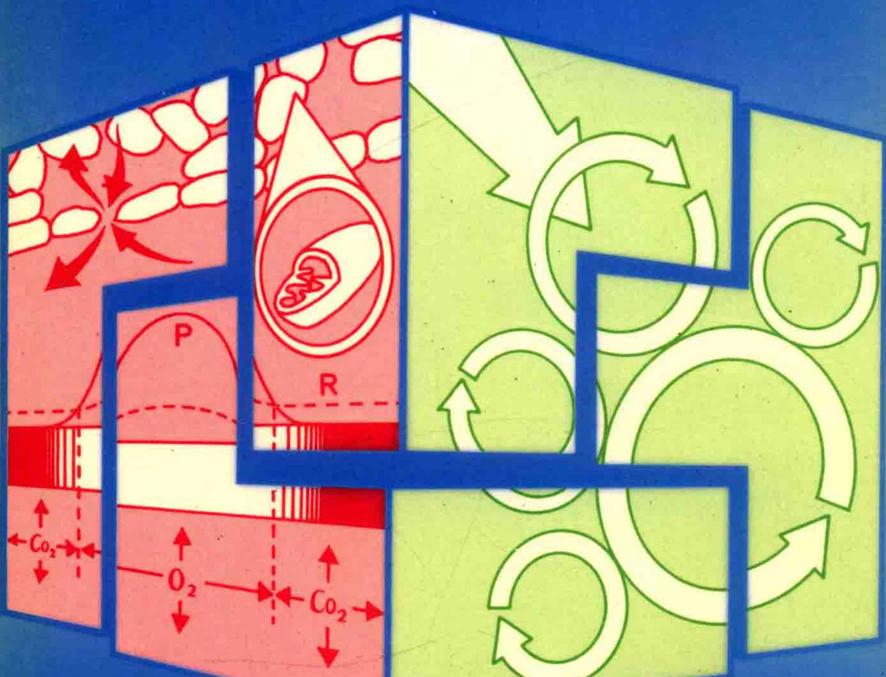
Energy and Cells

C.G. Gayford



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ENERGY AND CELLS

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ENERGY AND CELLS

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To John-Paul, Libby and Claire

Series Editor's Preface

This book is one in a Series designed to illustrate and explore a range of ways in which scientific knowledge is generated, and techniques are developed and applied. The volumes in this Series will certainly satisfy the needs of students at 'A' level and in first-year higher-education courses, although there is no intention to bridge any apparent gap in the transfer from secondary to tertiary stages. Indeed, the notion that a scientific education is both continuous and continuing is implicit in the approach which the authors have taken.

Working from a base of 'common core' 'A'-level knowledge and principles, each book demonstrates how that knowledge and those principles can be extended in academic terms, and also how they are applied in a variety of contexts which give relevance to the study of the subject. The subject matter is developed both in depth (in intellectual terms) and in breadth (in relevance). A significant feature is the way in which each text makes explicit some aspect of the fundamental processes of science, or shows science, and scientists, 'in action'. In some cases this is made clear by highlighting the methods used by scientists in, for example, employing a systematic approach to the collection of information, or the setting up of an experiment. In other cases the treatment traces a series of related steps in the scientific process, such as investigation, hypothesising, evaluating and problem-solving. The fact that there are many dimensions to the creation of knowledge and to its application by scientists and technologists is the title and consistent theme of all the books in the Series.

The authors are all authorities in the fields in which they have written, and share a common interest in the enjoyment of their work in science. We feel sure that something of that satisfaction will be imparted to their readers in the continuing study of the subject.

Preface

CELLULAR ENERGETICS AND EXCHANGES

The aim of this book is to provide an up-to-date discussion of some of the basic ideas of cell biology and biochemistry appropriate for students who are completing their advanced level studies and who are approaching undergraduate and other comparable courses. A problem faced by many students at this stage is that explanations of some of the basic biochemical and physiological phenomena that are acceptable at GCE A-level, stop significantly short of what is expected in more advanced texts. This book sets out to provide a useful bridge between these two levels.

