

A High-School Program in Software Engineering

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Abstract

We describe a comprehensive three-year program in Software Engineering (SE) for high-school which has been operated in Israel for the last two decades. The aim of the program is to expose young students to the field of computing, and to motivate them to continue their academic studies in that field. The program has evolved over the years in accordance with the changes in the discipline of computing. It introduces students to scientific methods, principles of design, and implementation of computer systems. Currently it consists of a three-phase modular structure: (a) natural sciences, (b) computer science, and (c) advanced specialized topics in computing. During the third year, students are required to develop as a final assignment a comprehensive software project, namely a computer system in a specific, specialized domain.

1. Introduction

Educators have noted the importance of teaching software designing skills to high school computer science students [e.g., 13,15,28]. During the last two decades a program in Software Engineering (SE) especially designed for high-school level has been in operation in Israel. Since "*computing has changed dramatically over time in ways that have a profound effect on curriculum design and pedagogy*" [1, p.1], the program presented here, similarly to others, has evolved over the years and was influenced by changes in the computing field and the development of computer technology.

1.1. The high-school education system in Israel

The education system in Israel is basically centralized and the studies in high-schools have a uniform basic structure. The schools are classified according to one of three tracks: general (academic, theoretical), technological (vocational) and agricultural. Students attend classes 32-36 hours weekly and may study up to 15 subjects at a time. Subjects are taught in instructional units of 90 hours. Upon completion of Grade 12, students may take the matriculation exams. The requirements for obtaining the current Matriculation Certificate are 20 units in a range of 20-25; a minimum of 15 units in compulsory subjects are required. In addition, students who take the technological track have to be examined in 7-15 units in technological subjects in order to get a Technological Certificate in addition to the Matriculation Certificate.

One of the outcomes of the education system's centralization is that the programs of all the

technological sub-tracks have always had a common modular structure, which evolved during the years in accordance with the development of technology. Currently, all technological programs consist of the following 3-phase general structure: (a) an elective topic in natural sciences/introduction to technology sciences, (b) a basic mandatory specialized topic, and (c) an elective advanced specialized topic.

In spite of its uniform structure the program allows flexibility to some extent. It includes, besides mandatory units, elective units, meaning that the teachers in each school are entitled to prepare a specific program according to their professional preference that suits their students' background, abilities, interests, and needs.

1.2. The program's evolution

Originally, The Software Engineering program for high school was uniform and consisted of three mandatory topics: *Introduction to CS*, *Management Systems Analysis*, and *Design & Programming (D&P) of Information Management Systems*. COBOL was chosen as a suitable programming language to teach the implementation of systems of that type. Although the main learning objectives of the program were to teach the basics of the development and implementation of information management systems (e.g. system modeling and analysis, data organization, and system's life cycle) it mostly emphasized technical aspects of programming at the expense of discussing the basic concepts and principles of the science of computing.

In the early 1990s as a result of the computing field's expansion, a special committee selected by the Ministry of Education recommended to modify and update the curriculum. The committee stated that the advanced specialized topic should be elective, and suggested syllabi for 3 additional specialized topics: *Computer Graphics*, *Operating Systems*, and *Expert Systems* [4]. The committee also recommended that students should learn natural sciences as additional enriching topics. However, that recommendation was avoided by many principals who operated the program in their schools mostly because of: (a) pedagogical considerations - they were afraid that learning an additional advanced scientific topic might be a burden for the students and might cause a cognitive overload; (b) budget constraints – based on local institutional priorities and specific problems related to management.

A significant change aimed at establishing a scientific background for the program and at promoting students' understanding of the scientific method was initiated by the first author, who served (1996-1998) as the head of the computer science and information technology section of the Ministry of Education. To promote the studies of natural sciences by SE students, it was decided to change previously mandatory management systems analysis topic to be an elective topic together with the natural sciences topics (physics, chemistry, biology). Nevertheless, a 90-hour learning unit, which was part of the management systems analysis topic and concentrated on introduction to information systems implemented in a (computing) application builder (e.g. ACCESS), was declared mandatory for all SE students. Consequently, since then, most of the students who had specialized in information management systems chose to learn the original syllabus of the management systems analysis topic, whereas most of the students who specialized in computer graphics, operating systems, and expert systems instead chose to study natural sciences. Since the science-oriented high-school studies have always been highly appreciated by the Israeli academic system, this change markedly promoted the status of the SE high-school studies. As a result, there was a significant ongoing growth in the number of schools that decided to operate the software engineering program and in the number of students who chose to participate it (Figure 1).

