Chapter 2
Life and Water

Water is an essential element for life. Life, especially extraterrestrial life is discussed in many textbooks. Astrophysical and astrochemical insights into the origin of life were reviewed by Ehrenfreund et al., 2002 [114] and Chyba and Hand, 2005 [68]. In this chapter we will outline how life can be defined and has evolved on Earth and the role of water for this process.

2.1 Life and Environment

2.1.1 The Importance of Water

In living organisms, water has a number of roles:

- solvent
- temperature buffer
- metabolite
- living environment
- lubricant—to minimize friction (e.g. synovial fluid is encapsulated within the joints).

The water amount in the human body constitutes about 60% of the body weight. Of this, 20% is extracellular body fluid which is made of 5% plasma and 15% tissue fluid. The tissue fluid and the plasma are in a steady state with the fluid inside the cells. There is a strict balance between water intake and water losses (homeostasis). In Fig. 2.1 the balance between daily water intake and water losses for the human body is given in percentages (from a total of 2.5 litres) per 24 hours.

2.1.2 Definition of Life

What are the differences between life and matter? This question appears very simple, however it is not. A philosophical review on that question is given by Gayon,

A. Hanslmeier, *Water in the Universe,* Astrophysics and Space Science Library 368,
DOI 10.1007/978-90-481-9984-6_2,

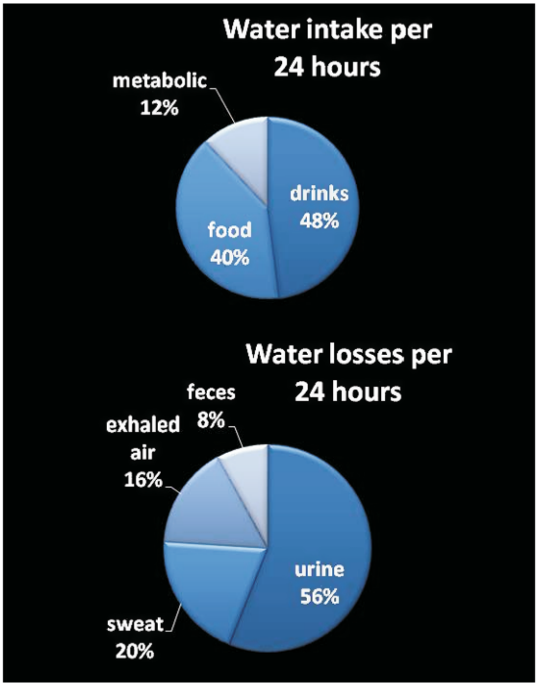

Fig. 2.1 The balance between water intake and water losses in the human body

2010 [138]. Aristotle defined life as animation, life can be also defined as mechanism or organization (Kant). Until very recently, viruses were not considered in discussions on the origin and definition of life. This situation is rapidly changing, and it has been recognized that viruses have played (and still play) a major innovative role in the evolution of cellular organisms (Forterre, 2010 [134]). Life scientists and chemists have not come to a conclusive definition of life. There are several characteristics for life as we know it from Earth:

- *Cells*: all living organisms consist of cells, there exist unicellular and multicellular organisms. A typical cell size is 10 μm; a typical cell mass is 1 nanogram. Cells mainly consist of cytoplasm bound by a very thin membrane. This membrane serves also as a protection against the environment. There exist basically two types of cells: prokaryotic and eukaryotic. The prokaryotic cells are simpler than the eukaryotic, they contain no nucleus. Bacteria are prokaryotic. The first cells appeared on Earth up to 3.8 billion years ago (see e.g. Mojzsis et al. 1996 [234]).
- *Growth and reproduction*: when organisms reproduce, the offspring resemble the parents. Cells must be able to divide. There are two mechanisms, the *mitosis* and the meiosis. For example, the human body loses about 50 million cells each seconds that must be replaced. In the mitosis genetic information is equally distributed to two daughter nuclei. During the crossing over, the chromosomes are aligned in the cell's equatorial plane, the DNA gets replicated. Each new cell gets one of the two daughter nuclei. In the process of *meiosis* which is essential for sexual reproduction and might have appeared first 1.4 billion years ago, one par-

ent cell produces four daughter cells (autocatalytic replication). Daughter cells contain half the number of chromosomes found in the original parent cell and with crossing over, are genetically different.