The topics included are those that are often considered to be difficult by students and teachers alike. Part of the purpose of the book is to reconcile what students may be taught in physical science courses with the biological topics included here, and in this way to provide an intellectually satisfying and coherent view of the subject. Also, it has been the intention to convey something of the way in which science is a growing and developing area of human activity with its own method of enquiry and creative speculation.

Throughout the text an effort has been made to use units and chemical nomenclature accepted by most authorities. Occasionally this has been problematic because some of the older terms are so well established in the literature that a change of name at this stage is likely to cause confusion. Such organic compounds are pyruvate whose new name is 2-oxopropanate, and ketoglutarate which is used in preference to 2-oxoglutarate.

Energy — An Introduction

The problem when writing about energy is that there is no satisfactory definition to begin with. Most physics texts start discussions about energy with definitions of work; this can have some helpful things to say to biologists, since work relates to change of energy in a system. In this way there is a concentration on the transfer of energy; however, this is not particularly helpful in thermodynamics but it does focus attention on energy conversion. The idea of the relationship between energy and work is only really helpful in mechanics, and it is a pre-condition in some other processes such as lighting and heating.

Broadly, energy can be said to be the ability of material systems to bring about changes in themselves or the environment. Even this type of statement causes difficulties since it depends on what is meant by 'change'.

The concept of energy shows one of the important characteristics of science in that it is an abstract idea, which although very useful is still only an aid to understanding. When thinking about energy there is a tendency to think of it as a commodity, but really it probably relates to a potential. Thus it is more helpful to think of ways in which energy can be obtained from a system rather than of a body possessing energy.

Really, no simple statements summarising energy are adequate. However, energy is absolutely fundamental to cell physiology and some understanding of its nature and interrelationships in the functioning of cells is essential. Perhaps we can only begin to understand energy through the network of concepts and laws which make up its supporting theories. These relate to the conversion, exchange and conservation of energy and the two laws of thermodynamics. It is the purpose of this short book to throw some light on these associated concepts in a biological context so that students may be able to better understand the relationships that exist between energy and living organisms and the total dependence that life has on energy. Also it is an area of science where impressive discoveries have been made and where researchers have used remarkable ingenuity in order to piece together even the partial picture that we have today.

Contents

1 Energy

Energy is of central importance to all living things. There are many activities and processes that sustain life and take place inside the cells of living things and energy is needed for them to take place. Such activities include synthesis of a large range of organic compounds, active uptake into cells of ions against concentration gradients between the cell and the environment, movement of part or the whole of an organism, and conduction of nerve impulses (figure 1.1).

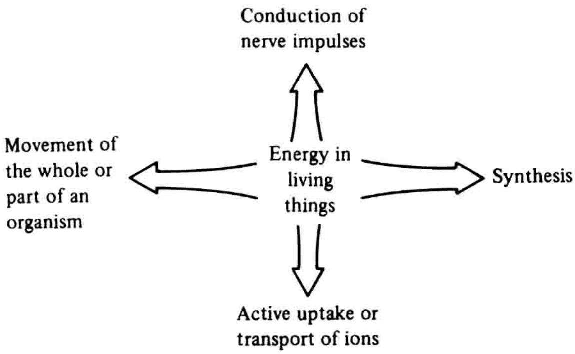

Figure 1.1

While the range of energy-demanding activities is large, many of the basic principles relating to energy are the same and the purpose of the first part of this book is to explore some of these principles.

Energy in the environment is often in a form that cannot be used by organisms. However, living things have the ability to convert unusable energy into forms that can be used in their cells and this is a fundamental requirement for life.

Thus in biology, energy is involved in processes where it is converted from one form into another. These energy-conversion processes are therefore very important and they are, in fact, fundamental to life. Photosynthesis and respiration are the two conversion processes and they supply energy in a form which can be used to drive the great range of activities in cells. Photosynthesis is the means by which an outside source of energy in the form of light or solar energy is converted to chemical energy in the cells of living plants. This provides the basis of the energy as well as the materials of all living things. Respiration begins with the food and energy made available by photosynthesis and converts this energy into a form that is readily usable and available within living cells (figure 1.2).

