SYSTEMIC APPROACH TO TEACHING AND LEARNING CHEMISTRY: SATLC in Egypt

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INTRODUCTION

In 1997, on the occasion of a visit by A. F. M. Fahmy to The University of Texas at Austin, extensive discussions between A. F. M. Fahmy and J. J. Lagowski laid the basis for the development of the Systemic Approach to Teaching and Learning (SATL) Chemistry. Our interest in developing the SATL strategy arose from the recognition of the increasing globalization of a wide spectrum of human activities such as economics, media, politics, and entertainment. We are not interested here in a value judgment concerning globalizetion, rather our position is that globalization is occurring at a rapid rate and we have an obligation to our students to help them cope with this phenomenon. Globalization implies a broader context when considering human activities than a regional or a local perspective. Specifically, our interest is in a vision of science education—that process by which progress in science is transmitted to the appropriate cohort of world citizens—that is sufficiently flexible to adapt to an uncertain or, at best, an ill-defined future. That future, however, ultimately must include an appreciation of the vital role that scientists and chemists, in particular, have in human development. Thus, the future of science education must reflect a flexibility to adapt to rapidly changing world needs. It is our thesis that a systemic view of science with regard to principles and their internal (to science) interactions as well as the interactions with human needs will best serve the future world society. Through the use of a systemic approach, we believe it is possible to teach people in all areas of human activity—economic, political, scientific, as well as ordinary citizens—to exhibit a more global view of the core science relationships and of the importance of science to such activities.

As a start, we suggest the development of an educational process based on the application of "systemics" (*vide infra*), which we believe, will affect both teaching and learning. The use of systemics, in our view, will help students begin to understand interrelationships of concepts in a greater context, a point of view that ultimately should prove beneficial to the future citizens of a world that is becoming increasingly globalized. Moreover, if students learn systemics in the context of learning chemistry, we believe they will doubly benefit by learning chemistry and learning to see *all* subjects in a greater context.

Concept Mapping and Systemics. In retrospect, the key feature of systemics (SATL) can be imagined as an extension of concept mapping. In the early 1960's, when behaviorist theory prevailed among educational psychologists, Ausubel published his theory of meaningful learning, portions of which appeared in his book (1963) entitled "The Psychology of Meaningful Verbal Learning" *(1)*; a more comprehensive view of his ideas was published later. *(2)* Contemporary assimilation theory stems from Ausubel's views of human learning which incorporates cognitive, affective, and psychomotor elements integrated to produce *meaningful* learning (as opposed to *rote* learning). To Ausubel, meaningful learning is a process in which new information is related to an existing relevant aspect of an individual's knowledge structure and which, correspondingly, must be the result of an overt action by the learner. Teachers can encourage this choice by using tools such as concept maps. *(3)* It is postulated that continued learning of new information relevant to information already understood (presumably) produces constructive changes in neural cells that already are involved in the storage of the associated knowledge units. In our view, an important component in Ausubel's writing has been the distinction he emphasized between the rote-meaningful learning continuum and the reception-discovery continuum for instruction. The orthogonal relationship between these two continua is illustrated in Figure 1.

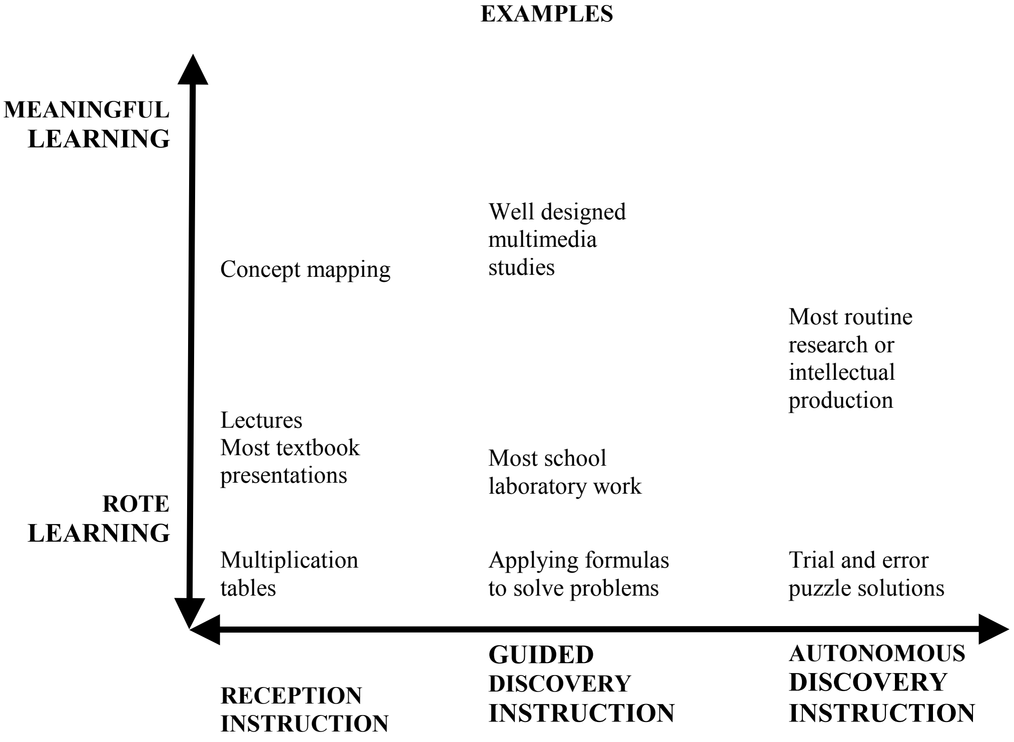
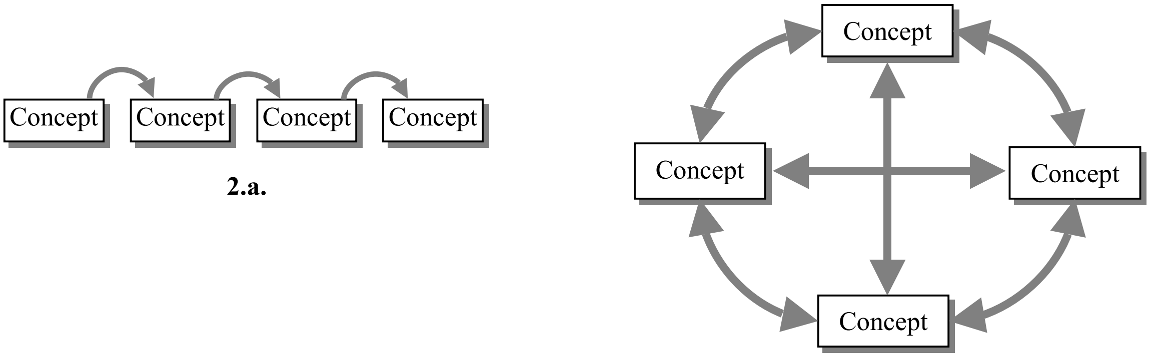


Figure 1. Examples of instructional techniques displayed on the orthogonal rote-meaningful learning continuum and the reception-discovery continuum. (Adapted from Novack, J. D., "Learning, Creating, and Using Knowledge," Laurence Erlbaum Associates, 1998, Mohawk, NJ.)

According to Ausubel, the essence of the meaningful learning process is that symbolically expressed ideas are related to what the learner already knows. Thus, in a sense, Ausubel's work also incorporates the elements of contructivism. Meaningful learning presupposes that the learner has a disposition to relate the new materials to his or her cognitive structure and that the new material learned will be potentially meaningful to him or her. In other words, it takes an overt act by the learner to make learning meaningful. Concept mapping *(3)* is a device that can be used to communicate to the learner as well as providing a vehicle to help the learner with meaningful learning tasks (*vide infra*). Of the types of meaningful learning that Ausubel described—representational learning, propositional learning and concept learning—the latter is of interest here. The acquisition of subject matter primarily consists of concept learning. Concept mapping *(3)* is a device that provides the basis of relating new knowledge to previously assimilated knowledge in a systematic way. Concept mapping also incorporates a strong element of constructivism, in the sense that a student can build his/her understanding of new concepts on those he/she has a deep familiarity. Concept maps have been used as metacognitive tools to help teachers and learners to improve both teaching and learning. Concept maps created by students are an idiosyncratic representation of a domain specific knowledge and provide teachers with information on what students know because such maps can show the students initial concepts, how they are contextually related, and how learners reorganize their cognitive structures after a special teaching activity. It might be tempting to try to use concept maps as the focus for the assessment of students' acquisition of concepts, however, a number of observations on attempts to "score" concept maps suggest that, currently, they are not good assessment tools *(4)*, mostly because there are many possible concept maps that "correctly" show the relationships among a given collection of concepts.

