Educational research

Matching Higher-Order Cognitive Skills (HOCS) promotion goals with problem-based laboratory practice in a freshman organic chemistry course

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Abstract: The development of students' higher-order cognitive skills (HOCS) is central to the problem-based component of a freshman organic chemistry course. HOCS within science education is strongly connected to critical thinking (CT) and problem solving (PS), and often manifested by question asking and decision making. The laboratory, if utilized effectively, can be fertile ground for HOCS/PS development and CT advocacy. The ultimate goal is to develop a student culture having a broader, deeper, and more interconnected level of scientific literacy, conceptual understanding, and the contextual applications of knowledge. The concluding 6-hour laboratory session of the course 'Introduction to Modern Organic Chemistry' is presented here as an example of problem (not exercise) solving, and is proposed as a model for a 'HOCS-promoting'—CT/PS-requiring laboratory activity in organic chemistry teaching. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 153-171]

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Introduction: background, rationale and purpose

This paper deals with the systematic integration of three components involved in chemistry education in the context of the development of students' HOCS: problem solving, critical thinking and laboratory practice. The problem-based laboratory component of a one-semester freshman organic chemistry course, 'Introduction to Modern Organic Chemistry' provides a vehicle for research and an experience-based model for laboratory practice targeted to promote students' HOCS, particularly the bridge between problem solving and critical thinking.

A dominant component of the current reform in science education is a purposeful effort to develop students' higher-order cognitive skills (HOCS) of question-asking, critical thinking (CT), system thinking, decision making and problem solving (PS), as opposed to 'traditional' algorithmic-based lower-order cognitive skills (LOCS) (Zoller, 1993). This means a paradigm shift from the prevalent algorithmic teaching to 'HOCS learning' (acquiring the capabilities of *evaluative thinking* and transfer) and HOCS-promoting assessment methodologies leading to improved student PS capabilities (Zoller, 2000). This shift requires teaching and learning which take PS well above the level of algorithmic manipulation, into the realm of creativity, thus combating the common feature of traditional school science that all problems have a unique correct solution (Wood, 2006). Indeed, instruction in thinking skills was found both to improve academic performance and to enable students to become better problem solvers in other situations in and outside school

(Whimbey, 1985). Furthermore, instructional strategies incorporating cognitive activities that involve both knowledge and skills bases were found to be effective in assisting students to develop their CT and PS skills (Lyle and Robinson, 2001; Taconis et al., 2001).

Many educators perceive the development of learners' CT as one of the most important goals of education at all levels, particularly in the context of HOCS-promoting learning in science education (Zoller, 1993). CT is logical and reflective thinking that focuses on one's decisions about beliefs and doings (Ennis, 1989) and was later defined as the skill of taking responsibility and control over our mind (Paul, 1996). In the context of science education, CT has been conceptualized as a results-guided activity, reflective and evaluative in nature, requiring decisions about what to accept or reject and/or what to believe in. This is followed by a decision what to do (or not to do), an appropriate action, and the taking of responsibility for the consequences (Zoller, 1993).

Science education researchers have pointed out that students quite often fail in performing assignments that require CT skills (Bailin, 2002). Others have shown that students may be successful in performing such assignments, provided they were exposed to teaching that included both critical thinking and required student practice (Adey and Shayer, 1990; Zoller, 1993; Zoller et al., 2000; Ten Dam and Volman, 2004). There appears to be agreement that students' CT capability is developed by implementing instructional strategies that support and foster other HOCS such as *question asking* and *decision making* in problem solving situations (Potts, 1997; Halpern, 1999; Ben-Chaim et al., 2005).

Science and chemistry teaching is traditionally based on lectures and textbooks presenting unambiguous and authoritative theories, rules of nature and, ultimately, one correct solution to each problem (in most cases, an *exercise,* because it seeks to confirm previously taught and learned content) posed (Nakhleh, 1993). Similarly, much traditional university-level science (e.g., chemistry) teaching emphasizes rules, formal definitions, equations and algorithms, in terms of 'knowing', 'remembering', 'defining', identifying', understanding and 'applying' which, primarily, require just LOCS in order for the students to respond 'correctly' to examination questions; that is, *one correct* answer to one well-defined question.

A major issue of concern is whether such traditional teaching practices promote students' HOCS (such as CT and PS capabilities), which require more than just knowledge and application of known algorithms. The potential contribution of laboratory practice to the development of students' HOCS is clearly a related issue.

Laboratories have been described as contrived experiences where students interact with materials to observe phenomena (Hofstein, 1988), and thus involve students taking an active part in the learning procedure (Klainin, 1988). University chemistry departments rarely question the importance of laboratory work as an essential component of the experiences they provide for their undergraduates, despite the large number of resources committed to this work. However, institutions have begun to consider just how much *learning* is, in fact, taking place during laboratory sessions (Rollnik et al., 2001).

For three decades, laboratory work in school science courses was claimed to provide students with insight into, and experience and practice of, the methods of science. It was argued, however, that from 'discovery learning' in the 1960s – to process-led science – to contemporary constructive approaches, each of these styles of the laboratory work has seriously misrepresented and distorted the nature of scientific inquiry (Hodson, 1996). Recent studies suggest that appropriate models of laboratory practice can contribute conceptual benefits to participating students (Johnstone, 1997; Rollnik et al., 2001; Roth and Welzel, 2001).

