THE CHEMISTRY OF LIFE

ANAGH PURANDARE & ANIRUDDH SASTRY

Living organisms can be studied at different levels of organization — from molecules to ecosystems. Our current understanding of chemistry sheds some light on the way we understand living organisms at each of these levels. This article offers a glimpse of some interesting aspects of 'life' through the lens of chemistry.

Imagine you are walking on a road, and you see an insect sitting on a rock. Both the rock and the insect are, at a fundamental level, made up of matter. Yet they are very different from each other. While the rock can be composed of all 92 naturally occurring elements, the insect sitting on it can be made up of only 30 of these elements. What makes these 30 elements special? And, does the chemistry of an insect make it so different from a rock?

Life on Earth is carbon-based

While it has been suggested that alien life forms could be silicon-based, all life forms on Earth are carbon-based.

Question to ponder: Why are C-C bonds much stronger than Si-Si bonds? (Hint: look up the periodic table).

Both silicon and carbon have four valence electrons, and silicon is right below carbon in the periodic table. However, carbon-carbon (C-C) bonds are stronger and much more stable in water than silicon-silicon (Si-Si) bonds. Also, on being completely oxidized, carbon forms carbon dioxide, a gas; while silicon forms silicon dioxide, a solid. And, a gas (carbon dioxide) is more suitable than a solid for diffusion and recycling — processes without which life cannot be sustained.

Dihydrogen monoxide (H_2O) sustains life

A unique combination of chemical properties makes water as essential as we know it to be in sustaining life on Earth.

For the millions of life-sustaining reactions that need to take place in a cell, molecules have to collide against each other. These collisions are more likely to occur in a liquid medium (as compared to solid or gaseous media). The huge difference in its boiling and freezing points (~100 °C) means that most water on Earth has existed in liquid state at the wide range of temperatures experienced on the planet in the last 3.5 billion years. Being composed of two of the most abundant elements in the universe — hydrogen and oxygen, water has been abundantly available during this period.

Water helps dissolve a large number of solutes. Also, it can act both as an acid

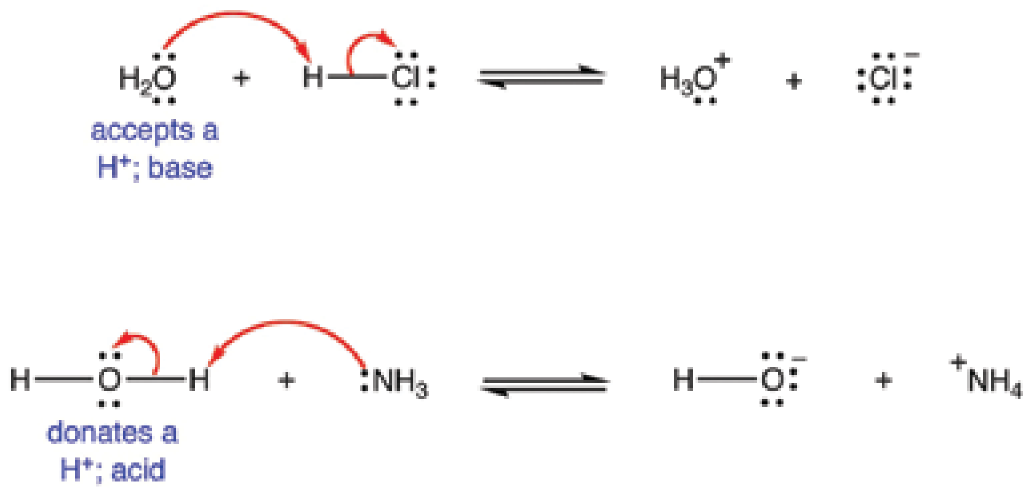

Fig. 1. **Water has the capacity to act both as an acid and as a base.**

Credits: Adapted from Gamini Gunawardena, OChemPal. URL: http://www.ochempal.org/index.php/alphabetical/a-b/amphoteric/.

Question to ponder: Why are liquids the most suitable medium for chemical reactions?

and a base — accepting a proton in the presence of a stronger acid and donating an electron in the presence of strong base (refer **Fig. 1**). This unique combination of properties makes water an ideal candidate as a medium for biochemical reactions.

Find out: How the density of water changes with temperature. What effect would this have on the evolution of living processes?

Temperature limits the chemistry of life!