THE SYSTEMIC APPROACH TO TEACHING AND LEARNING

We introduce now the basic ideas of the systemic approach to teaching and learning (SATL) as applied to chemistry. By "systemic" we mean an arrangement of concepts or issues through interacting systems in which all relationships between concepts and issues are made clear, up front, to the learner using a concept map-like representation. In contrast with the usual strategy *(3)* of concept mapping, which involves establishing a hierarchy of concepts, our approach strives to create a more-or-less "closed system of concepts"—a concept cluster—(Figure 2b) which stresses the interrelationships among concepts; Figure 2 also illustrates diagrammatically the difference between a linear representation of concepts (2a) and our systemic representation (2b). We believe it is more difficult to obtain a global view of a collection of linearly arranged concepts (2a) than with the systemic representation (2b), which stresses *all* relationships among concepts. Further, our use of the term "systemics" stresses recognition of the *system* of concepts that form the closed cluster of concepts under consideration. "Systemics" means in our hands, the creation of closed-cluster concept maps for the purposes of helping students learn; "systemics" is an instructor-oriented tool and, hence, requires teacher and student materials to be created about the closed-cluster concept map strategy.



2.a.

2.b.

Figure 2. Diagrammatic relationship between a linear approach (2.a.) and the systemic approach (2.b.) in the presentation of concepts.

In practice, the systemic approach allows the teacher to build up sequentially a single concept map starting with prerequisite background information required of the student before he/she starts on a systemic approach to learning. Figure 3 shows this strategy for developing the closed cluster concept

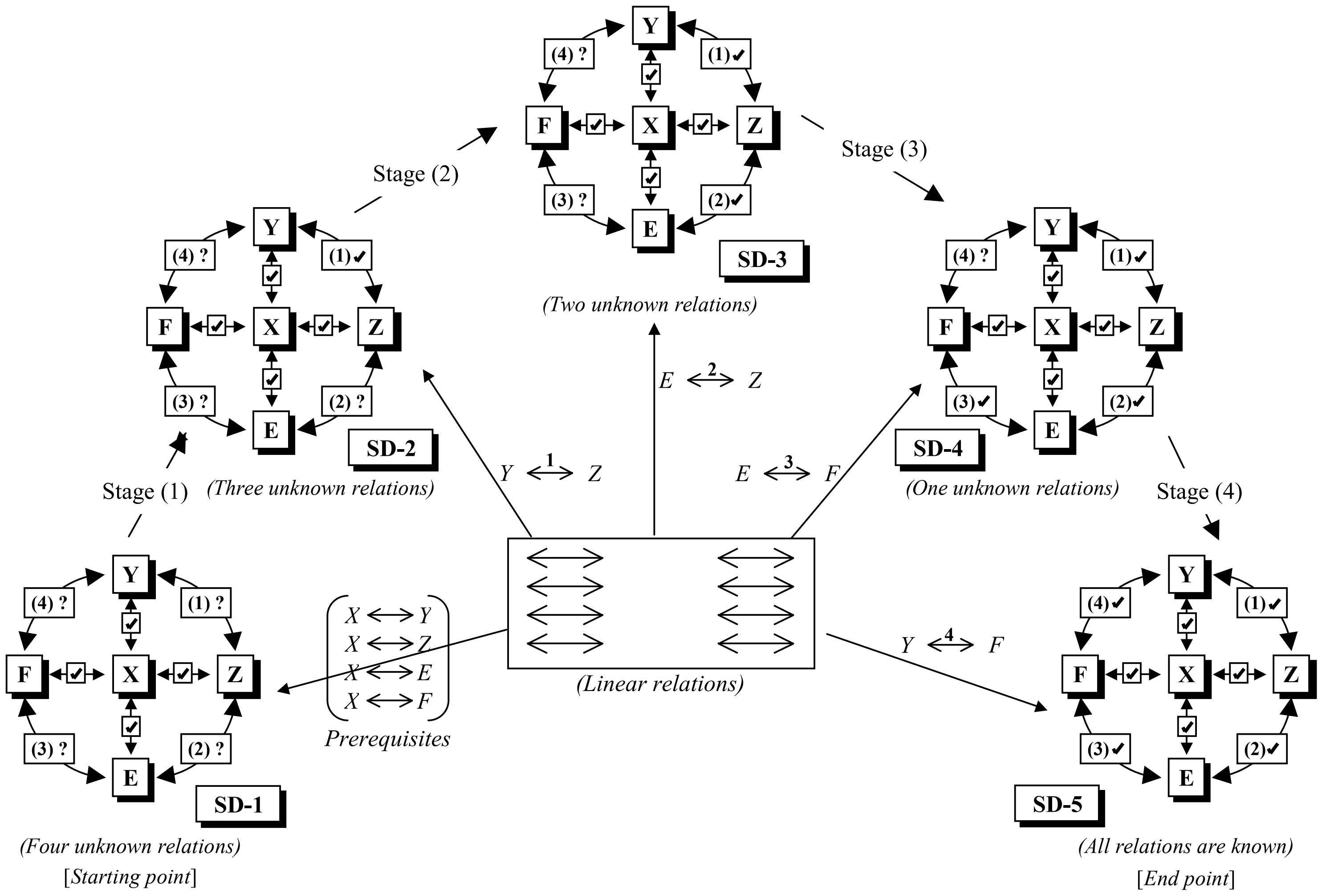


Figure 3. The evolution of a completed closed concept cluster from a starting point exhibiting four unknown (to the student) relationships.

map involving the five concepts entitled E, F, X, Y, Z. The instructor has in mind the concept structure shown in Figure 2a, which he/she wants to develop into the closed cluster shown as Figure 2b. The prerequisites are simple bi-directional relationships between the concepts. Thus, initially, there are four unknown (to the student) relationships in the final cluster of concepts (Figure 2a). The full closed cluster concept map can be developed in four stages by sequentially introducing the (initially) four unknown concepts. At each step, another part of the final closed concept cluster is added and developed. This process clearly illustrates the systemic constructivist nature of our SATL approach.

THE APPLICATION OF SYSTEMICS TO CHEMISTRY INSTRUCTION

After a preliminary study of the application of SATL techniques in secondary schools in Cairo and in Giza, we embarked on a number of studies to probe the extent (content material-subject matter) and level of instruction that could be effectively expressed using such methods and whether such methods helped students learn. A list of these studies is given in Table I. All of these studies required the creation of new student learning materials (as shown in Table 1), as well as the corresponding teacher-oriented materials. The statistical analysis of student achievement results shows that the students engaged with SATL materials and taught by teachers trained in systemics achieve at significantly higher levels than those taught by the standard linear methods.

Table 1. A list of experiments conducted using the SATL strategy using various aspects of the subject chemistry. The initial experiment was conducted in 1998 in the secondary schools of the Cairo and Giza school districts.

Student Sample	Title of SATLC Material	Duration / Date	Data
Pre-University - Secondary School (2nd Grade).	***SATL-*** Carboxylic acids and their derivatives (Unit) (5)	**(9 Lessons Two weeks)** March 1998.	Presented at the 15th ICCE, Cairo, Egypt, **(August, 1998).**
University Level - Pre-Pharmacy. - Second year, Faculty of Science.	***SATL-*** Aliphatic Chemistry. (Text book) (6)	**One Semester Course: (16 Lects - 32hrs).** During the academic years (1998/ 1999-1999/2000-2000/2001).	Presented at the 16th ICCE, Budapest, Hungry, **(August, 2000).**
- Third year, Faculty of Science.	***SATL-*** Heterocyclic Chemistry. (Text book) (7)	**(10 Lects. - 20 hrs).** During the academic years: (1999/2000-2000/2001).	Presented at the 7th ISICHC, Alex., Egypt **(March, 2000).**
- Second year, Faculty of Science.	***SATL-*** Aromatic Chemistry (Text book) (8)	**One Semester Course: (16 Lects-32 hrs).** During academic year (2000-2001).	In preparation.

More SATL chemistry courses were produced by the Science Education Center at Ain Shams University, which are still under experimentation in different university settings (e.g., Inorganic Chemistry and Systemic Organic Experiments). A description of these courses was presented at the 1st Arab Conference on Systemic Approach in Teaching and Learning, Organized by the Science Education Center at Ain Shams University and the UNESCO regional office in Cairo, Egypt in February 2001.

SATL COURSE EVALUATION

When it is feasible, we attempt to evaluate the SATL courses that have been created using student achievement as primary criterion for success. Our evaluation strategy generally involves experimental groups of students that use SATL materials taught by instructors trained in SATL methods (Figure 2b) and an equivalent (as far as background is concerned) control group of students taught by conventional methods, which are often based on a linear strategy (Figure 2a).