- *Response to stimuli*: a major characteristic of all living things. Plant responses to stimuli are generally much slower than those of animals.
- *Metabolism*: collective product of all the biochemical reactions taking place within an organism. New cytoplasm is produced, damage repaired and normal cells are maintained. Metabolism includes photosynthesis, respiration, digestion and assimilation. All these include complex chemical processes.
- *Movement*: also plants can move. Leaves of sensitive plants (e.g. Mimosa pudica) fold within a few seconds after being disturbed or subjected to sudden environmental changes.
- *Complexity of organization*: cells are composed of large numbers of molecules (usually more than 1 trillion in a typical cell). The molecules are organized into compartments, membranes and other structures in the cell. Bacteria are considered to have the simplest cells known, yet such a cell contains at least 600 different kinds of proteins and 100 other substances. Other organisms are more complex.
- *Adaption to the environment*: living organisms respond to their environment, to air, light, water, soil, etc. Natural selection leads to adaption to their environment. Today, many species are threatened with extinction because they are not able to adapt fast enough to the changing environment.

2.1.3 Evolution of Life

Nature has always worked bottom up, from the simplest assemblies to more complex structures. There exist many examples of self-organization in biology: spontaneous folding of proteins and other biomacromolecules, formation of lipid bilayer membranes but also social animals like social insects (bees, ants, termites), formation of flocks by birds etc. Molecular self-assembly is crucial to the function of cells: self-assembly of lipids to form the membrane, the formation of double helical DNA through hydrogen bonding of the individual strands etc. Molecular self assembly seems to be the key for the transition from non-living to living substances. The question is, however, what are the conditions of the environment (temperature, pressure, atmosphere, solvents) that are required that such a self assembly occurs.

In the 1950s it was assumed that the primitive Earth atmosphere consisted of methane CH_4, ammonia NH_3, hydrogen H_2 and water H_2O and S.L. Miller and H.C. Urey[1] carried out a famous experiment at the University of Chicago. They simulated the primitive Earth atmosphere and ran continuous electric currents simulating lightning storms, which were very common on the early Earth, to this environment. After one week, 10–15 amino acids were found in this primordial soup.

[1] In: Miller, S.L. "Production of amino acids under possible primitive Earth conditions", Science, 117, 528 (1953) and Miller, S.L., and Urey, H.C. "Organic compound synthesis on the primitive Earth", Science, 130, 245 (1959).

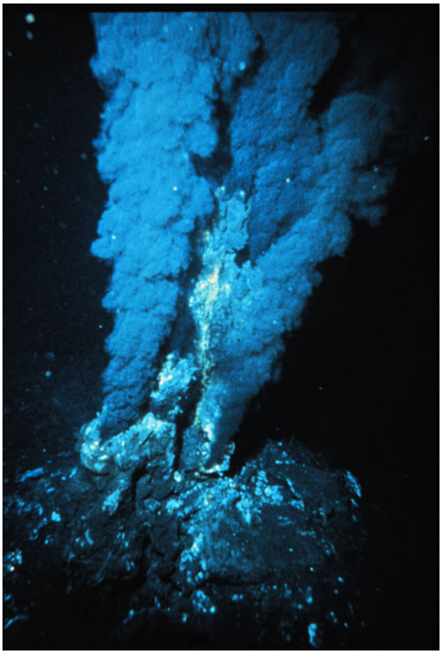

Fig. 2.2 Black smoker at a mid-ocean ridge hydrothermal vent. Credit: OAR/National Undersea Research Program (NURP); NOAA

Sagan and Chyba (1997) [287] proposed that the early Earth had an organic haze layer in its atmosphere. Such a layer can be found in the atmosphere of Titan, the largest satellite of Saturn and is produced by methane photolysis in the presence of nitrogen. An organic haze layer would preferentially absorb ultraviolet light, thereby allowing ammonia and methane to persist in the atmosphere.

