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**REVIEW OF RESEARCH
(INVITED CONTRIBUTION)**
*(a) Problem-solving and other
higher-order cognitive skills (HOCS)
(b) Science-Technology-Environment-Society (STES)*

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INTERDISCIPLINARY SYSTEMIC HOCS DEVELOPMENT – THE KEY FOR MEANINGFUL STES ORIENTED CHEMICAL EDUCATION

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ABSTRACT: The strong commitment to disciplinary strength in chemistry teaching has resulted in failing to strengthen the links between the social/behavioral sciences, and advances in the physical and biological sciences and technologies. Although science and technology may be useful in establishing what we can do, neither of them can tell us what we should do. The latter requires *evaluative thinking* by capable science, technology and sociologically literate, rational citizens within a continuous process of problem-solving and decision-making. Meaningful environmental education is envisioned as an interdisciplinary critical thinking-, problem solving- and decision making-oriented teaching and, consequently, higher-order cognitive skills (HOCS) learning in the science-technology-environment-society (STES) interface context, leading to the capacity of transfer beyond the subject(s) or discipline(s) specificity. Since the integration of research-based findings and predictions, and HOCS-oriented science (and chemistry) education is a necessary precondition for people's responsible environmental behavior and action, it is vital for our students to develop their HOCS rather than simply learn to apply algorithms to "exercise" sets. This objective should be targeted by teachers and students alike as partners in a collaborative interactive-reflective process. Examples of multidimensional research-based HOCS promoting, STES-oriented courses, teaching strategies and, in accord assessment instruments, that have been developed and successfully implemented within on going chemistry teaching are described, and the research-based implications for future chemical and science education critically discussed. [*Chem. Educ. Res. Pract. Eur.*: 2000, *1*, 189-200]

KEY WORDS: *science and technology; environmental education; science-technology-environment-society (STES); higher-order cognitive skills (HOCS); evaluative thinking; critical thinking; problem solving; decision making; assessment instruments*

INTRODUCTION, RATIONALE AND PURPOSE

In view of the overly high expectations of people in a world of conflicting/competing values and *finite* unevenly distributed resources, modern life has turned into a continuous process of *evaluative thinking* and *decision making,* or decision-selection, from either available or as yet to be generated options (Zoller, 1991). However, although science and technology may be useful in establishing what we *can* do, neither of them (solely or jointly) can tell us what we *should* do.

The latter requires the application of value judgements by *socially responsible, rational citizens* as an integral part of their critical system thinking capacity. Thus, a major purpose of science, technology, environment, society (STES) education is the development of the students' reasoning, critical thinking, evaluative thinking and decision-making capabilities in the context of both the specific content and processes of science and the reality based S-T-E-S interfaces, for so they can be effective citizens (Zoller, 1990).

Education is a key factor in determining, affecting and/or modifying human behavior, individuals and societies alike. Yet, contemporary education has not prepared people to handle local, national and global international systems of such size and complexity as emerged within our science-based and technology-driven world.

Virtually any discussing concerning the current and future state of science is typified by statements about the importance of enabling researchers to work seamlessly across disciplinary boundaries and declarations that some of the most exciting and tough problems in contemporary research span the disciplines and …"do not care about disciplines" (Service, 1999). Inter/transdisciplinary research starts from real, complex problems relevant to society (Scholz & Tietje, 1999). The task ahead is to avail this evolving interdisciplinary scientific knowledge for dealing with contemporary society's problems in a satisfying way. The current strong commitment to disciplinary strength in chemistry teaching in which knowledge is typically extracted from an integrated whole via courses where that knowledge is disintegrated and disaggregated has resulted in failing to strengthen the links between the social/behavioral sciences and advances in the physical and biological sciences and technologies. On the other hand, meaningful environmental education is envisioned as an *interdisciplinary* critical thinking-problem solving- and decision making-oriented teaching and, consequently, in accord, higher order cognitive skills (HOCS) *learning* in the STES interface context, leading to the capacity of *transfer* beyond the subject(s) or discipline(s) specificity (Zoller, 1993, 1997).

