*Химия*, год. XV, кн. 2 (2006) *Chemistry*, Vol. 15, Iss. 2 (2006)

**• *Учебно съдържание, планове и програми* •**
**• *Curriculum Matters* •**

# PROBLEMS OF THE GENERAL CHEMISTRY COURSE AND POSSIBLE SOLUTIONS: THE 1-2-1 GENERAL/ORGANIC/GENERAL CURRICULUM AND ITS CHALLENGES

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**Abstract.** A review is presented of the literature concerning the problems associated with teaching general chemistry and their possible solutions. These problems tend to be associated with three factors: the eclectic nature of the course content, the lack of logical organization of the chemistry topics presented in textbooks, as well as the students, their interests and level of preparedness. Different institutions deal differently with these challenges. One of the ways to address the problems in general chemistry is the non-traditional, 1-2-1 curricular organization of chemistry courses, which is especially appropriate for smaller, relatively less selective colleges that follow the liberal-arts model of education found in the United States. In this sequence, students take one semester of general chemistry, followed by two semesters of organic chemistry, and then the second semester of general. Such re-organization requires textual materials which are not currently available on the market. An example of such preliminary, textual materials and their pilot classroom evaluation is described. The topics are hierarchically ordered starting with *what* is the structure of matter (from atoms to bonding to molecules), moving on to *how* and then *why* matter gets transformed. The presentation does not assume any background chemistry knowledge, so that it could serve today's under-prepared yet able students who may follow the 1-2-1 sequence of chemistry courses.

*Kewwords:* general chemistry teaching; 1-2-1 curricular organization; chemistry in Mary Baldwin College

## Problems of General Chemistry

The general chemistry course is arguably the most critical course that prospective science students take in their college careers. At the same time, this course has been plagued by several problems that have been the subject of discussion and reform for many years [1—11]. The challenges in teaching general chemistry are associated primarily with two major factors: the course content as well as the students, their interests and level of preparedness:

### *A. Content of the General Chemistry Course.*

First, the content of a typical general chemistry course (in contrast to organic or biochemistry courses, for example) naturally represents a mish-mash of seemingly disconnected topics. Hence, general chemistry textbooks also lack logical organization. Initially, students are bombarded with an avalanche of often misunderstood concepts and foreign-sounding terms that are to be quickly memorized. Then, students are subjected to jumping around from the atom to some bonding between atoms, to reactions, to some thermochemistry, then back to the atom, and again some more bonding between atoms, more thermochemistry (months later), etc. In the meantime, the chapter on gases flows somewhat freely in the air by itself.

Second, these topics are usually drowned in a sea of dull, abstract calculations in which even good student swimmers may lose sight of the underpinning chemistry concepts [12,13]. The emphasis is on the physical at the expense of the biological context [2,7]. General chemistry is often described as a "baby p-chem" class that for most students takes four years to master.

A third major problem for general chemistry is the lack of carry-over knowledge from one course to the next due to the disconnection between general and organic. "The sophomore organic chemistry class is seen neither as a logical continuation of nor as development based upon the first year's experience" [6]. No more than half of the topics covered in the general chemistry course may actually be relevant to understanding organic chemistry.

### *B. Students Enrolled in the General Chemistry Course.*

There are two aspects of the students enrolled in general chemistry that are of particular importance. First, the vast majority of these students plan careers in the bio-medical sciences. In the US, where students follow a flexible, liberal-arts curriculum, less than 5% of them become chemistry majors. Furthermore, most chemistry majors will eventually find work as organic or biochemists. Students' majors are no longer indicated as simply "chemistry". More than a quarter of the undergraduate chemistry degrees conferred in 2002 were listed as "biochemistry" [14]. Therefore, an emphasis on the biological connections and on the conceptual side of chemistry that relates to organic and biochemistry seems more appropriate for beginning students.

Second, today, at least in the US, nearly every high-school graduate eventually pursues some form of postsecondary education [15]. In addition, about 60% of the 3000-plus colleges in the US admit almost everyone who applies [16]. Many of our students come to the general chemistry classroom without having taken a single physical science course in high school. This may not be the case for larger or comparatively more selective institutions. The educational systems of East Asia and Europe generally produce better prepared freshmen because of the more demanding national curricula that are being followed in their high schools. In contrast, in the US, less than half of the entering college freshmen meet or exceed the recommended years of high school study in the biological and physical sciences [17]. Practically every chemistry teacher has noticed that today's students are indeed less prepared for college-level work.