In the 1970s black smokers (Fig. 2.2) were detected. These are chimney-like structures above hydrothermal vents.[2] In these smoker chimneys sulfides of iron, copper and zinc are found. At the mixture of the hot mineral rich water with cold water, these sulfides are precipitated and the vent water therefore appears black in color.[3] The most striking discovery was that these warm chemical rich environments are the living space for many species. Huber and Wächtershäuser, 1998 [166], modelled volcanic or hydrothermal settings. They showed that amino acids were converted into their peptides by use of precipitated (Ni, Fe)S and CO in conjunction with H_2S (or CH_3SH) as a catalyst and condensation agent at 100°C and pH 7 to 10 under anaerobic, aqueous conditions. Thus a thermophilic origin of life seems plausible.

Summarizing there are basically three different theories about where life has evolved on our planet: the primordial soup theory (Urey-Miller experiment), life has originated in the atmosphere (Sagan) and black smokers (hydrothermal vents). The primordial soup theory seems to be no longer acceptable without strong mod-

[2] Sometimes also called underwater geyser.

[3] Hydrogen sulfide H_2S is the closest chemical analogue of water.

ifications since the primitive Earth's atmosphere contained much less reducing molecules. It did not consist mainly of NH_3, CH_4 but most probably of CO_2, CO, N_2. In any case water played an important role by acting as a solvent for the different molecules.

In the early twentieth century S. Arrheniusdeveloped his panspermia hypothesis. According to this theory life might have originated somewhere in the universe and would have spread out automatically.

The origin of life seems to be strongly connected to the presence of water for another reason. The Sun emits also UV radiation which is extremely hostile to life. Today we are protected against this radiation by the Ozone layer. This layer was slowly formed when the plants enriched the atmosphere with free oxygen. At the time when the first cells developed (about 3.8 billion years ago), there was no UV protection because there was no free oxygen in our atmosphere. However water, liquid or as ice, provides a good protection against this radiation. Therefore, it seems logical that life originated in such an environment.

Because the early Sun was less luminous, the temperatures could have been lower on Earth. A global frozen ocean (several 100 m thick) could have provided an ideal shield against UV radiation.

A frozen Earth could also be the result of a close encounter of the solar system with a nearby passing star, when the Earth is expelled out of the solar system or at least to larger distances from the Sun. Adams and Laughlin, 1999 [3] showed that for some time due to radiogenic heating life would still be possible around hydrothermal vents. Nisbet and Sleep, 2001 [248], discuss early hyperthermophile life near hydrothermal systems. The development of anoxygenic and then oxygenic photosynthesis would have allowed life to escape the hydrothermal setting. By about 3 500 million years ago, most of the principal biochemical pathways that sustain the modern biosphere had evolved.

The construction of the basic building blocks for life (monomers) is easy to explain (extraterrestrial origin, Urey-Miller experiment, black smokers…). However, it is much more difficult to explain the formation of polymers out of monomers. According to Darwin's Soup theory, mixtures of monomers should produce polymers. For the process of polymer production water plays also a negative role in an aequous environment, hydrolysis transforms the polymers into their constituent monomers. By hydrolysis the water molecule H_2O is split into H^+ and OH^-.

