Enhancing Systems Thinking among High School Pupils:
An Interdisciplinary Program in Electro-Optics

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INTRODUCTION

A unique interdisciplinary program in electro-optics was recently offered to excelling high-school students in Israel. The program, which integrates physics and engineering, has three study phases: fundamentals of optics and electronics in 10th grade, an introduction to electro-optics in 11th grade, and electro-optical systems in 12th grade. A central part of the program is the final project, which is executed during the final year of study and requires the students to design and implement an electro-optical system.

Besides the desire to arouse interest among the students, the program was also designed to develop the students' systems thinking skills [1], which are increasingly needed in our age due to the fact that technological systems (including electro-optical systems) are becoming way more complex and interdisciplinary than ever before [2].

The research presented in the paper examined the change in the systems thinking skills of 12th grade students who attended the program. The authors chose to focus on 12th graders since in this phase of the program, the students execute their final project of designing and implementing an electro-optical system, during which they are expected to develop their systems thinking skills.

1 SYSTEMS THINKING

A system is a collection of components undergoing dynamic interaction with each other [3]. Systems thinking provides a framework for observing interaction between the system's different components [1] and argues that studying the properties of system components alone is not enough, but one must learn the interaction between the different components as well [4].

The characteristics of systems thinking were studied by many scholars [5]-[7]. When comparing the results of these studies [8], one can note the prominent features of systems thinking skills:

- Viewing the entire system beyond its components;
- Comprehending the interaction between the system's components;
- Comprehending system function without requiring all the details;
- Understanding the synergy within the system;
- Observing the system from several points of view;
- Ability to consider non-engineering issues (e.g. financial, organizational, etc.).

While some believe these skills are inherent [9], others argue systems thinking is a combination of inherent talent and experience and may be taught [10]. Application of systems thinking in education shows that students' active involvement in their learning environment promotes acquisition of systems thinking skills, although the progress rate depends on the students' cognitive skills [11]-[12].

2 THE CURRICULUM

The study program in electro-optics comprises three phases of studies: fundamentals of geometrical optics (e.g. basic optical components) and electronics (e.g. operational amplifiers) in 10th grade; an introduction to electro-optics (e.g. wave optics and light-matter interactions) in 11th grade; and electro-optical systems such as optical communication systems in 12th grade. Studies include theoretical lessons as well as practical lessons in the laboratory and in simulation environments such as MATLAB.

In light of the challenges of developing interdisciplinary curriculum [13], emphasis was placed on achieving a balance between the interdisciplinary and disciplinary components of the program, as shown in *Table 1*.

A central part of the program that aims at developing the students' systems thinking skills is the final project, which is executed during the third year of study. The project spans 180 hours, during which the students design and implement an electro-optical system based on an 8051 microcontroller. The project, which is carried out in teams of two to three students and is guided by a teacher, involves both hardware and software components. Examples of projects are a system that tracks the sun's movement and produces electricity throughout the day and night, and an electro-optical system that identifies contact with a security fence and directs security forces to the said location.

Table 1. Curriculum of the electro-optics program

Academic Year	Topic	Description
10th grade	Introductory studies	a. Geometrical optics (24 h): Reflection law, refraction law, total internal reflection, mirrors, lenses, the eye, camera, telescope, microscope* b. Electricity (6 h): Electrical current, electrical voltage, electrical resistance, Ohm's law, equivalent resistance, Kirchhoff's laws* c. Electronic components and systems (12 h): Sinusoidal signals, operational amplifiers**
11th grade	Introduction to electro-optics	a. Electromagnetic waves and the electromagnetic spectrum (7 h)* b. Wave optics (12 h): Interference, diffraction, dispersion and polarization* c. The dual nature of light (2 h): The photoelectric effect* d. Atomic structure (2 h): Energy levels and Franck-Hertz experiment* e. Light-matter interactions (2 h): Absorption, spontaneous emission and stimulated emission* f. Fundamentals of modulation (18 h): AM/FM**
12th grade	Electro-optical systems	a. Optical fibers (15 h): Structure and principle of operation, applications*** b. Light sources in optical communication (15 h): LED, laser*** c. Radiation detectors (15 h): Detector characteristics, noise sources, photodiodes, solar cells*** d. Optical communication systems (30 h): Structure and principle of operation, applications*** e. Final project (180 h)***

*Disciplinary component (Physics)
**Disciplinary component (Engineering)
***Interdisciplinary component

3 RESEARCH GOAL AND METHODOLOGY

The research goal was to track changes, which took place during the final phase of the electro-optics program, in students' systems thinking skills. The research population comprised of fourteen 12th grade students who attended the program. The students were asked to fill out an anonymous questionnaire both at the beginning of the academic year and at its end. Additionally, six semi-structured interviews were held with students at the end of the year.

