

iwonder...

Rediscovering School Science

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Metal-organic frameworks:

The new all-rounders in
chemistry research

i wonder

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i wonder is a science magazine for school teachers. Our aim is to feature writings that engage teachers (as well as parents, researchers and other interested adults) in a gentle, and hopefully reflective, dialogue about the many dimensions of teaching and learning of science in class and outside it. We welcome articles that share critical perspectives on science and science education, provide a broader and deeper understanding of foundational concepts (the hows, whys and what nexts), and engage with examples of practice that encourage the learning of science in more experiential and meaningful ways. i wonder is also a great read for students and science enthusiasts.

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Printers

SCPL Bangalore - 560062
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Acknowledgements

Special thanks are due to Satyajit Mayor and Smita Jain of IndiaBioscience, National Centre for Biological Sciences, Bangalore, for their support in bringing out this issue.

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i wonder...

REDISCOVERING SCHOOL SCIENCE

Editorial

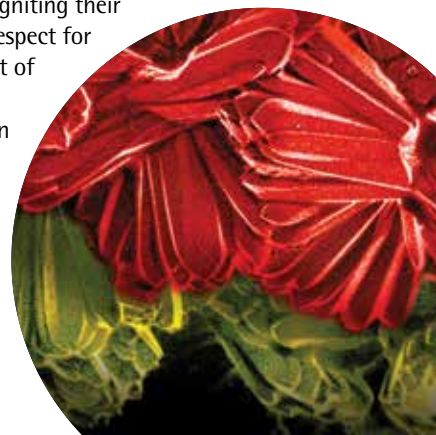
As a child growing up in rural Kerala, my chief entertainment was reading: mostly science, history of science and, also, biographies of scientists. To me, science seemed pure and uncluttered by politicking. I thought of scientists as completely rational beings, driven only by a desire to uncover the mysteries of the universe. In my mind, they were impartial observers, experimenters and thinkers, untouched by personal prejudices.

But, as I grew up, I came to realise that this was far from the truth. No doubt, the history of science has many examples of cooperation between scientists, often from multiple disciplines, working together to uncover the mysteries of nature. But, it is also peppered with examples of prejudice, power play, factionalism, politics and one-upmanship. One such example is the exciting story of the uncovering of the structure of DNA shared in this issue's 'Discovering the Helical Staircase'. Every time I dwell on this path-breaking discovery, I am left with deep sadness at how one of the scientists who contributed significantly to this achievement – Rosalind Franklin – received hardly any credit for it. This is a reflection of how women scientists were systematically relegated to the background in those days. The men who dominated science wanted to keep it that way – dominated by men. How much more would science have progressed if women had been given their rightful say and encouragement?

An equally heart-breaking story, for me, is that of Subrahmanian Chandrasekhar. As a young man of twenty five, he was given an opportunity to present his path-breaking theory on the evolution of massive stars to the august gathering of members of the Royal Astronomical Society in London. I can well imagine how apprehensive and, at the same time, excited Chandrasekhar must have been on this occasion. To his shock and dismay, his presentation was ripped apart by none other than his mentor and friend – Arthur Eddington. A colossus in the field of astrophysics in those days, it was Eddington who had, in fact, encouraged Chandrasekhar to make the presentation in the first place. But, he chose to ridicule Chandrasekhar's ideas rather than counter it scientifically. Eddington's stature ensured that Chandrasekhar's theory, which had to wait for almost half a century for a Nobel Prize, wasn't taken seriously by his peers for decades. Even if some of them did see merit in it, they lacked the courage to express it. Imagine how much more astrophysics would have progressed if it was not set back by several decades due to this incident. And, how much more Chandrasekhar himself may have contributed to his chosen field if he had not left it in frustration. How many young scientists across the world may be afraid to come up with original theories because of some version of Eddington in their own lives? How much more, and faster, can science progress if every mentor, every senior scientist, is nurturing and encouraging as opposed to being dismissive?

As science educators, it is essential that we keep in mind that inculcating wonder and curiosity in young minds is only one part of igniting their scientific temperament. We must also inculcate respect for individuals, fairness of mind, courage to break out of stereotypes, a collaborative mind-set, and even kindness. Science, like any other aspect of life, can progress best when people respect each other's abilities and differences, and support and nurture each other unstintingly.

RamG Vallath
Editor



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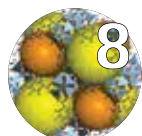
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WHY SYNTHESIZE NEW ELEMENTS

SUSHIL JOSHI

We are in a race to synthesize new elements — each with more protons and neutrons than ever before. Unlike naturally occurring elements, these newly created elements seem ephemeral — ceasing to exist almost as soon as they are created. What makes them so unstable? Why do we synthesize them? What does their creation reveal to us?

In September 2009, a team of scientists from the U.S. Department of Energy's Lawrence Berkeley National Laboratory confirmed a claim made by a team of Russian scientists at the Joint Institute for Nuclear Research in Dubna in 1998 — it was possible to create element 114. The Russian team (led by Yuri Oganessian) had described element 114, now called flerovium, as being "very stable". Today, however, this element does not exist.

The short-lived element 114 is not an exception. A number of super-heavy elements invented or created (refer Box 1) in the last couple of decades don't seem to be very stable. In contrast, 92 elements, the heaviest of which (uranium) has 92 protons, occur naturally. This has led to the hypothesis that elements with more than 92 protons may not be stable in nature. What is it that makes one element stable, and another unstable? And why invest effort in creating new elements, if they are literally *kshan-bhangur* (transient)?

The effect of proton number

Every element is identified by its atomic number, which is the number of protons in its nucleus. For example, flerovium has an atomic number of 114 — the number of protons in its nucleus. For each atom of this element to be electrically neutral, it would require the same number of electrons. Another property of an element is its atomic weight, defined as the sum total of protons and neutrons in its nucleus. Irrespective of where the element is found, its atoms carry the same number of protons, but may have a variable number of neutrons. For example, the element hydrogen has just one proton in its nucleus. Atoms of its most abundant form have no neutrons, making their atomic number and atomic weight equal. However, some hydrogen atoms have one or two neutrons, with atomic weights of 2 (deuterium) or 3 (tritium) respectively, although their atomic number remains the same (refer Fig. 1). Atoms with the same atomic

Box 1. Synthesis of new elements

In theory, all it takes to create new elements is to bombard atoms of two elements with appropriate atomic numbers at each other at very high speeds. Some of these will fuse and gift you with new elements. The atomic numbers of the new elements will be a sum of those of the individual elements with which you start the process.

In reality, this is easier said than done. To achieve these high speeds (~10% of the speed of light) of collision, atoms are accelerated in a cyclotron. When two atoms collide, the repulsive force between their nuclei tends to throw them apart. Consequently, most atoms in such energetic collisions are shattered; but a few may fuse to give rise to a new element.

The presence and nature of new nuclei is inferred from piecing together data from a series of disintegrations and a careful analysis of the products of their decay. For example, new elements tend to be much bigger in size, move far more slowly (~2% of the speed of light), and respond differently to a magnetic field.

number but differing atomic weights are called isotopes of that element.

Most elements have two or more isotopes. In fact, the existence of isotopes seems more a rule than an exception. While isotopes can vary in their physical properties, their chemical properties are identical. For example, charcoal has a mixture of the three isotopes of carbon – all of which have the same atomic number (= 6), but atomic weights of 12, 13 and 14 respectively (refer Fig. 2). On combustion, all three isotopes burn with equal ease and are found in the same proportions in the resulting carbon dioxide as in charcoal. Naturally, all isotopes of an element are placed in the same house in the periodic table. However, the isotopes of an element can vary with respect to their individual stabilities. For example, atoms of carbon-12 and carbon-13 are quite stable, while atoms of carbon-14 are relatively unstable and break down spontaneously. Thus, if you were to keep 10g of a carbon-14 sample for 6000 years (called the half-life of carbon-14), you would find only 5 g left at the end of this period, with the rest having disintegrated into nitrogen and escaped

Different mass numbers



Same atomic number

Fig. 2. The three isotopes of carbon.

Credits: Adapted from Brecksville-Broadview Heights' physical science homepage. URL: <https://sites.google.com/a/bbhcsd.org/physical-science/home/chemistry/ch-14-atoms/isotopes>.

into air. Why are some isotopes of an element stable while others are not?

One explanation attributes this difference in the stability of isotopes to the number of protons in an atom. While protons and neutrons are packed into the nucleus of an atom, electrons revolve around it. Since the mass of an electron is negligible, all the mass of an atom is packed into its nucleus. However, the volume of the nucleus is negligible compared to that of the atom. In fact, if the size of an atom were like that of a football field, the nucleus is likely to occupy the volume of a tennis ball. Since protons are positively charged and neutrons are electrically neutral, any two protons in the nucleus will repel each other while neutrons will not interact with each other or with protons. With an increase in atomic number, the number of protons packed into the tiny volume of the nucleus increases. So does the repulsive force acting between them. Consequently, the stability of the atom is likely to decrease. Indeed, elements with an atomic number of 20 and less are observed to be relatively stable; whereas atoms of elements with an atomic number greater than that show increasing instability. The stability of helium, however, presents an interesting exception. If stability is based solely on the amount of repulsion between the protons in its nucleus, this element with its two protons should have been unstable.

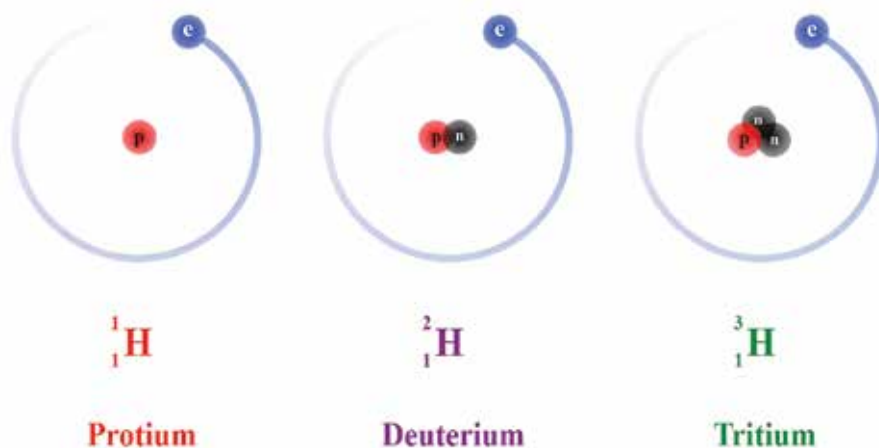


Fig. 1. The three isotopes of hydrogen.

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The strength of forces that hold the nucleus together

Fortunately for the universe, nuclear interactions are not shaped solely by repulsion between protons. According to the laws of physics, subatomic interactions are shaped by another force – the strong force. This is an attractive force, but acts only across the short distances between individual protons and neutrons within the nucleus. Thus, at any given point of time, there are two forces acting between the protons in a nucleus – an electrical repulsive force and an attractive strong force. If an atom has a small number of protons and a small nuclear volume, the strong force between the protons overcomes their electrical repulsion, and the atom remains stable. An increase in the number of protons increases both the electrical (repulsive) force and the strong (attractive) force between them. Since distances between protons in the larger nucleus will also increase, the attractive force will get weaker, and the atom will show a higher probability of disintegrating. Does this mean that all elements with higher atomic weights are unstable?

This is where neutrons seem to play an important role. Being situated amidst the protons in a nucleus, neutrons can shield protons from the repulsive force

acting between them. Neutrons are also capable of exerting the strong force, thereby increasing the total attractive force in the nucleus and adding to its stability (refer Fig. 3). This implies that an element with an atomic number over 20 will be stable if it has more neutrons than protons in its nucleus. In reality, however, all heavy (atomic numbers > 20) and super-heavy (atomic numbers > 100) elements have more neutrons than protons (N:P ratio > 1). And, the most abundant isotopes of light elements (or elements with an atomic number less than 20) have an equal number of neutrons and protons in their nuclei (N:P ratio = 1). This has led to the hypothesis that beyond a certain atomic number, any increase in nucleons (protons and neutrons) in an atom will increase its instability. In other words, heavier atoms are, in general, more unstable. Broadly speaking, this turns out to be true.

The existence of ‘islands of stability’

While the instability of elements tends to increase with increasing atomic number, this does not happen as a continuum. The sudden appearance of atoms that are relatively stable (or more stable than is expected from their atomic numbers alone) punctuates it.

Box 2. Electron configurations

Electrons of an atom are arranged in concentric shells around its nucleus, with certain arrangements being more stable than others. This distribution of electrons is expressed by the mathematical rule: $2(n^2)$, where n is the serial number of the shell. Thus, the first shell can have 2 [$= 2(1^2)$] electrons, the second can accommodate 8 [$= 2(2^2)$] electrons, the third can have 18 [$= 2(3^2)$] electrons and so on. This rule has one proviso, referred to as the famous rule of eight – the last or outermost shell of an atom cannot contain more than 8 electrons. When the last shell is completely filled, as in the case of noble gases, the atom is stable. If the outermost shell has less than 8 electrons, the atom tends to react with other atoms to either complete or empty (give up this shell altogether) its outermost shell. The only exceptions to this rule are hydrogen and helium – both have one shell that can accommodate a maximum two electrons. With only one electron in this shell, hydrogen is very reactive. On the other hand, with a completely filled shell (having two electrons), helium is inert.

This creates a zigzag trend of increasing instability (sea of instability) with some **islands of stability**. In other words, certain atoms are relatively more stable than predicted on the basis of their atomic number. The atomic numbers of these atoms, dubbed as magical atomic numbers, have been calculated to be 2, 8, 20, 28, 50, 82, and potentially 126. Of these, elements with atomic numbers as high as 92 exist naturally. Scientists are attempting to create elements with atomic numbers as high as 118 in laboratories in the hope of testing these theoretical predictions.

The existence of islands of stability implies that nucleons may not be randomly packed in the nucleus; they may exist in some definite arrangements. That certain electron configurations tend to be more stable than others lends support to this

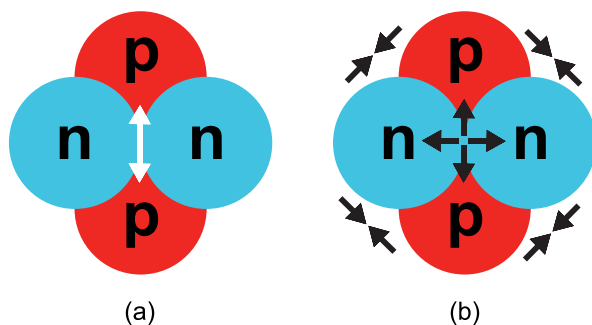


Fig. 3. The stability of an atom is determined by two opposing forces in the nucleus of an atom. (a) An electric repulsion pushes the protons in a nucleus apart. (b) An attractive strong force between the protons and neutrons holds the nucleus together.

Credits: Adapted from Matt Strassler, What Holds Nuclei Together? Of Particular Significance, March 4, 2013. URL: <https://profmattstrassler.com/articles-and-posts/particle-physics-basics/the-structure-of-matter/the-nuclei-of-atoms-at-the-heart-of-matter/what-holds-nuclei-together/>. License: CC-BY-NC.

idea (refer Box 2). This has led to the hypothesis that certain arrangements of nucleons may contribute to the unexpected degree of stability that some elements exhibit. While several models of nuclear arrangement have been proposed, attempts to express the supposed magical atomic numbers in some kind of mathematical formula are yet to succeed.

Some interesting observations

There have been other attempts to explain the stability of atoms. For example, it has been observed that elements with even atomic numbers (2, 22, 76 etc.) show greater stability and have more stable isotopes than those with odd atomic numbers (refer Table 1).

Number of stable isotopes of elements with even atomic number	170
Number of stable isotopes of elements with odd atomic number	63

Table 1. Elements with even atomic numbers have a larger number of stable isotopes.

Analysis shows that the stability of these isotopes may also depend on the number of neutrons (refer Table 2). An atom seems to achieve maximum stability when it has even numbers of protons as well as neutrons. If

either of these numbers is odd, it compromises the stability of the atom. While the calculations that explain these patterns are quite complicated, scientists have used them to speculate that an element with an atomic number of 114 would be relatively stable. On synthesis, this element did indeed turn out to be relatively (to its atomic number) 'stable'.

Number of protons	Number of neutrons	Number of stable isotopes
Even	Even	163
Even	Odd	53
Odd	Even	50

Table 2. Elements where both protons and neutrons are even-numbered tend to have a larger number of stable isotopes.

To conclude

While the synthesis of super-heavy elements may seem pointless from a

utilitarian view of science, it helps refine our understanding of factors responsible for stability. It may be pertinent to note that often, we tend to measure the stability of an element in terms of its ability to survive for years, decades or even centuries. Element 114 is not stable with respect to such time scales. It is not even as stable as predicted and, therefore, not a hypothetical island of stability (refer Table 3). However, given that most elements break down the instant they are created, element 114 is stable in the sense that it survived long enough for us to know that it exists. Its synthesis has strengthened our quest to answer questions like – do islands of stability really exist? Are there any limits to the periodic table? The next stability island is predicted to occur at an atomic number of 126. Can this element be created in laboratory? Will its synthesis bring us any closer to these answers? We'll have to wait and see.

Name	Symbol	Atomic number	Most stable isotope	Half-life of its most stable isotope
Nihonium	Nh	113	²⁸⁶ Nh	9.5 s
Fleovrium	Fl	114	²⁸⁹ Fl	1.9 s
Moscovium	Mc	115	²⁹⁰ Mc	650 ms
Livermorium	Lv	116	²⁹³ Lv	57 ms
Tennessine	Ts	117	²⁹⁴ Ts	51 ms
Oganesson	Og	118	²⁹⁴ Og	0.69 ms

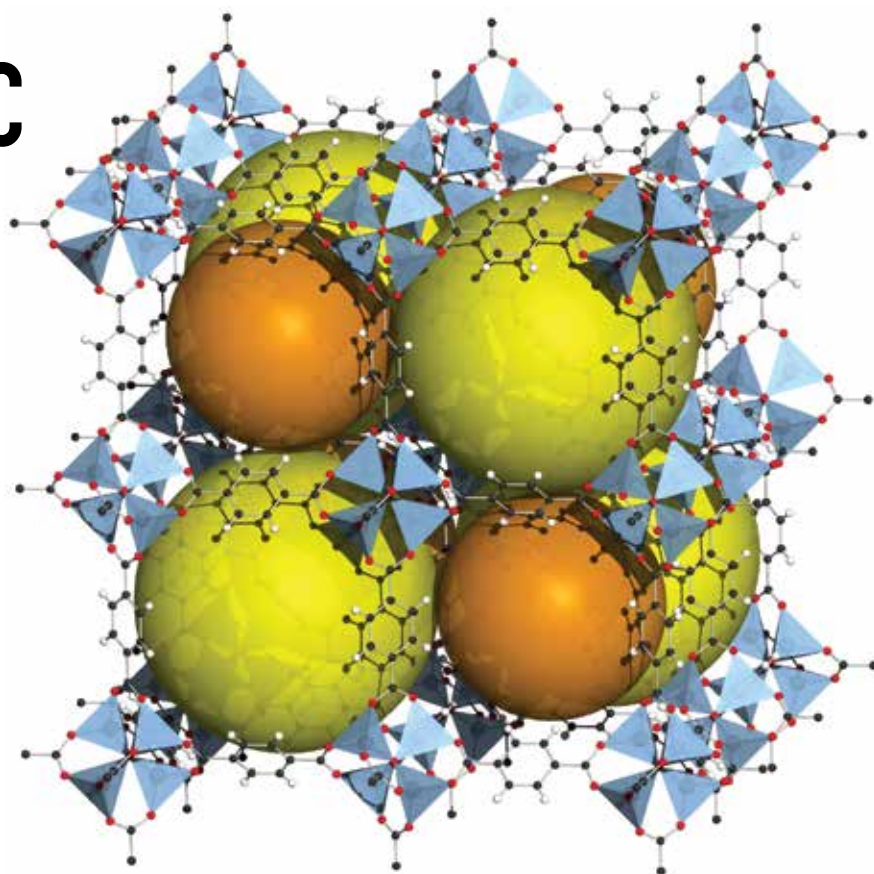
Table 3. The relative stability of some newly synthesized elements.

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METAL-ORGANIC FRAMEWORKS: THE NEW ALL-ROUNDERS IN CHEMISTRY RESEARCH

JOEL CORNELIO



Metal-Organic Frameworks (MOFs) are a newly developed class of materials that allow us to store vast amounts of gases at low pressures in small volumes. Why do these materials matter? How do we use them? This article explores advances in our understanding of MOFs.

In April 2017, collaborators from the University of California, Berkeley and the Massachusetts Institute of Technology (MIT) reported the successful design of the prototype of a device that used sunlight to harvest moisture from the air¹. Listed as one of the year's top ten emerging technologies by the World Economic Forum², this prototype is just one of many applications of a new class of designer crystals (materials with pre-determined structures and properties) called metal-organic frameworks (MOFs).

What are MOFs?

The International Union of Pure and Applied Chemistry (IUPAC) defines Metal-Organic Frameworks (MOFs) as 'coordination networks with organic ligands containing potential voids'³. Simply put, MOFs are a class of crystalline compounds with exceptionally large pores that can bind molecules or ions of different shapes and sizes. First predicted by the chemists Bernard Hoskins and Richard Robson in 1990^{4,5}, the term 'metal-organic framework' was coined in 1995 by Omar Yaghi, a Jordanian-American chemist

working at the University of Michigan, USA. In 1999, two groups headed by Ian Williams and Omar Yaghi, working independent of each other, reported the synthesis of the first MOFs — called HKUST-1 and MOF-5 respectively^{4,6}.

To make a MOF, you need a metal salt and an organic compound (ligand) capable of forming multiple covalent bonds with the metal ion. The relative arrangement of the ligand and metal ion can generate structures that are porous and highly crystalline. For example, MOF-5 is synthesized (refer Fig. 1) by combining zinc nitrate (metal salt) with 1, 4-benzenedicarboxylic acid

Box 1. Adsorption: refers to the capacity of external or internal surfaces of solids to attract and bind ions or molecules of gases, liquids or dissolved solids they are in contact with. Solids with this capacity are called adsorbents, and the gases or solutions they bind are called adsorbates. When a gas or fluid is adsorbed, it does not permeate the solid (as it would if it were absorbed) — it accumulates as a film on the surface of the solid.

(terephthalic acid). As long as a linker can form multiple coordinate bonds, a MOF can be made using it. Thousands of new MOFs have been synthesised in this way in the last decade. The most famous among them are HKUST-1, a copper MOF developed by Hong Kong University of Science and Technology; **UiO-66**, a zirconium based MOF from University of Oslo, Norway; **MIL-101**, a chromium MOF reported by Institute Lavoisier, France; and the zinc-based MOFs **ZIF-8** and **MOF-74** developed by Omar Yaghi⁷. Unlike the water-sensitive MOF-5, most modern MOFs remain quite stable on exposure to air, water and many common solvents. However, they can be destroyed by exposure to acids or bases (with some exceptions), and at temperatures high enough to burn their organic ligands to CO₂ and water.

Applications of MOF's

(a) Gas Sorption

MOFs are known for their high capacity to trap gases. Gas molecules are held together by weak intermolecular forces. Consequently, packing large amounts of gas into small volumes is possible only under conditions of high pressure – an energy-intensive requirement. Using MOFs allows us to bypass this requirement – like activated charcoal, MOFs bind gas molecules through adsorption (refer Box 1). Unlike activated charcoal, MOFs offer variety – a wide range of them can be synthesised using different elements and methods.

A MOF's ability to trap gases stems from its high surface area, ranging from 2500-5000 m²/g of mass. Some MOFs, such as NU-109E, have surface areas as high as 7000 m²/g. To give an analogy, a gram of NU-109E would have the size of a sugar crystal but an internal surface area equal to that of 27 tennis courts⁸! Since every bit of its internal surface area can adsorb gas molecules, MOFs can be used to pack large amounts of gas into a small volume. Each MOF can be reused multiple times, with slight heating or application of a vacuum to remove (desorb) trapped gases.

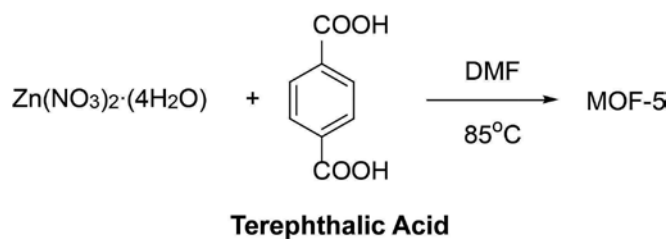


Fig. 1a. How to make MOF-5.

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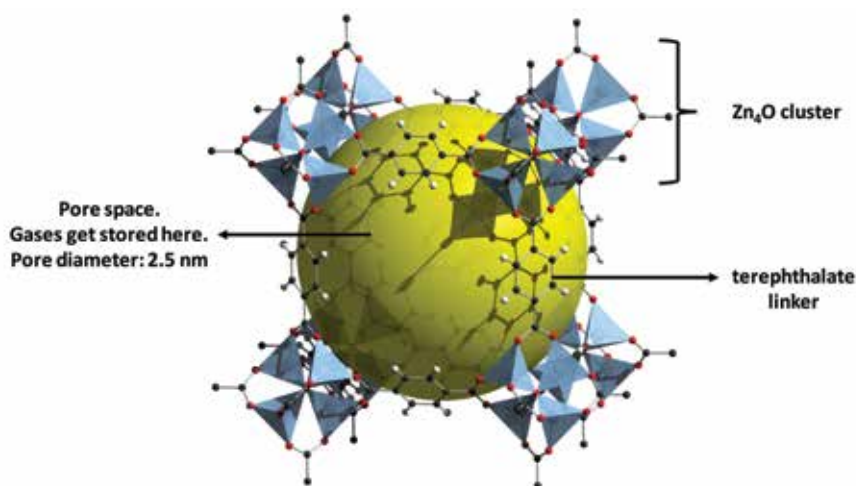


Fig. 1b. The structure of MOF-5. Notice that all the zinc atoms (represented by blue tetrahedra) are attached to a central oxygen atom (in red) to form a Zn₄O cluster, derived from zinc nitrate. The Zn atoms are also attached to oxygen atoms in terephthalic acid. Each molecule of terephthalic acid links a couple of Zn₄O clusters, forming a pore (represented by the yellow sphere) where gases are trapped.

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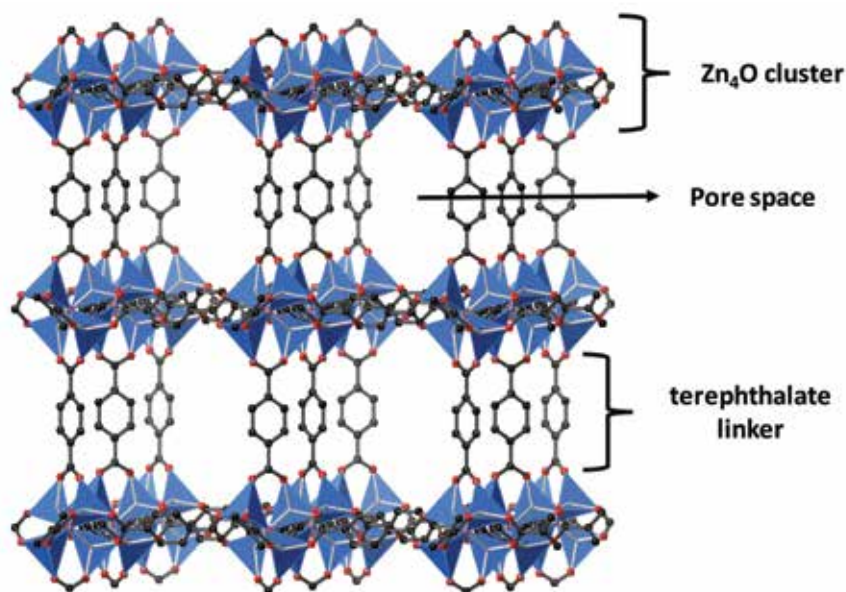


Fig. 1c. The extended crystal structure of MOF-5.

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Box 2. Catalysis: refers to the process of accelerating a chemical reaction using a catalyst. It is of two broad kinds, called homogenous and heterogeneous catalysis. In homogenous catalysis, the reactants and the catalyst are dissolved in the same solvent. Thus, once the reaction is complete, additional chemicals and energy need to be invested in separating the catalyst from the reaction mixture. Since heterogeneous catalysis uses insoluble, high surface area materials to catalyse reactions, the catalyst is separated from the reaction mixture by simple filtration. Consequently, most industries prefer using heterogeneous catalysts for chemical synthesis. Examples include the use of vanadium pentoxide with platinum (for sulfuric acid production) or finely powdered iron (in Haber's process for ammonia production).

The ability of MOFs to adsorb gases has found many interesting applications. One example of this comes from the automobile industry. The German chemical company BASF (Badische Anilin und Soda Fabrik) has developed MOF-containing cylinders to store CNG (Compressed Natural Gas) in vehicles like the truck model Ford F-550⁹. Since MOFs increase the amount of CNG stored to twice or thrice that of a conventional cylinder, they reduce the frequency at which the cylinder needs to be refilled. While this is seen as a significant advantage, MOF-containing vehicles are yet to be made available on

sale. The sudden drop in international crude oil prices in 2014 has made CNG much cheaper and reduced the economic incentive to commercialise such vehicles¹⁰. In another example, companies such as NuMat Technologies have developed MOF-containing cylinders (called ION-X7) to store toxic gases such as arsine (AsH_3), phosphine (PH_3) or boron trifluoride (BF_3). While these gases have important applications in the semiconductor industry, they are highly toxic and can cause severe damage when inhaled. MOF-containing cylinders can store these gases at sub-atmospheric (below atmospheric)

pressures. Given that gases flow from areas of high pressure to lower pressure, this decreases the chances of their leakage, even from improperly sealed cylinders¹⁰.

(b) Catalysis

Gas sorption is not the only feature typical of MOFs – their high surface areas make them ideal for catalysis (refer Box 2) of chemical reactions.

MOF-based catalysis can involve one of three strategies. In the first strategy, metal nanoparticles are adsorbed onto the pores of MOFs. Reactants diffusing into the MOF pore interact with the adsorbed nanoparticles achieving catalysis (refer Fig. 2a). This is used for the hydrogenation of alkenes and the synthesis of epoxides, hydrogen

Box 3. Aldol reaction: involves the combination of two carbonyl compounds (compounds containing a carbon-oxygen double bond) to form a product called an aldol.

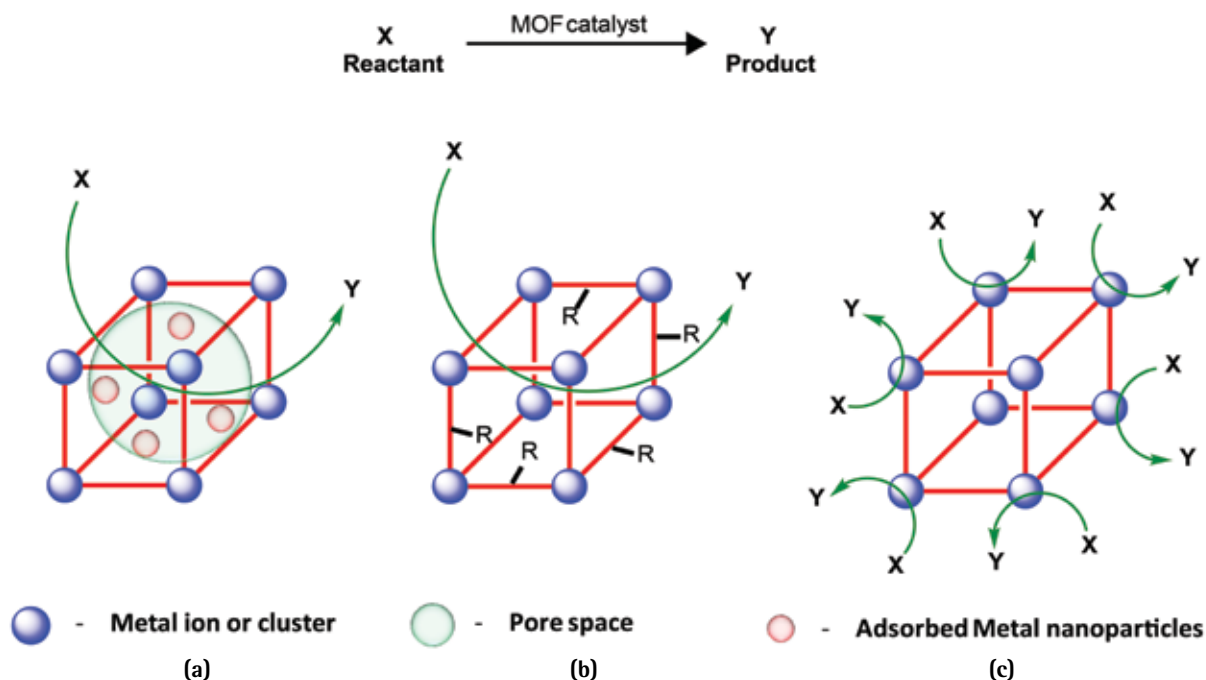


Fig. 2. Strategies for achieving MOF-based catalysis. X and Y represent reactant and product respectively. MOFs are represented as cubes. Organic linkers are represented by red lines which form the sides of the cube, and the blue spheres are the metal ions or clusters. (a) Using the MOF pore space as a catalyst support for metal nanoparticles. (b) Functionalising the organic linkers with catalytic groups (represented by R). (c) Using the metal ion or cluster for catalysis.

Credits: Joel Cornelio. License: CC-BY.

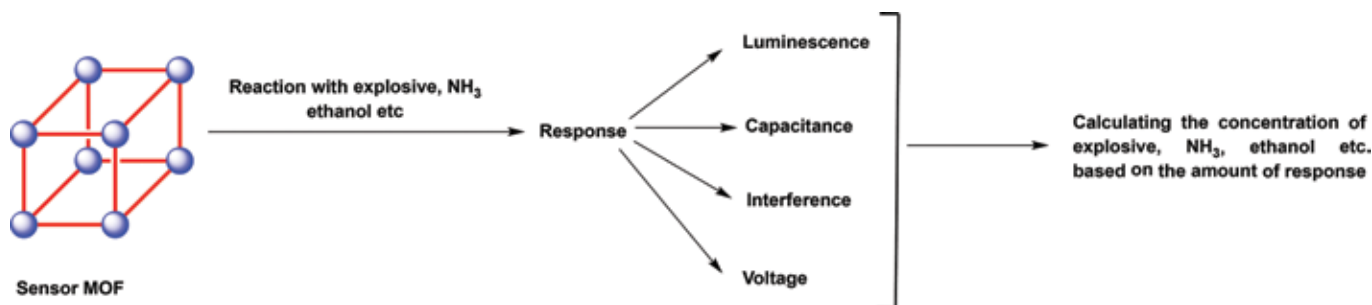


Fig. 3. A general scheme for using a MOF as a chemical sensor.