Similar problems, albeit still in a more attenuated form, are beginning to surface in many of the former Eastern block countries, including Bulgaria. Since the fall of the Berlin Wall in 1989, the societies of Eastern Europe have been undergoing dramatic transformations. The rigor of high-school preparation and the preparation of the students for college-level work has steadily declined. The gradual democratization and de-centralization of the educational system has lead to a sharp increase in the number of institutions of higher learning and also an increase of the number of students pursuing post-secondary degrees. At the same time, a huge number of young people had left Bulgaria and enrolled in universities in the West. In many ways, our two countries have been coming ever closer. These developments indicate the need for science educators with different educational traditions to unite their efforts in addressing the challenges of teaching chemistry. These challenges are common to all of us.

### *C. The General Chemistry Textbook.*

Despite the dramatic changes in the student population in the last 20 years, both the general chemistry course and its accompanying textbooks have hardly changed [2,18]. Commercially available general chemistry textbooks have two major inadequacies. First, they are written for an audience that must be familiar with many of the chemistry concepts and terminology. For example, the recently published ACS-sponsored general chemistry textbook [19] states in its introduction that

"...a very large percentage of students who take the general chemistry course in a college or university have already had at least one year of a high school chemistry course. We assume that you are in this category and have probably been exposed to a good deal of the nomenclature and methods that are part of the study of chemistry".

Unfortunately, while this assumption may be correct for some institutions, it is not correct for other, less selective schools [17]. In fact, many four-year colleges, as well as community colleges, offer general chemistry classes to all science-interested freshmen without distinguishing between people who have already had chemistry in high school and those who have not had any physical science classes. Furthermore, research shows that even students who have actually taken chemistry classes in high school often carry with them a load of scientific misconceptions [20—22] and lack enough preparation to read and comprehend the material.

The second major inadequacy of general chemistry textbooks (already mentioned above) is related to their lack of systematic approach in the order in which the seemingly disconnected topics are presented. Instructors have long recognized the fact that teaching chemistry is about a gradual build-up of concepts into a larger hierarchical edifice of knowledge, which is so characteristic of the sciences. In contrast to general chemistry textbooks, whose logic is hard to follow, organic and biochemistry textbooks, for example, are elegantly woven along some common themes, leading the student in a stepwise manner to more complex phenomena. This may be one of the reasons why a survey of over 3,200 students at nine colleges and universities showed that organic chemistry students report spending approximately 40% more time using textbook resources than do general chemistry students [23]. A simple review of the tables of contents of the general chemistry textbooks available from publishers in the United States [24, 25] reveals that not one of them presents the structure and function of matter in a systematic, hierarchical manner.

Frequently, commercially available general chemistry textbooks are viewed as desk references that complement the syllabus with problem-solving exercises and appendices. Many of our beginning students, who feel under-prepared, experience frustration when attempting to navigate a desk reference. They need a teaching tool. Regardless of the rush of new educational media, research shows that the textbook with its printed ancillaries remains the chief tool for learning used by students [23].

The lack of a systematic approach in general chemistry texts often creates a negative perception of chemistry as a subject, which is as fuzzy as the orbitals of the atom. Such impression may lead to a loss of potential chemistry majors to fields that appear more logically structured. The number of bachelor’s degrees in chemistry has remained flat for the past 25 years [14]. At the same time, the overall number of bachelor’s degrees has increased by 50% and the number of degrees in biology and psychology has nearly doubled [26, table 255].

### Possible Solutions to the General Chemistry Problems

To address the three sets of problems mentioned above, chemistry educators have suggested different solutions. Typically, teachers try to make some sense of the rambling, disconnected general chemistry topics by creating their own, more logically ordered syllabus or even creating their own customized textbooks. Other solutions involve the chemistry curriculum.

### *A. Curricular Solutions.*

Many educators have suggested a fusion of the general chemistry course with a more biologically oriented course like organic chemistry [6, 8, 9], cell biology [10], or general biology [11]. Although this approach provides direction and context for the general chemistry course, as well as a smooth transition to the next level of courses, it faces a number of obstacles. First, the "biological fertilization" of general chemistry might create logistical problems when course work is transferred from one institution to another. Second, some faculty may perceive the non-traditional fusion of courses as too dramatic a change in terms of curricular re-organization.

