

EVOLUTIONARY SCIENCE FOR A CHANGING WORLD

Review and insights for
Australian evolutionary science

ACKNOWLEDGEMENT OF COUNTRY

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Cover: Countless lakes, sloughs, and ponds are scattered throughout this scene of the Yukon Delta in southwest Alaska. One of the largest river deltas in the world, and protected as part of the Yukon Delta National Wildlife Refuge, the river's sinuous waterways seem like blood vessels branching out to enclose an organ.

Credit: NASA/USGS/Landsat.

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PREFACE

Charles Darwin's theory of evolution by natural selection is foundational to modern biology. The principle underpinning this theory is elegant in its simplicity: things that reproduce more successfully will come to predominate in subsequent generations. Such a principle has widespread application beyond biology to broader society, such as through the development of language and the transmission of new ideas ('memes') in popular culture. The digital world and social media are greatly amplifying the rate of cultural evolution.

This paper, led by the National Committee for Ecology, Evolution and Conservation, explains how evolutionary science can help society tackle some of its most pressing challenges. It also calls for more cross-disciplinary collaboration for the development and application of evolutionary theory and identifies mathematical modelling as a key tool for bridging disciplinary divides.

This discussion paper arose through frustration with the perception that evolutionary science is narrow in scope and fails to communicate its benefits and potential. As the paper sets out, evolutionary science cuts across biology, linguistics, economics, engineering and more, and it has the potential to enrich our understanding of how systems respond to change. The narrowing of scope to domains of biology undermines this potential.

To take this concept further, the Australian Academy of Science convened a trans-disciplinary group of mid-career researchers who apply evolutionary science in their research. The working group produced this forward-looking synopsis to promote further discussion and encourage interactions between evolutionary science researchers and educators.

Evolutionary science is itself a dynamic and evolving field, and this paper addresses some contentious issues. One of these is the role of multilayered selection, where higher levels of organisation such as social groups may possibly function as adaptive units. This concept suggests that altruistic groups can outcompete selfish groups and thus promulgate altruistic behaviour.

Mainstream evolutionary theory states that selection can only operate at the individual level, with altruistic behaviour evolving because this benefits individuals through reciprocation ('reciprocal altruism'). By contrast, evolutionary science researchers point to the potential for hierarchical layers of selection with strong feedback among them and to the changing environment itself.

Such processes have parallels with the evolution of social attitudes relating to cultural diversity. Traditional society is often highly 'tribal', viewing cultural differences with suspicion and intolerance. In modern society, where different cultures live together, this results in considerable social tension. However, with increasing socialisation, people are becoming not just tolerant of diversity but are actively embracing it, leading to more harmonious and more highly functioning communities. This includes a higher quality of science produced by culturally diverse and gender-diverse teams.

The Australian Academy of Science is committed to leadership in diversity, equity and inclusion in science, and empowering the next generation of scientists. Recognising the challenges faced by Australia's emerging researchers, the Academy undertakes programs to support and promote the voice of Australia's next generation of scientists. In 2011, the Academy established the EMCR Forum for early- and mid-career researchers to provide a vital connection between Australia's most eminent scientists and tomorrow's future science leaders.

Under the direction of the National Committee for Ecology, Evolution and Conservation, *Evolutionary science for a changing world* is another example of how the Academy serves as a platform for the next generation of scientists to bring fresh ideas to Australian science.

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**NATIONAL COMMITTEE FOR ECOLOGY,
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SUMMARY

Evolutionary science is the study of change. It underpins our ability to understand how living and non-living systems adapt and innovate. In this paper, directed at non-specialists, we show how evolutionary science remains relevant today. Its power lies in the simplicity of the basic evolutionary principle: the selection of variants over successive trials creates change in populations of organisms, technologies, languages and economies.

We further emphasise how understanding, predicting and managing evolution requires going beyond this basic principle. It requires us to consider the **evolvability** of populations, taking into account the many sources of variation and pathways of **inheritance** that can operate alongside random change.

We use four case studies to show that the benefits of evolutionary science extend well beyond the traditional domain of biological systems and far beyond the academic sciences.

The coral case study exemplifies the potential to engineer evolution. Reef biodiversity worldwide is rapidly declining, and climate change threatens to outpace the rate at which these ecosystems can adapt to warming oceans. Evolutionary scientists have shown that reef-building corals have many pathways to thermal resilience. They are now focused on time-buying interventions to slow extinction by manipulating these adaptive processes.

The COVID-19 case study is a prominent example from a long history of evolutionary science contributions to public health. Evolutionary scientists predicted the potential for a virus to jump from another species to our own. They identified the nature of the virus as it emerged and then evolved in humans.

Case studies of language and cultural evolution demonstrate how the concepts and tools of evolutionary science can be applied across disparate domains. The parallels between the evolution of genetic elements within genomes and linguistic elements within languages are being used to understand Indigenous language loss in northern Australia.

Similar approaches to understanding change in online social networks using hashtags have yielded new insights into phenomena such as political polarisation and vaccine hesitancy, which can inform effective public policy.

These case studies highlight the inherent cross-disciplinarity of evolutionary science. They show that evolving systems are best understood by bringing together classic evolutionary theory and experimental evolution with mathematics, philosophy and data science.

Australia has strengths in all these areas, yet this expertise has remained largely disconnected. We identify broad opportunities for connecting and growing Australia's evolutionary science capabilities in the immediate future.

The first is to build a cohesive, cross-disciplinary community of evolutionary scientists in Australia and our region. We can tackle the most complex challenges we face by taking advantage of the diversity of training, knowledge and expertise across different specialisations, including policymakers and industry. Success will depend on our ability to rethink how we collaborate across disciplinary and institutional divisions and to deliver opportunities for educational curricula and research training.

The second is to support evolutionary science endeavours with fit-for-purpose funding systems and greater connection with policymakers and industry. As a community, evolutionary scientists and their transformative contributions must be uplifted by a strong base of fundamental research. Evolutionary science must be empowered to deliver its diverse benefits to Australia.

Ultimately, we hope this paper stimulates dialogue between scientists and educators with a common interest in understanding evolving systems in a rapidly changing world.

GLOSSARY

assisted evolution	Active interventions to alter the outcomes or rate of natural evolutionary processes to enhance adaptation to environmental change.
big data	Very large datasets, often generated by technologies such as massively parallel genome sequencing platforms in biology. Big data poses challenges to processing software but can be used to tackle complex and previously intractable problems.
cultural inheritance	The transmission of culturally relevant information – such as language in humans and tool building in chimpanzees – by teaching, imitation, learning, and sharing of attitudes. In biology, this is an important source of non-genetic inheritance.
drift	A random change in the frequency of variants in a population over time, due to chance events rather than natural selection. In biology, chance events like natural disasters can mean that unexpected phenotypes actually come to dominate populations. For example, a flood might wipe out half of a population and the ‘fittest’ individuals might just happen to be among those lost by chance. Evolutionary scientists are interested in drift because it is particularly likely to impact smaller (e.g. endangered biological) populations.
ecological inheritance	The transmission of acquired resources and conditions – such as bird nesting sites and termite mounds – through niche construction. Inheritance of material wealth is a uniquely human form of ecological inheritance.
evolvability	Features of agents which make their populations more or less capable of change over time (i.e. more evolvable or less evolvable). Evolutionary scientists are interested in these internal features as they (alongside selection) help us to understand past evolution and the potential for systems to evolve under future environmental and social change.
experimental evolution	The investigation of evolutionary changes in organisms over multiple generations in controlled laboratory or field conditions.
fitness	Rate of self-replication of agents in the environment. In biology, this is survival and lifetime reproduction of organisms or systems. Those organisms that are best suited to their environments (the ‘fittest’) are more likely to survive and reproduce. Differential fitness is one of the three necessary conditions for evolution by natural selection.
genetic assimilation	A process in which a phenotype that initially arises as a response to an environmental cue (see plasticity) becomes genetically encoded by natural selection.
genetic drift	A type of drift in biology that results in changes in allele frequency due to random chance in the survival and reproduction of organisms in a population.
inheritance	The mechanisms via which current characteristics of agents depend on the characteristics of past populations. In biology, these are the mechanisms through which offspring come to resemble their parents, such as through the transfer of genetic material from parents to offspring (as well as other sources of inheritance – see non-genetic inheritance). Inheritance is one of the three necessary conditions for evolution by natural selection.
modularity	The organisation of an agent’s features into relatively independent units. Often applies to the genome or developmental systems. Modularity facilitates change to one feature without affecting the viability of other features.
multi-level selection	Evolution at multiple levels of organisation at the same time. For example, in the coral case study, evolutionary processes act on each of the symbiotic partners (the coral animal, microalgae, and bacteria) and the system as a whole (the holobiont).

neutral theory	Describes how neutral variation (that is, phenotypic variation that does not impact the survival and reproduction of organisms) changes in a population. Most genetic variation does not result in phenotypic variation. Allows study of the mutation rate and population structure without the influence of natural selection.
niche construction	The process by which an agent alters its own (or another agent's) local environment in such a way that it alters selection pressures over multiple generations.
non-genetic inheritance	In biology, evolution by natural selection simply requires that organisms resemble their parents. But there are many factors, aside from genetic inheritance, that can contribute to this in biological systems, such as cultural, epigenetic and environmental inheritance. In recent decades, evolutionary scientists have come to understand that these non-genetic forms of inheritance are perhaps more prevalent and important than first thought, generating whole new streams of research.
phenotype	The observable features of agents. For biological organisms these include their size, metabolic rate, behaviour, and so on. Can also refer to the features of cultural artefacts or elements, such as the phrase structure rules of a language.
phenotypic plasticity	The ability of organisms with the same genomes to produce different phenotypes under different environmental conditions. There are many possible mechanisms behind plasticity; the simplest is due to the inherent sensitivity of developmental and physiological processes to environmental variables such as temperature and oxygen availability.
phenotypic variation	Variation in the observable characteristics of agents. Variation is one of the three necessary conditions for evolution by natural selection.
phylogenetic contingency	The influence of a population's evolutionary history on its present-day traits and the range of possible adaptive pathways available for future evolution.
recombination	The exchange of DNA between chromosomes or between regions of the same chromosome; this 'genetic shuffling' results in offspring with new combinations of traits.
redundancy	When more than one feature in an agent performs the same function, so that loss of one feature does not affect the function. In biology, the loss of one of several copies of a single gene with minimal change to the phenotype is a form of genetic redundancy.
robustness	The property that allows a system or characteristic to remain viable under internal (e.g. genetic) or external (e.g. environmental) change.