Pre-college courses. Our initial experiment probing the usefulness of the SATL approach to learning chemistry was conducted at the pre-college level in the Cairo and Giza school districts. Nine (9) SATL-based lessons in organic chemistry taught over a two-week period were presented to a total of 270 students in the Cairo and Giza school districts; the achievement of these students was then compared with that of 159 students taught the same material using standard (linear) methods. The details of a statistical summary of the results of achievement tests on these experimental groups before and after the SATL treatment and for the reference group before and after the same material was presented in the conventional linear way is available for inspection (5), but we address here only the overall results (Figures 4 and 5) for the sake of brevity. The results indicate that a greater fraction of students exposed to the systemic techniques, the experimental group, achieved at a higher level than did the control group

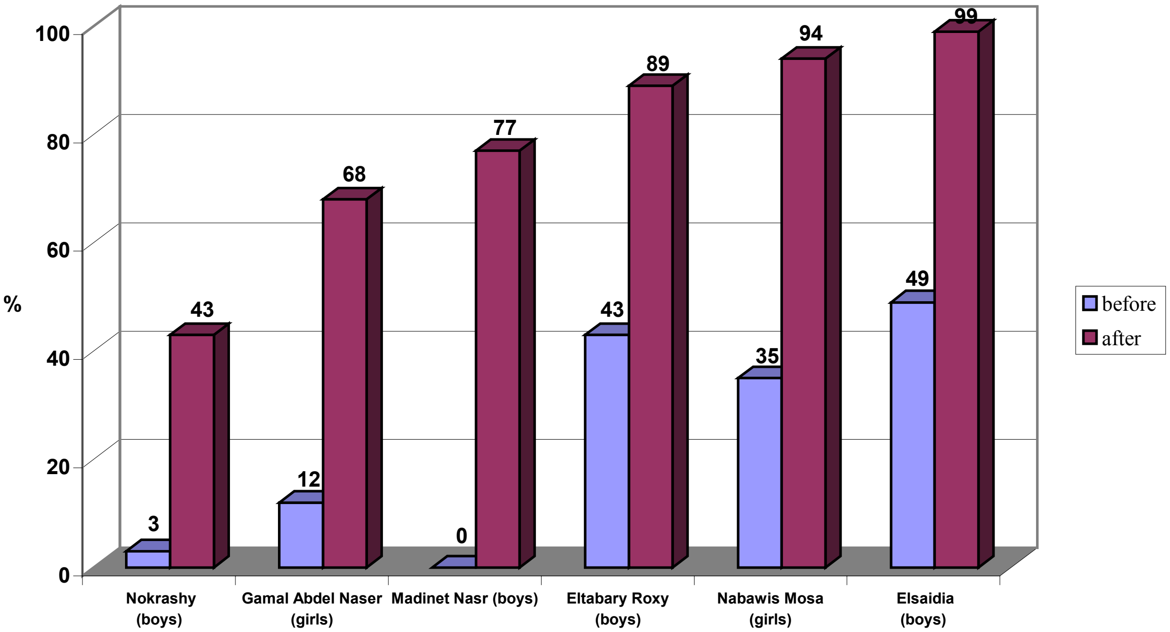


Figure 4. Percent of students in the experimental classes who succeeded (achieved at a 50% or higher level). The bars indicate a 50% or greater achievement rate before and after the linear intervention period.

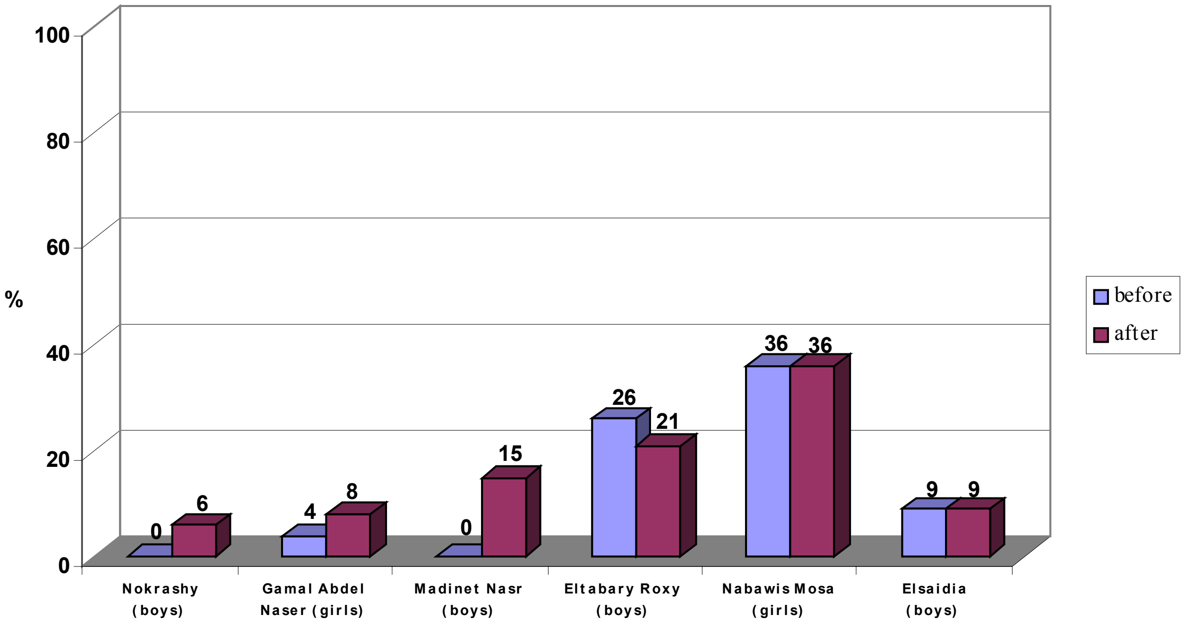


Figure 5. Students in the control classes who succeeded (achieved at a 50% or higher level). The bars indicate a 50% or greater achievement rate before and after the systemic intervention.

(taught by conventional linear techniques). These results are statistically significant (5). The experimental (Figure 4) and control (SATL) group (Figure 5) are separated into the individual schools in the Cairo and Giza school districts. All of the students were tested before the experiment began to establish the common background of these groups. The experimental group was taught by SATL-trained teachers using SATL techniques with specially created SATL materials, while the control group was taught using the conventional (linear) approach.

Our results from this pre-university experiment point to a number of conclusions that stem from the qualitative data(5), from surveys of teachers and students, and from anecdotal evidence.

1. Implementing the systemic approach for teaching and learning *using one unit of general chemistry within the course has no negative effects on the ability of the students to continue their linear study of the remainder of the course using the linear approach. (The students in the experimental group resumed their studies using the conventional linear approach.) Moreover, teacher feedback indicated that the systemic approach seemed to be beneficial when the students in the experimental group returned to learning using the conventional linear approach.*
2. *The systemic approach can be introduced successfully in mid-course at the secondary school level without problems for the students, teachers, or schools, which addresses the question, "at which stage can we begin to teach in a systemic way?"*
3. *Teachers from different experiences, professional levels, and ages can be trained to teach by the systemic approach in a short period of time with sufficient training.* The training program in systemics seems to impact teachers' performances during the experiment. Thus, virtually any teacher with appropriate training and materials can use SATL methods. The teacher training program requires the development of special SATL materials.
4. Anecdotal evidence collected well after the experiment concluded suggests that both teachers and learners retain their understanding of SATL techniques and continue to use them.

Organic chemistry. A study of the efficacy of systemic methods applied to the first semester of a typical second year organic chemistry course (16 lectures, 32 hours) at Zagazeg University was conducted after the usual course materials on aliphatic chemistry were converted to a systemic approach (6). We present now the details of the transformation of the usual linear approach usually used to teach this subject that involves separate chemical relationships between alkanes and other related compounds (Figure 6) and the corresponding systemic closed concept cluster that represents the systemic approach

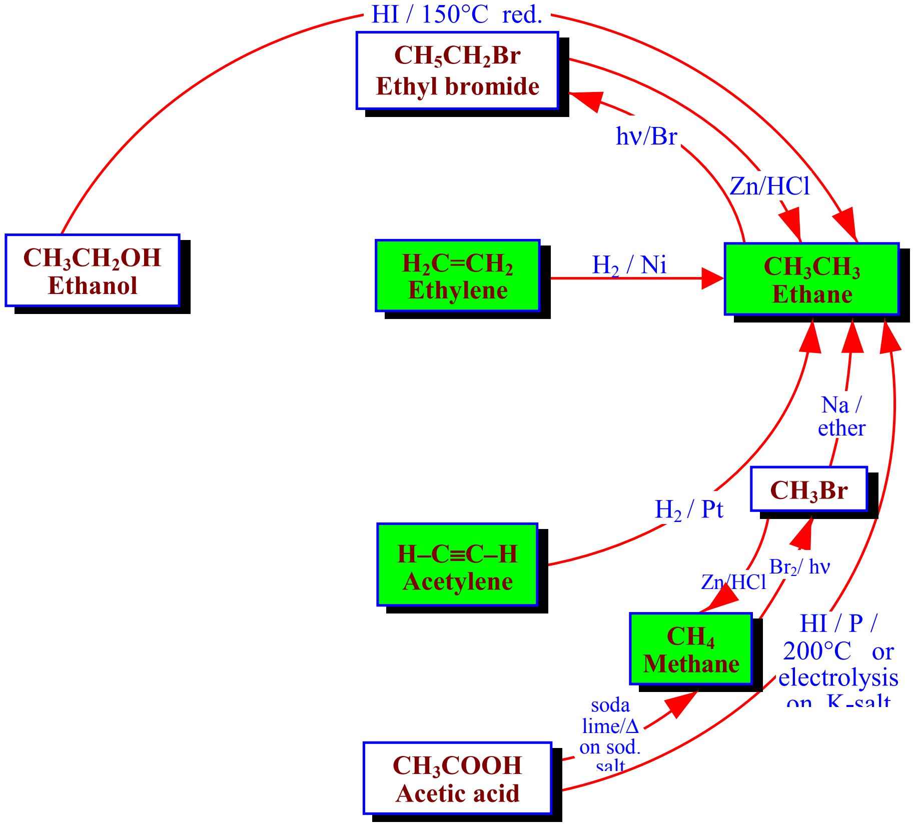


Figure 6. The classic linear relationship involving the chemistry of the alkanes organized to begin to create a systemic diagram of the corresponding chemistry.

