Basic Biology Course

8 Metabolism and Mitochondria

BASIC BIOLOGY COURSE
UNIT 3
REGULATION WITHIN CELLS

BOOK 8

Metabolism and Mitochondria

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Foreword

This book is part of a Basic Biology Course for undergraduates written by the Inter University Biology Teaching Project team at the University of Sussex.

It is the fourth in a series of five books (Books 5–9) comprising a unit called 'Regulation within Cells' (see outline of course structure). The book has three main aims.

(1) To provide you with an understanding of the principal metabolic reactions going on inside cells and how these pathways were elucidated and located.

(2) To illustrate some of the ways in which the cell co-ordinates and controls these activities.

(3) To show how food taken into the cell provides for both its structural and energetic requirements.

Brighton, Sussex, 1975

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* The Appendices have been abstracted from M. Tribe & P. Whittaker (1974). *New Movements in the Study and Teaching of Biology*, Chapter 1. Temple Smith, London.

Contents

Introduction

Discussion

It was thought at one time that living organisms possessed some mysterious 'vital force', which enabled them to do work contrary to physical (thermodynamic) laws. We now know that this is not so. Certainly it is true that living organisms are unusual in that they have the ability to maintain themselves in a higher energy state than the ground state (lowest energy level), *provided* that they have a constant input of energy. This input of energy is ultimately derived from sunlight, which can be trapped and converted into chemical energy by photosynthetic organisms (see Book 6, *Photosynthesis*). Animals and non-photosynthetic plants (heterotrophic organisms) must, however, rely on a food supply from photosynthesizing plants (autotrophic organisms) to meet the energy demands of their cells. The conditions are that the supply of energy, in the form of food, must more than balance the organism's energy output. If it does not, the living system will soon break down and die, since the organism is no longer able to maintain the higher energy state. Thermodynamic laws are, therefore, obeyed by living organisms, since energy is transformed from one form to another in maintaining the higher energy state. When the organism dies disorganization ensues and entropy in the system increases (as predicted by the second law of thermodynamics; see Book 7, *Enzymes*).

Essentially this book is about energy transfer inside cells and how it is controlled. This has been a major area of research for the past fifty years, although the emphasis has shifted from the elucidation of biochemical pathways and their location in the cell to the control of these pathways and their association with specific organelle substructures. It is the confluence between biochemistry and cell biology.

The general term employed for all the biochemical reactions going on inside cells is *metabolism*; and it has two main aspects: *anabolism*, the synthesis of macromolecules from smaller molecules with an input of energy, and *catabolism*, the degradation of macromolecules to smaller molecules with release of energy. In these reactions, energy transfer between molecules occurs in two ways; (i) by the transfer of electrons and, (ii) by transfer of chemical groups, particularly phosphate groups, between molecules.

The conservation and transduction of energy is necessary for cellular work, such as the synthesis of new cell constituents (growth), osmotic work or active transport. It is also connected with particular activities like cell division, nervous conduction or muscular contraction. Yet in all these aspects, energy must be channelled and controlled with careful precision. The cell is not simply a flexible bag full of chemicals. It is a highly sophisticated and highly organized structure where control is exhibited through compartmentation by membranes (Book 5), by allosteric control of enzymes (Book 7) and by thermodynamic and feedback control. These control mechanisms will be given special attention in this book, which also attempts to set out the gross features of metabolic processes. The emphasis throughout is on function and general chemical characteristics rather than the detailed presentation of chemical formulae and reactions. Some attention is given to structural changes in mitochondria in the last part of the book.

Preknowledge requirements

This book presumes: (i) a biochemical knowledge of biological membranes and transport of metabolites across cell membranes as given in Book 5; (ii) a knowledge of the light-dependent and light-independent reactions of photosynthesis as given in Book 6; (iii) a knowledge of reaction rates, equilibria, standard free energy changes and catalysis as given in Part I of Book 7; and (iv) a knowledge of enzyme structure, enzyme function and control as given in Part II of Book 7.

