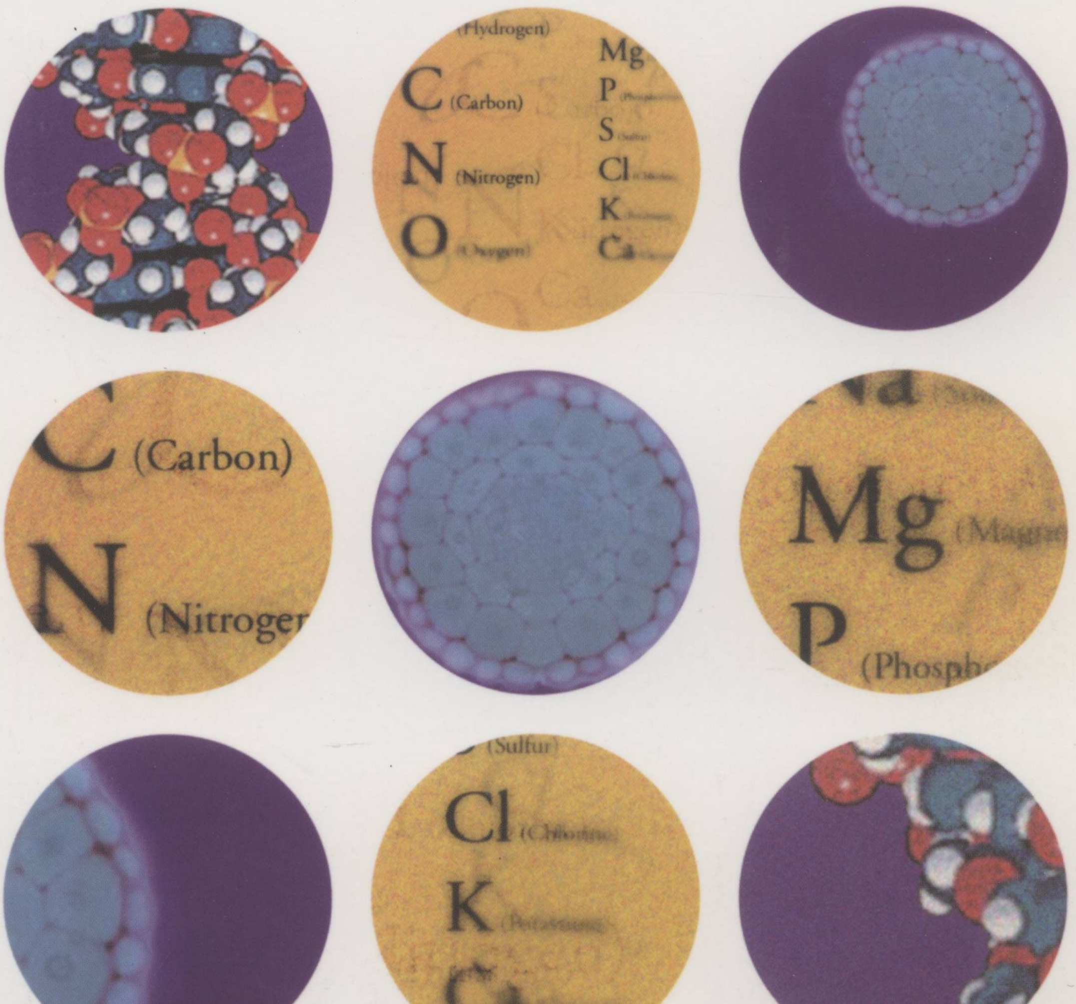
Revised and Expanded

Chemistry for the Life Sciences

Second Edition

Raul Sutton, Bernard Rockett, and Peter Swindells



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Preface

Introduction and Use of This Text

This book is intended as a self-study text for first-year undergraduate life scientists. As such a student, you will be expected to study some biochemistry during your course and will need understanding of selected fundamental chemical concepts in order to underpin this teaching. Thus, we aimed to include only those aspects of chemistry that would be relevant to you, the life scientist. So, each chapter begins with an introduction that explains the biological relevance of the contents. We have made a conscious effort to eliminate the overlap with conventional biochemistry textbooks. The relevance of the material to you is given importance by the choice of biologically relevant examples, wherever possible. The text expects little in the way of prior knowledge of chemistry and introduces concepts at a basic level. However, the depth that the text seeks to achieve means that many concepts are introduced and expanded within a short space. This keeps each chapter brief while covering most of the necessary material that you will require during your undergraduate course. The text provides you with a concise introduction to chemistry.