(Figure 7). This systemic diagram in Figure 7 can be constructed from Figure 6 by answering the following questions:

1. What are the systemic chemical relationships among methane, ethanol, ethylene, and acetlyene?
2. What are the systemic chemical relationships among all the compounds in each of the following groups: ethane ethylene, acetylene; ethyl bromide, ethanol, acetic acid; succinic acid?
3. What are the systemic chemical relationships between ethyl bromide, ethanol, and acetic acid?

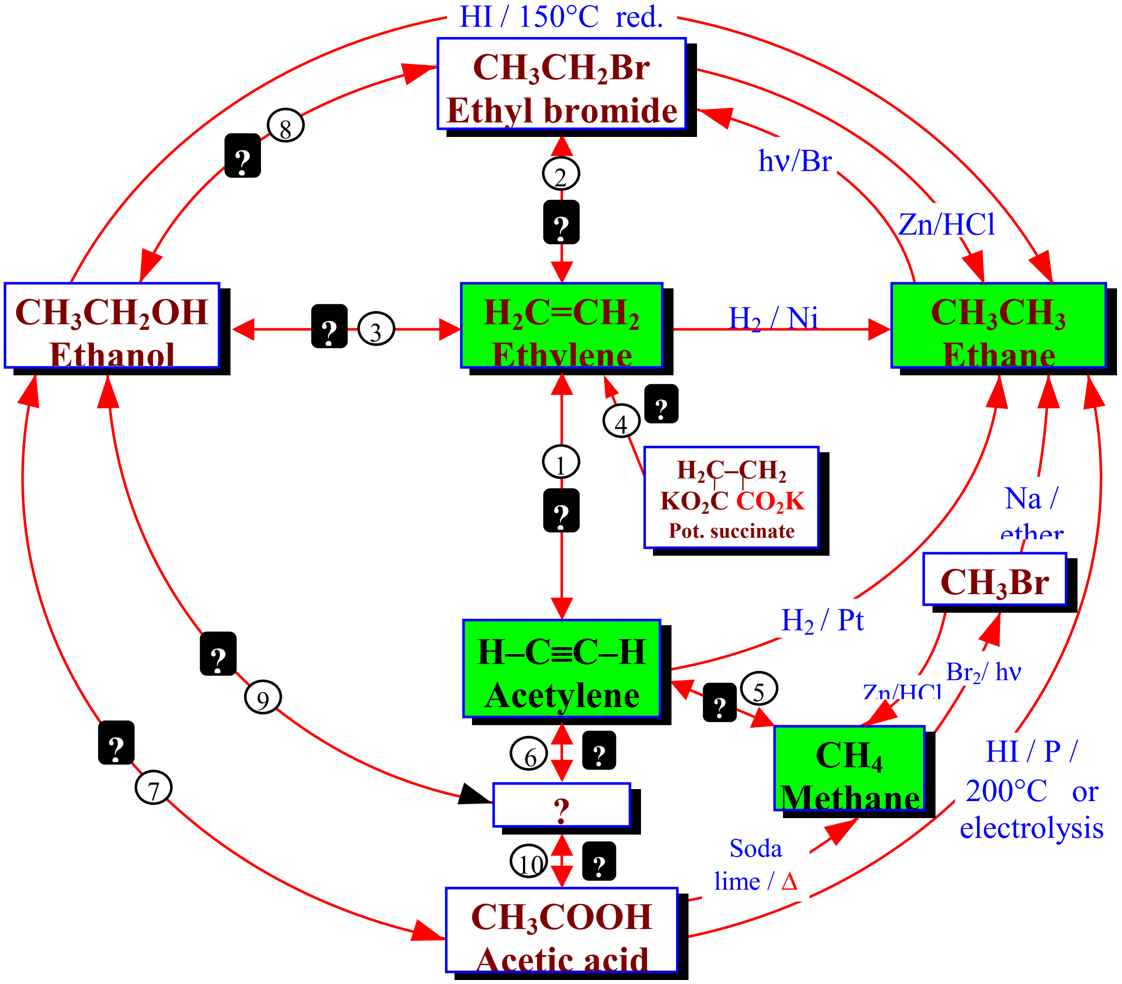


Figure 7. The systemic diagram that represents some of the major chemistries of alkanes.

The answers to these questions are displayed in the systemic diagram shown in Figure 7. Notice that, in Figure 7, some chemical relationships are defined whereas others are undefined. The undefined chemical relationships are collected in Table 3. These undefined relationships are developed systematically. After a study of the synthesis and reactions of alkenes we can modify the systemic diagram shown as

Table 3. The following relationships are undefined in Figure 7. The "number" (No.) is the number of the reaction on the systemic diagram (Figure 7).

No.	Reactions
1	Ethylene and acetylene
2	Ethylene and ethyl bromide
3	Ethylene and ethanol
4	Pot.Succinate and ethylene
5	Methane and acetylene
6	Acetylene and acetaldehyde
7	Ethanol and acetic acid
8	Ethanol and ethyl bromide
9	Ethanol and acetaldehyde
10	Acetic and acetaldehyde

Figure 7 to accommodate other chemistries as shown in Figure 8. Expanding the chemistry of acetylene converts the systemic diagram in Figure 7 to that shown in Figure 9.

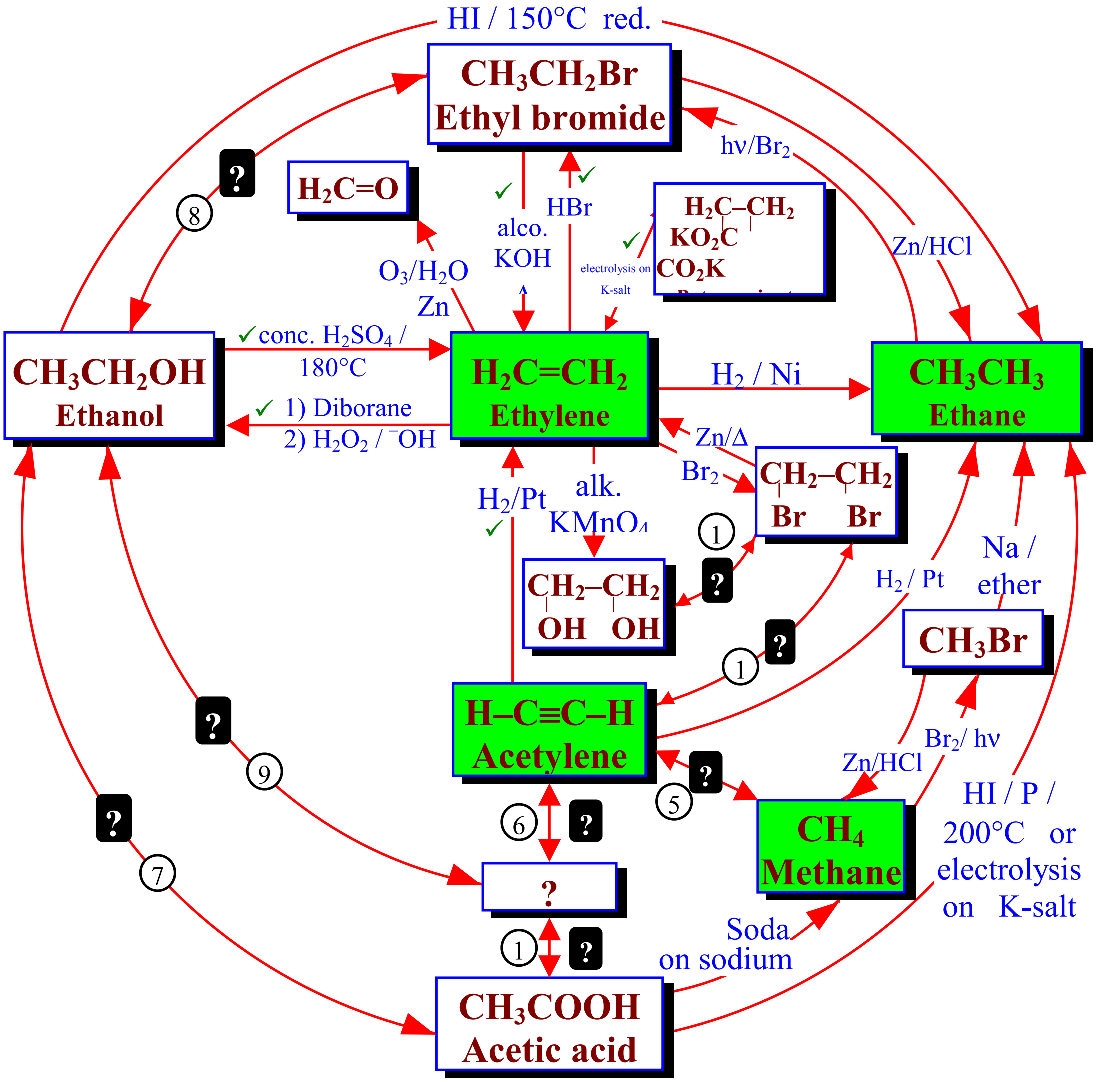


Figure 8. The SATL chemistry of alkanes (from Figure 7) as expanded to include the alkenes. Note that reactions 5-12 (and the reagents involved) are key issues.