Most importantly, all of the above-listed approaches assume either a fairly good high-school chemistry background or a preliminary, introductory chemistry class taken in college. They do not take into account the dramatic changes observed over the past 15—20 years in the level of preparedness of students enrolled in general chemistry courses in the US.

The problem of inadequate preparation is addressed differently at different institutions. Large universities may offer remedial chemistry classes [27] or their students with solid science background simply self-select themselves into the sciences. Some institutions may even use the traditional year-long general chemistry sequence as a weeding-out tool. The central mission of many relatively less selective schools and community colleges is to serve mostly underprepared yet able students. This is of particular relevance to students of disadvantaged backgrounds and students of color, who are still significantly underrepresented in the physical sciences [26], Table 269].

Another possible curricular solution involves a separation of the general chemistry course by a year of organic. In fact, quite different and prominent schools, like North Carolina State University, Williams College, the University of Richmond, the College of William and Mary, (among many others), have already adopted a modified curricular sequence of chemistry courses, in which students take *only one* semester of general chemistry, followed by two semesters of organic chemistry and then the second part of general chemistry.

The 1-2-1 sequence alleviates most of the problems associated with the general chemistry course without creating any additional complications. Topics (unrelated to organic), which often turn our beginning, more biology-oriented students away from chemistry, are left for general chemistry II. This approach also provides the foundation for a smooth transition from general to organic chemistry. The modified curriculum does not disturb any of the other science offerings, and allows for an easy transfer of credits to other schools.

### *B. Textbook solutions.*

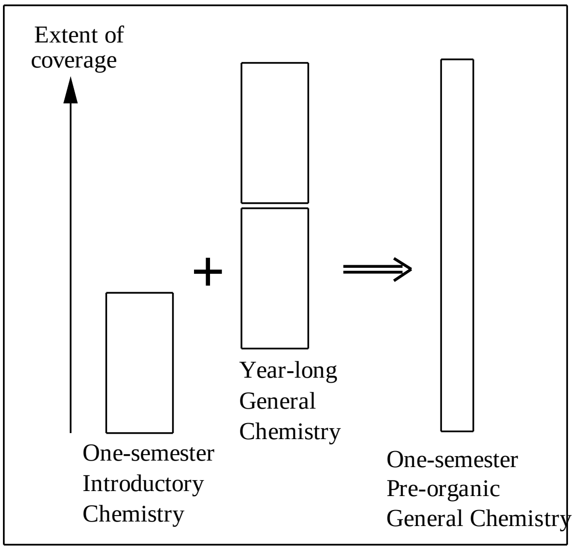
Several instructors have recognized the need of a general chemistry textbook that is organized in a hierarchical manner [28]. Recently, a group of educators from Northeastern University developed a two-semester general chemistry textbook where an attempt is made to order the topics more logically from atoms to bonding to molecules [29]. This text, however, assumes a good high-school background (undoubtedly true for Northeastern students) and is aimed at schools teaching the traditional, year-long general chemistry course. Also, the important, hierarchical connection between the topics in this book is largely lost due to the sheer size of the material covered, and the strong emphasis on the contextual side of chemistry. Another author, Dennis Wertz, has created a text that corresponds to the 1-2-1 curriculum; however, his product also assumes considerable prior chemistry knowledge and is more narrowly tailored to the needs of his own students at North Carolina State University [30].

There are general chemistry textbooks that often follow a more logical order of representation and do not assume prior exposure to chemistry. These are the one-semester, introductory texts like the one authored by Russo and Silver [31] or the texts for allied-health majors [32]. Other introductory chemistry texts simply represent a shortened version of the same disconnected general topics seen in their larger counterparts [33, 34].

Typically, introductory chemistry texts are aimed at students who will continue with only one semester of either organic, or a combination of organic and biochemistry (allied-health majors). In all introductory texts, the coverage of the topics is neither sufficiently extensive nor appropriately in-depth for taking the two-semester long course of organic chemistry. Potential chemistry majors who have taken an introductory chemistry class will need to eventually enroll in the regular, two-semester long general chemistry course. Overall, introductory texts are not suitable for the 1-2-1 curriculum.

