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What Chemistry Should Be Taught in Modern Schools?

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Abstract—The goals of school education and the role of lessons in natural sciences, particularly chemistry, in intellectual development of school children are analyzed. The reasons for the negative attitude to chemistry from the young people and the society are determined. The problems arising from the forthcoming reform of school education are discussed. The structure of the chemistry course for modern general schools is presented.

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In our country chemical education is in an obvious crisis. Its problems are partly caused by the general crisis of education, which has been shaken by continuous ill-conceived reforms for twenty years now. In appearance these reforms seem attempts to transplant the Western system and standards of education to the Russian soil, whereas in fact such reformation is a purposeful movement towards general fee-based education and transformation of education into a paid service (from this point of view the ongoing reforms look well thought out).

Another root of problems is not of Russian but of global origin. It is a universal decline of interest in natural science (technical) disciplines among the youth [1]. It is astonishing but this trend is most pronounced in developed countries, such as the United States and Japan. The modern youth of the United States prefer the sphere of humanities, whereas the formed niche in research and production is filled by immigrants from China, India, and countries of the former Soviet Union. School children from African countries are the most motivated to receive natural science education. Russia occupies an intermediate position [2] in strict compliance with the level of technological development; nevertheless, the decline of interest to natural sciences is evident, which cannot but raise concerns.

This problem manifested itself most clearly in the course of the recent broad public discussion of yet another reform of our school education, transferring natural sciences into the category of optional disciplines, elective subjects. It is fair to say that the public attitude to this reform is negative in general. According to a survey conducted by the All-Russian Center for the Study of Public Opinion on February 19–20, 2011 [3], 61% of the respondents spoke in favor of maintaining the existing educational system, in which senior school children have to learn 20 major subjects at the basic level. It is indicative that the reform opponents were mostly represented by 25–44 year old Russians (57%), who are the most active part of the population, and residents of medium-sized cities (61%), who are a stronghold of common sense.

At the same time, almost a quarter of the respondents supported the idea of the reform; a lot of unpleasant words about education in chemistry were said in the course of the Internet discussion. The key-note of these comments was as follows: why did I have to study chemistry at school for four years if I have never used it in all my life? Of course, it is possible simply to dismiss these words as obviously absurd. However, it should be honestly admitted that the above statement reflects the negative attitude of a large part of our society towards chemistry.

That is another problem of modern chemical education and, maybe, the biggest one. It is quite satisfactory in case of working with gifted children; there is much less success in training future research and production staff, which manifests itself in a steady decline in the average level of knowledge of school graduates applying to institutes specializing in chemistry. The overwhelming majority of school children acquire a strong immunity against chemistry, if not disgust, and they will retain this immunity in their adult life.

This regrettable phenomenon has many reasons. Some of them are beyond the school boundaries; they originate from the society, the state, and the government agencies; correspondingly, they can be solved only at this level. For example, it is necessary to resume the practice of school laboratory works, which were excluded de facto due to economic reasons as long ago as the beginning of the 1990s. It is impossible to raise interest in chemistry without practical works with different substances.

Another tangle of problems is chemophobia, which is actively initiated and exaggerated by the mass media with their apocalyptic stories and disaster reports. When receiving no positive information, common people get the impression about absolute harmfulness, danger, and uselessness of chemistry.

At the same time, part of the blame, and it is a major part, is on school education as such. Judging by the outcome, schools teach not what they should and not how they should. Let us try to understand what the point is and what can be done to improve the situation. This problem is multifaceted; therefore, let us focus only on one aspect, namely, on the content of the school textbook on chemistry intended for *modern* general school. Let us try to formulate requirements to such a textbook, make a list of topics that should be covered by the textbook, and discuss methods to present the educational material. Let us start the discussion with a fundamental question about the necessity to teach chemistry at school.

Why Teach Chemistry at School?

This question can and must be formulated more broadly as a question about the objective of education in general and education in chemistry in particular. The answer to this question is far from unambiguous; moreover, some authors (see, for example, [4]) believe that the Russian education has lost its objective, which explains the chaotic and inconsistent character of the ongoing reforms.

In fact, here is a by no means exhaustive list of the declared objectives of education, inhomogeneity of which only highlights the chaos prevailing in this area of pedagogy:

(1) preparation for a future profession, acquisition of professional knowledge (skills);

(2) preparation for socially useful work;

(3) preparation for future activities in society (in this context such activities can be considered as a function of the individual or, in a broader sense, as a function of the society as a whole; in this case the individual only takes part in implementation of these activities [4]);

(4) preparation for independent adult life;

(5) personal development, "creation" of a cultured person, and harmonious development; and

(6) development of intellectual and creative abilities.