In this context we also mention autocatalytic reactions. In such reactions, one or more of the products are the same as one or more of the reactants. For example

$$A + B \rightleftharpoons 2B \tag{2.1}$$

The rate equations are non linear. The non linearity can lead to the spontaneous creation of order out of chaos. In nature there are many examples for such processes. Out of the random motion of air molecules a hurricane can be formed where the molecules all follow a vortex motion. This does not stand in contradiction with the second law of thermodynamics. The order created by living systems on Earth is produced at the expense of the increasing entropy inside the Sun which provides the necessary energy.[4] In 1995 Stuart Kauffman proposed that life initially arose as autocatalytic chemical networks.[5]

2.1.4 Life Under Extreme Conditions

In many textbooks you will find that for life to exist, the presence of liquid water is a necessary condition. Even habitability is defined very often as the zone around a star in which, on a hypothetical planet, water can exist in liquid form.

However, there are organisms that live under extreme physical or geochemical conditions, the extremophiles. Most of them are microbes including representatives of all three domains (Bacteria, Archaea, and Eucarya). Some types of extremophiles are listed in Table 2.1.

As it can be seen from the table, there are organisms that live under extreme "dry" conditions: the endoliths live in microscopic space within rocks, halophiles need salt to grow, the endolithic or cryptoendolithic microorganisms thrive inside rocks or in the pores between mineral grains of a rock.

The hyperthermophiles were discovered in the 1960s in hot springs in Yellowstone National Park. The hyperthermophile *Strain 121* is able to survive a temperature of 121°C and even to double its population within 24 hours in such an environment. It consists of hyperthermostable proteins. Another example is *Pyrolobus fumarii*, an Archaea living at 113°C in Atlantic hydrothermal vents.

Autotrophs produce food from inorganic compounds, the heterotrophs use organic molecules as food. Some bacteria and some archaea have this ability.

But note that all these lifeforms consist of cells with cytoplasm, where water is an important part. The cytoplasm is the part of a cell that is enclosed within the plasma membrane. For example halophilic bacteria produce energy to exclude salt from their cytoplasm to avoid protein aggregation.

The detection of life under such extreme conditions makes us hope to find life also under the harsh conditions on our neighbor planet Mars.

Cavicchioli, 2002 [64] provided a review on extremophiles and the search for extraterrestrial life.

2.2 Water and Other Solvents

2.2.1 The Importance of Solvents to Life

Solvents are extremely important for the formation and maintaining of life. Their main properties are:

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[4]See also: Ilya Prigogine (1980). From Being to Becoming: Time and Complexity in the Physical Sciences. San Francisco: Freeman.

[5]Stuart Kauffman (1995). At Home in the Universe: The Search for the Laws of Self-Organization and Complexity. Oxford University Press.

Table 2.1 Some types of extremophiles

Name	Environment
Acidophiles	Live in pH levels ≤ 3
Alkaliphiles	Live in pH ≥ 9
Barophiles	Live under high pressure
Piezophiles	–
Endoliths	Live in microscopic spaces within rocks
Cryptoendoliths	Live in fissures, faults in deep subsurface
Halophiles	Need salt to grow
Hyperthermophiles	Live at $T = 80$–120°C, hydrothermal vents
Hypoliths	Live underneath rocks in cold deserts
Litoautotrophs	Source of carbon is CO_2, derive energy from mineral compounds
Metallotolerants	Capable of tolerating high levels of metals like copper, cadmium, zinc
Oligotrophs	Grow in nutritionally limited environment
Osmophiles	Grow in sugar concentration
Piezophiles	Live at high hydrostatic pressure; e.g. oceanic trenches
Polyextremophiles	Extremophiles more than one category
Psychrophiles, cryophiles	Grow at $T < -15°$; permafrost, polar ice...
Radioresistants	Tolerate high levels of ionizing radiation
Thermophiles	Live at temperature up to 80°C
Thermoacidophiles	Prefer temperatures of 70–80°C and pH between 2 and 3
Xerophiles	Grow in extremely dry conditions

- dissolution of chemical compounds,
- transport of nutrients in a cell,
- transport of waste,
- mixing of different chemical compounds,
- regulation of temperature; a constant temperature is required for complex organisms.