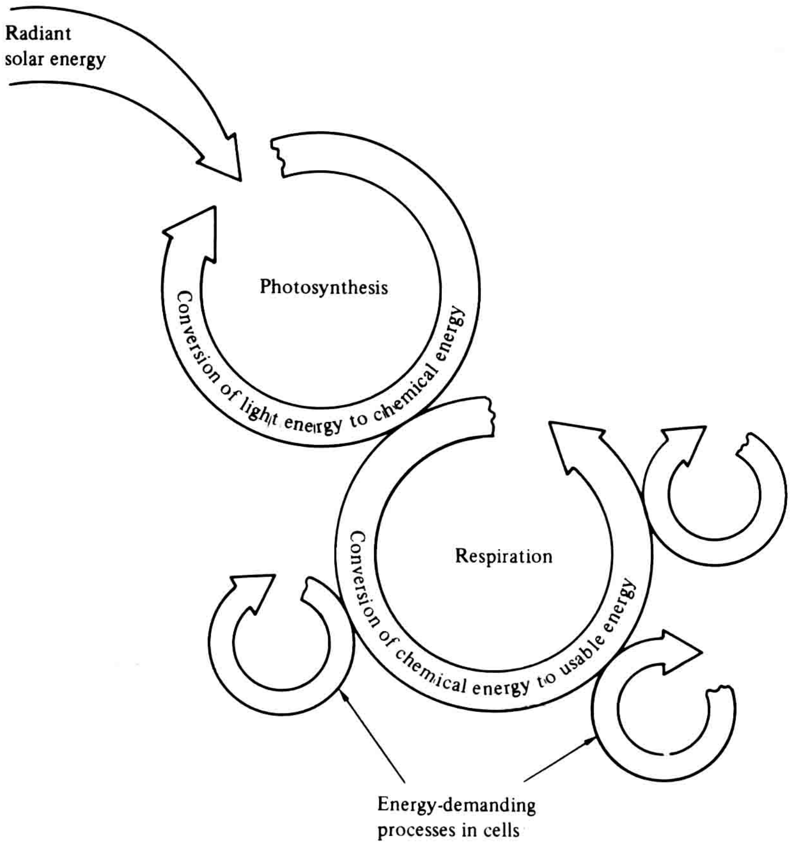

Figure 1.2

WHAT IS ENERGY?

Before we discuss the energy-conversion processes in biology, it may be helpful at first to consider some other aspects of the nature of energy and to mention some of its properties. Already some important things have been said about energy in the introduction, but further discussion is required.

Energy exists in a number of different forms such as light energy, mechanical energy and heat (figure 1.3).

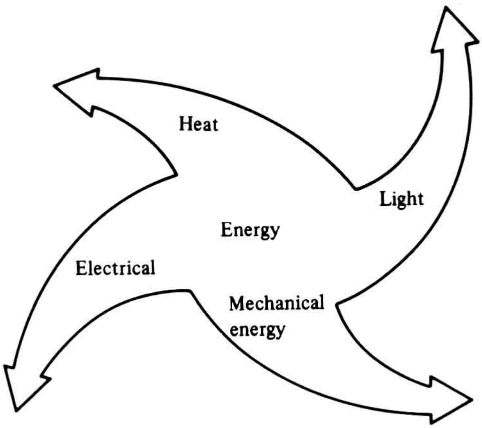

Figure 1.3

Simply speaking, energy would be defined by a physicist as 'the ability to do work'! For our purposes this statement is not very helpful and we need to delve more deeply into what is actually going on inside matter. First let us consider what is happening at the molecular level.

The atoms and molecules themselves show a number of different types of movement. This movement is often referred to as **kinetic energy**. For instance, molecules are moving about from one place to another in a random way, sometimes colliding with other molecules. This form of kinetic movement or energy is called **energy of translation**.