Words in this glossary appear **bolded** throughout the report.

1. WHAT IS EVOLUTIONARY SCIENCE? A CONTEMPORARY PERSPECTIVE

KEY POINTS

- Evolutionary science provides the tools for understanding change in dynamic systems that are at the core of humanity's most pressing challenges. Biodiversity, pathogens and technologies all evolve via selection of variants over successive trials.
- The broad explanatory power of evolutionary science stems from Darwin's elegant theory of evolution by selection. Its application across the sciences highlights the many forms of variation, **inheritance** and selection that can shape change in disparate systems.
- Processes and phenomena beyond natural selection play a role in evolution, including reciprocal causation, **phenotypic plasticity**, **non-genetic inheritance**, group selection, and biases in variation.
- **Evolvability** – the capacity to change adaptively – unites studies of contemporary change in living and non-living systems and shifts the focus of evolutionary science from explanation to prediction.

1.1. DARWIN'S BIG IDEA AND BEYOND

The importance of Charles Darwin's contribution to evolutionary science cannot be underestimated. His leap of imagination lay in the realisation that when the individual organisms within a population vary in their success, and success is heritable, the population will become increasingly suited to its environment over time (see Box 1 for more detailed explanation).¹ This simple evolutionary algorithm has the power to generate the astonishing diversity and richness of life on our planet. Although evolutionary science has come a long way since Darwin's *On the origin of species*, his big idea still sits at its core more than 150 years later.

Central to Darwin's big idea is population-level thinking:² the understanding that although selection acts on individual variation, evolutionary change occurs at the population, rather than individual, level. However, plants and animals are not the only entities that form populations. All sorts of living and non-living things – languages, ideas, viruses, cells – form groups whose change over time can be understood through the prism of Darwinian population-level thinking. This sort of thinking leads to answers for questions such as:

- how our social behaviours (a population of ideas and actions) collectively shape our cultures and values
- how our immune system (a population of cells) responds to viruses with the aid of vaccines
- how organisations (a population of agents) interact to cause rise and fall in our economy.

The sophistication of contemporary evolutionary science reflects this broad applicability of population-level thinking. It informs a wide array of problems across biology, linguistics, epidemiology, engineering, computing, and economics. Although Darwin's revolutionary idea remains at the core, successive advances in explanatory and predictive power have built on his legacy (see section 1.2).

With these advances, evolutionary science has the potential to answer big questions right at the heart of humanity – such as our kinship with all other life on Earth – and to provide solutions to the problems we face as a society. For example, evolutionary scientists can infer the mutation history of pathogens and trace when and where pandemic disease outbreaks originated using genome analyses. More broadly, practitioners of personalised medicine use knowledge of how natural selection has influenced human genetic variation to guide risk assessments of various diseases and tailor treatments to individual patients.

The power and reach of evolutionary science also generate moral and ethical conundrums that humanity urgently needs to address. Gene editing technologies utilise the knowledge and tools of evolutionary science and make it possible for us to engineer novel genes that can cheat the usual rules of **inheritance**. Similarly, computing infrastructure and algorithms underpin the asynchronous evolution of large-scale collective behaviour, such as social media recommender systems, with surprising and unintended effects on our

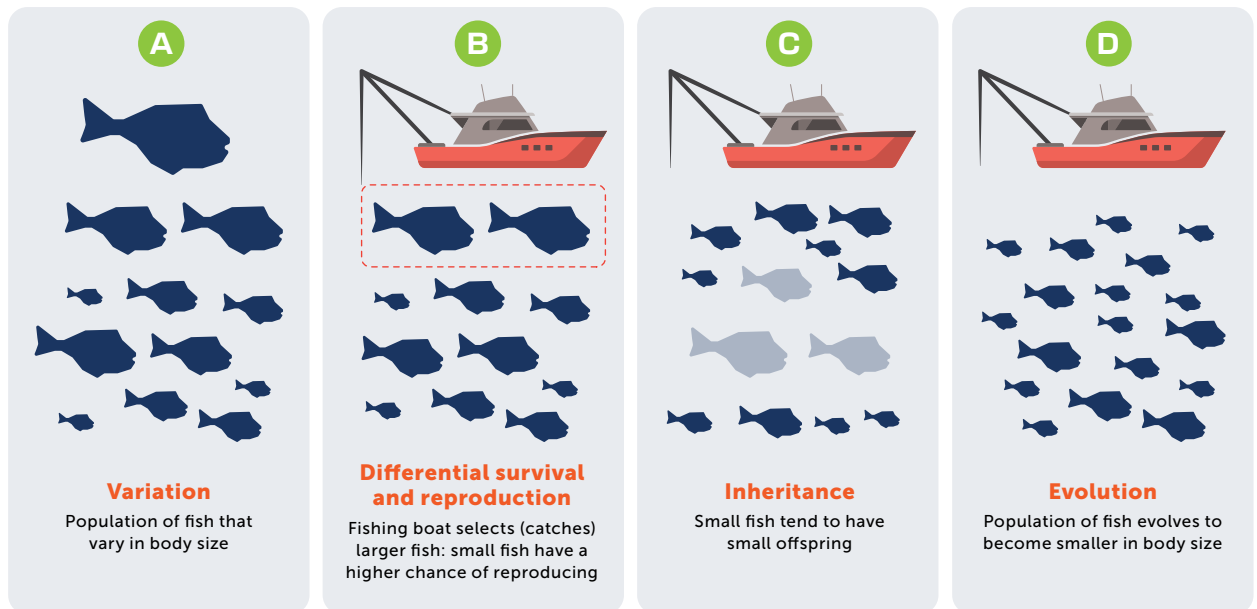
1. Alfred Russel Wallace independently conceived the same idea, and his correspondence with Darwin prompted the idea to be aired among the broader scientific community.

2. This aspect of Darwin's work was partly inspired by the earlier work of social economist Thomas Malthus. Malthus' views on human overpopulation led Darwin to the insight that many more individuals are produced in a population than contribute to the next generation.

modern life. With this new ground, there is much promise and a great need for government and public policymakers to understand the limits and risks of predicting and controlling evolution.

This document provides a contemporary overview of evolutionary science. In it, we offer four examples that demonstrate the exceptional power of evolutionary thinking in facing some central challenges of our time: climate change, novel pathogens, loss of cultural diversity, and online life. Evolutionary science straddles all fields of science. In doing so, it offers insights which are not limited to the past or the natural world but are deeply significant to our everyday lives.

Figure 1: Fisheries-induced selection.



BOX 1: EVOLUTION, A PROCESS OF CHANGE

Charles Darwin was the progenitor of a simple but astonishingly powerful theory for explaining how organisms evolved into the complex forms we observe today. His central insight, the process of evolution by natural selection, requires three simple ingredients. These are:

- variation among individuals within populations (Figure 1A)
- some form of selection that results in the differential survival and reproductive success of these variants (Figure 1B)
- the capacity for this variation to be inherited across generations (Figure 1C).

Over time, variants that survive and reproduce more frequently become more prevalent within the population because they contribute more offspring to subsequent generations. As a result, populations evolve (Figure 1D).

At the time Darwin conceived of the theory of natural selection, he knew little about the factors that contribute to the similarities between parents and offspring, nor how such factors could be transmitted across generations. It was not until the rediscovery of Mendel's work on **inheritance**, and the later discovery of DNA,

that genes became recognised as the biological route by which parents can pass on their similarities to their offspring.

As such, evolutionary biologists are often interested in the genetic variation that underlies **phenotypic variation** (for example, the genes contributing to body size), because genes are transmitted with a high degree of accuracy across generations. Understanding how genetic variation arises, is passed on, and interacts with the rest of the genome and the environment to form a **phenotype** is, therefore, of great interest when speaking about biological evolution.

Random mutation and **recombination** give rise to new genetic variants that can result in changes to the **phenotype**, providing new variation that selection can act upon. As selection operates on the **phenotype**, the underlying gene variants change in their frequency, leading to changes in the mean **phenotype** (e.g. body size) over time (Figure 1); an adaptive response to selection. Evolutionary biologists conduct experiments and sequence genes to understand how specific changes have helped contribute to adaptation to challenging environments in the recent and distant past.

