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Bio. Sci. 4 - Microbiology
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Characteristics of Life and Biochemistry

Microbiology is the science or study of microscopic life forms, and these, like all other living organisms have a number of characteristics in common that can be used to distinguish them from non-living materials. These **characteristics of life** include the **ability to reproduce** (both sexually and asexually), the **ability to carry out metabolic processes** and to **grow by assimilation**, the ability to **respond to environmental stimuli** (both external and internal), the **ability to mutate**, and the ability to **maintain a high degree of organization**.

Reproduction is a characteristic common to all living organisms, because living cells arise only from preexisting living cells (**biogenesis** as opposed to **abiogenesis**). Most microorganisms reproduce themselves by a process called **fission** that involves the division of one cell into two new cells (daughter cells). This form of reproduction is considered to be **asexual** because it does not involve a reorganization of the genetic material present. The daughter cells formed are genetically identical to the original cell. Most, if not all, organisms also engage in some sort of **sexual reproduction**. This involves the reorganization of genetic materials and results in the formation of genetically unique individuals.

Growth by **assimilation** is another characteristic common to living organisms. Assimilation is the process organisms use to take in materials from their environment, break them down, and then reorganize them into new cellular components. Assimilation involves **metabolism**, another characteristic of living organisms. Metabolism can be defined as all the chemical reactions that take place within living organisms, and includes both **catabolism** (breakdown reactions) and **anabolism** (building reactions). Although growth typically involves an increase in size and weight, the growth of living organisms also involves an increase in cell numbers, so involves reproduction. Microorganisms such as bacteria and yeasts, when maintained under certain conditions (typically on solid media), grow from single cells into masses of cells called colonies. These represent populations of cells in the millions or billions. Although an individual bacterium or yeast cell is not visible to the naked eye, a colony is readily visible (is **macroscopic**).

Another characteristic of living organisms is **response** to environmental stimuli or changes in their environments both internal and external. Responses that are rapid may be referred to as **irritability** or **behavior** and typically involve movement. Many microorganisms move through their environment in response to stimuli such as light, temperature, chemicals, magnetic fields, and/or gravity. This type of response is often clearly visible to the naked eye. Response to environmental change that occurs slowly may be referred to as **adaptation**, and may be less readily observed. Many microbes form specialized cell types that allow them to survive unfavorable conditions such as the heat and dryness of summer or the freezing temperatures of winter. Adaptations that appear as changes in populations over many generations involve reorganization of genetic materials due to sexual reproduction and **mutation**, changes in the composition of nucleic acids (DNA and RNA). These adaptations are often visible as specialized structures, behaviors, or abilities and are indicative of **evolution,** i.e., changes in populations over time.

The complex structure of even the simplest living organism represents a high degree of organization. The material that cells are made of contains billions of **atoms** (**elements**) arranged into simple and complex **molecules** (**compounds**) that interact continuously in metabolic processes. Organisms must expend a tremendous amount of energy to maintain their organization, and without it, their life processes will stop.

The Composition of Protoplasm

Protoplasm may be defined as living substance, or as the chemical and physical basis for life. It is a dynamic, changing material and is what all cells are made of. One way to visualize protoplasm is to think about a boiling soup that is constantly being added to and taken from. Imagine the contents of that soup.

The smallest particles of protoplasm we are concerned with are the **atoms** or **elements**. There are thirteen different elements that make up approximately 99% of all living organisms (by weight). These can be arranged into a pattern that makes them easy to remember as follows: **C**, **H**, **O**, **P**, **K**, **I**, **N**, **S**, **Ca**, **Fe**, **Mg**, **Na** and **Cl.** These may be remembered as C HOPKINS CaFe, Mg (mighty good) but you also need salt (NaCl). Though handy, this sequence is not always accurate since many cells also use other elements such as copper, zinc, manganese, silica, and molybdenum, though these are present in very small amounts. Of those listed above, certain elements are more important than others. The five elements, C, H, O, N and P are said to make up about 96% of the weight of living organisms.