The questionnaire designed to characterize systems thinking skills was a binary questionnaire based on the CEST (Capacity for Engineering Systems Thinking) questionnaire developed by Frank et al. [14]. The questionnaire included six pairs of statements that reflect the properties of systems thinking mentioned above. Students were requested to indicate, for each statement pair, which statement best describes his or her attitude. For instance, in the following statement pair, Statement (a) reflects a high level of systems thinking skills: "(a) When I am responsible for the development of a certain component that is part of a product, it is important that I understand how the component is integrated into the overall product; (b) When I am responsible for the development of a certain component that constitutes part of a product, I am not interested in the rest of the components for whose development I am not responsible." In the following statement pair, on the other hand, it is Statement (b) that reflects a high level of systems thinking skills: "(a) The economic aspects of an engineering project are the concern solely of the project manager; (b) When I am involved as an engineer in an engineering project, it is important that I familiarize myself with the economic aspects of the project." All statements were validated by two engineering education experts.

4 FINDINGS

Figure 1 presents the mean systems thinking score (ranging between 0 and 10) on the pretest, filled out at the beginning of the school year and on the posttest, completed at its end. The graph shows that students' systems thinking skills improved over the course of the academic year. Cohen's d was found equal to 0.43, indicating moderate level of effect size.

Excerpts from students' interviews reveal that they recognized the importance of viewing the entire system beyond its components:

"Had I not seen the entire system [which I designed as part of the final project], I would not have been able to decide how each component was to work… I had to have a general theoretical view of the way the system is supposed to work".

In addition, students acknowledged the importance of understanding the interaction between the system's components:

"There were changes during the course of the project… there was supposed to be an automotive battery but we ended up using batteries [which are smaller in size] because we didn't initially take into consideration the space required for the other parts of the system".

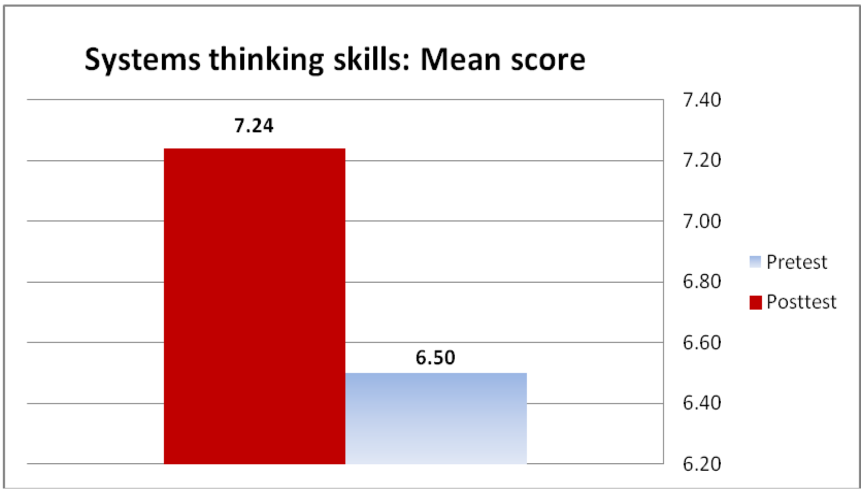

Fig. 1. Systems thinking skills: Mean score

5 SUMMARY AND ACKNOWLEDGMENTS

A three-year high-school program in electro-optics was recently developed. The curriculum integrates engineering principles into the teaching of physics with the objective of enhancing students' interest in these subjects and developing their systems thinking skills. This study evaluated changes in the systems thinking skills of 12th grade students who attended the program.

The research found that students' systems thinking skills improved over the course of the year and that they began adopting some of the systems thinking properties, such as viewing the entire system beyond its components and understanding the interaction between the system's components.

It is important to note that universities offer courses aimed to develop systems thinking skills of freshman engineering students [2]. The results obtained in the study show that it is possible to improve the capacity for engineering systems thinking earlier, namely, at high school level.

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