None of the commercially available general chemistry textbooks are easily adaptable to address the needs of the under-prepared, yet able students, who may also follow the modified 1-2-1 sequence of chemistry courses. Therefore, during a year-long sabbatical in 2002, I began to develop some new general chemistry course materials that address those needs.

### Characteristics of the Preliminary Web-based Materials



On the one hand, regular, two-semester general chemistry textbooks assume considerable background knowledge. On the other hand, introductory texts are not preparing adequately our science majors for the two semesters of organic. Therefore, the preliminary materials were designed as a hybrid between the approach seen in one-semester, introductory texts and half of the material presented in regular, year-long general chemistry courses, but only that particular half that is essential for understanding organic chemistry. These materials target a specific student audience at comparatively less selective 4-year schools and community colleges. They may also be appropriate for advanced high-school students, allied-health majors who after a semester of general continue on with a semester of organic and biochemistry as well as for for engineering schools whose students take only one semester of chemistry.

The proposed materials combine all of the following characteristics many of which are evident form the tentative table of contents (TOC) in *Appendix 1*:

1. They are appropriate for the first semester of general chemistry leading directly into organic in the non-traditional 1-2-1 curriculum. Topics that are not directly related to the study of organic chemistry are omitted from the first-semester. They are left for the fourth semester of the 1-2-1 chemistry sequence (general II): the chapter on gases, the more comprehensive and quantitative treatment of thermodynamics and chemical kinetics, standard enthalpies of formation, phase diagrams, K calculations, solubility equilibria, precipitation and qualitative analysis, chemistry of the main-group elements, transition metals, electrochemistry, nuclear chemistry.

2. The topics for discussion are hierarchically ordered, reflecting the way scientific knowledge is organized. The perennial sequence of questions about what, how, and why is followed, beginning with *what* is the structure of matter (from atoms to bonding to molecules), moving on to *how* matter gets transformed physically and chemically; and then *why* matter gets transformed from one form to another. To emphasize the main ideas and facilitate student learning, the title of each section is written as an affirmative declaration presenting

a chemical concept to be remembered. The first chapter covers the most basic chemical ideas with the aim of priming students for work in the laboratory without burdening them with an avalanche of new vocabulary and chemical reactions. Special emphasis is placed on the concept of the stable particles of matter. Keeping a constant eye on the big picture of the corpuscular nature of matter is an important part of the way chemists think. Research shows that the majority of students from high school through university level perceive matter as a continuous medium, rather than as an aggregation of particles [23].

3. The proposed preliminary materials present the subject matter using an introductory style without expectation of any background chemistry knowledge. For example, instead of just mentioning examples of physical vs. chemical changes, their difference is explained in the very first chapter in terms of *inter*- vs. *intra*-particle forces. An informal pedagogical language is used throughout the text so that students feel less intimidated by the new vocabulary and abstract ideas.

4. Each major chemical concept is covered comprehensively. For example, chapters 2 and 3 deal with all relevant aspects of the atom. Similarly, the interconnected features of covalent bonding are presented in two consecutive chapters. Thus, Lewis dot structures is treated parallel to hybridization and molecular orbital explanations, as different models of one and the same phenomenon.

5. The bio-organic aspects of chemistry are highlighted and emphasis placed on qualitative understanding. The quantitative side of chemistry is kept at a minimal level as needed for re-enforcement of the underpinning chemical concepts. For example, enthalpy is explained quantitatively in terms of bond dissociation energies and entropy only in qualitative terms. Proportional reasoning is used in mathematical solving of problems. Research shows that proportional reasoning helps students develop better critical thinking skills and keeps the abstract numbers constantly connected to the chemical concepts [35]. Special emphasis is given to the distinction between physical, chemical, and nuclear changes because even advanced students sometimes lose sight of the big picture.

### Pilot Assessment of the Preliminary Web-based Materials

At my home institution, whose students represent a typical slice of the US college student population, with average SAT scores of around 1000, we have already begun a curriculum reform that addresses the needs of our diverse student body. We have modified the chemistry curriculum sequence. Our students have been following the 1-2-1 modified sequence of chemistry courses since the 1990s. Several of my colleagues (chemists and biologists) have been reviewing the preliminary materials and have provided me with extremely valuable ideas for many revisions. Furthermore, I was able to evaluate our materials on two occasions.

