Problem Solving in Organic Chemistry, Impact Outside The Classroom?

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In 1975, E.A. Harrison, Jr. and I published a note (that was all they would accept!) in *J Chem Ed* titled "A Non-Lecture Approach to Organic Chemistry."[1] We reported providing lecture notes to our students in advance of a class and requiring students to copy or to outline those notes prior to the class. This insured at least nominal pre-class exposure to the material. In-class lectures were reduced to short explanations and the class time gained was used to follow-up explanations with in-class problem solving and other student –centered learning activities that could be varied to accommodate the many different learning styles that we saw in our students.

Some of the earliest work with critical thinking and learning strategies, including problem –solving, was reported in the 1940s and 1950s.[2] [3] It was more broadly researched in the 1970s and 1980s.[4][5][6][7][8][9] *The Journal of Chemical Education* has reported articles on problem solving since about that same time.[10][11][12][13][14] In addition, Donald R. Woods, co-developer of the "McMaster Problem-Solving Program," a 25-year study of successful teaching of problem solving strategies to engineering students,[15] has, for a number of years, written a regular feature on problem solving called "P S Corner" in the *Journal of College Science Teaching.* Thus, literature on successful problem solving and how to teach it is abundant. Whether we actually accomplish teaching problem solving has not been unequivocally shown except, perhaps, in the McMaster study.[16] Furthermore, we must remember that it is likely that sophomore organic students are at Perry's "dualistic" level. Thus they expect their instructor to tell them what to do, and they believe the textbook to be the correct source of all knowledge. Moreover every problem has a right answer! Perry's model has been thoroughly discussed in the literature.[17][18]

In 1990 I gave a talk on critical thinking and problem solving at the "Conference on Critical Thinking: Focus on Science and Technology." It was printed in their proceedings.[19] I had searched the literature on critical thinking/problem solving in science, philosophy, engineering, psychology and education and reported excerpts from it along with my own work, which was new at the time. From that search, I concluded that there is substantial overlap between disciplines in how critical thinking/problem solving is taught or explained. I presented an abbreviated form of the comparison between problem solving methodologies made by Edys Quellmalz from the School of Education at Stanford[20] and I reproduce it below because it is the basis for the process that I currently articulate to my students as a part of teaching them problem solving strategies.

Philosophy	Psychology
1. Clarify, formulate questions, analyze components & define terms	1. Identify (analyze) the problem, identify essential elements and terms
2. Judge credibility of support	2. Identify relevant information and procedures
3. Infer: use deduction, induction, value judgements	3. Connect and use info to solve problem
4. Judge adequacy of solution	4. Evaluate success of solution(s)

I have somewhat simplified the psychology steps after a few years of using them and finding that students didn't remember the original steps nor did they relate to the words well enough to use them.

My current, simplified problem solving steps are:

1. Define the scope of the problem
2. Collect all relevant information and procedures
3. Link information and procedures to form all possible solutions
4. Evaluate solutions and choose the best

With each class, I have articulated the process and, later, the class has completed a group exercise in which they linked those problem solving steps to the steps in a process for solving synthesis problems, spectroscopy problems and reaction mechanisms problems. I have always articulated the process as well as facilitating that linkage because that seemed reasonable to me and because of Woods[16] findings that engineering students did not do well with problem solving taught only by example. He found that students needed to articulate the process, see it demonstrated and do it themselves in order to grasp it.

Applications of the Problem Solving Process (above):

Synthesis:

Statement of the Problem: Starting with only alcohols of four carbons or less and using any needed inorganic reagents and/or conditions, synthesize 2-methyl-2-butanol.