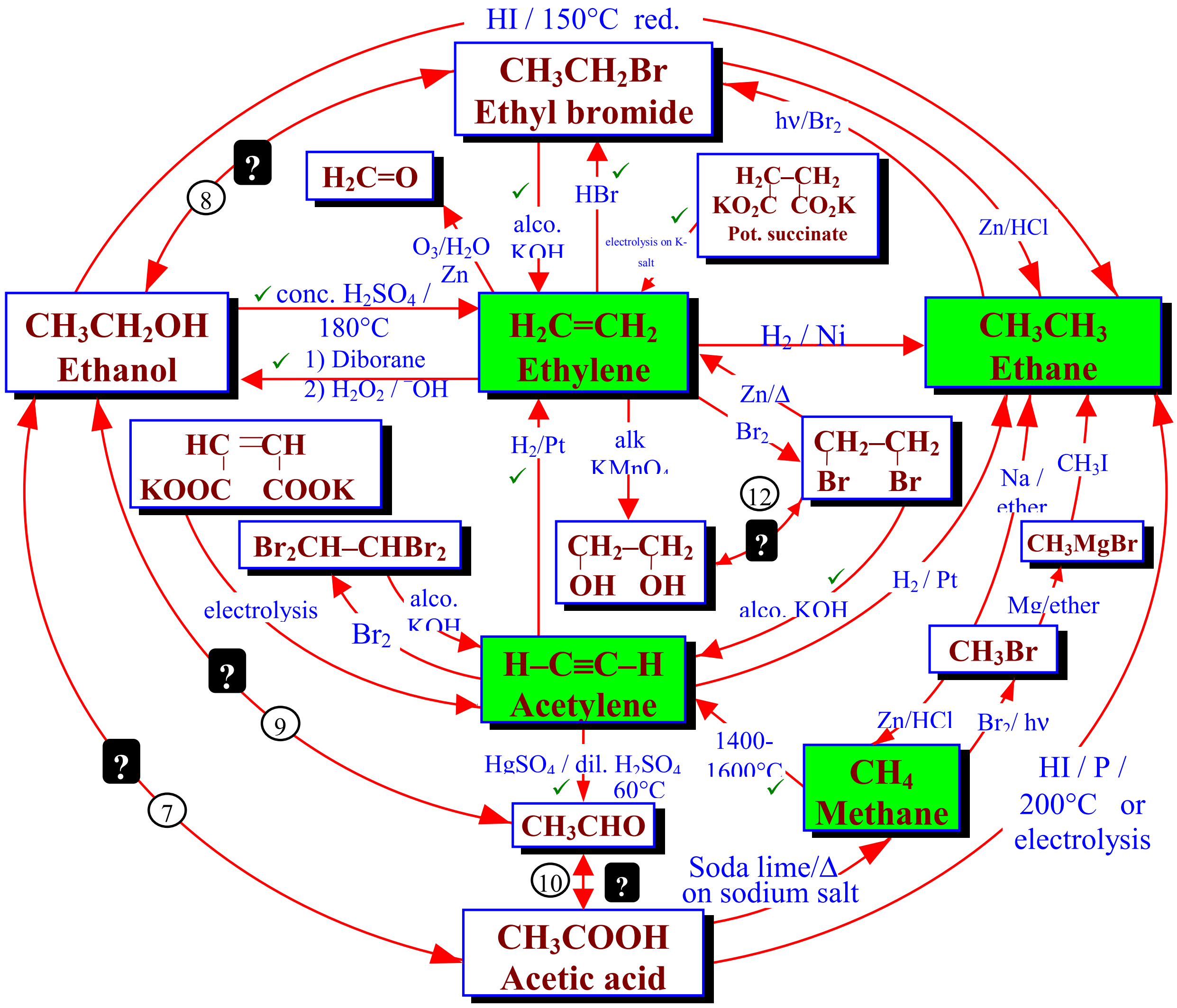


Figure 9. The SATL relationship between the hydrocarbons and derived compounds.

In a similar fashion, the systemic diagram shown in Figure 7 can accommodate to the chemistries of ethyl bromide and ethanol yielding the new systemic diagram shown in Figure 9.

The systemic diagrams developed in Figures 7 through 9 were used as the basis for teaching an experimental organic chemistry course at Zagazeg University (Egypt). The experiment was conducted within the Banha Faculty of Science, Department of Chemistry with second year students. The experiment involved 41 students in the control group, which was taught using the conventional (linear) approach; 122 students formed the experimental group, which was taught using SATL methods illustrated in the systemic diagrams shown as Figures 7 through 9.

The success of the systemic approach to teaching organic chemistry was established by using an experimental group, which was taught systemically, and a control group, which was taught in the classical—linear—manner. The equivalence of these groups was established by means of an examination before the intervention. The examination for *both* groups that was used to measure the achievement over the subject matter incorporated *both* systemic- and linear-type questions. Figures 10 and 11 show the final data in terms of student achievement. The bars in Figures 10 and 11 represent the percent of the students' average scores on the examination components indicated (linear questions or systemic questions). For each pair, the left-hand bar of each pair represents the scores before the intervention and the right-hand bar represents the scores after the intervention. Thus, the control group (Figure 10) had an average score of 32.09% on linear-type questions and an average score of 21.54% on systemic-type questions before the intervention. The experimental group (Figure 11) had an average score 31.30% *on linear-type questions, and an average score of 13.10% on systemic-type questions before the intervention. These data indicate a marked difference between the control and experimental groups. As might be expected, the control students did not fare well on systemic questions, not having been exposed to systemic reasoning. However, although the experimental students started less able to answer systemic questions than the control students (13.10% *versus* 21.54%), they did considerably better after intervention (59.10% versus 22.73%) as might be expected. The experimental group clearly achieved at a higher level as measured by the *total average* score on the examination (62,10% *versus* 27.08%). Finally, the use of systemics in teaching these students did not appear to affect the ability of the experimental group of students to answer linear questions (31.30% versus 65.60%).

