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Assessing Advanced High School and Undergraduate Students' Thinking Skills: The Chemistry—From the Nanoscale to Microelectronics Module

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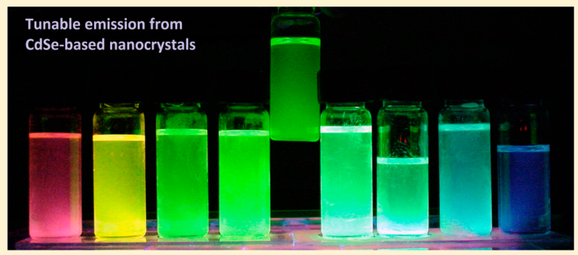
Supporting Information



ABSTRACT: Chemistry students in Israel have two options for studying chemistry: basic or honors (advanced placement). For instruction in high school honors chemistry courses, we developed a module focusing on abstract topics in quantum mechanics: Chemistry—From the Nanoscale to Microelectronics. The module adopts a visual−conceptual approach, which replaces mathematical derivations and includes interdisciplinary, real-life applications. The module has also been used as enrichment material for an undergraduate mathematically oriented quantum chemistry course. We assessed the comprehension of quantum mechanical concepts and the thinking skills of high school honors students and undergraduate chemistry students who studied this module. These skills included visual and textual chemical understanding, graphing, and far transfer of learning. Participants included over 100 high school honors students in high and intermediate levels, and over 60 undergraduate students, with students separated into groups of those exposed to the module and those who received mathematics enrichment instead. The questionnaires revealed that both high school honors students and undergraduate students improved their scores. High-level academic students outperformed their undergraduate peers, and undergraduate students who had been exposed to the module outperformed undergraduates who had studied the topic with mathematical enrichment. The research contributes to the field of teaching quantum mechanics and thinking skills, suggesting that high school honors students and undergraduate students could benefit from studying quantum mechanics using a visual−conceptual approach along with real-life applications. This contribution is part of a special issue on teaching introductory chemistry in the context of the advanced placement (AP) chemistry course redesign.

KEYWORDS: *High School/Introductory Chemistry, Upper-Division Undergraduate, Nanotechnology, Testing/Assessment, Quantum Chemistry, Curriculum*

■ INTRODUCTION

In the past decade, educators and researchers have been trying to shift the goals of science education from emphasizing the acquisition of scientific content and facts to developing students' scientific literacy and higher order thinking skills.[1] Even in advanced rigorous chemistry courses like Advanced Placement Chemistry there is an emphasis on conceptual understanding through inquiry and combining essential knowledge with scientific practices, putting less focus on breadth and factual knowledge.[2] These goals guided the national chemistry subject committee in Israel that led a fundamental reform in high school chemistry education. Especially in chemical education, researchers emphasize the importance of integrating visualization tools and interdisciplinary application aspects as ways to achieve meaningful conceptual understanding, which is a chemistry understanding at different levels such as macroscopic, microscopic, symbol or process.[3−6] Israeli high school chemistry students have two options for studying chemistry: basic or honors (advanced). The basic option is a prerequisite for the honors, which is similar to the Advanced Placement (AP) courses in the U.S. We have developed a new learning module for honors students, titled *Chemistry—from "The Hole" to "The Whole": From the Nanoscale to Microelectronics*. The module, hereinafter referred to as *Chemistry—from the Nanoscale to Microelectronics*, includes abstract topics in quantum mechanics taught in chemistry courses. The goal of the study described here is to assess the contribution of the module to students' understanding of quantum mechanical concepts through integration and fostering of higher order thinking skills. The teaching and learning of the module includes abstract topics from quantum mechanics theory and focuses on chemical properties derived from the substances' electronic

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structure, such as orbitals in atoms and molecules and energy bands in bulk semiconductors. The latter topic had never been taught in high school chemistry courses in Israel before. There are difficulties and obstacles associated with teaching and learning quantum mechanical concepts at the high school, college, and university levels. Even AP students often experience difficulties understanding the quantum atom model, which involves orbitals, energy levels and related ideas.[7−9] While conventional approaches to teaching undergraduate physical chemistry and quantum mechanics courses are mathematical-oriented, we have adopted a visual−conceptual approach to teaching quantum chemistry. This qualitative approach emphasizes interdisciplinary real-life applications and integration of visualization. The visual−conceptual approach helps bypass the need to introduce mathematical aspects of quantum theory, since most high school students lack proper background in mathematics at the required level. Originally aimed at high school honors students, this learning unit served also as enrichment material during an undergraduate mathematically oriented quantum chemistry course at the Technion, Israel Institute of Technology, titled *Introduction to Quantum Mechanics and its Applications in Chemistry*. Subjects (including content and scientific practices) that are being taught through the module are equivalent to subjects being taught in AP chemistry in the U.S. and general chemistry at college/university levels.

In what follows, we briefly overview each one of three thinking skills that were embedded in the module and emphasized in order to foster students' quantum chemistry understanding: (1) visual and textual chemical understanding, (2) graphing, and (3) far transfer of learning. These skills are instrumental for learning chemistry in general and quantum mechanics in particular. The development of thinking skills as an integral part of the learning process is in line with science education reforms that draw attention on teaching the practices of science.[1] We then describe the module, explain its quantum mechanics content, and exemplify assignments that require thinking skills for understanding and integrating various quantum chemistry concepts. Finally, we present and discuss the investigation of students who practiced these skills while learning the module.

