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i wonder...

Rediscovering School Science

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Do Dinosaurs Still Walk the Earth?

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About Us

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 lifelong 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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Editorial

Darwin's theory of 'evolution by means of natural selection' is among the most defining contributions to our understanding of the rich diversity of life as well as the origins and evolution of species. In fact, biology makes so much more sense when it is viewed through the lens of evolution. But what is equally, if not more, important is the process that Darwin employed to arrive at, refine, and popularise this theory.

Darwin used the classic scientific method – systematic observation and deep reflection on observed patterns – to formulate a hypothesis. He used experimentation and further observation to modify, fine-tune, and validate his hypothesis, and arrive at a comprehensive theory. In Darwin's case, this entire process was driven by a burning curiosity to better understand nature. This curiosity led him to explore fields as diverse as geology, zoology, botany, taxonomy, anatomy, palaeontology, and even sociology. He learnt by reading the works of experts in these fields, and bolstered this knowledge with first-hand observations of nature. It was this ability to connect knowledge from diverse fields with observations of the natural world that led Darwin to his hypothesis.

The high point of this process was Darwin's circumnavigation of the globe on board the HMS Beagle – he spent these five years making prolific observations of diverse terrains, flora, fauna, and fossils. For the next two decades, Darwin painstakingly collected evidence to prove his theory, and plug every possible gap or objection to it that he could think of. In this process, he befriended and learned from such diverse sets of people as dog breeders, farmers, gardeners, zoologists, botanists, taxonomists, palaeontologists, geologists, explorers, and museum curators. He cultivated flowers to understand their breeding behaviour, and bred several varieties of pigeons to study their lineages. Recognising taxonomy and anatomy as his weaknesses, he set himself the task of improving his understanding of these fields by studying, dissecting, and classifying the barnacles that he had collected on his journey. This task took eight years! He even dabbled in embryology to get a better understanding of comparative anatomy.

Darwin's personality played almost as important a role in his success as his method. His determination and tenacity helped him smell out and follow any trail with the potential to lead to new evidence for his theory. He sought new information and specimens through regular correspondence with a vast number of people across the world, some from as far away as India, the Americas, and Australia. In the mid-19th century, this would entail waiting patiently for as long as two years to get a reply. It was his friendly, helpful, and collaborative attitude that helped Darwin create a vast globe-straddling network of support.

As science educators, we have much to learn from Darwin's life to help guide our students in their journey to become successful scientists. We can ignite a student's curiosity to explore nature, enable them to reflect deeply on what they observe, and help them explore natural phenomena through perspectives from different fields. A science teacher is the best person to encourage students to persevere in their scientific quest without losing the ability to enjoy the journey of exploration. Another important role that a science teacher plays is to inculcate critical thinking in students by constantly encouraging them to question the how and why of every 'fact'. Last, but not the least, science teachers need to guide their students to become collaborative learners.

A great science teacher is quite possibly the most important ingredient in the making of a successful scientist. After all, if it weren't for the initial encouragement of his professor John Henslow, Darwin's theory of evolution might never have come to be.

RamG Vallath
Editor



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UNDERSTANDING EVOLUTION BY NATURAL SELECTION

GEETHA RAMASWAMI

Living organisms show incredible diversity. But what role does evolution by natural selection play in this diversity? What is natural selection? And, what role does the environment play in shaping evolution?

Evolution is a difficult concept to grasp. The earliest explanation offered for our existence, usually by an elder in the family, is that 'we were created by a higher power'. This explanation is often accompanied by descriptions of fantastical beasts and awe-inspiring natural phenomena that seem easier to explain as the whimsy of an all-powerful being.

Often, students of science get their first taste of the theory of evolution by natural selection in high school. Unfortunately, the nuances of this theory are often left unexplored at this stage. Most students are left equating the theory with four words 'survival of the fittest'. But these words do no service to the elegant mechanism by which this theory explains all the diversity of life on earth.

Box 1. How do variations in traits arise in the first place?

Since an organism's genome is like a blueprint of all its traits, variations in traits arise from variations in its genetic material. These variations are the result of non-fatal mutations (fatal mutations would 'kill' individuals carrying it).

Foundations of the theory

Independently proposed by Charles Darwin and Alfred Russell Wallace, the theory of evolution by natural selection is based on the premise that organisms have traits that are variable and inheritable. Simply expressed, **trait** refers to an attribute of an organism.

Traits can vary at every level of organization of the living world (see **Box 1**). For example, the human trait of height is expressed as a range – people can be tall, short, or of medium height. This range may be different for different ethnic groups. For example, the tallest people in Southeast Asia may be shorter than the tallest people from northern Europe. This means that the trait of height is highly variable in humans (see **Box 2**).

Traits are also heritable. Children of tall parents are more likely to be tall themselves. Like height, there can be a number of other inheritable traits – like eye colour, skin colour, even the presence of dimples in your cheeks! Traits are transmitted from one generation to the next through genes (see **Box 3**). Our genes contain the underlying code for each and every trait that is present in an organism. These codes are inherited by offspring from parents.

Individuals with traits most suited to a certain environment are better equipped than others in the same population to survive and reproduce in it. Thus, an organism's environment acts as a filter, increasing the likelihood of individuals with certain traits to be present in each successive generation (see **Box 4**).

What does natural selection mean?

When variable and inheritable traits pass through the sieve of the environment, those most favourable for survival and reproduction are found at a higher frequency in the next generation. This process is called **selection**.

An example of how a change in environment over space creates selection pressures can be seen in the connection between malaria and sickle-cell anaemia. Malaria, caused by a single-celled parasite that is transmitted by mosquito bites, is more prevalent in some geographies (hot, humid, tropical) than others (cold, dry, temperate). Sickle-cell anaemia, on the other hand, is caused by a mutation in genes coding for hemoglobin (a protein that binds and transports oxygen to every cell of the body). This mutation contorts otherwise doughnut – or *uddinavada*-shaped (with a depression in the middle instead of a hole) red blood cells (RBCs) into sickle – or crescent-shaped cells with reduced capacity to bind oxygen (see **Fig. 2**). It so happens that a sickle-shaped cell is bad not just for humans, but for the malarial parasite too. The parasite requires healthy, round RBCs to complete its life cycle. Consequently, in areas endemic to the malarial parasite, humans with sickle-shaped RBCs are more likely to survive and have children than humans with only normal RBCs. In other words, the trait of sickle-shaped RBCs is selected for in an environment where malaria is prevalent.

Box 2. Are variable traits found in all life forms?

Well, yes. Variable traits have been observed in bacteria, fungi, plants, insects, birds, as well as mammals. Here are some examples:

- Tolerance to antibiotics in bacteria.
- The depth at which nectar (for pollinators) is located in the floral tubes of orchids.
- The number and size of eggs that a bird can lay at a time.

Can you think of another one?

Box 3. How do we know that traits are inheritable?

One of the first descriptions of the inheritability of traits came from Gregor Mendel's experiments on pea plants. When Mendel crossed pea plants with certain variable traits with each other, these traits were expressed in their offspring at a frequency that confirmed their inheritability (see **Fig. 1**).

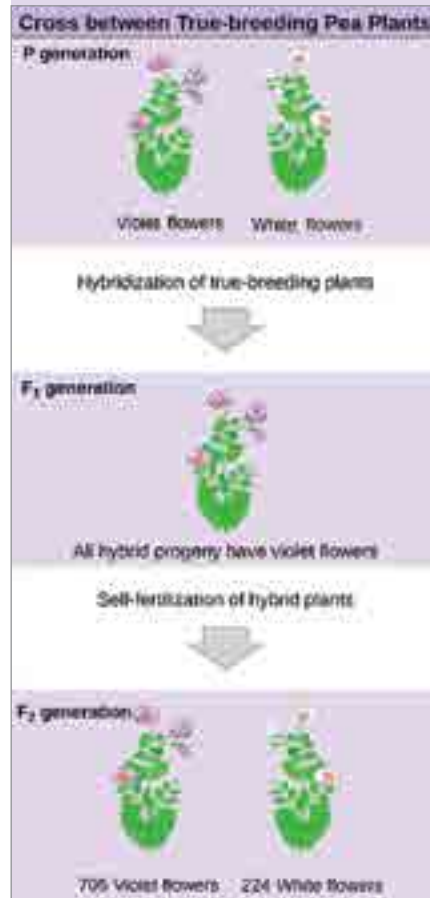


Fig. 1. The results of Mendel's breeding experiments with pea plants could only be explained by the heritability of its traits.

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Three of the traits that Mendel studied in these experiments were flower colour (purple or white), seed colour (yellow or green), and seed texture (smooth or wrinkled). Do you know of any others?

Box 4. How does the 'environment' act as a 'filter of selection'?

All the abiotic and biotic factors that can affect the survival and reproduction of individuals in a population comprise its environment. For example, these are some factors in the environment of a flowering plant that could act as a filter for selection:

- Soil quality (its nutrient status, water content, and microbial community),
- Air quality (its carbon dioxide and water-vapor concentrations),
- Light source (the amount of shade or sun, and the length of exposure),
- The presence of predators (herbivores and/or parasites) and mutualists (pollinators and/or dispersers).

Similarly, these are some environmental factors that exercise selection pressures on a herbivore, like a deer:

- Accessibility and quality of food (area over which edible plants are found) and water,
- Availability of mates (that could be separated by natural barriers such as rivers, mountains, or seasonal droughts),
- The presence of predators (carnivores, hunters) and diseases (caused by bacteria, fungi, and viruses).

We know that no organism lives in a static environment. Its environment changes over both space (imagine temperate vs. tropical latitudes, mountains vs. valleys, grasslands vs. forests, marine vs. terrestrial) and time (imagine summer vs. winter, year 1857 vs. year 2019, Jurassic era vs. Cretaceous era).

Can you identify some selection pressures in your immediate environment? Have you seen them change over space and time? In what ways have they changed?

Similarly, the effectiveness of the pesticide dichlorodiphenyltrichloroethane (DDT) offers an example of how changes in environment over time can create unique selection pressures. This extremely toxic chemical was initially very effective in controlling mosquitoes in urban areas. But, soon, it was observed that increasingly higher concentrations of the pesticide were needed to achieve the same level of control. Why? Let us suppose that coded into the genetic material of mosquitoes, was an inheritable, variable trait for pesticide resistance that confers no-, low-, or high-tolerance for DDT-like pesticides (see Fig. 3). In an environment with low concentrations of DDT, mosquitoes with

no form of resistance to the pesticide die. Those that can tolerate the pesticide survive and reproduce. Since the trait of resistance to pesticides is heritable, most mosquitoes in the next generation will carry some form of the resistance gene. Consequently, higher concentrations of the pesticide will be needed to kill them. However, any increase in the dose of pesticide will only kill mosquitoes with the lowest tolerance for it. Mosquitoes with a higher tolerance for the pesticide will continue to survive and reproduce. Therefore, each increase in pesticide concentration will cause a corresponding increase in the frequency with which the trait for high tolerance to pesticide is seen in the next generation of

mosquitoes. This, in turn, will mean that increasingly higher concentrations of the pesticide will be needed to control each new generation of mosquitoes. Once the concentration of pesticide required for effective control of mosquitoes reaches a level where it has toxic effects on humans, DDT becomes unsafe to use.

The key to the evolution of a trait is the transmission of its genes from one generation to the next. Thus, how fast traits evolve in different organisms depends on how fast they can reproduce (see Box 5). The reproductive fitness of any individual in a population is determined by the number of its offspring that survive into adulthood. In this sense, 'survival of the fittest' does not refer to, say, an individual that emerged victorious from a fight because of its brute strength. Instead,

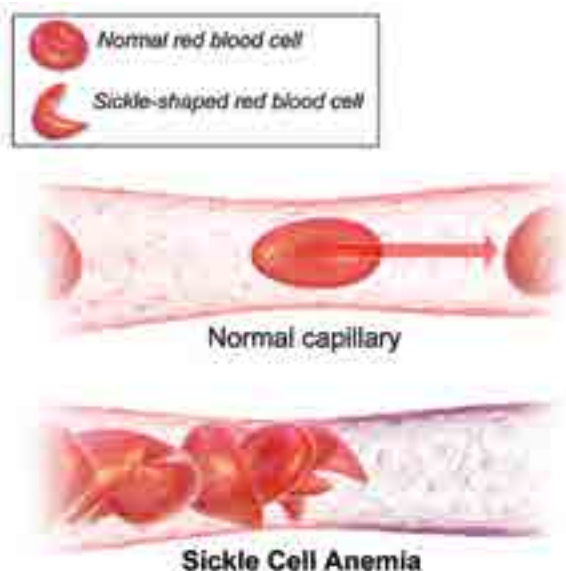


Fig. 2. A pictorial representation of sickle-shaped and normal RBC's.

Credits: BruceBlaus, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Sickle_Cell_Anemia.png. License: CC-BY-SA.

Box 5. Do all traits evolve at a similar pace?

No. The rate of evolution of a trait depends on how fast the next generation can inherit it. For example, some bacteria can reproduce in a matter of minutes. This means that several new generations of this bacteria are produced in a single day, and each bacterial trait has the potential to evolve in a matter of days. For long-lived species with long generation times, the rate of evolution of traits would be much slower.

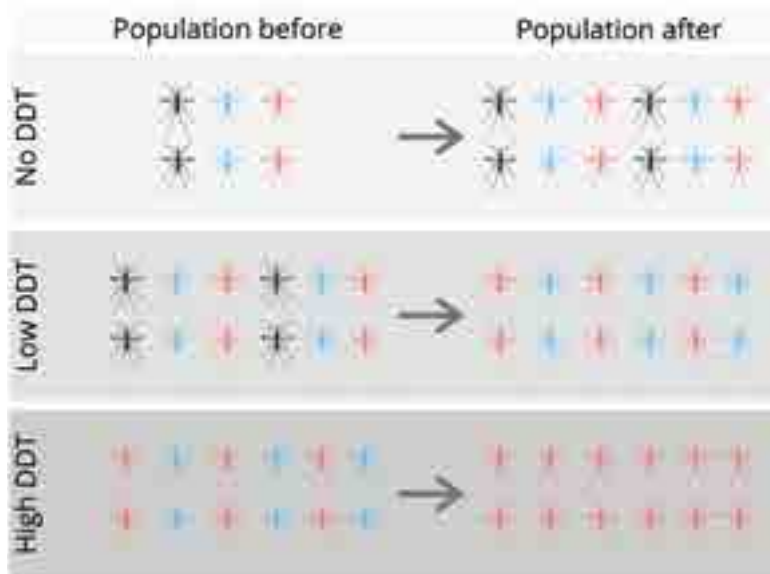


Fig. 3. The effect of varying concentrations of DDT on mosquito populations showing variability in the trait for DDT resistance. The black mosquitoes in the image represent individuals with no resistance to DDT. The blue ones represent individuals with low resistance, and the red ones represent individuals with high resistance to DDT. When low concentrations of DDT are sprayed, the black mosquitoes die out. But the blue and red mosquitoes are able to survive and reproduce. This increases the frequency of blue and red mosquitoes in the population. If higher concentrations of DDT are sprayed on this population, the blue mosquitoes die out. The surviving population is dominated by red mosquitoes or individuals with high-resistance traits. Increasing the concentration of DDT beyond this point might have negative impacts on other organisms, including humans.

Credits: Geetha Ramaswami. License: CC-BY-NC.

it refers to individuals with traits that improve their chances of survival into adulthood, and the effectiveness with which they transmit their traits to the next generation, under prevailing environmental conditions.

How do different species arise?

Based on their ecological requirements and evolutionary origins, the term 'species' can be defined in many ways. In the 'biological species' concept, two sets of organisms are thought of as different species if they cannot interbreed to produce fertile offspring (see Box 6). This is why leopards and cheetahs, which may seem very similar in their carnivorous habits and spotted fur, are thought of as two different species. In contrast, a Doberman pinscher and a Labrador retriever may seem very different in their behavior and appearance, but belong to the same species (see Fig. 4).

An estimated 8.7 million species (some described, many yet unknown to man) inhabit the earth. These species are further classified under five large groups of living organisms (called kingdoms) – Archaea, Bacteria, Protists, Plants, and Animals. In spite of this remarkable diversity, we know that all life emerged over 3.5 billion years ago, from the same primeval ancestral form, through a process called **speciation**. The splitting of ancestral forms into daughter species is known as **diversification** (see Box 7). Diversification is caused, primarily, by prolonged reproductive isolation.

Let us imagine a population that has evolved a set of traits suitable for mostly arboreal habits on a densely forested landmass. Say, some individuals of this population happen to venture over a temporary land bridge (formed, for example, by the sea freezing up during an extremely cold climatic event) to another landmass with much fewer



(a)



(b)



(c)



(d)

Fig. 4. Understanding the 'biological species' concept: A leopard (a) and cheetah (b) look similar, but cannot interbreed to produce viable offspring. They are, therefore, considered to be different species. A Labrador retriever (c) and Doberman pinscher (d) look very different, but can interbreed to produce viable offspring. They are, therefore, thought of as belonging to the same species.

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Box 6. Have humans evolved from apes?

The most common image that a Google search for the term evolution throws up shows what seems like a linear progression of traits from apes to modern day humans (see Fig. 5a). Often, people interpret this to mean that evolution has caused apes to turn into humans! A simple question proves the flaw in this logic – if apes turned into humans, then why are there still so many apes on the planet? Are they also in the process of turning into humans?

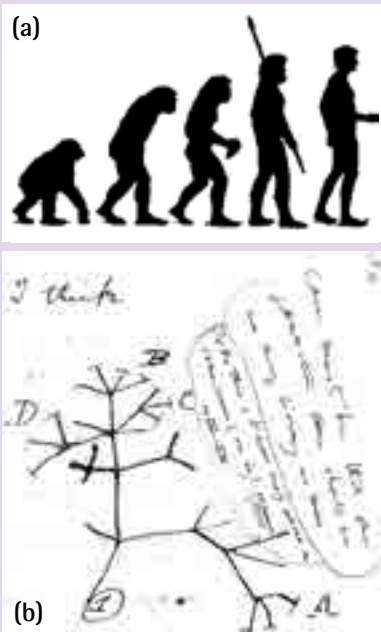


Fig. 5. Depicting evolution. (a) Incorrect depiction of human evolution as a linear progression from ape to man. (b) Darwin's depiction of organisms related by ancestry in the form of a tree.

Credits: (a) Peter Griffin. URL: <https://www.publicdomainpictures.net/en/view-image.php?image=54539&picture=human-evolution>. License: Public Domain. (b) Charles Darwin. URL: https://commons.wikimedia.org/wiki/File:Darwins_first_tree.jpg. License: Public Domain.

A more accurate representation of speciation is in the form of a tree that shows how a common ancestral species with certain traits split into daughter species with their own set of traits (see Fig. 5b). This process has repeated itself over time, with each daughter species splitting into another set of daughter species, and so on. Seen from the perspective of an evolutionary tree, it becomes clear that humans came, not from apes, but from an ancestral species that we share with apes.

trees. Once the land bridge melted, these individuals would be cut-off from the rest of the population. This would mean that the individuals on either side would no longer have any way of inter-breeding – a large, uncrossable water body would lie between them. Natural selection would take its course

– selecting for more and more arboreal traits on one landmass, and for less and less arboreal traits on the other (see Box 8).

If these two populations remained separated from each other for long enough (~ thousands or millions of

Box 7. How do we know how closely two species are related to each other?

Earlier, the external appearance (morphology) of a species was used to estimate how closely related it is to another species. But this technique is not always reliable – similarities in the physical appearance of two species can also arise from **convergent evolution**. This is a phenomena where distantly-related species evolve similar characteristics. For example, both birds and bats can fly; but bats are mammals with a very different evolutionary history from birds.

More modern methods look at how the genetic material of a present day species is likely to have changed over time. These methods are based on certain assumptions about the average rate of mutation, geological occurrences that are likely to have influenced it in the past, etc. They have proven to be more reliable in deciphering the evolutionary history of present day species.

Box 8. Does evolution make species 'better'?

People often assume that speciation has a definite direction, and evolution is progressive – moving from worse to better, from simple to complex, from less to more (intelligence, skill, capability).

But natural selection is a stochastic process, not a conscious force. While evolution does select for organisms that are 'better' adapted to a 'certain' environment, given the dynamic nature of change in the environment, what we think of as 'better' today may prove to be a disadvantage tomorrow. We see many examples of this in carefully preserved remains of organisms from the past (fossils) that are extinct today (see Fig. 6).

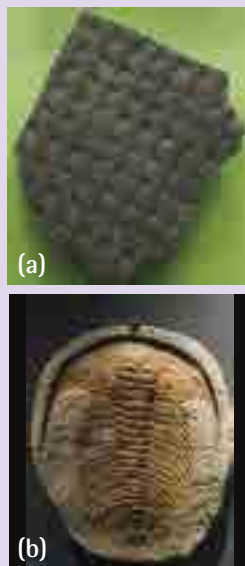


Fig. 6. Other examples of a successful species going extinct. (a) A fossil of leaf scales on the trunk of a plant from the genus *Lepidodendron* – a dominant life form in the Carboniferous era, more than 300 million years ago. Members of this genus did not produce woody tissue like present day trees, but could grow to a great height and girth supported by a profusion of small leaf-scales. They are extinct today, probably because of the emergence of a more efficient group of competitors that are present on earth even today – the gymnosperms. (b) The fossil of an extinct marine arthropod, classified as a 'trilobite'. These creatures flourished in their sea habitats for nearly 300 million years (from ~ 500 to ~ 250 million years ago) before going extinct for causes that are still unknown.

Credits: (a) Jstuby, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Lepidodendron_PAMuseum.jpg. License: Public Domain. (b) Juan Carlos Fonseca Mata, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Trilobite_fossil,_Desert_Museum.jpg. License: CC-BY-SA.

For example, a global-scale natural disaster wiped out all non-avian dinosaurs, bringing the age of the dinosaurs to an end. But many groups of animals, including mammals, that were less successful than dinosaurs before the disaster, managed to survive its impacts.

Box 9. Do we know of any examples of allopatric speciation?

Scientists speculate that a species of laughing thrushes endemic to the Western Ghats in southern India shares an ancestor with a species of laughing thrushes found in the Himalayas. It is believed that more than 10 million years ago, many large tracts of moist forests in central and peninsular India dried up due to a climatic aridification event. This trapped some birds of the ancestral species in the remnant moist forests along the Western Ghats. With the persistence of large tracts of hostile habitat between the Western Ghats and the Himalayas over time, this population became reproductively isolated from the Himalayan population. Today, the two populations of thrushes are clearly different species.

years), they would lose the ability to interbreed altogether and form two different species (see Box 9). This process, where a natural barrier causes the

Box 10. Do we know of any examples of sympatric speciation?

Large-eared horseshoe bats communicate, like other bat species, using echolocation. The frequency of their calls vary with the body size of the individual emitting them. What may seem more remarkable is that the frequency of calls that a bat 'hears' also depends on its body size. A study shows that the calls of larger-sized bats of this species may be out of the hearing

range of smaller-sized bats, leaving the latter 'deaf' to the former. If this selective deafness impacts the likelihood of cross-breeding between differently sized bats; over a period of time, the smaller-sized bats may be isolated behaviorally and, later, reproductively. This would result in the emergence of two different bat species in the same locality.

genetic isolation that gives rise to a new species, is known as **allopatric speciation**.

Physical barriers are not the only reason two populations become genetically isolated over time. In some cases, environmental conditions may be localized in such a way that two different types of selection pressures act on different members of a population at the same time (see Box 10). If these different sets of individuals do not cross-breed for long enough, this process of **sympatric speciation** could give rise to a new species.

Parting thoughts

The ever-changing environment is constantly selecting for traits that make organisms more likely to survive and reproduce than others. When selection acts on reproductively isolated groups of individuals, it can lead to speciation. This process can be used to explain the vast diversity of life that we see on earth today. New species and their evolutionary histories continue to be discovered every day, leading us one step closer to unravelling the mystery of how life originated on earth.

Key takeaways

- The theory of evolution by natural selection can be used to explain the vast diversity of living organisms on earth.
- This theory is based on the premise that all organisms have variable and inheritable traits.
- Changes in the environment of an individual (over space and/or time) act as filters or sieves that select for certain traits.
- Traits that are favourable for survival and reproduction in a certain environment are likely to be inherited by a higher percentage of individuals in the next generation.
- Evolution is not a linear process where one species changes into another. Instead existing life forms split from their ancestral life forms at specific times in the earth's evolutionary history.
- The splitting or diversification of species is caused by the reproductive isolation of ancestral populations.
- Reproductive isolation between individuals of the same species can occur because of physical barriers or highly localized environmental conditions.



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

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HOW MUTUALISM EVOLVED IN NATURE: THE CASE OF ANT-PLANT INTERACTIONS

JOYSHREE CHANAM

Certain species of ants and plants are seen to interact with each other in ways that benefit both. In a world of constant competition and struggle for survival, how does one explain the prevalence of such non-combative, non-competitive, and seemingly friendly interactions?

Have you ever noticed a butterfly or bee pollinating a flower? Do you know that the plant gives the insect a meal of nectar and pollen in return for this service? Philosophers from the time of Herodotus and Aristotle have observed such bizarre 'friendships' in nature. Another example is of the plover rooting around the open jaws of a crocodile. Why do you think it doesn't get eaten up by the crocodile? Because the bird picks and eats juicy blood-sucking leeches from the crocodile's mouth (see Fig. 1).

Are you wondering why such observations seem bizarre? Species interact with each other in myriad ways (see Box 1). However, most such interactions are antagonistic – either one species ends up becoming food for another species,



Fig. 1. A small bird, like a plover, feeds on leeches from the open mouth of a crocodile.

Credits: Henry Scherren, Popular Natural History (1909), Wikimedia Commons. URL: <https://en.wikipedia.org/wiki/File:PloverCrocodileSymbiosis.jpg>. License: CC-BY.

Box 1. What are some other kinds of interspecies interactions?

Here are some that you may have observed in your own home or backyard –

- **Antagonism:** one organism against another like in predator–prey relationships. For example, a grasshopper feeding on grass.
- **Competition:** two or more organisms competing for the same limited resources, such as food. For example, lions and hyena competing for killed prey.
- **Commensalism:** only one party benefits from the interaction while the other is unaffected. For example, house lizards are safe from predation in the safety of human homes, while humans are not significantly affected by them.
- **Parasitism:** one party benefits at the cost of another. For example, a variety of microbes cause diseases in plants, animals, and humans.

or has to compete with it for limited resources such as food and shelter. An inter-species interaction where the two interacting species benefit each other is called **mutualism**. But why do such interactions exist?

The puzzle of mutualism

As the evolutionary biologist Dobzhansky (1973) famously said, 'nothing in biology makes sense except in the light of evolution'. According to Charles Darwin: '*... if it could be proved that any part of the structure of any one species had been formed for the exclusive good of another species, it would annihilate my theory, for such could not have been produced through natural selection...*' As a result of Darwin's theory, competition and predation came to be seen as key drivers of evolution (see Box 2). On the face of it, one may assume that mutualisms would not be evolutionarily successful. After all, why would natural selection favor organisms that help others?

Today, we know that mutualisms exist because they are actually forms of mutual exploitation that involve a delicate equilibrium of costs and benefits (see Box 3). This means that for every 'give' in such friendships, there is a 'take' that recovers the cost of what is given and more. In other words, rewards are given in exchange for services rendered. Since rewards are a costly investment:

- An individual that gives the smallest possible reward in return for a particular service is likely to be more successful than one who offers more. For example, a plant that produces just enough nectar to attract insect pollinators is likely to conserve more resources for its survival and reproduction than a plant that produces an excess of nectar.
- The friendship will survive only as long as both parties reap a net benefit from it. For example, nectar production in many plant species stops as soon as the flower is pollinated.

Box 2. Are competition and predation key drivers of evolution?

In his paradigm shifting book, 'On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life', Darwin proposed that all organisms present on earth today possess traits that have helped them survive threats in the past.

Individuals that are better at escaping predation, more efficient at competing for scarce resources (such as food or mates), or more capable of adapting to a changing environment have a higher chance of

survival and reproduction. Since their progeny are likely to inherit these traits, and be better at surviving similar contexts, the 'better' trait will spread within the population. Darwin called this process **natural selection**.

Over a period of many generations, the continuous selection of traits that allows a population to adapt more successfully to a challenging environment could even lead to the **evolution** of a species that is very different from its ancestor.

- Such friendships are sustained only as long as the benefit for each party exceeds its costs. Any imbalance, such as cheating (yes, cheating is a technical term in ecology!), in this equation could lead to its breakdown. For example, some flowers falsely advertise nectar to attract pollinators, but don't provide this reward. Pollinators are smart – they quickly learn to avoid cheater flowers.

Mutualistic interactions are, therefore, not as genial as one imagines them to be. Not surprisingly, cheating does still work, but only when cheaters are a small fraction of a population of honest mutualists.

Box 3. Mutualism is of two types – obligate and facultative:

In an obligate mutualism, the two partners evolve so closely together that they cannot exist without each other. For example, each species of the fig tree provides shelter to a specific wasp species that pollinates it.

Facultative mutualisms are more opportunistic. For example, some plants can be pollinated by multiple species of bees and butterflies; and many of these bee and butterfly species pollinate flowers of many different plant species. Neither partner in these mutualisms is entirely dependent on the other.

Mutualisms in ant–plant interactions

The term 'mutualism' to describe inter-species interactions that were beneficial to both species was coined in 1873, by the Belgian biologist Pierre-Joseph van Beneden. Studies on mutualism were mostly based on natural history observations till 1966–67, when Daniel Janzen, an evolutionary ecologist, experimentally demonstrated that certain species of Acacia trees and ants in Central America depended on each other.

We now know of many more plants, mostly from the tropics, that form mutualistic interactions with ants. Such ants protect the plant against herbivory.

