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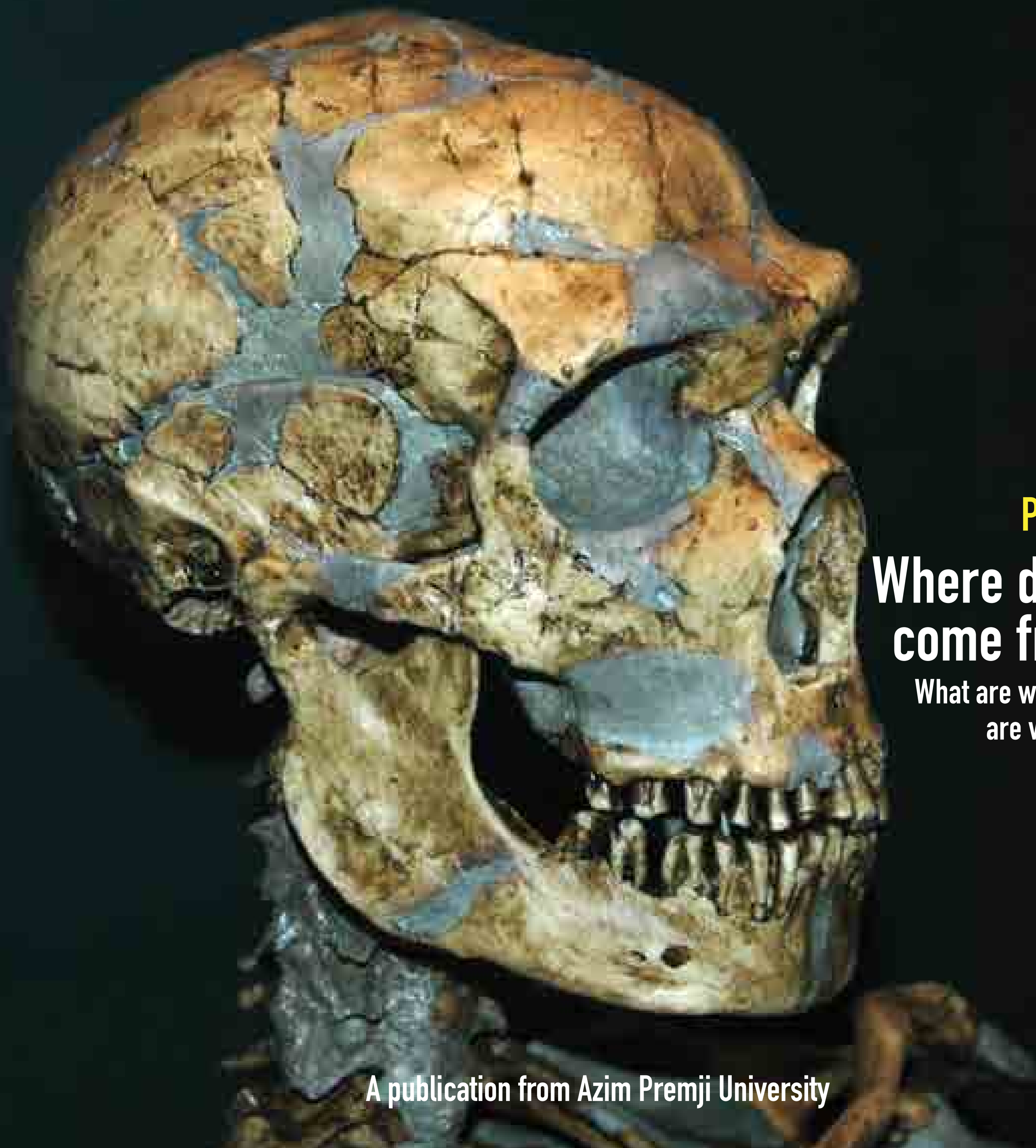
i wonder...

Rediscovering School Science

Azim Premji University



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Where do we come from?

What are we? Where are we going?

A publication from Azim Premji University

i wonder
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i wonder...
REDISCOVERING SCHOOL SCIENCE

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Editorial

On 27th December, 1831, after much delay, a ship lifted anchor from Barn Pool, near Davenport, England. Soon to become one of the most famous ships in history, it was headed on a two year expedition to conduct a hydrographic survey of the southern coasts of South America. Just before it set out, the captain of the ship, a 24-year old aristocrat, gave his companion, a 22-year old naturalist, a copy of a recently published book. Little could he have imagined the profound impact that this simple action would have on his companion's life or on our understanding of the natural world.

The ship was the HMS Beagle. It was commanded by Captain Robert FitzRoy, who was already making a name for himself as an able leader and a meticulous surveyor. The young naturalist was Charles Darwin. Nearly rejected by FitzRoy because the shape of his nose seemed to indicate a lack of determination, Darwin seemed well-suited for this role in every other way. As the grandson of Erasmus Darwin, a well-known philosopher, he fit FitzRoy's criteria of being a 'gentleman'. Six feet tall, with a tendency to stoop, and an abiding interest in natural history, Darwin nurtured a keen desire to visit the tropics once, before he became a parson. The book that FitzRoy had handed him was called the 'Principles of Geology' and marked an important transition in the career of its first-time author, the Scottish aristocrat Charles Lyell. Lyell had turned to geology after his attempt to become a barrister was scuttled by his deteriorating eyesight. In his book, Lyell used an evidence-based approach to argue that all great geological changes, historical as well as current, were the outcome of a gradual process of accumulation of minute changes over long time spans. Although Darwin had initially found classes in geology dull, he had developed a strong interest in the subject on a field-trip with Adam Sedgewick, one of the founders of modern geology. Reading Lyell's book, and later seeing rock formations at the Cape Verde islands through 'Lyell's eyes', left a lasting impression on Darwin's long-standing reflections on the origins of species.

Needless to say, this issue of iwonder is centered on evolution, a concept that today is almost synonymous with Charles Darwin. However, in a strange but fitting way, the word evolution, derived from the Latin *'evolvere'*, was originally used to refer to the 'unrolling of a book'. And it was, in fact, Charles Lyell who first used this term with its modern meaning – twenty-seven years before Darwin used it once in the final paragraph of his 'On the Origin of Species'. Thus, it is Lyell's notion that 'the present is the key to the past', a key first principle in almost every field of science, which is the underlying thread linking the articles in this issue – from the evolution of stars and the Earth to that of living organisms, humans, or even the phenomenon of ocean acidification. Join us in this exploration, and don't forget to share your thoughts with us at *iwonder.editor@azimpremjifoundation.org*.

Chitra Ravi

Co-editor

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THE EVOLUTION OF STARS

ANAND NARAYANAN

Compared to the human lifespan, the Sun and other stars seem eternal. But stars also are born, and they die. If they did not, we would not be here to tell their story. Life on Earth was, in a very unique way, made possible by stars that died long ago. This article explores the fascinating story of stellar evolution.

We all know what the periodic table of elements looks like, with its many rows and columns featuring the fundamental chemical building blocks of all living and non-living matter on Earth (refer **Fig. 1**). But, have you ever wondered where these elements come from? The oxygen we breathe, the calcium in our bones, the iron in our blood, and the nitrogen in our DNA — what processes lead to such variety?

Incredible as it may seem, there is only one place in the entire universe where naturally occurring elements can be synthesized — the interiors of stars. But for stars that lived and died long ago, a planet like Earth and life as we know it would not have been

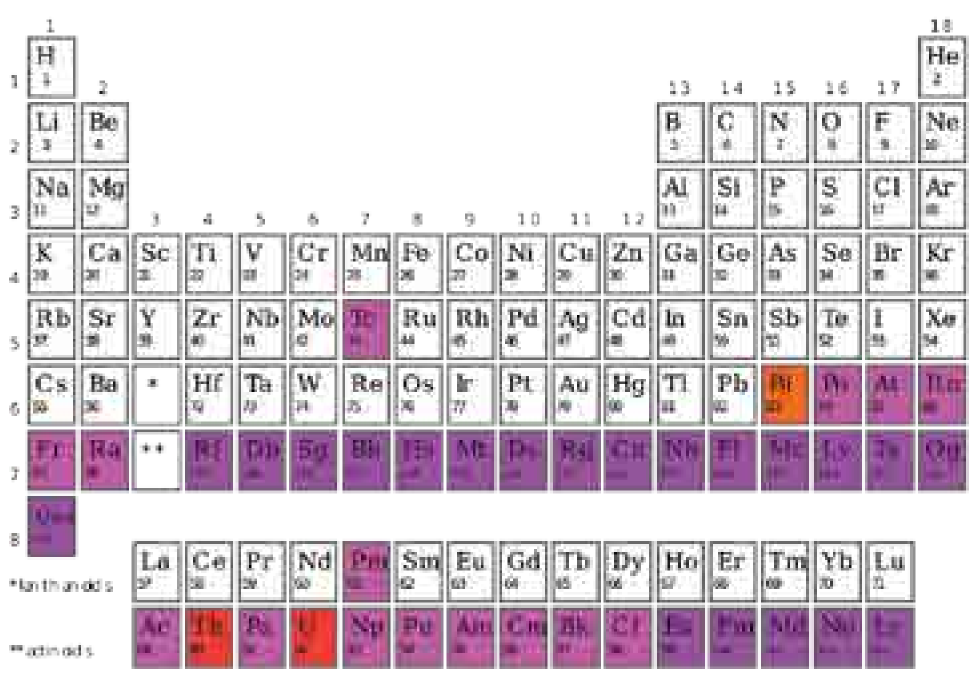

Fig. 1. The periodic table.

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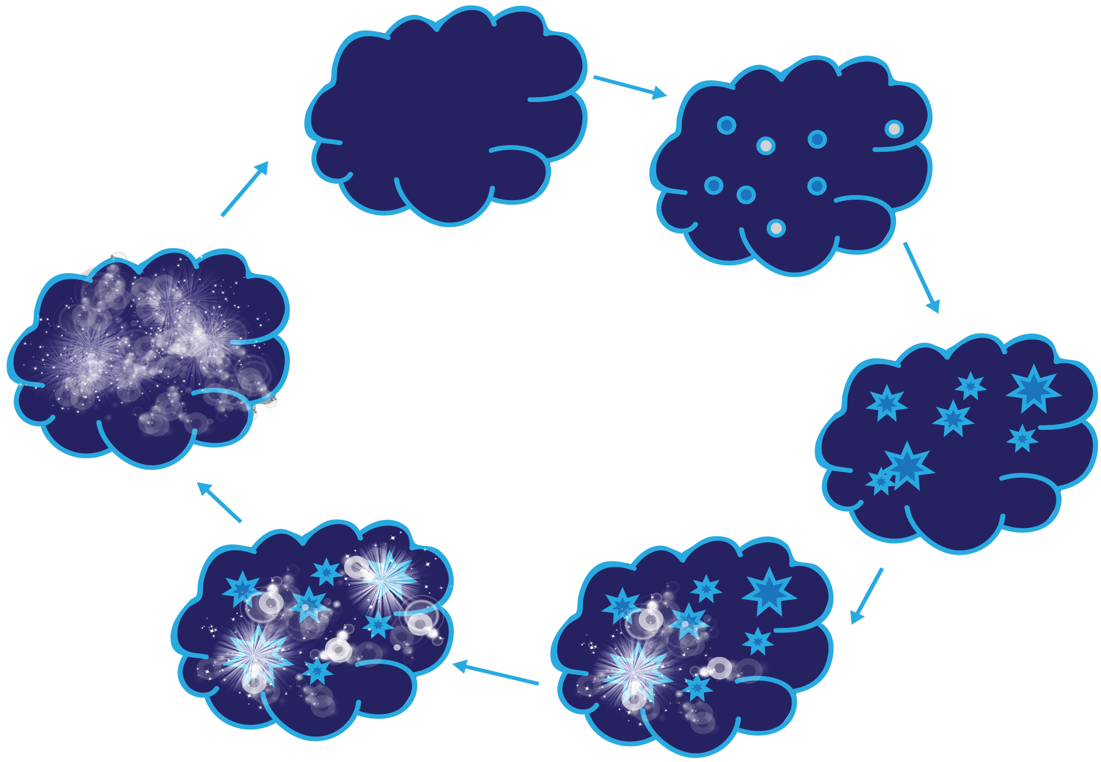

Fig. 2. The stellar life cycle. Stars are born out of interstellar gas clouds. Fragmentation within such a cloud gives birth to not one, but many stars, some of which will be of low mass (like the Sun) and some very massive. The stars live for a few hundred million to billions of years. When they end their life they throw back the heavier elements they synthesized during their life time into the interstellar medium.

possible. To understand how the evolution of stars has led to that of life, let's take a closer look at their spectacular lives – what makes them shine so brilliantly and what happens when they cease to do so?

The stellar lifecycle

Astronomers refer to the life of stars – from their birth, their evolution to more mature forms, and finally to their death – as the stellar lifecycle (refer **Fig. 2**). The term 'lifecycle' suggests that this is a process that continually repeats itself, which is indeed so.

Stars are born out of clouds of hydrogen gas in the interstellar medium (the region between stars). When they die, they replenish the interstellar medium with the same gas, with one major difference. The gas the stars fling back into the interstellar medium is abundant in elements heavier than hydrogen, synthesized by the stars in the course of their lives. Thus, the death of every star enriches its surrounding interstellar medium with heavier elements. Since new generations of stars are born out of this interstellar gas, the cycle repeats itself.

The birth of stars

Stars are born as huge balls of hydrogen gas, with trace amounts of helium. Their entire life is characterized by the creation of heavier elements from lighter elements, starting with hydrogen. But, how do we know this?

Although there are a billion stars in our own galaxy, they are too far away for us, and even if we found a way to travel such distances, we could not land on them – we would not survive the enormous amounts of energy that they release (refer **Fig. 3**). In spite of these difficulties, we have found some ingenious ways to study them, many of which are based on the star closest to us – the Sun. Studies of the light from the Sun, initially through prisms, and later by increasingly sophisticated spectrometers, show a curious pattern of dark lines. Our understanding of atomic spectra tells us that these lines are produced because atoms in the surface layers of the Sun absorb light of certain wavelengths. We have also been able to infer that the atoms that produce these lines are most likely to be of elements like hydrogen, sodium, helium, magnesium and calcium. However, these observations only allow us to study the composition of the Sun at its surface.

How do we know the composition of the Sun at its core? The idea that hydrogen atoms could fuse to form helium, by a process called **nuclear fusion** (refer **Fig. 4**), that would release huge amounts of energy began to attract attention in the 1930's. However, it was only in 1985 that we started finding evidence to suggest that this process could occur at the core of the Sun and produce the

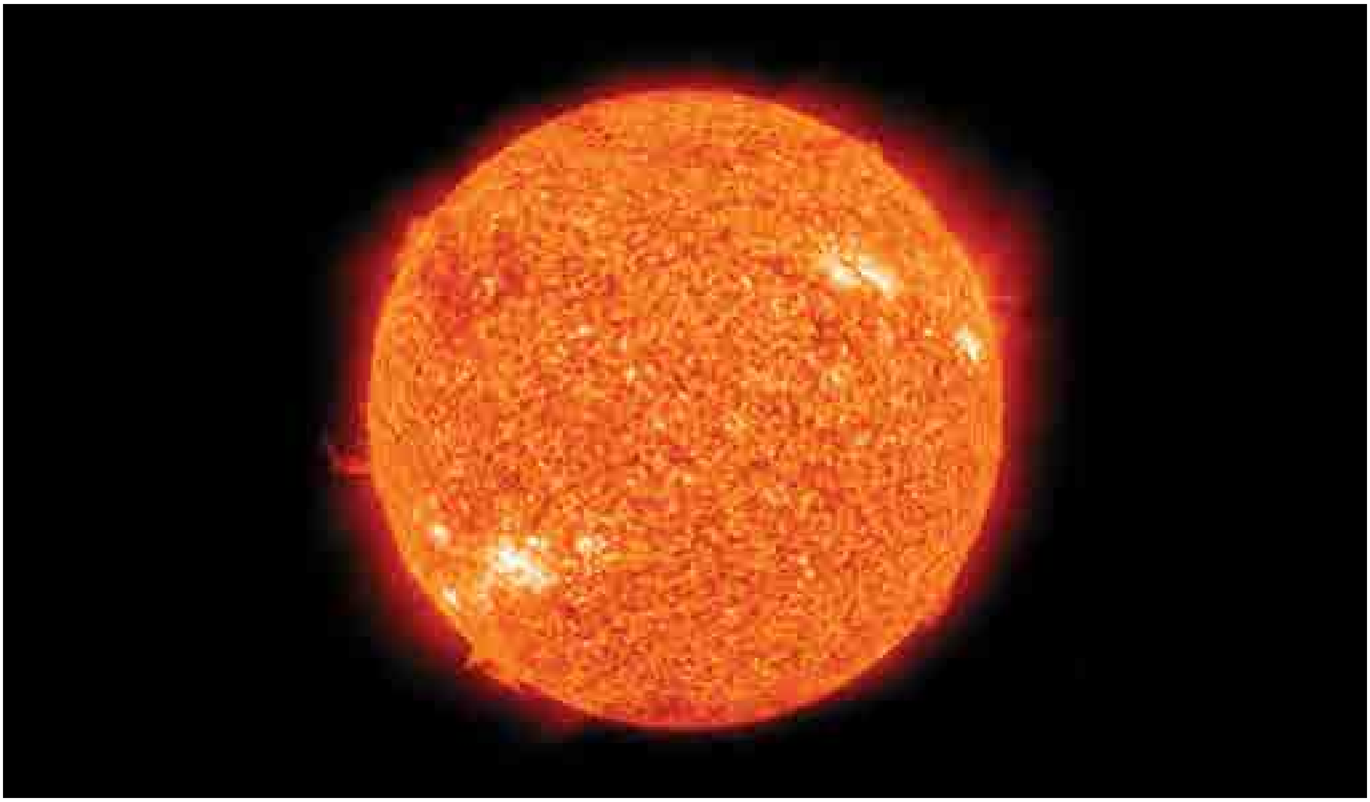

Fig. 3. A photograph of the Sun taken by SOHO space observatory. The surface of the Sun has a temperature of nearly 6500 Kelvin.

Credits: NASA/SDO (AIA), Wikimedia Commons. URL: https://simple.wikipedia.org/wiki/File:The_Sun_by_the_Atmospheric_Imaging_Assembly_of_NASA%27s_Solar_Dynamics_Observatory_-_20100819.jpg. License: CC-BY.

energy to power it. This evidence came from the development of devices called Kamiokande (Super-K) detectors. Buried about 1000m below the Earth's surface, these detectors are designed to trap and study subatomic particles like solar neutrinos. Neutrinos, or ghost particles as they are often called, are tiny, nearly massless and charge-less particles that travel at speeds close to that of light. Since we know of no other method by which they could be produced, the fact that they exist is believed to be direct evidence of the nuclear fusion occurring within the Sun's core.

The surface of the Sun, visible to our unaided eyes, is called its photosphere. Estimates suggest that it is through this layer that about 3.8 x 10^{26} Joules of energy escape into space every second in the form of photons (refer **Box 1**). This is a billion times more than the power produced by all the hydroelectric power plants in India in an entire year! Of course, the Sun produces much more energy than it loses through its photosphere — a great deal of this energy goes back into heating up its interior (refer **Fig. 6**).

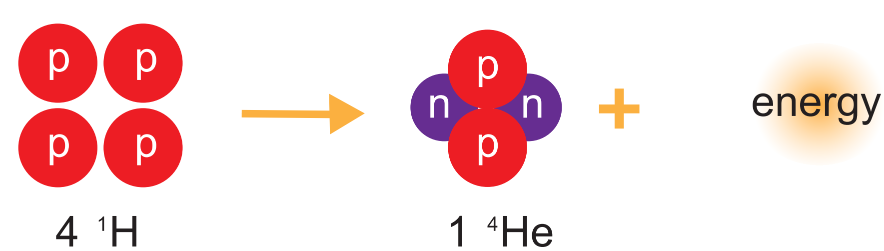

Fig. 4. The Sun is able to shine because of the fusion of hydrogen nuclei (protons) to form a helium nucleus. Four hydrogen nuclei fuse together to form a helium nucleus. The mass of a single helium nucleus is about 0.7 percent less than the combined mass of the four protons. This deficit in mass is released as energy, which heats up the interior of the Sun, and gets radiated from its surface.

Credits: Adapted from Pearson Education, publishing as Addison Wesley.

Based on how bright the Sun appears to us, physicists have calculated the rate at which nuclear fusion reactions must be happening at its core — and they are staggeringly high (see **Box 2**). With such a large energy yield, one may wonder why the Sun does not explode. As it turns out, all stars have some kind of in-built safety valve that prevents this from occurring. But, how does this valve work?

A cloud of gas (predominantly consisting of hydrogen) becomes a star when gravity starts pulling its atoms together.

Box 1. The journey of a million years:

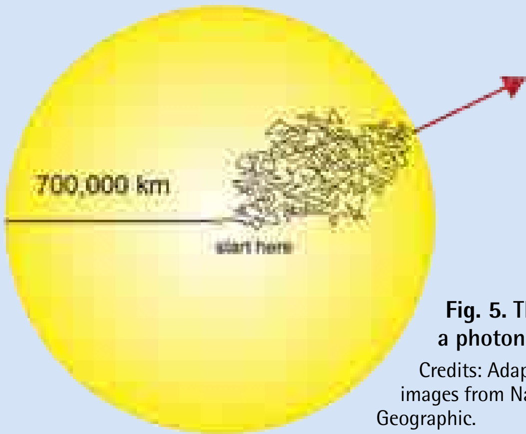

Fig. 5. The path of a photon of light.

Credits: Adapted from images from National Geographic.

Photons are light particles. While inside a star, photons are constantly scattered by gas particles, losing energy in each of these interactions (refer **Fig. 5**). Thus, by the time they get to the outer layers of the Sun, their energy has become a million times less than what it was in the beginning. It is these photons that free-stream into outer space, and that we see as sunlight.

Calculations show that any photon manages to travel only a tenth of a millimeter before slamming into electrons and ions inside the star. Thus, the path a photon takes would have to be extremely zigzag, covering small distances every step of the way. Physicists call such motion a **random walk**, and have devised some models to describe it. In one such model, if 'd' is the distance that a particle travels between successive scatterings, then after 'N' such scatterings, the particle would have covered a net distance of sqrt(N) x d.

Challenge: You can easily calculate how long it would take for a given photon generated at the core of the Sun to find its way to the surface (the photosphere). The radius of the Sun is 700,000 kilometers. Assume that a single photon manages to travel a distance of about one-tenth of a millimeter between successive scatterings. The photon has the speed of light, which is about 300,000 kilometers every second.

Hint: Calculate how many small steps the photon has to take to cover the distance within the Sun (radius of the Sun) = this is the N in the above expression. Multiply that with 0.1 mm = the distance of each step. This will give you the total distance that a photon would have traveled from the core to the surface of Sun. Divide that distance with the speed of light to get the time it would take for a photon produced at the core to reach the surface.

You should get a value that is close to half a million years. That's how long it takes for sunlight to escape the Sun. Think about this for a while. A photon produced at the core of the Sun takes half a million years to travel the 700,000 kilometers to the surface of the Sun. Once it gets past the photosphere, the photon takes only about 8 minutes to cover the 150,000,000 kilometers to the Earth! What causes this difference is the density of material that the photon encounters *en route*. The density of material inside the Sun is a hundred thousand times more than the density of matter in the vastness of space that separates the Earth from the Sun.

The nebula gradually turns into a ball of gas as the gravity between the gas particles keeps compressing the material into smaller sizes. As it shrinks, the density of the gas in this nebula grows, gradually becoming high enough to cause nuclear fusion reactions (refer **Fig. 7**).

However, once fusion begins, a counter pressure to gravity sets in. The photons produced by the fusion of hydrogen at the core of the Sun exert an outward pressure on consecutive layers of gas as they push their way to the photosphere. Physicists refer to this as the radiation pressure. This pressure is highest at the core, and reduces steadily in the outer layers of the sun. As the radiation heats up the gas, another form of pressure called the gas pressure builds up. The hotter the gas, the higher its gas pressure. This gas pressure acts in the same manner as the radiation pressure pushing layers of gas outward. In every layer of gas inside a star, the collective radiation and gas pressure acting outwards gets balanced out by the pressure due to gravity acting inwards. This balance keeps the star in a state of equilibrium, not allowing it to shrink further due to gravity, or swell in size because of the combined thrust of the

Box 2. The energy yield of the Sun:

It's easy to calculate the energy yield from hydrogen fusion inside the Sun.

Our starting point is a reaction where four hydrogen nuclei (protons) fuse together to form one helium nucleus. Now, we know that the:

Mass of a single proton = 1.67 x 10^{-27} kg

Mass of a single Helium nucleus = 6.64 x 10^{-27} kg

The difference in mass, Delta m = (4x 1.67 – 6.64) x 10^{-27} kg

According to Einstein's mass-energy equivalence principle, it is this difference in mass that is converted to energy, or E = Delta mc^2.

For the energy released in this process, we get a value that is approximately 4 x 10^{-12} Joules (using a light speed of c = 3 x 10^8 m/s).

This is the amount of energy set free from the fusion of four hydrogen nuclei. Inside the Sun, a lot of these reactions are happening at once, and together they drive its energy output. We can also estimate the number of hydrogen fusion reactions happening every second:

Number of fusion reactions every second = total energy released by the Sun every second / energy from a single fusion reaction = 3.8 x 10^{26} Joules/sec / 4 x 10^{-12} Joules, which is approximately 10^{38} fusion reactions every second. In other words, at every instant, about 10^{38} hydrogen nuclei in the Sun's core are getting converted into Helium!

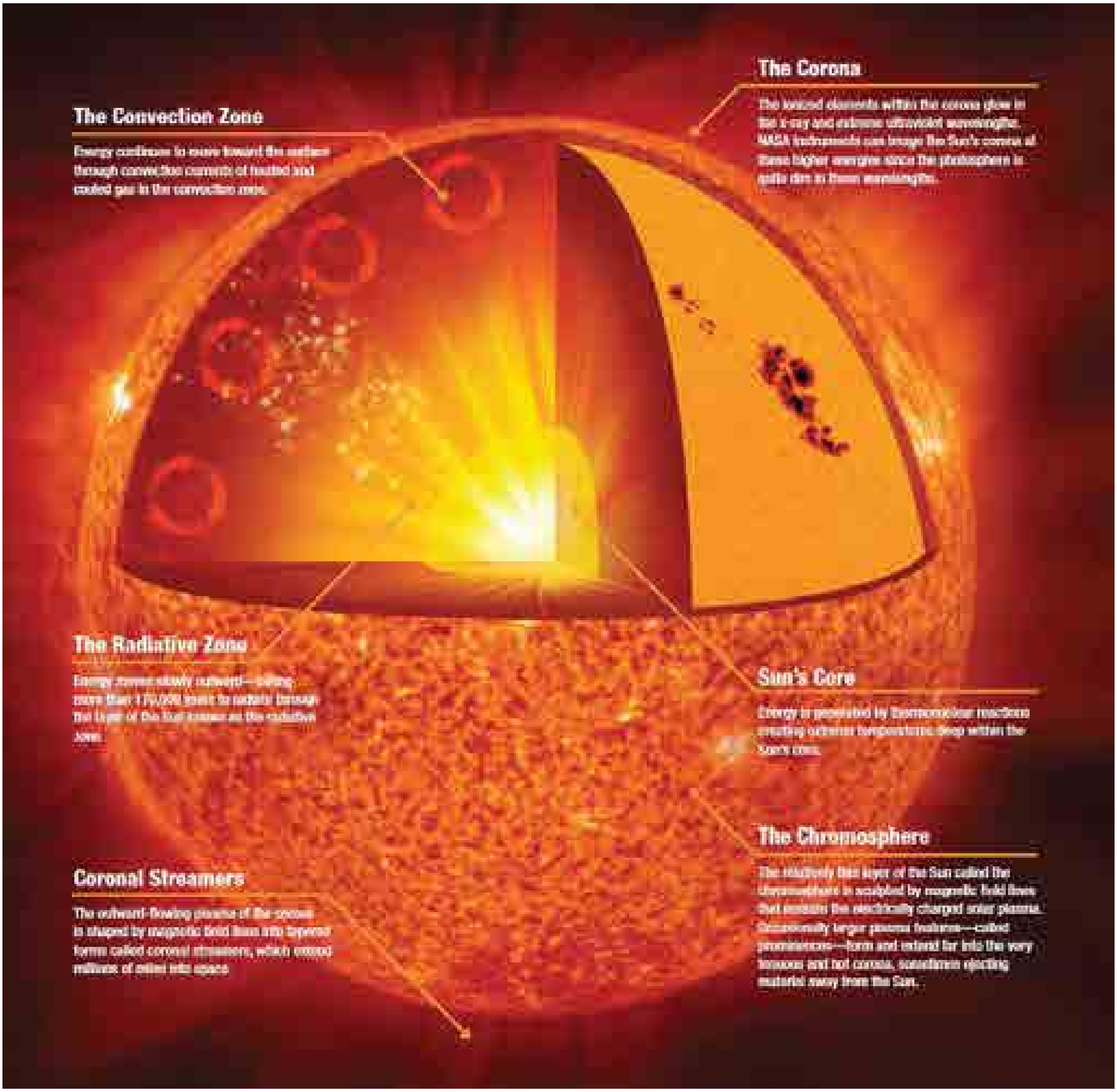

Fig. 6. A cross-section of the Sun. The surface of the Sun is called the photosphere. Below it are several layers of gas that surround and hide the core of the Sun from our view. But, it is only at the core that the density and temperatures are high enough to allow nuclear fusion. The energy generated by this process slowly makes its way through many gas layers to reach the photosphere. Once it reaches the surface of the Sun, it gets radiated outwards in the form of photons.

Credits: © NASA/SOHO.

radiation and gas pressure acting inside out. This state of hydrostatic equilibrium (as it is called by physicists) acts as a natural safety valve in stars (refer **Fig. 8**). Any disruption in this balance can lead to dramatic changes that can, at times, be detrimental to the star.

As stars mature

The mass of a star determines its life span. The Sun may be dear to us. But in the vastness of cosmos, the Sun is a mediocre star. There are many stars, even within our own Galaxy that are more massive and, consequently, more luminous than the Sun (see **Fig. 9**). These stars tend to live much shorter lives – the higher their mass, the greater the pressure due to gravity squeezing the star. To resist this inward crush, and sustain its hydrostatic equilibrium, these stars — referred to as high mass stars — burn the hydrogen at their core at a significantly faster rate. So, for example, estimates suggest that a star that is three times the mass of the Sun would burn out all the hydrogen in its core in about half a billion years, while a star that is 15 times more massive than the Sun will do this in less than 15 million years. By that very same token, the hydrogen at the core of a star that is only about 10% of the mass of the Sun will be able to burn for as long as a thousand billion years!

(a) The long life of low mass stars

Astronomers classify the Sun, and stars up to eight times the mass of the Sun, as low mass stars. The major events in the lives of such stars are more or less alike.

The longest stage in any star's life is that involving a hydrogen to helium conversion. For a star like the Sun, this lasts for about 10 billion years. When the core hydrogen is fully consumed, nuclear fusion shuts off. With no radiation or gas pressure to counter the gravitational pressure, the core of the star shrinks. The compression of the core by gravity causes its density and temperature to increase (much like what happens when you compress any fluid in a closed container). This continues till, finally, the temperature and density at the core become large enough to trigger helium fusion.

At this stage, therefore, two kinds of nuclear fusion reactions begin to

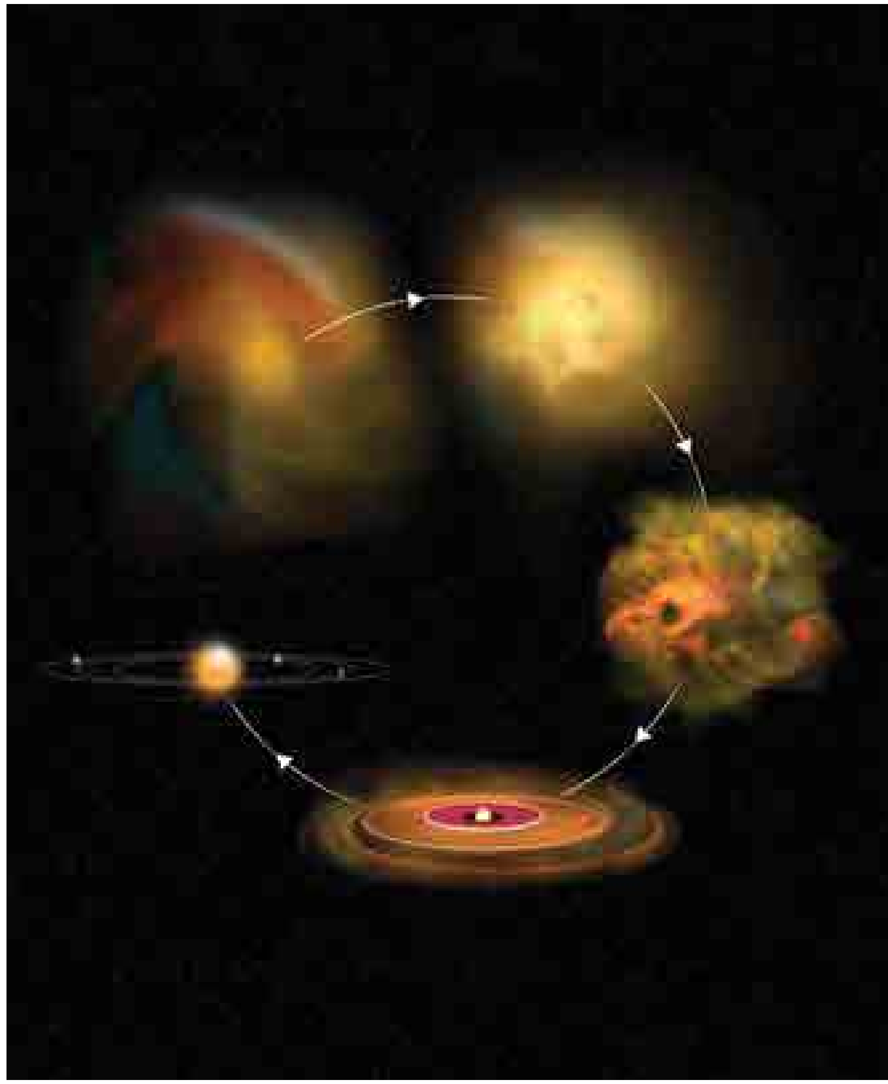

Fig. 7. The sequence of steps that leads to the birth of a star. Inside a cold dense cloud of gas, a fragmented region starts collapsing under its own gravity. The collapse continues until a star forms at its centre, along with planets around it. A star is born when the temperature at the central region of the collapsing fragment equals 10 million Kelvin, and the density approximately 160 gms/cc (about 10 times the density of lead).

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Box 3. The lifespan of the Sun:

Like every other star in the universe, our Sun too is destined to die. How much longer do we have before it burns out?

Fortunately estimating this time scale involves a straightforward calculation. We need to know three things to make this calculation:

1. How much energy does the Sun give out every second?
2. How much mass in the form of hydrogen is available at the core of the Sun for fusion?
3. How efficient is hydrogen fusion in converting mass into energy?

The total mass of the Sun is 2×10^{30} kg. About 10% of this mass, which is 2×10^{29} kg, is at the core where fusion reactions occur.

The hydrogen to helium fusion reaction occurs with an efficiency of 0.7%. In other words, only 0.7% of the total mass in the core of the Sun gets converted to energy. Knowing these two facts, we can calculate the total amount of energy the Sun is likely to radiate over its entire lifetime, which is 0.7% of $2 \times 10^{29} \times c^2$ Joules (using Einstein's $E = mc^2$ equivalence principle).

From this, we can infer that the amount of energy coming out of the Sun every second (also called its luminosity) is 3.8×10^{26} Joules /Sec.

The Sun can continue shining with that luminosity for $t = 1.3 \times 10^{44} / 3.8 \times 10^{26} = 3 \times 10^{17}$ seconds, which is equal to 10 billion years. At present, the Sun is about 5 billion years old, which means that it has completed half of its lifespan. It has another 5 billion years to go, before it uses up all the hydrogen fuel at its core.

occur within the star. One of these occurs within its core, and involves the fusion of helium atoms to form carbon and oxygen (refer **Fig. 10**). The other is the fusion of hydrogen to helium in a shell surrounding the core. The energy released from both these fusion reactions oppose the gravitational pressure acting inwards, re-establishing equilibrium.

As a result of these changes within, the star undergoes a major transformation in its external appearance. It swells up tremendously, becoming a hundred to a thousand times bigger. Astronomers call such inflated stars — red giants (refer **Fig. 11**). Estimates suggest that our Sun will undergo such a transformation in about 5 billion years.

Unlike the fusion of hydrogen to helium, the fusion of helium to carbon and oxygen does not last very long. A star like the Sun will be able to sustain the burning of Helium at its core for

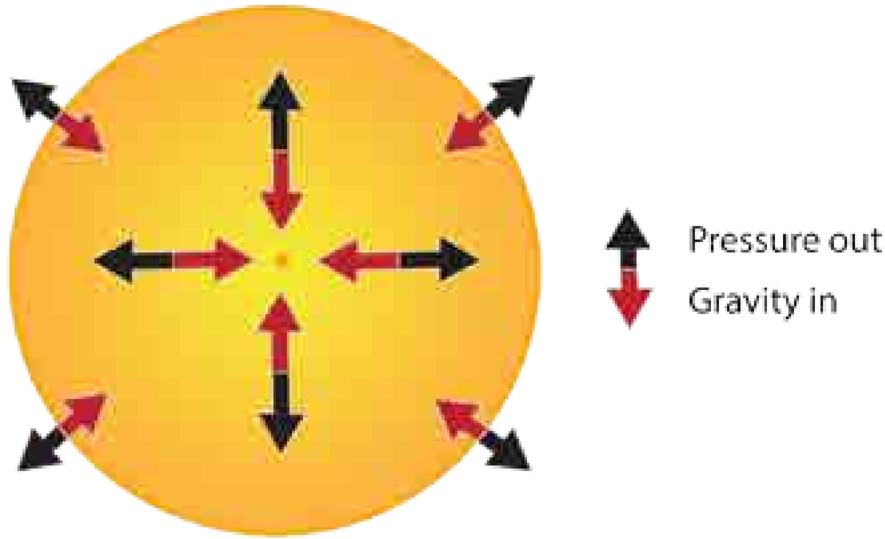

Fig. 8. Hydrostatic equilibrium balances two competing pressures within a star. Every layer of a star exerts its weight on the layer just beneath, to compress the star to a smaller size. This pressure due to gravity is least on the surface of the star, but increases in successive inner layers. Thus, the gravitational pressure is maximum at the core, as it experiences the maximum weight from all the layers of gas above it. At every layer of gas inside a star, the gravitational pressure acting inwards is balanced by a combination of its gas and radiation pressures acting outwards.

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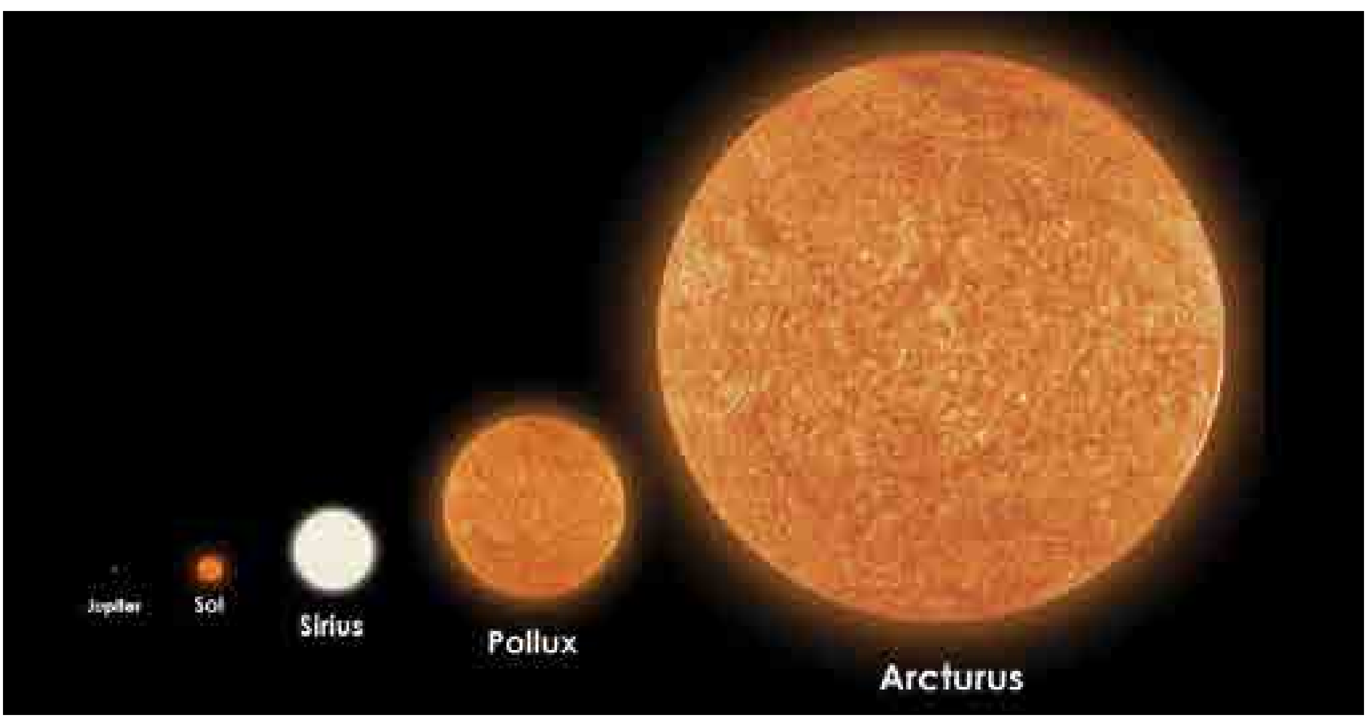

Fig. 9. The size and mass range of stars. Our Sun is an ordinary star with mass, size, temperature and luminosity smaller than many other stars in the Milky Way. This figure shows examples of how big stars can be. Sirius is about two times the mass of the Sun, nearly twice as big, and has an energy output (luminosity) that is about 25 times greater than the Sun's luminosity. The star Pollux is twice as massive as the Sun, but 8 times bigger, and therefore has a luminosity that is much greater than Sirius. The star Arcturus is about the mass of the Sun, but 25 times bigger in size. It is also a lot older than the Sun and, hence, at a much later stage of its life. Arcturus has evolved to become what astronomers call a Red Giant, a star that has blown itself to a large size. Because of its size, Arcturus is also very bright, nearly 150 times brighter than the Sun.

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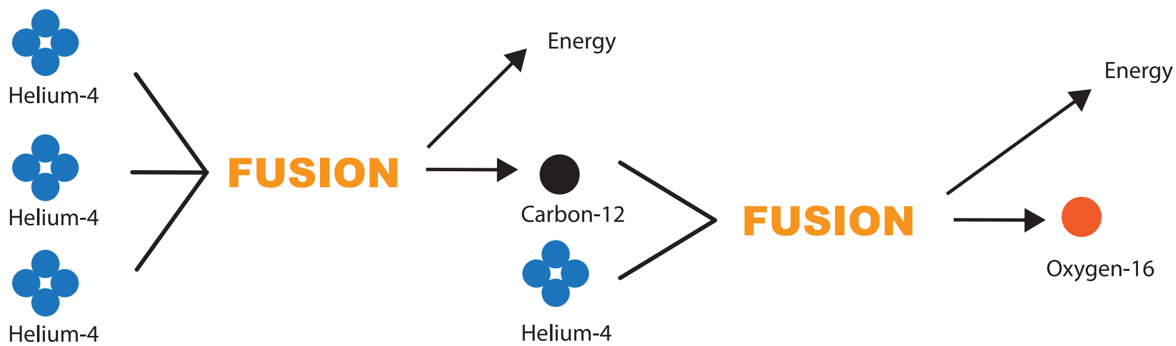

Fig. 10. Helium nuclei fuse to form carbon and oxygen nuclei. These reactions result in the release of energy, some of which goes into heating up the gas in the star, while the rest escapes into outer space.

only about a billion years or less. Thus, for low mass stars like the Sun, the formation of carbon and oxygen marks the last stage of their lives (see **Box 3**). As the nuclear reaction in their core shuts off, such stars prepare for their death in a slow but spectacular way. As it reaches its final stages, energy in the star is generated in a fairly unsteady manner, causing the star to rapidly pulsate (grow and shrink in size, and in brightness). As a result of these pulsations, the star begins to slowly puff out its layers of gas. The blown-out outer layers recede to the ambient space, gradually exposing the star's inner core of carbon and oxygen nuclei. These dying stars, called **planetary nebulae** by astronomers, look stunning (refer **Fig. 12**). The brightly-shining exposed core of the star is called a **white dwarf.**

There are as many as 10,000 planetary nebulae within the Milky Way. A minor fraction of the helium, carbon and

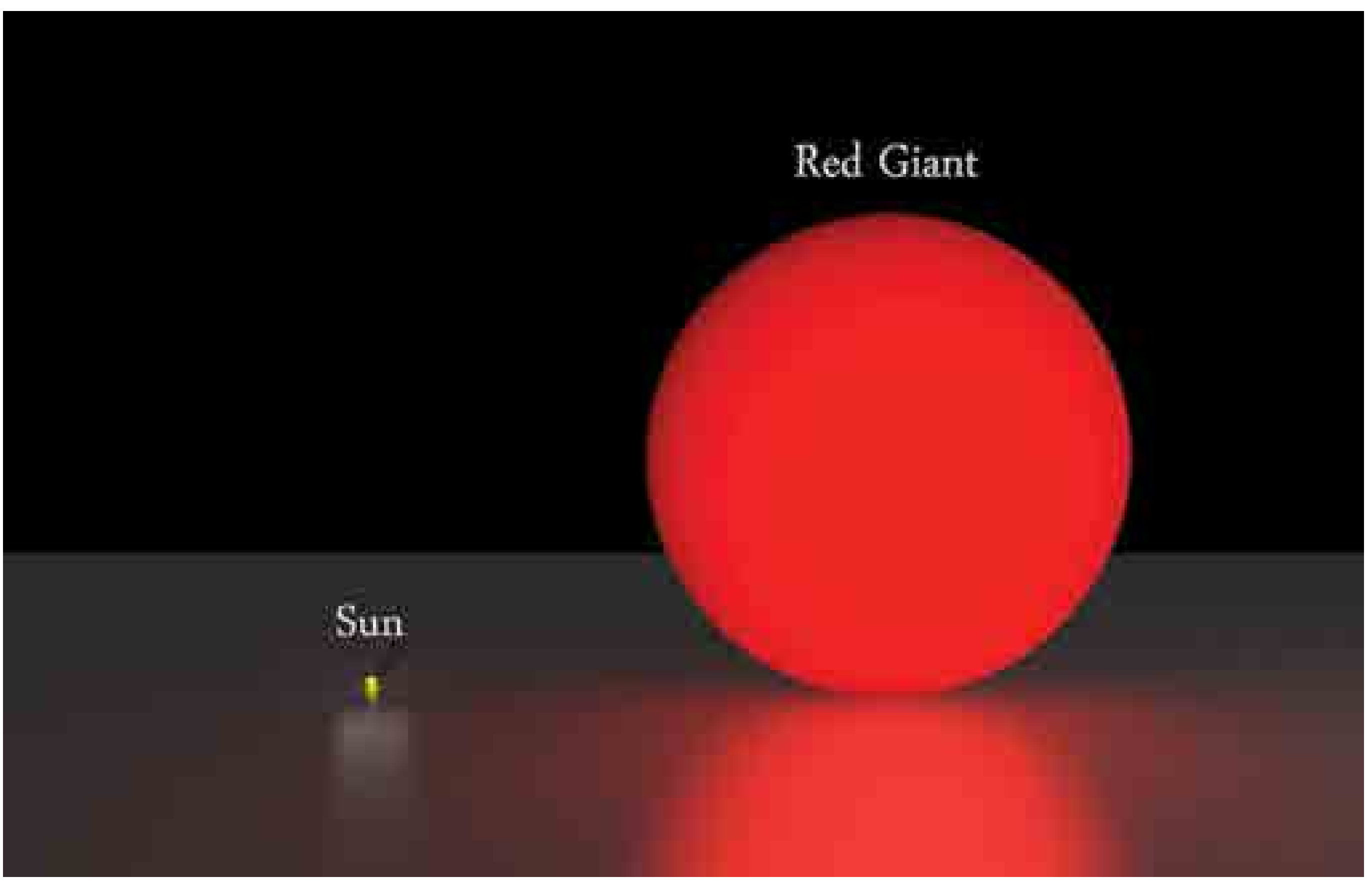

Fig. 11. The present Sun compared with its future as a red giant. As it ages, the Sun will swell up and fill the inner solar system. It will engulf Mercury, and grow to a size close to the orbit of Venus. The Earth will become much hotter, oceans will evaporate, and the hot atmosphere will escape Earth's gravity to outer space, all because of the blazing Red Giant Sun.