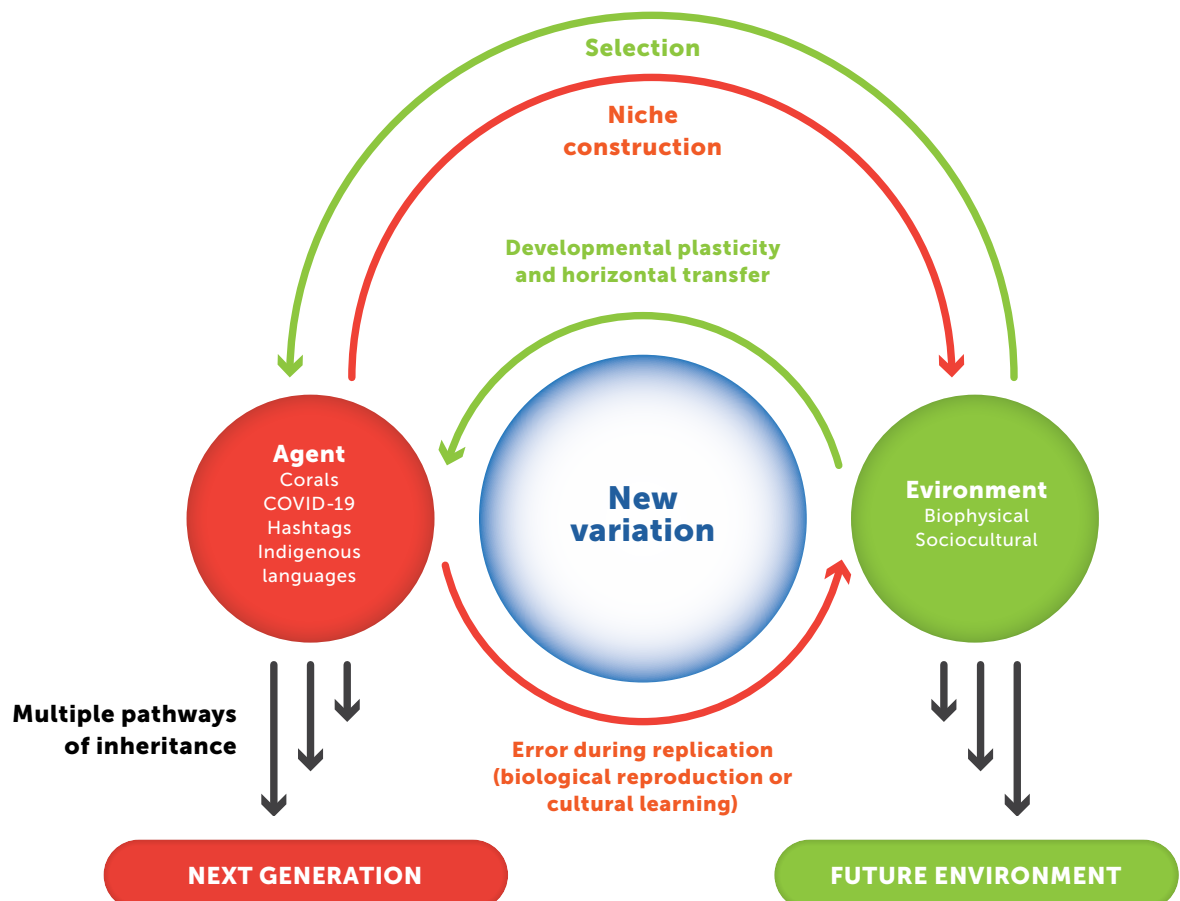
1.2. THE EXTENDED VIEW OF EVOLUTION: NEW OPPORTUNITIES FOR MANAGING CHANGE

Darwin drew from all fields of science to develop his theory of evolution. From the outset, he recognised its broad applicability to explain change in disparate systems, including human languages and the famous Galápagos finches. Yet when Darwin wrote *On the origin of species*, genes had not been discovered, microscopy was still in its infancy, our understanding of development was rudimentary, and supercomputers had yet to be imagined. Little wonder then that evolutionary science today looks very different to how Darwin originally conceived it.

Our understanding of evolution has grown and matured as we have developed new ways of investigating the world. We now recognise that the three ingredients of evolution – variation, **inheritance** and selection – can take many forms, and these together contribute to the capacity to change adaptively through time (**evolvability**). Importantly, we now also appreciate that meaningful evolutionary change can occur over short timescales, which has important consequences for managing contemporary problems.

These conceptual advances in evolutionary science have emerged from connections among different sciences over recent decades. Far from superseding the simple evolutionary algorithm (Box 1), they have built on Darwin's core principles and, in doing so, have greatly extended the explanatory power of evolutionary science. In this section, we draw particular attention to the perspectives that are most relevant to understanding the evolution of living *and* non-living systems under rapid environmental and social change. While some of these perspectives have traditionally been on the fringes of evolutionary science, new experimental and theoretical approaches are increasingly bringing them into the mainstream.

Figure 2: Evolving systems involve much more than the sum of their parts. There are many integrating forms of variation, inheritance and selection that operate alongside environmental feedback to drive change and innovation in living and non-living systems.



1.2.1. NOT ALL INHERITANCE IS GENETIC

All evolutionary change requires the **inheritance** or transmission of information. In biological populations, **phenotypic variation** is typically encoded by DNA modifications inherited vertically from parents to offspring. Many **non-genetic mechanisms** are now understood to contribute to biological **inheritance**. Most notably, epigenetic markers on the genome can have a heritable influence on gene expression without changing the genetic sequence itself. Environmental cues trigger epigenetic effects, often during early development, to induce phenotypic changes, contributing to a phenomenon known as **phenotypic plasticity**.

Beyond the epigenome, there are other non-genetic mechanisms of **inheritance** seen in both living and non-living systems. **Cultural and behavioural inheritance** (learning and the persistence of artefacts across generations) enable the transmission of acquired resources, behaviours, and information, ranging from birdsong to foraging site locations to techniques for tool use and manufacture. This transmission can follow vertical (parents to offspring) and horizontal (environmental) pathways. This report's case studies illustrate inclusive **inheritance**. For example, reef-building corals acquire their microbial symbionts by trans-generational and **ecological inheritance**. Furthermore, human language variants are transmitted through learning both vertically from parents to their offspring and horizontally among peers.

Non-genetic mechanisms of **inheritance** have several characteristics that are important in the context of managing rapid environmental change. Foremost is that non-genetic pathways can facilitate change over very short timescales. In the face of contemporary climate change, for example, the spread of new nesting or migration behaviours through social learning and epigenetic responses to thermal stress during incubation can facilitate the persistence of bird populations without any genetic evolution having occurred. These environmentally induced responses are often less stable and shorter-lived than genetically encoded adaptations. Yet, they play a critical role in buffering populations from extinction by providing resilience in unpredictable environments. Genetic and non-genetic mechanisms frequently interact; for example, environmentally induced responses can evolve to become genetically encoded ('fixed') in a population through a process called **genetic assimilation**.

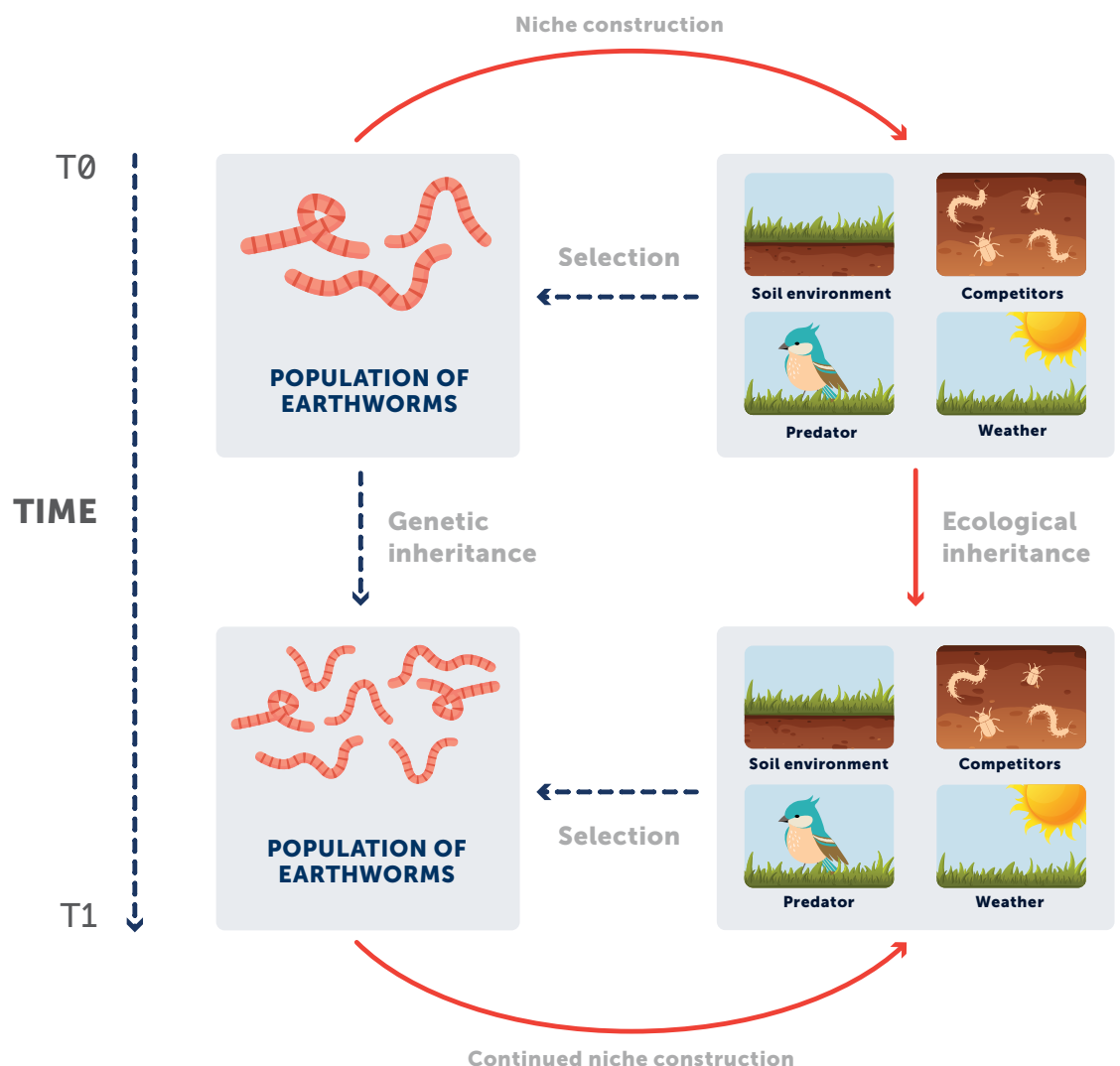
1.2.2. EVOLVING AGENTS SHAPE, AND ARE SHAPED, BY THEIR DEVELOPMENTAL AND SELECTIVE ENVIRONMENT

Textbook examples of evolution typically describe evolving organisms as passive agents gradually responding to their external selective environment. Yet organisms can shape their environments and, in doing so, alter their future evolutionary trajectories. This reciprocal interaction between organisms and their environments means that they themselves can play a role in evolution, an idea known as **niche construction** (Figure 2).

Proponents of **niche construction** theory have used the earthworm to illustrate how organisms can co-direct evolutionary change by altering the selective environment to which they (and other organisms) respond. Earthworms have retained the aquatic physiology of their freshwater-inhabiting ancestors. Their success on land derives from an ability to change the structure and chemistry of the soils in which they live; in effect, earthworms build their own ecological niche.

This is relevant to evolutionary causation because, by creating and maintaining specific environmental states, earthworms bias selection to favour particular evolutionary outcomes. It is the statistical bias in the direction of selection imposed by ecosystem engineers that distinguishes the role of **niche construction** from that of environmental change more generally. Further examples of **niche construction** in nature are provided in the case studies on reef-building corals and pandemic viruses. Similarly, technologies shape the human selective environment, creating new opportunities for further technological and economic progress.

Figure 3: Illustration of niche construction, highlighting how organisms are both products and agents of evolutionary change. The arrows indicate the direction of influence. Black dashed arrows indicate the evolution of worms in response to their environment. Orange arrows show the niche construction process: worms modify their environment, altering soil structure and chemistry, which in turn changes the selection pressures that shape future generations.



Phenotypic plasticity may also manifest as an organism responding to the external environment. For example, behavioural plasticity is one way an organism can level the selective playing field.