First, in the fall of 2002, general chemistry students at Mary Baldwin College were using a commercially available general chemistry textbook. Twice during the semester, those 60 students were asked to compare their textbook with chapters 2, 3, 4 and 5 of the preliminary materials, which were posted on the web. My colleagues and I were elated to read their responses. Practically all students indicated that the most important strengths of the on-line materials were the gradual build-up of chemical concepts from atoms to bonding to molecules as well as the clarity of explanations. The only weaknesses pointed out were associated with the preliminary format of the text (e.g. lack of color, not enough worked-out examples, and lack of end-of-chapter exercises).

Second, in the fall of 2003, a rough draft of the preliminary materials was used by our first-semester general chemistry students as the only text source. On the very first day of classes, all students took our in-house, non-multiple choice general chemistry diagnostic test. Based on their performance (percentage of correct answers) all students were divided into three groups with statistically significant differences in their levels of prior chemistry knowledge: students with low, average, and high levels of background chemistry knowledge. The first group (with low background knowledge) consisted of 13 students whose average score was 5.8% (ranging between 0 and 9%) with a standard deviation value of 3.6. The second group consisted of 23 students with average background knowledge whose average score on the diagnostic test was 24% (ranging between 15 and 33%) with a standard deviation of 5.5. The last group consisted of 13 students with high background knowledge. Their average score on the diagnostic test was 48% (ranging between 39 and 78%) with a standard deviation of 10.2.

At the end of the semester, results showed no statistically significant difference in the performance on the final exams between students with different levels of prior chemistry knowledge. This fact serves as evidence that the text being used works for all students regardless of their prior exposure to chemistry.

The innate potential of the students was determined using their performance on GALT (Group Assessment of Logical Thinking), which has been shown to correlate with student success in chemistry [36]. This was also confirmed in our study. Interestingly, students with average chemistry background tended to perform lower than predicted from their GALT scores. Perhaps those students do not try as hard because they have some false perceptions about their *actual* level of understanding of the material.

The most important and encouraging finding was that the retention rate from general to organic chemistry jumped from around 45% in academic years 2001 and 2002 to 75% in 2003. Since our students at least for the last 15 years, have been following the 1-2-1 curriculum, the only difference between the previous two years and 2003 was the type of textual materials used — a commercial textbook that goes back and forth between seemingly unrelated topics versus web-based materials that follow a logically interconnected gradual build up of the chemistry principles. Apparently, in 2003, our students liked chemistry as it was presented in the new materials and decided to continue.

In the fall of 2004, when our students used again only a commercial text (*Chemistry* by McMurry and Fay) that goes back and forth between topics, the number of students continuing with the second semester of chemistry in the 1-2-1 curriculum (Organic I) dropped back to the same number as in the years before 2003. Finally, in the fall of 2005, our students were offered again the newly developed materials which led to an unprecedented 92% retention rate from general chemistry I to organic chemistry. These encouraging results indicate an overall positive impact of the new textbook materials on students' perception of chemistry and learning.

### Acknowledgments

The author is grateful to Dr. Lundy Pentz of the Biology Department at Mary Baldwin College for his essential help in reviewing this manuscript and for performing the ANOVA analysis.

*Appendix*

### Table of Contents

1. Nature of Chemistry
1.1 Chemistry is a science.
1.2 Chemistry is a technology.
1.3 Chemistry is the *central* science.
1.4 Chemistry studies matter.
1.5 Matter consists of stable particles — molecules and ions.
1.6 Molecules and ions remain intact during physical changes of matter.
1.7 Molecules and ions change during chemical reactions.
1.8 Changes of matter are accompanied by energy changes.
1.9 Matter is measured with *SI* units using scientific notation.
1.10 Density measures the compactness of matter.
1.11 Heat and temperature measure the energy of matter.
1.12 Measurements have different levels of accuracy and precision.