The plants, called **ant-plants**, reward the ant with shelter and/or food:

- Ant-plants that **only** provide food rewards to their ant partners are called **myrmecophiles** (= myrmeco: ant related + phile: loving). These rewards take the form of extrafloral nectar (or EFN) and food bodies. EFN is secreted from non-floral parts such as leaf stalks, leaf laminae, and bracts. Solid food globules are secreted from the tips of leaflets or the base of leaf stalks.
- Ant-plants that **also** provide shelter to their ant partners are called **myrmecophytes** (= myrmeco: ant related + phyta: plants), and the shelters are called **domatia**. Domatia are formed by spontaneous modifications of plant parts like leaves, thorns, or branches (see **Box 4**). For example, some domatia consist of branches that are hollow on the inside and swollen up on the outside.

Since ants do not reside on myrmecophiles, they forage on these ant-plants opportunistically and, therefore, may or may not protect it. In contrast, the constant presence of ants on myrmecophytes means that they are more likely to protect their plant partners against herbivory. But is this the only way in which these mutualistic interactions may vary? Are there other selection pressures that can influence the delicate balance of costs and benefits that drive mutualistic associations? Let's explore this question through three examples.

Case I: Ant-plant interactions in bull's horn acacia

The most famous of these mutualistic associations is seen between the Central

American tree *Acacia cornigera* and ants belonging to the genus *Pseudomyrmex* (see **Fig. 2**). The tree provides shelter to the ants in the form of huge hollow thorns (which give the tree its common name – bull's horn). It also provides food in the form of both EFN and food bodies (called Beltian bodies in honour of Thomas Belt who first noticed them in the 1800s). The resident ants patrol the tree day and night, and aggressively guard it against herbivory. For example, they have been observed to bite and drive away caterpillars and bigger insects from feeding on leaves. These ants have also been seen to cut off trespassing vines that try coiling around the host tree.

This ant-plant association is not only an example of obligate mutualism, but also of coevolution (see **Box 5**). Janzen's studies show that the host tree becomes fatally vulnerable to herbivory if *Pseudomyrmex* ants are experimentally removed from them. Therefore, the more ferocious the ants that are attracted to it, the better protected the tree is against herbivory. The greater the

Box 5. What is coevolution?

It is a process where two interacting species reciprocally influence each other's evolution through the process of natural selection. In mutualistic relationships, this process can lead to a stronger partnership over time.

rewards (shelter and food) provided by the host tree, the more attractive the tree becomes to these ants. The more aggressive an ant, the more likely it is to out-compete other ants in finding shelter and food on the host tree. It is through these reciprocal selection pressures that coevolution has helped maintain this obligate mutualism.

Case II: Ant-plant interactions in the *Haasige mara*

Another interesting ant-plant association is seen, closer home, in the *Humboldtia brunonis* (colloquially referred to as the *Haasige mara*) – a small tree endemic to a thin belt of rainforest going north to south along the Western Ghats.



Fig. 2. An *Acacia cornigera* branch showing thorns (domatia) and yellow food bodies on tips of its leaflets. This plant was growing at the Botanical Garden in Gottingen University, Germany. Credits: Joyshree Chanam. License: CC-BY-NC.

Box 4. What is NOT a domatia?

Have you seen those big ant nests, made of leaves, on the mango tree in your garden? They are not domatia. The leaf nests on mango are stitched together by weaver ants, whereas domatia are ready-made shelters provided to ants by their plant partners.

Like *Acacia cornigera*, the *Haasige mara* provides its ant partners with domatia in the form of swollen hollow branches with ready-made entrances, and food in the form of EFN on the leaves and bracts of flower buds (see Fig. 3). However, this mutualism is different from that of the bullhorn acacia in some important ways:

1. Only some individuals of this tree species provide domatia. Therefore, the *Haasige mara* is better described as a semi-mycorrhizal.
2. A number of ant species (~16 species) have been found to nest in the domatia of this tree species throughout its distribution range.
3. Only one ant species, called *Technomyrmex albipes*, has been found to offer any protection to the tree.
4. The domatia of this tree species host invertebrates other than ants. The most interesting of these is a peculiar 'tree-earthworm' called *Perionyx pullus*, that has been seen only in the domatia of this tree (see Fig. 4).

The obvious question is – does protection from herbivory have any influence on this ant–plant association? A study of the *Haasige mara* across its distributional range showed us that trees to the south were more commonly occupied by the protective ant species. A greater number of these trees showed domatia. They also produced larger volumes of EFN, with higher concentrations of amino acids. This is significant because an earlier study suggests that the protective ant species shows a preference for EFN with amino acids; whereas non-protective species feed on any EFN, as long as it is sweet. Not surprisingly, we also found that herbivory pressure was highest on trees to the south. The presence of ants significantly reduced herbivory on these trees, confirming a protective role. In contrast, the threat of herbivory and, therefore, the need for protection by ants, was lower among trees in the northern range.



Fig. 3. *Humboldtia brunonis* offers both shelter and food to ants. (a) Domatium with self-opening slit. (b) Extrafloral nectar on leaves.

Credits: Joyshree Chanam. License: CC-BY-NC.



Fig. 4. The arboreal earthworm *Perionyx pullus* inside a domatium of *Humboldtia brunonis*.

Credits: Joyshree Chanam. License: CC-BY-NC.

But our most interesting discovery was the fact that about one-fifth of the nitrogen on a domatia-bearing branch came from ants – protective and non-protective. This explains the presence of domatia and extrafloral nectar on trees to the north where the herbivory pressure is so low that investing in protection by ants may be too costly. Nitrogen is a crucial nutrient for plants, and tropical rainforest soil (where the *Haasige mara* grows) shows poor nitrogen availability. It also explains the presence of the earthworms – we found that, at any given time, about 90% of the nitrogen in a domatia-bearing branch

was derived from its excreta! The tree absorbs nitrogen from the earthworm's decomposing excreta through the walls of the domatia. Scanning electron microscope (SEM) images revealed that the inner walls of domatia were lined with a mat of fungal hyphae, which could help in the breakdown of ant and earthworm excreta (see Fig. 5). This means that the non-protective invertebrates on *Haasige mara* are mutualists, and not freeloaders or parasites as we had previously believed. In return for the food and shelter it provides, the host plant receives the nutrition from these inhabitants.

This is not only the first known example of a nutrition-based mutualism, it shows that such mutualisms could evolve alongside, or even in the absence of, protection-based mutualisms.

Case III: Non-mutualistic ant-plant interactions

Do ants always form protection- or nutrition-based mutualistic associations with plants? Not true. You can see a

different kind of association in your own garden – one that is, in fact, a step more complicated than the *Haasige mara* example.

If you have ever done some gardening, you may have been in the unpleasant situation of seeing your plants being attacked by tiny insects such as aphids, scale insects, and mealy bugs. These insects use their syringe-like mouthparts, called stylets, to suck phloem sap from plants. Phloem sap, as you know, is nutrient-rich food made by photosynthesis and transferred to various plant parts to provide energy for growth and reproduction. The sap-suckers retain the amino-acids from the phloem sap, and excrete most of its sugars. The excreted sugar is in the form of sweet-droplets, called honeydew. Honeydew sounds and tastes sweet – but, remember, it is aphid poop!

Often, you will also see some ants on these infected plants. If you think that they may protect your plants against the sap-suckers, think again! Quite a few of these ant species form mutualistic alliances with the sap-suckers. Ants love honeydew, lapping it up as soon as each droplet is excreted. In return for this treat, the ants groom and clean the sap-sucking insects, much like cowherds tending their cows (see Fig. 6). Without this care from ants, the honeydew that collects around sap-feeder colonies invites fungal infections that present themselves as black blotches on the insects and their host plants. Ultimately, such insect colonies and their hosts tend to succumb to the fungal infection.

The protection that ants offer sap-suckers does not, however, extend to the host plant. The continued loss of phloem and the open wounds created by the sap-sucker stylets make the plant increasingly vulnerable to other pathogens. In contrast, even the amino acid-poor EFN in the *Haasige mara* trees to the north of its range serves to distract ants from tending to sap-suckers. This could be because ants are known to prefer the simpler sugars of the EFN to the more complex sugars in honeydew.

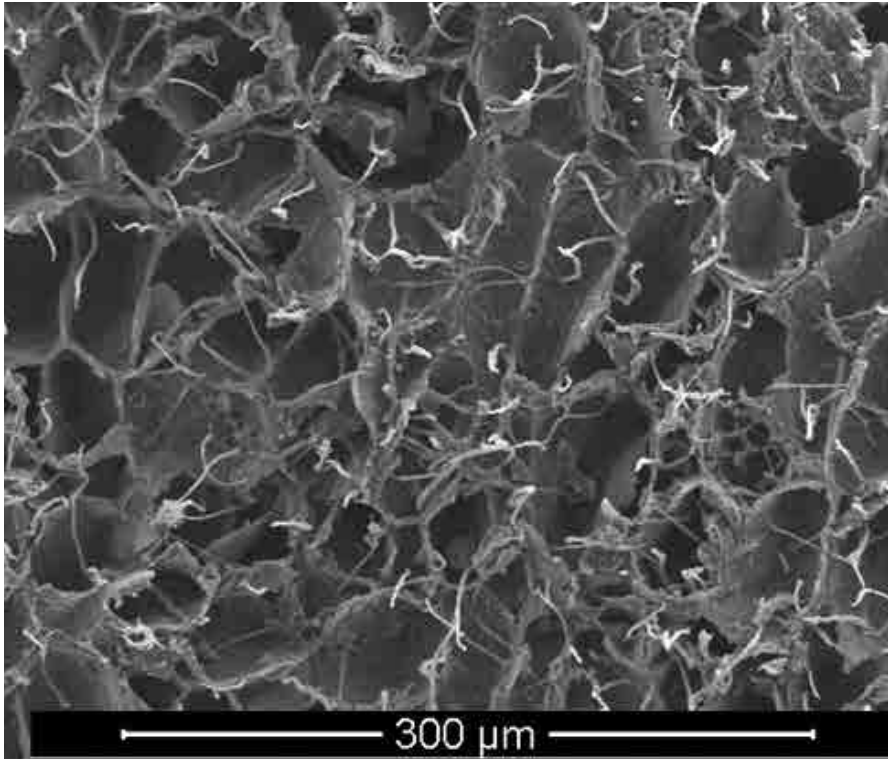


Fig. 5. An SEM image of fungal hyphae lining the inner wall of a domatium of *Humboldtia brunonis*.

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Fig. 6. Ants tending aphids on a plant.

Credits: Joyshree Chanam. License: CC-BY-NC.

Parting thoughts

Mutualistic interactions are widely prevalent in nature. In the 'struggle for survival' that drives organisms to adapt and evolve, often with aggression and competition, some organisms have evolved the ability to participate in give-and-take interactions.

Since they improve the chances of survival and reproduction of both interacting partners, mutualisms are favored by natural selection. For example, *Acacia cornigera* offers an aggressive ant species food and shelter in return for protection against herbivory. On the other hand, *Humboldtia brunonis* offers food and shelter to many species of ants and some invertebrates, in return for both protection and nutrition. In this case, the quality and quantity of

rewards provided by the host plant depend on the intensity of the threat of herbivory they face. In contrast, the case of phloem-feeding insects and their attendant ants is an example of how some mutualistic interactions between two species can happen at the cost of a third species.

These are just a few of the many examples of mutualism that are abundant around us (see **Box 6**). Can you identify some mutualistic interactions in your neighbourhood? All you'll need is a little bit of curiosity and some time to observe life more closely.

Box 6. Teacher's toolkit:

Take students on a walk in the garden to see if they can identify plants that attract ants. In particular, look for common flowering plants, like *Passiflora* spp. with extrafloral nectaries on their leaf stalks.

- Do ants come to feed on them?
- Is the EFN produced only in young leaves vulnerable to herbivory? Or is it produced even in mature and toughened leaves? Why?

Also look for ants tending aphids or other sap-sucking insects on plants. If you notice black soot-like smudges on these plants, observe them carefully to see if the sap-suckers and their stray honeydew are the culprits.

Key takeaways



- Mutualisms are favoured by natural selection because they are forms of mutual exploitation that involve a delicate equilibrium of costs and benefits for both interacting partners.
- Interacting partners in a mutualistic relationship can coevolve by reciprocally influencing each other's evolution.
- Ant-plant interactions offer some interesting examples of mutualism. Plants can provide food and/or shelter to ants. Ants can offer protection and/or nutrition in return.
- Some mutualisms between two species exist at the cost of a third species.
- *Humboldtia brunonis* is the only well-studied myrmecophyte (or plant that offers food and shelter to its ant partner) in India. If I were you, I would head off to the Western Ghats to see it at the earliest opportunity!

Note: Source of the image used in the background of the article title: <https://www.flickr.com/photos/viamoi/1468093483>. Credits: Stuart Williams, Flickr. License: CC-BY.



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A green dinosaur with a spiky back is running in a desert landscape. In the background, another dinosaur is visible. The ground is reddish-brown and there are some small green plants.

DO DINOSAURS STILL WALK THE EARTH?

SHREYA GHOSH

While most branches of the dinosaur family tree were wiped out during a mass-extinction event 65.5 million years ago, some of their direct descendants still live on. What do we know about these creatures, their mysterious survival, and their relationship to the dinosaurs of yore?

The tiny town of Chicxulub Puerto in south-eastern Mexico houses only a few thousand residents. A casual glance at the sleepy settlement suggests a peaceful community, one amongst many dotting the vast Yucatan peninsula. Yet, buried just about a kilometre beneath Chicxulub's surface and written in lines of quartz and melted rock lies the evidence of its uniquely violent history. The ground where Chicxulub Puerto stands today was once ground zero for one of the most catastrophic events in the history of life on earth.

On a day 65.5 million years ago, a piece of extra-terrestrial rock as big as a mountain crashed into earth with the

explosive power of over a hundred trillion tons of TNT (see Fig. 1). Releasing more than a billion times the energy of the atomic bomb dropped on Hiroshima, the rock's impact created an almost perfectly circular crater, nearly 180 km in diameter, right atop the centre of which Chicxulub stands today (see Fig. 2). It resulted in a massive heat pulse, vaporizing all living forms for miles around, followed by earthquakes and massive tsunamis that radiated out in all directions. The debris and dust thrown out into the atmosphere blocked out sunlight for over a year, resulting in a nuclear winter where plants failed to grow, and predator and prey alike starved to death (see Box 1).



Fig. 1. Artist's rendering of an asteroid slamming into the tropical, shallow seas of the sulfur-rich Yucatan Peninsula in, what is today, southeast Mexico.

Credits: Donald E. Davis, NASA/JPL-Caltech, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Chicxulub_impact_-_artist_impression.jpg. License: Public Domain.

All of this occurred in the background of an earth that was already ravaged by severe volcanism and global climate change. The **Cretaceous-Tertiary (K-T) mass extinction event**, as it is called today, ended up wiping out nearly two-thirds of all the species inhabiting the planet at the time (some estimates go as high as 80% of all life on earth).

Amongst these was a massively successful group of reptiles, of which more than a thousand species of every size had once roamed the jungles. The age of the dinosaurs had come to an end (see **Box 2**).

However, not every dinosaur perished in the K-T extinction. One unlikely group survived, and they persist to this date,

nesting on our windowsills, stealing bits of food from roadside stalls, and waking us up in the morning with their cacophonous warbles.

Birds are the last living dinosaurs on our planet, and this is their story.

Box 1. The biggest asteroid collisions in earth's history:

The Chicxulub asteroid collision is rather well known because of its relative recentness and the mass extinction that followed. But it is nowhere near unique in earth's tumultuous history, and is only the third-biggest asteroid impact on earth known to humankind. Here are a couple of other big 'impacts' that have changed the face of the earth in the past:

- (a) The Vredeford Crater, located in South Africa, is believed to be the second oldest and the largest known impact crater on earth. A roughly 10 km wide asteroid struck earth about 2 billion years ago, creating a crater that is more than 300 km across. Life on earth at the time consisted of single-celled organisms. We know little about the consequences of this massive event on them.
- (b) The Sudbury Crater in Ontario, Canada, that is around the same size as Chicxulub, was formed by an asteroid impact about 1.8 billion years ago. This impact crater later filled up with molten rock rich in minerals like nickel, copper, platinum, and gold, making this area extremely lucrative for both mining and agriculture.



Fig. 2. This shaded relief image of Mexico's Yucatan Peninsula shows a subtle, but unmistakable, indication of the Chicxulub impact crater.

Credits: NASA/JPL-Caltech, modified by David Fuchs, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Yucatan_chix_crater.jpg. License: Public Domain.

Box 2. How did the Cretaceous-Tertiary (K-T) mass extinction event impact human evolution?

The aftermath of the Chicxulub impact is often known as the Cretaceous-Tertiary mass extinction event because it marks the dividing boundary between the Cretaceous and Tertiary geological eras in earth's history. Almost three-quarters of all life on earth (including plants, animals, and micro-organisms) is believed to have perished as a result of the global environmental changes that resulted from the impact.

Interestingly, a few groups of animals, including mammals, that were overshadowed by the majestic dinosaurs in the previous era, underwent massive diversification and population growth following their extinction. Perhaps, at some level, we humans owe our existence to the Chicxulub asteroid impact!



Fig. 3. The 'Berlin specimen' of *Archaeopteryx*.

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

The ancient wings of Archaeopteryx

It was not always known that birds were related to dinosaurs. Sometime in the mid-1870s a German farmer named Jakob Niemeyer discovered a strange fossil in the Blumenberg quarry near the town of Eichstätt in Germany. In need of money to buy a cow, Niemeyer decided to sell the fossil to a local innkeeper. After changing hands a few more times, the fossil was finally bought by the Natural History Museum of Berlin in 1881, for the princely sum of 20,000 gold marks. This 'Berlin specimen', as it came to be called, contains an excellently preserved skeleton and skull of a creature with spread wings, a bony tail, and three claws at the end of each 'hand' (see Fig. 3). What Niemeyer had discovered, and sold for want of a cow, remains one of the most perfect and complete specimens of *Archaeopteryx* till date. With a name derived from Greek 'archaios' meaning ancient, and 'pteryx' meaning wing, it was our first clue to the mysterious origins of modern birds.

Archaeopteryx was first described in 1861, by the German palaeontologist Christian Erick Hermann von Meyer, using a single fossilized feather. The first skeleton was unearthed in the same year from a quarry near Langenaltheim in Germany. In an uncanny parallel with Niemeyer, the unknown discoverer of this specimen gave the fossil as payment to a local doctor, who sold it to the Natural History Museum in London. So, what makes this prehistoric bird, that lived almost 160 million years ago, unique?

Archaeopteryx had a near-perfect mix of reptile-like and bird-like features. About the size of a big crow, it had a long tail and jaws with sharp teeth like a reptile, but also sported two large feather-covered wings and three-fingered hands like modern birds (see Fig. 4). "Hardly any recent discovery shows more forcibly than this how little we as yet know of the former inhabitants of the world," wrote Charles Darwin, the father of evolutionary biology, in the 4th edition of *On the Origin of Species* (1866).



Fig. 4. Illustration of *Archaeopteryx lithographica* chasing a juvenile compsognathid (*Compsognathus longipes*) through Late Jurassic Germany at night.

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

New theories and old theories

Thomas Huxley, an English biologist and a great proponent of Darwin's theory (to the extent that many people called him 'Darwin's bulldog'), was the first to note the similarities between the skeletons of birds and theropods. Theropods are a class of dinosaurs characterized by hollow bones, and three toes on each arm and leg (see Fig. 5). Based on this

observation, he suggested that birds might have evolved from theropod dinosaurs (see Box 3).

However, this theory soon fell out of favour, particularly with the publication of an influential book, in 1926, by the Danish anatomist Gerhard Heilmann. Through a detailed comparative analysis of the skeletal features of birds and other closely related groups, Heilmann concluded that birds are more closely related to

Box 3. How did Darwin explain the evolution of new species?

According to Darwin's theory of evolution, new species arise due to a process of gradual change and continuous selection. Individuals in a population always differ from each other in many small ways — this is called **variation**. Variations arise because of differences in the genetic makeup of individuals.

When environmental conditions change, individuals with certain traits or genetic makeup have a better chance of survival. These individuals are also, therefore, more likely to reproduce and pass their genes onto the next generation. As a result, some traits become more and more prevalent as generations go by. With time, populations which accumulate a number of such unique traits may change to an extent that they can no longer mate with other populations of the same species. This is known as **reproductive isolation**. Coupled with the slow accumulation of different traits, it can lead to the formation of a completely new species.

Therefore, when we try to reconstruct the evolutionary history of a species, we often look at which other species or groups it shares the most similarities with. The assumption is that two similar groups must have had a common ancestor at some point in the recent past. A population of this ancestral species split at some point since then and slowly accumulating changes, over millions of years, gave birth to two completely different species.



Fig. 5. (a) An artist's reconstruction of *Utahraptor*, a theropod dinosaur. (b) Cast of a theropod dinosaur footprint from the Moenave Formation, Utah, on display at the BYU Museum of Paleontology.

Credits: (a) Emily Willoughby, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Utahraptor_updated.png. License: CC-BY-SA.

(b) Etemenanki3, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Theropod_track_BYU.jpg. License: CC-BY-SA.

theropod dinosaurs than any other group of animals. However, certain anatomical differences, particularly the presence of a fused collarbone in birds but absent in dinosaurs, make it impossible for the former to have evolved from the latter. Instead, he suggested that birds and dinosaurs may have evolved from a common ancestor called **thecodont**. So popular was this theory (and this book) that, over the next half a century, the 'thecodont hypothesis' came to be accepted by almost every expert in the field.

It was only in the late 1970s when a convergence of evidence from multiple sources resurrected the dinosaur → bird theory. Along with anatomical and fossil-based studies, the new science of cladistics (in which organisms are classified into groups based on how recently they shared a common ancestor) played a big role in this resurrection. Today, the dinosaurian origins of birds, and hence their status as 'living dinosaurs' is widely accepted.¹

What was the evidence that cinched the deal? Fossils from many sources, particularly from the Jehol Biota of China, showed that early birds and certain groups of theropod dinosaurs shared many features. These include characteristics that we assume as being peculiar to modern birds, and that differentiate them from almost all other groups of animals living today. Examples of such features include feathers, wishbones, egg-brooding, two-legged walking, and even flight (see **Box 4**).

Let's take feathers, for instance. Bird feathers are complex structures that help in the aerodynamics of flight. They also help perform a number of other functions, such as maintaining body heat, egg-brooding, and attracting mates. Some fossils of early theropod dinosaurs show hair-like filaments that can be called **protofeathers**. Later theropods appeared to have feathers whose structures are much more similar to those of birds. Interestingly, as many fossil studies have shown, many non-bird dinosaurs were also covered in feathers.

Feathered wings may have helped some of these, like microraptors (four-winged dinosaurs covered with feathers that are virtually indistinguishable from the feathers of modern birds), glide expertly (see **Fig. 6**). In other (clearly non-flying) dinosaurs, feathers may have served a completely different function. All of these point towards the idea that feathers probably evolved for a function other than flight – perhaps these colourful plumages were used to attract mates, or scare predators and competitors. Only later were they co-opted into helping the animal fly, and became specialized for the purpose.

Apart from feathers, birds have extraordinary sensory capabilities.

These are helped by a large forebrain, which aids them in the rapid sensory processing and decision-making required for flight. Scientists have found evidence that some dinosaurian ancestors of birds also had largish forebrains, suggesting that their brains had already started achieving a state that would allow them to eventually evolve flight (in a sense, becoming "flight-ready"). Birds also have a rapid metabolism, which supplies the massive amount of energy required for flight. While reptiles are cold-blooded, birds are not; and evidence suggests that dinosaurs may have fallen somewhere between the two in the spectrum (see **Box 5**).



Fig. 6a. An artist's rendition of a pair of microraptors searching the forest of Liaoning in spring.

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



Fig. 6b. A fossil of *Microraptor gui* (scale bar at 5 cm) showing the preserved feathers (white arrow) and the 'halo' around the specimen where they appear to be absent (black arrows).

Credits: David W. E. Hone, Helmut Tischlinger, Xing Xu, & Fucheng Zhang, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Microraptor_gui_holotype.png. License: CC-BY.

The first true birds appear in the fossil record around 150 million years ago, about 85 million years before the Chicxulub collision (see Box 6). Scientists often have difficulty distinguishing the fossils of these early birds from non-bird dinosaurs, showing how similar the two branches could sometimes

Box 4. What makes birds special?

Many of the features that we consider to be unique to birds are in fact not so unique. Apart from a few flightless cousins, most birds can fly – but so can bats, and many species of insects. Birds have hard beaks which they use for feeding, nest-building, and a variety of other tasks. But beaks are also present in certain turtles, and even mammals like the duck-billed platypus. Egg-laying is also not specific to birds, as most fish and reptiles also bring forth their young in this way.

What, then, are the unique features of birds? The first and most obvious of these are feathers. No other currently living group of animals possesses true feathers. Bird feathers serve a variety of functions – they help in flight, insulation, and ornamentation. Interestingly, while this feature is considered unique to birds today, it wasn't always so – feathers have been found on both bird-like and non-bird dinosaurs.

Other, less obvious, features that are unique to birds include bones that are lightweight and hollow to aid flight, and egg brooding. However, egg brooding (which involves incubating eggs, and providing them with body heat) is arguably also seen in certain reptiles and amphibians, as well as egg-laying mammals like the Platypus.

be (see Box 7). The early forefathers of birds coexisted alongside their dinosaur brothers for nearly 100 million years, with small gradually accumulating changes distinguishing them from each other. The closest relatives of birds at the time were the small-bodied, feathered, large-brained dromaeosaurids and troodontids – theropod dinosaurs that resembled birds almost more than they resembled other dinosaurs (see Fig. 7).

Box 5. Teachers toolkit – learning comparative anatomy:

1. Divide students into two groups – Birds and Dinosaurs.
2. Encourage the 'Bird group' to research and list features they find unique and interesting in birds, and the 'Dinosaur group' to do the same for dinosaurs.
3. Invite students to present and compare the two lists to pick up on similarities and differences.

Surviving apocalypse

All of this gives rise to the question – how did birds survive the mega-extinction event that marked the end of the age of the dinosaurs? Well, our first clue lies in the fact that not all birds did. Most bird species did go extinct in the aftermath of the Chicxulub impact, and only a tiny fraction survived. We can only speculate on what marked this handful of species for survival.

A recent hypothesis suggests that the surviving branches of the bird-family consisted of birds that had evolved hard beaks, specialized to feed on grains or seeds, to replace jaws and teeth.² While much of plant foliage, fruits, and small prey would have been destroyed in the aftermath of the impact, seeds are much harder. Their ability to feed on seeds may have been the one factor that tipped the scale in favour of these birds,

Box 6. How do we know the age of fossils?

While finding a fossil can be exciting for the amateur palaeontologist, figuring out exactly how old it is can be a tricky process. Scientists determine the age of fossils by two main methods – relative dating and absolute dating. In relative dating, fossils are compared to something whose age is already known, for example, the rock layer in which it was found. In absolute dating, scientists use trace amounts of radioactive minerals in the fossil, or (more commonly) its surrounding rocks, to determine its approximate age.

protecting them from death by starvation. However, some scientists have disputed this hypothesis based on the existence of some toothed and beakless ancestors of birds that were also known to have fed on seeds. In addition, this hypothesis doesn't explain why certain species of beaked birds (especially small ones) appeared more likely to survive than others.



Fig. 7a. A large, short-armed, winged dromaeosaurid from the Early Cretaceous of China indicating the presence of feathers.

Credits: Junchang Lü & Stephen L. Brusatte, Wikimedia Commons. URL: <https://commons.wikimedia.org/wiki/File:Zhenyuanlong.jpg>. License: CC-BY.



Fig. 7b. Cast of the fossil dromaeosaur specimen NGMC 91 (nicknamed "Dave", cf. *Sinornithosaurus*) at the American Museum of Natural History in New York, showing early bird-like features.

Credits: Dinoguy2, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Sinornithosaurus_Dave_NGMC91.jpg. License: CC-BY-SA.

Box 7. Teachers toolkit – understanding evolutionary distance:

1. Create a randomized set of about twenty to thirty anatomical features (e.g. long tail, five fingers, blue feathers etc.)
2. Print four copies of each of these features on small index cards.
3. Divide students into 5-10 small groups, and have each group draw five cards from the pack.
4. Encourage students to use their cards and the features printed on them to create an imaginary animal and name it whatever they like.
5. Invite students to compare the features of the different imaginary animals to figure out how closely related they are to each other.
6. Get students to create an evolutionary tree to connect their animals.

Another hypothesis contends that it is the habitat that these early birds were adapted to live in that made the biggest difference to their survival.³ There is evidence of massive global deforestation occurring in the aftermath of the Chicxulub impact – the initial shockwave is itself estimated to have

flattened all trees within a 1500 km radius. For a long time afterwards, dust and minerals released by the impact would have blocked out photosynthesis and resulted in frequent acid rains. When we consider these factors, it seems likely that tree-dwelling creatures would have swiftly run out of luck. The only

birds to survive this period were much like today's chicken and other fowl – ground-dwelling, and small in size.

Parting thoughts

While it is still unclear how birds managed to survive the Chicxulub impact, today they are one of the most successful groups of animals on the planet. With more than 10,000 different species, birds have colonized almost every habitat on earth. Their powerful flight muscles allow them to soar for thousands of kilometres and, sometimes, at a height of over 9000 m above sea level.

So the next time you look out of the window and observe a crow scowling at you, remember that its ancestors once ruled the earth and, somewhere in its genes, the same majesty lives on.