The next change in the program occurred at the beginning of the 2000s as part of substantial organizational changes that were made in the technological track. The Ministry of

Education decided to reduce the gap between the general (academic, theoretical) track and the technological track in order to enable student movement between tracks. The underlying objective was to motivate science-oriented students in the academic track to specialize in advanced technology topics. The need for an adequate scientific background for taking the technological track was noted, and all the technological sub-tracks programs were reorganized in a common modular science-based structure (previously described in section 1.1). Specifically, changes were made in the software engineering program: the management systems analysis elective topic and the mandatory introduction to information systems learning unit were removed and the program consisted of the following components: (a) an elective topic in natural sciences/introduction to technology sciences, (b) computer science, and (c) an elective advanced specialized topic in computer science. As a result, the program was now based on scientific foundations and can be viewed as an extension of the computer science program described in [13, 14]. In addition, the second author, who currently serves as the head of the computer science and information technology section in the Ministry of Education (1998-now), decided to extend the program with new elective specialized topics, with the aim of reflecting and incorporating the latest development of computing technology: *XML Web Services* and *D&P of Network Systems*.

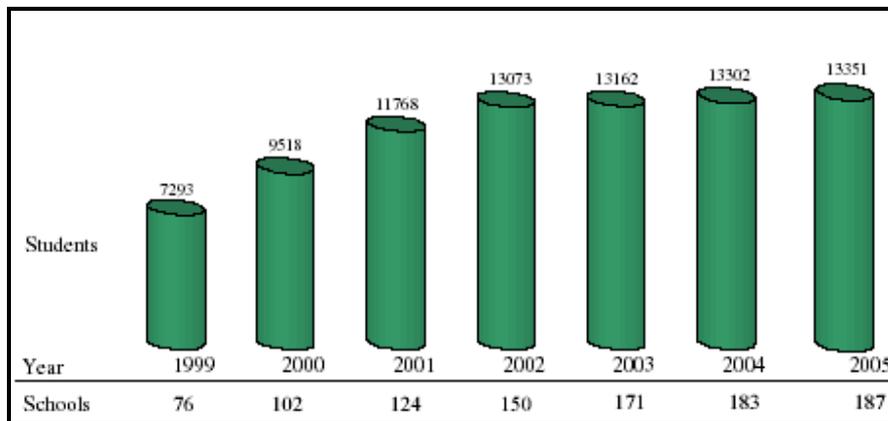


Figure 1. Number of schools/students attending the SE program (Grade 10-Grade 12)

Currently, the target population of the software engineering program consists of (1) students from the technological track who decided in advance to specialize in computing, and (2) students from the general-academic track who choose to learn computer science as an elective topic and became interested in expanding their knowledge of the subject.

1.3. Further Studies

The SE graduate students may continue in a special study track: one-year program toward achieving a SE technician diploma, or a two-year program toward achieving a SE practical engineer diploma. Graduates of the two-year continuation program may get accreditation in various academic computing studies, depending on their achievements (e.g. B.Sc. in computer science or software engineering).

2. Description of the Program

The Joint Task Force on Computing Curricula 2001 stated, among others, the following guidelines:

"Computer science, after all, is an ever-expanding field that includes many activities beyond programming. Courses that emphasize only this one aspect fail to let students experience the many other areas and styles of thought that are part of computer science as a whole" [1, p. 35].

"Because of the importance of computer systems and the wide applicability of computer-based skills, introductory computer science experience should certainly expose students to the design, construction, and application of computer systems and offer them training in skills that have demonstrated utility" [1, p. 26].

The software engineering program for high school presented here was developed following a similar pedagogical approach.