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Box 4. Michael addition: occurs when a C-C unsaturated carbonyl compound reacts with a nucleophile (a compound that can donate a pair of electrons). The C-C unsaturation should occur between the carbon atoms next to the carbonyl carbon.

peroxide and methanol (refer Fig. 2b). In another strategy, functional groups with catalytic activity (such as guanidine, phenylalanine, proline, imidazole etc.) are linked to the organic ligands of MOFs. Such MOFs can be used to catalyse some fundamental organic transformations such as Aldol reactions (refer Box 3), Michael additions (refer Box 4) etc. In a third strategy, catalysis occurs at the metal clusters of the MOFs (refer Fig. 2c). For example, titanium-based MOFs have been used to catalyse the famous Zeigler-Natta reaction (polymerisation of ethylene to polyethylene). MOFs containing metal clusters of noble metals (such as rhodium, platinum, ruthenium or palladium) have proven to be effective catalysts for hydrogenation reactions. Ongoing research is aimed at making more efficient and more stable MOFs, capable of catalysing more than one kind of reaction¹¹.

(c) Luminescence

MOFs can be made luminescent (refer Box 5) if luminescent materials like lanthanide elements (e.g. europium, dysprosium etc.) or organic compounds (e.g. porphyrins, dyes) are used to make them^{12,13}. MOFs offer the advantage of

Box 5. Luminescence: is the emission of light by a substance when any form of energy (other than heat) is applied to it. This energy can be in the form of incident photons (photoluminescence), mechanical forces (mechanoluminescence), electricity (electroluminescence), or sound (sonoluminescence). A luminescent substance absorbs this energy and emits light of lower energy. Examples of such substances include glow sticks, 'glow in the dark' watch dials, road signs etc.

being able to achieve luminescence in any desired colour. For example, the ability of MOFs to generate pure white light has important applications in the lighting industry¹⁴.

(d) Chemical Sensors

The most common class of MOF sensors (refer Box 6) are based on their ability to produce measurable changes in luminescence. For example, MOFs with tetraphenylene linkers or lanthanides have been used to sense explosives and heavy metal ions. A change in luminescence is caused by the formation of hydrogen bonds between the nitro (NO₂) groups in explosives and linkers in MOFs. Another class of MOF sensors are based on their ability to cause changes in capacitance. Some of these, for example, have been reported to sense ammonia at concentrations as low as 25 ppb (parts per billion)¹⁵. A third class of MOF sensors are used to detect measurable changes in the interference

Box 6. Chemical sensors: are molecules which react with other molecules to produce a measurable change in voltage, capacitance, luminescence or other physical attributes. They find applications in a variety of devices including glucose meters (for measuring blood glucose levels) and breath-analysers (for measuring alcohol in breath).

of ethanol, propane, and water (refer Fig. 3)¹⁶.

Current research on using MOFs as chemical sensors is aimed at making simpler devices with higher specificity. Synthesizing MOFs which respond to only one specific analyte has proven to be particularly difficult and is an active area of research.

To conclude

The field of MOF chemistry has expanded considerably in the last two decades. Beginning from the first few MOFs to be synthesised in 1999, today structures of at least 6000 new MOFs are published every year. Research has helped refine their use in a range of applications – from gas sorption and catalysis, to luminescence and chemical sensors. It has also opened up new applications – from the use of MOFs for the heating and cooling of buildings and the production of anti-microbial coatings for healthcare products, to the capture of moisture from air and carbon dioxide from power

plant emissions¹⁰. These advancements have fuelled the synthesis of the next generation of porous materials – called COFs (Covalent Organic Frameworks¹⁷) and HUMs (Hybrid Ultramicroporous

Materials¹⁸). The biggest challenge that MOFs face today is their high production costs due to the special methods and skills required for the production of organic linkers. With the

first few MOF-based products hitting open markets in 2016¹⁰, there is hope that this may not remain a challenge for much longer.



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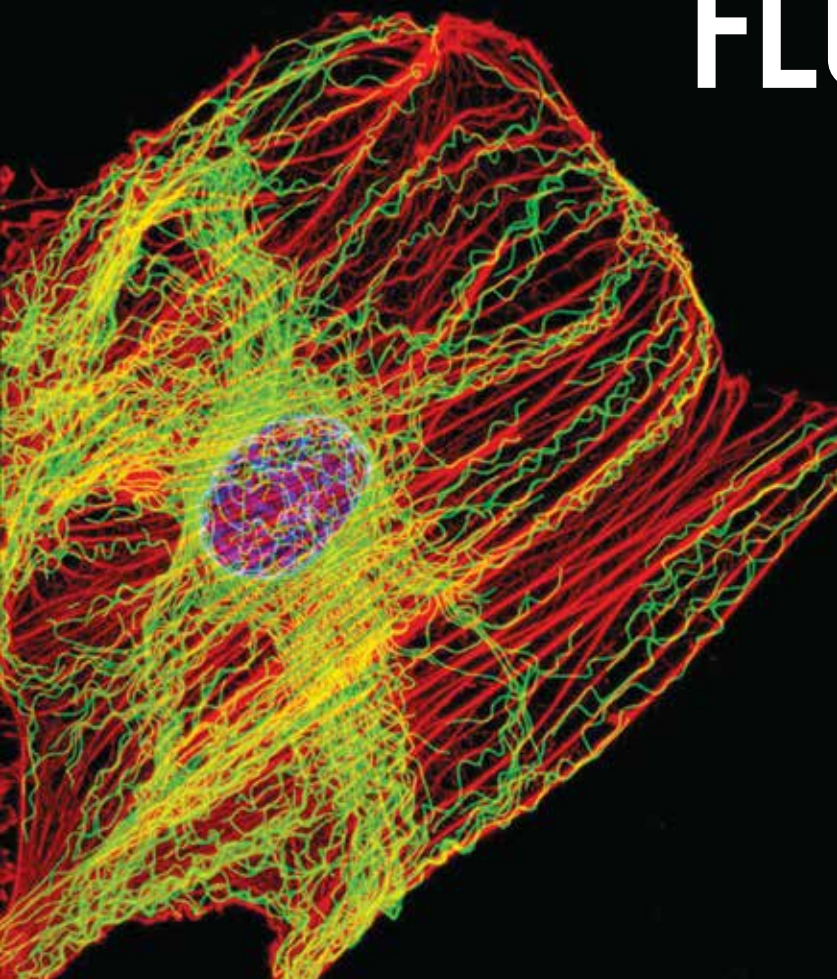
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FLUORESCENT TAGS: INDISPENSABLE TOOLS IN MEDICINE

NEERAJA DASHAPUTRE



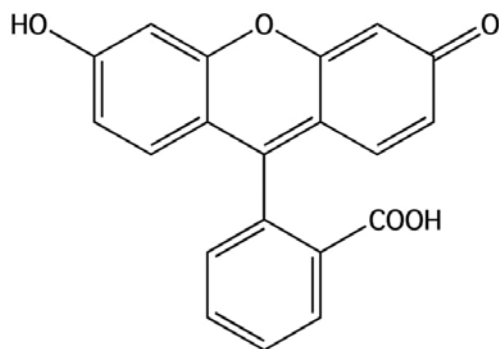
The use of fluorescent tags in imaging and disease detection has been part of many important scientific discoveries. What is fluorescence? How was it discovered? How are fluorescent molecules used to detect disease?

In the year 2008, the Nobel Prize in Chemistry was jointly awarded to Osamu Shimomura, Martin Chalfie, and Roger Tsien for discovering and using a fluorescent jellyfish protein to study the inner workings of a cell. In their announcement, the Nobel Foundation emphasized the role these contributions had played in making it possible to “*watch processes that were previously invisible, such as the development of nerve cells in the brain or how cancer cells spread*”¹. In doing so, it acknowledged the rapid strides that the discovery of fluorescent molecules and their applications as tags have precipitated in other fields, particularly biology and medicine.

What are Fluorescent Tags?

Fluorescence refers to a physical phenomenon where certain materials emit light when (and as long as) they are exposed to electromagnetic (visible, ultraviolet etc.) radiations. This process involves three stages. Fluorescent materials have certain molecules (usually aromatic) called fluorophores that absorb photons (or energy) from the radiation. Consequently, electrons in these fluorophores jump to a higher and more unstable energy state. Unable to remain there for longer than a few nanoseconds, the electrons fall back to lower and more stable energy states by releasing some of the excess energy into the environment as light. As a result, such objects look like they are glowing from within.

Fig. 1. Fluorescein.



(a) Structure.

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(b) A red dye in powder form.

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(c) The bright green glow of fluorescein dissolved in water, as seen under UV light.

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The earliest description of fluorescence dates back to 1565, when the Spanish physician and botanist Nicolas Monardes observed the bright blue glow that the bark of *Lignum nephriticum* (Mexican Kidneywood) showed in water. This glow came from the fluorophore matlaline, naturally produced by the oxidation of flavonoids in the tree bark. The fact that synthetic materials could also exhibit fluorescence was first demonstrated by Adolf Von Bayer, a German chemist, in 1871. Bayer produced a red dye, called Fluorescein, that became bright green when diluted with water (refer Fig. 1). An investigation into Fluorescein's structure showed a network of alternating single and double bonds, known as conjugation. Chemists have, today, used this knowledge to synthesize a library of conjugated fluorescent dye molecules that display a wide spectrum of colors.

One of the most famous uses of Fluorescein was discovered during the Second World War. German pilots were instructed to open vials of Fluorescein from their emergency kits to indicate their locations when they were shot down into the ocean. On being diluted, Fluorescein would

produce a bright patch of fluorescent green in the surrounding waters that could be detected by air sea rescue operations over long distances. This ability of some fluorescent materials to act as 'tags' has found extensive applications. For example, apart from being used in sea rescue operations even today, Fluorescein is also used in detecting oil and water leakages. But, more importantly, both natural and synthetic fluorescent materials have found extensive applications in science as fluorescent tags, probes or labels. These tags can be chemically or enzymatically attached to biomolecules like amino acids, proteins, antibodies or nucleic acids. When exposed to certain wavelengths of light, the tags fluoresce revealing the presence, location and patterns of the linked biomolecules in cells, tissues or organs (refer Fig. 2).

A key breakthrough in fluorescence imaging involved the discovery of naturally occurring fluorescent proteins in 1962. Osamu Shimomura, a Japanese organic chemist and marine biologist, was studying the blue-green glow of a jellyfish species *Aequorea victoria*. While isolating a bioluminescent protein (capable of

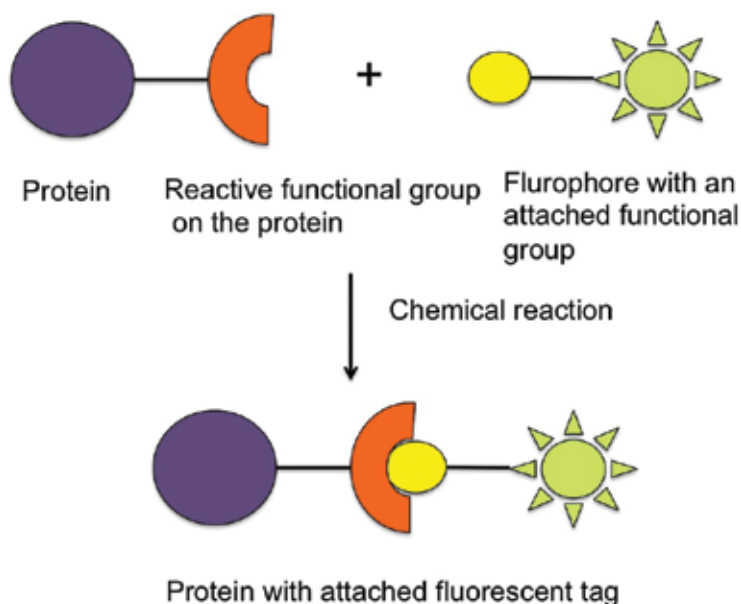


Fig. 2. A schematic showing the synthesis of a fluorescently tagged protein.

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producing light by absorbing energy from a chemical reaction) from the jellyfish, Shimomura stumbled upon the discovery of another protein that seemed to be bound to it. He named the bioluminescent protein Aequorin after the genus of jellyfish it was isolated from; and the other one **Green Fluorescent Protein (GFP)** for its bright green fluorescence under UV light. Further analysis showed that the jellyfish's greenish-blue fluorescence was produced by Aequorin and GFP together – Aequorin produces blue light by bioluminescence and GFP absorbs this blue light to produce green fluorescence. Being a natural fluorophore, produced by a sequence of amino acids, GFP is much easier to incorporate in cells than synthetic fluorophores. However, the tediousness of extracting pure forms of this protein from jellyfish limited its applications till Douglas Prasher, an American molecular biologist, was successful in cloning the GFP gene in 1992. This opened up immense possibilities – GFP could now be attached as a tag to proteins or cell organelles, or coded into the genome of the cell and expressed on demand. Martin Chalfie, an American neurobiologist, was the first to report this potential in 1994 through his results from a series of experiments on identifying specific neural circuits in the roundworm *Caenorhabditis elegans*. For example, in one of his first experiments, Chalfie used Prasher's clone to color and track six individual cells in the transparent body of the worm. In 1994, Roger Tsien, a Chinese-American biochemist, identified the chemical basis of GFP's fluorescence. Based on this understanding, he and his collaborators created a range of genetic and structural variants of GFP to intensify its natural fluorescence and expand its colour palette (to, for example, pink, yellow, red and blue fluorescence). Today, GFP and its derivatives are routinely used for imaging and have played a key role in many scientific discoveries (refer Fig. 3).

Applications of fluorescent tags

(a) In research: How does a cell function? How do different organelles in a cell communicate with each other? How does a cell respond to an attack by a pathogen? These are just some

of the questions that have always puzzled scientists. Although cells can be visualized under a microscope, understanding submicroscopic molecular interactions and cellular processes in real-time is not possible by microscopy alone. This is where fluorescent tags play a significant role.

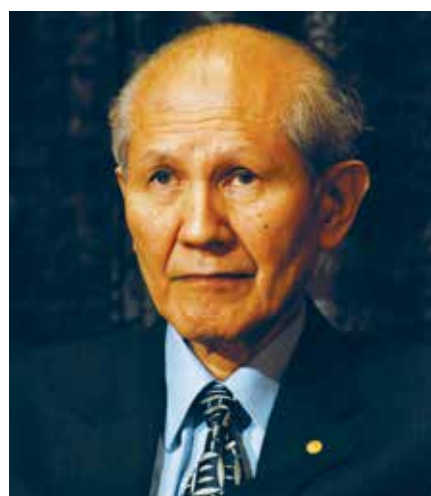
Fig. 3. Green Fluorescent Protein.



(a) The jellyfish *Aequorea victoria* exhibiting blue light using bioluminescence.

Credits: Mnolf, Wikimedia Commons.

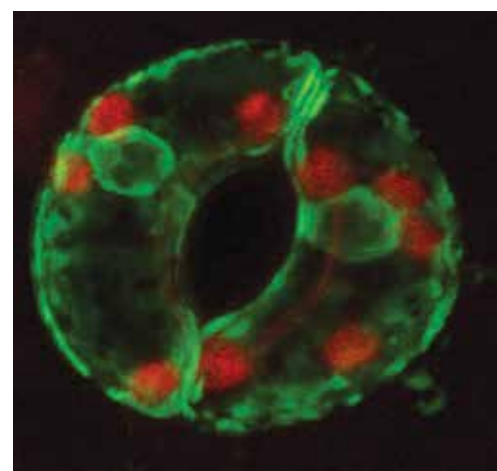
URL: <https://commons.wikimedia.org/w/index.php?curid=727670>. License: CC BY-SA.



(b) Osamu Shimomura.

Credits: Prolineserver, Wikimedia Commons.

URL: https://commons.wikimedia.org/wiki/File:Osamu_Shimomura-press_conference_Dec_06th,_2008-2.jpg. License: CC-BY-SA.



(c) A fluorescence microscopy image showing tubulins, mitochondria and the nucleus of a cell bound to fluorescent proteins.

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The presence and interactions of a biomolecule of interest can be studied by fluorescence tagging it through the formation of a covalent bond with a fluorophore (fluorescent core of the dye). For example, a chemically modified fluorophore can be linked to the functional group (like amines, hydroxyl and thiols) of an amino acid or protein of interest (refer Fig. 4). Similarly, Ethidium Bromide (EtBr) can intercalate (stacks along the hydrogen bonds) with DNA molecules to produce a bright orange glow under UV light. Thus, specific cellular processes can be

visualized in real-time by selectively tagging the specific biomolecules involved in them. For example, when attached to the genome of a virus, GFP can be used to track the pathogen's movement inside a cell. These robust and easy-to-monitor methods are widely applicable to a large range of fluorophores.

(b) In diagnosis: Diagnostic methods in the field of pathology help doctors and medical care specialists confirm if a patient suffers from a particular infection. Historically, the detection of disease has been a time-intensive

process, taking anywhere between a couple of days to a few weeks. This process involves the isolation of infected samples from the patient, culturing cells from the infected sample outside the body, and confirming the presence and nature of the pathogen. Speed and precision in diagnostic assays can, however, play a significant role in determining the efficacy of treatment.

More rapid diagnostic assays used today are designed to identify specific antibody-antigen interactions. On exposure to a pathogen, specific cells (called B lymphocytes) in our body

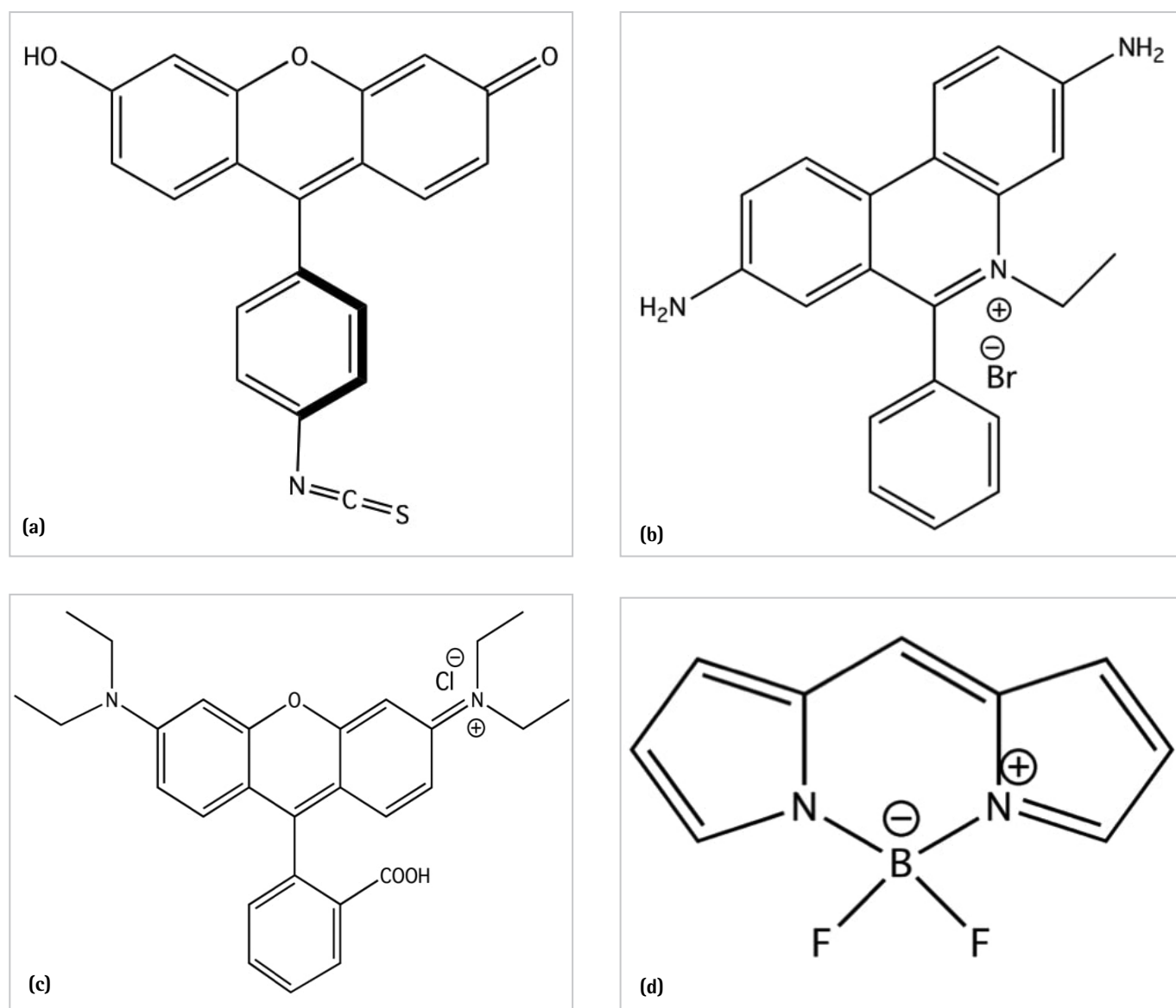


Fig. 4. The various fluorophores commonly used as protein tags. (a) Fluorescein isothiocyanate. (b) Ethidium bromide. (c) Rhodamine dyes. (d) BODIPY dyes.

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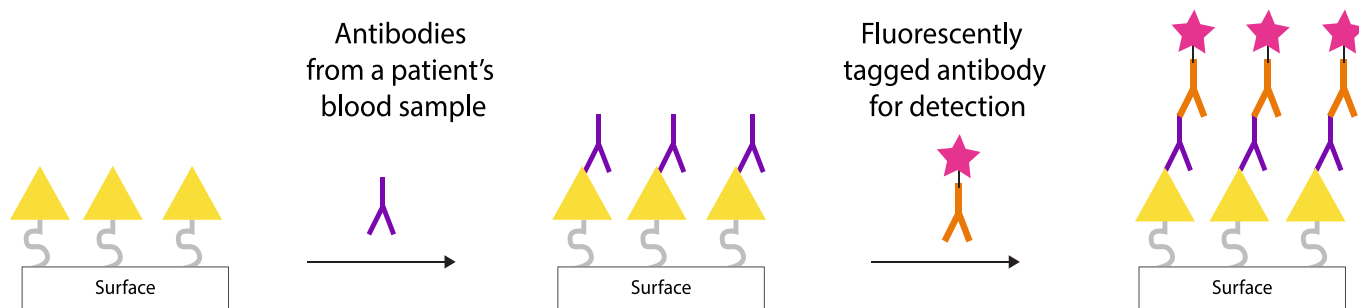


Fig. 5. Schematic of an antibody-antigen assay to detect presence of antibodies

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produce special Y-shaped proteins (called antibodies) that can bind to specific molecules (called antigens) like proteins, polysaccharides or lipids on the surface of the pathogen. The synthesis and binding of antibodies to antigens is rapid and specific.

To develop a diagnostic test, antibodies or antigens specific to a pathogen are either isolated and/or synthesized. Antibodies specific to a pathogen are immobilized/adsorbed on a solid support to which a patient's blood or serum sample is added. If the patient is infected with the pathogen, the antigens present in her blood sample bind to the antibody attached to the surface. The solid support is washed to remove any free, unbound antigen. Then, a second antibody tagged with

a fluorescence marker and capable of recognizing the bound antigen is added. Special instruments are used to detect and measure the presence and intensity of fluorescence, allowing us to determine the presence and quantity of pathogen in a patient's sample. This 'sandwich' immunosorbent assay is far more rapid than conventional tests. In some cases, a viral infection is detected by adsorbing antigens unique to the pathogen onto a solid surface. These bind the antibodies specific to the blood sample of an infected person. After the unbound antibody is washed off the support, a second fluorescently tagged antibody that recognizes the bound antibody is used to detect the presence of the pathogen (refer Fig. 5).

To conclude

Through its many applications in diagnostics and medicine, fluorescence tagging has made immense contributions to health care. Fluorescent tags have shed light on many biological processes and enabled the study of functions of various proteins. Immunosorbent assays that use fluorescent tags offer many advantages over solution-based detection tests as they require less sample volume, are more accurate and less time-intensive. However, the vast potential of fluorescence tagging is yet to be explored fully and is likely to prove to be an indispensable tool in the future.

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Neeraja Dashaputre is an Assistant Professor of Chemistry at the Indian Institute of Science Education and Research (IISER), Pune. She has been teaching for the last eight years and has participated in many chemistry demonstration shows. Neeraja loves to interact with students and help them learn chemistry by designing newer methods of instruction.



INTERVIEW

WITH VENA KAPOOR

Vena Kapoor works with the Nature Conservation Foundation (NCF), Bangalore on nature education, outreach and public engagement. She is fascinated by the natural world and enjoys sharing this passion and wonderment with children and young adults. She has a soft corner for spiders – taking unsuspecting people for spider walks whenever possible.

Your current role

As a member of the Education and Public Engagement Programme Team at NCF, a large part of my work focuses on nature education, research and outreach. We help children and young adults develop an interest in and excitement for the natural world by designing nature- and wildlife-related educational resources and collaborative projects with educators. We also use a variety of citizen science initiatives to encourage people from different walks of life to collect scientific data on biodiversity. In addition, I work with colleagues across different organisations on certain aspects of conservation research and practice, and help organise conservation-related student conferences, workshops and outreach programmes. As a member of the executive board of NCF, I help in decision-making, planning and execution of long-term processes in the organisation.

A typical day at work

There are no typical days. Each day is different. On most days, I read, write, research or brainstorm with my colleagues on various aspects of our programmes. We travel on some days – meeting potential collaborators, educators and colleagues. On a slow day, you might see us bird- or tree-watching from our office balcony. This is often accompanied by animated discussions about our observations!

Rewards of your profession

The opportunity to observe, record, and understand the natural world – the incredibly diverse life forms that inhabit our backyards, forests and beyond. In spite of having worked in this field for many years, many aspects of the natural world continue to fill me with wonder and awe.

Also, the fact that I can afford to stare out of the window and observe the

drama of nature unfolding before us – indeed, this is very much a part of my job! Luckily, my office is in an area that still has some open spaces and lots of trees. I am, in fact, listening to the calls of at least three bird species as I am responding to these questions!

Important ethical aspects of your profession

I think of animal and human welfare as being equal and therefore an important ethical aspect of the work I do. Of course, the specific forms that these considerations take is often influenced by personal choice. For example, describing species taxonomically has traditionally required the collection of specimens. My discomfort with this requirement meant a conscious decision to avoid pursuing a career in taxonomy. Luckily, today, we have developed a variety of taxonomic tools that allow us to move beyond this requirement. Sometimes ethical considerations can be shaped by the collaborators and the institutions we work with. For example, all research projects at NCF go through a rigorous review process by an ethics

committee that includes some members from outside the organization.

Early experiences that shaped an interest in science

I was lucky to have a school with open spaces and many large mature trees; and a house with a garden and many plants. It also helped to have supportive parents and friends. For example, my parents did not discourage my fascination for snakes, even though they did not understand it. I, in fact, managed to sneak quite a few creatures into the house, including a rescued snake or two! But, I wish that our school library had been better-stocked. We had only a few books on animals, which I would grab as soon as I could. I still remember my excitement at finding a copy of Joy Adamson's 'Born Free' there. I was in Class VII, and completely besotted with this famous book's description of life in the wild – replaying details of its people, lions and the African landscape endlessly in my head. I also have a clear memory of the amusement on my

teacher's face when I asked to borrow the book a second time.

Decision to become a scientist

I've been in love with plants and animals for as long as I can remember. As a teenager, I would pore over every issue of a BBC Wildlife magazine sent over by a family friend. I would also watch countless episodes of Jacques-Cousteau's programme on marine and underwater life on Doordarshan. But, having never met a wildlife biologist or conservationist in real life, I did not think that it was possible to build a career in this field, especially in India. So, for the longest time, my fascination for wildlife remained limited to my interest in the books, magazines and documentaries I could get hold of. Then, one day, I spotted an advertisement by a Bangalore-based organization seeking volunteers interested in spreading awareness about wildlife and conservation. This was a turning point in my life. I was enrolled in an undergraduate programme in Commerce, but spent summer breaks



Fig. 1. A large part of my work focuses on nature education.

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volunteering with this organisation. A large part of my work involved interactions with children and teenagers through nature camps, talks and demonstrations at schools and colleges. For example, one live demonstration was aimed at showing children the difference between poisonous and non-poisonous snakes, and debunking some of the myths surrounding them. It was through these nature camps that I got my first real exposure to the outdoors. As my interactions with other people with similar interests increased, so did my exposure to Indian wildlife and conservation as a profession. It was around this time that I discovered the worlds and lives of Gerald Durrell, Jane Goodall, and Salim Ali through their extraordinary books. Reading their radical (and often humorous) conservation stories and descriptions of their fascinating adventures cemented my determination to pursue

wildlife conservation and ecology as a profession.

Choosing current area of work

I think life's come full circle! I started my journey in this field by taking kids out on nature camps. My research on spiders was, in large, encouraged by Dr. Vijayalakshmi and A.V Balasubramanian of the Centre for Indian Knowledge Systems in Chennai, who I worked with in my first job after undergraduation. The literature and image documentation on spiders that they had collected opened up a whole new world for me. Also, they encouraged me to spend time in the forests of the Western Ghats and meet wildlife researchers working there to get a sense of this field of work. This opportunity was my first experience and understanding of what it meant to do ecological research.

I went on to dabble with ecology and wildlife conservation research and practice for a few years. This included efforts to document urban wildlife, and help raise a nursery for rainforest seeds and saplings for a long-term rainforest restoration programme in the Western Ghats. For a while, I helped raise funds and manage the running of NCF. I also co-wrote a couple of children's books on nature. After a long hiatus from academics, a full scholarship from the The Ravi Sankaran Inlaks Foundation allowed me to pursue an MPhil in Conservation Leadership from the University of Cambridge, UK. The course helped me get on track with current conservation research and practice, and develop a wider understanding of the field. As part of my thesis, I did a short research project on how conservation organisations were using geographic co-location to improve their collaborative potential.

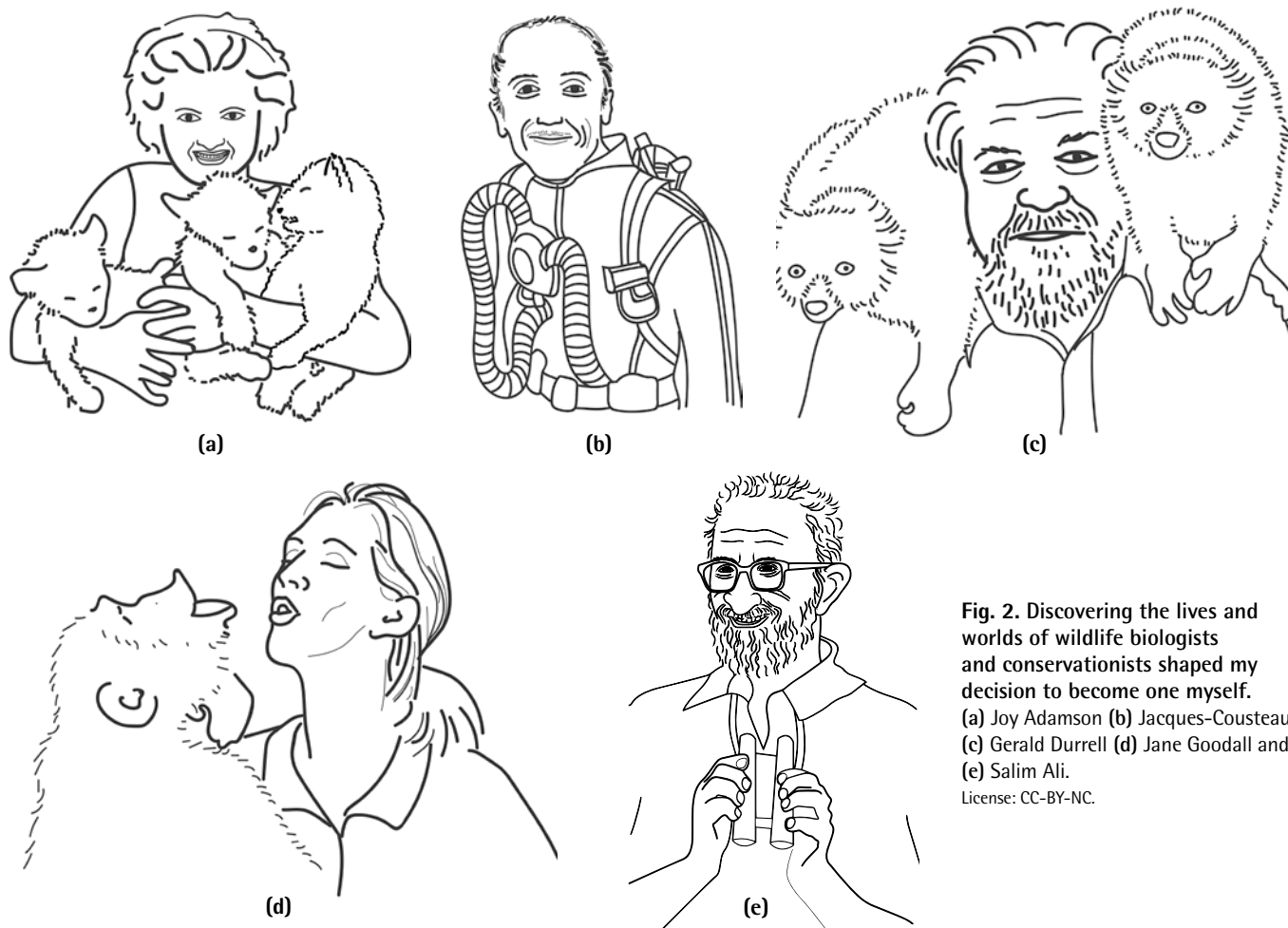


Fig. 2. Discovering the lives and worlds of wildlife biologists and conservationists shaped my decision to become one myself.
(a) Joy Adamson (b) Jacques-Cousteau (c) Gerald Durrell (d) Jane Goodall and (e) Salim Ali.
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Fig. 3. My first job involved research on spiders from the Western Ghats.