Elementary biological knowledge of the location of the liver and kidneys within a mammal is presumed, together with an understanding of how these organs are concerned with excretion (although this is by no means their only function).

Knowledge of cell fine structure, particularly the structure of mitochondria as revealed by electron microscopy (Book 2).

Instructions on working through programmed text

In the programmed text, questions and answers are arranged sequentially down the page. You are provided with a masking card and a student response booklet. All the book except the Introduction and Appendices are programmed. Cover each page in turn, and move the masking card down to reveal two thin lines

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This marks the end of the first question on that page. Record your answer to the question under the appropriate section heading in the response booklet provided. Then *check* your answer with the answer given. If your answer is correct, move the masking card down the page to the next double line and so on. If any of your answers are incorrect, retrace your steps and try to find out why you answered incorrectly. If you are still unable to understand the point of a given question, make a note of it and consult your tutor. The single thick line

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is a demarcation between one frame and the next. *Intermissions* in this book are convenient stopping and starting points in the programme, since it is unlikely that you will have time to read through the whole book in one session. Always read the appropriate Intermission again before going on to a new section. Additional stopping points are marked by bold double lines.

Overview

The book is conveniently divided into three parts:

Part I Metabolic overview and glycolysis
Part II Aerobic catabolism and interconvertibility
Part III Regulation and the role of mitochondria

At the back of the book there is a pull-out sheet showing an overall view of some of the major metabolic pathways. The pathways included are those directly relevant to this book and you will be advised when to use this metabolic chart as you work through the text.

There is also a tape/slide sequence accompanying this book, which is an integral part of Part III.

Part I Metabolic overview and glycolysis

Objectives to Part I

At the end of Part I you should be able to:

(1) Define all terms in the Glossary relating to Part I, except specific chemical formulae.

(2) Show that metabolism is essentially a three-stage process in which macromolecules are synthesized from basic organic building-block molecules and may eventually be degraded again to simple inorganic materials with release of energy.

(3) Describe in outline the common features (notably the cofactors and coenzymes) and end-products of glycolysis and fermentation respectively.

(4) Describe how specific metabolic inhibitors have been used to elucidate the reaction sequences in glycolysis and fermentation.

(5) Show that it is the sugar phosphates or phosphorylated intermediates rather than their unphosphorylated forms which are reactive in the glycolytic and fermentation sequences.

(6) Demonstrate how standard free energy changes (ΔG°) obtained from in-vitro measurements of individual reactions enable you to predict the overall equilibrium position of the glycolytic sequence.

(7) Relate ATP synthesis to ΔG° and indicate where phosphate-group transfer in glycolysis gives rise to a net production of 2ATP molecules per mole of glucose.

(8) Correctly interpret reported, graphical or numerical data related to metabolic pathways.

A metabolic overview

1 The organization of cellular systems depends on large molecules in a number of ways. The previous three books were devoted to examining three of these:

(1) the physical compartmentation of cells and organelles by membranes (Book 5);
(2) the capture and storage of energy via photosynthesis (Book 6);
(3) the controlled catalysis of chemical reactions by systems of enzymes (Book 7).

The following book (Book 9) will be concerned with yet a fourth:

(4) the storage and control of information.

With which of these functions are the following types of large molecule associated? (Some are associated with more than one.)

(*a*) Polysaccharides or carbohydrates
(*b*) Proteins
(*c*) Lipids or fats
(*d*) Nucleic acids

(*a*) with (2)
(*b*) with (1), (3) and (4)
(*c*) with (1) and (2)
(*d*) with (4)

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2 Each of these large molecules, or macromolecules as they are often called, is constructed from a particular type of small molecule by a chain of covalent bonds. Which type of macromolecule is constructed from each of the following types of molecular building-block?