Introduced cane toads (*Rhinella marina*) have plagued the Australian continent since they were intentionally introduced in 1935 – causing all sorts of havoc on native fauna. The northern quoll (*Dasyurus hallucatus*), a carnivorous marsupial, has experienced severe mortality from ingesting these toxic toads. Australian research shows that conservation efforts that make it possible for quolls to learn to avoid eating cane toads prior to the toads' arrival may reduce the impact of the invasive pest. While these learned behaviours are not heritable, the capacity for learning is of evolutionary significance.

Adapting to evolutionary change via learning, rather than undergoing rapid genetic evolution, is one way species can maintain population size and genetic variation that is a valuable reserve for responding to uncertain future threats. This illustrates how conservationists can manipulate behavioural plasticity (i.e. learning) to promote survival in the face of novel environmental challenges.

In a more general sense, plasticity appears to be important in responding to novel situations, propelling populations to new adaptive solutions more quickly than genetic variation on its own. The environment is not just a part of selection but a means of directing the supply of novel **phenotypic variation** to change.

1.2.3. SOME EVOLUTIONARY OUTCOMES ARE MORE PROBABLE THAN OTHERS

While random mutation and **recombination** generate variation at the genetic level, the **phenotypic variation** that arises is inherently biased.

Some novel traits are more likely to evolve than others because of how developmental systems are organised (whether or not this organisation reflects past selection or simple contingency). For example, some aspects of development are functionally integrated – changes to one trait can have deleterious downstream effects that constrain evolutionary change in another trait. In contrast, independent trait modules can change freely under selection without interfering with the rest of the system.

These mechanisms make some evolutionary transitions more likely than others. This means that the direction evolution takes can no longer be assumed to be the product of current selective processes alone. Understanding evolutionary change requires us to understand both selection *and* the developmental biases that can constrain or induce variation within populations.

The recognition that the developmental and genetic architecture of organisms shapes their evolution highlights some important commonalities between innovation in nature and technology. This perspective shifts our focus from the adaptive origins of human and biological innovations to the kinds of structures and design principles that might constrain or enhance how systems can change over time.

For example, software developers are tasked with building complex software systems that are robust to errors but open-ended enough so that new features can be easily integrated into future versions. The developmental systems of organisms must be similarly robust – able to integrate novel mutations that arise while remaining functional. In this context, design features that increase **robustness** – such as **modularity** – can be seen as universal principles shared by natural and human-engineered systems. In both cases, **modularity** enhances the capacity to respond to an unpredictable future. For more on this, see Box 2.

1.2.4. RANDOM CHANCE AND HISTORICAL CONTINGENCY PLAY A ROLE IN EVOLUTION

The end products of evolution that we observe today are only partially explained by selection pressures and biased development. Chance and contingency act alongside these more deterministic processes to influence evolutionary change. We see this in the loss or fixation of genetic variants as a result of chance reproductive success (**genetic drift**), and the contingent flow of genes from distant populations.

For example, the genes of individuals which found new populations following natural disasters disproportionately contribute to future generations. Similar processes can influence language evolution, with the chance loss of speakers of a language altering the linguistic variation on which selection and **drift** will act in future populations.

The influence of such chance events in shaping future trajectories is just one way that contingency can direct evolutionary change. Another is the influence that evolutionary background might have in constraining the adaptive pathways available to diversifying lineages (a phenomenon known as **phylogenetic contingency**). Evidence of such phylogenetic constraints is found in broad-scale trends, where distantly related lineages find divergent phenotypic solutions to similar ecological challenges.

Quantifying the relative influence of selection, chance and contingency presents a major challenge for evolutionary science. However, this knowledge is fundamental to understanding the limits of our ability to predict evolving systems. If change is highly contingent on chance events, we will succeed only by considering this history.

1.2.5. EVOLUTION CAN ACT AT MULTIPLE LEVELS OF SELECTION

Although the idea of a singular evolving organism is pervasive, higher levels of organisation, such as social groups, might also function as adaptive units. Darwin first invoked group selection theory to explain the paradox of altruism in human societies: why are altruistic behaviours, such as cooperation and helping others, widespread?

We should expect selfish individuals to outcompete and exploit altruists and ultimately dominate, but this is not always what we see. As Darwin pointed out, while selfish individuals outcompete altruists *within* groups, altruistic groups outcompete selfish groups.

In most instances, however, selection pressures at higher levels of the biological hierarchy are often expected to be weaker than selection on individuals, rendering group selection, at best, a minor player and, at worst, implausible. From this perspective, altruism is explained by its positive effects on individuals via kinship and reciprocity (a process referred to as reciprocal altruism).

In its most recent branding as 'multilevel selection theory', group selection involves careful consideration of relative **fitness** between genes within individuals, between individuals within groups, and between groups. It provides a framework for understanding phenomena such as the transmission of 'junk DNA' elements and the symbiotic associations of organisms.

Beyond traditional biological systems, human cultural evolutionists have embraced cultural group selection as an explanation of large-scale human cooperation. As a species, we are unique in forming extremely large cohesive and cooperative groups far beyond what can be explained by kinship and reciprocity at the individual level. Consider, for example, all the people you have interacted with today that you are not related to, nor could reasonably be expected to interact with again. What stops you from behaving in an antisocial or selfish way in these sorts of interactions? These sorts of interactions are omnipresent in modern human life. In explaining the civility of these one-off interactions, cultural group selection theories cite socially learned group norms (around behaviour, punishment and morality) and institutions (such as religions and judicial systems) that are ubiquitous in human societies.

Specifically, they postulate that large-scale human societies evolved through a multi-level process of cultural groups selection: those cultural groups with more effective group-level social norms for morality, punishment and behaviour tend to be fitter and thus persist. In turn, these group-level dynamics have influenced individual-level selection for characteristic features of human psychology such as social cognition, norm psychology and conformist social learning which further reinforce cultural-group-level norms for cooperation. This example illustrates the importance of going beyond the basic evolutionary algorithm to understand the evolution of complex systems.

BOX 2: EVOLVABILITY

The familiar picture of evolution (Box 1) is about the population-level dynamics that lead to increases in fit between organisms and their environments. It focuses on the change in the frequency of traits in populations over time and says very little about the features of organisms that make this possible. Those studying 'evolvability' examine these features. The idea that complex integrated systems, whether living or engineered, share universal principles which affect the way they change over time is fundamental to this. Understanding these universal principles has far-reaching benefits from building better computer software, to predicting the adaptive responses of populations under changing climates.

Evolvability is the ability of a population to evolve adaptively. In a biological context, it varies depending on the features of the organisms that constitute the population. The overall mutation rate of a population, for example, contributes to its **evolvability**. High mutation rates – as long as they are not so high as to undermine **fitness** – can increase the speed of adaptive evolution. Effectively, this means that species with higher mutation rates are more evolvable than those with lower mutation rates (all else being equal). It is this **evolvability**, rather than selection alone, which might help explain why we see unequal species richness among branches in the tree of life.

The organisation of the genome and developmental system is also an important part of **evolvability**. Building a complex system like an organism requires treading a fine line between stability and change. Where the level of interaction between genes in producing traits is very high, we expect to see lower **evolvability**. This is because mutations are more likely to have large effects and be lethal. Where the interaction is very low, however, **evolvability** is also reduced, because such interactions are a key source of novelty, and thus contribute to species richness and diversity. **Evolvability** thus requires a balance between **robustness** and lability. There are various ways the developmental system of an organism can be organised to help achieve this balance and maximise **evolvability**. Having a less integrated or

modular developmental system, where genes have only limited effect, is one way (see Figure 4).

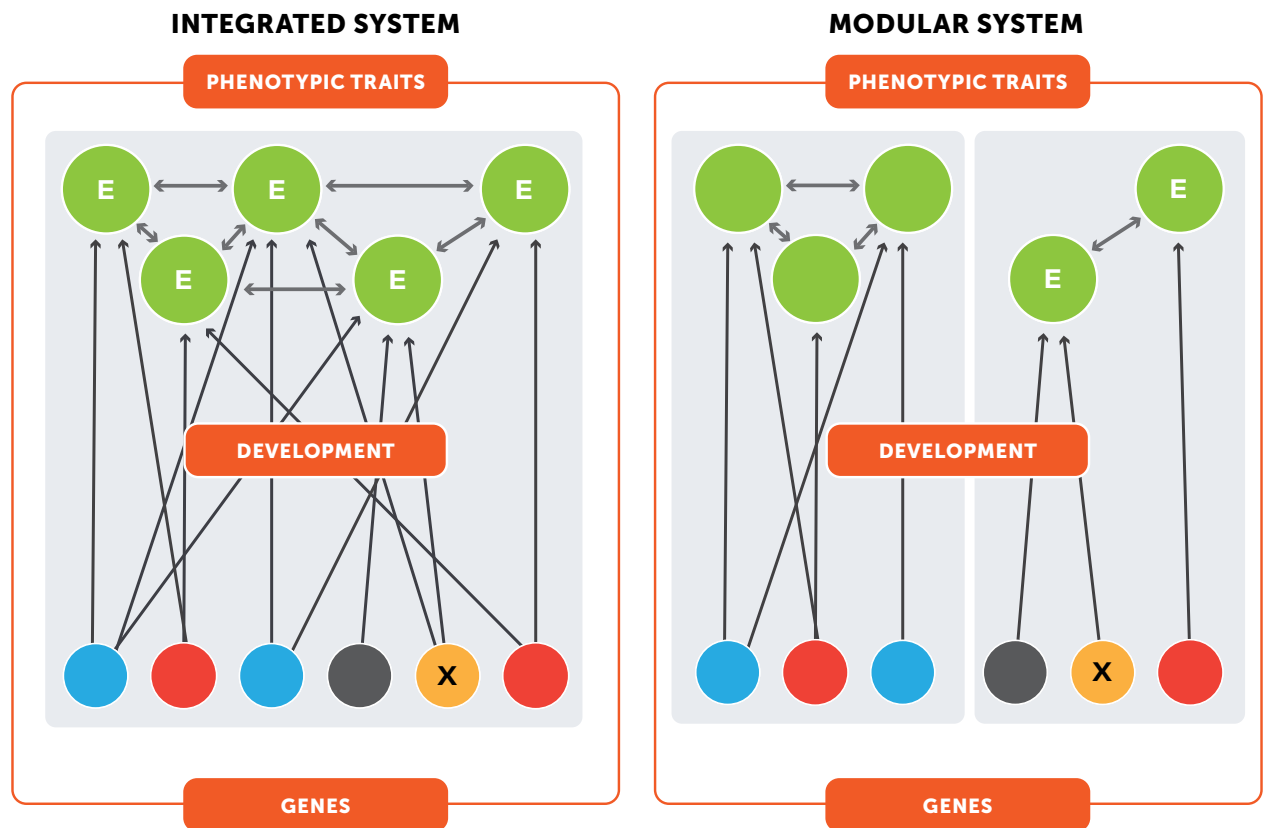
Modularity reduces the risk that mutations will be lethal (i.e. increases developmental **robustness**) but may allow for local specialisation and innovation. It can also enhance **evolvability** by facilitating co-option – the reuse and **recombination** of existing modules to create new traits and functions. For these reasons, developmental **modularity** is associated with increased species richness and diversity as well as the capacity to respond to environmental change. Such 'facilitated' variation is seen in the regulatory circuit that controls the development of cells in the wings of insects, which is repurposed to also determine the formation of eyespots on butterfly wings.