Many undergraduate life scientists have not studied mathematics beyond the General Certificate of Secondary Education (GCSE), and we have assumed little prior knowledge of mathematics when writing this text. Chemistry relies, in part, on physical principles, many of which are derived from fundamental considerations of equilibrium thermodynamics. The origin of equilibrium thermodynamics requires a reasonable grasp of algebra and calculus. We have removed such derivations from the text and presented only the equations that you will use when performing calculations. You may wish to satisfy your natural curiosity, and so the derivations and origins of important equations are included in an appendix.

We realise that you may not feel confident in tackling problems of which you have had little prior experience. Each chapter helps you in areas involving calculations by illustrating each important type of calculation with step-by-step worked examples. You can then test your understanding of the steps involved by attempting the questions provided in the text. These in-text questions are supported by a set of fully worked answers that are available from the publisher so that you can check your approach to problem solving.

Some of the material covered in the chapters will require rote learning, and this is something that you will have to work toward. It would not be practical for you to remember all such names at the first attempt. Rote learning can be made easier by breaking down the material into small parts. The regular review of such material will also aid your memory. It is similar with other ideas that are introduced in the text. Physical concepts can sometimes seem daunting to the life scientist, but rereading material that you find difficult, slowly and carefully, will help you to gain a much clearer understanding of its meaning. In all areas of the book, there are worked examples of answers to questions that help you to learn and in-text questions to help you reassure yourself that you understand the part of the book that you are reading.

We use the term "biomolecule" freely throughout the text to denote a molecule that is an important constituent of living organisms. Many of the chemical reactions undertaken by living organisms take place in a controlled environment, often at or near pH 7.0. Consequently, pH 7.0 and 25°C are assumed to be standard conditions for the purposes of this text.

The chemistry that you learn here will be used in many areas of your future study in subjects such as physiology, pharmacology, microbiology, and biochemistry. A deeper understanding of biology can come only when the structure, reactivity, and physical processes of the molecules that make up the varied living world around us are understood. This book will help you to appreciate this important area of the life sciences.

The Second Edition

We thought carefully about the structure of the first edition and in this text have made several improvements. One of the major improvements is the introduction of important chemical concepts that cover aspects of life sciences chemistry. Thus, the new edition includes amended and extra topics in the following subject areas:

- A separate chapter on the behaviour and properties of water
- Structure, behaviour, and reactivity of aromatic molecules
- Metals in biological organisms
- Gases, diffusion, and osmosis

We have removed the answers to self-assessment questions from the text and placed these in a Solutions Manual available through the publisher. This keeps the text concise, and the price competitive, while still making the worked answers to questions available to you.

We are also conscious that the material presented in this text may be used to support the creation of a lecture series in relevant areas of first-year chemistry teaching. Thus, many of the tables and figures used in the text are available on the publisher's Web site in downloadable format. This will enable you to integrate the text into your lecture series to create a consistent whole for the chemistry that you teach.

In addition, we recognise that the nature of chemistry changes as does the impact of such chemistry on our understanding of biology. Advances in biology mean that there may be changes to the focus of a text such as this. We have, after careful research, covered the most important topics of chemistry relevant to the life scientist. However, we welcome feedback on the text, in order to keep abreast of necessary changes in subject focus in the future.

Finally, we wish to thank Dr. John Edlin for permission to reproduce the periodic table used in Chapter 1.

Raul Sutton
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Peter Swindells

Contents

Elements, Atoms, and Electrons

1

1.1 Introduction

In order to understand the nature and reactions of biological molecules that often have large or complex structures, it is helpful to examine the simplest units of matter first. This topic will show how a few elementary particles, protons, neutrons, and electrons, can be used to build the atoms of elements and how the electrons are organised within atoms. This organisation determines the properties of the atom and how elements will combine within a living organism.