Living organisms cannot convert one type of element into another, but they do carry out metabolic processes in which elements combine to form a wide variety of **molecules** or **compounds**. This is where a high degree of organization comes into play. **Molecules** are combinations of atoms joined together by chemical bonds.

Water - an essential compound

Water is an inorganic compound that is essential to life as we know it. It is a major component of protoplasm in all types of cells. A molecule of water contains two atoms of hydrogen and one atom of oxygen ($\mathbf{H_2O}$). Water has a number of features making it essential to living organisms including:

1. Water is made up of **polar molecules** (those having an unequal distribution of charge) and so is an important **solvent** (many types of **solute** will dissolve in it). It is also involved in many chemical reactions. Reactions that involve the splitting of organic compounds by adding water to them are called **hydrolysis reactions** (hydro = water, lysis = to split). Hydrolysis can be used to break down a wide variety of organic compounds. Reactions that involve the formation of larger molecules by removing water are called **dehydration synthesis** or **condensation reactions**. Macromolecules such as proteins, polysaccharides and nucleic acids are formed in this way.

2. Water is liquid, so is **essential to transport**. It allows materials to be moved readily within cells, and allows cells to move through a variety of habitats.
3. Water **helps to maintain cell size and shape**. It moves freely through most cell membranes and has a high surface tension due to cohesion between water molecules.
4. Water **resists temperature change**, and plays an important role in temperature regulation in macroscopic organisms (such as ourselves). It also influences weather and climate.
5. Water with ions in it can **conduct electricity**. This feature is important in various life processes, and is useful in the laboratory during electrophoresis experiments.
6. Water as a solid is less dense than it is as a liquid, so **ice floats**. Imagine what our world would be like if it didn't.

Water accounts for the bulk of protoplasm (usually around 70%) and provides a background matrix for the support of other materials. Certain substances (**electrolytes**) will dissociate in water to form charged particles called **ions**. Table salt (NaCl) is one of these. When table salt is dissolved in water each sodium atom gives up one electron to form a positively charged particle called a **cation** (Na^+) and each chlorine atom takes on one extra electron to form a negatively charged particle called an **anion** (Cl^-). These charged particles play important roles within cells. Some important cations include: Na^+, K^+, Ca^{++}, Mg^{++} and Fe^{++} , while some important anions include: Cl^-, $HCO3^-$ and OH^-.

Some Important Types of Organic Compounds

Organic compounds are those containing carbon (with the exception of CO, CO_2, and HCO_3^-) and are generally larger and more complex than inorganic compounds. Some organic molecules are very large (macromolecules) being composed of one thousand or more atoms. Such molecules are generally composed of repeating smaller units and so are called **polymers** (poly = many).

For note taking purposes, the major groups of organic compounds are indicated in different colors. This will make it easier for students to keep track of them as they occur in cellular structures.

Carbohydrates (sugars and starches) – Color these pink or red

The carbohydrates are organic compounds made up of the elements C, H, O, and sometimes N. (A variety of specific molecular structures are shown in the text.) If they are simple sugar molecules, they are called **monosaccharides**, and may contain three, four, five, six or seven carbon atoms. These are referred to as triose, tetrose, pentose, hexose or heptose monosaccharides, respectively. For our purposes the **pentose** and **hexose** monosaccharides are the most important. These can exist in cyclic forms and are often represented visually as rings.

Hexose monosaccharides typically have the molecular formula $C_6H_{12}O_6$, and include glucose, fructose, galactose, and mannose. The **pentose monosaccharides** typically have the molecular formula $C_5H_{10}O_5$ and include arabinose, rhamnose, ribose and deoxyribose (note that the last one does not have the typical formula because it is missing an oxygen).