Another goal of education was announced after the events on Manezhnaya Ploshchad' (Manezh Square), in which many senior school children participated. There is an opinion that schools teach too much and not what they should, that time allocated to different subjects should be reduced, and that special attention should be paid to patriotic and moral education. All this could be considered as a curiosity (someone simply confused education with upbringing), if it did not come from the mouth of a State Duma deputy.

Let us consider the above-listed objectives that are defined more clearly. The main goal is to develop intellectual abilities, which includes memory training, learning logic, mastering the ability to establish cause-and-effect relationships, model building, and development of abstract and spatial reasoning. The determine-ing role in this formation of personality is played by natural sciences, reflecting the objective laws of nature development. Chemistry with its variability, multiplicity of directions of chemical reactions, and diversity of means of influence on the system occupies a special, if not central, place among natural sciences exactly as a tool for development of intellectual abilities. It may happen that a person will never face chemical problems in his or her professional activities; however, the ability to think is developed, in particular, in the course of studying chemistry at school; therefore, this purely utilitarian approach (will need/will never need) is not applicable in this case. It should be noted that the today's situation with chemistry is very much like a situation with foreign languages in the past. The overwhelming majority of the population of the Soviet Union did not need a foreign language at all; reading materials in foreign languages were limited to scientific journals for a narrow circle of specialists. Nevertheless, even at the height of the struggle against cosmopolitism and obsequiousness before the West foreign languages were taught at school; moreover, this subject was taught in volumes exceeding the today's chemistry course. There is a very simple explanation for this paradox, which is that learning foreign languages contributes to the development of intelligence in general and memory in particular. Thus, to do justice to the Soviet pedagogy it should be mentioned that it took previous experience into account and relied upon it.

However, it should be repeated that learning foreign languages and other humanities alone is not sufficient to develop intelligence of the modern individual. A clear understanding of how some phenomena inevitably give rise to others, developing a plan of action, modeling situations, searching for optimal solutions, and predicting the consequences of undertaken actions are skills that can be learned only on the basis of natural sciences. Such knowledge and skills are necessary for everyone, from housewives to major public officials.

We constantly observe the results of the lack of these knowledge and skills by the example of various actions undertaken by our government, which is almost entirely formed by lawyers, economists, and state managers. How can they combine calls for innovations in the technological sphere, for deeper processing of raw materials, for implementation of energy-saving technologies etc. with a course for total reduction of natural science subjects in schools and technical specialties in higher educational institutions? It is not clear. Anyway, the government has a ready recipe, namely, information technologies (although, understood in a very lopsided and utilitarian way). In their opinion, the most important is to improve the links between science and production, to carry out PR activities in relation to achievements of the Russian science, and to train specialists in this field. At the same time, they absolutely overlook the fact that the first thing that is needed to implement this wonderful scheme is science and production, the second is personnel able to work in science and production, and the third is a system of training such personnel.

The next very important objective of school education is preparation for future adult life. Young people have to start adult life fully equipped with knowledge about the world, which includes not only the world of people but also the world of things and the natural environment. Knowledge about the material world is given by natural sciences. The growing shift towards humanities leads to the fact that young people cease to understand the material world and, as a consequence, begin to fear it, which results in their escape from reality into virtual space.

A majority of people, nevertheless, live in the material world in a constant contact with various substances and materials and even subject them, often unconsciously, to different chemical and physico-chemical transformations. People learn how to deal with various substances in the course of school chemistry lessons. They can forget the formula of sulfuric acid but will handle it with caution all their life. They will not smoke near a filling station; and it is not because they saw gasoline burn but because at school chemistry lessons they were informed that gasoline tended to evaporate, form explosive mixtures with air, and burn.

Another characteristic feature of our time is saturnalia of all kinds of obscurantism, belief in the supernatural, in paranormal phenomena, and in astrology, as well as abundance of mages, fortune-tellers, soothsayers, folk healers etc. It has long been known that the best way to fight prejudice is education of people, first of all, in natural sciences. Disregard of natural sciences inevitably leads to saturnalia of obscurantism, which we can see with our own eyes.

This problem can be also considered in a broader sense, namely, as an ability to adequately evaluate information. For people, who unconditionally believe everything that is presented by the mass media, life can become scary. In this situation it is simply vital to be able to distinguish imaginary from real dangers and to use common sense, which is nothing else than understanding of how things work. And such understanding can be given only by natural sciences learned, at least, at the level of basic principles.

Another vast array of information is advertising, represented by various attractive offers promising to solve all your problems without any effort on your part and with great discounts. In this case it is also necessary to have a certain reserve of knowledge in natural sciences in order to avoid swallowing the bait of swindlers and charlatans, especially as they often refer to achievements of modern science and use different impressive terms (impact matrix, wave genome, DNA code, molecular recognition, bio-energy fields etc.). Reckless following of advertisements and such advice can cause irreparable harm to health.