2.1. Objectives and underlying principles

The main goal of the program is to open a window for young students to the field of computing, and to motivate them to continue their academic studies in this field. The program was not designed to train students to become software professionals; instead, its aim is to expose the students to a fundamental scientific domain whose principles are characteristic of algorithmic thinking as well as system-level perception. It introduces the students to a sort of "high-level scientific language" for algorithmic problem solving, knowledge representation, and formalization of processes. Specifically, its aim is to enhance students' problem-solving abilities and reasoning skills; to promote their creativity; to help them to gain a system-level perspective and a basic understanding of larger systems and their organization principles, and to enable them to construct an integrative and generative knowledge of a variety of computer science topics.

Since educators found a large disparity between the thinking habits and attitudes toward system development process of beginning students and those of expert software developers [e.g. 12], it is important that students (even if not trained specifically to become software professionals) should *"acquire correct programming habits, suitable for the development of large complex programs.... [so that they will be able to] cope with developing large software systems in the future"* [15, p. 26].

The following underlying principles of the CC2001 curriculum reflect the objectives and the pedagogical approach of the presented program:

- *System-level perspective* - Graduates must develop a high-level understanding of systems as a whole: the structure of computer systems and the processes involved in their construction and analysis.
- *Understanding the interplay between theory and practice* - Graduates must understand not only the theoretical underpinnings of the discipline but also how that theory influences practice. Accordingly, conceptual and experimental issues should be interwoven throughout the program [13].
- *Familiarity with common principles* - Graduates must recognize recurring concepts and principles such as recurring themes, e.g., abstraction, complexity, modularity, and reusability.
- *Integrative knowledge* - To ensure that graduates can successfully apply the knowledge they have gained throughout the program, they must be involved in at least one substantial software project.

- *Capabilities and skills* - Graduates should develop a wide range of cognitive capabilities and practical skills, some of them related to computer science and others of a general nature and applicable in many other contexts as well.

2.2. Components of the program

The three-phase program is modular and flexible and can be easily adapted to various student populations (e.g., diverse classes and individual students in heterogeneous classes). Phase A and B consist of 3-unit modules (270 hours) or 5-unit modules (450 hours) each of which is composed of compulsory and elective 90-hour instructional units. Phase C is a 5-unit complete module of compulsory units. Its flexibility is achieved by final projects which students may develop in different levels (1-unit, 3-units, or 5-units). The flexibility of the program allows students to do matriculation exams at different levels that are suited to their learning abilities. To successfully address the requirements of the SE track students must pass 3 matriculation exams (one of each phase) consisting of 7-15 units.

2.2.1. Phase A – Natural Sciences: According to the recommendations of Computing Curricula 2001 [1] a successful computer science graduate needs skills beyond the technical ones found in the CS body of knowledge. For example, "*computer science students must have a certain level of mathematical sophistication, familiarity with the methods of science Students must develop an understanding of the scientific method and experience this mode of inquiry.... Students may acquire their scientific perspective in a variety of domains, depending on program objectives and their area of interest*" [1, p. 40-41]. This approach is reflected in the SE program presented here, since students participating in the program are obliged to study 3-5 units of mathematics and at least one advanced scientific subject (e.g., physics, chemistry, biology) or a basic subject - introduction to technology sciences, following a program that was especially designed for "non-scientifically oriented" students. Actually, most of SE students choose to study mathematic in advanced level (4-5 units).

2.2.2. Phase B – Computer Science: During the last decade a new program in computer science has been taught in Israeli high schools. The program emphasizes the foundations of algorithmic, and introduces CS concepts and problem-solving methods independently of specific computers and programming languages, along with the practical implementation of those concepts and methods in programming languages. The 5-unit (450 hours) program is modular and includes 2 mandatory modules: Fundamentals of Computer Science (2-units; 180 hours) and Software Design (1-unit; 90 hours), and 2 elective modules: Second Paradigm/Applications (1-unit; 90 hours) and Theory (1-unit; 90 hours). The underlying principles and pedagogical framework of the program are presented in [13]; the curriculum and course syllabi are presented in [14].