The importance of students' HOCS development in science and chemistry education is apparent and supported by many science educators. Our recent studies have demonstrated that the development of students' PS and CT capabilities is feasible via persistent purposeful HOCS-promoting teaching and assessment strategies (Ben-Chaim et al., 2005, 2006). In this special themed issue of *CERP*, this three-component-based paper, dealing with PS and CT on the theoretical level and the related laboratory practice on the practical level, constitutes a modest contribution to the intended LOCS teaching-to-HOCS learning paradigm shift in science education.

While problem solving, critical thinking and progressive pedagogical and curricular practices are advocated in science education literature (e.g., Zoller, 1990, 1993; Zohar, 2004; Flick and Lederman, 2005; Pushkin, 2007), there is no consensus on the specific definition of 'critical thinking'. Pushkin (2007) notes a wide spectrum of contexts for critical thinking (e.g., decision-making, cognitive self-consciousness, paradoxical situations). However, a primary connection to critical thinking is with scientific problem solving, most notably chemistry and physics (e.g., Zoller, 1987, 1994; Carnine, 1993; Lewis and Smith, 1993; White, 1993; Maloney, 1994; Zoller et al., 1995; Pushkin, 1995, 1999, 2000, 2007; Zoller and Tsaparlis, 1997 Ben-Chaim et al., 2006;).

The union between critical thinking and problem solving forms an 'umbrella' that encompasses levels of thinking, levels of knowledge, levels of cognitive skills, the implications of these different levels, and how these different levels interact. The HOCS-promoting components of this umbrella, specifically CT and PS, clearly require consistent and persistent employment of explicit pedagogical and curricular practices. This requires flexible and contextual learning activities, as well as HOCS developing teaching strategies and assessment modes – all to be consistent with related course goals, as well as contribute to these goals, and encouraging student attainment of them. The first part of this paper is a review of HOCS-relevant pedagogical research and theoretical literature. The second part focuses on the concluding six-hour laboratory session of a one-semester introductory organic chemistry course involving HOCS-promoting, CT/PS-requiring laboratory practice. This practice, which has been successfully applied for more than two decades, will be described and its relation to assessments and evaluations critically discussed.

Review of HOCS-related literature

Levels of thinking

A hierarchy of thinking levels is established in the literature (e.g., Fogarty and McTighe, 1993; Lewis and Smith, 1993; Pushkin, 1999, 2000, 2007). These levels are known as lower-order thinking, higher-order thinking, creative thinking, and critical thinking. Two additional levels of thinking are known as systemic/lateral thinking and evaluative thinking (Zoller, 2000).

The lowest level of thinking is referred to as *lower-order thinking*. Lower-order thinking typically reflects rote memorization, regurgitation, or recitation of basic facts, or perhaps performing a simple one-step computation with assistance of a calculator (e.g., addition, subtraction, multiplication, division, squaring numbers or determining a logarithm). For example, stating the name of a chemical formula, or identifying an element on the periodic table, or stating that the pH of an acid is typically below 7.0, all illustrate lower-order thinking. On the other hand, *higher-order thinking* (one step up on the hierarchy) typically reflects taking new information and combining it with *a priori* information, or rearranging such information to find possible answers to perplexing situations (Lewis and Smith, 1993). For example, a student combining principles of stoichiometry with the ideal gas law or the concept of molarity, or determining the mass of a liquid based on its density and measured volume, illustrate higher-order thinking.

In many respects, algorithmic exercises are the classic illustration of lower-order thinking. This does not, however, imply that conceptual exercises illustrate higher-order thinking. In fact, lower-order thinking is hardly conceptual, even though it is primarily concept-focused (e.g., Pushkin, 2007). Conceptual thinking is actually more evolved than higher-order or algorithmic thinking, for it requires learners to understand on a broader level what computational exercises address (Tobias, 1990, 1992; Tobias and Tomizuka, 1992; Pushkin, 1998). For example, to determine the limiting reagent for a chemical reaction and calculate an expected yield correctly, does not necessarily mean one genuinely understands the role of a limiting reagent and its implications on product formation.

Problem solving has been defined as what people do when they do not know what to do (Wheatley, 1984) and as a get-oriented sequence of cognitive operations (Anderson, 1980). The process of PS is difficult to outline, but psychologists and educational researchers agree that it involves cognitive, operative and affective variables. In the thus far dominant algorithmic-LOCS science teaching, PS has been perceived as a process by which the learner discovers a combination of previously learned rules that can be applied to achieve a solution (Holroyed, 1985). In other words: problem solving is a process of applying previously taught and learned algorithms to achieve a solution to an **exercise**. However, in the context of our concern, students' ability to resolve HOCS-requiring **problems**, we perceive a problem to exist when there is a gap between where a person is and where he wants to be, without knowing how to cross the gap (Hayes, 1981).

Several 'composite-type' models of, and/or associated with, the PS process in relation to its cognitive functions have been put forward (Newell and Simon, 1972; Tsaparlis, 1998; Shin et al., 2003; Stamovlasis and Tsaparlis, 2003, 2005). Researchers agree that: (a) the context of the problem is a critical determining factor in the process (Raine and Symons, 2005; Tsaparlis, 2005), and (b) by the application of appropriate relevant teaching and assessment strategies, the improvement of students' problem solving capability is attainable (Sawrey, 1990; Zoller, 2000; Danili and Reid, 2004; Perels et al., 2005).

