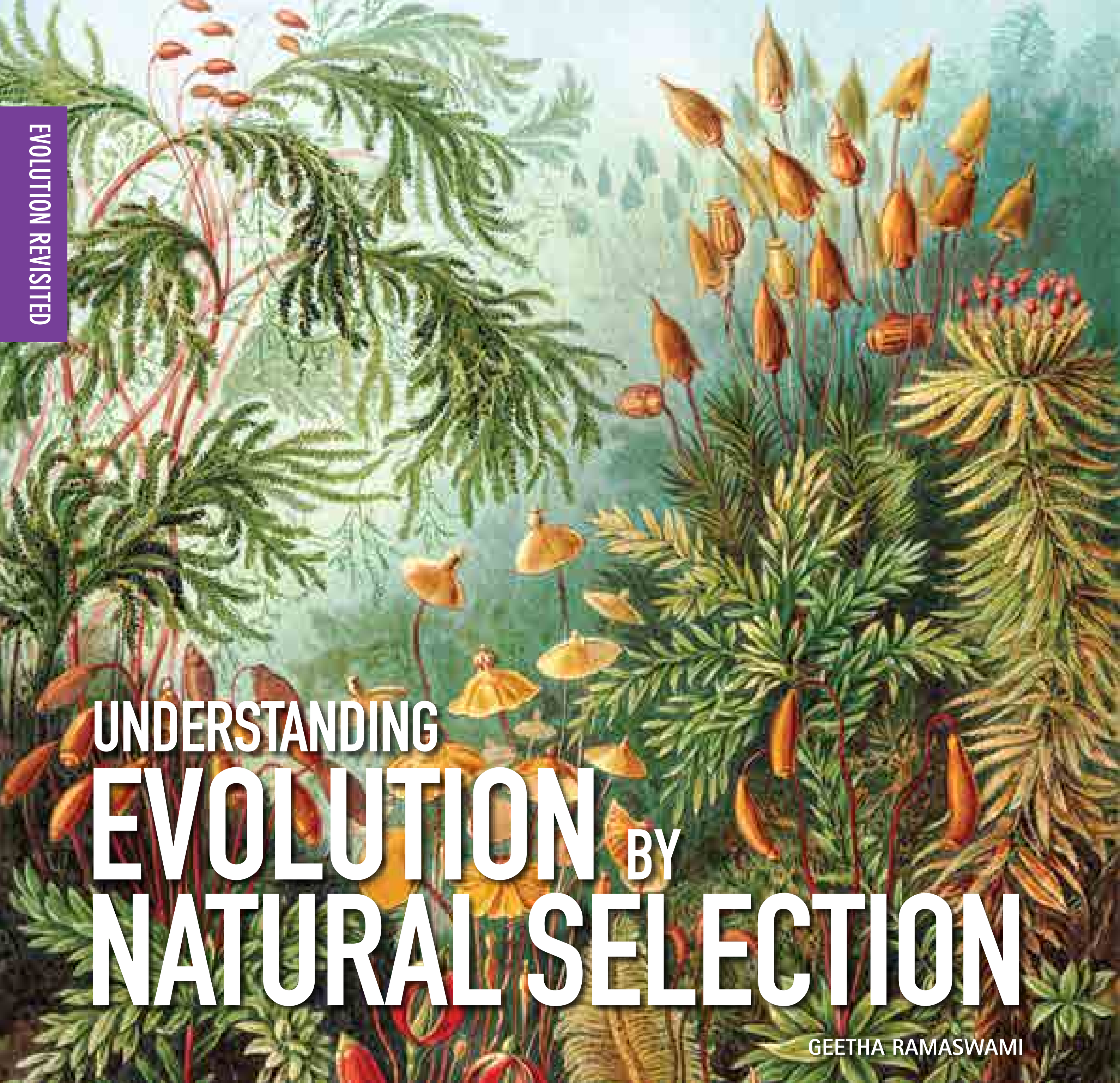

UNDERSTANDING EVOLUTION BY NATURAL SELECTION

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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**).