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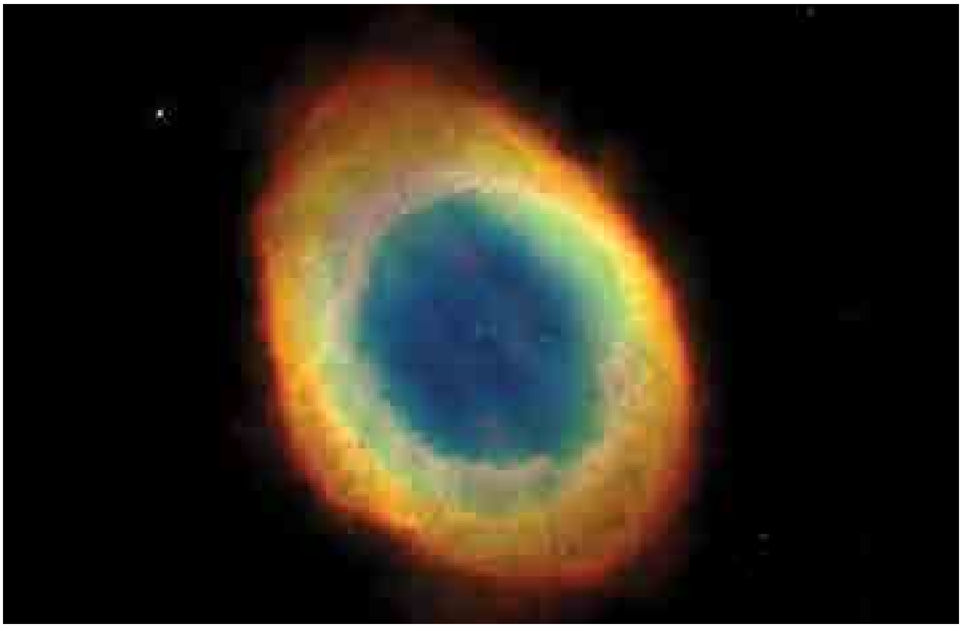

Fig. 12. The Ring Nebula, a famous planetary nebula, remains a low mass star that once used to shine like the Sun. The red, orange and blue glow comes from diffuse gas that was once part of the star. At the end of its life, the star slowly ejects its outer envelope, revealing the core. The exposed core is a white dwarf, where nuclear reactions used to take place. It is composed of carbon and oxygen nuclei. Despite its relatively small size, the white dwarf shines bright because it is at a temperature of about 100 million Kelvin. As the white dwarf radiates energy in the form of photons, it slowly cools.

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Fig. 13. A gallery of planetary nebulae within the Milky Way. Each image in this gallery represents the death of a low mass star like the Sun. The ring like structure is gas that was once part of the star and is now pushed out in a slow outburst. At the center of each planetary nebula is the white dwarf.

Credits: © NASA/ESA Hubble Space Telescope.

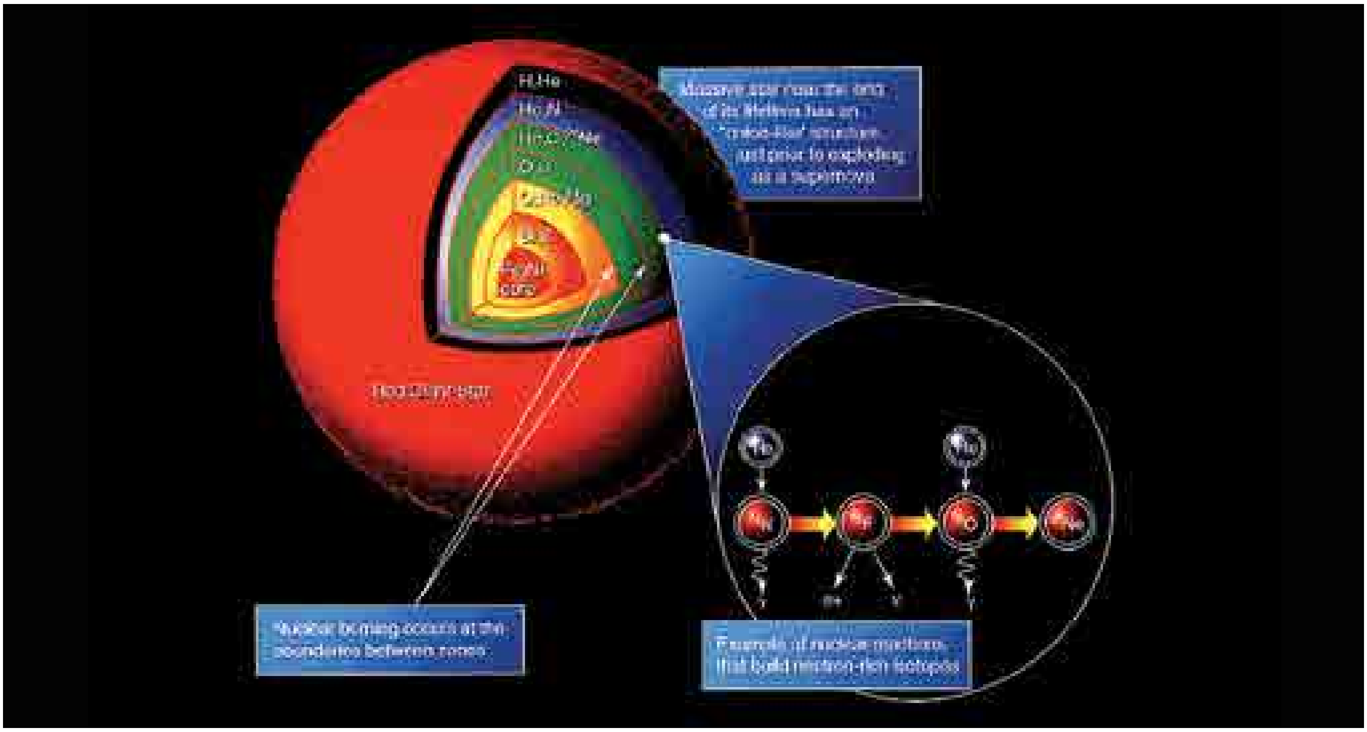

Fig. 14. Fusion reactions in a high mass star. From an initial phase of hydrogen fusion, different fusion reactions occur at different stages of the star's life in its core and the layers of gas close to the core. This results in the synthesis of various elements, a process that continues until iron nuclei start forming at the core.

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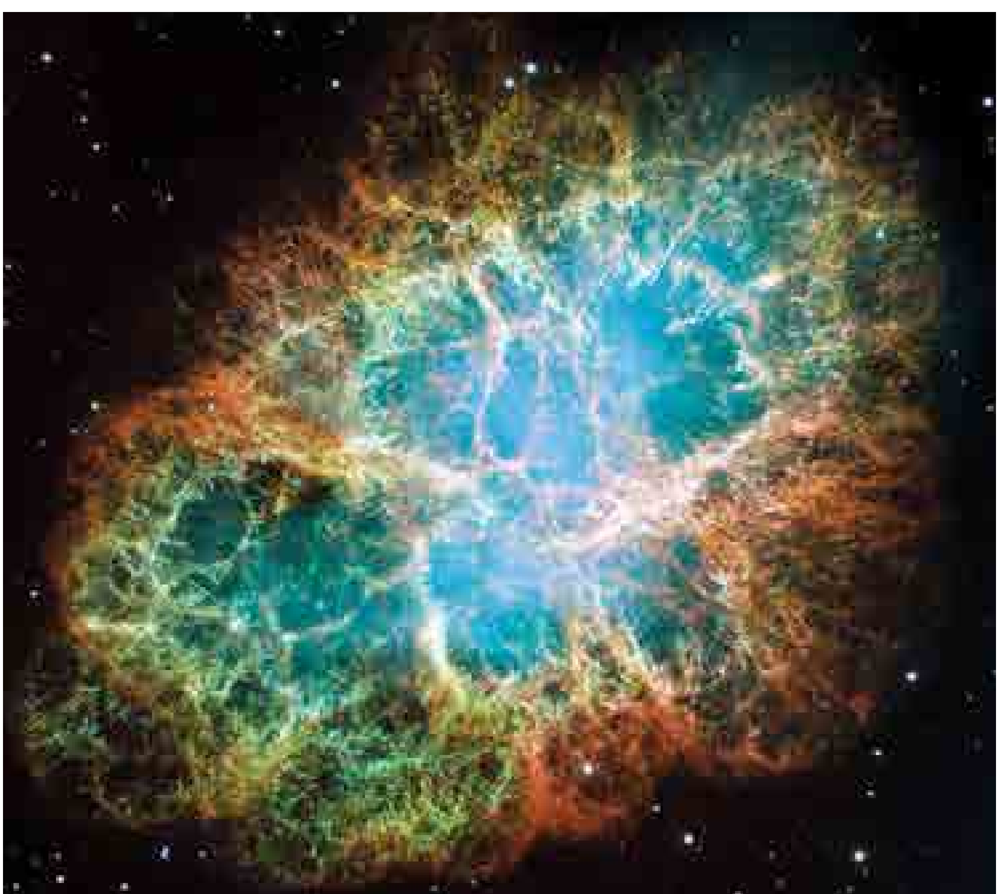

Fig. 15. The remains of a supernova explosion in our own galaxy. Astronomers estimate that this star must have exploded sometime around 1054 CE. The glowing gaseous structure was once part of the star. The gas expanding outwards from the explosion contains many heavier elements synthesized by the star. At the centre of this supernova is a neutron star, which is not visible in this image.

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oxygen in our galaxy is thought to have come from previous generations of planetary nebulae, and the stellar winds that preceded them. Thus, the death of every low mass star supplies the surrounding interstellar medium with these heavier elements (refer **Fig. 13**). Nonetheless, the heavy element contribution from the death of low mass stars is meager. The true source of chemical elements is the death of high mass stars.

Box 4. Unsolved questions:

The life history of stars is a favorite topic of astronomers. Nearly a century of painstaking research has yielded many fascinating insights into the secret lives of stars. But many questions still remain unanswered. For example, one of the big unknowns in astronomy is the exact nature of the first objects to have formed in the universe? The consensus seems to be that these were stars, but not quite the kind that we see in our Galaxy at present. The first stars, that formed billions of years ago, were a 100 times or more massive than the Sun, living very short (a few hundred thousand years) but spectacular lives. Astronomers are still trying to figure out how these first stars formed, and how they affected the environment around them when they went supernovae.

Another area of active investigation concerns the remains of stars — white dwarfs and neutron stars. Both of these are some of the densest objects in the universe. There are no laboratories on Earth where one can create such dense material. Our understanding of the physics of these exotic objects is far from complete. With the aid of supercomputers, astronomers are creating virtual stars, watching them evolve in fast forward, and testing out the best models that match with observations.

(b) The short spectacular life of high mass stars

High mass stars live comparatively shorter lives, but play a more important role in enriching the interstellar medium with heavier elements. Much like low mass stars, nuclear fusion at the core of high mass stars starts with the conversion of hydrogen to helium, and then moves to the conversion of helium to carbon and oxygen. However, both these reactions in high-mass stars occur at a much faster rate in order to keep the pressure due to gravity in balance. High mass stars thus inflate into **Red Super-Giants** (which are bigger than Red Giants) much sooner than a star like the Sun. Also, the synthesis of carbon and oxygen is not the end of the road for fusion in high mass stars. Instead, fusion reactions continue to occur beyond this stage, forming much heavier elements, such as neon, magnesium, silicon, sulphur etc. In fact, a new element is synthesized at every stage of nuclear fusion; and such reactions occur not just at the star's core, but also in the different gas layers surrounding it. This is a stage in stellar evolution that low mass stars never get to.

This cascading process of nuclear fusion continues till the formation of the first few iron nuclei at the core of the star. Since iron nuclei are very stable, they are incapable of fusing together to release energy. Thus, with the core getting entirely converted to iron, the star reaches the end of its life (refer **Fig. 14**). But just before dying off, the star treats us with one last spectacle. The core of the star collapses rapidly, sending a shock-wave which literally shreds the star apart in a violent explosion. Such explosions are called supernovae, after the Latin word *nova* meaning 'new'. When such an explosion happens within a galaxy, the supernova outshines the light from all the stars in the galaxy. Thus, for an observer looking at the night sky, these supernovae reveal themselves as sudden bright objects in the sky. Such events are so spectacular that they can be seen from distances at which even galaxies are hard to detect.

Only the inner core of the star, with its high density, survives the explosion (refer **Fig. 15**). This core transforms itself into either a neutron star (made entirely of neutrons) or a black hole (which is so dense that nothing, not even light, can escape from it). Both neutron stars and black holes are objects that are studied with great interest by astronomers. The rest of the material that was once part of the star is flung out into space as a result of the explosion. The brilliance of a supernova does not last very long. Its light fades out slowly, over a span of several weeks. Observations of the dimming of light from many supernovae have shown that it captures free neutrons to synthesize many new elements heavier than iron. Thus, over a period of a hundred million years, a high mass star transforms some of its hydrogen into an assortment of heavier elements — all of which, become part of the neighbouring interstellar gas clouds. It is out of these clouds that a new generation of stars and planets are formed, with a mixture of all these elements blended into them.

Rough estimates suggest that there could be about 100 million neutron stars and as many black holes within the Milky Way. This gives us an estimate of the number of supernova events that must have occurred in the past. Astronomers reckon that in a galaxy like the Milky Way, there could be at least one supernova explosion every century. Given that this seems like a very rare occurrence, imagine how long the Milky Way and other galaxies must have been in existence.

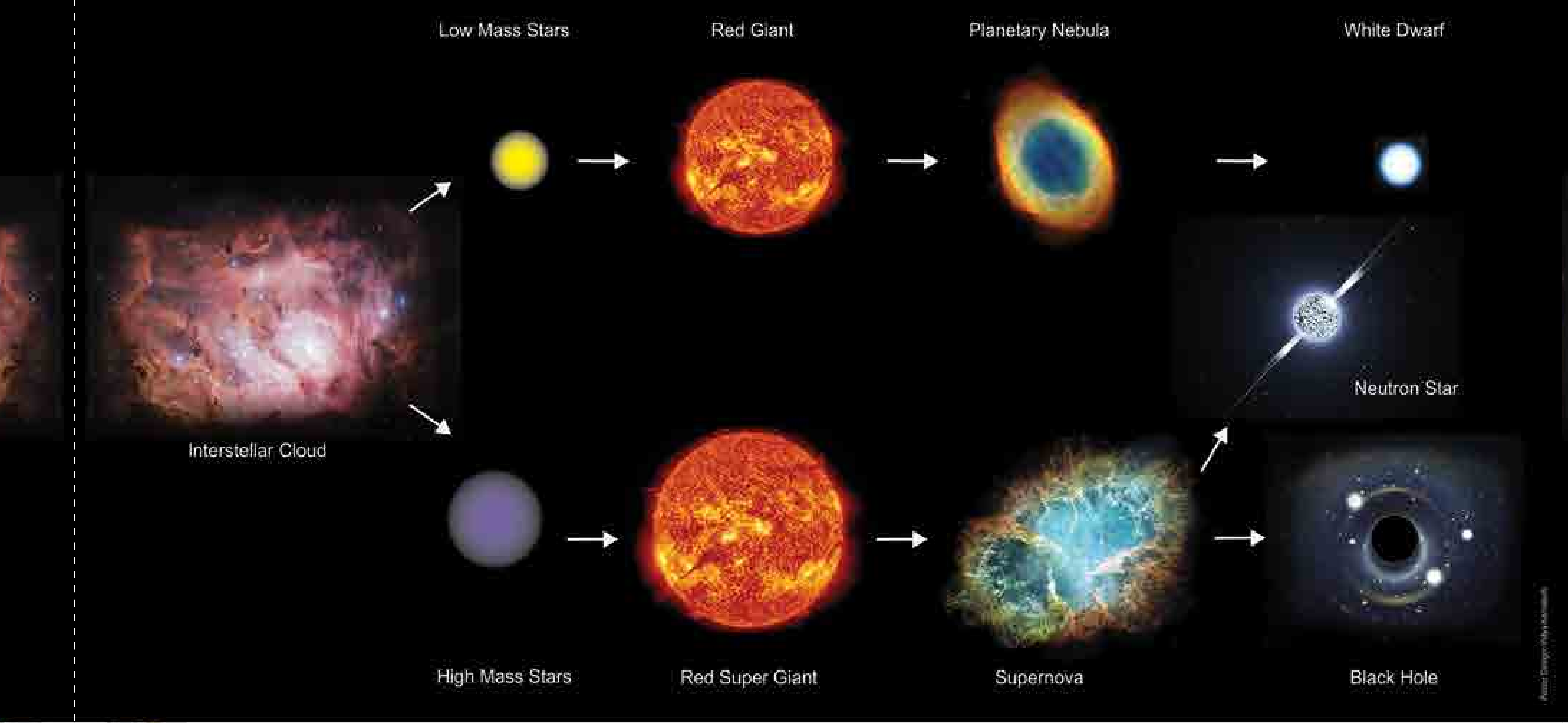
The cosmos is also within us

The story of stellar evolution is as much about the stars, as it is about us (refer **Box 4**). Imagine this for a moment: what if stars never existed? Or, even if they did, what if it was not in their destiny to die? What if they produced their energy by some process other than fusion? The universe would have never synthesized

Evolution of Stars

Author: Anand Narayanan

The mass of a star dictates its life. Low mass stars live long, ending their life in a puffy slow explosion called a planetary nebula. A white dwarf is what remains of it. High mass stars live comparatively shorter lives, ending their lives in violent supernova explosions, leaving behind either a neutron star or a black hole.



Anand Narayanan teaches astrophysics at the Indian Institute of Space Science and Technology. His research is on understanding how baryonic matter is distributed outside of galaxies at large scales. He regularly contributes to astronomy-related educational and public outreach activities. Every so often he likes to travel, exploring the cultural history of south India

i wonder...
Azim Premji University

elements heavier than hydrogen and some helium. Planets like the Earth, made mostly of heavier elements, would have never formed. Life, as we know it, would never have taken shape.

That's how important stellar evolution is to us. Every atom in our body had its origin in some star that lived and died more than 5 billion years ago. And with some stretch of imagination we could even say that the atoms in our body could have come from not one, but possibly a few different stars that went supernovae long before the birth of the solar system. In a more poetic sense, we are literally stardust.

The next time you are out in the open on a clear night, under the vast canopy of a starry sky, remember that the stars that are out there at vast distances from us, are also very much within us.

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MAJOR EVENTS IN THE EARTH'S EVOLUTION

S. MOHANA KUMAR

Nothing in this universe is unchanging. Change may be instantaneous, or may involve time-spans of several hundreds to millions of years. In the context of the Earth's history, we use the term 'evolution' to represent the progression of major changes that have shaped the planet; and the gradual development of the planet to the complex form that we know of today.

Our little planet was formed along with all the other planets of the solar system about 4.6 billion years or 4600 million years ago (one billion is equivalent to10^9). Earth scientists divide this long time span into divisions which provides a chronological reference of the Earth's evolutionary history. The larger and more major divisions in this time scale are called **eons**. Each eon is subdivided into smaller time units called **eras** and even further into **periods** and so on (as shown in Table 1).

Eons	Eras	Duration
Precambrian	Hadean	from 4000 million years to about 4600 million years (600 Myr)
	Archean	from 2500 million years to 4000 million years (1500 Myr)
	Proterozoic	from about 540 million years to 2500 million years (1960 Myr)
Phanerozoic	Palaeozoic	from about 252 million years to about 540 million years (288 Myr)
	Mesozoic	from 66 million years to about 252 million years (186 Myr)
	Cenozoic	from the present day to 66 million years (66 Myr)

Table. 1. The geological time scale (the abbreviation Myr stands for 'million years'). Note that the numerical ages shown above are subject to revision in the future.

The Precambrian eon

This eon is the first major division of geologic time covering about 88% of the Earth's history. It started with the formation of the planet (about 4.6 billion years ago) and lasted till the sudden diversification of multicellular organisms about 540 Myr ago, in what is known as the **Cambrian Explosion** (in the **Cambrian Period** at the commencement of Phanerozoic Eon).

All the planets of the Solar System were formed from a nebula — a spinning interstellar cloud of dust, hydrogen, helium and other ionized gases several light years in diameter surrounding the young Sun after its formation. The small particles of dust in this cloud collected together into larger and larger objects called planetoids. Planetoids were composed of pebbles, rocks and boulders that became massive enough to attract more and more material with the force of gravity. **The Giant Impact Hypothesis** (refer **Fig.1**) suggests that our moon was probably formed somewhere close to about 4500 billion years ago, not long after Earth's formation. An object about the size of Mars (which has been named **Theia**) smashed into the Earth and threw up a huge cloud of debris. The particles in this debris began to clump together, becoming larger and larger, resulting in our Moon.

(a) Hadean Era: This era, the earliest of the Precambrian Eon, lasted for nearly 600 myr. The history of the Hadean time is poorly understood because no rocks from this period have survived for our study. The Hadean Era would have been a terrible time to live in. During this time there were a lot more comets, meteoroids and asteroids in space, which often came crashing into the Earth's surface, creating much heat. The numerous craters found on the Moon

Fig. 1. The Giant Impact Hypothesis to explain the formation of the Moon.

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and other planets are evidence for the conditions that existed during the infancy of the Solar System. Scientists also believe that the Earth and other planets would have been molten at this stage of development (refer **Fig. 2**). The atmosphere of the Earth in this era would also have been very different from what we breathe today. Composed of methane, ammonia, and other gases, this reducing atmosphere would be toxic to most life on our planet today. With time, the Earth gradually cooled. The heavier molten iron sank into the centre of the planet to form its core; while lighter materials rose to the surface, cooled, and formed the crust. The Earth and the Moon continued to be bombarded by extra-terrestrial objects throughout the Hadean.

Box 1. Prokaryotes vs. Eukaryotes.

The difference between prokaryotic and eukaryotic organisms is a fundamental one. While the latter have a nucleus and other membrane-bound structures called organelles; cells of prokaryotes are devoid of these. Prokaryotes were the first forms of life on Earth, appearing between 3900 Myr and 2500 Myr ago. These organisms also remained the only forms of life on Earth for several millions of years. It was only much later (about 1850 myr ago) that eukaryotic organisms with their more complicated structures and larger sizes came into being.

(b) Archean Era: During this era, which lasted between 4000 Myr and 2500 Myr ago, there was little free oxygen in the Earth's atmosphere. As a result of the prevailing high temperatures, all the water in the Earth's atmosphere was in the form of vapour. Towards the later part of this era, some forms of bacteria evolved ways of harnessing sunlight to make sugar from carbon dioxide and water just like green plants today. These bacteria started releasing oxygen, a waste product of this reaction, into the atmosphere. This led to the gradual development of an oxygen-rich atmosphere. As the Earth continued to cool down, water vapour in its atmosphere condensed and fell as torrential rain, filling its depressions to form the earliest oceans. Although highly debated, most scientists consider the origin of life to be a natural event in the evolution of the Earth. The oldest fossils to be discovered, in rocks called stromatolites, are those of 3.8 billion years old colonies of single-celled prokaryotes, called cyanobacteria that obtain their energy through photosynthesis (refer **Fig. 3**) The appearance of these single-celled forms of life, much like modern bacteria, marks the origin and development of the biosphere.

(c) Proterozoic Era: This era extended from about 540 Myr to 2500 Myr. There were two **ice ages** during the period – one between 2400 Myr to 2100 Myr, and another one between 720 Myr and 635 Myr. Around about 2000 Myr ago, the first definite eukaryotes made their appearance (refer **Fig. 4**). By 1800 Myr, the atmosphere became oxidising. Oceanic cyanobacteria, which evolved into multicellular forms more than 2.3 billion years ago, are believed to have become the first microbes to produce oxygen by photosynthesis which was free to escape into the atmosphere. The

Fig. 2. The Hadean Earth was frequently bombarded by comets, meteoroids and asteroids.

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Fig. 3. Modern Stromatolites.

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oxygen in the atmosphere gradually increased from <1% to 21% somewhere around 500 Myr, as a result of continued organic evolution and the consequent increase in biological activity. Available fossil records show that in a period of 100 Myr towards the close of this era, a group of complex, soft-bodied multicellular organisms or metazoans made their first appearance, and progressively became more common towards the end of Precambrian Eon. Because there were no predators, these earliest metazoans lacked any hard parts and have left perfect fossils. This assemblage of organisms is called the **Ediacara fauna** as these were first discovered in the Ediacara Hills of Australia.

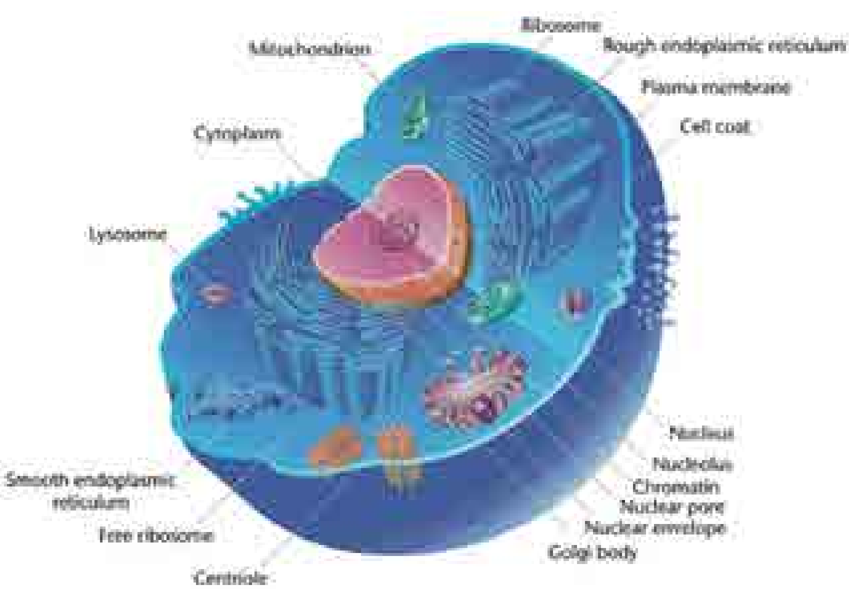

Fig. 4. Modern eukaryotic cells evolved from ancestors that first appeared about 1850 Myr ago.

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Plate tectonics, one of the most important discoveries of the 20th century, is a modern theory developed from an earlier concept — that of **continental drift.** This theory is widely accepted today, and has almost entirely replaced the earlier concept of continental drift. According to plate tectonics, the relatively rigid lithosphere of the earth is divided into seven large **plates** and a number of smaller plates which float on and travel independently in different directions, over the underlying partially molten mantle. This movement happens very slowly — as slow as the growth of your finger nails (refer **Fig. 5**). Movements of these lithospheric plates (not continents, as believed earlier) over millions of years result in significant changes in the global geography. Much of the Earth's activity — earthquakes, volcanoes, the rising of mountains etc. — are confined to the boundaries of these plates. Earth scientists believe that

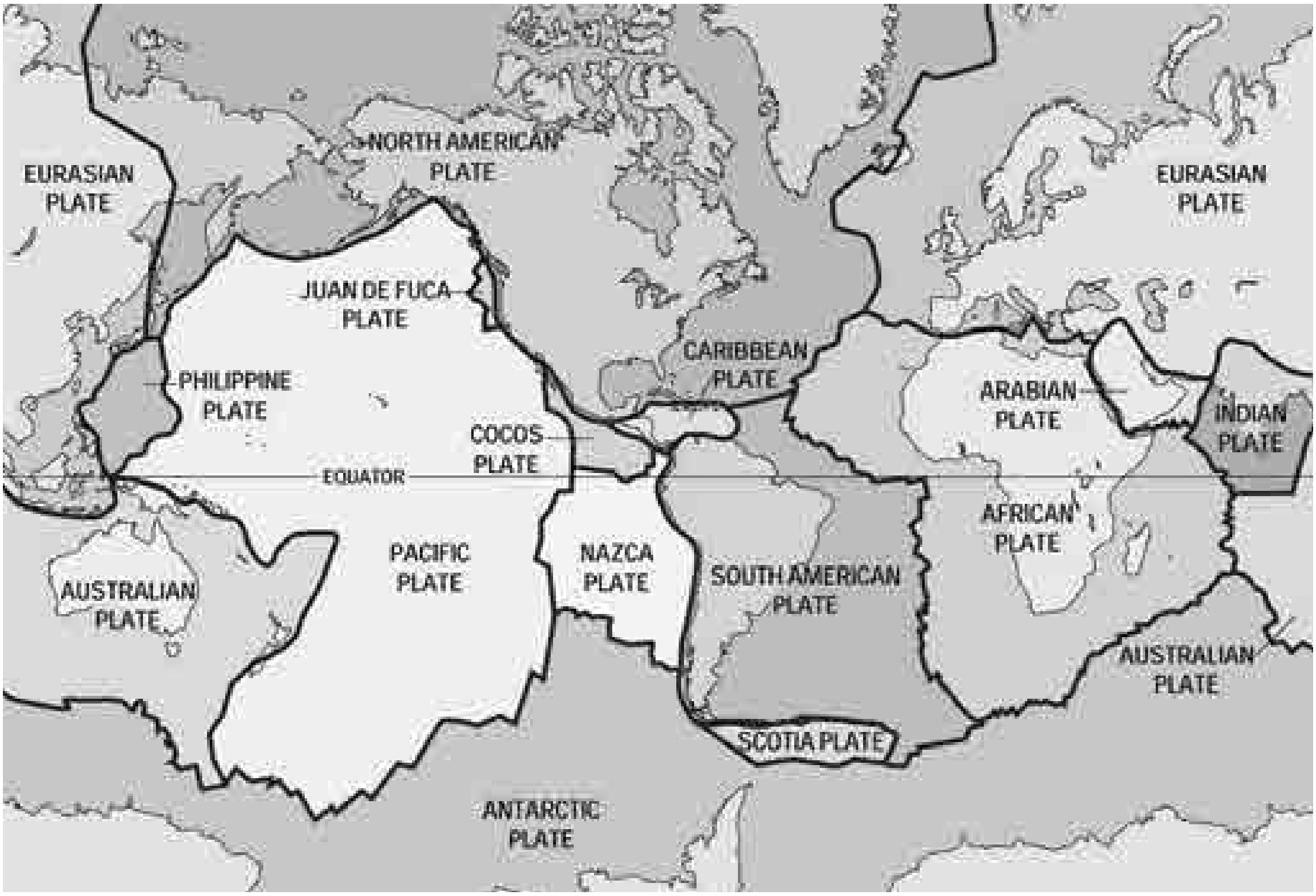

Fig. 5. According to Plate Tectonics, the Lithosphere of the Earth is divided into seven large plates and numerous small plates.
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plate tectonics in the Earth's outer shell commenced earlier than 3000 Myr ago.

The most important development in Earth sciences since the advent of plate tectonics is the discovery that the history of the Earth has been interposed by the development of supercontinents. A **supercontinent** is produced by the gathering or clustering of most or all of Earth's continental blocks, resulting in a single large landmass. During the history of the Earth, these supercontinents subsequently fragmented and the resulting continental blocks drifted apart to produce a new global geography. We know that the spatial disposition of the continents of today is really only a temporary arrangement in a long history of lithospheric plate movement. During the Precambrian Era, **Ur** was a supercontinent that formed somewhere around 3100 Myr ago. **Columbia** was another one formed between 2500 Myr and 1600 Myr ago, and **Rodinia** was yet another supercontinent that existed between about 1000 Myr and 750 Myr ago. **Pannotia** was a supercontinent that existed at the end of the Precambrian somewhere around 650 Myr ago. **Pangaea** — yet another supercontinent that existed about 300 Myr, started to split about 280 Myr to 230 myr (refer **Fig. 6**).

The last known supercontinent, called **Gondwana**, was comprised of what are now Africa, India, Madagascar, Australia and Antarctica (refer **Fig. 7**). Numerous studies have indicated that the formation and disruption of supercontinents during different portions of Earth's history, known as the **supercontinent cycle**, has profoundly influenced the evolutionary course of the lithosphere, hydrosphere, atmosphere and biosphere.

Phanerozoic eon

The name Phanerozoic was derived from the ancient Greek words phanerós and zoe, meaning **visible life.** This is based on the once-held understanding that life began in the Cambrian period of this eon. This eon is characterised by the appearance of organisms with hard parts (that are capable of preservation as fossils in contrast with the traces and chemical fossils left from organisms in earlier times). The Phanerozoic Eon is divided into three eras.

(a) Paleozoic Era: This is the earliest and the longest era of the Phanerozoic eon, covering a period of about 288 Myr. This era is further subdivided into six geologic periods — known as the

Fig. 6. Pangea – one of the many supercontinents formed during the Earth's changing geography.

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Cambrian, Ordovician, Silurian, Devonian, Carboniferous and **Permian** periods in decreasing order of age.

The beginning of the Palaeozoic Era is defined by the appearance of the first skeletal or shelly fauna — the first animals with hard parts. The atmospheric CO_2 levels were ten times higher in the early Paleozoic. The sea level was much higher than today, and was reduced to modern levels by the end of the era. Between 450 Myr and 420 Myr, the Earth was swept by the third ice age — evident through the glacial deposits of different periods now preserved in rock records. Following this, shallow seas flooded continental interiors. Earlier forests were dominated with the **lycopsid** group of plants; woody plants evolved somewhere around 420 Myr ago. The accumulations of these plants and their later transformation is what gave rise to the coal deposits that are now found in many parts of the world (refer **Fig. 8**).

Fossil records indicate that with the beginning of this era, organisms with mineralized hard parts, which were capable of preservation in rocks during fossilization, first appeared in the oceans. These, then, suddenly became very numerous. The earliest fossils of this era consist mostly of trilobites, brachiopods, reef-forming archaeocyathids, and small little marine shells (refer **Fig. 9**). As discussed earlier, the rapid radiation and diversification of life-forms, probably from a common ancestor, during the 540–520 Myr interval in the Cambrian Period is known as the Cambrian Explosion. All known phyla had appeared by then. This produced the first representatives of almost all modern marine invertebrate animal groups. Because there was no vegetation, most of the land surface of the continents, which were clustered in the Southern Hemisphere at this time, was probably dry, rocky or blanketed with a microbial soil crust. The period about 440 Myr ago was marked by an extinction in which nearly 86% of all species of some groups of organisms disappeared from the Earth. This is known as **Ordovician-Silurian Extinction Event**.

It was during this era that the Appalachian, Ural, and mountains of Mongolia were formed by the collision of lithospheric plates. Towards the end of this era, the first modern plants (conifers) appeared on Earth, and molluscs and arthropods dominated the oceans. The appearance of vertebrate animals is one of the notable events of this era.

TRIASSIC-200 million years ago

Fig. 7. Gondwana – the last known supercontinent in the Earth's history.

Credits: LennyWikidata, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Laurasia-Gondwana.svg. License: CC-BY.

Fig. 8. **Lycopods (like club mosses) are some of the oldest living vascular plants.**

Credits: Mokkie, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Club_Moss_(Lycopodium_carinatum)_1.jpg. License: CC-BY-SA.

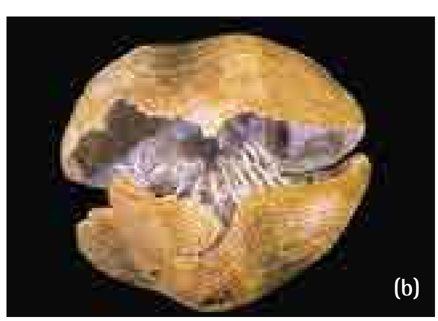
In the period between 415 Myr and 355 Myr ago, fishes of many different types appeared in the oceans. Lobe-finned fishes – ancestors to the amphibians and the early sharks – made their appearance in this period. This period of the history of the Earth is therefore called the **Age of Fishes.** The appearance of fishes led to extinction of about 75% of the species of some primitive groups of marine organisms, including trilobites.

The Earth witnessed a fourth ice age between 360 Myr and 260 Myr ago. A major mass extinction that occurred at about 250 Myr seriously affected nearly 95% of the species living at that time, including tabulate corals, and most extant trees. Described as the **Great Dying**, this resulted in the disappearance of many earlier forms of animals and plants from the Earth.

(b) Mesozoic Era: This era included three periods – **Triassic, Jurassic** and **Cretaceous** – in deceasing order of their age. The Mesozoic era began 252.2 Myr ago, and lasted for another 186.2 Myr. The continents of today began to move into their present locations during the later stages of this era. The ancestors of major plant and animal groups that exist today evolved during this portion of Earth's history. Called the **age of reptiles**, it is in this era that dinosaurs began to appear, roughly 20 Myr after the major extinction event that wiped out almost all life on Earth 250 Myr ago. Terrestrial life diversified rapidly, and giant reptiles, dinosaurs and other monstrous beasts roamed the Earth till the end of this era. Another major mass extinction occurred at about 200 Myr ago, when about 20% of marine families and many terrestrial vertebrates vanished from the Earth. It is believed that an asteroid with a diameter of about 10km hit the Earth and caused another major mass extinction at the end of this era. This resulted in the extinction of the dinosaurs and several other terrestrial animal groups (refer **Fig. 10**). In the marine world, all the ammonites, reef-building bivalves, and marine reptile species also died off.

(c) Cenozoic Era: the era of new life: This era covers the last 66 Myr period. In this era, a drying and cooling trend culminated in the last known ice age –

Fig. 9. **Fossils of Trilobites (a), Brachiopods (b) and Archaeocyathids (c) from the Palaeozoic era.**



(a) Tim Evanson, Smithsonian Museum of Natural History - 2012-05-17, Flickr. URL: https://www.flickr.com/photos/timevanson/7282110704. License: CC-BY-SA.

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Fig. 10. Dinosaurs appeared in the Mesozoic Era.

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known as the **Quaternary Glaciation**, which began 2.58 Myr ago. The polar ice caps and continental ice sheets of the northern hemisphere began to expand as far as 40 degrees latitude, and thickened repeatedly in North and South America, Europe, Asia, and Antarctica. At the peak of this ice age, nearly 30% of the Earth's surface was covered by glacial ice. The major consequence of glaciation was a world-wide drop in the mean sea level. The extinction of the dinosaurs towards the close of Mesozoic Era allowed mammals to diversify, with many becoming larger in size during the Cenozoic. As large mammals (such as mammoths, mastodons and several others), birds (including large flightless ones) and flowering plants formed the major groups of organisms in regions not covered by ice, this era is described both as **Age of Mammals** and the **Age of Birds** (refer **Fig. 11**).

Most of these animals became extinct during the Quaternary extinction event, at the end of the glacial period, about 11,700 years ago. Most scientists believe that all the modern humans alive today have descended from a small population which lived in Africa 150,000 to 200,000 years ago. Later, about around 100,000 years ago, modern humans migrated to Europe and Asia. The Indian subcontinent collided with Eurasia to form the Himalayas. The collision of Africa and Europe resulted in the Alps.

Early humans first appeared in Africa and migrated into Asia, probably between 2 million and 1.8 Myr. Species of modern humans populated many parts of the world much later. The beginnings of agriculture and the rise of the first civilizations occurred within the past 12,000 years. The term **Anthropocene** is often used as an informal term to describe the current geological period in which we are living. The significance of this term is that for the first time in the history of the planet, human activity is influencing planetary conditions — experienced in the form of climate change, sea-level rise, mounting environmental degradation, and air and water pollution.

From this very brief summary of the Earth we know that the lithosphere, atmosphere, hydrosphere and the biosphere of our planet are constantly changing. And the effects of these changes are likely to manifest themselves over long periods of time, involving millions of years. These processes will definitely continue to influence our future and the future of all other life on Earth.

Fig. 11. The Cenozoic Era was characterized by mammals (like the woolly mammoths, equids, woolly rhinoceros, European cave lions and the reindeer carcass shown in this image) that diversified and became larger in size.

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EARTH EVOLUTION

The Intersection of Geology and Biology

The Earth is approximately 4.6 billion years old. Over this vast span of time, the planet has changed dramatically from an inhospitable sphere of molten rock to a diverse world rich with life. The world we live in today is the product of complex interactions between life and the environment.

Eons: PHANEROZOIC, PROTEROZOIC, ARCHEAN, HADEAN

Eras: Cenozoic, Mesozoic, Paleozoic

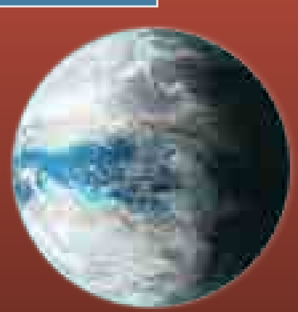
Periods: Quaternary, Neogene, Paleogene, Cretaceous, Jurassic, Triassic, Permian, Carboniferous, Devonian, Silurian, Ordovician, Cambrian, Ediacaran, Cryogenian

Time Before Present (millions of years): 0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, 3000, 3200, 3400, 3600, 3800, 4000, 4200, 4400, 4600

- Ice Age
- Snowball Earth
- Snowball Earth
- Rodinia breakup
- Supercontinent Rodinia forms

- Early supercontinent (Nuna)

- Snowball Earth



At the beginning and end of the Proterozoic Eon, glaciers extended all the way to the equator. The ice eventually receded as greenhouse gases ejected by volcanoes accumulated in the atmosphere, warming the planet.

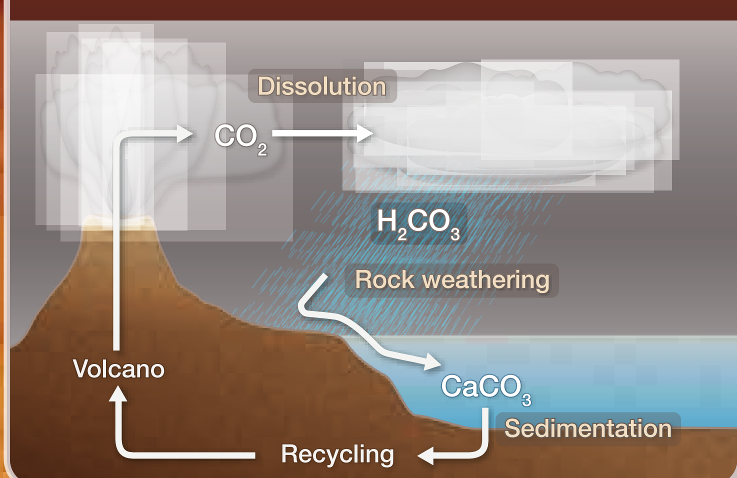
- Earliest evidence for plate tectonic movements
- Oldest rock
- Earliest date for liquid water on Earth
- Earth forms by accretion from solar dust cloud

Mass Extinctions

There have been multiple mass extinctions during the course of Earth's history in which dominant organisms were wiped out, opening up new evolutionary possibilities for survivors. The mass extinction at the end of the Cretaceous Period 65 million years ago is thought to have been caused by the impact of a large (11 km) meteorite. Other mass extinctions, however, appear to reflect environmental perturbation caused by Earth processes such as volcanism and climate change.

Geologic Carbon Cycle

Volcanoes release carbon dioxide—a greenhouse gas—from the lithosphere into the atmosphere. Warmer temperatures accelerate rock weathering reactions, which remove carbon dioxide from the atmosphere. This cycle acts as a global thermostat.



Greenhouse Effect

As sunlight warms the Earth, it re-radiates energy back to space. Greenhouse gases absorb this energy, resulting in further warming. Without the greenhouse effect, Earth would be too cold for life, but too much of it can create an inhospitable environment.

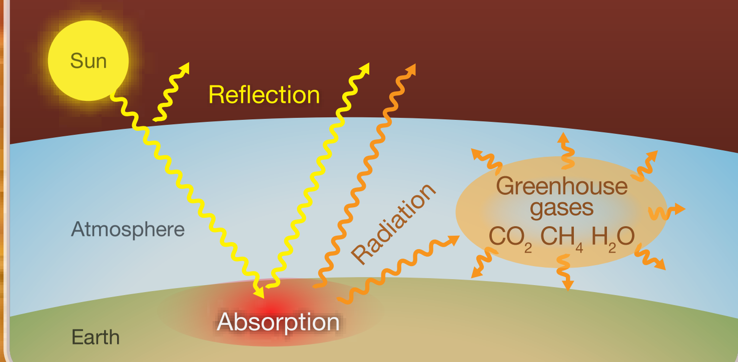
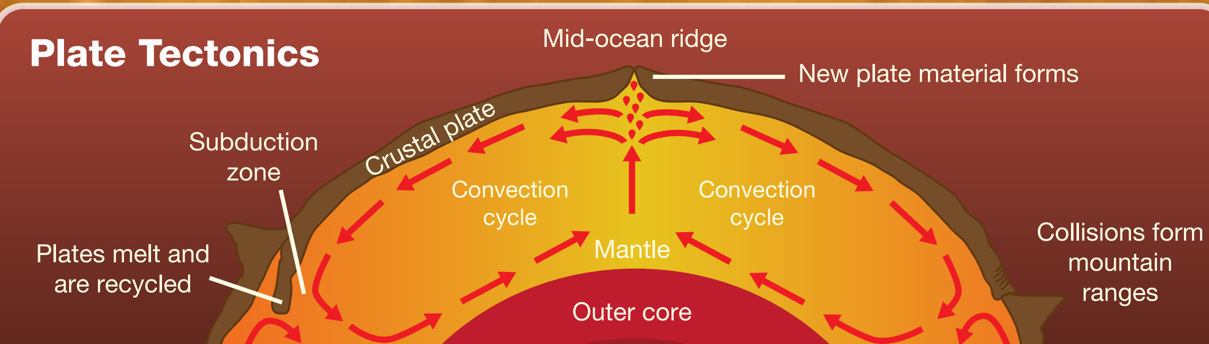


Plate Tectonics



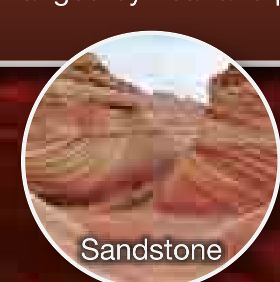
Earth's crust is composed of large plates that move in response to forces generated by convection of material in the underlying mantle. Plate movements have resulted in the formation of supercontinents such as Nuna, Rodinia, and Pangea, at different times in Earth's history.

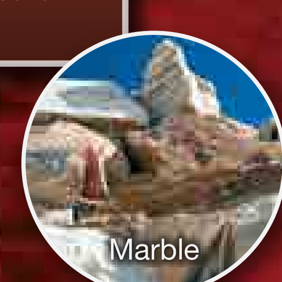
Rock Types 101

Igneous: Form when molten materials cool and harden, either beneath the Earth's surface or in a volcanic eruption.

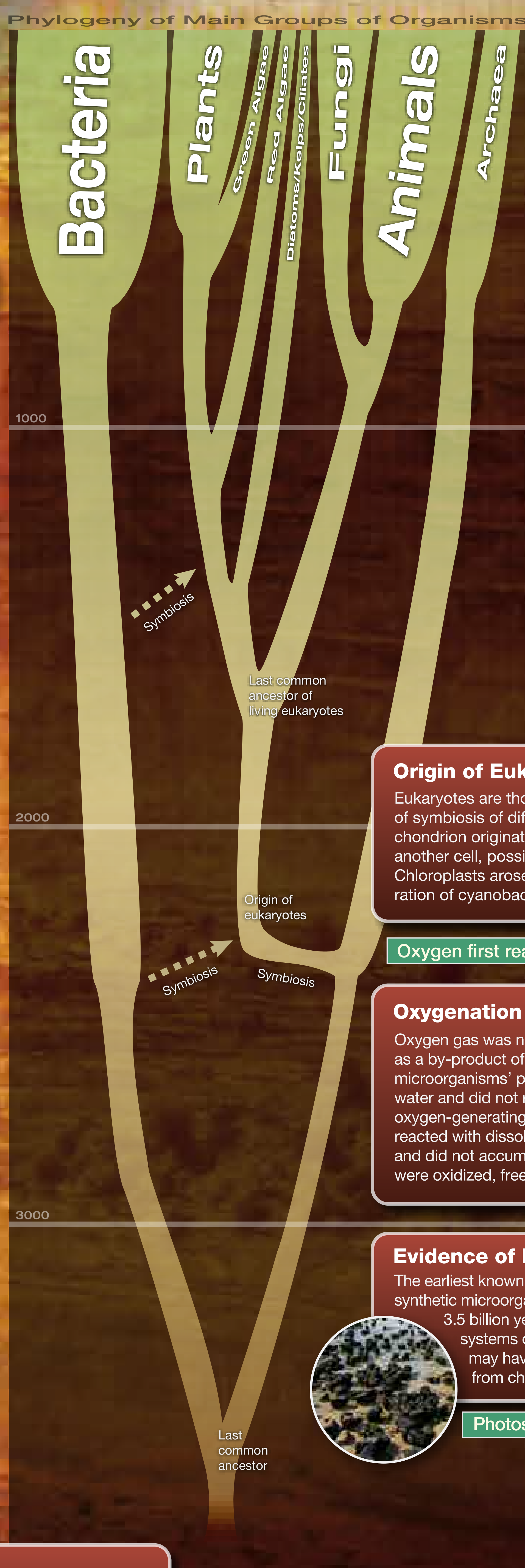
Sedimentary: Form at the Earth's surface when particles eroded from older rocks accumulate or when minerals from lake, river, or ocean water precipitate.

Metamorphic: Form when existing rocks are changed by heat and pressure.





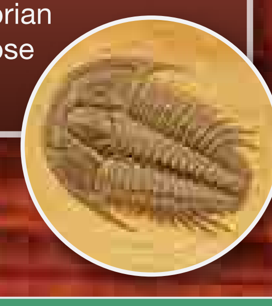
Phylogeny of Main Groups of Organisms



- Genus *Homo*
- Dinosaur extinction; Mammalian dominance
- Permian extinction
- First land vertebrates
- First land plants
- Cambrian explosion
- Ediacaran diversification of large animals

Oxygen and Animal Size

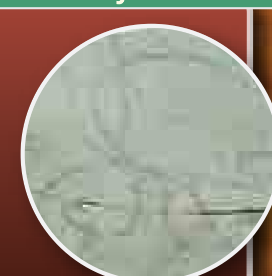
Large active animals require high levels of oxygen. They did not evolve until the Ediacaran and Cambrian Periods, when oxygen rose to near-modern levels.