Since the integration of research-based findings and predictions, and HOCS-oriented science (and chemistry) education for STES literacy is a necessary precondition for people's responsible environmental behavior and action, a STES-oriented *HOCS teaching,* regardless whether within specifically designed environmental programs, or ongoing chemistry and other science courses, should not only be consonant with the environmentally imperative transdisciplinary HOCS orientation in teaching, but should also foster *HOCS learning.* Therefore, HOCS such as question asking or generating, problem solving, decision making and critical system thinking – all of which require *evaluative thinking* – should become legitimate important learning outcomes to which good chemistry teaching should aim (Zoller, 1995). These skills constitute the core of the assembly of performance processes needed for (a) coping with previously unprecedented complex problem situation, (b) conceptual understanding transfer and system (inclusive) thinking with respect to both the chemistry discipline and real-life problems within the science-technology-environmental-society (STES) and their inter-relationships context.

It is vital for our students to develop their HOCS rather than simply learn to apply algorithms to "exercise" sets. This learning objective should be targeted by teachers and students alike as partners in a collaborative interactive-reflective chemistry teaching-learning process. Any progress towards the attainment of this goal would require the application of new teaching-learning and evaluation strategies within innovative STES-oriented courses that would mesh with these desired learning outcomes.

Therefore, the thesis of this state of the art/position/review/'how to do it' –type paper is that:

1. The superordinate goal of the current reform in science and chemical education worldwide is the induction of a switch from the currently dominating lower-order cognitive skills (LOCS)/algorithmic teaching to HOCS/evaluative teaching and, ultimately, *learning* (Zoller, 1993; Zoller, Lubezky, Nakhle, Tessier & Dori, 1995; Zoller, 1997; Zoller & Tsaparlis, 1997).
2. Although the road to attain this goal is rocky, we can teach for HOCS learning and, ultimately, for interdisciplines *transfer* (Solomon & Perkins, 1989), provided that appropriate teaching and corresponding assessment strategies, which proved to be successful via research (Zoller, 1997) will be purposely and creatively implemented (Zoller, 2000).

Guided by the above rationale, multidimensional research-based HOCS-promoting, STES-oriented courses, teaching strategies and, in accord, assessment instruments have been developed and implemented accompanied by a follow-up research within on-going chemistry teaching. Selected representative-illustrative examples of these will be described and the research findings-based implications for future chemistry and science education critically discussed in terms of interdisciplinary systemic HOCS development for *transfer* in chemical education. Such a development is the key for meaningful STES-oriented chemical education. Therefore, a major issue of our concern is how to foster the growth of our students' HOCS capability for interdisciplinary problem-solving in the STES context within contemporary ongoing chemistry teaching at all levels.

THESIS, GOAL AND RELATED QUESTIONS

The main thesis here presented is that STES-oriented chemical education requires:

- Inter/transdisciplinarity as a core-element in chemistry teaching.
- Teaching-assessment of contextually-bound skills/competencies on the expense of knowledge *per-se.*
- Conceptualization by students of basic inter/cross-disciplinary concepts.

All of the above is aimed at HOCS learning and transfer via attaining the superordinate goal of the "STES problem solving-decision making act" capacity (Zoller, 1990):

1. Ability to look at a problem and its implications, and recognize it as a problem.
2. Understand the factual core of knowledge and concepts involved.
3. Appreciate the significance and meaning of various alternative possible solutions (resolutions).
4. Exercise the problem-solving act: Recognize/select the relevant data information; analyse it for its reasonableness, reliability and validity; evaluate the dependability of resources used and their degree of bias; devise/plan appropriate procedures/strategies for further dealing with the problem(s).

5. Apply value judgement (and be prepared to defend it).
6. Entertain the Decision-making act: make rational choice between available alternatives, or generate new options; make a decision (or take a position).
7. Act according to the decision made.
8. Take responsibility!