Also the electrons of the atoms in the molecules are moving by orbiting the nucleus of the atom; thus each electron of each atom has kinetic energy of its own. Not only are these forms of movement going on but also the atoms in the molecules are constantly vibrating relative to each other and the whole molecule is rotating as well (figure 1.4). There are thus three main types of movement involved. These atomic and molecular

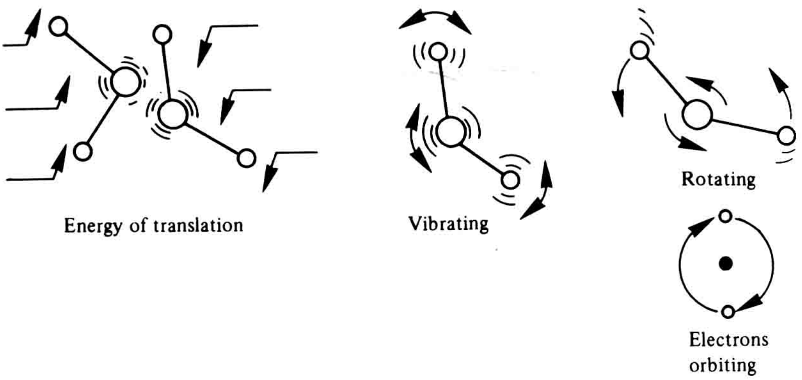

Figure 1.4 *Different types of kinetic energy.*

movements are greatest in gases, considerably less in liquids and even further reduced in solids. As temperature increases, so the molecular and atomic movements also increase and speed up.

The atoms which make up molecules are held together by forces of electrical attraction between the positively charged central nuclei of the atoms and the negatively charged electrons orbiting around it.

There are also forces of repulsion that exist within the same molecule between similar charged particles. These forces of attraction and repulsion are exactly balanced and they are therefore in equilibrium. Living things are able to accumulate essential chemicals within their cells. These chemicals are a form of stored energy which may be called **potential chemical energy**. The term 'potential energy' is often used. This means that when this equilibrium between the different forces is disturbed in a chemical reaction, energy is released or absorbed as a result of changes in the equilibrium. Thus when chemical bonds are broken or created, changes in the equilibrium occur which result in release or absorption of the energy within the cell.

The different forms of energy, such as light, mechanical energy and heat, are all the result of kinetic energy of the atoms and molecules. The calculation of the sum total of the energy, both potential and kinetic, of just a single molecule is an extremely difficult task, and even when it has been achieved it is not very useful. In the study of biochemistry we are much more concerned with the energy changes that go on when reactions take place rather than with absolute energy levels.

THERMODYNAMICS

This is rather an off-putting term and in the narrow sense it is used to mean the study of the relationship between heat and other forms of energy. However, in a more general way it relates to energy in all of its forms and it does have some useful things to say to biologists who want to understand the fundamentals of energy and its relationship to living things.

A major principle of thermodynamics is that one form of energy can be converted into another. This is an important idea in the study of living organisms because energy conversions are an essential process, as has already been mentioned.

The principles of thermodynamics further state that when energy conversions occur there is no net loss or gain of energy, but that in all such processes, at least some of the energy is converted into heat which then tends to be lost. A simple non-biological example of these principles is an electric light bulb. The bulb is an energy converter in which electrical energy is converted mainly to light, but some of the energy is converted into heat instead. The heat is lost to the surrounding environment (figure 1.5).