Researchers distinguish between well-structured and ill-structured problems (Zoller and Tsaparlis, 1997; Shin et al., 2003), or between conceptual and algorithmic problems (Nakhleh, 1993; Stamovlasis et al., 2004, 2005). As a result, questions and/or exam items have been categorized into those that require LOCS and those that require HOCS for their solution and resolution (exercises and problems) respectively (Zoller et al., 2002). Accordingly, exercises are categorized as questions, exam items, assignments, or tasks which require mainly or exclusively LOCS on the part of the solver, namely simple recall of information or a routine application of known method, theory or knowledge to familiar situations and contexts. Such items can be solved by means of algorithmic processes (mechanistic application of what procedures are taught/recalled/known, but not necessarily understood), already familiar to the learners through previous specific directives or practice, or both (Johnstone, 1993; Zoller, 1993; Zoller and Tsaparlis, 1997). Exercises are, usually, familiar to the students and solving them is simply a matter of writing out the solution and checking for mistakes (Lyle and Robinson, 2001). Problems, on the other hand, require for their solution the application of HOCS.

Problems (as opposed to exercises), whether qualitative or quantitative, are intellectually and cognitively challenging 'conceptual' questions that may require several cycles of interpretation, representation, planning, deciding, execution, evaluation and re-evaluation. These problems are operationally defined as quantitative or qualitative conceptual questions, unfamiliar to the student, that require for their solution more than knowledge and application of known algorithms; namely, the HOCS of reasoning, analysis, synthesis and problem solving, making of connections and critical evaluative thinking, including the application of known theory or knowledge or procedure, to unfamiliar situations or situations with an unusual element or dimension (Zoller et al., 2002). When solving a problem, the student not only arrives at a resolution, but also acquires a new or revised knowledge (Lyle and Robinson, 2001), as well as a higher level of cognition. Meta-analysis of forty case studies indicated that providing learners with guidelines and criteria that can be used in judging their own problem-solving process and product, and with immediate feedback, are prerequisites for the acquisition of PS skills (Taconis et al., 2001).

While there are similarities between creative thinking and critical thinking, distinctions are evident (Fogarty and McTighe, 1993). *Creative thinking* is often associated with visualizing, personifying, associating relationships, making analogies, and dealing with ambiguity and paradox. *Critical thinking* is often associated with attributing, comparing/contrasting, classifying, analyzing for bias, solving for analogies, and evaluating. It would seem that creative thinking involves recognition of novel situations, while critical thinking involves consideration of the implications of such situations. For example, consider the following problem previously given during an organic chemistry lesson to pharmacy students:

> Liver alcohol dehydrogenase (LADH) is an enzyme in the liver responsible for the 'breakdown' of ethanol into ethanal (i.e. acetaldehyde), according to the following reaction,
>
> $$CH_3CH_2OH + NAD^+ \rightleftharpoons CH_3CHO + NADH + H^+$$
>
> (Note: NAD^+ = Nicotinamide adenine dinucleotide, a coenzymatic form of Niacin, one of the Vitamin B complex)
>
> A) The kinetics for this reaction is zeroth order. What does this tell you about commonly known methods to 'sober up' after getting drunk?
> B) Is dehydrogenation an example of oxidation or reduction? Why? How?
> C) Could this reaction possibly explain to you why drinking 'wood alcohol' (i.e., methanol) has far more serious consequences than drinking 'grain alcohol' (ethanol)? Might it explain why rubbing alcohol is now made of isopropyl alcohol (i.e., 2-propanol, $CH_3CH(OH)CH_3$)?

In the context of Fogarty and McTighe's (1993) definition, a student identifying the issue that exists within part A of the problem reflects creative thinking. Students must understand of what "zeroth order kinetics" means. It appears that the liver, which produces the enzyme needed to "break down" (a common term used in biology textbooks to describe catabolism to first-year biology students (e.g., Starr and Taggart, 1987)) alcohol, does this independently of the amount of alcohol in one's body, and appears to do its job at its own rate, regardless of any efforts on our part to speed things along. This realization on the part of students reflects critical thinking, for students must attribute prolonged inebriation to the behavior of LADH.

Part B is a question to assess students' understanding of what oxidation and reduction mean, and combines aspects of creative and critical thinking, for it forces a comparison and evaluation of various operational definitions encountered by biology majors. Many students learn contrasting definitions of oxidation and reduction in their introductory biology and chemistry courses. A common conception among students from an introductory biology course is that oxidation involves a reaction with oxygen while reduction is associated with electrons and/or oxygen removal, or reactions involving water and/or carbon dioxide (Garnett and Treagust, 1992; Schmidt, 1997). In an introductory chemistry course, students encounter that Red-Ox reactions involve an exchange of valence electrons.

However, in an organic chemistry course, students encounter a new context for electron exchange. In the given LADH reaction, ethanol is converted to acetaldehyde; thus two covalent bonds (i.e. sigma bonds) are converted into one unsaturated covalent bond. Thus, oxidation not only involves removal of an electron pair; it results in the formation of a multiple bond as an alkyl carbon is converted to a carbonyl carbon.

In part C, students not only need to consider the size of the alcohol molecule ingested relative to this enzyme's effectiveness, they must also consider the historical context of methanol as a substitute for the ethanol found in wine, beer, and liquor. Methanol (once the main ingredient in rubbing alcohol) is too small a molecule for LADH to act upon, thus methanol remains unmetabolized by the liver, and this toxic chemical builds up in the body with catastrophic consequences (e.g., blindness or death). Thus, the importance of *a priori* knowledge should not be overlooked relative to learners' thinking skills and evolving conceptions (e.g., Ausubel, 1968; Posner et al., 1982; Millar and Driver, 1987; Vosniadou and Brewer, 1992; de Jong et al., 1998; Duit and Treagust, 1998; Gitomer and Duschl, 1998; Tamir, 1998).