Problem Solving Step	Synthesis Thought(s) - Operation(s)
1. Define the scope of the problem	1. Determine whether the number of carbons in the target compound is more or less than four. This categorically defines certain reaction paths. 2. Determine the target's functional group as compared to the functional group, alcohol. 3. Determine whether there are groups in the target that require special considerations.
2. Collect all relevant information and procedures	1. Recall all reactions by which the target functional group can be prepared in one step, and their limitations. 2. For each reaction recalled, determine whether the starting material would be an alcohol of four C or less and, if not, recall all reactions from which the "new" starting substances could be made 3. Repeat Step 2 for all "new" starting substances generated by the considerations in Step 2, above. 4. Delete reactions listed for which there is no known reaction to prepare the "new" starting material.
3. Link information and form all possible	Link the listed reactions to form chains of

solutions	reactions which supply the final target and for which the "new" starting materials supply an intermediate target until the starting material is an alcohol of four C or less.
4. Evaluate solutions and choose the best	1. Evaluate each chain of reactions to determine the best by criteria that are part of the problem. a. Shortest possible may be required b. Safest may be required 2. Accept all solutions that meet the problem requirements.

Proton NMR Spectroscopy:

Problem Solving Step	Process Step for Proton NMR Elucidation
1. Define the scope of the problem	1. Look to see what data is given in addition to the proton spectrum a. Empirical formula and/or molecular wt b. Presence of electronegative atoms c. Presence of unsaturation d. Presence of other spectra
2. Collect all relevant information and procedures	1. Determine number of sets of equivalent H. 2. Compare positions of absorptions to known information about positions due to neighboring electronegative atoms. 3. Determine splitting of each proton set and the meaning of this for number of adjacent hydrogens. 4. Calculate relative integrations and relative numbers of hydrogens in each set. 5. Compare total number of H to empirical formula, if given.
3. Link information and form all possible solutions	1. Suggest possible groups for each absorption based on integration and spectral position 2. Compare total atoms to a saturated formula and deduce whether there is unsaturation on rings in formula (validate phenyl rings by appearance of absorption near 7.27ppm. 3. Subtract all tentatively determined groups from empirical formula (or group weights from molecular weight) to find atoms not otherwise

	observable. 4. Suggest possible adjacent H-groups based on splitting pattern. 5. Consider end groups (one point of attachment) and middle groups (two or more points of attachment) and construct possible structures. 6. Predict the NMR spectrum of all molecules constructed in Step 6 and watch for subtle differences due to splitting pattern errors, incorrect shifts of absorptions, proton groups next to chiral centers, etc.
4. Evaluate solutions and choose the best	1. Based on Steps 6 and 7 above, some solutions can be eliminated. Many times a unique solution will be obtained by using the first three steps of the problem solving process given above.

Mechanisms:

Problem Solving Step	
1. Define the scope of the problem	1. Write the overall reaction for which the mechanism is to be written. 2. Determine whether the functional group in starting material and product are in the same place in the structure.
2. Collect all relevant information and procedures	1. Bring to mind the kinds of mechanisms seen with other starting materials of the same functional group. 2. Bring to mind the first step for each of the mechanisms related to this starting material. 3. Using the starting material at hand, apply each known mechanism.
3. Link information and form all possible solutions	1. Compare the "standard" mechanism used on the starting material to see whether or not the product is obtained for which the mechanism was to have been written.
4. Evaluate solutions and choose the best	1. Discard mechanisms that lead to an incorrect product. 2. If two mechanisms lead to a correct product, consider possible laboratory information that may be used to distinguish between the two.

I find that students consistently leave out, either in articulation of the problem solving process or in carrying it out, the gathering of information and linking of it to provide all possible solutions. Rather they leap from a poor definition of the scope of the problem, to a solution. Interestingly enough, as a volunteer worker for a listening line for human problems, I find this to be one of the major stumbling blocks for individuals who are trying to solve personal problems. The person poorly defines the scope of the problem and jumps to one solution that is the only one they immediately think of.

Since I am interested in the extent to which such classroom learning impacts the remainder of students' lives, I found a critical thinking test (non-chemistry)[21] that I administer to students before and after the first and after the second semester of the organic sequence. Analysis of data for those years when I have taught organic chemistry through the problem solving (critical thinking) framework, described above, indicates a statistically significant gain in critical thinking/problem solving for that group. In years where I have taught organic chemistry without identifying the critical thinking/problem solving process, the group has shown no statistically significant gain on the same test. Since the test has nothing to do with organic chemistry, but students' performance shows statistically significant improvement, I believe that teaching problem solving in organic chemistry may have far-reaching effects on students and their lives outside the confines of organic chemistry.

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