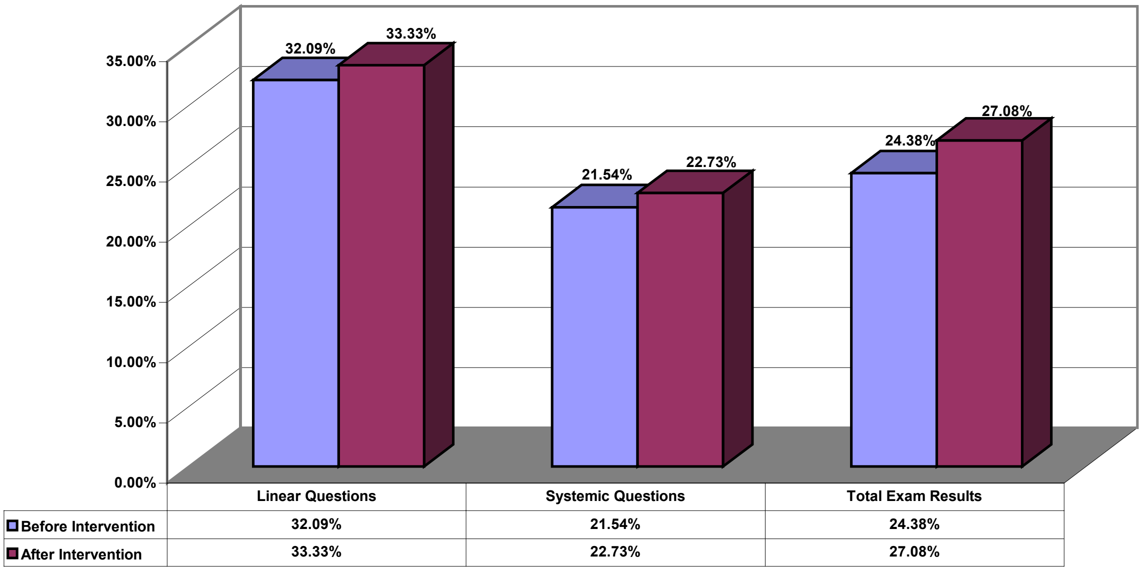
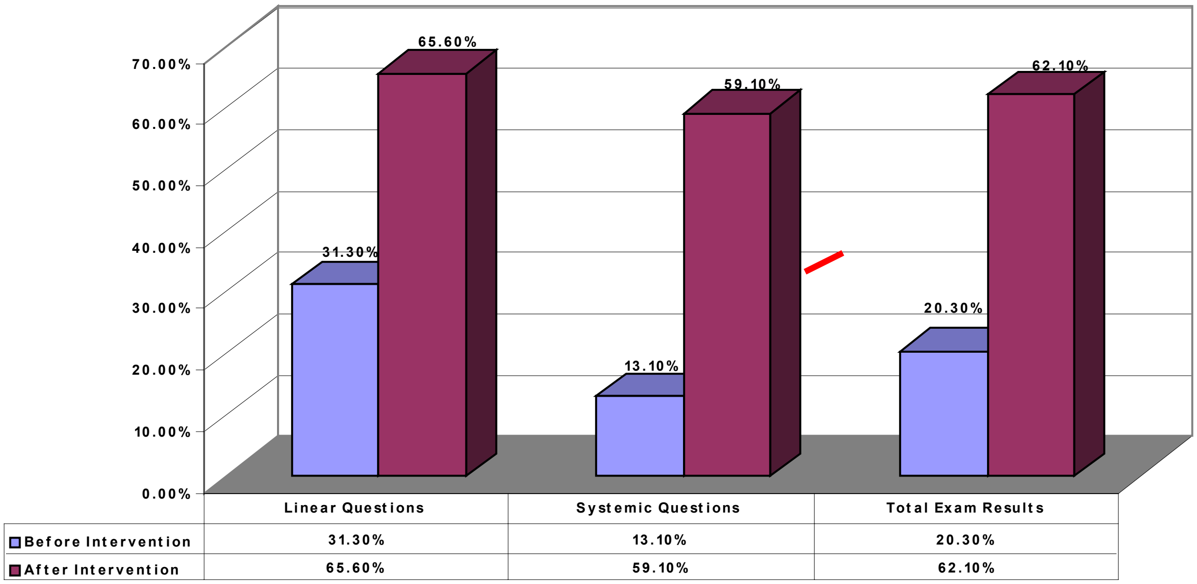


Figure 10. Average scores for control groups before and after intervention. See text for details.



	Linear Questions	Systemic Questions	Total Exam Results
🟦 Before Intervention	31.30%	13.10%	20.30%
🟥 After Intervention	65.60%	59.10%	62.10%

Figure 11. Average scores for experimental group before and after intervention. See text for details.

Heterocyclic chemistry. A course on heterocyclic chemistry using the SATL technique was organized and taught to 3rd year students at Ain Shams University. A portion of the one-semester course (10 lectures, 20 hours) was taught to 53 students during the 1999-2000 academic year.

We use heterocyclic chemistry to illustrate, again, how a subject can be organized systemically. Figure 12 summarizes all the significant reactions of furan, the model heterocyclic

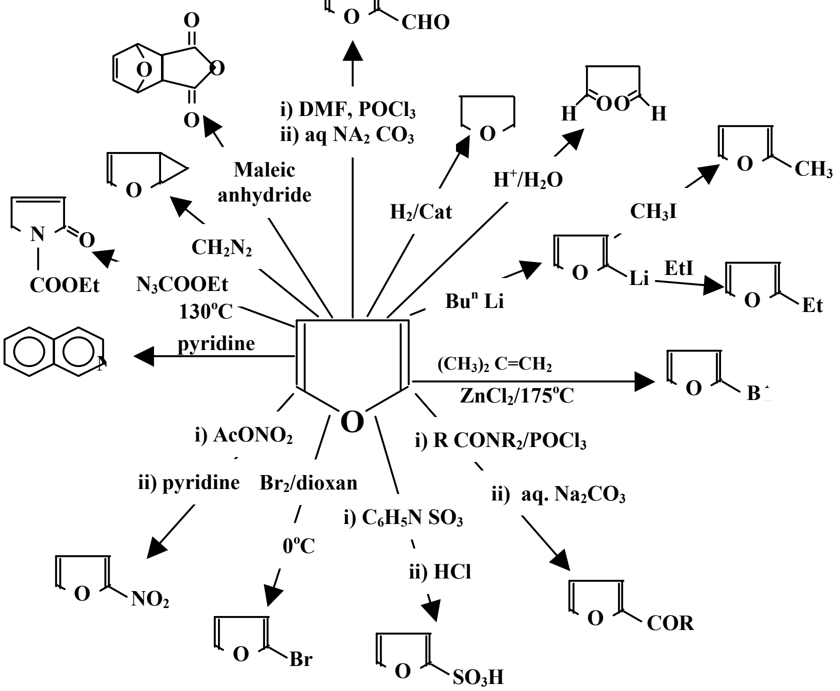


Figure 12. Some of the more important reactions of furan.

compound. These are the reactions that are generally discussed in a linear fashion (Figure 2a) in the conventional teaching approach. However, these reactions can be organized systemically as shown in Figure 13.

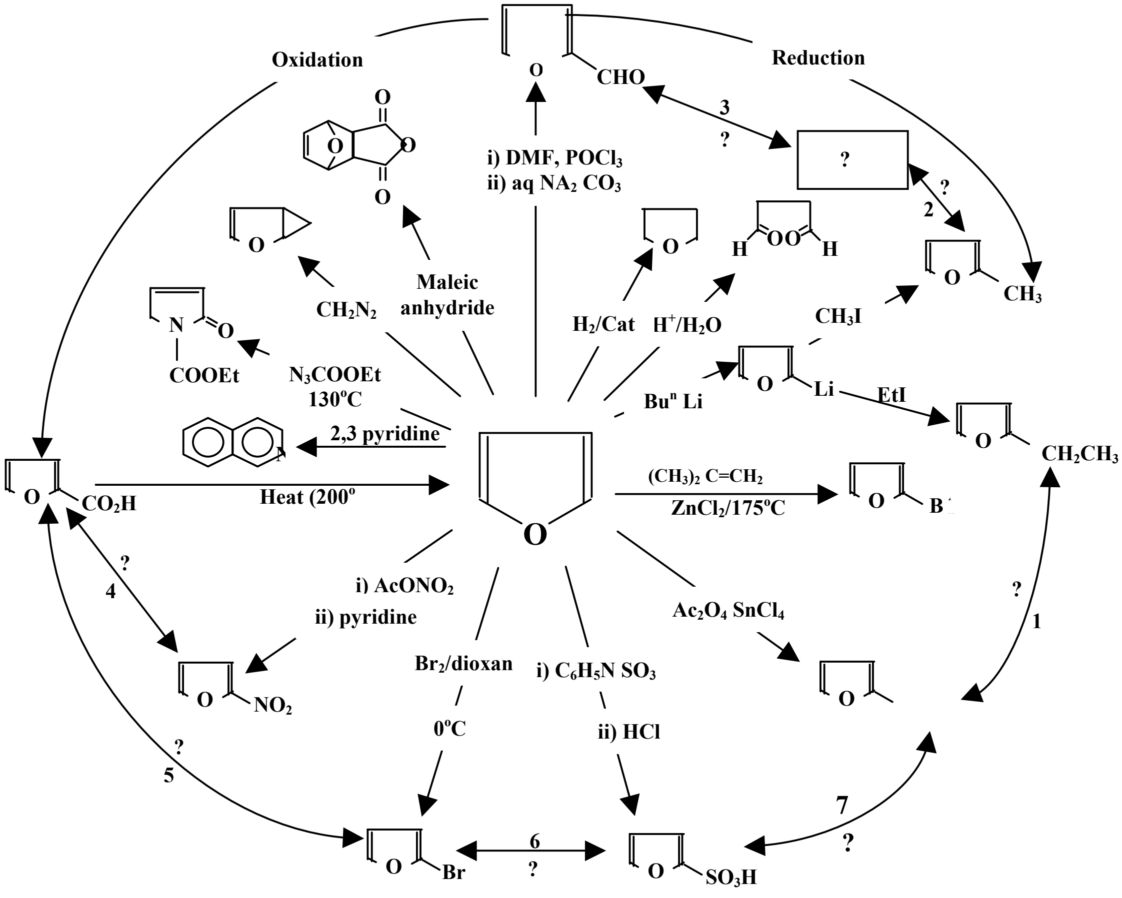


Figure 13. The systemic organization of the furan chemistry shown in Figure 12. Notice the undefined species and reagents that are necessary to complete the diagram.

But inspection of Figure 13 reveals seven unknown reactions among the furan compounds; these are listed in Table 3.

Table 3.