Key takeaways

- A few families survived the catastrophic asteroid impact that led to the extinction of most dinosaurs.
- Birds are the natural descendants of theropods – a branch of one of these surviving dinosaur families.
- The survival of theropods may be linked to their ability to eat seed-like food (that was more abundant in the aftermath of the impact).
- Theropod ancestors of birds may also have survived the asteroid impact because they were small in size, and ground-dwelling rather than tree-living (trees were decimated by the asteroid impact).
- Many of the features we associate with birds today, like flight or feathers, were already present in their dinosaurian ancestors.



Note: Source of the image used in the background of the article title: <https://pxhere.com/en/photo/690156>. License: CC0.

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WORKHORSES OF BIOLOGY RESEARCH: MODEL ORGANISMS

DEEPTI TRIVEDI

In two centuries of modern scientific history, model organisms have contributed to our understanding of human physiology, cell biology, and diseases. But what are model organisms? What discoveries have they contributed to? What are some limitations and ethical dimensions associated with them?

Living organisms vary widely in their shape, size, habitat, and the nature of their interactions with their environment. Despite this great diversity, all living organisms share some common features. The use of model organisms began, more or less, with the knowledge that all organisms had evolved from a common ancestor. The theory of evolution put forth by Charles Darwin and others in the late 19th century suggested that all organisms had branched out from a temporal evolutionary tree (see Fig. 1). This meant that these organisms would share a lot of biology. Data accumulated from different model organisms in the 20th century proved this – we know that all organisms are quite the same in the way they inherit genetic material, use energy, and make their own building blocks. Their shared origins also mean that more closely related species are likely to share greater similarity than more distantly

related species. Therefore, investigating the biology of organisms from one species can be a proxy to understanding organisms from other, evolutionarily close, species. The specific organisms selected by researchers (based on their amenability to experimental studies) for this purpose are called **model** or **reference organisms**.

Many bacteria, fungi, insects, worms, fishes, plants, and mammals are used as model organisms worldwide. These organisms not only help us gain in-depth knowledge of their own species, but also of closely related species, genera, and kingdoms. Many scientific advances in terms of our understanding of human anatomy, biochemistry, physiology, development and genetics would not have been possible without their use. In fact, if all research on human biology had to be done in humans, and not in model organisms, biological research would have lagged, and been a lot more expensive.

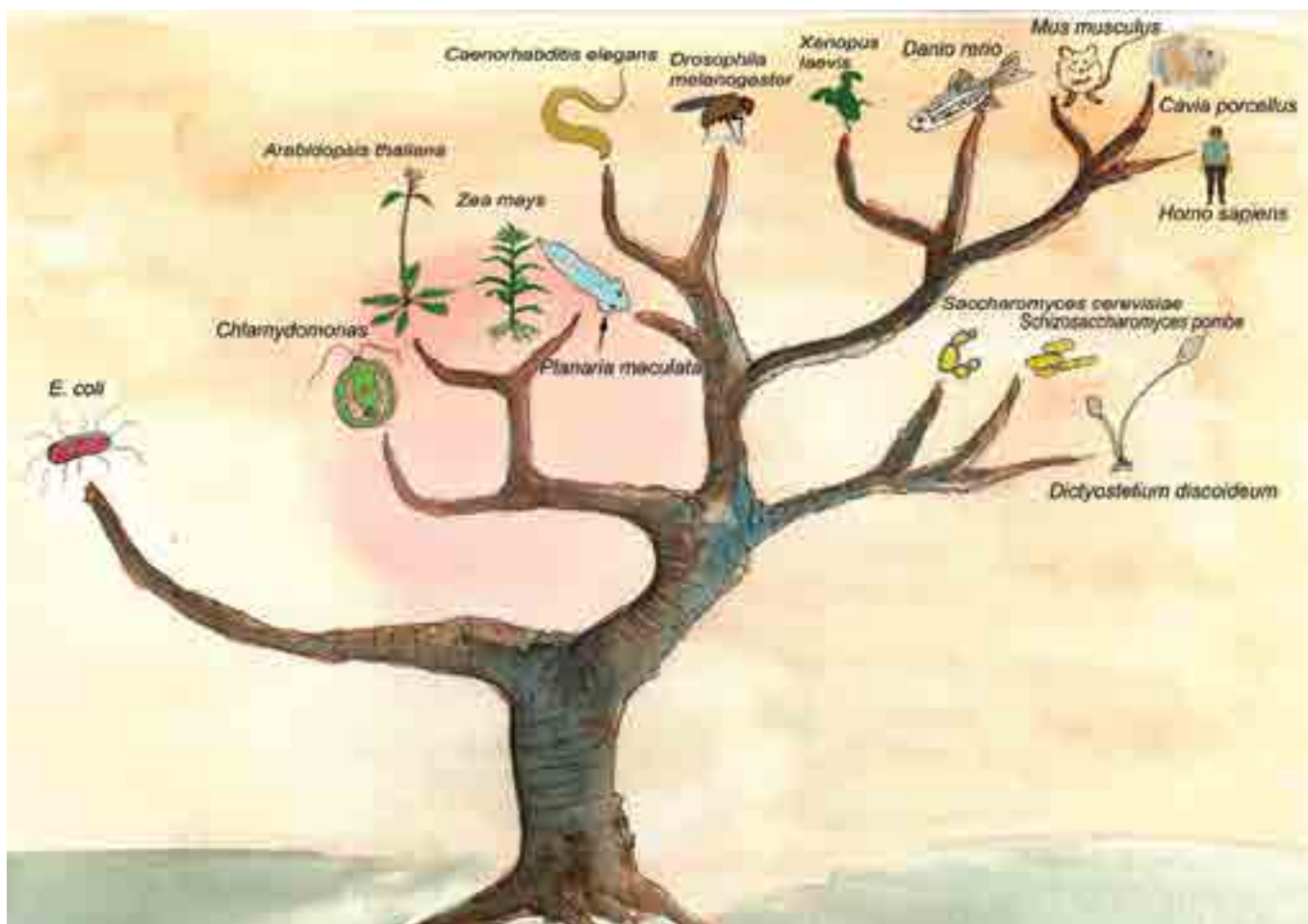


Fig. 1. An evolutionary tree depicting the relationships between different model organisms with each other and to us humans. The closer two species are to each other in terms of their evolutionary history, the more similarities they share with respect to their biochemistry, physiology, anatomy, and genetics.

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Choosing a model organism

These are some of the things a scientist considers before choosing a model organism for her research:

- 1. The research question:** It should be possible to address one's research question in the model organism of choice. For example, mechanisms of photosynthesis can be studied in algae or plants, but not in animals.
- 2. Practicality:** It should be practical to do a certain kind of research in the organism selected. For example, one may not want to study evolution or population dynamics in organisms that take years to grow and reproduce. At the same time, one would prefer that the lessons learnt from their studies be as widely applicable as possible. Other practical considerations include availability of funds, logistics and space, and ease in growing and maintaining the model organism. For example, a project using penguins as models may require huge infrastructure and maintenance costs if done in India.
- 3. Methods:** The experiments that one designs should be doable in the organism of choice. Some experiments may simply be too difficult to perform in a certain model organism with currently available methods. For example, to study effects of certain mutations that do not already exist in the model organism, one first needs to create these mutations. Certain model organisms are more amenable to this requirement as the resources and methods to create mutations in them are already available.
- 4. Evolutionary conservation:** Some specific phenomena may not be conserved across species. Hence, one may need to study closely related species to understand those phenomena better. For example, although breast development and cancer cannot be studied in insects, the molecular pathways that play an essential role in these phenomena are conserved in insects. Insect models can, therefore, offer insights into molecular interactions that form their genetic basis.

Box 1. Why did Morgan choose the humble fruit fly as a model organism?

Morgan was looking for a model organism that would provide an example of evolution that he could see occurring in front of his eyes. He was not completely convinced about Darwin's theory and wanted to study how organisms evolve (or if they even really evolve). This meant that Morgan's model organism had to have these specific attributes:

1. A short generation time: This would allow him to track the transmission of traits over many generations in a comparatively short amount of time.
2. The ability to grow *in vitro*: Darwin's work was based on observations in the wild that spanned millions of years, but

Morgan wondered if evolution could be recaptured in a laboratory setup. Also, since Morgan expected evolutionary changes to happen at a very low frequency, the model organism had to be easy and relatively inexpensive to grow in comparatively larger numbers within the confines of a small lab space.

3. The ability to study it with available methods: Morgan wanted to be able to see evolutionary changes, if any, with the equipment available to him. Remember, in the early 20th century, many of the sophisticated methods that we know today were unavailable. All that Morgan had were some simple microscopes.

After much thought and discussion, he chose *Drosophila melanogaster* as his model organism. This tiny fruit fly was easy to grow in large numbers and developed from egg to adult in just 10 days. The genetic studies that Morgan was able to do in months in fruit flies would have taken hundreds of years in humans, been a lot more expensive, and required the participation of an entire country's population! The data it yielded would have been far more complex to interpret. And, even if it were actually possible to do so, such a study would have given the exact same result.

Examples of model organisms

(a) *Drosophila* as a model organism to study genetics: Thomas Morgan, an American evolutionary biologist, was the first to choose a fruit fly, *Drosophila melanogaster*, as a model organism (see Box 1). Thanks to Morgan and his colleagues, and later work by many other scientists, these insects that hover around in

the kitchen on ripe fruit, especially bananas, are now very well-established model organisms.

Interestingly enough, Morgan's studies with the fruit fly had little to do with evolution. Yet he and his colleagues ended up providing incontrovertible evidence for the highly debated chromosomal theory of inheritance – knowledge that is pertinent across kingdoms. They showed that genes reside on chromosomes in a linear

fashion, the distance between genes could be calculated based on genetic markers, and mutations in genes lead to changes in phenotypes.

Given the many similarities fruit flies share with us, *Drosophila* biologists have been using these insect models to understand the genetic basis of body patterning and development, circadian rhythms, immunity, and olfaction (see Fig. 2). All these discoveries have led to Nobel Prizes.

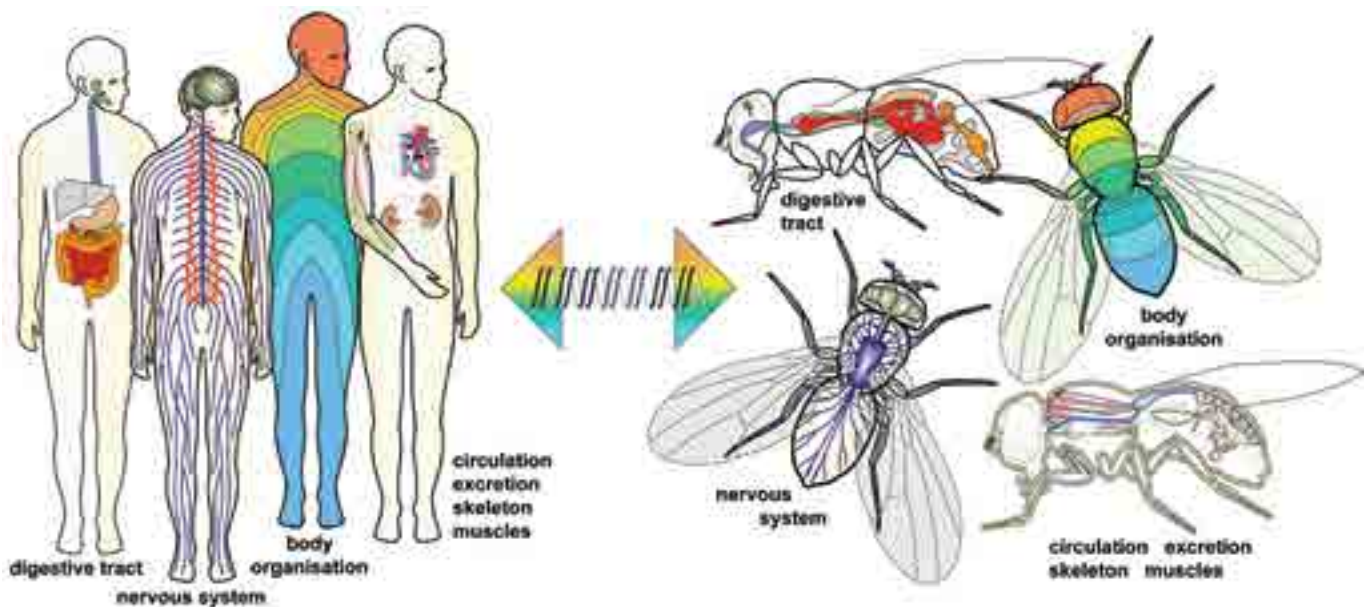


Fig. 2. *Drosophila* shares many similarities with humans.

Credits: A. Prokop from the Manchester Fly Facility, Faculty of Biology, Medicine & Health of The University of Manchester. URL: <https://droso4schools.files.wordpress.com/2015/06/fig2-organs.jpg>. License: Used with permission of the rights owner.

Box 2. Bringing biology from one system to another for genetic engineering:

Basic research to study the same process in different organisms not only helps bridge gaps in our understanding, it may also help in the development of technologies that use this process to manipulate other organisms. One example is the use of bacterial biology for genetic engineering.

Like humans, bacteria also get infected by viruses. Infected bacteria may either die, or survive by fighting the infecting virus. Those that survive, develop immunity against the infecting virus by 'remembering' their DNA sequences – pieces of these viral sequences get written into the bacterial genome. The next time the same virus infects them, they recognize and chop the viral DNA sequences much faster. This process helps the bacteria fight the virus more effectively than the first time.

The ability of bacterial cells to recognize and chop a foreign DNA sequence has been studied in great detail. The specific bacterial genes and proteins (called **Cas9 proteins**) responsible for performing these functions have been isolated. These proteins can be used to chop specific DNA sequences in any organism. As part of a technological

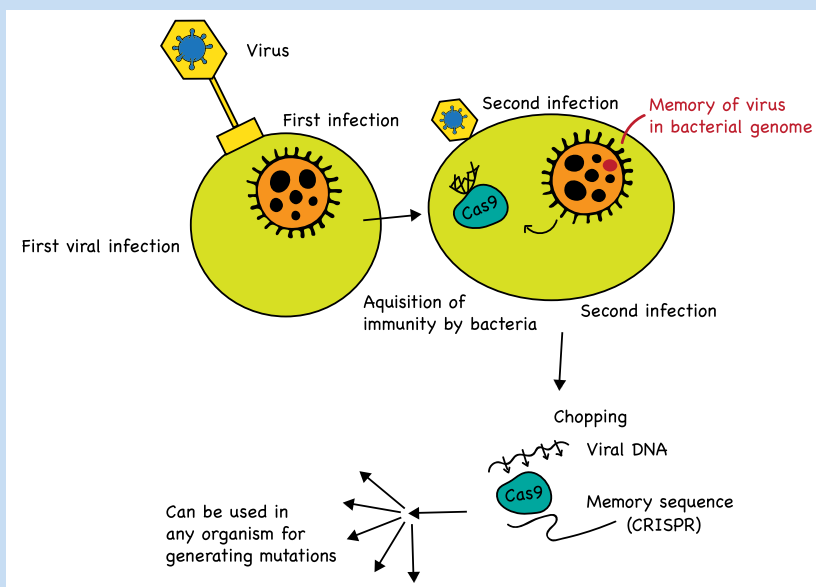


Fig. 3. CRISPR Cas9 technology.

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application, called **CRISPR–Cas9 technology** (see Fig. 3), they are used to generate specific mutations in different organisms, and have great potential in treating genetic diseases.

(b) Bacteria as model organisms: There are many compelling practical and technical reasons to study bacteria for their own sake.

First, and perhaps most importantly, bacteria cause many human, animal, and plant diseases. Therefore, we study bacteria in the hope of finding better ways, including more effective antibiotics and vaccines, to control diseases caused by them. Secondly, bacteria have been used as models in many key studies and contributed to our understanding of the general principles of growth, replication, transcription, and translation in living organisms. In addition, bacterial phenomena have been used in eukaryotes for genetic engineering (see Box 2).

(c) Planarians as a special model to understand regeneration and aging:

What happens when you get bruised from a fall? The bruise heals in a few days, with new skin cells replacing the older, injured tissue. Soon, you may not even remember where the bruise was. But what if you were to lose a finger,

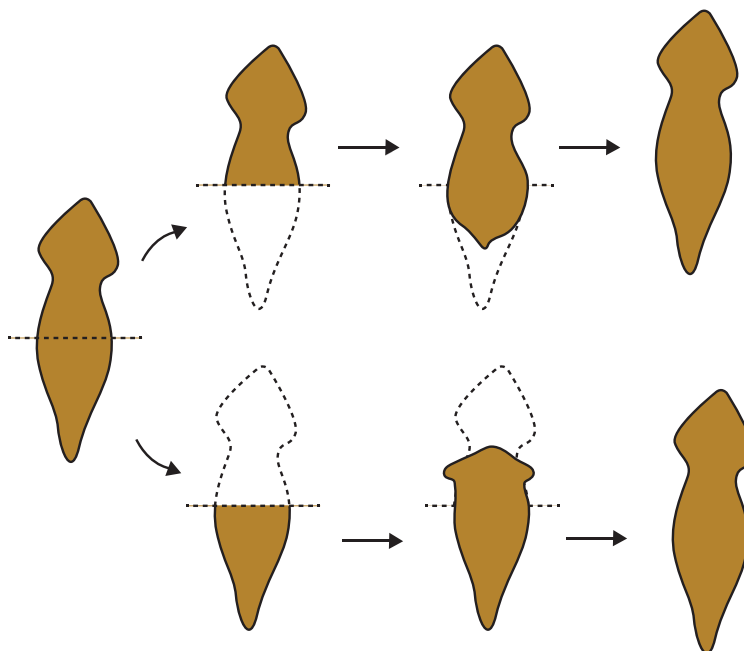


Fig. 4. Planarians are studied for their regenerative potential.

Credits: Adapted from <https://www.shutterstock.com/image-vector/science-cartoon-teaching-about-regeneration-planaria-1389132521>.

or a complete arm, in an accident? Is it likely that these body parts would grow back?

Compare this with planarians – these flatworms exhibit the extraordinary ability to regenerate lost body parts. For example, a planarian split lengthwise or crosswise will regenerate into two separate individuals. If given sufficient time, even a hundredth piece of a planarian will develop into a fully-grown organism (see Fig. 4)!

Their regenerative potential makes planarians a model system for investigating a number of biological processes, many of which have important implications for human health and disease. For example, planarians are used in the identification of genes responsible for regenerating body parts. With their apparently limitless regenerative capacity, these 'effectively immortal' worms also make a great model for aging studies. For example, studies showing that the chromosomal ends of these worms are protected suggest that this protection may be important to prevent aging.

Use of model organisms in drug discovery

Often, when we fall sick, medicines or drugs are prescribed to help us get

better. But have you ever wondered how drugs specific to a disease are made?

Drug discovery is a tedious process. Every disease has some physiological basis – it is either an infection, a genetic disorder, an allergy, or an injury that causes a disturbance in our body function at the cellular and molecular level. Often, this leads to over-activation or suppression of molecular pathways in our body. These molecular pathways are the targets of drugs that help restore them to normal function by blocking or activating specific enzymes. Since many cellular and molecular pathways are conserved across species, model organisms are used to screen millions of compounds for their ability to block or activate these specific enzymes. The compounds identified by these screening methods (as potential drugs) are tested in higher organisms (lower mammals, primates, and humans in that order) to study their efficacy and toxicity before they come into the market (see Fig. 5).

Ethics

Historically, human beings have used other living beings, including animals and plants, for their own benefit, without

much consideration to these organisms. In fact, the use of animals in research dates back to ancient Greece, with Aristotle (384–322 BCE) and Erasistratus (304–258 BCE) being among the first to perform experiments on living animals. However, in the recent past, many questions have been raised regarding the ethics of using other organisms for research that benefits humans.

The use of model organisms is based on the premise that all organisms (including humans) are distant cousins of each other and, therefore, share similarities in their cellular and molecular architecture. By the same logic, there is a high probability that our animal models experience pain and suffering just like we do.

All research is focused on at least one of two outcomes – medical innovations or increased knowledge. Increased knowledge improves our understanding of the human mind and body, and can lead to medical innovations in the long run. However, the benefits of research for the sake of increasing knowledge may not always justify the costs of the suffering inflicted on the animals used for it. How well justified this kind of research is will vary depending on the extent of suffering a certain research project inflicts on its model organisms, and their psychological complexity.

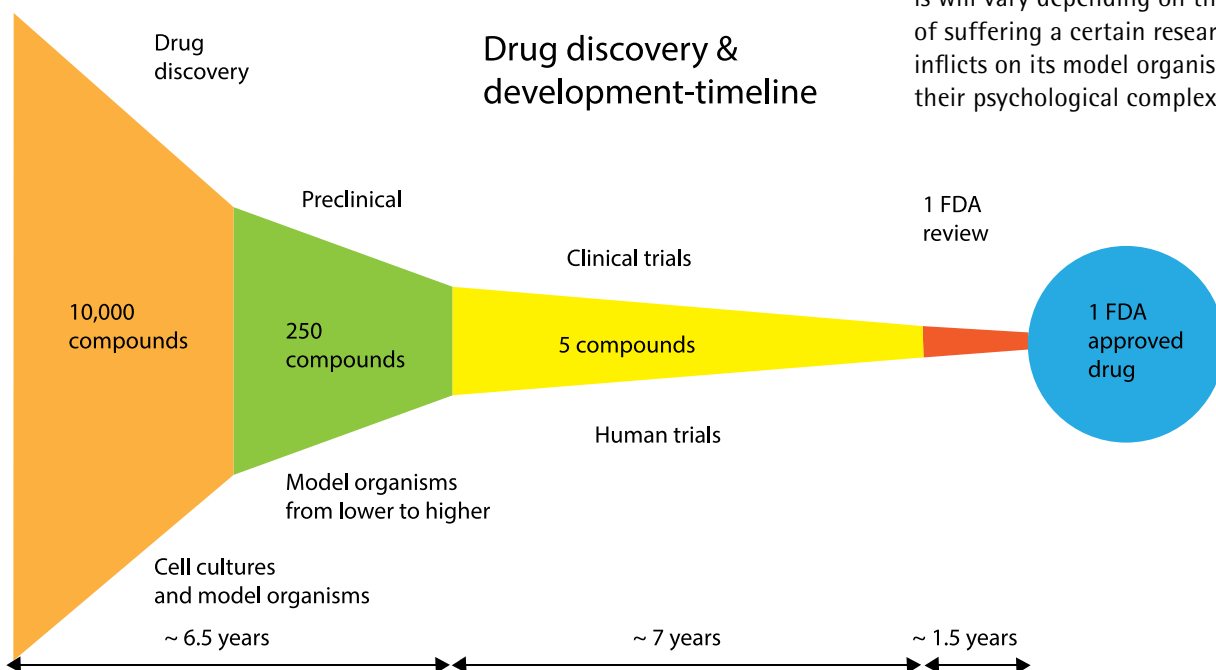


Fig. 5. A schematic of drug discovery.

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To address these ethical issues, most scientific research on model organisms is governed and regulated by ethical committees at the institutional level. These committees review the justification for a research project, among other considerations. They also attempt to ensure that Russell and Burch's (scientists appointed for the systematic study of laboratory techniques in their ethical aspects by Universities Federation of Animal Welfare in USA) three R's are followed in each project:

- **Refinement:** research methods should focus on minimizing pain and suffering.
- **Reduction:** using fewer animals in each experiment without compromising scientific output, quality of research, and animal

welfare. This means that the research project should, for example, follow optimal colony management strategies.

- **Replacement:** using non-sentient materials to replace the use of conscious living vertebrate animals completely, partially, or relatively.

The use of most lower organisms, including bacteria, yeast and insects, does not currently require clearance from ethical committees.

Limitations

Although fundamental discoveries can be made in model organisms, not all them hold true for humans. For example, many drugs that are successfully tested in model organisms may not work in humans. This is

because many processes either do not exist or function differently in model organisms as compared to humans. In such cases, evolutionarily closer model organisms are used for a final round of testing before they are approved for use in humans.

Parting thoughts

Model organisms have been used to understand basic biology that has, in turn, led to many important discoveries. These have revolutionized core practices in diverse disciplines, such as medicine, surgery, psychiatry, and ecology. Today, the use of model organisms needs to be justified before regulatory bodies, which also attempt to ensure practices that minimize the number, suffering, and use of more psychologically complex organisms for research.

Key takeaways

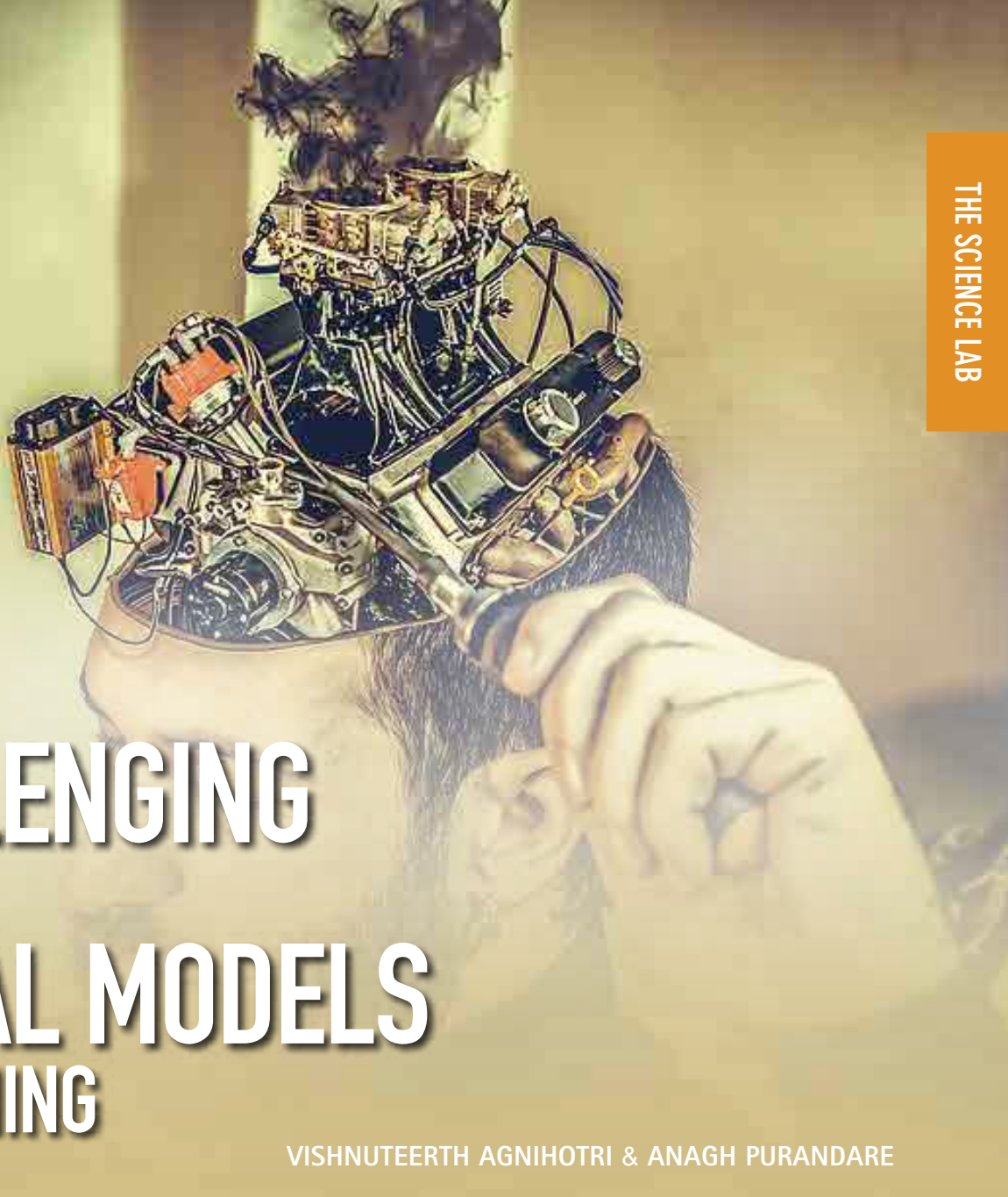
- Model organisms are organisms that scientists use for research to understand general principles of biology.
- Model organisms have been used in many different fields of science, including genetics, development, physiology, neuroscience, biomedical research, and drug discovery.
- The choice of model organisms for a project is based on the research question, the specific methods of research, practical considerations, and the extent of similarity between model organisms and the organisms of interest.
- Ethical committees ensure that the intended outcomes of a research project justify the use of model organisms, and the 3R's of Refinement, Reduction and Replacement are followed.
- Model organisms enhance our knowledge, and contribute to our understanding of our environment and ourselves. However, every model organism has its own limitations.



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Deepti Trivedi is in charge of the Fly Facility at the Bangalore Life Science Cluster, where she works on tiny fruit flies that have revolutionized biology research. If you'd like to know more about using *Drosophila* in school- and college-level experiments and research, Deepti can be contacted at fly@ncbs.res.in.



CHALLENGING PRIOR MENTAL MODELS OF LEARNING

VISHNUTEERTH AGNIHOTRI & ANAGH PURANDARE

Children enter the science classroom with 'mental models' of real-world phenomena surmised from their day-to-day experiences. Unchallenged, these models can persist into adulthood. Are these models scientifically accurate? How do we help a learner recognise and replace inaccurate models with scientifically accurate ones?

We learn from our observations of the world around us. A two-year-old may learn that food always falls down by repeatedly throwing it up (to our consternation). Similarly, it is through repeated observation that our mature selves learn that a *dosa* will not stick to a pan at a temperature that is high enough, but not too high. These common-sense learnings from everyday observations are useful and, often, even critical for survival. Are they scientifically accurate? Let us examine this through some examples of everyday phenomena.