It is easier to manipulate people who have no educational basis in natural sciences both at the household and at the state level. It was fully felt by Soviet leaders as the main opposition in the Soviet Union came from the technical intelligentsia.

However, the Communist Party of the Soviet Union had to increase and multiply this class of people, without which it was impossible to gain an advantage in the military-political confrontation with the West. The today's Russian government has other priorities; in domestic policy it relies on manipulating people. Can it be one of the reasons for consistently pressing natural sciences out from the school curriculum? If so, the government risks falling into the pit it is digging. More skilled manipulators can make a crowd, obediently voting for somebody, move in the opposite direction, which was proved, in particular, by the above-mentioned events on Manezhnaya Ploshchad' in Moscow. If we want young people to enter adult life without a burden of prejudice (including racial and nationalistic bias), to be able to adequately evaluate propaganda and make informed choices, and to be *free* people, we cannot do without natural sciences.

Another declared objective of education is preparation for future activities in society. At first sight, in this context it is possible to apply a utilitarian approach of "will need/will never need." In fact, it is this approach that is used by the advocates of the forthcoming reform, asking why a school student, who wants to become a fashion designer, a financial director, or president of the country, should waste time on physics, chemistry, or biology. Let us allow school children to choose by themselves what subjects to study and in what volumes in accordance with their aptitudes and abilities. The problem is that, with very few exceptions, school children of 14 do not know what they want themselves; they are susceptible to the influence of their friends, the mass media, their idols, or family members. In former times the choice what to do after school was made in the final year (or after serving in the army). Today the moment of truth is a few more years away; many young people start seriously thinking about where to work and what to do only after they receive a diploma of higher education. That is when they make their choice on the basis of their aptitudes and abilities. That is one of the reasons why a significant proportion of graduates even from prestigious institutions of higher education, who can work in professions in demand, do not take jobs in their area of specialization.

However, are all paths really open for them? It depends on what education they have received. A graduate from a higher educational institution specializing in natural sciences can transform into any specialist, which we saw with our own eyes during the post-perestroika economic collapse, when following the closure of institutes and enterprises researchers, engineers, and teachers of technical higher educational institutions turned into businessmen, stockbrokers, governors, real estate agents, accountants, journalists, or mechanics. Many of them achieved success in this new profession; it is sufficient to say that the majority of Russian oligarchs have natural science or technical education. Looking further into the past, let us recall how many great Russian writers were doctors by education. At the same time, the reverse transition seems impossible as a specialist in humanities cannot turn into an engineer or experimental researcher.

A possibility and success of a drastic change of activity is determined by a special way of thinking characteristic of people with natural science education, the bases of which were laid at school. Giving school children a right to "free themselves" from natural sciences by making a "democratic" choice, in reality the reform ideologists significantly limit school children's choice of their future area of activity. It is a defective way both with respect to ensuring personal rights and freedoms and in the context of the state strategy, as it is impossible to predict what professions will be in the highest demand 20 years from now.

The considered educational goals are general and apply to all or most school children. The objective of preparation for a future profession and acquisition of professional knowledge (skills) is more specific, as certainly less than 10% of the today's school children will work in areas directly related to, for example, chemistry. Therefore, it could be possible to argue the statement of authors [5] that "one of the most important goals of chemical education is to attract young people to study chemistry and create conditions for them to continue education in higher educational institutions;" all the more so as in the absence of the other above-listed objectives this task automatically becomes dominant. Such is the point of view of people who are directly related to higher educational institutions and take to heart the catastrophic situation with training of personnel for science and chemical industry.

The Goals of Education and the Content of the School Chemistry Course

The content of the school course in chemistry and, correspondingly, the school textbook on chemistry is directly related to the objective of education. The best modern chemistry textbooks, written in line with the

Soviet (German) school of education, cope with the task to develop systems thinking quite satisfactorily. In principle, such approach is justified, as the best way to develop thinking is by using classic, multiply proven examples.

This approach is also acceptable for preparation for a future profession, envisaging many years of systematic education and gradual movement from the "classics" to modernity. In fact, students meet modernity only after graduation from higher educational institutions, when they start working within the framework of the corresponding area of specialization. However, a percentage of such students does not exceed 10%, whereas for the overwhelming majority of people their acquaintance with chemistry begins and ends at school. In terms of preparing school children for future adult life it is important to give them as much information as possible about the material world around them, about different substances, materials, and technologies that they can encounter in everyday life. It is not theories or theoretical schemes but specific knowledge that comes to the fore. We are no longer talking about systematic education but about fragmentary coverage; and the task facing school curricula developers and textbook authors is to ensure that the parts of this mosaic form a more or less complete picture.