■ THEORETICAL BACKGROUND

Learning quantum mechanics in order to describe the atomic model accepted by scientists requires that students have high level of mathematical abilities. The abstraction and the mathematical orientation of the quantum model have been identified as an inhibiting factor for students who are required to develop comprehension of quantum mechanical concepts.[7,8,10] For example, the use of probabilities and discrete energies are necessary in order to describe the quantum mechanical model of the atom.[11] Researchers report that students have difficulties with models that are not deterministic and concrete when it comes to learning about the atomic model. Students are often captive of the planetary model, in which electrons move in a known, well-defined orbit, and they are confused by the orbital of quantum mechanics.[8,9,12,13] To overcome such difficulties, there is a need to develop proper pedagogical strategies so students can understand qualitatively ideas related to quantum mechanics.[14−17] Our strategy was to incorporate quantum mechanics implications with higher order thinking skills in the context of everyday life in order to motivate students.

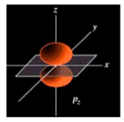
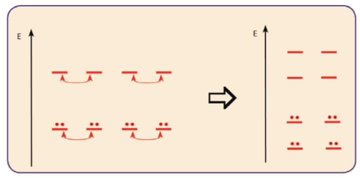
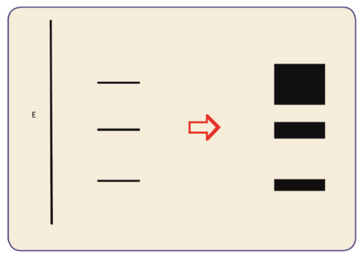
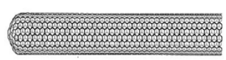
Visual and Textual Chemical Understanding

Researchers argue that chemistry should be taught at four levels: macroscopic, the sensory level; microscopic (also referred to as submicroscopic), the particulate nature of matter; symbolic, the notational level (e.g., formulas, equations, and graphs); and the process, the dynamic level.[18−20] Developing the competence of visualization is critically important in chemistry since by using visual models chemists build the bridge between the mental models of the chemistry they cannot see (microscopic level) and the phenomena they observe (macroscopic one). Thus, meaningful chemistry understanding can only be achieved by using different strategies of visualization.[3,4,21] Moreover, Kozma[22] argued that the use of multiple representations to present a scientific idea increases the ability to explore it and develop a meaningful conceptual understanding. Yet, many students lack this visualization competence. Explicit instruction that encourages and utilizes the use of different visual representations, including the ability to choose the right visualization mode and move across different representation, can overcome students' initial limited ability.[4] Using visual representations as well as textual representations and moving across these two modes can also increase students' conceptual understanding of chemistry while they translate one mode to the other.[23] Mayer[24] referred to that skill as moving between different modes of representations that are aspects of different working memory, and when combined, result in a more comprehensive understanding. Indeed, in this study, students learned through a variety of visual representations related to quantum mechanics. The representations include atomic and molecular orbitals in a variety of representations modes, energy and conductivity band representations, computerized simulations, and animation (see Supporting Information A, Examples of Assignment from the Module). The variety of representations in the module and the assignments in it contributed to meaningful learning.[1,2]

Graphing Skills

Graph construction and interpretation are identified as important skills in science education; however, many students do not succeed in acquiring these skills.[25,26] Students have difficulties in scaling the axes and use the best fit line and usually do not perform well on tasks that involve graphical questions.[27,28] Graphing skills are especially important in science education since they can assist in the process of conceptual change. Students can create connections between mathematical principles and scientific concepts when they are encouraged to predict graph shapes, collect relevant data, and compare their results to their predictions.[29,30] The understanding of mathematical equations can be very abstract for students; thus, using graphs and present data visually can foster students' understanding of a new phenomenon presented to them.[26,31] This is especially important when learning quantum mechanics, nanotechnology and nanoscale phenomena. Learning through graphical representations helps students to conceptually understand abstract topics without the difficulties associated with mathematics. It provides them with the opportunity to develop a mental model closer to the atomic model acceptable by scientists these days.[32,33] In the module we developed, students learn to interpret and move across different graphical representations (see Table 1 and Box 2) and to connect graphical representations to wavelength, color, and related phenomena.

Table 1. Characteristics of the Module, Chemistry—From the Nanoscale to Microelectronics

Topics	Key Concepts	Visualization Example	Application Examples
The electronic structure of atoms	• Atomic orbitals • Energy levels • Emission spectrum	• Representation of atomic orbitals 	• Pyrotechnics • The fireworks' colors
The electronic structure of molecules	• Molecular orbitals • Pi-conjugated molecules • Absorption spectrum of molecules	• Representation of qualitative rules for adding molecular orbitals of nearby units (see also Supporting Information B) 	• Why do organic pigments have colors? • Light sticks
The electronic structure of solid state	• Conductors and Insulators • Energy bands • N- and P-type semiconductors	• Diagram of energy bands 	• Microelectronics devices • Light emitting diodes (LEDs)
Quantum-size effect applications	• Size-dependent characteristics of nanoparticles	• Carbon nanotubes 	• Light-emitting semiconductor nanocrystals

Transfer Skill

Transfer of learning, an important higher order thinking skill, is crucial in science education, since we expect students to use knowledge and skills in new learning contexts[34,35] and apply what they learn in school beyond the boundaries of the educational system.[36] Dori and Sasson[35] suggested a more comprehensive framework, claiming that the transfer skill is problematic since students often encounter difficulties applying knowledge and skills in new learning situations. They suggested a theoretical framework based on three transfer attributes: task distance, interdisciplinarity, and skill set. Further, they distinguished between near and far transfer assignments and applied this distinction in a research involving honors chemistry students. The ability of students to perform a task requiring transfer depends, among other factors, on the instruction methods to which they were exposed. Usually, transfer of learning does not occur spontaneously and different learning environments can foster different attributes of the transfer skill.[37] For example, integrating everyday observations that relate to quantum chemistry, such as light-emitting diodes or fluorescence, enables students to transfer their chemical knowledge and skills to everyday phenomena.[33] As stated by *The College Board*,[2] meaningful understanding is when a student connects atomic levels and models to the macroscopic level and link ideas across domains (p 88). In the module, *Chemistry–from the Nanoscale to Microelectronics*, assignments for students included integrating chemical concepts with interdisciplinary phenomena and applications (see Box 1). Thereby, the students learn to apply and connect their chemical understanding to interdisciplinary aspects and everyday applications.