Redundancy is another universal principle of **evolvability** with relevance to both living and non-living systems. **Redundancy** can be defined as an excess of similar components that contribute the same function. In a genetic context, **redundancy** in the form of duplicate gene copies can enhance **evolvability** by compensating for damaging mutations in a gene copy that serves the same role (i.e. by contributing to **robustness**). Alternatively, **redundancy** can create large reserves of similar, neutral variants from which novel, beneficial variants arise. This latter is especially relevant when thinking about the origins and repeatability of innovations.

Phenotypes encoded by larger amounts of genetic information were less likely to evolve *de novo*, relying instead on co-option and modification of existing variation.

Since **evolvability** concerns the ways in which complex systems (such as organisms) are suited to change over time, understanding **evolvability** is partially an engineering problem, and thus a great example of the value of evolutionary science as a cross-disciplinary endeavour. Understanding **evolvability** in biological populations informs how we build evolving systems such as machine learning and AI algorithms. Conversely, understanding the features which generate **robustness** in non-biological systems guides the study of biological **robustness**.

Figure 4: Comparison of integrated versus modular systems. The left panel depicts an integrated system where mutations (X) can have multiple downstream phenotypic effects (E). The right panel shows a modular system, in which the downstream phenotypic effects (E) of mutation (X) are constrained to the module in which they occur.



2. CASE STUDIES OF CUTTING-EDGE EVOLUTIONARY SCIENCE

KEY POINTS

- Four case studies demonstrate how the concepts and tools of contemporary evolutionary science can be applied across domains to enrich our understanding of how living and non-living systems respond to change.
- Case studies from the biological domain show the potential for time-buying interventions to fast-track the natural adaptive pathways to thermal resilience in reef-building corals, and emphasise the crucial role played by evolutionary science in identifying and tracking of spread of the COVID-19 virus.
- Case studies of language and cultural evolution highlight the shared features of evolving systems and show how the parallels between linguistic, digital and biological variation and **inheritance** can be understood to inform effective public policy.

2.1. CASE STUDY 1: CORALS

The Great Barrier Reef (GBR) is one of the most celebrated ecosystems on Earth. The exceptionally high biodiversity of this system, and all coral reefs, depends on mutual partnerships between coral animals (relatives of jellyfish in the phylum Cnidaria), their resident microalgae (Symbiodiniaceae), and various other microorganisms. Coral hosts provide photosynthetic algae with a safe home in their tissues and access to critical nutrients. In exchange, these colourful algae supply the energy that skeleton-forming corals use to build complex reef systems, including the GBR. These coral-algae-bacteria partnerships are collectively referred to as 'coral holobionts'.

Coral ecosystems are facing existential challenges due to the changing climate. Ocean heatwaves, compounded by increasing ocean pollution, are forcing reef-building corals to expel their algal symbionts, ultimately resulting in the starvation of the coral hosts (Figure 5). Such 'coral bleaching' events, which have dramatically increased in frequency in recent years, have already depleted over 50% of GBR corals as compared to the coral cover in the 1990s. Climate scientists warn that without action, unrelenting thermal events will render the GBR virtually extinct by 2050. Even with global climate action today, the amount of warming already built into the system means that coral holobionts must rapidly adapt to warming oceans if they are to survive.

Evolutionary science is critical for both understanding and addressing this problem. The first challenge is to understand coral adaptation itself. Holobiont evolution is complex, involving multiple species and different levels of organisation all at once. However, with the help of genome sequencing and laboratory experiments, an arsenal of genes linked to stress response and protection has now been identified in corals and their symbionts.

Genetic change in any component of these collective genomes might provide selectable variation and facilitate adaptation to the changing climate. Research has focused on algal and bacterial genomes. This is because coral genomes change relatively slowly over time, with mutations inherited vertically (from parents to offspring) over generation times of several years. In contrast, algal and bacterial genomes are considerably more dynamic than their animal hosts. Large population sizes and rapid turnover across short generation times increase the chance of beneficial new variants and, just as importantly, provide a larger pool of existing targets for selection (standing genetic variation).

Laboratory researchers have found that these algae can be selected to withstand higher temperatures and appear capable of conferring thermal tolerance to their coral hosts. The challenge now is whether such tolerance can evolve beyond the lab and on the short decadal timescale required to respond to climate change.

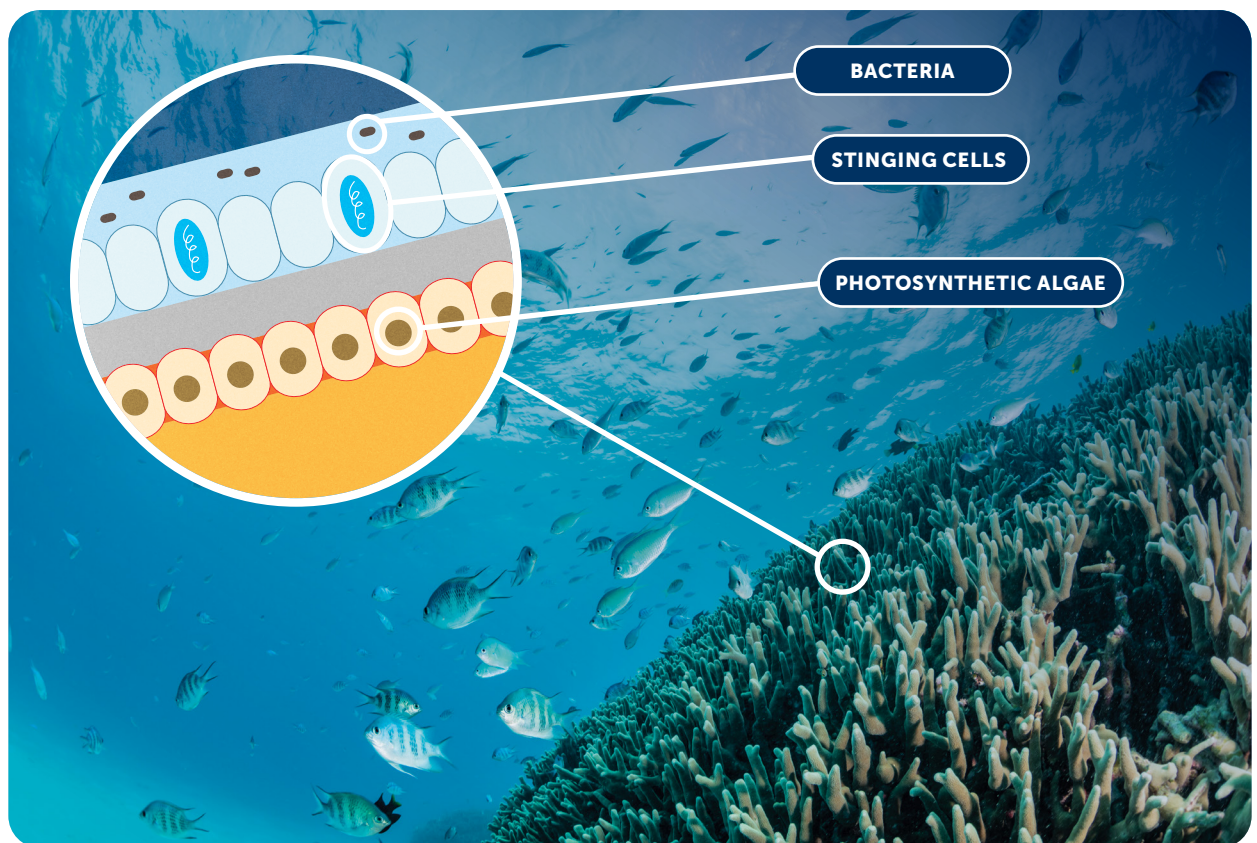
The coral-algae-bacteria partnership arises through a number of alternative pathways. Direct vertical **inheritance**, from parent to offspring, allows coral hosts to retain advantageous symbionts across generations. Novel symbionts can be acquired each host generation through horizontal transmission from other unrelated corals and the environment. In this way, a coral host's microbiome can fluctuate dynamically in response to environmental conditions. This provides some hope for coral holobionts to acclimatise to rapidly warming oceans.

Advances in synthetic biology open the promising (but fraught) possibility of engineering resilience to heat stress in corals. This approach, called **assisted evolution**, has been explored with GBR corals in laboratory trials using selective breeding, genetic manipulation and inoculation of corals with selected symbiont strains.

We can also forecast the potential outcomes of interventions with evolutionary science. Could lab-bred 'super corals' outcompete all other coral holobionts, reducing the diversity of the ecosystem they were meant to protect? Or is it more likely that lab-bred, heat-tolerant holobionts will fail to establish themselves in the reef ecosystem?

While exciting, these are time-buying interventions at best. Any application of evolutionary engineering would be an attempt to preserve elements of the reef long enough for the necessary international action on climate change to take place. This would have major environmental and ethical implications.

Figure 5: The coral holobiont is a co-evolving partnership between the coral animal and its microbial symbionts, including the photosynthetic algae that are expelled from 'bleached' corals during heatwaves made more likely by human-induced climate change.



2.2. CASE STUDY 2: COVID-19

In late 2019, a coronavirus found itself a new host. This is a commonplace evolutionary event. But on this occasion, the tiny bundle of protein and RNA known as SARS-CoV-2 brought the world to a standstill through a global pandemic.

Evolutionary scientists were not taken aback by this event, as such occurrences have taken place several times in the last century. Virologists, who rely on epidemiological and evolutionary studies, have been warning us for decades that it was only a matter of time before a jump from one host to another would lead to a pandemic. This preparedness means that we were better equipped to face a pandemic than at any other point in human history. Evolutionary science played a pivotal role in our response to SARS-CoV-2 – which causes COVID-19 – from the initial identification of the virus to monitoring and predicting the spread of new variants.

