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THE STATES-OF-MATTER APPROACH (*SOMA*) TO INTRODUCTORY CHEMISTRY

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ABSTRACT: Chemistry, as an upper-secondary school subject for all, should aim to supply students with chemical literacy and chemical culture, to cultivate higher-order cognitive skills, and to be a useful, interesting, and enjoyable subject. A recently proposed chemistry programme for all students in grades ten and eleven (ages 15-17) in Greece, introduces chemistry through the separate study of the three states of matter [the *states-of-matter approach* (*SOMA*)]. There are three major units in the programme, namely: air and gases; salt, salts, and solids; water and liquids. The gaseous state is introduced first because it is the best prelude to the study of atoms and molecules; only a few non-metals and compounds, with small and simple molecules are studied. Ions, ionic bonds, or intermolecular forces are not involved until the unit of solids, as only the covalent bond is needed in the unit of gases. By placing the solid state second, we can study liquid solutions as well as acids and bases within the unit of liquids. The programme then moves into the applications of chemistry: plastics and polymers; drugs; foodstuffs; energy. Inorganic and organic chemistry are partially integrated. The overall approach is intermediate between a formal ('academist') and a science-technology-environment-society (*STES*) ('practicalist') one, while constructivist teaching and learning is incorporated. [*Chem. Educ. Res. Pract. Eur.*: 2000, *1*, 161-168]

KEY WORDS: *upper-secondary school chemistry; chemistry for all; programme of studies; Greece; states-of-matter approach; constructivist teaching and learning; integration of inorganic and organic chemistry*

INTRODUCTION

Chemistry, as an upper-secondary school subject for all, should aim at two central targets, namely to provide students with:

1. *chemical literacy*, that is, the basic chemical knowledge that is useful and essential for living, especially in the modern technological society;
2. *chemical culture*, that is, a satisfactory knowledge of how nature functions chemically.

In addition, students should be left with the feeling that chemistry is not only a useful, but also an interesting and aesthetically enjoyable subject. Finally, it must cultivate higher-order cognitive skills (HOCS) (Zoller & Tsaparlis, 1997).

A new chemistry programme of studies has been initiated and completed recently (February 1998) in Greece for the upper-secondary level by a committee of seven experts. The *Pedagogic Institute* (a department of the Greek *Ministry of Education and Religious Affairs*) set up the committee in July 1997, after an open invitation. For the names of the members of that committee see the Acknowledgments.

The programme consists of two parts, one *elementary*, dealing with chemistry for all, the other *advanced*, directed at students who follow the ‘science and applied science (technology, medicine)’ optional route (roughly, half the student population). In this paper, we concentrate on the general education programme, which makes an approach to the introduction of chemistry through the separate study of the three states of matter. An outline of the advanced optional programme is given in the Appendix.

RATIONALE

There are various methods of treating chemistry in school. Traditionally, the method of descriptive chemistry was followed (Tsaparlis & Angelopoulos, 1993; Tsaparlis, 1994). The Sputnik era saw the demise of descriptive inorganic chemistry and the shift of emphasis to theories and principles, that is, to a physical-chemistry orientation. Organic chemistry, on the other hand, maintained its autonomous descriptive character. This post-sputnik formal approach emphasises a linear development of chemical concepts (atomic structure, periodic table, molecular structure, states of matter, gas laws, chemical reactions, solutions, acids-bases-salts, oxidation and reduction), without taking into account either students’ cognitive development and their conceptual difficulties, or the relationship of chemistry to technology, environment, and society (everyday life). In the linear formal approach, the applications and uses of chemistry are relegated to some ‘small-print’ information, which is not set in examination questions, and consequently not read by the students. It could be said that, the linear approach simply constitutes an adaptation to secondary education (*transposition didactique*) of university general chemistry programmes and textbooks. Research in science education considers such approaches as being unsatisfactory, and recommends that school science should be an entirely new construction that takes into account educational and cognitive psychology, as well as science education theory (Johnstone, 2000). It is noteworthy, that at the lower-secondary level, some programmes, based on educational and psychological grounds, make a distinction of chemistry into the macroscopic, the representational-symbolic, and the submicroscopic parts (Johnstone, A.H., 1982, 1991; Tsaparlis & Georgiadou, 1993; 2000). For another approach that is also educationally driven see Nussbaum (1997).