A metal coin is colder than a wooden spoon in the same room

We bet many of you believe this statement to be true (you certainly don't want some prankster slipping a metal coin down your shirt on a cold winter day)! But, in fact, the metal coin and the wooden spoon will be at the same temperature. Unless one of them had just been brought in from outside, heated, or taken out from a refrigerator. How is this possible? After all, a metal coin feels so much colder to touch than the wooden spoon!



A metal coin may feel colder to touch than a wooden spoon at the same temperature because of the rate at which heat is conducted away from our body to the metal.

Credits: piqsels.com. URL: <https://www.pikrepo.com/ftjzy/person-holding-pile-of-coins>. License: CC0.

Here's a hint – if you were in a room at 55° Celsius somewhere in the Sahara desert, you would find the metal coin hotter than the wooden spoon. Human beings do not make very good thermometers. When we touch a coin, heat gets conducted away from our body to the metal (a better conductor) at a faster rate than that to wood (a poorer conductor). It is this loss of heat that we interpret as 'feeling colder'. If you used a thermometer, you would find the coin and spoon to be at the same temperature (see Box 1).

Not surprisingly, 86 % of Grade VIII students presented with a similar thought experiment (see **Concept Builder: Which is hotter?**) predicted that a metal spoon that has been in hot water for half a day would be hotter than a wooden or plastic spoon given the exact same treatment (see Table I).

Box 1. Check out this interesting video, of a researcher trying this 'trick' out on many different people: <https://youtu.be/vqDbMEdLiCs>. How would you explain what is happening here?

We begin to see things in the dark after we've been there for a while

Again, you may be tempted to agree with this statement. So do many middle school students when presented with a similar thought experiment (see **Concept Builder: Can you see in a dark room?**). Why do we believe this to be true?

Do you remember the many instances when you've been unable to see anything in a 'dark' room immediately after entering it? You may also recall that you were able to see at least a few things

in the room after your eyes had a few minutes to adjust to the 'darkness'. Right? Many of us rely on these memories to respond to this statement. Would the same thing happen in a room that is completely dark? Few of us have experienced a completely dark room in our day-to-day lives (there is always some light trickling into any room, like from the moon or a street lamp). So we tend to assume that our observations of relatively 'dark' rooms would hold true – we would be able to see things, at least dimly, after our eyes have had some time to adjust to the darkness. We may even believe that this adjustment would take more time than usual. However, in reality, if no light enters the room, we will not be able to see anything, however much time we spend in it. This is because we only see an object when the light it reflects strikes our eyes.



We only see an object when the light it reflects strikes our eyes.

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A heavier object always falls to the ground faster than a lighter object

Let's suppose that you were to drop a heavy brick and a small book (taped so that it won't open up), from the 3rd floor of a building, at the same time. Which of these do you think will be likely to hit the ground first? If you find this hard to answer, imagine dropping a book (taped to prevent it from opening up) with a piece of paper placed on it. Do you expect the book and paper to reach the ground together? Or, do you expect the paper to 'stay back'?

We have posed these questions (among many others) to several students, teachers, and intelligent adults over the years. Most are surprised at what they find – heavier objects fall at the same rate as lighter ones. For example, 50% of Grade IX students presented with a similar thought experiment (see **Concept Builder: Do heavier objects fall faster than lighter ones?**) predicted that the heavier ball would fall to the ground faster than the lighter one (see Table II).

Which will be hotter after being in hot water for half a day?	Option	Percentage of Grade VIII students who chose this option (%)
The metal spoon	A	86.4
The plastic spoon	B	4.2
The wooden spoon	C	3.9
All three spoons are at the same temperature	D	5.2

Table I. Which is hotter?

Credits: Data based on ASSET, a diagnostic test from Educational Initiatives: <http://www.ei-india.com/asset/>.

The Science Lab

CONCEPT BUILDER: IS METAL COLDER THAN WOOD / PLASTIC?

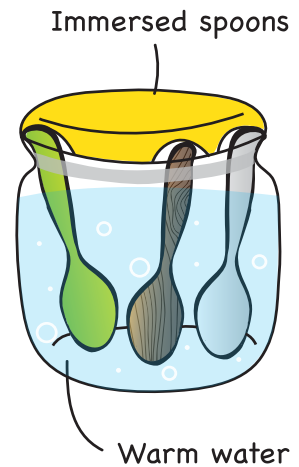
Imagine:

A metal spoon, a wooden spoon, and a plastic spoon are placed in hot water for half a day. The water is maintained at the same temperature throughout.

Predict:

At the end of the experiment, the spoons are taken out and their temperature is measured immediately. Which of the following is likely to have the highest temperature?

- The metal spoon
- The plastic spoon
- The wooden spoon
- All three spoons will have almost the same temperature



Explain:

Your reason for choosing the outcome you predicted.

Discuss:

- How would you test if your response is correct?
- What are some ways to measure and compare the temperature of the spoons?
- Would your answer change if you used a different way? Why?
- What if you also kept a steel spoon in the hot water – which spoon would be the hottest?
- If the spoons were kept in the fridge instead of warm water, which spoon would be coldest?



The Science Lab

CONCEPT BUILDER: CAN YOU SEE IN A DARK ROOM?

Imagine:

You are in a room which is **completely** dark. The room has one chair.

Predict:

If you were to look around the dark room, which of these is likely to be true? You will:

- Not be able to see anything in the room.
- Be able to see at least a dim outline of the chair in a few minutes.
- Be able to see the chair only after standing in the room for more than a few minutes.

Explain:

Your reason for choosing the outcome you predicted.

Discuss:

- If you knew the chair was yellow in colour, would you search for the chair by its shape or colour?
- How would you test if your response is correct?
- How would you make a room completely dark?



The Science Lab

CONCEPT BUILDER: DO HEAVIER OBJECTS FALL FASTER THAN LIGHTER ONES?

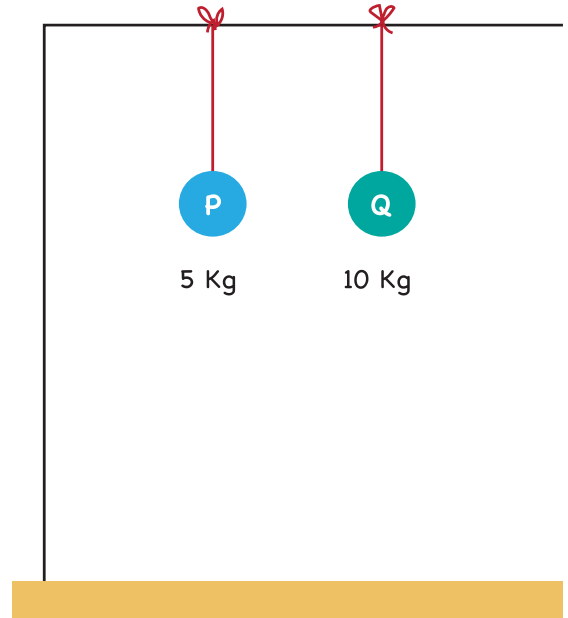
Imagine:

Two balls, P and Q, of equal size but unequal mass (P weighs 5 kg and Q weighs 10 kg) hanging from strings of the same length at a certain height above the ground.

Predict:

The strings are simultaneously cut. Which of them would fall to the ground faster?

- Ball Q because heavier objects always fall to the ground faster.
- Ball P because lighter objects always fall to the ground faster.
- Both would take the same time because the time taken to fall is independent of their mass.
- We cannot say because it would depend on the height from which they are falling.



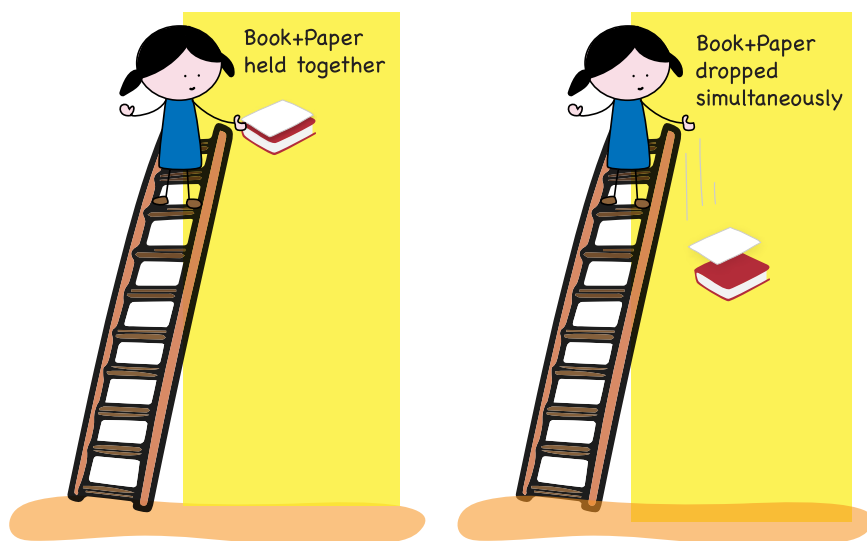
Explain:

Your reason for choosing the outcome you predicted.

Discuss:

- How would you test if your answer is correct? What everyday objects would you use to replace the balls?
- If the balls were of different sizes, would your answer change? For e.g., if you were to repeat this experiment with a cricket ball and a marble, which would fall to the ground faster? Why?
- If the balls were replaced with objects of different shapes, would your answer change? For e.g., if you were to repeat this experiment with a dictionary (with its pages tied together) and a brick, which would fall to the ground faster? Why?





Will the book and paper fall together? Will the paper fall slower?

License: CCO.

Strangely, many of us have learnt the science behind the phenomenon. We have read how the rate at which objects fall to the ground is independent of their mass and, even, solved problems based on equations that show this. Yet, when presented with a real-world example, many of us continue to believe that heavier objects fall faster than lighter objects. Why does this happen?

One possibility is that we may not have grasped the idea of air resistance. As a result, we interpret our observation of the slow drifting fall of a leaf or a feather as evidence for the idea (or 'mental model') that 'lighter objects fall slower' (see Box 2).

Even those of us (including older children and adults) who do understand

the idea of air resistance may hold on to this inaccurate mental model. Often, this is because we wrongly extrapolate the idea that heavier objects experience a higher gravitational pull to conclude that they would also fall at a faster rate. In fact, it is quite 'intuitive' to think that a heavier object would fall faster than a lighter one; and, not entirely wrong either (see Box 3). However, as a limited idea that applies only to special cases, it is certainly not the general scientific principle that we tend to use it as.

Applying to practice

The three examples we have discussed here reveal some common 'mental models' that children, and even adults, use to interpret real-world phenomena

Box 2. Does some small part of you still doubt that a feather would reach the ground at the same time as a heavy bowling ball in the absence of air resistance?

The only way one can be completely sure of this is by dropping these objects in a vacuum environment (an expensive environment to create). Fortunately for us, this experiment has been tried out (watch this amazing clip from BBC's Human Universe series <https://youtu.be/E43-CfukEgs>), and has proven this particular mental model inaccurate.

(see Box 4). Not only do students come to the classroom with scientifically inaccurate models, they may leave it with their understanding unaltered by what they learn. More often than not, neither the teacher nor the learner is aware of these mental models. It may even appear as if students have clearly understood a scientific concept ... till they face a situation of 'cognitive conflict'. A good science teacher recognizes that working through such confusion and conflict is critical for deep learning.

Let us see how this might play out in the case of the falling objects. First, a teacher could create a cognitive conflict by encouraging students to try out the experiment with the 'paper on the book'.



Observing the slow drift of a feather can lead to the mistaken assumption that 'lighter objects fall slower'.

Credits: Louise Docker, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Bird%27s_Feather_in_Flight.jpg. License: CC-BY.

Which of these balls will fall faster to the ground?	Option	Percentage of Grade IX students who chose this option (%)
Q will fall faster than P because heavier objects always fall faster to the ground	A	43.7
P will fall faster than Q because lighter objects always fall faster to the ground	B	7.8
Both will fall at the same rate because the time taken for an object to fall does not depend on its mass	C	41.9
We cannot say because it depends on the height from which the two fall	D	6.6

Table II. Which will fall faster?

Credits: Data based on ASSET, a diagnostic test from Educational Initiatives: <http://www.ei-india.com/asset/>.

Box 3. In his book 'The unnatural nature of science', the eminent British biologist Lewis Wolpert argues that *"scientific ideas are, with rare exceptions, counter-intuitive: they cannot be acquired by simple inspection of phenomena and are often outside everyday experience"*

Do you think any of the three examples discussed here support this claim? Why?

This experiment may alert students to the existence of air resistance, and create sufficient doubt about what had previously seemed self-evident (that heavier objects fall faster). The teacher

Box 4. Would you like to discuss these examples in more detail?

Visit our blog posts:

1. Does a heavier object fall faster? URL: <https://tostudentandteacher.wordpress.com/2015/01/17/does-a-heavier-object-fall-faster-to-the-ground/>
2. Power of demonstration on unlearning. URL: <http://blog.ei-india.com/2015/02/power-ofdemonstrations-on-unlearning/>

could guide a group discussion to help students think through the different factors that might have played a role in the outcome of the experiment. Students may identify factors like the windiness in the classroom; or the relative surface area, hollowness, and roughness of the two objects. Having done this, the

teacher could encourage students to test these factors by designing and performing a variety of experiments with different objects. These would help progressively clarify student ideas till they arrive at the conclusion that lighter objects do indeed fall at the same rate as heavier objects.

Key takeaways



- Children may enter the classroom with scientifically inaccurate mental models of natural phenomena.
- Unless recognized, these mental models may remain unaltered by the concepts students are introduced to in the science classroom.
- Teaching-learning processes that recognize this possibility attempt to bring such mental models to the surface, so that the learner, as well as the teacher, becomes aware of them.
- Teachers can use a variety of methods, discussion, and supporting exercises to help the learner replace incorrect prior mental models with scientifically accurate ones.

Notes:

1. This is a revised & reformatted version of an article (with the same title: 'Challenging Prior Mental Models') that first appeared under the section 'Myth or Fact' in the November 2015 issue of *i wonder*.
2. Source for the image used in the background of the article title: <https://pixabay.com/photos/mechanical-brain-man-machine-2033446/>. Credits: ayuguluturk, Pixabay. License: CC0.

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TIME FOR A SWING

KAVITA KRISHNA

Pendulums have an important place in the history of science and technology. They are also excellent devices for exploring science because they illustrate several fundamental concepts in mechanics, and are simple to make and manipulate. What opportunities do they provide in the science classroom?

A playground swing or a tyre suspended from a tree by a rope are familiar examples of a pendulum. In a classroom, pendulums can be used to illustrate several fundamental concepts in middle- and high-school physics, like periodic motion, simple harmonic motion, velocity and acceleration, gravity, the laws of motion, and conservation of energy (see Box 1).

A **simple pendulum** is an idealized pendulum in which we assume that a mass (the pendulum bob) is suspended from a rigid, massless string, and is free to swing back and forth (see Fig. 1). We

also assume that there is no friction or air resistance. When the bob is displaced by a small angle from its equilibrium position, it moves back and forth in a regular and repetitive manner – an example of simple harmonic motion.

The velocity of the pendulum bob changes as it oscillates about its equilibrium position. The velocity is maximum at the lowest point, and is zero when it is at its highest point. Thus, as the bob moves upwards, the kinetic energy decreases and the potential energy increases. The total amount of energy remains constant (see Box 2).

Pendulums in the classroom

Pendulums are ideal devices for classroom investigations – they are simple, inexpensive, and easy to manipulate. Initial discussions in the classroom can uncover students' preconceptions about pendulum motion, and can help them design an investigation to test their beliefs (see Box 3).¹ For example, students may believe that a heavier pendulum moves slower than a lighter one. Or that a

Box 1. Topics in NCERT's science curriculum that are linked to pendulums:

1. Grade VI: Motion and measurement of distances
2. Grade VII: Motion and Time
3. Grade IX: Motion, Force and laws of motion, Gravitation, Work and energy

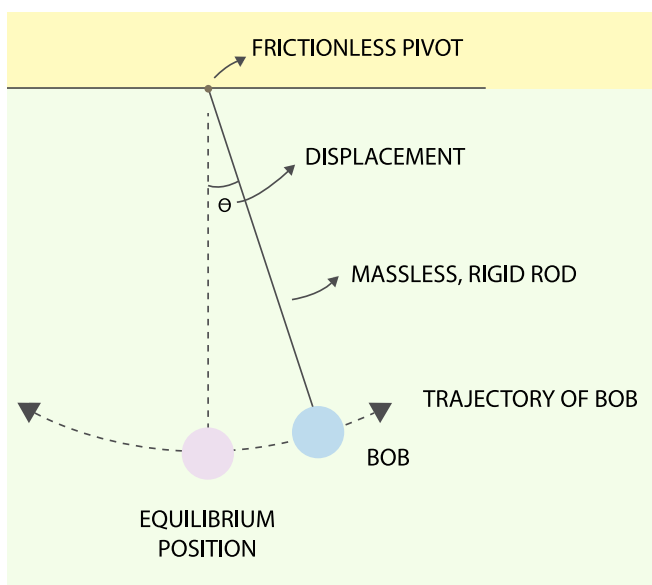


Fig. 1. Diagram of a simple pendulum.

pendulum takes longer to complete an oscillation if its displacement is greater. The **Activity Sheets (I–VI)** accompanying this article can help students investigate these ideas, and discover factors that affect the time period of a pendulum.

Pendulums beyond the classroom

Pendulums have always existed – a child on a swing or a lamp hanging from the ceiling are common examples. But the idealized pendulum that we study

China.³ The first scientific investigation of the motion of a pendulum was conducted by Galileo, in 1602, after he observed the chandeliers in a church swinging periodically. His investigations led to the use of the pendulum as a timekeeping device. Accurate time measurement was necessary to determine longitudes when navigating on open seas. This was important to European colonizers who were seeking to expand their trade beyond Europe. Thus, pendulum research in the

in a science class is a more recent concept.

One of the earliest known uses of a pendulum was in a 1st century seismometer device developed by Zhang Heng, a scientist from Han Dynasty,

18th and 19th centuries focussed on the quest for more accurate timekeeping.⁴ This, in turn, led to more accurate mapmaking, as well as the expansion of European commerce, colonization, and exploitation, with far reaching effects across the world.

The pendulum was also studied by Huygens, Newton, and Hooke – other prominent 17th century scientists (see Fig. 2). It has also played a significant role in establishing the value of gravitational acceleration 'g', its variation with latitude and, hence, in establishing the shape of the earth.⁵

The many ways in which the pendulum has featured in the history of science and technology, and in the making of the modern world are fascinating. Cross-curricular projects around these ideas can provide an opportunity for students to understand how science and technology evolve and how they are

Box 2. You can find more about the physics of pendulums here:

1. Henderson, T. The Physics Classroom Tutorial. Retrieved December 26, 2019, from <https://www.physicsclassroom.com/class/waves/Lesson-0/Pendulum-Motion>
2. University of Colorado Boulder. (2019) Pendulum lab. Retrieved December 26, 2019, from http://phet.colorado.edu/sims/html/pendulum-lab/latest/pendulum-lab_en.html

Box 3: Classroom investigations

Students have many ideas about natural phenomena based on their daily experiences and superficial observations. The science classroom can provide students with opportunities to explore these ideas, and modify them based on their own investigations. These kinds of investigations have multiple benefits. Students gain experience in conducting a practical activity, and in developing their ideas based on evidence and reasoning. They develop science process skills like systematic observation, careful measurement, and conducting a 'fair' test – all of which are an essential part of learning the methods of science. These activities also increase engagement with, and understanding of science.

Process skills enable students to use the methods of science in exploring and understanding concepts.² They include both mental skills like predicting or evaluating, and physical skills like using tools and materials effectively. Investigations and accompanying discussions in the science classroom can help students develop

process skills at an age-appropriate level. Some examples of process skills that can be developed in the accompanying pendulum activities include:

- **Devising an investigation:** identifying what variables are to be kept constant for a fair test, identifying what is to be measured, deciding the order of steps in the investigation.
- **Handling and manipulating equipment:** using tools and instruments effectively and carefully, assembling the parts as planned.
- **Measuring and calculating:** measuring variables like time and length accurately, thinking about different errors in measurement and how to minimise them, recording data systematically, calculating average results correctly.
- **Finding patterns and relationships:** identifying a relationship between variables, checking an inferred relationship against evidence.

The Science Lab

ACTIVITY SHEET I: HOW TO MAKE A SIMPLE PENDULUM

Aim:

In this activity you are going to make a simple pendulum, and observe how it moves.

You will need:



String
(about 1 m)



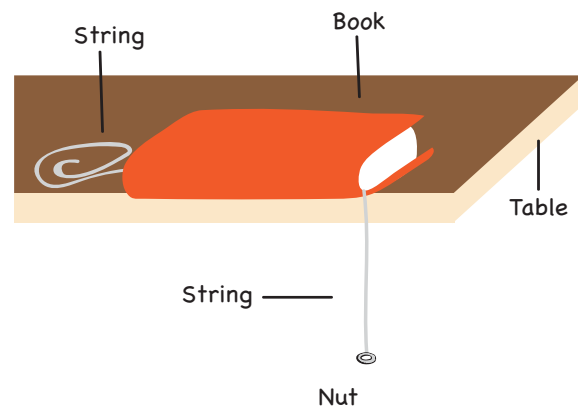
One weight
(metal washer or nut)



Heavy book

What to do:

1. Tie the weight to the end of a string.
2. Suspend the weight so it can swing freely. You can use a heavy book on a table, or tie the string to a hook. Make sure the weight can swing freely without any obstructions.
3. Make the weight swing by pulling it to one side, and releasing it. Make sure that the string is taut as you do this, and release the weight gently without applying any force.
4. Observe the movement of the weight. How does it move?



Discuss:

- Can you think of other objects which move periodically?
- Do you remember swinging on a swing? In what ways is it similar to a pendulum? In what ways is it different?
- How does the swing move during one oscillation — does it move at the same speed throughout? Where does it seem to move the fastest? Does it seem to stop anywhere?



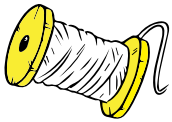
The Science Lab

ACTIVITY SHEET II: HOW TO MEASURE THE TIME PERIOD OF A PENDULUM

Aim:

In this activity you are going to measure how long a pendulum takes to complete one oscillation. One complete back and forth movement is called an oscillation. The time taken for one complete oscillation is called the **time period of the pendulum**.

You will need:



String (about 1 m)



One weight (metal washer or nut)



Stopwatch (or phone with timer)

What to do:

1. Make the weight swing as you did in Activity Sheet I.
2. Use a stopwatch to measure how long it takes to make 10 complete oscillations.
3. Make sure you count an oscillation when the pendulum bob (or weight) is at the same point each time. (Tip: It is convenient to count a completed oscillation when the pendulum bob returns to the point where you released it from.)
4. Record your observations in the table.

Trial	Time for 10 oscillations	Time for 1 oscillation
1.		
2.		
3.		
Average time period		

5. Calculate the time period for one oscillation by dividing the time you measured by 10.
6. You can repeat this a few times and then calculate the average time period for one oscillation. (Tip: To calculate the average, add up the time for one oscillation for each trial and divide by the number of trials).

Discuss:

(a) Measuring time period:

- Was the time period of one oscillation the same in each trial? Why do you think there are differences?

- Do you think you measured the time for 10 oscillations accurately? What could you do to measure the time more accurately?
- Is it better to measure 100 oscillations or 10 oscillations to find the time period? Why?

(b) Making the pendulum move faster:

- Do you think you can reduce the time period of the pendulum (make the pendulum move faster)? How?
- Do you think the position from which you let it go (its initial displacement) makes a difference to the time period of the pendulum? Why do you think so?
- Do you think the length of the string makes a difference to the time period of the pendulum? Why do you think so?
- Do you think the weight of the pendulum makes a difference to the time period of the pendulum? Why do you think so?
- Can you think of other factors which could change the time period of the pendulum?
- How would you test your ideas?



The Science Lab

ACTIVITY SHEET III: DOES THE TIME PERIOD OF A PENDULUM DEPEND ON THE INITIAL DISPLACEMENT?

Aim:

In this activity, you will test whether the initial displacement of the pendulum makes a difference to its time period. For a fair test, make sure that you change only the initial displacement, while keeping the pendulum exactly the same in all other ways.

You will need:



String
(about 1 m)



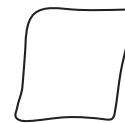
One weight
(metal washer
or nut)



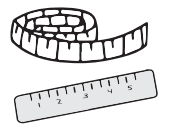
Stopwatch
(or phone
with timer)



Protractor



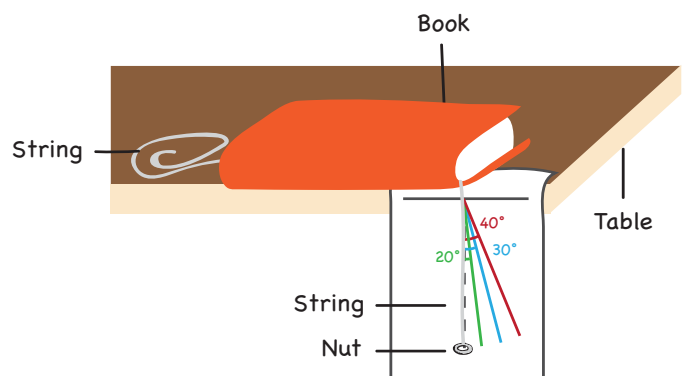
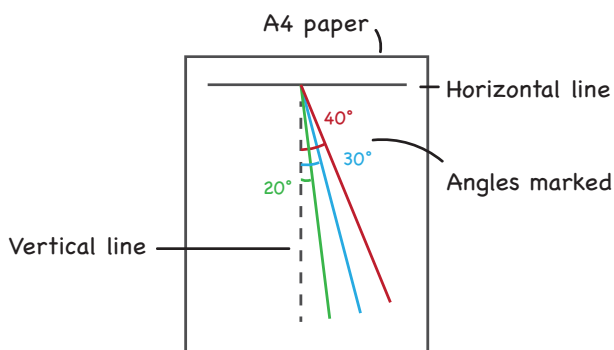
Paper



Metre scale or
tape measure

What to do:

1. Measure the length of the pendulum — the distance from the point it is suspended till the point it is tied to the metal nut. Note this down.
2. Draw a vertical line on the paper and mark the angles at 20° , 30° , and 40° . You can use these markings to check where you are releasing the pendulum weight from.
3. Fix the paper behind the pendulum so that the string is in line with the vertical line when it is stationary (see image of set-up). The pendulum should hang free and not touch the paper.
4. Release the weight from the 20° position. Make sure the pendulum is moving parallel to the paper and not touching it.
5. Measure the time for 10 oscillations like you did in Activity Sheet II.
6. Conduct at least three trials, releasing the weight from the 20° position. Calculate the average time period.
7. Repeat these steps to find the average time period when you release the pendulum weight from the 30° position, and then the 40° position.



Record: your observations of time taken for 10 oscillations in each trial. Use this to calculate the time for one oscillation in each trial. Then calculate the average time period for each angle of release.

Angle of release	Trial	Time for 10 oscillations	Time for 1 oscillation	Avg. Time Period
20°	1.			
	2.			
	3.			
30°	1.			
	2.			
	3.			
40°	1.			
	2.			
	3.			

Discuss:

- What did you keep the same in this experiment? What did you change?
 What I kept the same:
 Length of the pendulum = _____ cm
 Number of nuts used as the weight = _____
 What I changed: _____
- Did the time period of the pendulum change when you changed the position you released it from?
- If yes, did the time period of the pendulum increase or decrease when you increased its initial displacement?
- What can you conclude from this experiment? Does the time period of a pendulum depend on the initial displacement of the weight?



The Science Lab

ACTIVITY SHEET IV: DOES THE TIME PERIOD OF OSCILLATION DEPEND ON THE LENGTH OF THE PENDULUM?

Aim:

In this activity you are going to test whether the length of the pendulum makes a difference to its time period. For a fair test make sure that you are changing only the length, while keeping the pendulum exactly the same in other ways.

You will need:



String
(about 1 m)



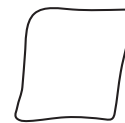
1 weight
(metal washer
or nut)



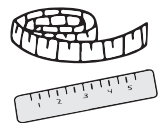
Stopwatch
(or phone
with timer)



Protractor



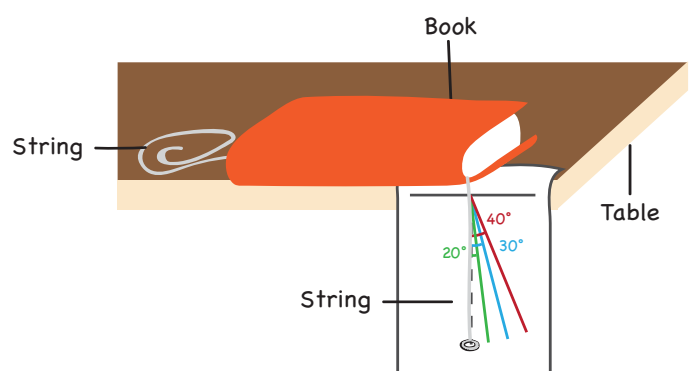
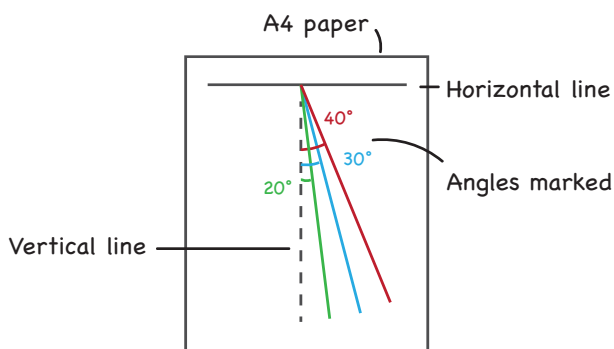
Paper



Metre scale or
tape measure

What to do:

1. Measure the length of the pendulum. Note this down.
2. Decide where you will release the weight from. Note down this position (this is the angle marked on the paper you fixed behind the pendulum in Activity Sheet III). You need to release the weight from the same position in each trial.
3. Release the weight from this position and find the average time period like you did in Activity Sheets II and III.
4. Increase the length of the pendulum by 10 cm. Measure the length and note it down.
5. Find the time period for the pendulum again. Make sure you are releasing the weight from the same position you did in Step 2.
6. Increase the length of the pendulum by another 10 cm. Measure the length and note it down.
7. Find the time period for the pendulum again. Make sure you are releasing the weight from the same position you did in step 2.