System/lateral thinking essentially addresses the question of whether a learner solves problems with a defined conceptual framework (i.e., is there a "game plan"?). For example, consider the following critical thinking problem involving solution stoichiometry, limiting reagents, and percent yields, closely-related to a laboratory setting typically experienced by students in their first chemistry courses:

> *50 milliliters of 0.5M ammonium sulfate are added to an excess solution of barium chloride. A precipitate results.*
>
> 1. If you recover 3.25 grams of precipitate, what is your percent yield?
> 2. How might your result differ if you used 50 milliliters of 0.1M silver nitrate instead? Please justify your answer quantitatively. (Pushkin, 2000, p. 211)

Solving this problem requires several steps and considerations along the way. First, for part 1, learners need to be able to write a balanced chemical reaction with the correct chemical formulas for all reactants and predicted products. Second, they need to determine which reactant-product pair provides the relevant stoichiometric relationship for calculations. Third, they must determine the number of moles of ammonium sulfate in a given molarity and volume, then the number of moles of barium sulfate (i.e., the precipitate) by means of a mole ratio. This will lead them to determine a theoretical yield based on stoichiometry, and a percentage yield based on the actual yield of 3.25 grams.

On the other hand, learners need to consider a new reactant (and limiting reagent) in part 2, thus leading to a different precipitate and theoretical yield. As noted by Pushkin (2007), the theoretical yield calculated in part 2 forces a learner to realize that 3.25 grams of recovered precipitate is an impossible outcome in a laboratory setting, thus creating an opportunity to consider the implications of using different reagents and amounts in similar-type reactions (i.e., precipitation). Again, to solve part 2 of the problem, a learner must return to the initial foundation established in part 1 (i.e., a balanced chemical equation and mole determinations).

This finally leads to *evaluative thinking*, which involves a learner making attributions for the results obtained during problem solving. For example, returning to the stoichiometry problem, does a learner see a connection between the given problem, its solution, and the relevant principles one must understand in order to solve the problem? In other words, does a learner recognize any cause-effect relationships within a problem to reinforce concepts encountered during several class lessons and/or laboratory sessions?

In many respects, both system/lateral thinking and evaluative thinking are similar to critical thinking, as a dimension of *cognitive regulation*, or consciousness of knowledge exists (Shin et al., 2003). In both, a learner must be able to take information, analyze it, and discuss the implications of that information, including any paradoxical situations. However, in order truly to appreciate the amorphous definition of critical thinking, one should consciously consider the connection thinking has with knowledge. More importantly, one needs to consider the parallels between levels of thinking with levels of knowledge.

Levels of knowledge

As with thinking, knowledge has a hierarchy (e.g., Ryle, 1949, cited in Gagné et al., 1993; Gagné, 1977, 1985; Schoenfeld, 1978; Anderson, 1990;, Maloney, 1994; Pushkin, 2007;) – declarative knowledge, procedural knowledge, and conditional knowledge. Conditional knowledge has two subcategories, situational knowledge and strategic knowledge.

In the relationship between thinking and knowledge there are parallel hierarchies. Declarative knowledge is the lowest level of knowledge and is parallel to lower-order thinking. Procedural knowledge is parallel to higher-order thinking. The combination of situational and strategic knowledge, *conditional knowledge* (Schoenfeld, 1978), is parallel to critical thinking.

"***Declarative knowledge*** *is knowing that something is the case…* ***procedural knowledge*** *is knowing how to do something,*" suggesting that declarative knowledge is a collection of "*facts, theories, events, and objects*" (Gagné et al., 1993, pp. 59-60), while procedural knowledge involves steps of doing things.

Does this mean that declarative knowledge is conceptual, and procedural knowledge is algorithmic? Or, does this mean the opposite, declarative knowledge is algorithmic and procedural knowledge is conceptual?

It is somewhat awkward to apply the term 'conceptual' to either declarative or procedural knowledge (Pushkin, 2007). The term 'conceptual' is defined as "coming from, or belonging to, the concepts, ideas, or principles something is based on" (Microsoft Office 2001 Dictionary); this makes for a poor description of declarative or procedural knowledge. It might be best to consider 'conceptual knowledge' or 'conceptual understanding' as the **sum** of declarative and procedural knowledge, although 'conceptual understanding' was previously related to declarative knowledge, and 'skills/strategies' to procedural knowledge (Gagné et al., 1993).

When we consider conditional knowledge, and its two components, *situational knowledge* (deJong and Ferguson-Hessler, 1986) and *strategic knowledge* (Schoenfeld, 1978), we need to appreciate that this level of knowledge relates to *situated cognition*, an alternative term for critical thinking (Kincheloe et al., 1992, 1999; Kincheloe, 1999, 2000; Pushkin, 1999, 2000, 2007). What does this mean? It is the level of thinking that takes the *context* of a learning situation into account. More specifically, conditional knowledge brings together a learner's declarative and procedural knowledge, especially with regards to *problem solving*.

Looking back at either chemistry problem presented earlier in this paper, it appears that both situational and strategic knowledge go hand-in-hand when solving problems. Learners cannot truly identify a problem solving strategy without contextualizing the problem, nor can they contextualize a problem without considering available problem solving strategies within working memory. While conditional knowledge may be more prevalent in physics, chemistry problems involving stoichiometry or reaction mechanisms could also create opportunities to develop this level of knowledge (e.g., states of matter of reactants and/or products, orders of kinetics, structures of reactants and/or products).

