 10\,fF/\mu m^2$ |
| $L_{min} = 0.1\mu m$ | $\lambda \rightarrow 0\ ;\ \gamma \rightarrow 0$ |
| $W_{min} = 1\mu m$ | |

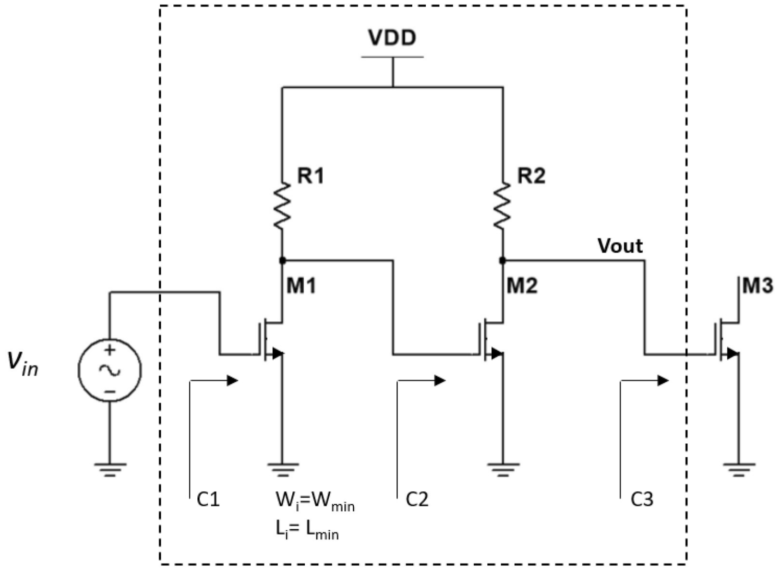


**Fig. B1.** "Electronic Circuits" Course – Achievement Test (Part I).

1. Determine the resistor values $R_1$ and $R_2$, so that the logic threshold $V_M$ of the inverters is equal $V_{DD}/2$.
2. Assume that the input signal $V_{IN}$ is an ideal step function (either increasing or decreasing) ranging between 0 and $V_{DD.}$
   a. Calculate the exact delay time ($t_{pLH}$) of the first stage. Assume that $V_{OL} \approx 0$.
   b. Assuming that during the discharge phase the resistor current is negligible, $I_R \approx 0$, and $V_{OL} \approx 0$, calculate approximately the delay time $t_{pHL}$. Justify your approximation.
   c. What is the ratio between the delay times calculated above and the delay times of the second stage?

*Part II*

The circuit is now operated as a small-signal amplifier (Fig. B2), where $V_{IN} = V_{DD}/2 + v_{in}$ and $v_{in}$ is a small-signal source.

3. How many poles does the transfer function of the amplifier have? What are the frequencies? Is there a dominant pole?
4. Apply the zero-value time constant method to calculate approximately the frequency $\omega_{-3dB}$.

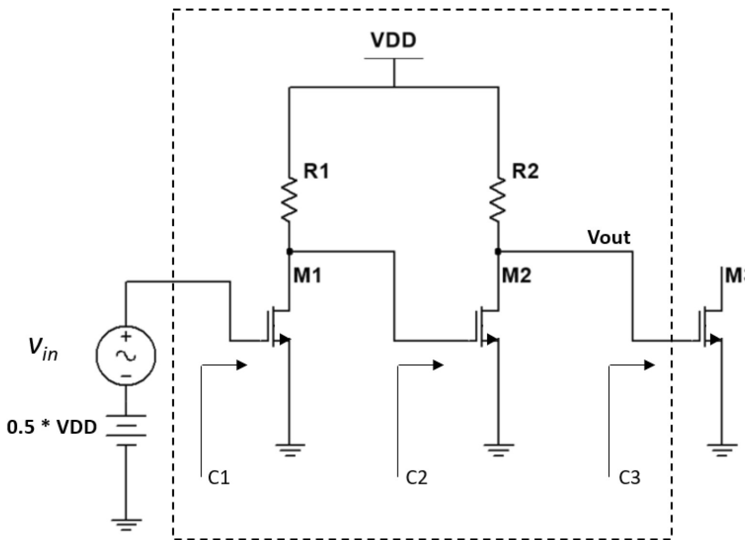


**Fig. B2.** "Electronic Circuits" Course – Achievement Test (Part II).

*Part III*

The resistors $R_1$ and $R_2$ of the original circuit are now replaced with PMOS transistors, so the circuit is comprised of CMOS inverters.

5. What is the effect of the change on power efficiency in the case where the circuit operates as a buffer?
6. What is the effect of the change on power efficiency in the case where the circuit operates as a small-signal amplifier?
7. What is the effect of the change on the low frequency small-signal amplification?

**Beto Catz** holds a BSc in Electrical Engineering, a BSc in Technology and Science Education (Summa Cum Laude) and an MSc in Technology and Science Education (Cum Laude), all from the Technion – Israel Institute of Technology. In addition, he has an MBA (Cum Laude) from the University of Derby, UK. Mr. Catz has many years of experience in electronics design and has served in technological and management positions in leading companies. He is an adjunct lecturer in the Department of Electrical and Electronic Engineering at Braude College of Engineering (Israel) and serves as the coordinator for interdisciplinary and entrepreneurship academic programs at the College's Engineering Education and Entrepreneurship Center. Currently, Mr. Catz is a PhD student in the Department of Education in Technology and Science at the Technion.

**Avinoam Kolodny** is a professor (emeritus) of electrical engineering at Technion – Israel Institute of Technology. After completing his doctorate in microelectronics at the Technion in 1980 he joined Intel corporation in Santa Clara, CA. During twenty years with the company he was engaged in diverse areas including non-volatile memory device physics, electronic design automation, and organizational development. He pioneered static timing analysis of processors at Intel, served as Intel's corporate CAD system architect, and managed Intel's performance verification CAD group in Israel. He has been a faculty member at the Technion since 2000, doing research on VLSI circuits and systems. Prof. Kolodny is a fellow of IEEE, for his contributions to VLSI design methodologies and automation tools.

**Aharon Gero** holds a BA in Physics (Summa Cum Laude), a BSc in Electrical Engineering (Cum Laude), an MSc in Electrical Engineering, and a PhD in Theoretical Physics, all from the Technion – Israel Institute of Technology. In addition, he has an MBA (Cum Laude) from the University of Haifa, Israel. Dr. Gero is an Assistant Professor in the Department of Education in Technology and Science at the Technion, where he heads the Electrical Engineering Education Research Group. Before joining the Technion, he was an instructor at the Israeli Air-Force Flight Academy. Dr. Gero's research focuses on electrical engineering education and interdisciplinary education that combines physics with electronics, at both the high school and higher education levels. Dr. Gero has received the Israeli Air-Force Flight Academy Award for Outstanding Instructor twice and the Technion's Award for Excellence in Teaching 16 times. He received the Israeli Air-Force Commander's Award for Excellence (2006), the Yanai Prize for Excellence in Academic Education (2016) and the Technion's Award for Continuing Excellence in Teaching (2022). Dr. Gero is an Associate Editor of IEEE Transactions on Education.