Another problem is to motivate school children to study chemistry. This problem has always existed; it has been and is solved by organizing a system of extracurricular chemical activities, study groups, lectures, chemical competitions of different level etc. In this way school children were prepared for future professional education. The overwhelming majority of school children, who were unmotivated to study chemistry, received at least some minimum knowledge within the framework of the compulsory school course. In the context of the forthcoming reform[1] the situation is getting worse: school children's education in chemistry can end, hardly having begun, if they do not choose chemistry as a subject for further study. The reform can lead to the fact that an introductory chemistry course will become a kind of advertisement of the widest possibilities of chemistry and its extremely important role in our life. It will become pure propaganda as the provided information will not be based on understanding of how things work but will have to be only believed blindly. To inspire school children and to induce them to study a certain science is possible only by catching their imagination. Our generation was impressed by such chemical experiments as a "volcano" and the "Pharaoh's serpent." It is obviously not enough for the generation of the Internet and virtual reality. New, more vivid, modern examples are necessary.

Achievements of Modern Science and Technology and the School Chemistry Course

A problem of developing modern school textbooks on chemistry is in the optimal choice of concepts, research methods, and technologies that could be recommended for inclusion in the school chemistry course.

This problem can be approached from different angles. In the first place, it is to make knowledge received from the textbook as close to the realities of our life as possible. It is necessary to ensure that school graduates at least understand chemical terms that they can encounter in everyday life. Amazingly, this problem has been hardly studied by pedagogy. Authors of a unique research [6] analyzed mass media materials (newspapers, television, radio, and the Internet, with the exception of specialized publications and websites) and found out that 80 out of the 240 most common chemical terms were not presented in the school chemistry course. These terms include such materials as ceramics, liquid crystals, and composite materials. The list of "outcasts" in the section of "chemical technology and ecology" is even longer and includes the following: renewable resources (energy sources), fuel cells, biofuels, explosive substances, toxic agents, batteries, NPP (nuclear power plants), OEL (occupational exposure limit) etc. It is clear that this situation is unacceptable; all the more so because many of the above-listed terms are directly related to life safety and are a subject of active discussions in our society.

Another point is the most significant achievements in chemistry for the last 30–40 years. There is no "approved" list of such advances; therefore, I will provide my very subjective list consisting of ten achievements of this kind.

(1) *Discovery of fullerene, carbon nanotubes, and graphene*. In a wider sense it is progress in chemistry of simple compounds; in an even wider sense it is renaissance of inorganic chemistry. The discovery of graphene in 2004 and the Nobel Prize in chemistry

[1] Let us cherish no illusions. In our country the public opinion is interesting only for the public, whereas the government, with a persistence worthy of better application, will go through with the announced reform, whatever it may cost them and whatever obvious negative consequences it may have in future.

received by our compatriots for this discovery in 2010 are exactly the facts that can capture the imagination of school children.

(2) *Superconducting ceramics*. It is another example of phenomenal progress in inorganic chemistry.

(3) *Creation of scanning probe microscopes*, making it possible to "see" atoms and study the structure of substances with atomic resolution.

(4) *Conductive organic polymers*.

(5) *Solid-phase synthesis of peptides and oligonucleotides*. In more general terms it is machine synthesis of complex organic compounds. "Programmed" synthesis fully corresponds to the mindset of modern school children.

(6) *Deciphering of the human genome*. Development of various methods to transform DNA, production of genetically modified organisms, gene therapy etc.

(7) *Polymerase chain reaction (PCR)*. It is a unique reaction making it possible to reproduce fragments of the DNA molecule. It has supplemented numerous types of chemical reactions with a principally new one, namely, reproduction by template. Kary Mullis, the creator of PCR, was awarded the Nobel Prize in chemistry.

(8) *Progress in microelectronics*. In more general terms it is progress in production of semiconductor materials and structures.

(9) "*Green*" *chemistry*. It is principled orientation towards the development of as environmentally friendly technologies as possible, as well as technologies based on renewable resources.

(10) *Abiogenic natural gas*. A possibility of abiogenic formation of natural gas in the Earth's crust moves natural gas into the category of renewable sources of energy and raw materials and allows for a new look at the prospects for the development of civilization.

It is also necessary to take into account the fact that for the last decades chemistry as a science has undergone significant changes and has moved far away from the concepts presented in the school course. The gap increased sharply when the science entered the epoch of nanotechnologies. Failure to understand and accept nanotechnologies both by non-specialists and by many people who are directly related to chemistry is caused in some degree by the fact that nanotechnologies contradict the principles learned in school.

Let us note only several characteristic features of modern chemistry, focusing attention on their relationship with the school course.