This essentially comes down to the extent of schema development for a learner; the broader and more in-depth a learner's schema, the stronger and more flexible their problem solving strategies potentially become (Fischler et al., 2001). As with critical thinking, conditional knowledge depends on a level of cognitive consciousness by learners. In order to solve problems, learners first need to be able to recognize relevant aspects of problems and connect them to specific principles, which in turn are connected to specific methods of qualitative and/or quantitative analysis.

Levels of cognitive skills

According to Zoller (1993), cognitive skills fall under two categories: LOCS (lower-order cognitive skills) and HOCS (higher-order cognitive skills). Zoller defines LOCS in terms of simply knowing (i.e., basic recall of memorized information) or simply applying basic or memorized information to familiar situations, and/or applying algorithms to repetitious *exercises* (e.g., end-of-chapter textbook problems or exam questions). On the other hand, HOCS involve question asking, critical thinking, system/lateral thinking, decision making, problem solving (as opposed to mere exercises), evaluative thinking, and knowledge transfer (Zoller, 1987, 1990, 1993, 1994, 1997, 2000; Zoller and Tsaparlis, 1997; Zoller et al., 1995, 2002). Most importantly, what distinguishes HOCS from LOCS is the confronting of learners/problem solvers with unfamiliar situations, non-algorithmic and/or open-ended questions, as opposed to familiar and routine situations (Zoller and Tsaparlis, 1997).

How does this work? Consider Pushkin's (2000) precipitation problem. The first part of the problem can be considered quite routine, and calculating a percent yield from stoichiometric data can very well represent a typical end-of-chapter textbook problem. However, the presentation of a problem requiring students to 'fill in missing information' is often criticized as not being pedagogically direct enough (Pushkin, 2000). To some chemistry educators, the process of gathering and identifying information as well as the need of applying critical and/or evaluative thinking (not to mention transfer) towards problem solving, seems 'unfair' to learners. To them, proper assessment of learning should either involve *automatized* (i.e., robotic) regurgitation of lecture material or reproduction of algorithmic steps with concrete information. The sad reality is that writing balanced chemical equations from the names of reactants followed by stoichiometric analysis is too fundamental to qualify as representative of HOCS, but to chemical educators convinced that LOCS pedagogy is 'rigorous enough', expecting more of students seems beyond the scope of a university-level introductory chemistry course (Pushkin, 1999, 2000, 2001).

Such chemical educators fail to recognize that it is the second part of the problem that more substantially presents HOCS pedagogy, asking students to make predictions and consider the implications of using a different limiting reagent (silver nitrate as opposed to ammonium chloride). Consequently, students need to consider new products, different solubility rules (for silver chloride and barium nitrate, as opposed to barium sulfate and ammonium chloride) and, finally, observe the quantitative evidence of how the second reaction will produce something different from the first (Pushkin, 2007). The mere presentation of open-ended questions (even if a definitive answer is expected by an educator) encourages learners to consider a wide array of information and *make connections* between such information with existing schematic or related, relevant knowledge, a process identified by Bransford (1979) as *spread of activation*. HOCS-oriented problems encourage learners to have a broad and deep consciousness of a problem, its context, implications, connections to and relationships with relevant issues, and their *activated* (as opposed to existing) knowledge base. Thus, it appears that HOCS, like CT and PS, are contextually-bound but not, necessarily content or discipline bound.

When discussing cognitive skills development, it becomes evident that such discussion overlaps with discussion of levels of thinking and levels of knowledge. Chemistry educators who advocate the pedagogic advantages of introducing HOCS into the curriculum also need to advocate creative, critical, systemic/lateral, and evaluative thinking, as well as situational/strategic knowledge. Advocates (perhaps unintentional) of LOCS erroneously believe that rigorous content equates with critical thinking. They fail to recognize that 'lots of information' does not translate to knowledge if a learner's working memory is inactivated. Simply reiterating or confirming the known, the familiar, and 'standard facts' does not stimulate or challenge the mind; rather, this approach stunts the mind and limits its potential, creating what Kincheloe et al. (1992, 1999) refer to as a "cognitive illness."

HOCS advocacy is more than pedagogical and curricular; it is also *socio-cultural*. From Vygotsky's (1978) concept of the zone of proximal development, to Perry's (1970) levels of adult intellectual schema, to Freire's (1985) and Giroux's (1988) concept of teaching and learning as "transformative intellectualism," two pre-requisites for changing thinking are to change the learning culture and to change the classroom dynamics. If a specific cognitive outcome is desired, explicit pedagogical and curricular practices need to be consistently employed; short-term actions will not necessarily result in long-term effects (e.g., Jonassen, 1993; Pushkin, 1995). Furthermore, if flexible and contextual thinking are expected of learners, educators should provide flexible and contextual learning activities as well as use flexible and contextual modes of assessment, so the even the practice of critical thinking does not become an automatized routine (e.g., White and Gunstone, 1992).

The same is applied to PS, transfer, and other components of HOCS, since CT and PS are both quite global, as are what constitutes knowledge, and what constitutes and represents HOCS. Together, knowledge, thinking and cognitive skills serve as a metaphorical lens of maximum aperture. To see all, to be aware of all, to interconnect all, systematically, and to recognize potential implications of all, learners (and educators) need to focus on scientific literacy not as a vast collection of information, but as means of understanding a continuum of ideas, principles, and methodologies towards the capability of evaluative thinking.

Attaining this overriding goal requires the 'matching' of teaching practice and students' experiences with intended learning outcomes. In the following section, a HOCS-promoting, CT/PS requiring problem-based laboratory session at the end of an introductory organic chemistry course for freshman biology majors and the practice employed therein will be described and discussed. This will be followed by a summary of active research-based conclusions and implications for HOCS-oriented science (e.g., chemistry) teaching.