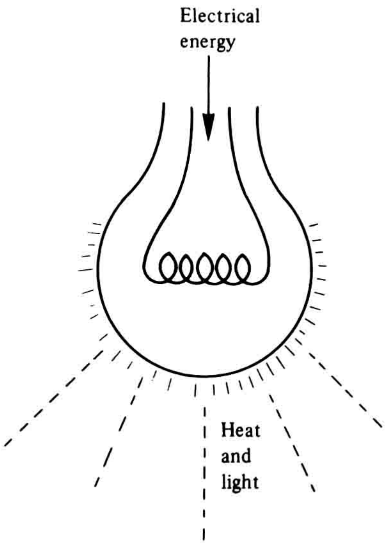

Figure 1.5

What we have considered so far can be summarised in the first and second laws of thermodynamics. The **first law** states that energy cannot be either created or destroyed. That is to say that there is no net loss or gain of energy in these reactions and also that the energy that you start with is equal to the amount that results from the reaction. The **second law** states that whenever an energy-conversion process takes place, then at least some of the energy takes the form of heat.

The scientist Joule developed a system of units which is used in thermodynamics and it can be used as a measure of all forms of energy. This means that these units can be usefully employed in energy conversion. The unit is the Joule and it is now the universal unit of energy, although in many texts you will often see calories quoted instead of Joules, especially in relation to diet and medicine (1 calorie is equal to about 4.2 Joules). The Joule is a very small unit and values often result from reactions which are measured in many thousands of Joules; thus the kiloJoule is often used (1 kJ = 1000 Joules).

As we have seen previously, the energy of organic molecules or compounds which is useful to living organisms is considered to be 'chemical energy'. This refers to the energy which is within the actual chemical bonds which hold the atoms together in the molecule. Compounds possess this chemical energy, which can be looked upon as potential energy, and this is released only when it is converted into other forms of energy, for instance heat. This bond energy has higher positive values for stable covalent bonds.

Heat is a special form of energy which, to all practical purposes, cannot pass from a colder to a hotter body. Therefore it will move in one direction only.

TYPES OF CHEMICAL REACTIONS

When a chemical reaction takes place, the molecules of the reactant are disrupted and the molecules of the product are formed (figure 1.6).

The energy changes that occur when chemical reactions take place are the result of changes in the relative positions of atoms in the molecules.

Chemical reactions are therefore accompanied by the production or absorption of heat. Where a reaction results in the loss of heat to the surroundings it is said to be **exothermic** and where heat has to be taken in it is then **endothermic** (figure 1.7). This change in heat content taking place during a reaction is called the change in **enthalpy** and it is given the symbol ΔH. When heat is given off, enthalpy is negative ($-\Delta H$) and energy is lost as heat. Most reactions that proceed spontaneously produce heat and

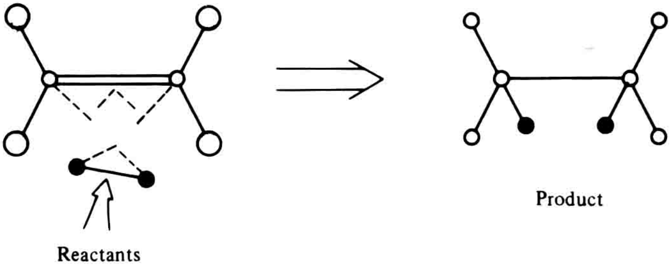

Figure 1.6

therefore have negative enthalpy. Endothermic reactions have positive enthalpy ($+\Delta H$). Thus enthalpy tells us something about the energy conversions that are going on. Absolute enthalpy (H) is a measure of the internal energy of a system; thus it is the total of the many energy constituents of that system. It is not a very helpful value even if it could be measured satisfactorily. All energy changes show heat changes in a reaction. Thus all reactions are characterised by heat changes. This is because energy changes are involved in all reactions and some of these energy changes take the form of heat, as was made clear when we introduced the second law of thermodynamics.

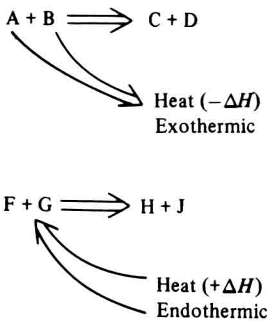

Figure 1.7

SYSTEMS

When discussing thermodynamics, scientists often refer to the situation within a 'system'. The term 'system' relates to the energy and materials