Within weeks of the disease outbreak in Wuhan, China, the virus was isolated, and its entire genome was sequenced. By comparing this genome with a database of other viral genomes amassed over the last few decades, we could rapidly place the new virus on a family tree and give it a name. This 'phylogenetic' approach used a principle at the core of evolutionary science – descent with modification – to understand how viral lineages have evolved from ancestral forms based on shared patterns of genetic variation.

SARS-CoV-2 has since become the most sequenced pathogen in history. Evolutionary epidemiologists now routinely compare the genetic sequences of the virus from infected individuals across the world to track its spread and distinguish within-community transmission from outside transmission. We take this forensic tracking of viral lineages for granted, but it is only possible because of the progress made in evolutionary science and genetic technology over the many decades leading up to the pandemic.

After establishing the basics of identification, the focus shifted to developing a vaccine. Vaccine development is sophisticated biochemical work, but the aim is to have an individual's immune system recognise the virus before it encounters it.

The human immune system is an evolving system; it produces a diverse population of immune cells that can respond to different parts of the pathogen. As the infection progresses, those cells that are most effective at recognising and attacking the pathogen are selected for and proliferate. This selection process efficiently leads to the emergence of immune cells with novel abilities to fight the infection. A vaccine prepares the body to fight a virus before exposure. Administering enough vaccines can pre-adapt an entire population.

Finally, ongoing monitoring of the genetic and structural diversity of SARS-CoV-2 allows tracking of the evolutionary response of the virus in near-real time. Each time the virus infects a host, it has the potential to mutate and create a new variant. While SARS-CoV-2 has become 'fitter' with each wave of infection, this does not necessarily mean it is more virulent or pathogenic. The highly contagious and virulent Delta variant was quickly succeeded by the even more highly transmissible Omicron variant. Work across a range of disciplines now aims to predict the potential **evolvability** of SARS-CoV-2 in the face of our changing immunity.

This coronavirus is now circulating in the human population, and likely will for many decades to come. Each time we identify and track a new variant of concern, it will be thanks to the close interconnection of epidemiological and evolutionary science.

2.3. CASE STUDY 3: LANGUAGES

The history of ideas around language evolution is strikingly like the development of Darwin's theory of evolution by natural selection. Both featured a transition from typological thinking – which views variation in individuals as imperfect manifestations around an ideal type – to modern evolutionary thinking, in which there is no ideal type and variation among individuals is the essential raw material for selection and evolution.

For example, an Australian-based typological approach to language accepts one correct way to refer to swimwear. In contrast, a modern evolutionary approach allows multiple solutions for achieving the same goal, thus considering both 'swimmers' and 'togs' as acceptable words for swimwear – except that residents of New South Wales tend to use swimmers, while Queenslanders tend to use togs.

This ideological transition has reshaped the focus of research from 'the why' of language changes, to 'the how'. These analogies with biological evolution mean that how languages change over time can be understood using some of the same models used by population geneticists to understand **genetic drift** and mutation.

This approach transforms a central dilemma into a systematically understandable question. Rather than asking: why do we observe qualitative changes in language if only random noise is allowed around an ideal type? We instead ask: how does variation at the individual level (either quantitative or qualitative) spread among speakers?

The similarities between language and biological evolution extend to the similar algorithms used to understand how genes and the use of language elements change in their frequency over time (Figure 6). Consider a language variable (e.g. a noun like 'mother') which has many variants (e.g. 'mum', 'mamma', 'mummy', etc.). If 'mummy' is used repeatedly in conversation, this increases the number of times that variant is heard by other speakers in the community. We can think of this process as analogous to the reproduction or survival of a genetic variant in a biological population. Importantly, speakers are more likely to use those variants they hear most commonly.

In effect, those more prevalent variants are more likely to be reproduced by speakers. They are, in a manner akin to biological **fitness**, more fit than other less commonly used variants.

Such analogies have helped understand the drivers of Australian Indigenous language loss and how to combat it. More than 250 languages existed within Australian Indigenous communities before European settlement, evidence suggests. Fewer than half of those languages are still spoken today. Many are on the brink of total loss. The replacement of traditional languages with Kriol, a Creole language based on English, is a significant threat.

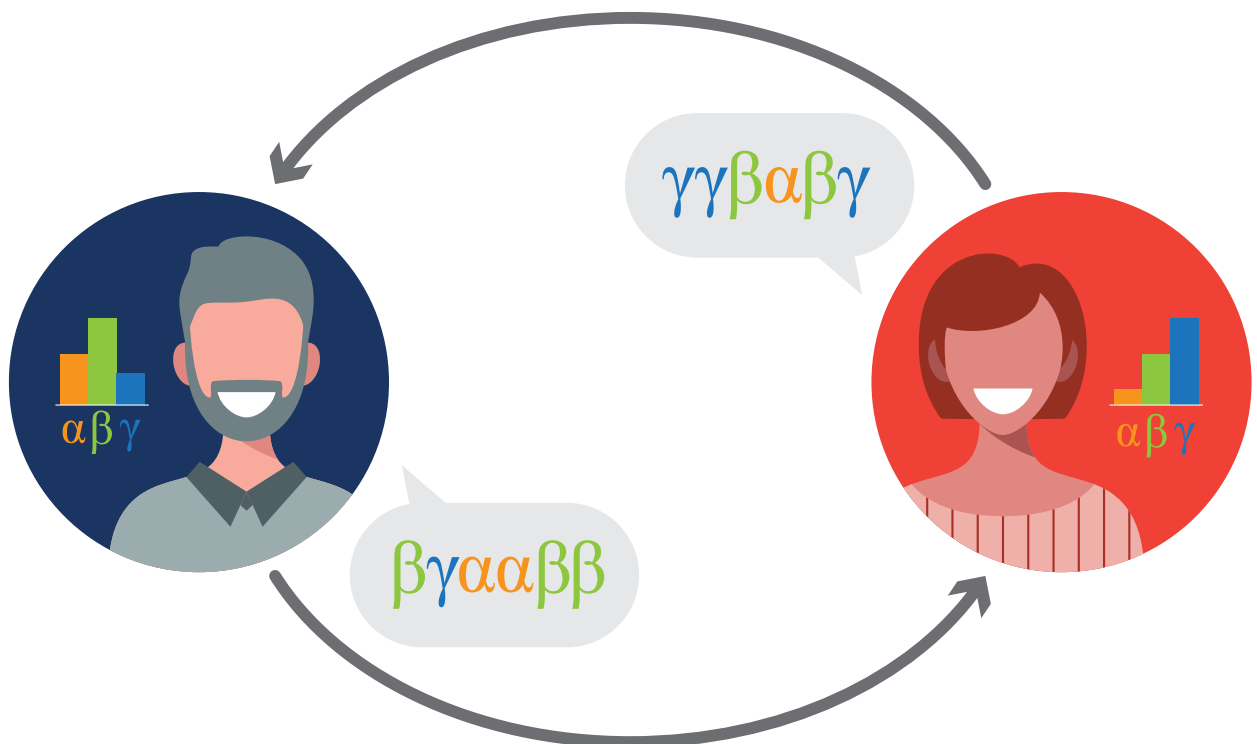
A recent close collaboration between linguists and biologists working in the Gurindji community in the Northern Territory aimed at understanding this trend. Their research, drawing on techniques in evolutionary science for studying genome change, revealed that there is a significant selection for using Kriol words rather than using the traditional language of the community. They also showed that this selection is associated with peer pressure and formal education in the community, delivered in English.

These studies provide important scientific evidence for the negative impact of English-only education on the erosion of Aboriginal and Indigenous languages in Australia. In turn, this evidence can drive meaningful and successful public policy initiatives.

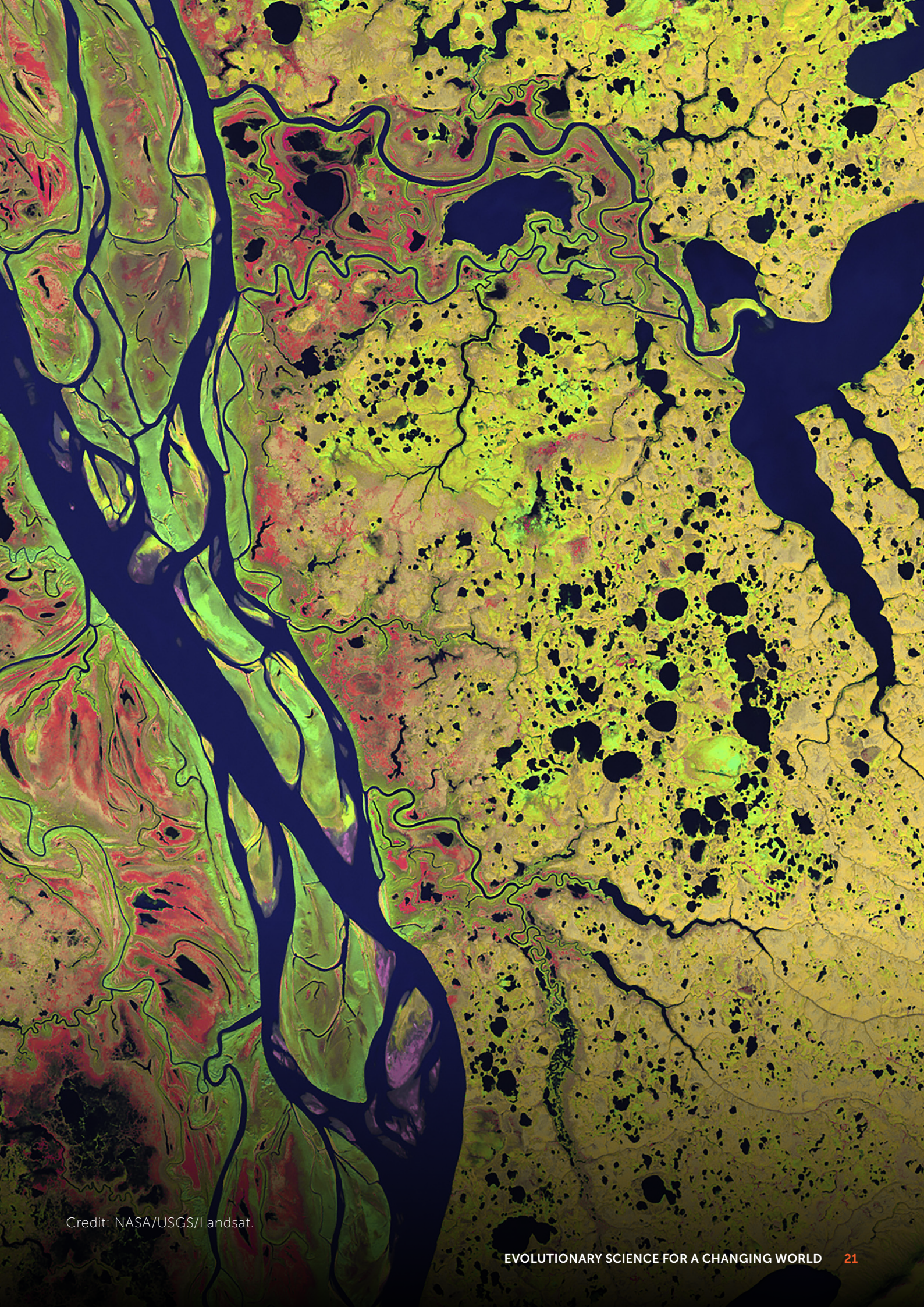
This is just one example of how evolutionary science helps linguists appreciate variation and conduct empirical research on language changes in the context of sociocultural changes.