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

When I rejoined NCF, I was given the opportunity to engage with nature education and outreach full-time. I think that the multiple roles I've had the opportunity to work in during my career have helped me think out of the box and given me the ability to develop a variety of skill sets.

Misconceptions about 'being a scientist'

Often, the term 'scientist' conjures up images of a bespectacled person (usually a man!) in a white lab coat with beakers surrounding him. But, many scientists work outside lab-like settings. This is especially true in fields like ecology and conservation science, where our lab is the outdoors! This is where many of our observations and discoveries take

place. In some cases, however, biologists and ecologists may have to recreate situations and experiments in labs to mimic natural phenomena that are difficult or time-consuming to observe in the wild.

The other popular belief about scientists is that they have many educational degrees. While formal training in science is useful and important, I think an enquiry-based approach coupled with an aptitude for logical reasoning may be more essential to the practice of science.

Perspective on school science education

We need a complete overhaul of how science is perceived and taught in school. But, while we may have a long way to go to achieve this, I can see small and

positive changes in the way science is being taught in school classrooms today. These changes are largely the result of sustained efforts by many institutions and individuals pushing for a more hands-on and enquiry-based approach to science. For these changes to be more impactful, we need to get many more people on board — especially those involved in framing educational policy.

Suggestions for teachers to encourage an interest in science

Get children to read books other than their textbooks. Initiate classroom research around curriculum topics and point them to other resources they can use. Always encourage students to ask 'why' questions so they can reason

with themselves, their classmates and you. Encourage group discussions on problems and phenomena in science. Get students to play out stories based on their understanding of the subject. Engage with wider conversations on science education. One such conversation is that of fair representation of gender, race and class in textbooks and the teaching of science. For example, 'The Life of Science' platform by Aashima Dogra and Nandita Jayraj chronicles life stories of women scientists across the country.

The role of observation and wonder in science education

Encouraging curiosity, a sense of wonder, and a keenness to observe are necessary first steps for children to develop an interest in the natural world. Extensive research shows the

positive impacts of outdoor teaching on learning outcomes. Teachers could design classes that take these principles into consideration. They could also reach out to individuals or organizations in specific fields of science, like ecology and conservation, to help with this process.

The importance of engaging researchers in school science

This may seem radical, but I think it may be good for researchers, especially in the early stages of their career, to engage with some form of school science teaching. Such experiences, preferably facilitated by their institutions, may be very useful in also developing a researcher's ability to contextualise his/her understanding of science. Researchers can also help put together resources that school teachers may not have access to – especially

those related to the latest discoveries in their fields. It may also help to include at least some early- and mid-career researchers in government consultations for textbook content and teacher training programmes.

Environmental education in school science

School science should engage with environmental education. Governments and school boards have begun to recognize this need. In recent years, the lower-grade school curriculum has a mandatory Environmental Science (EVS) component.

While this is an important step in recognizing the necessity to sensitize children and young adults to environmental issues, many of us in the field believe that the way the EVS component is framed and delivered has made it a burdensome additional



Fig. 4. It is important to encourage children to develop a connection to nature.

Credits: Vena Kapoor. License: CC-BY-NC.

EARLY BIRD NATURE DETECTIVES BINGO

GO OUTDOORS AND FIND ANY FOUR DOWN OR ACROSS AND SAY BINGO!

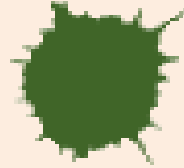
On the ground



Flying



Bird dropping



Two birds together



Bird with something
in its beak



Colourful bird



Feather



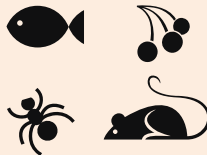
Bird with a long tail



Bird with long legs



Something a bird
could eat



Bird on a branch



Mostly black bird



Mostly white bird



On a wire or roof



Bird sound



Somewhere a bird
could hide



**nature
conservation
foundation**

*Produced as part of a not-for-profit initiative to
introduce children to birds and nature.*

Learn more about us at www.early-bird.in





Resources on ecology and nature from NCF that educators can use in the classroom and outside:

1. Themed outdoor activities on 'nature around us': www.edu.ncf-india.org.
2. Activities and games around common birds in India: <http://www.early-bird.in/resources/>.
3. Adopt a tree, observe and record their flowering and fruiting patterns when seasons change: <http://www.seasonwatch.in/>.
4. A series of articles on nature, written for children that can be read out in class, enacted or modified with alternate storylines: <http://ncf-india.org/projects/writing-about-nature-for-children>.

'subject'. Textbooks for EVS highlight issues like pollution, deforestation, and global warming that can leave students with a feeling of helplessness. We argue that this can be detrimental in getting children to engage with nature and the environment. Ideally, the curriculum should be designed to encourage young students to engage with their own immediate surroundings and to experience, be awed by and develop a connection to nature. And, ideally, it is only once the child begins to recognize this connection (usually in a higher class), should she be introduced to more complex perspectives and environmental issues.

Suggestions on teaching about nature and the environment

Try and keep interesting resources like field guides, magazines and natural history books on birds, butterflies, animals and insects of India in your classroom and school library. Some of us working in fields like ecology and conservation education have been creating content and modules that a teacher can directly use to help students feel connected to their immediate surroundings (refer detachable Activity Sheet — **Early Bird Nature Detectives Bingo**). Use and refine these resources in the context of your neighbourhood.

In our experience, keeping a bird attendance register in the school or classroom can be a big hit! Each day, encourage your students to tick off birds that they have observed in their school campus. Ask questions about their observations — what were the birds doing? Why do they look a particular way? How are they grouped? Get them to compare these observations across months and years. Why are they seen only in a particular time of the year? Display visuals of common birds, insects, trees and flowers that you can see on campus. This makes it easier for students to connect with nature in their immediate surroundings. There is a special thrill in being able to identify something you come across!

Remember, don't get daunted by the fact that you may not be able to identify or remember the scientific name of a bird, tree or insect. Encourage your students to observe the natural world, describe their observations in their own words, and preferably record these in a nature journal. Stress that it's not important to correctly name a species but to ask why and how they are classified and grouped.

STUDENTS AS TEACHERS:

HOW SCIENCE TEACHERS CAN COLLABORATE WITH THEIR STUDENTS USING PEER INSTRUCTION

KEVIN CLOSE, NICOLE BOWERS,
ROHIT MEHTA, PUNYA MISHRA &
J. BRYAN HENDERSON

This article explores peer instruction in the science classroom. The authors use research in science education to illustrate, practically, how teachers can work with their students to increase learning using peer instruction.

'Learning is least useful when it is private and hidden. It is most powerful when it becomes public and communal.'

— Lee Shulman

'The facts of science and, à fortiori, its laws are the artificial work of the scientist; science therefore can teach us nothing of the truth; it can only serve us as rule of action.' — Henri Poincaré

Teachers often forget that science is social and rhetorical in nature. Group consensus and peer review, not political discourse, define scientific facts. Therefore, scientific instruction should embrace the push-and-pull and back-and-forth of scientific dialogue and argumentation. When instructors speak of the scientific method in school, they focus on generating hypotheses and conducting experiments, but often fail to present the whole process as what it really is — a way of crafting a convincing argument. In other words,

science is a way of harnessing facts, logic, and evidence in order to convince others that a particular idea is likely to be correct.

With this in mind, we present a way to introduce meaningful scientific discussion in the classroom using the most valuable classroom resource — the students themselves. This technique, called **Peer Instruction**, wrests control from the teacher and gives it to students. According to a recent paper by Dr. Trisha Vickrey, a Professor of Chemistry at the Brevard College, North Carolina, United States, and four of her co-authors, it is one form of research-based instructional reform that has been widely adopted by instructors in science, technology, engineering, and math¹.

Peer Instruction allows students time to talk, debate, and teach each other during instruction. Students can serve as tutors, models, and sounding boards for their peers. In fact, research shows that much learning occurs during these

peer-to-peer interactions. According to John A.C. Hattie, a renowned professor of education, *"If you want to increase student academic achievement, give each student a friend."* Social interaction, he asserts, drives students to become their own teachers. It is this social interaction that Peer Instruction seeks to provoke.

Additionally, Peer Instruction replicates something that is fundamental in the scientific process — convincing others of the 'truth value' of one's approach. This is a process of argumentation — or systematically marshalling data and logic to explain one's point of view. This rhetorical turn is crucial, forcing students to not only come up with the right answer, but also to explain how and why and convince others of the same. A student with a different explanation would approach their partner's statements with a questioning attitude — and, also, an open-mindedness to being wrong. What is interesting is that such conversations do

not necessarily mean that the student with the right answer necessarily believes their own logic. A situation could arise where a student with an incorrect understanding manages to convince their partner (who may have had the right explanation) of its correctness. In fact, this situation may reveal weaknesses in the understanding of even those students who are able to come up with the right answer. Essentially, Peer Instruction stresses conceptual understanding and the logic of the argument, over merely getting the correct answer.

What does the research say?

Eric Mazur, a Professor of Physics at Harvard, was interested in the practice of interactive voting. According to Drs. Eugene Judson and Daiyo Sawada of Arizona State University and the University of Alberta respectively, this practice has been used in science classrooms since the 1960s but has

become popular on some campuses since the mid-1990s². A teacher using interactive voting solicits student responses to a question through a class vote or poll, often with flashcards or 'clicker' systems. In some cases, the question may be intended to increase student curiosity; while in others, it may be designed to check for student understanding. Mazur discovered that in certain circumstances, students learned more if they discussed their answers with their peers after voting³. He coined the phrase Peer Instruction to describe this observation, and outlined a specific model for implementing it:

1. Pose a question
2. Give students time to think
3. Have students record their individual answers
4. Have students convince their neighbors (peer discussion)
5. Have students record their revised answers
6. Calculate the results
7. Explain the correct answer

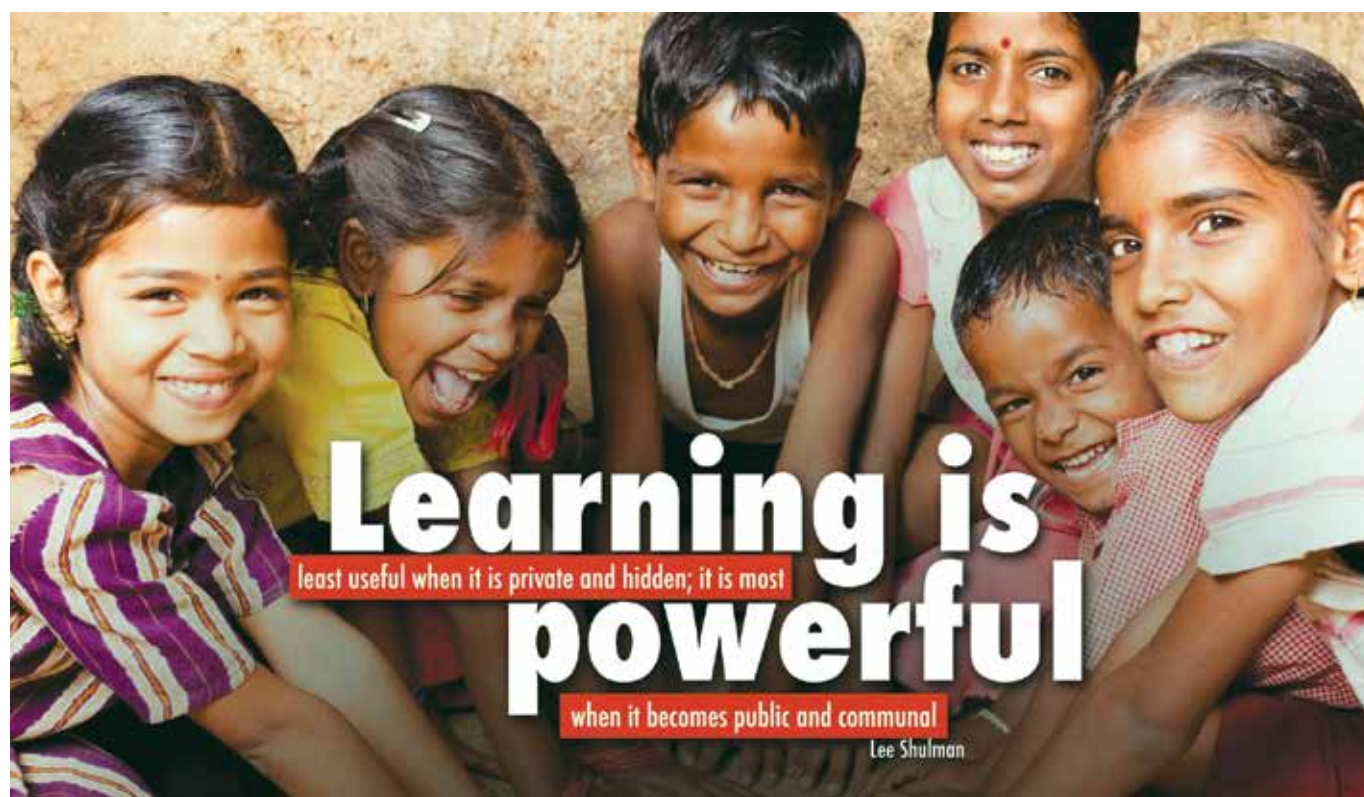


Fig. 1. Learning is least useful when it is private and hidden. It is most powerful when it becomes public and communal.

Credits: Quote by Lee Shulman. Illustration by Punya Mishra. License CC-BY-NC.

Mazur's findings and his model for Peer Instruction inspired a generation of follow-up research. A ten-year study by Mazur and Catherine Crouch, his colleague at Harvard University, looked for differences in performance of students in an introductory Physics course taught by traditional lecture method versus those that used some element of Peer Instruction. They measured student performance by giving students conceptual Physics tests before and after class. Through this study, Mazur and Crouch showed that students who took the course with Peer Instruction consistently and significantly outperformed those who took a course without it. Often, learning gains of students in classes using Peer Instruction were twice as high as those in classes without it. Other studies showed that Peer Instruction improved learning in classes on geoscience, computer science, and calculus^{4, 5}. This suggested that Peer Instruction may be suitable as a general teaching strategy, not confined to Physics.

Though Peer Instruction appears straightforward, each step contains subtle considerations for effective implementation. The following sections will unpack each step and give examples of best practices.

How can teachers support Peer Instruction in their classrooms?

Guide 1: Choose the right question

Teachers know that questions differ in their degree of challenge. Questions that fit well with Peer Instruction represent a conceptual challenge for the students. A test question like, "Name the phases of mitosis in order," provides students with the opportunity to recall information. A test question like, "How does alternation of generations represent an effective evolutionary turn for the survival of some plant species?" requires students to think through several concepts and link them together. Recall questions do not require Peer Instruction; simply providing the correct

answer allows students to understand how their own answer was incorrect. Providing the correct answer for a conceptually challenging question does not allow students to understand how their answer was not correct. For such questions, merely providing answers without explanation honors the answer above the explanation. Without access to and practice with explanation of phenomena, students cannot truly develop an in-depth understanding of either scientific concepts or the central nature of argumentation in science.

Regarding the central nature of argumentation in science, Peer Instruction strengthens the conceptual fluency of students with correct answers. Such students may or may not fully understand all of the concepts behind the correct answer. Peer Instruction provides these students with a chance to talk through their thinking, particularly when a peer asks questions. As a result, it helps them think through their response and articulate it so that another student can understand it.



Fig. 2. A diagram of the seven steps in the peer-instruction process.

Credits: Illustration by Punya Mishra. License CC-BY-NC.

Challenging questions require a deeper level of understanding, and Peer Instruction allows students to work through that deeper level of understanding together, regardless of their initial answer. Essentially, Peer Instruction emphasizes **understanding** over merely getting the right answer, while allowing students to participate in the authentic practice of argumentation in science.

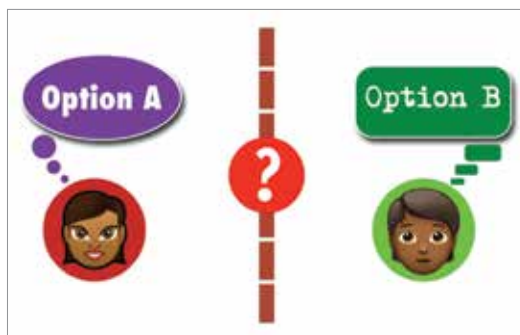
How to Implement:

Think of Peer Instruction as a perfectly timed learning opportunity for your students. Will any old question do? Clearly, factual questions with answers that can be looked up do not work well. The trick, research shows, is to choose questions that focus on concepts, not on facts⁶. Also choose questions that incite curiosity – questions that may divide the class. Often, questions based on common misconceptions (e.g., *“in a frictionless world, which falls faster: a bowling ball or a tennis ball?”*) drive rich peer discussion.

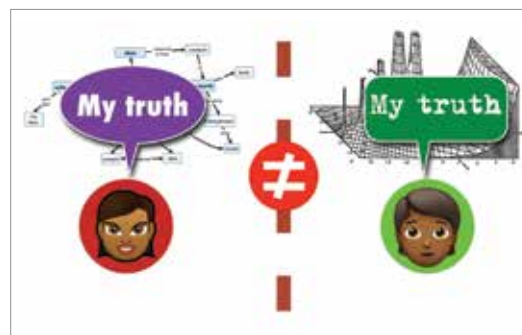
Guide 2: Elicit individual responses

It seems counter-intuitive that individual responses are necessary for a technique called Peer Instruction, but research shows that Peer Instruction does not work without this crucial step. It is important for students to think initially through the question because it lights the fire of curiosity in the student. They make a decision and commit to it. When students do not engage in this step, peer discussion lacks robust peer critique. In these cases,

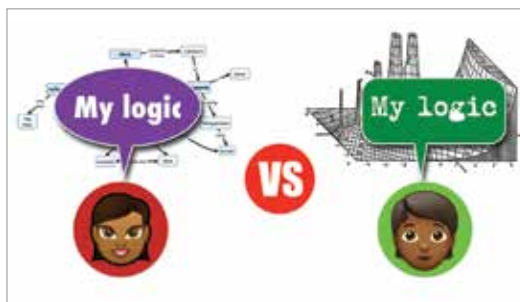
Fig. 3. How peer instruction works. Credits: Illustrations by Punya Mishra. License CC-BY-NC.



(a) When faced with a problem, students work in isolation with little knowledge of each other's understanding.



(b) By sharing their solutions with each other, students realize that their perspectives, frameworks, and understanding differ from each other.



(c) In attempting to convince each other of the correctness of their solution, students have to explain their logic and perspective on attacking the problem at hand.



(d) Through explaining their logic, the students have a higher probability of developing a correct shared understanding of the problem.

less confident students often just go along with more confident students without deep discussion. Individual responses allow students time to engage with the question thoughtfully once without the influence of a peer. This initial commitment produces a deeper discussion between peers.

How to Implement: Ask the question and allow students to share their individual answers in class. Introduce white boards, flash cards, paddles with 'yes' or 'no' written on each side, (or, if you have access, technology like iClickers or free online tools like Braincandy.org) for them to brainstorm and note their answers. Give them time and space to form an individual response and commit to it. This creates more engagement in the peer discussion to follow. Students report that taking the initial responsibility to answer the question individually forces them to think more deeply about the question and the answer.

Guide 3: Peer discussion

Implementing peer discussion may be the single most important part of the whole Peer Instruction process. However, not every question posed to the class requires peer discussion. Research shows that when a question is too easy (over 70% of students get the correct answer on the first vote), teachers should just skip peer discussion because learning gains are negligible. If the question is too hard (under 35% of students get the correct answer on the first vote), teachers should provide more explanation or hints before discussion.

Additionally, teachers should prompt students to discuss not only their answers, but the **reasons behind their answers**. This is key because the focus of learning should be on conceptual understanding rather than getting the right answer. Research shows that when teachers prompt 'reason-centered'

discussions instead of 'answer-centered' discussions, learning gains increase.

How to Implement: Observe students carefully during the first round of voting to see if the question is too easy or too difficult for peer discussion. If the question lies in the sweet spot between the two, then encourage students to turn to their neighbor and explain why they chose their individual answer. Give the students time to discuss; trust that they are acting as their own teachers.

Guide 4: Explaining the answer

Peer Instruction is incomplete without a final explanation by the teacher after voting, discussing, and re-voting. Studies

indicate that combining peer discussion with instructor explanation outperforms other similar pedagogical approaches. Presumably, this is because students are now primed and motivated to hear the instructor's explanation. Which of their answers was correct — the first one (i.e., their individual answer), or the new one co-created with a peer? After the first steps of the Peer Instruction cycle, students are ready to hear their instructor's point of view.

How to Implement: Once student re-votes are collected, identify and explain the correct answer. Try to draw on some of the popular answers, explaining why a certain answer reflects a common misconception or why a certain answer is correct.

Conclusion

Peer Instruction empowers students to create their own ideas, defend their own thoughts and in the process bring clarity to their own thinking, and construct meaning with their peers. It motivates students, incites curiosity, and allows students to experience the collaborative aspect of finding answers. Peer Instruction works in a variety of disciplines and with students at different levels of engagement. And, if implemented correctly, it seems to improve not just factual knowledge but also conceptual knowledge. Peer Instruction belongs in the tool-box of every educator precisely because it is empowering and effective.

Note: Credits for the image used in the background of the article title: Illustration by Punya Mishra. License CC-BY-NC.

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DETERMINATION OF THE MOLAR MASS OF STUDENTS IN A CHEMISTRY CLASS

Hydrochloric Acid
 HCl

Sulphuric
 H_2SO_4

Nitric
 HNO_3

Carbonate CO_3^{2-}
Sulphate SO_4^{2-}

Nitrate NO_3^-
Hydroxide OH^-

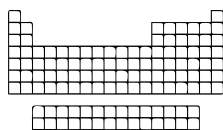
Phosphate PO_4^{3-}

SANGEETHA BALAKRISHNAN

A not-quite-procedure for not-really-an-experiment for chemistry educators

Aim: To determine the molar mass of students in a chemistry class¹.

Things required:



Periodic Table



Paper



Pen

Non-things required: A group of chemistry students.



Principle: Ineffably fun. And funnily ineffable.

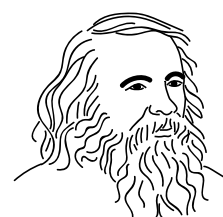
Setting: Best done impromptu. Especially when you begin to detect signs of boredom in the class.

Procedure

1. Pose the following question or some variant of it (semantics is your friend) to the students: "So, shall we continue with this topic, or do you want to play a game?" Chances are exceedingly high that upon posing the question, you'll go unimpeded to the next step².
2. Tell the students that they'll now be playing a game called 'Who is the heaviest of all?' involving the periodic table. Make sure your enthusiasm is infectious.
3. This step is titled: A **very, very** short introduction to the periodic table. Lavoisier, Doebereiner, Newlands, Mendeleev and the four newly discovered elements – that's more or less your timeline here. You are, in essence, covering 300 plus years of work on the periodic table in a minute. Foray into the philosophy of the periodic table. This part of the step may be omitted depending on factors best known to you. Time for testing waters: 4 seconds. Time for your entire monologue: 56 seconds (because: foray³).
4. This step shall never be omitted. Talk to the students about some of the ways in which the periodic table has been used outside of curricular instruction. Do not forget to mention the **Periodic Table Table**⁴.



Antoine Lavoisier



Johann Wolfgang Döbereiner



John Newlands

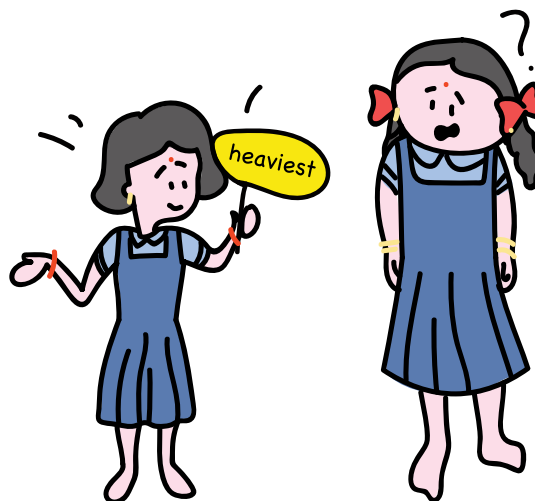


Dimitri Mendeleev



5. This is the **procedure per se** of the procedure. Write your first name on the black /green /white board in the classroom. Make the letters big and bold. Circle symbols of elements in your name. Write down the atomic masses of those elements on the board. Add them up. The resultant number is your molar mass in atomic mass units (amu). Put a big, bold polygon around it.
6. Task for the students: ask students to calculate their molar mass as per the **procedure per se** of the procedure. Instruct students to choose the heavier combination of elements in their first name. For example, if **Marvin the Paranoid Android** were your student, among the following two elemental combinations available to him in his first name, Marvin would go with the first one:
 - a. Ar (argon), V (vanadium), I (iodine) and N (nitrogen). This combination affords a molar mass of 231.8006 amu.
 - b. Ar (argon), V (vanadium) and In (indium) which affords a molar mass of 205.7075 amu.

7. Announce a small prize for the 'Heaviest student of all'.
8. Announce another small prize for students with Nh (nihonium), Mc (moscovium), Ts (tennessine) and Og (oganesson) in their first names.
9. Ask students to carry out the task, and shout out their mass if they beat yours written on the board.
10. Brace yourself for gleeful outbursts from the students⁵.
11. Record every new 'top chemical molar mass' on the board with the student's name.
12. Look for the 'winner' as per 7.

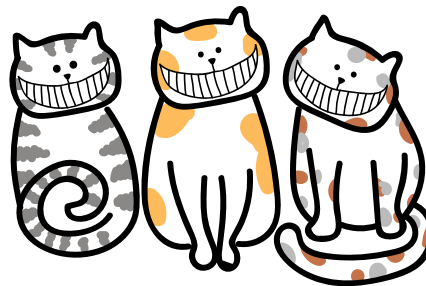


13. Separately, look for 'winners' as per 8.
14. Grin. Put an entire clowder of Cheshire cats to shame.

Result

Happy students. They think the Periodic Table was never more fun.

A happier teacher. You think the Periodic Table was never more fun⁶.



Precautions

Colleagues might pop their heads into your classroom wondering if you and your students have smuggled nitrous oxide from the lab into the class.

On detection of such quizzical looks, smile beatifically.



Notes:

1. Exercise done in class with inspiration drawn from Journal of Chemical Education 2015, 92 (10), 1757-1758.
2. Personal experience and anecdotal evidence.
3. Foray (n): a short period of time being involved in an activity that is different from and outside the range of the usual set of activities. Source: <http://dictionary.cambridge.org/dictionary/english/foray>. Also, it is assumed that a foray lasts less than a minute.
4. <http://theodoregray.com/periodicTable/>
5. Being in the midst of this will be a heartening experience.
6. Each class is unique, and the teacher is the best judge of when and how to introduce any activity therein. The author used this activity to break the monotony of lecturing. However, it can easily be used as an add-on activity for school students when introducing the Periodic Table to them; or better yet, when teaching molar masses. It is hoped that since this activity engages students on a personal level, it will help them grasp the underlying chemical concepts better.
7. Credits for the image used in the background of the article title: Chemistry Test. Thebarrowboy, Flickr. URL: <https://www.flickr.com/photos/thebarrowboy/6283758878>. License: CC-BY.

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DISCOVERING SCIENCE

G S RAUTELA

Many scientific concepts can be understood and demonstrated through simple experiments, using locally available low-cost material. This article presents a few simple but exciting experiments that can be used to understand foundational principles in physics.

We often come across natural phenomena that amaze us or leave us astonished. Observing these phenomena keenly and exploring the science behind their occurrence can make such experiences a lot more enjoyable, and can result in a better understanding of scientific concepts.

Similarly, explaining foundational concepts described in science textbooks through simple experiments, using low-cost material or activities in the classroom, can make teaching learning processes in science education far more enjoyable and effective. Such experiments not only excite students but also enhance their interest in, and promote their understanding of science.

We present a few simple experiments here, which you could perform in class or encourage your students to perform at home. Each of these experiments will help students question and discover the underlying scientific concepts for themselves and, in the process, learn a great deal of science.

Experiment 1: Lung capacity

Describe the experiment in the corresponding activity sheet to your students. Ask them what they expect to find. Then, encourage them to perform the experiment in groups of two and share their results. Surprisingly enough, the bag will be fuller when it's held away from the mouth and opened wider. Once they have arrived at this response, ask your students if they can explain why this happens?

LUNG CAPACITY

- Keeping an unused garbage bag close to your mouth (a), blow into it once with as much force as you can. Observe how much air you can fill in the bag.
- Now keep the mouth of the bag fully open and the bag a little away from your mouth (b). Blow into it with full force again.



(a)



(b)

Which of the two seems fuller?

1. Bag in (a)
2. Bag in (b)
3. Both bags seem equally full.

Contributed by:

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DRINKING WITH STRAWS



(a)



(b)

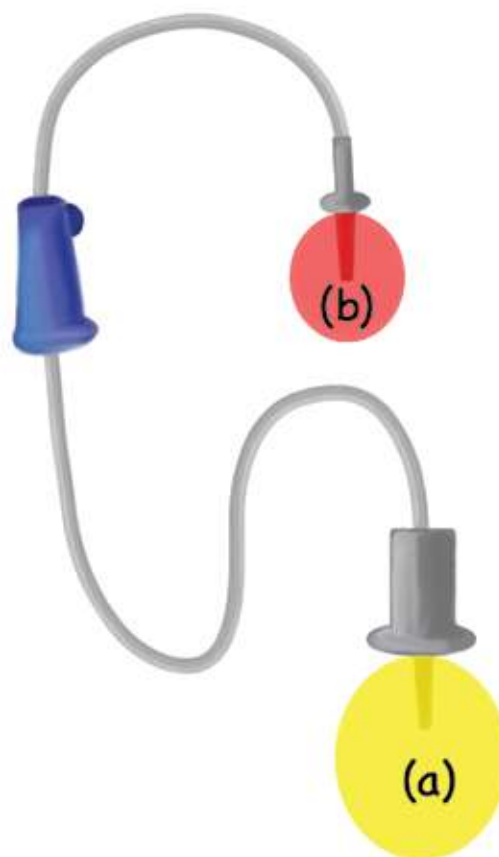
- Use a straw to empty the water in a glass tumbler as fast as possible (a).
- Fill the glass with the same amount of liquid again, and repeat the experiment with two straws. Keep one end of both straws inside your mouth. But ensure that the other end of one straw remains inside the liquid; and that of the other straw remains outside the glass (b).

Which of the two empties faster?

1. Tumbler in (a)
2. Tumbler in (b)
3. Both empty at the same rate

DEFLATING BALLOONS - I

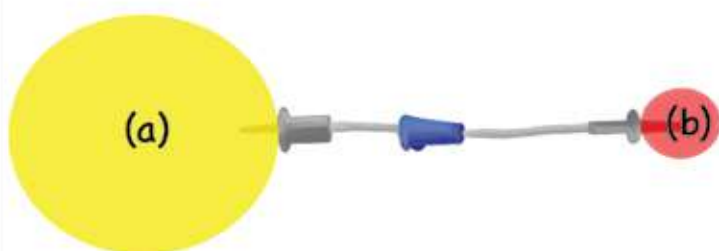
- Cut the sharp end of an intravenous tube set and insert this into balloon filled to about $\frac{3}{4}$ th of its volume.
- Keeping the valve of the intravenous tube closed, secure the mouth of the balloon around its blunt end to ensure that none of the air escapes (a).
- Fill an identical balloon to about $\frac{1}{3}$ rd its volume and secure its mouth around the other end of the intravenous tube (b).



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DEFLATING BALLOONS – II



Which of the two deflates sooner?

1. Balloon (a)
2. Balloon (b)
3. Both remain the same size

- To check if the valve of the intravenous tube is closed and the mouths of the two balloons are sealed properly, observe the size of the balloons for a few minutes – both should retain their sizes.
- Now, gently open the valve of the intravenous tube.

In the first case (a), the only air that enters the bag is what you exhale or force out of your lungs. While a healthy adult can hold about 6 l of air in her lungs (called vital capacity), she can inhale/exhale only about 0.5 l of air in a single breath (called tidal volume). However, in the second case (b), the air that enters the bag is more than what you can exhale. This phenomenon could be explained by Bernoulli's principle which states that: 'for a streamline fluid flow, the sum of the pressure, the kinetic energy per unit volume and the potential energy per unit volume remain constant'. When you force air out of your mouth, the high velocities at which the air molecules travel cause an increase in their kinetic energy. But, since their potential energy remains unchanged, the pressure of the air forced out of your mouth drops. As a result, surrounding air rushes in to fill this partial vacuum and gets trapped in the bag.

Experiment 2: Drinking with straws

Describe the experiment in the corresponding sheet to your students. Again, ask them to predict the results of the experiment before actually testing it out. Again, divide them into groups of two and ask them to share the results of the experiment. It may seem strange, but drinking with two straws is really difficult. Encourage your students to think about why this is so.

In the first case (a), as you start sucking from one straw, you draw out all the air from the straw into your mouth, creating a partial vacuum inside the straw. This leads to a drop in air pressure inside the straw. However, atmospheric pressure continues to act on the water in the glass. The difference in pressure at the two ends of the straw makes the liquid rise up into the straw and flow into your mouth, allowing you to drink the liquid from the glass. In the second case (b), when you try to drink with one straw inside and one outside the glass, air gets sucked up from outside the glass through the second straw. As a result, there is no vacuum created inside the straw, and its air pressure remains the same as the atmospheric pressure on the liquid in the glass. Without a

difference in pressure to pull it upwards, the liquid doesn't rise up, and drinking becomes very difficult.

Experiment 3: Deflating balloons

Set up the experiment in the corresponding Activity Sheet – I with your students. As with the previous experiments, ask students to predict the result of the experiment before you open the valve of the intravenous tube as in Activity Sheet – II. Once you open the valve, ask students what they observe. Also ask them if they can come up with the reason for their observation.