No matter how clear, and even agreed upon, an educational goal and teaching objectives might be, an all important practical issue is how to translate these objectives (the HOCS-promoting in our case) into STES-oriented, interdisciplinary chemistry and/or science courses and curricula, teaching strategies and, in accord, alternative assessment methodology of the teaching/learning outcomes. As far as STES or environmental education is concerned, decision making-oriented and/or interdisciplinary courses and programs may help facilitate or enhance the transfer of HOCS. As chemical educators, however, we should ask: will HOCS taught in a disciplinary context (such as chemistry) transfer when students are faced with STES issues? Or, are HOCS gained in chemistry, bound to be used only in chemistry? These and similar questions are important for designing and gauging the effectiveness of courses, programs of study, teaching and assessment strategies that have, as their primary goals, the development of students' critical thinking, problem solving, and decision making capacities. Additional related questions should be asked and addressed by chemistry teachers, science educators and researchers:

- Does the existing science educational system foster the growth of autonomous learners who have the capability of evaluative-critical system thinking in problem-solving decision making situations?
- Are HOCS achieved in a disciplinary context transferable into interdisciplinary contexts?
- Is the major goal of science teaching – to do justice to the taught disciplines (physics, biology, chemistry, mathematics), or to the student learners? (or to both?)
- Is the goal of HOCS learning attainable? …How?
- What are the implications of HOCS-oriented teaching to the future of science/STES/ teaching, assessment and learning?
- The all-pervasive questions are: *Do we, can we, how can we, teach for HOCS learning, and are getting it right?*

Partial answers to several of the above questions can be found in the relevant educational and research literature, e.g., American Association for the Advancement of Science, 1994:

> *"...Most Americans are not science-literature ... methods of instruction, far from helping, often actually impeded progress toward science literacy. They emphasize the learning of answers more than the exploration of questions, memory at the expense of critical thought, bits and pieces of information instead of understanding in context, recitation over argument ... For its part, science education ... should help students to develop the understandings and habits of mind they need to become compassionate human beings able to think for themselves ... science ... [mathematics and technology] ... literacy has become necessary for everyone ... science education will have to change to make that possible…"*

And

"...many students still leave school with decifient or distorted view of scientific inquiry ... [including such myths as] ... scientific inquiry is a simple algorithmic procedure and science-free activity..." (Bencze & Hodson, 1999).

Relevant research findings:

"... Our students are not doing well at thinking, reasoning ... analyzing, predicting, estimating, or problem-solving ... Teachers teach most content only for exposure, not for understanding ... [they] tend to avoid thought-provoking work and activities and stick to predictable routines..." (Kennedy, 1991).

"Moreover, in international comparisons, American students are falling behind, particularly in those areas that require higher-order thinking" (Matheis, Spooner, Coble, Takemura, Matsumoto, Matsumoto, & Yoshida, 1992).

"The highest scores (of college students) *were for the algorithmic questions, suggesting that students in both countries (US and Israel) were proficient in using algorithms to solve exercises. The lowest scores were for the conceptual questions ... suggesting (in view of the no correlations found) that success in solving algorithmic test problems does not mean conceptual understanding ... (and) that traditional methods and instructional strategies of teaching chemistry are not compatible with attaining conceptual learning and utilizing HOCS...* (Zoller, Lubezky, Nakhle, Tessier & Dori, 1995).

Clearly, at present, we as a community of science teachers, do not teach for HOCS learning, in spite of the fact that all involved agree, that advanced thinking skills – including the abilities to analyze, evaluate, make judgements and draw appropriate conclusions – are of particular importance (Jones, Hoffman, Moore, Ratcliff, Tibbetts, Click, 1994).

The following selected illustrative examples of HOCS-promoting, STES-oriented courses, curricula, teaching strategies and assessment methodologies, reflect the response of the author, via research and teaching, to the HOCS learning-related questions previously asked. Critical reflection on the part of the reader is welcomed.

HOCS/STES-ORIENTED COURSES AND CURRICULA

Instead of the classical guiding question "what to teach and in what order?" – leading to the generation of the "classical" traditional core sillabi when a new course is being designed, we suggest the following sequence of queries to guide the development of new HOCS-promoting STES-oriented interdisciplinary curricula:

1. What should be done? (clarifying desirable goals);
2. What can be done? (feasibility within given constraints);
3. How to do what is agreed upon? (choosing methods, strategies, means);
4. What should be taught and at what level to serve the above? (selecting content and subject matter).

Using the above guiding 'model', the course "The Chemistry of Man's Environment" or "Environmental Chemistry in the Modern Socio-Technological Context" has been ideated, developed, and successfully implemented in a university setting for junior and senior science students, mainly biology majors. A somewhat different version of this course "Quality of Basic National Resources: Water and Air" is included, as a mandatory graduate course, within a master program at the Department of Natural Resources and Environmental Management of the same university.