Record: your observations from steps 1 to 7:

Length of string (cm)	Trial	Time for 10 oscillations	Time for 1 oscillation	Avg. Time Period
	1.			
	2.			
	3.			
	1.			
	2.			
	3.			
	1.			
	2.			
	3.			

Discuss:

- What did you keep the same in this experiment? What did you change?
 What I kept the same:
 Angle from where I released the pendulum = _____
 Number of nuts used as the weight = _____
 What I changed: _____
- Did the time period of the pendulum change when you changed its length?
- If yes, did the time period of the pendulum increase or decrease when you increased its length?
- What can you conclude from this experiment? Does the time period of a pendulum depend on its length?



The Science Lab

ACTIVITY SHEET V: DOES THE TIME PERIOD OF OSCILLATION DEPEND ON THE WEIGHT OF THE PENDULUM?

Aim:

In this activity you are going to test whether the weight of the pendulum bob makes a difference to its time period. For a fair test, make sure that you are changing only the weight, while keeping the pendulum exactly the same in other ways.

You will need:



String
(about 1 m)



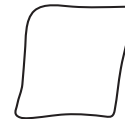
3 equal weights
(metal washers
or nuts)



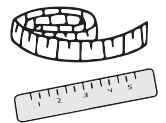
Stopwatch
(or phone
with timer)



Protractor



Paper



Metre scale or
tape measure

What to do:

1. Make the pendulum by attaching one metal nut to the end of the string.
2. Measure the length of the pendulum. Note this down. You will be keeping this the same throughout this experiment
3. Decide where you will release the weight from.
Note down this position (marked on the paper you fixed behind the pendulum as in Activity Sheets III and IV). You need to release the weight from the same position in each trial.
4. Release the weight from this position and measure the time period like you did in Activity Sheets II, III, and IV.
5. Increase the weight of the pendulum by adding another metal nut to the end. Make sure you adjust the length so that it remains exactly the same as before.
6. Measure the time period for the pendulum again. Make sure you release the weight from the same position as you did in Step 3.
7. Increase the weight of the pendulum by adding a third metal nut to the end. Make sure you adjust the length so that it remains exactly the same as before.
8. Measure the time period for the pendulum again. Make sure you release the weight from the same position as you did in Step 3.

How to tie the 3 nuts correctly



Record: your observations from steps 1 to 7:

No. of equal weights	Trial	Time for 10 oscillations	Time for 1 oscillation	Avg. Time Period
1	1.			
	2.			
	3.			
2	1.			
	2.			
	3.			
3	1.			
	2.			
	3.			

Discuss:

- What did you keep the same in this experiment? What did you change?

What I kept the same:

Angle from where I released the pendulum = _____

Length of the pendulum = _____

What I changed:

- Did the time period of the pendulum change when you changed the weight of the bob?
- If yes, did the time period of the pendulum increase or decrease when you increase the weight of the bob?
- What can you conclude from this experiment? Does the time period of a pendulum depend on the weight of the bob?



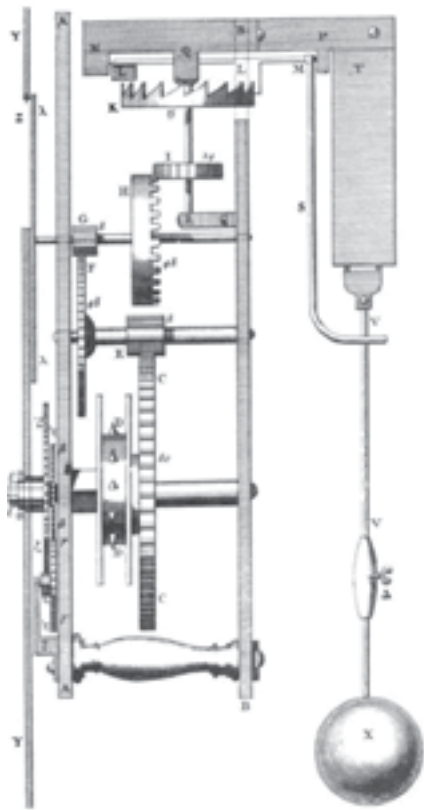
The Science Lab

ACTIVITY SHEET VI: DISCUSS TOGETHER

Discuss together:

1. What can you conclude from Activities III, IV and V? What affects the time period of a pendulum?
2. Were your initial predictions about changing the time period of the pendulum correct?
3. What other factors do you think might affect the time period of a pendulum? How would you test them?
4. Why do we change only one thing about the pendulum in each experiment? What would happen if you changed more than one thing at a time in an experiment?
5. If you were to choose a swing to swing on, which one would you choose – the longer one or the shorter one? Why?





inextricably linked with the economic, social, and cultural issues of the time (see Box 4).

Box 4. Some cross-curricular project ideas related to pendulums:

- Researching and replicating Galileo's pendulum experiments.
- Researching the history of timekeeping devices.
- Researching European expansion – navigation, the longitude problem, and timekeeping.
- Where are pendulums used today?
- What is a Foucault's pendulum?
- Constructing a clock escapement.

Fig 2. Christiaan Huygens, inventor of the pendulum clock, built this clock around 1673. This drawing is from his treatise *Horologium Oscillatorium*.

Credits: Retrieved June 27, 2008 from Harold C. Kelly (2007) *Clock Repairing as a Hobby: A How-To Guide for Beginners*, Skyhorse Publishing, ISBN:160239153X, p.38, fig.13 on Google Books. URL: https://commons.wikimedia.org/wiki/File:Huygens_clock.png. License: CC-BY.

Key takeaways



- Pendulums can be used to illustrate many fundamental concepts in mechanics like motion, gravity, and energy.
- They are easy for students to make and use for investigations in the science classroom.
- Students can explore the significance of pendulums in the history of science and technology through cross-curricular projects.

Note: Source for the image used in the background of the article title: <https://www.flickr.com/photos/eileendelhi/125635185/>. Credits: Eileen Delhi, Flickr. License: CC-BY-NC.

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Kavita Krishna graduated from IIT Madras and worked as an engineer for 10 years. She retrained as a teacher, and has over 15 years of experience in teaching, curriculum development, and teacher education in rural and urban schools. She can be reached at kavitak2006@gmail.com.



INTERVIEW WITH SAURAV SHOME

Saurav Shome works in an Azim Premji School at Uttarkashi, Uttarakhand. In this interview, he shares his experiences and insights on a life in science.

Saurav, to start with, tell us something about your current role

I am associated with an Azim Premji School at Uttarkashi, Uttarakhand. Azim Premji Schools are places of experiment, and demonstrate what pedagogies work in real classroom settings. I am engaged in coordinating and consolidating our learning in the school. I teach students and facilitate the school-based professional development of my team members.

Shaping a career in science education

Could you tell us some of your earliest experiences as an educator?

As a student (from school to university), I was a science enthusiast, and used to volunteer to teach science in local schools. I worked for a year at a national science

museum, where I would explain the models and exhibits to visitors. As a graduate student at the Homi Bhabha Centre for Science Education (TIFR), Mumbai, I began to engage with science communication for school students and teachers. It was here that I developed an understanding of science education and science education research. Regular science teaching at the middle-school level, and workshops for teachers started only after I joined Azim Premji Foundation in 2014, and an Azim Premji School in 2018.

What are some qualities that may help chart a career in science education?

The ability to handle knowledge uncertainty, see coherence and connectedness between different domains of knowledge, as well as a strong sense of integrity in negotiating content, classroom pedagogy, and in all human conduct. Also, a fondness for getting your hands dirty!

Life as a Science Educator

What is a typical day at work like?

It is almost the same as my colleagues. I plan out the topics I intend to teach. Every day, I look around for objects that can be used as resources in science classes. I teach, document students' and teachers' ideas, look for possibilities for pedagogic improvisations, try to read and write a little in order to reflect on my work, design and try out some experiments. You will find me talking to my colleagues, school teachers, and students a lot. I also talk to my six-year-old son to understand how he looks at nature and the universe.

Could you walk us through the process of planning a class?

Mostly, I plan my teaching with my colleagues. This process starts with brainstorming sessions where we arrive at a tentative sequence to transact a topic in the classroom, think of alternatives, and design activity problems around this plan. We go through related literature and resources, identify and discuss common alternative conceptions associated with a concept, the opportunities it provides for subject integration, as well as possibilities for group work and assessment. Before class, we anticipate the resources we need to put our plan into action and ensure that they are kept ready for use.

After class, we record/document our experience, reflect on classroom practice in the same group that we planned the topic with, and begin planning for the next day's topic. This cycle is repeated, with the occasional omission of one or two elements.

If one walked into your classroom, what are they most likely to observe?

Usually, I am part of a co-teaching team at school. On a typical day, you'll find students in my science class solving problems. They will be engaged in planning, discussing, and sharing their design ideas, executing their plan, and evaluating their own work. You will find me acting as a moderator in this process. I try my best to encourage students to simulate the specific details and context of the problem task (including an experiment) so that they can arrive at a conclusion. I also include narratives of relevant discoveries and inventions, and some interesting historical anecdotes in the classroom discourse.

As a science educator, do you remember any 'teacher as a learner' moments?

Certainly. I have encountered many moments where my understanding of science was challenged by students or teachers. For example, a teacher in a workshop asked me how the velocity of an electromagnetic wave differs

in different mediums. My conceptual clarity was inadequate to meaningfully tackle the question. But, I must admit, students' questions are more difficult to answer than those of adults.

What are some of the biggest rewards and challenges of your profession?

My colleagues, many students, and several teachers appreciate my teaching. These are the rewards I have received till date in my profession.

On many occasions, I have had to engage with perspectives and ideas in the classroom that have challenged my personal views and ideology. This is particularly tough in interactions with people who are resistant to dialogue on long-held views. Another challenge is that many of us have a poorly formed understanding of science concepts, pedagogy, and ideas about science. This is true of even many experienced science educators. Talking about anything radical becomes quite challenging in such spaces.

And some of the most important ethical aspects of your profession?

I think the principle of non-discrimination. Believe in everyone's capability to excel in science at least till the higher secondary level, and create learning environments accordingly. I also





evidence they come up with. We need to avoid giving ready-made answers, especially during the early stages of science learning.

What kind of science education is important at the middle-school level for students who don't intend to engage with it academically after high school?

In the emerging context, democratic societies are becoming very complex. There is an increasing threat of technological dominance, information overload, and unequal power and resource distribution across the globe. At this stage, we need to create citizens capable of taking active part in a democratic society. The process of teaching and learning of science has some intrinsic values associated with these broader values. Good quality science teaching, even till high school, can help achieve this goal.

Your thoughts on some students having a 'natural aptitude' for science?

Since humans are inherently curious, I believe that if taught well, science can be made interesting to all or, at least, most children. Such teaching acknowledges and respects each students' alternative conceptions. So, we pose problems relevant to the students' real-world experiences, and build

strongly believe that science education must be planned and designed in such a way that it reflects the values needed in order to create an egalitarian, democratic society.

School science education

Your perspective on school science education?

In general, school science education is still imprisoned in the obsession of completing content. This needs more careful planning. It is important to inculcate a culture of science among students with a judicious balance of content, concepts, and skills. The six criteria (cognitive, content, process, historical, environmental, and ethical) set for the validity of the science curriculum in the National Curriculum Framework 2005 are the best to my knowledge.

Could you share three insights on how children learn science?

- a. In a broader sense, students learn science like they learn any other subject. What is crucial to remember is that students encounter many science concepts at an early age. A child's engagement with concepts like space, mass, time, motion, light, heat, evaporation, etc., is closely connected to her cognitive development and understanding of her natural and social worlds.
- b. Science learning in the classroom is more effective when it starts with

problematizing a familiar context. So, you use the students' social context to create a situation of cognitive conflict, and provide students with resources to resolve that conflict. You facilitate a process of enquiry by encouraging self- and peer-evaluation, providing opportunities for discussion on what children learn as well as any new theories or conclusions they arrive at, and helping them identify opportunities for further study. This should be seen as a continuous process.

- c. It is important to welcome all kinds of responses in the classroom. Give equal weightage to the validity testing of all ideas that students offer, and help students select more accurate responses based on the



context from their existing knowledge base. We choose practices that empower each child in engaging with the process of science, encourage the inclusion of a variety of creative elements, and help students find their own voice. Also, we present science as a social endeavor, not a product of just a few brilliant minds.

Your perspective on a science teacher's role.

A teachers' role is crucial. To help children cultivate an interest in science, science teachers need to present science in a social context, encourage students to participate in the culture of science, and generate science knowledge.

They also need to provide a culture of disciplined thinking, help students see coherence in concepts, and encourage creativity. Teachers can help students develop the ability to design experiments, an integrity in conducting them and towards available evidence, the willingness to hold ideas or even conclusions tentatively rather than dogmatically, and an empathy towards one's surroundings. I think it is a science educator's responsibility to instill these values in students, and design her pedagogy accordingly.

What are some of the most important challenges that science teachers face?

a. The biggest challenge is dealing with students' misconceptions. While good content knowledge has no substitute, knowing the most widely accepted answer is not enough for a science teacher. Teachers need to be familiar with the potential misconceptions that students associate with a science concept, as well as specific pedagogical interventions to address these misconceptions. Interestingly, you will find that these misconceptions are relics of history – even some of the most well-known scientists have held similar views in the past.



Some aspects of this challenge can be addressed by planning a teaching sequence that allows you to gradually build an understanding of the key concepts in a topic. In this way, you can minimize the need for children to make a huge leap at the end of the lesson.

- b. Another challenge is integration. It is important to look at science without fragmentation, but how do you achieve this in the classroom? Giving a word problem on finding the running speed of a Cheetah does not integrate biology with physics. In contrast, if you want to understand the functioning of the heart, you need to understand the essence of force, pressure, Pascal's law, etc. This requires an integration of concepts in physics with concepts in biology.
- c. It may not be possible to teach or introduce any science concept at the middle-school level in a 'complete' way. Attempts to do this tend to be unproductive. You will find that most students in your class don't understand these concepts and, often, ask very fundamental questions that we can't answer.

A development in science education that you find exciting?

While no single method or strategy

is effective across diverse contexts of science teaching and learning, project-based or problem-based teaching effectively addresses the goals of science education till middle school. I also think if students find appropriate and relevant science articles/reference materials, they will definitely read them. Humans, by nature, want to 'know'. A teacher needs to motivate this desire to know more by providing challenging problems or contexts. Design and technology education may be another exciting emerging direction in science education.

Thank you, Saurav. A thought or question you'd like to leave our readers with?

Yes. A point that directly touches my profession is that the goals of science education are viewed very narrowly. But what if we were to engage with science education in alignment with the idea of Deweyan democracy? In other words, if democracy is seen as an ethical ideal for societies to operate on, and the essence of democracy is participation, what does the perspective and process of science offer to this goal? If the purpose of all education is to prepare citizens to actively engage with and participate in democratic decision-making processes, what would we choose to teach in science? And how would we teach it?



COLOUR CHANGING FLOWERS AND CHOOSEY POLLINATORS

APARNA KRISHNAN & DIVYA UMA

Flowers come in a spectrum of colours of reds, blues, yellows and so on. Did you know that some flowers can change colours over time? Or that flowers use colours to communicate with insects that visit them for nectar?

Flowers act as billboards. Just like large advertising boards that tell potential customers where to go to obtain lucrative gifts, flowers advertise the nectar hidden in them to pollinators (see Box 1). Through their size, shape, scent, texture and colour, flowers attract insects, birds, and even mammals to their nectarine reward. Reward for carrying pollen from one flower to the other, thereby pollinating it, and aiding the plant in making seeds (see Fig. 1).

In typical flowering plants, flowers bloom in a particular colour that fades as they become older and wither away. Interestingly, in some plant species, flowers bloom in one colour and, almost magically, change to another colour well before they start ageing! These flowers use colour to convey messages to pollinators and influence pollinator behaviour in order to increase their chances of pollination.

There are more than 450 species of plants whose flowers are known to undergo colour change. These changes involve a wide spectrum of colours in different

Box 1. Anatomy of a flower:

Each flower has a stalk (pedicel), colourful petals, male (anther with pollen grains) and female (ovary) parts, and nectaries that store sugary nectar.

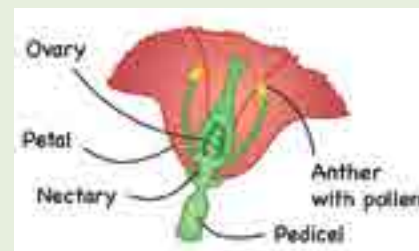


Fig. 1. Where is nectar present in a flower?

Credits: Mariana Ruiz LadyofHats, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Mature_flower_diagram.svg. License: Public Domain.

parts of the flower.¹ This phenomenon is seen in species spread over several families of the plant kingdom, and is believed to have evolved multiple times through evolutionary history.² We find several of these floral colour changing plant species in India (see Fig. 2).

Fig. 2. Some common examples of colour changing flowers in India



2a. The peacock flower (*Caesalpinia pulcherrima*), a common ornamental plant, changes from yellow to red.

Credits: Jim Evans, Wikimedia commons. URL: https://commons.wikimedia.org/wiki/File:Peacock_Flower_or_Pride-of-Barbados_-_Caesalpinia_pulcherrima.jpg. License: CC-BY-SA.



2b. Flowers of Mountain pomegranate (*Catunaregam spinosa*), found in deciduous forests throughout India, change from white to yellow.

Credits: J. M. Garg, Wikimedia commons. URL: [https://commons.wikimedia.org/wiki/File:Catunaregam_spinosa_\(Mountain_Pomegranate\)_W_IMG_9381.jpg](https://commons.wikimedia.org/wiki/File:Catunaregam_spinosa_(Mountain_Pomegranate)_W_IMG_9381.jpg). License: CC-BY.



2c. Flowers of the Chinese honeysuckle (*Quisqualis indica*), a climber native to Asia, are white when they open at night, and turn red the next morning.

Credits: Tatiana Gerus from Brisbane, Australia, Wikimedia commons. URL: https://commons.wikimedia.org/wiki/File:Quisqualis_indica_1.jpg. License: CC-BY-SA.



2d. Only the centers of flowers of Woolly Rock Jasmine (*Androsace lanuginosa*), a plant native to the Himalayas, change from yellow to red.

Credits: David Short, Wikimedia commons. URL: https://commons.wikimedia.org/wiki/File:Androsace_lanuginosa.jpg. License: CC-BY.



2e. The flowers of a variety of *Lantana camara*, one of the most notorious invasive plants found across India, change from yellow to orange to red/pink.

Credits: J. M. Garg, Wikimedia commons. URL: [https://commons.wikimedia.org/wiki/File:Catunaregam_spinosa_\(Mountain_Pomegranate\)_W_IMG_9381.jpg](https://commons.wikimedia.org/wiki/File:Catunaregam_spinosa_(Mountain_Pomegranate)_W_IMG_9381.jpg). License: CC-BY.

Box 2. Colour pigments in plants:

We know that leaves are green because of the pigment chlorophyll. Similarly, colours in flowers and fruits are produced due to different types of colour pigments. Carrots get their colour from a class of pigments called carotenoids, which produce yellow and orange shades. The red of hibiscus flowers comes from anthocyanin pigments, which produce blue, purple and red colouration. Beetroots get their colour from betalain pigments, which produce shades of red.

How does colour change happen?

Colour change in flowers is believed to occur due to the accumulation, depletion, or change in the composition of colour

pigments (see Box 2). It may also happen when a pigment changes colour due to changes in pH or temperature. For example, the pigment anthocyanin is red in an acidic cellular medium, but changes to blue as the medium becomes basic.

These physiological changes are in turn triggered by factors like a flower's age, its sexual maturity, or its day/night cycle etc. Interestingly, in some plants, colour change is triggered and hastened once an animal pollinates its flowers.

Why do flowers change colours?

A plant has to expend energy for its flowers to change colour. In many plant species, change in flower colour is also coupled with a loss of nectar and pollen (but see **Box 3**). Hence, after colour change, flowers don't serve the purpose of aiding pollination. So, why do plants still spend energy in changing colour and maintaining these seemingly useless flowers? What purpose does this change serve?

The size of a floral display is important in attracting pollinators at long distances, while the colour of the flowers in a display 'arrests' pollinators at short distances. Scientists suggest that colour changing flowers may help in both:

a. Long-distance attraction:

Maintaining flowers after colour change, even if they are not reproductively viable, increases the size of the overall floral display of the plant. This is particularly effective in plants like *Lantana camara* where individual flowers are very small and are bunched together in an inflorescence. Larger floral displays make flower signals, saying "come to me", more noticeable to a pollinator flying at a distance. These signals can, hence, be seen by and attract more pollinators. Scientists have shown that pollinators prefer larger inflorescences, and visit them more than smaller ones.³

b. Short-distance arrestation:

When you are picking a mango to eat, you know by experience that yellow ones are likely to be sweet, and green ones sour. Similarly, the different colours in colour changing flowers often signal differences in the quality and quantity of the nectar they offer to pollinators. Pollinators can use this information to forage more efficiently by selectively visiting flowers of colours associated with more nectar. Since flowers of colours associated with more nectar have more mature pollen, the targeted

Box 3. Colour change in Chinese honeysuckle:

Unlike many colour changing plants, colour change in flowers of the Chinese Honeysuckle (*Quisqualis indica*) is not accompanied by a loss in pollen or nectar. Instead, it is coupled with a change in the intensity of their smell – the white flowers that bloom at night are more fragrant than the red ones they turn to the next morning. But why?

In this fascinating plant, colour change helps attract different types of pollinators at different times of the day! Moths are nocturnal, and rely more on odour than visual cues to find food. Also, white coloured flowers are more visible at night, and are known to be preferred by moths. On the other hand, bees and butterflies are diurnal, and use visual cues to forage. Hence they are more likely to be attracted to the distinctive red colour of these flowers in day light.

Box 4. Colour change in *Lantana camara* flowers:

The flowers of one of the more common varieties of *Lantana camara* are yellow to start with, and change to pink after two days (use **Activity Sheet I** to encourage your students to observe the nature of colour change in *Lantana* flowers). This change in colour takes about four hours, with the pink flowers in the inflorescence withering away in a couple of days. Not all varieties of *Lantana* show such dramatic colour change. Some have all-yellow flowers, some all-white, while some have lavender flowers (see **Fig. 3**).



Fig. 3. Different varieties of *Lantana*: some colour changes are dramatic (a), while others are more subtle (b).

Credits: Abitha Chakrapani and Aparna Krishnan. License: CC-BY-NC.

We, and other researchers, have found that yellow *Lantana* flowers have more nectar with higher sucrose (sugar) concentrations than pink flowers (use **Activity Sheet II** to encourage your students to compare the quantity of nectar in differently coloured *Lantana* flowers). We've also found that insects like butterflies and bees prefer yellow flowers over pink ones (see **Fig. 4**). Not only do they spend more time drinking nectar from yellow flowers, they also visit yellow flowers more frequently than pink ones (use **Activity Sheet III** to encourage students to test this out for themselves). Associating flower colour with nectar and pollen availability is a strategy common to many colour changing plants.

visits of pollinators to mature flowers is also beneficial to the plant (see **Box 4**).

How do insects choose some flowers over others?

A pollinator like a butterfly or a bee, flying over a meadow, often encounters

flowers of different colours, shapes, and sizes. How do you think pollinators choose which flowers to forage from? More specifically, how do you think butterflies and bees know that visiting yellow *Lantana* flowers is likely to be more rewarding than visiting pink ones?

Fig. 4. Some common butterfly pollinators of *Lantana*:



(a) Common emigrant

Credits: Charles J Sharp, Wikimedia Commons. URL: [https://commons.wikimedia.org/wiki/File:Common_emigrant_\(Catopsilia_pomona\)_male_crocale_underside.jpg](https://commons.wikimedia.org/wiki/File:Common_emigrant_(Catopsilia_pomona)_male_crocale_underside.jpg). License: CC-BY-SA.



(b) Common Mormon

Credits: Dr. Raju Kasambe, Wikimedia Commons. URL: [https://commons.wikimedia.org/wiki/File:Common_Mormon_Papilio_polytes_from_stichius_Kerala_by_Dr._Raju_Kasambe_DSC_8444_\(3\).jpg](https://commons.wikimedia.org/wiki/File:Common_Mormon_Papilio_polytes_from_stichius_Kerala_by_Dr._Raju_Kasambe_DSC_8444_(3).jpg). License: CC-BY-SA.



(c) Pioneer

Credits: Anagha devi, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Belenois_aurota-Pioneer_butterfly.jpg. License: CC-BY-SA.



(d) Common rose

Credits: Yathin S Krishnappa, Wikimedia Commons. URL: <https://commons.wikimedia.org/wiki/File:2005-common-rose.jpg>. License: CC-BY-SA.



(e) Common crow

Credits: © 2010 Jee & Rani Nature Photography, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Euploea_core_by_kadavoor.jpg. License: CC-BY-SA.



(f) Common leopard

Credits: Anton Croos, Wikimedia Commons. URL: [https://commons.wikimedia.org/wiki/File:Common_Leopard_\(Phalanta_phalantha\).jpg](https://commons.wikimedia.org/wiki/File:Common_Leopard_(Phalanta_phalantha).jpg). License: CC-BY-SA.

Box 5. Innate floral preferences in insects:

A newborn insect has certain inherent or hardwired preferences in floral features like size, colour, pattern, and symmetry. These preferences help it choose flowers to feed from. However, these initial preferences can rapidly change based on floral rewards that change over space and time.

They learn! Like us, they can learn to associate flower colours with pollen and nectar rewards. This is called associative learning. Insects have innate preferences – that is, naive insects (which are just born, and have no experience) have some biases and preferences to different colours (see Box 5). But, depending on what is available in their environment, they can often learn to change their innate preference. So, if a butterfly

innately prefers red, it would initially go to red flowers. But, if it finds out that yellow is more rewarding than red, it learns to prefer yellow over red, and forages more frequently on yellow flowers. The ability to learn helps insects forage more efficiently from flowers of different colours and forms, and several floral colour changing plant species have evolved to take advantage of this ability to direct pollinators to mature flowers!

Parting thoughts

The natural world is full of captivating wonders. You only have to be curious and observant to discover them. Plants are thought to be passive, and relatively less dynamic than animals, because of their stationary lifestyles. But, if

you observe them carefully, you will see that they constantly change, and communicate with the world around them. One doesn't have to go far to find this. You can, in fact, observe the dynamic dialogues between plants and animals, like that of colour changing flowers and their choosy pollinators,

right in your own backyard! The next time you spot a bunch of flowers, observe them carefully. If you see differently coloured flowers on the same plant, go back the next day to see if any of its flowers have changed colours. If they have, you'd have discovered a plant that has colour changing flowers!

Key takeaways

- Flowers of certain plant species change colour over time.
- A change in flower colour occurs as a result of the accumulation or depletion of pigments and changes in pH triggered by the age of the flower, its sexual maturity or the day/night cycle etc.
- Older flowers in altered colours help increase the size of the floral displays of colour changing plant species and, thereby, attract more pollinators.
- Flowers of colour changing plants also use colour to signal information about the quality and quantity of nectar they contain.
- While insect pollinators have innate colour preferences, they can readily learn to forage from novel flower colours associated with better/more nectar rewards.
- Insects can benefit from the information provided by colour changing flowers to selectively pollinate flowers of colours associated with better/more nectar. The plant also benefits from this selective foraging, as flowers with nectar tend to contain more viable pollen.



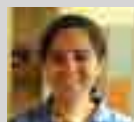
Note: Source of the image used in the background of the article title: <https://www.needpix.com/photo/662473/lantana-butterfly-nature-garden-insect-wings-flowers-floral-yellow>. Credits: cosmicart (pixabay.com). License: CC-BY.

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Divya Uma is an Assistant Professor at Azim Premji University where she teaches Biology, and works on insects and spider behaviour. In order to survive working in Bengaluru, she needs to get away from the city into the wilderness! She can be contacted at divya.uma@apu.edu.in.

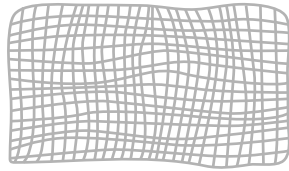
Life in Your Backyard

ACTIVITY SHEET I: COLOUR CHANGE IN LANTANA

Aim:

To study colour change in a *Lantana camara* inflorescence.

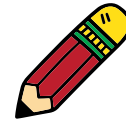
You will need:



Mosquito net/ Muslin cloth



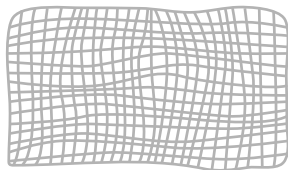
Notebook



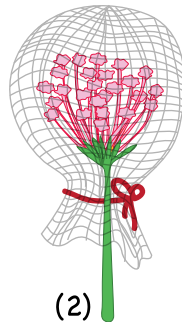
Pencil

What to do:

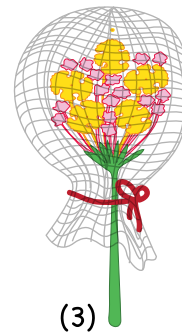
- Make small bags out of mosquito net. Bags can also be made from thin tracing paper.
- Locate an unopened Lantana inflorescence, and cover the buds with the bag.
- A day later, open the bag and choose around four flowers that have opened. Note down their colours (typically yellow).
- Bag the inflorescence again.
- Visit the inflorescence every day for a week in the morning, afternoon, and evening, and note down the colour of the chosen flowers.