Many of us tend to think that once the valve is opened, the bigger balloon (a) would deflate just enough to make the smaller balloon (b) equal to it in size. However, in reality, it is the smaller balloon that deflates – making it even smaller and the bigger balloon even larger. To understand this, let's look at how air pressure inside a balloon varies with its diameter. When air is initially forced into a balloon, the elasticity of the rubber opposes its expansion, causing the air pressure inside it to increase rapidly, reaching a peak. The small balloon in our experiment is at or close to this level of air pressure. Once it reaches this level, the balloon starts expanding in size and increasing in volume more easily. Any further addition of air only causes a drop in pressure inside the balloon. In other words, the internal pressure of the bigger balloon reaches a maximum and then drops to a minimum as its size increases. You can observe this behavior the next time you blow up a balloon – you will need a great deal of force in the beginning, but after the balloon expands to a particular size, less force is needed to inflate it further. Therefore, when the valve allowing air flow between the two balloons is opened, air flows from the region of high pressure (or the small balloon) to that of low pressure (or the big balloon). As a result, the bigger balloon becomes even larger in size. Once the air pressure is equalized between the two balloons, the flow of air ceases and their sizes remain unaltered.

Note: Credits for the image used in the background of the article title: Colourful balloons in a calm sky. Tirachard Kumtanom. URL: <https://www.pexels.com/photo/balloons-calm-clouds-colorful-574282/>. License: CC-0.

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1. Wikipedia contributors, "Two-balloon experiment," Wikipedia, The Free Encyclopedia. URL: HYPERLINK "https://en.wikipedia.org/w/index.php?title=Two-balloon_experiment&oldid=830073077%20"https://en.wikipedia.org/w/index.php?title=Two-balloon_experiment&oldid=830073077 (accessed June 5, 2018).



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WHY IS THE FISH BLUE?

NAVODITA JAIN & SWAGATHA GHOSH

The accidental discovery of the novel property of an enigmatic blue protein answered a question that had nagged a fish biologist for two decades. This is the story of Wayne Schaefer and his pursuit of an observation – a blue fish in a lake famous for its yellow ones.

The large number of lakes in North-eastern America and Canada (the Great Lakes region) may explain the huge popularity of fishing as a recreational activity in these regions (refer Fig. 1). And,

sometimes, when a person with a keen sense of observation goes fishing, she (or he) might just come back with a scientific breakthrough. This is the story of one such observant angler – Wayne Schaefer.



Fig. 1. The Great Lake region of North America and Canada.

Credits: Jonnie Nord – U.S. Army Corps of Engineers, Detroit District, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Great_Lakes_1.PNG. License: Public Domain.

Fig. 2. The yellow walleye



(a) The Fish.

Credits: Engbretson, Eric / U.S. Fish and Wildlife Service, Wikimedia Commons.
URL: https://commons.wikimedia.org/wiki/File:Sander_vitreus.jpg. License: CC-BY.



(b) The Mascot (Wally the Walleye).

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Schaefer, now a Professor Emeritus at the University of Wisconsin, United States, is a fish biologist with a special interest in one species – *Sander vitreus* or the yellow walleye (refer Fig. 2a). Every year, for the last 25 years, Schaefer has been heading down to a cabin he owns in Ontario, Canada, to study these fish in their natural habitat.

What is the walleye?

This fish is believed to get its unusual name from the fact that its eyes are opaque and glassy. Native to Canada (and North America), the walleye is a local delicacy in the region. With a length of about 76 cm and a weight of about 9 kg, this fish is a golden catch indeed! Interestingly, an ice hockey team – the Toledo Walleyes of Ohio, United States, has Wally the Walleye as its mascot (refer Fig. 2b)!

“Hey! I caught a blue walleye!”

In the summer of 1992, something unusual happened – Wayne caught what seemed like a new species of fish with bluish scales (refer Fig. 3a). On handling the fish, however, he found that the blue colour came from a mucus-like substance that rubbed-off on the palms of his hands (refer Fig. 3b), leaving behind a steel-grey fish with an uncanny resemblance to the yellow walleye. This story may have ended here, but for Wayne's acute sense of enquiry.

With his experience in fishing in those waters, Wayne identified the catch to be a walleye. Back in his lab, he used DNA studies to confirm this conclusion. But, what was the blue-coloured substance? Why was it there? Was this a one-time occurrence? To the scientist in Wayne, this anomalous observation was an irresistible challenge.

As other reports of blue walleye sightings started pouring in from

both recreational and professional anglers fishing in the same region, Wayne discovered that this was no rare occurrence. He himself continued to catch more of these fish on subsequent fishing expeditions. In 2006, Wayne decided to compile his data on the walleye into an online database. Then, he invited other people to add to this database with details of their own sightings, and requested that mucus samples of each specimen be shipped to him. Looking through these records, Wayne and his group discovered two interesting patterns – most sightings of the blue walleye were in the summer (June to August), and none of them were from lakes in Minnesota or Wisconsin, United States. These patterns were supported by the field observations of Wayne and his research group over a period of 16 years. Based on these parallel sources of data, Wayne went on to conclude that blue walleyes were found at latitudes north of 45° and, therefore, only in lakes on the Canadian side.

Fig. 3. The blue walleye.



(a) As compared to the yellow walleye.

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(b) With mucus that rubs off while handling.

Credits: Gary Skrezk, Walleye Heaven. URL: <https://www.walleyeheaven.com/bluewalleye/bluewalleye4.png>. License: Obtained with permission from the rights owner.

Wayne's group also continued to analyze different samples of the blue mucus that rubbed off from the fish's surface, arriving at many different hypotheses to explain it. One of these attributed the blue colour to the acidity of the water in this region; another speculated that the mucus may be the result of algae or bacteria growing on the skin of the fish. Finally, through collaborations with expert chemists, Wayne managed to isolate the specific substance that gave the mucus its blue hue. This substance turned out to be proteinaceous in nature, ruling out the possibility of it being a bacteria or algae surviving on the skin of the fish.

The fishy blue protein

The blue protein, much like the fish, has an interesting story of its own. Through extensive chemical analyses, Wayne and his collaborators discovered that its blue colour came from a protein-chromophore complex. The protein turned out to be unique to the fish, and was named Sandercyanin after it. The chromophore turned out to be Biliverdin — a chemical that is highly conserved across species. Biliverdin is produced

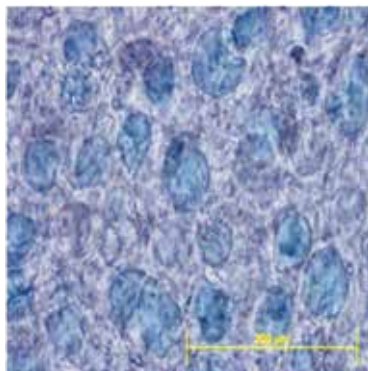
by the breakdown of heme (during the recycling of hemoglobin in red blood cells). Given the patterns of occurrence of the blue fish, this gave rise to the question — why was this protein-chromophore complex produced only during summers, and only in walleyes found in Canadian lakes?

One piece to this puzzle came from a high school student who pointed out that regions above 45° latitude received unusually high amounts of ultraviolet (UV) radiation in summer. A study from southern Sweden had recorded a similar increase in UV radiation during summer in regions above 55° latitude. The authors of the study had attributed the increase to a seasonal depletion of ozone near the poles. The second piece came from studies on the synthesis of Biliverdin. While the degradation of heme is usually mediated by enzymes, it is also known to occur on exposure to UV radiation. With this key bit of information, Wayne and his colleagues seemed closer to forming a hypothesis — higher amounts of UV radiation in Canadian lakes could be triggering the increased breakdown of heme. This in turn could lead to the increased

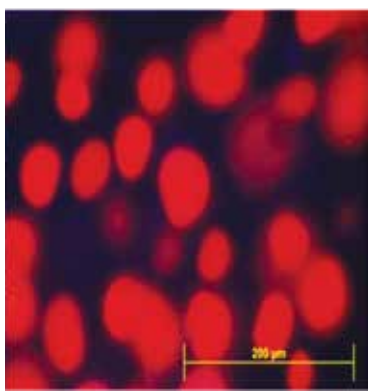
production of the Sandercyanin-Biliverdin complex or the blue mucus.

The final piece of the puzzle came purely by chance. A collaborator suggested that Wayne view the blue mucus under a bright-field microscope (white light). On trying this, Wayne was surprised to see many bright red spots in the sample. Hearing this, his collaborator wondered if Wayne was "sure that the incident light was set to white". This was when Wayne realized that he had been looking at the sample under UV (with a wavelength of about 375 nm) light in a fluorescence microscope. Excited, he illuminated the sample first with white light, and then with UV light. Every time he did this, he got the same result. The sample looked almost uniformly blue under white light (refer Fig. 4a) but appeared to have bright red spots under UV light (refer Fig. 4b). Some component of the mucus was capable of absorbing UV light (of a lower wavelength) and emitting red light (of a higher wavelength) — in other words, it could fluoresce. Wayne hypothesized that the fluorescing component was Sandercyanin. This was confirmed when he and a collaborator,

Fig. 4. The blue mucus under a fluorescence microscope.



(a) Observed under white light.



(b) Observed under UV light.

Credits: Ghosh S et al ©National Academy of Science. URL: <http://www.pnas.org/content/113/41/11513>. License: CC BY-NC-ND.

S. Ramaswamy, managed to isolate the protein.

This very naturally led to the next question – was the mucus simply a by-product of a seasonal reaction, or did it provide some kind of survival advantage to the blue fish?

The serendipitous discovery that Sandercynanin could absorb UV light helped provide clues to this mystery. While Wayne could not find any genomic differences between the yellow and blue walleyes, he inferred that the blue mucus could be a seasonal 'adaptation'. By absorbing the high levels of UV radiation at the surface, the Sandercynanin-Biliverdin complex in the mucus could be protecting deeper tissues from its damaging effects. Ramaswamy suggests another possible advantage. Since water preferentially absorbs light of higher wavelength, only lower wavelengths of light (in the blue and UV spectrum) are able to penetrate deeper waters. Fish that inhabit deeper waters have adapted to this by developing the ability to 'see' objects by the UV light they reflect (called UV vision). Pikes, natural predators of walleyes in Canadian waters, tend to rely on their UV vision to hunt for prey. Thanks to their seasonal adaptation, blue walleyes absorb UV instead of reflecting it. Thus, the blue mucus acts as an invisibility cloak – making the fish invisible to their primary predators! But, walleyes also inhabit deeper waters and rely on UV vision. Does this mean that the blue walleyes become invisible not only to pikes but also to a potential mate? Ramaswamy hypothesizes that external fertilization in the walleye may rule out the necessity of 'being visible' to a potential mate.

It's not just the fish that find this protein useful. Swagatha, a researcher

in Ramaswamy's laboratory, was part of the team that studied the fluorescent properties of Sandercynanin in detail. This team found that Sandercynanin is quite small in size – perhaps, the smallest red fluorescent protein known till date. However, because of its chemically unique nature, it can fluoresce for long periods of time. Keeping these two properties in mind, Swagatha plans to explore Sandercynanin's role as a fluorescent tag in research and clinical diagnosis. This will involve identification of the coding regions of the Sandercynanin gene, and engineering it into live cells and tissues of other organisms to track their activity in real-time.

To conclude

The spark of curiosity that led one scientist to question why some fish looked blue instead of yellow marked the beginning of a long process of scientific research. This process has involved scientists from many different disciplines and fishing enthusiasts from across the Great Lake region in Canada. It has also led to the 'accidental' discovery of a new fluorescent protein – one that is currently being studied for its potential in unlocking other mysteries of life through its applications in research and diagnostics. Serendipity, most often, strikes minds sharpened by hard work – offering an explanation and leading the way. Did you spot something today that seemed out of the usual? Did you follow it and discover pieces of a greater puzzle?

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THE MYSTERY OF DARK ENERGY

AMITABHA MUKHERJEE

We are told that we live in a universe filled with a mysterious entity called dark energy. In this article we try to explain what scientists mean by dark energy, and how we infer it exists.

It was the year 1920. At a meeting of the National Academy of Sciences, USA, the leading astronomers of the day were having a debate on 'The Scale of the Universe'. Their arguments were centred on cloudy-looking objects like the Great Andromeda Nebula (Latin *nebula* ~ little cloud), also known as M31 (refer Fig. 1a). According to one school of thought,

nebulae were just clouds of gas and dust within the Milky Way. The other school of thought agreed with only part of this argument — there were indeed some gas clouds in the Milky Way. However, they argued that many nebulae were collections of stars that were too far away to be within our galaxy.



Fig. 1a. The Andromeda Galaxy: a modern view.

Credits: NASA/JPL-Caltech, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Andromeda_galaxy_2.jpg. License: CC-BY.



Fig. 1b. Immanuel Kant.

Credits: A photograph (<http://www.philosophie.de/kant-bilder/bilddaten.html>) of a painting by Johann Gottlieb Becker uploaded by Daube aus Böblingen, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Kant_gemaelde_3.jpg. License: CC-BY.

The latter was not a new idea. As far back as in 1775, the philosopher Immanuel Kant (refer Fig. 1b) had conjectured that nebulae, which he called 'island universes', were 'distant' objects. By 1925, detailed observations – especially those made by the American astronomer, Edwin Hubble – had settled the debate. Hubble started by successfully resolving individual stars in M31 using the Hooker Telescope at Mt. Wilson Observatory, California (refer Fig. 2). Soon, he and his colleagues were able to estimate the distance to these stars. This showed that not only was M31 too distant to be within the Milky Way; it was a galaxy in itself, containing billions of stars. This proved that the universe was much bigger than

previously believed. Not surprisingly, the light emitted by M31 shows spectral lines of the various chemical elements seen in stars.

The universe is expanding

During 1916–1919, it was found that while some 'nebulae', such as Andromeda, showed a blue shift in their spectral lines, a majority exhibited a red shift. This was particularly true of the more distant galaxies. The Doppler Effect (refer Box 1) allows us to relate the spectral shift to the motion of an object, and leads us to conclude that most galaxies are moving away from us. In the latter part of the 1920s, Hubble and his collaborators measured the red shifts of most galaxies known at the time. They found that the galaxies which were further away from us had higher red shifts, i.e. they were moving away



Fig. 2a. Edwin Hubble.

Credits: Johan Hagemeyer, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Studio_portrait_photograph_of_Edwin_Powell_Hubble.JPG. License: CC-BY.

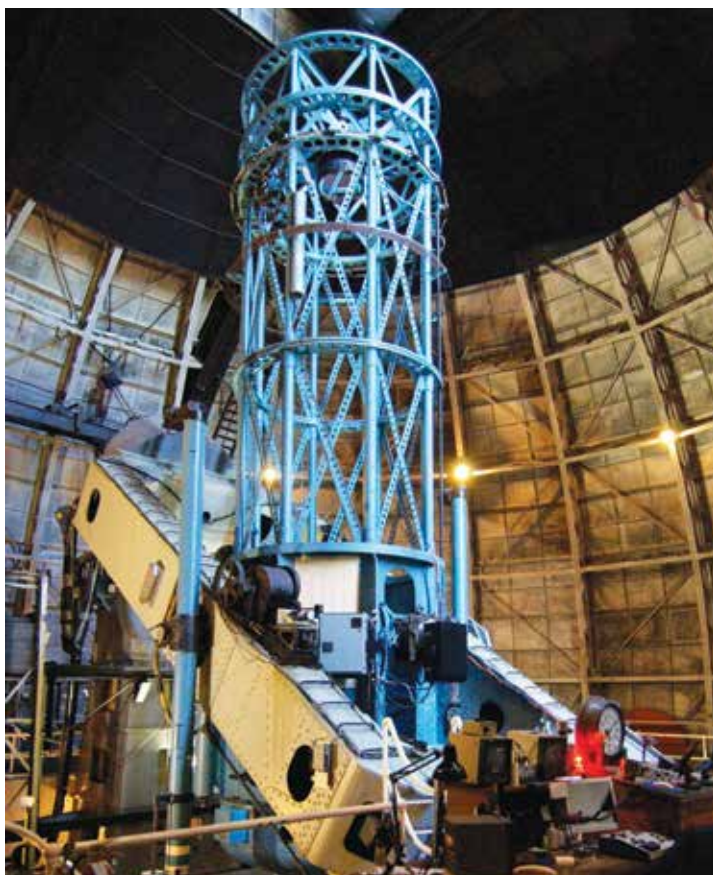
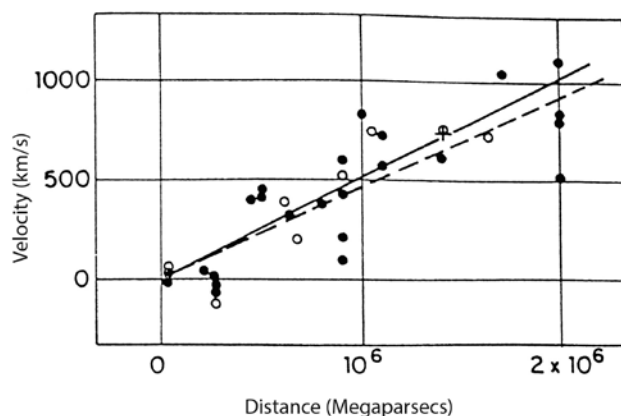


Fig. 2b. The 100 inch Hooker Telescope at Mt. Wilson Observatory in Los Angeles County, California.

Credits: Ken Spencer, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:100_inch_Hooker_Telescope_900_px.jpg. License: CC-BY-SA.

Fig. 3. Hubble's plot.

Credits: Edwin Hubble, Proceedings of the National Academy of Sciences, vol. 15 no. 3, pp.168-173. URL: <http://www.pnas.org/content/pnas/94/13/6579/F3.large.jpg>. License: Copyright PNAS.



(receding) from us at higher speeds. A plot published in Hubble's first scientific paper in 1929 showed that the speed of recession of a galaxy was proportional to its distance from us (refer Fig. 3). This is today known as Hubble's Law (refer Box 2).

By the 1930s, as more data became available, Hubble's Law was confirmed. Indeed, the redshift (the preferred spelling nowadays) of a galaxy is used as a measure of distance. Yet, Hubble and

his collaborators could not explain the reason for this phenomenon.

Today, we no longer believe in the ancient notion that human beings are privileged and occupy the centre of the universe. We recognise the Milky Way as being just one of the billions of galaxies in the universe. We also believe that the universe as a whole looks the same to all observers, wherever they are located – this deeply philosophical statement is called the Cosmological Principle. In

other words, according to Hubble's Law, intelligent beings in another galaxy would also observe other galaxies receding from them. This would mean that all the galaxies in the universe are receding from one another with speeds proportional to the distances between them. To give an analogy, think of a balloon with printed patterns on it. As we blow air into the balloon, it expands, and each printed bit moves away from all others (refer Fig. 6). While technically this analogy is not quite correct, it does

Box 1. The Doppler Effect and Galactic Redshifts

You may have noticed the change in pitch in the sound of an approaching motorcycle as it passes us. This change in pitch happens when the source (~ the motorcycle) emitting the wave (~ of sound) moves towards or away from us. This is called the Doppler Effect.

Galaxies, like other luminous objects in the universe, emit electromagnetic waves (gamma radiation, x-ray, ultraviolet, visible light, infrared etc.) consisting of spectral lines of various chemical elements. Some of this light reaches the Earth.

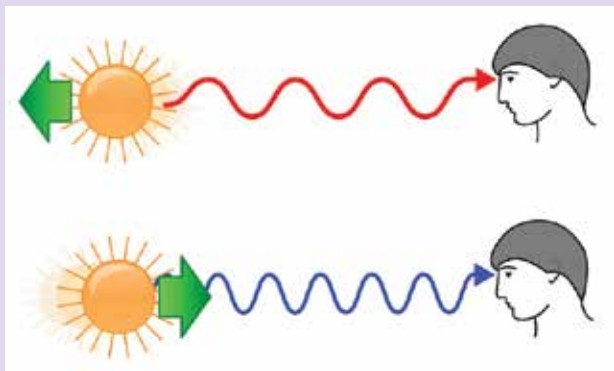


Fig. 4. Redshift and Blueshift of light by Doppler Effect.

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In a manner similar to that for the motorcycle, the Doppler Effect allows us to study the motion of galaxies relative to us. If a galaxy is moving towards us, its spectral lines will shift to shorter (more blue) wavelengths; and, when it is moving away from us, the lines will shift to longer (more red) wavelengths (refer Fig. 4).

Box 2. Hubble's Law

Interestingly, what is today known as Hubble's Law should perhaps have been called the Lemaitre-Hubble Law, after the Belgian priest and physicist Georges Lemaitre who published it in 1927 – two years before Hubble did (refer Fig. 5).



Fig. 5. Georges Lemaitre.

Credits: Adapted from Orion Blog, ESA. URL: <http://blogs.esa.int/orion/2014/03/20/over-13-billion-years-after-the-big-bang-georges-lemaitre-heads-to-space/>.

As a matter of fact, Lemaitre had not only predicted that the universe was expanding, but had also suggested that the red shifts of galaxies could be used to determine the rate of expansion. However, since these results were published in a little-known Belgian journal, they got wider recognition only a few years later.

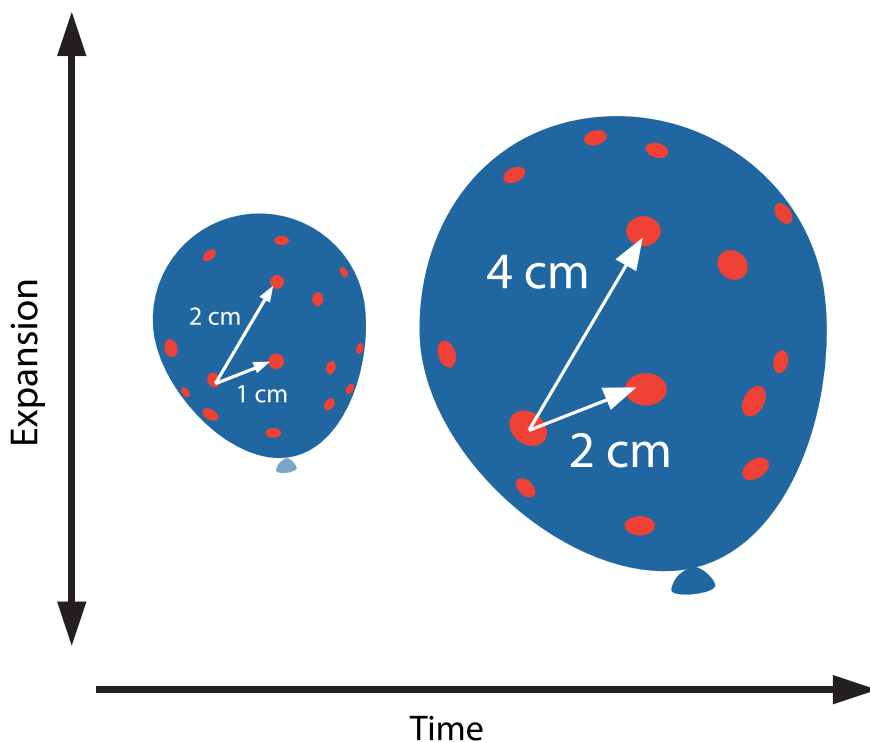


Fig. 6. The printed bits on the surface of an expanding balloon move apart at a rate proportional to their distance.

Credits: Adapted from an illustration by Yuen Pui-ho (translation by Wong Ka-lei) on Hong-Kong Physics World. URL: http://www.hk-physics.org/articles/univexpand/univexpand_e.html.

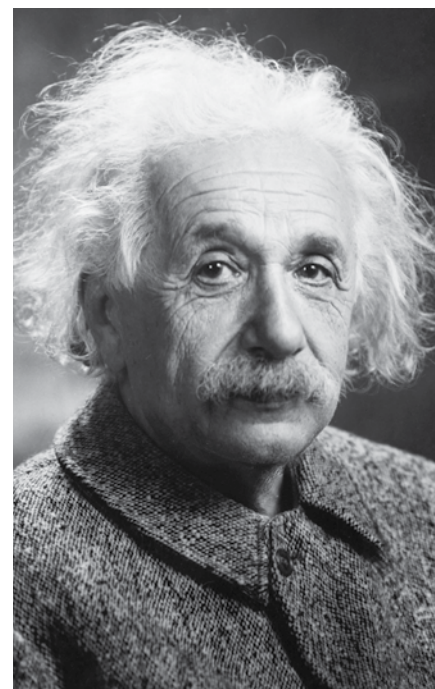


Fig. 7. Albert Einstein.

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help us visualise the physical meaning of Hubble's Law – the universe as a whole is expanding.

The theoretical basis for Hubble's Law came from the work of a German theoretical physicist, Albert Einstein (refer Fig. 7). In 1917, Einstein had solved the equations of his General Theory of Relativity to find a mathematical model for the structure

of the universe (refer Box 3). The original theory had led to solutions indicating that everything in the universe changed with time. While this implied that the universe was either expanding or contracting, there was no observational evidence for either at the time. This led Einstein to add a new constant, called the cosmological constant, to his equations – which had the effect of making the universe

static. This paper went on to become so influential that it is believed to mark the origins of modern cosmology as a science that studies the universe as a whole. However, years later, when Einstein heard of Hubble's redshifts, he recognised it as evidence for the idea of an expanding universe. This led him to describe the introduction of the cosmological constant as the 'biggest blunder' of his life.

Box 3. General Theory of Relativity

In 1905, Einstein put forward the (Special) Theory of Relativity. This was based on the idea that the laws of physics are the same for all inertial (non-accelerating) observers, and the speed of light in vacuum is the same, regardless of motion of the source or the observer. This gave rise to the idea of spacetime – space and time linked together.

He later generalised the theory to take into account accelerated observers. He proposed that the effect of gravity is equivalent to that of acceleration of the observer, and that massive objects distort spacetime. In other words, gravity is just the effect of warped spacetime. In 1915, Einstein succeeded in putting his ideas into mathematical form. The equations of General Relativity (GR) relate the curvature of spacetime to the matter contained in it. This has been referred to as being "probably the most beautiful of all existing physical theories" (Lev Landau and Evgeny Lifshitz, *The Classical Theory of Fields*, 1975).

The first observational test of GR came in 1919, when the bending of light due to a massive object was detected during a total solar eclipse. Since then, GR has been tested in many different astrophysical settings – most recently with the detection of gravitational waves in 2015, the centenary year of the theory.

Box 4. Supernovae

From time to time, a star in our galaxy may flare up – becoming much brighter than it was and remaining so for many days. Such a 'new' star is called a nova (plural: novae). In 1885, a nova-type event was observed in the Andromeda galaxy. Once it became clear that this galaxy was far away from us, this event was recognised as being much brighter than a typical nova. Thus, the term 'supernova' was coined to describe it.

While supernovae are known to be of many types, one type – called Type Ia Supernovae – are particularly important in cosmology. This type occurs when a white dwarf star merges with another star, resulting in a runaway reaction that blows the white dwarf apart (refer Fig. 8). Since the maximum brightness that these events reach is remarkably constant (about 5 billion times brighter than the Sun), their observed luminosity allows us to infer their distance from us.



Fig. 8. The remnant of a Type Ia supernova.

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The expansion is speeding up

In physical terms, the fact that the graph remains a straight line in Hubble's plot implies that the expansion of the universe remains constant with time. However, the 1930s brought the

realisation that the relationship between the distance of a galaxy and its speed of recession may be more complicated than that. The 'actual' shape of the graph would depend on the mathematical model of the universe.

In most models of the universe, its rate of expansion decreases with time

because the force of gravity pulls all matter together. Cosmologists even defined a deceleration parameter to measure the rate of this decrease. However, observations made over a period as long as the next fifty years were unsuccessful in establishing the value of this parameter. Was it zero –



Fig. 9a. Saul Perlmutter.

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Fig. 9b. Brian Schmidt.

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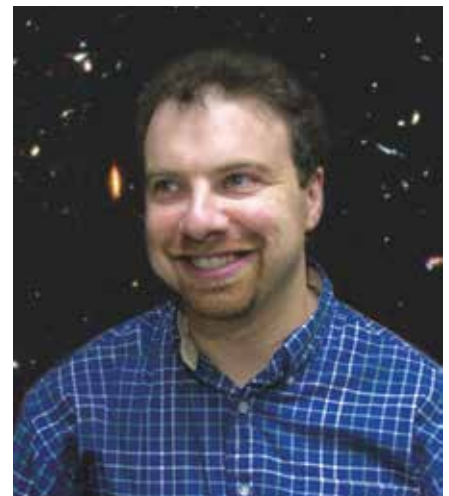


Fig. 9c. Adam Riess.

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meaning that the Hubble plot would be an exact straight line? Was it positive as most theoretical arguments suggested? Or, was it perhaps negative? For years, students entering the field were told that observations were consistent with all three possibilities.

The year 1998 saw a major breakthrough. Two groups, independently working on exploding stars called supernovae (refer **Box 4**), arrived at a surprising conclusion: the deceleration parameter appeared to be negative. They observed that the distances of high-redshift supernovae appeared to be systematically 10–15% greater than expected. This is possible if the universe had expanded more slowly in the past than it does today. Since light would then have to travel a longer distance to reach us, the supernovae would appear fainter. In other words, contrary to expectations, the expansion of the Universe appeared to be speeding up.

This was the biggest discovery to be made in cosmology in three decades. The American astronomers Saul Perlmutter, Brian Schmidt and Adam Riess were jointly awarded the Nobel Prize in Physics in 2011 for their contribution to it (refer **Fig. 9**). By then, several other observations, not related to supernovae,

had confirmed the accelerated expansion of the Universe.

The mystery of accelerated expansion

As mentioned before, any kind of matter is expected to slow down the rate of cosmic expansion. Thus, observations implying accelerated expansion are puzzling – how is this possible in a universe filled with ordinary matter and radiation? Even the presence of a large quantity of dark matter does not help explain this phenomenon.

Theorists hypothesised that the accelerated expansion was caused by the presence of a still unknown form of energy that pushes galaxies apart. In an analogy to dark matter (DM), the term 'dark energy' (DE) was coined for this 'mysterious' form of energy. This is, in fact, a misleading name. The only thing common between DM and DE is that neither can be seen with telescopes. Dark matter behaves like ordinary matter under the force of gravity – it clumps together to slow down the expansion of the universe. In contrast, dark energy is simply shorthand for 'whatever is causing the expansion of the universe to speed up'. This, of course, doesn't **explain** anything.

Box 5. The negative pressure of vacuum energy

Think of a container filled with a gas, with a sliding piston. To compress the gas, we have to push the piston in. The amount of energy we have to put in is equal to the pressure of the gas p times the change in volume. Now imagine the same container has a vacuum with a constant energy density ρ . When we push the piston in, the total energy becomes less by an amount equal to p times the change in volume. The two expressions match if we think of the vacuum as having a negative pressure $p = -\rho$.

The nature of dark energy has been a subject of speculation for the last twenty years. One approach to this 'problem' assumes that Einstein's theory of general relativity is correct, but the universe is filled with something that does not behave like matter. Among the many theoretical models that fit this category – collectively called DE Models, the most popular one at the moment is based on Einstein's idea of a cosmological constant. According to this model, dark energy can be imagined to fill all the empty space in the universe – thus, called vacuum energy – at a density that remains constant with space and time. Using thermodynamics, it is easy to see that if an empty space or vacuum has energy, it necessarily has a negative pressure (refer **Box 5**). Thus, if the universe expanded slightly, the empty space would expand too. This would increase the amount of dark energy, which would in turn cause more expansion. This sounds weird, but offers the simplest explanation for the accelerated cosmic expansion (refer **Fig. 10**). Other DE models, in which dark energy is known as 'quintessence' or 'phantom', can be thought of as dynamic models of vacuum energy. While we will not describe these models in detail here, they hypothesize that the density of dark energy in the universe is not a constant; it varies with space and time.

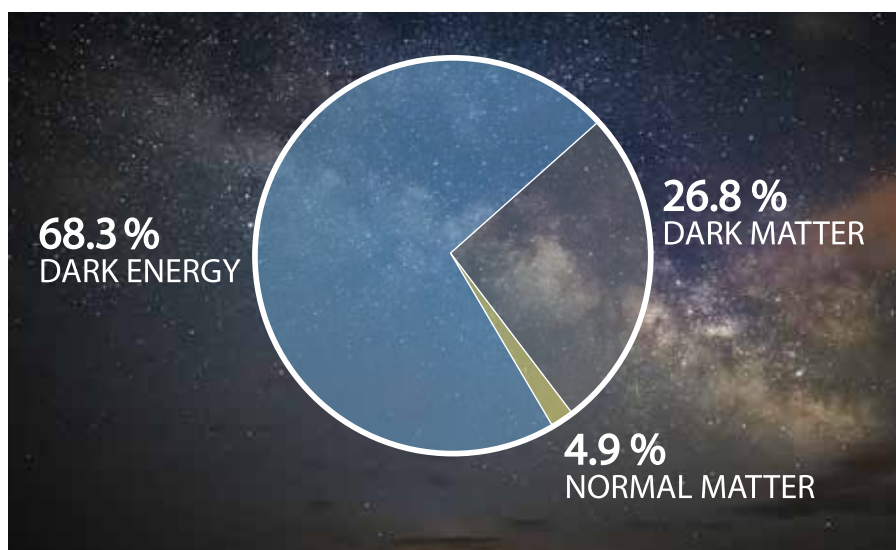


Fig. 10. Energy distribution in the Universe according to Planck probe measurements, March 2013.

Credits: Adapted from an image by Szczureq, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:DMPie_2013.svg. License: CC-BY-SA.

Another approach is based on the possibility that Einstein's description of gravity by general relativity may be incomplete. An alternate version may account for the accelerated cosmic expansion and do away with DE altogether. If this turns out to be true, the important question to consider is — would such a model be able to satisfy the other observational tests that Einstein's theory does? While there are many alternate theories of gravity, none of them have seemed convincing enough yet.

A natural question that arises from these discussions is — how much

energy must the empty space in the universe have in order to account for its accelerated expansion? Data from the Planck satellite shows that over 68% of the total energy of the Universe is contributed by dark energy. Ordinary matter — we ourselves, other life on earth, the Earth, the solar system, and all the stars in the visible parts of galaxies — makes up less than 5%.

In the future

Although observations of the universe seem to support the model based on the cosmological constant, this story is far from over. Our present understanding

of elementary particles and the forces between them relies on a framework called quantum field theory. This framework has been used to calculate how much energy empty space should contain. The predicted value turns out to be several ($\sim 10^{120}$) times bigger than the value of the cosmological constant inferred from observations related to the accelerated cosmic expansion. Thus, the current challenge is to explain not only why vacuum energy exists, but why it has the observed value. This is an exciting field for further work, with the potential to improve observations and refine existing theories.