Course Outline

1. Introduction: Fundamental environmental issues. Environmental chemistry in perspective.
2. Chemistry and ecology; system approach.
3. Biogeochemical cycles.
4. The evolution of the environment, natural resources raw materials.
5. Water: resources, properties and relevant technological aspects. A case study: Water, environment and politics in Israel.
6. Atomic structure and chemical bonding (selected topics).
7. Water: Selected water pollutants, water desalination, treatment and reuse, and related technological aspects.
8. Properties of solutions.
9. Air: the atmospheric physico-chemical composition; selected chemical pollutants.
10. Gases and their properties.
11. Fundamental concepts in organic chemistry: bonding hybridization and the tetrahedral carbon; stereochemistry, basic chemistry of alkanes, alkenes and alcohol.
12. Air: atmospheric reactions and smog, aerosols and ozone (a case study). Smoking and cigarette smoke.
13. Food: production, quality and distribution in a world of population explosion: chemistry and food production.
14. The basic chemistry of carboxylic acids and amines. Some chemistry of selected basic food ingredients: carbohydrates, amino acids-proteins, fats.
15. Food: Analysis of organic constituents in food: selected food pollutants: insecticides and herbicides – the D.D.T. and methyl bromide (2 case studies).
16. Drugs and alcohol in medicine and substance abuse in modern society.
17. Conclusions: i. students presentations of final projects; ii. Chemistry – science – technology – environment – society: chemistry and the quality of future life and environment.

Interestingly (and significantly!) most of the students in the master program do not have traditional science background based on their undergraduate studies, since they come from geography, economics, social studies and management.

Based on the philosophy, rationale, objectives and guiding model outlined above, an interdisciplinary modular, HOCS and STES-oriented course "Science, Technology and Environment in Modern Society (STEMS)" has been developed and currently being implemented, as a three year mandatory course for non-science 10-12 graders in Israel high schools. The seven developed modules – accompanied by a "superordinate" teaching/learning guide, common to teachers and their student, are presented in Table 1. The particular learning approaches, student skills to be developed and fundamental concepts to be conceptualized are summarized in Table 2 (Tal, Dori, Keiny & Zoller, 1999).

Since what students learn and appreciate is that what shows in term and final exams, a STES-oriented HOCS teaching, regardless whether within specifically designed environmental programs or ongoing science courses, should not only be consonant with the environmentally imperative transdisciplinary HOCS orientation in teaching, but should foster *HOCS learning* (Zoller, 1993; 1997). The key role of, in accord, *alternative* HOCS promoting assessment/evaluation methodologies and examinations is clearly apparent. Within our longitudinal research we were delighted to learn – via specifically developed TOPE survey/questionnaires (Figure 1) that science students, prospective teachers in particular, do prefer HOCS-oriented examinations. The results depicted in Table 3, with respect to Israeli and American college science teachers point to this effect (Zoller & Ben-Chaim, 1996).

TABLE 1. *STEMS modules – Contents.*

STEMS module	Contents/topics	STEMS module	Contents/topics
1. The White Gold in Deep Soil Ground Water	Ground water as a natural ecological system, groundwater as a resource, the impact of human activity on ground water	4. The Quality of Air Around Us	Oxides and particles in the atmosphere, the greenhouse effect, ozone depletion, odor and its effects, civil involvement, regional and global effects
2. The Brain Behind the Power	The time-tunnel, man physical limitations, simple machines, the industrial revolution, the moving band, Hi-tech industry in Israel, the human brain vs. the computer, man and machines	5. Biotechnology, Environment and What is in Between	Biotechnology and genetic engineering, past and future agriculture and medicine, the impacts of biotechnology upon environment and society
3. The Metropolitan Animal, Development and Preservation, Tel-Aviv- Jaffa	Science-technology-environment interrelation problems of a metropolitan city, construction and development of transportation, business, culture and entertainment	6. Desert and Desertification	The desert from different perspectives, natural, social and humanistic aspects, past and present history
		7. Progress as a Tension Between a Blessing and a Curse	Science, history and philosophy from disciplinary to interdisciplinary conception

