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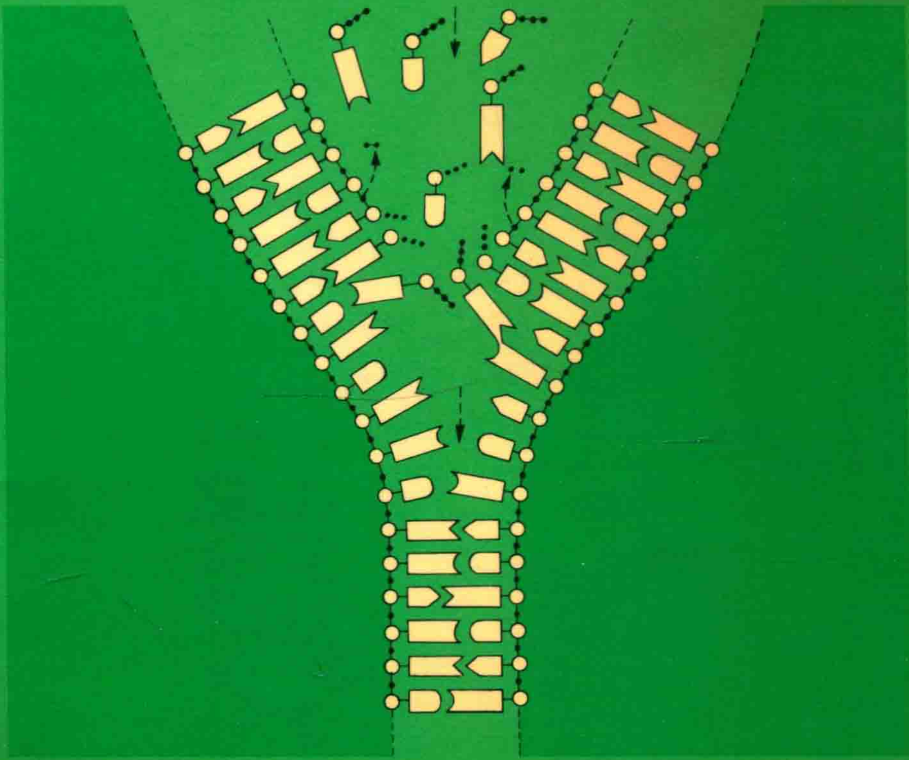

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PREFACE

In recent years we have experienced great advances in the chemistry, physics and technology of macromolecular materials. Their application in industry and in our households has reached an unforeseen extent. The spectrum of the technological applications of polymers ranges from plastics as constructional materials through foams, foils and elastics, i.e., rubber-like materials and synthetic fibres, to paints and adhesives. We might be tempted to consider these materials as being of exclusively technological importance and to take their further development as the subject of technological research. Adopting this view means completely ignoring the fact that macromolecules are of far greater importance for biological processes than they are with respect to technological applications. Consequently we are not at the end of a scientific development but at its very beginning and we can expect the next hundred years to be full of surprising discoveries in this field. As our fossil resources, and in particular petroleum, become exhausted, modified biomolecules, e.g., cellulose, will gain even more technological importance.

Life functions are mostly investigated by biologists using the wealth of knowledge acquired by botany and zoology as a basis. Starting from an organism as a whole they come to the cell, then the cell nucleus, then the chromosomes and finally the macromolecule. It is a fascinating idea to take the opposite direction for once, i.e., to apply the laws concerning the formation, structure and mobility of macromolecules to biomolecules, and to consider the immense variability in the composition of these molecules and the associated possibilities for storing information and fulfilling various functions. This approach may bring up some aspects which are unfamiliar to biologists but better known to polymer scientists and physicists. Above all, it is hoped that the attention of young scientists can be drawn to this promising field. The present booklet addresses chemists and physicists, with the intention of showing that with the technological application of macromolecules this research subject has by no means been exhausted.

Some facts that are well known to the biologist have been included in an easily comprehensible form so that physicists and polymer scientists will be able to follow the essential arguments. Similarly, a few fundamentals of the physics and chemistry of macromolecular substances are elucidated for biologists. Also, the areas of thermodynamics, information storage and closed-loop control, with which a physicist is quite familiar, are considered. It is not attempted to treat these topics exhaustively but to ensure that the subsequent considerations will be understood.

This booklet cannot be, and is not intended to be, a compendium of biology. Those who want to study the fundamentals of biology should refer to reputable textbooks. It is meant to contribute towards making the diverging and narrowing disciplines approach one another again. The treatment of the subject matter centres around the concept of the 'macromolecule'. An attempt is made to promote scientific research in its entirety and to check the narrow specialist approach.

