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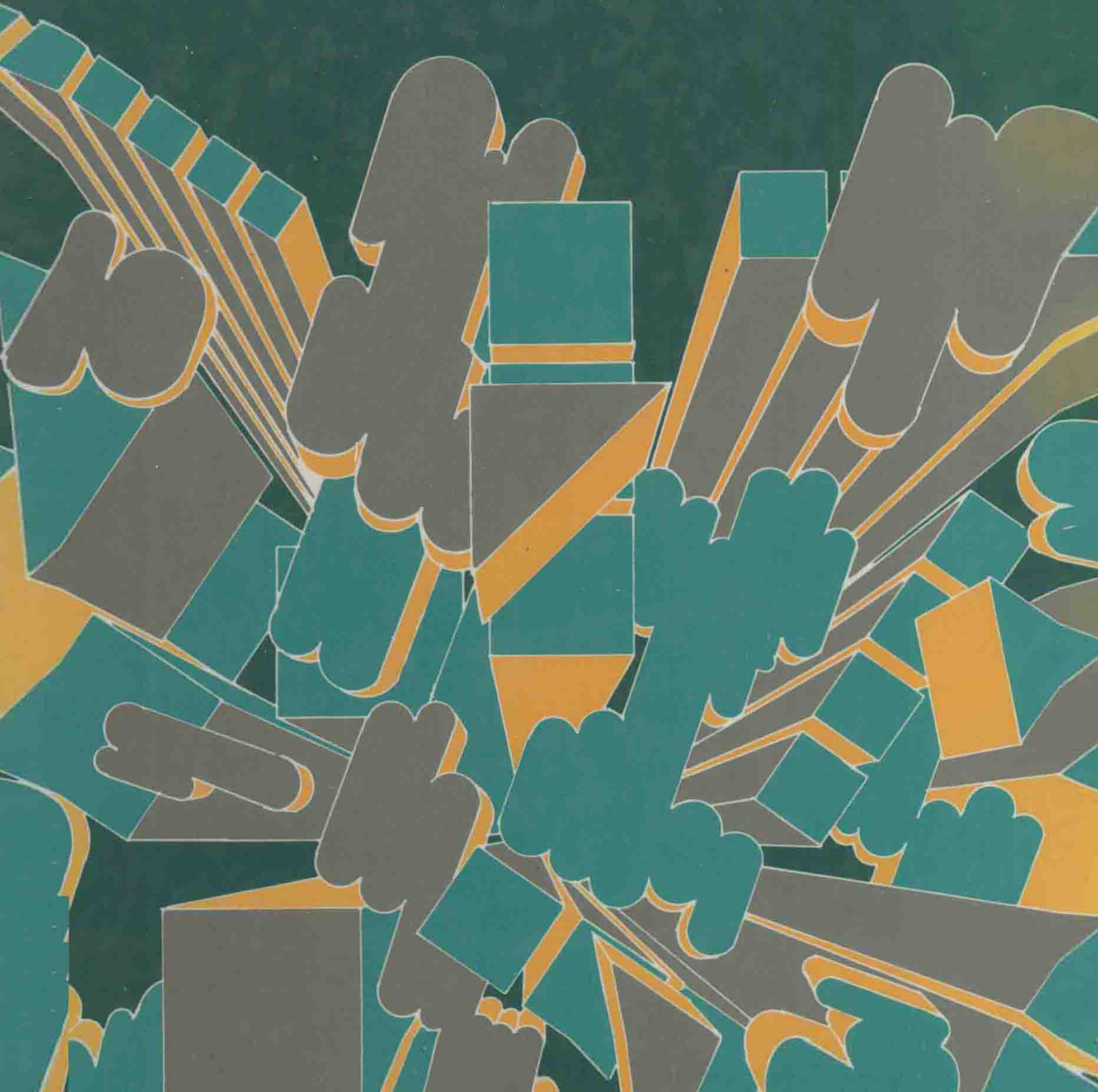
BIOLOGY AND BIOCHEMISTRY FOR CHEMISTS AND CHEMICAL ENGINEERS

W. J. Mitchell and J. C. Slaughter



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Preface

In the early 1980s, The Institution of Chemical Engineers in London introduced the study of elementary aspects of biochemistry and microbiology into their approved syllabus for undergraduate studies. This was in acknowledgement of the growing importance of biological processes in industry and a wider concern with the use of renewable, and hence biological, materials. Successful engineers of the future will need a grasp of the special properties, advantages, and disadvantages of living organisms and their products as well as of conventional chemistry.