The use of atoms as chemical reagents. In what way are the properties of a particular chemical element presented in the school course from the methodological point of view? The description starts with the atomic structure of the element and the structure of its electron shells, which is followed by simple and, then, complex compounds of the element. The description of each group of compounds includes their structure, properties, and application. There is an obvious omission in this familiar scheme, namely, the properties and applications of the element atoms are not presented. In previous times it looked well-justified. Chemistry as such started with molecules of matter; whereas atoms, even if they were recorded in chemical reaction equations, only appeared as intermediate short-lived reactive particles. Perhaps the only example in the school textbook on chemistry is the atoms of chlorine in the process of radical chlorination of hydrocarbons.

Meanwhile, atoms are widely applied as chemical reagents both in scientific research and in technology, in particular, for direct synthesis of chemical compounds. It can be exemplified by the method of molecular beam (atomic beam) epitaxy, which is used for production of semiconductor heterostructures, consisting of nanosized layers of different substances. Methods to produce atomic gases of various elements and manipulate them are well developed. The synthesis of such practically important materials as metal nanoparticles and fullerenes passes the stage of atomic gases formation.

However, what are the chemical properties of, for example, the atom of gold? The school chemistry course gives no answer to this question. Moreover, even many specialists project the properties of simple substances to the properties of atoms[2] and, as a consequence, consider atoms of gold to be chemically inert, which is not true. Atoms of gold are reactive particles, easily interacting with components of the

[2] Probably, the roots of this analogy are in the above-mentioned unique example on chlorination of hydrocarbons, in which the high reactive capacity of chlorine atoms is associated with the high chemical activity of chlorine molecules.

environment and between themselves with the formation of clusters, consisting of several atoms of gold, and as they grow – of nanosized particles. With the formation of chemical bonds between atoms of gold their reactive capacity decreases; in terms of chemical activity gold nanoparticles occupy an intermediate position between atoms of gold and solid samples. The "special" properties of nanoparticles receive a simple logical explanation, which is clear even to school children who have been told about the chemical properties of gold atoms.

Dependence of the properties of materials on their production method. It is a very tough formulation, which can cause protests of professional research chemists; however, it looks exactly that way. Let us once again use gold as an example. Depending on the synthesis method, gold nanoparticles can have different color varying from violet to red; they can be both electrical conductors and insulators; they can be catalytically inactive or exceed the best platinum-based catalysts in activity. In every case we are talking about elemental gold and these data are in flagrant contradiction to the information provided by the school chemistry textbook.

The methodological basis of the school chemistry course is Proust's Law stating that the composition and properties of chemical compounds do not depend on their production method. Of course, textbooks mention the limitation of this law; however, school children soon forget it, especially as all further information is given strictly within the framework of this law.

Impurities as one of the most important factors influencing the properties of substances. The school course provides information on the properties of individual perfectly pure substances, which is absolutely correct from the methodological point of view; however, in real life we always deal with mixtures of substances. Throughout the entire history of chemistry development professional chemists have also considered impurities a drag, affecting the course of chemical reactions and resulting in irreproducibility of experimental results. That is why new, more perfect purification methods have been developed.

At the current stage of development of the technology for production of highly purified substances and analytical control methods there is a possibility to start controlled introduction of small and ultra-small quantities of impurities, allowing for reproducible production of new materials with unique properties. Let us use silicon-based semiconductor materials as an example. Two samples of silicon, containing alloying additives of phosphorus or boron in the amount of 10^{-5} (wt %), are absolutely identical both in terms of their chemical properties and according to the results of various analyses carried out using the majority of available methods. At the same time, the samples are fundamentally different with regard to the type of conductivity and from this point of view they represent two different materials.

Nonstoichiometric compounds. Apart from Proust's Law, the school course is methodologically based on Dalton's theory. Again, non-absoluteness of the law of multiple proportions is mentioned; the historical dispute between Dalton and Berthollet is noted; the Russian scientist N.S. Kurnakov is mentioned in connection with the existence of compounds with nonstoichiometric composition. However, all this information, which is not supported by any examples in the further course, does not remain in the memory of school children, which greatly distorts their understanding of modern chemistry, its methods, and possibilities.

Supramolecular chemistry. The school chemistry course gives no explanation of the essence of this concept. The textbook focuses attention on the molecule, on the type of bonds inside the molecule, and on transformations of molecules as a result of chemical interaction. At the same time, interactions between molecules that do not lead to redistribution of electrons and chemical bonds (i.e. interactions that cannot be described with chemical reaction equations) are considered in a much lesser extent and do not remain in the memory of school children. Hydrogen bond is presented as a rather exotic type of chemical bonding, which is mostly necessary to explain the properties of water. The van der Waals interactions are left outside the boundaries of chemistry, although it is the two above-mentioned types of interactions that are largely responsible for transformation of an ensemble of molecules into a chemical substance, which is the main subject of chemistry.