1.2 Matter and Elements

Picture on the one hand the darting flight of an iridescent dragonfly and on the other hand a pile of soil. The first is brilliant, dynamic, and organised; the second is dull, featureless, and inert. It does not seem possible that the two can be related in any way, but we know that each is composed of the simple substances called **elements**. The 92 naturally occurring elements combine in a variety of ways to make up all the organisms and materials of the world we live in.

An element is a single substance that cannot be split by chemical means into anything simpler. Carbon is the building block of life; it is an element and cannot be split into anything simpler. Of the large number of natural elements, only a few are of importance in the living world. Some assume major significance as macronutrients, and others are required in small quantities as trace elements; these are shown in Table 1.1 and Table 1.2.

Each element is a single, simple substance; it cannot be split by chemical means.

In order to write biological substances in as clear and accurate a form as possible, the different elements or atoms can be represented in a brief, simple form called a **symbol.** Each element has a single capital letter as the symbol; thus, carbon is represented as C and hydrogen as H. When more than one element begins with the same letter, then the symbol may have a second, small letter added to it in order to avoid confusion. In this way, calcium is shown as Ca, and chlorine is Cl. The conventional way of writing a symbol should always be used; chlorine cannot be written as CL or as cl. Symbols for biologically important elements are listed in Table 1.1 and Table 1.2. An extended list is given in Table 1.5.

A symbol is used as a shorthand form for an element.

1.3 Atoms

Each element is made up of a large number of tiny but identical particles called **atoms**. Thus, the element carbon is composed entirely of carbon atoms; oxygen consists only of oxygen atoms. An atom is described as

Table 1.1 Elements of Major Importance to Plants and Animals

Element Name	Symbol	Role in Living Organisms	Source Used by Man
Carbon	C	Constituent of protein, carbohydrate, fat	Meat, fruit, vegetables
Hydrogen	H	Body fluid, essential for protein, carbohydrate, fat	Water
Oxygen	O	Essential for respiration, body fluid, protein, carbohydrate, fat	Air and water
Nitrogen	N	Constituent of proteins, nucleic acids, chlorophyll	Meat and fish
Phosphorus	P	Essential for ATP, phospholipids, nucleic acids	Meat and milk
Sulphur	S	Component of proteins, coenzyme A	Meat, fish, eggs
Chlorine	Cl	Ion balance across membranes, stomach acid	Table salt, salted foods
Sodium	Na	Ion balance across membranes	Table salt, salted foods
Potassium	K	Anion–cation balance across membranes, nerve impulses	Meat, green vegetables
Calcium	Ca	Component of bones, teeth, invertebrate shells, plant cell walls, essential for blood clotting	Hard water, milk

the smallest particle into which an element can be divided while still retaining the properties of the element. The very small size of a carbon atom can be appreciated when it is found that 12 g of carbon contains 6×10^{23} individual atoms; this value is the Avogadro number. It is important to us because it enables the masses of different elements to be compared. One atom is much too small to be weighed easily, so we take the mass of 6×10^{23} atoms of an element and call this the **atomic mass** of the element. Thus, the atomic mass of carbon is 12 g. It is convenient to compare the atomic mass of an element to one-twelfth of the atomic mass of carbon and call the value obtained the **relative atomic mass** (**A_r**). The relative atomic mass of carbon is 12 (there are no units), the value for hydrogen is 1, and the value for oxygen is 16.

1.4 Atomic Structure

An atom consists of a nucleus made up of protons and neutrons, which is surrounded by electrons.

Even though an atom is the smallest chemically distinct particle of an element, it does consist of smaller units, the **subatomic particles**. There are three types of subatomic particles found in atoms: **protons, neutrons**, and **electrons**. The number and arrangement of these particles in the atom determine which element it is and how it will react in biological or chemical processes. Each proton carries the same positive electrical charge, and the neutron is electrically neutral. These two particles have almost the same mass and are joined tightly together in the tiny central part of the atom, the **nucleus**. Each electron carries a negative electrical charge that exactly balances the positive charge on the proton. Electrons have a very small mass compared with protons and neutrons. They are