(*a*) Amino acids
(*b*) Fatty acids and glycerol
(*c*) Sugars
(*d*) Mononucleotides

(*a*) Proteins
(*b*) Lipids
(*c*) Polysaccharides
(*d*) Nucleic acids

---

3 How are these *building-block molecules* obtained by green plants?

By photosynthesis from low-molecular-weight inorganic material (water, carbon dioxide, nitrate, phosphate, sulphate, etc.).
Non-green plants (e.g. fungi) have to ingest their food in the form of soluble (low-molecular-weight) organic compounds.

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4 Suggest three routes by which building-block molecules might be obtained by animals.

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(1) By ingestion as food; some sugars are already present in food in small quantities.
(2) By degradation of their parent macromolecules, which are either ingested as food (e.g. starch, protein) or retrieved from storage (e.g. glycogen, fat).
(3) By synthesis from smaller molecules.

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5 Although there is no overall synthesis of building-block molecules from smaller molecules in animals, there are mechanisms for the interconversion of building-block molecules which involve smaller molecules as intermediates. Why should such interconversion be necessary?

The chances of the right kinds of building-block molecule being available at the right time and in the right quantity are very slender indeed. This applies not only to the overall balance between amino acids, nucleotides, fatty acids and sugars, but also to the balance between different kinds of amino acid and different kinds of nucleotide. If shortages are to be avoided and a controlled flexible system maintained, there must be some interconvertibility between building-blocks. (Just imagine the demands on an organism's feeding pattern if there were no interconvertibility!)

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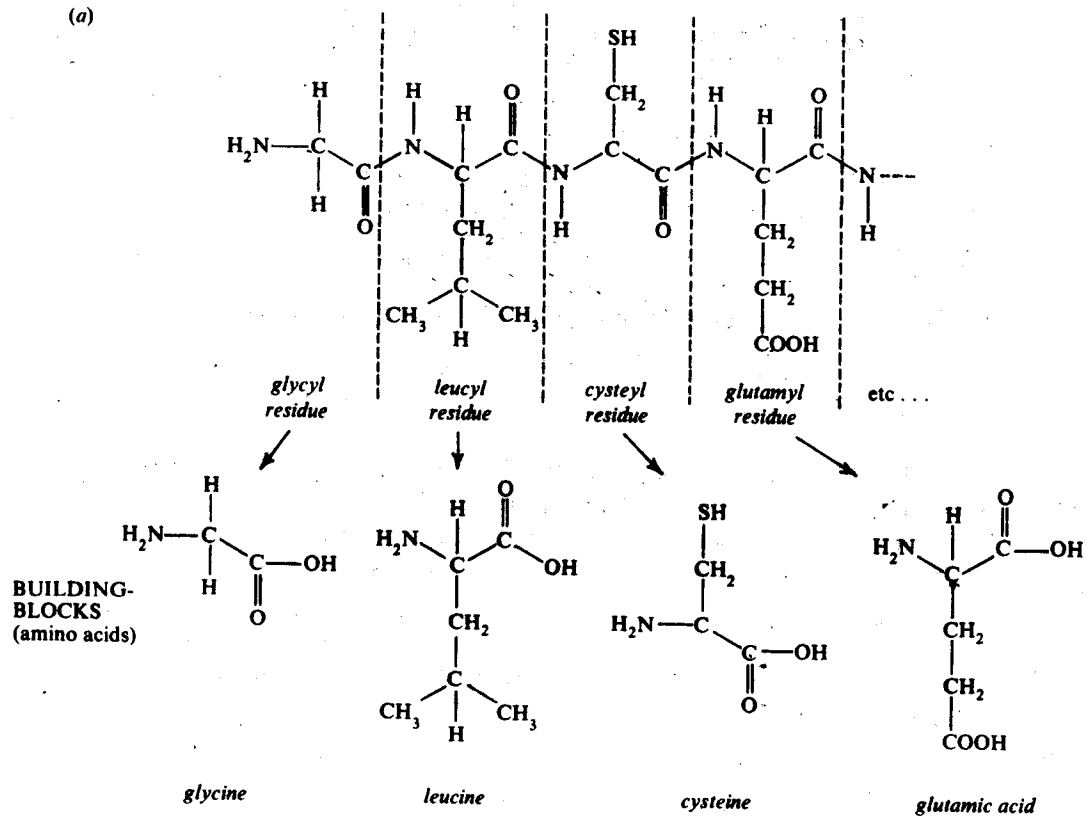
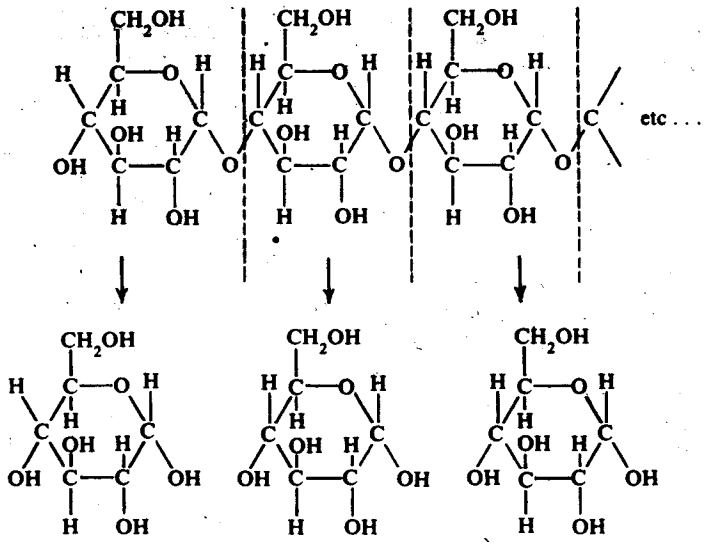
6 Below you see (*a*) part of a polypeptide chain in a protein, and (*b*) part of a starch molecule.