OVERVIEW OF THE MODULE CHEMISTRY—FROM THE NANOSCALE TO MICROELECTRONICS

The module Chemistry–from the Nanoscale to Microelectronics is oriented toward overcoming difficulties that students in high school, college and universities have with learning quantum mechanics. The module emphasizes how different systems, such as atoms, molecules and solids, behave according to the same quantum mechanics rules. This approach broadly exposes the students to different scientific concepts and to relevant technological applications. High school students are usually not exposed to solid state structure at the quantum level, neither in chemistry nor in physics courses. Hence, the module is unique in giving such a broad overview. Moreover, the teaching methodology, which emphasizes the common grounds for phenomena in different fields, demonstrates to students that transfer of knowledge across various domains is a powerful tool for understanding basic science concepts and their relevant applications. Qualitative conceptual tools, which rely on graphical aids rather than on heavy mathematical formulation, facilitate this approach.

As an example, consider the transition from atomic orbitals to molecular orbitals and to lattice (solid state) orbitals. Chemists usually use three-dimensional orbitals in order to explain in detail the electronic properties of atoms and small molecules. However, these graphical tools are not scalable for

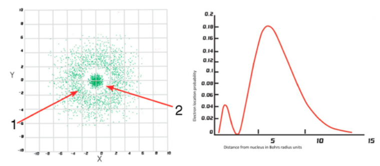
Box 1. Main Thinking Skills in the Module and Examples of Assignments

-Thinking skills in the module:

- The student will be able to create, describe and explain various representations of quantum mechanics concepts (such as atomic and molecular orbitals).
- The student will be able to explain and move across schemes and graphs (e.g., electron energy diagrams, emission and absorption spectra of atoms and molecules, see Box 2).

-Visualization Elements in Students' Assignment:

❖ Different graphical representations of the 2s orbital in the hydrogen atom (Full assignment is in Supporting Information A).

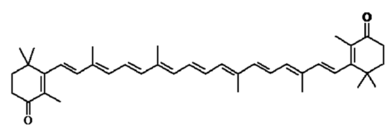


-Thinking skills in the module:

- The student will be able to connect and explain macroscopic phenomena (such as the colors of pigments and how semiconductor devices work) with the electronic structure of atoms molecules and solid state

-Visualization elements in students' assignment:

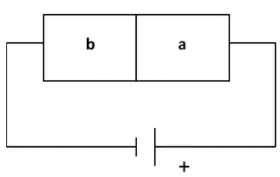
❖ Based on the representation please explain why the substance is colorful (Full assignment is in Supporting Information A).



❖ The illustration below shows a schematic description of a diode. The diode is made out of a Silicon (Si) crystal. Areas a and b went through doping. In the schematic illustration, the diode conducts electricity.

❖ Please determine which of the crystals (a or b) is an N-type and which is a P-type.

❖ Based on your answer above, what element was used for doping area a and what element was used for doping area b in the crystal. Please explain (there is more than one option).

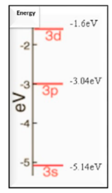


larger molecular systems such as chromophores or solid lattices. To explain properties related to such larger systems, chemists tend to use particle-in-a-box and Huckel type models. Physicists use periodic lattice models, which require additional mathematical formulation, as well as new conceptual and computational tools. In this module, a graphical heuristic approach is used to continuously link atoms, molecules, and solids, and to explain the main principles underlying their electronic structure. The approach is based on an abstract graphic representation of the orbital energy levels, and the qualitative rules for adding orbitals of nearby units (see Table 1, second example, and Supporting Information B).

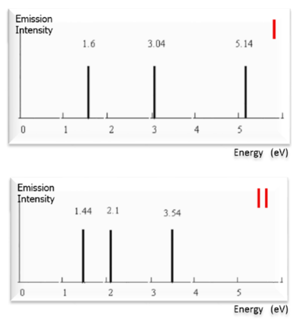
Finally, the pedagogical structure, in which the study of each major topic starts with exposure to a "real life" problem or phenomenon, is a unique characteristic of the module. In summary, the innovation elements in our module are represented along four integrated directions: unprecedented broadness of knowledge, transfer of concepts and knowledge across different fields, qualitative and conceptual learning tools as models and graphs, and "problem-driven" learning motivation. This supports the specific goals of the module

Box 2. Example of a Post-Questionnaire Assignment - Transfer between Graphs

The following diagram describes part of the energy levels of the Sodium atom Na.



Which of the following two graphs, I or II, can describe part of the emission spectrum of Na? Explain!



which are to expose students to the principles of the electronic structure of materials and the quantum mechanical origin of electronic structure, to correlate observed properties such as color and conductivity to the electronic structure of materials, to establish the connection of fundamental science and chemistry in particular to real-life experiences and applications, and to foster the development of thinking skills. Table 1 and Box 1 specify the core ideas and scientific practices (skills) in the module. The respective topics and concepts, as well as scientific practices in AP chemistry curricula,[2] are represented in Supporting Information C1 and C2.