The advanced study unit of the curriculum, Software Design, is actually an introductory course in software engineering. It aims at taking the students beyond stand-alone algorithms, and introduces them to various aspects of software systems design. One important goal of the unit is to demonstrate "*full integration of the conceptual material and the actual hands-on experience in designing and constructing a real system*" [15]. After studying this unit the students are better prepared to proceed to a higher level of system design and development.

2.2.3. Phase C – Specialization in an advanced topic: Phase C is designed to enable

the students to achieve expertise in an advanced computer science topic. The specialization phase is called: *Design & Programming (D&P) of Software Systems* since it is designed to teach, in addition to theoretical principles, also design methods and implementation tools that are suitable for the specific advanced topic. Currently the program suggests 6 alternative topics: *Information Management Systems, Computer Graphics, Operating Systems, Expert Systems, Web Services, and Network Systems*.

Students study the advanced topic for 450 hours during the two last years of high school. Theoretical principles and practical experimental issues of the topic are introduced and practiced in the laboratory. The studies include the learning of a programming language/environment that is suitable for implementing the theoretical material of the advanced topic. During the third year, students are required to develop as a final assignment a comprehensive software project.

3. Developing Software Designing Skills

The Software Engineering 2004 Curriculum states that incorporating real-world elements (e.g., case studies, project-base courses and capstone courses) into the curriculum is necessary to enable effective learning of software engineering skills and concepts [3]. Specifically, capstone projects have been recognized as an essential part of SE education [7,10,22].

The academic CS community believes that the role of projects in the curriculum is of great importance, since it is a means for effective learning, and also demonstrates the student's mastery of skills appropriate to professional practice [11,22,28]. Project development enables students to construct knowledge and to enhance cognitive and reflective skills; it also encourages the student to become a creative and independent learner. In addition, it enables students to encounter real life experience as project developer [9,15,25].

Software design skills and problem solving abilities are gradually developed during the studies of the presented program: (1) The Second Paradigm/Applications module of the CS program (phase B) requires a mini-project in which the student has to utilize the specific knowledge he acquired studying this module; (2) When studying the Software Design module of the CS program students solve problems that focus on various aspects of design; (3) During the last year of the specialization studies (phase C) the students develop a final project- a software system typical for the learned advanced topic, where they apply, in addition to the design methods and implementation tools that are suitable for the specific advanced topic, the integrated knowledge that they have acquired during their three years of studies.

The projects are developed in the following stages: choosing a problem; analyzing and planning; programming and testing. In the end, the students have to submit a working system and a written report that describes the problem and documents the outcomes of each stage of the development process; it must include a documented code. The role of the teacher is to guide and to control the students' progress in various stages of developing the project, for example, checking if the product addresses the initial specification and requirements; checking if the student progresses according to a planned time table; assessing the use of design methods, and assessing the quality of the programming [20, 24, 25, 29].

In order to support project-based learning and the instruction of CS/SE didactical approaches and appropriate learning materials were developed [13,21,24,27]. Workshops for in-service teachers were conducted to discuss pedagogical aspects of

project-based learning, such as students' difficulties, project development, and assessment issues [26].

4. Assessment

The software engineering program for high school has been operating in Israel for the last two decades. Figure 1 illustrates how the program has been disseminated in the last few years. Here we will refer to the following aspects of the program's implementation: (a) advantages and disadvantages of the program, and (b) its outcomes in terms of the students' acquired knowledge.

The assessment of the students' knowledge has been formally conducted by the Ministry of Education in the form of matriculation exams. In addition, there is also a large body of research that has been conducted by education researchers aimed at evaluating learning materials and their influence on students' performance, as well as inquiring about the students' conceptual knowledge [6, 8, 15, 16, 17, 18, 19, 20, 21, 24, 25, 27, 29].

4.1. Formal assessment of students' performance

According to the instructions of the Ministry of Education in Israel, the formal assessment of the students' performance is based on a combination of traditional (i.e. written exams) and alternative evaluation (i.e. project assignments).