Life processes depend on interactions between two or more cellular molecules. For these interactions to occur, it is important that these molecules bump into each other. In the chaotic inner world of a cell, molecules are jiggling around all the time. This jiggling and bumping of molecules depends on the amount of kinetic energy they have (taken from their surroundings), which in turn depends on the ambient temperature of the organism. It also depends upon how many molecules are present in a given volume of the cell, which in turn depends on their cellular concentration. Thus, each biochemical reaction occurs within a specific range of temperatures and concentrations.

Find out: How some organisms (known as extremophiles) live in extreme environments?

While all living organisms are limited by these temperatures, cells have evolved some ways of increasing the effective concentration of molecules. For example, eukaryotic cells achieve this by evolving membrane-bound organelles (refer **Fig. 2**).

The information of life is stored as a chemical sequence

While proteins perform most cellular

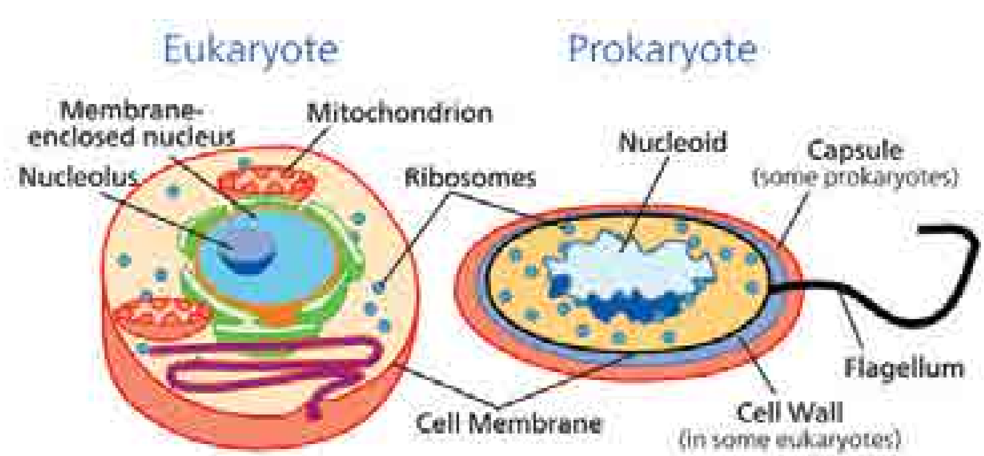

Fig. 2. **Membrane-bound organelles in eukaryotic cells help increase effective concentrations of biomolecules.**

Credits: Owned by Science Primer (National Center for Biotechnology Information), vectorized by Mortadelo2005 and uploaded on Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Celltypes.svg.

functions, instructions to make specific proteins are stored in deoxyribonucleic acid (DNA).

Each DNA molecule consists of two strands of organic molecules called nucleotides. Depending on the nature of their nitrogenous bases, these nucleotides are of four kinds – adenine (A), guanine (G), thymine (T) and cytosine (C). The two strands are held together in a double helix by ladder-like hydrogen bonds. These hydrogen bonds are formed between the nitrogenous bases of complementary nucleotides. Thus, at any given position, an adenine (A) from one strand can only form hydrogen bonds with a thymine (T) in the same position on the other strand, and vice versa. Similarly, a guanine (G) from one strand can only form hydrogen bonds with a cytosine (C) in the same position on the other strand, and vice versa (refer **Fig. 3**).

The precise sequence of nucleotides in each strand of DNA determines the specific types of proteins that a cell can produce. The complementarity of its bases guides the reliable copying of information from one DNA molecule to another during replication[1]. This is essential for cell division.

Question to ponder: What do you think would happen if there were errors in the formation of hydrogen bonds between the two chains of DNA?

High-energy bonds drive life reactions forward!

All cells require energy. They obtain this energy through the oxidation of sugars (mainly glucose). The energy released in these reactions is stored in a molecule called adenosine triphosphate (ATP). Thus, ATP is also called the energy currency of a cell.

Each ATP molecule contains a nitrogenous base (adenosine), a sugar (ribose), and a tail with three phosphate groups. The three phosphate groups bind sequentially to the ribose molecule forming AMP (adenosine monophosphate), ADP (adenosine diphosphate) and finally ATP (refer **Fig. 4**). Two of the three phosphate bonds are high-energy bonds. Thus, each ATP molecule can be broken down – first to an ADP and, then, to an AMP molecule – to drive energetically unfavourable reactions forward in the cell (refer **Fig. 4**)[2, 3, 4].

Question to ponder: Why are only two of the three phosphate bonds in ATP high energy bonds?