This book is based on a series of twenty lectures given to pre-Honours year students of Chemical and Process Engineering at Heriot-Watt University in which we cover the structure and growth of microorganisms together with the main types of biological molecules, the action of enzymes, and metabolism. The theme throughout is to encourage understanding of the biological principles involved rather than provide exhaustive detail, and this approach has been continued in the book. However, principles can be relatively meaningless statements without information, and so detailed examples of biochemical molecules, cell structure, and microbial growth characteristics are provided along with a summary of the main biological industries both ancient and modern. A selected list of biological science textbooks is provided at the end of the book, and we feel that our purpose will have been fulfilled if the student, previously knowledgeable in the physical sciences and engineering but ignorant of the biological sciences, can access these more comprehensive, specialized, and detailed texts without difficulty or confusion.

Beyond the chemistry and engineering students of today, we hope the book will be useful as a starting point to any physical scientist or engineer, teacher, researcher, or practitioner who needs to establish a firmly-based understanding of modern biology and the biotechnological industries.

We are grateful to the various authors and publishers who have allowed us to reproduce illustrations and data. Our particular thanks go to John Stewart who produced many of the figures, and to David Sharp for his critical reading of the manuscript and many useful suggestions.

1

Introduction

SUMMARY

The biochemical activities of living organisms have been exploited by man for several thousand years. However, until the discovery of microorganisms, and the demonstration that they were capable of carrying out chemical transformations, the biological basis of traditional processes was not appreciated. The development of modern microbiology and biochemistry, and thus of biotechnology, stems largely from the work of Louis Pasteur during the 19th century. Pasteur demonstrated that the alcoholic fermentation was due to the metabolic activity of yeast, that all fermentations were biological processes, and that different fermentations were due to the activities of different microorganisms. The subsequent discovery, by Hans and Eduard Buchner, that chemical transformations could be catalyzed by cell-free extracts, stimulated the study of biological catalysis by enzymes, and this has resulted in a detailed understanding of the mechanism and control of metabolism in living cells.

Our present knowledge of the biochemistry and genetics of microorganisms has reached the stage where it is possible to manipulate the properties of the organisms in the laboratory. This ability has underpinned the rapid development of the biotechnological industries in recent years.

The emerging discipline of biotechnology has been defined as 'the application of biological organisms, systems or processes to the manufacturing or service industries'. The application of biochemical processes to the benefit of man is commonly perceived as a recent innovation, but this is far from true. For example, the traditional processes of brewing and baking, which have been practised for thousands of years, are dependent on the biochemical activities of yeasts. What is new is a detailed understanding of the mechanism and control of the biochemical conversions carried out by living organisms, together with the ability to alter the properties of organisms in a defined manner by genetic manipulation. The burgeoning biotechnology industries are underpinned by the newly-developed genetic techniques which allow an organism to be programmed to carry out specific conversions or to manufacture specific products. The most significant advances have been made by using microorganisms. With the advantage of simple nutritional needs and rapid growth, it is possible to obtain large yields of either the organisms or specific products, and microorganisms therefore constitute ideal biological systems from a practical point of view, both in an experimental and an applied context.

1.1 THE DISCOVERY OF MICROORGANISMS

Microorganisms, by definition, are invisible to the naked eye. It follows that observation of microorganisms is dependent on an optical aid, i.e. the microscope, and the existence of microorganisms was unknown before microscopes were developed. Microorganisms were discovered in the late 17th century by Antony van Leeuwenhoek, a Dutch merchant who made lenses as a hobby. His microscopes were really nothing more than powerful magnifying glasses consisting of a single glass lens and capable of magnification up to 300-fold. He referred to the organisms which he saw as 'animalcules' or little animals. Many important discoveries were made by using simple microscopes of this type, although a detailed understanding of the structure of microorganisms, and the cells which make up larger organisms, has required more powerful microscopic techniques (Chapter 3).

The discovery of microorganisms prompted the question of their origin. The majority of scientists in the 18th century believed in the notion of spontaneous generation of microorganisms from organic matter. This idea was supported by the fact that preparations of organic matter (called infusions) which were sterilized by boiling became contaminated with microorganisms after only a few days. However, a series of well-designed experiments, by Louis Pasteur and others, demonstrated that boiled infusions remained sterile provided that care was taken to exclude airborne microorganisms. Thus it was established that microorganisms in the air were the source of contamination of organic infusions, and the theory of spontaneous generation was abandoned by the mid-19th century. It should be realized that this refers only to the spontaneous appearance of microorganisms over a period of days, and does not in any way refute the theories of the origin of life from inanimate molecules over a span of millions of years.