(1)



(2)



(3)

Discuss:

- Does the same flower change color over time?
- Do flowers change color at a particular time of the day?
- Why do you think we bag inflorescences?

Contributed by:

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Divya Uma who is an Assistant Professor at Azim Premji University where she teaches Biology and works on insects and spider behaviour. She can be contacted at divya.uma@apu.edu.in.

Life in Your Backyard

ACTIVITY SHEET II: NECTAR IN LANTANA

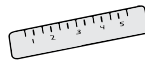
Aim:

Observing if floral colour indicates differences in relative quantities of nectar.

You will need:



Filter paper



Scale



Pencil

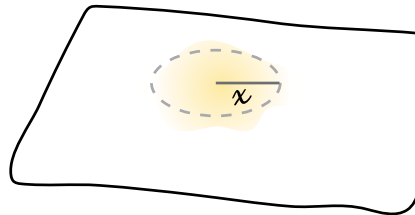
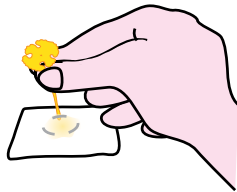


Notebook

What to do:

- Gently pluck a few yellow and pink flowers from a few fully bloomed *Lantana camara* inflorescences.
- Squeeze the nectar from the stalk of each flower onto a filter paper, and let the drop spread on the paper. Expect a tiny drop of liquid – this is likely to be the nectar.
- Do this for the yellow flowers and pink flowers separately.

(1) Squeeze



(2) Measure χ for pink and yellow flowers

Observe:

Before the nectar drop dries up, mark its spread, and measure the diameter of the spread using a scale.

Discuss:

- Is the quantity of nectar different in yellow and pink flowers?
- If you were an insect looking for sweet nectar, which colour flower would you find it more rewarding to go to?



Life in Your Backyard

ACTIVITY SHEET III: CHOOSEY BUTTERFLIES

Aim:

Observing if number of pollinator visits varies with floral colour.

You will need:



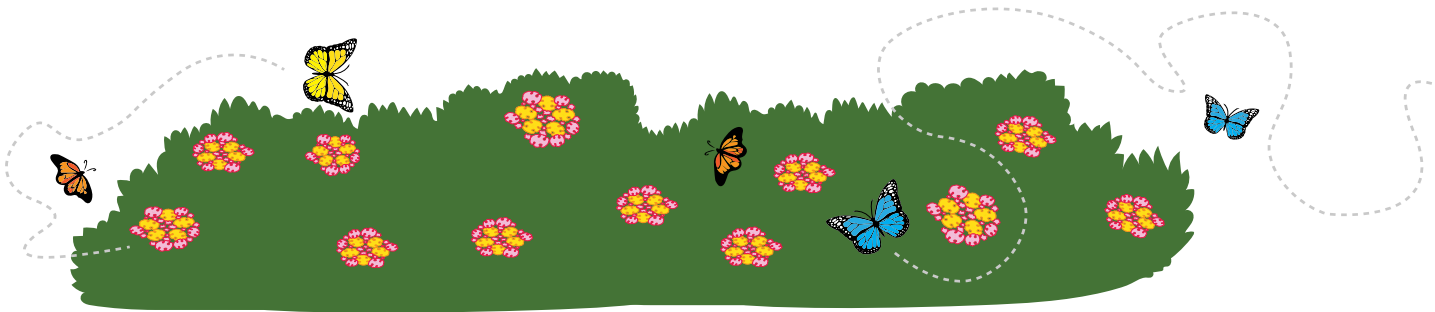
Pencil



Notebook

What to do:

- Locate a *Lantana camara* bush that has a lot of flowers blooming.
- On a sunny day, position yourself near one or a few inflorescences such that you can observe butterflies feeding on the Lantana flowers.
- Observe which flowers are visited most.



Discuss:

- Does the butterfly land on yellow or pink/red flowers? Count the number of times it visits yellow or pink/red flowers.
- Which of these flowers (yellow/pink) do you observe it feeding from more often?
- Repeat the same activity with other butterflies in the area. Do you find that they prefer one flower colour over the other? If so, why do you think this happens?





DIVING INTO THE WORLD OF REGENERATION

SRAVANTI UPPALURI & HARSHITHA KANCHAMREDDY

Some animals and most plants can regrow lost body parts. Why do some organisms regenerate, while others don't?

All of us have seen movies or heard stories of fights between gods and demons where hands or heads get severed, but grow back magically. In reality, humans do not have the ability to grow new hands or heads, but there are many organisms that do. The ability to regrow lost or damaged parts of the body is called **regeneration**.

Almost all regeneration occurs due to the presence of stem cells. Stem cells have the potential to 'become' any other kind of cell in the body through a process called differentiation. This process allows cells to perform specific functions. For example, the cells in our liver (called hepatocytes) are different from the cells in our heart (called cardiomyocytes). Hepatocytes cannot function as cardiomyocytes, and vice versa. Therefore, as you can imagine, the regeneration of the liver will require stem cells capable of differentiating into hepatocytes (see Fig. 1).

Regeneration can occur at many levels, ranging from the microscopic cell to the macroscopic body. For example, we lose

nearly 200,000,000 skin cells every hour, but these cells are continuously replaced by new ones.¹ If a lizard on the wall loses its tail in an accident, it can regrow it. Its cousin, the axolotl, can regrow not only a new tail, but also new limbs, retina, and even parts of its brain and heart. The common earthworm, which we see emerging from the soil after the rains, also has some regenerative capacity. It may be evident from these and other observations (see **Examples I-V**) that not all organisms have the same regenerative capacity.

Regeneration in humans

At first glance, humans don't seem to have the regenerative capacities that amphibians and plants do. But keep in mind that regeneration can have a wide ranging definition.

On the one hand, the most common example of regeneration in humans is seen in the skin. Our skin cells are constantly being replaced, and our wounds getting healed (often without scars). On the other hand, the human liver can fully recover its

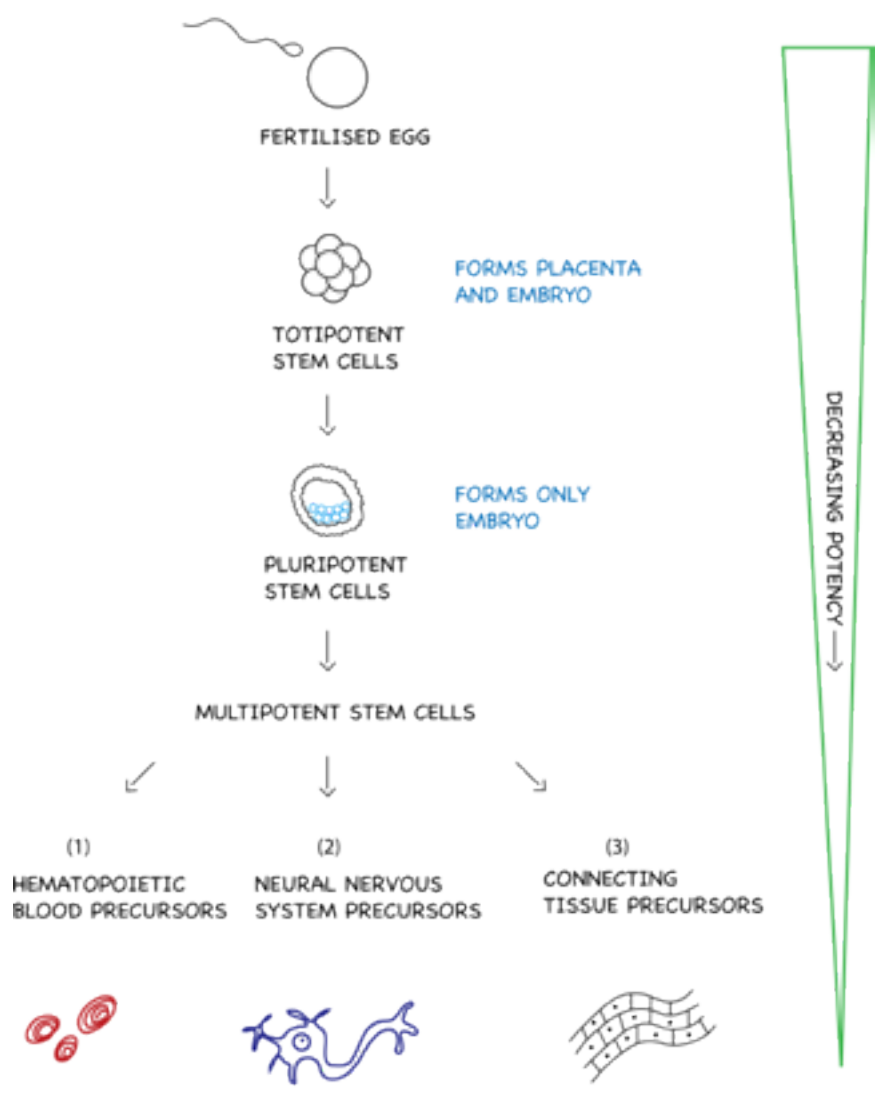


Fig. 1. Stem cells differentiate into various cell types. A fertilized egg divides to form a cluster of 'totipotent' stem cells. Each cell in this cluster has the potential to form all other cell types in the human body, as well as extraembryonic or placental cells. Some cell divisions later, these totipotent stem cells differentiate into pluripotent ones. Pluripotent embryonic cells can form any of the cell types in the human body except the placenta. Each pluripotent embryonic cell divides and specializes to form multipotent cells. Multipotent stem cells can develop into a limited number of cell types within a particular lineage. The different multipotent cells divide and differentiate into blood cells, neurons, muscle cells etc. Each of these can only grow into cells of their own kind.

Credits: Sravanti Uppaluri & Harshitha Kanchamreddy. License: CC-BY-NC.

form and function from as little as one fourth of its original mass. In fact, this organ has the strongest regenerative ability in our body.

Why does this organ retain this ability, and not others? We don't have a complete answer to this question, but can take a guess by looking at the liver's regenerative capacity from an evolutionary perspective. As a

detoxifier and regulator of blood glucose, ammonia, and lipid levels in the body, the liver is essential for the functioning of the brain and other essential organs. It also processes all circulation exiting the intestines, spleen, and pancreas. Consequently, the liver is prone to damage from chemical toxins and diseases. Left unchecked, this damage can result in liver failure. Not surprisingly, in most vertebrates, the

liver retains its regenerative capacity – a capacity that is most likely to have been selected for in the hostile environment of our evolutionary past.²

While humans cannot match the regenerative capacities of an axolotl, the genes that give the axolotl the ability to regenerate parts of its brain and heart muscle also allow the regeneration of our fingertips. Yes, you read that correctly – up to a certain age, humans can replace relatively small amputations of a fingertip. A similar ability in mice depends on stem cells found under their nails. Since we share many regeneration genes with mice, it is likely that the same mechanism may be at play in humans.³

Parting thoughts

Regeneration in different organisms has mostly been studied by removing a body part (cells, tissues, limbs, organs etc.) and observing subsequent processes. As we develop increasingly sophisticated laboratory techniques, we are beginning to identify the genes and proteins involved in regeneration.

Apart from how awe-inspiring this process is, it may be useful to study regeneration in nature because:

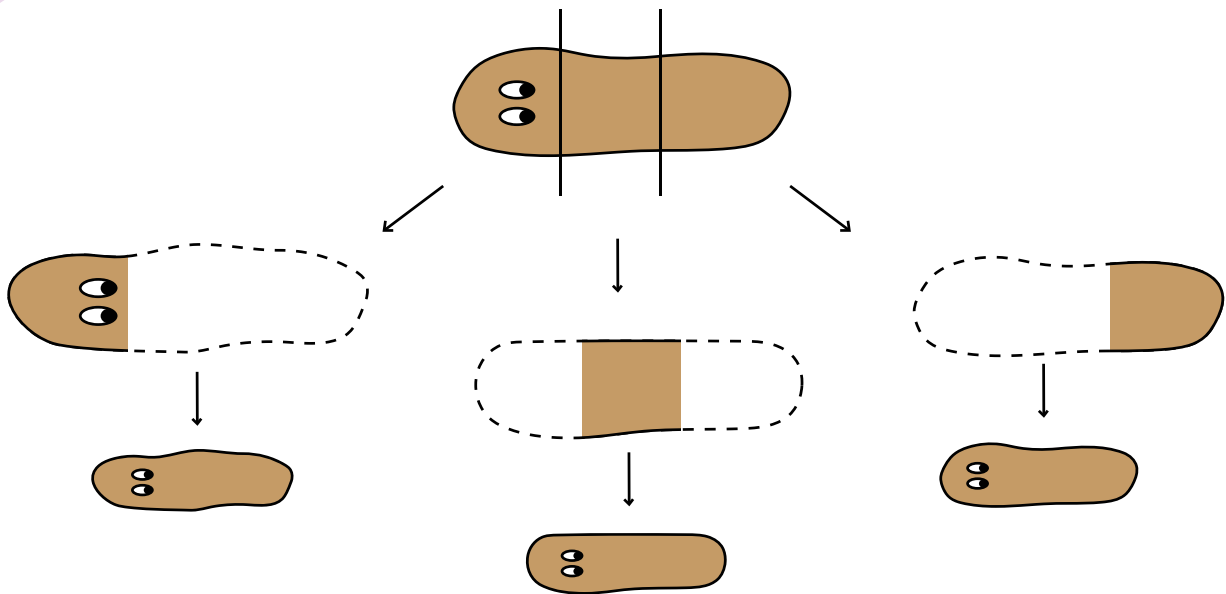
1. Humans lose limbs due to accidents, infections, or even birth defects. Understanding the regenerative process at the level of genes, cells and organs across the plant and animal kingdoms is likely to yield useful insights for medical applications.
2. Regeneration is not very different from a dividing embryo – both processes involve the division of cells to form functional body parts. Since it is often difficult to study an embryo, capturing the process of regeneration offers us a window to understanding how embryos develop.
3. Studying organisms that have adapted their regenerative capacities to their environment can show us how such diversity has come about. It can also provide insights into the evolution of these organisms.

Big Questions

EXAMPLE 1: REGENERATION IN PLANARIA

Planaria is the common name for a group of flatworms with regenerative capabilities. For example, *Schmidtea mediterranea*, a flatworm found near the Mediterranean sea, is commonly used by scientists to study regeneration.

Within its brown, paper-thin body, this flatworm has a nervous, digestive, and reproductive system — sharing a lot in common with humans. However, unlike most organisms, not only do planaria survive after being cut into pieces, each piece can regrow into the whole functional organism! Each such regenerated organism is an exact replica of the original worm. What is even more surprising is that even a piece as small as $1/279^{\text{th}}$ of the initial worm can regenerate!



Planaria can regenerate from very small amputated fragments.

Credits: Sravanti Uppaluri & Harshitha Kanchamreddy. License: CC-BY-NC.

The stem cells in planaria that are responsible for this extraordinary capacity for regeneration are called neoblasts. When a flatworm is cut, neoblasts move towards the cut site, divide, and specialize to recreate the missing worm. But, how do the neoblasts know how much of the body is missing? How do they know whether the missing region is a head or a tail? We are still very far from answering these questions.



Read more here: *Playing with wormies* (2011). Baldscientist. URL: <https://baldscientist.wordpress.com/2011/09/23/playing-with-wormies/>.

Big Questions

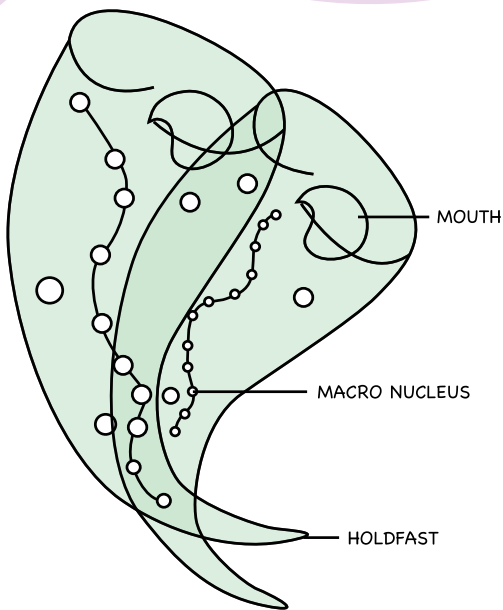
EXAMPLE II: REGENERATION IN *STENTOR COERULEUS*

Stentor Coeruleus was discovered by Abraham Trembley, an 18th century naturalist. It is a very large unicellular organism with remarkable regenerative properties. As unicellular organisms go, *S. coeruleus* is so huge that it is visible to the naked eye! With a length of about 1-2 mm, this blue-green organism's body is shaped like a 'shehnai' or 'nadaswaram'.



Stentor coeruleus is a large unicellular organism.

Credits: Micropix, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Stentor_coeruleus_1.JPG. License: CC-BY-SA.



Any piece of the Stentor that contains a portion of its nucleus and cell membrane has the capacity to regenerate into a full organism.

Credits: Sravanti Uppaluri & Harshitha Kancharreddy. License: CC-BY-NC.

The wider end of a Stentor contains its mouth regions with cilia (thin thread-like structures) that move water into its body. The Stentor feeds on the bacteria, algae, and other smaller ciliates in the ingested water. The other, narrower, end of the Stentor helps the organism attach itself to rocks and plants in water. Any piece of the Stentor that contains a portion of its nucleus and cell membrane has the capacity to regenerate into a full organism.

When we cut a planarian, we are cutting an organism with multiple cells. In contrast, when we cut a Stentor, we are cutting a single cell with almost 'tomatoish' consistency. How does the cell maintain its integrity after being cut? Why don't the cell's contents leak into the water around? These are questions that we don't have answers to yet.



Read more here: Slabodnick, M. M. & Marshall, W. F. *Stentor coeruleus*. *Curr. Biol.* CB 24, R783-R784 (2014). URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5036449/>.

Big Questions

EXAMPLE III : DO HYDRA LIVE IN YOUR NEIGHBOURHOOD?

The multicellular hydra also shows remarkable regenerative capacity, which is believed to be basis of its immortality! Hydra are usually found in freshwater ponds. If you live near a clean pond or stream that flows softly, and are equipped with a magnifying glass and a little patience, it may not be too hard to spot some of these ~1 cm creatures. One can find them attached to the underside of leaves and other vegetation. Try your luck — it is an interesting expedition for students and teachers alike. If you do find some hydra, store them in some filtered pondwater in a clear glass or plastic container.



The multicellular hydra shows remarkable regenerative capacity.

Credits: Neeharika Verma

Use a scalpel or blade to cut individual hydra at different positions along its body. Store the cut pieces in pond water in clear glass or plastic containers, and leave these in a cool place (18-24 °C). Observe the fragments every 24 hours. Record the following:

- Are there some parts that regenerate into functional organisms, and others that don't?
- Do all fragments regenerate at the same rate? Why would this happen?

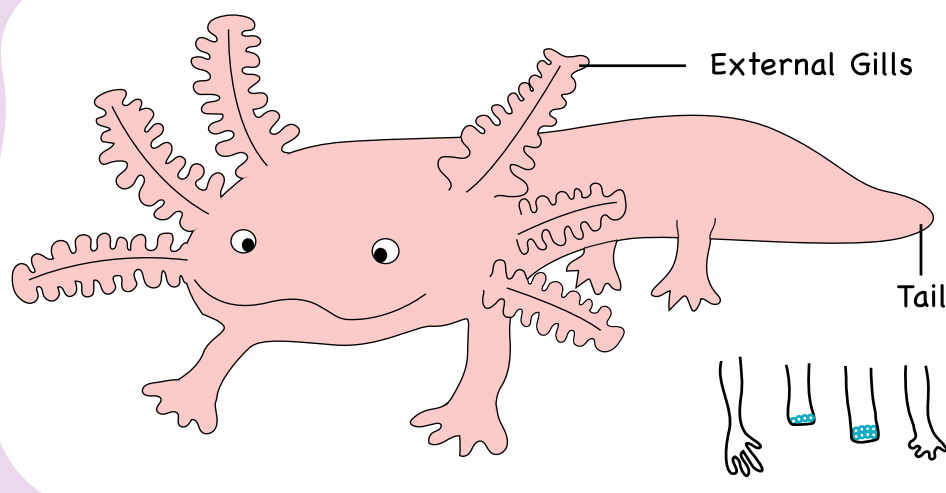


Big Questions

EXAMPLE IV : REGENERATION IN THE AXOLOTL *AMBYSTOMA MEXICANUM*

The axolotl (pronounced ack-suh-lot-tul) is a salamander that looks a lot like the lizards we find in our homes, but is actually an amphibian that lives its entire life in water. Unlike most frogs that we know, the axolotl remains at the larval stage, never metamorphosing to an adult.

The axolotl can regenerate many of its body parts, including its limbs, spinal cord, heart, even parts of its brain, without forming any scar tissue whatsoever. It can also receive transplanted organs (anything from eyes to limbs) without rejecting them. Imagine if humans had the ability to recover from spinal cord injuries in the same way? The permanent larvae-like stage of the axolotl could be one reason for the axolotl's impressive regenerative capacities — they just don't really ever 'grow up'. After all, the regenerative capacities of many species, including humans, are much stronger in their early stages of growth and development, and are lost over time.



A sketch of axolotl, with external gills. Inset: Form develops gradually as cells divide (blue) and the morphology of a regenerated limb returns to its original state.

Image credits: Sravanti Uppaluri & Harshitha Kanchamreddy. License: CC-BY-NC.

Native to lakes in and around Mexico city, axolotls have become highly endangered in the wild, largely due to pollution arising from urbanization. Funnily enough, since they can be grown in captivity, axolotls are reared around the world as both household pets and model organisms in scientific laboratories. Not being able to study them in the wild makes it difficult for us to understand how their environment has shaped their evolution. Many scientists are currently investigating the genetic basis of the axolotl's regenerative capacity — interestingly, the axolotl's genome is much larger than that of humans.



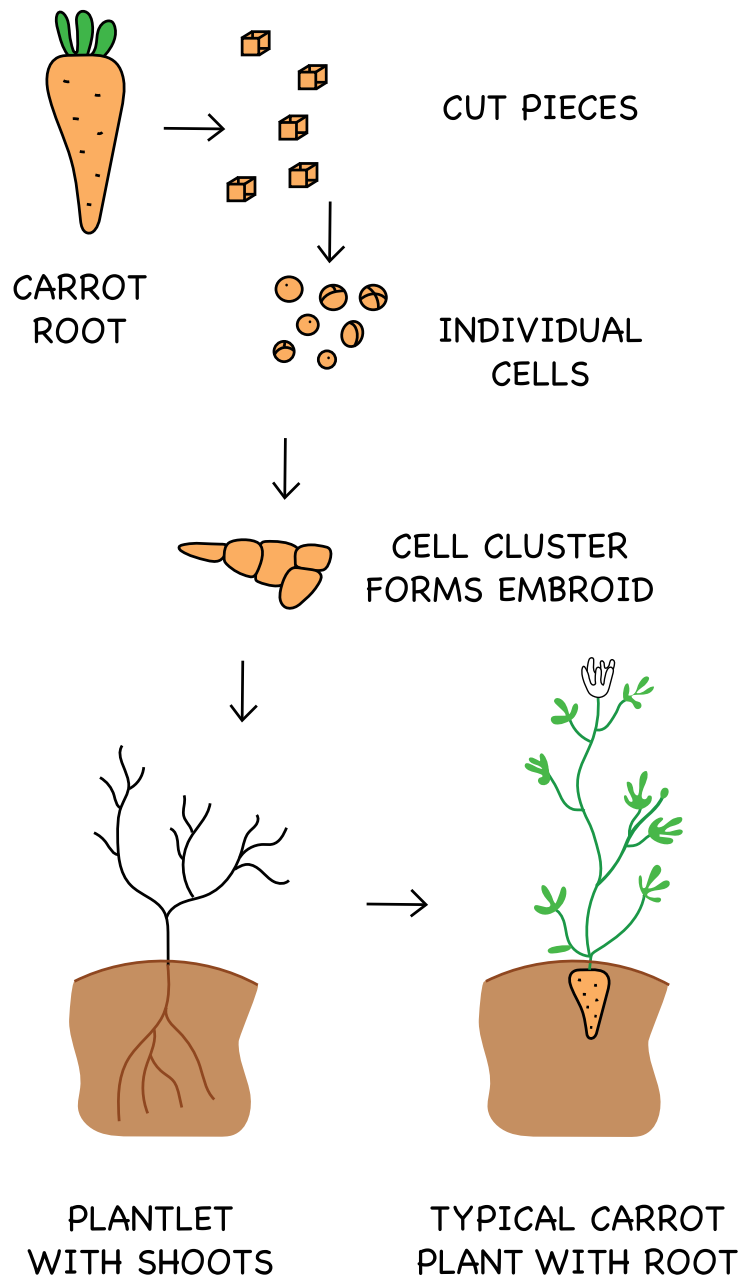
Read more here: (1) Biology's beloved amphibian — the axolotl — is racing towards extinction. URL: <https://www.nature.com/articles/d41586-017-05921-w>. (2) Regeneration: The axolotl story. Scientific American Blog Network. URL: <https://blogs.scientificamerican.com/guest-blog/regeneration-the-axolotl-story/>.

Big Questions

EXAMPLE V : REGENERATION IN PLANTS

It may not be an exaggeration to say that regeneration in plants is far more versatile than that in animals. In fact, in 1958, Frederick Steward from Cornell University showed that a whole carrot plant could be regenerated from a single cell derived from the phloem of the plant. While this is an extreme example, we regularly see plant cuttings develop shoots and roots when placed in a moist environment.

Often regeneration is seen as a process in which the organism has a fixed set of instructions on how the body should look (this is called the body plan). Therefore, if a portion of the body is lost, regeneration must involve a return to its original shape, size, and function. However, this definition does not hold true for the plant kingdom, because most plants don't have a fixed body plan! This is something we may all see in our day-to-day interactions with plants. Break off a leaf from a plant, and it may not be replaced in the same way a limb is replaced in animals. But, the plant will survive, compensate, and adapt to a new body plan. What is most fascinating is that a leaf may, in many plants, sprout roots and become another plant — much like how planaria regenerate!



An entire carrot plant can be regenerated from single isolated phloem cells.

Credits: Sravanti Uppaluri & Harshitha Kanchamreddy. License: CC-BY-NC.

TRY THIS OUT!



Many plants provide a readily available experimental system that even children can use to study different aspects of regeneration. These include common houseplants such as aloe vera (*Aloe barbadensis*) and the money plant (*Epipremnum aureum*), as well as outdoor shrubs such as lantana (*Lantana camara*) and touch-me-nots (*Mimosa pudica*).

To identify plant parts that can regenerate by producing roots or shoots, encourage students to choose one of these species for study. It may be useful to keep a set of control plants, and another set of plants for experimentation. Students could amputate some or all of the roots, leaves, apex, or even branches of a plant by systematically removing them with a sharp instrument. Ask students to record the proportion of plants that survive and recover from each type of amputation.

Similarly, to study the effect of environmental factors on regeneration, conduct the same experiment under varying conditions of temperature, moisture content of soil, etc.

These exercises will encourage students to think about the following:

- Do all plants have the same regenerative capacity?
- Which amputations do plants find it easier to recover from?
- What environmental conditions are required for regeneration?



Read more here: Steward Experiment and Application of Totipotency (2014). Biology Discussion. URL: <http://www.biologydiscussion.com/plants/steward-experiment-and-application-of-totipotency/5832>.

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Learning more about the different mechanisms for regeneration used in the animal world could help us replicate this process in humans too. We have already made a lot of progress in this field. For example, we have identified

stem cells in multiple human tissues. By inducing these cells to grow into different cell types, we are able to produce organ and tissue replacements to damaged parts in humans. While many mysteries about regeneration

remain, with ever-increasing knowledge, we might just be able to imagine a day when we can grow back an amputated head, like the demons from many Indian stories!

Key takeaways



- Regeneration is the capacity to regrow a lost body part, and recover a function.
- Regenerative capacity varies across the plant and animal kingdom. Some organisms can regenerate cells, others can regenerate full organs.
- Investigating regenerative capacity is possible even at the school level by studying simple invertebrates and plants.
- Gaining an understanding of regeneration has applications in medicine and developmental biology.

Note: Credits for the image used in the background of the article title: Sravanti Uppaluri & Harshitha Kanchamreddy.

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WITNESSING EVOLUTION AS IT HAPPENS

SHAMPA M. GHOSH

Natural selection and evolution evoke images of processes that happened in the distant past. Can we observe evolution in real time? Can we use such observations to understand evolutionary changes in nature?

Evolution is commonly perceived as a process that happened millions of years ago. But, the development of dichlorodiphenyltrichloroethane (DDT) resistance in mosquitoes, and the emergence of the pandemic causing novel coronavirus are just two examples that demonstrate that evolution is an ongoing process. It is occurring, this minute, all around us.

How do we study evolution? Most of us are aware of studies that investigate prehistoric fossils (palaeontology), or compare different species (comparative studies). Few know that this process can also be studied in real time, under the controlled conditions of a laboratory, through an exciting approach called 'experimental evolution'. To do this, lab-grown populations of organisms are subjected to specific selection pressures, and any changes that occur in response to these pressures are tracked over a number of generations. The organisms that are commonly used in this approach

are bacteria, nematode worms, fruit flies, etc (see Fig. 1). In addition to being easy to grow in lab, these organisms have short generation times, and are genetically tractable. This means that any evolutionary change in these organisms become apparent within a span of a few months or years, and scientists are able to track their underlying genetic causes more easily.