2. Structure of the Atom
2.1 The atom consists of protons, neutrons, and electrons.
2.2 The number of protons determines the atomic number of an element.
2.3 The sum of neutrons and protons equals isotope's mass number.
2.4 Mass and weight measure two different characteristics of matter.
2.5 Atoms are weighed relatively using the atomic mass unit (amu).
2.6 Atoms are weighed and counted using the mole concept.
2.7 Light is a form of matter/energy that is emitted in discreet amounts

5.5 The molecular compounds made of C, H, O, and N are most abundant.
5.6 Polyatomic ions have a charge, while radicals have unpaired electrons.
5.7 Molecular structures follow periodic-table trends.
5.8 Determining the 3-D structure of a molecule involves sequential steps.
5.9 Delocalization of p electrons leads to resonance.
5.10 Formal charges indicate uneven distribution of electrons in a molecule.
5.11 Molecular stability depends on the covalent bonds' characteristics.
5.12 Summary of the key terms and concepts.

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6.3 Charges on ions in formula units reflect ions' noble-gas configuration.
6.4 Charges on transition-metal cations correspond to the anions' charge.
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6.6 Acids and bases are ionic compounds containing $H^+$ and $OH^-$.
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6.11 Hydrogen bonding is the strongest form of dipole-dipole interaction.
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6.17 Matter is classified into pure substances and mixtures.
6.18 Summary of the key terms and concepts.

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7.4 Solutions are described quantitatively by percentage concentration.
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7.6 Mole fraction and molality do *not* depend on solution's temperature.
7.7 Dilute solutions are described quantitatively by ppm and ppb.
7.8 Strong electrolytes conduct electricity.
7.9 The colligative properties determine the processes of osmosis and dialysis.
7.10 Particles in colloids or suspensions are larger than particles in solutions.
7.11 Summary of the key terms and concepts.

8. Chemical Changes of Matter
8.1 Chemical equations show the transformation of reactants into products.

8.2 The law of conservation of matter requires balancing of chemical equations.
8.3 Balanced equations are used for mole-to-mass stoichiometric calculations.
8.4 Stoichiometric calculations determine yields and limiting reagents.
8.5 Empirical formulas may be deduced from combustion analyses.
8.6 Chemical reactions may be studied and classified at three levels.
8.7 Reaction mechanisms follow a radical or polar-ionic pathway.
8.8 Precipitation reactions are represented by net ionic equations.
8.9 Acid-base reactions involve $H_2O$ and its derivatives ($H^+$ and $OH^-$).
8.10 The Bronsted-Lowry theory is about the proton in acid-base reactions.
8.11 Lewis acids and bases emphasize the electron pair in acid-base reactions.
8.12 Redox reactions usually involve the transfer of electrons.
8.13 Summary of the key terms and concepts.

9. Direction and Rate for the Changes of Matter
9.1 Bond dissociation energies reflect the energy levels of covalent electrons.
9.2 The net enthalpy change is the major component in chemical reactions.
9.3 Entropy is the driving force for changes of matter.
9.4 The Gibbs free-energy change D*G* reflects both enthalpy and entropy changes.
9.5 The equilibrium constant $K_{eq}$ measures the direction of a chemical process.
9.6 Acid-base equilibria determine the strength of acids and bases.
9.7 The self-ionization of water is used to calculate pH and acids' strength.
9.8 The direction of a chemical process is determined experimentally.
9.9 Le Chatelier's principle explains how to propel a reaction forward.
9.10 Hess's law explains how living systems overcome unfavorable reactions.
9.11 The direction of a chemical change is absolutely independent of its speed.
9.12 The reaction rate drops with time and it may be affected by some factors.
9.13 Energy diagrams describe why changes of matter occur.
9.14 Summary of the key terms and concepts.

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10.2 Isomerism and chirality.
10.3 Aromatic compounds, alkyl halides, alcohols, and ethers.
10.4 Chemistry of the carbonyl compounds.
10.5 Polysaccharides and lipids.
10.6 Proteins and nucleic acids.

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# ПРОБЛЕМИ НА КУРСА ПО ОБЩА ХИМИЯ В РАННИТЕ ЕТАПИ НА ВИСШЕТО ОБРАЗОВАНИЕ

**Резюме.** Направен е преглед на преподаването на обща химия в американските колежи. Статията съдържа преглед на основната литература по въпроса и са дадени и някои от често използваните учебници по обща химия. Направени са предложения за реорганизация на учебните планове. Предложена е системата 1-2-1: един семестър обща химия, два семестъра органична химия и заключителен семестър обща химия. Описана е една възможна диспозиция на основните методични единици на такъв курс заедно с нейната пилотна оценка в клас. Тази схема не предполага някаква предварителна химическа подготовка на обучаваните студенти.

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