Note: Credits for the image used in the background of the article title: Dark Energy Survey — distant galaxies by UCL Mathematical and Physical Sciences, Flickr. URL: <https://www.flickr.com/photos/uclmaps/14958324522>. License: CC-BY.

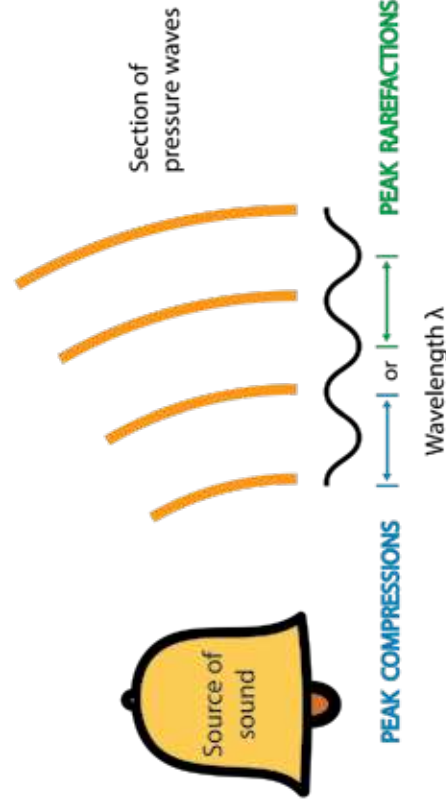
Amitabha Mukherjee retired as a Professor at the Department of Physics and Astrophysics, University of Delhi. Email: amimukh@gmail.com.

Discover Doppler Effect

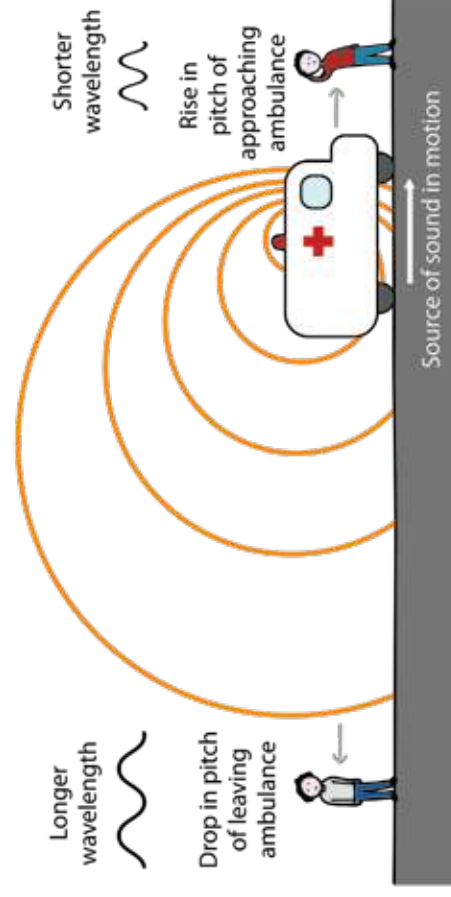
Ramgopal (RamG) Vallath

Can there be anything common between the change in pitch of the sound of a motorbike as it zips past us and the light emitted by distant stars as they move away from us? Yes! They are both subjected to the Doppler effect.

Sound travels when its source generates pressure waves in the medium surrounding it. These waves move outwards from the source in alternating patterns of varying high and low pressure referred to as **compressions** and **rarefactions**. The distance between two successive peak compressions or rarefactions is called the **wavelength** of the wave. The number of compression or rarefaction peaks passing any point in a second is called its **frequency**.



As the source of sound (~ the ambulance) moves towards an observer, each successive compression or rarefaction peak is emitted a bit closer to the observer. In effect, the wave gets compressed, causing its frequency to increase and its wavelength to reduce. This effect is also seen when the observer moves towards the source, with each successive peak hitting his eardrums sooner. Conversely, when the source moves away from the observer, or the observer moves away from the source, the wave gets elongated and its frequency is reduced.



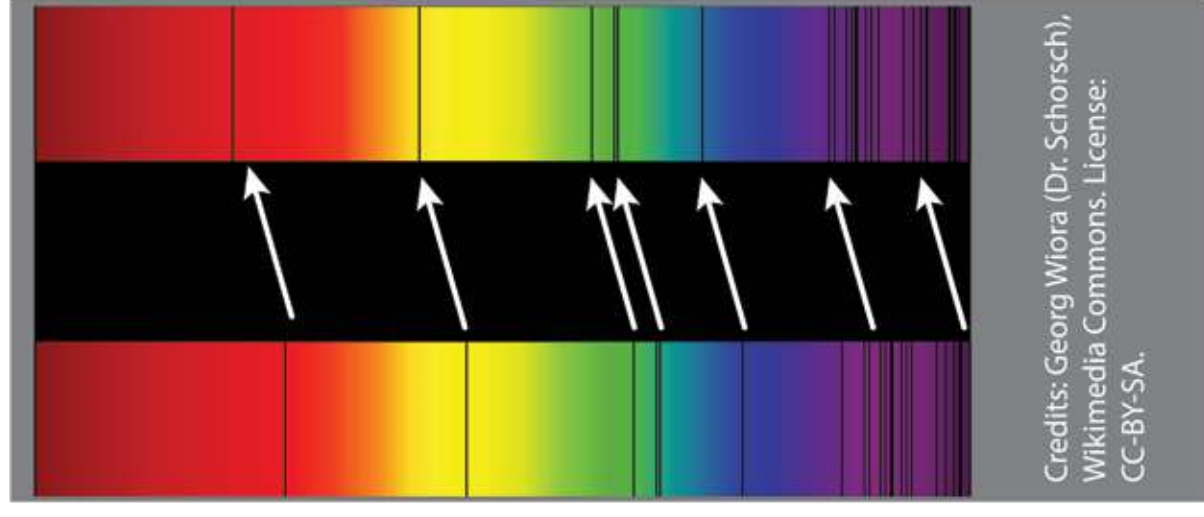
This can be observed in the sudden drop in the pitch of the sound of a vehicle as it races towards us, passes us, and races away. This phenomenon is called Doppler effect after the physicist Christian Doppler who first proposed it in 1842.



sound (a constant 343 m/s in air), the frequency at which it is emitted, and its observed frequency. In fact, this is how police speed guns help determine if a vehicle is speeding. Conversely, we can calculate the observed frequency of sound if we know the velocities of the wave, the source of sound and the observer.

This is also true for all electromagnetic radiations such as visible light, x-rays, gamma rays, infrared rays, ultraviolet rays and radio waves. We know the typical frequencies of radiations emitted by stars. We also know that some of these frequencies are absorbed by chemical elements in the outer layers of the stars. These absorbed frequencies appear as gaps (called **absorption lines**) in the radiation pattern (called **spectrum**) of the star.

Absorption lines in the optical spectrum of a supercluster of distant galaxies (BAS11) (right), as compared to those in the optical spectrum of the Sun (left). Arrows indicating Redshift.



Credits: Georg Wiora (Dr. Schorsch), Wikimedia Commons. License: CC-BY-SA.

If we observe a shift in the absorption lines of a star's spectrum to higher frequencies, called **blueshift**, it indicates that a star is moving towards us. Conversely, a shift to lower frequencies, called **redshift**, indicates that the star is moving away from us. The amount of shift helps us calculate the speed at which this movement occurs.



Ramgopal (RamG) Vallath is a motivational speaker. He is also the bestselling author of the children's science fiction, 'Oops the Mighty Gurgle'. He delivers motivational talks and science workshops in schools. He can be contacted at ramgopal.vallath@gmail.com



POWERING (HUMAN) LIFE ON EARTH

RADHA GOPALAN

Our energy needs are posing a severe threat to the climatic conditions that have allowed life to exist and flourish on earth. What are the sources of energy? How do we use it? Can we make energy choices that minimize our impact on the climate? This article is a tentative step towards exploring these questions.

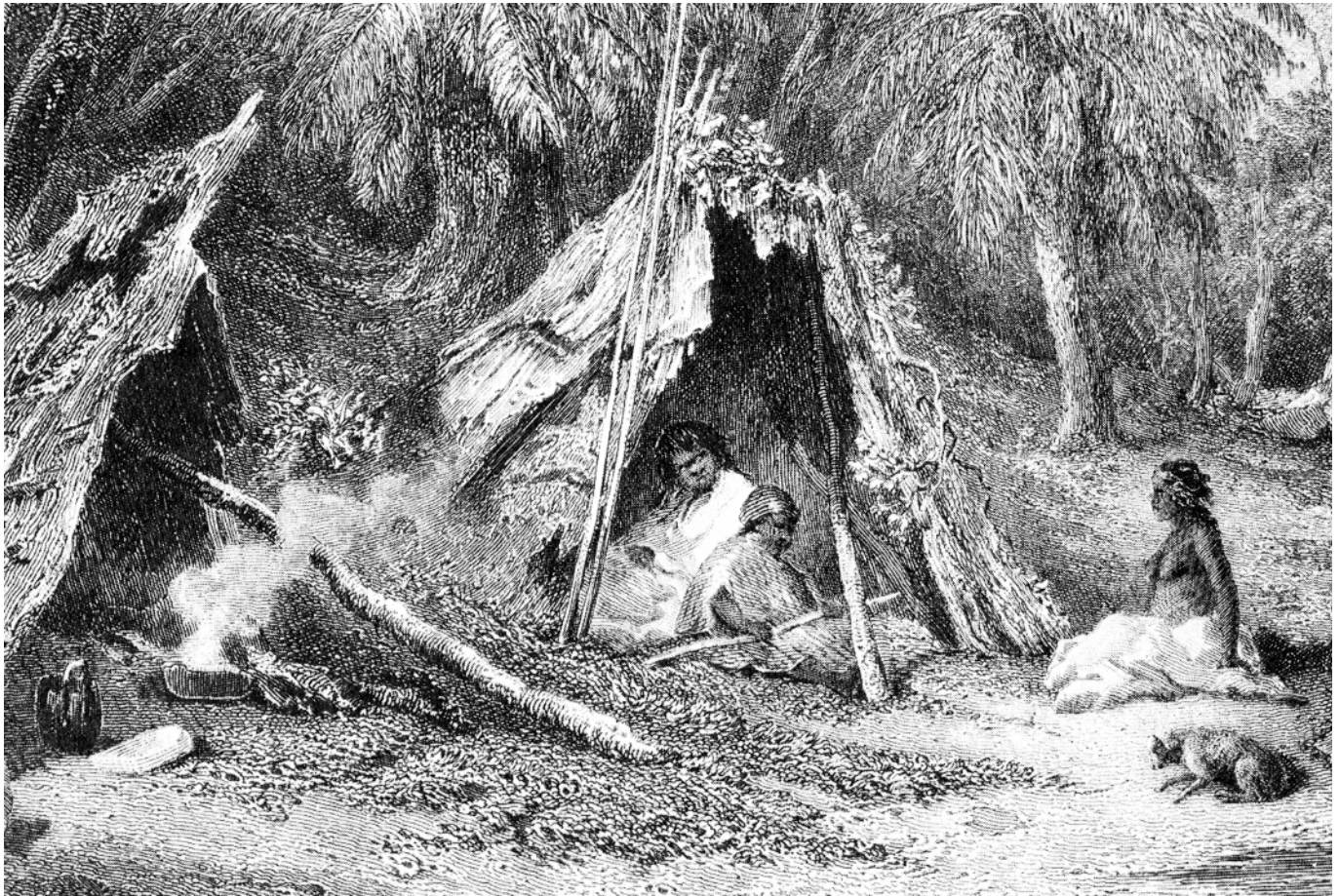
While energy is the basis of existence of all life forms, our energy needs and ways of meeting them have played a key role in shaping human civilization. Over time, we have moved from harnessing heat from fires to developing a collective understanding of other sources of energy, ways of converting one form into another, and a range of specific uses for each form. This knowledge has helped unlock energy for uses well beyond our basic survival (access to food, water, shelter) — in mobility and transportation, health care, recreation, communication, managing waste, research, and the discovery of even more uses. Consequently, hunting-gathering societies have changed to agricultural, and then industrial societies (refer Fig. 1).

The Industrial Revolution in 1750 marked a turning point in the course of human civilization and our relationship with the planet. We became a civilization with high-energy needs, dependent largely on fossil-fuels (refer Box 1). Every form of energy that we

have used since then has had impacts on the planet — from local clearing of land and deforestation, to global changes in atmospheric composition. When we burn fossil fuels to meet our needs — carbon, sulphur and nitrogen are released as gases into the atmosphere (refer Fig. 2). Thus, any shift to more energy-intensive ways of living, growing our food, or transportation, causes a corresponding increase in the levels of carbon dioxide, methane, oxides of sulphur and nitrogen released into the atmosphere.

This increase has a variety of impacts on life on earth. For example, it can lead to acid rain when oxides of sulphur and nitrogen combine with rainwater (refer Fig. 3). It can also result in an increase in average global temperatures as carbon dioxide, methane and nitrous oxide contribute to the Greenhouse Effect. Based on over four decades of climate data, we know that for the first time in the history of the planet, human activity has become a dominant factor in transforming planetary climatic conditions (refer Box 2).

Fig. 1. Our energy needs have shaped the evolution of human societies.



(a) Hunting-gathering.

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(b) Agrarian.

Credits: Pieter Bruegel the Elder, Uploaded by Dcoetzee, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Pieter_Bruegel_the_Elder_-_The_Harvesters_-_Google_Art_Project.jpg. License: CC-BY.



(c) Industrial.

Credits: William Bell Scott, Uploaded by Hohum, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:William_Bell_Scott_-_Iron_and_Coal.jpg. License: CC-BY.

Fig. 2. Carbon, sulphur and nitrogen oxides are produced by combustion of fossil fuels in (a) Power plants (b) Vehicles.



Credits: Pixabay. URL: <https://www.pexels.com/photo/air-air-pollution-climate-change-dawn-221012/>. License: CC0.



Credits: Ruben de Rijcke, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Automobile_exhaust_gas.jpg. License: CC-BY-SA.

Fig. 3. Acid rain is caused by the reaction of sulphur and nitrogen oxides with atmospheric water molecules.



(a) Acid clouds grow from emissions from a refinery on the island of Curaçao.

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



(b) Its severe effects on vegetation in Great Smoky Mountains National Park, United States.

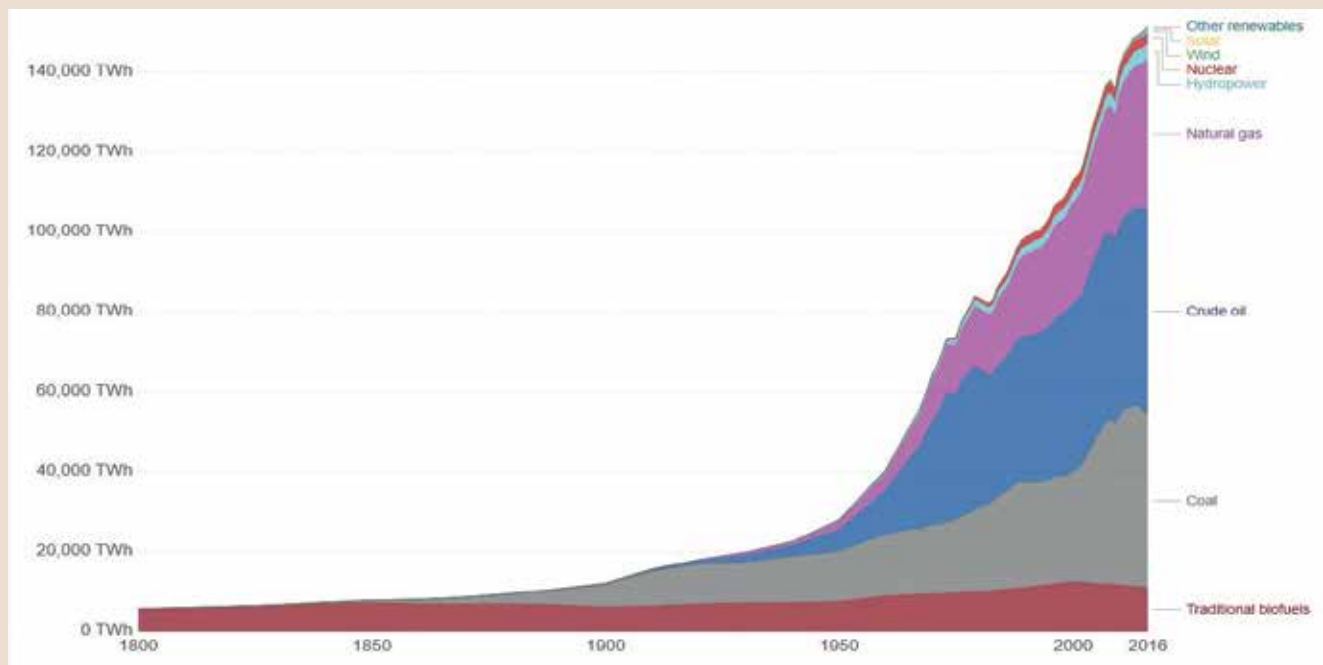
Credits: The Shared Experience, Flickr. URL: <https://www.flickr.com/photos/numbphoto/6221399095/in/photostream/>. License: CC-BY-NC-ND.

Box 1. What are fossil fuels?

As the name suggests, fossil fuels are fuels formed through the fossilization of organic matter. This process reportedly began about 4 to 2.5 billion years ago. It involved the gradual transformation of decaying and decomposing plant and animal matter through heat, pressure and geological processes into dense, combustible material. Examples include coal, crude oil (petroleum), natural gas, bitumen, oil shale, tar sands and heavy oils. All of these have to be extracted, processed and transported before they can be burnt to provide energy.

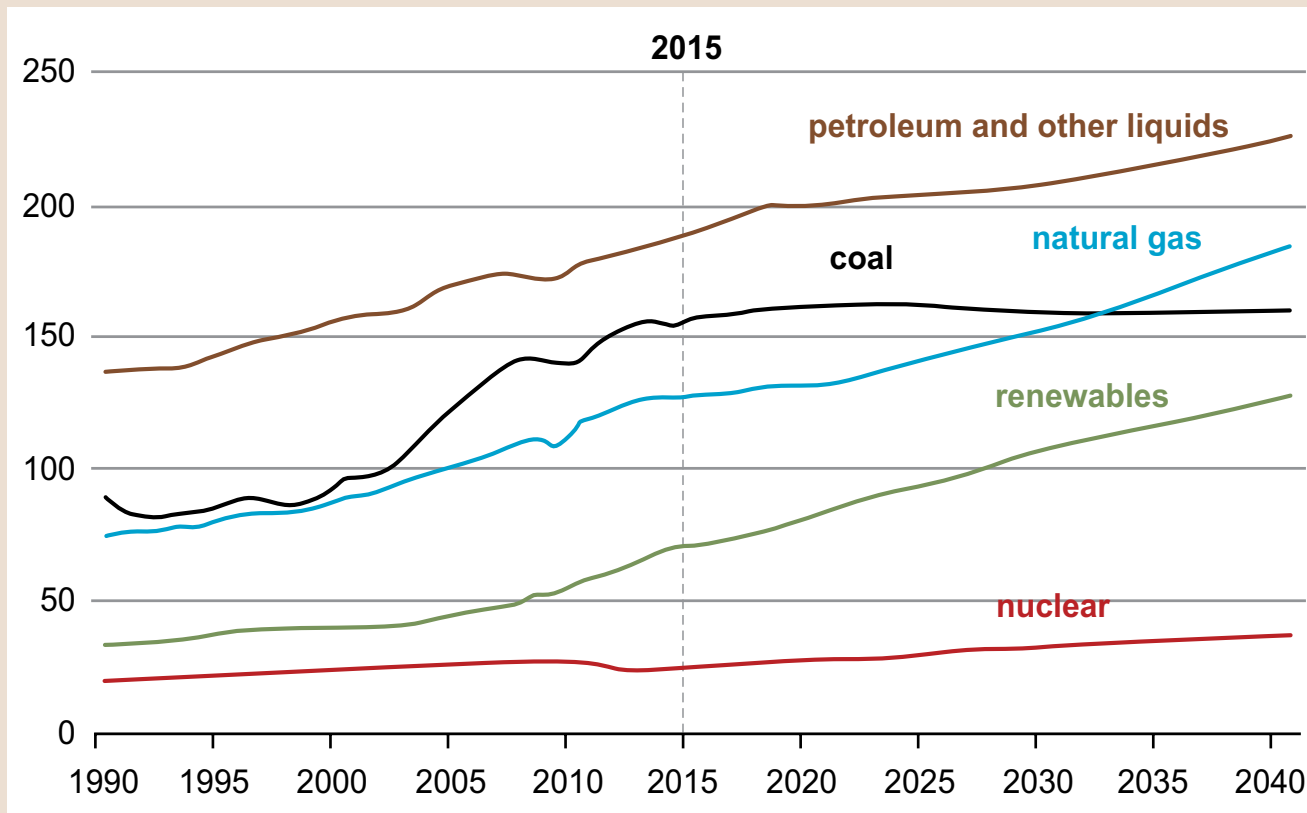
Our current energy needs are met primarily by the combustion of oil, followed by coal, and, then, natural gas. It seems likely that these may continue to be our fuels of choice well into the future (refer Fig. 4).

Fig. 4. Fossil fuels meet most of our current (a) and projected future (b) energy needs.



(a) Global primary energy consumption measured in terawatt-hours (TWh) per year. 'Other renewables' are renewable technologies not including solar, wind, hydropower and traditional biofuels.

Credits: Vaclav Smil (2017). Energy Transitions: Global and National Perspectives & BP Statistical Review of World Energy. URL: <https://ourworldindata.org/grapher/global-primary-energy>. License: CC-BY-SA.



(b) World energy consumption by energy source.

Credits: Created by EIA, International Energy Outlook, U.S. DOE Energy Information Administration 2017, and uploaded by Delphi234 on Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:World_energy_consumption_outlook.png. License: CC-BY.

Can we make energy choices that minimize the impact of human activity on planetary conditions? Is it possible to imagine a world without fossil fuels? A world powered by 'renewable sources' of energy like wind, water, and the Sun (refer Box 3)? And, more importantly, one where we consume less and, therefore, use less energy?

Something to think about as we move to new forms of energy!

".....Every transition to a new form of energy supply has to be powered by the intensive deployment of existing energies and prime movers: the transition from wood to coal had to be energized by human muscles, coal combustion powered the development of oil, and ... today's solar photovoltaic cells and wind turbines are embodiments of fossil

energies required to smelt the requisite metals, synthesize the needed plastics, and process other materials requiring high energy inputs..." — Vaclav Smil, *Energy and Civilization*, MIT Press, 2017, p. 230.

The energy choices we make are not just about technology: they are social, economic, ecological and political choices, with the power to affect the quality of life of humans and other life forms.

The main source of energy in pre-industrial times was solar power! Unlike today, however, this power was in a form captured by plants — biomass. Biomass (wood, agricultural residue, dung cakes etc.) continues to be used even today for heating and cooking in several countries, including India, in Asia, Africa and Latin America (refer Fig. 7). Some forms of biomass are also used to meet other needs. For example, floating logs of wood are used

to transport goods and people down a river (what do you think is the source of energy in this example — biomass or water?). Wind powered sails enabled trade till the early 19th century. On land, wind and water (refer Box 4) have been used for at least 2000 years for milling and grinding grain, extracting oil from oilseeds, and powering industry. These were replaced by coal-powered steam engines in 1820.

While shifting from non-renewable to renewable sources of energy can reduce the amount of carbon dioxide released into the atmosphere, it is not a magic bullet — solar power plants and windmills need land (refer Fig. 8); and the machinery for both are manufactured using fossil fuels (refer Box 5). The real question then is — can we reduce how much we consume so that we need less energy?

Box 2. Fossil Fuels and Climate Change

The burning of fossil fuels for energy combines carbon in the fuel with oxygen in the air to produce carbon dioxide. Carbon dioxide is a greenhouse gas – it traps enough heat to keep the global average surface temperature of the planet at a level essential for sustaining life. But, excessive concentrations of this gas in the atmosphere can lead to global warming (refer Fig. 5).

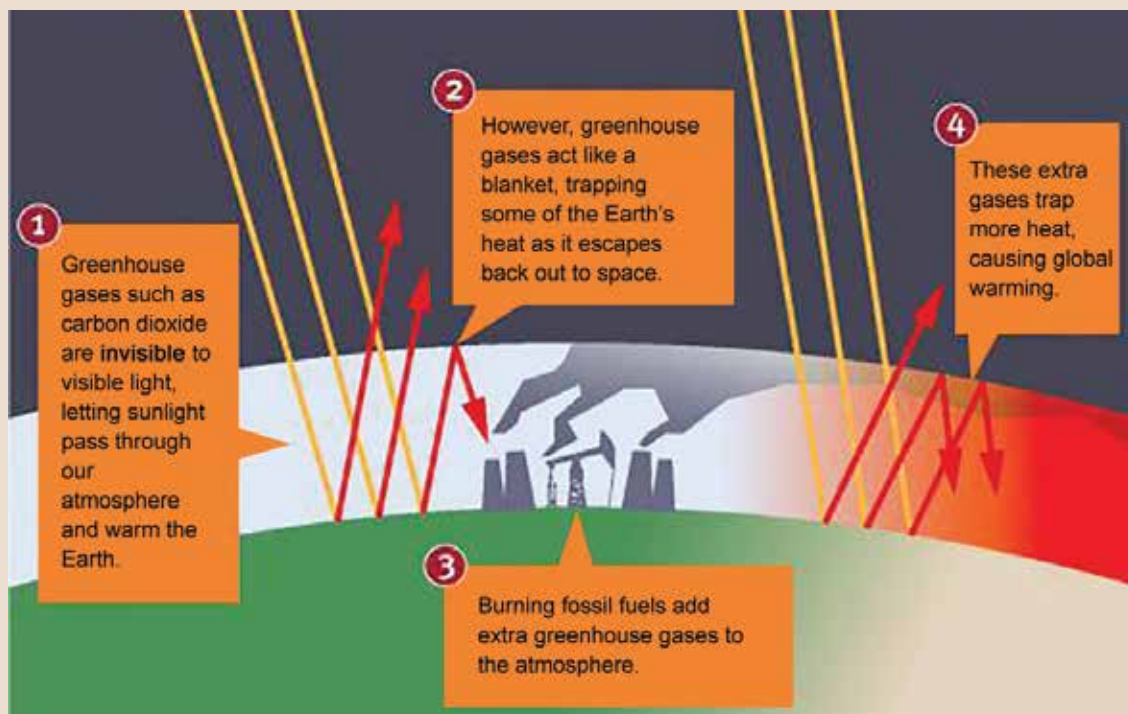


Fig. 5. Excessive concentrations of greenhouse gases like carbon dioxide can lead to global warming.

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According to the Intergovernmental Panel on Climate Change (IPCC), the concentration of carbon dioxide in the atmosphere has increased by more than 30% since pre-industrial times. Given our current energy needs, atmospheric carbon dioxide is still increasing at an average rate of $\sim 0.4\%$ per year. This has led to a corresponding increase in global average surface temperatures (refer Fig. 6), with serious impacts on global climate and climatic patterns.

What does this mean for human society and other life forms? Higher surface temperatures result in the faster melting of glaciers (as shown by scientific data from the Arctic, Antarctic and, closer home, the Himalayas), leading to a rise in sea levels and the submergence of coastal areas. Changing climatic patterns result in extreme weather conditions (higher-than-average temperatures, changing precipitation patterns, the increased incidence of storms and cyclones) and their associated impacts on life and property.

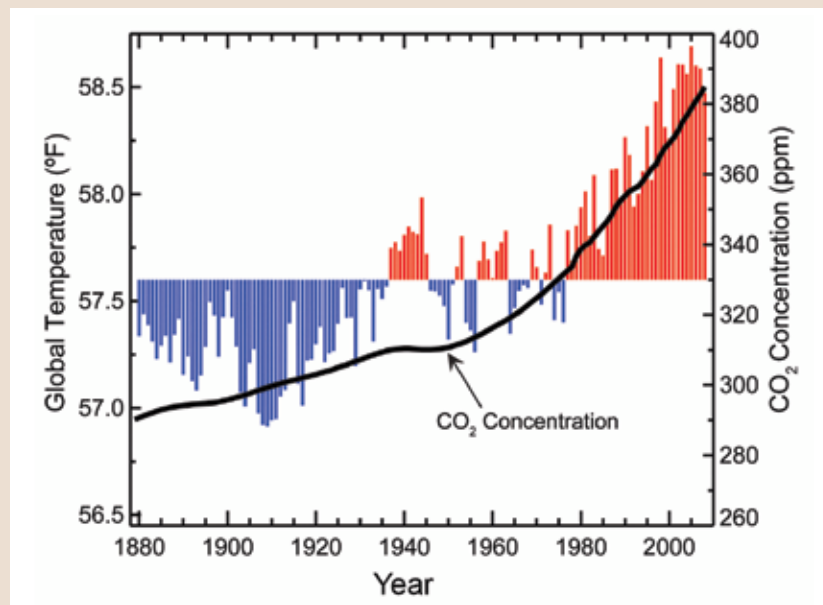


Fig. 6. Atmospheric carbon dioxide concentrations and global annual average temperatures in the period 1880-2009.

Global annual average temperature is measured over both land and oceans. Red bars indicate temperatures above and blue bars indicate temperatures below the average temperature for the period 1901-2000. The black line shows atmospheric carbon dioxide (CO₂) concentration in parts per million (ppm).

Credits: Created by NOAA/NCDC in Global Climate Change Impacts in the United States, Cambridge University Press; and uploaded by Enescot on Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Atmospheric_carbon_dioxide_concentrations_and_global_annual_average_temperatures_over_the_years_1880_to_2009.png. License: Public Domain.

Box 3. Renewable and Non-Renewable Energy Sources

Based on their origins, energy sources can be classified into two categories – renewable and non-renewable. A renewable source of energy is one that is replenished at a rate faster than it is consumed. Examples include solar, wind, geothermal, hydro, and some forms of biomass. According to the International Energy Agency (IEA), renewable sources of energy contributed 13.2% of the world's total primary energy supply in 2012, and 22% of it in 2013. By the year 2020, their contribution to the total energy supply is predicted to increase to 26%. In contrast, a non-renewable energy source is one that is formed by geological action on organic matter over extremely long periods of time. Even if non-renewables were consumed in decades or centuries, the rate of their consumption would be much faster than the rate at which they are formed. Examples include coal, oil, and natural gas.

It is interesting to note that both renewable and non-renewable energy sources are ultimately derived from the Sun.

Photosynthesis converts solar energy into organic matter or biomass, which decomposes under high pressure to form fossil fuels. Sunlight is directly converted into solar energy by photovoltaic cells; while heat from the Sun drives the wind and water cycles used to generate renewable energy.

Fig. 7. Different forms of biomass are still used in India to meet energy needs for cooking and heating.



(a) Firewood.

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(b) Agricultural residue.

URL: <https://www.maxpixel.net/Summer-Sunset-Landscape-Autumn-Field-Straw-Farm-1677853>. License: CC0.



(c) Dung cakes.

Credits: The International Livestock Research Institute (ILRI), Flickr. URL: <https://www.flickr.com/photos/ilri/4574444944>. License: CC-BY-SA.

Fig. 8. Setting up solar and wind farms has impacts on land-use.



(a) A solar farm.

Credits: Brahma Kumaris, Flickr. URL: <https://www.flickr.com/photos/brahmakumaris/13993984261>. License: CC-BY-NC.



(b) A wind farm.

Credits: sarangib, Pixabay. URL: <https://pixabay.com/en/wind-mill-energy-alternative-2251810/>. License: CC0.

Box 4. Is water renewable?

Share details of the increasing scarcity of water resources due to:

- (i) Changes in precipitation patterns
- (ii) Increasing contamination of surface and ground water sources
- (iii) Overexploitation of groundwater sources and
- (iv) Over-extraction of surface water sources.

Encourage students to use this information to debate on whether water can really be thought of as a renewable resource today.

Parting thoughts...


Imagine a scenario where coal and oil have not been discovered. Would the use of wind, water and biomass as sources of energy have made our lives different from what they are today? How?

Box 5. Questions & Activities for students:

1. Can you think of an activity which does not use some form of energy?
2. Can you identify a task that requires only human energy?
3. Map your day to list out things you can do without using electricity.
4. Find out: (a) what the primary source of electricity in your home and city is, and (b) where the raw material for this source is derived from. For example, if the primary source of electricity in our home is a coal- or gas-fired thermal power plant, where is the coal or natural gas coming from?
5. In which aspects of your daily life can you replace energy from fossil fuels with that from renewable sources? How would you do this?

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Radha Gopalan is an environmental scientist with a Ph.D from Indian Institute of Technology Bombay, 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.



CLEAN ENERGY

A. Q. CONTRACTOR

A significant source of air pollution, so visible in our urban centers, is emissions from motorized vehicles. This article describes a clean energy approach to vehicular transport. Solar energy can be harnessed to produce hydrogen, which can be converted to electricity on-demand to drive electric vehicles.

Humans, most likely, first started harnessing energy for their use by learning to keep fires (discovered accidentally) alive. The fuel to feed these fires may have initially consisted of dead leaves, twigs and branches from the forest floor. Once the technology for the necessary tools became available, humans may have graduated to chopping down trees for fuel. With the discovery of coal and peat, we had access to fuels with much greater energy density (amount of energy stored per unit volume of a given mass of substance) in seemingly limitless supply. Coal powered the Industrial Revolution in 18th century Europe. Early automobiles were powered by steam engines which used coal as fuel. The invention of the internal combustion engine made liquid fuels like gasoline or petrol important. The discovery of vast reserves of oil has transformed almost every aspect of modern life to such an extent that we have become addicted to it.

Our consumption of energy has increased significantly. In fact, per capita energy consumption is considered one of the measures of 'development'. However, today, as the consequences of this excess are being experienced in terms of air quality, Global Warming and Climate Change, we need to seek 'cleaner' fuels.

Deriving energy from hydrogen

Ideally, a fuel should combine two properties — high energy density, and the ability to burn cleanly and efficiently. Of course, there can be no such thing as an 'ideal' fuel. While carbonaceous fuels — like coal, oil and gas — have high energy densities; 'clean' fuels do not produce greenhouse gases (GHGs), suspended particulate matter (SPM), or oxides of sulphur and nitrogen (refer **Box 1**). Among the many alternatives we are currently exploring, hydrogen appears to be

Box 1. GHGs and SPMs:

Greenhouse gases (GHGs) refer to those gases in the Earth's atmosphere that absorb infrared rays reflected from its surface, preventing them from escaping into space. Their heat-trapping ability results in an increase in surface and atmospheric temperatures. Examples include water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4).