When sugar units bond to other molecules having hydroxyl groups they form **glycosides**, and the bond between the two molecules is called a **glycosidic linkage**. When two monosaccharides bind together via a glycosidic linkage, they form a pair of sugar units called a **disaccharide**. (The process involves the removal of a water molecule, so is a dehydration synthesis reaction.) The three most common of these are: lactose (milk sugar) which is glucose + galactose, maltose (two glucose molecules), and sucrose (table sugar) which is glucose + fructose. If three monosaccharides are joined together they form a short chain known as a **trisaccharide** (two water molecules are removed). Raffinose is a trisaccharide made up of glucose, galactose and fructose. All sugar molecules have some characteristics in common. They are sweet to the taste and soluble in water.

Chains of four to six sugar units may be referred to as oligosaccharides, but more commonly these join to form long chains containing many sugar units, or **polysaccharides**. These are macromolecules and are sometimes huge. The most common polysaccharides are starch (the storage product of plants), glycogen (the chief storage product in animals), cellulose (the primary structural component of wood) and agar (which we use as a solidifying agent in our culture media). Polysaccharides are not sweet to the taste and are not soluble in water, so are ideal for storage.

Carbohydrates are quantitatively the most common biochemicals found. They serve as an important source of energy to maintain metabolic functions. They are also involved as structural components supporting materials within cells and can bind with proteins to form **glycoproteins** involved as receptor sites on cell surfaces.

Proteins (enzymes, antibodies, flagellins, etc.) – Color these blue.

Proteins contain the elements C, H, O, N and sometimes S. They are macromolecules or polymers composed of many, small repeating units called **amino acids**. There are twenty different types of amino acids typically found in nature although bacteria contain a few unusual types not found in proteins. Amino acids are all similar in structure in that they all possess a **carboxyl group** (COOH) at one end and an **amino group** ($-NH_2$) at the other. The remainder of the amino acid structure is variable. Amino acids are bounded to one another by covalent bonds called **peptide bonds**. The formation of each peptide bond requires the removal of one water molecule, so again involves dehydration synthesis. When many amino acids are bound together, the result is a long string of peptide bonds, or a **polypeptide**. This may or may not form a complete protein.

All proteins are made of amino acids, but they are not all the same. The most important factors making one protein different from the next is the number of amino acids present, and more importantly the sequence in which they are arranged. This is referred to as the **primary structure** of the protein. The type and arrangement of amino acids in proteins allows for tremendous variation, just as the type and arrangement of letters makes up variation in words. Proteins are considerably longer than words however, with some of the smallest being around 500 amino acids in length. Proteins do not usually remain as long strands, but instead tend to roll up in very specific ways. This gives them additional structure as follows:

Primary structure = sequence of amino acids present

Secondary structure = development of a helix or pleated sheet due to hydrogen bonding between amino acids.

Tertiary structure = folding of a protein into a globular form. Some amino acids contain thiol groups (-SH) capable of forming disulfide bonds or cross-bridges (S-S) between amino acids. The tertiary structure of a protein is loosely stabilized by hydrogen bonds, and held more firmly by the disulfide bridges. Much of its surface structure is changeable, a factor important to enzyme function. Such changes are called allosteric changes. The difference between a normal brain protein and an infective agent known as a prion (etiological agent of mad cow disease) is a change in three-dimensional configuration or tertiary structure.

Quaternary structure = when a protein contains more than one polypeptide chain. Many proteins are functional only as complexes of several polypeptide chains. The quaternary structure is this complexing. The various chains are held together by disulfide bridges and by hydrogen bonds.

Because of their globular structure, most proteins tend to have polar surface groups, and so are externally **hydrophilic** (water loving), while their internal portions are **hydrophobic** (water fearing). Proteins then, are like phospholipids in that they are amphipathic or amphiphilic (see lipid section below).

Proteins are important structural components of cells occuring in cell membranes, microtubules, fibrils, ribosomes, flagella, etc. Other types are functional proteins such as enzymes (the catalysts for chemical reactions within cells), hemoglobin, hormones, antibodies, etc. Proteins may also be catabolized and so serve as a source of carbon and energy.

Lipids (fats, oils and waxes) – Color these yellow.