(*a*)



(*b*)



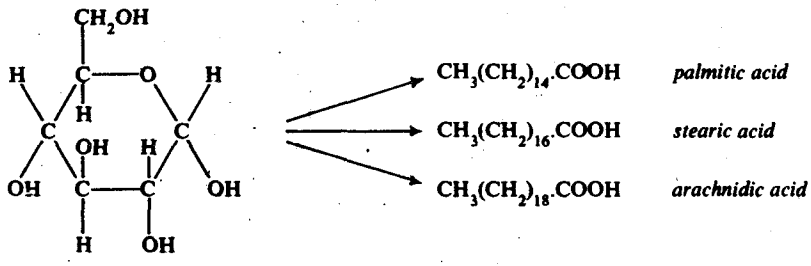
In changing these macromolecules into their respective building-block molecules, i.e. amino acids and hexoses respectively, (i) what types of bonds are broken and, (ii) by what mechanism?

(i) C – N bonds (polypeptide ⟶ amino acids)
C – O bonds (starch ⟶ hexose sugars)
(ii) By hydrolysis
Similarly, in changing the building-block molecules back to their parent macromolecules, water can be removed and C – N or C – O bonds formed.

7 What energy changes would take place in (*a*) the change from macromolecules to building-block molecules, and (*b*) building-block molecules to macromolecules?

Energy is (*a*) *released* when macromolecules are degraded into building-block molecules of smaller molecular weight, and (*b*) *consumed* when building-block molecules are synthesized into macromolecules.