- Origin of chloroplast by symbiosis
- Oldest eukaryotic fossil

Origin of Eukaryotes

Eukaryotes are thought to have arisen as a result of symbiosis of different prokaryotes. The mitochondrion originated as a bacterium captured by another cell, possibly a member of the Archaea. Chloroplasts arose later by the symbiotic incorporation of cyanobacteria into a eukaryotic host.



- Oxygen first reaches significant (about 1% of current) levels

Oxygenation of the Planet

Oxygen gas was not present in Earth's early atmosphere; it arose as a by-product of oxygenic photosynthesis. Initially, early microorganisms' photosynthetic reactions did not use water and did not release oxygen. Once oxygen-generating organisms evolved, oxygen reacted with dissolved iron and sulfide in the ocean and did not accumulate. After these compounds were oxidized, free oxygen started to accumulate.

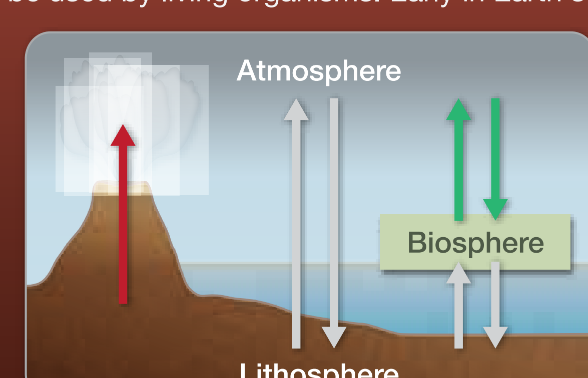
Evidence of Early Photosynthesis

The earliest known stromatolites—layered deposits made by photosynthetic microorganisms—suggest that photosynthesis arose at least 3.5 billion years ago. Today, photosynthesis fuels most ecosystems on Earth, but Earth's earliest biological communities may have been driven by chemosynthesis, gaining energy from chemical reactions to form organic compounds.

- Photosynthesis; Oldest fossils on Earth; Stromatolites
- Oldest chemical signature of life

Life and Chemical Cycling

All life depends on carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorous. These elements are abundant in the lithosphere and/or atmosphere and cycle between the two. Naturally occurring forms of sulfur and nitrogen cannot be used by living organisms. Early in Earth's history, microorganisms evolved mechanisms to extract these elements from the environment, allowing rapid growth of Earth's ecosystems (biosphere). These microbial mechanisms remain essential to life on Earth—billions of years later.



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WHERE DO WE COME FROM? WHAT ARE WE? WHERE ARE WE GOING?

AVINASH KUMAR

Beginning with an account of the discovery of some fossilized 'cave bear bones' in a small valley in 19th century Germany, this article describes the evolution of our genus *Homo* and the many species that comprise it. It ends with outlining some suggestions on how the study of human evolution can be integrated with science classrooms.

It was August of the year 1856. Summer was turning to autumn in Elberfeld, a small town in western Germany. Johann Carl Fuhlrott, a teacher at the local high school and an amateur naturalist and fossil collector, was heading purposefully in the southwest direction.

Fuhlrott had received a message from a mining foreman working in a nearby valley called Neanderthal: workers in his limestone-quarry had broken through the rock-hard layers of clay at the entrance of a cave (refer **Fig. 1**), accidentally unearthing some fossilized bones. It had seemed to the foreman that they were the remains of an ancient cave bear, and he wanted Fuhlrott to come and take a look[1].

A few hours later, Fuhlrott found himself in a cave about 18m above the valley floor and 30m below the top of a cliff. The cave was 2m high, 2.5m wide, and 4.5m deep. He was standing on loam, almost 1.5m thick, which covered the floor of the cave[2].

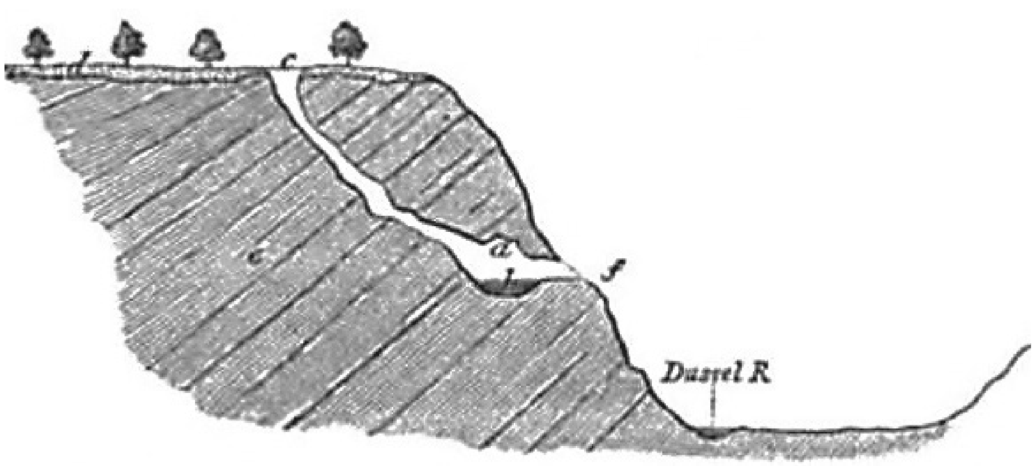

Fig. 1. The location of the cave where Johann Carl Fuhlrott made his discovery.

Credits: Gerbil & HerrAdams, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Kleine_Feldhofer_Grotte.jpg. License: Public Domain

Fig. 2. (a) The bones found in the Neander Valley.

Credits: LVR-LandesMuseum Bonn. URL: http://donsmaps.com/neanderthaloriginal.html. License: Public Domain.

(b) A reconstruction of a Neanderthal man.

Credits: Matanya, Wikimedia Commons. URL: https://en.wiktionary.org/wiki/File:%D7%A0%D7%99%D7%90%D7%A0%D7%93%D7%A8%D7%98%D7%9C%D7%99.jpg. License: CC-BY-SA.

The fossilized bones, he was informed by the miners, had been found in the loamy floor at a depth of about 0.5m. Though initially ignored, they had later fortuitously come to the attention of the quarry owners who managed to salvage 16 bones and bone fragments from the rubble. Knowing Fuhlrott's keen interest in the subject, they now offered these to him.

Back home in Elberfeld, Fuhlrott took stock of the fossilized collection of bones — it included a skullcap with a fragment of the left temporal bone (situated at the sides and base of the skull), a part of the right shoulder bone, a right collarbone, both long bones of the forearm, a complete forearm bone along with some other fragments of the forearm, five ribs, the left half of a pelvis, and both thigh bones[3]. Bent over his desk studying the fossilized remains, the intuition that Fuhlrott originally felt in the cave grew even stronger — the bones were clearly not that of an ancient bear as the miners had assumed; but more importantly — **they seemed like the remains of a human being who was significantly different from modern humans!**

Within a month of Fuhlrott's visit to the cave, a local newspaper published the story of his curious find. This drew the attention of Hermann Schaaffhausen, a Professor of Anatomy at the University of Bonn, who was researching the prehistoric humans of Europe.

Fuhlrott and Schaaffhausen met in Bonn the following November, and Fuhlrott passed on the bones to Schaaffhausen. After about six months of detailed study, they jointly presented the results of their investigations at an academic gathering — with Fuhlrott highlighting the age of the bones as proved by the depth of the stratum in which they were discovered and the mineralization and dendrite formation on the surface, and Schaaffhausen describing the unusual shape of the skull cap (low, sloping forehead and the bony ridges above the eyes) as well as the remarkable thickness of all the bones in general (refer **Fig. 2**).

Both suggested that the bones belonged to a human of pre-historic times, who had inhabited Germany before the arrival of the ancestors of modern humans.

Box 1. Species, Genus and Family:

Starting from Aristotle's time until the late 18th century, it was commonly believed that species do not change or go extinct; and are not genetically related to each other, even if some of them appeared to be similar. It was only in the early 19th century that the idea that species could change over time started to take root among some European naturalists and scientists, such as Lamarck. In 1859, Charles Darwin famously suggested that populations evolved (into different species) through the selection of naturally-occurring variations among its individuals.

Broadly, all organisms that tend to mate naturally, and produce fertile offspring easily, are considered as being from the same species. At times, however, different groups (or populations) of the same species may become isolated from one another. Over thousands of years, each of these different populations tend to accumulate certain genetic changes (or mutations) which are beneficial to their members but may not be present in the other populations of the same species. After a point, such genetic and behavioral changes make inter-breeding between the individuals of these different populations increasingly rare and, subsequently, impossible. These populations are then said to have become distinct species.

Two or more species that have evolved in this manner from a common ancestor are grouped under one genus, and similar genera are grouped under one family. For example, lions, tigers, jaguars, leopards and snow leopards are all considered distinct species as they tend to not mate with each other, and in the rare cases that they do, their offspring tend to not be fertile. These five species are, however, related to a common ancestor, believed to have lived about 6 to 10 million years ago, and hence, these species are grouped together under the genus *Panthera* (refer **Fig. 3**).

The scientific name of each species consists of two parts – the first part, which is common to all five, is the name of the genus; whereas, the second part is specific to each species. So, for example, in scientific terms, lions are called *Panthera leo*, tigers *Panthera tigris*, jaguars *Panthera onca*, leopards *Panthera pardus*, and snow leopards *Panthera uncia*.

These five species of the genus *Panthera*, along with some other species such as those of cougars, cheetahs and domestic cats (which belong to various other genera), together, form the family *Felidae* – more commonly known as the 'family of cats'.

Fig. 3. Some species in the family *Felidae*.

Credits: LittleJerry, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:The_Felidae.jpg. License: CC BY-SA.

Where do we come from?

The practice of identifying organisms using binomial nomenclature, and classifying them using different 'levels' (kingdom, class, order, genus, and species) was formalized by a famous Swedish scientist of the 18th century — Carl Linnaeus. It was also Linnaeus who coined the scientific name of our species: *Homo sapiens* (literally: sapient/wise human).

For almost a century thereafter, it was believed that our genus *Homo* had no other species and other members of our family *Hominidae* (commonly known as the family of great apes) were believed to be our closest relatives (refer **Fig. 4**). The great ape family comprises of four extant (meaning: surviving) genera and seven extant species: the Bornean and Sumatran orangutans (genus: *Pongo*), eastern and western gorillas (genus: *Gorilla*), chimpanzees and bonobos (genus: *Pan*), and humans (genus: *Homo*).

Six years after Fuhlrott and Schaaffhausen had presented the findings of their investigations on the fossilized bones of the Neandertal (*tal* is German for valley), William King, an Irish geologist, began a process that continues to change our understanding of ourselves and our place in this world — he proposed that the Neanderthal bones were neither those of *Homo*

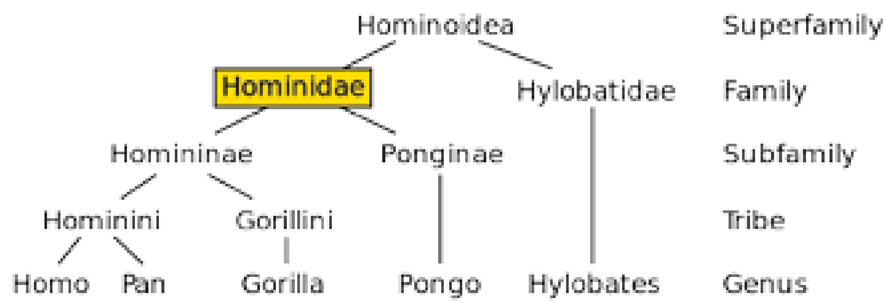

Fig. 4. Members of the family Hominidae.

Credits: Fred the Oyster, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Hominidae_chart.svg License: CC BY-SA.

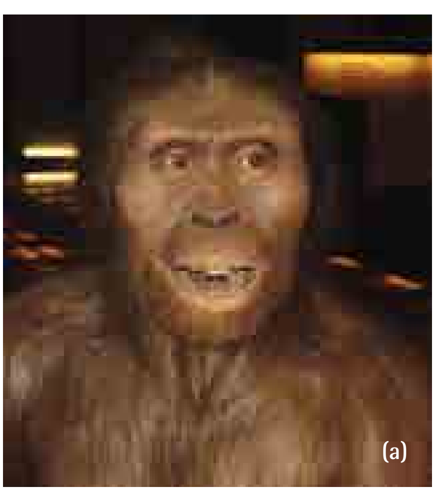

Fig. 5. (a) A reconstruction of *Australopithecus.*

Credits: Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Australopithecus_afarensis.JPG License: CC BY-SA.

(b) 3.7 million years old fossil foot-prints.

Credits: Momotarou2012, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Laetoli_footprints_replica.jpg. License: CC BY-SA.

sapiens, nor of any other genus of the *Hominidae* (great apes) family but that of **another human species** — which he called Homo neanderthalensis[4, 5].

Over the last one and a half centuries, with the help of hundreds of newly found fossil records and archeological sites in different parts of the world as well as advancements in fields such as molecular biology and genetics, we have managed to piece together a relatively clearer picture of our evolution as a species.

These detailed investigations tell us that our genus, *Homo*, originally evolved from a now-extinct genus of the great ape family: *Australopithecus* (refer **Fig. 5**). The *Australopithecus* evolved in eastern Africa about 4 million years ago, and gradually spread throughout the African continent. Although their brain size (about 450 cm^3) and jaw-shape were very different from modern humans, *Australopithecans* were obligate (i.e. habitual) bipeds. This was first indicated by a 24m line of 3.7 million old fossil foot-prints of three of its members, that were found preserved in volcanic ash (and discovered in 1976) in what is now Tanzania[6, 7].

An isolated population of one species of the Australopithecus genus is believed to have given rise to our genus *Homo* between 2 and 3 million years ago, before this entire genus became extinct about 2 million years ago.

The oldest known species of the *Homo* genus that is believed to have evolved from *Australopithecus* — i.e. the first humans — were *Homo habilis* (refer **Fig. 6a**). Members of this species were shorter than us in stature (about 4 feet 3 inches tall) with disproportionally long arms, but a much-enhanced cranial capacity of about 600-650 cm^3 as compared to Australopithecans. They were also the first to use advanced stone-tools and flakes regularly, often to butcher and skin dead animals.

The next to evolve were the two closely related *Homo* species – *Homo ergaster* and *Homo erectus. Homo ergaster* is believed to have evolved (either from or independent of *Homo habilis*) about 2 million years ago, and lived in eastern and southern Africa till about 1.4 million years ago. Their cranial capacity, at about 900 cm^3, was higher than that of *Homo habilis* and they used much more advanced and diverse tools, such as bifacial axes.

Although it has not been proven conclusively yet, many scientists believe that *Homo ergaster* was the first human species to migrate out of Africa into Europe and Asia, and it was this branch of the *Homo* genus that later evolved into another species: *Homo erectus*. Others hold the view that *Homo erectus* evolved in Africa, and then spread to Asia and Europe. *Homo ergaster* specimens, in their view, are not of a separate species, but of a population of *Homo erectus* that stayed back in Africa. What is commonly agreed upon in the scientific community, however, is that *Homo erectus* spread to regions as far as Georgia, India, Sri Lanka, China, Vietnam and Indonesia between 1.8-1.3 million years ago. This is also believed to be one of the most enduring human species, surviving in some parts of the world till 70,000 years ago.

Homo erectus stood 5 feet 10 inches tall on average, and the cranial capacity of some of the specimens is as high as 1100-1200 cm^3 — which is similar to modern-day humans. They are also believed to be the first humans to cook their food and make controlled use of fire (refer **Fig. 6b** and **6c**).

Fig. 6. **Reconstructions of a *Homo habilis* (a), *Homo erectus* man (b), and *Homo erectus georgicus* woman (c).**

Meanwhile, a population of *Homo ergaster* (or, of the *Homo erectus* that had stayed back in Africa – depending on which version is finally proven to be right) evolved into another species: *Homo heidelbergensis*, which shared anatomical features with both *Homo erectus* and modern humans. This species seems to have appeared around 700,000 years ago in Africa.

Between 300,000 and 400,000 years ago, some groups of *Homo heidelbergensis* migrated into Europe and some others into Asia. Archaeological sites linked to the European groups have been found in Spain, Italy, France, England, Germany, Hungary and Greece. It was these groups that eventually evolved into the species whose specimen was found by the limestone miners in the picturesque Neander valley of western Germany in the August of 1856: *Homo neanderthalensis*.

The Asian groups of *Homo heidelbergensis* developed into Denisovans (described in the next section) and a group of this species that had stayed back in Africa (and is, at times, categorized as *Homo rhodesiensis*) gradually evolved into our own species: *Homo sapiens* or 'modern humans' (*Homo heidelbergensis*, *Homo neanderthalensis* and *Homo rhodesiensis*, are generally grouped together as archaic/ancient humans).

Recent developments in the field

In everyday language, being called a Neanderthal is taken as an insult – the image of Neanderthals as uncivilized, stupid and uncouth 'cavemen' developed as a result of wrong interpretation of scanty evidence in the 19th century, as well as the religious/political biases of the experts of the time.

Neanderthals evolved approximately (300,000-400,000 years ago) around the same time as modern humans (approximately 200,000 years ago) and shared a common ancestry till *Homo heidelbergensis*. Physically, they were more than a match for us modern humans – comparable in height (about 5 feet 6 inches on average), they had proportionally shorter, but stronger limbs, a reduced chin, a large nose, and a larger, barrel-shaped rib-cage. Overall, they are believed to have been stocky and very strong (refer **Fig. 7**). They also had a greater cranial capacity (1600 cm^3) as compared to us (1300 cm^3).

Neanderthals made highly advanced tools out of bones, antlers, wood and stones – such as hammers, task-specific axes and spears. They kindled fire at will; could use artificial lighting when inhabiting caves; and built dwellings and hearths. They were apex hunters (laying sophisticated traps and hunting in groups to bring down even large animals such as woolly mammoths). While they generally lived in groups of 10-15 individuals, they were, nevertheless, capable of forming larger and more complex social groups at times. Some early mitochondrial DNA evidence indicates that males of this species usually remained in the same social group, while females joined the groups of their 'partners'.

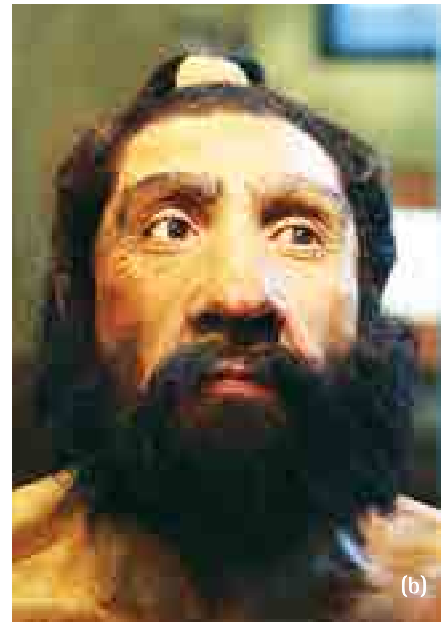

Fig. 7. Reconstructions of Neanderthals.

(a) Credits: Stefan Scheer, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Neandertaler_reconst.jpg. License: CC BY-SA.

(b) Credits: Tim Evanson, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Homo_neanderthalensis_adult_male_-_head_model_-_Smithsonian_Museum_of_Natural_History_-_2012-05-17.jpg. License: CC BY-SA.

Fig. 8. Hollow bear femur with spaced holes.

Credits: File Upload Bot (Magnus Manske), Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Fl%C3%BBte_pal%C3%A9olithique_(mus%C3%A9e_national_de_Slov%C3%A9nie,_Ljubljana)_(9420310527).jpg. License: CC BY-SA.

We have also discovered skeletal evidence which shows that Neanderthals buried their dead at times, took care of their injured — nursing them back to health, were capable of uttering words, and may even have had a language. Other than meat, their diet consisted of cooked and uncooked plant matter, nuts, mushrooms, seals and shellfish. Although we do not know if they traded, we do have evidence that they were navigating the Mediterranean Sea in dug-outs as early as 110,000 years ago. Some archeological sites indicate that they extracted glue from birch bark by heating it at extremely high temperatures; used jewelry and dyes, and collected bird-feathers — possibly for personal ornamentation. One of these sites has also yielded a hollow bear femur with what appears to be intentionally spaced and neatly cut holes (refer **Fig. 8**). It has been suggested that this may have been part of a flute or some other musical instrument.

Homo neanderthalensis and *Homo sapiens* — lived in the same regions (roughly from present-day England to Uzbekistan) for many thousands of years; at times even dwelling at the same sites or in the same caves in which a group of the other species had lived a few decades or centuries earlier. The last group of Neanderthals seem to have survived (in Southern Spain) till about 25,000 years ago. For a comparative perspective, consider the fact that the Halfan culture of Egypt started to appear around the same time, and the first agricultural settlements of modern humans date back to about 12,000 to 10,000 years ago.

Studies of the DNA recovered from bone fragments of a Neanderthal female, by the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, have helped answer a question that has been on the mind of many researchers: did our species inter-breed with Neanderthals? The answer is a stunning yes! Between 1- 4% of the genes of modern humans outside Africa come from *Homo neanderthalensis*. This includes genes that regulate our immune system; our skin, hair growth and pigmentation; even our metabolism, and our tolerance for cold weather. What is more — in 2010, scientists found the remains of another subspecies of humans (temporarily being called *Homo sapiens ssp. Denisova*) in a remote cave in Siberia, which had also been inhabited, at different times, by both Neanderthals and modern humans.

Box 2. Teaching resources on human evolution:

Some of the many resources that you can use to help students explore questions related to evolution are listed below:

- **Teaching Evolution through Human Examples** (http://humanorigins.si.edu/education/teaching-evolution-through-human-examples): Using examples such as evolution of human skin colour and humankind's adaptation to altitude, these four curriculum units help explain the difference between acclimation and adaptation, the scientific evidence for natural selection, and how evolution is a continuous process.
- **Comparison of Human and Chimpanzee Chromosomes** (http://www.indiana.edu/~ensiweb/lessons/chromcom.html): What can a study of our chromosome, especially when compared with chromosomes of other species, tell us about our evolutionary history? This lesson plan helps students compare the banding patterns seen on stained chromosomes from humans and chimpanzees and explore their evolutionary relationships.
- **Mystery Skull Interactive** (http://humanorigins.si.edu/evidence/human-fossils/mystery-skull-interactive): How do scientists know whether a newly discovered fossil is that of an already identified species or a new species? This interactive website allows students to identify a 'mystery skull' using methods similar to that scientists use in their work.
- **Becoming Human** (a documentary): Based on recent scientific findings, this documentary explains the significance of *Australopithecus* in human evolution. It also describes a nearly-complete specimen of *Homo erectus* found in Kenya and explores the fate of Neanderthals. The website http://www.pbs.org/wgbh/nova/evolution/ has many more audio-visual resources for teaching evolution.
- **A Different Flesh**: A collection of short stories by Harry Turtledove set in an imagined world in which *Homo erectus* survives till modern times.

The fact that perhaps there were a dozen or more species of humans could also lead to rich and lively discussions in classrooms. After all, some of these species were barely distinguishable from us; others ultimately survived for as many as 2 million years (as compared to 0.2 million years that we have been around) in harsh and ever-changing climatic and geographical conditions. Some even existed at the same time and in the same geographical regions as our own species! Explore some of these questions with your students - are *Homo sapiens* as different from other 'animal' species as we often assume? Are we really, as many religions and cultures would like us to believe, at the 'pinnacle' of evolution? Assuming one other human species had managed to survive till the present time, how do we think we'd have treated them? Would these humans — who bequeathed part of their genomes to us — be part of our societies, or our zoological gardens? Would 'human rights' be extended to them? And, also, why have none of the other human species survived till modern times when they had managed to survive for hundreds of thousands of years before our species appeared? What role, if any, did our ancestors have in their mass disappearance? And what does their disappearance and our evolutionary history mean for our future?

Denisovans shared their origins with Neanderthals, and were spread across Siberia to South East Asia. Genetic studies have indicated that modern humans interbred with this species as well, and between 3-5% of the DNA of modern-day Melanesians and Aboriginal Australians come from Denisovans. In fact, the specific gene-variant that allows native Tibetans to survive better than others in the low-oxygen and high altitude conditions of their homeland is likely to have been acquired from our Denisovan ancestors[8].

The only *Homo* species, other than ours, to have survived to modern times may have been *Homo floresiensis*. This species is believed to have evolved from migrating populations of *Homo erectus*, and lived on the geographically isolated island of Flores in Indonesia. Some studies suggest that they may have survived on this island till about 12,000 years ago — long after the island was also inhabited by our own species!

Conclusion

The story of evolution of our genus and species attempts to (at least partly) answer some of our eternal questions — who are we, where do we come from, and where are we headed. But it is also fascinating because it presents a good example of how scientists work: hypothesizing, assiduously piecing together evidence over generations, building on findings and contributions of others, discarding hypotheses that are no longer tenable in the face of new evidence, and, of course, the occasional strokes of serendipity! This story draws from fields as diverse as anthropology, geology, biology, anatomy, physics, chemistry, and molecular biology — and can thus also be used as an example of how different scientific fields are brought together to answer questions that were once considered 'unanswerable' or outside the 'scientific magisterium'.

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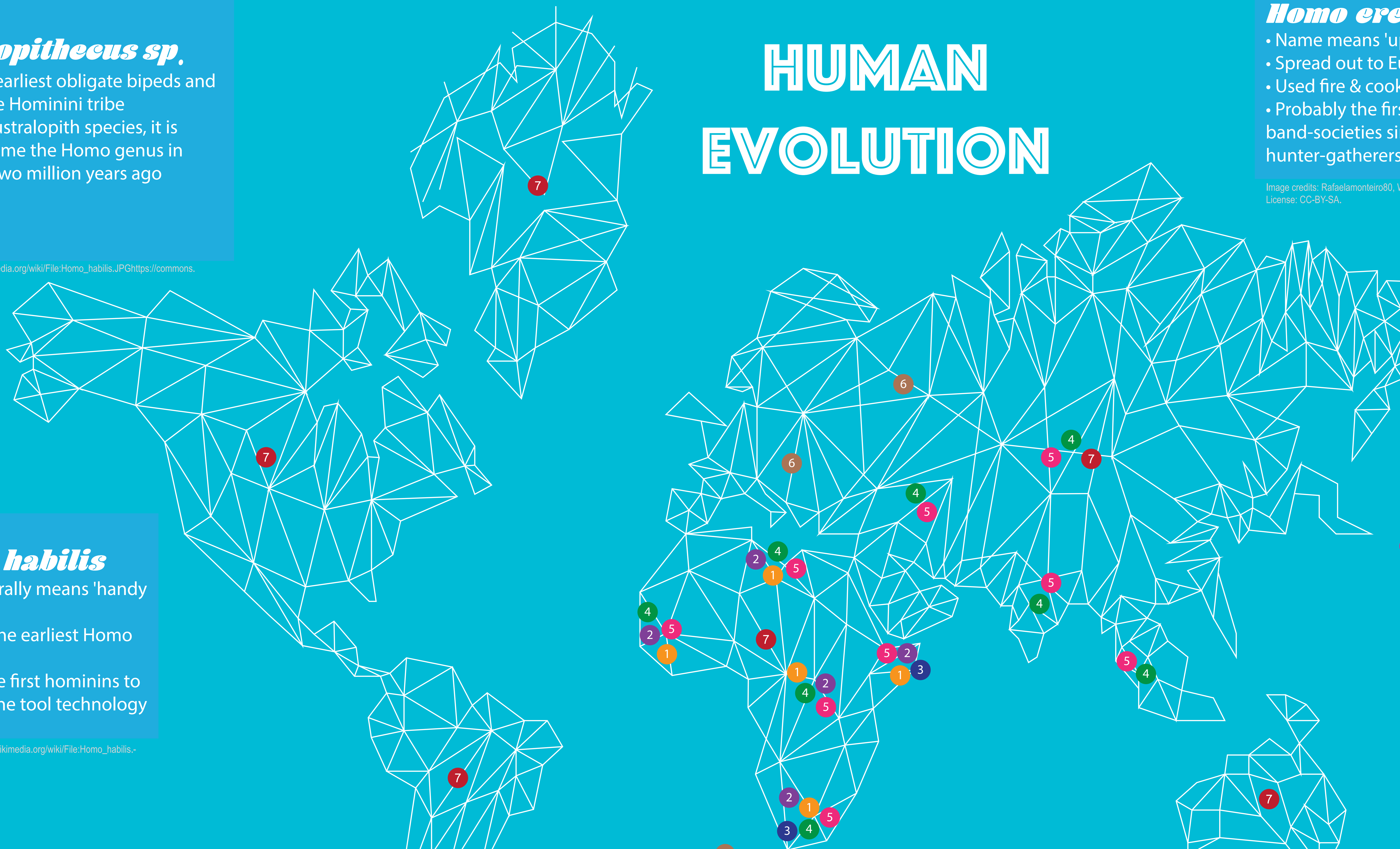
HUMAN EVOLUTION

Australopitheeus sp.

- Possibly the earliest obligate bipeds and member of the Hominini tribe
- One of the australopith species, it is believed, became the Homo genus in Africa, about two million years ago

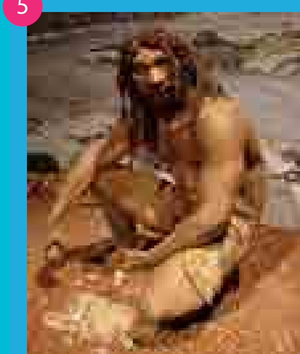
Homo erectus

- Name means 'upright man'
- Spread out to Europe and Asia
- Used fire & cooked their food
- Probably the first hominin to live in band-societies similar to modern hunter-gatherers



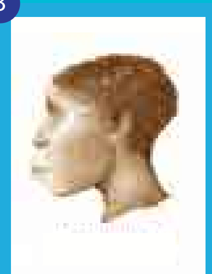
Homo habilis

- Name literally means 'handy man'
- Possibly the earliest Homo species
- One of the first hominins to master stone tool technology



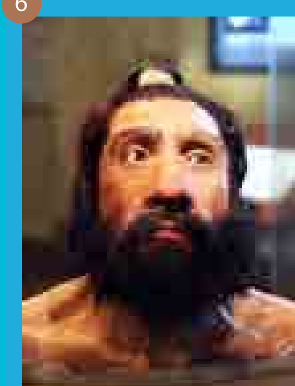
Homo heidelbergensis

- Shares features with *Homo erectus*
- Believed to have evolved into Neanderthals



Homo ergaster

- Name means 'workman'
- Used diverse and sophisticated stone tools such as bifacial axes
- Perhaps the first Homo species to move out of Africa



Homo neanderthalensis

- Share 99.7% of their DNA with modern humans
- Were apex hunters, built dwellings and lived in small groups
- Believed to have used art and adornment and were capable of symbolic thought

Genus/ Species	Temporal Range (KYA*)	Habitat	Adult Height	Adult Mass	Cranial Capacity (cm³)	Key Fossil Records in
1. *Australopithecus sp.*	3,900 - 2,900	Africa	120 cm (4 ft)	28 - 40 kg (60 - 90 lb)	450	Ethiopia (Lucy)
2. *Homo habilis*	2,100 - 1,500	Africa	110 - 140 cm (4 ft 6 in)	33 - 55 kg (73 - 121 lb)	510 - 660	Tanzania
3. *Homo ergaster*	1,900 - 1,400	Eastern & Southern Africa	160 cm (5 ft 3 in)	55 - 60 kg (120 - 130 lb)	700 - 900	Kenya (Turkana Boy)
4. *Homo erectus*	1,900 - 70	Africa, Eurasia (Java, China, India, Caucasus)	178 cm (5 ft 10 in)	60 kg (130 lb)	850 (early) - 1,100 (late)	China (Peking Man)
5. *Homo heidelbergensis*	700 - 300	Africa, Eurasia	175 cm (5 ft 9 in)	62 kg (136 lb)	1,100 - 1,400	Atapuerca Mountains, Spain
6. *Homo neanderthalensis*	350 - 40	Europe, Western Asia	170 cm (5 ft 7 in)	55 - 70 kg (121 - 154 lb) (heavily built)	1,200 - 1,800	Germany
7. *Homo sapiens*	200	Worldwide	150 - 190 cm (5 ft 7 in - 6 ft 3 in)	50 - 100 kg (110 - 220 lb)	1,300 - 1,500	

* kilo years ago. 3,900 KYA is thus 3.9 million years ago

Credit: Table adapted from https://en.wikipedia.org/wiki/Human_evolution

i wonder... Rediscovering school science

Avinash Kumar works with Wipro Applying Thought in Schools, a social initiative of Wipro, which supports civil society organizations that are working to improve the quality of Indian school education in different states of the country. He can be contacted at avinash.kumar@apu.edu.in

Azim Premji University

Interview with SUDHA RAJAMANI

Sudha Rajamani is an Assistant Professor at the Indian Institute of Science Education and Research (IISER) at Pune. Her research in the field of Astrobiology focuses on discerning the series of events that might have led to the origin and evolution of early life on prebiotic Earth. In this interview with Reeteka Sud, she shares her experiences and insights on the life of a scientist.

Tell us something about your current work

I run an Astrobiology lab at the Indian Institute of Science Education and Research (IISER) at Pune. Astrobiology is a really broad area of scientific research that uses basic principles from several fields — including chemistry, biology, geology, cosmology, to name just a few — to answer fundamental questions about how life came about on Earth. Within this broad area, my lab is attempting to characterise the series of events that would have allowed the chemistry of matter to transition to the biology of life. We focus on some specific questions — how informational molecules were formed, how they persisted and evolved to perform biologically relevant functions. We also have other projects aimed at studying the interaction of amino acids, RNA and other relevant molecules in the prebiotic soup.

What is a typical day at work like?

A typical day at work starts at about 10am. I talk with my students about their work, sit through committee meetings, tend to any upcoming deadlines (for manuscripts/grants) etc. Twice a week, we have lab meetings where students take turns presenting updates on their projects; and a journal club where we discuss papers relevant to our area of work. In teaching semesters, preparing for classes and teaching them is also included in my workday.

What are some of the most rewarding aspects of being a biologist?

That I have the absolute liberty to pick and choose any question, anything I want to study. This, I think, applies not only to biologists, but scientists in other fields as well. Except those in the industrial sector who probably have to work within the mandate of their employers.

For example, my current area of research — the chemical origins of life — is generally something that scientists pursue after having established themselves or as a side project. It is rewarding beyond words that I can choose this, at this stage, as the main focus of my research.

However I also love being a biologist because I am fascinated by all aspects of biology, even those beyond my current area of research. I love understanding different aspects of nature, especially pertaining to life — how it came about, how it survives, how it evolves.

> I have always been a very curious person. Curious about how things work, why they work the way they do, and what could be done to make them work differently. This, I believe, is fundamental to how any scientist views the world.

What are some important ethical aspects of your work?

Two aspects, in particular, are of great value to me. One is being completely honest about interpreting results of my work. Scientists are rewarded for publishing their work, especially in journals with high impact factors. The need to publish in a certain journal or at a certain rate can make it tempting to take the easy route – embellish data ever-so slightly to make it seem more than it is. This should be a strict no-no to everyone involved in research! I am very strict about this with my students. It is important to me that they understand that as scientists, we start with a working hypothesis based on valid information and are very careful about designing experiments to test this hypothesis. However, if the results we get do not entirely support or even disprove our hypothesis, so be it.

The other ethical concern that matters a great deal to me is related to managing people. This is a big part of running your own lab – there's a certain inherent power that comes with it. It is very easy to become the kind of person who makes things horrible for people working under you. I am very conscious of this possibility. It is important to me that I know what my boundaries are, and respect boundaries of other people in my lab. I strive to be ethically appropriate while dealing with members of my lab and also extend this to interactions with everyone who I am associated with in my line of work.

Do you remember when and why you made the decision to become a scientist?

There is no one moment when I made this choice. I have always been a very curious person. Curious about how things work, why they work the way they do, and what could be done to make them work differently. This, I believe, is fundamental to how any scientist views the world. By this criterion I believe I have always been a scientist at heart.

> For a teacher to be excited about science herself, goes a long way in getting her students interested in it too. Let your excitement infect your students naturally!

Any early experiences, at school for example, which encouraged this interest?

I think my science teacher, Ms. Usha Thakur, from when I was in the 4th or 5th standard was probably the one person, I would say, who 'stirred the pot' of my innate interest in science. Apart from that, I used to love going to the science library in BHEL Township, Hyderabad, where I grew up. Also, some really interesting documentaries on science-related topics, screened occasionally on Doordarshan, added to the intrigue.

How did you choose your current area of research?

My current area of research – Astrobiology – 'happened' to me. I call it a 'cosmic convergence of events'. I was trained in protein biochemistry, a field largely un-related to what I am studying now. Although I have always been curious about questions like, when did life begin and how, I didn't actively search for ways to make these questions part of my research. In fact, I wasn't even aware that a field called Astrobiology existed. till I stumbled into it by chance, and realised that there are many people who are addressing these questions scientifically. I'm really glad that my professional career took these unplanned detours to lead me to where I am now!

Have you come across any misconceptions about 'being a scientist'?

Ah! Misconceptions galore! One is that scientists are whacked out, lost in their own world, and talk to themselves – things of that nature. Another is that we are one-dimensional, potentially boring people, who are interested in nothing but science. This is definitely not the case – certainly not for me, or for the many other scientists that I know. I need the arts, interaction with social scientists – all that jazz! In fact, I can remember many occasions when I have been chatting with co-passengers on a flight, for example, and they've been very surprised to hear that I am a scientist, often exclaiming that I don't behave like one! There is also the idea that choosing to be a scientist is only about following one's passion, but there is really no money in this profession. Again, not true! Like anyone else, I too care about getting a reasonable salary, which I do.

Fig. 1. Why does the leaf of a papaya plant have this shape? Bringing things from outside to use as props in your class can make science classes more engaging.

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Could you share your perspective on science education at the school level?

While I wouldn't say that any of my science teachers have discouraged me

I would also strongly encourage teachers to take their students out of classrooms while teaching science. Simply put, nature is the best teacher! You could also bring in things from outside to use as props in your class. Saying, for example, *"Here are branches from two different trees. Why do you think these leaves are small, and these other ones large?"* This could start a discussion on leaf sizes that can eventually lead to one about the differences in their transpiration rates etc.

from choosing this career, now that I am a science teacher myself, I do wish that science was taught differently in school. Science classes should expose students to a wide variety of things related to nature and its workings. The best way to get young people interested in science is to pique their interest early on, at the school level.

Can you tell us some things that you think teachers could do to encourage an interest in science?

For a teacher to be excited about science herself, goes a long way in getting her students interested in it too. Let your excitement infect your students naturally!

Use inquiry, use their sense of curiosity, make observations a natural part of science classroom. Getting your students to ask how nature works can do wonders. So, for example, have them think about why a leaf is shaped a certain way; or why one plant is a shrub, while another is a tree. Or, how a rainbow is formed and why it has seven colours. If you involve them in inquiring about such aspects of the natural world, very soon they will be thinking seamlessly about the underlying concepts in various fields of the natural sciences like physics, botany, chemistry etc.

I would also strongly encourage teachers to take their students out of classrooms while teaching science. Simply put, nature is the best teacher! You could also bring in things from outside to use as props in your class. Saying, for example, *"Here are branches from two different trees. Why do you think these leaves are small, and these other ones large?"* This could start a discussion on leaf sizes that can eventually lead to one about the differences in their transpiration rates etc. Similarly, you could look at bugs as a model to study diversity in animal kingdom. These are just some examples that come to my mind at this point. But, this is possibly the most interesting and engaging way to introduce students to all of the natural sciences and, perhaps even, mathematics.

Another thing that can help is to use an integrated approach while introducing students to science. After all, the study of nature involves an understanding of principles from different fields of the natural sciences. Rishi Valley School, I am told, follows one such system. They teach science without breaking it up into biology, chemistry, physics etc. This is probably the most organic way of learning science.

Do what you can to make sure that students read extensively — including biographies of scientists. Badger (if you have to) your school administrators to take students to good libraries. Schools should also do whatever is possible to introduce student's first-hand to experiences where you have them see how science is really pursued. As part of IISER, Pune's outreach activities, we arrange for school students to visit our labs and research facilities on campus, and the students are just mesmerised — it's amazing to see that!

How important are observation and wonder in science education?

Oh, so important! Observation is absolutely fundamental to science. Sticking to teaching strictly from textbooks is the issue, maybe even the

Fig. 2. What causes the immense diversity we see among insects? Getting your students to ask how nature works can do wonders.

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stumbling block if I may say so. Every now and then, close your textbook, step outside with students and look around...to observe science-in-action all around us.

Curiosity and wonder are intricately linked to learning science. We don't even need to inculcate curiosity — kids are just naturally curious, more so than adults. Instead, teachers can help channelize their innate curiosity to learning about things in their environment: how do tiny ants make giant ant-hills, sometimes the height of a thousand-storey structure (for an ant)! How do they do that?! Asking questions about things you see around you, being in awe of things around you — that is the way to learn (and teach) science.

How important is it for researchers to be involved in school science?

Absolutely important, in my opinion. It is unfortunate that a lot of researchers are either completely disconnected or do not find the time to do science outreach. I think we should all try and make time to contribute in whatever way we can to excite young and bright minds.

It is especially important for us to reach out to middle- and high-school students to talk about our work. Most textbooks incorporate a lot of subject-specific jargon. It is in meeting scientists from a certain field that students get a real sense of what many of these terms mean, what the value of knowing about them is, etc. We (scientists) also stand to gain from it in many ways — science outreach greatly helps improve our communication skills. I try and do this in whatever way possible, whenever I can. In fact, I was recently in a college in Ahmednagar with two of my colleagues. The science faculty of this college are unusually proactive about exposing their students to various aspects of biology. This is particularly striking in a city like Ahmednagar, where opportunities to do so are far more limited than in bigger cities like Mumbai or Pune. I am also trying to be associated with a group of scientists from the Blue Marble Space Institute of Science or BMSIS (https://www.bmsis.org/), a virtual gathering of Astro-biologists, who are committed to education and outreach in this field. Some research organisations, like IISER have a very vigorous outreach program. Others, like the National Centre for Cell Science and National Chemical Laboratory, have open days when anyone can walk into their labs, check out the research happening there. Platforms like this provide a wonderful opportunity to engage with not just school and college students from across the globe, but also with the general public at large.

> Do what you can to make sure that students read extensively — including biographies of scientists. Badger, if you have to, your school administrators to take students on trips to good libraries.

Fig. 3. Can other planets sustain life? How do we colonise other planets? These are just some of the questions that are interesting to many people, across different age groups.

Credits: ESA - European Space Agency & Max-Planck Institute for Solar System Research for OSIRIS Team ESA/MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:OSIRIS_Mars_true_color.jpg. License: CC-BY-SA.

What are some of the most important ways in which the practice of science as a profession is evolving?

The number of institutes offering advanced training in science has increased, as has government funding for research and salaries for junior trainees and research fellows. A career in science, today, offers umpteen choices. It is no longer limited to teaching or doing bench-work (e.g. lab research). Just off the top of my head, there are opportunities in science communication, pedagogy, writing, outreach, policy and administration. However, a lot more needs to be done to further the practice of science as a profession. For example, it is important for the government to support and create opportunities in these alternative science careers.

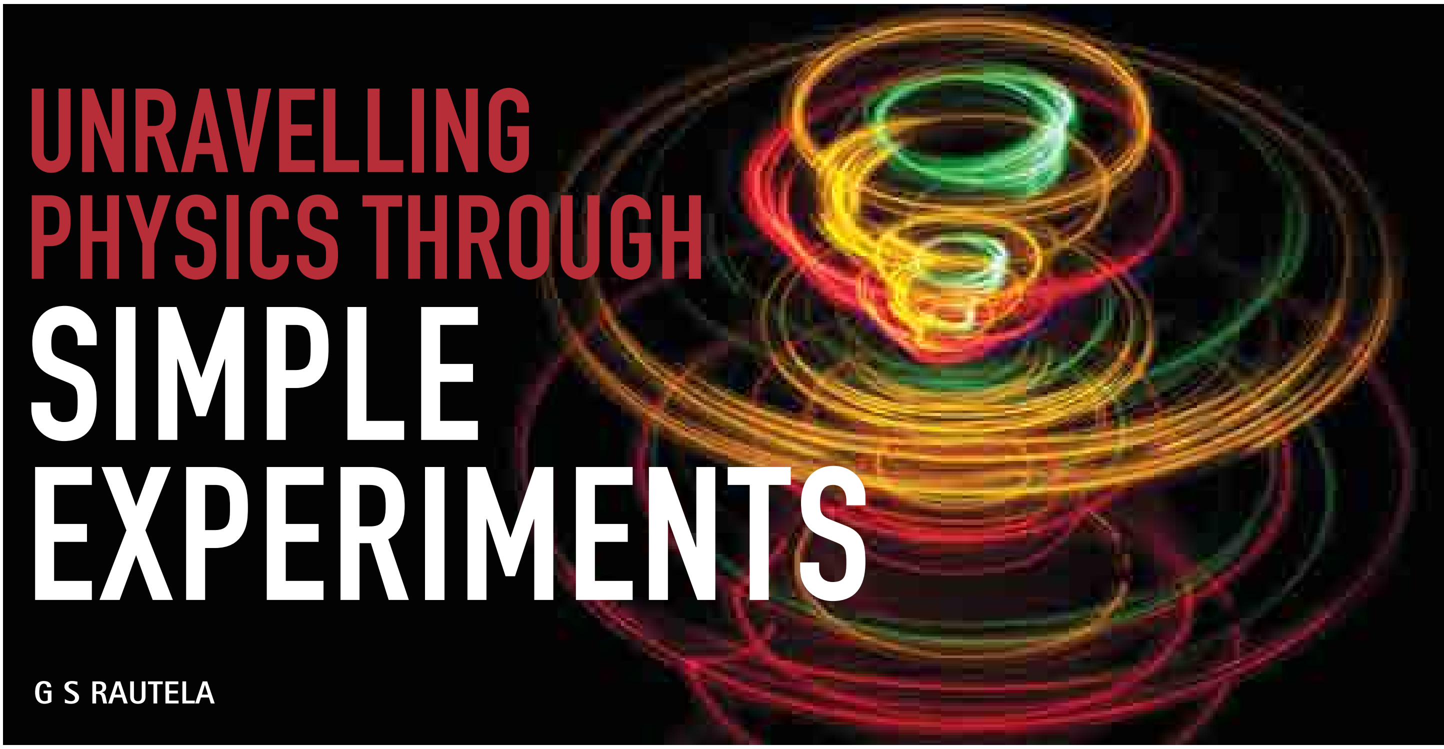
What are some of the fields in science that you think are going to take centre-stage in the next few decades?

Astrobiology, human cognition, areas of science at the intersection of social and natural sciences — these are all interdisciplinary in nature — and, I believe, some of the hot areas in science that are going to take center-stage in the coming decades.

What are some questions in science that you think can interest anyone (8 years or older)?

I think this goes back to something we were discussing earlier — how do things in nature work? It's almost like we can't stop wondering about it, ever! And there are several aspects to this question. One of the grandest (and a very challenging one too) of them all is — how did we come about? More fundamentally, how did life originate on Earth? Then, there is the other mystery human beings have been grappling with for so long — how does our brain function? Another problem that is immediately relevant to this day and age: how will the Earth sustain all of us given the way the world population is growing and how humans are mistreating the planet? This brings us to another relevant and pertinent question — whether life (as we know it) can be sustained on other planets or moons, and if yes, how do we colonise these planets or moons? Will that be possible at all? All of these are questions that are interesting to many people, across age groups.

Note: Credits for the image used in the background of the article title: Sudha Rajamani at her office at the Indian Institute of Science Education and Research (IISER), Pune; provided by Sudha Rajamani.



UNRAVELLING PHYSICS THROUGH SIMPLE EXPERIMENTS

G S RAUTELA

A great deal of science can be explained through simple experiments, performed at home, using locally available and low-cost material. Similarly, science can also be discovered by questioning a phenomenon or incident. This article presents a few simple but exciting experiments that can be used to understand some foundational principles in physics.

Science is fun

We often come across phenomena that leave us with a feeling of astonishment or wonder. Questioning the science behind them can make our observation of these phenomena far more enjoyable and also result in learning. Similarly, concepts in science textbooks can be brought to life in classrooms through simple experiments using a variety of locally available low-cost materials. Such teaching learning experiences create excitement in students, enhancing their interest and understanding of concepts.

We present a few such experiments here, which you could perform in the classroom or encourage students to perform at home. Each of these experiments will help students reflect on the underlying science and, in the process, learn a great deal of science themselves.

Experiment 1: Lazy stick

Take two identical wooden sticks (or aluminium/pvc pipes), each of about 1m length and 2cm width. Hold both sticks together, pointing vertically upwards but slightly inclined (refer **Fig. 1a**) and let go of them at the same time. You will observe that both sticks drop to the floor at about the same time.

Now tie a small weight of about 250g or a stone to the upper end of one of the sticks. Then, hold them together like before, with the weight or stone on top, and, again, let go of them simultaneously (refer **Fig.1b**).