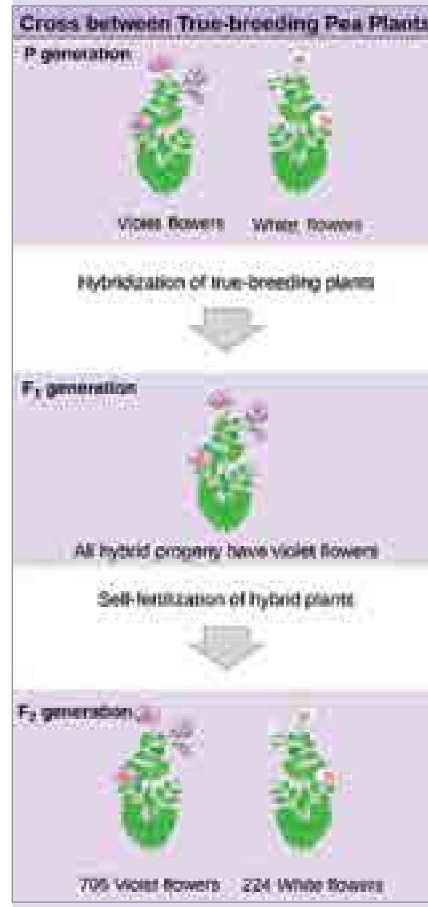

Fig. 1. The results of Mendel's breeding experiments with pea plants could only be explained by the heritability of its traits.

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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,

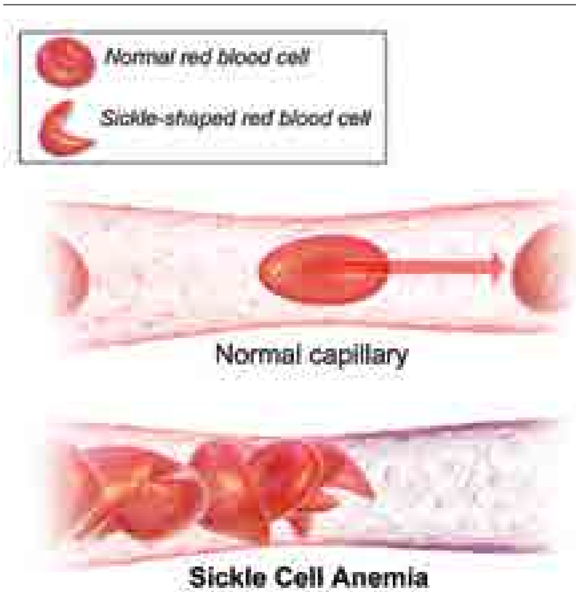

Fig. 2. A pictorial representation of sickle-shaped and normal RBC's.

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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.

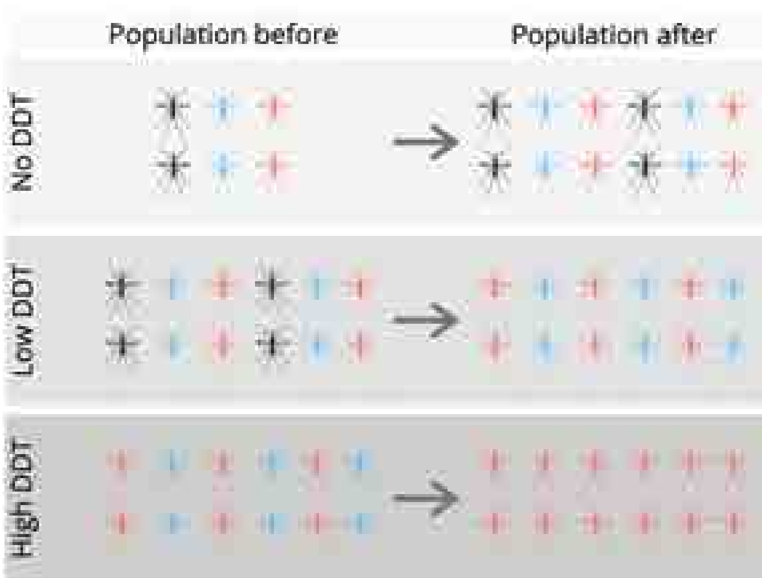

Fig. 3. The effect of varying concentrations of DDT on mosquito populations showing variability in the trait for DDT resistance. The black mosquitoes in the image represent individuals with no resistance to DDT. The blue ones represent individuals with low resistance, and the red ones represent individuals 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.