The theory and logic-guided formal programmes were unsuccessful with all but a few able and motivated students. As a result, new programmes were introduced that were more practically oriented towards technology-and-society. These *Science, Technology, Environment and Society* (*STES*) approaches [*Salter’ s* (Waddington, 1993), *Chemistry in Context* (Schwartz *et al*., 1997) *ChemCom*] pay attention to the connections between chemistry and everyday life and society, and have, as starting points, issues and problems of social and/or technological interest, in which the science of chemistry is involved, e.g. environment, energy, natural resources, issues of human health, agricultural matters. Formal chemistry is introduced and developed through these topics.

Returning to the formal/logical approaches to introductory chemistry, we must take into account three such approaches that, according to Fensham (1994), are designated as: (a) the substances approach; (b) the atomic structure approach; and (c) the chemical reactions approach.

While approaches (a) and (c) may be more suitable for the very first chemistry courses, the atomic structure approach is the most popular for the upper secondary level.

In this work, we propose an educationally driven method that is a mixture of the above three approaches. We introduce chemistry through the separate study of the three states of matter: the *states-of-matter approach* (*SOMA*). [Although Fensham (1994) is critical of the emphasis paid by chemistry programmes and books to the study of the three states of matter, we must point out that we use states of matter as a means, not as an end.] In addition, we have adopted in *SOMA* an intermediate approach, which combines aspects of both formal ('academist') and *STES* (practicalist') teaching (Mintzes & Wandersee, 1998). This must be attributed, not only to personal preferences, but also to the fact that teachers in Greece (and it can be assumed in many other countries too) are familiar with formal methods, and mostly unfamiliar with *STES* approaches. An additional reason is that the full development of an *STES* programme requires, in our opinion, far more teaching time, something which at least in Greece is not available. Finally, it should be pointed out that *SOMA* seems to have some features in common with two other *STES* approaches, an older, and a more recent one (Gymer, 1973; Schwartz *et al*., 1997).

THE PROPOSED PROGRAMME (*SOMA*): DESCRIPTION AND DISCUSSION

The content of the programme

SOMA includes seven units: (1) air and gases; (2) salt, salts, and solids, (3) water and liquids; (4) plastics and polymers; (5) drugs; (6) foodstuffs; and (7) energy. The Table provides the detailed contents of each unit. In addition, in the submitted proposal, the objectives of each unit and each particular topic have been added, together with detailed technical specifications for other components, including experiments, models, *CD-ROM*s, and historical information.

One should read the list as a flexible framework that provides the possibility for addition and/or deletion of topics, depending on the available teaching time. For instance, the coverage of the topic of crystal structure can vary considerably. In this spirit, the author of this paper has made some necessary additions, and these are marked with an asterisk in the Table. The inclusion of Lewis structures as well as of the molecular shapes according to VSEPR theory will greatly reinforce the course, providing two powerful tools. (Note that these topics are included in the advanced optional programme – see the Appendix.)

The list of topics and concepts shown was directed and restricted by the extremely low time allocated to this course in the Greek educational system, that is one 45-minute per week period in each of the grades ten and eleven. (A third period in grade twelve was deleted by the Ministry of Education. That period would have provided the chance to add some modern aspects of chemistry on structure, analysis, synthesis, and new materials.)

The states-of-matter approach (*SOMA*) to introductory chemistry (ages 15-17)

With the first three major units, an original approach to chemistry is attempted through the three states of matter: (i) air, the gaseous state, and gases; (ii) solid state and solids; (iii) water, the liquid state, and liquids.

The introduction of the gaseous state first was based on the following facts:

TABLE. *The seven units and their detailed content of the proposed programme of study (SOMA) for chemistry in Greek upper secondary schools (general education programme).*

1. AIR AND GASES
- Physical and chemical identity of the air.
- Qualitative and quantitative analysis of the air.
- Air: A gas mixture / p.p.m & mg/L.
- Gaseous mixtures - Mixture, compound, element.
- Atoms: Structure, isotopes, relative atomic mass (*RAM*).
- Periodic table.
- Hydrogen molecule, covalent bond, hydrogen sulphide.
- Single, double, triple bond.
- Relative molecular mass *(RMM)*.
- Avogadro constant, the mole.
- Ammonia molecule - Bond polarity.
- Lewis structures of molecules. *
- Molecular geometry (VSEPR theory). *
- Synthesis of ammonia.
- Collision theory.
- Energy evolved or absorbed in a chemical reaction.
- Stoichiometric calculations - Reaction yield.
- Oxygen - respiration, combustion, oxidation, photosynthesis, oxides.
- Noble gases.
- Ideal gas - Ideal gas law.
- Saturated and unsaturated hydrocarbons, cyclic and non-cyclic: nomenclature, molecular, structural, strereochemical formulae, isomerism.
- Air pollution - Pollutants, smog, greenhouse effect, the ozone hole, interaction of matter and radiation.