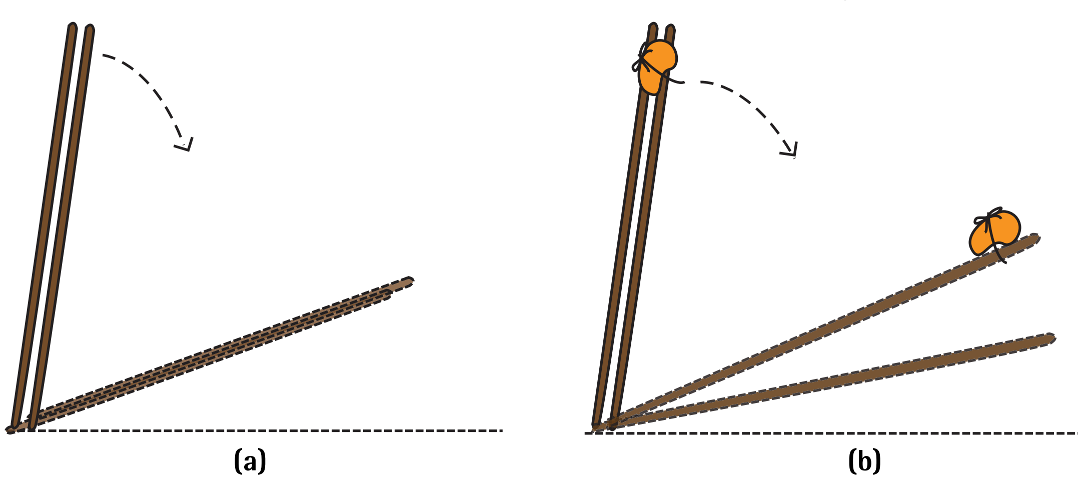


Fig. 1. Why is the stick with a weight a lazy stick?

a) The sticks reach the ground at the same time.

b) The stick with the weight attached to it reaches the ground later.

You may think that the stick with the weight attached to it will reach the floor first. But exactly the opposite happens. Why?

What's going on?

This unusual observation can be explained by a property of matter called 'Inertia'. Inertia is the tendency of an object to resist any change in its position or state of motion.

In the experiment, each stick is undergoing rotary motion, pivoting on a point resting on the floor. The kinetic energy and momentum with which each stick falls to the ground depends upon its moment of inertia. And the moment of inertia, in turn, depends upon the distribution of mass within the stick and the position of the axis along which the stick pivots.

How do we calculate the moment of inertia of each stick? By using the standard formulae: $I = \sum mr^2$, where I = moment of inertia, m = mass of each particle within the stick, r = the distance between that particle and the point at which the stick pivots along its axis, and $\sum$ indicates the sum of each of the values of mr^2 that we obtain for the entire stick.

Based on this relationship, it becomes evident that the stick with a weight tied to it will have a greater moment of inertia than the one without. The moment of inertia can be thought of as representing the stick's resistance to its angular velocity in rotational motion. Therefore, a higher value for the moment of inertia will mean greater resistance to motion, or, in other words, slower rotational motion — which explains why the stick with the mass tied to it, falls slower than the one without.

Explore this concept!

What would happen if you repeat this experiment but with sticks of two different lengths? Or with a weight tied at the centre or at the bottom of one stick rather than to the top? Can you predict the conditions under which the two sticks — one with a weight attached to it — will fall to the ground at the same time?

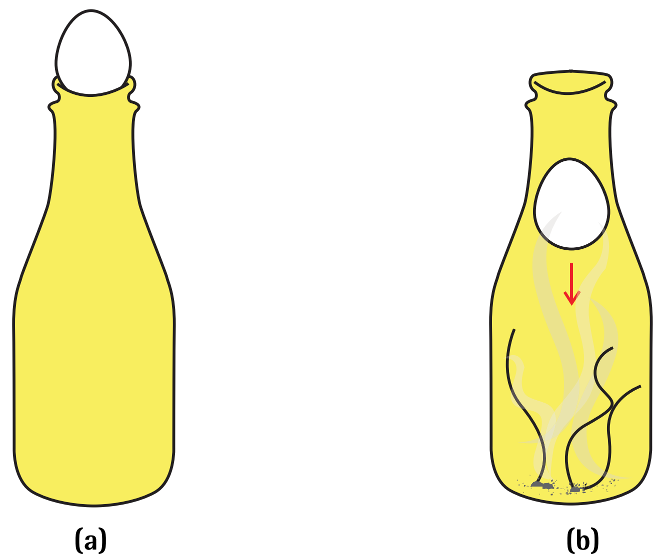


Fig. 2. Why does the egg shrink? a) The peeled boiled egg remains balanced on top of the bottle. b) The egg slips into the bottle immediately after the flame of the paper extinguishes.

Experiment 2: Shrinking Egg

Choose a glass bottle with an opening that is of a diameter (of about 4cm) a little smaller than an egg (about 4.5cm). Peel the shell off a boiled egg. Now, place this egg on top of the bottle. As expected, the egg will remain balanced there, and not drop into the bottle (refer **Fig. 2a**).

Now remove the egg from the top of the bottle, and put a piece of burning paper inside the bottle instead. As soon as the flame dies out, place the egg on the top of the bottle again (refer **Fig. 2b**).

While you may think that the egg will stay balanced on top of the bottle, it gradually slides into the bottle! Why?

What's going on?

When a burning piece of paper is put inside the bottle, it heats up the air inside. The hot air expands and some of it escapes out of the bottle. This reduces the amount of air inside the bottle. When the egg is put back on top of the bottle immediately after the flame extinguishes, it seals the bottle, preventing any more air from escaping or entering the bottle.

What happens next can be explained through a gas law called Gay-Lussac's law, which states that for a constant volume, the temperature of a gas is directly related to its pressure. Why does this matter? With time, the air in the bottle starts cooling. Since the sealed bottle has a constant volume of air within it, a drop in temperature leads to a drop in air pressure.

The reduced air pressure in the bottle acts both on its walls and that part of the surface of the egg that seals the bottle's opening. But the rest of the egg, which remains exposed to the air outside, continues to experience normal atmospheric pressure. As a result of this imbalance, the higher atmospheric pressure exerts a differential force downward that pushes the egg into the bottle. With the egg no longer sealing the bottle, air from outside rushes into the bottle and balances the pressure within and outside.

Explore this concept!

What would happen if you repeat this experiment but instead of dropping a piece of burning paper, pour some hot or cold water into the bottle?

Experiment 3: Hiding Balls

Take a tin can with an open lid. Tie two highly stretchable and small elastic rubber bands at the bottom of the can. To the free end of each of these bands, attach steel balls (with a weight of about 100g). Let the two balls hang outside the can (refer **Fig. 3**).

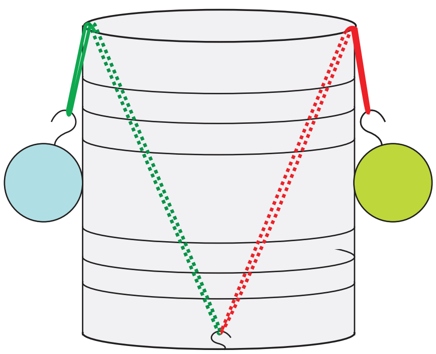


Fig. 3. Why do the balls hide within a free-falling can?

You will notice that the balls continue to dangle outside as long you hold the can. Would things change if you were to suddenly drop the can with the balls into free space?

While you may expect the balls to remain outside the can, you will observe that the elastic rubber bands suddenly retract and the balls go inside the can. Why?

What's going on?

When the can is held in hand, each ball experiences a gravitational force that stretches the elastic bands on both ends. This keeps the balls hanging outside the can. But when you drop the can, the free-falling balls, as well as the can become weightless. The weightless falling balls can no longer exert the force needed to stretch the elastic bands. The elastic bands retract and, as a result, the balls go inside the can.

Conclusion

Our quest to understand natural phenomenon arises from an inherent curiosity that we all possess. Through these simple experiments, we've looked at how day-to-day phenomena can be understood better by an appreciation for the science behind them. This can be extended to the science classroom, with teachers using experiments to create exciting and motivational hands-on learning experiences. Science is, after all, best understood by doing and discovering. Encouraging students to use the scientific method — including observation, questioning, experimentation, and analysis of data to draw conclusions — can only result in a better understanding of concepts. As science educators, therefore, our role is of paramount importance — go ahead and explore the science of other such phenomena!

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Discover

Arctic Sea Floor Fauna

Author: Geetha Iyer

If you were asked to guess some kinds of fauna living on the Arctic ice shelf – you'd probably think of polar bears, the Atlantic puffin, Greenland sharks, Arctic chars, Iceland gulls, Arctic foxes, and other such kinds of animals. But, did you know that the ocean beneath the ice shelf is also teeming with life? Found on the sea floor below the Arctic shelf, at a depth of 50 metres, are diverse species of brittle stars, feather stars, sea cucumbers, clams, bristle worms, snails and the occasional crab!

One of the reasons for this rich diversity is the lifecycle of marine zooplanktons! In winter, these microscopic animals enter their resting stage (diapause). The food that would otherwise be consumed by them falls to the bottom of the sea floor, allowing a rich benthic community to survive and flourish on it. These benthic communities are not averse to feeding on any organic matter coming to the sea floor, even if it's not fresh – from faecal pellets to decaying animal parts! And they are perfectly adapted to living at low temperatures permanently. For example, their metabolic functions, like respiration and reproduction, are much slower than those of animals living at warmer temperatures. As a result, they grow very slowly, but live for decades!

Benthic fauna from the Arctic shelf.

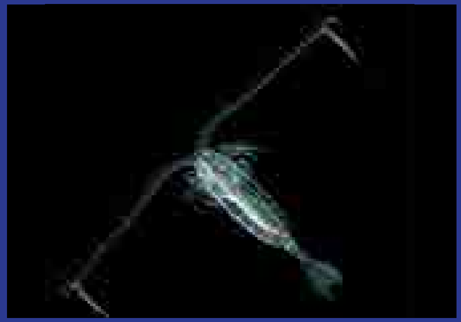
Credits: Copyright of Russ Hopcroft, University of Alaska Fairbanks, USA.

A brittle star making its way across the Arctic deep-sea plain at a depth of 3,000 meters below sea-level.

Credits: Xaime Aneiros Vazquez, Wikimedia Commons.URL:https://commons.wikimedia.org/wiki/File:Brittle_Star_back.jpg. License: CC-BY-SA.

An arrow worm (zooplankton) from the Arctic.

Credits: Copyright of Russ Hopcroft, University of Alaska Fairbanks, USA.



Encased in the same suite of armour used by insects, this copepod is among the best known zooplankton groups in the Arctic.

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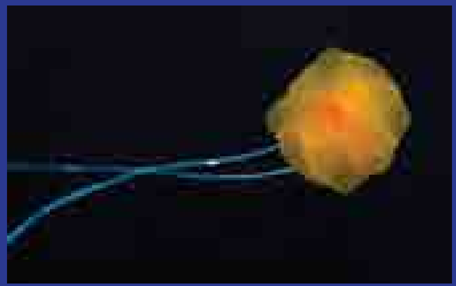
A pycnogonid or a sea spider is not a true spider.

Credits: Bernard Picton, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Nymphon-leptocheles.jpg. License: CC-BY-SA.



An unknown Arctic species, called Pumpkin.

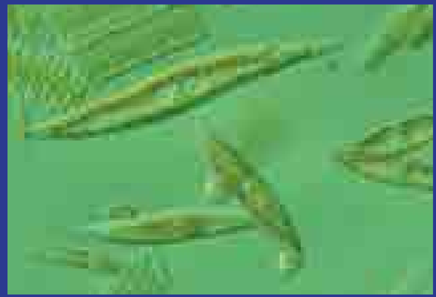
Credits: Copyright of The Hidden Ocean 2016, Chukchi Borderlands, Oceaneering International-DSSI.

***Beroe abyssicola* is a species of comb jelly found on the Arctic sea-floor.**

Credits: Copyright of Caitlin Bailey, GFOE, The Hidden Ocean 2016, Chukchi Borderlands.

***Clione*, a gastropod zooplankton.**

Credits: Copyright of the Microcosm Films, The Hidden Ocean 2016, Chukchi Borderlands, Oceaneering International-DSSI.



A microscopic view of ice algae from the Arctic.

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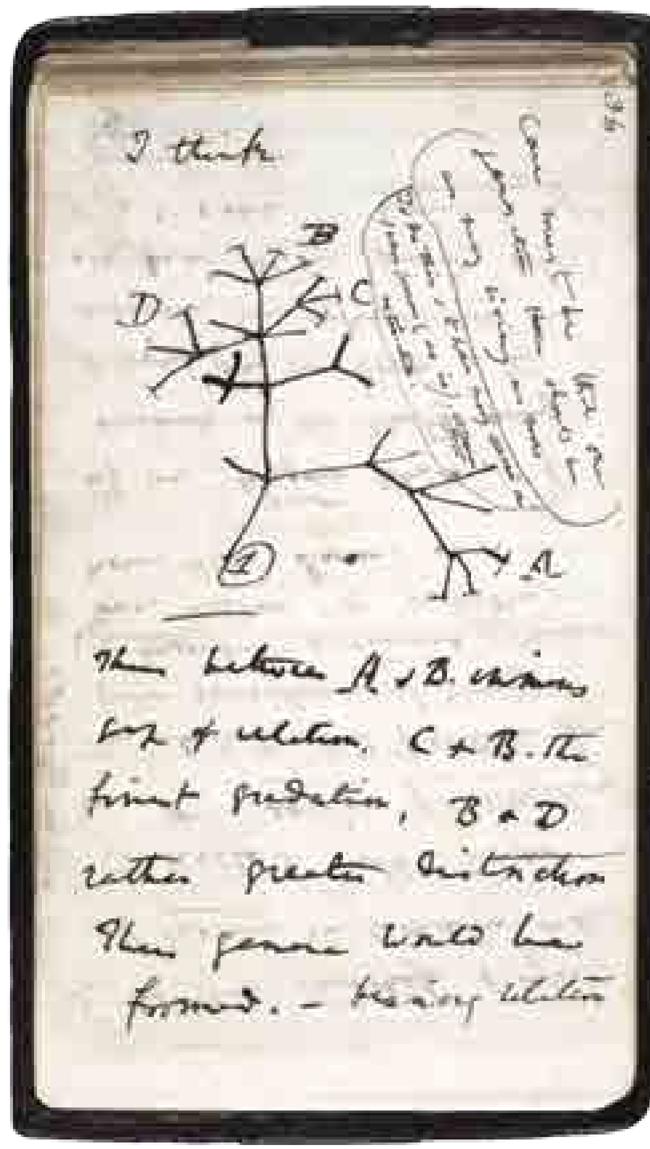
Poster Design: Vidya Kamalesh

Geetha Iyer is an author and independent consultant working in the twin fields of Education and Environment. She has written extensively on topics in education, environment and Natural History. Geetha can be reached at brownfishowl@yahoo.co.uk.

THE TREE OF LIFE:

THE POWERFUL MATHEMATICAL IDEA AT THE HEART OF EVOLUTION



MUKUND THATTAI

The way in which all living things — from microscopic bacteria to human beings to giant sequoia — are related to one another follows a deep and unexpected mathematical pattern, which we now know as the 'tree of life'. This pattern was discovered by naturalists over centuries, but it was Charles Darwin and Alfred Russel Wallace who realised that it held the key to understanding the origin and diversity of life on Earth.

We humans, like many other animals, have an instinct for finding patterns in the world around us. Our survival depends on this instinct — it allows us to separate friend from foe, to track the rhythms of the seasons, to plan ahead based on past experience. Science, or natural philosophy as it was once known, is based on this same instinct — it is an attempt to reduce the overwhelming diversity of the observed universe into reliable patterns, which we explain in terms of laws of nature. Ironically, our hard-wired skills of pattern detection are often at odds with the scientific ideal — we see patterns where there are none; we see structure in randomness. The history of science is the history of how we learned to distinguish true patterns from mere illusions.

Box 1. Observations, patterns, and explanations:

Most successful scientific theories have developed in three stages. The first to come are the **observations:** an enormous list of facts about the world as we find it; or of the world perturbed through experiments. These observations are often confusing and chaotic – it is unclear how they relate to one another; and difficult to predict what the next observation will point to. It is like watching an artist working on a canvas, filling part of the canvas here, another part there – the colours and shapes do not seem to make any sense, and we cannot guess what the subject of the painting is. As enough observations accumulate over the course of time, however, broad **patterns** start to become evident. There is often a singular moment in which the canvas suddenly gels into view, and we realise what we are looking at. In science, this realisation can often be stated in mathematical form, a simple set of rules or equations that summarise the broad structure of the observations. This, then, is the turning point. The final step is to provide an **explanation** of what we are seeing. This is the step where the viewer grasps the meaning of the painting, the idea the artist is trying to convey. For a scientist, this goes beyond a mere mathematical summary and involves looking for deep causes for the patterns. The greatest triumph of science has been to expose these deep causes as a handful of inviolate laws of nature, and not the capricious actions of some hidden cosmic artist. This is what allows science to be predictive rather than merely descriptive.

A few examples (Table 1) will make this process clearer. In the 1500s, the nobleman Tycho Brahe recorded the motions of planets across the sky with unprecedented accuracy. By using Brahe's data, the young mathematician and astronomer Johannes Kepler discovered his famous elliptical patterns of planetary motion. It took the genius of Isaac Newton to realise the meaning of Kepler's laws in terms of a deeper and more universal theory of mechanics, published in his book *Principia Mathematica* in 1687. Newtonian mechanics heralded the birth of the modern scientific era.

Similarly, in 1789, Antoine Lavoisier identified 33 chemical elements based on his study of chemical reactions, but was unable to find a simple description of their properties. In 1869, Dmitri Mendeleev showed that an element's chemical properties depended not on its atomic weight, but on its atomic number – its numerical position in the periodic table. However, the meaning of this pattern only became clear with the discovery of sub-atomic particles in the 1900s – it was the number of protons and electrons, not neutrons, which determined an atom's chemical properties.

The 1900s saw multiple scientific revolutions that overthrew centuries-old theories. The mathematical patterns in Maxwell's equations, which summarised nearly a century of observations about electricity and magnetism, led Einstein to discover special relativity. It was Rydberg's mathematical pattern describing the hydrogen spectrum that set the stage for a quantum-mechanical explanation of the universe. Relativity and quantum mechanics were combined through the 20th century to form our most precise theory of the nature of matter, known as the Standard Model. This model, too, is based on deep mathematical patterns of nature, known as symmetries.

The key point in all these cases is this – once a summary of data is available in the form of a mathematical pattern, the scientist can step away from observational details and begin searching for a deeper, and often simpler, explanation.

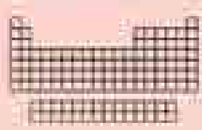
Observation	Mathematical patterns	Explanation
Planetary motion	Kepler's laws, $T^2 = R^3$	Newton's mechanics
Chemical properties of elements	Periodic table 	Atomic theory
Electricity and magnetism	Maxwell's equations $\nabla \cdot \mathbf{D} = \rho$, $\nabla \cdot \mathbf{B} = 0$, $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$, $\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$	Special relativity
Spectrum of hydrogen	Rydberg's law $\frac{1}{\lambda_{vac}} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$	Quantum mechanics
Classification of living things	Tree of life 	Evolution

Table 1. The development of scientific theories can be broken into three stages: observations, patterns, and explanations.

Credits: Mukund Thattai.

Fig. 1. The Great Chain of Being.

Credits: Charles Bonnet, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:BonnetChain.jpg. License: CC-BY.

The classification of living things

There have been many attempts to classify the diversity of life on Earth. One of the earliest, and most common, ways was based on quasi-religious grounds, and known as the Great Chain of Being (refer **Fig. 1**). Most commonly associated with Christian scholarship, similar attempts are seen in the Hindu *puranas*, and in ancient Greek and Egyptian philosophies. All versions of the Great Chain place living things on a strict ladder — at the bottom you have minerals and non-living matter; the next to come are the simplest forms of life, for example, the microbes (a modern addition); then plants; then animals; then, above all of these, human beings; and, sometimes, angels and deities above humans. This is a beguiling pattern, and fits with our natural inclination to place ourselves on top. Unfortunately, it is incorrect. It is not based on rigorous observations, but rather arises from our desire to make the universe fit with our own preconceptions.

A scientific approach to classification, firmly grounded in agnostic observations, is known as taxonomy. We first gather and record a huge volume of detailed information about the properties of every known living thing. We then start with the difficult task of separating these organisms into groups based on their properties. But, when we do this, we immediately encounter a problem: different authorities use different yardsticks; different traits by which to make the groupings. Some choose complexity, some choose size, some choose the mode of living; and some choose habitats. Which one of these is correct would seem to be a matter of faith or opinion, rather than fact; and each choice produces a different taxonomy.

Classification games reached a fever pitch in Europe in the 1600s. It was a time when European power reached across the world. Collections of exotic animals and plants, known as menageries, were brought from the farthest corners of their empires to their imperial capitals for the amusement of the citizenry (refer **Fig. 2**). I like to imagine a great hall in which, neatly stuffed and mounted, specimens of every type of animal is scattered across the floor. Amateur taxonomists wander the hall, moving these specimens here and there, and generally trying to out-do one another in terms of their grouping. How would this play out? One person might arrange everything based on colour, only to be upset the next day when someone else rearranges everything based on size. Everyone is at loggerheads with one another. Then, something remarkable happens. Some of our taxonomists, just for fun, start to use increasingly obscure traits as the basis of classification. Instead of size or colour, these taxonomists look at the number of bones in the ear, the arrangement of holes in the hip, the layering of muscles on the toes. Of course, some of these people still disagree with one another, and leave the hall in frustration. But slowly, a large group builds up in the hall, each person quietly working in their corner while the broader classification remains largely unchanged.

What is going on? How is it that a huge number of people using completely independent yardsticks suddenly start to agree? This is where we first notice a deep mathematical pattern. Let's consider any three animals in the hall, say X, Y, and Z; and two taxonomists A and B each using different traits for classification. We ask A, and find she believes that {X, Y} form one group and {Z} another, which we write as {{X, Y}, Z}. Suppose that B believes {Y, Z} form one group and {X} another, which we write as {{X}, {Y, Z}}. In this case, A and B will never be able to agree. Suppose, instead, that B believes {X}, {Y}, and {Z} represent three distinct

Fig. 2. **A European menagerie of exotic animals.**

Credits: Annelore Rieke-Müller, Lothar Dittrich: Unterwegs mit wilden Tieren. Wandermenagerien zwischen Belehrung und Kommerz 1750–1850 S. 70. Uploaded by Felistoria, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Menagerie.hermann.van.aken.1833.jpg. License: Public Domain.

groups, which we write as {{X}, {Y}, {Z}}. No problem, says A: all B has done is further sub-divide her classification. For example, A might be thinking of the animals as insects {X, Y} and birds {Z}, while B might be thinking of beetles {X}, bees {Y}, and birds {Z}. That is, we can write these groups down in a *nested list* {{{X}, {Y}}, {Z}}, and both A and B will be happy. More generally, two classifications A and B are said to be **consistent** if, for every choice of three objects X, Y, and Z, disagreements do not occur. What happened in our game (refer **Fig. 3**) is that thousands of taxonomists found their preferred groupings consistent with one another and, over the course of time, divided the entire hall into a series of nested groups and sub-groups.

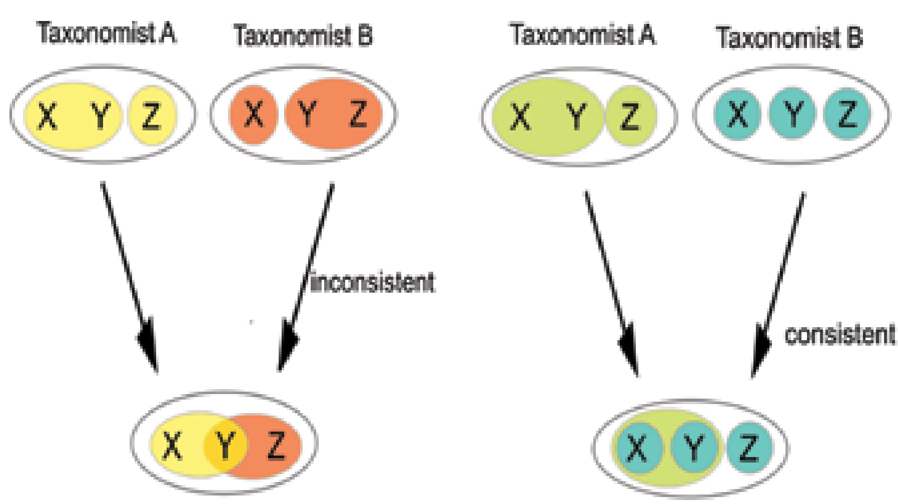


Fig. 3. **The classification game.**

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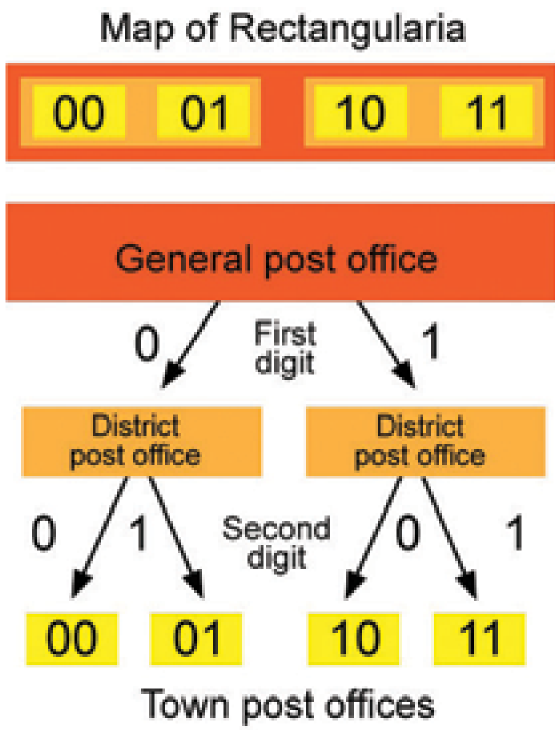

Fig. 4. The nested postal system of Rectangularia.
Credits: Mukund Thattai. License: CC-BY-NC.

Now comes the final piece of the puzzle. A process very much like our imaginary game played out over the course of the 1700s. When the dust settled, it turned out there was a single **unique** solution to the classification problem. There was one giant set of thousands and thousands of traits (mostly very obscure ones) each consistent with one another; and with traits (size and colour, for example) that were inconsistent, ignored. This was a fact, not a matter of faith or opinion. The ultimate expression of this fact is found in Carl Linneaus's book, Systema Naturae, published in 1735. From that date onwards, the Linnaean system of taxonomy became the single correct and accepted biological classification system. Whenever a new species was discovered, there were typically initial disagreements about where to place it but, eventually, the preponderance of evidence based on multiple traits would reveal its correct placement.

Darwin's and Wallace's insight: nested groups are also trees

By the time Charles Darwin set sail on the HMS Beagle in 1831, the classification of all living beings into nested groups was well established. Many naturalists, including Charles's grandfather Erasmus Darwin, had already realised how surprising this mathematical pattern was. Let's pause to consider this, by trying to classify some other type of objects. Furniture can be classified by size, shape, material, colour, and use; but you will never find any agreement among the different groupings. Words can be classified into nouns, verb, adjectives, and so on, but this system is not nested; it operates at a single level. Sounds can be classified by pitch and volume, and in a more modern sense by spectral components, but this is an additive system, not a nested one.

We can flip the problem around, and ask what kinds of things are usually found in nested groups. Here we have a very familiar example. Countries are broken up into postal codes, allowing mail to be efficiently delivered. Typically the left-most digits of the postal code represent large subdivisions, and the right-most digits represent small sub-divisions (refer **Fig. 4**). If we dig a little deeper into what these digits actually mean, we will find that each one is associated with a real object, namely a post office. Starting from the General Post Office, each digit going from left-to-right is the name of a district level, a town-level, and a street-level post office. Suddenly it becomes clear that a nested list is really a tree in disguise! Each node of the **tree** is a post office, and arrows show how mail flows from higher to lower levels.

What does this mean for biology? Taxonomists have always grouped all the living things known at a certain moment, implicitly assuming that this set never changed. Imagine a world in which all these species were designed at the moment of creation and remained unchanged. It would then be hugely surprising to find a single unique nested classification system. A world of fantasy animals whose traits were all jumbled together would look more like furniture, and be unclassifiable.

Darwin and Wallace independently suggested that the Linnaean classification system be seen as a tree rather than as nested groups. Darwin's study of finches, and Wallace's identification of biogeographic regions, both emphasized the role of the passage of time. This made a profound difference, because it provided a mechanistic explanation for the tree-like pattern. If we think of the arrows of the tree as representing the flow of time, then the relationships between all living things **today** (the nested list) tells us a great deal about the **past** (the ancestral limbs of the tree)! If animals and plants could change over time, accumulating trait differences from parents to offspring, then the nested grouping of present-day traits is easily explained. Of course, this is only the beginning. We would have to provide some explanation for how these traits changed, how heritable they were, or how certain traits were selected over others in each generation. It is only in the modern biological era that the molecular mechanisms underlying heritability and genetic encoding were elucidated. This collection of ideas together represents the modern synthesis of the theory of evolution by natural selection, and it began by recognising the tree of life.

“I think...”

In Darwin’s notebook, a sketch dating from 1837 represents his first depiction of a tree of living things. It is famously captioned *“I think”*. Darwin’s ‘Origin of Species’, published in 1859, contains a single figure, also representing the tree of life (refer **Fig. 5**). So what did Darwin think?

We can never know for sure. But, it is reasonable to guess that Darwin had just realised the connection between nested groups and trees. Both represent equally valid ways of summarising a large volume of observations about the traits of living things. However, the nested groups suggest immutability (unchanging), while the tree suggests **transmutation**, the gradual changing of one species to another. Once this was clear, Darwin immediately realised that not all branches of the ancient tree survive to the present day — there must have been strange forms of life in the past that have vanished since then, without a trace. Most importantly, Darwin had a further insight. Just like the nodes of the post-office tree represent real physical buildings, the internal nodes of the tree of life represent something real as well. Each of these nodes is an ancestral creature — microbe, plant and animal — that must have lived and died billions of years in the past. In other words, this nested taxonomic classification implies the existence of intermediate forms in the fossil record, buried in layers of rock as a record of the past.

Darwin’s and Wallace’s theory of evolution has been put to the test, and passed every challenge. The tree of life (and the process of natural selection), which was first developed to explain the diversity of plants and animals, is now known to apply to every form of cellular life on earth — including prokaryotic bacteria, archaea and single-celled microbial eukaryotes. There have been a few interesting deviations — we know now that cells can exchange DNA; and that two species can hybridize to make a third. But these processes are just embellishments on the central tree. The global set of consistent traits now ranges from classical macroscopic measurements to molecular-level information. Literally each base pair of a cell’s genome stands witness to the process of evolution. Beginning from Carl Woese’s first attempts at molecular classification in the 1970s, it has now become routine to find the location of an organism in the tree of life by the DNA evidence alone.

Understanding life’s history teaches us that each living form is precious and represents a single unbroken path reaching into the past. Evolution is on-going — the processes that generated life’s present diversity continue to operate. Evolution can happen in a matter of hours or billions of years; humans continue to evolve, just like all

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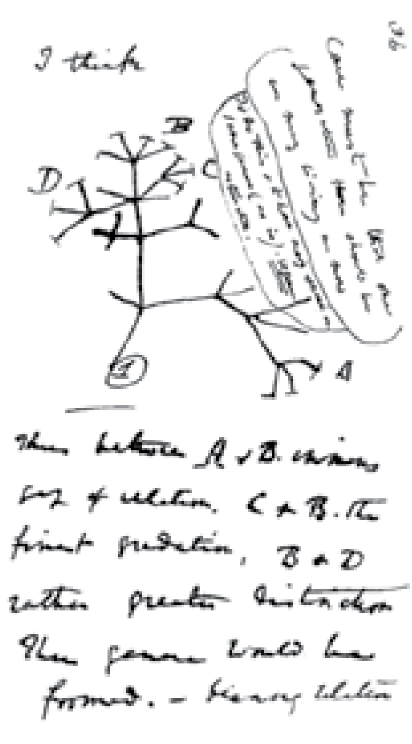

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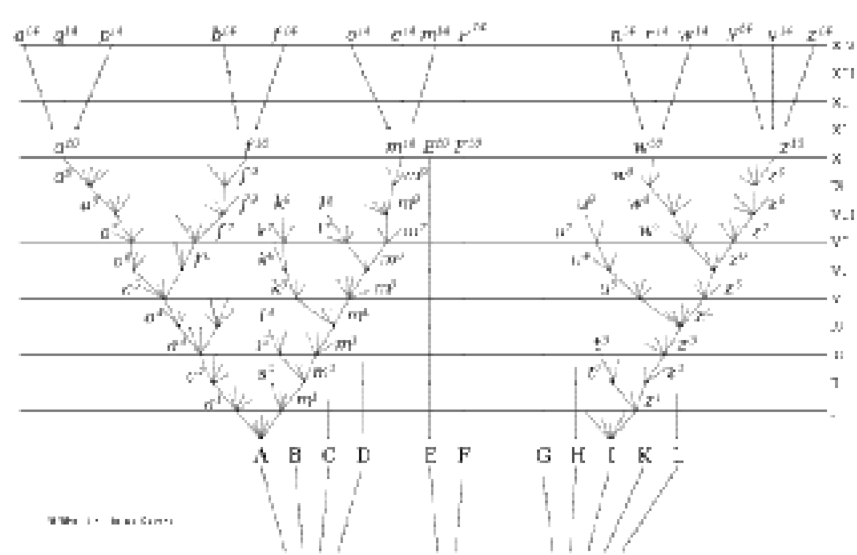

Fig. 5. Darwin’s Trees.

(a) From his first notebook on Transmutation of Species (1837).

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(b) In On the Origin of Species (1859).

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other organisms. New species continue to arise; but many more are wiped out by human activity in the sixth great extinction of life on Earth. This scale of extinction is unprecedented and irreversible. We have become poor custodians of the tree of life — preserving the diversity of living things is the single greatest challenge of our age.

Note: Credits for the image used in the background of the article title: Charles Darwin, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Darwin%27s_I_think.svg. License: CC-BY-SA.

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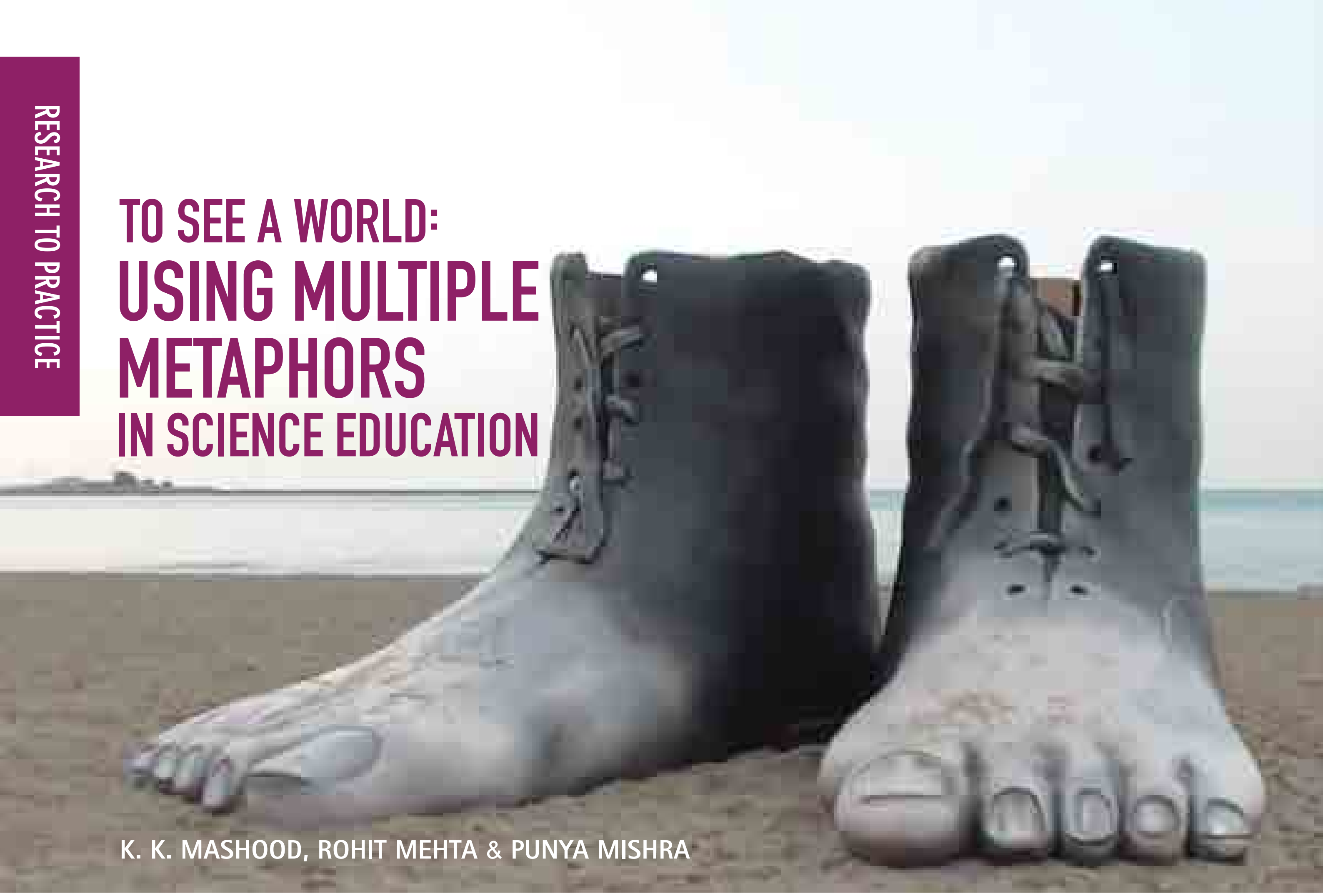

TO SEE A WORLD: USING MULTIPLE METAPHORS IN SCIENCE EDUCATION

K. K. MASHOOD, ROHIT MEHTA & PUNYA MISHRA

Metaphors play a crucial role in how we conceive and understand new concepts and ideas. Using insights from science education research on the teaching of energy, this article illustrates how the use of multiple metaphors can help present dry, abstract and complex science concepts to students in more lively, engaging and richer ways.

"Our ordinary conceptual system, in terms of which we both think and act, is fundamentally metaphorical in nature".
— George Lakoff.

"To see a world in a grain of sand
And a heaven in a wild flower
Hold infinity in the palm of your hand
And eternity in an hour".
— William Blake.

How do we learn something new? It can be argued that the only way we can understand something new is in terms of what we already know. Lying at the heart of metaphors, this argument is particularly significant when we seek to understand abstract ideas. For instance, consider the idea of energy, a complex foundational concept that is discussed seemingly differently in different domains of science. The challenge is to connect this abstract idea to something that learners already know; and, yet, do it in a way that prevents unitary, simplistic understandings.

As educators know, teaching a human being is not like programming a robot or a computer to do something. In the latter case, all we need to do is provide accurate instructional inputs. There is no room for interpretation or imagination, or for alternative conceptions or misconceptions. In other words, what is 'told' is 'taken' as it is, provided there are no technical glitches or errors. Teaching a human being, on the other hand, is far more complicated, even when we do it with (what we believe is) absolute clarity. Consider the following remark from Carl Wieman, a Nobel-prize winning physicist turned education-researcher[1]:

"When I first taught physics as a young assistant professor, I used the approach that is all too common when someone is called upon to teach something. First, I thought very hard about the topic

and got it clear in my own mind. Then I explained it to my students so that they would understand it with the same clarity I had. At least that was the theory ... [But] whenever I made any serious attempt to determine what my students were learning, it was clear that this approach just didn't work. An occasional student here and there might have understood my beautifully clear and clever explanations, but the vast majority of students weren't getting them at all".

Why does this happen? It is unlikely that someone like Wieman did not know the physics he was trying to teach, or lacked clarity in its exposition. The real reason could be the underlying complexity of human cognition. Rather than learning anything new exactly as it is told to us, we try to comprehend it using what we already know. Learners are active constructors of knowledge; and a range of factors (such as their prior experiences, social context, linguistic ability, and emotional setup) can influence how they receive, store and retrieve information.

The fact that learning builds on, or is constrained and framed by, what we already know is often taken to be a problem, since it widens the factors that educators need to consider as we design our lessons. However, we argue here that, as educators, we need to accept this, and learn to harness it to our advantage.

Metaphors offer one way of building on prior knowledge to explain new ideas. In fact, all teachers have knowingly or unknowingly used metaphors at some point in their work. However, single metaphors can cause a seductive reduction in complexity of an otherwise rich idea (see **Fig.1**). In this article, therefore, we focus on a strategy of using multiple metaphors to explain complex scientific ideas. We ground our discussion of this strategy in one specific example — that of teaching about energy.

Teaching the concept of energy

Energy is one of the most fundamental and overarching concepts in science. Students learn about energy in school in a variety of contexts. In biology, the idea of energy is the key to understanding important topics such as photosynthesis and nutrition. Energy in chemistry is integral to understanding concepts such as chemical bonds. In physics, energy is discussed in terms of work, in the form of kinetic and potential energy. Often the concept of energy, irrespective of what aspect of science is being taught, is introduced by giving textbook (or clichéd) definitions like, energy is 'the ability to do work'.

We reason that such an approach hardly encompasses or conveys the underlying conceptual richness of this important and complex concept. In addition, students hear the same word in different classes or contexts, but are not provided opportunities to connect its seemingly

Fig. 1. The seduction of using single metaphors: using just one representation reduces the complexity of a rich idea.

Credits: Illustration by Punya Mishra inspired by *Variante de la tristesse* by Belgian surrealist René Magritte. License CC-BY-NC.

different uses. Thus, students can end up having an incomplete and fragmented understanding of this concept. And, if these misunderstandings are related to core science concepts (such as energy), it can lead to further confusion and misconceptions down the road.

Multiple metaphors of energy: The research perspective

Rachael Lancor's research provides a perspective into the range of concepts that underlie the concept of energy, providing insights on how it can be taught effectively[2,3]. She considers how physics, chemistry, and biology textbooks (along with science education literature) conceptualize energy, and through this gives a picture of the web of ideas essential to understanding the concept. This study finds that each discipline, on its own, focuses only on a subset of the overarching concept. It is only by providing a framework that integrates these seemingly distinct views that we can hope that students truly understand it.

Lancor begins by stating five main characteristics associated with the concept of energy that students need to understand. These, relatively abstract ideas, are:

1. Energy is conserved.
2. Energy may dissipate from a system over time.
3. Energy can be transformed from one form to another.
4. Energy is transferred between parts of a system, and that
5. Energy could be received by a system from another source.

Lancor then follows this up with an analysis of introductory science textbooks (across domains such as physics, biology, and chemistry) to see how these abstract ideas are explained. In brief, she identifies six different key conceptual metaphors that ground the abstract ideas in ways that make sense to students. These are:

1. Energy, like money, can be accounted for and tracked.
2. Energy can take different forms, and changes from one to another.
3. Energy can flow like water through a pipe.
4. Energy can be carried by living organisms as well as inanimate entities like electrons.
5. Energy, like oil in a faulty machine, can be lost.
6. Energy can be stored in devices like a battery or a wound-up spring.

Of course, each of these metaphors, if used in isolation, leads to the distinct possibility that students develop a limited understanding of the nature of energy, and how it plays out across different scientific disciplines. It is here that the idea of weaving multiple metaphors together can help convey both the richness of the concept and prevent students from holding on to

Fig. 2. The six metaphors for energy.

Credits: Illustration by Punya Mishra inspired by the painting 'The key to dreams' by Belgian surrealist René Magritte. License CC-BY-NC.

one metaphor as being the only way to understand a concept (see **Fig. 2**).

What is important to note is that each of the six metaphors of energy highlight only some of its five main characteristics, while obscuring others. For instance, treating energy as a substance that can be tracked and accounted highlights its conserved quality but obscures its ability to be transformed from one form to another. On the other hand, the metaphor of energy as a substance that can be lost highlights the fact that it can dissipate, but obscures its ability to be conserved. Picking one or a few metaphors would therefore result in a situation like that of the blind men trying to describe the elephant – each one understands only a part and can never agree to the overall. To develop a coherent understanding of energy would require careful consideration of all the various characteristics associated with the concept. This necessitates weaving multiple metaphors together to reach a richer understanding of the whole picture.

Implications for instruction

Energy is often introduced in school classrooms by short definitions, like, the one stating that it is 'the ability to do work'[2,3]. This is not only ineffective, but provides students with an incomplete picture about a rich, critically important, foundational concept in science. Students merely memorize such clichéd statements and regurgitate them during examinations. This also has the implicit danger of giving students as well as teachers a false sense of knowing. A discussion of energy based on multiple metaphors may help resolve some of these issues. In addition to deepening student understanding, it can also facilitate their ability to connect ideas and disciplines. Included below are some guidelines on how to implement this strategy in science classrooms:

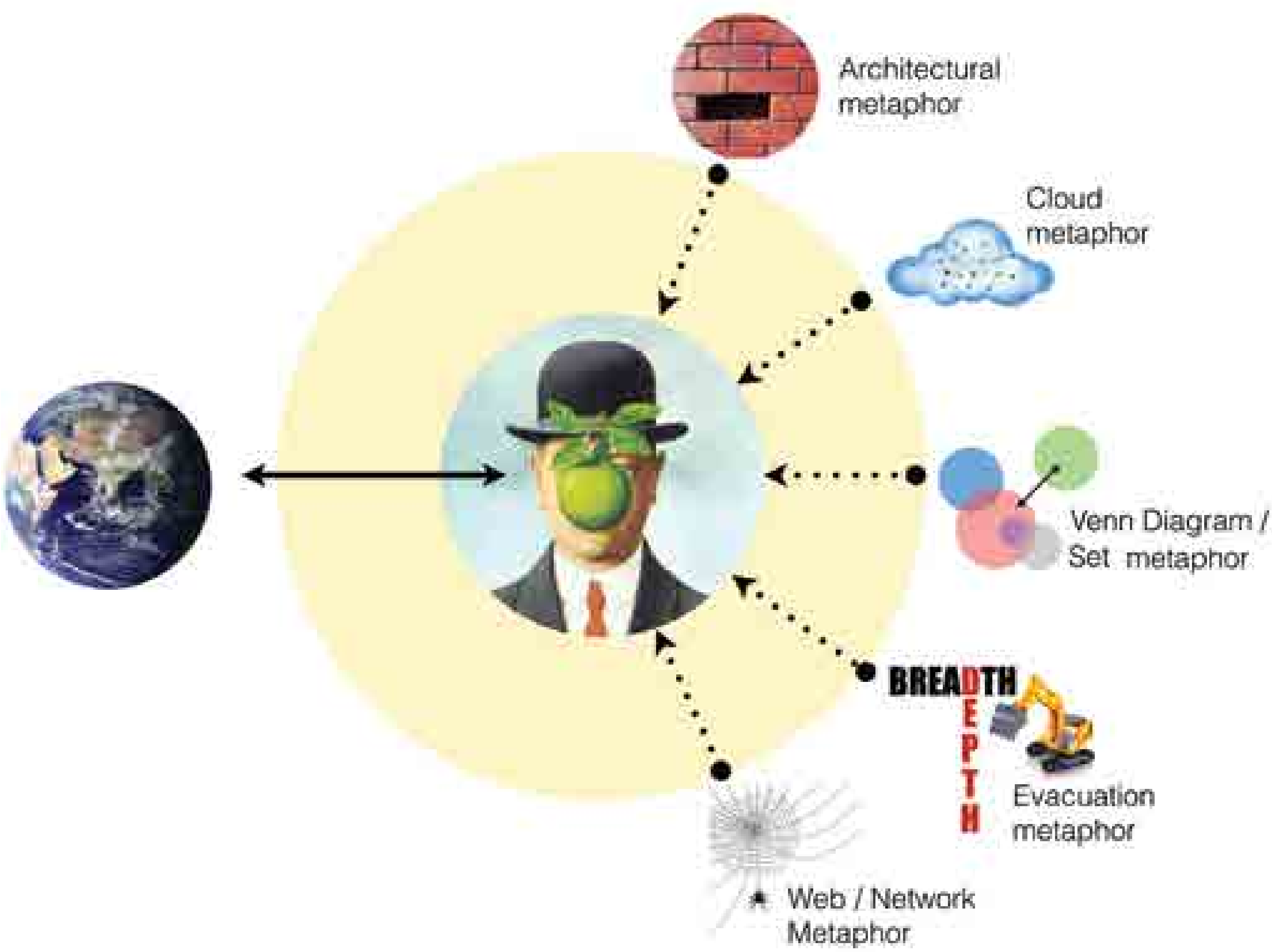

Fig. 3. Multiple metaphors of knowledge in understanding the world.

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(a) Learning to think like scientists.

Unlike scientists and experts, students are less likely to be proficient with the nuances associated with language. They may not have the depth of understanding to precisely interpret metaphors, and may take things literally. What we often refer to as misconceptions or alternative conceptions pertaining to energy are mostly imprecise re-conceptualizations of metaphors. The expertise and deeper understanding to appreciate these metaphors cannot be obtained overnight. It requires continuous engagement and development over time. It is, therefore, important to demonstrate the iterative process of scientific method.

How to implement? Feynman's lectures on physics provide an example of building arguments pertaining to energy conservation[4]. He starts with the story of the fictional character of Dennis the Menace playing with a set of blocks. With each block, the story containing metaphorical descriptions keeps growing in complexity, with mathematical equations making their entry towards the end. Similarly, there should be considerable engagement with the concept of energy in terms of metaphors. Once it is ensured that students have a considerable grasp with the metaphorical language and discourse pertaining to energy, the teacher may bring in formal definitions, equations, and numerical problems. Encouraging students to explore connections between non-mathematical and mathematical concepts will further boost coherence and rigor. This may often require revisiting the metaphors and a strengthening of concepts iteratively. This can be done in small groups.

(b) Transdisciplinary thinking.