Surface. As noted above, the school course describes the properties of individual perfectly pure substances, and, like in every model, there is no place for edge effects such as phase boundary. It is all the more so as the thin surface layer is different in properties and often in composition from the bulk of the material. However, it is the surface that determines catalytic and sorption properties of substances (by the way, such extremely important phenomena as catalysis and sorption are hardly reflected in the school course as well); many unique properties of nanoobjects are determined by surface atoms, the share of which can reach tens of percent of the material weight.

To what extent should these changes in chemistry as a science be reflected in the school chemistry course? Or, in more general terms: to what extent should the school chemistry course correspond to the level of modern science development?

The answer to this question is far from obvious. In any case, science is developing faster than any school curricula and textbooks can change and it is impossible in principle to catch up with it. In this situation, in the pursuit of "modernity" it is possible to lose understanding of the science fundamentals, which the school course is intended to explain.

Moreover, often a highly scientific character of the textbook can even hinder understanding of the subject. A classic example is the actual failure of the mathematics education reform, headed by A.N. Kolmogorov, an outstanding scientist and teacher. School children were absolutely unable to understand the new academic language of the textbook.

Such extreme cases can happen in chemistry as well. Thus, for example, one very respected scientist, an academician, believes that it is necessary to give Schrödinger's equation on page 5 of the chemistry textbook for the eighth grade and to present all further information on the basis of this equation. It is easy to imagine that in this case the residual amount of knowledge in chemistry will be zero. In the textbook written by N.E. Kuznetsova et al. the concept of entropy is introduced even before the description of properties of chemical elements and a variety of chemical reactions; this concept is then used to explain why chemical reactions take place. In fact, everything is correct; however the eighth grade school children are hardly able to comprehend this concept, which is understood quite formally even by many higher educational institution students specializing in chemistry.

Introduction of modern examples in the school chemistry course should be carried out in a balanced, cautious, pinpoint manner. These examples have to meet the following requirements:

– to be related to everyday life or to problems discussed in society;

– to be sufficiently simple and comprehensible for school children within the framework of the knowledge in chemistry and other natural science subjects that they already have;

– to illustrate the main principles and methods of chemistry;

– not to contradict the other examples contained in the chemistry course;

– to draw school children's attention to chemistry; and

– to contribute to creation of a positive image of chemistry.

However, the choice of examples depends on the content of the course; and there are two possible scenarios.

Modernization or Restructuring?

Introduction of modern examples in the school chemistry course, its modernization, is in fact a palliative. In this situation half measures will not give the desired results, especially as the chemistry course in its previous volume is in the future intended only for specialized classes, whereas in relation to secondary school it will be greatly reduced. Therefore, it is appropriate to talk about restructuring or radical revision of the school course. A new school chemistry course has to be constructed on the basis of different logic using a wide range of modern examples. (Discussion of specific methodological problems on how to combine an expanded range of modern examples with a reduction in the course volume is outside the boundaries of the present article. It should be noted, however, that it is very difficult but not impossible.)

For a start, let us once more try to understand why chemistry as a subject is so much disliked by many school children and their parents, former school children, including people who are not alien to natural sciences, for example, even professional experimental physicists. Apart from the "will never need" argument, which is already familiar to us, there are the following complaints: chemistry is a subject that is hard to understand; it is boring; it is a collection of disparate facts; there are no regularities, only exceptions to be learned; and there is too much formalism.

Of course, it is possible to complain about the absence of laboratory works and the reduction in the amount of academic hours allocated to study chemistry; however, part of the blame for such a negative image of chemistry as a school subject lies with chemists and teachers themselves. They fail to convey the beauty and importance of chemistry to school children. Having reread a few lines of the most commonly used school textbooks, I regret to admit that they are really boring.

Outlines of the Modern Chemistry Course

What a course in chemistry should look like to attract modern school children? It should be as close to real life as possible; it should be comprehensible, dynamic, impressive, and intriguing.

Below I will provide a tentative list of major ideas, which, in my opinion, have to permeate the entire chemistry course and have to be firmly learned by school children.

The area of chemistry is the whole material world. Of course, this idea is already central in the school course and all textbooks provide a lot of data on the structure and properties of natural substances. However, all this is overlaid by numerous reactions of synthesis. As a result, chemistry is associated only with synthetic, artificially produced substances, which are set in opposition to natural materials. "Coca-Cola is a chemical, whereas kvass is a natural product." I quite admit that some of the people who share this point of view will doubt the information that kvass consists of molecules because molecules "have something to do with chemistry."