4.1.1. Students' achievements in written exams

Generally, the aim of the written matriculation exams in computer science is to assess the students' problem-solving performance. It includes two types of open questions that require students to provide solutions to given problems or to analyze given solutions. Table 1 illustrates the students' achievements in written matriculation exams in the last three years (2003-2005) in the basic module (fundamentals of computer science) and in the advanced module (software design and theoretical subject). The distribution of the grades for each year is slightly skewed right with a slightly higher average grade in the basic exam than in the corresponding average grade in the advanced exam. The findings indicate that the students acquired the desired knowledge and performed satisfactory in the problem-solving assignments.

Table 1: Students' achievements in written matriculation exams in CS (2003-2005)

Module	2003		2004		2005	
	Basic	Advanced	Basic	Advanced	Basic	Advanced
No. of Students	12107	8418	11220	7297	10781	6679
Failed (Grade: 0-54)	15%	18%	11%	17%	9%	20%
High Achievers (Grade: 85-100)	40%	27%	52%	31%	55%	39%
Average	75	71	79	72	84	72
Median	80	74	85	76	93	89
STDV	20.1	19.1	19.1	19.4	20.3	23.2

4.1.2. Software design and project development

According to the Ministry of Education in Israel, the students who participate in the program are required to develop individual projects in some learning modules instead of a traditional matriculation exam: (a) a mini-project in which the student has to utilize the specific knowledge he has acquired studying the Second Paradigm/Applications module of the computer science program, and (b) a final comprehensive software project in the learned specialized domain. External examiners evaluate the projects using analytic rubrics especially designed for each specialized topic [5]. For example, the rubric for evaluating projects in the *Web Services* specialization domain is as follows:

Rubric for evaluating projects in the <i>Web Services</i> specialization domain
<ul style="list-style-type: none">• Project portfolio 30/100 points<ul style="list-style-type: none">○ Readability of project files: 2 pt.○ Description of the system and its purposes: 8 pt.○ Description of database, modules, relations and data flow: 8 pt.○ Site map and description: 6 pt.○ Users guide: 6 pt.• Programming 55/100 points<ul style="list-style-type: none">○ Readability of software: 3 pt.○ Modularity, classes and structure: 5 pt.○ SQL queries: 10 pt.○ Using ASP.NET: 10 pt.○ Using Web Services: 10 pt.○ Interfaces and their computability to system demands: 9 pt.○ Visualization and human engineering: 5 pt.○ Originality, creativity, and special sophistication: 3 pt.• Demonstration 15/100 points<ul style="list-style-type: none">○ At examination time the project must work, otherwise the student will FAIL○ The student must be familiar with every aspect of the project.

The study findings indicated that students are highly motivated to do this kind of assignment and usually prefer to develop projects rather than to complete a written exam [20,25].

The average grades of the mini-projects as well as the final projects are usually very high compared with the average grades of the written matriculation exams. For example, in 2005 the average grades were 94.8 for the mini-projects and 92.9 for the final projects—much higher than the corresponding average grades of the written exams (basic modules - 84; advanced modules - 72). The differences in the achievements in the traditional exam vs. the projects are due to the different characteristics of the traditional and the alternative evaluation: (a) the projects are gradually developed in a non-stressed environment (mostly at home) and under the mentoring of the teachers; and (b) students who attend a traditional written exam cannot consider dropping the course if they do not pass the exam. In contrast, students who fail, for any reason, to

produce a final working project may decide to drop the course and therefore do not take the exam.

4.2. Academic assessment of students' conceptual knowledge

Qualitative research studies have been conducted aimed at identifying students' difficulties and assessing their CS conceptual knowledge. Students' perceptions of basic computing concepts (e.g. variables [19], and correctness [8]) as well as advanced concepts were investigated (e.g. recursion [18], abstraction [15,21,29], efficiency [16,17], and non-determinism [6]). The study findings served as the basis for didactical recommendations and curricular enhancements. For example, Haberman and Scherz (2002) investigated students' conception of abstract data types (ADTs). The findings indicated that the students demonstrated an integrative knowledge of ADT boxes as programming tools, and employed unique autonomous problem-solving strategies when using ADTs in programming [21]. Ragonis, Shapiro, Ben-Ari and Scherz (1998) evaluated students' conceptual knowledge of expert systems (one specialized topic of the SE program). Evaluation of the course showed that it was successfully implemented and found suitable for the intended student population. The students' achievements were high, and the main concepts were successfully acquired [27].