Evolutionary thinking encourages cross-pollination between biology and linguistics. For example, linguists have adopted biology's 'tree of life' idea to appreciate languages as parts of a shared evolutionary history. Meanwhile, linguists have developed new tools to model word exchanges between dialects, before these dialects become too different for their speakers to understand each other. These tools may give biologists new ideas to delimit the boundary of a species, modelling gene exchanges between populations, before individuals from different populations carry genes that are too different to produce viable offspring.

Figure 6: Illustration of how a speaker's language usage is evolved through communication with other speakers. Figure modified from Baxter et al. (2006).



Suppose we have three ways to express a meaning: alpha, beta, gamma. Each speaker has a unique way to use language – that is how often the speaker use **alpha**, **beta**, or **gamma**, represented by the height of the corresponding bar. After a person expresses the meaning to another person, they will update their usage of the language to improve success in communication. For example, the male speaker may use gamma more often when talking to the female speaker, while the female speaker may use beta more often when talking to the male speaker. Please see Further Reading for the full reference.



Credit: NASA/USGS/Landsat.

2.4. CASE STUDY 4: HASHTAGS ON SOCIAL MEDIA

Hashtags can illustrate the evolutionary process on the social web, which is a living laboratory and rich data source for examining and modelling fundamental evolutionary principles.

Hashtags undergo variation, **inheritance**, and selection rapidly and simultaneously in a span of hours or days rather than years, decades, or millennia in the case of most biological traits and cultural phenomena. Other evolvable information – such as images, videos, and textual quotes – can be broadly understood using the same principles.

Misinformation is also rapidly proliferating on the web, and poses one of the main threats to our democracy and public health. Evolutionary science will be part of a suite of tools for humanity to understand and tackle this pressing challenge.

In 2007, #barcamp appeared as the first tag demarcated by a hash symbol on Twitter. Nowadays, world news can almost be chronicled by each of its iconic tags, from #ArabSpring, #BlackLivesMatter, to #Covid19. Hashtags have since spread to most popular social media services, including Facebook, Instagram, YouTube, and Weibo, as well as traditional media outlets such as television programs to encourage audience engagement online.

The two main roles of tagging in social media, which include hashtags, are organisation and communication. Hashtags help organise content into topics (e.g. #ClimateChange) and organise users into communities (e.g. #YesForEquality on the marriage equality vote in 2017). The value of hashtags transcends the written post alone – they serve to promote a cause (#SaveTheTurtles) and coordinate actions in social movements. The way that hashtags influence the attention and actions of users online can be understood through the lens of evolution and the three principles of variation, **inheritance** and selection.

There are two main forms of variation in hashtags. The first is the production of novel variations in the wording and word choices around the same topic (e.g. #ClimateChange, #Climate, #GlobalWarming, #SaveThePlanet). The second is more wholesale and involves the production of new hashtags in response to an external event (such as #Bushfire). These two types of simultaneously emerging hashtags are great for examining the production of hashtag variants and their long-term survival. The hashtag variants stem from the linguistic richness of community expression and correspond to differences in the goals of the narrative, such as reporting an event versus calling for voters to act.

Hashtags are reproduced or inherited through adoption by different members of an online community. Online users adopt hashtags for many reasons: to signal topical relevance, foster community membership, promote awareness and organise actions, influence consumers, drive political change, and control election narratives, to name a few.

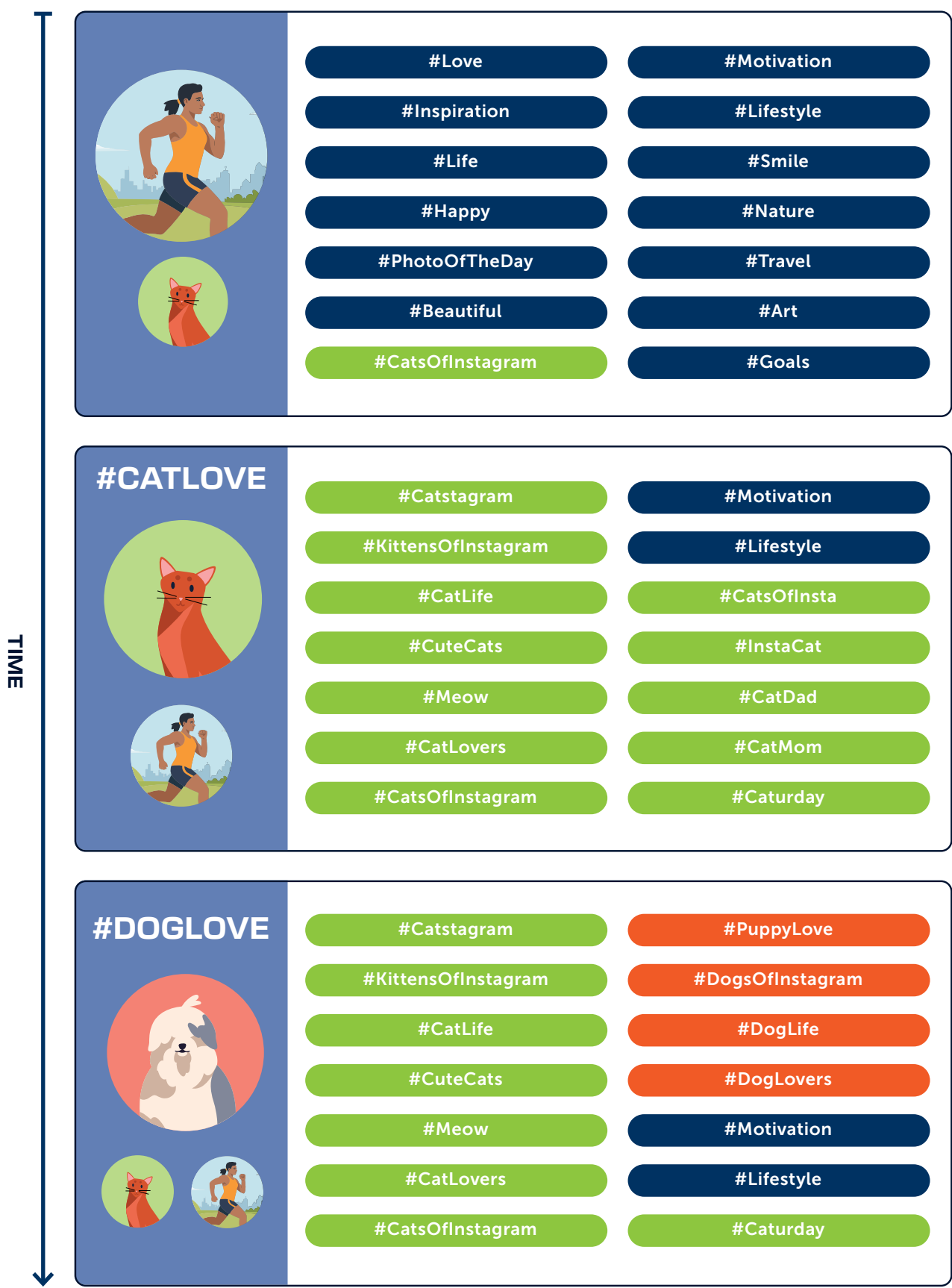
The selection of hashtags is collectively performed in the complex online information environment. ‘Fitter’ hashtags get used more widely and for longer. The overall result is also significantly influenced by random chance and external events.

Which tags are successful depends on many different factors. The first is topical relevance, analogous to the general compatibility of biological traits to the natural environment. The second is competition among memes.³ The resource here is the limited attention span of internet users rather than the limited natural resources in a given location. A third quality can be called ‘interactivity’, which measures how much a hashtag engages users who adopt, promote, or even rebut the messages. For example, widely adopted hashtags, such as #blm (Black Lives Matter) or #MeToo (a social movement against sexual abuse and sexual harassment), have chronicled important modern social movements.

Understanding collective attention in social media has far-reaching relevance to our personal, political and professional lives. An experiment by Facebook estimated that seeing friends’ faces in a message that promotes voting generated more than 300,000 additional votes among the 61 million users to whom the message was shown. Applying a broadened evolutionary theory enables analysis and inquiry into our online behaviours that would otherwise not be possible.

3. While the term ‘meme’ is in this literature, it should not be conflated with Richard Dawkins’ original intuition-driven approach to memetics which focuses on memes as cultural analogues to genes. The empirical approach employed in this work analyses the propagation of memes as units of information in cultural systems and change within cultural state spaces over time.

Figure 7: Evolutionary change within a hashtag population on the social web. Hashtag variation stems from modifications of existing tags and the emergence of new tags following cultural events. Inheritance occurs as influential hashtag variants are adopted by users of the online community. Selection operates through competition among hashtags for topical relevance within the finite attention span of the community.



BOX 3: TACKLING COMPLEXITY – TOWARDS A QUANTITATIVE, CROSS-DISCIPLINARY EVOLUTIONARY SCIENCE

Corals, COVID-19, languages, and hashtags all exemplify the challenges of describing behaviour in complex systems. In science, we are taught to seek the simplest explanation for our data. Indeed, evolutionary science has made powerful contributions by describing abstracted systems where a single selective force acts on a single agent. But, as our case studies show, simple models that focus on one part of an interacting whole can dramatically underestimate the capacity for change and risk losing the rich context that is of practical importance to policymakers. To move forward, we need to harness quantitative approaches that make complexity tractable while still capturing important phenomena. This is a daunting goal, but the foundations for this step-change in evolutionary science are in place. We now have access to huge repositories of diverse data as well as exponential growth in computing power, and new theories and models.