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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

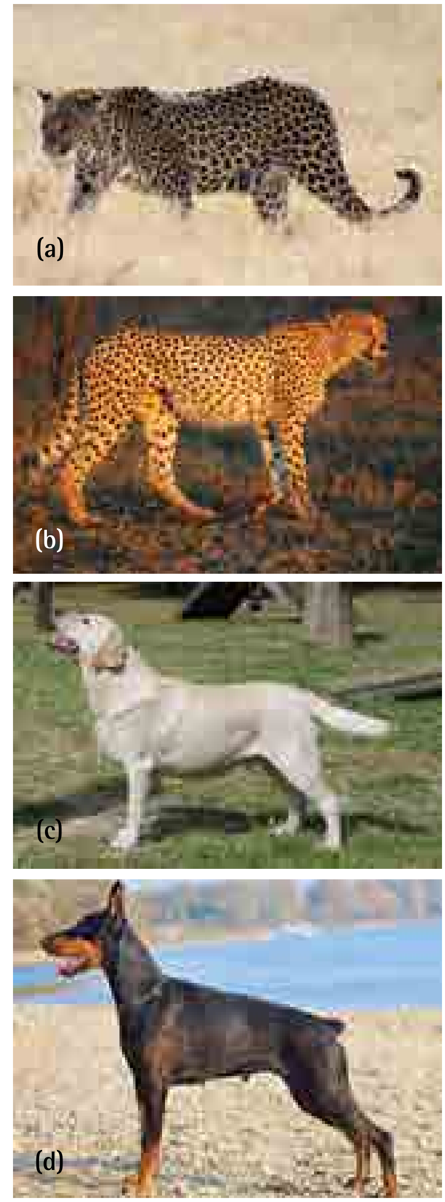

Fig. 4. Understanding the 'biological species' concept: A leopard (a) and cheetah (b) look similar, but cannot interbreed to produce viable offspring. They are, therefore, considered to be different species. A Labrador retriever (c) and Doberman pinscher (d) look very different, but can interbreed to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

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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 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?

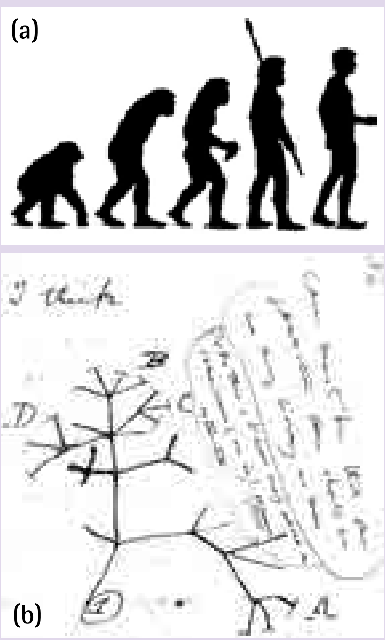

Fig. 5. Depicting evolution. (a) Incorrect depiction of human evolution as a linear progression from ape to man. (b) Darwin's depiction of organisms related by ancestry in the form of a tree.

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.

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**).

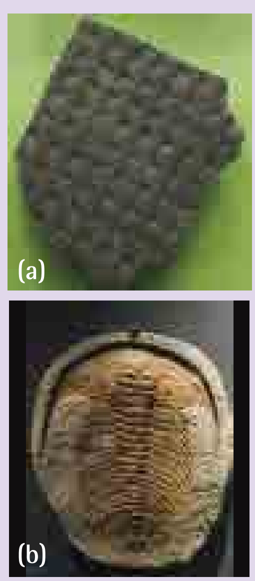

Fig. 6. Other examples of a successful species going extinct. (a) A fossil of leaf scales on the trunk of a plant from the genus *Lepidodendron* — a dominant life form in the Carboniferous era, more than 300 million years ago. Members of this genus did not produce woody tissue like present day trees, 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.

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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.

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.

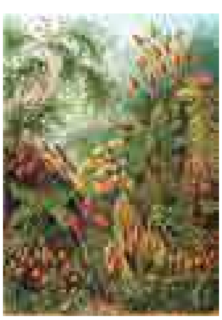
years), they would lose the ability to interbreed altogether and form two different species (see **Box 9**). This process, where a natural barrier causes the genetic isolation that gives rise to a new species, is known as **allopatric speciation.**

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.

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