Suspended particulate matter (SPM) is an insoluble mixture of liquids and solids suspended in the atmosphere. Composed of dust, ash, pollen or smoke, SPM is a major contributor to air pollution.

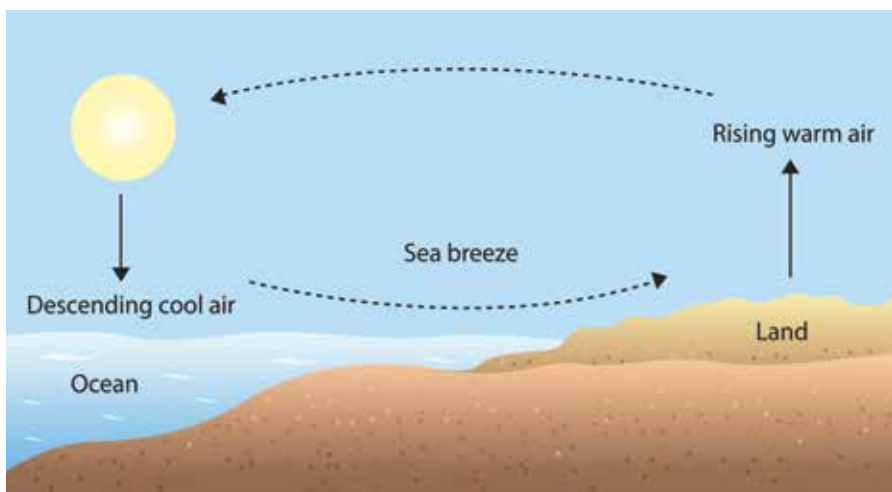


Fig. 1. Local winds are produced by the differential heating of land and sea by the Sun.

Credits: Adapted from an image by Crystal Wicker on Weather Wiz Kids. URL: <http://www.weatherwizkids.com/weather-wind.htm>.

promising as a clean fuel. It has a high energy density – almost three times as much as oil per unit weight. Also, on combustion in air, it produces water, not GHGs or SPMs.

The idea of using hydrogen as a source of energy was first proposed by J. B. S. Haldane in 1923. Then, in 1970, John Bockris used the term 'Hydrogen Economy' to describe the possibility of a global economy powered not by carbonaceous fuels, but by hydrogen. This calls for the invention of new technologies for the production, storage and utilization of hydrogen as a fuel. Unfortunately, molecular hydrogen is not freely available in nature. While it can be produced by splitting water into hydrogen and oxygen by electrolysis,

how does one derive electricity from it in a manner that does not harm the environment?

Like with most things, nature provides a clue – the Sun is the ultimate source of energy for all life on Earth. Thus, energy can be harvested directly from sunlight using devices called photovoltaic (PV) cells; or, indirectly from wind power, produced as a result of the uneven heating of the earth's surface by the Sun (refer Fig. 1).

The energy harvested through either of these approaches can be converted to electricity (refer Fig. 2). Solar energy may need to be stored for use at night or on days with poor sunlight. Chemical storage as hydrogen is one of the most stable ways of doing this.

Another option is to use the electrical energy from PV cells to charge a secondary battery like the lead-acid batteries used in automobiles, or a version of lithium cells used in portable devices (e.g. mobile phones, laptops etc).

Electricity can be stored in rechargeable batteries or used to electrolyze water to produce hydrogen and oxygen (refer Fig. 3). While burning hydrogen in a combustion engine would be too dangerous for normal use, it can be 'combusted' in a fuel cell to produce electricity as and when required.

Photovoltaic (PV) cells

These are devices capable of converting the energy from sunlight (~photo) into electricity (~voltaic) through a phenomenon called the Photoelectric effect (refer Fig. 4). In this phenomenon, certain materials release or eject electrons or ions (charge carriers) upon being exposed to electromagnetic radiations (such as visible light, ultraviolet, infrared etc.). Capturing the released charge carriers produces an electric current.

Since silicon has a band-gap that is close to optimum for the absorption of solar photons (refer Box 2), almost

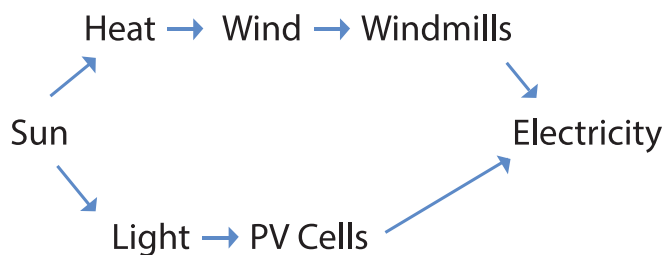


Fig. 2. Harvesting solar energy to produce electricity.

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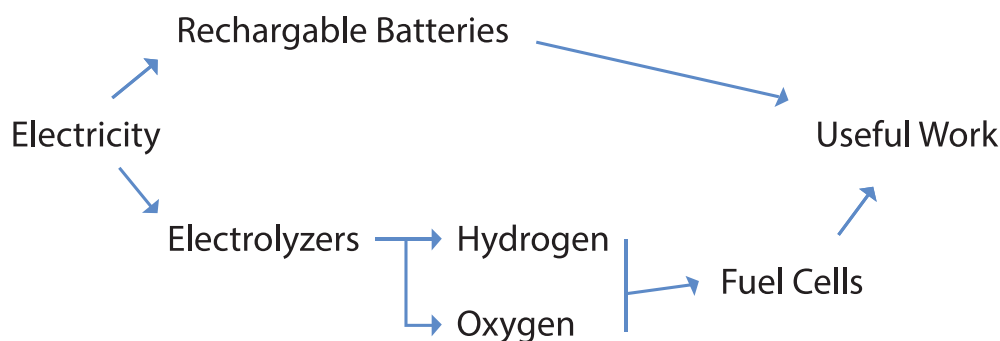


Fig. 3. Using electricity to produce hydrogen.

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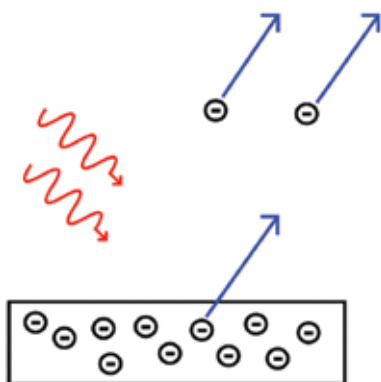


Fig. 4. The photoelectric effect.

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

all commercially available PV cells are based on crystalline silicon. In a silicon-based PV (Si-PV) cell (refer Fig. 7) cell, silicon atoms absorb a photon to release an electron. While the electron drifts to the surface and is conducted away through the silver (Ag) contact, the positively charged electron hole it leaves behind (refer Fig. 8) drifts to the aluminum (Al) contact, resulting in the flow of electric current from Al to Ag (refer Fig. 9). Since one silicon PV cell produces less than 1 V of electric potential, several of them are aggregated together in a modular form to produce higher voltage.

Box 2. Band gap and Photoelectric effect:

For a material to show the photoelectric effect, the energy required by excited electrons to cross the energy gap between its valence (lower energy electron orbital) and conduction (higher energy electron orbital) bands has to match the energy of a photon (refer Fig. 5). The more the number of electrons in the conduction band, the greater the electrical conductivity of the material. While the band gap in insulators is too high, the free electrons in conductors move too randomly to produce an electric current. Thus, it is in semiconductors, with their intermediate band gap, that charge carriers can be excited most effectively (refer Fig. 6).

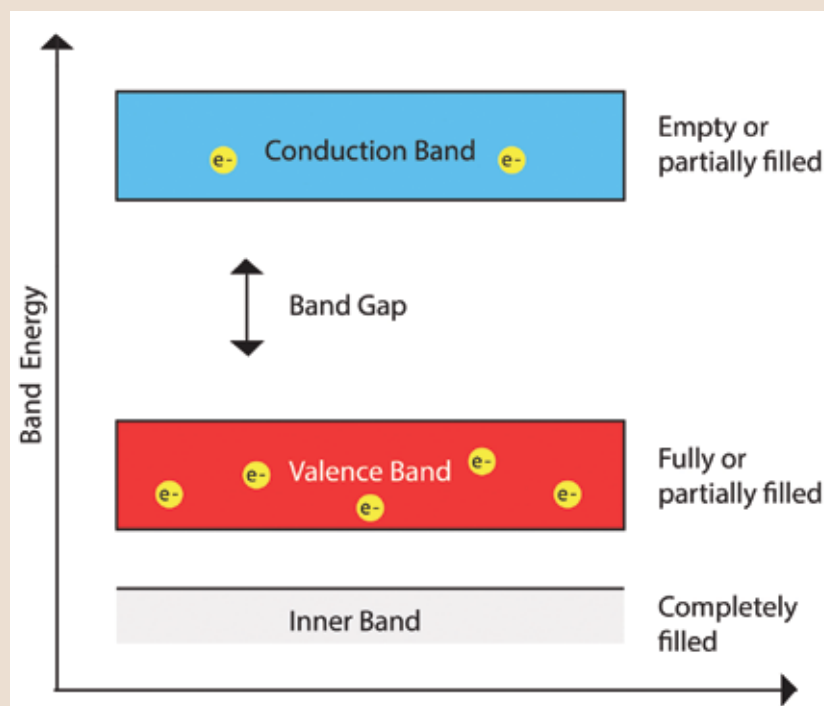


Fig. 5. The energy gap between the valence and conduction bands.

Credits: Adapted from an image on Physics and Radio Electronics. URL: <http://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor/hole.html>.

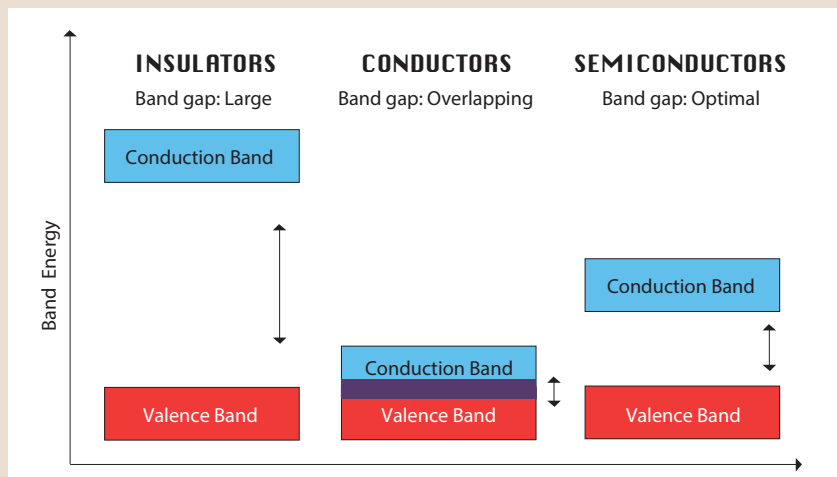


Fig. 6. The energy gap in a semiconductor makes it the most effective material in a PV cell.

Credits: Adapted from an image by Pieter Kuiper, Wikimedia Commons. URL: <https://commons.wikimedia.org/wiki/File:Isolator-metal.svg>.

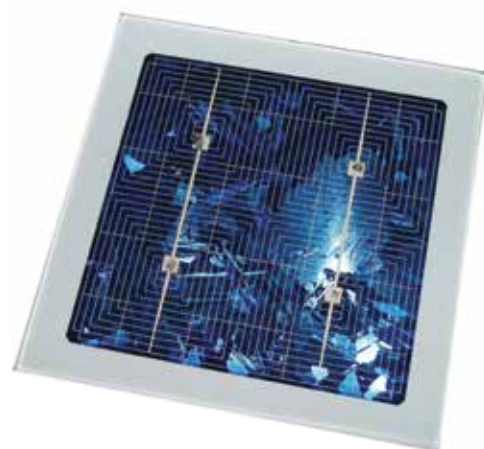


Fig. 7. A polycrystalline silicon-based solar cell.

Credits: Nosferatu it (modified by Rogilbert) Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:4inch_poly_solar_cell.jpg. License: CC-BY-SA.

Solar photovoltaic cells have now become a fairly common sight, particularly in street lighting. Panels of Si-PV cells are becoming a popular option for lighting in remote areas that are not connected to the grid, or do not receive an adequate power supply.

Electrolyzers

In the late 18th century, it was shown that water could be electrolyzed to decompose it into gaseous hydrogen and oxygen in the proportion 2:1. This reaction is the basis of modern electrolyzers.

In a typical water electrolyzer (refer Fig. 10), a proton-conducting membrane separates the cathode and anode compartments. Electron holes oxidize water to protons and oxygen gas at the anode, while their electrons are accepted by protons from the acidified

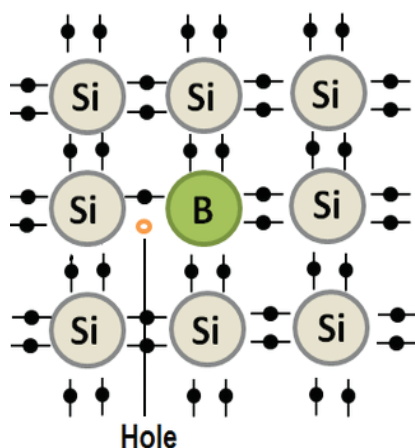


Fig. 8. The release of an electron from a silicon crystal lattice creates a hole.

Credits: J.M.K.C. Donev et al. (2018). Energy Education - Electron hole [adapted from HyperPhysics, (August 20, 2015): P and N-Type Semiconductors (<http://hyperphysics.phy-astr.gsu.edu/hbase/solids/dope.html>)]. URL: https://energyeducation.ca/encyclopedia/Electron_hole. [Accessed: August 28, 2018] License: CC-BY-SA.

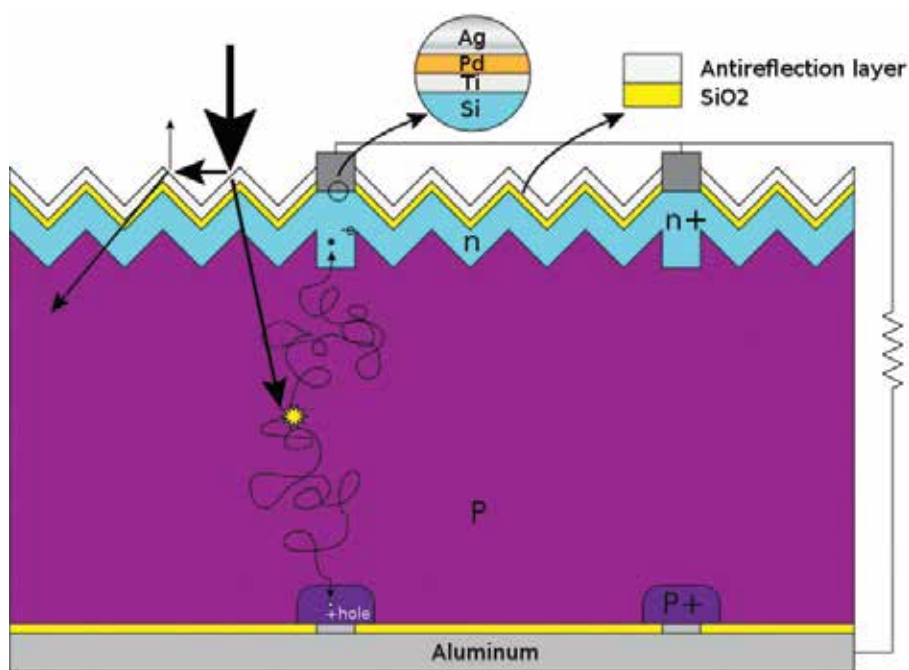


Fig 9. A cross-section of an Si-PV cell.

Credits: Cyferz, Wikimedia Commons. URL: <https://commons.wikimedia.org/w/index.php?curid=17902127>. License: CC-BY.

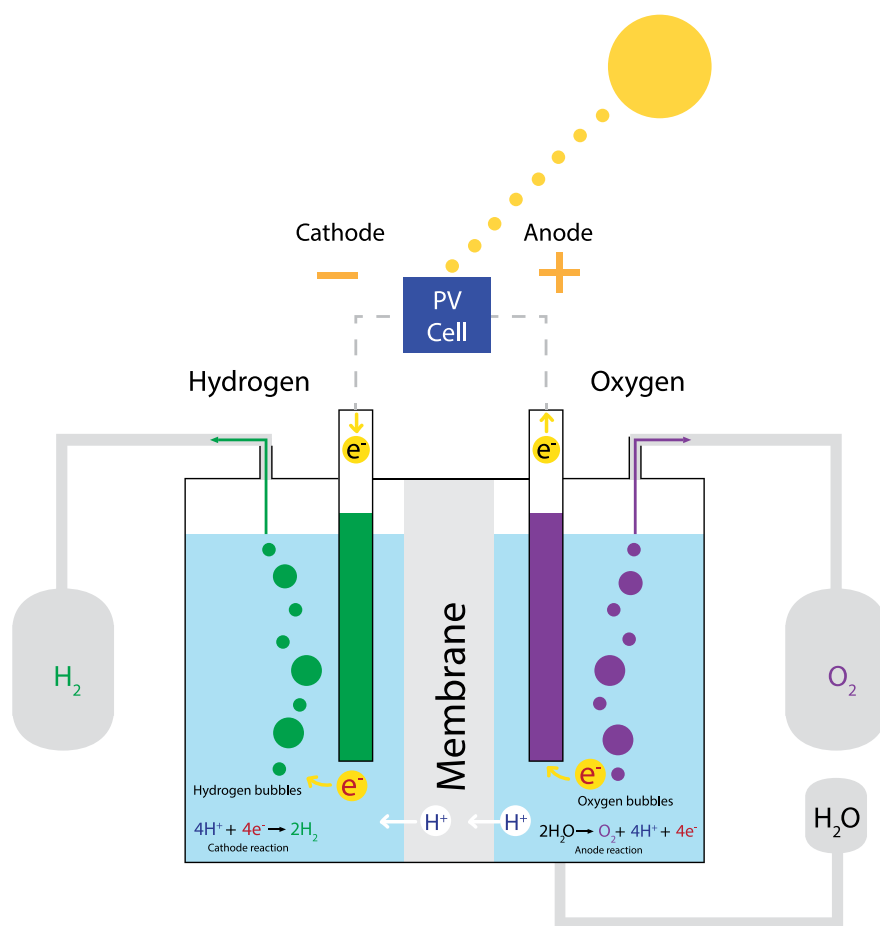


Fig. 10. Schematic of a typical water electrolyzer working on a DC current generated by a PV module.

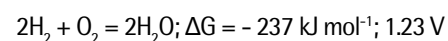
Credits: Adapted from images by The Office of Energy Efficiency & Renewable Energy, The U.S Department of Energy (URL: <https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis>) and Davidlfritz, Wikimedia Commons (URL: <https://commons.wikimedia.org/w/index.php?curid=26251918>).

water to produce hydrogen gas at the cathode. Water is continually fed into the electrolyzer to maintain the balance of the volume consumed. The two gases can be stored under pressure in cylinders, or in the lattice of a suitable storage material.

Fuel cells

These devices convert the energy from chemical reactions to electricity and heat. Any fuel cell consists of three adjacent segments – an anode, an electrolyte, and a cathode (refer Fig. 11). Chemical reactions occur at each of the two interfaces of this assembly.

Fuel cells can vary depending on the nature of the electrolyte they use. For example, the electrolyte in a proton-exchange membrane (PEM) fuel cell is in the form of an acidic, water-based polymeric membrane (refer Fig. 12). Electricity is produced from the energy released by combining oxygen (from the air) with molecular hydrogen (stored in a pressurized cylinder or tank). Since this reaction produces a potential difference of only about 1.23 V between the cathode and the anode, higher voltages are obtained by aggregating many fuel cells together in a modular arrangement similar to that used in PV cells.



Clean energy for transport

The transport industry is a major contributor to environmental pollution, particularly in urban areas. In fact, the crisis caused by vehicular emission in cities in China and India is frequently a subject of news headlines!

Electric vehicles are being considered as part of a broader strategy towards reducing vehicular emissions that includes improvements in mass transit systems. In fact, some of the earliest cars to be built, like Thomas Parker's model in 1895, were also electric! Conceptually, these early models of electric cars are not very different from their current counterparts – both

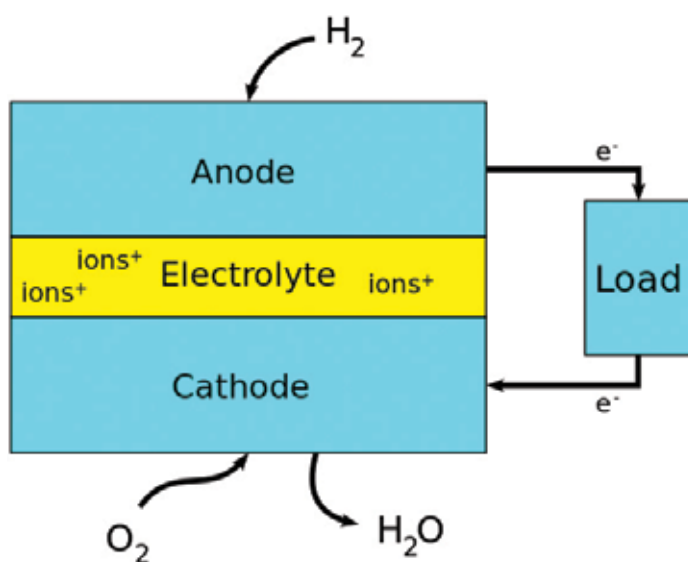


Fig. 11. Components of a fuel cell.

Credits: Paulsmith99, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Fuel_Cell_Block_Diagram.svg. License: CC-BY.

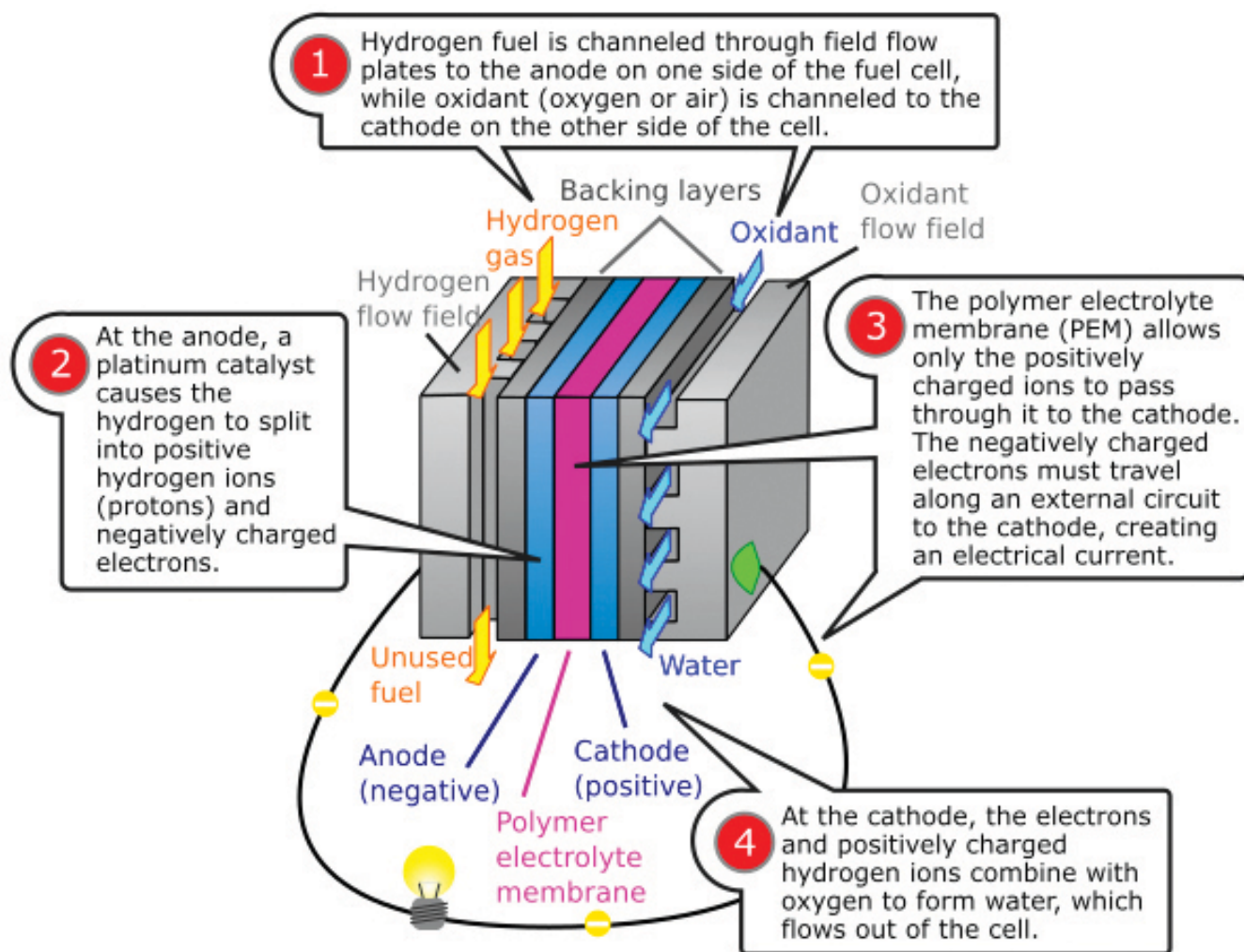


Fig. 12. A proton exchange membrane (PEM) fuel cell.

Credits: Jafet, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File%3APEM_fuelcell.svg. License: Public Domain.



Fig 13. A fuel cell powered bus — Toyota FCHV Bus (Expo 2005 Aichi Japan specification).

Credits: Gnsin, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:TOYOTA_FCHV_Bus.jpg. License: CC-BY-SA.



Fig. 14. The first fuel-cell powered automobile to be introduced in the market — a 2015 Toyota Mirai sedan.

Credits: Turbo-myu-z (modified by Mariordo), Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Toyota_mirai_trimmed.jpg. License: CC-BY-SA.

operate on rechargeable batteries. Current models are, however, built with light-weight material, and powered by batteries with much higher energy density and efficiency. Fuel cells could potentially replace rechargeable batteries in electric vehicles.

As of 2011, about 100 fuel-cell based buses have been deployed around the world, with 39-141% greater fuel economy than natural gas or diesel powered buses (refer Fig. 13). The use of fuel cells in the automobile sector is a relatively more recent development – the first model was introduced in the market in 2015 (refer Fig. 14). While

the fuel economy of fuel cell powered cars seems comparable to those powered with rechargeable batteries, the latter tend to have lower range. For example, a 2016 model of a fuel-cell-powered car has a fuel economy of more than 28 km/l, and a range as high as about 500 km.

To conclude

The idea of using hydrogen as a fuel is still very young. As with other new technologies, it will need to overcome several challenges to become a reality. For example, fuel cells are just beginning to make their appearance in applications like fully electric or hybrid cars. The

generic advantages of this application is the high energy conversion efficiency, silent operation and zero GHG emission associated with fuel cells. However, these vehicles are, at present, very expensive. While mass production is expected to reduce per unit costs of manufacturing, it is also likely that as more stringent emission standards come into force, the value of clean energy vehicles will begin to justify its additional cost.

Of course, this is only **one** sector of our energy economy. Tackling air pollution and climate change will require similar innovations in other sectors as well.



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DISCOVERING THE HELICAL STAIRCASE

ROHINI CHINTHA

Mittu is smitten by a photograph of what looks like an 'X' in his grandpa's scrapbook. In response to his questions, Grandpa narrates a story – that of the discovery of the 'molecule of life'. Does Mittu succeed in his quest to understand the mystery of 'X'? Let's find out.

Mittu came down from the attic bursting with curiosity. His project on 'how grandparents spend their holidays without gadgets' was about to take off. Mittu had just found a sketch of a mysterious black and white photograph of what looked like an X in Grandpa's scrapbook, and couldn't wait to ask Grandpa about it.

Grandpa was out in the garden, reading his newspaper. Mittu rushed to Grandpa, showed him the 'X' and said, "Let's start here."

Grandpa looked at the photograph gravely. "This is a copy of the famous Photograph 51. The most crucial evidence in the discovery of the **molecule of life** – deoxyribonucleic acid or DNA."

"DNA is the molecule of life? How?"

"Tell me what you know about cells? The ones that make up plants and animals?" Grandpa questioned.

"A cell..." Mittu tried to recollect, "...is the basic unit of life. It is made up of a protective outer covering called the plasma membrane, and a jelly-like substance called

the cytoplasm. The cytoplasm has many organelles which help the cell survive?"

"Go on," encouraged Grandpa.

"A cell's nucleus has DNA..." Mittu paused.

Grandpa patted Mittu. "Well, you've learnt your lesson well. Do you know that DNA codes for amino acids?"

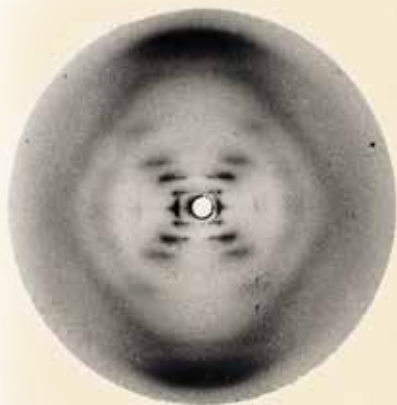
"I know amino acids!" Mittu looked excited. "Amino acids make up proteins. Proteins make up the cell and, the whole organism."

Grandpa smiled. "Yes. And some proteins act as enzymes that help in the formation of carbohydrates and lipids. Carbohydrates, lipids and proteins together make up life structures. This is why DNA is popularly called the '**molecule of life**'."

"DNA," Mittu added brightly, "passes characters (~traits) from parents to children."

"Yes! So it is also the '**molecule of heredity**' – the genetic material." Grandpa was silent for a minute and then sprang a question at Mittu. "But, Mittu, have you heard the story of how we know all this about DNA?"

Mittu shook his head.



The mysterious photograph.

Credits: From the 'Linus Pauling and the Race for DNA' website, OSU Libraries Special Collections & Archives Research Center, Oregon State University Libraries and Press (scarc@oregonstate.edu). URL: <http://scarc.library.oregonstate.edu/coll/pauling/dna/pictures/sci9.001.5.html>. License: Used with permission of the rights owner.

*Franklin's
Fingerprint
Type Q*

"The quest to understand heredity began centuries ago," Grandpa explained. "People like Pythagoras, Empidocles, Hippocrates, Aristotle, Leonardo-da-Vinci and Maupertuis came up with many ways of explaining it. But, the first real breakthrough came in 1866, with Gregor Johann Mendel's principles of heredity. Mendel, an Austrian monk with an interest in plant variations, had been conducting experiments to understand transmission of characters in the edible pea plant. Based on the results of these experiments, he proposed that parents pass on their characters to their

offspring (~children)."

"Mendel knew about DNA in 1866 then?" Mittu asked, surprised.

"No," Grandpa smiled, "Mendel used the term '**factors**' to refer to the units of transmission of characters or traits from parents to their children. According to him, factors were of two types. Some, which he called **recessive**, were associated with traits that were not seen in every generation. Others, that he called **dominant**, were associated with traits seen in all generations."

"Your sharp nose is a recessive character, right, Grandpa?" Mittu said eagerly

"Because dad (your first generation child) missed it, but I (your second generation child) got it?"

"Yes", Grandpa smiled. "But, of course, not all characters can be categorized as recessive or dominant. Some show intermediate features too."

Grandpa removed his spectacles and wiped them. Mittu pulled out a cobweb stuck on Grandpa's scrapbook and asked, "So, where does this photograph of X come in?"

"Not so fast," cautioned Grandpa. "That comes nearly a century after Mendel. To continue with our story, the next big discovery happened in 1869. A Swiss biologist called Friedrich Meischer happened to accidentally discover a new molecule while studying the proteins present in the white blood cells of pus. He knew this molecule was different from a protein because it formed a precipitate with acids, dissolved in alkaline solutions, and could not be digested by proteases (enzymes that digest proteins). Assuming it came from the nucleus of the cells he was studying, Meischer named this new molecule '**nuclein**'."

"How is nuclein related to Mendel's factor?" Mittu inquired.

Grandpa explained, "While Meischer was exploring the chemical nature or structure of nuclein, or what it looked like; Mendel had looked at the functions of nuclein, or how it passed on characters from parents to children."

"Oh!" Mittu pretended to understand.

Grandpa went on. "It was nearly a decade later that Albrecht Kossel, a German biochemist, discovered that Meischer's nuclein was, in fact, made up of 5 molecules – Adenine (A), Guanine (G), Cytosine (C), Thyamine (T) and Uracil (U). He called these sub-molecules '**nucleobases**'. Kossel was awarded the Nobel prize in Medicine in 1910 for his discovery."

Beginning to piece things together, Mittu wondered aloud, "So, nuclein is made up of nucleobases?"



Gregor Mendel is known as the 'Father of Modern Genetics'.

Credits: Uploaded by Dominikmatus, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Gregor_Mendel_2.jpg. License: CC-BY.



Friedrich Miescher discovered 'nuclein'.

Credits: Uploaded by MaxSem, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Friedrich_Miescher.jpg. License: CC-BY.

Nodding to show that Mittu was on the right path, Grandpa continued, "Nuclein is also called nucleic acid, chromatin, chromosome, or DNA."

Mittu added energetically. "Aha! Meischer was the first to observe DNA!"

Grandpa resumed his story. "Going back a bit, in 1900, three scientists – Hugo de Vries, Carl Erich Correns and Erich Tschermak Von Seysenegg, had independently confirmed Mendel's experiments. Hugo De Vries called Mendel's factors, pangenetes. Today, we know pangenetes as 'genes'. So, genes are nothing but Mendel's factors."

"Cool."

"Then, in 1902, the German biologist Theodore Boveri, suggested that chromosomes or nuclein carried genes or factors."

"Great!" Mittu was enthusiastic. "So, Boveri combined Mendel's work on factors of heredity with Meischer's work on molecules. Genes on chromosomes or DNA pass characters from parent to child through the nucleobases A, T, G and C!"

"Brilliant theory!" said Grandpa, patting Mittu.

Mittu looked pleased. "And, is this correct?"