One part of the body 'talks' to another part chemically!

The survival of a complex multicellular organism depends upon coordination between its different cells, tissues and organs. This coordination is achieved through communication – and all communication between different parts of the body occurs through chemicals.

For example, have you ever wondered why eating a piece of chocolate gives you a brief rush of happiness? Chocolates contain chemicals like tryptophan, theobromine and phenylethylalanine. These chemicals travel to the brain where they induce the release of a group of molecules, called endorphins. Endorphins are one type of neurotransmitters – chemicals that help in the direct transmission of messages between neurons and other cells in the body. More than 100 such neurotransmitters have been identified. Together, they help maintain a variety of physical and physiological functions

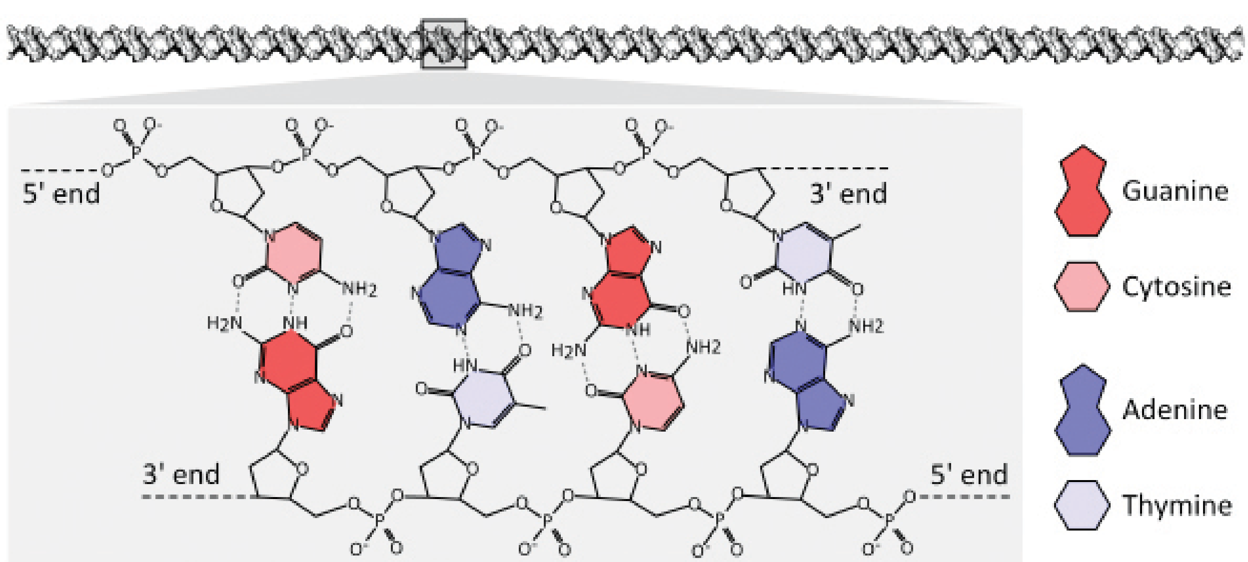

Fig. 3. The structure of a DNA molecule.

Credits: Thomas Shafee, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:DNA_chemical_structure_2.svg. License: CC-BY.