No.	Chemical relations
1)	2-Acetylfuran to 2-ethylfuran (reduction-Wolff Kishner).
2)	2-Hydroxymethylfuran to 2-methylfuran (reduction, H_2/Ni-Co, Δ).
3)	Furfual to 2-hydroxymethylfuran (reduction; $NaBH_4$).
4)	2-Furoic acid to 2-nitrofuran (nitration, HNO_3).
5)	2-Furoic acid to 2-bromofuran (bromination, Br_2).
6)	2-Bromofuran, to furan-2-sulphonic acid (sulphonation, H_2SO_4).
7)	2-Acetylfuran, to furan-2-sulphonic acid (sulphonation, H_2SO_4).

Figure 13 can be further refined to give Figure 14 by adding the unknown chemical relations shown in Table 3.

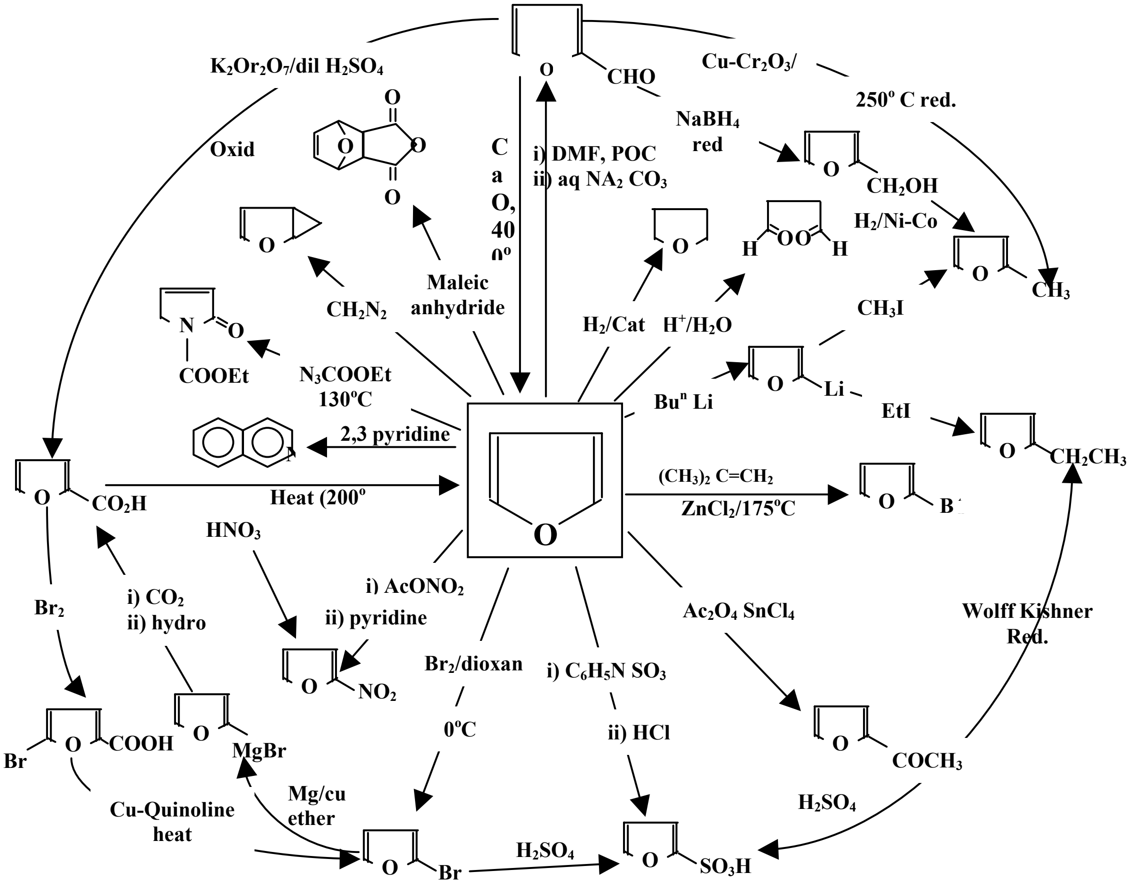


Figure 14. The result of completing the undefined reactions (Table 4) that appear in Figure 13.

Before the intervention, that is, teaching by systemics, the students in this class all took an examination—we call the "zero point" examination—which established their previous personal knowledge of organic chemistry as obtained from previous courses. The heterocyclic course using the SATL approach was not involved in the classic experimental intervention/reference experiment. Rather, a study was made of the improvement in achievement of the students involved. The students who were taught using the standard linear approach were tested with linear questions, while those who were taught using systemics and were examined at the end of the course using systemic questions. The data summarized in Table 4 show that students taught systematically improved their scores significantly after being taught using SATL techniques.

Table 4. Percentage increase in student scores.

	Percent increase in student scores	
	Before intervention	After intervention
Linear questions	37.32 %	49.53 %
Systemic questions	21.19%	90.29%
Total	32.52%	69.1%

These results are statistically significant at the 0.01 level. Statistical details are available from AFMF. (9).

SYSTEMICS AND LABORATORY INSTRUCTION

In this section, we discuss the use of systemics in laboratory instruction, specifically, conducting experiments that reveal the “chemistry of species” of interest (10). Applying Systemics to this phase of laboratory instruction reveals the following advantages:

- Smaller amounts of chemicals are used.
- Experiments are done more rapidly.
- Students easily acquire a working sense of the principles of green chemistry.

We start our discussions with the classical laboratory-oriented subject of qualitative analysis, which involves collecting chemical information on the species of interest from which pool of information the identities of the species of interest are deduced. Qualitative analysis involves the application of linearly obtained chemical information to an unknown solution in a linear way (Figure 15).

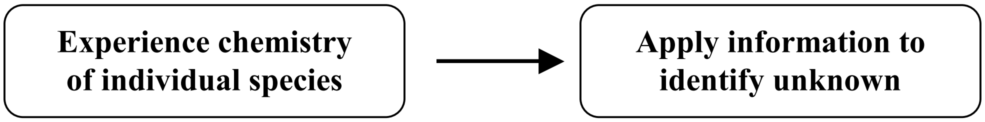


Figure 15. General linear strategy of qualitative analysis.

In contrast to the generally linear approach of learning descriptive chemistry of cations from a laboratory experience, a systemic method has been developed that focuses attention on individual species (Figure 16).

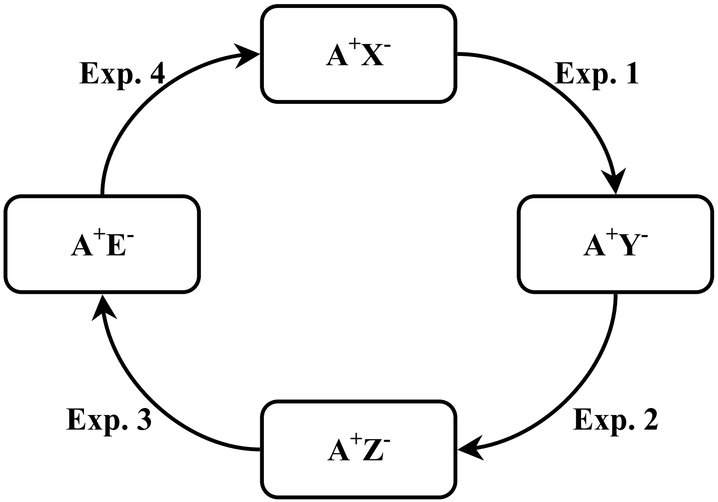


Figure 16. The systemic approach to the laboratory study of species A^+

The reactions can be performed in a single test tube on a small sample $(\leqq 0.5 ml)$. This approach allows students to experience the colors of chemical species, their solubility characteristics, and their redox behavior. The "green chemistry" aspects of this approach involve a very small amount of the cation-containing species, which is contained in a very small volume. We now show the development of a systemic closed-cluster cycle (Figure 17). This diagram shows the qualitative investigation of Cr^{3+} species, the preparation of Cr^{3+} compounds, and the interconversion of the species. Notice that the formulas of chemical species of interest are expressed in this diagram, but the reagents that bring about these conversions are not given in the diagram in Figure 17. These reagents are revealed experimentally in a series of reactions shown in Figure 18a-d, which the students can do

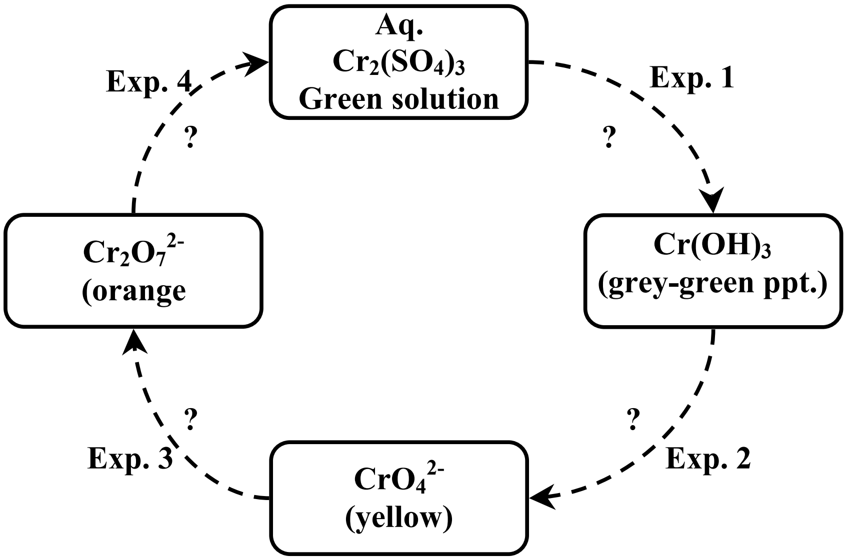


Figure 17. The systemic description of experiments defining the chemistry of Cr^{3+}.