Example I: Evolution of 'postponed ageing'

Why do we age? This question has intrigued us for centuries. Evolutionary biology offers one explanation for this process, called the evolutionary theory of ageing. This theory is based on the premise that the most significant contribution to any populations' reproductive success comes from its young. If an organism dies before it reaches the reproductive age, its genes die with it. Therefore, natural selection

The life cycle of *Drosophila melanogaster*

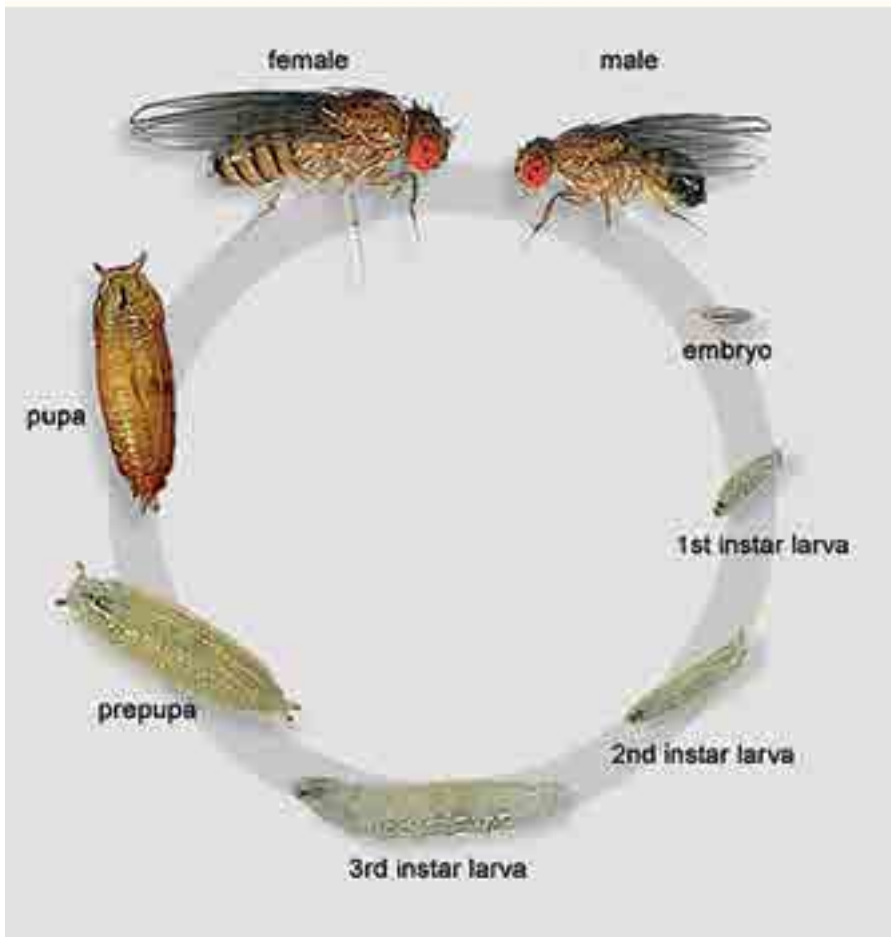


Fig. 1. The fruit fly has a generation time of just 10–12 days at 25 °C. This means that it takes only 10–12 days for a zygote to develop into an adult fly. This process involves several stages of development – embryo, larva (first instar, second instar and third instar), pupa, and adult.

Credits: Image Editor, Flickr. URL: <https://www.flickr.com/photos/11304375@N07/2993342324>. License: CC-BY.

favours genes or traits that help ensure that the young survive long enough to reproduce, and are able to produce healthy offspring. Once an organism survives long enough to mature and reproduce, the selection pressure on it reduces. Even if it dies after that, its genes have been transmitted to the next generation. Hence the selection pressure to keep organisms fit weakens with age, and hazardous late-acting genes continue to exist in the species. This causes a number of changes in the organism, like the accumulation of oxidative damages within cells or the weakening of body parts. As a result, the organism's health shows a gradual

decline, leading to ageing or senescence.

Can we delay ageing, and increase lifespan? Professor Michael Rose from the University of California (UC), Irvine, USA, attempted to answer this question in the fruit fly *Drosophila melanogaster* (see Fig. 2). The average lifespan of the adult fruit fly is about 35–40 days. The female lays eggs throughout its lifespan, but the number of eggs it produces reduces drastically as the fly ages. Rose decided to delay the age at which these flies reproduce for the first time, and repeat this in every generation. He predicted that flies in this population would show the evolution of two traits

– delayed ageing and longer lifespans. Why? Because under such conditions, natural selection would favour flies that lived longer, stayed fitter, and produced more eggs than other flies at that age.

To test his prediction, Rose and his colleagues started with five replicate populations of fruit flies. These lines were derived from a wild caught population to ensure that they showed more variation than many of the inbred lines of flies commonly used in the lab. They divided these populations into two groups – B (for 'Base') and O (for 'Old'). Eggs from flies in the B populations were collected at their normal reproductive age. In contrast, eggs laid by only the oldest living flies in the O populations were used to initiate the next generation, while those laid prior to that age were discarded. This selection regime was repeated for many generations, with egg collection pushed to a later age in each subsequent generation of the O populations.

Flies in the O populations responded to this selection for late-age reproduction remarkably fast. As predicted by Rose, they not only evolved the ability to produce more eggs at an advanced age, their lifespan also continued to increase through the course of the study. After a decade (~ 75 generations) of selection, the average lifespan of flies in the O populations was more than double that of the flies in the B populations. According to the latest report, O populations have evolved to live four times longer than a normal fruit fly!



Fig. 2. An adult fruit fly (*Drosophila melanogaster*) feeding off a banana.

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

Rose named these long-lived *Drosophila* populations 'Methuselah flies' after Methuselah, the longest living man according to the Hebrew Bible. But this was not all. The O flies also showed greater metabolic storage, and increased resistance to starvation, desiccation, and oxidative stresses. In effect, these flies remained young much beyond the normal age of *Drosophila*. These results supported the evolutionary theory of ageing by demonstrating that ageing could be postponed if natural selection remained effective in older animals.

Example II: Evolution of faster development

Can we shorten the duration of development of an organism? One answer to this question comes from observations of insects such as *Drosophila* in the wild. These insects develop within rotting fruit. As the larvae grow, they compete with each other for food. They also excrete their toxic waste within the fruit, making it increasingly inedible. Therefore, if all else remains equal, natural selection is expected to favour flies that can develop into adults more rapidly than others. Four research groups in the 1990s used this argument to successfully rear a population of fruit flies that developed faster than normal. One of these groups was headed by Professor Amitabh Joshi from the Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bangalore, India.

Joshi's group subjected four replicate populations of *Drosophila* (called JB for Joshi Baseline populations) to the following selection regime – in each generation, only 25% of the fastest developing flies were allowed to reproduce, while the remaining 75% were discarded. In addition, these flies were allowed to breed at a younger age than those in the control population. This imposed a strong selection pressure to develop fast, since the flies that could not do so were not allowed to pass on their genes to the next generation. By

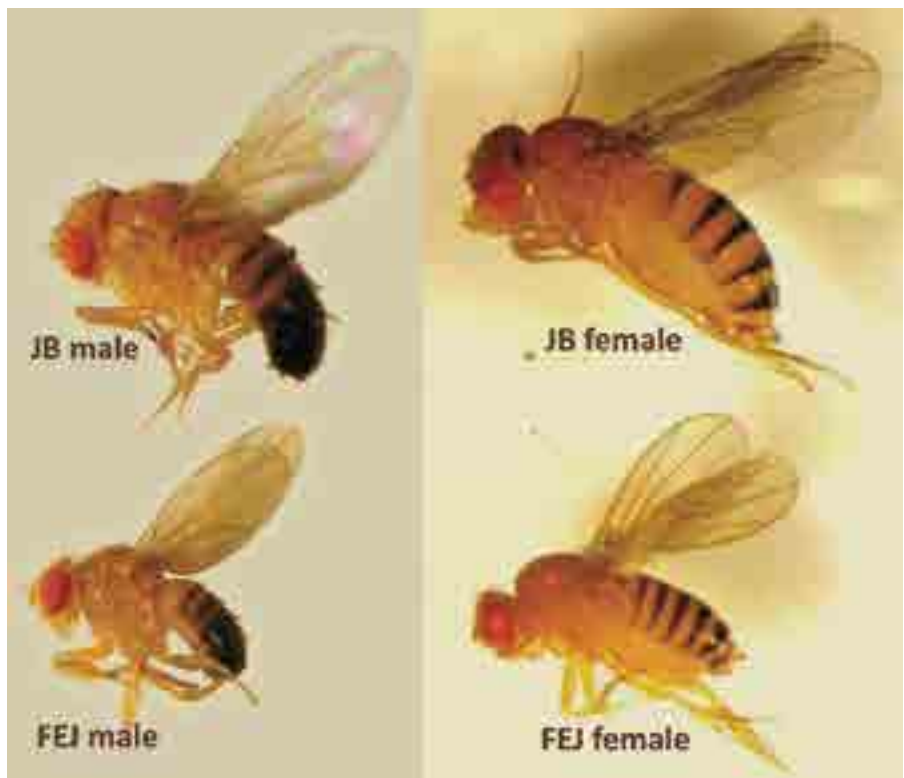


Fig. 3. Flies in the FEJ population are much smaller than those in the JB population.

Credits: Shampa M. Ghosh. License: CC-BY-NC.

the 100th generation, the time taken for egg-to-adult development in these FEJ (or Faster-developing, Early-reproducing, JB derived) fly populations was three-fourths that taken by their ancestors!

But they paid a heavy price for this ability – showing greater larval mortality, lower lipid reserves, reduced stress resistance, and lower reproductive output, among other things. This is because the duration of development is of utmost importance in the life history of *Drosophila*. As a larva, the fruit fly can feed voraciously and grow in size. But, once it gets encased in a pupal case for metamorphosis, the larva loses some of its body mass; and as an adult, the fly's hard exoskeleton prevents any further growth in size. This means that the size and energy needs of an adult fly, for the rest of its lifespan, are largely dependent on the amount of time it invests in larval feeding. This is why faster development in FEJ flies would result in poorer growth and lower energy reserves, leading to reduced

energy allocation for various traits, including egg production. This seems to suggest that it may not be possible to maximize or improve one trait, without affecting other traits. It also seems likely that the average duration of development that we see in nature is one that balances the various life history traits of an organism. Hence, contrary to what was expected, natural selection may not favour flies that develop so fast that it affects other traits.

Interestingly, FEJs also evolved smaller body sizes – by the 70th generation, these flies were only half the size of JBs (see Fig. 3). A series of crosses revealed that flies from the FEJ and JB populations were less capable of successful interbreeding. Since reproductive isolation between two groups of organisms defines them as two different species, the FEJ study also provides a rare example of progress towards speciation (or, the formation of a new species) in the laboratory.

Parting thoughts

Experimental evolution is an extremely powerful approach to study evolution. It offers us the opportunity to observe this process in real time, design replicable laboratory experiments to investigate

specific evolutionary hypotheses, and track the underlying genetics of evolutionary changes. In an era of massive environmental upheavals like deforestation, habitat loss, and

global warming, this approach can be a great tool to understand and predict evolutionary changes in nature.

Key takeaways



- Experimental evolution offers an exciting opportunity to observe evolution in real time within the laboratory setup.
- In this approach, evolution is studied by subjecting a population of organisms to specific selection pressures in the laboratory for many generations.
- The most common organisms used in this approach include bacteria, nematode worms, and fruit flies, although other small organisms can be used too.
- This approach allows us to study evolved responses, including genetic changes, in great detail.
- This approach has led to the evolution of fruit flies with longer life spans and faster development in the laboratory.


Note: Source of the image used in the background of the article title: <https://www.pxfuel.com/en/free-photo-obrql>. License: CC-0.

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THE BIRTH OF ANTIBIOTICS

ROHINI KARANDIKAR & SUBHOJIT SEN

Did you know that Alexander Fleming was not the only researcher involved in the Nobel Prize-winning discovery of penicillin? Or that it took 13 years for penicillin to be of use for humans? We present an interactive resource to unearth unsung surprises in the process of discovery of penicillin.

School textbooks devote limited space to 'the history of science', often reducing it to dates, names of scientists, a couple of photographs, and a few lines. Students miss out on the exciting 'process of science' and the *eureka* moments that led to those discoveries. Connecting experimental ideas with stories of discovery can offer students an introduction to the nature of science. Not only do students discover how to develop and test a hypothesis, they learn to appreciate the importance of careful observation, patience, and collaborative work in translating discoveries in the lab into applications in the real world. These connections also offer students the opportunity to recognize the time, effort, and rigor involved in serendipitous discoveries.

We explore one such activity-based approach around Alexander Fleming's discovery of penicillin (see **Box 1**). Based on the Vigyan Pratibha learning unit – 'The Accidental Discovery', this approach connects an experiment (**Activity Sheet I**) with an interactive story (**Activity Sheet II**).

Box 1. Curricular links:

This resource is suitable for grade IX and above. It is linked to:

1. Chapter 2 in NCERT's Grade VIII textbook – Microorganisms: Friend and Foe
2. Chapter 13 of NCERT's Grade IX textbook – why do we fall ill?

Activity I: Become a microbiologist!

Encourage students to engage with this activity after they have been introduced to the idea that not all microorganisms are harmful. Lactobacilli in curd and yeast in bread can be offered as common examples of microorganisms that are, in fact, beneficial to humans.

Can we demonstrate the presence of microbes in curd without the aid of a microscope? Surprisingly, one doesn't need to be a trained microbiologist to do this. This activity (see **Activity Sheet I**) allows students to grow microbes from curd (~bacterial inoculum/seed) on a cooked potato-slice (~solid substrate), thereby avoiding difficult techniques of classical microbiology (sterilization, media preparation, specific apparatus, and aseptic conditions). To do this, some curd is evenly spread out on a cooked potato slice, and incubated for 24–48 h. By the end of this period, students can see many small whitish dots on the slice – each of which is a *Lactobacillus* colony (see **Fig. 1a**). Each **colony** consists of several million bacteria growing in a single pile that is visible to the naked eye. Students may also observe that the colonies are quite diverse in terms of their size (smaller, bigger), appearance (some translucent, others opaque) and so on.

To observe the effects of antibiotics on microorganisms, some of the potato at

the center of each slice is scooped out to create a small, shallow well. Antibiotic solutions of different concentrations are added to different wells. Potato slices with only curd or only antibiotic can serve as parallel controls. By the end of the incubation period, students will be able to observe the presence of a clear zone of inhibition around a potato well with antibiotic solution. In other words, bacterial colonies will be fewer in number or absent from this zone (see **Fig. 1b**). Students may also observe that the size of the clearance zone increases with an increase in the concentration of antibiotic added to the well. Other factors that could lead to variations in zone size include handling of the slices, and errors while cutting, pipetting, and seeding.

Through this activity, students will not only observe what microbial growth looks like, but will also appreciate the visual concept of a microbial colony. Since these colonies appear only on potato slices with curd, students will be in a position to infer that they belong to the curd bacteria. Observing a clear zone of restriction around the antibiotic wells will give students visual proof of the inhibition of bacterial growth by a diffusing antibiotic (see **Box 2**). It will also help solidify the idea of what Fleming is likely to have observed around the fungal colony that produced penicillin.

Box 2. Extended activity:

Students can also use this experiment to check –

1. The presence of microorganisms in soil – by seeding the potato slices with a soil sample instead of curd, or
2. Differences in the nature of microbial inhibition – by using different sets of antibiotics.

Activity II: Retracing the accidental discovery of penicillin

This interactive story-based activity (see **Activity Sheet II**) describes the discovery of modern penicillin through questions that encourage 'critical thinking'.

The story introduces students to the process of science, while the questions

offer avenues for open thought and discussion. To ensure maximum participation by students, we highly recommend that teachers:

- Avoid offering direct answers, and encourage discussion instead.

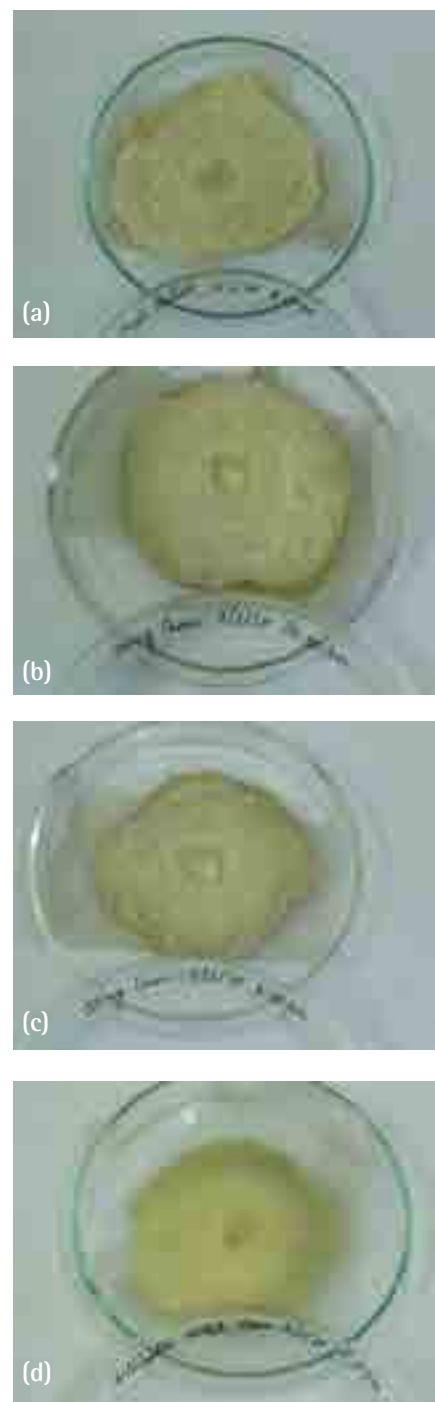


Fig. 1. Effect of Chloramphenicol (Cam) on potato slices spread with curd. Plates with – (a) curd control, (b) 20 mg Cam, (c) 50 mg Cam, and (d) antibiotic control (20 mg Cam). Fewer colonies are observed around the wells in the slices with 20 and 50 mg Cam. Clearance is seen on one side of the well in the slice with 20 mg Cam, and around the well for slice with 50 mg Cam. This clear zone indicates the inhibition of lactobacilli by the antibiotic, which diffuses into the slice along a concentration gradient (with the highest concentration at the center).

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Box 3. Teacher's box:

1. Teachers may need to introduce the idea that mould are fungi whose spores are ubiquitously present in the air around us. Most saprophytic fungi grow at moderate room temperatures (e.g., mushrooms at 25°C), while disease causing bacteria tend to grow better at 37°C (human body temperature).
2. A debate around who should've received the Nobel Prize for the discovery of penicillin can be an interesting exercise for students. Although the prize was awarded to Alexander Fleming, Howard Florey, and Ernst Chain, students may suggest that Heatley and the 'Penicillin girls' were deserving, yet unsung, heroes in this process.
3. The world wars reduced funds for research, forcing many scientists to limit their resources. But scientists involved in the discovery of penicillin were driven by the need to produce enough antibiotic to save soldiers wounded in war. Students may, therefore, conclude that in a way, the war pushed efforts to produce penicillin in larger amounts. This discussion is likely to help students explore the impact that politics can have on scientific discoveries.
4. Teachers may need to provide clarity regarding the role of antibiotics. Penicillin doesn't heal wounds. During an infection, bacteria multiply to very large numbers, which overwhelms the immune system. Penicillin slows down bacterial growth, indirectly giving the body's immune system a better chance at fighting the infection.

- Consider all student responses without classifying them as right or wrong. Many questions need not have one right answer, and not being too critical or disapproving of students' views will encourage open thinking.
- List all student responses/ideas on the board and moderate a student debate around them. This will allow students to engage with each idea, and reflect on their reasons for agreement/disagreement.

Discussion around this activity can take many directions (see **Box 3**). Consider one question in the activity – what in the bread mould helps wounds heal? Student discussion around this question can be followed up with another question – is it possible that the mould on bread releases some chemicals that could kill or inhibit the growth of bacteria in wounds? Once students have explored this possibility, teachers could present the fact that bread acts as a nutrient medium for all kinds of moulds to grow. Even if ancient Egyptians knew of 'ways' to help a wound heal better, they would have less control over what kind of moulds grew on bread. What if some of the fungi or mould on the bread piece used for healing were

non-beneficial or even toxic? Discussion around this part of the activity can help students differentiate between antiseptics used in traditional medicine from antibiotics in modern medicine. This could be used as an example of how the identification of the active component involved in the Egyptian healing technique by modern scientific principles allows us to minimize mishaps from use of ineffective or toxic moulds. It could also be used to illustrate how large-scale production and purification technologies have made penicillin available for use at the most effective clinical dose.

Before winding up, teachers could use some of the themes provided in parentheses to encourage students to think about the following open-ended questions:

- What **new** things did you learn from this exercise? (Themes: effect of chance, accidental discoveries, collaborations, working in teams).
- How is learning about the 'history of antibiotics' significant now? (Themes: drug discoveries today also have to go through similar time-consuming and rigorous procedures of animal and clinical trials before their benefits can reach patients).

- Bacteria and fungi have existed throughout human history. What was it that triggered the discovery of penicillin in 1928? (Theme: the accidental observation of bacteria and fungi growing on the same plate, uncovering their antagonism).
- If there were so many scientists and assistants involved in the discovery of penicillin, why is only Fleming's name popularly associated with it? (Theme: primary discoverer).

Parting thoughts

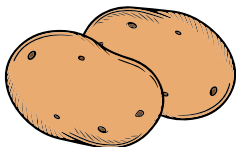
Students are never really offered an experience of the scientific process. How do ideas nucleate from observations of the natural world? How do we use the scientific principle of controls and rational thinking to find scientific explanations for observed phenomena? These activities aim to offer students this experience by engaging with both narrative and experimental evidence. They also provide an introduction to the world of microbes; helping students appreciate how some microbes are useful, while others are harmful. Finally, it helps students understand that the fruition of any idea in science involves many people, although only a fortunate few get recognized or awarded the Nobel Prize for their contributions.

Annals of History

ACTIVITY SHEET I: BECOMING A MICROBIOLOGIST!

You will need (per group of 3-4 students):

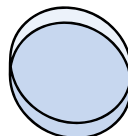
2 medium-sized potatoes



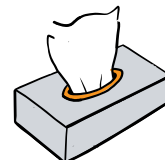
2-3 spoons curd



4 Petri-dishes or watch glasses



Tissue paper

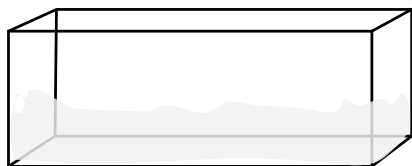
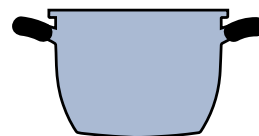


Amoxicillin or any broad-spectrum antibiotic (obtained from discarded medicines or a pharmacy) dissolved in water at a concentration of 100 mg/ml

A dropper or glass pipette (with graduated markings)



Boiled water (cooled to room temperature)



A large plastic box lined with tissues wet with a slight excess of boiled water to create closed moist chamber

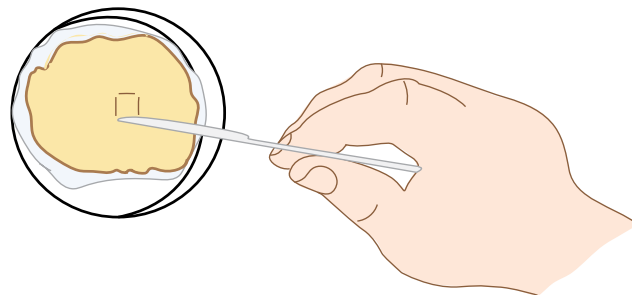
What to do:

1. Boil two medium-sized potatoes for ~20 min, and allow them to cool.
2. Clean a Petri-dish or watch glass and place a folded piece of tissue at the base. Keep the tissue moist with the boiled water.
3. Peel one of the potatoes and cut into ~0.5 cm thick oval slices along its length, maintaining uniform thickness.
4. Place a slice on the wet tissue in one watch glass. Do the same for the other three watch glasses.
5. To the centre of three of the slices, add 1 ml of curd/buttermilk each using a dropper or pipette. Use a clean spoon to spread the curd evenly on the slice until it gets completely absorbed. Label these slices as:
 - 'Curd control' or CC,
 - '20 mg', and
 - '50 mg'.
6. Take another slice of potato. Do not add curd to this slice. Label as 'Antibiotic control' or AC.
7. Use a scalpel to scoop out a shallow well in the middle of all four slices, ensuring that the wells do not get punctured at the bottom.
8. Place all four watch glasses in the moist chamber.

9. Add:

- 0.2 ml of antibiotic solution to the well in the slice labelled '20 mg'.
- 0.5 ml of antibiotic to the well in the slice labelled '50 mg' as well as the one labelled AC
- 0.5 ml of pre-boiled water to the well in the slice labelled 'CC'.

10. Without disturbing the plates or watch glasses, close the chamber and keep in a warm place for 24–48 h.



How to cut out a well from a potato slice.

Cautionary handling note:

Wash your hands thoroughly with soap after handling the rotten slices of potato, and do not bring eatables near them. Once the experiment is completed, boil all the used potato slices in a beaker for 10 minutes, strain, and discard as wet waste. Students with a history of prior allergies should take extra precautions.

Record: At the end of 24 h, observe each plate and record your observations in the table below.

Plate	What we see	What we infer from our observations
CC		
AC		
20 mg		
50 mg		

Discuss:

1. Do you observe any difference in the number of colonies that appear around the wells in the slices containing 20 mg and 50 mg antibiotic? If yes, why do you think this happens?
2. How would you use this experiment to find a treatment for infectious bacteria?



Annals of History

ACTIVITY SHEET II: RETRACING THE BIRTH OF ANTIBIOTICS

Did you know that the first antibiotic was discovered by accident? The fungus (*Penicillium notatum*) that produces penicillin was discovered in 1928, but it was first used in humans only in 1941. Why did such an important discovery take so long to reach the common man? Let's retrace the discovery of penicillin, and understand how it became a life-saving antibiotic. This activity will help you uncover this story using your own thoughts and ideas!

This story is told in many parts, with questions at the end of each part. Try and answer all the questions at the end of one part before moving on to the next part. If you skip the questions at the end of each part, you will miss out on all the fun.

Now, for the first part of the story.

Today, a small cut or wound is not a very serious thing to happen to anyone. Some pain/discomfort can be easily managed, thanks to a range of antiseptic creams, lotions, and powders. But, did you know that before antibiotics became available, people would die of even minor cuts, burns, or injuries? This was because their wounds would get infected by bacteria, causing severe infections, toxic shock, or even death. The lifespan of an average Indian was 32 years, as many suffered fatal infections. Treating such patients was a challenge to hospitals, doctors, and scientists all over the world. In fact, even until about 90 years back, the treatment of wounds was a big challenge.

QUESTION

How would you define an antibiotic?

In ancient India, turmeric was used to treat wounds. However, turmeric is considered as an antiseptic or Ayurvedic drug, and not an antibiotic. How would you define an 'antibiotic'? Here's a clue – one type of microbes produces it against other types of microbes.

Interestingly, although antibiotics were not known to the ancient Egyptians, they would apply a mouldy piece of bread on infected wounds to help them heal better.



Ancient Egyptians would apply a mouldy piece of bread on infected wounds to help them heal.

THINK

What in a mouldy piece of bread could help in the healing of wounds?

In Fleming's shoes

We know that certain bacteria and fungi produce compounds that can kill other microbes. These chemicals help the bacteria and fungi survive in a competitive environment. This discovery was first made in the year 1928 by the scientist Sir Alexander Fleming.

Fleming was studying an infectious bacteria called *Staphylococcus* (let's call it *Staph*) at a hospital in London. *Staph* causes a wide range of infections – from pimples and sore throats to pneumonia and major infections of the urinary tract. Fleming would grow *Staph* cultures in Petri dishes in his lab. One day, Fleming accidentally left a Petri dish near a window. It so happened that he left for vacation the next day.



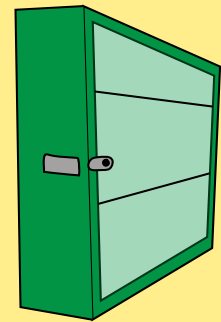
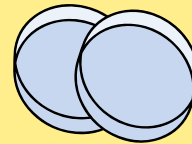
Alexander Fleming is credited for the discovery of antibiotics.

Do you know HOW bacteria are grown in laboratories?

Just like us, bacteria also require food. Scientists provide food in the form of a 'nutrient medium' to bacteria on plates called 'Petri dishes'. Each such dish has a lid which can be closed. Petri dishes with the nutrient medium are kept in a temperature-controlled closed chamber, called an incubator. The temperature in an incubator can be adjusted to best suit the particular bacteria or other microorganisms we intend to grow in them.

Bacteria can be grown in labs with:

Petri dishes.



An incubator.

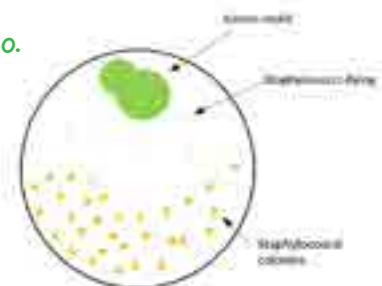
Upon returning from his vacation, Fleming noticed that a contaminating green mould (other than *Staph*) had grown on the plate by the window. Surprisingly, the *Staph* colonies closest to the mould were much smaller in size. Some appeared to be dying, as if the mould had released something in the area around itself!