Box 2 presents a post-questionnaire assignment related to the first chapter of the module, which focuses on the electronic structure of atoms, and demonstrates the approach, features and goals implemented in the module. To carry out the assignment presented in Box 2, students had to move across different graphs and diagrams, understand and interpret the graphs, and use different levels of chemistry understanding, such as emission spectrum of an atom, differences between the energy levels for electrons in that atom, and photon emission. The rubric for analyzing students' answers to the question in Box 2 is presented in Supporting Information D, Rubric for "Transfer between Graphs" Assignment. Table 2 presents examples of students' responses to the question in Box 2 and analysis of these responses. The analysis focuses on the extent of meaningful understanding of quantum mechanical concepts at the four level of chemistry understanding and in Table 3, which describes the criteria for analyzing the questions in the pre and post questionnaire.

■ THE STUDY

In this study, we investigated the effectiveness of the visual—conceptual pedagogical approach in teaching high school honors and undergraduate students the module *Chemistry—from the Nanoscale to Microelectronics*. As noted, the visual—conceptual approach replaces mathematical derivations and includes interdisciplinary, real-life applications and visualizations.

The research objectives were to

1. Assess the comprehension of quantum mechanical concepts and the thinking skills of the honors high school and undergraduate chemistry students.
2. Analyze the differences in three thinking skills between the research groups in the context of quantum chemistry understanding. The thinking skills included visual and textual chemical understanding, graphing, and transfer of learning.
3. Identify the perceptions of the students regarding the integration of visualization and real life applications into the learning of quantum mechanical concepts via the module.

Research Participants

The research subjects were (a) 122 honors students from eight high schools in Israel who studied all the module during about 45 lessons, and (b) 65 undergraduate volunteer students, who were studying in a mathematically oriented quantum chemistry course titled: *Introduction to Quantum Mechanics and its Applications in Chemistry*. In Israel, high school chemistry classes are usually small since not all the students who major in the basic level of chemistry at 11th grade elect to study honors chemistry (i.e., chemistry at the advanced level) at 12th grade. In the rural areas, classes might include 10−15 students, while in urban areas, class size are in the 20−25 students range. High school students took part in a national study to assess the new modules of the chemical education reform. The study was endorsed by the National Superintendent and approved by the Chief Scientist of the Ministry of Education. The high school

Table 2. Students' Responses and Grading for the Assignment in Box 2

Students' Responses	Content Domain		Understanding Level		
	Statement	Explanation	Microscale	Symbolic	Quantum-Mechanics
The matching graph is II because it fits the energy transitions between the levels: $3d \rightarrow 3p$ (1.44 eV) $3s \rightarrow 3p$ (2.1 eV) $3s \rightarrow 3d$ (3.54 eV) These energy transfers are part of the ones that electrons undergo following excitation and as a result of this, energy is emitted. (By high school student A)	Correct: 1/1	Full explanation: 2/2	Mentioned electron transitions: 1/1	Computed and explained the three transitions: 2/2	Linking energy transitions to discrete energy levels: 1/1
Graph II because in order for light to be emitted it must be in an excited state and then return to a stable state since if it is in the stable state it will not emit anything. (By undergraduate student B)	Correct: 1/1	Partial explanation: 1/2	Not mentioned	Not mentioned	Linking energy transitions to discrete energy levels: 1/1
Graph I because if we excite an atom it absorbs energy and therefore when energy is emitted the atom decays to a lower energy level. (By undergraduate student C)	Not correct: 0	Partial[a] explanation: 1/2	0	0	0
Graph I because it fits the distribution of energy levels based on Diagram I. (By high school student D)	Not correct: 0	Erroneous explanation: 0	0	0	0

[a]The result is incorrect, but the student's explanation from energy consideration does not contradict the quantum picture.

honors students were divided into two subgroups: intermediate and high academic levels. In Israel there are no chemistry honors classes for students of low academic level, and therefore, this subgroup included only students of high and intermediate academic levels.

The undergraduate students were divided into two subgroups: (1) *Visual-conceptual-oriented* (ViCo-oriented), students who participated in a short-term enrichment course that included the topics of the module, and (2) *Mathematically oriented* (Math-oriented), students who participated in a short-term mathematics enrichment course, which included topics taught in the quantum mechanics course. The ViCo-oriented students received enrichment through qualitative tools that enable making qualitative predictions with no need for using mathematical formulas. Thus, they were better trained to reach conclusions, skipping the tedious mathematical formulations, which sometimes obscure the simplicity of the principle. For example, counting conjugated π bonds is sufficient in order to predict changes in the absorption wavelength, and it does not require the tedious mathematical calculation that entails using complex formulas. The mathematical enrichment course extended the scope of the solution of the one-dimensional Schroedinger equation beyond the 'particle-in-an-infinite-box' model. This enables accounting for several physical effects that are beyond the scope of that model. In particular, the effect of replacing a carbon with a hetero atom in the chain, can be accounted for by a nonuniform box model. The possibility for ionization can be accounted for by considering a finite rather than an infinite box. The description of scattering processes can be accounted for by turning a finite well into a barrier. The students learned to solve the Schroedinger equation for a piecewise constant potential in one dimension, and analyzed the physical consequences of different potentials.

The undergraduate enrichment was taught in addition to the regular academic courses, over 3 weeks, for two sessions per week. The enrichment course was given in groups of 17−24 students. The students chose to participate in the subgroups based on their schedules, without any knowledge of the content.

Research Tools

The pre- and post-questionnaires assessed students' chemistry understanding of concepts in quantum chemistry and thinking skills, as well as students' feedback. The honors students responded to the pre- post-questionnaires prior to, and at the end of, learning the module. The undergraduate students responded to the pre- post-questionnaires during the first and last week of the semester.