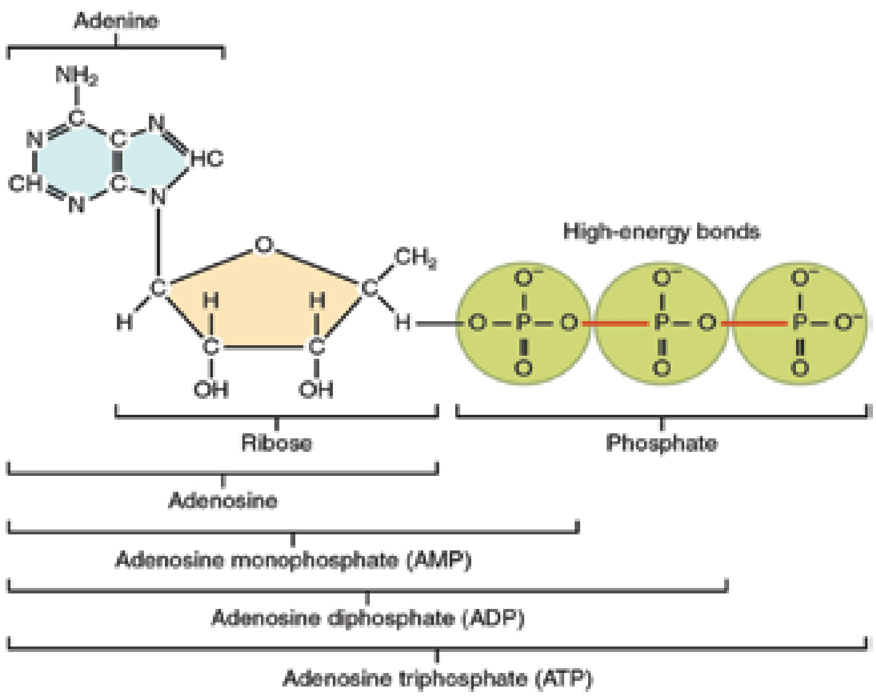

Fig. 4. The structure of an ATP molecule. The red lines represent its two high-energy phosphate bonds.

Credits: OpenStax College from Anatomy & Physiology, Connexions (http://cnx.org/content/col11496/1.6/), Jun 19, 2013, and uploaded on Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:230_Structure_of_Adenosine_Triphosphate_(ATP)-01.jpg. License: CC-BY.

Chocolates are meant to be poison!

Wait! Don't throw away all your chocolates yet. Chocolate, coffee and tea are derived from the plants *Theobroma cacao, Coffea sp.* and *Camellia sinensis* respectively. These plants produce chemicals like theobromine and caffeine to deter insect herbivores from feeding on them. These chemicals have been found to affect insect nervous systems and muscles adversely — reducing their appetite, causing uncoordinated movement, inhibiting their growth and reproduction etc.

Interestingly, the structure of the molecules (receptors) in the insect nervous system that bind to theobromine and caffeine is similar to that of receptors in the human brain. And, it is this conservation of chemical structures of neural receptors from insects to humans that allows humans to use these insect 'poisons' as stimulants.

(refer **Fig. 5**). These include regulation of not just happiness, but also of other 'moods' — sadness, boredom and sleepiness. Each of these feelings are associated with the release of certain neurotransmitters in specific regions of the brain.

In some cases, communication between different tissues or organs can be indirect. Chemicals that help transmit such messages are called hormones. For example, the pancreas produce a hormone called insulin that is released into the bloodstream and conveyed to different parts of the body. The insulin binds to specific chemicals called receptors on the surface of muscle cells. This binding instructs muscle cells to increase their uptake of glucose from the blood and burn it for energy.

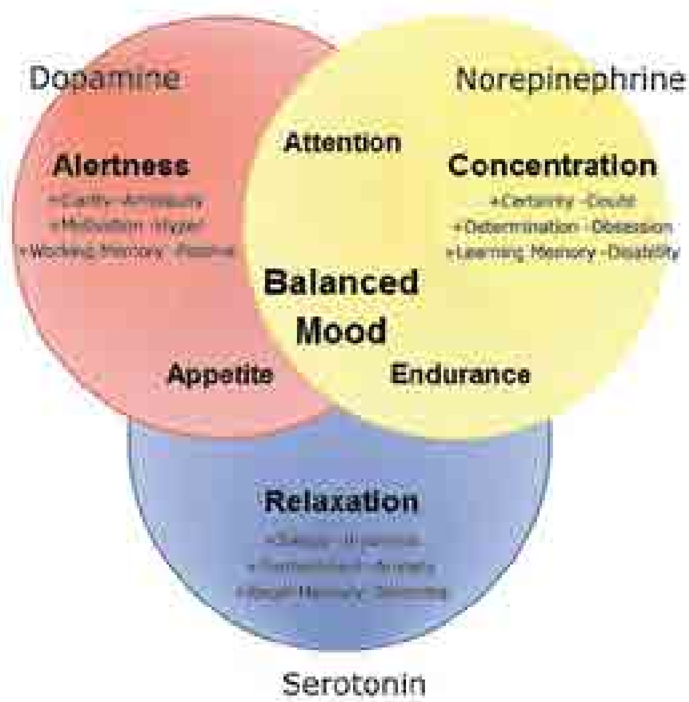

Fig. 5. Neurotransmitters (like Dopamine, Serotonin and Norepinephrine help maintain many physical and physiological functions.

Credits: Niklis Papageorgio, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Dopamine_Norepinephrine_Serotonin.png. License: CC-0.