Concepts like energy are present across disciplines. However, how the idea of energy is discussed in physics may differ (at least at a surface level) from how energy is discussed in biology or chemistry. A specific topic in a discipline may afford a certain metaphor[2]. A coherent, in-depth understanding of the concept requires reconciliation between its apparently different disciplinary manifestations. Unfortunately, this conceptually challenging task is often left wholly to students. A discussion based on multiple metaphors facilitates reconciliation between energy in physics, chemistry, and biology, and has the additional benefit of providing richer language and conceptual structures to talk and reason about these ideas.

How to implement? Identify the metaphors associated with a specific description of energy. For example, biology discusses the flow of energy through ecosystems. The metaphor of energy as a substance that flows like water through a pipe is relevant to this context. On the other hand, discussion of a stone rolling down a hill is found in physics. Here the metaphor of energy as a substance that changes from one form to another is apt as potential energy is getting converted to kinetic energy. Highlight the fact that though the metaphors are different, there is an underlying connection between them. It is only when we hold them together coherently that we achieve a complete picture of energy as a concept. Talk to other science teachers in your school and prepare complementary metaphors for physics, chemistry, and biology.

Conclusion

Our understanding of the idea of knowledge itself is metaphorical in nature (see **Fig. 3**). For instance, viewing knowledge as a web or network has very different consequences from having an architectural metaphor. Going deeper into these different metaphors is beyond the scope of this article, but something that all educators need to keep in mind.

The ability to connect ideas and disciplines is important for multiple reasons[5]. To be able to see the same thing from different perspectives and fathom the underlying unity between apparently distinct ideas is a wonderful experience. We can help our students climb to a vantage point which allows them to appreciate concepts, like energy, beyond the confines of textbook definitions and equations. The foundations for transdisciplinary thinking can be built as early as at the school level. And, as illustrated with the concept of energy, the use of multiple metaphors to teach science has the potential to facilitate such connections between and across disciplines.

Note:

1. All the illustrations in this article were created by Punya Mishra, inspired by the Belgian surrealist artist René Magritte. Magritte's art often points to the limitations and arbitrariness of using language to understand the world and thus provided a rich source of images to explore the idea of using multiple metaphors in science education.
2. Credits for the image used in the background of the article title: John Sheehan (@dogstar7tweets on twitter). License: CC-BY-NC-ND (used with permission).

DISCOVER

OCEAN ACIDIFICATION

By Tejas Joshi

Start here!

1 The surface of an ocean is its connection to the atmosphere above. It is here that the two constantly exchange gases. Many of you are aware of water vapour evaporating from the oceans into the atmosphere as part of the water cycle. Similarly, various gases from the atmosphere such as carbon dioxide (CO_2), nitrogen (N_2) dissolve into the water.

2 How is this connected to the increasing amount of CO_2 gas that we release into the atmosphere?

3 The higher the concentration of CO_2 in the atmosphere, the greater is its absorption by the oceans!

So what happens to all this CO_2?

4 The absorbed CO_2 combines with ocean water (H_2O) to form carbonic acid (H_2CO_3).

$$CO_2 + H_2O \rightarrow H_2CO_3$$

5 So, the more the CO_2 we release into the atmosphere, the more the concentration of carbonic acid in our oceans. The carbonic acid rapidly breaks down into hydrogen ions (H^+) & bicarbonate (HCO_3^-) ions.

$$H_2CO_3 \rightarrow H^+ + HCO_3^-$$

6 The concentration of hydrogen ions is a measure of acidity. Thus its increase means the oceans are now more acidic.

7 A significant and sudden change in acidity can be problematic! Like in our own bodies, there are innumerable delicate processes and systems in oceans which are inter-dependent and rely on specific environmental conditions.

Many of these processes are already showing signs of being adversely affected.

8 Organisms like bivalves (eg. *Mercenaria species*) with hard shells are unable to cope with the more acidic conditions in oceans, and actually die because their shells dissolve—a result of the changing carbonate chemistry...

Clam Shells (*Mercenaria sp.*) Image by Ken Hammond

9 Researchers have identified peculiar changes in the physiology, behaviour and reproduction of marine organisms. For example, high acidity has reduced growth of the Norwegian algal species *Emiliania huxleyi*.

Microscopic image of Emiliania cell by Alison Taylor

10 Imagine you were building your home, but did not have sufficient bricks and cement with you: difficult, isn't it? researchers have found something similar to be happening in the oceans because of increased CO_2 concentration. Coral reefs and many marine organisms rely on a process called **calcification** to build their protective exoskeletons. During this process, the calcium and carbonate ions in ocean water combine to form calcium carbonate.

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

When the CO_2 concentration is higher, another reaction between the carbonate ions, CO_2 and water occurs instead. This uses up the carbonate which would otherwise be available for calcification.

$$CO_2 + H_2O + CO_3^{2-} \rightarrow 2HCO_3^-$$

As the concentration of carbonate ions reduces, the exoskeletons of marine organisms become weaker. The reduced survival of these small shelled organisms affects the survival of other species (eg. fish) that depend on them for food/ shelter.

11 **Gradually, this effect is felt by an increasing number of marine species, as they are all part of an inter-connected food web.**

But this is not all.
Ocean acidification poses a serious threat to the lives and livelihoods of coastal human communities who depend on the oceans for fish and shellfish (for food and trade).

? **These apart, we are still trying to understand all the global impacts of this phenomenon.**

Design: Tejas Joshi

Good to know!

1. The United Nations (UN) has dedicated one of their 17 Sustainable Development Goals towards ensuring the good health and protection of oceans and marine resources.
2. What activities are helping contribute to this global aim, and what are the other goals?
   Visit: http://bit.ly/UN17SDG
3. Would you like to explore the oceans in more detail, and learn more about ocean acidification? Or watch some oceanographers in action?
   To learn more visit: http://bit.ly/techemoldocean

Become an oceanographer!

The above scheme presents a flavour of how vast, dynamic and inter-dependent life under the oceans is! In fact, ocean acidification is only one of the many emerging areas of research today.

And for the "oceanographers", who choose to research oceans, every day is an exploration into a less understood and challenging world. Would you like to become an oceanographer yourself?

A study of the oceans demands knowledge and interests in multiple fields such as biology, chemistry, physics, ecology and mathematics! It also requires perseverance, hard work and the readiness to work in less friendly environments and climates.

No doubt it is becoming a popular choice of profession; you might just be our next ocean explorer!

With your friends, search for recent topics of research in the oceans: are they connected to ocean acidification in any way?

How do we respond to the challenge of ocean acidification, locally and globally?

What is the life of an oceanographer like? Search for some oceanographers online, and try piecing together their work experiences.

What would you think are some of the greatest challenges in studying oceans?

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Recommended Articles to Learn More

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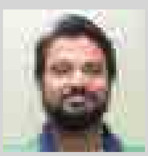

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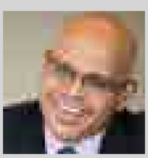

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LEARNING ABOUT SOIL: STUDENT'S VOICES

SANTOSH KUMAR

What do students know about soil? What experiences shape their understanding of it? What would they like to learn about soil? This article attempts to answer these questions by recording the voices of some urban and rural students in informal discussions about soil. It also provides pointers to help teachers make the classroom teaching of soil more informative, creative and interactive.

For most of us, one of the earliest memories of soil is a sensory one. Playing with mud as a child involved touch, smell and even taste (yes, definitely). With increasing urbanisation, many children spend their childhood in high-rise apartments, largely alienated from nature on the whole, and more specifically from 'this experience of soil'.

Soil, which, in itself, teems with diverse micro-organisms, and supports myriad life forms including humans, is often introduced to children as a dry collection of theoretical concepts in their Geography, Social science, or Biology curricula. As educators, however, we have a number of opportunities to bring this subject to life. Including activities that provide children a more hands-on, physical experience of soil, for example, would enable children to an understanding of soil that is more lively and interactive.

In designing activities to support classroom teaching, we often reach for the resources and experiences of other teachers etc. This time around, however, I thought it might be interesting to ask students what they would want to learn about soil and how. Looking at their responses closely and sensitively could hold lessons for us, as educators, in designing more enriching learning experiences around this subject.

A dialogue with students

Rather than a formal interview, I decided to have an informal dialogue with two groups of students from classes 7 and 8. One group included students from a predominantly urban background, but studying in a residential school located in a rural area. The second group of students belonged to a community of small farmers, pastoralists, potters, blacksmiths and landless labourers, and were day scholars in a local private school.

The students' responses were thought-provoking and, in some cases, quite unexpectedly lyrical.

For most of us, one of the earliest memories of soil is a sensory one. Playing with mud as a child involved touch, smell and even taste (yes, definitely). With increasing urbanisation, many children spend their childhood in high-rise apartments, largely alienated from nature on the whole, and more specifically from 'this experience of soil'.

Fig. 1. Classroom teaching about soil should focus on learning by doing.
Credits: Santosh Kumar. License: CC-BY-NC (used with permission).

This article presents the dialogue under various themes and also discusses some learning's for us as educators.

Matti ante manasulo yemi gurthiki osthundi – what is your first impression of soil?

Urban students responded to the word soil by sharing visions of crops, fertility, earthworms, agricultural fields, minerals, water table, soil pollution etc. One of the students was reminded of a Kabir composition: *"Maati kahe kumhar ko"*. Another student thought of a Hindi film song: *"Mere desh ki dharti sona ugle..."*

For students from the rural community, the word soil conjured up the idea of diversity – the different kinds of soil in their area, which they described using the local Telugu dialect – *nalla regada matti* (black cotton soil), *yerra matti* (red soil), and so on. Soil to them also meant microorganisms, earth worms, insects, farm yard manure, dry leaves, cow dung, sheep droppings etc. Many of them were reminded of the 'sweet smell' of the soil that accompanies the first spell of rains during or after the summer (known as *tulakari* in Telugu). For most of them, a wide variety of issues around fertility seemed to dominate their mental associations with soil.

What do you know about soil? What experiences shape this knowledge?

Students from the rural community seemed to have a very natural relationship with soil. Their understanding and knowledge about soil came mainly from observing and being part of agriculture-related activities at home. They knew, for example, the types of soil that support specific crops: groundnut, tomato, red gram, field bean – all of which are grown locally. These children had other opportunities to learn about soil as well. For example, they were able to discuss differences in the soils near water holes or on hills where they took their cattle to graze. They could identify the kinds of soil that could be used in pottery (two of the children are from a village with a lot of potters), to build houses, or make bricks. Some of them also talked about how they learnt about soil through conversations with their parents, grandparents, and other family members. At school, they mentioned learning about soil mainly through experiments with it, and a little bit of gardening that they were involved in – which included growing vegetables using waste-water from the school kitchen. However, it was clear that a significant part of their learning came from personal and practical experiences at home. In fact, this understanding of soil seemed to make their classroom learning quite simple.

In contrast, children from urban communities learnt most of what they knew about soil in school. Only two of the students (one whose grandparents live in an Agricultural University campus; and the other from Uttaranchal) mentioned having some exposure to soil at home as well. Geography and biology classes provided these students with several opportunities to learn about soil both in theory and from the outdoors. These included activities, such as gardening, field work including planting trees, creating bunds to store water, and conversations with farmers during visits organised by the school. Many of these students were familiar with the concept of soil ecosystems, and differences in soil types – from alluvial and black, to loamy and sandy soils. Some of them were capable of strongly articulating the importance of soil – referring to its capacity to support diverse flora and fauna; or correlating soil health with human health. Hearing these students discuss the impact of human activities on soil quality or how the agro-climate of an area could support only certain kinds of agriculture sustainably, was an interesting experience. In the context of sustainable agriculture, some of the students were even able to discuss the adverse impacts of mono-cropping on soil quality. Clearly, their theoretical understanding of soil was quite sound. However it was difficult to assess the extent to which these students were able to connect this understanding to their lifestyles, what they ate and their own health.

Students from the rural community seemed to have a very natural relationship with soil. Their understanding and knowledge about soil came mainly from observing and being part of agriculture-related activities at home.

What do you want to learn about soil?

The discussion on what they knew about soil spilled over into one where they expressed a desire to learn a lot more about it. Both groups of students had a number of suggestions about what should be discussed in school and how learning should happen.

In terms of what they would like to learn about soil there were a lot of similarities between both groups of students. For example, all of them wanted to learn about soil cultivation methods and their implications for human society; specifically – what remedial measures could be taken to arrest soil erosion/ degradation, and what were the different sustainable approaches that could be used to grow food? A lot of interest was expressed in learning to create a 'soil atlas' that would illustrate the various kinds of soils found across the country, what soils are suitable for what crops etc. The use of chemical fertilizers and pesticides and their impacts on soil ecology,
ground water aquifers and human health was another area of deep interest.

Some of the urban students were interested in the history of agriculture, traditional cropping practices, and impacts of the green revolution. They were also keen to learn more about celebrations around the cycle of agriculture — festivals, songs and dances associated with sowing, cultivation, harvesting etc.

In contrast, students from the rural community were eager to learn more about micro-irrigation systems, and crops that could be used both by humans and animals. This probably stems from the fact that this community is located in a drought-prone, semi-arid landscape which is constantly battling water scarcity. Construction techniques and pottery using different types of mud was another special area of interest among these students. Although many of these students celebrated local harvest festivals themselves, they were as keen as the urban students to know more about them, especially since many of these practises are rapidly disappearing from their own communities.

What emerged from this discussion was a deep desire to understand social practices around soil and to learn mainly by doing. Both groups of students also expressed an eagerness to learn about the various dimensions of soil. They seemed to view soil as a versatile, vibrant and multi-functional life-form, rather than being something to be connected only to agriculture: a view often seen in textbooks.

What feelings do you associate with soil?

Towards the end of our discussion, all the students were asked to share feelings that they most often associate with soil. Here are some of their sensory experiences in their own words:

"Playing with soil brings a lot of joy...";

"Observing a crop grow is an enjoyable experience...";

"It is fun to make idols of gods and other toys with clay and mud and to play with them..."; and

"Farming and working with soil is soothing, satisfying and fulfilling...".

Learnings for Educators

That sensory experiences can trigger some of the most powerful learning experiences was brought out in these discussions with middle school students in multiple ways. Some key learnings from this discussion could be used to develop ideas to introduce soil in classrooms:

1. Make hands-on activities with soil the central point through which learning should happen: depending on circumstances and constraints, pottery, gardening, composting, and roof-top vegetable cultivation are activities that can powerfully engage the senses. These activities can also be used to connect classroom learning about soil from biology, geography and general science. Growing food, in particular, helps inculcate a sense of respect for hands-on work and for farming as a way of life.
2. Organise visits to a neighbouring farm/roof-top garden and provide opportunities to interact with the farmer/ roof-top gardener.
3. Take children to a soil-testing lab and get them to interact with the technicians or scientists there. This will help them understand how scientific techniques can support experiential knowledge.
4. Work with children to trace the journey of their food from seed, soil, manure, compost, field and farm to their table in an attempt to answer the question: Where does your food come from?
5. Have students identify poems and songs about soil, mud, and earth in various languages. They could take the help of elders in their family and or their community. These could be shared in class.

Personal Learning

This interaction with students turned out to be an enriching learning opportunity for me. I was touched by the enthusiasm with which they tried to put across a point. These discussions broadened my own perspective on soil. They also made me think more seriously, and with renewed vigour, about various issues related to soil, and proved to me yet again that the teacher is a learner too!

Acknowledgements

I would like to convey my thanks to Radha Gopalan, friend & ex-colleague, but for whose guidance & support, this article would not have been possible.

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GETTING TO THE SOUL OF SOIL

RADHA GOPALAN

Soil is a living entity — the foundations of our food systems, and central to addressing climate change. The life in soil comes from the organic carbon that is held in humus. This article hopes to excite and encourage readers to dig into the soils around them to explore humus — its 'heart and soul'.

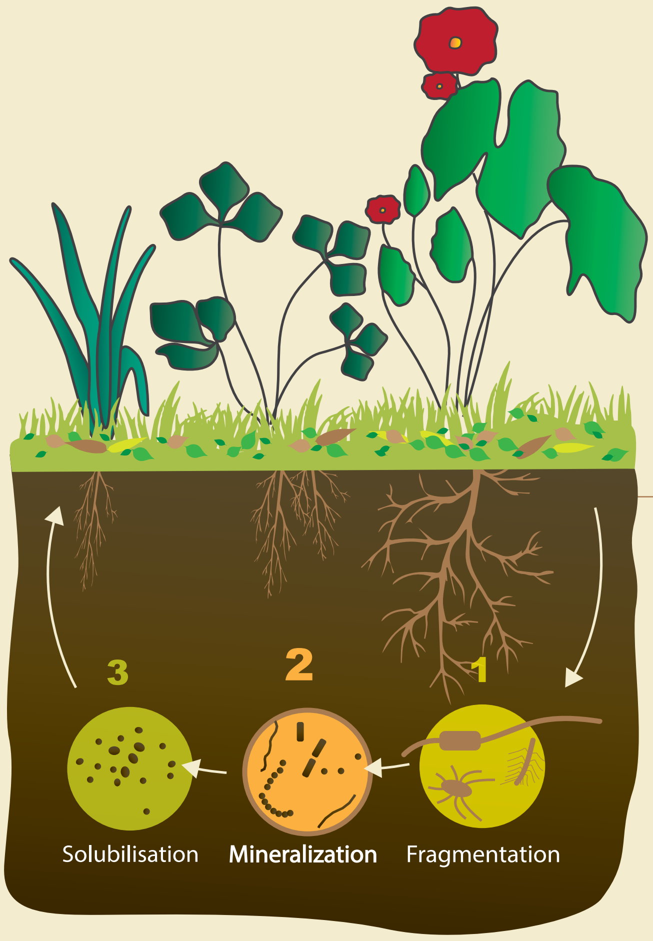
"Soil fertility is the condition which results from the operation of Nature's round, from the orderly revolution of the wheel of life, from the adoption and faithful execution of the first principle of agriculture – there must always be a perfect balance between the processes of growth and the processes of decay. The consequences of this condition are a living soil… The key to a fertile soil… is humus." — Sir Albert Howard, An Agricultural Testament, 1940.

"Humus is the product of living matter, and the source of it." — Albrecht Thaer, 18th century German agronomist.

In most middle school curricula, students learn about soil as a chapter in Science, Social Studies or Geography. This chapter usually discusses the physical structure of soil, types of soils, how soil is formed, soil profiles, and the crops supported by different types of soils. Learning about life in soils is generally restricted to a brief introduction to earthworms, or stating that chemical pollution can destroy life in soils. Interactions with middle school children, from both rural and urban schools, show that neither does this evoke a sense of wonder, nor an appreciation for the centrality of soil in our lives. While working with students from rural farming communities, it becomes particularly evident that what they learn from their textbooks does not relate to how they perceive soil in practice — as life-giving.

This article presents some activities that are designed to bring soils to life, making their study relevant and relateable to students — even those from rural farming communities[1]. These activities are shaped by our experience using them in a field programme for students of Class VI from an urban school in Hyderabad. Through these activities, we hope to encourage middle school students and teachers to explore humus — the 'heart and soul' of soil, integral to which are microorganisms — the often 'unsung heroes' of soil.

Why soil micro-organisms are essential



1. FRAGMENTATION:
Animals living in the soil break the litter into progressively smaller fragments, increasing its surface area.

2. MINERALIZATION:
Bacteria and fungi release enzymes that act on the exposed surfaces of the fragments to convert organic macromolecules to soluble nutrients.

3. SOLUBILISATION:
Small organic compounds and inorganic nutrients are released into the soil solution, from which they can be taken up by plants and other microorganisms.

Credits: Image adapted from Ecology 2e, Figutre 21.6. Copyrighted by Sinauer Associates, Inc. URL: https://www.colorado.edu/eeb/courses/2040bowman/EBIO2040/Syllabus_files/Ecology2e-Fig-21-06-0.jpg

Meet some soil microbes!

(a) **Bacteria** are the most abundant microbes in soil. They show extraordinary biochemical variability, decomposing organic matter and forming symbiotic relationships with root cells to make many essential nutrients available to plants.

(b) **Fungi** represent 2/3rds of the microbial biomass of the soil and perform diverse functions. They are the only organisms that can decompose lignin in the cell walls of plants. Since lignin is also the main source of humus in soil, this is the first step in the formation of humus. Spraying plants with fungicides destroys this very critical category of microbes, preventing humus formation.

(c) **Filamentous bacteria** enable numerous biochemical reactions like bacteria, but are filamentous in structure and can secrete antibiotics to keep other bacteria in check like fungi. Not only do they mineralize organic matter, some filamentous bacteria also form symbiotic associations with certain shrubs and trees to fix nitrogen.

(d) **Algae** grow on the surface of the soil because they need sunlight for photosynthesis. Most active when the soil is humid, algae play an important role in sourcing organic matter and fixing nitrogen.

Did you know that every gram of rich, fertile soil is likely to contain a billion living micro-organisms?
Surprising as this may seem – it is these microbes that cycle organic matter in soil, and nature in general. And, in doing this, they perform the indispensable function of bridging the mineral and the living world.

So, what would happen if they were to disappear from soil?
Without them, most naturally occurring elements that are essential for plant growth would remain stored away in inanimate plant and animal residues. In fact, if microbes did not exist at all, life as we know it, may have disappeared from our planet long, long ago.

Does this mean that we describe soil health in terms of the micro-organisms it contains?
Well, no. Most people (including scientists and agronomists) prefer to think of soil quality in terms of the crops and livestock it supports. This is because it is easier to see and handle crops and livestock, and measure soil fertility through yields and productivity. It's only rarely that we think about the microscopic organisms that form the basis of our entire agricultural system!

How does this change the way we see soil?
Understanding the role of micro-organisms, we begin to see soil as the site of a great living fermentation process. We also begin to appreciate why using purely chemical farming practices cannot ensure the balanced nutrition of plants or the sustainability of agricultural soils.

Poster Design: Vidya Kamalesh

Radha Gopalan is an environmental scientist with a Ph.D from IIT Mumbai. After 18 years of working as an environmental consultant, Radha taught Environmental Science at Rishi Valley School. She is a Visiting Faculty with the School of Development, Azim Premji University, and a member of the Food Sovereignty Alliance, India.

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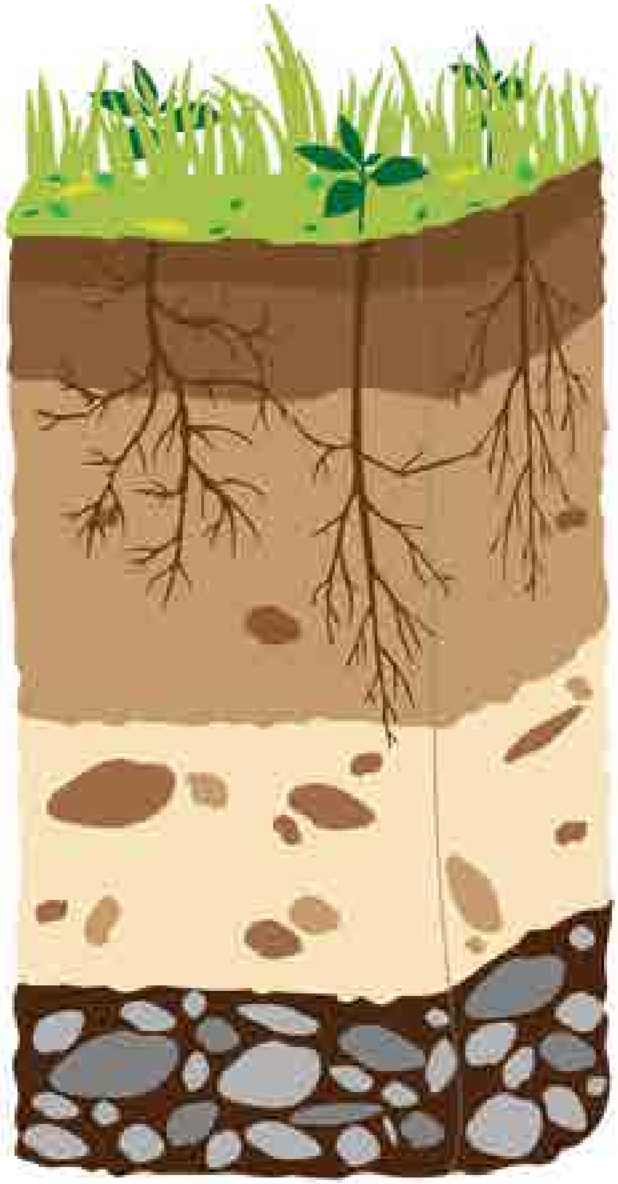

Fig. 1. Soil profile showing humus.

How is soil formed?

While most of us tend to think of soil as being static and inert, in reality, it is a complex medium which is constantly being formed. Most definitions of soil refer to it as a clay-humus complex, born of the fusion of mineral (derived from rocks) and organic substances (derived from plants and animals), which supports a large part of the living biomass on earth (refer **Fig. 1**).

This fusion of minerals and organic materials happens due to the:

(i) Breakdown of rocks – by changes in temperature that take place seasonally, erosion caused by water, corrosive action of plant roots, and action of the numerous acids secreted by microorganisms residing in soil,

(ii) Breakdown of leaf litter and animal material into debris – by the action of insects, and,

(iii) Further breakdown and transformation of the debris – by the action of microorganisms.

The slowly transforming organic material produced by the microbial breakdown of leaf litter and animal material forms **humus** (refer **Fig. 2**). The amount of humus formed at any given location depends on the presence of oxygen, moisture, soil temperature, and the amount of carbohydrates and proteins in the litter being decomposed.

Why is humus so important for life on this planet?

Humus makes soil more fertile, improving plant growth and preventing disease. It does this by influencing the quality of soil in three key ways:

(i) Physical – Humus modifies the color, texture, structure, moisture-holding capacity, and aeration of soil. For example, soil rich in humus is looser in consistency, allowing both air (oxygen) and water to move through it easily to reach the roots of plants.

(ii) Chemical – Humus contains many nutrients, like nitrogen, that are essential for plant growth. It influences the solubility of certain essential soil minerals such as sulphur and phosphorous, by enabling their combination with elements, such as iron, into compounds that are more readily available for plant growth. The organic content in humus resists changes in pH, increasing the buffering capacity of soil. For example, excessive application of fertilizers or pesticides or contamination by highly acidic or alkaline waste material in soil rich in humus will not affect plant growth. The organic material in the humus will bind the hydrogen or hydroxyl ions, buffering soil and protecting plant life.

(iii) Biological – By acting as a source of energy for soil microorganisms, and a slow but continuous stream of nutrients for plant life, humus makes soil a better medium (more fertile) for the growth of higher plants.

Can we see humus?

The activity described in this section is probably something that a lot of teachers use in the context of soil. Some of the questions that we can explore through this activity include: Can we see humus? Is soil the same everywhere? Is there more humus in some soils than in others — why? What kind of soil is more likely to have more humus — soil from the playground/ garden/under a tree/ pots/ cowshed etc.? Why and how do you know for sure?

Activity 1: Looking for humus!

Collect soil samples from a number of locations in and around your school campus. Decide on these locations with your students. These could include, for e.g., open ground, under a tree's canopy or any other shaded or heavily vegetated area, from a potted plant, a cultivated area (if available) or the school garden, a cowshed (if available) or a manure/compost sample (if available) etc. Assign a code for each location. Encourage your students to form groups of 5-6 members, with each group being assigned the task of collecting soil samples from a different location. Give each group a container, labeled with the appropriate location code, to collect their surface soil samples. Ask each group to make some notes about the location of their soil samples. Their observations can be recorded in **Table 1**. Once the different groups return with their soil samples, encourage them to observe their samples carefully and record their observations in **Table 2**.

Based on your analysis of each sample, discuss characteristics of the location from which it was collected. Typically, soils from more vegetated areas or under leaf litter will be darker, hold more water and smell like mud. This darker soil is rich in humus (refer **Fig. 3**).

When this activity was performed in a rural area, for example, students observed that the soil from around the cowshed, fields that were heavily mulched or where manure was used, was moister, darker, and had more insects and worms compared to soils from areas without vegetation or from fields with intensive chemical use. This led to the next question: since intensive use of synthetic fertilizers and pesticides destroys soil fertility, is there any way to bring humus back into these soils? Can farmers maintain soil fertility without chemicals, and still keep growing sufficient food?

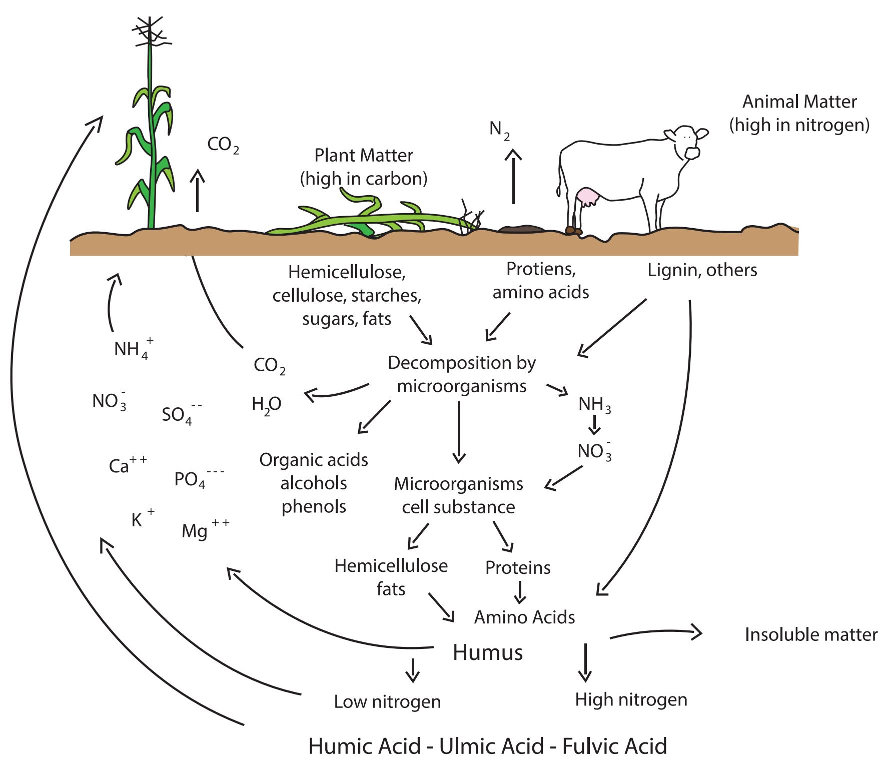

Fig. 2. Formation of humus. Leaves, twigs, and other plant material that drop to the ground pile up to form leaf litter. Plant matter that remains unconsumed or undigested by animals adds to this litter. When animals die, their remains add to the litter. Microbial life in soil breaks down leaf litter, recycling elements that were originally absorbed by plants for their growth. There are, however, some parts of the plant and animal residues that are not completely mineralized by microorganisms. This material is usually called **humus**. Typically dark brown to black in color, it decomposes slowly over a long period of time. Image adapted from US AG Florida, Inc.

Humus acts as a reserve and a stabilizer for organic life:

As a result of the formation and accumulation of humus, a part of the elements essential for organic life, especially carbon, nitrogen, phosphorus, sulfur, and potash, become locked up and removed from circulation. Since the most important of these elements — carbon, combined nitrogen, and available phosphorus — are present in nature in only limited concentrations, their transformation into an unavailable state, in the form of humus, tends to serve as a check upon plant life. On the other hand, since humus can undergo slow decomposition under certain favorable conditions, it tends to supply a slow but continuous stream of the elements essential for new plant growth.

Can we produce humus?

Humus, as we have seen, is produced as a result of the continual natural degradation of organic matter by soil micro-organisms. Fertile soils are therefore rich in organic matter, and provide a habitat for decomposing soil bacteria. While mineral layers of soil are found deeper down, its organic components remain concentrated near the surface — also called **topsoil.** Consequently, this is also the layer where soil bacteria accomplish their decomposition of organic matter to produce humus. To maintain soil fertility, it is critical that this topsoil be conserved. However, a variety of human activities, including deforestation or cultivation practices, like ploughing, destroy this surface organic layer.

Although humus is produced naturally in forests and fields, it can also be produced by us, outside of these areas, *Teaching as if the Earth Matters*

LOOKING FOR HUMUS - I

Identify a location to collect your soil sample - from your playground, the school garden, under a tree, just outside the school gate. Take a few minutes to observe it.

1. Use your hands or a small garden shovel to collect a sample of soil from some locations in and around your school campus. Seal each sample in a clean container or a zip-lock bag.
2. Use the field called 'Brief Description' to record the non-living and living components that you think influence the quality of the soil sample. For example:

- Is the location of the sample wet or dry? Does the soil sample feel moist to touch or does it feel sandy? Can you smell the wet mud or not?
- Is the location barren? If not, what kind of vegetation do you see there (including grass, small plants etc.)? Is the vegetation mainly in the form of trees, or are there other plants as well? Is the vegetation cover dense or can you see many bare patches of soil? Is there leaf litter on the ground? Did you collect soil samples below the leaf litter? etc.
- Are there any animals or birds at the location? Did you see any earthworms, ants, or snails?

You will need:


A small garden shovel


Zip-lock bag


Pencil

Table 1
Location Code:
Date:
Time:
Brief Description:

Contributed by:
Radha Gopalan is an environmental scientist with a Ph.D from IIT Mumbai. After 18 years of working as an environmental consultant, Radha taught Environmental Science at Rishi Valley School. She is a Visiting Faculty with the School of Development, Azim Premji University, and a member of the Food Sovereignty Alliance, India.

i wonder

Azim Premji University

LOOKING FOR HUMUS - II

Open each sample of soil. Take a few minutes to touch, smell and test it.

Table 2

Characteristics	Sample 1	Sample 2	Sample n
Colour			
Texture (loose/compact, dry or moist)			
Smell			
Water retention capacity *			
Presence of root hairs,fungal filament			
Presence of insects, worms etc.			
Any other observations			

* To determine water retention capacity of the soil sample, place a small amount of the soil sample on a plate. Add a few drops of water to it and leave for 5 minutes. Look at the surface to see what has happened to the water and record your observations. For example, does the water remain on the surface of the soil sample, or has it disappeared to the bottom of the plate? Or is it neither on the top nor at the bottom of the plate?

Contributed by:
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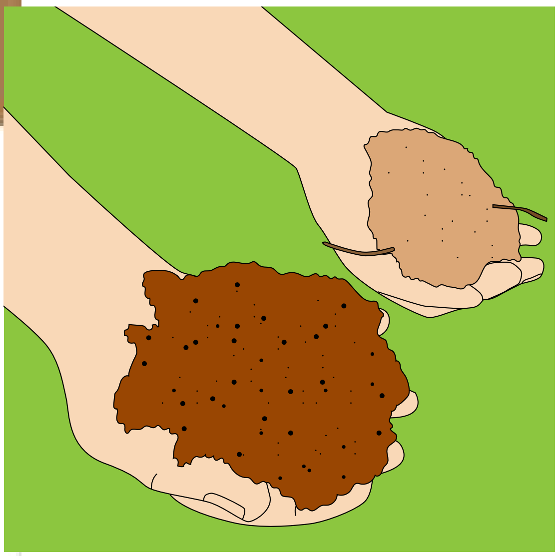

Fig. 3. Comparing soils: humus-rich living soil (darker in colour) and humus-poor soil (lighter in colour).

through the process of **composting.** Farmers do this outside their farm plots, for example, by piling up organic matter and directing its fermentation through microbial action.

Compost, like humus, is made of decomposed organic material (animal dung, human waste, decaying organic material, such as food and garden scraps etc.). Not surprisingly, the most widely used method for composting is inspired from the natural site of humus formation – the forest floor. In his compelling treatise on humus and composting, The Agricultural Testament, Sir Albert Howard places a lot of importance on the location for the compost pit. Composting is ideally carried out away from direct sunlight and dominant wind. Organic matter must be piled in such a manner that the oxygen necessary for **generating heat** and the survival of humifying fungi must easily penetrate the pile. When all these conditions are met, the pile heats up (with temperatures rising to even 80°C). This rise in temperature is caused by action of thermophilic microbes. Typically, after about 15 days, the temperature falls and insects and worms start breaking down organic matter. At this stage, the humifying fungi begin to multiply and manufacture humus from the cellulose and lignin released from the decomposing plant matter. In about 8 weeks, this process of composting fulfills its role of cleaning and humifying organic matter (refer **Fig. 4**).

Activity 2: Making humus

To understand the relationship between humus and compost, involve students in setting up a compost pit, using the method described above, within the school premises. Once the compost pit is set up, encourage students to monitor and record the colour, smell, and appearance of the organic matter within it on the first day and, again, after a week. They can continue to monitor it twice a week till the first batch of compost is ready (in about 6-8 weeks). This compost can be used by students to set up a little vegetable patch. To learn about microbial activity, students could use a small stick to poke the pile/pit and check the temperature within. The temperature can be monitored every day for the entire period and plotted in a graph. This graph can then be used to discuss the nature of microbial activity and its relationship with the formation of compost from vegetative and other organic material. It can also be used to explore how compost is produced by

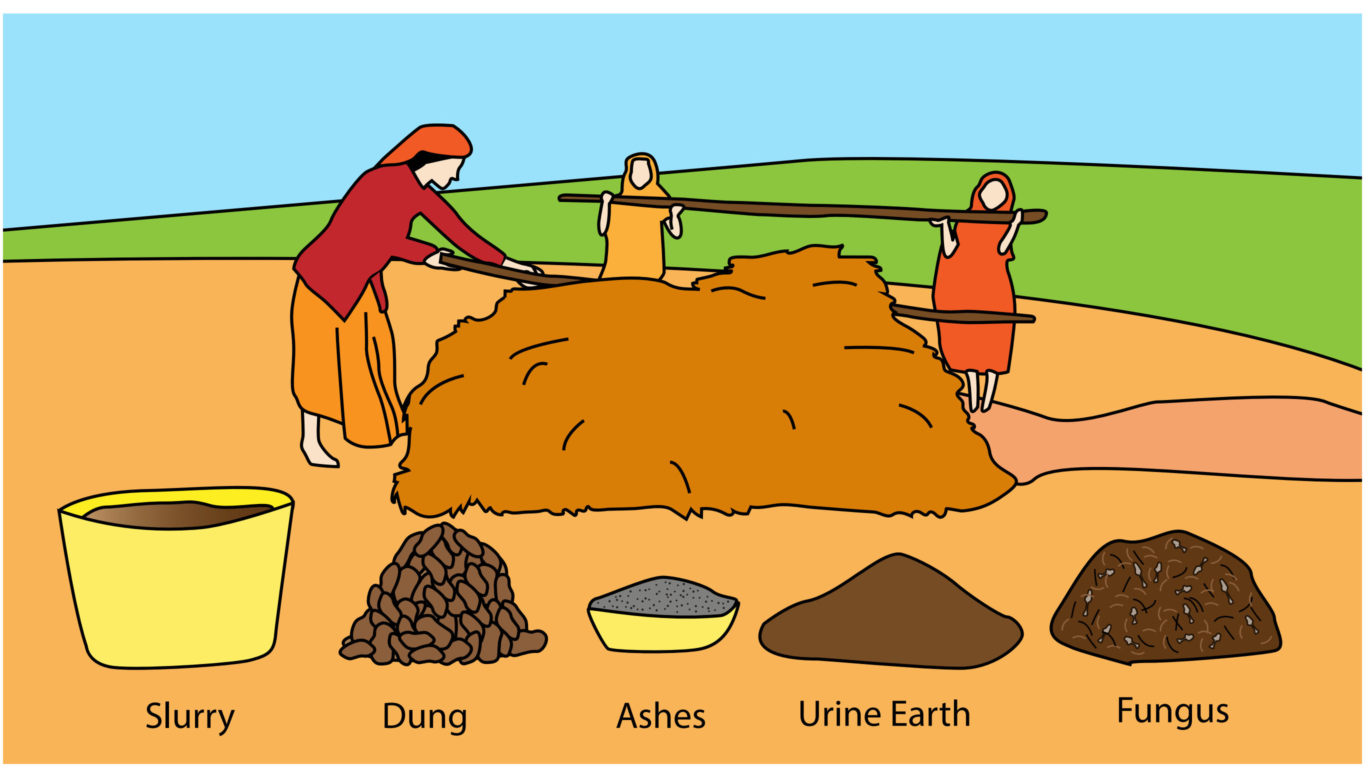

Fig. 4. Farmers building above-ground compost heaps instead of compost pits in monsoon to prevent water pooling.

the action of microbes followed by that of insects and worms, thus setting up a diverse food web in the compost pit.

Reflection on this activity may lead to another question — why not use animal dung / human waste directly on soil to allow the natural production of humus? Why is it more efficient to apply compost? While this can be done, the process of composting produces a larger quantity of humus from an equal mass of organic matter. For example, 30 tons of manure/dung spread on 1 hectare of land will yield about 3 tons of humus, but when the same 30 tons is composted, it can produce about 10 tons of compost, containing as much as 5-6 tons of humus. In addition, the organic matter is pasteurized during composting, which minimizes the possibility of spreading any pathogens from animal dung or plant waste from the field/garden.

Going beyond the biology of soil

As is evident, in the process of learning about soil, there are many other skills that students develop and hone: observation, learning through and by their senses, systematic recording of observations and arriving at inferences based on observations. Thus, soil provides a versatile medium for interdisciplinary learning.

An exploration of soil can be used to understand micro- and macro-perspectives to ecology. For instance, students learn about the versatility of microorganisms — through their beneficial role as nutrient enablers in production of fermented foods such as curd, bread, idlis, tofu, tempeh etc. *vs.* their role as disease causing agents. At the other end of the spectrum, they also learn about the significance of humus and organic carbon in soils in the sequestration of carbon, a function that is critical in mitigating climate change. Similarly, learning about soils is useful in introducing ideas of nutrient cycling, mineralization, and the significance of organic or chemical-free farming. Principles of surface tension, binding of water molecules to soil, the idea of interstitial spaces and capillary action can also be discussed and extended to an understanding of physics and chemistry.

Soil can thus be used to design a theme-based study in middle school across social studies, science, mathematics, languages (poems and essays) and history (use of soil in architecture, food, pottery). Imagination is all it needs to make soil come alive!

Note:

1. These activities were part of a module titled 'Soil's Health is Your Health' that was tested and used in a Government school and private rural school in Andhra Pradesh. Readers interested in accessing the entire module may contact the author for a copy.
2. Credits for the image used in the background of the article title: Soil photo. Pixabay, Pexels. URL: https://www.pexels.com/photo/grey-small-mushroom-on-brown-soil-68732/. License: CC0.

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Discover **CORPSE ECOSYSTEMS** | **Author: Geetha Iyer**

Corpses as ecosystems? No jokes! Don't think of human corpses – think decomposition. When a large animal like a wild buffalo, sambar, giraffe or zebra dies in the forest, or cattle dies on the road, their carcass (dead bodies) becomes an ecosystem – the starting point for new sets of food chains and food webs, but with a difference. The process of decomposition sustains this ecosystem.

It's easy to imagine this on land, but in oceans? The process of corpse decay in oceans has a special name – Whale Fall. When whales die, they either get washed onto the shore or sink to the bottom of the ocean. When the latter happens, it offers a feast to the community of invertebrates and microbes that live at depths of 300-900m below the ocean surface.

Scavengers, like hagfish, sleeper sharks, rattail fish and amphipods, are the first to feed on the meaty part of the carcass. They devour the muscles, visceral organs and blubber of the whale corpse, leaving behind only its skeleton. Does this signal the end of its potential to feed other life forms? No! Marine biologists, led by Dr Craig Smith, have found that depending on its age, a whale skeleton can hold anywhere between 2-2.4 metric tonnes of oil in its bones. This is yummy energy for hordes of polychaete worms, molluscs and unusual crustaceans that descend on the whale's bony remains.

Of these – the bone-eating worm leads the show, while others feed on the sediments around the whale skeleton. The Osedax or the bone-eating worm has no mouth, stomach or gut, no eyes and no legs. If this isn't unusual enough, the male is a tiny fella residing within the female. Females, on the other hand, have beautiful red plumes and root-like appendages. These appendages harbour many lipid-digesting symbiotic bacteria. When a female bone-worm encounters the skeletal remains of a decaying whale, it uses these appendages to bore through the bones and reach the marrow. Once they reach the marrow, the symbiotic bacteria break down the lipids in the bone oil, releasing energy that the worms use. Varying with the size of the whale, this process can take at least two years.

Some examples of bone-eating worms

(a) Most female bone-worms have long, graceful "palps" that wave in the ocean currents.

(b) The female of an as-yet un-named bone-worm species in the genus Osedax, which has been carefully removed from the whale bone.

Credits: Greg Rouse, Scripps Institution of Oceanography, UCSD, USA. URL: http://www.sio.ucsd.edu/. License: Copyrighted (used with permission)

Chemoautotrophic whale-fall community

Bacteria mats, (vesicomyid) clams in the sediments, (galatheid) crabs, polynoids, & other invertebrates.

Credits: Craig Smith, University of Hawaii. URL: http://oceanexplorer.noaa.gov. License: Copyrighted (used with permission)

WATCH bone-eating worms in action in this video from the Monterey Bay Aquarium Research Institute (MBARI), CA, USA – https://www.youtube.com/watch?v=UR8KcoVIks

The holes drilled by the Osedax act like open gates to a procession of bacteria that move into these remains. The first bacteria to enter are anaerobic. These are followed by yellow mats of chemosynthetic sulphophilic bacteria that cover the bony remains of the whale. About 200 different sulphophilic bacterial species have been found feeding on whale bones!

Marine biologists from Monterey Bay Aquarium Research Institute report that the last-stage whale-fall community is extraordinarily diverse, with as many as 190 different species of macroscopic communities feeding on a single corpse! Many of these species are not only unique to whale-fall, they are also constantly forming new ecological niches, with organisms that scavenge, prey on them, or form symbiotic associations with them! What's more – some of these communities last quite long – even as much as 50 years!

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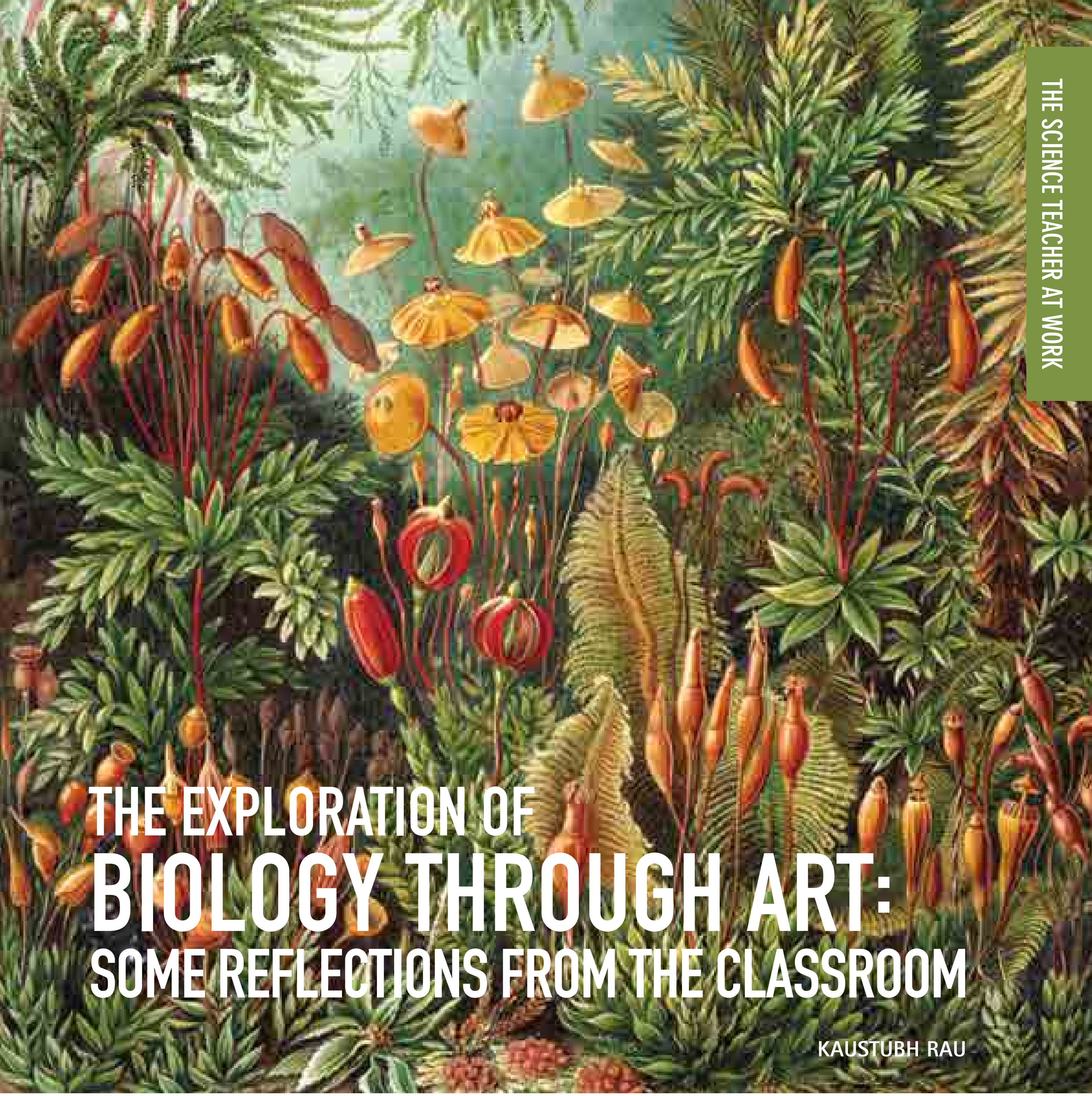


THE EXPLORATION OF BIOLOGY THROUGH ART: SOME REFLECTIONS FROM THE CLASSROOM

KAUSTUBH RAU

Are approaches to teaching Biology determined and constrained by its origins as a 'science'? Or, would an approach that incorporates 'art' into its teaching practice enhance student learning? The author attempts to answer this question through some classroom examples from his own practice.