1.2 MICROORGANISMS AS BIOCHEMICAL AGENTS

The ability to maintain sterile infusions soon led to the observation that these did not undergo chemical changes which were characteristic of contaminated infusions, and so implicated microorganisms as the agents responsible for those changes. The ability of microorganisms to carry out chemical conversions was conclusively demonstrated by Pasteur, whose pioneering work on fermentation processes in the mid-19th century can be considered as the beginning of biochemistry and microbiology as we know them today. Pasteur's work was largely oriented towards industrial fermentations for the production of alcohol as used in brewing, wine-making and distilling. The presence of yeasts in the fermentations was already known from microscopic observation, although the fact that they were living organisms converting sugar to alcohol had not been established. Instead, it was believed that yeast was a complex chemical substance which catalyzed the conversion of sugar to alcohol. Pasteur was able to isolate the yeast from fermentations and culture it in an artificial (synthetic) medium containing only sugar and salts together with an extract of yeast cells to provide any unidentified factors necessary for growth. Although the yeasts grew slowly, they were capable of multiplication under these conditions, and, furthermore, growth was accompanied by conversion of the fermentable sugar to alcohol. It was thus demonstrated that yeasts were the causative agents of alcohol production.

Investigation of a practical problem led Pasteur to another significant discovery. A distillery was experiencing problems with the alcoholic fermentation in that the alcohol produced was contaminated with undesirable substances. On examination of the fermentation broths, Pasteur found both yeasts and other, smaller particles. He reasoned that these were different organisms which carried out a different fermentation, forming substances other than alcohol. These organisms were in fact bacteria such as the lactic acid bacteria which ferment sugar to lactic acid. Pasteur went on to show that all fermentative processes are the result of microbial activity, and that different types of fermentation are due to different specific types of microorganism.

1.3 LIFE WITHOUT AIR

In the course of his work on fermentations, Pasteur discovered bacteria which live only in the absence of oxygen. These bacteria were referred to as anaerobic, as opposed to aerobic organisms which live and grow in the presence of oxygen. Some organisms, such as yeasts, were capable of growth in either the presence or absence of oxygen, and these were referred to as facultative anaerobes. However, the characteristics of yeast growth and fermentation were strongly influenced by the growth conditions. In the absence of air, yeasts were observed to grow slowly, and fermentation took a considerable time, but nevertheless the amount of sugar transformed into alcohol (and carbon dioxide) was extremely high. On the other hand, in the presence of air the yeasts multiplied rapidly and the yield of yeast cells was much greater, but only a small amount of sugar was fermented to alcohol. Pasteur then proposed that living cells could obtain energy in one of two ways:

(1) by a wasteful, oxygen-independent process yielding little energy: fermentation products such as alcohol were viewed as cell waste products;
(2) by efficient utilization of oxygen to oxidize sugars, providing the cells with a large amount of energy, and with very little waste product being formed.

These proposals have subsequently been shown to be remarkably accurate. The mechanisms of biological energy generation will be considered in Chapter 5.

1.4 BIOCHEMICAL CHANGES IN CELL-FREE EXTRACTS

A further major development in the understanding of fermentation was due to an accidental discovery by Hans and Eduard Buchner in 1897. In trying to preserve extracts of yeast cells by adding sugar, they found that alcohol was formed and carbon dioxide released. It was thus shown for the first time that intact yeast cells were not required for the fermentation to occur. The discovery of a soluble cell preparation with measurable chemical activity effectively marked the beginning of modern biochemistry. The alcoholic fermentation was subsequently shown to occur via a series of chemically distinguishable reactions each of which is catalyzed by a specific biological catalyst, or enzyme. This principle extends to all metabolic pathways, which consist of a series of enzyme-catalyzed reactions leading from the initial substrate to the final product (see Chapter 5).

1.5 BIOCHEMISTRY TODAY

Compared with the pace of developments up to the year 1900, the rate of advance during the 20th century has been staggering. Significant progress has been made in several key areas:

(a) The physical and chemical structure of cells and their molecular components (Chapters 2 and 3).
(b) The properties of enzymes (Chapter 4).
(c) The nature of the operation and control of metabolic pathways involved in breakdown of sugars and other molecules, and in synthesis of cell components (Chapter 5).
(d) The mechanisms by which utilizable energy is extracted from metabolizable molecules (Chapter 5).
(e) The mechanism by which genetic information is stored and expressed in the cell, and the mechanism of transmission of this information from one generation to the next (Chapters 3 and 5).

These studies have shown that there is a fundamental biochemical unity encompassing both simple microorganisms and the more complex animals and plants.

An understanding of each of the above aspects of biology has been essential in the exploitation of the properties of living organisms, and, as indicated, their description forms the basis of the following chapters.