Emerging tools provide unprecedented opportunities to create artificial systems for **experimental evolution** investigations. Such artificially engineered systems can be used to explore novel solutions beyond those found in nature. They can also provide more tractable models compared to most real-world systems, which evolve through complex interactions over long timeframes.

An engineered system's shorter timescales and simpler causal profiles, along with the power to intervene and tinker, provide powerful opportunities for understanding the general principles of evolution. For example, genome sequencing and gene editing technologies can be used to study how particular genetic variants respond to selection in a quantitative manner. Going a logical step further, the construction of entirely synthetic genomes could provide powerful new systems to understand the many factors that contribute to **evolvability** under environmental change.

In parallel with new technologies for laboratory evolution experiments, mathematical and computational advances have provided new ways of modelling and simulating evolution. For example, work in machine learning – such as that being used to understand evolving hashtags – has greatly expanded our capacity to predict the effects of genetic mutations with vast practical applications.

The socio-economic models used to inform policymaking provide another illustrative example. The economy is a multilayered system of distributed interactions which is subject to many internal and external constraints. Modelling such a complex system is extremely challenging. However, the population thinking inherent in Darwin's evolutionary algorithm has provided an opportunity to address this challenge. This approach considers multiple plausible trajectories of an economic system rather than attempting to define a precise or optimal single trajectory. For example, evolutionary algorithms are used to simulate the changing behaviours of companies in an industry, where behaviour is analogous to a trait under selection in biological evolution, and the behaviour of a company determines its competitiveness in the industry.

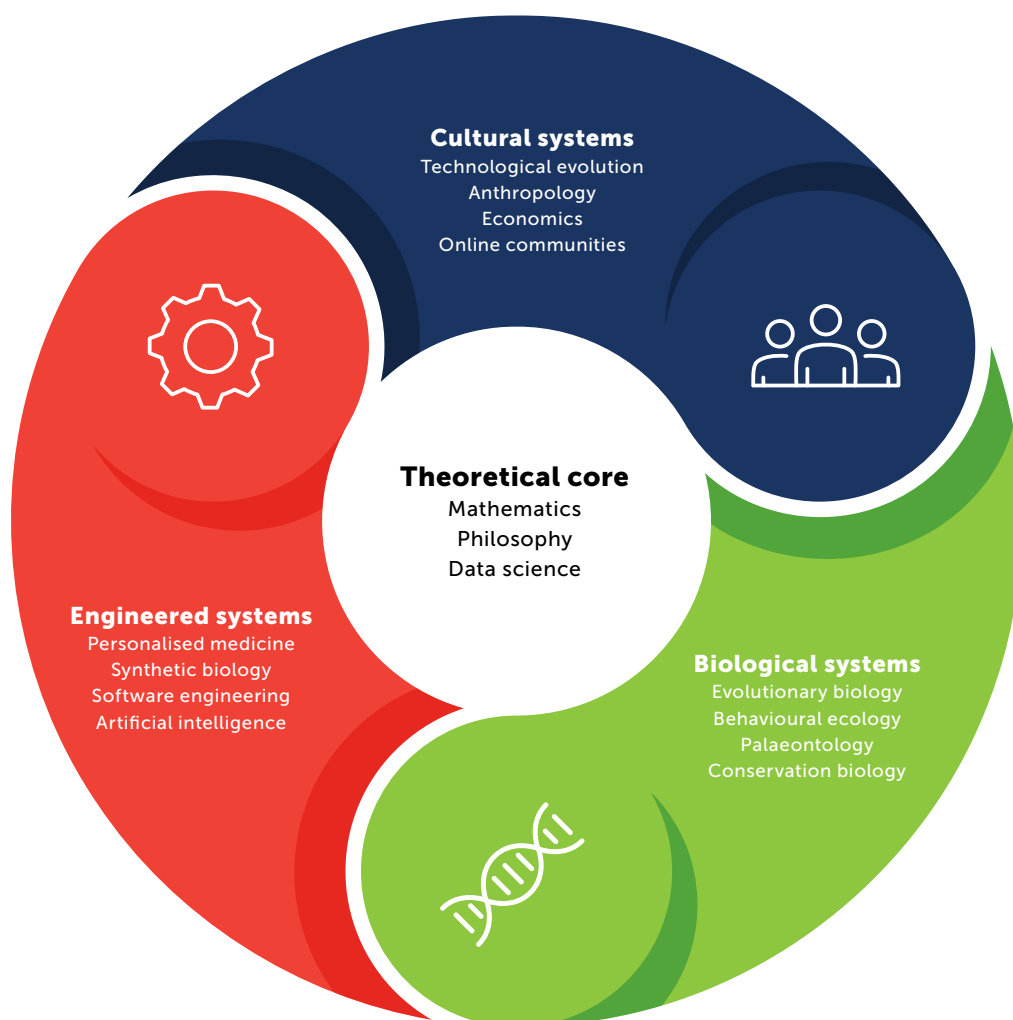
As we better characterise, disentangle, and quantify the interactions within evolving systems, a natural next step will be to quantify the connections among models of living and non-biological systems. By measuring the extent and nature of the evident parallels among systems that have emerged from qualitative studies, fundamental questions can be addressed; such as, how does evolution differ across domains and contexts?

3. OPPORTUNITIES FOR EVOLUTIONARY SCIENCE IN A CHANGING WORLD

KEY POINTS

- Evolutionary science is inherently cross-disciplinary and provides a ready toolkit for understanding rapid cultural and environmental change.
- Our national capacity in evolutionary science can be increased by connecting Australia's existing strengths in mathematical modelling, **experimental evolution**, and translation of science into policy.
- A cross-disciplinary evolutionary science community in Australia will help drive integrated educational opportunities and public engagement initiatives.

Figure 8: A cross-disciplinary evolutionary science community.



Contemporary evolutionary science provides a ready toolkit for understanding change in engineered and cultural systems, as well as biological systems. Yet it remains largely embedded within the biological sciences. This limits its full analytical potential and restricts its ability to deliver outcomes for the government and public. Australia is well-placed to unlock this potential, having cross-disciplinary strengths in foundational evolutionary theory, mathematical modelling, experimental studies, and translation of science into policy.

We see two key strategies for connecting and growing Australia's evolutionary science capabilities in the immediate future.

3.1. KEY STRATEGY 1: CONNECTING AND GROWING THE COMMUNITY

Understanding and solving the complex problems of evolving systems typically requires research across, rather than within, traditional disciplinary and institutional lines. Studying the drivers of Indigenous language loss, for example, requires collaboration between linguists, biologists and Indigenous stakeholders from multiple institutions and locations across the country.

The tools, models and theories developed in one domain are often applicable to others because of the shared features of evolving systems. For example, non-biological systems like social media networks such as X (formerly Twitter) can provide data-rich 'accidental experiments' to test more general evolutionary theories.

To move forward, we advocate fostering an integrated, cross-disciplinary evolutionary science community in Australia. The constituent disciplines of evolutionary science are mathematics, philosophy, and data science, and these intersect with applications in biology, engineering, computing, socioeconomics, and linguistics, among others. Our success will depend on bringing together researchers and educators from these disciplines rather than on individuals attempting to span multiple areas of competence.

Interdisciplinary workshops, research networks, and mentorship will be vital, as will the participation of early-career researchers who are deeply informed and enthusiastic about advances in evolutionary science. Building such networks requires establishing incentive structures and metrics that reward interdisciplinary engagement.

Real success here will not be possible without demonstrating to funding bodies (such as the Australian Research Council and government more broadly) that evolutionary science is a dynamic and inherently cross-disciplinary research area. We take this document to be one small part of such an effort.

3.1.1. EDUCATING THE NEXT GENERATIONS OF EVOLUTIONARY SCIENTISTS

To build and grow the next generations of evolutionary scientists, education and training resources are needed from early school through to postgraduate levels.

Australian high school students receive their first detailed introduction to evolutionary principles at senior Years 11 and 12. At the tertiary level, evolution is primarily taught as a niche sub-discipline within biology. Increasing emphasis on integrative learning creates an opportunity to deliver a coherent cross-disciplinary degree programs that welcome university students with diverse interests. Core subjects would include mathematics, philosophy, and data science, in addition to foundation courses in biology, linguistics, economics, and environmental sciences.

Specialist training, such as at the postgraduate level, should include the analytic and quantitative skills that are essential in translating ideas from different disciplines into common, measurable concepts. Information theory (the mathematical study of information) has provided a strong quantitative framework from which we understand phenotypic and cultural evolution. This will form the basis of an integrative evolutionary science and will involve using mathematics to conceptualise Darwin's evolutionary algorithm to model living and non-living systems that involve multiple agents linked together through complex feedback.

Integrative disciplines such as the history and philosophy of science are also of great importance in clarifying points of similarity and difference between different approaches and helping to span disciplinary divides in language and methodology. At tertiary and postgraduate levels, we must also support training in large-scale, cross-disciplinary collaboration and translation of science to policy through skills in science communication.

3.2. KEY STRATEGY 2: SCIENCE SYSTEMS THAT SUPPORT CROSS-DISCIPLINARY COLLABORATION

Evolutionary science has revealed the profound insight that common descent unites humanity in kinship with all life on Earth. We believe that further impactful insights across multiple domains are possible if we can unleash the potential of evolutionary science as a multidisciplinary powerhouse. However, current strategies of research funding allocation reward siloed thinking along well-worn lines of inquiry. This must be addressed if evolutionary science is to realise its full national potential.

To move forward as a multidisciplinary field, evolutionary science requires the policies and platforms that facilitate vital collaborations to drive novel science and applications.

Further, realising the potential of evolutionary science demands ongoing communication across academic disciplines and close links among evolutionary science researchers, government policymakers, and industry leaders. We must build research networks, simplify data-sharing, and ensure that scientific findings directly inform policy decisions that benefit humanity.

Evolutionary science in this country is extremely diverse and impactful. Australia has every chance to continue building on this success if we can create opportunities for interdisciplinary research and public policy engagement. Here, we have laid out the beginnings of a discussion that we hope will encourage further interactions between scientists and educators with a common interest in understanding evolving systems in a rapidly changing world.



Credit: NASA/USGS/Landsat.

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