To be useful, any solvent must remain liquid within a large range of temperatures. Otherwise variations in conditions on a planet or satellite of a planet will freeze or boil the solvent and living organisms will be destroyed.

Under conditions like on the Earth's surface, the temperature range for water to remain liquid is 100°C. As the external pressure decreases (e.g. on a high mountain), the boiling point of water decreases (see Chap. 1).

For regulating the temperature, the heat capacity is the relevant parameter. Water has a high heat of vaporization; a living cell can respond to a temperature increase by vaporizing just a small amount of water. The heat capacity of water is 4.19 J/g/K,[6] the heat capacity of ammonia is 5.15 J/g/K and of methyl alcohol 2.15 J/g/K. To vaporize water requires 2491 J/g while ammonia needs 1256 J/g and methyl alcohol only 1214 J/g. Thus water seems to be ideal for temperature regulation. Mammals have a complex brain and precise temperature regulation allows to function this complex brain and cell systems properly.

In order to form aggregates of organic compounds, the surface tension of a solvent is relevant and water has a high surface tension. Thus water is much more appropriate for life regarding its heat capacity, heat of vaporization, surface tension and dissolving capability than other substances. Another important property of water is that it extends as it freezes. The cells of organisms that freeze will rupture. Putting the crew of an interstellar spaceship on ice would not help since humans consist mainly of water and the cells are destroyed by freezing. Ammonia does not expand upon freezing.

Another aspect has to be considered: as we have mentioned, stars produce UV radiation. Water molecules will be dissociated under intense UV radiation and the free oxygen contributes to ozone production. A planet with oceans consisting of ammonia does not produce such a shield.

2.2.2 *Other Solvents than Water*

In this section we will discuss two other well known solvents, ammonia and methyl alcohol.

The temperature range for liquid ammonia is from −78 to −33°C. The temperature range for liquid methyl alcohol is from −94 to +65°C. The parameter surface tension for ammonia and alcohol (ethanol, methanol) is only 1/3 that of water.

Life based on ammonia or methyl alcohol will be in some respects more robust and better protected against cosmic catastrophes than life based on water. However, it seems that complex life cannot be based on these because an effective regulation of temperature of the organisms is needed.

Let us speculate further. There is one advantage for Astronauts whose life chemistry depend on ammonia as solvent: they could easily be frozen and then waked up at arrival on some distant stellar system since ammonia does not expand when frozen and the cells are not destroyed.

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[6] Also called 1 calorie.

2.3 Energy for Life

2.3.1 Energy

To keep biological processes running, a constant supply of energy (mainly from the Sun) is needed. The two laws of thermodynamics are fundamental: (i) Energy is conserved, neither created nor destroyed. Energy may be transformed e.g. from the energy in a chemical bond to heat energy; the total amount always remains unchanged. (ii) Entropy measures disorder in natural systems. The entropy tends to increase in all natural systems.

These two laws can be applied to biological systems. Organisms are highly organized. This organization can only be maintained by a constant supply of energy. This energy is used by the cell to do work, some of that energy is lost as heat, we call this dissipation.

2.3.2 Metabolic Diversity

Metabolism can be defined as by all chemical reactions that occur inside an organism.

ATP (Adenosine triphosphate) transports chemical energy within cells for metabolism. One molecule of ATP contains three phosphate groups, and it is produced from inorganic phosphate and adenosine diphosphate (ADP) or adenosine monophosphate (AMP). The standard amount of energy released from hydrolysis of ATP is:

$$\mathrm{ATP} + \mathrm{H_2O} \rightarrow \mathrm{ADP} + \mathrm{P}_i, \qquad \Delta G = -30.5\ \mathrm{kJ/mol} \tag{2.2}$$

$$\mathrm{ATP} + \mathrm{H_2O} \rightarrow \mathrm{AMP} + \mathrm{PP}_i, \qquad \Delta G = -46.5\ \mathrm{kJ/mol} \tag{2.3}$$

P denotes a phosphate, PP_i a pyrophosphate.