The concluding laboratory session

The content of the course "Introduction to Modern Organic Chemistry" is quite similar to 'classical' freshman organic chemistry courses, provided in the following syllabus excerpt:

- Introduction: Fundamental concepts, the tetrahedral carbon atom, the chemical bond.
- The structure and chemistry of – Alkanes, alkenes, alkynes and aromatic compounds.
- Stereochemistry: stereoisomerism, chirality and optical activity.
- The chemistry of alcohols and sulfur analogs, aldehydes and ketones, spectrophometric methods for structure determination: UV, IR, NMR and MS.
- Amines and related nitrogen compounds, carboxylic acids.
- Esters, amides, and related derivatives.
- Organic synthesis.
- Amino acids and the peptide bond.
- Selected topics in modern organic chemistry in the modern biological/sociological context.

This introductory first-year course is mandatory for biology majors, offered annually in the second semester of the academic calendar. Forty to sixty students are typically enrolled each year, dividing into smaller laboratory sections of approximately 20 students. The laboratory component of this course constitutes an *integral* part of this course and was consistently taught by a course instructor (one co-author of this paper), together with a laboratory guide and assistance of a lab technician. The semester-long course usually consists of three ‘lecture’ hours per week and five, bi-weekly, 4-5-hour lab sessions. Students work in pairs during laboratory sessions. This laboratory component provided a significant vehicle for HOCS and CT development for more than two decades.

The specific HOCS-oriented objectives for this course, all made explicitly known to course participants, intended to develop and foster students’ (1) self-learning as a major component in the learning process within the course framework; (2) system thinking and PS capabilities which will enable them to understand the chemical-molecular basis of the functionality and operational mechanisms of biological systems; (3) critical lateral/evaluative thinking which will enable them to solve *problems* in the context of basic organic chemistry; (4) capabilities of analysis, synthesis, decision making and transfer in the context of organic chemistry; and (5) getting closer to modern organic chemistry and subjects within this discipline relevant to, or pertaining particularly to the science-technology-environment-society (STES) context.

The very ambitious goals of this course cannot, nor should expect to be achieved during a one-term course; similarly, the extent of attainment of these goals will differ among students. What is important, however, is the conscious effort and collaborative persistence of both teachers and students in going ahead on this rocky trail (Zoller, 2000). Several teaching, assessment and learning strategies made gains in this direction (see e.g. Zoller, 1987, 1990, 1994, 1997, 2000; Heppert et al., 2002; Wang, 2005), all of which have been extensively applied to this course, including in its fourth and final fifth laboratory sessions (4 and 6 hrs each, respectively).

With respect to our five HOCS-oriented objectives, the following teaching and assessment strategies were applied throughout the course:

- There was no one textbook assigned for this course. Students were encouraged to use any textbook they find individually appropriate and/or useful. A list of 20-25 recommended textbooks was provided to the students at the course outset.
- Course participants were requested to come self-prepared, bringing their *questions* to the lecture sessions *before* hearing the instructor lecture on each of the course topics.
- Students, encouraged to work in groups, were required to respond to bi-weekly homework problem sets; a substantial portion of the sets required system CT/PS capabilities for their resolution.
- Students submitted their problem set responses for review by the instructor and former course students; *feedback* and grading were done individually for each student (see example questions in Appendix A).
- Self-assessment and grading of both homework assignments and examinations were an integral part of the course (Zoller et al., 1999), as was occasionally the examination where the students ask the questions (Zoller, 1994).
- There was occasional inclusion of short STES-oriented, interdisciplinary modules, relevant to the course syllabus (e.g., “Freones-the hole in the ozone layer-UV radiation-cancer induction and society response”).

Relevant illustrative examples of a laboratory-related mixed HOCS/LOCS-type take-home exam question in this course are given in Appendix B (Zoller, 1993, and more recent unpublished sources).

During the semester, students were requested to respond to 5-6 homework problem sets, to be worked out collectively, in small groups, or individually (students must submit solutions individually) approximately every other week. These problem sets were usually assigned in parallel with, but occasionally before, class coverage of relevant chemistry content. The students’ responses were reviewed and graded by the course instructor and two graduates of this course (sophomores by then), who were extensively briefed by the instructor beforehand. All three reviewed each student's works thoroughly and provided detailed written feedback on each individual student's submitted set. Three illustrative questions related to the laboratory course and taken from the last home problem set (just before the concluding laboratory session) are provided in Appendix B.

The assessment methods were in full compliance with the course HOCS objectives; all pertained to the assessment of students' performance and also included learning in the laboratory. Examinations were administered in either in-class individual, oral or take-home format. For either examination format, students were permitted to use their textbooks and/or notes, as well as any other material they wanted to bring with them. Regardless of examination format, the students have sufficient time to read the questions (20-30 minutes in the oral exams), to <u>think</u> about them, and ultimately select 3-4 questions (out of 5-6 available) to be examined on and respond to.

Given the integration of the lecture and laboratory components of this course, examinations selectively integrated all that was taught and was supposed to be learned. The final course grade was determined by the following weighted criteria: final exam 50%, homework problem sets 20%, mid-term take home exam 10%, and laboratory work 20%.