Our modern understanding of science is of it being a rational, objective, observation-based endeavour. Conversely, art is understood as being a wholly subjective means of self-expression, with an approach completely at odds with that of science. However, this distinction has not always been as rigid. Historically, many artists have used a scientific approach to understand perspective, light and form; and, many scientists have revealed themselves as fine artists in their use of art to document natural phenomena.

Historical connections

Biology, in particular, readily lends itself to being rendered as art; and, artists have been recording natural history for hundreds of years. Court artists in the Mughal Empire, for example, were renowned for the accuracy with which they depicted flora and fauna in their paintings. The most famous of these is a painting of a Mauritian Dodo, by an artist called Ustad Mansur, based on one of two living specimens brought to Emperor Jehangir's court in 1625 (refer **Fig. 1**). This painting is believed to be the archetype on which all subsequent drawings of the Dodo were based – hence assuming an importance beyond its artistic value. The four other bird species that share this frame with the Dodo — Blue-crowned Hanging Parrot (upper left), Western Tragopan (upper right), Bar-headed Goose (lower left), and Painted Sand-grouse (lower right) — are also painted with such accuracy as to be readily identifiable.

In colonial India, many naturalists mainly of British descent travelled the length and breadth of the country, assiduously collecting (and naming) our biological heritage. The British were also excellent at documentation, leaving behind a rich legacy of books on India's natural history that are still referred to by specialist and amateur biologists. Among the most famous of these is Robert Wight's *Icones Plantarum Indiae Orientalis*, a six volume compendium of Indian plants. Wight employed many local artists, the most well-known of them being 'Rungiah and Govindoo' *[sic]*, whose proficiency in painting life-like representations of plants is evident in the lithographic colour-plates in Wight's books (refer **Fig. 2**). Perhaps the most glorious example of this kind of natural history can be seen in Ernst Haeckel's painstaking drawings of organisms (particularly small marine animals) in his book, 'Art forms in Nature'. With each drawing composed to maximise its artistic impact, this book went on to deeply influence varied fields, including engineering design and architecture.

Fig. 1. Painting by the Mughal artist Ustad Mansur from c1625.

Credits: By Ustad Mansur - Hermitage, St. Petersburg (http://julianhume.co.uk/wp-content/uploads/2010/07/History-of-the-dodo-Hume.pdf, and an earlier version: http://www.natuurinformatie.nl/nnm.dossiers/natuurdatabase.nl/i005387.html), Wikimedia Commons. URL: https://commons.wikimedia.org/w/index.php?curid=3224929. License: Public Domain.

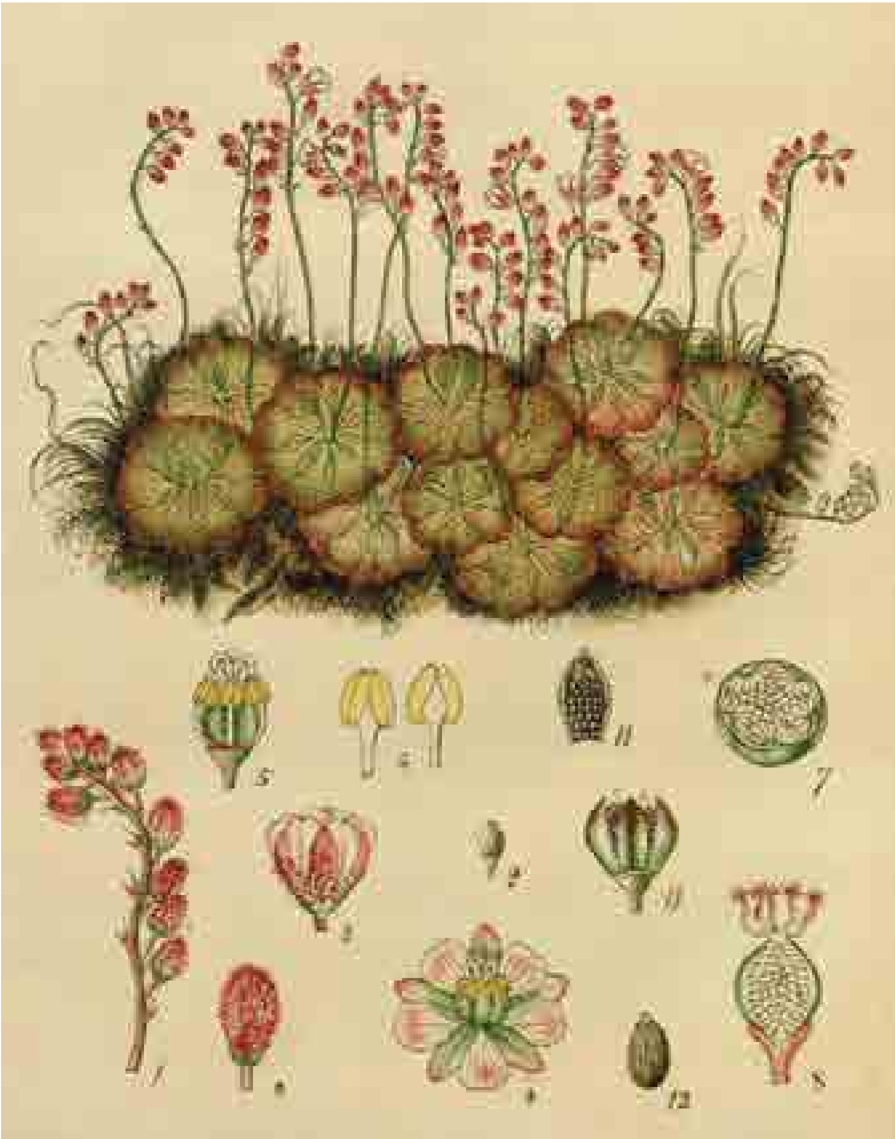


Fig. 2. ***Drosera burmanni*** **by the artist Rungiah from** ***Spicilegium Neilgherrense*****.**
Credits: Robert Wight (http://www.botanicus.org/item/31753002447933), Wikimedia Commons.
URL: https://commons.wikimedia.org/w/index.php?curid=19375800. License: Public Domain.

Art in the Biology classroom

I have always found myself fascinated by these artistic depictions of Biology, the perfect amalgam of art and science. Whether it be the delicate lines and colours of Mughal paintings, or the breath-taking detail of 19th century botanical drawings, these works of art speak to us across the passage of years — bestowing a living, breathing quality to their subjects that a mere photograph couldn't. This interest has seeped into my classroom practice, and I have found myself showing students links between art and biology in many different classes.

Conventional teaching practice draws a sharp distinction between art and science. We tend to assume that very different skills are required for 'doing' art versus 'learning' science. Classroom practice, however, is not rigidly defined, and children are more flexible about applying concepts and skills learnt in one area to another (although this flexibility seems to diminish as they move up to higher grades — perhaps as a direct consequence of teachers reinforcing the compartmental approach in school). Based on my own classroom experiences, I can now see that the lines between art and biology are fluid, and learning and practices from one field can inform and enhance understanding in the other. Also, certain requirements, such as the need for acute observational skills or the ability to synthesize information from varied inputs to develop a coherent image, are common to both fields.

In this article I provide examples from classroom teaching of Grade VIII Biology (and one from Grade XI) where certain scientific concepts were rendered as works of art. I also explore the idea that in producing such art, children may develop a deeper understanding of the concepts themselves.

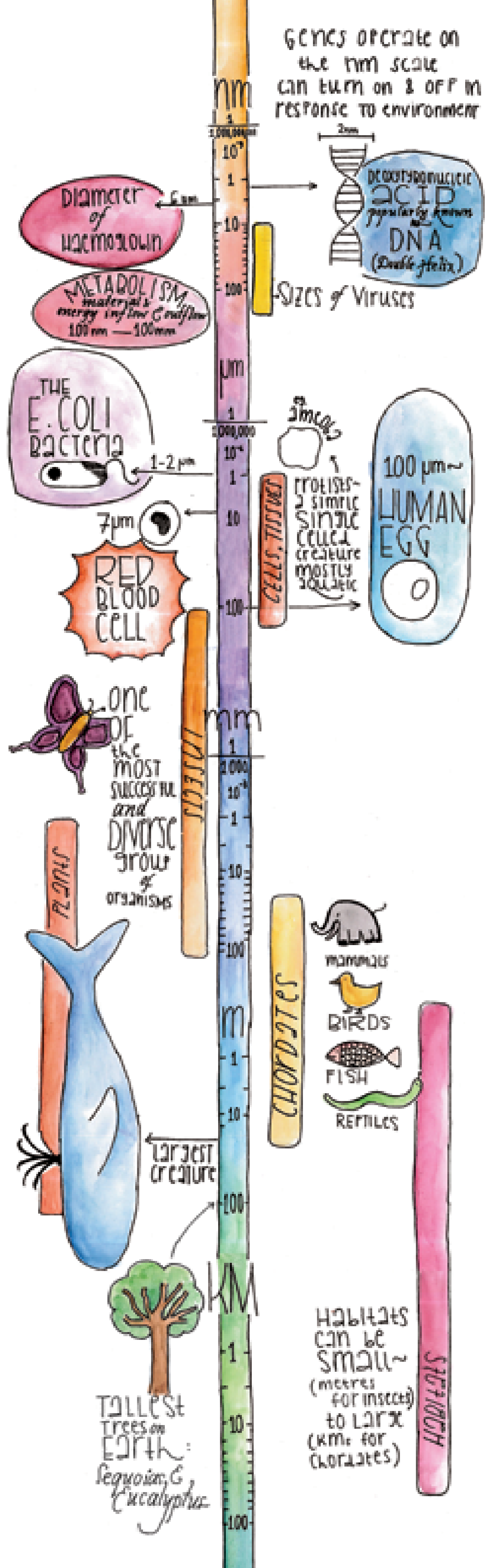
Representing scale

We begin Grade VIII Biology by looking at the scale of life, particularly the size ranges at which certain mechanisms operate. Students of Biology can find a ready-made version of this scale in every textbook. However, the question of whether the essence of Biology can be conveyed through one drawing depicting the various scales at which organisms exist has always seemed fascinating to me. What is even more interesting is to engage students in the exercise of creating such a drawing and discovering their individual artistic interpretations of it (refer **Fig. 3**).

While the teacher's inputs may be needed to guide the basic components of such a drawing, there is sufficient scope in this exercise for a student's unique individual conception of size to also come through. It is also likely that Grade VIII students may not grasp the deeper aspects of some of the processes (genetics, metabolism, evolution) depicted in such a drawing. However, in the process of working on it, they become familiar with these terms and the range at which their effects can be seen. Also, this exercise helps fix certain standard size markers (diameter of the double helix,

Fig. 3. Drawing of length scales of organisms.

Credits: Tanmay Pandya and S. Sanjushree (ICSE 2018), Rishi Valley School. License: CC-BY-NC.



the size of red blood cells, the tallest organisms on earth etc.) in their mental make-up of biology.

Depicting Biological Classification

Another concept that offers interesting possibilities to explore Biology through art is that of the classification of life. While discussing this idea with one batch of Grade VIII students, I touched upon the fact that there are many depictions of the 'Tree of Life'. This seemed to capture the students' imagination and they wanted to paint their own version of the tree.

Having an excellent art department in the school really helped on this project. While I dug out different artistic representations of the Tree of Life, the art teacher, Sreekumari J. L., helped students create their own. She chose a style for the mural, and expertly guided students in working on it, while also ensuring that they sustained the energy to complete it. The finished piece turned out to be a large 4.5m X 2.5m mural on a wall of the main school building (refer **Fig. 4**). Although our class discussion may have provided the initial spark for this project, it acquired a life of its own in the students' minds. Not only did the students volunteer to take on the project, they also devoted many weekends working on it.

As a teacher, listening to the discussions between students while they worked on the mural was quite informative. In spite of many class discussions on how all life on earth originated from a group of bacteria more than 3.5 billion years ago, it was only while drawing branches of the tree that several students truly experienced that *aha* moment. Discussions on ways of depicting extinct species or evolutionary 'dead-ends' gave students a better appreciation of the forces underlying natural selection. These were finally depicted as dried leaves that had dropped off the branches of the tree. Such discussions led to a richer understanding of evolution and primarily of the fact that it needn't always be linear and progressive with man at its pinnacle.

While it resulted in a wonderful visual, this project left me with a lot of questions. Should there be a specific learning purpose underlying such work? Is it necessary that it convey scientific information in addition to its existence as a work of art? Is the learning in such a project dependent on the teacher shaping it with scientific facts (in this case, related to evolutionary relationships)? Or, is it enough that some learning comes about in the doing of it, even if it occurs in an unstructured fashion? Is it necessary that this project ends with students having a better understanding of classification? Or, is it enough that they produce a beautiful work of art, something that is appreciated by and will, perhaps, inspire other students and teachers?

It is probably best to conclude that it is too early to tell the impact of such a project on the students' minds. One can hope, however, that it leaves students with the memory of a richer way of understanding this basic idea about life on Earth that they continue to revisit till much later in their lives.

Nature journaling

Biological art seems to crop up in many areas — big and small — even when students don't consciously set out to produce it. A drawing made with the specific intention of recording a biological concept or phenomenon can have an artistic by-product.

One such area where all students of a class have been able to show their creativity is in journaling walks in and around the school. Fairly common in many schools now, the main purpose of such walks is for students to develop observational skills and familiarise themselves with the biodiversity of the campus. Students are encouraged to maintain records of their observations on the walks and, on occasion, use drawings to indicate places they have

Fig. 4. Tree of Life mural painted by a group of students when in Grade VIII (2015-16).
Credits: K. Natarajan. License: CC-BY-NC

explored. This is particularly delightful because students respond to this activity with much enthusiasm, pouring their energy into recording their observations. In fact, it can keep them so engrossed that a class of students may work on their journal entries quietly, for the entire duration of a one hour class! The intense observation this activity entails brings about a natural slowing down of thought processes. Students tend to become aware of details or processes (insect moults, rock patterns, signs of animal passage etc.) that may have otherwise slipped their attention or been ignored. This focus also seems to 'free their hands' and in recording what they observe, what emerges sometimes is art.

I have used journaling in a variety of ways. For example, it was part of a challenge that I had asked my students to test during their vacations. They were asked to record their observations after five minutes of looking at the same area every day for a month. At the end of this period, they had to decide for themselves if observing the same field of view daily had led them to notice more details. I believed that getting students to engage in this process of actively observing their surroundings would help them develop a sense of association or belonging, and with it a growing sense of care for their immediate environment. While student journals were written mainly to document their observations, some of their entries (refer **Fig. 5**) had the flavour of a painting, conveying some sense of their enjoyment in creating it.

Fig. 5. A journal entry.

Credits: Aman Gwjwn (ICSE 2018), Rishi Valley School. License: CC-BY-NC.

Another joy from journaling has come from using it in working outside the classroom and curriculum with students who aren't necessarily from a science background. For example, we had been working on the idea of making maps of popular walks to familiarise visitors with the biodiversity of our school campus. On being presented with this idea and a rough sketch, a student took it upon herself to produce a stunning rendition of a map. This map showed the trail on one side, and the plants, birds and insects that could be encountered on it painted in explosions of colour on the overleaf (refer **Fig. 6**). Each image reflects the artistic eye of the fine-arts student, but is also biologically accurate. Working on this map offered the student, who may not have been actively interested in biology, the opportunity to develop a connection with her natural surroundings. It is because of this connection, perhaps, that this student chose to not produce a purely subjective version of a landscape or life-form.

Some parting thoughts

In this article, I have shared a few examples of projects in which students have been able to learn while also expressing their creativity. As a teacher, it has been both interesting and inspiring to see how students incorporate a biological concept into their art-work. However, I continue to feel ambivalent about pinning down the academic outcomes arising out of these attempts. In some cases, being fully engaged in these moments of creation, students may arrive at a biological truth in the form of an insight or observation that they make — and, perhaps, this is

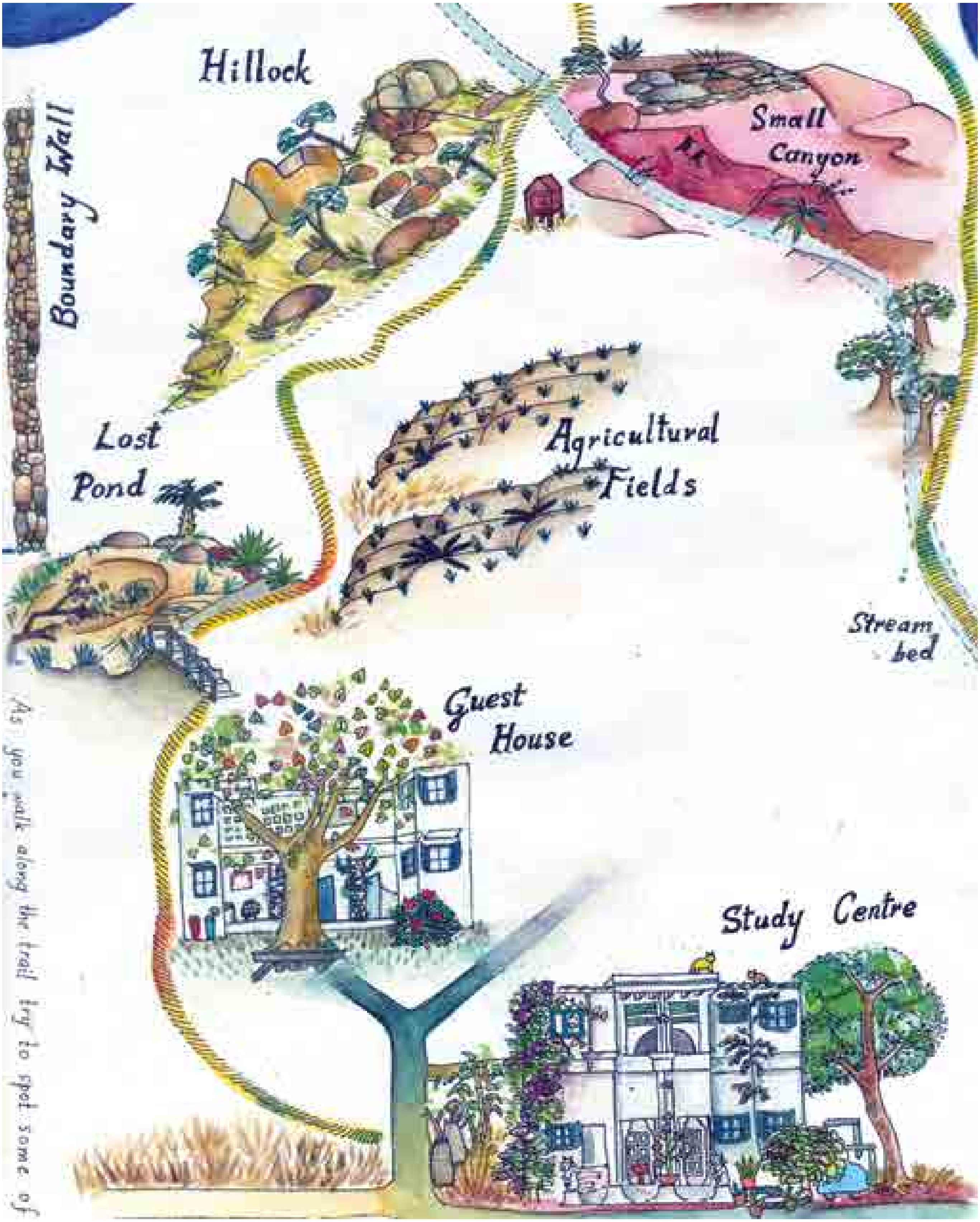
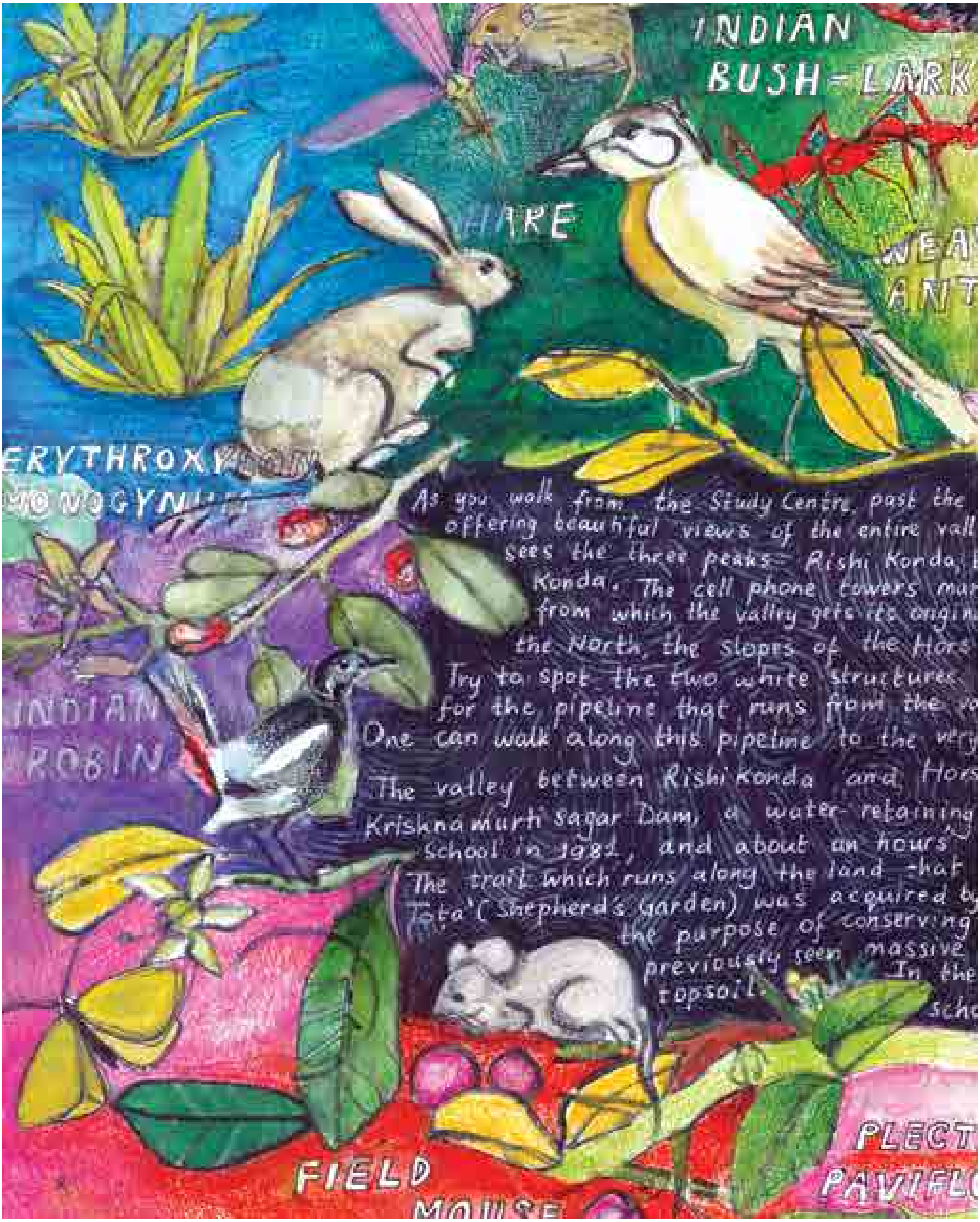


Fig. 6. Trail map with flora and fauna. The original map is two sided, with the trail directions drawn on one side and the information provided overleaf.

Credits: Painted by Rahi de Roy (ISC 2016), Rishi Valley School.


INDIAN
BUSH-LARK
HARE
WEA
ANT
ERYTHROXY
MONOGYN
INDIAN
ROBIN
As you walk from the Study Centre, past the
offering beautiful views of the entire vall
sees the three peaks - Rishi Konda,
Konda. The cell phone towers
from which the valley gets its origin
the North, the slopes of the Hors
Try to spot the two white structures
for the pipeline that runs from the
One can walk along this pipeline to the very
The valley between Rishi Konda and Hors
Krishnamurti Sagar Dam, a water-retaining
School in 1981, and about an hours
The trail which runs along the land that
Tota (Shepherd's garden) was acquired by
the purpose of conserving
previously seen massive
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enough. Often, the close observation required to produce these works of art leads to a better understanding of our world, a greater appreciation of the inter-relatedness of things.

New ideas emerge quite naturally in the classroom if one keeps an ear to the ground. For example, as an ever-fascinating subject for school children, a variety of art-related activities could be built around the human body that encourage them to go beyond the diagrams in textbooks. There are, after all, many ways of showing this 'home' of ours so as to bring out its beauty and connections to other organisms. In another example, students could paint the Hillis plot — a variant of the 'Tree of Life' theme in which the tree is wrapped around itself in such a way that it almost meets in a circle. Many artistic versions of this plot are now available, with some scientists even having them tattooed on their bodies. Another possibility, suggested by a friend who is a landscape architect, is to get students to create a walk depicting main events from the Earth's evolutionary timeline, starting with its origins. The length of this walk would correspond to approximately 4 billion years of the Earth's history, and important events could be shown as sculptures, drawings or writing on the stones of the walkway. The possibilities are endless.

Note: Credits for the image used in the background of the article title: Haeckel Muscinae (Mosses). Source: Ernst Haeckel, Kunstformen der Natur or Art forms in Nature (1904), plate 72: Muscinae, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Haeckel_Muscinae.jpg. License: CC-BY-SA.

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SPIDERS: THE WEAVERS AND STALKERS AMONGST US

VENA KAPOOR & DIVYA UMA

They may be tiny, but like us, the life of a spider is filled with lots of drama! Spiders have to decide where to build their webs and find food, how to escape their enemies, find potential mates, and take care of their young ones. Intrigued? Discover the fascinating world of spiders with us.

Spiders evoke many feelings in us – fear of hairy, 'creepy', eight-legged tarantulas; shudders at cobwebs that need to be cleaned periodically from homes; or excitement at the Marvel comics hero, Spider Man, who shoots silk from his wrists and saves many lives!

So, what is a spider?

Spiders belong to a large group of animals classified as arthropods (Greek: *Arthro* = jointed; *poda* = legs) with eight legs, and two fangs to inject venom to stun their prey. Some of their closest relatives include scorpions, whip scorpions, mites, ticks, and harvestmen.

Known for their immense species diversity, spiders are found almost everywhere in the world (except Antarctica), and in every type of habitat. So far, scientists have been able to discover more than 45,000 different species of spiders from across the world. More than 1400 of these species, belonging to 59 families, are found in India

Box 1. How strong is spider silk?

Spider silk is very strong – you may have even heard the phrase, "as strong as spider silk". The silk of some kinds of spiders require five times more energy to break than an equivalent volume of Kevlar (which is a synthetic fibre similar to steel). What makes spider silk this strong is its elastic, stretchy property. Over the last decade, there has been extensive work on the use of spider silk in biomedical applications.

Through genetic engineering techniques, researchers have managed to isolate the spider genes responsible for silk production, and used them to produce spider silk in bacterial and mammalian cells. Scientists are now trying to mimic the silk of spiders to produce artificial silk. Spider silk is also being used in modern medicine as a natural polymer to help regenerate neurons and cartilage.

itself. While these may seem like huge numbers, most naturalists and spider taxonomists seem to think that there are far more spider types that we don't know about yet. In fact, many areas of the world are yet to be sampled for spiders, and there are so few of us who are out in the field looking for them! Little wonder then, that new species of spiders are continually being discovered from different parts of the world. Once they are discovered, classifying these spiders into different species is also quite a challenge! Interestingly, arachnologists (the term used to refer to those who study spiders) identify and group spiders based on an examination of their genitalia.

Gossamer threads and silken yarns

All spiders produce silk. But they are not the only animals capable of producing silk. Many insects, including the silkworm, have the ability to do so. However, hardly any insects use silk for as many different functions as spiders do. Spiders use silk not only to build their webs, but also to act as their safety and harness lines to get from one place to another. They also use their silk to build protective, cushiony shelters to rest and avoid predators; to sense males from females through gender-specific chemical cues; and to protect their egg sacs.

Spider silk is made up of a complex mixture of proteins (known as spidroin), with some additional lipids, sugars or pigments (see **Box 1**). It is stored in liquid form in silk glands, located at the rear end of the spider's abdomen. A silk gland functions and looks like a balloon with a long duct that ends in a tiny nozzle (called a spinneret). Once secreted, the liquid silk solidifies as soon as it makes contact with air. The spider, then, uses its various pairs of legs to pull, draw and comb the silk that is secreted from the spinnerets. So, as you can see now, Spider Man shooting silk from his wrist is not really correct. Spider silk has another interesting property — it has an acidic pH, making it immune to bacterial and fungal attacks!

Depending upon the purpose for which it is used, the strength and thickness of the silk that a spider may need varies. Consequently, spiders have at least six different types of silk (and silk glands), with each type used to perform one among the many different functions mentioned previously.

Box 2. Do spiders get stuck in their own webs?

Unlike their prey, spiders can actually walk on their own webs without getting stuck in them. This is because a spider web consists of sticky and non-sticky parts. Spiders 'tiptoe' around the sticky parts, avoiding them through a series of clever, quick movements, helped by the hundreds of dense hairs on their legs that are covered with a special non-stick coating.

Spinners and Stalkers—the different kinds of spiders and where to find them

Based on how spiders catch their prey, we can classify spiders into two broad groups — those that build webs to hunt for their food; and those that don't. Spiders that don't build webs use other methods — like actively stalking, or sitting still and camouflaged — to hunt and capture their prey. One of these types of spiders even spits a glue-like substance to stun and capture its prey!

(a) The Spinners: Depending on the group or family they belong to, **web-building spiders** build various types of webs to catch their prey (see **Box 2**). Some build wheel-shaped webs (also known as orb webs) or webs which resemble mini tents (called tent webs); while others build webs that look like delicate sheets, particularly prominent after a dewy morning (refer **Fig. 1**). Still others build webs that look like a messy mass of lines (like in the cobwebs we often find in our homes) with no clear pattern.

Often, just by looking at them, you can distinguish basic and simple webs on

Fig. 1. Types of webs.

(a) An orb web.

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(b) A tent web.

Credits: Dinesh Valke, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:..._web_--_tent_spider_web_(4305043541).jpg. License: CC-BY-SA.

(c) A sheet web.

Credits: James K. Lindsey, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Linyphia.hortensis.web.jpg?uselang=en-gb. License: CC-BY-SA.

Box 3: The spider's signature:

The signature or cross spider is an orb-web spider that sometimes incorporates white, zigzag, silken structures as part of its web. These structures are called **stabilimenta**, based on a long-disproved theory that they give 'stability' to the web. According to one hypothesis, these structures are used to reflect ultraviolet light (UV), which (although invisible to humans) attract many species of insects (spider food) to the web. Another hypothesis suggests that the stabilimenta are used to protect the spider against it predators by either making it look bigger, or by deterring predators (like birds) from destroying the web structure.

Some, more recent, theories suggest that these 'signatures' may be used as signals by a female to indicate to a male that she is ready to mate, or simply because they are a nice decoration!

Fig. 2. A cross spider (ventral side).

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the one hand, and very complicated and elaborate structures on the other (see **Box 3**). The simple ones (like the basic orb webs) are made afresh everyday, or sometimes, every few days. In some cases, depending on the extent of damage, older webs may either be recycled or repaired. In contrast, the more elaborate webs like the tent and sheet webs, that require a great deal of energy and resources to be built anew, are repaired more often than they are rebuilt.

(b) The Stalkers: Spiders that do not build webs to catch their prey are called **hunting spiders** (refer **Fig. 3**). Many hunting spiders actively move around looking for their prey. In contrast, spiders that are more sedentary, use stealth and camouflage (like the crab spider) as hunting techniques. Since this group of spiders does not use webs to capture insects, they depend on visual or vibrational cues to find and hunt their prey. Consequently, active hunting spiders (like, the jumping spider and wolf spider) tend to have better vision than their more sedentary web-building relatives (see **Box 4**).

I am bigger than you!

Male spiders are often smaller than female spiders (refer **Fig. 4**). In some species, like the Giant Wood Spider, the female can be almost 3-5 times the size of the male! Apart from a difference in size, mature males can be distinguished from females by the presence of enlarged bulb-like palps, used to store their sperm.

Once a male spider reaches maturity, he either builds a temporary shelter or wanders in search of a potential mate. Even when he does come across a female of his species, the male has to carefully plan a strategy to get her attention. If the female mistakes him for prey, it's likely that she'll pounce on him and wrap him up like she would wrap an insect! If he belongs to a family of web-building spiders, the first thing the male does is to announce his arrival to her using a particular plucking motion which he strums on her web. If this plucking motion is even slightly inaccurate, he may end up becoming her next meal! Males from hunting spider families may not have webs to strum on, but they've evolved various kinds of courtship rituals that would make even a hero envious. These include strategies like moving their legs in elaborate swaying and dance-like movements, or presenting a wrapped-up dead insect to the female to distract her while he mates with her. Also, the males of these spider species are often very colourful, since they use a lot of visual cues to attract a potential mate.

Here an eye, there an eye, everywhere an eye eye?

Some spider experts group and classify spiders by the number and arrangement

SPIDER BINGO

Break out into groups and look for these outdoors. If you find any three of these spiders down or across – say BINGO!

Camouflaged spider

Jumping spider

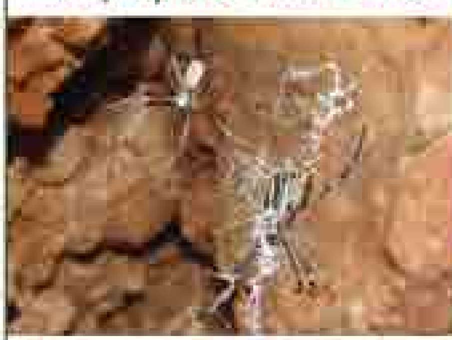
Spider on a flower

Ant-mimic spider

Spider with egg-sac

Spider food

Many spiders on a web



Spider on a web

Spider in leaf litter

Source: Adapted from Nature Conservation Foundation's nature education material on birds and trees.

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Life in the Outdoors

OBSERVE SPIDER WEBS

Find a spider web – in your classroom, home or outdoors! Take a few minutes to observe it.

Illustrate and describe your web

1. Is it simple or complex? Is it vertical or horizontal, symmetrical or messy, funnel or tent shaped? If the web is not clearly visible, gently spray some water with a water spray for better visibility.
2. Where did you find the web (on the ground, on a plant, inside a house)? Are there any patterns between the kind of habitat you found it in and the kind of web built? For example, have you noticed that funnel webs are always built on the ground amidst grasses and shrubs? Or that orb webs are built higher up on a plant, where there are gaps between two branches?
3. Can you spot a spider in the web? If yes, where is it and what is it doing?
4. If it's a simple web, try and observe the spider when it starts building its web early in the morning, or towards dusk. How long does it take to build the whole web? And can you describe the process it follows to build it? Check with your friends to see if all web building spiders follow the same process and time?
5. Are there other things on the web? Other spiders, insects or debris, twigs, leaves?

You will need:

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of eyes in their head region. Most spiders have eight eyes, but some have six eyes or fewer. However, unlike the compound eyes of insects, spider eyes are simple and similar to our own or those of other mammals.

Most web-building spiders navigate and capture prey using vibrations on their webs; their eyes can barely detect light-dark intensity changes and movements. In contrast, the more active hunting spiders, such as jumping spiders, wolf spiders, net-casting spiders and crab spiders, have much better vision for distinguishing prey, mates and predators.

The vision of one group of hunting spiders, called the jumping spiders, has been studied extensively. These fairly common (even around our homes), small, and often colourful spiders get their name from the way they move around, and stalk their prey (refer **Fig. 5**). If you get a chance to see such a spider, it is fascinating to see it hunt! Jumping spiders sense the movement of their potential prey from a distance, using six of the eight relatively small eyes located at the sides of their heads. Once they detect a movement, they turn to face the prey with their larger middle front eyes; while their remaining pairs of eyes provide information about the size, colour and distance of the prey. Next, they stalk it with cat-like movements. Once the spider is only about a few centimetres from its prey, it crouches and jumps to capture it.

What do spiders eat?

Spiders are largely carnivorous, feeding on various insects as well as other spiders. Web-building spiders use their strong webs to capture prey larger than themselves, including flying insects such as flies, butterflies, moths, beetles, and bees (refer **Fig. 6**). Spiders that do not build webs, capture a variety of insects — including mantids, crickets, ants and cockroaches — either by ambush, stealth or cleverly camouflaging themselves. But, this is not all. Spiders have also been reported to prey on millipedes, tadpoles, small frogs, fishes, geckos and even the occasional bird accidentally caught in a large web.

Spiders do not eat their food whole. They bite into their prey, injecting venom into it. This venom has enzymes that liquefy the insides of the prey that the spider then sucks up! When they catch very large prey, spiders sometimes restrain it by wrapping it up in silk. Web-building spiders often have to do this very quickly to minimise the damage that a newly caught prey can cause to their web by thrashing around to free itself (refer **Fig. 7**). If there's no prey in sight, hungry spiders will sometimes (see **Box 5**) resort to cannibalism (eating their own species if they are in close proximity) or hunting and feeding on any other spider species that they come across.

But, there's one group of spiders, called the **Portia** spiders (refer **Fig. 8**), which are a lot like the King Cobra in that they only seek out other spiders to feed on! That these spiders often look like a mass of dried-up debris may help them blend into the webs of the web-building spiders (with poor eyesight) that they prey on. Research has shown that the Portia spiders exhibit remarkably intelligent hunting behaviours, often resorting to trickery and deceit to capture spiders to feed on. For example, once a Portia spider reaches the web of its prey, it mimics the vibrations or movements of a struggling insect or potential mate. When the web-building spider comes to investigate that part of the web, it is promptly captured by the Portia. Sounds like a scene from a horror movie, doesn't it?

Much to the excitement of scientists, we now know of a species of jumping spiders, called *Bagheera kiplingi*, which is

Fig. 3. Hunting spiders.

(a) A wolf spider.

Credits: Sara. License: Commissioned and copyright image used with permission.

(b) A jumping spider.

Credits: Sara. License: Commissioned and copyright image used with permission.

(c) A crab spider.

Credits: Robin Rozario, License: Commissioned and copyright image used with permission.

Fig. 4. Female spiders are larger than their males.

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Fig. 5. A jumping spider.

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mainly herbivorous. Recently discovered from Central America, this spider's diet consists of the sugar, lipids and proteins present in the leaves of some plants.

What creatures eat spiders?

This may seem strange, but the main enemies of spiders are other spiders! Large spiders typically eat smaller spiders, and different species of spiders eat each other. Other predators and enemies of spiders include birds, lizards, and insects like wasps and praying mantids.

In fact, some species of solitary wasps specialise in preying on spiders of various kinds – from small web-building or hunting spiders to large giant spiders like the tarantula. Research suggests that such wasps use a combination of visual and chemical cues to locate spiders. Once

WEB GEOMETRY AND MATH

Ever observe how spider webs come in different geometric shapes?

You will need:

1. Select 4 or 5 webs that are differently shaped.
2. Compare the area and circumference of these webs (Hint: an orb web can be approximated as a circle: a tent web as a trapezium, and a funnel web as a triangle).
3. Which of these webs is or may be more efficient in capturing insects? Why?

REMEMBER:

There is trade-off for spiders that build different kinds of webs. A large orb web may help trap more insects, but is also more expensive in terms of the amount of silk and additional energy the spider needs to put into building it. Many simple orb webs are recycled (the spider ingests its web) and rebuilt every morning! On the other hand, the more elaborate tent and funnel webs are built over many days, and only the portions that are badly damaged are mended by the spider.

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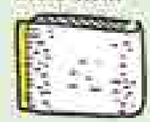
SPIDER DIVERSITY IN LEAF LITTER

Did you know that even leaf litter (fresh and dried leaves that have fallen from a tree and accumulated over time) houses many spiders and insects (spider food)?

A spider feeding on a leaf-litter toad.

REMEMBER:
To wear shoes and avoid handling spiders and insects with bare hands.

You will need:



A piece of white cloth

Pencil

Measuring tape

Some paper

A long stick to sift leaf litter

Try and separate all the spiders you see in the leaf litter from the insects. Then, try and categorise individual spiders based on their colour, shape, legs, and behaviour.

1. Find a tree that sheds leaves or an area with lots of leaf litter.
2. Mark 2 plots – one with an area of 1m square and the other with an area of 4m square – in the leaf litter.
3. Place a piece of white cloth next to each of the marked squares.
4. Scoop and quickly place small scoops of dried leaves on the cloth.
5. You will soon see insects or spiders crawling out of the leaves and onto the cloth. Count the number of spiders and insects in both plots. Which one has more spiders and insects?

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Fig. 6. Spider prey caught in a web.

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located, the wasp stings its prey with a paralysing neurotoxin and carries the spider's inert body to its nest. After it has collected one or more such paralysed spiders, the wasp lays an egg on one of them. When the egg hatches, the barely alive spiders become fresh food for the wasp larvae to feed upon (refer **Fig. 9**). Gruesome as this may sound, it's fascinating to watch a predator like a wasp hunt down another predator like a spider.

Spiders have evolved in many ways to escape predation. Many web-building

Box 5. Social spiders:

Most spiders are solitary predators. Often, if you put two spiders together in a container, depending on how hungry these spiders are, only one spider will be left in the container at the end of the day. But, in a few families of spiders, individuals of the same species are known to live in groups or colonies, and are fairly tolerant towards their colony-mates. These spider species are called communal or social spiders.

Social spiders are particularly interesting, as they live in fairly large colonies of ten to hundreds of individuals. They cooperate in hunting prey, building a web, and taking care of their young! Many of them also have 'personalities' — while all individuals are capable of doing all the tasks (such as hunting prey or building a web), some individuals do certain tasks more often than others.

Fig. 7. The web of a social spider.

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spiders hide in the corner of their webs, or inside a curled up leaf. Others, like the debris orb-weaving spiders, add web decorations that distract and confuse predators (refer **Fig. 10**). Some spiders, like the *Gasteracantha* (also known as the spiny orb weaver), have spiny and spiky exoskeletons that make it difficult for predators like birds to grasp them. These hard spikes are also believed to deter their parasitic wasp enemies.

Up, up and away with the wind!

Spiders undergo incomplete metamorphosis. This means that a spider does not go through the different stages of development (from an egg, larva, pupa, to an adult stage) that, for example, a butterfly does. Instead, spiderlings (young spiders), which look like miniature versions of the adult, hatch directly from their eggs. Their first source of nutrition is some dried up yolk from their egg sacs. Soon after, they disperse via a phenomenon called ballooning (see **Box 6**).

Spiderlings grow by moulting (removing their old outer skin) periodically, until they become 'mature adults'. Many insects and spiders have a hard chitinous protective layer outside their body, called the exoskeleton. Like snakes, spiders cannot grow unless they are able to shed this exoskeleton, a process called moulting (refer **Fig. 11**).Moulting is a risky process, as spiders are almost immobile during this time, and therefore, most vulnerable to predators.

I take care of my young

Many species of spiders are known to exhibit some kind of maternal care – from females carrying their egg sacs in their mouths for many weeks (like the long-legged house spiders), and therefore not feeding herself during this period; to having the egg sac attached to the female's spinnerets, or straddled to its abdomen (refer **Fig. 12**). Females of one group, known as the nursery web spiders, build elaborate silken structures, much like a nursery, to house their egg sacs and spiderlings. The female wolf spider not

Fig. 8. A Portia spider feeding on a spider it has just caught.

Credits: Sara. License: Commissioned and copyright image used with permission.

Fig. 9. A wasp larva on a spider.

Credits: Miller, J. A.; Belgers, J. D. M.; Beentjes, K. K.; Zwakhals, K.; van Helsdingen, P. (2013). "Spider hosts (Arachnida, Araneae) and wasp parasitoids (Insecta, Hymenoptera, Ichneumonidae, Ephialtini) matched using DNA barcodes". Biodiversity Data Journal 1: e992. DOI:10.3897/BDJ.1.e992, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Live_Tetragnatha_montana_(RMNH.ARA.14127)_parasitized_by_Acrodactyla_quadrisculpta_larva_(RMNH.INS.593867)_-_BDJ.1.e992.jpg?uselang=en-gb. License: CC-BY.

Life in the Indoors

SPIDER TERRARIUM

You will need:

An old but useable empty aquarium/transparent plastic box

REMEMBER:

To **not capture spiders with your bare hands** – if they feel threatened, they may nip your fingers. Instead, try easing them into small plastic boxes with lids with small breathing holes. Also, be gentle – spiders are delicate and may easily get injured.

1. Get hold of an old aquarium. Put a thick layer of mud in it and plant some hardy, fast growing plants (placing small potted plants is also fine). You can cover the terrarium with a mesh cloth for aeration.

2. Release a few non-web building spiders (jumping spiders can be found on walls of buildings, wolf spiders can be found in a grassy patch) into the terrarium.

3. You will need to collect food for your spiders every few days. They will happily accept small grasshoppers, fruit flies or houseflies. You can catch these with a small fish or butterfly net. But, make sure the insects you are providing are alive, as **spiders do not feed on dead things!**

4. This setup can be kept for weeks as long as your spiders are fed. Make sure you spray the plants with water occasionally – this also serves as a source of moisture for spiders.

5. Observe and note down the hunting behaviour of your spiders. Are they active hunters or the more sedentary sit-and-wait predators? When are they most active?

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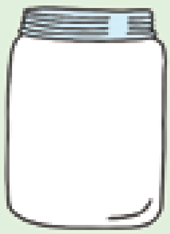
Life in the Indoors

SPIDER OR INSECT?

You will need:

A small pocket magnifying glass (10x will do)



2 transparent boxes or jars with holes (for air) in their lids

Paper

Pencil

1. Carefully collect a spider and an insect in separate transparent jars/boxes. You can also use a dead spider or a dead insect for this activity.
2. Use a magnifying glass to compare the two. How are they similar? In what characteristics are they different from each other?

Spider:

Insect:

	Spider	Insect
External skeleton?		
Antennae present?		
Wings present?		
Number of eyes?		
Body segmented?		
Number of segments?		
Number of legs?		
Jointed appendages?		

REMEMBER

To avoid handling spiders/ insects with your bare hands. Try catching them both using small plastic boxes with holes in their lids. Also, be gentle – insects and spiders have delicate bodies and may easily get injured. Once you've finished observing the differences between the two, gently release the spider and the insect, preferably in the same places where you found them.

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Fig. 10. **The debris orb weaver spider is well-camouflaged by a string of collected debris like twigs, dried leaves and beautiful silken decorations.**

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Fig. 11. **A spider with its moult.**

Credits: Judy Gallagher, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Crab_Spider_-_Synema_parvulum_and_its_moult,_Leesylvania_State_Park,_Woodbridge,_Virginia.jpg?uselang=en-gb. License CC-BY.

Fig. 12. **Females of many species of spiders are known to show some form of maternal care.**

SPIDER MYTHS AND FOLKLORE

1. Do some research online, scan some spider books and articles, or speak to some elders about spiders. Find out what spiders are called in your local language.
2. We remember our grandparents telling us that when they were young, they used to come across large hairy spiders in houses with thatched roofs! Become a journalist and record these stories. Then, create your own short story, play or poem using the information you have gathered and share it with your classmates.
3. Like lots of other animals, spiders also have been the focus of lots of mythological stories in many cultures. After doing some of your own research on spider myths, narrate your favourite myth, or even make a play and present this to your classmates and teachers.

Hindi:
Makadee
मकड़ी

Assamese:
Makaraā
মকৰা

Punjabi:
Makari
ਮੱਕੜੀ

English:
Spider

Marathi:
Koli
कोळी

Tamil:
Cilanti
சிலந்தி

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Fig. 13. **Female wolf spiders carry their young ones (baby spiders) on their backs till the spiderlings are ready to start their own lives.**
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Box 6. Ballooning spiders:

Spiders do not have wings, and yet they are found across the world and in different habitats including islands. How do spiders manage to colonize these areas? Spiderlings do this by employing a technique known as ballooning (visualise a person trying to fly a kite). Spiderlings climb up to an elevated point, like a twig or the tip of a leaf, raise their abdomen up, and release a silken thread in a direction against that of the wind. Usually a gentle breeze is enough to lift up these minute and delicate spiderlings, carrying them to far-away places, where they start their own lives and families. The further they balloon away, the less they need to share resources with their siblings.

only carries around the egg sac attached to her spinnerets until it hatches, but also allows her young spiderlings (baby spiders) to scramble up and ride on her back. The spiderlings clutch onto the minute hair on her abdomen for many weeks before they balloon away to lead independent lives (refer **Fig. 13**). Ask your students if they know of any close relatives of spiders, where females of the species are similar in carrying their newly-born on their backs.

Yikes! A spider brushed past me/it bit me!

Are spiders poisonous or venomous like some snakes? Spiders are venomous, but often the venom is potent only to their natural prey. So far, no Indian spider species has been found to be venomous to humans. However, it is best to avoid handling spiders with bare hands. Spiders can give you a nip if they feel threatened or an itch/rash from the minute hair on their bodies.

Why should we care or know about spiders?

Spiders not only share this marvellous diverse world with us and other living creatures, but also perform many essential biological functions. For example, as predators, spiders keep a check on insect populations. Scientists have used the presence or absence of certain types of spiders as indicators of change in an area. Due to its unique properties and strength, the silk produced by spiders is used in biomedical engineering and material science.