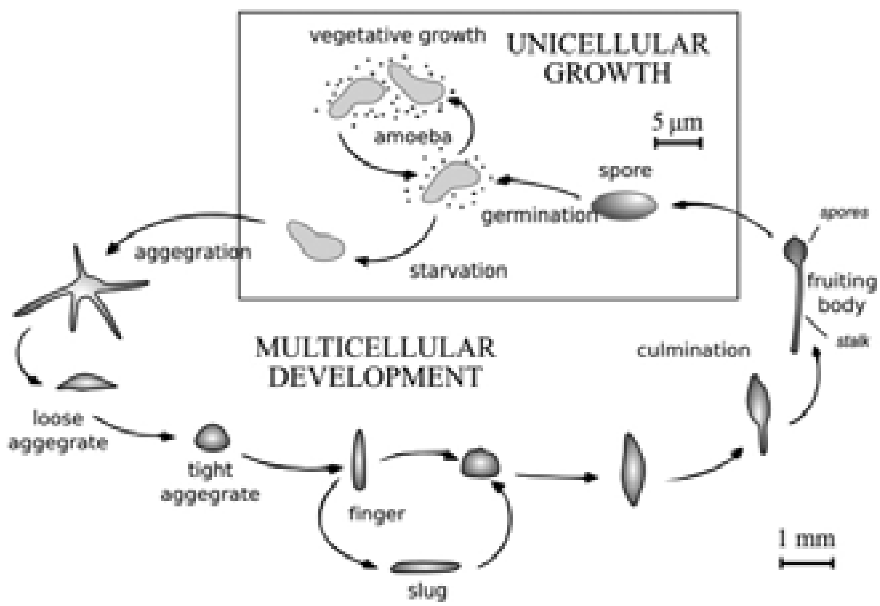

Fig. 6. The life cycle of *Dictyostelium discoideum.*

Credits: Drawn by the user Hideshi and converted to SVG by Tijmen Stam and IIVQ on Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Dicty_Life_Cycle_H01.svg. License: GFDL & CC-BY-SA.

Find out: Why do chillies taste spicy to us but not to parakeets?

Chemicals: the universal language all organisms use to communicate with each other!

Communication in the living world doesn't just happen at the level of tissues or organs. Organisms of the same or different species also communicate with each other, often through chemicals. For example, the soil amoeba *Dictyostelium discoideum* (lovably called Dicty) is unicellular under favourable environmental conditions. However, when environmental conditions turn unfavourable, these amoebae secrete a chemical called cyclic-adenosine monophosphate (c-AMP) that causes other single-celled organisms in its vicinity to come closer. These organisms then aggregate into a multicellular structure called a fruiting body. A fruiting body is composed of a long rod-like stalk topped by a group of cells called spores. The spores are dispersed, with the stalk providing some elevation and increasing the probability that some of them will land far enough (from the parent) to find more favourable conditions for survival (refer **Fig. 6**).

Individuals of other species use chemicals called pheromones for communication. For example, many insects (such as ants) use pheromones to communicate danger, the presence and source of food, and the location of a nest. Strikingly, some plants communicate signals of herbivore stress by releasing specific chemicals into the atmosphere. Other plants, of the same or different species, that come in contact with this chemical warning produce anti-herbivore chemicals in response. Often this response occurs even before the herbivore has reached these individuals!

Chemicals can 'see' light!

Some chemicals help organisms perceive light. For example, vertebrates have special photoreceptors called rhodopsin in the retina of their eyes. Consisting of a retinal molecule bound to a protein, rhodopsin can absorb light of certain wavelengths. On absorbing light, the retinal molecule changes structure. This causes a change in the structure of the protein attached to it. The altered protein becomes capable of triggering a cascade of chemical reactions that generates a nerve signal to the brain regarding the quantity and quality of light received. This process occurs in retinal cells every time light enters the eye. Since the retinal molecule is an aldehyde of vitamin A (retinol), a deficiency of this vitamin can lead to night blindness.

Find out: Do living organisms have other such light-sensitive molecules? What chemical property do they share that makes them 'see' light?

Molecular motors pull the weight in your hands!

Whenever you pick up a pen or a bucket of water, the muscles in your forearms and biceps contract. This contraction is brought about by the action of two long, fibre-like cellular proteins — myosin and actin.

These proteins lie parallel to each other within a resting muscle cell. But, as soon as the cell receives a signal to contract, myosins and actins bind with and slide over each other, reducing the length of the muscle fibre (refer **Fig. 7**). Fuelled by the conversion of the chemical energy of ATP to mechanical energy, this process results in the contraction of muscles.