Lipids always contain C, H and O, but often include smaller amounts of elements such as P and N as well. Lipids as a group are soluble in organic solvents rather than water, so are said to be **hydrophobic** (water fearing). Some important groups of lipids include fats, oils, waxes, phospholipids and steroids.

Fats and oils are structurally **triglycerides** (complexes composed of three fatty acid molecules attached to a single molecule of glycerol). The fatty acid chains are either **saturated** or **unsaturated** depending on the number of hydrogen atoms they contain. Saturated fatty acids contain a maximum number of hydrogen atoms while unsaturated forms are missing some. The reduction in hydrogen is due to the presence of double (or sometimes triple) bonds between carbon atoms. If there are two or more double bonds formed between the carbons present within a fatty acid, it is said to be **polyunsaturated**. Fats tend to be saturated, and are usually solid at room temperature while oils are unsaturated and are liquid. Most fats and oils are actually mixtures of various types of triglycerides. Waxes have a structure similar to triglycerides, but the alcohol involved is much larger. Some examples of waxes include beeswax, carnuba and lanolin.

Phospholipids are similar to triglycerides except that in these molecules one fatty acid chain is replaced by a polar phosphate group. This is a very important factor since it influences how the phospholipid molecules react with water. The polar phosphate is hydrophilic (water loving) while the fatty acid chains are **hydrophobic** (water fearing). The result is a molecule that loves and suffers in two different types of environments. Such molecules are said to be **amphipathic** or **amphiphilic** (amphi = two ways or both ways, pathos = suffering, and phil = love). Phospholipid molecules play a major role in the structure of cell membranes where they form an interface between water and lipid layers.

Steroids are lipids with ring-form structure. They do not contain fatty acid chains. Cholesterol and cortisone are examples of steroids. Lipids serve as important structural components of cells (as in cell membranes), as insulation and as hormones. Lipids can also be broken down and utilized as an energy source.

Nucleic Acids (DNA and RNA) – Color these violet.

The **nucleic acids** are the molecules that carry the genetic information within cells (and also within viruses and viroids). There are two major types, **deoxyribonucleic acid** (**DNA**) and **ribonucleic acid** (**RNA**). Like proteins and polysaccharides, the nucleic acids are long chain molecules (**polymers**) made up of many smaller units. The smaller units in this case are called **nucleotides**. Each nucleotide contains a pentose monosaccharide (either ribose or deoxyribose), a phosphate group, and one nitrogenous base. The nitrogenous bases vary, and may be adenine, guanine, cytosine, or thymine (in DNA) or uracil (in RNA). Adenine and guanine are called purine bases (or purines) while cytosine, thymine and uracil are called pyrimidine bases (or pyrimidines). The structural differences between DNA and RNA as well as their function within cells will be covered extensively later.

Nucleotides have a number of important functions within cells as follows:

1. When joined within polymers they form the nucleic acids that carry genetic information (DNA and RNA).

2. Individually they can be used as a form of "**energy currency**". Nucleotides that have three phosphate groups instead of one are called **nucleoside triphosphates** (NTPs) or activated nucleotides. These high-energy compounds are essential to cell function. The most commonly encountered nucleoside triphosphate is **adenosine triphosphate** (**ATP**), but it is not the only one.

3. Nucleotides can be used to form molecules known as **coenzymes**. These serve as electron carriers in association with metabolic processes. Two important coenzymes are **NAD** (nicotinamide adenine dinucleotide) and **FAD** (flavin adenine dinucleotide), both of which are B-complex vitamins.

4. Ring-form nucleotides sometimes serve as **regulatory molecules**. They interact with proteins and regulate a variety of cellular functions. Two important regulatory nucleotides are **cyclic-AMP** and **cyclic-GMP**.

There are many types of organic compounds not specifically included in this section. Some of these will be covered later in the section on metabolism. In addition to the major groups of organic compounds as described above, there are complexes formed by joining different types. Lipids and carbohydrates can join to form **lipopolysaccharides** or **glycolipids**, proteins and lipids can join to form **lipoproteins**, and proteins and carbohydrates can join to form **glycoproteins**.