Table 1.2 Trace Elements of Importance to Animals and Plants

Element Name	Symbol	Role in Living Organisms	Source Used by Man
Boron	B	Healthy cell division in the growing points of plants	
Fluorine	F	Constituent of teeth and bones	Hard water, milk
Iodine	I	Essential for thyroxine in thyroid	Drinking water, sea food, iodised table salt
Selenium	Se	Removal of active oxygen species by glutathione peroxidase	Fruit and vegetables
Manganese	Mn	Growth of bone	Present in a range of foods
Iron	Fe	Oxygen carrier in myoglobin and haemoglobin, cofactor in many reduction/ oxidation (redox) reactions	Liver, red meat, spinach
Cobalt	Co	Essential for vitamin B_{12} promoting red cell development	Liver, red meat
Copper	Cu	Oxygen carrier in haemocyanin for certain invertebrates; component of cytochrome oxidase, an enzyme found in the respiratory chain of almost all eukaryotes	Present in a range of foods
Zinc	Zn	Essential in carbonic anhydrase for carbon dioxide transport in blood	Present in a range of foods
Molybdenum	Mo	Plant enzymes involved with nitrogen fixation and formation of amino acids	
Silicon	Si	Cell walls in plants, exoskeletons of marine invertebrates	

distributed around the nucleus in discrete **energy levels** or **orbitals**. The three subatomic particles are compared in Table 1.3. The same three subatomic particles are present in the atoms of every element but occur in different numbers and proportions in different elements.

An electron in an atom is in rapid, random motion.

The number of protons in the nucleus determines to which element the atom corresponds. For example, hydrogen always has one proton in each of its atoms, carbon has six protons, and oxygen has eight protons. This number of protons in the nucleus of an atom of a given element is called the **atomic number** or **proton number**. An atom is electrically neutral, which means that the number of protons and electrons must be equal. Hydrogen has one proton and so has one electron, nitrogen has seven protons and therefore must have seven electrons. The atomic nuclei of the lighter elements often contain an equal number of neutrons and protons;

The number of protons in the atom of an element is the atomic number of the element.

Table 1.3 Subatomic Particles

Particle Name	Approximate Relative Mass	Relative Electrical Charge
Proton	1.0	1+
Neutron	1.0	0
Electron	0.002	1–

Table 1.4 Atomic Structure and Electron Structure of Isotopes of Biologically Important Elements

Element Name	Symbol	Number of Protons (Atomic Number)	Number of Neutrons	Number of Electrons	Full Symbol
Hydrogen	H	1	0	1	${}^{1}_{1}H$
Deuterium	H	1	1	1	${}^{2}_{1}H$
Boron	B	5	6	5	${}^{11}_{5}B$
Carbon	C	6	6	6	${}^{12}_{6}C$
Carbon	C	6	7	6	${}^{13}_{6}C$
Carbon	C	6	8	6	${}^{14}_{6}C$
Nitrogen	N	7	7	7	${}^{14}_{7}N$
Oxygen	0	8	8	8	${}^{16}_{8}O$
Sodium	Na	11	12	11	${}^{23}_{11}Na$
Magnesium	Mg	12	12	12	${}^{24}_{12}Mg$
Phosphorus	P	15	16	15	${}^{31}_{15}P$
Sulphur	S	16	16	16	${}^{32}_{16}S$
Chlorine	Cl	17	18	17	${}^{35}_{17}Cl$
Chlorine	Cl	17	20	17	${}^{37}_{17}Cl$

carbon has six protons and six neutrons, and oxygen has eight protons and eight neutrons. Heavier elements tend to have a greater number of neutrons than protons (see Table 1.5), but hydrogen is unique in having no neutrons in the nucleus. The elements of biological importance are shown in Table 1.4 with the numbers of subatomic particles in the atom.

The number of protons and neutrons in the atom and by implication, the number of electrons, may be represented in a shorthand form based on the symbol for the elements. The number of protons is shown below (subscript) and to the left of the symbol—this is the **atomic number**. The sum of the number of protons and neutrons is shown above (superscript) and to the left of the symbol—this is the **mass**.

The mass number is the sum of the number of protons and neutrons in the element.

Worked Example 1.1

The element nitrogen, which is important in amino acids, has seven protons and seven neutrons in the nucleus of the atom.

(i) Show this in terms of the element symbol.
(ii) How many electrons are there in the atom?

Answer

(i) Write the symbol for nitrogen — N
Add the number of protons (7) below and to the left of the symbol — ${}_{7}N$
Add the sum of the protons (7) and neutrons (7) above and to the left of the symbol — ${}^{14}_{7}N$