Albrecht Kossel was awarded the Nobel Prize in Medicine in 1910 for his discovery of nucleobases.

Credits: Owned by George Grantham Bain Collection (Library of Congress), and uploaded by MaterialsScientist, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Friedrich_Miescher.jpg. License: CC-BY.

"It is. And this was confirmed by Fredrick Griffith in 1928; Avery, Mcleod and McCarty in 1944; and Hershey and Chase in 1952!"

"Oh," said Mittu interrupting Grandpa. "A little slow please".

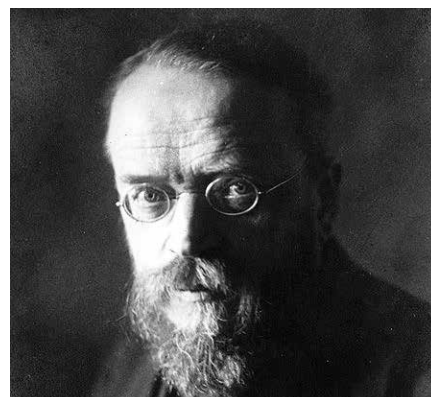
"Sure. Let us begin with 1928."

Three scientists independently confirmed Mendel's experiments:



(a) Hugo de Vries.

Credits: Uploaded by Ineuw, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:PSM_V67_D338_Hugo_de_Vries.png. License: CC-BY.



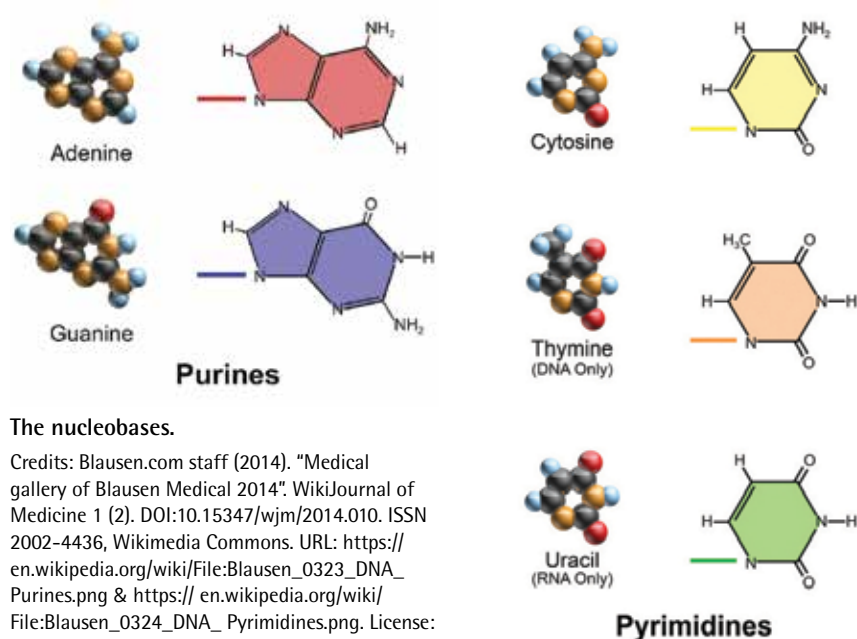
(b) Erich Correns.

Credits: Owned by Mondadori Publishers & uploaded by MaterialsScientist, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Carl_Correns_1910s.jpg. License: CC-BY.



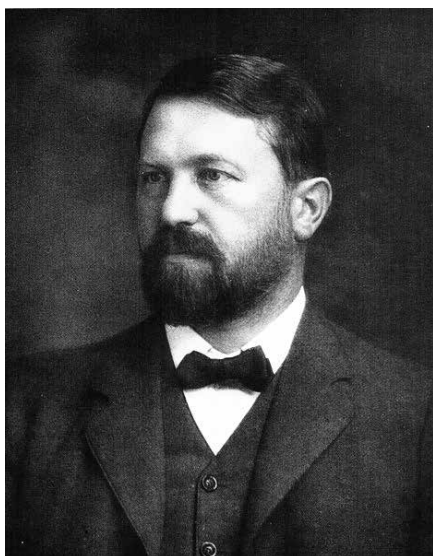
(c) Erich Tschermak Von Seysenegg.

Credits: Acta horti bergiani bd. III, no.3 (1905), Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Acta_Horti_berg_-_1905_-_tafl._124._-_Erich_Tschermak.jpg. License: CC-BY.



The nucleobases.

Credits: Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Blausen_0323_DNA_Purines.png & https://en.wikipedia.org/wiki/File:Blausen_0324_DNA_Pyrimidines.png. License: CC-BY.



Theodor Boveri suggested that chromosomes or nuclein carried genes.

Credits: Theodor Boveri. In: Hugo Freund und Alexander Berg (Hrsg.): Geschichte der Mikroskopie. Leben und Werk großer Forscher. Bd. 1, Biologie, Umschau Verlag, Frankfurt am Main 1963, S. 121-132, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Theodor_Boveri_high_res-2.jpg. License: CC-BY.

"But Grandpa, did nothing important happen between 1902 and 1928?" Mittu inquired.

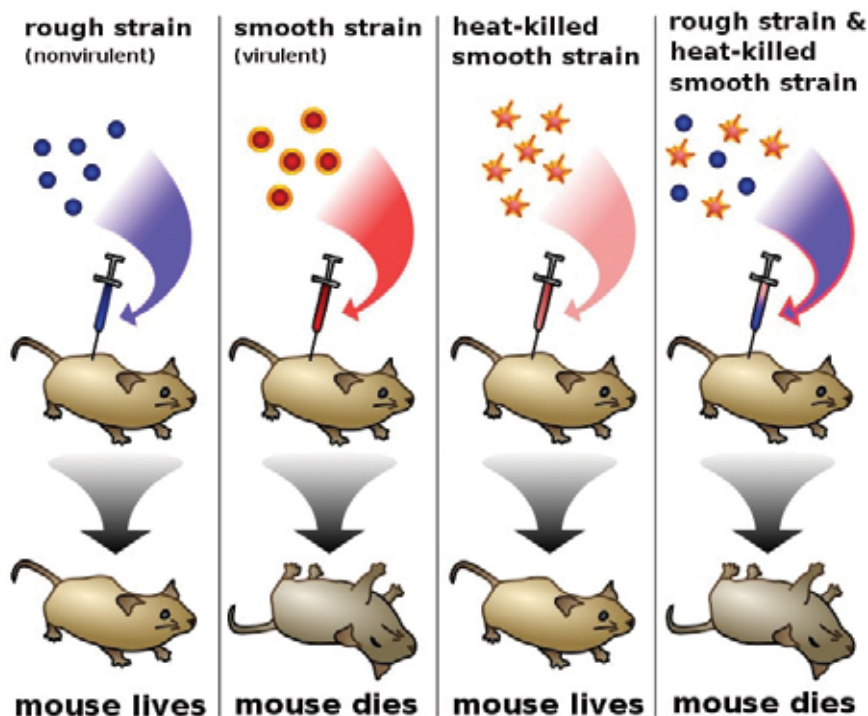
"Well, between 1902 and 1910, mutations were identified. Mutations are improper combinations of A, T, G and C, leading to wrong amino acids."

"Like misspelt words?" Mittu was curious.

"Yes. Garrod identified that mutations in DNA led to functional defects and caused human diseases. Around the same time, T.H. Morgan identified the first mutant in the fruitfly *Drosophila*. Then, in 1928, Fredrick Griffith, a British bacteriologist, used experimental evidence to show that nucleic acids do indeed transfer characters from one individual to another, through a process called 'transformation'."

"How did he do that?"

"Griffith used two strains of the bacteria *Streptococcus pneumonia*. One, called the S strain, caused disease in mice; while the other, called the R strain, did



Griffith's transformation. Griffith took two strains of the bacteria *Streptococcus pneumonia* – the non-virulent Type II R (rough) strain and the disease-causing Type III S (smooth) strain. Panel 1: When Griffith injected the rough strain into mice, the mice lived. Panel 2: When he injected the smooth strain into mice, the mice died. Panel 3: When Griffith injected heat-killed cells of the smooth strain into mice, the mice lived. Panel 4: Surprisingly, when he injected a mixture of heat-killed cells of the smooth strain and live cells of rough strain, the mice died. Griffith proposed that the rough strain was 'transformed' into a virulent strain because it took in nucleic acids from the heat-killed smooth strain.

Credits: Uploaded by Madprime, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Griffith_experiment.svg. License: CC-BY.

not. When he used a mixture of heat-killed cells of the S strain, which he knew to be non-virulent, and live cells of the R strain to infect mice, the mice showed symptoms of disease. This led Griffith to postulate that the S strain passed on its disease-causing trait to the non-virulent R strain through its DNA." Grandpa paused.

"But how do we know that the disease-causing trait was passed on by DNA?"

"Because Avery-MacLeod-McCarty and Hershey-Chase used slightly altered versions of Griffith's experiment. Oswald Avery, Colin MacLeod and Maclyn McCarty, three American geneticists, showed that mixing the DNA of the S strain of *Streptococcus pneumonia* with live cells of the R strain could transform the R strain to the disease-causing S type. Proteins

of the S strain were, however, unable to transform cells of the R strain in the same way. In a similar experiment, the two geneticists, Alfred Hershey and Martha Chase showed that radioactively labelled Phage DNA was capable of causing infection in bacterial cells by a process they called 'transduction'."

"Was photograph 51 the next clue?"

Grandpa laughed. "No. Next, we move back to discoveries around the chemical nature and structure of DNA."

"But why?" Mittu was impatient.

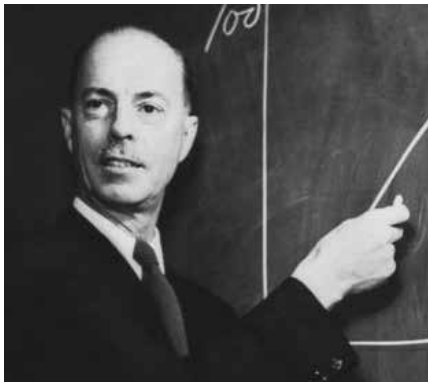
"Because Photograph 51 is an important clue to the chemical nature of DNA. So, moving on, in 1929, Phoebus Levene, an American biochemist, showed that in addition to Kossel's nucleobases, nuclein had a sugar molecule and a phosphate

Three scientists confirmed that Griffith's 'transforming molecule' was DNA



(a) Oswald Avery.

Credits: Owned by Rockefeller Archive Center (http://profiles.nlm.nih.gov/CC/A/A/L/P/_/ccaalp_.jpg) and uploaded by Jacopo Werther on Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Oswald_T._Avery_portrait_1937.jpg. License: CC-0.



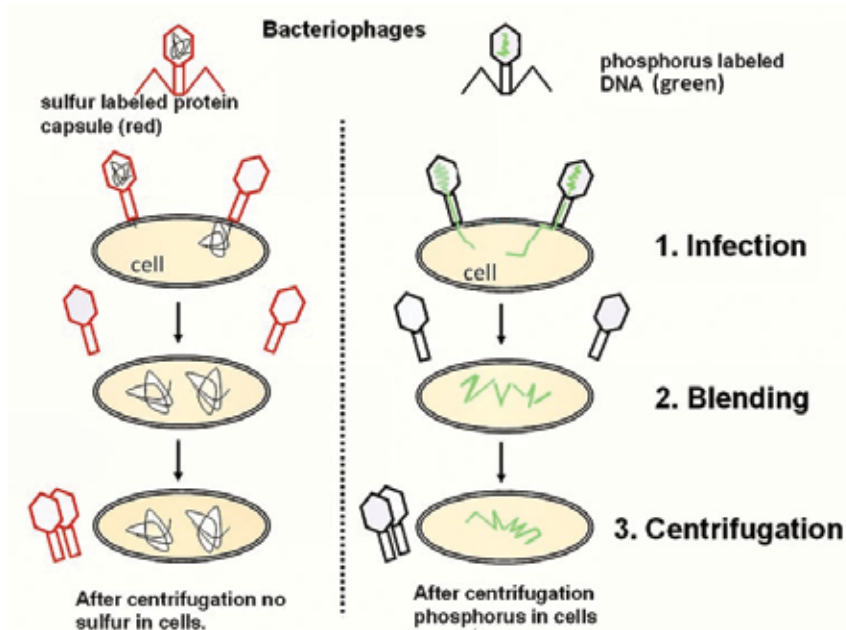
(b) Colin MacLeod.

Credits: Owned by National Institute of Health (https://history.nih.gov/exhibits/nirenberg/popup_html/03_macleod.htm) and uploaded by Giac83 on Wikimedia Commons. URL: <https://commons.wikimedia.org/wiki/File:ColinMacCleod.jpg>. License: CC-0.



(c) Maclyn McCarty (to the extreme right).

Credits: Owned by Acc. 90-105 - Science Service, Records, 1920s-1970s, Smithsonian Institution Archives, and uploaded by Giac83 on Wikimedia Commons. URL: [https://commons.wikimedia.org/wiki/File:Maclyn_McCarty_\(5493933573\).jpg](https://commons.wikimedia.org/wiki/File:Maclyn_McCarty_(5493933573).jpg). License: CC-0.



Hershey and Chase's transduction.

T2 phage is a virus that infects the bacteria, *Escherichia coli* (*E.coli*). To confirm that DNA was the transforming molecule in Griffith's experiment, Hershey and Chase labelled the DNA of a virus (T2 phage) with radioactive phosphorus and its protein capsid with radioactive sulphur. When the radioactively labeled virus was used to infect *E.coli*, Hershey and Chase found phosphorous labelled DNA in the infected cells. This confirmed that it was DNA, and not protein, that was the 'molecule of life'.

Credits: Graham Beards, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Hershey_Chase_experiment.png. License: CC-BY-SA.

group. He named this combination of a nucleobase, a sugar molecule, and phosphate, a 'nucleotide'. But, Levene didn't stop here. He went on to propose

that each DNA molecule had a tetra-nucleotide structure, or consisted of one set of A, T, G and C. Clear?" questioned Grandpa.

"Clear".

By 1934, two Swiss scientists, Torbjorn Caspersson and Einar Hammersten, showed that DNA was a polymeric molecule with long stretches of nucleotides that were not necessarily in multiples of four. So, of course, the tetra-nucleotide structure was rejected. Then, in 1937, William Astbury took the first photograph of DNA through X-ray crystallography, using a sample supplied by Caspersson."

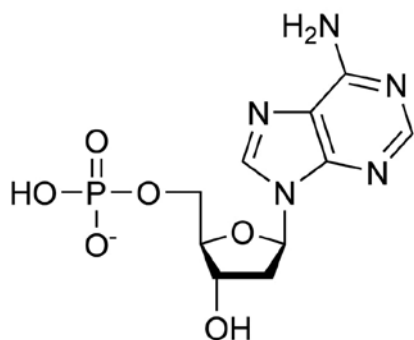
Mittu sighed. "Is photograph 51 next?"

Grandpa ignored the interruption. "In 1950, Erwin Chargaff discovered that the cells of all organisms showed a 1:1 ratio of purine (adenine and guanine) and pyrimidine (thymine and cytosine) bases. He also proved that A always pairs with T, and G always pairs with C."

"Why A-T and not A-C?"

"Stable hydrogen bonds can only be formed between A-T and G-C, but not otherwise. In 1951, Edward Ronin suggested that DNA may have phosphate groups at its centre and nucleobases jutting outwards. Then, came a discovery in 1952."

"Too many details. Can we just skip all this?" Mittu snapped.



A nucleotide has a nucleobase (upper right), a sugar (centre) and a phosphate group (left).

Credits: Cacycle, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:DAMP_chemical_structure.png. License: CC-0.

"Sure," said Grandpa innocently.

"Photograph 51 was taken in 1952. But let us skip that part."

Mittu growled.

Grandpa chuckled. "This photograph was taken by Rosalind Franklin using x-rays."

"A woman scientist in 1952?"

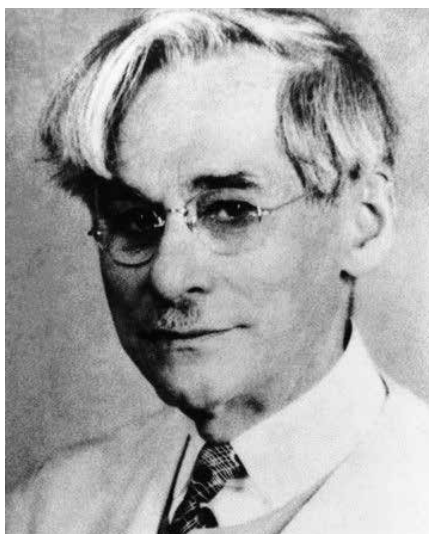
"Yes. A very accomplished yet under-recognized scientist."

"Under-recognized?"

"Yes. If you check your textbook, it's very likely that you'll find a copy of photograph 51, but without any mention of the fact that Franklin was responsible for taking it."

"But, why?"

"Because there were many scientists racing towards identifying the structure



Phoebus Levene identified the chemical structure of nucleotides.

Credits: Uploaded by Materialschemist, Wikimedia Commons. URL: <https://en.wikipedia.org/wiki/File:Levene.jpg>. License: CC-0.

of DNA. Franklin was only one among them. In fact, it's likely that she had nearly cracked the structure of DNA with this Photograph. Looking at it, she had identified DNA to be a double helix — that's your mysterious X," said Grandpa.

"This is a photo of a DNA molecule?!"

Mittu looked at the image again. Then, "what is a double helix, Grandpa?"

"Well, every molecule of DNA is composed of two strands of nucleotides that are anti-parallel to each other. Franklin was aware of Chargaff's rule. Based on the 'X' in this photo, she had, correctly, deduced that the nucleobases were on the inside of the helix and the

phosphate groups were on the outside (unlike earlier models). And, nucleobases on these strands were held together in pairs through hydrogen bonds. She is also supposed to have deduced that each base pair is 3.4 angstrom apart."

"Did she write about this?" asked Mittu.

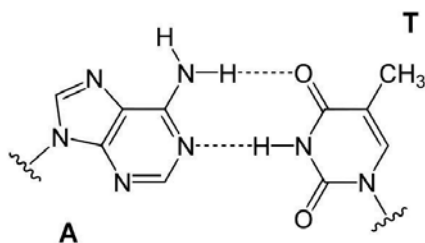
"She intended to, but wanted to wait till she had more evidence. In the meanwhile, she showed this photograph to a colleague, Maurice Wilkins. Wilkins was very keen on deducing the structure of DNA. So keen that his complaints had convinced Sir Braggs, head of the Molecular Biology Laboratory at Cambridge, to ask two scientists who worked there — James Watson and Francis Crick — to abandon their pursuit of the structure of DNA. Wilkins also turned down Linus Pauling's request to see Photograph 51. Pauling, a Nobel Laureate in protein chemistry, needed this evidence to confirm the 'triple helical' structure for DNA that he had proposed. Since Wilkins had declined his request, Pauling based his model on Astbury's images instead. The race got harder. Sir Braggs advised Watson and Crick to rejoin it. On a visit to King's college, Watson coaxed Wilkins into showing him Photograph 51. Wilkins



Rosalind Franklin used x-rays to photograph DNA.

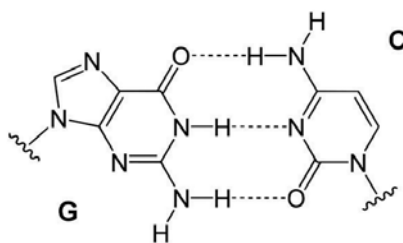
Credits: National Portrait Gallery, London. URL: <https://www.flickr.com/photos/retusj/29075235396>. License: CC-BY-NC-ND.

Erwin Chargaff's base pairing.



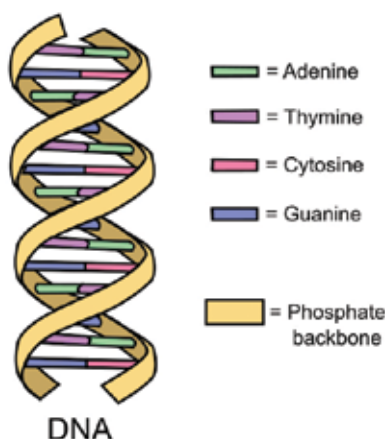
(a) Adenine-Thymine.

URL: https://en.wikipedia.org/wiki/File:Base_pair_AT.svg. Credits: Yikrazuul, Wikimedia Commons. License: CC-0.



(b) Guanine-Cytosine.

URL: https://en.wikipedia.org/wiki/File:Base_pair_GC.svg.



The double helix.

Credits: Forluvoft, Wikimedia Commons.

URL: https://pa.wikipedia.org/wiki/%E0%A8%A4%E0%A8%B8%E0%A8%B5%E0%A9%80%E0%A8%B0:DNA_simple2.svg.

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did this without Franklin's knowledge or consent. As soon as he saw it, Watson recognized the significance of this photograph. Combining what they knew from the photograph and Pauling's protein structure, Watson and Crick built the first correct model of DNA in 1953. Watson, Crick and Wilkins were jointly awarded the Nobel Prize for Medicine in 1962 for this achievement."

"And, Rosalind Franklin?"

"She remained the 'Dark Lady of DNA.'"

Mittu looked at the photograph and sighed, "That is so unfair!"

Both remained silent for a while. Then, Mittu asked, "What is the point of all this discovery Grandpa?"

"Well, it helps us understand DNA replication, protein synthesis from DNA, DNA's role in disease, its use in treating diseases and also its application in solving crimes."

Mittu looked up at Grandpa questioningly.

"Francis Crick proposed the '**central dogma**' in 1957. Central dogma explains the flow of information from DNA to Proteins through RNA. According to it, DNA first passes on information to an intermediate molecule, RNA. RNA is then translated into the amino acids that make up proteins. Crick also proposed that the information for each amino acid was encoded in the sequence of three consecutive bases on each strand of DNA. This is called the '**genetic code**.'"

"And was this correct?"

"Yes." Grandpa replied. "The genetic code represents the words of DNA, made up of 3 nucleotides each (ATC, GAG, GTT, CCC...), which code for one amino acid each. It was discovered by Gamow in 1953, and Nirenberg, Khorana, Holley and Leder in 1965-68. So, you see, understanding DNA revolutionized science," Grandpa beamed.

"How?"

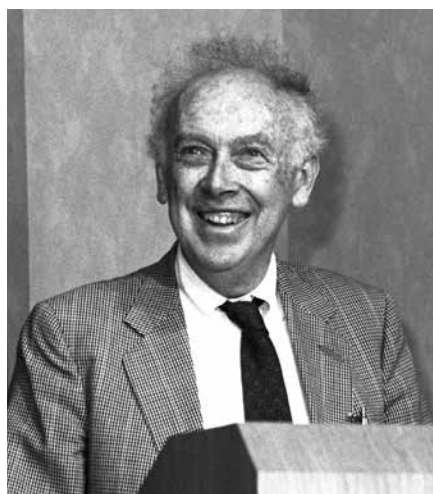
"Well, recombinant DNA technology (rDNA) was developed by Herbert Boyer in 1973. Using rDNA, we can mix DNA of different species, like plant and bacteria, human and bacteria or bacteria and viruses etc., to produce synthetic DNA of our choice."

"Like chimeras in Greek Mythology?" Mittu wondered.

"Something similar. rDNA is used to produce many new medicines and vaccines as well as control diseases like diabetes. For example, when the gene coding for human insulin is inserted into bacteria, large quantities of 'Humulin' can be produced to treat diabetes. Bacteria are easy to grow, and its products are simple to collect."

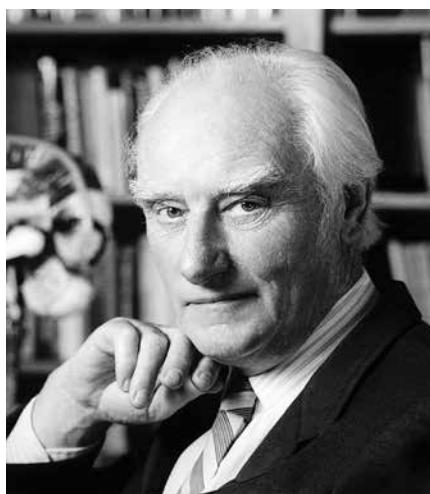
"How do you solve crimes using DNA?"

Three scientists were jointly awarded the Nobel Prize in Medicine for the discovery of the structure of DNA



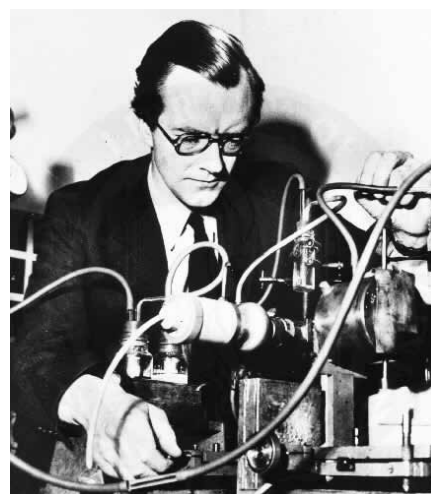
(a) James Watson.

Credits: Owned by National Cancer Institute (NCI) & uploaded by Jan Arkesteijn, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:James_Dewey_Watson.jpg. License: CC-0.



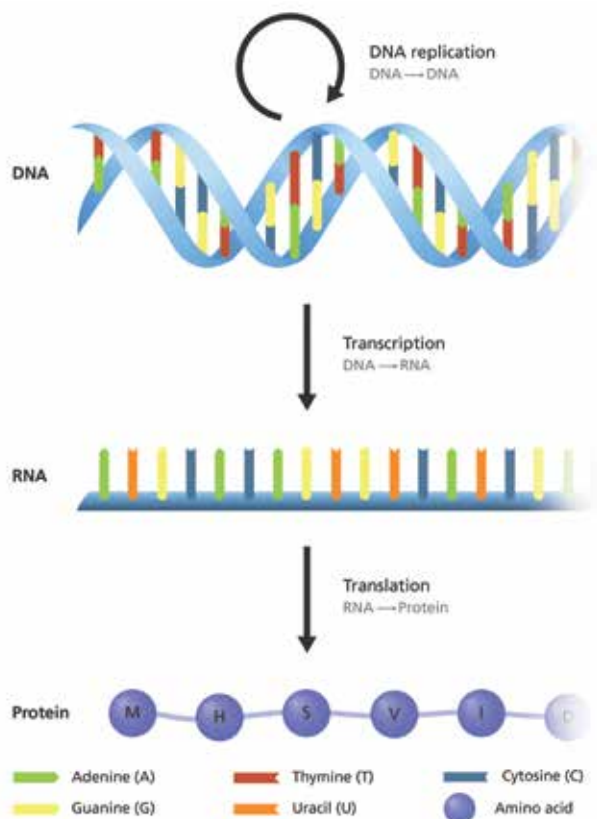
(b) Francis Crick.

Credits: Photo by Marc Lieberman, uploaded by MaterialsScientist on Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Francis_Crick_crop.jpg. License: CC-BY.



(c) Maurice Wilkins.

Credits: Owned by the National Institutes of Health and uploaded on Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Maurice_H_F_Wilkins.jpg. License: CC-0.



The Central Dogma.

Credits: Owned by Genome Research Limited & uploaded on Flickr.
URL: <https://www.flickr.com/photos/yourgenome/26344048984>. License: CC-BY-NC-SA.

Mittu asked eagerly.

"In 1977, Sanger Maxam and Gilbert developed a method to sequence DNA. Sequencing allows us to identify the order of nucleotides in each strand of DNA. In the same year, Alec Jeffrey developed a technique called 'DNA fingerprinting' and used it to solve crimes. This technique works on the principle that each individual has a unique order of nucleotides. Therefore, we can be identified by sequencing our DNA," explained Grandpa.

"So, Alec Jeffreys is the Sherlock Holmes of DNA science?"

Grandpa smiled and nodded.

"So, understanding DNA made life better?" Mittu expounded.

"Uh-huh."

"Okay!" Mittu remained thoughtful for a moment but sounded cheerful again. "So, you spent your holidays collecting stuff, right?"

"Who said so?" asked Grandpa.

"I thought your scrapbook was proof of that!" Mittu seemed perplexed.

"No," Grandpa laughed. "I just wanted to look up some old photographs. Thanks for bringing my scrapbook down from the attic. Now, if you are ready, let's begin the interview on 'how I spent my holidays back then without gadgets.'"

Mittu's jaw dropped. "Grrr...." He said pretending to bite Grandpa.

Note: Credits for the image used in the background of the article title: DNA, Max Pixel. URL: <https://www.maxpixel.net/Microbiology-Biology-Gene-Dna-Analysis-Medicine-163466>. License: CC-0.

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THE SCENT ORCHESTRA OF FLOWERS

V. S. PRAGADHEESH & SHANNON OLSSON

While walking through a beautiful garden, you are met with a lovely bouquet of fragrances from its many flowers. These smells are so pleasing that we use them in our homes, food, and even on our bodies. Have you ever considered what makes these flowers smell sweet, and how plants might benefit from these scents?

Shakespeare once said that *"...A rose by any other name would smell as sweet..."* – (Romeo and Juliet, Act II, Scene II).

A flower is the reproductive organ of a flowering plant, and contains its male and/or female gametes (refer Fig. 1). The male gametes are the pollen grains. Pollen is found on the anther of the flower. These grains need to be transferred to the stigma, the female organ, for fertilization to take place. After fertilization, the plant produces seeds that can germinate into new plants. The process by which pollen is transferred from the male to female organs is called pollination.

The transfer of pollen within the same flower is called self-pollination, and between different flowers is cross-pollination. Pollination can occur

abiotically by wind, water, or even gravitational force; and, biotically through insects, bats, birds and many other animals. Around 90% of flowering plants are pollinated by animals¹ (refer Fig. 2). The colorful butterflies, buzzing bees, hovering flies, moths, bats, and hummingbirds that you see in your garden are performing this vital job of transferring pollen, day and night (refer Fig. 3). Thus, pollination is what we call an essential 'ecosystem service' or, in other words, a natural process within ecosystems that benefits humankind. Without pollination, there would be no flowering plants. No more fruits and vegetables. Life, as we know it, would not exist! But, have you ever considered how plants attract these animals for pollination in the first place?

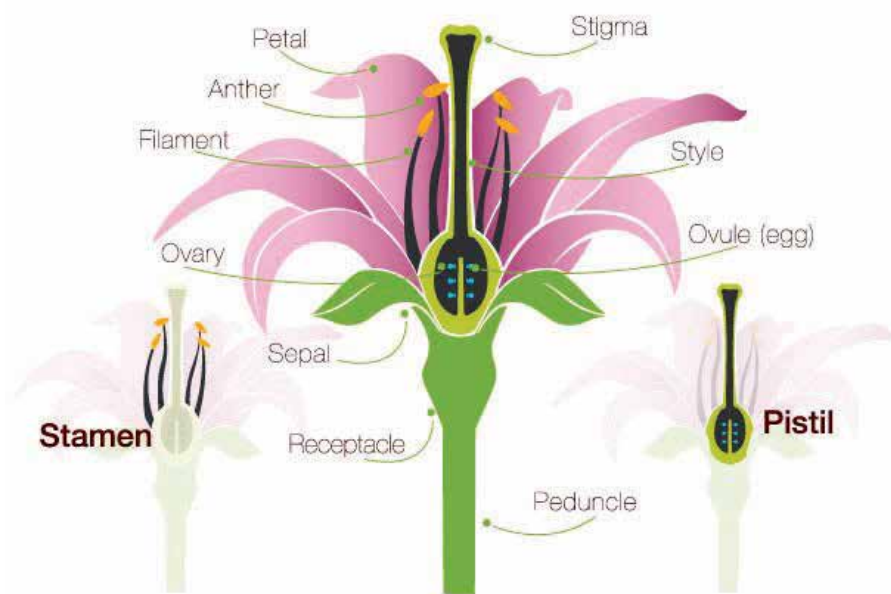


Fig. 1. The reproductive parts of a flower.

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variation of floral scents in plants is produced mainly from three groups of chemical compounds – terpenoids, phenylpropanoids, and fatty acid derivatives². Lavender and rosemary release odours from mostly the terpenoid group; whereas rose, jasmine, and lily have scents produced by all three floral scent groups. Phenylpropanoids are also involved in the production of pigmentation (color) in flowers, whereas terpenoids act as a deterrent against herbivores in other plant parts, such as the leaves and stem³.

Floral scents also serve other functions that include warding off non-pollinating flower visitors such as nectar robbers, and inviting natural enemies of the herbivores that feed on the plant. For example, leaves, stems, and flowers of plants release several chemicals when

Flower scent

Plants attract pollinators using the fragrance and visual characteristics of their flowers, such as color and shape. Odors can travel in the air over several meters. As such, scent is a particularly important cue to attract pollinators to flowers from a distance.

All chemical compounds produced by plants can be divided into two categories – primary and secondary metabolites. Glucose, proteins, and lipids that are necessary for the growth and development of the plant are classified as primary metabolites. Compounds produced as byproducts of these metabolites, including terpenoids, flavonoids, steroids, alkaloids, and the many other chemicals not related to growth and development, are known as secondary metabolites. Secondary metabolites can also benefit the plant by protecting them from disease, drought, sun damage, and plant-eating animals (herbivores) through pigments, noxious taste, and water-retaining waxes, among other mechanisms.