Particular emphasis is placed on the peculiar characteristic of polymeric molecules of being highly variable chemically due to the combination of a few different monomeric units. The compounds thus formed are characterized by thermal and mechanical stability. The possibilities of correlating information with the structures of macromolecules are discussed extensively. Similarly structured but chemically different macromolecules reflect the multiplicity of life processes.

The growing importance of the biosciences and their penetration by the principles and methods of physics justify the publication of this monograph. Obviously, owing to the great extent of the subject it cannot be covered completely. This would require a team of authors with consequent loss of uniformity in the treatment of the material. As a nonbiologist I have ventured to write such a booklet alone and I hope it will still meet with a friendly reception.

The bias of the book is towards physics. Here the basic laws of phenomenological thermodynamics, in particular the second law, are applied to biological processes. The application of statistical thermodynamics to the storage and processing of information shows that there exists more than a formal analogy. Applying the equations of control technology to flow equilibria gives a better insight into the existence and maintenance of thermodynamic nonequilibria.

The possibilities for macromolecules constituting cybernetic systems are also discussed. Finally, comparisons are made between computers and living organisms. Life as a whole and as a hierarchic process of development is contrasted with an analytical approach. Philosophical aspects are also of importance. It will be shown that life in our world has not originated by chance. In agreement with Hoyle [49*a*] the question is discussed that life is omnipresent in the universe. Thus, no perpetual motion of the second kind is necessary to understand the origin of life. Our beautiful world must be understood as a whole, fulfilling the laws of ecology.

The content of this booklet coincides in part with some papers read by the author at meetings of the Physical Society of the GDR in the years 1970–75.

My thanks are due to the publishers for the support they have given me and to the referees for their critical remarks, which I have considered in revising the manuscript. I am also grateful to Dr. M. Hecker who has done much to make a good English translation.

SYMBOLS

A	affinity
	work
a	monomer length
	molecular chain unit
	constant in van der Waals' equation
b	molecular chain unit
	constant in van der Waals' equation
c	concentration
c_a	concentration (generalized)
c_v	specific heat at constant volume
F	free energy (work)
G	free enthalpy
H	enthalpy
	information value/content
h	Planck's constant
I	flux
	information (content)
K	constant in information theory
$K(T)$	rate constant
k	Boltzmann's constant
M_b	molecular weight of basic unit (monomer)
M_p	molecular weight of polymer
M_z	number average of molecular weight
m	mass
	number of neighbours exerting influence
N	number of macromolecules
	number of messages
	degree of polymerization

N_A	Avogadro's number
N_i	mole number
n	number of monomers in a coil
	number of microstates of a system
P	probability
P_i	number of monomers in polymer
	degree of polymerization
$\bar{P}_w$	weight average for degree of polymerization
$\bar{P}_z$	average degree of polymerization
p	pressure
	number of polyads
p_a	pressure (generalized)
Q	quantity of heat
R	gas constant
r_0	van der Waals' radius
r_0, r_1, r_{-1}	coefficient determining correcting value
S	entropy
s_0, s_1	coefficient determining control quantity
T	thermodynamic temperature
T_a	temperature (generalized)
t	time
U	potential
	nonuniformity
	internal energy
V	volume
w	desired value
X_a	generalized forces
x	control deviation/quantity
x_a	auxiliary control variable
y	correcting value
y_a	auxiliary correcting variable
Z	extensive quantity
z	disturbance
α	low-molecular weight combination of nucleotides
	information content in bits per purine or pyrimidine base
	error rate in copying
β	low-molecular weight combination of nucleotides
γ	low-molecular weight combination of nucleotides
λ	wavelength
μ_i	chemical potential of *i*th component
ν	frequency

CONTENTS

1

Life and its molecular carriers:

a reflection

We live in a real, recognizable world. This world of ours is governed by irrefutable, inviolable laws, the laws of nature. They are an expression of the law of causality: equal preconditions for an event cause equal effects. In this world, life has developed. It has been subjected to the laws of nature without any restriction. All life processes are associated with recognizable material changes [121].

As recently as in the nineteenth century the existence of a *vis vitalis*, a force acting outside nature and controlling life, was assumed. The research work of Darwin, Wöhler, Fischer, Hill, Eigen [25] and Watson & Crick [116], to mention but a few, has shown that this concept is untenable. Moreover, ingenious statistical considerations are put forward which provide arguments for the existence of life in a random world [63]. On the other hand there are concepts which interpret life as a cosmic development that is taking place by necessity [6, 7, 8, 28]. Again, in many works much emphasis is placed on the assignment of information to material carriers and the applicability of information theory to all life processes [88, 91, 118].