To conclude

"They are in you and me; they created us, body and mind; and their preservation is the ultimate rationale for our existence. They have come a long way, those replicators. Now they go by the name of genes, and we are their survival machines." — Richard Dawkins in 'The Selfish Gene'.

Richard Dawkins provides a striking example of how chemistry is believed to dictate biological processes. While this is a radical view, we know that over millions of years, natural selection has resulted in some types of chemistry being recruited in biological systems more often than others. It is these chemicals and their chemistry that have not only made an insect different from a rock, but have also led to the successful existence of all living organisms.

This article provides some examples of how an understanding of the principles of chemistry enriches our understanding of living organisms and vice-versa. However, given how integral chemistry is to the understanding of biology, there are many other such connections just waiting to be discovered. For example, have you ever thought about our need for food in chemical terms? What does converting food into energy really mean? And, what is this energy used for? Can you think of other such connections?[4]

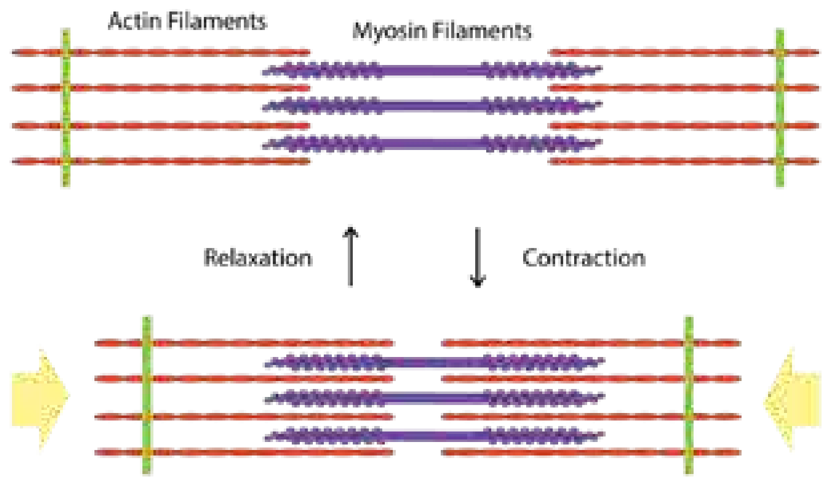

Fig. 7. Contraction of actin and myosin filaments in muscle cells.

Credits: Adapted from an image created by Alli Sarfati on Proteins of the Deep Sea, Kier Laboratory, UNC Chapel Hill as part of the HHMI Internship for Future Teachers. URL: http://www.unc.edu/depts/our/hhmi/hhmi-ft_learning_modules/octopusmodule/images/contraction.png.

Note: Credits for the image used in the background of the article title: *Dictyostelium discoideum*, Usman Bashir, Queller/Strassmann Research Group at Washington University in St. Louis, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Dictyostelium_discoideum_43.jpg. License: CC-BY-SA.

Additional Resources

1. Cooper GM. The Cell: A Molecular Approach. 2nd edition. Sunderland (MA): Sinauer Associates; 2000. DNA Replication. Available from: https://www.ncbi.nlm.nih.gov/books/NBK9940/.
2. Lodish H, Berk A, Zipursky SL, et al. Molecular Cell Biology. 4th edition. New York: W. H. Freeman; 2000. Section 2.4, Biochemical Energetics. Available from: https://www.ncbi.nlm.nih.gov/books/NBK21737/.
3. Cooper GM. The Cell: A Molecular Approach. 2nd edition. Sunderland (MA): Sinauer Associates; 2000. Metabolic Energy. Available from: https://www.ncbi.nlm.nih.gov/books/NBK9903/.
4. Westheimer, F. (1987). Why nature chose phosphates. Science, [online] 235(4793), pp.1173-1178. Available at: http://archives.evergreen.edu/webpages/curricular/2006-2007/m2o2006/seminar/westheimer.pdf [Accessed 6 Jun. 2018].

Anagh Purandare teaches science and biology at Rishi Valley School. His previous work experience has involved the design of assessment tools to test conceptual understanding of school children. He is interested in integrating different topics to facilitate science learning. He can be reached at anaghp@rishivalley.org or anaghrv@gmail.com.

Aniruddh Sastry has a PhD from his work on temperature tolerance in plants from Indian Institutes of Science Education and Research (IISER), Pune. He has worked with gifted students through the ASSET Summer Programme, and is interested in designing curricula, assessment tests and other educational tools for science education. He currently works with Educational Initiatives. He can be reached at aniruddh0810@gmail.com.