TABLE 2. *STEMS learning approaches, skills and fundamental concepts in modules 1-3.*

Teaching/learning approach	Student skills	Curriculum constructs/Fundamental concepts
1. Mini-research, investigating lab-work, field work, analyzing data, simulation games and concept maps, self- and group learning, model design	Question asking, interdisciplinary problem-solving, evaluative thinking, value judgement	Dynamic equilibrium, reversible and irreversible process, system and its components, exponential growth, sustainable development.
2. Brain-storming, question asking, class discussion, inquiry (lab), visiting science museum and industry, watching movie, performance of engineering task, role playing	Technology assessment, evaluative thinking, decision making, value judgement.	Sustainable development, technology assessment, reversible and irreversible process, exponential growth, optimization.
3. Working with data graphs, field observation, teamwork, decision making, problem-solving, interdisciplinary question asking, inquiry-based learning.	Data analysis, interdisciplinary problem solving, technology assessment, inquiry-based decision making.	Quantitative and qualitative change, dynamic equilibrium reversible and irreversible process, exponential growth, sustainable management and development.

Before, in-parallel and following this and related studies innovative HOCS-promoting examinations have been developed and successfully implemented, two examples of which are here presented for illustration. The first – the *Eclectic Examination* (EE) constitutes a means for simultaneous assessment of both students' performance and HOCS-oriented courses (Zoller, 1993; 1997). It consists of:

QUESTIONS	to be answered
PROBLEMS..	to be worked out
TASKS	to be performed
SUGGESTIONS	to be developed
IDEAS	to be generated and rationalized
OPINIONS	to be defended or rejected
STIMULATIONS	to respond to
EXPERIMENTS	to be suggested/devised/designed
ALTERNATIVES...	to be chosen and backed consistently

	Low			High
	1	2	3	4
A. Final Project/seminar work	-	-	-	-
B. "Take-home" exam, any materials may be used	-	-	-	-
C. Oral; separately, no materials may be used	-	-	-	-
D. Oral; separately, any support material may be used	-	-	-	-
E. Oral; in groups of 2-3, no materials may be used	-	-	-	-
F. Oral; a "class forum," format, all students present	-	-	-	-
G. Written exam in class, time limited, no materials allowed	-	-	-	-
H. Written exam in class, time limited, any materials allowed	-	-	-	-
I. Written exam in class; time unlimited, any materials allowed	-	-	-	-
OPTIONAL: Indicate (below) the reason(s) for your preferences:				

FIGURE 1. *Type of Preferred Examinations (TOPE) survey/questionnaire (Ben Chaim & Zoller, 1997).*

All the above are assembled together in various combinations and in different proportions of each component – under a variety of conditions in different situations/setting – and administered within chemistry and/or other science and/or interdisciplinary courses. The second is the Examination Where the Student Asks the Questions (ESAQ) (Zoller, 1994):

> The core element of the EASQ is a prearranged oral-examination class session in which the *course professor is examined by class students.* In this contradictory to the traditional "pencil and paper" class examination (in which the students response to a series of questions/problems prepared and/or assembled by the professor), the students examine their professor *orally,* using their home prepared written questions related to the course. Each student is required to formulate two to three relevant and *meaningful* questions, one of which is to be used for the class examination, followed by the submission of all of them to the professor – for grading – towards the end of the examination

TABLE 3. *Preference of examination types: Comparison between Israeli and American college science students (Zoller, Ben Chaim & Kamm, 1996).*

Exam Type [a]	Israel Students X	Israeli Students S.D.	American Students X	American Students S.D.
A	3.02**	0.87	2.18	0.84
B	3.57**	0.73	2.67	1.17
C	1.98*	0.98	1.61	0.74
D	2.33	1.05	2.18	0.89
E	1.73	0.83	1.91	1.01
F	1.34	0.64	2.00**	0.94
G	2.21	0.87	2.98**	0.85
H	3.03	0.81	3.02	0.91
I	3.47*	0.85	3.14	1.05

[a] See TOPE questionnaire in Figure 1.

*$t_c = 2.5748$, $t_I = 2.3969$, $p \leq 0.01$.