Prokaryotes[7] use many compounds to obtain energy in the form of ATP and this enables them to habitate a wide variety of environmental habitats. The process to obtain energy in non photosynthetic cells is as follows:

- energy source: this source provides an electron,
- this electron is transferred to,
- electron acceptor.

An oxidation is the following reaction:

$$A \rightarrow A^+ + e^- \tag{2.4}$$

These organisms are called chemotrophs. Organisms that derive energy from sunlight are called phototrophs. The chemotrophs are further divided into:

[7] These organisms have no cell nucleus. Most are unicellular; they are divided into bacteria and archaea.

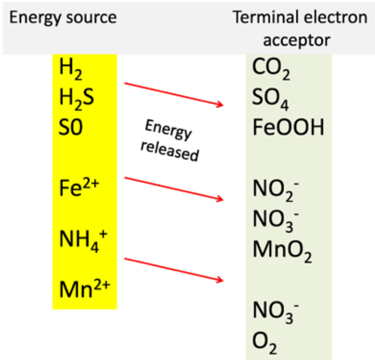

Fig. 2.3 Different types of chemotrophic metabolism

- chemoorganotrophs: they oxidize organic compounds;
- chemolithotrophs: obtain energy by oxidizing inorganic chemicals

In Fig. 2.3 different types of chemotrophic metabolism are given.

Let us consider for example the methanogens: they generate ATP by oxidizing hydrogen gas, using CO_2 as terminal electron acceptor.

$$4H_2 + CO_2 \rightarrow CH_4 + H_2O \tag{2.5}$$

Methanogens are found in anaerobic environments where the gases hydrogen and carbon dioxide are available. These are produced by chemoorganotrophs using fermentation of organic material.

2.3.3 *Solar Energy*

The Sun provides warmth. This is essential for all organisms most of which can survive only within a narrow temperature range. At high temperature (above 40°C), the biomolecules start to break down, at low temperatures (near 0°) the chemical reactions for metabolism occur too slowly. The organisms stop to grow and reproduce. Two important factors help to moderate and maintain temperatures on Earth: the earth's atmosphere and the oceans.

At the top of our atmosphere 1.372 kW/m^2 (1 W = 1 J/s) solar energy is received. More than half of the incoming sunlight may be reflected or absorbed by clouds, dust and gases. Short wavelength radiation is filtered out (e.g. UV by ozone) and cannot reach the surface.

The distribution of the incoming solar radiation is illustrated in Fig. 2.4. Incoming solar radiation is absorbed by land and sea and reflected into space by water, snow and also land surfaces. Half of the energy plants absorb is used in evaporating water, only 1–2% of the sunlight falling on the surface is available for photosynthesis. However, this small percentage is the energy base for any life in the biosphere.

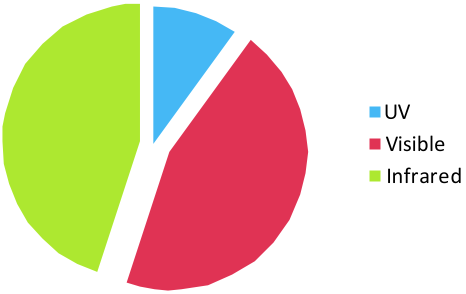

Fig. 2.4 The different percentages of solar radiation that reach the Earth's surface. Photosynthesis use *blue* and *red* light; most planets reflect *green* wavelengths, therefore, they appear *green*