The concluding problem-based laboratory session

The entire laboratory practice, in this concluding session, is devoted to the identification of unknown (to the students) organic compounds and whatever this process involves in the organic chemistry research context. It is based on what has been learned throughout the course and requires the application of skills, both cognitive and practical, that the students have already acquired, LOCS and HOCS as far as the former are concerned. The students are requested to come "ready" to this lab session, meaning going *beyond* just a routine review and study of all that has been learned in the course in the class, the laboratory, at home, the library or any other relevant resources. The laboratory booklet, pre-adjusted and edited by the chemistry laboratory team, provides the students with the essence of the relevant practical information, guidance, and methodologies to be used, a couple of worked examples, and tables of relevant data; e.g., boiling points and solubility and basic spectrophotometric data (UV, IR, NMR). The identification process scheme – preliminary qualitative analysis of organic unknowns (e.g., identification of nitrogen, sulfur, or halogen-containing compounds via the sodium fusion test), solubility in acidic and/or basic aqueous solution, identification of functional groups, spectroscopic data (UV, IR and NMR) and, finally, the procedures for preparation of derivatives (e.g., dinitrophenylhydrazones from ketones; esters from carboxylic acids), necessary for the 'ultimate' proof of the identified unknown. It should be emphasized, however, that the essence of the identification of the unknown process does <u>not</u> reflect LOCS-oriented protocols. Rather, students initially receive *all* the *necessary* information and data relative to the 'unknown' and what is required of them in order to solve the problem (i.e., thorough systemic CT and application of their HOCS). The role retention and LOCS play in this process is very minor.

The lab session is divided into two parts: in the first, the students, in teams of two, are provided with two *known* 'unknowns' samples; that is, the provided samples A and B are fully identified and were made known to the students to begin with. All the relevant data, including physical data, derivatives, UV, IR and NMR spectra and the data provided has already been analyzed for the students (in the laboratory booklet) and is used by each team while they simulate the relevant identification process, making sure that they have understood each step in the process and the conclusions derived. The students are then required to demonstrate their comprehension via an in-depth oral summary of the simulation and to respond to the instructor's questions, comments, or suggestions, in 2:1 (students: instructor) mini-sessions. These are intended to prepare the students for dealing with real “unknowns,” which for their full identification require the students to undergo a process similar to the one they have just experienced, but now demanding much more application of HOCS compared to LOCS.

Finally, in the last part of this summative laboratory session, each student team is confronted with real *problems* to solve; namely, to identify the two unknowns. Each team received samples of unknowns accompanied by the corresponding relevant physical, chemical and spectroscopic data: m.p./b.p., M.W., the presence of nitrogen sulfur and halogens, if applicable, uv, ir and nmr. This problem solving process has to be performed and is followed by each team explaining to the course instructor and assistants, their mental (thinking, logic, analysis and synthesis) operations they have applied in each step throughout the process and what has been learned from it specifically. This includes the conclusions reached and consequently applied, and what was shown later to be correct in accord with UV, IR, and NMR data as well as the related properties of the derivatives prepared by each team, following the identification of the two “unknowns”. The particular process, conducted by each of the teams and the conclusions derived from the findings were summarized and discussed by each team, and after the session were submitted to the instructor for review and feedback.

The two unknown compounds used in this stage of the course included simple alkenes, aromatic compounds, aldehydes/ketones, amines, esters, and amides. More significantly, however, the identification process emphasized PS-based thinking, rather than laboratory practiced-oriented.

Concluding comments

Throughout the years, the students’ achievement (in terms of scores) on HOCS-requiring exam questions related to laboratory practice and learning were, in most cases, similar to those related to other course topics dealt with mainly or exclusively in lecture sessions. Students’ overall final laboratory grades were, in most cases, higher than their final course grade. Course letter grades correlated, in most cases, with each student’s homework problem set grades. Taking these results into account, as well as previously reported related results (e.g. Zoller, 1987, 1993, 1994; Zoller et al., 1999; Tsaparlis and Zoller, 2003), there appears to be a positive academic affect from a problem-based laboratory that promotes HOCS.

This laboratory activity contributed to the participating students’ advancement on the lengthy, rocky trail of HOCS development. Students’ responses of appreciation and satisfaction, at the end of the course, were gratifying and encouraging for future design of similar laboratory practices in organic chemistry and other science courses.

Relating HOCS promotion goals to problem-based laboratory practice is one way to achieve HOCS-promotion advocacy. The proposed model, here described, of a CT/PS-requiring laboratory activity, is plausible and feasible. Not only can it be done; it should be done. It is crucial to match goals and practice.

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Appendix A

1. a. Which product would you expect to receive on heating of compound **1** in high dilution conditions? Draw the structure of the expected product **2** and explain the reason for its formation.

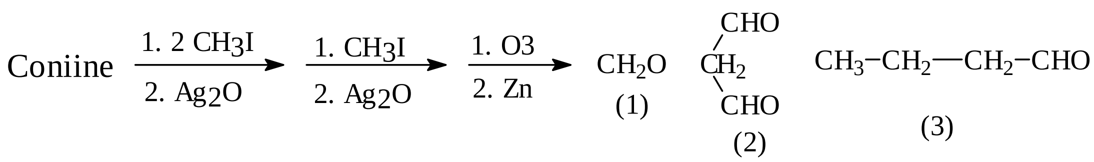
$$O{=}CH - CH_2 - CH_2 - CH_2 - CH_2 - NH_2$$

1

b. Draw, qualitatively, the IR and NMR which you would expect to get from **1**.

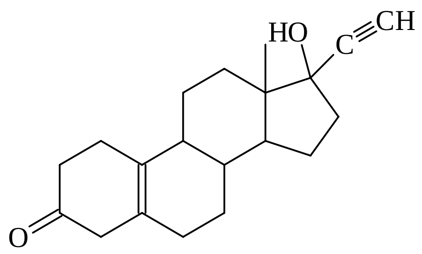
c. Can you, based on the IR spectrum of **2** (when taken), determine that, indeed, the expected reaction did take place? Explain!