Moreover, it is not even all synthetic substances and materials that are associated with chemistry. When asked about chemical products, common people will call washing powders and detergents, synthetic fabrics, plastics, and mineral fertilizers (often, with a negative tinge, once again setting them in opposition to natural substances). It is a dull list; however, such is the residual knowledge from the school chemistry course.

Apparently, the reason for this is that the school course is focused on the processes that can be described with chemical reaction equations. All other processes of production and transformation of substances are only briefly described or even left outside the boundaries of the course as less interesting from the didactic point of view. In this respect the most illustrative is the section about silicon. The majority of textbooks give a paragraph or two to the processes of superpure monocrystalline silicon production, doping, and transformation into a microcircuit, as well as to the numerous chemical reactions taking place on the surface of the silicon plate in the course of these processes. Therefore, it is not surprising that school children see no chemistry in computers, mobile phones, players, and other devices that fill their lives.

Chemistry is understood as an impact of a chemical agent resulting in a certain chemical reaction that can be described with a particular equation. All other effects from the arsenal of modern science and technology, including different kinds of radiation, plasma, even temperature, and electric current, causing transformations of substances, are considered physical; correspondingly, all substances and materials obtained with their use are strongly associated with physics.

In order to return chemistry its rightful place in the picture of the world it is necessary to put an emphasis on substances as the main subject of chemistry, on materials, and on the widest opportunities for their transformation with the use of various impacts, including application of chemical agents.

Modern chemistry is a "*feast of high technologies*." Chemistry, as presented by the majority of school textbooks, looks as a very antediluvian science and this impression is intensified on the background of mass media reports and different popular science TV programs on phenomenal successes and amazing discoveries in the fields of biology and physics (for various reasons, chemistry is paid much less attention to by the mass media and popular science literature).

Of course, color qualitative reactions and titration are important from the methodological point of view, especially if by using them school children determine the content of selected substances in objects of the environment by themselves. However, in the absence of laboratory works it is quite depressing to look at corresponding pictures in the textbook. The same applies to synthesis of substances using century-old equipment. (It is amazing but a lot of my acquaintances, who are doctors of science in different areas excluding chemistry, consider the retort one of the main laboratory instruments. It is this word that for some reason is stuck in their minds, which fail to remember even the formula of sulfuric acid from their school years). Chemical technologies are represented by blast furnaces and rectification columns, which are loathsome for all school children, especially for those who like chemistry. It is necessary to show school children that chemistry is an advanced science, implementing, among other things, all the latest achievements of the allied sciences and technologies. Moreover, it has to be done from the very first day of learning chemistry, but not in the final school year when the interest towards chemistry has been hopelessly lost.

School children have to get acquainted with modern methods of analysis. It is easy to include the method of atomic absorption (emission) spectroscopy into the existing course, linking it to the description of the structure of the atom's electron orbitals. No additional data are required to explain the operating principle of the atomic force microscope as well; however, the appearance of this device and the description of its capabilities will undoubtedly impress school children. After they learn about X-ray radiation and interference within the framework of the school physics course, it is useful to tell school children about the principles of X-ray phase and, especially, X-ray diffraction analysis, which makes it possible to determine the exact geometry of molecules.[3] It is also advisable to mention chromatography, although, strange as it may seem, it is harder to explain the principle of chromatography than the operating principle of the atomic force microscope and the other above-mentioned devices. It will require a deeper description of the surface properties and the surface phenomena in the school course, which is, however, in line with modern science and is useful from this point of view as well.

It is necessary to demonstrate several modern technological methods for production of various substances to school children. For example, it is possible to present the method for direct synthesis of substances from atoms in the version of molecular-beam epitaxy. It is extremely easy to explain this method even at the initial stage of learning chemistry and it will not require any special knowledge. This chemical process can be linked to lasers, which are so much liked by school children; moreover, even specialists are delighted by the appearance of molecular-beam epitaxy systems, prototypes of mini-factories of the future.

[3] The school course contains many considerations about the geometry of molecules and the direction of bonds, as well as numerous data on the lengths of bonds; however, how all this information was obtained by chemists remains a mystery for school children. On the contrary, the physics course provides detailed description of how to determine, for example, the charge of the electron or other fundamental constants.

Machine synthesis of substances should be also mentioned both in the version of solid-phase synthesis of polypeptides and oligonucleotides and in the version of combinatorial chemistry. There is no need to dip into the specific detailed chemistry of these processes as it requires additional time and knowledge; the most important is to explain the principle of operation and to demonstrate the possibilities to use these processes. It is necessary to show school children that chemistry can satisfy their interest towards various automated installations, research instruments, and monitor screens.

Omnipotence of chemistry. The keynote here is that with the help of chemistry it is possible to produce anything that is not forbidden by nature; it is possible to give predefined properties to substances; and it is possible to determine the structure of any substance and its content in objects of the environment.