8 However, in converting glucose into one of the three fatty acids shown below, there is a different problem:

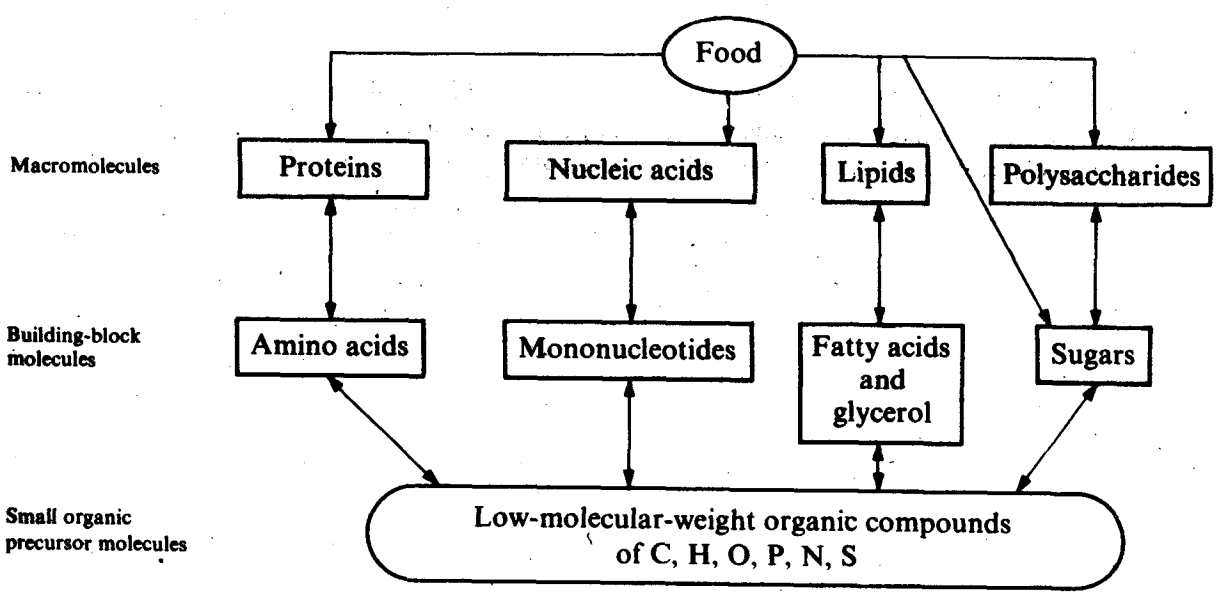


α-glucose

Firstly, the three fatty acids contain longer carbon chains than glucose, so there must be some C – C bond formation. Secondly, only stearic acid with eighteen carbon atoms can be made from an exact number of glucose molecules, so smaller molecules must be involved as intermediates, and there must be some breaking of C – C bonds.
Could the same molecule be a precursor (see Glossary) for all these fatty acids, or would they require different precursors?

A common precursor would be possible if it was small enough (i.e. containing no more than two or three carbon atoms); otherwise a variety of precursors of different sizes would be necessary.

9 In animals, therefore, we have the following picture:



All these processes constitute what we call *metabolism*, and they can be divided into two types:

(1) *catabolic processes* which involve the degradation of food to *provide energy* and raw materials for biosynthesis;

(2) *anabolic processes* which synthesize building-block molecules and macromolecules and *consume energy*.

What evidence do you have that catabolic processes go beyond the small organic precursor stage, i.e. that even these precursors undergo further degradation?