Life processes are complex and manifold; the variability and adaptability of the material carriers attached to them must accordingly be great. Only complex, structured, stable macromolecules existing in innumerable variants can reflect the many-sided phenomena and forms of life. If we want to recognize these relationships we must study the life processes on the one hand and find out the corresponding changes at the molecular level on the other. The successes of the past few years speak for this approach. Even for thinking processes we find a relation between the mental content and the formation of both networks and measurable electrical potentials in the cortex [2, 4, 107, 110]. Frederick Engels pointed to this dialectic correlation in his book *The Dialectic of Nature* [29] (see also Section 10.1).

The research worker of our day resembles the discoverer of the ancient hieroglyphs and the archaeologist who collected stones covered with ancient inscriptions and deciphered them. But the biologist is faced with a more difficult job. He has to recognize the slabs with the inscriptions, i.e., the molecules carrying the information, and study their structure before he can think of deciphering them. All the time he is aware that the molecular characters, or rather, the molecular structure and composition, convey a message to him but that the content of the message, the information, has quite a different quality.

The words of Socrates 'I know that I understand nothing' are unreservedly applicable to our knowledge of the functions fulfilled by the carriers of life processes. With respect to the material structure of the correlated macromolecules we can say with some pride, but also in due modesty, that we have begun to unveil nature's secrets.

In trying to acquire knowledge the scientist works analytically. He examines all life processes; he observes simultaneously-occurring cellular changes; he employs radionuclides to explore certain molecular changes; and he gains insight into details using the electron microscope, X-ray analysis, especially small-angle scattering, spectroscopy at all wavelengths, chemical indicators and trace analyses. Some researchers, such as the Soviet scientist Engelhardt [28], consider life as a whole. They recognize the hierarchy of all living organisms and the interplay of the functions of life.

Mental functions and molecular processes are complementary to each other. Therefore, in dealing with the material carriers of spiritual relationships we shall repeatedly refer to the theory of reflection.

Living beings and life processes are analogous to computers and, in the figurative sense, they resemble the latter in their functions. The computer represents an exactly operating machine made up of electronic components. All components are interconnected and cooperate faultlessly according to the intention of the designer of the machine. The arithmetic unit with its components, such as diodes, transistors, digitizers, switches, storage and graphic displays constitutes the hardware. But programming, the language of the machine, the mental content of the addresses and the logical interplay are also constituents of the computer. It is the programmer's job to design all this; he provides the software. Without programs and algorithms a computer would be a useless device. Conversely, the most elegant and faultless programs, designed to be economical and written in the most modern programming language, are absolutely worthless without an appropriate computer. The software and the hardware belong together and make a unit. This is also true for the phenomena of life: intellectual processes, emotion and will on the one side, and the correlated material, recognizable molecular changes on the other, go together.

The term 'living being' will be used throughout this book in its widest sense. The boundary between animate and inanimate nature is very difficult to define. Usually, the transition from macromolecules to microorganisms, i.e., the formation of coacervates (precellular systems), is taken to be the lower limit, while man at his present stage of development is considered to represent the upper limit of the concept of living being. There exists a correlation between the appearance (phenotype) and the mental qualities of a living being on the one hand and a molecular arrangement (an arrangement at the molecular level) on the other. This will be discussed extensively in Chapter 10.

The observable characteristics of a living being are called its phenotype while the correlated molecular configurations realized in the cells are termed its genotype. The concept of genotype is attributed to a very definite macromolecular structure.

Besides the connection between macroscopic phenomena and their molecular reflection, which is fundamental to life processes, there is a development from simple to complex or from primitive to highly sophisticated taking place in the course of time. This evolution concerns not only the mental qualities and appearance of an organism but also their molecular reflection. We speak of a Darwinism of the molecule [47, 56].

So far, the expression 'Darwinism of the molecule' has not been used in the literature; its meaning is defined as follows. Starting from Darwinism as the theory of the phylogenetic development of living beings we associate with it a theory of a simultaneous development of the macromolecules carrying the genotypic information. We assign to the individuals characterized by a greater ability to survive, a greater complexity and a better adaptability to the environment a correspondingly greater complexity of the molecules storing their genotypic information. 'Survival of the fittest', therefore, does not only mean the survival of the individual but also the survival of the macromolecules specific to it. Just as the carriers of improved genotypic information have a better chance to survive, the same applies to the macromolecules storing the genotypic information.

Biological happenings do not resemble the mechanistic operation of clockwork but are characterized by a directionality which does not define the single events. Those who want to explore the origination and continuation of life must comprehend the interplay and complexity of life phenomena. They must not only see certain processes of motion, growth and reproduction but also understand life as a whole [28, 47]. Philosophical discussion of this point can be found in the work of Fuchs-Kittowski [33].

Scientists want to deduce comprehensive laws from the wealth of experience and, if possible, to give them a mathematical form. Thus, in physics, the laws of conservation, the symmetry principles, the laws of thermodynamics and the extremal conditions have been established as basic principles. Is there anything similar in biology? I think there is and have formulated some general biological laws. The following list does not claim to be complete.