Floral scents are produced by plants as byproducts of glucose synthesis and are, therefore, considered to be secondary metabolites. The remarkable

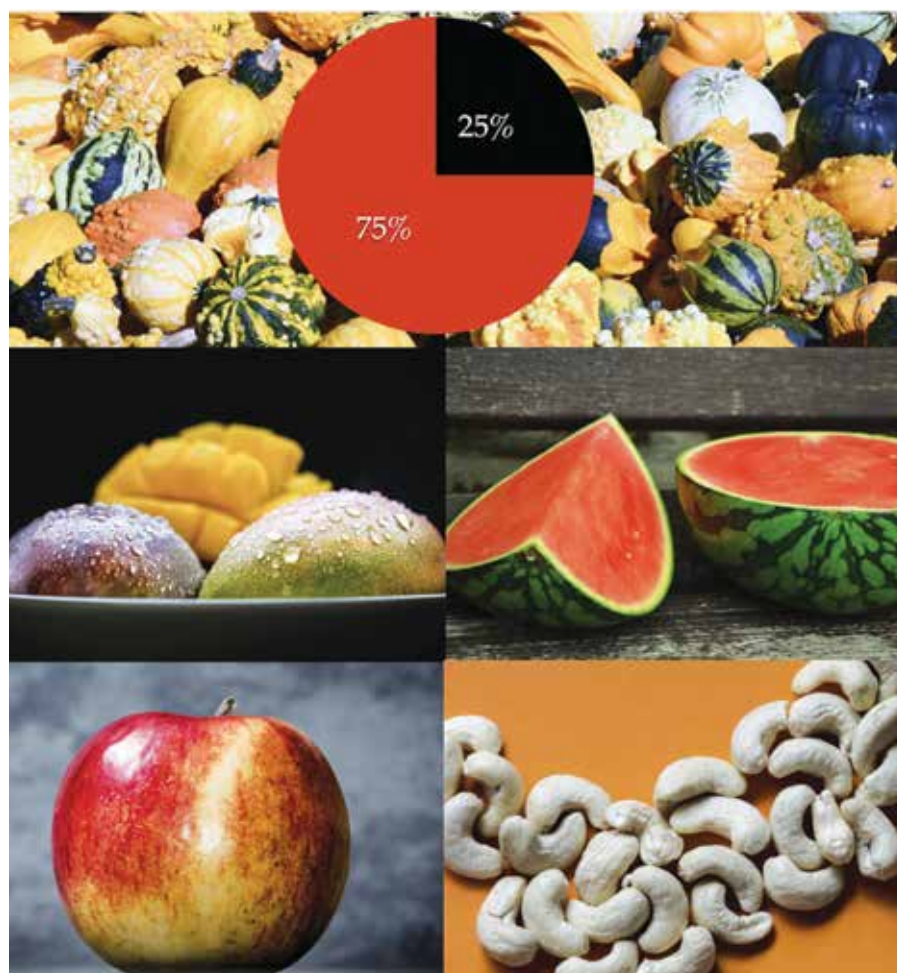


Fig. 2. Common crops for which animal pollination is vital. A pie chart showing percentage of crops (75%) that rely in part on animal pollination (FAO).

Credits: Shannon Olsson.

chewed or broken. You will be familiar with this if you enjoy the smell of fresh-cut leaves and grasses. Crab spiders use chemicals like β -ocimene, released by flowers when they are chewed on by insects, to locate and feed on these insects. Indeed, flowers may even emit larger amounts of β -ocimene when attacked by florivores (refer Fig. 4)⁴. In another example, the presence of methyl anthranilate, a bird repelling compound, in flowers may help repel birds that feed on pollinating insects. The chemicals responsible for floral scents can also possess anti-microbial properties that inhibit microbial growth in the flower.

Flower constancy and specialisation

Each plant species uses a small number of chemical synthesis pathways to generate a large variety of low molecular weight volatile organic compounds (VOCs). It is the unique blend of its VOC's that gives the flowers of each species their specific fragrance.

VOCs can attract a variety of pollinators – ranging from insects to birds to small animals. However, the cacophony of many plants, many pollinators, and many scents can create a problem – if pollinators visit flowers of different species, how can a plant ensure that its pollen gets transferred to another flower of the same species?

Pollinators like honey bees visit a number of plant species, and are called generalists. However, many of these generalist pollinators show a certain degree of flower constancy. Flower constancy is the tendency of a pollinator to visit several flowers of the same species and transfer pollen within that species. The specific composition of the flower scent of each species plays a key role in maintaining this flower constancy by allowing pollinators to identify and learn the flower species.

Alternatively, some pollinators only visit a single species of flowering plant throughout their lifetime. Such pollinators are termed as specialists. In



Fig. 3. An insect pollinating a flower.

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Fig. 4. A florivore feeding on a Hibiscus flower.

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turn, the flowers of such plant species are often visited only by that pollinator species. For example, *Vanilla planifolia*, the plant responsible for producing the vanilla bean, is pollinated only by a single species of *Melipona* bee. Thus, when this plant is cultivated outside the range of these bees, it cannot survive⁵ unless it is hand pollinated – as is done, here, in India to allow for the production of vanilla flavoring from its beans.

Diurnal and nocturnal flower scents

Many plants tend to emit scents rhythmically over the length of a day and night. The floral scent of diurnal (day-blooming) flowers is different from that of nocturnal (night-blooming) flowers.

The time of the day when the maximum scent is emitted from a flower is associated with its nectar availability, pollen maturation, and the activity of its pollinators. For example, diurnal flowers, like the rose, emit maximum concentrations of odour during the day and attract bees, beetles, butterflies, flies etc. In contrast, nocturnal flowers, like jasmine, release their maximum scent in the night to attract pollinators such as bats, mice, and nocturnal moths. The scents of night-blooming flowers are composed of chemicals such as linalool, nerolidol, certain aromatic esters, and nitrogenous indole and oximes. These chemicals are collectively referred to as the 'white floral-olfactory image'⁶.

Pseudocopulation

Flowers can sometimes go to great lengths to attract pollinators. One of the ways to help ensure pollination is to evolve a specialized relationship so that you attract only one species of pollinator – increasing the likelihood that the pollinator will visit only your species. One of the most ingenious methods flowers can employ is to "pretend" they are pollinators themselves!

Some orchids, like *Ophrys sphegodes*, mimic the appearance and volatile pheromones of the females of the bee

species *Andrena nigroaenea* to attract males of that species to visit and transfer their pollen. The process by which the male confuses the flower with a female is known as 'pseudocopulation' (refer Fig. 5). Interestingly, the scent of the flower changes after pollination – the chemical farnesyl hexanoate

increases in concentration and inhibits further visitations by male bees⁷. Since the biosynthesis of flower scent is a costly effort, plants like the *Ophrys* orchid use these chemical odours judiciously to maximize pollination by reducing the attraction of insects to already pollinated flowers.



Fig. 5. A mining bee (*Andrena nigroaenea*) pollinating an early spider orchid (*Ophrys sphegodes*).

Credits: Keith Wilson. URL: <https://www.flickr.com/photos/wislonhk/27042427467/in/photostream/>. License: CC-BY-NC.

Teaching Tips

Guess the Pollinator: Take a trip outside and observe several flowers. Have the students guess what types of pollinators could be attracted to these flowers (e.g. Are they night-blooming? Are they insect or bird-sized?). Then, using the internet, try to identify the flowers and their pollinators.

The Perfumery: Obtain several essential oil samples from flowers. Have the students guess which plants they come from. Which scents are similar? Which are different? Is there something about the flower biology that makes some flower scents similar – for example, do they have similar pollinators (do they bloom in the same areas at the same times of day)? If possible, try to observe the real flowers and test your hypotheses!

Make a Flower: Create your own artificial flower experiment! Using paper, crayons or pencils, and toothpicks, create artificial flowers to test outside in the morning. Did you trick any pollinators to visit your artificial flowers? Add a drop of essential oil from a flower or some perfume and see if this enhances the attraction of pollinators to your artificial flower. Were you successful? Why or why not?

Importance of Pollinators: Have the students use reputed websites such as FAO.org to research the importance of pollinators to our crops. See if they can guess which fruits and vegetables are 100% reliant on animal pollination. How many of these crops grow here in India?

Studying flower scents

Flower scents are studied by collecting gaseous compounds emitted from flowers and analyzing them in the laboratory. Several techniques are available for the collection of volatiles. Floral odours can be collected from the air around the plant, known as headspace collection; or by directly extracting compounds from the floral tissue using solvents (much like we make tea). Plant volatiles can also be collected by trapping them on adsorbent surfaces, like charcoal or polymers, through a process known as solid-phase extraction (refer Fig. 6). To analyze floral volatiles using solid-phase extraction, they must then be removed from the adsorbent surface using either solvents or heat and separated from the mixture by fractionation. After collection, individual floral scent compounds are further isolated using a technique known as gas chromatography and identified using techniques such as mass spectrometry.

To understand the function of individual floral volatiles in nature, we can create artificial 'dummies' or 'flower lures' with the colours, shapes, and odours of real flowers, and observe how pollinators respond to them (refer Fig. 7). These artificial flower lures can mimic a flower with or without its scent, with a different colour, or with different combinations of floral scents. Scientists

Fig. 6. Examples of solid-phase extraction of plant volatiles.



(a) Solid-phase extraction of volatiles using Polydimethylsiloxane (PDMS) tubes from an inflorescence of *Pentas lanceolata*.



(b) Solid-phase micro extraction of volatiles in the inflorescence of *Hedychium* species.

Credits: V. S. Pragadheesh. License: CC-BY-NC.



Fig. 7. An insect visiting an artificial flower made of paper and artificial odour.

Credits: Shravathi Krishna. License: CC-BY-NC.

can then use these lures to test how different colours, shapes, and scents change the preference of pollinators in different ecologies^{8,9}.

Conclusion

"Perfumes are the feelings of the flowers" – Heinrich Heine

The next time you walk in a garden, don't just smell the beautiful fragrances of flowers.

Take a moment to stop and think how these lovely odours are the plant's means to interact with its ecology. This is the language of nature. At any given moment, there are thousands of chemically-mediated interactions happening in your own backyard – in each plant, animal, and microbe you see. If you have any questions or observe any of these interactions, do write to us.

Glossary

Ecosystem: The interactions between a community of living organisms and the non-living components in a particular area.

Terpenoids: A class of organic compounds formed by the combination of five carbon units, linked together in a head-to-tail fashion.

Flavonoids: A group of organic compounds with two phenyl groups attached to a ring of carbon and oxygen atoms. Most color pigments in plants belong to this group.

Steroids: Another group of organic compounds with three six membered carbon rings and a five membered carbon ring attached to each other in a specific arrangement.

Alkaloids: A group of nitrogenous organic compounds that have significant physiological effects on humans.

Phenylpropanoids: A class of organic compounds having a phenyl group attached to a propane (three carbons) side chain. Phenylpropanoids are derived from the amino acids phenylalanine and tyrosine.

Fatty acid derivatives: Volatile organic compounds derived from fatty acids present in the cell wall, and released during cell wall rupture.

Nectar: A sugar-rich solution produced in plant glands called nectaries. Plants secrete this solution in flowers to attract pollinators, and in vegetative parts like stems and leaves to attract animals, such as ants, that can deter herbivores.

Microbes: Unicellular or multicellular organisms such as bacteria, fungi, etc. that are too small to be seen with the naked eye.

Volatility: The relative tendency of a substance to evaporate into the air.

Linalool: A terpenoid alcohol present in most plant volatiles.

Orchids: Members of the family *Orchidaceae*, with flowers that are often colourful and fragrant.

Pheromone: Chemical compounds released by animals as signaling compounds to another member of the same species.

Extract: A process of separating chemical compounds from any material (mainly biological) using solvents.

Solvents: A liquid, solid, or gas used to dissolve a substance (called a solute) without changing the nature of the solute.

Gas chromatography: A separation technique mainly used to separate gaseous compounds based on the partition between a stationary liquid (or solid) phase and a mobile gaseous phase.

Mass spectrometry (MS): An analytical technique that ionizes a chemical compound, separates its ions, and quantifies them, to obtain a chemical fingerprint that allows identification of the compound.



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Life in your Backyard

Some interesting scents of flowers

V. S. Pragadheesh & Shannon Olsson

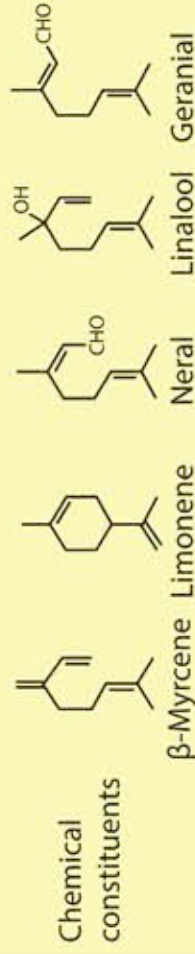
Here are some of the most common flower scents that are pleasing to us. How many of these do you recognise?



Bee on citrus blossoms

CITRUSY

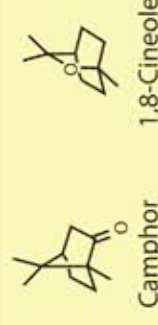
An odour like that of oranges or lemons, produced by a combination of compounds such as β -myrcene, limonene, linalool and citrals. Seen in the fragrance of flowers of citronella, lemongrass and bergamot.



Flowers and aerial parts of rosemary

CAMPOROUS

A sharp and cooling fragrance produced by compounds such as camphor, 1,8-cineole, and pinenes. Seen in the fragrance of the flowers, leaves, and stems of rosemary.



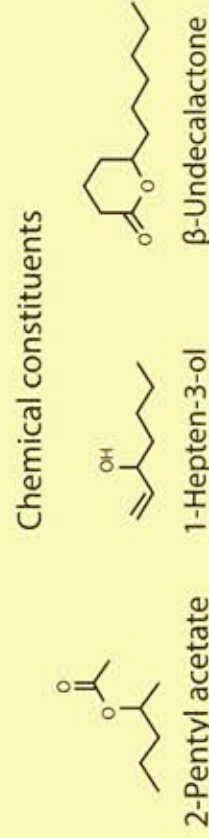
Chemical constituents



A ylang ylang flower

FRUITY

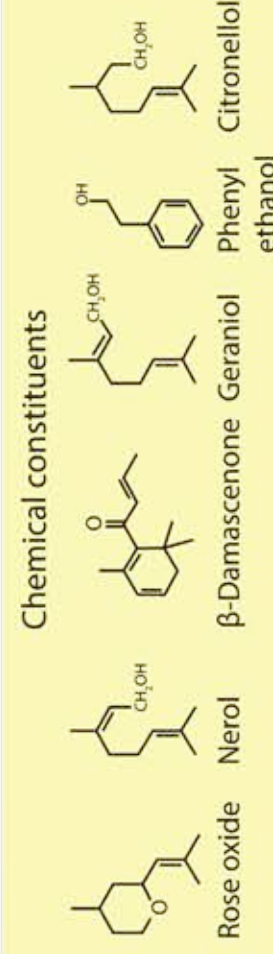
Sweet, pleasant and strong odours arising due to compounds such as alcohols, esters, and lactones. They sometimes act as long-range cues, allowing detection of flowers from a distance.



A rose flower

ROSE

A unique smell produced by chemicals like rose oxides, β -damascenone, phenyl ethanol, geraniol, nerol, and citronellol. The leaves and stems of geranium (*Pelargonium graveolens*) also produce these compounds. Historically, one of the most preferred scents in perfumes, foods, and ceremonies. The perfume (attar) made from rose petals is highly valued in the fragrance industry.

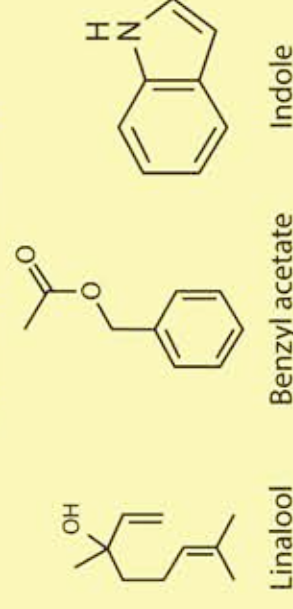


WHITE FLORAL OLFACTORY IMAGE

Compounds responsible for this fragrance include linalool with aromatic esters like benzyl acetate, methyl benzoate; and nitrogenous indole and oximes. Mostly found in night blooming white flowers, such as Jasmine, Evening Primrose, etc., to attract nocturnal pollinators.



A jasmine flower visited by a moth



THE CHEMISTRY OF LIFE

EXPLORE

ANAGH PURANDARE & ANIRUDDH SASTRY

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

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

Life on Earth is carbon-based

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

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

Both silicon and carbon have four valence electrons, and silicon is right below carbon in the periodic table. However, carbon-carbon (C-C) bonds are stronger and much more stable in water than silicon-silicon (Si-Si) bonds. Also, on being completely

oxidized, carbon forms carbon dioxide, a gas; while silicon forms silicon dioxide, a solid. And, a gas (carbon dioxide) is more suitable than a solid for diffusion and recycling – processes without which life cannot be sustained.

Dihydrogen monoxide (H₂O) sustains life

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

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

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

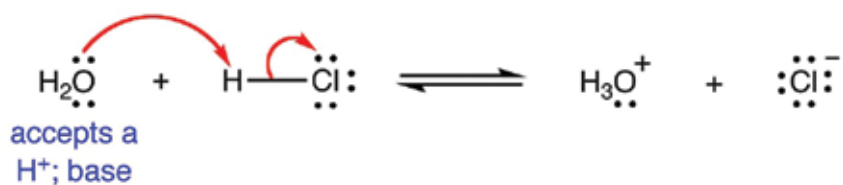
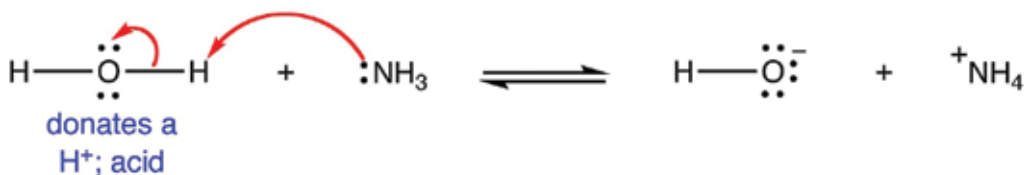


Fig. 1. Water has the capacity to act both as an acid and as a base.

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



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

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

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

Temperature limits the chemistry of life!

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

within a specific range of temperatures and concentrations.

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

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

The information of life is stored as a chemical sequence

While proteins perform most cellular

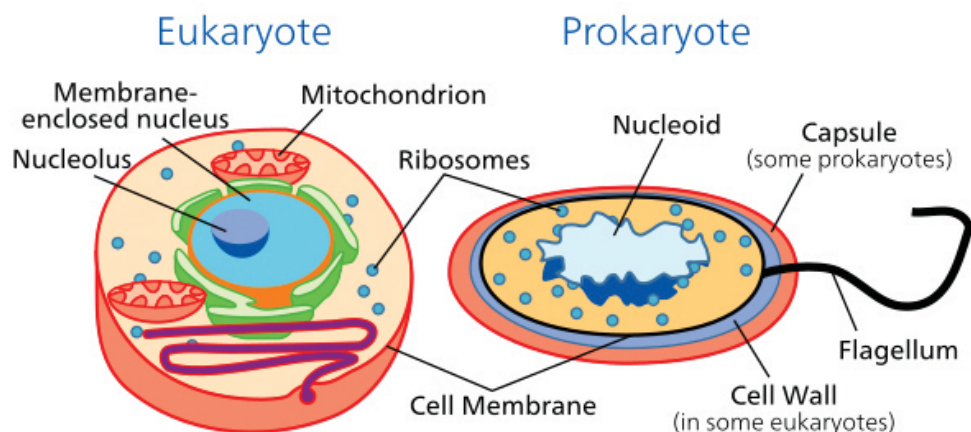


Fig. 2. Membrane-bound organelles in eukaryotic cells help increase effective concentrations of biomolecules.

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

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

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

The precise sequence of nucleotides in each strand of DNA determines the specific types of proteins that a cell can produce. The complementarity of its bases guides the reliable copying of information from one DNA molecule to another during replication¹. This is essential for cell division.

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

High-energy bonds drive life reactions forward!

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

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

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

One part of the body ‘talks’ to another part chemically!

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

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

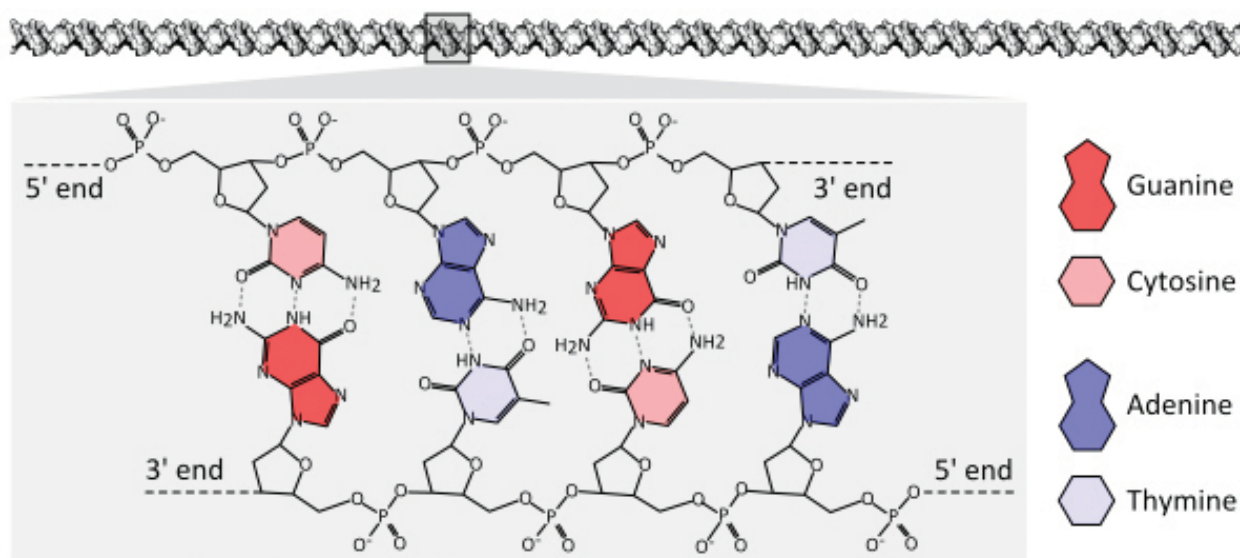


Fig. 3. The structure of a DNA molecule.

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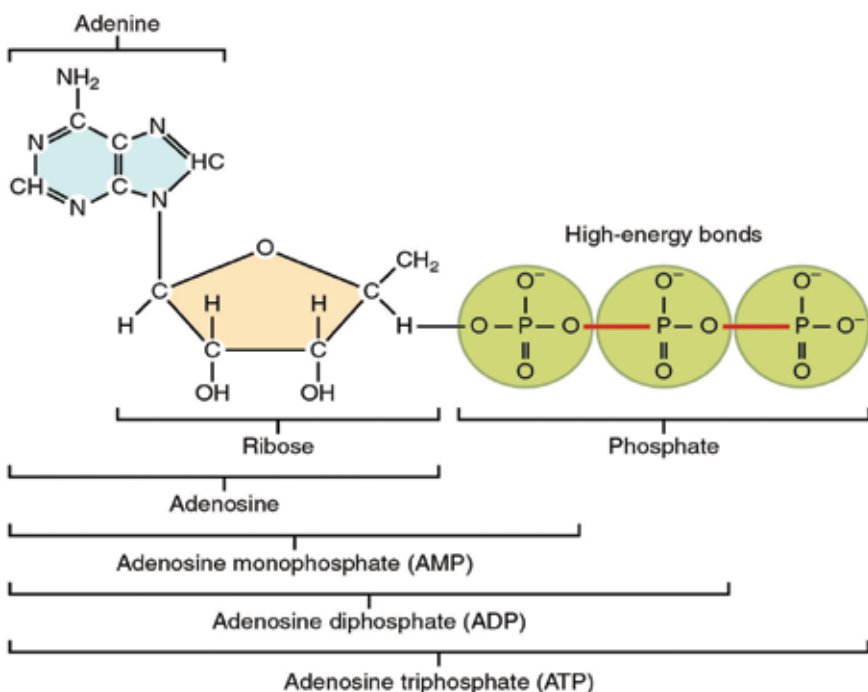


Fig. 4. The structure of an ATP molecule. The red lines represent its two high-energy phosphate bonds.

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

Chocolates are meant to be poison!

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

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

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

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

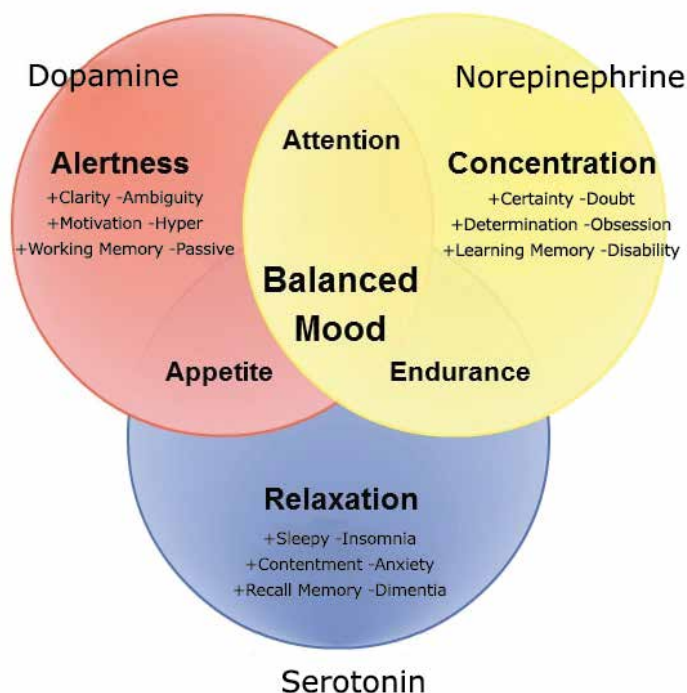


Fig. 5. Neurotransmitters (like Dopamine, Serotonin and Norepinephrine help maintain many physical and physiological functions.

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

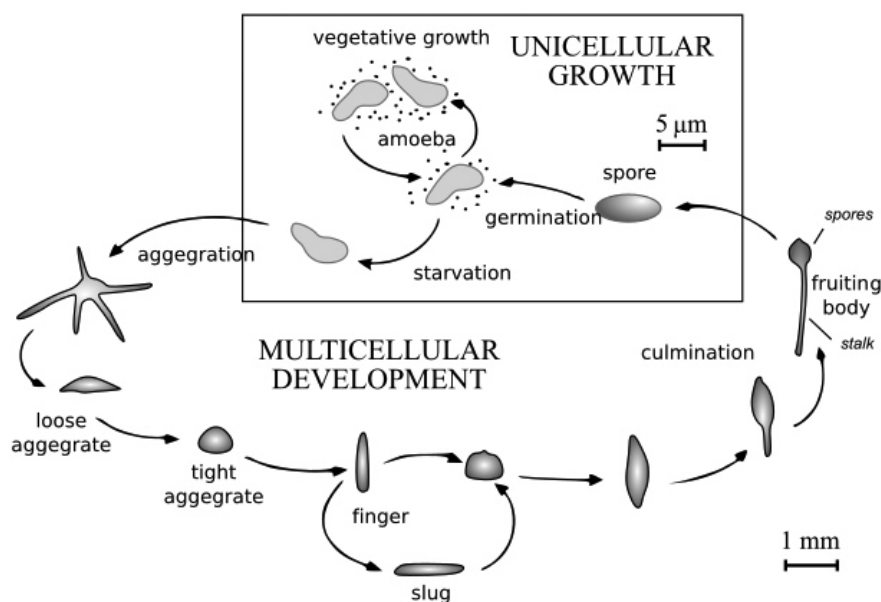


Fig. 6. The life cycle of *Dictyostelium discoideum*.

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

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

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

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

and increasing the probability that some of them will land far enough (from the parent) to find more favourable conditions for survival (refer Fig. 6).

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

Chemicals can 'see' light!

Some chemicals help organisms perceive light. For example, vertebrates have special photoreceptors called rhodopsin in the retina of their eyes. Consisting of a retinal molecule bound to a protein, rhodopsin can absorb light of certain wavelengths. On absorbing light, the retinal molecule changes structure. This causes a change in the structure of

the protein attached to it. The altered protein becomes capable of triggering a cascade of chemical reactions that generates a nerve signal to the brain regarding the quantity and quality of light received. This process occurs in retinal cells every time light enters the eye. Since the retinal molecule is an aldehyde of vitamin A (retinol), a deficiency of this vitamin can lead to night blindness.

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

Molecular motors pull the weight in your hands!

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

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

To conclude

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

Richard Dawkins provides a striking example of how chemistry is believed to dictate biological processes. While this is a radical view, we know that over millions of years, natural selection has resulted in some types of chemistry

being recruited in biological systems more often than others. It is these chemicals and their chemistry that have not only made an insect different from a rock, but have also led to the successful existence of all living organisms.

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

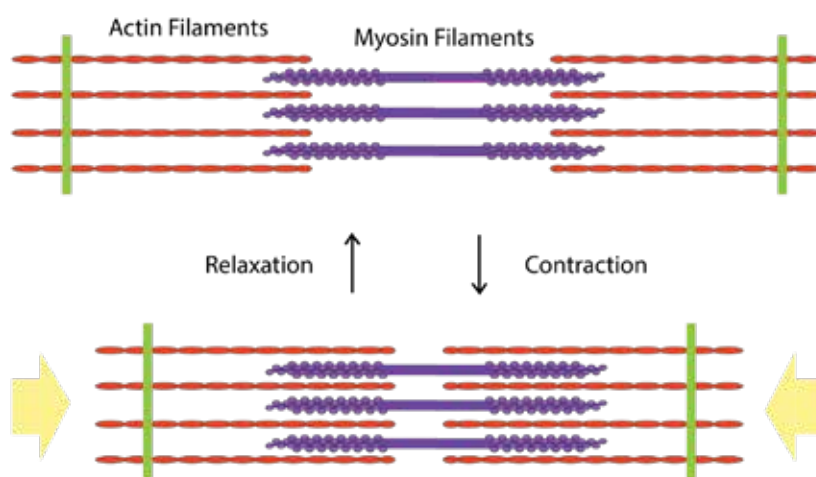


Fig. 7. Contraction of actin and myosin filaments in muscle cells.

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

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

Additional Resources

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Content and ideas for **POSTERS** or **ACTIVITY SHEETS** that teachers can directly use in their classrooms are particularly welcome!

The theme for our 7th issue is **Darwinian Evolution**. Proposals for articles on this theme need to reach us latest by 15th January.

Proposals for articles for our recurring sections are accepted throughout the year:

The Science Lab	Tried-and-tested thought/practical experiments to teach a concept.
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Science Online	Ideas and activities to use an open-access online resource as a teaching aid.
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Can't find a match? Get in touch with us. We'll help identify the section that your article fits best.

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We are looking for short (200–500 words) **SCIENCE SNIPPETS** on 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.

Printed and published by Manoj P on behalf of Azim Premji Foundation for Development.

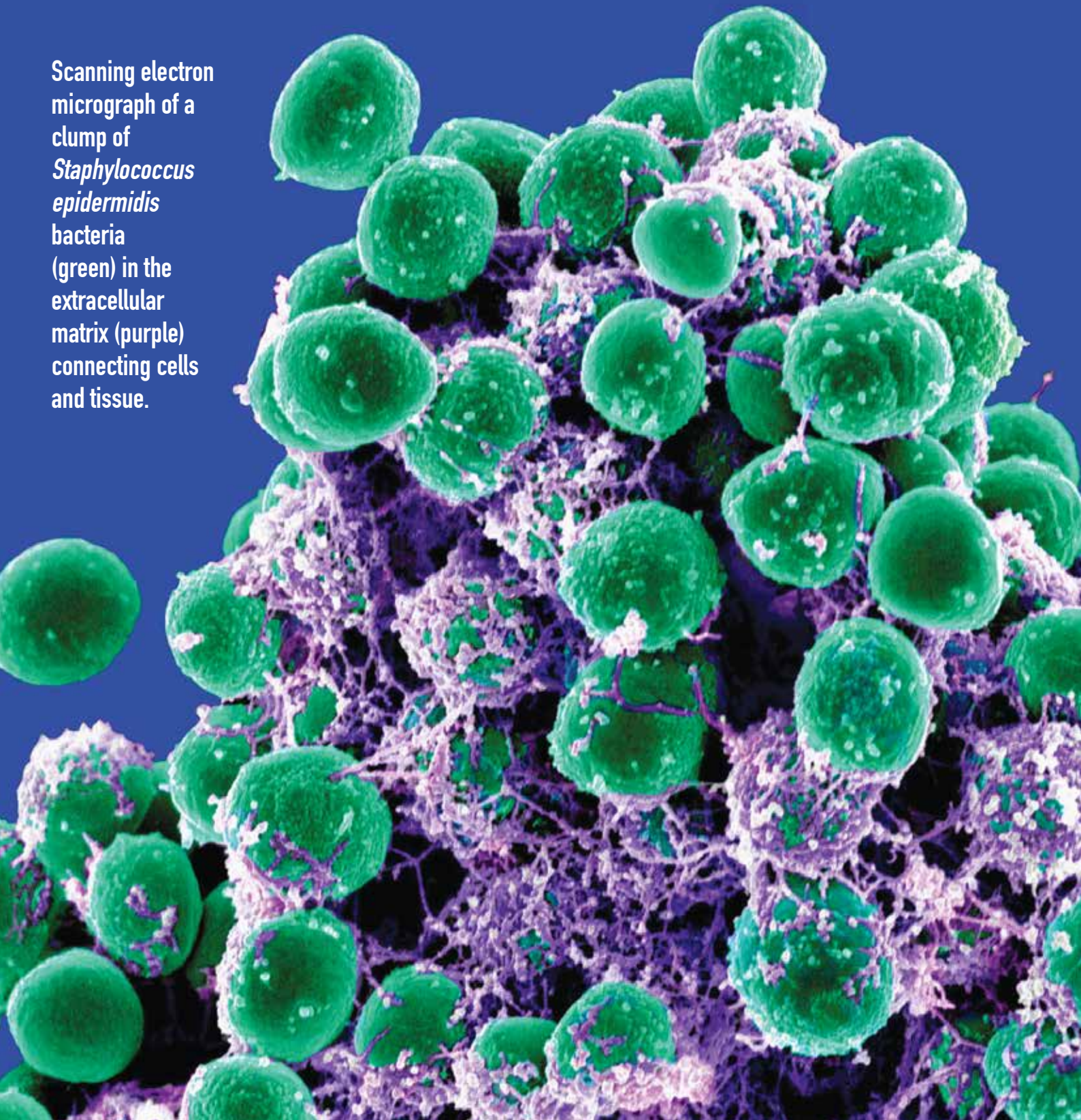
Printed at Suprabha Colorgrafix (P) Ltd., No. 10, 11, 11-A, J.C. Industrial Area, Yelachenahalli, Kanakapura Road, Bangalore 560062.

Published at Azim Premji University, Pixel B Block, PES College of Engineering Campus, Electronics City, Bangalore 560100.

Editor: Ramgopal Vallath

Catch the next issue of i wonder to engage with some Big Questions!

Scanning electron micrograph of a clump of *Staphylococcus epidermidis* bacteria (green) in the extracellular matrix (purple) connecting cells and tissue.



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