The pre- and post-questionnaires included open-ended questions for assessing conceptual understanding and three thinking skills:

(a) Visual and textual chemical understanding, the understanding of various representation and visualization modes, and the ability to apply visual and textual modes to explain quantum mechanical concepts; (b) Graphing skills, the ability to explain and move across various types of diagrams and graphs related to quantum chemistry; and (c) Far transfer skill,[35] the ability to apply chemistry knowledge to other domains, such as biology and technology, and respond to a task that is remote from the task the student had been exposed to in the module. Regarding hierarchy within the thinking skills, far transfer is at the upper level along the thinking skills spectrum. We assume it requires

Table 3. Structure of the Pre- and Post-Questionnaires

Skills	Assignment	Categories for Analysis of the Questionnaires
Visual and textual chemical understanding	Describe a concept via illustration, and textually explain it (see Supporting Information E)	a. Correctness (of the explanation or illustration)
		b. Complexity (of the illustration)
	Explain an illustration (see Supporting Information F)	c. Coherence (between the illustration and the explanation)
		d. Chemical understanding levels
Graphing	Explain a graph	a. Description of the graph
	Transfer between graphs and explain (see Box 2, Table 2, Supporting Information D)	b. Correctness of the explanation
		c. Chemical understanding levels
Transfer	Far transfer (see Supporting Information G)	a. Correctness of the explanation
		b. Chemical understanding levels
		c. Application in another discipline (such as biology or technology)

higher cognitive abilities than graphing skill and visual and textual chemical understanding.

The content of the pre-questionnaire was chemical structure and bonding, while that of the post-questionnaire was quantum mechanics. Understanding of chemistry was assessed via the four chemistry understanding levels—macro, micro, symbol and process—using a method developed in prior research on textual and visual responses.[38,39] The four levels of chemistry understanding were used as a basis for analyzing all the thinking skill assignments. Students' responses to these assignments showed that it is necessary to define a new, fifth understanding level in addition to the micro level—the *quantum-mechanical level*—the ability to describe the electronic structure of atoms, molecules, and solid state materials.[40]

Table 3 presents the structure of the questionnaires as well as the specific assignments, which included the three thinking skills mentioned above.

As Table 3 shows, the assignments in the questionnaires were based on quantum chemistry concepts whose meaningful understanding requires integration of various higher order thinking skills, including visual and textual chemical understanding, graphing skill, and far transfer. Quantum mechanics, the foundation of the module, provides for explaining connections across a broad range of phenomena while emphasizing the higher order thinking skills. The visual and textual chemical understanding and graphing skills are necessary for students' understanding of quantum mechanical principles in a nonmathematical way. The hierarchy regarding the thinking skills as they relate to quantum mechanics can be conceptualized as follows: the far transfer skill, which is needed in order to cross disciplines, requires understanding of quantum mechanical principles, which, in turn, develops the other thinking skills—the visual and textual chemical understanding and graphing skills.

For each assignment an assessment tool was developed. The assessment tool (as shown for example in Table 2 for the Assignment in Box 2) consisted of a detailed rubric that was graded independently by qualitative content analysis, followed by a quantitative score. One of the categories we applied was chemistry understanding levels for assessing the extent of chemistry comprehension of quantum chemistry concepts. The scores of the different categories were summarized and normalized on a 1-to-100 scale, and were then statistically analyzed. For the visual and textual chemical understanding skills, an average score was calculated for each student based on assignments 1 and 2. For the graphing skill, average scores of assignments 3 and 4 were calculated. Students' responses were scored and validated by four chemistry educational experts, achieving 90% inter-raters' reliability.

Feedback Questions

The honors students responded to the feedback questions after they had studied the module. One of the questions in their questionnaire was: *Did you find special characteristics in the module, which other modules lacked? Explain and compare with other learning materials.*

At the end of the enrichment course, the undergraduate students also responded to feedback questions. They were asked whether they had found the enrichment course to be useful and whether they would recommend the enrichment course to their friends. The students' responses, which were both positive and negative, were divided into several categories.

FINDINGS

Students' responses to the assignments in the pre- and post-questionnaires were analyzed according to the rubrics in Tables 2 and 3, and Supporting Information D. We first analyzed the responses using content-based qualitative analysis according to the rubrics and then carried out quantitative statistical analysis. We present here the quantitative analysis. Examples of the qualitative analysis are presented in Supporting Information E.

We analyzed the quantitative data based on groups and subgroups. First we present the comparison between high school honors students and the undergraduate students. This comparison aims to determine whether there were any differences between undergraduate and high school students in their abilities to learn quantum mechanical concepts through the three different thinking skills—visual and textual chemical understanding, graphing, and far transfer. The second comparison is between the three subgroups who were exposed to and studied the module—high academic level honors students, intermediate academic level honors students, and ViCo-oriented undergraduate students. We did not compare our high school students to other high school students who studied quantum chemistry in a different approach, since quantum chemistry had never been taught in honors chemistry courses in Israel, so no comparison group could have been established. Our last comparison is between different undergraduate students based on the enrichment course type they had taken. The subgroup of undergraduate students who had taken the mathematically oriented enrichment course served as a comparison group only for the ViCo-oriented undergraduate subgroup of undergraduate students who had studied using the module.