(1) Living beings (organisms) are self-reproducing systems which change only slightly from generation to generation.

(2) In order to stabilize an individual life a multitude of controlled chemical reactions are continually taking place under isothermal and isobaric conditions in the organisms. These are closed loops (feedback reactions). I will try to show (Chapter 9) that closed-loop processes in control theory and dissipative systems in thermodynamics describe the same facts.

(3) All life phenomena, including thinking, are connected with material, recognizable processes in the cells and the nervous system.

(4) All biological processes obey the laws of nature without exception. They may be included in causal chains or start causally-related actions consciously or unconsciously.

(5) Living beings tend toward higher complexity. This is accomplished by selection and evolution. Darwin's laws apply not only to the phenotype but also to the molecular events.

(6) Living beings are in contact with their environment. The laws of thermodynamics govern these interactions.

(7) All living beings constitute a whole (system) (the concept of unity is to be expressed) and the laws of ecology control the interrelations between them.

(8) There are no immortal organisms propagating by sexual reproduction.

(9) The decisive factor for the preservation of life is energy transfer. Owing to the absorption of quantum radiation comparatively high initial energies are available at the molecular level.

(10) Mutations and coupled mutations do not occur by chance, but by necessity. The periods of time in which they take place are not determined in advance.

These postulates will be discussed in the subsequent chapters.

The principles of biological development put forward here require the existence of a number of environmental conditions which are thoroughly dealt with in my monograph *Unsere Umwelt – ihre Entwicklung und Erhaltung* (*Our Environment, its Development and Conservation*) [47]. It is there pointed out that only carbon with its great bonding versatility is a suitable basic element of organic matter. The resources of carbon, hydrogen, oxygen and nitrogen are fed into the organic cycle over and over again. Also of great importance are sulphur, phosphorus, calcium and the alkali metals.

If the elements mentioned above are combined to form low-molecular weight compounds the number of different molecules possible is of the order of only millions. This number is far too small to account for the great variety of life processes, in particular the storage of innumerable messages in the organisms. The mere requirement that all chemical processes in organisms have to take place in the temperature range 0–50 °C at atmospheric pressure in an aqueous environment implies the formation of more than 100 000 organic catalysts. Such organic catalysts are called enzymes.

The same basic processes take place in all plants and animals. Assimilation, dissimilation, reduplication (replication), protein synthesis, energy transfer, cell formation and division and the use of membranes, active and passive diffusion, and so on proceed alike in the different species. With growing differentiation, additional functions become important. These can be referred to here only in passing: metabolism, the supply of cells, an enormous extension of self-regulating processes (feedback) at all levels of living systems, regeneration, the sense organs (receptors), the locomotor system, the storage of instinctive reactions and acquired abilities, the formation of a biological equilibrium and so on. For higher organisms such as mammals, it must be assumed that over a thousand million bits of genetic information have to be stored in the germ cells. Ideally, this information should be transmitted free from errors. However, as an error is multiplied by template polymerization, error copy might lead to an unexpected change in phenotype. This can be prevented only if there is multiple storage (see Chapter 7.6).

The information must be stable. For example, it must not be destroyed by simple molecular rearrangements. This stable fixation of information can only be accomplished by the formation of definite, characteristic, primary valency bonds, bond combinations and cross-linking in macromolecules. Low-molecular weight substances are excluded because their chemical variability is insufficient. It would also be hopeless to interpret the storage of many millions of sensations in learning processes as being due to chemical bonding in small molecules. Storage by means of the formation of molecular conformations stabilized through simple dipole bonding forces and dispersion forces does not have the stability required to conserve the information.

Magnetic storage, which has a very fast response and a high capacity, is also out of the question on account of its too low stability. Life based on magnetically operating systems might be easier to realize than life forms based on silicon chemistry. This assumption is purely speculative. Living beings of such a fictitious nature are called macrobes. Organisms having magnetic storage systems, i.e., those working like technical computers, and living beings which are not based on the chemistry of carbon are quite unlikely to exist in the universe.

A certain amount of molecular mobility allowing the formation of superstructures is also of importance. The transmission of information is an essential function and is carried out most simply by means of long chainlike molecules. It is also known, from technological experience, that macromolecules make excellent constructional materials. Thus they are well suited to constituting the connective tissue in organisms. Hence, highly elastic polymeric compounds are involved in the formation of muscles and sinews. If, in the course of development, more information is added, macromolecules can be enlarged without destroying the basic structure.

In conclusion, by virtue of the necessity to satisfy principles (1) to (10) above, and from direct experimental observations, it can be inferred that macromolecules play an indispensable part in biological events. Hence, it is appropriate, after these introductory remarks, to deal with the structure, bonding variability and formation of macromolecules.