Chemistry as a quantitative science. It is necessary to strengthen physical chemistry sections in the school course, such as thermochemistry, kinetics, and equilibrium, with performance of calculations for several specific examples or, at least, with explanation of the principles of such calculations.

The predictive ability of chemistry. Chemistry has many regularities, making it possible to predict the properties of substances. However, in the existing school textbooks these regularities are overlaid by various particularities and exceptions, which are really in abundance in chemistry. In our opinion, the emphasis should be still made on regularities at the expense of particularities and exceptions. It is necessary to acquaint school children with the works dedicated to determination of structure-property relationships, as well as with the methods for designing molecules and materials.

The role of computer technologies. Modern school children cannot imagine life without computers; therefore, it is necessary to constantly emphasize wide use of computer technologies in chemistry for calculating the characteristics of molecules, designing of molecules, structure determination, machine synthesis etc.

Prospects. There is no need to be afraid of showing school children that there is still much that is unclear in chemistry; that there are points of growth; and that there are whole new directions in store for them to develop if they choose chemistry as their lifework. Hydrogen energy, materials for quantum computers, utilization of carbon dioxide and saving our planet from the climate catastrophe, industrial implementation of the photosynthesis process, development of a new chemical technology on the basis of renewable resources, and production of metamaterials with a negative index of refraction to create an invisibility cloak are the tasks that have to inspire young people and draw their attention to chemistry.

On the Structure of School Education in Chemistry

The forthcoming reform leaves no room to maneuver. One or, at most, two school years will be allocated to teach the fundamentals of chemistry in general education schools. A sober assessment of the realities of our life and a vast experience of the pervious reforms make us assume the worst scenario.

The first year of education is a kind of introductory course. School children will be given a very general impression about chemistry with an emphasis on major regularities, descriptions of substances they encounter in nature and in everyday life, practical importance of chemistry, and ecology. One of the main objectives of the course is to attract their attention to chemistry and to prevent chemophobia, which, unfortunately, reigns in the society now. It is at this stage that it is extremely important to use different examples reflecting the achievements of the modern chemical science and technology.

The following two years of training motivated students in chemistry can be dedicated to the "classical" chemistry course taking into account "modern" additions and amendments, which are described above. It is hardly advisable to introduce radical changes in the content of the course and the methods of teaching, as in general they are quite successful in pursuing their main task, which is to develop school children's thinking ability. Apart from that, it is necessary to take into account the level of competence of the teaching personnel.

Education in chemistry should be concluded with a summary course. In fact, this idea is implemented in the existing school chemistry course, which is absolutely justified, because school children come to understand generalizing concepts only in senior years at school. However, there is one nuance, namely, whether generalization should be performed within the framework of chemistry or all natural sciences.

The idea of a natural science course is not new. It is actively promoted by the ministry of education. This idea causes a strong negative reaction both among specialists (see, for example, [7]) and many parents. I fully share their opinion. The introduction of the natural science course in the existing Russian school system instead of separate courses in physics, chemistry, and biology, will lead to the fact that school graduates will know nothing in physics, chemistry, or biology. And yet…

I dare to assume that the idea of the natural science course was taken by our government officials responsible for education from the West, like many other ideas forming the basis for the ongoing reforms, and not only in the field of education. Like these other ideas, the idea of the natural science course was perceived quite mechanically without understanding its essence or implementation mechanism. It is true that such a course is actively implemented in U.S. schools [8], which looks very well-justified. The point is that modern science has reached "grand unification" not in words but in deeds [9].

The field for such integration is nanotechnology. In the United States the natural science course has been introduced in schools since 2000. This reform is carried out consistently, gradually, and methodically, including development of curricula, creation of textbooks, and training of teachers in universities. The same applies to nanotechnology courses in universities aimed to train specialists for research and production.

A specialist employed in the area of nanotechnologies has to orient freely in physics, chemistry, and molecular biology. To accustom people to such a view of science and the world in general is possible only during their school years. That is exactly why it is advisable to introduce the natural science course in schools but only as a summary course given after school children have received a set of basic knowledge in physics, chemistry, and biology. The natural science course for specialized classes has to include the study of specific examples of the unity of sciences, not only demonstrating interdisciplinary connections but also applying methods of different sciences in order to create a common object. Some examples of this type have been mentioned earlier. They include the polymerase chain reaction and different methods of medical diagnostics and identification based on PCR, computer processors, magnetic memory elements and liquid crystal displays, high-temperature superconductors, and solid-phase synthesis of proteins and DNA fragments.

It is clear that such a course is a matter of the distant future, as it requires new curricula, textbooks, trained teachers, and pedagogical experiments.

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