High School Honors versus Undergraduate Students

The results of honors students' thinking skill scores vs undergraduate students' thinking skill scores are presented in Figure 1. In two of the three thinking skills, visual and textual chemical understanding and graphing skills, both honors and

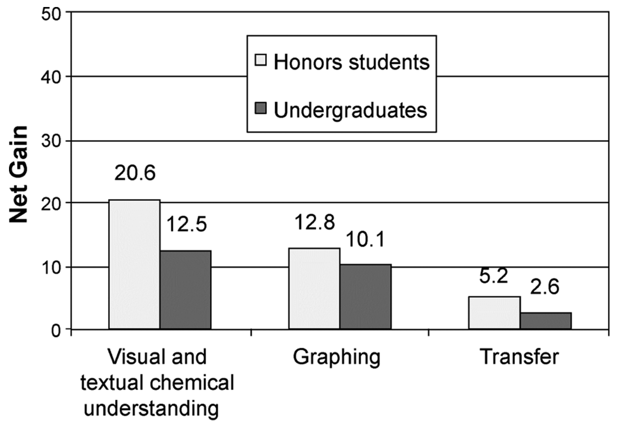


Figure 1. Students' net gain scores in the three thinking skills: honors students, $N = 122$; undergraduates, $N = 65$. Please note that the number of honors students that responded to the transfer assignment was smaller (N total = 84; high academic level, $N = 55$; intermediate, $N = 29$) as the task was more difficult and they were not exposed to such an assignment before.

undergraduate student groups improved their average score significantly from the pre- to the post-questionnaire (visual and textual chemical understanding—honors, $t = 10.57$, $p < 0.0001$; undergraduate, $t = 5.39$, $p < 0.0001$; graphing—honors, $t = 5.25$, $p < 0.0001$; undergraduate, $t = 3.9$, $p < 0.0001$). These findings indicate that the ability of both student groups to describe quantum chemistry concepts visually and textually, move across them, explain graphs, and translate diagrams to graphs improved significantly after studying the module.

Analyzing the students' transfer skill scores showed an improvement from the pre- to the post-questionnaires for both the honors and undergraduate students, however this was not statistically significant.

The net gains (post minus pre-questionnaire scores) of the two student groups are presented in Figure 1. The net gain in graphing skill for both groups was smaller than their net-gain in the visual and textual chemical understanding skills. Honors students' net-gain scores of the visual and textual chemical understanding were significantly higher than those of the undergraduate students ($t = 2.57$, $p < 0.05$). Figure 1 also shows that the honors students' net gain score was higher than that of the undergraduate students in both the graphing and the far transfer skills, but this difference was not statistically significant.

Comparison of Subgroups: Intermediate- and High-Level Honors and ViCo-Oriented Undergraduates

Using the repeated measures test, we compared the mean scores of three subgroups who studied the module: high academic level honors ($N = 73$), intermediate academic level honors ($N = 39$), and ViCo-oriented undergraduate students ($N = 34$). In the honors subgroups there were less students due to missing teachers' grades, which were needed in order to assign each student to a subgroup.

Examining the visual and textual chemical understanding skills, the repeated measures test within-subjects effect revealed an interaction effect between time (pre- and post- questionnaires scores) and subgroups ($F_{(2,143)} = 6.12$, $p < 0.005$); see Figure 2. The source of the interaction effect was the scores of the ViCo-oriented undergraduate subgroup and the scores of the high-level honors subgroup. High academic level honors students' pre-questionnaire mean scores were lower than those

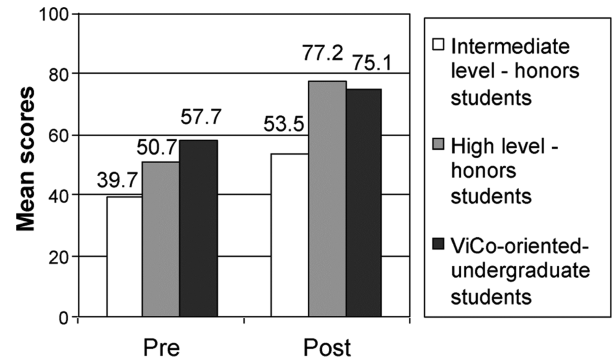


Figure 2. Visual and textual chemical understanding, comparison of subgroups.

of the ViCo-oriented students, but their improvement was larger and their post-questionnaire scores were higher than those of the undergraduate students (see Figure 2). A repeated measures test of between-subject effects revealed that there was a significant difference between the three groups ($F_{(2,143)} = 30.27$, $p < 0.0001$). We carried out a pairwise comparisons Bonferroni test, which indicated that the high academic level honors subgroup scored significantly higher than the intermediate academic level honors subgroup ($p < 0.0001$). A significant difference was also found between the ViCo-oriented undergraduate subgroup and intermediate academic level honors subgroup in favor of the ViCo-oriented undergraduate subgroup ($p < 0.0001$). We did not find a statistically significant difference between ViCo-oriented undergraduates and high-level honors students.

In the graphing skills, repeated measures test within-subjects effect revealed that there was also an interaction effect between time (pre- and post- questionnaires scores) and academic subgroups ($F_{(2,138)} = 3.13$, $p < 0.05$). Even though the interaction was less significant than what we found in visual and textual chemical understanding skills, the same tendency came out. As can be seen from Figure 3, high-level honors

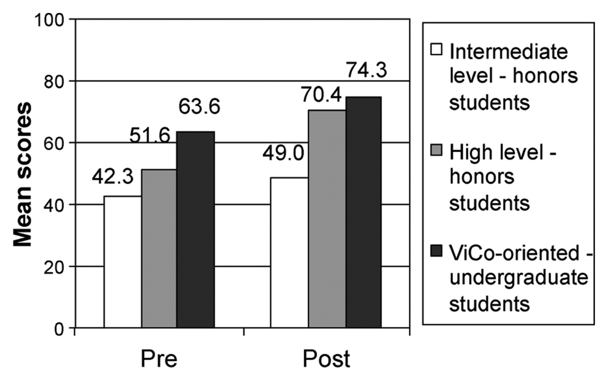


Figure 3. Graphing skill, comparison of subgroups.

students gained more than ViCo-oriented undergraduate students, while intermediate-level honors students' scores were lower at the pre- and the post-questionnaire. Repeated measures test of between-subjects effects revealed that there was a significant difference between the three groups ($F_{(2,138)} = 20.32$, $p < 0.0001$). We carried out the pairwise comparisons Bonferroni test. The test indicated that the high-level honors subgroup scored higher than the intermediate-level honors subgroup and the result was statistically significant ($p < 0.001$).