Can you see a single bacterial cell with a naked eye?

Guess not, right? What if millions of bacterial cells clump together? Well, then you can see them with the naked eye! When a single bacterial cell divides into millions of cells in a pile, this mass becomes visible to the naked eye, and is called a 'colony'. The size of a bacterial colony can vary from that of a pin head to a small button.

THINK

- Q. Fleming was trying to grow bacteria on his plates. But, he ended up getting some mould too.
- How do you think the mould entered the plate?



Green mould on a plate containing Staphylococci.



- Is the mould a fungus or a bacterium?

- Why do you think bacteria were not able to grow near the mould?

Q. The contaminated plate had been left near a window. What if Fleming had remembered to keep the plate inside an incubator (at the optimum temperature for growing *Staph*)? What do you think is likely to have happened then? Would the fungus have grown more slowly (since mould grows on bread left at room temperature)?

Q. Imagine you were Fleming – what would you have done if you saw the plate with the strange unwanted mould?

The contaminated plate got Fleming thinking: why were bacteria unable to grow near the mould? He identified the mould to be *Penicillium notatum*, and wondered if the mould was releasing some antibacterial chemical into the plate. So, he grew the mould in a nutrient-rich liquid. The liquid also showed antibacterial activity. Fleming named the antibacterial chemical that the mould had released into the nutrient media 'penicillin'.

Fleming wondered if penicillin could be used to control bacterial infections in humans. There were two challenges. The antibacterial activity of the culture media in which the mould was grown was short-lived. And, to be useful for humans, the chemical with the antibacterial activity would need to be separated from the rest of the chemicals in the culture media. Over the next 10 years, Fleming tried several different ways to purify an active form of penicillin from the mould's culture media, but remained unsuccessful.



THINK

If you were in Fleming's shoes, how would you have addressed this problem?

The first human use of penicillin

Fleming addressed this problem by handing it over, in 1939, to Howard Florey and Ernst Chain, scientists at Oxford university. The two of them teamed up with another scientist – Norman Heatley. They used methods different from what Fleming had been using, and managed to get an 'active' form of penicillin that same year.

To check how effective this active form of penicillin was against infections, the three scientists infected some laboratory mice with a highly infectious bacterium, and gave only half of them penicillin.

THINK

Q. Why do you think the scientists gave penicillin to only half the infected mice?

Q. What do you think happened to the infected mice which:

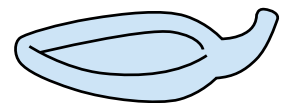
- Received penicillin?
- Did not receive penicillin?

Q. Why do you think the scientists tried the active form of penicillin on mice first?

Hint: Did they know if penicillin was safe for human consumption?

The infected mice that didn't receive penicillin died. Thankfully, the ones that received penicillin survived the infection. This confirmed that the active form of penicillin was not just active and harmless to mice, but also helped control bacterial infection.

The next task was to produce penicillin in sufficient quantities for human use. On the one hand, Florey went on to employ six women, famous as the 'Penicillin women', at £2 per week to 'farm penicillin' from the mould. On the other hand, Heatley used literally every food tin, bed pan, and bottle he could find to grow the mould. He even designed 500 stackable ceramic bedpans for this purpose. In spite of their best efforts, and cultivating the mould in hundreds of litres of culture media, the three scientists were only able to obtain a few milligrams of the active form of penicillin.



Heatley designed 500 stackable ceramic bedpans to grow Staph.

We started this story by describing how this was a time in history when even minor injuries caused death. One example of this came in 1941, when a man called Albert bruised his mouth with rose thorns. The bruises slowly developed into a life-threatening infection. Albert was given penicillin and

showed some signs of recovery. But, he died soon after because there wasn't enough penicillin to cure him completely. This shows how badly penicillin was needed at the time – even for minor wounds.

The wonder drug

Research in British universities was badly hit by the Second World War. Florey and Heatley moved to the U.S. to continue with their efforts on producing sufficient amounts of active penicillin. It was here that they made an unexpected discovery. An assistant brought along a fruit with a 'golden mould' growing on it. It turned out that this mould (*Penicillium chrysogenum*) was a close relative of *Penicillium notatum* (the green mould observed by Fleming). To their delight, Florey and Heatley discovered that the golden mould yielded 200 times more penicillin than Fleming's green mould!



THINK

Can you guess the name of the fruit with the golden mould?

(Hint: It is a summer fruit)

M _ _ K _ _ L _ N

Eventually, these scientists succeeded in producing active penicillin in large amounts. The antibiotic saved many hundreds of soldiers injured during the war from death by bacterial infection. This wonder drug has since become one of the most important discoveries of the millennium!



THINK

Q. In what ways do you think the war may have affected the process of discovery of penicillin?

Q. How do you think penicillin helped save millions of lives during the war? Does it help in the healing of wounds?

Q. Imagine that you are part of the committee deciding who should be awarded the Nobel Prize for the discovery of penicillin. You can only choose three people to award this prize to. Now that you have read the entire story, which people would you choose? Why?



Q. Connect the words here using arrows. Write an appropriate linking phrase above each arrow. You may choose linking phrases from these – ‘if left’, ‘may lead to’, ‘could result in’, ‘if treated with’. Or, you could choose any other phrase you find appropriate. The first one is done for you.

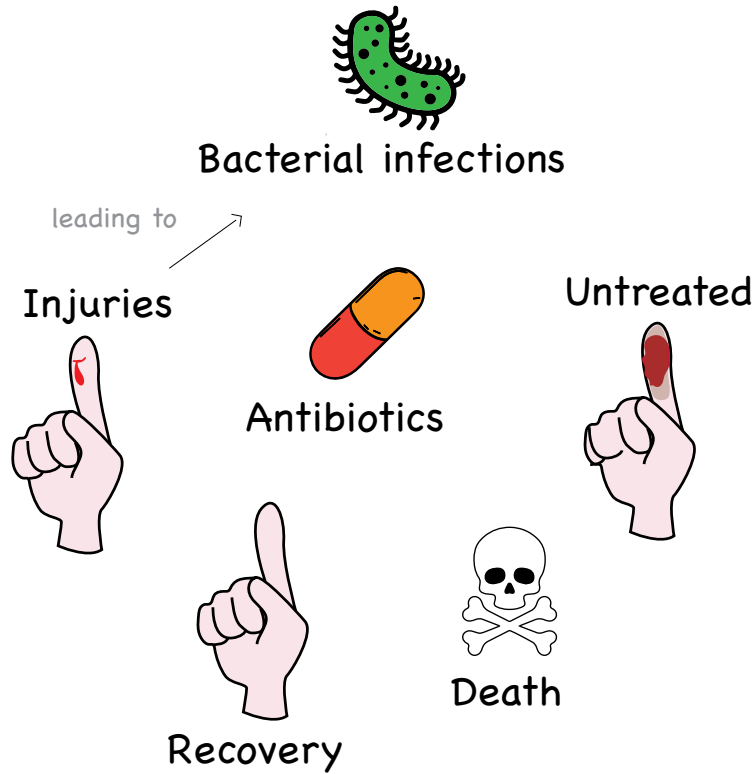


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Key takeaways



- Re-tracing Fleming's chance discovery of penicillin will offer students an appreciation for the importance of keen observation in science, and the role it plays in serendipitous discoveries.
- An understanding of the struggle to generate penicillin in amounts required for human use will help students appreciate that a chance observation is only the beginning of a complex (scientific) process that demands time, patience, and rigor.
- Recognizing the contributions of Howard Florey, Ernst Chain, Norman Heatley, and the 'Penicillin girls' in bringing penicillin from the bench to the bedside will help introduce students to the highly collaborative nature of modern science.
- Reflection on the role of war, and the unsung contributions of many people involved in the story of penicillin will offer students a better understanding of the political and human dimensions of science.
- By actually growing microorganisms in the presence of antibiotics, students will be able to appreciate Fleming's initial observation and learn a new way to query the world of microbes around them using simple kitchen equipment.

Acknowledgements:

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Notes:

1. This article is based on the learning unit 'The Accidental Discovery' from the Vigyan Pratibha project (<https://vigyanpratibha.in/index.php/the-accidental-discovery/>), currently undertaken by the Homi Bhabha Centre for Science Education, TIFR, Mumbai. Vigyan Pratibha is a central government initiative for students of grades VIII-X of Kendriya Vidyalayas, Jawahar Navodaya Vidyalayas, and Atomic Energy Central Schools. This science nurture programme aims to develop critical thinking skills among students of diverse backgrounds by engaging them in an activity-based approach to learning school science and mathematics.
2. Source for the image used in the background of the article title: https://commons.wikimedia.org/wiki/File:Three_tubes_of_penicillin_powder,_two_of_International_Stand_Wellcome_L0059014.jpg. Credits: Wellcome Images (<https://wellcomeimages.org/indexplus/image/L0059014.html>), a website operated by Wellcome Trust, Wikimedia Commons. License: CC-BY.

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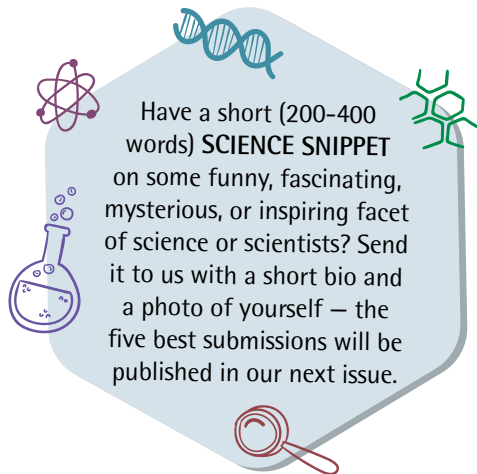
We invite submissions of proposals for our theme —
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Mona or Monu?

Author: Rohini Chintha



Mittu was still asleep when Mom sneaked into his room, placed his gift on the study table, and started singing "Happy birthday to you!" Mittu sat up in bed with a grin, and rubbed his eyes. "Thank you!" he muttered joyously. After a moment, Mittu's eyes opened wide. "Oh! A clownfish! How awesome. I love it. Thank you!"

He hopped off the bed, and hugged her. "Umm...Mom, I know your gifts are always unique - what is special about this clownfish?"

Mom smiled. "Well, this particular clownfish was found abandoned, and I volunteered to care for it. Also, did you know that clownfish groups are headed by a single large, dominant female..."

"Like you, mom?" Mittu winked.

Mom continued "And, clownfish are one of the few species that can change gender. Unique enough?"

"What?" Mittu looked stumped. "But how? Why? I mean...wow!"

"Let's discuss this over breakfast?" Mom suggested.

Mithu got ready in no time. "Tell me now", he pleaded gulping down his favourite hot dosas.



Mom plopped onto an empty chair beside Mittu. "Clownfish live in small schools, among the reefs, hidden away from predators. All the fish in a school are born with inactive sexual organs. Their only function is to compete with each other for food. The one that outcompetes the others, grows faster than them. When this fish reaches a certain size, specific hormones get activated in its body. These hormones lead to the development of male sex organs. And, quite rapidly, the fittest juvenile in the school transforms into a male."

"Does every juvenile turn into a male once it gets big enough?"

"Not really. Once one of them becomes a male, it dominates over the other juveniles in school – they are so stressed that they never grow that big."

"So, the fittest fish in a school becomes a male, and bullies the other fish into remaining juveniles?" Mittu repeated.

"The second fittest. Remember, each school is headed by a female?" said Mom. "She's the fittest, the largest, and the most aggressive. She's also the only female in the school. She uses her much larger size to keep the male in check, and prevent him from growing to her size."

"How?"

"Much like the male keeps the juveniles in check. She controls which parts of the reef the male can visit, and how much he eats. If the male survives her bullying, and can bond with the female, the two stay paired for a lifetime. But the female is always in charge." Mom explained.

"Really?"





Gender neutral clown fish

Fittest juvenile turning male...



Female in-charge



...and caretaker!

Replacing the female in-charge



"Yes. In fact, you can see the male following the female around. But that's not all - after the male fertilizes the eggs that the female lays, he takes care of them till they hatch into the next generation of clownfish."

"Wow!" Mittu exclaimed.

"When the dominant female dies, the male clownfish changes into a female, and takes charge of the school."

"What?" Mittu exclaimed.

"Meanwhile, the largest juvenile transforms into the next male." Mom continued. "This helps ensure that the clownfish can continue reproducing, without leaving the safety of their little reef."

"Can a female change back into a male?"

"No. Once a female, always a female. And since this change in gender happens in sequence - immature to male to female, clownfish are called sequential hermaphrodites."

"How do they do that, Mom?"

"The DNA of every clown fish carries genes for both female and male hormones. While the female fish is around, the male fish expresses only male hormones. But once the female fish dies, the male fish can feed without bullying. Once he reaches a certain size, he stops expressing male hormones, and begins expressing female hormones instead."



These hormones lead to the development of female sex organs, and the male transforms into a female."

Mittu thought for a while "So, clownfish do this to protect themselves from being eaten up by bigger fish? Have other fish also evolved in this way?"

"I know of Wrasses and Guppies."

"What about earthworms?"

"Earthworms are a little different. Each earthworm has both male and female reproductive parts. That's why earthworms are called simultaneous hermaphrodites".

"So, earthworms are both male and female at the same time." Mittu pondered. "Are bacteria also like that, Mom?"

"Bacteria are asexual." Mom replied.

"Please, Mom, can you explain that clearly?"

"Okay. All living things reproduce – this is what ensures the survival of their species, yes? Bacteria, plants, animals, humans..."

Mittu nodded "Fishes too.."

"At first, there were no males or females. No boy or girl plants or animals. Just living beings. Like bacteria".

"Okay."

Earthworms



Guppies



Wrasses





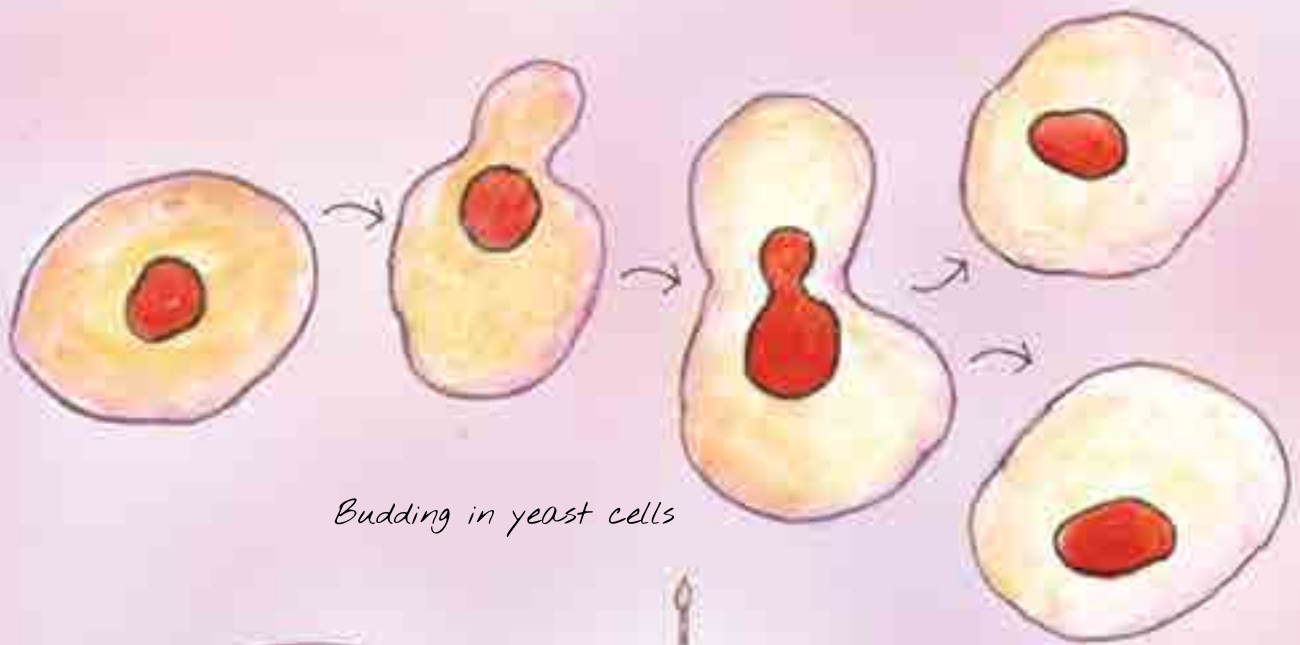
"This bacterium produced daughters asexually. This means that one parent cell divided into two daughter cells. In other words, it just copied itself". Mom took Mittu's pink clay dough, and divided it into two balls of equal size. "Like this. Copies. But first the bacterium needs to grow large enough to divide. So, the daughters in every generation are the same size as the parent, not smaller." Mom demonstrated.

"Got it!" Mittu beamed. "Each of these balls can also divide into two?"

"Excellent!" Mom smiled. "Now, can you see any differences between these four daughters?"

Mittu examined the dough balls carefully. "Yes, Mom. Some of them have more cracks than others. This one is smaller. And that one looks softer."

Mom nodded. "The environment in which bacteria grow is always changing. So, even when a bacterium makes copies of itself, each of its copies is slightly different from the others. Each time a daughter cell divides, it produces cells with more differences. These differences are caused by heritable changes called mutations. Ultimately, mutations result in the evolution of different strains of bacteria. The DNA of each strain is at least slightly different from that of other strains. This is how newer life forms evolved. Clear?"



Budding in yeast cells



"Some of these bacteria happened to mix their DNA. Not consciously though. This intermixing or recombination of genetic material allowed more differences. The more the difference in a population of bacteria, the greater the chance that at least some of the bacteria from that strain survived changing environments. In other words, in each generation, the environment would select for the bacteria with the intermixed DNA to become more in number. This process is called natural selection."

"What kind of intermixed DNA helps bacteria?"

"Many kinds. For example, say a bacterium that grows at very high temperatures mixes its DNA with another bacterium that can resist antibiotics, and produces a daughter with both these traits. See, double advantage because of intermixing? But, sometimes, intermixing also kills bacteria."

"Do other organisms mix their DNA too, Mom?"

"Yes. All eukaryotes do. Like, yeast. It also produces copies of itself by an asexual process called budding. But, unlike bacterial DNA, yeast DNA is coiled inside the nucleus into rod shaped structures called chromosomes."

"So, bacteria intermixes its one strand of DNA, and yeast intermixes a whole bunch of chromosomes?" Mittu interrupted.

"Correct. It is likely that variations in yeast DNA gave rise to two different mating types (strains) called A and alpha. An A strain of yeast can mix only with a cell from the alpha strain, not with another yeast from the A strain." Mom remarked.

"So A and alpha are like male and female?"

"Somewhat similar..." Mom continued.

"So, first there were asexual bacteria. Then there were A and alpha strains of yeast." Mittu added.

"Good!" Mom patted him.

"Then?" Mittu enquired.

"Then, multicellular organisms evolved. And every function in a multicellular organism is carried out by specialized cells or organs.

Sperm & egg

Peacock & peahen



So multicellular organisms had separate reproductive organs and separate reproductive cells to produce offspring."

"What about us?"

"In humans, one type of reproductive cell is large, round, and called the egg. The other type of reproductive cell is small, oval, has a tail, and is called the sperm. We call the organism producing eggs – female. And the organism producing sperms – male. When an egg and sperm fuse, a zygote is formed. In humans, this zygote is the first cell of a baby. This cell divides into the other cells in a baby's body."

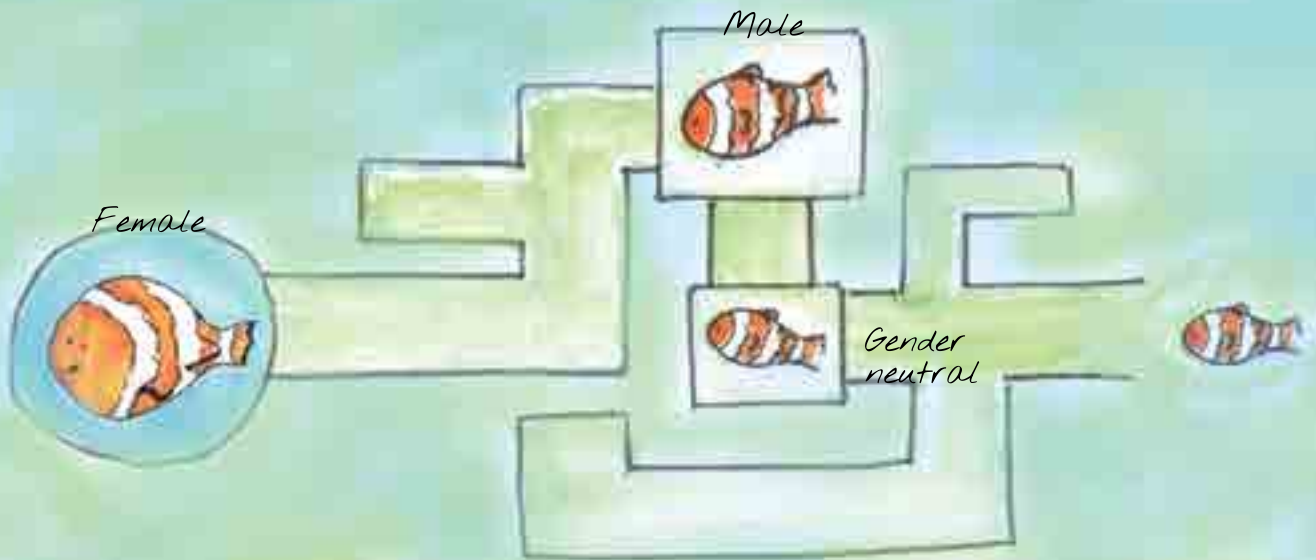
Mittu was thoughtful. "So, are peacocks and lions like us?"

"Yes. Humans, peacocks, and lions all are unisexual organisms. In all three, the males look different from the females. The difference in appearance of males and females of a species is called sexual dimorphism."

Mittu dropped two grains of fish food in the tank. "But you said that when my pet was born, it wasn't male or female?"

Lion & Lioness





"Yes. It could turn into a male and a female." Mom explained. "But, remember, that at any given time in its life, a clownfish can only be one of the three – gender neutral, male, or female. Never all three at the same time."

"Did hermaphrodites evolve after unisexual organisms?"

"Most probably. Different sexes is a more advanced way of mixing traits than the kind of intermixing of DNA seen in bacteria. More intermixing meant more variation in their traits. More variation means a higher chance that at least some organisms of this species will survive and reproduce in new environmental conditions. But, if clownfish remained unisexual, it is likely that they would have to move around more in search of a mate. This would increase their risk of being eaten up by bigger fish. So, clownfish that remained in their corner of the reef would have a better chance of surviving and reproducing. But, if at some point, all the surviving clownfish in a school were male, no new fish would be produced."

"What if all the fish were female?" Mittu asked.

"Again, no new fish. But if some changes in the fish's DNA made it a hermaphrodite, the school would have a higher chance of producing new fish without leaving the safety of their reef homes. In such species, hermaphrodites are more likely to survive and produce offspring, right?"

"Seems so." Mittu was lost in thought.

"So, it would seem that asexual bacteria were the first to evolve. Then, A and alpha of yeast, followed by unisexuals. And, hermaphrodites were the last to evolve."

"One last question, mom. Have you planned any activities after the party?"

"Umm...not yet..."

"Then don't. I have a plan for a game that lasts all evening." Mittu said, pointing to his clownfish "Name it - Monu or Mona? Like it?"

Mom laughed. "I love it!"



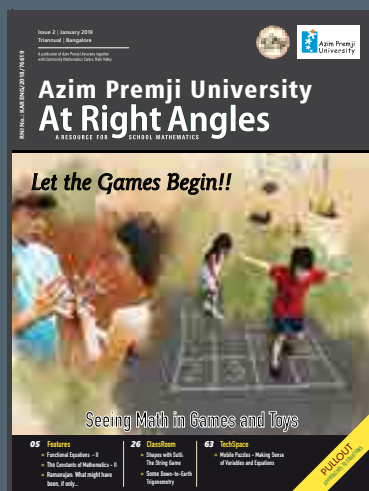
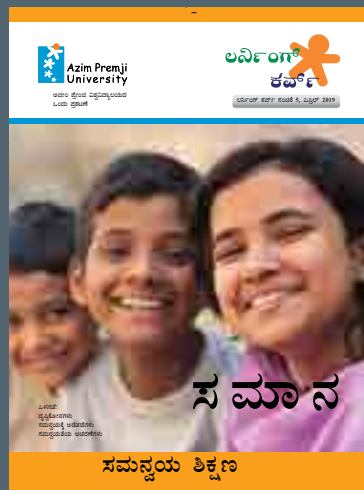
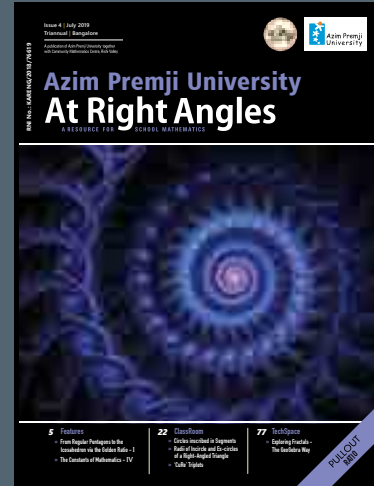
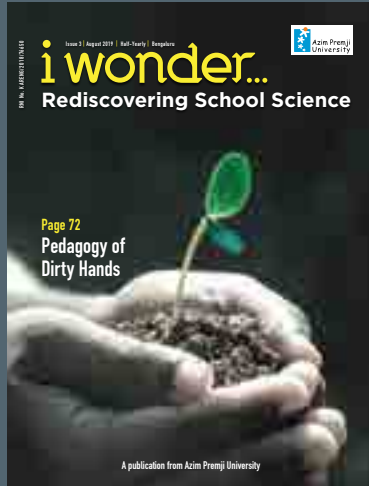


About the Author

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

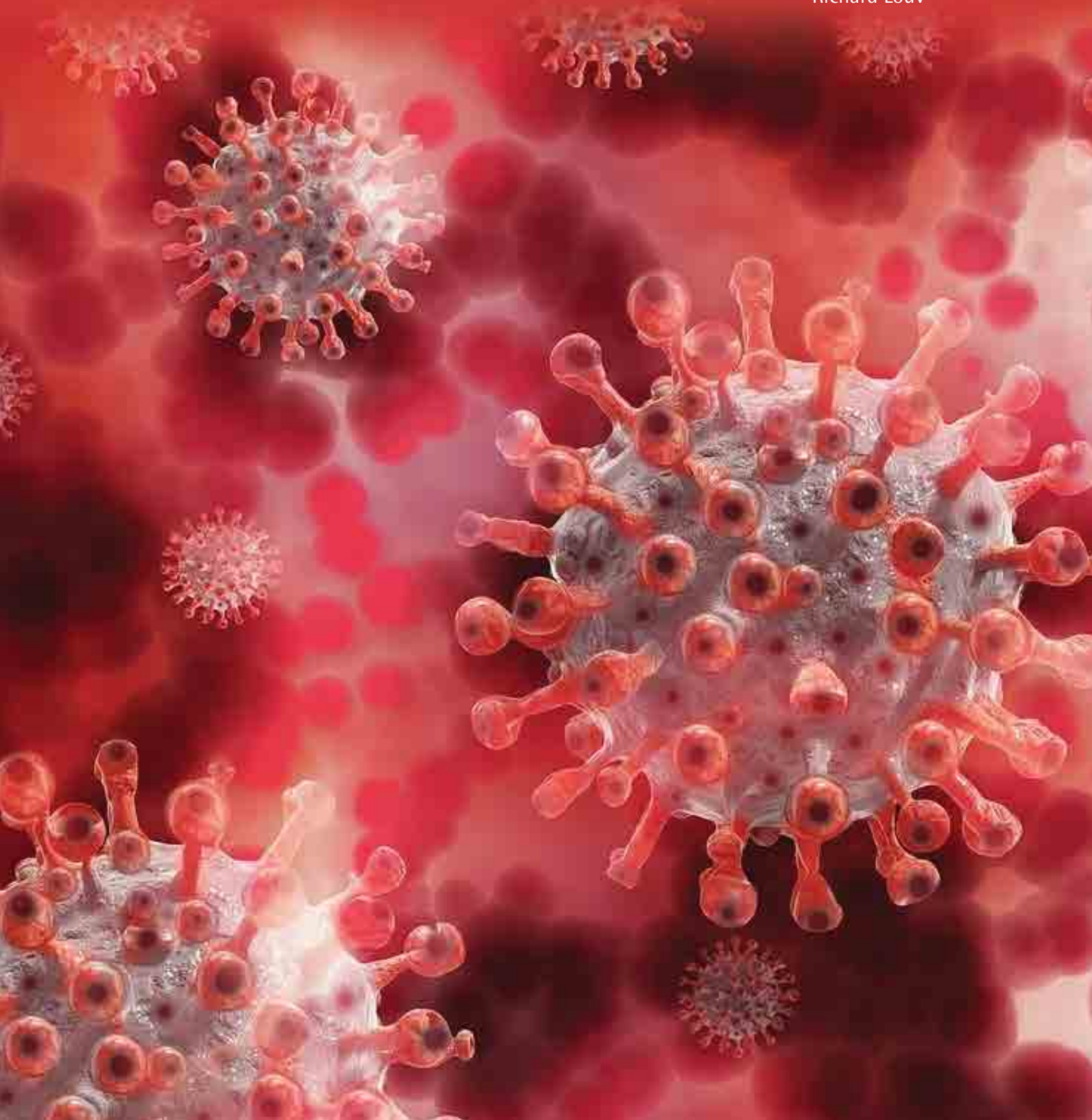
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"Science is founded on uncertainty. Each time we learn something new and surprising, the astonishment comes with the realization that we were wrong before."

— Richard Louv



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