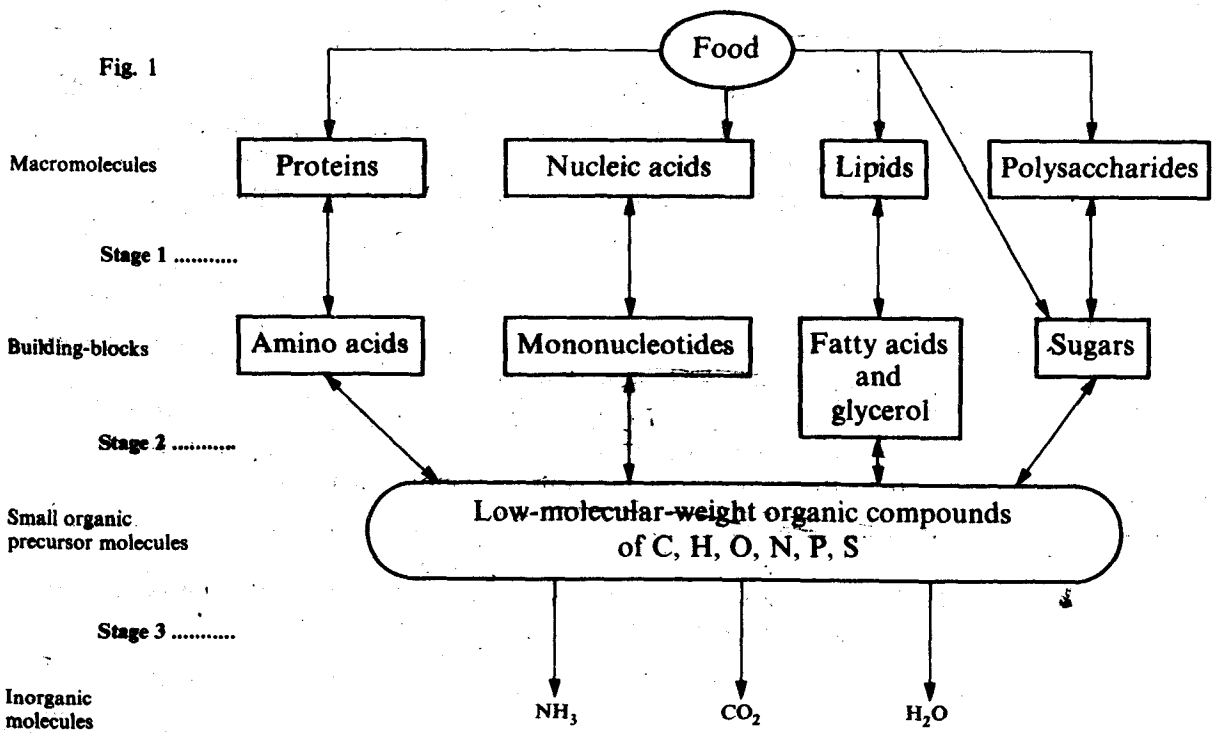
That in respiration by plants and animals carbon dioxide and water vapour are emitted and lost

10 What do you think is the advantage of respiration if it is responsible for removing useful raw materials from the system?