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Furthermore, a significant difference was found between the ViCo-oriented undergraduates subgroup and intermediate-level honors subgroup in favor of the ViCo-oriented undergraduates subgroup ($p < 0.001$). In this skill we did find significant difference between ViCo-oriented undergraduates and high-level honors students in favor of the ViCo-oriented undergraduate subgroup ($p < 0.05$).

Analyzing the results regarding far transfer skill, the repeated measures test within-subjects effect showed no interaction (see Figure 4). The test revealed that there is a significant difference

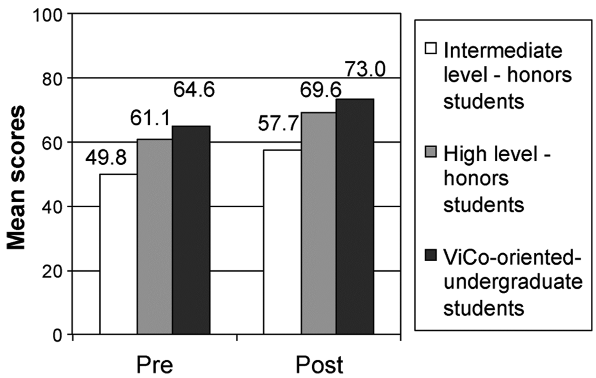

Figure 4. Far transfer skill, comparison of subgroups.

between the three groups ($F_{(2,114)} = 3.30$, $p < 0.05$). The Bonferroni test revealed that there was a marginally significant difference between ViCo-oriented undergraduate students and intermediate-level honors students ($p = 0.055$) in favor of the undergraduate students.

ViCo-Oriented versus Math-Oriented Undergraduate Students

The mathematically oriented undergraduate subgroup served as a comparison for the ViCo-oriented subgroup, since the former had studied quantum chemistry but were not exposed to the module. We compared these two groups regarding their conceptual understanding of quantum chemistry as analyzed through the three different thinking skills. Regarding the visual and textual chemical understanding, the students in the ViCo-oriented subgroup significantly outperformed their peers (75.1 vs 59.1; $t_{(56)} = 3.37$, $p < 0.001$). This implies that the approach the module takes enhanced undergraduate students' visual and textual chemical understanding. Comparing the graphing skill within these two subgroups, we found significant differences in their pre-questionnaires. Therefore, we used an ANCOVA test, which showed that the students in the ViCo-oriented subgroup significantly outperformed their peers (72.5 vs 59.2; $F_{(56)} = 7.85$, $p < 0.01$). No significant differences were found regarding far transfer skill in the post-questionnaire, but the ViCo-oriented group scored higher (73) than their peers (61.2).

Results of the Feedback Questionnaire

In the feedback questionnaire, the high school honors students were asked what unique characteristics, if any, they found in the learning module. Students' answers to this question were analyzed and divided into categories. Out of 105 statements, which were provided by 80 honors students, 94% were positive. The categories they emphasized most were interdisciplinary applications, followed by interest and motivation, and then visualizations.

The ViCo-oriented undergraduate students were asked if the enrichment course they had taken made any contribution. Out of the 43 statements, which 34 students wrote, 76% were positive. The students emphasized the contribution of the module to their understanding of chemistry followed by interest in the subject and then interdisciplinary applications. Supporting Information H presents examples of students' statements sorted by categories.

■ CONCLUSIONS AND DISCUSSION

Quantum mechanics is a challenging yet important subject, which should be taught starting at the high school level. Indeed, its importance is addressed in the AP chemistry course description.[2] Innovative instructional methods are needed to overcome students' difficulties in this area.[15−17] In this paper, we presented a research on the learning module *Chemistry—from "The Hole" to "The Whole": From the Nanoscale to Microelectronics*, which we had developed for teaching quantum mechanical abstract concepts.

Our findings indicate that the visual−conceptual approach that enables avoiding the need for advanced mathematical background, which is a prominent obstacle for students not only in high school but also at the undergraduate level, was beneficial for both student groups.[14,32]

The module was found to promote and improve higher order thinking skills, especially due to the use of a variety of visualization modes and multiple representations throughout the module. For example, chemists usually use 3D orbitals to describe electronic properties of atoms and small molecules and the transition from atomic orbitals to molecular and to lattice orbitals. The difference of our visual−conceptual approach from the 3D orbitals is that ours is based on an abstract graphic representation of the orbital energy levels and qualitative rules for explaining the principle of addition and subtraction of local orbitals to obtain extended orbitals (see Supporting Information B). With this approach, students can refer to atoms, molecules, and solids, and explain their electronic structure.

Another aspect of our approach is similar to that of the AP Chemistry Course document,[2] which also emphasizes linking quantum mechanical concepts to applications (see Supporting Information C1 item 1.B.1 of AP). Both high school and undergraduate students' answers to the feedback question indicate that this aspect contributed to students' motivation and satisfaction.