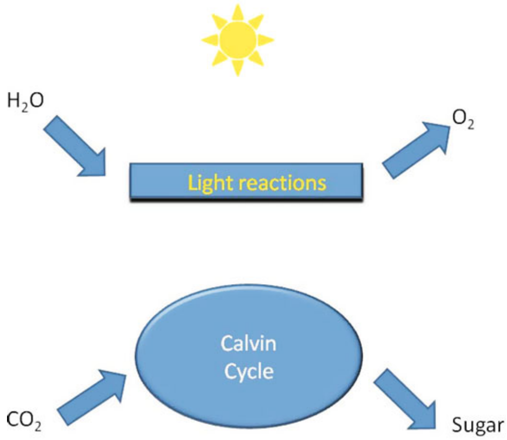

Fig. 2.5 A simplified diagram of photosynthesis

2.3.4 Photosynthesis and Respiration

Within plant cells there are the chloroplasts that contain chlorophyll. The chlorophyll molecules absorb light energy and create chemical bonds that serve as the fuel for all subsequent cellular metabolism. There occur two types of reactions:

- Light-dependent reactions: the chloroplast receives light. Enzymes split water molecules and release molecular oxygen, O_2. This is the source for all the oxygen in our atmosphere on which all animals depend for life. During the light-dependent reaction two types of mobile, high-energy molecules are created: ATP (adenosine triphosphate) and NADPH (nicotinamide adenine dinucelotide phosphate). These provide energy for the next process.
- Light-independent reactions: the enzymes extract energy from ATP and NADPH adding carbon atoms (from carbon dioxide) and the result is a sugar molecule (e.g. glucose). These glucose molecules provide the building blocks for larger, more complex organic compounds.

The photosynthetic reactions can be summarized as (see also Fig. 2.5):

$$6H_2O + 6CO_2 + h\nu \rightarrow C_6H_{12}O_6 + 6O_2 \qquad (2.6)$$

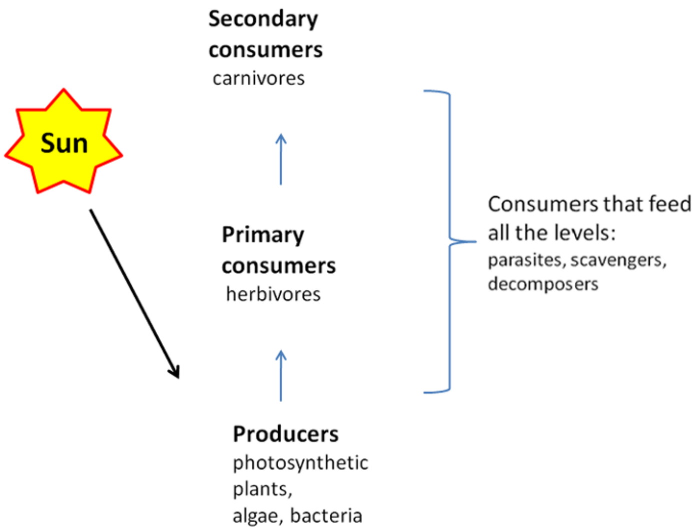

Fig. 2.6 How organisms obtain food for their life processes

where $h\nu$ denotes the energy of an incoming solar radiation quantum. Glucose, $C_6H_{12}O_6$ is an energy-rich compound. Other enzymes release the energy in these compounds and other complex molecules such as lipids, proteins, nucleic acids are formed, or movement of ions across membranes, changes in cellular structure etc. Photosynthesis occurs in plants, algae, and many species of Bacteria, but not in Archaea. The amount of energy trapped by photosynthesis is approximately 100 terawatts per year.[8]

The reverse process to photosynthesis is cellular respiration (Fig. 2.6 summarizes both the connection between both processes). From the sugar molecule, carbon dioxide and water is released.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + \text{energy} \tag{2.7}$$

Note that:

- photosynthesis: energy is captured,
- respiration: energy is released.

Animals and humans eat plants or other animals that have eaten plants. Organic molecules in the food are broken through cellular respiration to obtain energy.

Note that in both, photosynthesis and respiration, water plays an important role. Photosynthesis as an energy source is limited to at most the top few hundred meters of water bodies, and to the land surface.

[8]This is about seven times larger than the yearly power consumption of human civilization.

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