Conclusion

Through this article, we hope that we have given you a glimpse of the interesting and sometimes bizarre world of spiders... a world that you can observe and learn from. If you look around carefully, you will start finding spiders everywhere — behind the curtains in your house, on your school walls, on asbestos sheets, on barks of trees, under and between leaves, in the corners of ceilings and, sometimes, cheekily jumping around right in front of you! These fascinating eight-legged animals are still being discovered and named in different habitats across the world. Can you imagine all the habits and behaviours that we are yet to discover about them? Someday you too may discover a new species of spiders, or describe some of its behavioural traits that are new to science. So keep your eyes peeled, carry a magnifying glass, and go exploring the wonderful world of spiders.

Notes:

1. Wherever possible, we have referred to the different spiders described in this article through their commonly accepted names, instead of their scientific names.
2. If you would like to learn more about spiders, and their role and behaviour intrigue you as well, we encourage you to use the many resources (online and in books) mentioned in the reference section to find out more.
3. Pictures by Sara in this article were commissioned by Vena Kapoor as part of a project on documenting spiders in the forests and coffee estates of Valparai, in the Western Ghats, and supported by Nature Conservation Foundation and an ATREE small grant.
4. Credits for the article title and the image used in its background: Jumping Spider, ROverhate, Pixabay. URL: https://pixabay.com/en/jumping-spider-spider-insect-macro-1130449/. License: Public Domain.

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5. The authors' research and field observations over many years!

Vena Kapoor works with the Nature Conservation Foundation, Bangalore. Even since she was shown the architecturally perfect web of a tent spider, she was hooked to these creatures. Some of her fondest memories are looking for and documenting spiders found in the lush rainforests of the Western Ghats, India. Vena can be contacted at vena@ncf-india.org

Divya Uma works at the School of Liberal Studies, Azim Premji University, Bangalore. She teaches biology to undergraduate students, and works on predator-prey interactions as well as mimicry in spiders and insects. She has a special soft corner for jumping spiders. Divya can be contacted at divya.uma@apu.edu.in

Life in your Backyard

Some bizarre habits of spiders...

Here are some of the many bizarre spiders that we have come across over the years. Have you spotted any of these?

Vena Kapoor & Divya Uma

1. The spitting spider:

As its name suggests, this small and globular spider ejects a glue-like substance from its mouth to capture and stun its prey. Once stunned and captured by this glue-like substance, the spider then moves closer to it, injects it with venom and rapidly wraps silk around it to feed on it at leisure.

A spitting spider

2. The net-casting spider:

As you may have guessed from its name, this nocturnal (active at night) spider's web is shaped like a small net. It dangles this net with its first two pairs of legs. When an unsuspecting insect happens to pass by, the spider drops this net web and entangles it.

A net-casting spider

3. The scorpion spider:

Because of its extended abdomen and posture in its orb-web, one has to look twice to detect this spider! As if that's not confusing enough, the brown coloured variety of this spider resembles a dried up leaf!

A scorpion spider

4. The bird-dropping spider:

There's a reason this spider has been given such a strange name – one of its hunting techniques involves resembling the fresh dropping of a bird! Research shows that because of this, birds (its main predators) are unable to detect these spiders. And butterflies that visit bird droppings to get a few essential nutrients, can get fooled into becoming food for these spiders!

A bird dropping spider

5. An ant with eight legs?

Spiders belonging to around 12 different families mimic the external appearance and behaviour of ants, and are called Ant-Mimic spiders. Very often they are found close to the ant colonies that they mimic. Why do some spiders mimic ants? Research has shown that many predators of ants, including birds, mantids and wasps, tend to avoid catching ants because they can be aggressive or unpalatable. If a spider looks like an ant, however, they are avoided as well! Some spiders may also look and smell like ants, emitting a pheromone (scent) similar to the ants they mimic. By doing this, these spiders can confuse ants in the colony, and hunt ants or ant eggs that are otherwise well guarded.

An ant-mimic

Vena Kapoor works with the Nature Conservation Foundation, Bangalore. Even since she was shown the architecturally perfect web of a tent spider, she was hooked to these creatures. Some of her fondest memories are looking for and documenting spiders found in the lush rainforests of the Western Ghats, India. Vena can be contacted at vena@ncf-india.org

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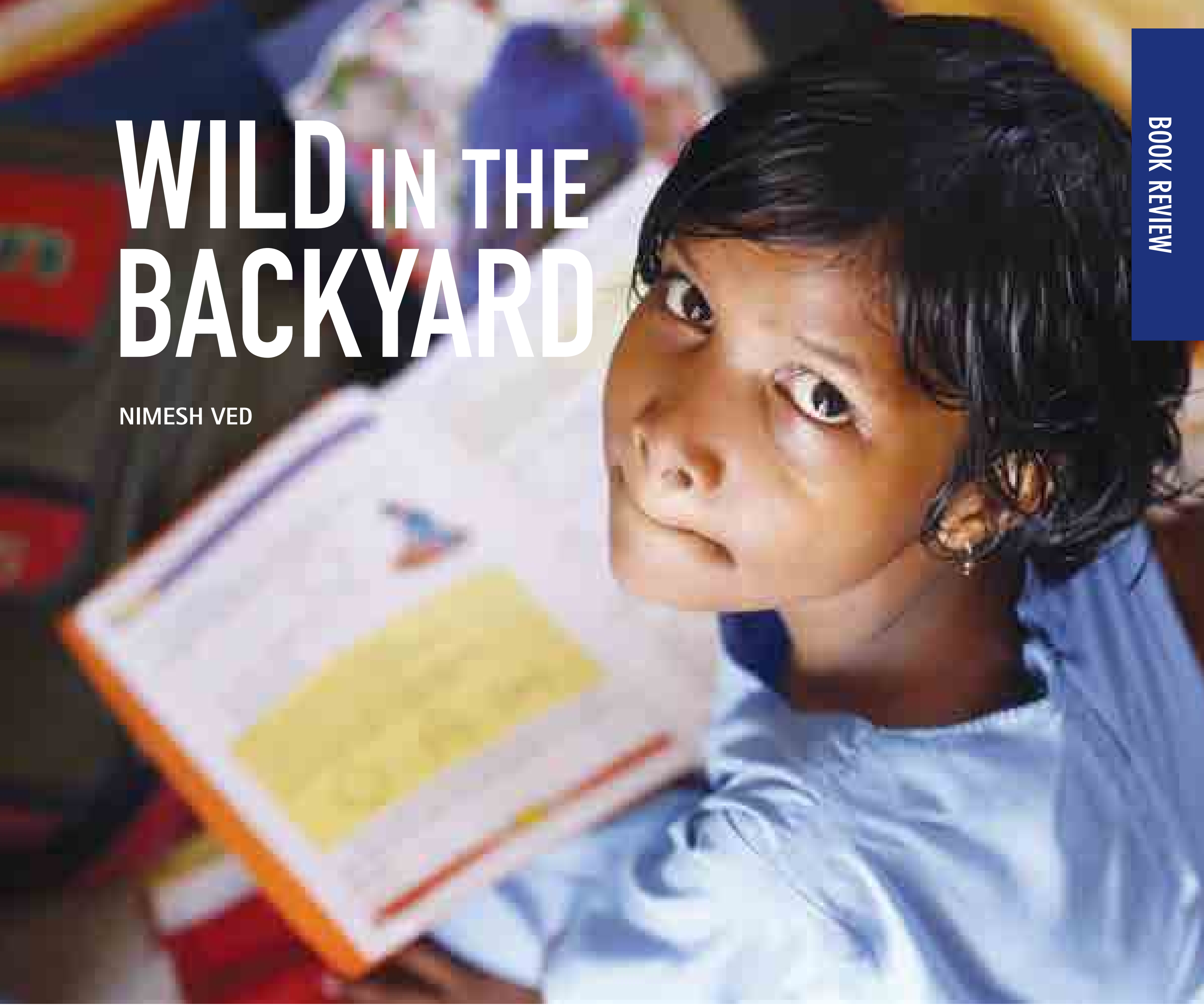


WILD IN THE BACKYARD

NIMESH VED

Written by Arefa Tehsin, this book takes us into a world inhabited by the different species that visit our backyard — species we often see, but know little about. Each species is brought to life through in-depth research into its habits, sketches, anecdotes and questions.

The beginning

A prolific writer, Arefa Tehsin has authored multiple books for children, including 'The Land of the Setting Sun and Other Nature Tales' with Raza H. Tehsin. She also writes columns and articles for newspapers and magazines. She begins this book, Wild in the Backyard, with a dedication that brings together bookstores and forests in an interesting way: "*To my father, who took me to the bookstore and the jungle, who held my hand, yet left me alone. At both places".* Few lines could have captured the spirit of the book more aptly.

The first line of the introduction too is both pertinent and striking: *"We may think that wilderness and wildlife are confined to forests. But there is a whole lot of wild in our own backyards"*. Most of us do associate wildlife with large pristine forests far away from where

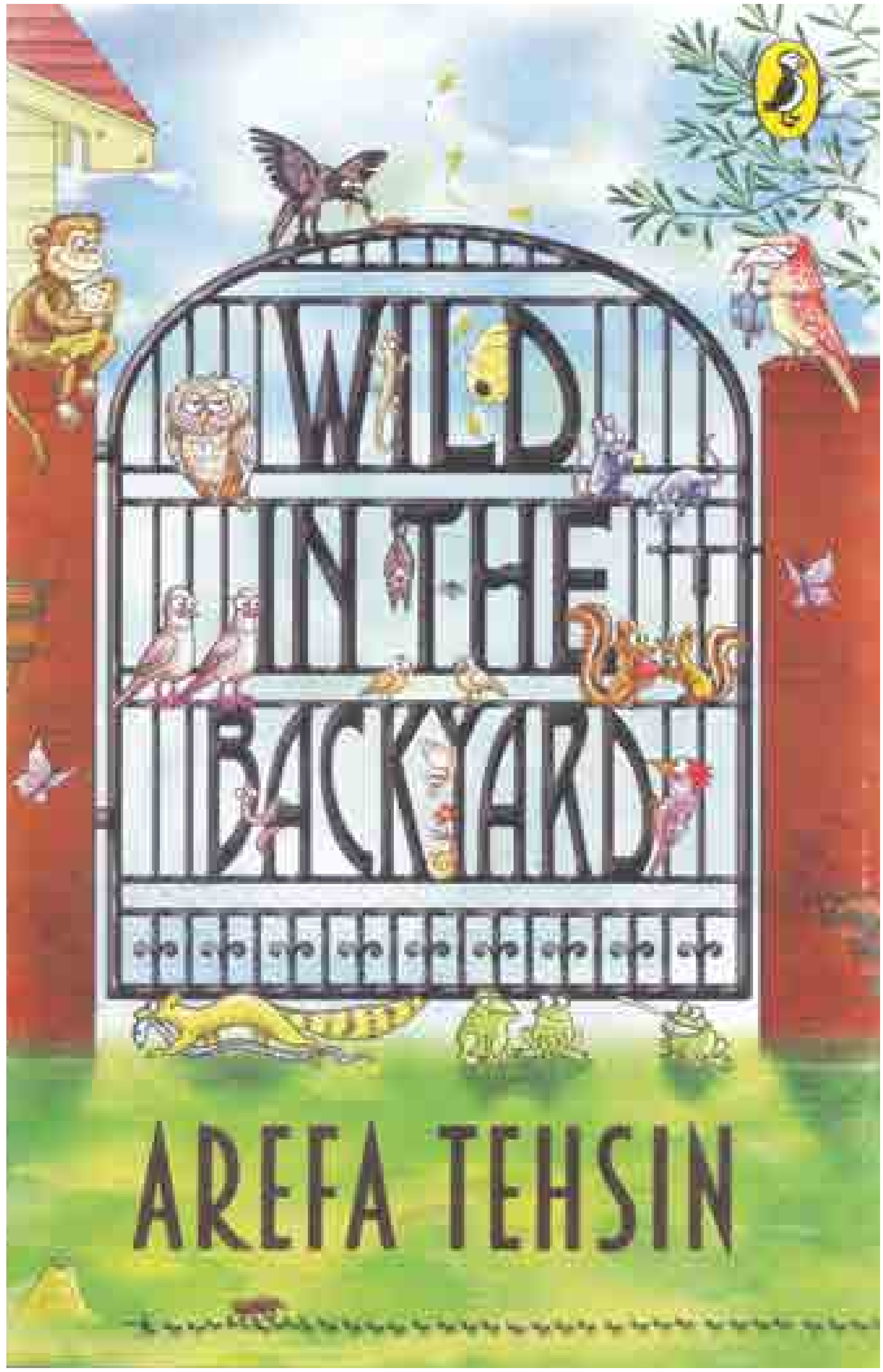
In a snapshot:

Author:	Arefa Tehsin
Publisher:	Puffin Books — Published by Penguin Group
Year:	2015
Pages:	229
Chapters:	25

we stay. While numerous studies have shown that forests have hardly ever been pristine spaces devoid of humans, this perception has remained largely unchanged. This has led people to believe that wildlife should be present only within forests; and any 'wild' species seen outside forests should be sent back to forests or culled. This perception has led us to neglect or ignore the many species that share our rural and urban homes. Arefa's book challenges both these notions.

Strengths

One of the biggest strengths of the book is that the author shares her experiences of natural history in a conversational manner and with great clarity. For example, the first chapter titled 'The Devil's Own', introduces young readers to the life of bats with lucid, yet informative, descriptions. One wishes that other educational material on these fascinating mammals could be designed along these lines, rather than being packed with the usual dry-as-dust statistics and names alone. In many cases, the author shares nuggets of natural history that are bound to awe a majority of her readers. The chapter on 'Centipedes: The Hundred Legger', for example, states that: *"Centipedes can have 30 to more than 300 legs, but not 100. . . they have only an odd number of pairs of legs... each pair of legs is longer than the one in front".* In another case, the author shares gems like, *"Some super-smart Capuchin Monkeys and Lemurs upset these millipedes and then rub the awful-looking liquid (that the millipedes release) on their skins to repel mosquitoes!"*, without making any attempt to qualify this observation with a human-centric value-based explanation. Her writing often leads readers to mull over interesting questions, like: how does rain affect an organism's ability to use echolocation? In other chapters, she introduces readers to some of our more interesting discoveries on animal behaviour. For example, in the chapter on 'Crows: Crafty Crows', the author describes how:



The front cover of the book.

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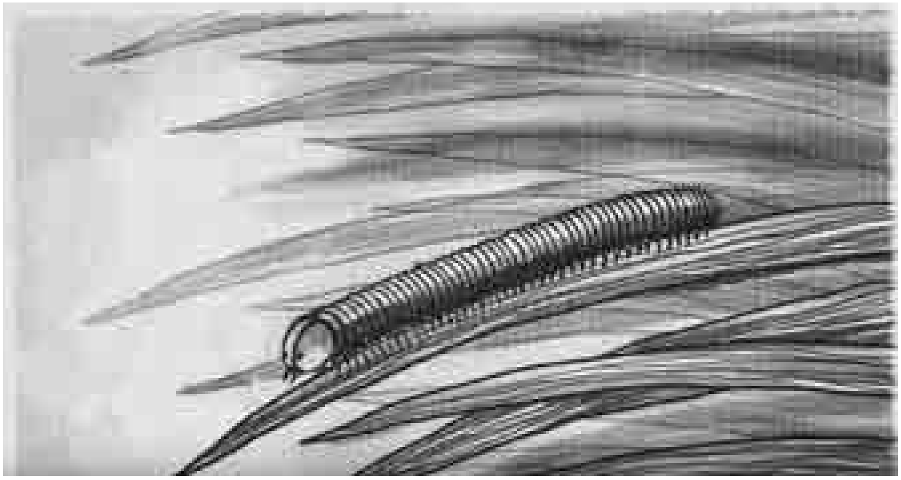
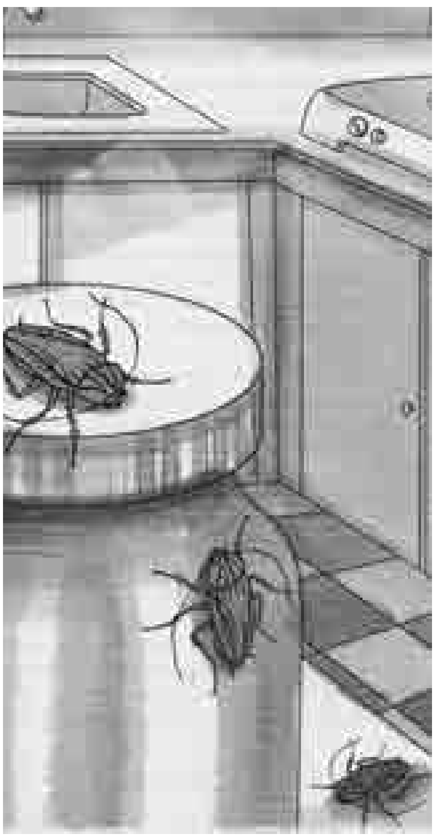
"A few scientists in Auckland decided to try out the thirsty crow story in their lab. Remember the story of the crow dropping pebbles into a pitcher to raise the level of the water in it? The results of the experiment point out that crows are as clever with some tasks as human seven-year olds"! She adds to this by mentioning how crows are known in some cases to *"...drop the nuts they're carrying at traffic signals so that the cars passing by can break the nuts' hard shells"*. Showing how intelligent crows are, she points out that phrases like *"'He's a birdbrain"*, may hold little weight. In the chapter on 'Squirrels: The





Some illustrations from the book.

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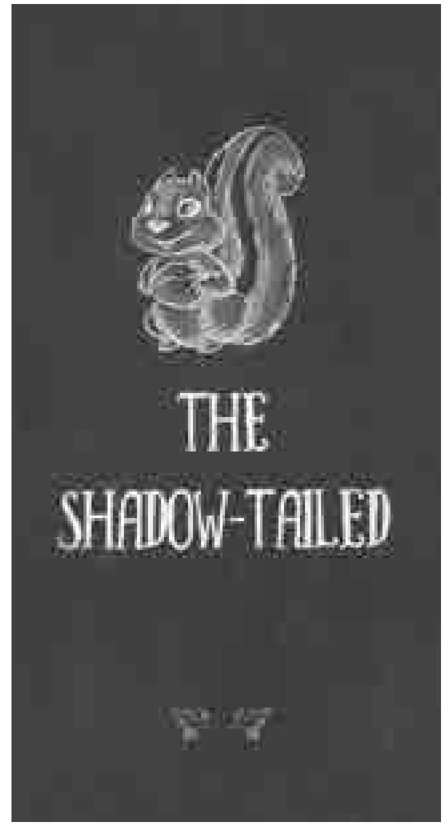
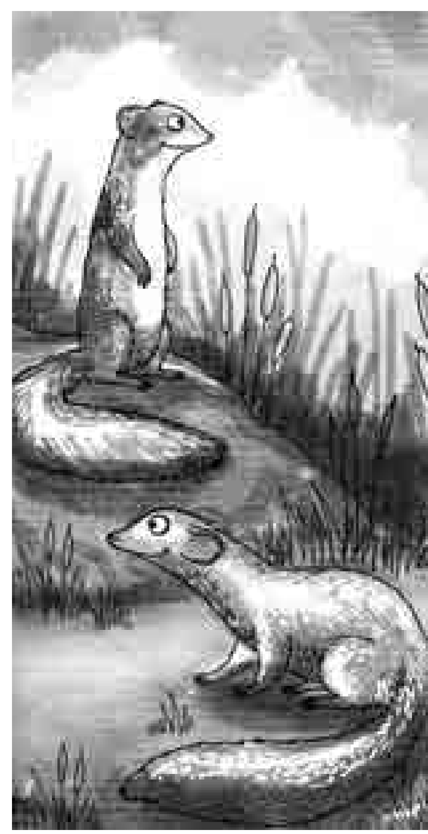
Shadow-tailed', the author illustrates how superstitions do not have rational basis and can be disproved. In other cases, she speaks directly to her young readers with passages like this one. *"Monkeys sure know how to have fun! You should send your Ma and Pa to go and learn from the monkey elders, who let their kids have fun all the time".*

Pitfalls

Although a wonderful read, this book had some errors that could have been avoided. For instance, in the chapter on 'Rats: Rats! Who is that', the author wrongly attributes the gregarious bamboo flowering or *Mautam* to Nagaland instead of Mizoram. In other cases, the author seems to offer an overly simplistic perspective to otherwise complex issues. This is evident in the same chapter, where she connects the flowering of bamboo in the 1960's with the Mizo armed movement without adequately addressing the complex socio-political and economic dimensions of this connection. It may have been better if the author had stuck to describing how this flowering attracted rats that ate more than 90% of the crops in the fields, and led to a famine not only in 1960, but again in 2007-08. The chapter on 'Butterflies: Fluttering Fairies' mentions the Bombay Natural History Society without providing any context. In another case, the author suggests that readers invest in keeping an owl-box in their homes. Is this really safe for the owl, and for those who keep them? Apart from practical problems such as how and where to procure these boxes and how to feed the owls, is it ethical or legal to keep a bird in captivity? This book would have been more interesting if it had included more Indian words and descriptions of the beliefs and practices that local communities have towards the 'wildlife





...And some more illustrations from the book.

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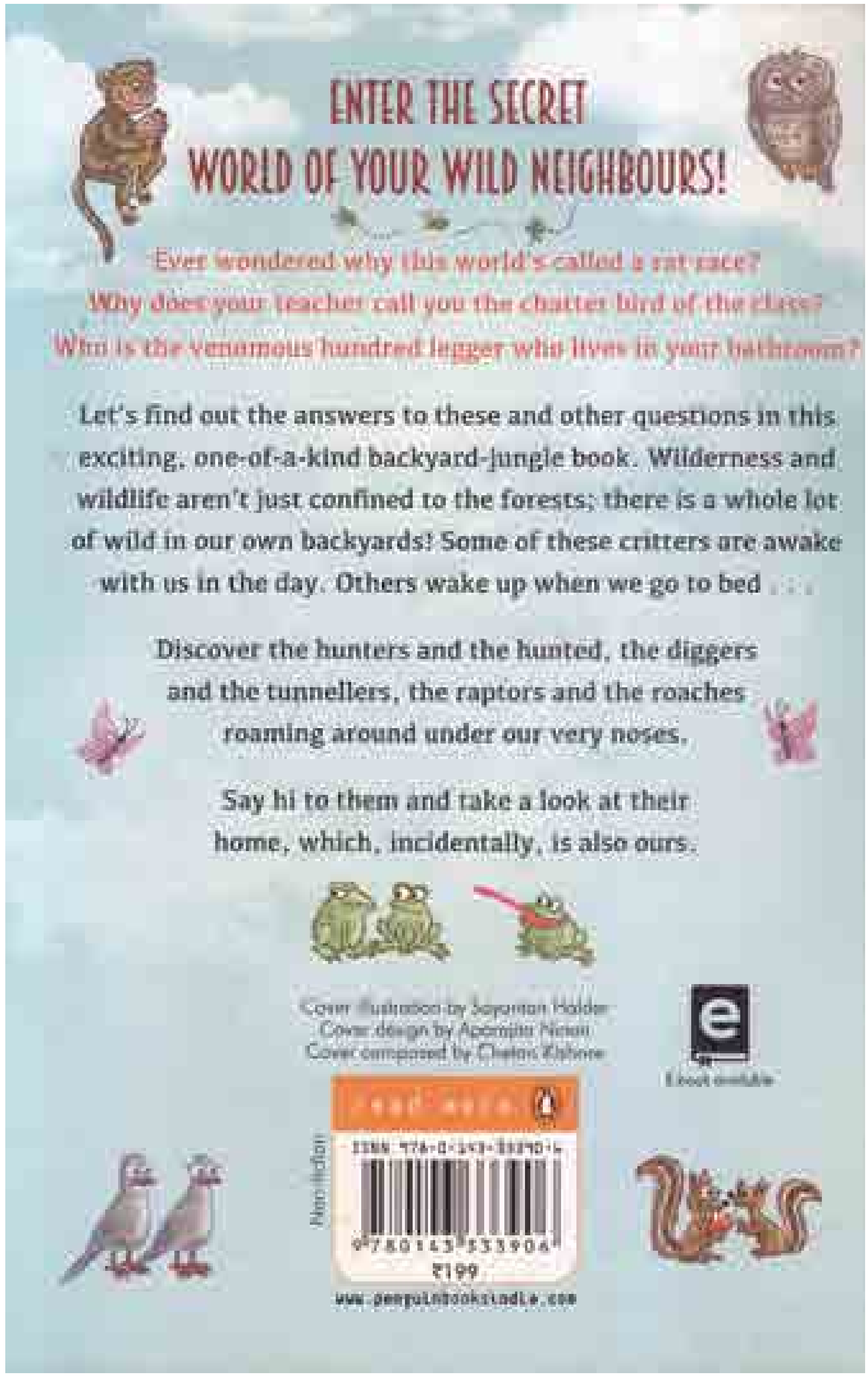
in their backyards'. The reference section could also have been a lot richer!

To conclude

There are many reasons to enjoy this book. The most important one, though, is for the author's writing and her insights. For example, the author brings humans down from the pedestal that we usually place ourselves on *vis-à-vis* wildlife subtly, yet successfully: *"There are many creatures that have got used to our noisy and clumsy habits"*. This is followed some pages later by: *"Sadly, humans do more monkey business than monkeys themselves"*. In another instance, the author makes the observation: *"Who knows, we may be putting dried cockroaches on our dry lips every day"*! By hinting at how we may be consuming animal products without our knowledge in this way, the author succeeds in teaching without preaching. Also delightful are the many succinct one-liners, like *'the mongoose is bold but shy'* and *'butterflies are beauties with brains'*. Not only does the author pose questions in a non-monotonous manner, she also frequently uses words that the younger generation is likely to relate to. But, for me, the highlight of the book was the simple explanations of many terms that we come across frequently, yet choose to skip over even though we may not understand their meaning or import. This book talks of some of these terms with rare simplicity. For eg. the difference between locusts and grasshoppers is presented in a single line: *"When thousands and millions of them form a gang, we call them locusts; and when they live alone in our gardens and meadows, we call them grass hoppers"*.



The back cover of the book.

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Nimesh Ved enjoys meandering on cycles. He blogs at nimesh-ved.blogspot.com and can be contacted at nimesh.explore@gmail.com.

THE INDOMITABLE EVOLUTIONIST: LYNN MARGULIS

MEENAKSHI PANT

The evolutionary biologist Lynn Margulis is best known for her work on the Serial Endosymbiotic Theory (SET) to explain the origins of eukaryotic cells. This article presents key facets in the life of this *avant-garde* biologist and her work that has changed the way we perceive life on Earth.

"To me, the human move to take responsibility for the living Earth is laughable — the rhetoric of the powerless. The planet takes care of us, not we of it. Our self-inflated moral imperative to guide a wayward Earth, or heal our sick planet, is evidence of our immense capacity for self-delusion. Rather, we need to protect ourselves from ourselves."

This very courageous statement that challenges the self-acclaimed supremacy of humans over nature was made by Lynn Margulis (refer **Fig.1**). She is believed to be one of the most creative scientific theorists of the modern era, who transformed the idea of how life evolved on Earth. Many of her contemporaries, including the famous socio-biologist E.O Wilson, have acknowledged her as being the 'most successful synthetic thinkers of modern Biology' due to her holistic approach towards the idea of evolution.

Early life and education

Born on March 5th, 1938, in Chicago, Lynn was the eldest of the four daughters of Morris Alexander, a lawyer and businessman, and Leone Alexander who ran a travel agency. At the age of 15, she completed her education at Hyde Park High School, and got enrolled in a special early admission program at the University of Chicago (UC). There, Lynn had the opportunity to read the original works of many famous scientists, which furthered her interest in science. In 1957, she graduated with a degree in Liberal Arts, and moved to the University of Wisconsin to study Biology under Walter Plaut (who was to become her supervisor) and Hans Ris. In 1960, she graduated with an MS degree in Zoology and Genetics. She then began her research career in the University of California, under the guidance of Max Alfert, earning her doctoral degree in 1965. Lynn was offered her first job — a research assistantship and the position of a lecturer in Brandeis University — even before she could finish her dissertation. However, it was only after she had been awarded a PhD that she moved to Boston University, where she taught Biology for 22 years. She had a remarkable career, going on to become a Distinguished Professor of Geosciences — a position she held till her death in 2011.

Important influences

While in graduate school, Lynn was very impressed by her teacher James F. Crow who taught her General and Population Genetics. Her deep interest in this subject led her to believe that it was only through Genetics that the process of evolution could be reconstructed. She was also fascinated by a form of cellular reproduction that involved genetic material found in a cell's cytoplasm.

The popular notion at the time was that DNA was present only in the nucleus of a cell. Lynn pored through the works of biologists like Ruth

Fig. 1. Lynn Margulis.

Credits: Javier Pedreira from La Coruña, Spain, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Lynn_Margulis_2005.jpg. License: CC-BY.

Sager, Francis Ryan and E. B. Wilson. In his book, *The cell in development and heredity*, Wilson discussed the similarities of two cellular organelles — the chloroplast and the mitochondria — to free living bacteria. His book also included references to the works of Konstantin Merezhkovsky and Ivan Wallin. According to Wilson, the Russian botanist Mereschkowsky (1905) arrived at the notion that the division of chloroplasts in green plants closely resembled that of Cyanobacteria (refer **Fig. 2**) based on observations made by the German botanist Andreas Schimper (1883). He, therefore, concluded that green plants may have arisen from a symbiotic union of two organisms. Similarly, Ivan Wallin (1923), an anatomist in the University of Colorado, referred to the symbiosis of bacteria in animals as 'the establishment of micro-symbiotic complexes' or 'symbionticism'. These ideas did not gain much recognition until Stocking and Gifford (1959) discovered that plastids and mitochondria contained their own DNA. This discovery was supported by detailed electron microscopic comparisons between cyanobacteria and chloroplasts by biologists like Hans Ris and Singh (1961). Consequently, the 1960s saw a revival of these explorations, and helped Lynn to further her own ideas on endosymbiosis.

Advancing Endosymbiosis

In 1966, Lynn wrote a paper 'On the Origin of Mitosing Cells' that was rejected fifteen times before it was eventually published in the March 1967 edition of the *Journal of Theoretical Biology*. In this article, Lynn proposed a theory for the origin of eukaryotic cells (cells with their nuclei enclosed within nuclear membranes). She suggested that three components of the cell — namely, its chloroplast (specialized structures in plant cells involved in photosynthesis), mitochondria (the energy generating part of cells), and basal bodies (structures giving rise to flagellum) — were once free-living organisms (refer **Fig. 3**). Lynn postulated that, for example, the mitochondria had originated from a bacterium capable of aerobic respiration. At some stage of evolution, each of these organisms had entered primitive eukaryotic cells, and have permanently resided there ever since. She postulated that interactions between these organisms and primitive eukaryotic cells led to the evolution of new 'hybrid' organisms with components that performed unique life processes. Further evolution of complex life forms initiated as a result of this division of labour. Thus, while the term 'symbiosis' is used to refer to the close association of two organisms, 'endosymbiosis' refers to the merging of two different organisms to form a single new organism. This idea was later explained in detail in her book *'Origin of Eukaryotic Cells'* published in 1970.

Bacteria as enemies?

Bacteria have always been labelled as the cause for diseases waiting to be conquered by the modern weapons of medicine. In contrast, Lynn ceaselessly promoted the idea that bacteria are the under-appreciated designers of Earth's biosphere. In her view, bacteria had already been subject to evolutionary processes for about 2000 million years before other plants or animals appeared on Earth. Not only did they help establish all vital life processes — from

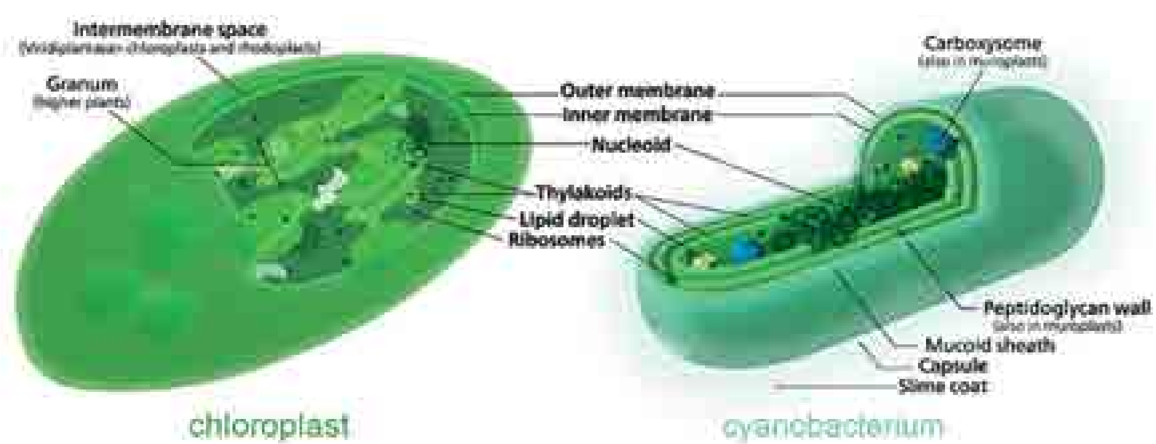

Fig. 2. **Margulis's endosymbiotic theory was influenced by the botanist Mereschkowsky's comparison of similarities between choloroplasts and cynabacteria.**

Credits: Kelvin13, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Chloroplast-cyanobacterium_comparison.svg. License: CC-BY-SA.

photosynthesis to respiration – that sustain life, but also played key roles in the origin of crucial biomolecules, like DNA, RNA, proteins, etc. According to Lynn, bacteria evolved mainly by sharing genes with each other and forming symbiotic partnerships rather than competing for survival.

In *Acquiring Genomes: A Theory of the Origins of Species* published in 2002, Lynn argued that symbiotic relationships between organisms of different species drive evolution. This argument challenged the Neo-Darwinian ideology that suggested that inherited variations arise mainly from random changes in the genes of an organism (mutation). According to Lynn's theory, this acquisition of mutations, and their accumulation in subsequent generations, is not sufficient to explain how inherited variations occur. Rather, she argued that genetic variation involved the fusion of genomes (the complete set of genetic material in every cell of any organism) of organisms from different species.

Lynn faced a lot of criticism, and even ridicule, in the 1960's and 1970's for her revolutionary ideas, but she went on to defend her theory relentlessly. Today, many biologists believe this remarkable view of eukaryotic cell evolution to be one of the great advancements in 20th century science. This belief is supported by findings of the Human Genome Project that show that substantial sections of the human genome are either bacterial or viral in origin. Also, genome-mapping techniques have shown that family trees of major taxonomic groups appear to be largely cross-linked, possibly due to transfer of genes through bacteria as Lynn Margulis had predicted.

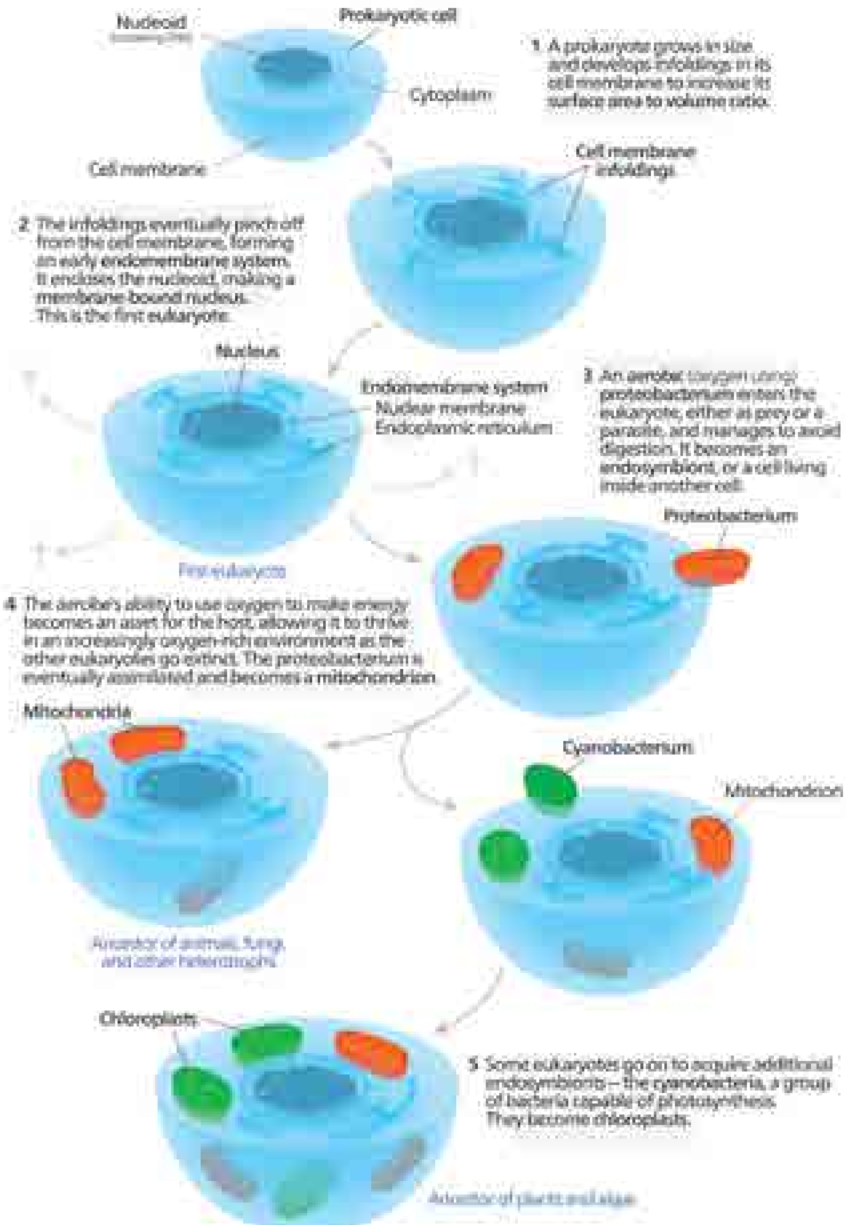

Fig. 3. The origin of eukaryotic cells through serial endosymbiosis.

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Support to the Gaia hypothesis

Lynn's holistic view of Biology led her to support the Gaia (name for the Greek goddess of the Earth) hypothesis proposed by the British biologist James Lovelock (1968). According to this hypothesis, the Earth is a self-regulatory living entity that functions as a unified whole with all living things interacting to create conditions needed for life to continue. Endosymbiosis and Gaia were linked in Lynn's mind as components of a coherent unit that were based on cooperation rather than competition.

However, Lynn's enthusiasm for this hypothesis was not shared by the rest of the scientific community. Many scientists criticised Lovelock's approach in the book *'Gaia, a New look at Life on Earth'* for being teleological, or based on the belief that all things have a pre-determined purpose. Stephen Jay Gould criticised Gaia as being a symbolic description of Earth processes that did not elucidate its actual mechanisms of self-regulation. Realising that this hypothesis invited criticism mostly due to its phrasing, Lovelock made many efforts to remove the teleological elements of the hypothesis. In her book, *The Symbiotic Planet*, Lynn refuted the personification of Gaia and emphasised that Gaia is *"not an organism"*, but

Fig. 4. Lynn Margulis co-authored many books with her son Dorian Sagan.
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"an emergent property of interaction among organisms". But, Lynn's support of this highly-critiqued hypothesis earned her a considerable amount of displeasure from the scientific community. Today, this hypothesis has evolved considerably, becoming a potentially viable and testable scientific hypothesis or theory. Some scientists even believe that the Gaia hypothesis offers us a better understanding of complex environmental problems.

Personal life

In 1957, Lynn married the renowned astronomer Carl Sagan, who she met as a graduate student in Physics while studying at the University of Chicago. The couple had two sons – Dorian Sagan became a famous science writer (refer Fig 4), while Jeremy Sagan founded 'Sagan Technology'. Lynn and Sagan were divorced seven years later. Then, in 1967, Lynn married the crystallographer Thomas N. Margulis, and had two kids with him. But, by 1980, this second marriage had also come to an end. When Lynn was asked about her unsuccessful married life, she expressed her belief that it was not possible to balance the duties of a wife and a scientist simultaneously – one had to let go of one thing to concentrate on the other.

Throughout her life, Lynn advocated science education, especially in less developed countries. She was admired and respected by students across the globe. She held the view that the more students were encouraged to explore the basis of life, the more they'd understand the numerous symbiotic associations around them and, consequently, the idea of evolution. She said, *"If you really want to study evolution, you've got to go outside sometime, because you'll see symbiosis everywhere!"*

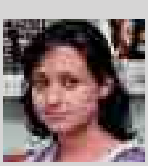
Lynn gave talks all over the world, serving as a member of many associations and committees. She worked with NASA, and wrote many books, film scripts, and articles. These, for example, included books like 'Symbiosis in cell evolution' (1981), 'Origins of Sex: Three Billion Years of Genetic Recombination' (1986), 'Micro-cosmos Colouring Book' (1988), 'Mystery Dance: On the Evolution of Human Sexuality' (1991), 'What Is Life?' (1995), and 'Symbiotic planet' (1998).

Awards and acclaim

Lynn has many honours to her credit. She was elected to both the National Academy of Sciences and The Russian Academy of Natural Sciences. She also received honorary doctorates from several universities. In March 2000, President Bill Clinton presented the U.S. National Medal of Science to her. In 2008, she was awarded the 'Darwin-Wallace Medal of the Linnaean Society of London'. Her papers are permanently archived at the Library of Congress. Just a few days before her untimely death, she was included in the list of twenty most influential scientists alive – one of only two women on this list, which includes scientists such as James Watson, Jane Goodall and Stephen Hawking.

On November 22nd, 2011, Lynn Margulis died of a haemorrhagic stroke. She was 73 years old. In an interview published in the April 2011 issue of the magazine *Discover*, she was asked "Do you ever get tired of being called controversial?" Lynn Margulis replied to this question by stating that: *"I don't consider my ideas controversial. I consider them right"*. Such was the conviction of this great crusader of evolutionary biology, who worked relentlessly towards resolving the mysteries shrouding the evolving of life on this planet.

Note: Credits for the image used in the background of the article title: Lynn Margulis, Distinguished University Professor in the Department of Geosciences at the University of Massachusetts-Amherst speaks during the "Seeking Signs of Life" Symposium, celebrating 50 Years of Exobiology and Astrobiology at NASA, Thursday, Oct. 14, 2010, at the Lockheed Martin Global Vision Center in Arlington, Va. Credits: NASA HQ PHOTO, Flickr. URL: https://www.flickr.com/photos/nasahqphoto/5081810526. License: CC-BY-NC-ND.



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Discover

The Hard Problem of Consciousness

Author: Reeteka Sud

What about the physical structure of the brain makes it capable of subjective experiences? And, why do we have subjective experiences at all? Questions such as these, now known as the 'hard problem' of consciousness, have intrigued scientists and philosophers for thousands of years. Are we any closer to finding answers to them?

Your consciousness – it is what makes you, you.

We recognize consciousness not only in ourselves but in others as well. Here you are sitting, reading this magazine. You are aware of that. As you look out on the street, you are aware of other people going about their lives. Maybe you see someone checking their phone as they walk, not aware they are about to walk into a pole.

At any and every moment, consciousness is the sum total of your experience – how you feel, and thoughts about how you feel.

How you feel: the neural basis of subjective feelings

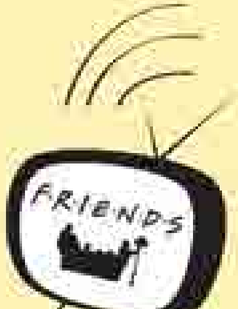
Any feeling, physical or emotional, has its foundations in the workings of the brain. We have known this since the time of Hippocrates (fifth century BCE), who observed that people with brain damage tended to lose the ability to be aware [1], or what we call 'be conscious'.

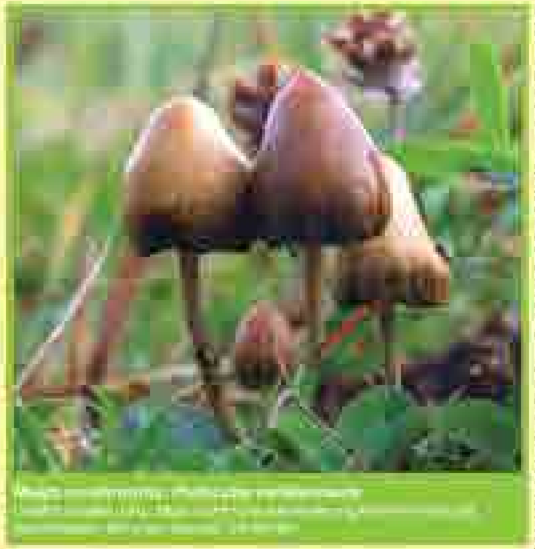
Let's look at psychosis – a condition that causes patients to experience the world differently than those around them [2]. This could be in the form of hallucinations (seeing/hearing someone or something that's not there), or delusions (illogical views not based in reality, for instance, a patient may be convinced their family is trying to poison them through medications or food). Hallucinations or delusions can be on account of any number of brain diseases that change the brain, physically and chemically. Thus, changes to the brain affect how we perceive ourselves and the world around us.

Progress in neuroscience has made it possible for us to learn a lot about how the brain computes incoming information. We also know that the brain is aware of this information. How does the brain accomplish this? And, why does this ability exist? This has been a hard nut to crack and, therefore, is aptly characterized by scientists and philosophers alike as the 'hard problem of consciousness'.

What is the 'hard problem' of consciousness?

In an episode of the TV show 'Friends', one of the characters describes his mental state as "I feel like somebody reached down my throat, pulled out my small intestine and wrapped it around my throat!". It doesn't take much to figure out that this character is despondent or just generally dispirited with his life. There is emotion, and then there is the 'felt quality' of that emotion (including the mental images his words conjure up) – and these can be different for different individuals, even when faced with similar circumstances. Modern neuroscience has made impressive strides in describing the brain circuits that process physical and emotional feelings – this is the 'easy problem'. In comparison, the question of experience, 'the hard problem' – why, and how does brain activity produce subjective experience – is still beyond our grasp. So, how are scientists today attempting to answer this age-old mystery?

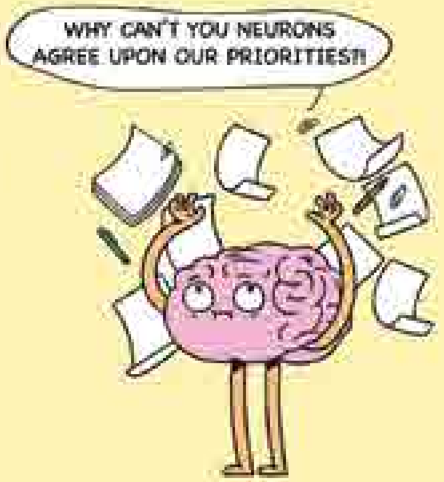




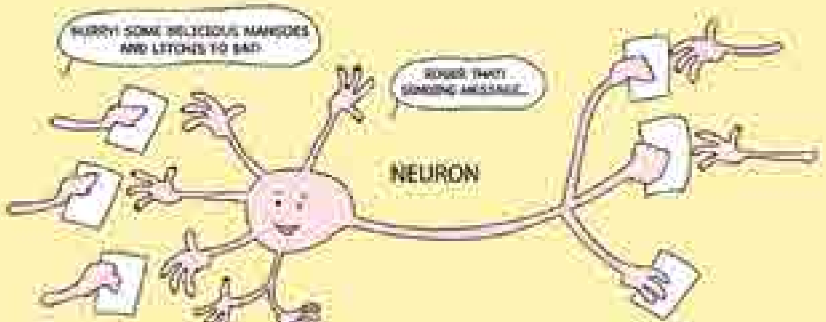
Dr. Robin Carhart-Harris at the Imperial College in London (UK), is probing the existence of the mind using psychedelic drugs. The word 'psychedelic' means 'to make the mind manifest'. This class of drugs is believed to be unrivalled in its ability to elicit mind-altering (mind-expanding, to be more specific) effects. "I study them because they can reveal the very depths of human mind", he says. Certain mushrooms have a psychedelic ingredient called psilocybin in them, earning them the nickname of 'magic mushrooms'. The effect of psilocybin on the brain is no magic though. Brain scans show that its activity patterns are vastly different after psilocybin, indicating 'freer communication pathways'. "We are beginning to uncover some key principles about how psychedelics alter consciousness – and the profound thing is ..... It can tell you something fundamental about the nature of brain function itself and its relationship to the mind," says Carhart-Harris [3].

Why does a scientific understanding of consciousness matter to us?

Dr. Michael Graziano, faculty at Princeton University (New Jersey, USA), has proposed what he calls 'attention schema theory' [4] that explains consciousness as an evolved form of attention. For the brain to function, attention is extremely important – what and where should the brain's resources be directed at any given moment? Different groups of neurons give their own answers. Inevitable competition ensues, with the winning group of neurons dictating what you pay attention to; until the next moment, which could have a different winner; and so on and so forth. To be able to control attention, says Graziano, the brain needs an internal model of it, a map of attention if you will.



Say you were to walk by a fruit vendor when you're hungry. You spot juicy mangoes and litchis in his shop, and your mouth starts watering – by its very nature, something as simple as this requires integration of information across multiple domains within the brain. Incoming information has to get integrated with information about the self and the environment. Attention is invaluable for predicting behavior – your own as well as of others. "In the attention schema theory, awareness serves this function....to usefully describe the constantly changing state of attention," says Graziano.



According to Graziano, we are not far from a future where knowledge of consciousness will be practically applicable to all human beings. Artificial intelligence is no longer the stuff of movies only. Google and Facebook have been using artificial intelligence software for some time now. As machines get increasingly sophisticated in how they process information, could we, one day, have machines that can 'feel' or are 'conscious'? Consciousness, believes Graziano, is a matter of engineering – an inevitable quality of a complex processing machine. While this still remains to be tested, remarkable progress is being made in developing neuromorphic chips [5]. Modelled on brain circuitry, these computing systems are designed to integrate the ability to process information with that of learning from experience. If internal models do indeed lead to consciousness in the human brain as the attention schema theory predicts, it could one day be possible to build that into man-made machines!