Not only is the module innovative in the approach it takes, but we also investigated possible reasons for differences between two students groups—honors and undergraduate students. Both groups significantly improved their visual and textual chemical understanding and their graphing skills. These two groups improved their far transfer skill, albeit insignificantly. Notably, these skills were grounded in quantum mechanical concepts and principles.

The visual and textual chemical understanding skill is fundamental in learning chemistry, especially when abstract concepts are involved.[4,6,22] The significant improvement in this skill is an indication of the effectiveness of the approach. High school honors students had a higher net-gain than the undergraduate students, suggesting that longer exposure to the approach is more beneficial. Alternatively, this might indicate that the rate of improvement in these skills is higher for less experienced students. The relatively moderate improvement in the graphing skills can be explained by the fact that graphing skill is difficult for students since it also requires some mathematical knowledge.[25,26,41] Regarding transfer, as describe in the AP Chemistry Course document,[2] Science Practice 7 (a thinking skill specified in this document) specifies that students should "relate knowledge across various scales, concepts, and representations in and across domains" (p 88). Students may need more practice and explicit assignments for improving this skill, which takes longer to develop.[37,42] Furthermore, researchers recommended to start with an assignment that requires a near transfer ability rather than a far transfer ability.[35]

At a more refined level of analysis, we probed the students at the level of their three subgroups. Honors students at high academic level improved their ability in visual and textual chemical understanding and graphing skills more than the ViCo-oriented undergraduate students. This does not imply that these high school students are better than the undergraduate students, but rather that they benefited more from studying the module.

With respect to far transfer, there was almost no difference between the subgroups; the improvement was similarly small and intermediate-level honors did not improve as much as the two other groups. It seems that in spite of the approach underlying the module, students still had difficulty conceptualizing and transferring abstract concepts. This finding contradicts the findings of Kaberman and Dori,[38] who had found that honors students at a lower academic level benefited more from a computerized molecular modeling learning environment while studying the structure of molecules. It seems that lower academic level students require more time to digest quantum theoretical abstract concepts than they need to grasp molecular models.

Finally, we compared the two undergraduate student subgroups—the ViCo-oriented and Math-oriented ones. An encouraging finding was the statistically significant contribution of the enrichment course to undergraduate students' achievements. Undergraduate students who participated in a short-term enrichment course, which included topics and learning materials from the module, exhibited better performance in terms of visual and textual chemical understanding and graphing skills than their peers who had participated in a short-term mathematically oriented enrichment course. This finding strengthens our claim that the qualitative visual–conceptual approach promotes conceptual understanding, whereas a mathematically oriented teaching approach might not be sufficient for understanding quantum mechanical concepts.[43,44]

Limitations and Suggestions for Further Students' Skills Development

The *Chemistry–from the Nanoscale to Microelectronics* module we developed engages honors students in concepts and topics related to quantum mechanics. These subjects were not part of the *traditional* (pre-reform) advanced high school chemistry curriculum in Israel, so we could not compare high school honors students–our research participants who learned quantum mechanics using the module–with students who studied these topics using different learning materials. Another limitation relates to the transfer skill. The assignment we investigated required far transfer ability, for which we found no or small improvement. However, we did not include a near transfer assignment, so we could not investigate near transfer.

We recommend developing and applying assignments that require not only far transfer but also near transfer for both honors and undergraduate students. Specifically, since intermediate academic level students had lower achievements than their high academic level peers, the new assignments and additional tools should cater to the needs and capabilities of the intermediate academic level students so they too will be able to further improve their higher order thinking skills.

Study Uniqueness and Implications

The *Chemistry–from the Nanoscale to Microelectronics* module is probably the first learning material geared for high school students, in which each chapter related to quantum mechanics opens with an everyday application, such as fireworks, organic pigments, or semiconductor electronics. This is followed by raising a related question, which is explained using quantum mechanical concepts and principles while avoiding the use of complex mathematical equations. Our study applies a fifth level of chemistry understanding—the quantum-mechanical level, which focuses on the electronic structure of atoms, molecules, and solid state materials. This level elaborates the microscopic level by emphasizing atomic and molecular orbitals, energy bands, and absorption and emission spectra. The novelty of this research is not just in its use of the quantum-mechanical level, but also in that it is among the very few studies[7,13] to examine higher order thinking skills as they relate to quantum mechanics for high school students. Our visual–conceptual rather than mathematically oriented approach is key to enabling high school students to be able to successfully tackle this highly abstract topic. We have demonstrated that development, field implementation and field research of this important, yet under-attended topic are feasible and meaningful.

Our research confirms the view that high school AP students can and should be exposed to quantum mechanics, and that appropriate teaching methods can help students conceptualize abstract quantum mechanical concepts. The integration of higher order thinking skills into the learning process is of paramount importance for achieving conceptual understanding. We also recommend that everyday applications be integrated into the learning materials and processes,[45,46] not just anecdotally, but as a main thrust. Examples include relevance to solid state materials and their applications in ICT, notably mobile devices, to which the young generation is highly connected.

The visual–conceptual approach that replaces mathematical derivations and the integration of interdisciplinary, everyday observable phenomena with the promotion of higher order thinking skills can likely be applicable in other domains where abstract concepts require unconventional approaches, and research and assessment programs should accompany such implementations.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

A, examples of assignments from the module; B, pictorial explanation of the principle of linear combination of atomic orbitals to obtain extended molecular orbitals; C1, core ideas learned in the module and equivalent examples in AP curricula; C2, main thinking skills in the module and equivalent examples in AP scientific practice (skills); D (related to Box 2 in the article), rubric for "Transfer between Graphs" assignment; E, responses of students to the description of the concept "Forbidden Band"; F, an example of assignments from the post-questionnaire; G, far transfer skill assignment; H, examples of students' responses by categories. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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