2. a. Based on the following reactions, try to suggest the structure of coniine. [Guidance: try to work out the problem backwards, i.e., reconstructing, first, the partial structures from which (1), (2) and (3) were obtained.]



b. Assuming that you have succeeded in separating (2) and (3) from the reaction mixture in (a), will you use UV, IR or NMR in order to determine which is which?

3. The steroid **4** suppresses the egg fertilization process and is therefore used as a component in the birth control pill, enovid.



4

a. Draw (crude approximation only) the expected IR spectrum of **4**. Is the IR spectrum sufficient, in this case, to determine the structure of **4**? Explain.

b. Suggest two chemical reactions (one for each functional group) on the results of which you will be able to determine that **4** contains both hydroxylic and carbonyl groups. Provide the relevant chemical equations in full.

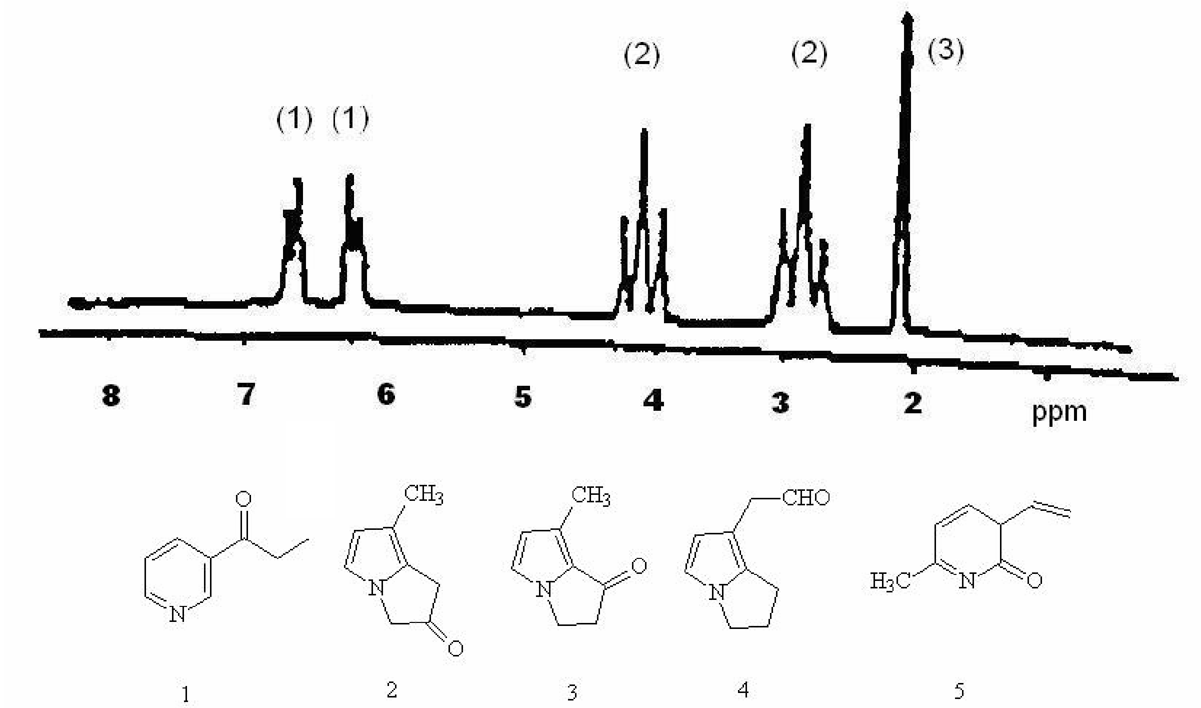
c. Would you expect **4** to be soluble in water? Explain your answer! Will an addition of 2-propanol to an aqueous solution of **4** increase or decrease the solubility of **4** in the new solution?

d. What is, in your opinion, the final product that would be obtained in the reaction of **4** with $NaBH_4$ followed by acidification of the reaction mixture?

Appendix B

Question I.

The Florida 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 five possible structural isomers of A are given in the figure below.



NMR spectra and some possible structural isomers of compound A

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 any) would you recommend concerning compound A? Be specific and rationalize your answer.

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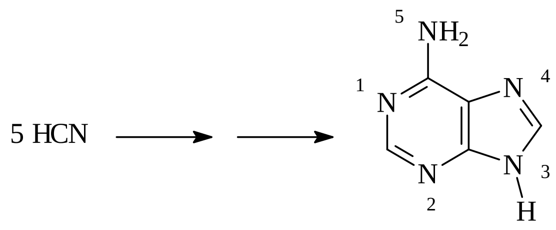
* These are HOCS questions.

Question II.

One of the theories concerning life formation on earth attributes a special importance to the HCN molecule, which was apparently abundant in the primary global atmosphere. Thus, for example, it is possible to envision Adenine (**1**) as an HCN pentamer:



1

1. Is **1** an aromatic substance? Rationalize.
2. * Which of the Adenine's nitrogen atoms (1-5) is the most basic? Explain and rationalize.
3. Which spectroscopic method (UV, IR, NMR) would you suggest to use for determining the Adenine structure? Explain!
4. * Suggest at least one chemical reaction to apply to Adenine, from the result(s) of which you would be able to obtain some idea about the chemical properties of **1**.
5. In your opinion, are hydrogen bonds possible in **1**? Explain and rationalize.

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* These are HOCS questions.