Further readings:

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2. [illegible]
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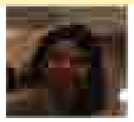

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ABT: All you need to know to tell stories

RANDY OLSON

Science can be made a lot more engaging if we incorporate elements of storytelling. But, how do you actually get started with a story? The answer lies in using the universal narrative template of "and, but, therefore" or the ABT.

We all like stories AND for over four thousand years storytelling has been our most effective means of communication, BUT not everything is a story, THEREFORE to draw on the power of storytelling, we need to begin by actually knowing what is and is not a story.

A resume is not a story. A timeline is not a story. They are merely lists of facts. But, with a little bit of editing, they can be turned into a story — it just requires some work.

There are three main forces involved in creating a story — agreement, contradiction, consequence. These forces come together to form what is known as the **classical design** for stories. This is the shape we find in most myths, fables and allegories that have persisted over the ages. There are countless variations on this form, but it is the simplest, clearest, and thus most powerful.

Classical design begins with agreement. This is the part before the storytelling process begins — before anything 'happens'. In a murder mystery, this is the beginning, where we get to know the people of a town or business or a family. Nothing is 'happening' yet; everyone seems to be just fine. It is the country before the war, the married person before the betrayal, or the sports game before one team has a lead in the score. The most common connector word used in this first part is **and.**

The story begins 'when something happens'. This is the second part, which is contradiction. The most common word for this is **but**. This means that we can go to a small town AND get to know a family AND everything seems fine, BUT then the father is found lying dead in the back yard. Now we have a story.

The third part, often referred to as 'advancing the narrative' is the force of consequence. We found the father dead, which means we immediately want to know what the consequence is going to be. For example, "... the father is found lying dead in the back yard; THEREFORE the police begin an investigation." For this third term, **therefore** is actually not the most common word of consequence. **So** is much more common, but in constructing a story 'therefore' is often a more powerful word, and so it is better for structural reasons.

Now we have our three functional words — and, but, therefore. Let's see how they work to create a story.

There are three main forces involved in creating a story — agreement, contradiction, consequence. These forces come together to form what is known as the **classical design** for stories.

Fig. 1. The ABT exercise: ABT gives a 'formula' to apply in any case. Fill in the blanks to create the ABT for this photo. "This boy was _____ AND _____ BUT _____ THEREFORE he is _____." For example, "This boy was tired AND sweaty, BUT he needed to get clean, THEREFORE he is washing in the river." Now do your own version!

Take Aesop's fable about the tortoise and the hare for example. This was the story of a race between the two; AND the hare being much faster, was way ahead of the lumbering tortoise. BUT she got so confident she took a nap as the tortoise plodded onward, passing the sleeping hare; THEREFORE the tortoise won the race.

That is the ABT. It captures the narrative core of the story. And because narrative principles are universal, it works just as well for non-fiction as for fiction. For a non-fiction narrative you can think of it as three things: set up, problem, solution. For example, you have the set up (we are fighting litter), problem (but there are no laws), solution (therefore we need laws).

What does that have to do with teaching science? Let's take a look at some examples of how this formula can be applied to science classrooms. Here's an ABT for dietary choices: Palak-paneer (Spinach-cottage cheese) is a popular food choice AND palak (spinach) seems like a logical pairing for a meal, BUT palak contains oxalic acid that prevents absorption of calcium[1] from dairy items (paneer, in this case). THEREFORE these two should not be eaten together.

Let's look at another example. In the 1800's, people thought species never changed AND did not know about extinction, BUT fossils showed that species do change, THEREFORE Charles Darwin developed the theory of evolution by means of natural selection, which was eventually shown to be how species evolve over time.

The core challenge of creating a good ABT is to have it be both concise and compelling. To make it concise you want to cut it down to the bare minimum number of words. But ... if you cut it too much, it is no longer compelling. For example, with our litter story, if we cut it all the way to, "We are doing things, but not all that is needed, therefore we're doing more," that may be an extremely concise statement of the narrative, but it's so short as to have no impact. We need to know the context (combating litter) and what is being done (passing a law) a little more precisely. This means that to make it compelling we need to add back a few pieces of information.

The ABT is a powerful tool for the development of narrative strength. It functions in two ways. It is a template for constructing concise and compelling statements, as well as structuring over-arching narratives. But, the ABT is also

> The core challenge of creating a good ABT is to have it be both concise and compelling.

the ideal workout device, in the longer term, for those who want to truly master the communication power of narrative. It is the central tool for training that will eventually lead to the ultimate goal of narrative intuition, which is the ability to not just see narrative structure but to feel it as well.

Note:

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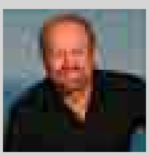
Further readings

1. Weaver CM, Martin BR, Ebner JS, Krueger CA. Oxalic acid decreases calcium absorption in rats. The Journal of Nutrition vol 117, 1903-1906, 1987. URL: http://jn.nutrition.org/content/117/11/1903.extract



Randy Olson earned his PhD in biology at Harvard University AND achieved tenure as a professor of marine biology at the University of New Hampshire, BUT then he developed an interest in the mass communication of science, THEREFORE he resigned his professorship, moved to Hollywood and became a filmmaker. He is the writer-director of many award-winning films and has written three books, including 'Houston, We Have A Narrative: Why Science Needs Story' (University of Chicago Press, 2015). To know more about him, check out his web page: http://www.randyolsonproductions.com/randy_olson/randy_olson_index.html

WALKING ON THE MOON

RAMGOPAL (RAMG) VALLATH

This is the story of a private Indian company, TeamIndus, that is competing in the Google Lunar XPRIZE challenge to land a rover on the moon.

Ek Chotisi Asha — one small hope, that is what I am named: ECA for short. But the hope I represent is anything but small. I represent the hopes of 1.3 billion people of India as they make giant strides across all facets of science and I represent the hope of humanity to spread wings, move out of the security of mother Earth and settle on distant planets. I am a small but giant step in that direction. You see, I am a small rover (refer **Fig.1**) that is designed to travel from the Earth to the Moon, land there and drive around on the moon. By the time you read this story, I will be on my way to the moon or would have already landed there.

I was conceived and built in the office of the young start-up company, TeamIndus, in Bengaluru, India. It all started when Google announced the Lunar XPRIZE (GLXP for short), a global competition. It is a $30M

Fig. 1. ECA (Short for Ek Chotisi Asha- one small hope) is the moon rover designed by TeamIndus.
Credits: TeamIndus. License: Copyrighted and used with permission.

Fig. 2. ECA along with the spacecraft, photographed at the TeamIndus facility in Bangalore.
Credits: TeamIndus. License: Copyrighted and used with permission.

competition to challenge and inspire engineers, entrepreneurs and innovators from around the world to develop low-cost methods of robotic space exploration. To win the Google Lunar XPRIZE, a privately funded team must be the first to a) successfully place a spacecraft (refer **Fig.2**) on the moon's surface, b) have it travel 500m, and c) transmit high definition images and video back to the Earth.

Initially when the prize was announced, no Indian teams were participating and this motivated my makers to come together, form a team and register for GLXP. I believe they signed up for the competition on the very last day, 31st December, 2010. Phew! I may not even have been conceived, let alone be born if they had missed that deadline!! And you know what? It was just five people who formed the initial team of TeamIndus. Today, there are over one hundred and twenty people in the team (refer **Fig.3**), including about two-dozen experienced space experts from ISRO and a whole lot of young engineers, pretty much fresh out of college. Imagine the excitement for them – sending a rover to the moon within five years of coming out of college!

I believe this challenge is only for privately funded companies, and the participants had to acheive the mile-stones set by Google Lunar XPRIZE. Our turning point came in 2014.There was an interim Milestone Prize announced by GLXP to check the progress of the competition. Three prizes were announced for showcasing robust hardware and software to overcome key technical risks in the areas of imaging, mobility and lander systems. TeamIndus won the $1M prize for demonstrating its landing technology.

My launch will happen from Sriharikota. I will be travelling inside a spacecraft that was also designed by TeamIndus. The spacecraft in turn will be carried on the nose of an Indian Space Research Organization (ISRO) rocket, the Polar Satellite Launch Vehicle (PSLV). We collaborate extensively with ISRO; and, also, PSLV has an amazing record of thirty nine consecutive successful launches. Only the very best for me!

There are specific days that are ideal for lift off – this is when the moon is crossing the Earth's ecliptic plane – that is, when it crosses the Earth's orbital plane around the sun. This occurs every fifteen days. Hence the window for launch would be that day or maybe a day before or after. This window repeats up every fifteen days and we could catch any of these windows after 28th December, 2017.

I won't be travelling alone, though. My spacecraft will be shared by my competitor! HAKUTO is a team from Japan which is one of the five final teams still in the competition, and their rover, Sorato, will be making the journey along with me on TeamIndus' spacecraft. I can see you are speechless with wonder — why should we help our competitors? But let me tell you, in science, there is no competition. We are all working towards widening the horizons for humanity and there is only collaboration among scientists. In fact, that is the only way in which we can understand the universe.

The spacecraft itself will be designed to be able to carry the payloads — both my friend Sorato and I along with some experiments we will be carrying, all adding up to around 20kg. You must appreciate that it is really important to keep the weight as low as possible and my own design has been changed many times to finally reach a weight of just 7kg. Imagine if one of you guys have to reduce so much weight just how much dieting you have to do! But to carry this payload mass of just 20kg, there is a whole paraphernalia that is required, all together adding up to a whopping 600kgs!! Let me explain the details.

First of all, when the spacecraft starts its descent on to the moon surface, it would be falling at a speed of about 1.7km/s. This has to be decelerated using a propulsion system to almost zero speed as it touches down. This propulsion system will be about 60kg in mass. Mind you, this is just the propulsion system — without any propellant. The whole housing for the payload and the thrusters will add up to another 60kg (here again, after multiple design iterations, we brought down the mass from 90kg to 60kg). Then there would be a guidance navigation system, communications system, computer, battery, solar panel etc. — all together another 60kg. So the total dry mass — without fuel — would be about 200kg. The fuel required for the above deceleration for soft touchdown is another 200kg. But that is not all: we also need propellant to get us to the moon. That will be another 200kg. Altogether, that makes 600kg for the spacecraft for carrying 20kg payload. Talk about the tail wagging the dog!

The distance from the Earth to the moon is all of 3,84,400km. The journey starts with a series of four stages of propulsion by PSVL. The first stage will take us up to 150km altitude, outside the Earth's atmosphere; the second stage will take it to about 400km and the third stage to almost 800km. At the end of all four stages, the spacecraft will be placed at a highly elliptical orbit of 880km X 70,000km (perigee of 880km and apogee of 70,000km) around the Earth. The spacecraft that carries me will initially make a few manoeuvres while going around the Earth, finally reaching a speed of 10.4km/s. This is forty times the speed of a normal commercial aircraft! I hope I don't get dizzy with all that speed! Once this maximum speed is reached, the propulsion system shuts off and we continue to go towards the moon, losing some of our speed due to continued gravitational pull from the Earth (refer **Fig.4**).

Throughout this journey, the spacecraft will be communicating back to the Earth and also getting instructions from the Earth using a particular band of micro-wave frequency called the S-Band.

There is also a guidance and navigation system on-board the spacecraft, consisting of a star-sensor and sun-sensor that ensures the position and the orientation of the spacecraft — referred to as the attitude of the spacecraft — is right (it

Fig. 3. Members of TeamIndus.

Credits: TeamIndus. License: Copyrighted and used with permission.

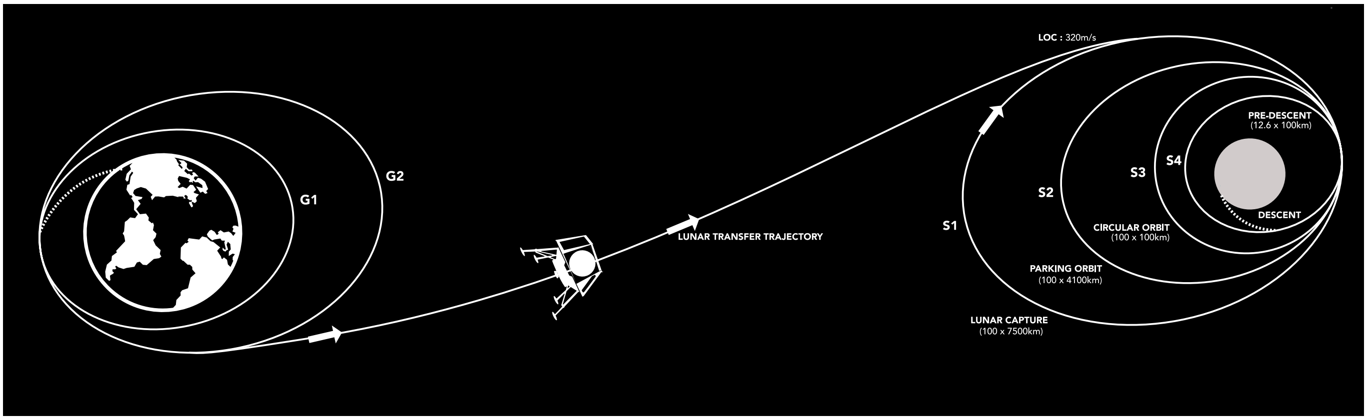


Fig. 4. The trajectory of the spacecraft.

Credits: TeamIndus. License: Copyrighted and used with permission.

is not only in life that you need to have the right attitude to succeed!!) Once the craft has the proper attitude, direction can be changed accurately using the data from the inertial measurement unit – consisting of a gyroscope and accelerometer. Imagine the precision required to exactly position, orient, and direct a spacecraft freely hanging in space using just the thrust of propellants! My digital mind boggles!

Once the spacecraft nears the moon, it has to decelerate, though. Otherwise it will be travelling too fast to be grasped by moon's gravity. For this, some more propellant fuel has to be used. After this, we take some orbits around the moon and then the spacecraft starts its descent to the surface. During this phase, it requires terrain relative information – i.e. the information regarding the distance to the moon and where exactly it is heading on the moon. This is done using the laser range finders, the laser altimeters and the cameras on board the craft.

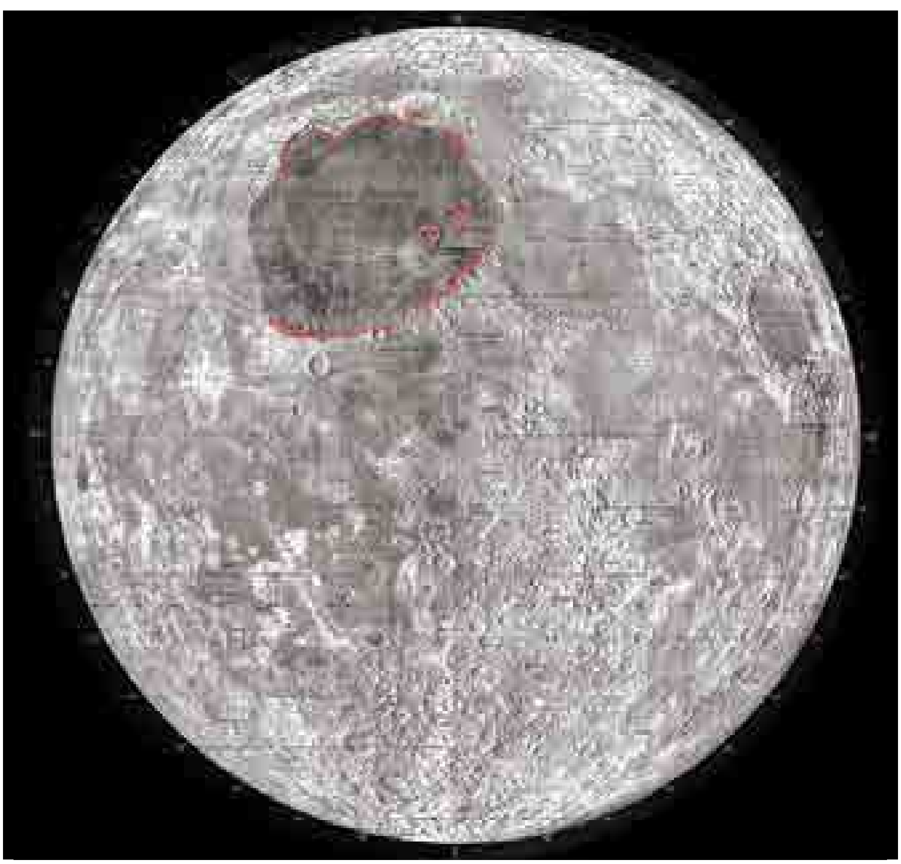


Fig. 5. Mare Imbrium.

Credits: Srbauer, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Imbrium_location.jpg. License: CC-BY-SA.

All these different gizmos on the craft are powered by the battery on board, which in turn is recharged using the solar cells.

The four legs of the craft and the touch down velocity are designed, taking into account the type and hardness of the terrain it will be landing on. This information is available from previous missions to the moon. Again, as I said, it is all the information from so much of past scientific work that will help us to succeed. That is how science works.

Once the craft (now called the lander) lands, it is time for me to act. You recall of course that my primary goal is to travel 500m on the lunar surface, take pictures and videos, and send them back to the Earth. To navigate through lunar terrain, I have specially designed wheels. They all have independent suspension and movement. They are all fitted with these special fittings called grousers that increase the contact area with the ground and increases traction. I am also built to be flat and low in shape so that my centre of gravity is very low. This ensures that I don't topple. Also, knowing the exact kind of terrain I am going to be landing on has helped my designers cut out unnecessary features to reduce my mass. For example, I cannot climb up slopes that are greater than 40° incline. But we do know beforehand that where I will be landing on — Mare Imbrium (refer **Fig.5**) — will not have such steep inclines. It is a vast lava plane.

Even though I have a lot of artificial intelligence algorithms built into me, till I travel the first 500m, I will be controlled remotely from the Earth. This can be done because the two cameras that serve as my eyes continuously send images and video back to the Earth through the lander. I will send images to the Earth, they will analyse these images and send me simple text instructions such as move three steps forward and one to the right etc. Of course, I will be making only one move at a time. One just cant be too careful when letting a baby walk — and I am a baby for all practical purposes.

Once the initial milestone is achieved, like a growing baby, I will be allowed to wander around a little more on my own, since my algorithms will be continuously learning and would have learned how to better navigate the terrain on my own.

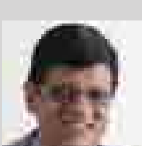
In the meanwhile, the experimental setups in the lander would have started their work. These were identified through an outreach program launched in 2016 called Lab2Moon, specifically targeting young minds across the globe. In the quest to catalyse humankind as a multi-planetary species, TeamIndus invited youth under twenty-five years to imagine, design and build an experiment that will help humanity build sustainable life on the Moon. Three thousand entries from fifteen countries and over three hundred cities across the globe were received in the first round.

After Phase 2 — the shortlisting process, Team Space4life from Italy won this competition and their experiment will be flying to the moon. They are working on developing a radiation shield using bacteria. Other on-going projects include Team Zoi (India) which works on photosynthesis on the moon by extremophile cyanobacteria, Team Ears (India) which works on an Electrostatic radiation shield experiment, Team Kalpana (India) which works on Instrument for Lunar dust analysis, and Team Callisto (India) which works on a Lunar dust accumulation analyser.

The whole program is so exciting. But my life will be a short-lived in all probability. Daylight lasts only for fourteen days on the moon. To maximise our mission, we will be landing at dawn. So I have fourteen days of sunlight to complete the 500m, then to do my wandering around. After that darkness will descent. Since there is no atmosphere on the moon, the heat doesn't get trapped and stay on the surface. By the next sunrise, fourteen days away, the temperature will reach about -200°C. If you think that is bad, remember that during the first fourteen days of daylight, the temperature would have reached over 100°C! I might look small and frail, but I am tough. My creators have designed me to be functional at temperatures at which water will vaporise. But it is very much doubtful if I will survive the intense cold. Of course, I know my friends at TeamIndus will be waiting with bated breath to see if I will pop back into life and start transmitting after fourteen days of night when the sun rises again. But for me, it doesn't really matter. I would have given my life for the progress of humanity.

Note:

1. According to the latest news reports (Jan 10th, 2018), the official contract between TeamIndus and ISRO has fallen through because TeamIndus has not been able to raise the funds required to pay for the use of ISRO's launch services. Hence, inspite of their technological readiness, TeamIndus may not be able to meet the deadline set by GLXP. Even so, we have decided to carry this article, because our account of their attempt reveals important aspects of this multidisciplinary scientific effort. It also illustrates how the history of science is filled with ambitious leaps of faith, many of which do not succeed. Nevertheless, without these risks, science wouldn't be where it is today.
2. Credits for the image used in the background of the article title: A historic extraterrestrial sky—the Earth viewed from the Moon, Apollo 8 mission, Lunar orbit, 24th December, 1968. URL: https://upload.wikimedia.org/wikipedia/commons/a/a8/NASA-Apollo8-Dec24-Earthrise.jpg.



Ramgopal (RamG) Vallath is a bestselling author and motivational speaker. He has conducted dozens of science workshops in schools based on the story of his children's sci-fi book, Oops the Mighty Gurgle. He also delivers motivational talks to students on how to find success.

i wonder...
REDISCOVERING SCHOOL SCIENCE

Write for us

i wonder... is a magazine for middle school science teachers. This not-for-profit effort is published twice a year - June and December, and available in free online and print formats. Each issue is originally available in English, and later translated into Hindi and Kannada.

We are always on the lookout for articles that capture new perspectives to the teaching and learning of science, building on concepts covered in middle school curricula. Submissions from practicing science teachers and teacher educators are particularly welcome. We'd like to read more about the methods, activities, and examples you've tried and tested in your classrooms to engage the curiosity and imagination of your young learners.

Send us a science snippet! We are looking for short (200-500 words) science snippets that bring out the funny, fascinating, mysterious and inspiring facets of science and scientists. Send one of these to us, along with a short bio and a photo of yourself - the five best submissions will be published in our next issue!

Apart from a theme section that is unique to each issue, **i wonder...** features many of these non-theme sections that are common across issues:

The Science Lab	Tried-and-tested thought/practical experiments to teach a concept.
Life in Your Backyard	Concepts and activities to use immediate surroundings for ecological literacy.
Science Online	Ideas and activities to use an open-access online resource as a teaching aid.
Earth Matters	Ideas, activities and experiments in education for sustainability
Annals of History	The history of one major scientific idea/innovation/concept.
Serendipity	The story of an accidental scientific discovery.
Biography of a Scientist	Her life and times through the prism of her contribution to science.
Myth or Fact	Identifying and addressing common mental models through science.
Book Review	Review of a book that can add to the teaching/learning of science
Hot off the Press	Why recently reported scientific work has grabbed headlines.

Can't find a match? Get in touch with us. We'll help you identify the section that the article you'd like to write fits best. Our word limit for most articles is between 2000-2500 words. **Content and ideas for a poster or resource material that teachers can directly use in their classrooms are particularly welcome!**

We accept submissions throughout the year, but ideas for articles for the next issue must reach us latest by 5th March, 2018. So, hurry - please send a brief outline (<500 words) and a bio (<100 words) to iwonder.editor@azimpremjifoundation.org. We'll get in touch with you as soon as possible.

The Editors.

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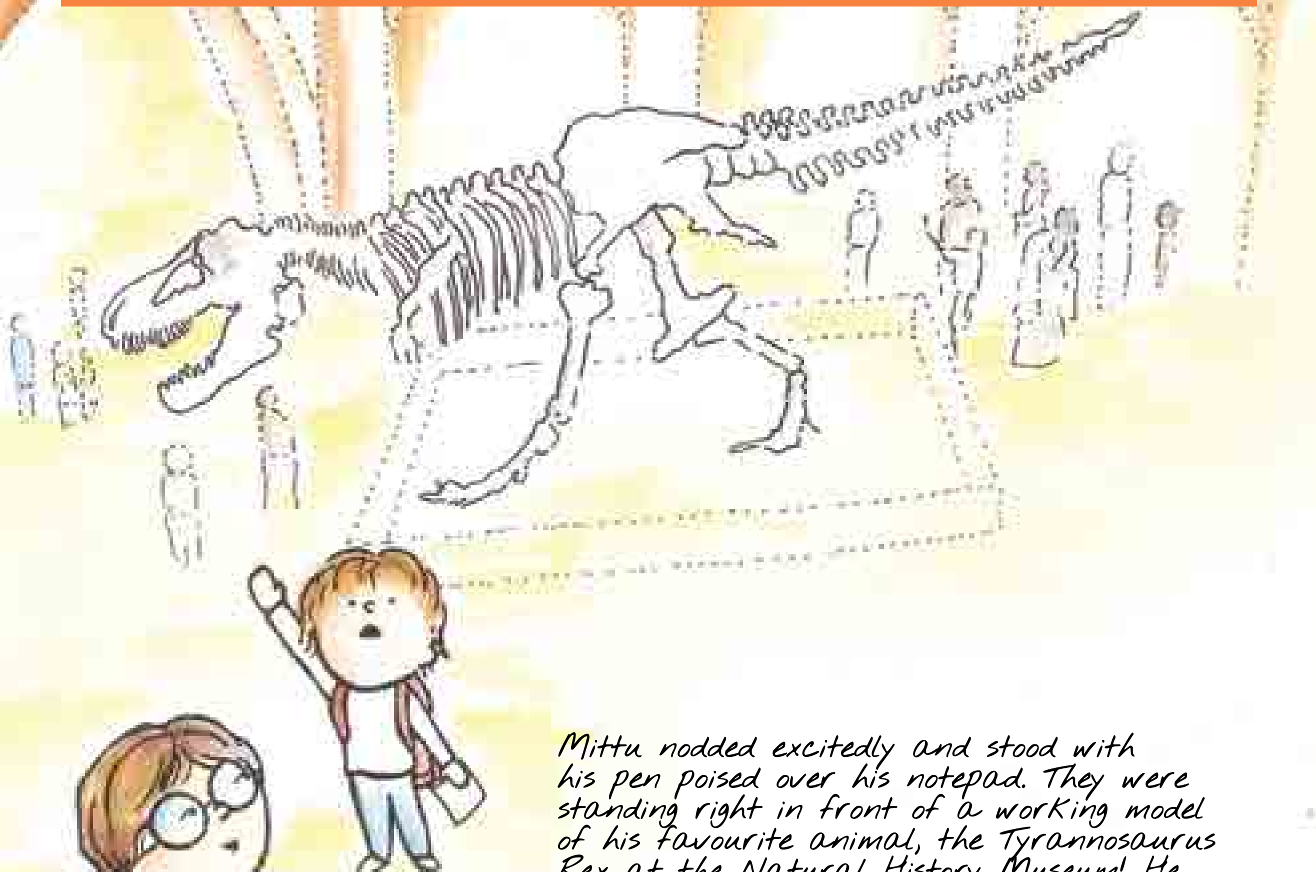
LUCA, Version 4.01

Author: Rohini Chintha

"Are we ready?"

On a trip to a natural history museum with his mother, Mittu is upset by his mother's insistence that all the life exhibits are fossils of his distant cousins. Join Mittu as he sets out to check the truth of this statement and begins his journey of understanding 'Evolution'.



Mittu nodded excitedly and stood with his pen poised over his notepad. They were standing right in front of a working model of his favourite animal, the Tyrannosaurus Rex at the Natural History Museum! He waited for mom to begin.

"Dinosaurs lived in the Jurassic and the Cretaceous period of the Mesozoic era. Remember the movie, 'Jurassic park'...?" Mom looked at Mittu. "Now you know why it is called Jurassic, right?" Mittu nodded knowingly.

Mom continued "Dinosaurs belonged to a class of animals called 'Archosaurs'. After the Triassic extinction over 200 million years ago, which wiped out a large number of living things on earth, dinosaurs grew in number and became dominant. And...." Mom gave a significant pause.

"Yes...!" Mittu looked up expectantly.

"The dinosaurs are your distant cousins!" Mom ended matter-of-factly and moved on.

Mittu gaped for a moment, wondering if he had heard it right, but quickly recovered and rushed to join Mom at the next exhibit, a stuffed 'Secretary Bird'.

Mom began "This is a bird of prey found in the Sahara deserts of Africa. It looks partly like an eagle, partly like a crane, and has very long legs which help it catch prey. It walks through its hunting grounds on foot in the day, and flies up to its nest, usually built in an Acacia tree, at night. Can you see its eyelashes?" Mom paused again, and Mittu looked up.

"This too is your distant cousin". Mittu frowned.

"Yes. You heard me right." Mom smiled "The Secretary bird is a distant cousin of yours, and of the dinosaurs too".

Mittu thought the whole thing was a joke, and laughed heartily. He pointed to the skeleton of a whale in the next section and said mockingly, "Oh yeah..? And that is your distant cousin, right?"

"Yes" said Mom solemnly, "and yours and the dinosaur's too".

Mittu was perplexed. He wondered if he had been rude to any of his cousins lately and called them names. Try as he might, he could not remember quarrelling with anyone this summer, let alone his cousins. In fact, he'd been especially good the whole month because he wanted mom to come with him to the museum. And, now, this! Maybe, it was a joke after all.

The next few sections of the museum had displays of the skeletons of mammoths, stuffed Rhinos, and the skulls of humans who'd lived during the Indus Valley Civilization. Mom explained each of them in detail, but always ended with the same phrase "And this too is your distant cousin!"

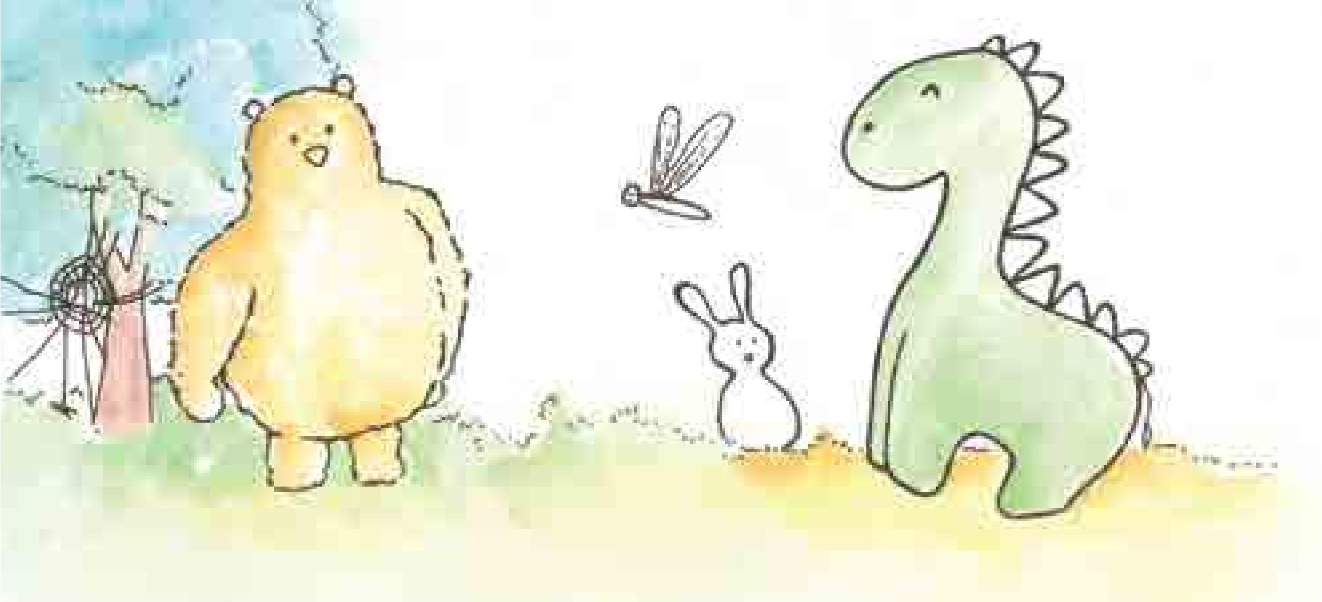
This wasn't funny anymore! Mittu was so annoyed, he wanted to scream out loud, but he knew he would be thrown out of the museum if he did - so he tried to keep his cool.

"Ahem" Mittu cleared his throat, and began with as much sarcasm as he could muster "Mom, what else here is my distant cousin? You see, I would like to know exactly how big my family tree is."

"Well, all the life exhibits!" Mom replied placidly.

"Will you please stop it?" Mittu snapped. "It's not funny. In fact, it's pretty annoying".

"What is so annoying about it? They ARE your very, very distant cousins" Mom replied moving to the nearest bench.



"So, the dinosaurs, birds, every species of animals, plants and bacteria are related to me and also to each other?" Mittu asked in exasperation.

"Yes!"

"No!"

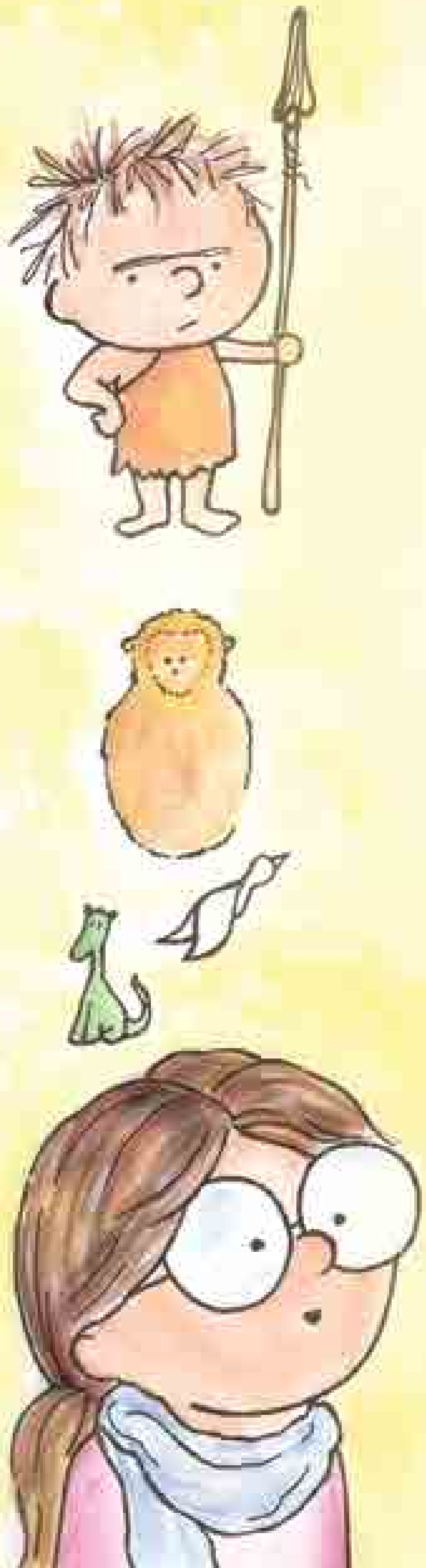
"Why not?"

"Because they are plants, insects, and animals, and I am a human".

"Aha" said Mom encouragingly.

Mittu tried to reason with her. "I am different. I am more evolved"

"How?" Mom asked "From what did you evolve?"



"Early man?" Mittu answered thoughtfully.

"And who did 'early man' evolve from?"

"Chimps..?"

"So, are chimps your distant relatives?"

"Well...Yes. Chimps, gorillas, apes in general..."

"Good. But, why not the birds and the dinosaurs? Why not any of the other animals?"

Mittu thought aloud, "Dinosaurs are huge, birds fly, and other animals...there is no way I could have evolved from them" his voice trailed off.

"Fishes, birds, dinosaurs, reptiles, amphibians and other animals have two pairs of limbs – fore limbs and hind limbs – don't they? And, they have a spinal column and blood?"

Mittu brightened "But, some animals, like the octopus, do not have skeletons...so, they are not my cousins, are they? And, what about snakes?" he smiled proudly.

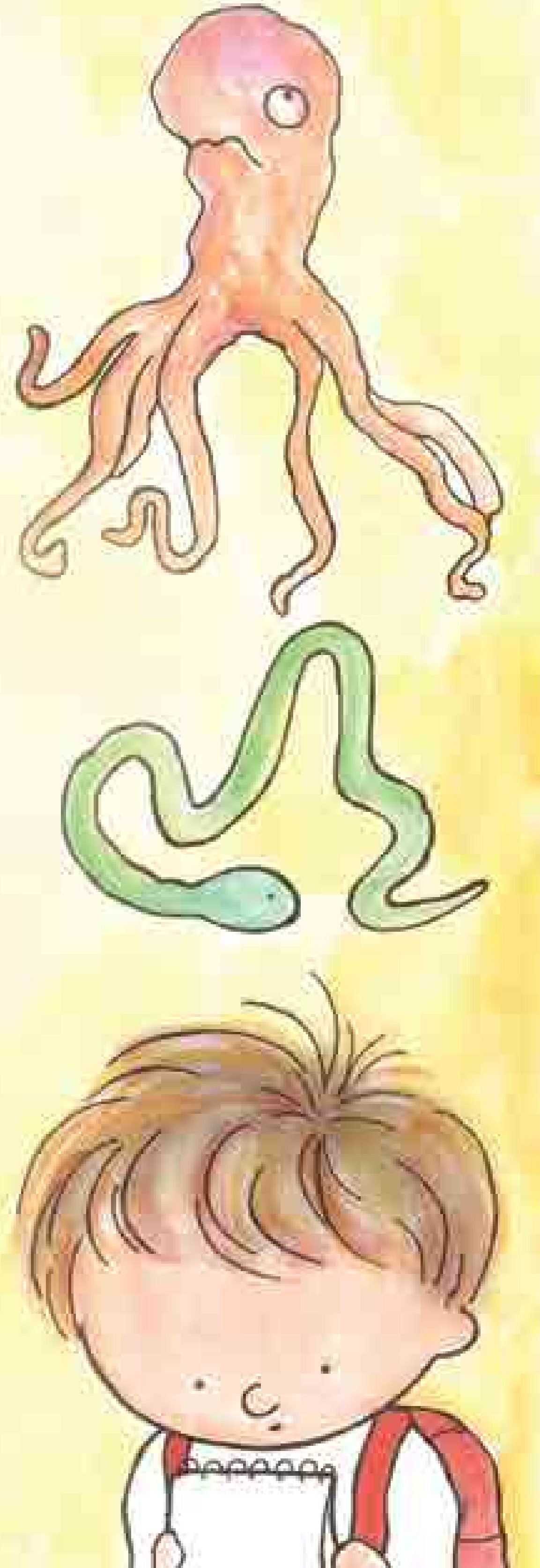
"But, all these animals have eyes and nerves, don't they?" Mom asked. Mittu nodded quietly.

"So, are we not similar? How could we be similar, if we haven't evolved from something common?"

Umm..maybe, all animals evolved from a common ancestor," Mittu replied sheepishly, "but definitely not trees and micro-organisms!"

"Why not?" Mom probed.

"Animals can move about, talk, eat, grow, respond and..."



"Plants too can grow and eat. They too respond to light in the sky and water in the earth – by spreading their branches to get maximum light, and their roots to long distances. Remember your favourite plant – the 'Touch-me-not'? It does respond to your touch, doesn't it?"

Mittu wondered at this.

Mom continued, "Do you remember, Mittu, last month we went to a 2-acre park, where we saw many trees growing from the same mother tree? That too, is one kind of movement, isn't it?

"Well..." Mittu was not sure anymore, "but, do plants have blood and blood vessels?"

"Of course!" Mom smiled, "but their blood is called sap, and their blood vessels – xylem and phloem. See, we are similar to plants too. And, again, we can only be similar if we have a common ancestor".

"But, what about micro-organisms?

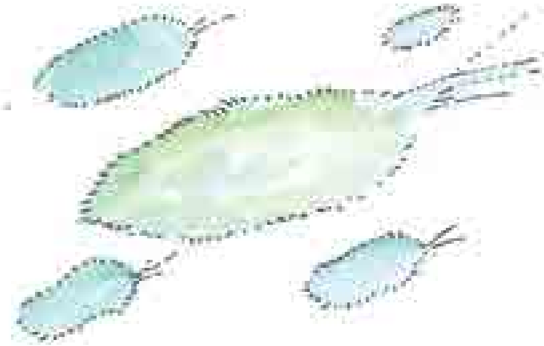
"What are all living things made up of?" Mom answered Mittu with a question.

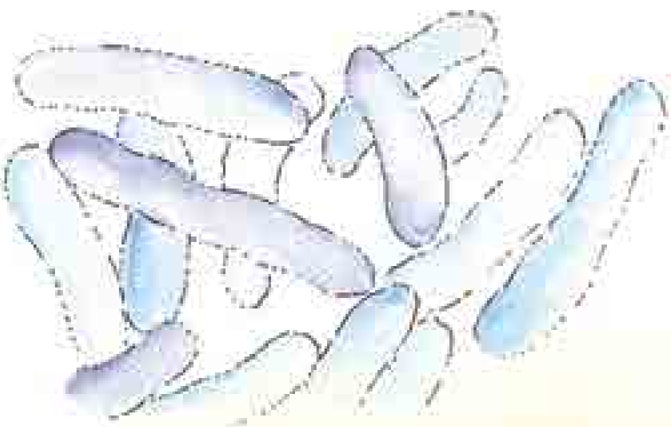
"Cells!" Mittu said brightly.

"And aren't micro-organisms made up of one or a few cells!" Mom replied easily.

"But..." Mittu looked doubtful.

"Come on Mittu," Mom pleaded. "Accept it. Micro-organisms too eat, grow and respond to stimuli. Otherwise, how do you think they live? The difference is that all these processes in a micro-organism happen in one cell, instead of many cells. If you were to take out one cell from your body, and put it beside a bacterial cell, you would find many similarities. Both cells would have a cell membrane, DNA, and cytoplasm! Don't you see? We are similar to micro-organisms too, at the cellular level".





"But, we are different too, aren't we Mom?"

"Yes, we have developed these differences to suit our surroundings. In other words, we've adapted to our environment. One cell befriended another cell so that they could help each other. Then, some more cells joined these two, and they formed colonies. Cells in these colonies lived together for so long that they started functioning together as one unit, and, thus, evolved into multicellular organisms like plants, animals and humans. Each species, then, adapted differently, and so you see all these variations" Mom explained.

Mittu sat swinging his legs for a while. Mom waited.

After a while, Mittu began slowly, "So...all life forms are distant, distant relatives of each other, no matter how different they look from each other?"

Mom nodded, and looked pleased.

"We are relatives because we have so many similarities, which could come only if we have all evolved from a common ancestor, right?"

Mom smiled.

"And, because we are all made up of cells, would it be okay for me to assume that our common ancestor could be a single-celled micro-organism?" Mittu smiled.

Mom was elated. "Great going, Mittu!" she said and patted him on the back.

"So, when did this single-celled organism...my actual ancestor begin evolving?"

"Approximately 4 billion years ago...and, it is called LUCA (or the last universal common ancestor)," Mom answered happily.

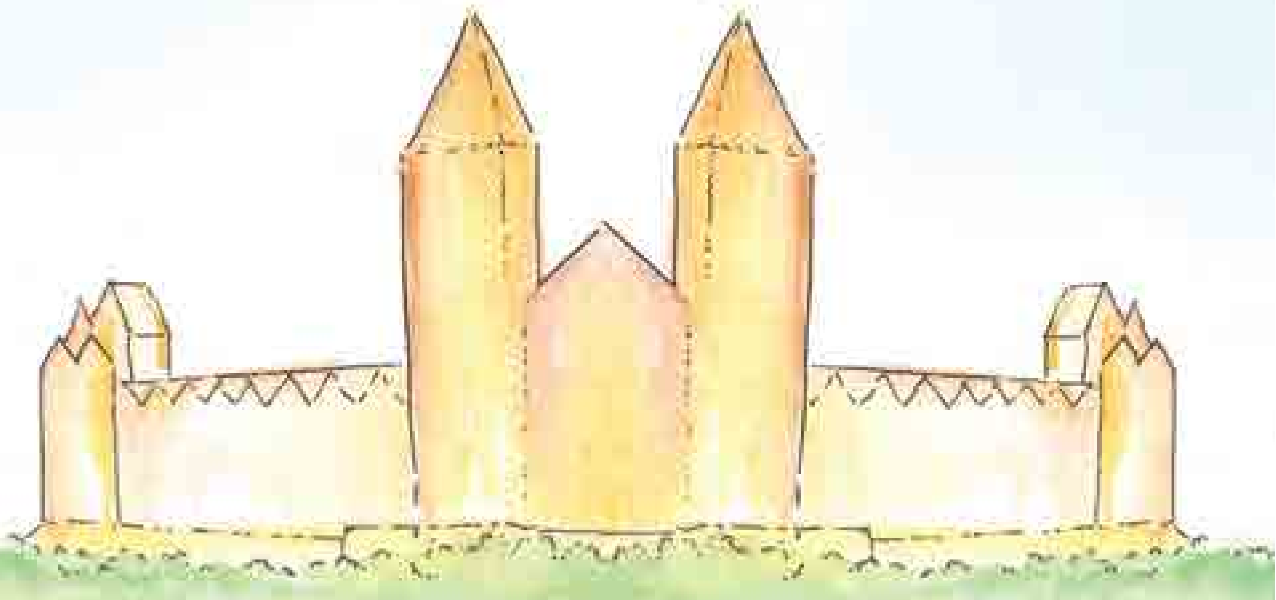
"One last question mom," Mittu said mischievously, "What is my name?"

"Mittu"

"No!"

It was mom's turn to look perplexed.

"My name is LUCA, version 4.01 billion!"



About the Author

Rohini Chintha is an Assistant Professor (C) at the Department of Genetics and Biotechnology, University College for Women, Hyderabad. She writes in Telugu and English, is passionate about writing for children, and believes that 'A Happy Childhood builds a Happy Society'. About 75 of her stories for children have been published in various magazines.

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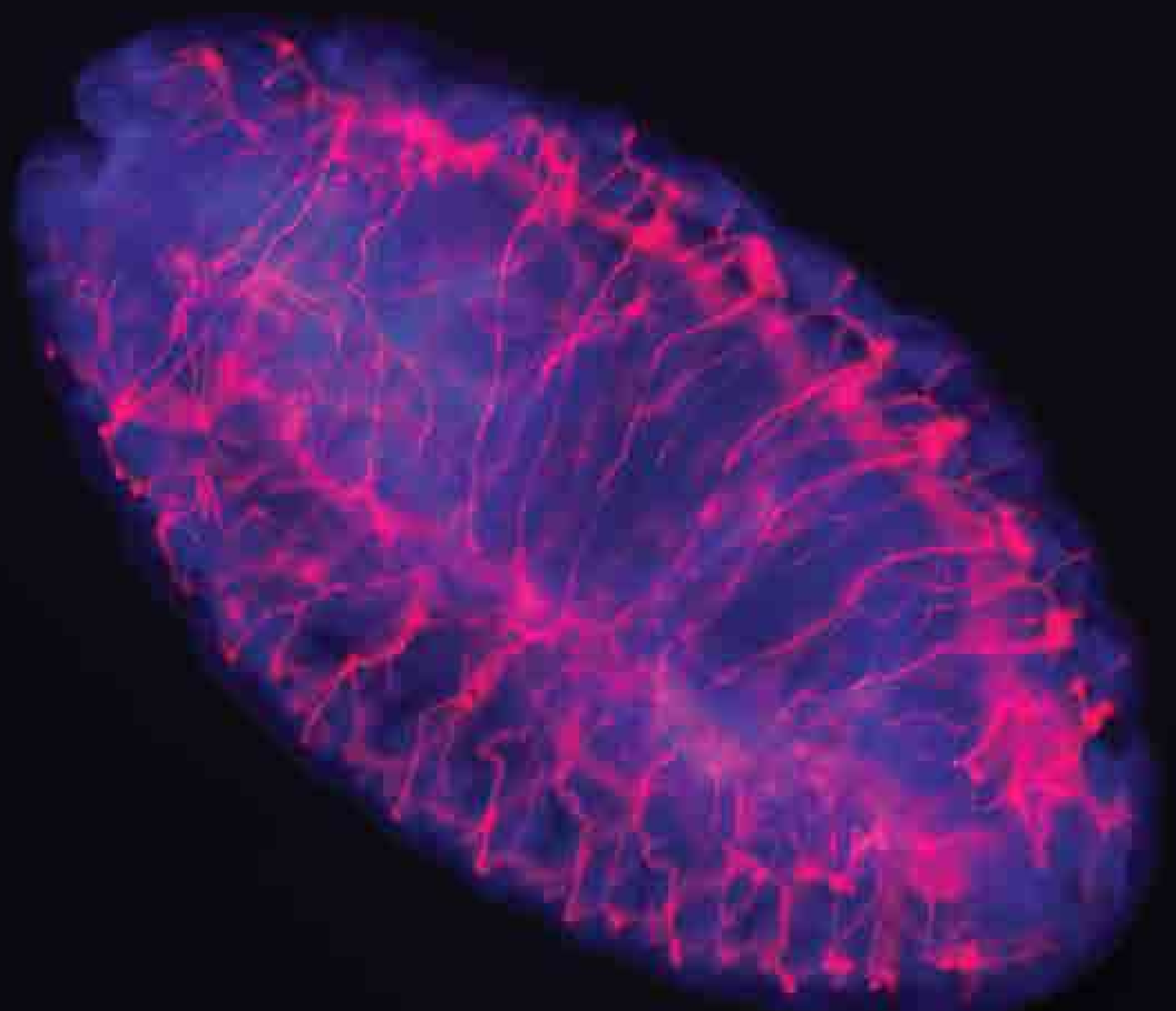

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