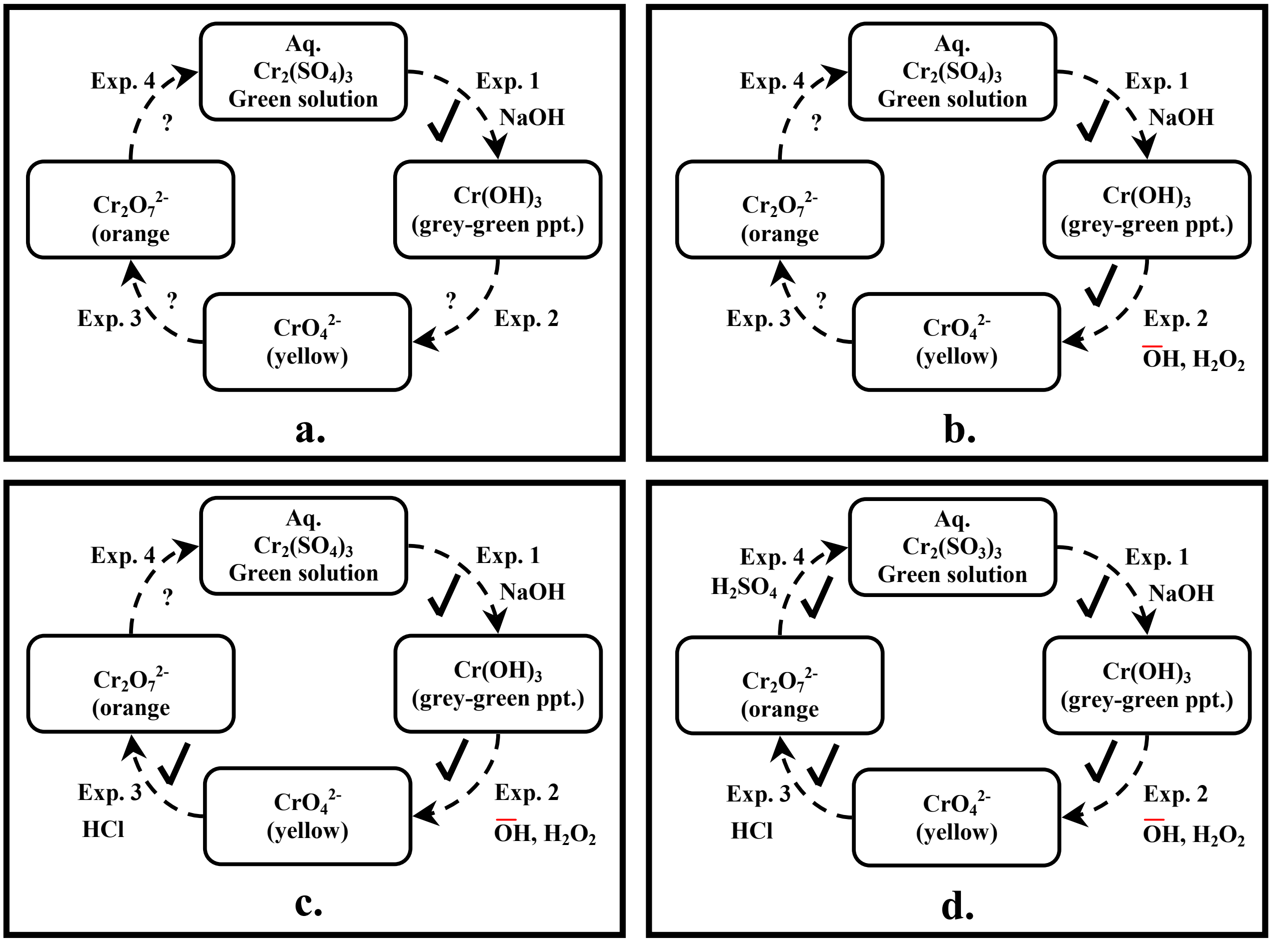
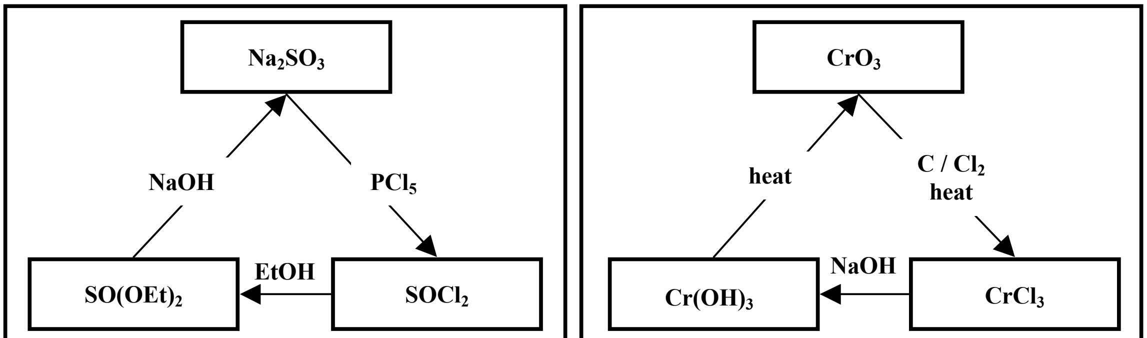


Figure 18 a-d). The laboratory-based evolution of the chemistry of chromium as performed by students.

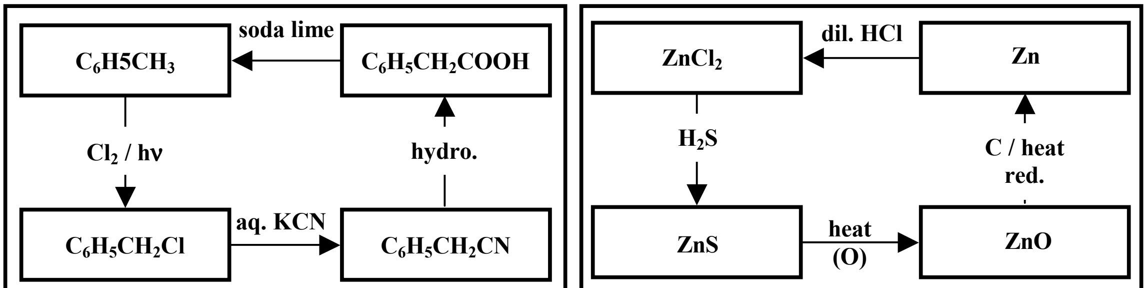
in the laboratory on a small single sample of chromium-containing species. Thus, the experiment diagrammed in Figure 18a reveals that hydroxide ion (OH^-) converts the green aqueous solution of $Cr_2(SO_4)_3$ into the grey-green precipitate of $Cr(OH)_3$; the addition of hydrogen peroxide converts the green precipitate into the soluble, yellow-colored chromate ions (CrO_4^{2-}); and so forth.

The systemic technique can also be used to create an activity that develops equation-writing skills (Figure 19).



a. Draw a systemic diagram for illustrating the chemical relationship between sodium sulfite,thionyl chloride, and diethyl sulfite.

b. Draw a systemic diagram for illustrating the chemical relationship between chromium hydroxide, chromic oxide, and chromic chloride.



c. Draw a systemic diagram illustrating the chemical relationship among the following species: C6H5CH3, C6H5CH2Cl, C6H5CH2CN, C6H5CH2COOH.

d. Draw a systemic diagram illustrating the chemical relationship among the following species: Zn, ZnO, ZnS, $ZnCl_2$.

Figure 19 (a-d). Examples of student activities using SATL techniques.

We suggest that the systemic diagrams shown in Figure 19 can be used as a new assessment tool.

TRAINING PROGRAMS

Over and above the activities involving the creation and evaluation of systemic materials, the Science Education Center (SEC) has been engaged in the last two years in training programs using the systemic approach. These programs included Chemistry Professors from several Egyptian Universities where the training is focused on using the systemic approach in teaching chemistry at the university level. In addition, training programs were carried out for pre-college teachers, which involved video conferences attended by about 8,000 school teachers as well as smaller groups in face-to-face training sessions.

The Center is now engaged in preparing more of these programs at all levels of instruction because of the success of the earlier training programs.

SUMMARY

We have attempted to describe the application of systemics to a variety of chemistry-oriented courses starting with pre-college instruction through advanced organic chemistry subjects as well as laboratory-oriented instruction. In addition, we have presented the results of the evaluation of this approach on student performance.

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