2. SALT - SALTS - SOLIDS
- Salt.
- Blue stone (copper sulphate hydrate).
- Salts - Crystal structure.
- Representative salts in the earth's crust.
- Molecular solids: Ice, iodine.
- Structure of ice - Permanent dipoles - Hydrogen bonding.
- Structure of iodine - Instant dipoles - Van der Waals forces.
- Atomic (polyatomic) solids.
- Allotropy of carbon: Diamond, graphite, anthracite, lignite (brown coal), fullerenes.
- Metals - Metallic bond.

3. WATER - LIQUIDS
- Role of liquid state for life.
- Temperature range for the liquid state.
- Mobility in the liquid state.
- Bromine and mercury.
- Inorganic liquid compounds (e.g. sulphuric, nitric, phosphoric acid). *
- Organic liquid materials and compounds (diesel fuel, petrol, alcohols, ethers, aldehydes, ketones, acids, esters). *
- Water - Structure, unusual properties - Hydrogen bonding.
- Water as a solvent.
- Liquid solutions.
- Other solvents. *
- Solubility - Concentration.
- Colligative properties. *
- Chemical reactions in solutions.
- Acids and bases: Uses, electrolytic dissociation (Arrhenius) - Acidity of solutions - The pH scale - Indicators - Neutralisation.
- Water purification, water pollution, waste water treatment. *

4. PLASTICS - POLYMERS
- Polymerisation - Copolymerisation.
- Structure and properties of plastics.
- Environmental problems - Recycling.

5. DRUGS
- Aspirin.
- Contraceptive pill - Anabolic drugs
- Hashish - Heroin - Methadone.
- Functional groups in drugs.

6. FOODSTUFFS
- Sugars (carbohydrates).
- Fats and oils - Soap and detergents.
- Proteins.
- Energy in living things.
- Vitamins.
- Inorganic elements in the human body.

7. ENERGY
- Energy production in the sun - Fusion of hydrogen nuclei.
- Nuclear reactions.
- The sun: Source of energy.
- Hydrogen: Fuel for future.
- Other fuels.

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* *Additions to the programme by the author of this paper.*

a. Being the simplest, it is the best understood by scientists.
b. Being macroscopically 'non-concrete' for most students (a misconception), it is the most suitable prelude to the study of the invisible submicrocosmos of atoms and molecules.
c. The elements and compounds which are, under normal conditions, in the gaseous state have small and simple molecules. We work with only few non-metals (H, O, N, halogens, and noble gases), and compounds (H_2O, O_3, NH_3, NO_x, CO, CO_2, gaseous hydrocarbons, H_2S, SO_2, HCl).
d. We start with the covalent bond (Johnstone, Morrison, & Reid, 1981; Johnstone, 2000). Neither ions nor the ionic bond are necessary. In the case of the ideal gas, intermolecular forces are absent - but mention of real gases should be made.
e. The study of organic compounds is introduced early (Johnstone, Morrison, & Reid, 1981; Johnstone, 2000). In this way, some integration of inorganic and organic chemistry is achieved.

A key feature of *SOMA* is the minimal coverage of the chemistry of elements and compounds; only those properties and reactions connected to practice are given. On the other hand, although we wanted to avoid the extensive calculations that accompany the ideal gas law, we have included that law because it is only the ideal gas which is described by a universal equation, an indispensable fact of chemical culture.

Although the logical follow-up of the gaseous state is the liquid state, we have placed the solid state second because it is suitable for the study of the ionic bond; in addition, liquid solutions, as well as acids and bases can be studied within the liquid state. It is to be noted that further integration of organic and inorganic chemistry can be achieved by studying, within the liquid state, liquid compounds and materials like diesel fuel, petrol, alcohols, ethers, aldehydes, ketones, organic acids, and esters.