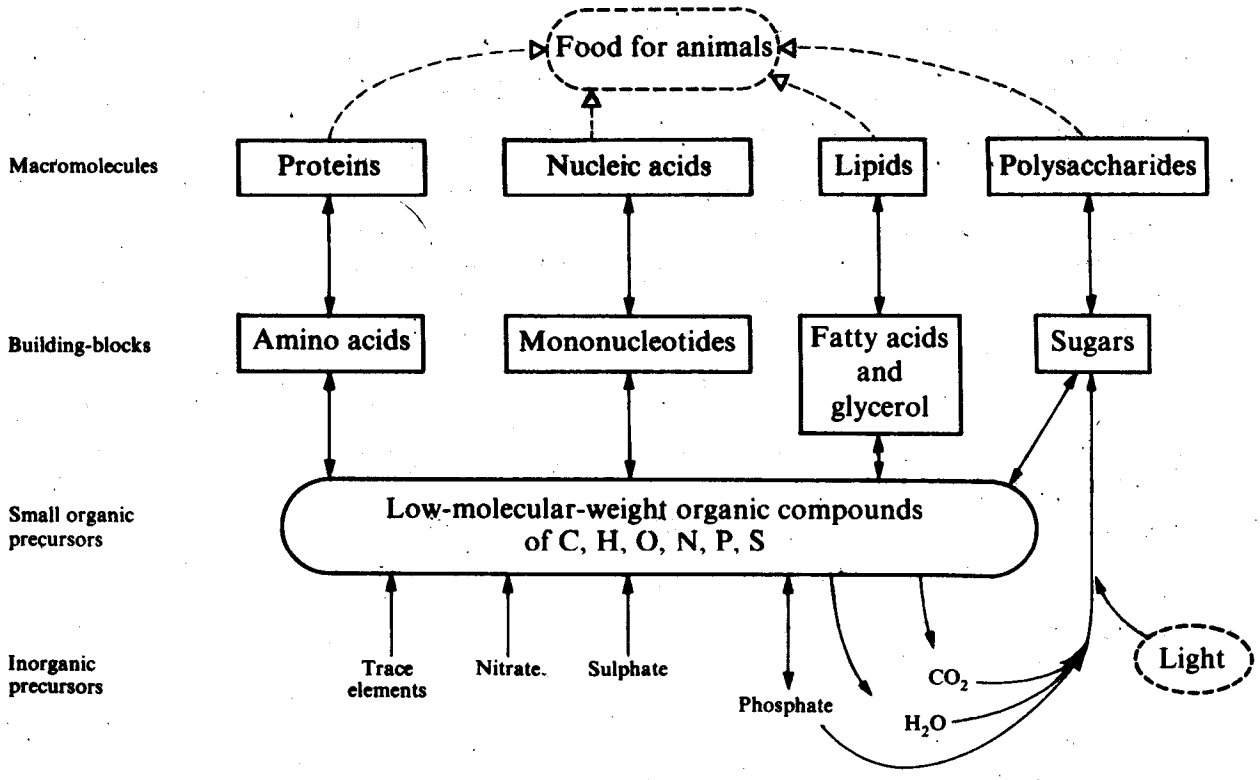
It releases energy

11 Our picture of animal metabolism has now expanded as follows:

Fig. 1



Using the knowledge gained in **Books 4** and 6, draw the corresponding diagram for plants.



12 Characterize the following processes in fig. 1 above (frame 11) by their effects on the supply of energy and biosynthetic precursors.

(*a*) Stage 1 anabolism (*c*) Stage 2 anabolism
(*b*) Stage 2 catabolism (*d*) Stage 3 catabolism

(*a*) Consumes energy (indirect consumption of small organic precursors via building-block molecules)
(*b*) Releases energy and provides more small organic precursors
(*c*) Consumes energy and consumes more small organic precursors
(*d*) Releases energy and consumes more small organic precursors

13 For what other purposes besides biosynthesis do living things need to consume energy?

(*a*) Transport; (*b*) movement; (*c*) growth
(There are also some less important ones which we have not yet discussed.)

14 Why would you not expect the transfer of energy between these processes to be 100% efficient? (Two reasons.)

(1) Because a dynamic, organized system is bound to lose energy as entropy (it uses energy merely to maintain its state of organization)
(2) Because, as in all other energy transfers, energy is lost as heat

15 In unicellular organisms all these processes take place within a single cell and all the energy consumed in biosynthesis and movement has to be provided elsewhere in the same cell. But in most multicellular organisms specialization results in some cells, e.g. root cells in plants and muscle cells in animals, being predominantly consumers of energy. In what forms might this energy reach them? (Refer to stages in fig. 1 again.)

Either in the form of organic precursors, which can release energy through Stage 3 catabolism; or in the form of building-block molecules, which can release energy through both Stage 2 and Stage 3 catabolism. Most macromolecules are too large to be transported across membranes.

16 Examination of animal blood and plant sap shows that transport of molecules between cells is mainly in the form of building-block molecules, especially sugars and amino acids. In animals, fats are the only macromolecules to be transported; they are degraded to fatty acids during digestion and reconstituted as relatively low-molecular-weight fats before entering the bloodstream. Can you suggest *two* main advantages of transportation at the building-block level rather than at the precursor level?

You should have thought of two of the following:
(1) More energy is transported per molecule.
(2) On arrival at their destination building-block molecules can quickly be converted to either macromolecules (for function or energy storage) or biosynthetic precursors (for conversion/storage or energy provision).
(3) In animals digestion need only be concerned with the cleavage of C – O and C – N bonds. If degradation of building-block molecules were required, digestion would have to break C – C bonds, a more complicated process which requires careful control.