Qualitative research studies have been also conducted aimed at (a) evaluating the software designing skills developed by students, and (b) identifying the students' project development strategies. For example, Gal-Ezer and Zeldes (2000) found that high-school students who studied the software design module exhibited difficulties in designing general top-down solutions for a given problem; and instead, they preferred to deal with specific examples. The students, however, were able to reuse general structures to distinguish complex tools from basic tools [15]. Scherz and Haberman (2005) found that students who used problem-solving organizing tools in developing their projects were more likely to use abstract data types that resulted in a structured and well-organized development process [29]. Pollack and Scherz (2003) investigated the influence of supportive learning materials on high-school students' motivation, performance, and final products regarding the projects in computer science that they developed. The study findings indicated that students who tended to perceive projects as a school activity were mainly motivated by outside rewards such as the projects' external assessment. Moreover, students who did not use supporting materials for project-based learning tended to modify the original problem according to their ability to develop a proper project [24,25].

4.3. General evaluation of the program

The Computing Curricula 2004 Overview Report discusses the similarities and differences of CS and SE academic curricula: *“Both CS and SE curricula begin by requiring a foundation in programming fundamentals and basic CS theory. They diverge in what they focus on beyond those core elements. CS programs tend to keep the core small and then expect students to specialize selectively in one or two of areas of CS concentration (such as systems, networking, database, artificial intelligence, theory, etc.). In contrast, SE programs generally provide less freedom of choice about advanced computer science topics, and instead expect students to focus on a range of topics that are essential to the SE agenda (problem modeling and analysis, software design, software verification and validation, software quality, software process, software management, and so on)”* [2, p.38].

According to this distinction, the program presented here has the characteristics of

an academic CS program since it is composed of a fundamental core and offers the students the possibility of specializing in one specific advanced CS topic. Moreover, the SE program for high school does not include formal topics that are essential for the academic SE programs (e.g., software verification and validation, software quality).

We believe that the program manages to expose the high-school students to the field of computing and enables them to experience software design and development processes. However, the settings of the project development assignment have several shortcomings:

- Usually the projects' performances provide evidence of students' high programming skills and their in-depth investment in developing the project; however, the development processes do not resemble actual research and development industrial processes, and the products are rarely applicable to real-world situations.
- Usually, the specifications of the product are not provided by a real external client;
- The teachers are not members of the SE community of practice, and they usually lack practical industrial experience;
- The school labs are far too inadequate to provide the infrastructures characteristic of high-tech industry.
- The students develop individual projects (team-projects are not approved for formal external evaluation by the Ministry of Education). However, as long as this policy continues, teachers may apply alternative solutions to initiate group-work. For example, they may encourage students to perform peer-assessment of their intermediate products and the development of the final projects. Moreover, the teachers may incorporate project-based classes into their teaching [12,13].

5. Concluding remarks

In this paper we presented a three-year software engineering program for high-school students. The main goal of the program is to open a window of opportunity for young students in the field of computing, and to motivate them to continue their academic studies in this field.

The study findings indicated that the program succeeds in exposing the students to a fundamental scientific domain whose principles are characteristic of algorithmic thinking as well as system-level perception. Moreover, the final project assignment, which is part of the presented program, enables high-school students to experience software design and the processes of development, as well as to acquire a system-based perception of software engineering

However, although the program was not designed to train students to become software professionals, it is recommended that the students be exposed, as part of their studies, to "real-world" research and industrial development processes that are related to the software engineering projects of the high-tech industries. This can be partially achieved, for example, by informal enrichment meetings in which CS/SE scientists and practitioners will give appropriate lectures to the students [30]. In addition, "visiting the industry" tours should be encouraged.

Moreover, we believe that it is most important that the high-tech industry will take

an active part in educating potential newcomers, and will contribute to making the software engineering professional domain more attractive, especially in view of the last high-tech crises.

6. References

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Captions for figures:

Figure 1. Number of schools/students attending the SE program (Grade 10-Grade 12)

Captions for tables:

Table 1: Students' achievements in written matriculation exams in computer science (2003-2005)