** $t_A = 6 .4246$, $t_B = 6.6111$, $t_F = 5.7610$, $t_G = 5.7067$, $p \leq 0.001$.

session. Two to five of the *students' formulated question* (which have not been treated during the class session) are selected by the Professor and redistributed to all course participants to serve as a *students'* designed 'take home' examination (Tsaparlis & Zoller, 1995).

The following are *HOCS-type* exam questions (Zoller, 1993; Zoller, 1994; Zoller et al., 1995; Zoller & Tsaparlis, 1997) which were designed developed and incorporated within on going disciplinary – HOCS oriented – college chemistry courses, *per-se* and STES-oriented courses respectively.

Question 1. (Zoller, 1993, 1999): *The Florida Queen Butterfly produces a compound A having the formula C_8H_9NO, which is essential for attracting the males for mating and reproduction. The NMR spectrum of compound A and the five possible structural isomers of A are given in the figure below* (see J. Chem. Educ., Zoller, 1993).

1. *Which of these structural isomers best fits the given spectral data? Explain.*
2. *Suggest two simple chemical reactions, the results of which will enable you to confirm your conclusion in (1). Provide the chemical reactions involved.*
3. *Which of the given isomers may, in principle, be optically active?*
4. *Draw qualitatively (crude approx. only), the IR spectrum you expect for one of the given isomers of your choice.*
5. *Is the use of UV for the identification/characterization of this isomer effective? Explain.*
6. *[optional] What direction of research (if at all) would you recommend concerning compound A? Be specific and rationalize your answer.*

Question 2. *Ionization potential refers to the energy required to remove an electron from an atom. The first ionization potential refers to the energy required to remove the first electron, the second potential refers to the removal of the second electron, etc. Which of the following two would you expect to have a higher ionization potential: a sulfur atom or a phosophorus atom? Explain. (Zoller, Fastow, Lubezky & Tsaparlis, 1998).*

Question 3. *Adding an electron to an oxygen atom is a reaction which is associated with emission of energy. Adding a second electron to the resulting O ion is associated with energy absorption. What is your explanation to these phenomena?*

Question 4. *This question is aimed at assessing students' system thinking HOCS (part 1) and their extent and depth of conceptualization of the fundamental dynamic equilibrium concept within high school and college courses.*

Part 1: A farmer raises cotton in a field near his/her house. In your opinion, which of the following 7 decisions has an impact on the quality of the environment? For each item mark an "X" on the appropriate line.

	Has an Impact	*Has no Impact*
1. Irrigating the cotton with the well water in the field area.		
2. Irrigating the cotton with raw sewage water		
3. Using pesticides and herbicides		
4. Raising vegetables between the rows of cotton		
5. Covering the vegetables with plastic sheets as in a greenhouse.		
6. Applying an organic fertilizer		
7. Burning in the field, the organic waste that remains at the end of every growing season		

Part 2: On many occasions we hear or read that in the groundwater (or in the atmosphere or the desert) an equilibrium exists without human interference. In 2-3 sentences give your interpretation of the concept equilibrium in terms of its relation to groundwater for the atmosphere or desert.

These and additional "HOCS-type" exam questions were shown to be valid, reliable and suitable for students' HOCS assessment within ongoing chemistry interdisciplinary STES and EE courses at secondary and tertiary level.

SUMMARY

If one believes that indeed interdisciplinary systemic HOCS development is the key for meaningful STES-oriented chemical education, then the following should serve as the guiding model for chemistry teaching:

- A holistic, systemic interdisciplinary approach as the guiding construct.
- An independent inquiry-based learning in which the learner/researcher constitutes an integral part of the investigated system – as a foundation for meaningful conceptualization and learning.
- A personal involvement and responsible *action*, not just awareness and low-order understanding on the part of the learner.
- The educational objectives and *students'* (not disciplines') needs are (should be) the determinants of the science and STES-oriented courses. The development of students' HOCS and their conceptualization of fundamental/unifying concepts should be the focus of the science learning process in Chemical Education.
- The essence of the learning process: (Relevant) question-asking/problem-raising and their investigation, reflection on, and critical thinking about, by the student learner – for position-developing, decision-making and action-taking, accordingly.

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