The applied aspects of chemistry

With units 4-7, we move more consistently into the applications of chemistry. In unit 4 (polymers), one can study unsaturated compounds too - although representative compounds can be studied within the gaseous state. In unit 5 (drugs), more organic chemistry (especially cyclic and aromatic compounds) is included. In unit 6 (foodstuffs), we study mainly proteins, fats, and sugars. Finally, in the last unit (energy), we deal with elements of nuclear chemistry, electrochemistry, and photochemistry (photovoltaic cells), while thermochemistry is covered together with combustion reactions, in the unit of gases.

Teaching and learning of structural concepts

Taking into account the difficulty students have with the submicro concepts of molecules, atoms, electrons, bonding, etc. (Johnstone, 1991; 2000; Nussbaum, 1997; Tsaparlis, 1997a; 1997b), we suggest that these concepts should be treated with great care, and introduced wherever this is possible through the concrete experience offered by experimental facts; thus, mass spectra can be used for the determination of relative atomic and molecular masses (*RAM* and *RMM*), infrared spectra for molecular vibrations, and so on. It goes without saying that such a methodology is necessary for the application of constructivist teaching and learning methodology. In the literature there are evidence and arguments that support that constructivist methods may lead to better conceptual understanding as well as to the development of higher-order cognitive skills (*HOCS*) in students.

As a rule, we avoid the use of old theories and views; for instance, atomic structure is given through its current version, not with old concepts such as Boor' s orbits which have to be unlearned later (Johnstone, Morrison, & Reid, 1981). However, taking into account the relevant literature (Tsaparlis, 1997a; 1997b; and references therein), as well as the limited teaching time available in Greece, we do not recommend the detailed study of current structural views; so though we introduce the concepts of atomic and molecular orbitals, and the electron cloud, we do not recommend the use of the so-called orbital shapes, or the use of orbital diagrams in the construction of molecular orbitals from atomic orbitals (the *LCAO* method).

CONCLUDING REMARKS

We believe that a programme such as *SOMA* brings together the internal logic of chemistry and the psychology of learning, being thus in agreement with Johnstone's (2000) premise. It could fulfill the set cognitive and affective targets of providing chemical literacy and chemical culture to all students, as well as making them appreciate chemistry as an interesting and aesthetically enjoyable subject, and above all help them to realise its usefulness for their future career and life. In addition, we are optimistic that *SOMA* fits well into a constructivist teaching and learning methodology, so that it can provide opportunities for meaningful learning and conceptual understanding, as well as for the development of higher-order cognitive skills. We thus hope that *SOMA* has the potential to give school chemistry a new impetus and status.

POSTSCRIPT: The proposal with the above elementary general-education chemistry programme was rejected by the (Greek) *Pedagogic Institute*, in favour of a traditional programme that is now in force.

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APPENDIX: The advanced chemistry programme

In order that readers have a complete view of the whole proposed programmes of studies for the upper secondary level (*lykeion*) in Greece, we provide here an outline of the proposed advanced programme for the ‘science and applied science’ optional route (for grades eleven and twelve). Note that this programme is in addition to the general programme that is reported in this paper, that is students who take the advanced course, will have taken the elementary one too.

1. Atomic structure: Quantum numbers, atomic orbitals, electronegativity, ionisation energy, electron affinity, periodic table, structure and property relationships.
2. Molecular structure: Molecular orbitals, Lewis structures, molecular geometry (VSEPR theory), complex ions, spectra, colour.
3. Chemical thermodynamics (including chemical equilibrium).
4. Chemical kinetics.
5. Acids and bases (Brönsted-Lowry and Lewis definitions, plus ionic equilibrium).
6. Oxidation and reduction [including electrochemistry (redox potentials)].
7. Organic chemistry: Alkanes, alkenes, alkynes, alkadienes, alkylhalides, alcohols, ethers, aldehydes, ketones, acids, esters, amines, nitriles, aminoacids, benzene and substituted aromatic compounds with one aromatic ring, organic synthesis.

Note that this programme is almost the same as the approved advanced one which is now in force. The differences are that the approved programme contains additional chapters on colligative properties and on thermochemistry (the latter is treated in our elementary programme), while in the topic of ionic equilibrium it includes also the concept of solubility product, which our programme omitted because of its complexity.

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