D4.1 Natural selection

Continuity and change—Ecosystems

Standard level and higher level: 2 hours

Additional higher level: 2 hours

Guiding questions

- What processes can cause changes in allele frequencies within a population?
- What is the role of reproduction in the process of natural selection?

Recommended prior learning: A4.1 Evolution and speciation

SL and HL

D4.1.1—Natural selection as the mechanism driving evolutionary change
Students should appreciate that natural selection operates continuously and over billions of years, resulting in the biodiversity of life on Earth.
Natural selection is the process by which better adapted organisms with favorable alleles survive and pass their genes to offspring, taking over the population's gene pool and weeding out deleterious ones to produce the *fitter*, not *fittest* (since it operates continuously). It is the main mechanism driving evolutionary change. Natural selection benefits the *individual* and not *necessarily* the species. A strong group of lions may kill a weaker group and breed with the females. Although the total number of individuals within the species has momentarily decreased, genes from stronger lions increased in frequency to allow for more adapted offspring.

D4.1.6—Requirement that traits are heritable for evolutionary change to occur
Students should understand that characteristics acquired during an individual's life due to environmental factors are not encoded in the base sequence of genes and so are not heritable.
Only heritable traits (those that are encoded within an individual's genome) are able to be passed down and be a part of an evolutionary change due to natural selection. Characteristics acquired during an individual's life due to environmental factors, such as certain behaviors or knowledge, are not part of the genome and thus are not heritable. **Additional higher level**: although epigenetic tags could be inherited in gametes and thus passed to offspring (gene imprinting), they do not change DNA sequences and thus far are not regarded as having a role in evolutionary change.

D4.1.5—Differences between individuals in adaptation, survival and reproduction as the basis for natural selection
Students are required to study natural selection due to intraspecific competition, including the concept of fitness when discussing the survival value and reproductive potential of a genotype.
Intraspecific competition occurs between individuals of the same species. '**Fitness'** is how well-adapted an individual is to their environment; the fitter they are the greater their survival value and reproductive potential. Thus, they will contribute the most to the gene pool of the species (their alleles will spread the most within the species) and evolutionary change will occur.

NOS: In Darwin's time it was widely understood that species evolved, but the mechanism was not clear. Darwin's theory provided a convincing mechanism and replaced Lamarckism. This is an example of a paradigm shift. Students should understand the meaning of the term "paradigm shift".

A **paradigm shift** is a fundamental change in the basic concepts and approaches in a scientific discipline. Lamarckism was a previously accepted evolutionary theory until Darwinism came and providing more a more convincing mechanism of evolution, leading to a paradigm shift in biology.

D4.1.2—Roles of mutation and sexual reproduction in generating the variation on which natural selection acts

Mutation generates new alleles and sexual reproduction generates new combinations of alleles.

Variation within species provides different alleles of the same gene which allows natural selection to decrease or increase allele frequency already within the population. If there is no variation, all individuals have the same reproductive and survival success rate because they all have the same traits, thus natural selection will not operate because no alleles of which to choose from even exist.

Mutations drive the genetic variation which natural selection acts on. Although mutations are random in the sense that they occur regardless of whether they are harmful or beneficial, natural selection is not random as it only chooses the *beneficial* mutations that result in better adaptations. These mutations produce new alleles by single point mutations, insertions, and deletions, among others.

Sexual reproduction also contributes to variation within a species through crossing over in prophase I of meiosis and random/independent assortment of homologous pairs in metaphase I.

D4.1.3—Overproduction of offspring and competition for resources as factors that promote natural selection

Include examples of food and other resources that may limit carrying capacity.

In nature, population sizes are limited by many factors, some of which are density-dependent or density-independent. These factors act as **selection pressures**, which are biotic or abiotic agents that affect the ability of an organism to reproduce and survive.

Density-dependent factors arise from biological phenomena like competition between populations, competition, disease, and predation. They arise due to interactions between organisms, and can either increase or decrease population size and mortality through changes in reproduction and survival, driving natural selection. These factors usually serve to regulate population size and keep it within a narrow range.

For instance, species have the tendency to overproduce offspring beyond what the environment can provide in terms of resources. This leads to competition between individuals of the same species, which promotes natural selection as only those with favorable alleles can successfully compete and utilize the limited resources. Thus, natural selection acted due to the presence of a density-dependent factor.

D4.1.4—Abiotic factors as selection pressures

Include examples of density-independent factors such as high or low temperatures that may affect survival of individuals in a population.

Density-independent factors arise from physical or chemical phenomena (abiotic factors) like natural disasters, weather conditions, quality and quantity of food, and pollution. For example, a rise in temperature may kill some plants within a species, but those who survive are better adapted and thus able to reproduce. Thus, natural selection selects those adapted to hotter temperatures.

D4.1.7—Sexual selection as a selection pressure in animal species
Differences in physical and behavioural traits, which can be used as signs of overall fitness, can affect success in attracting a mate and so drive the evolution of an animal population. Illustrate this using suitable examples such as the evolution of the plumage of birds of paradise.
Sexual selection is a subset of natural selection that allows sexually selected traits to evolve if they offset the male's diminished survival with an increase in his reproduction. Females prefer males with stronger traits (disease resistance, size, etc.), and certain aesthetic features that serve as indicators for these strong traits (like brighter colors). For many species, these traits do not help the organism adapt to its environment, and expediate quite a lot of energy despite natural selection being responsible for their development. The whole process of sexual selection stops only when the male trait becomes so exaggerated that any further increase reduces his survival more than it attracts females, so that his net production of offspring suffers. For example, colorful plumage in male birds of paradise have evolved to attract female mates by indicating desirable traits in the male. An experiment was done to add a white aesthetic feature to the plumage of male birds, and it was observed that females were heavily attracted to it and mated more with males who possess the added white feature. A possible explanation by scientists posits that female birds line their nests with white feathers, so the white addition on the male plumage indicated to the females that they are mating with a male who can take care of their offspring after birth. In any case, evolutionary theory shows that in events of sexual selection, *three* types of genes will all increase in frequency together: genes for a male "indicator" trait reflecting that he has good genes, genes that make a female prefer that indicator trait, and the "good" genes in males whose presence is reflected by the indicator.

D4.1.8—Modelling of sexual and natural selection based on experimental control of selection pressures
Application of skills: Students should interpret data from John Endler's experiments with guppies.
John Endler investigated sexual selection through guppies, a type of fish. Male guppies living in environments with dangerous predators were less colorful than those living in safer waters as they camouflaged better, even though females prefer those with more colors. He conducted modelling experiments by transferring male guppies living in dangerous waters to safer areas, and after 2 years (around 15 generations) sexual selection favored those with brighter colors.

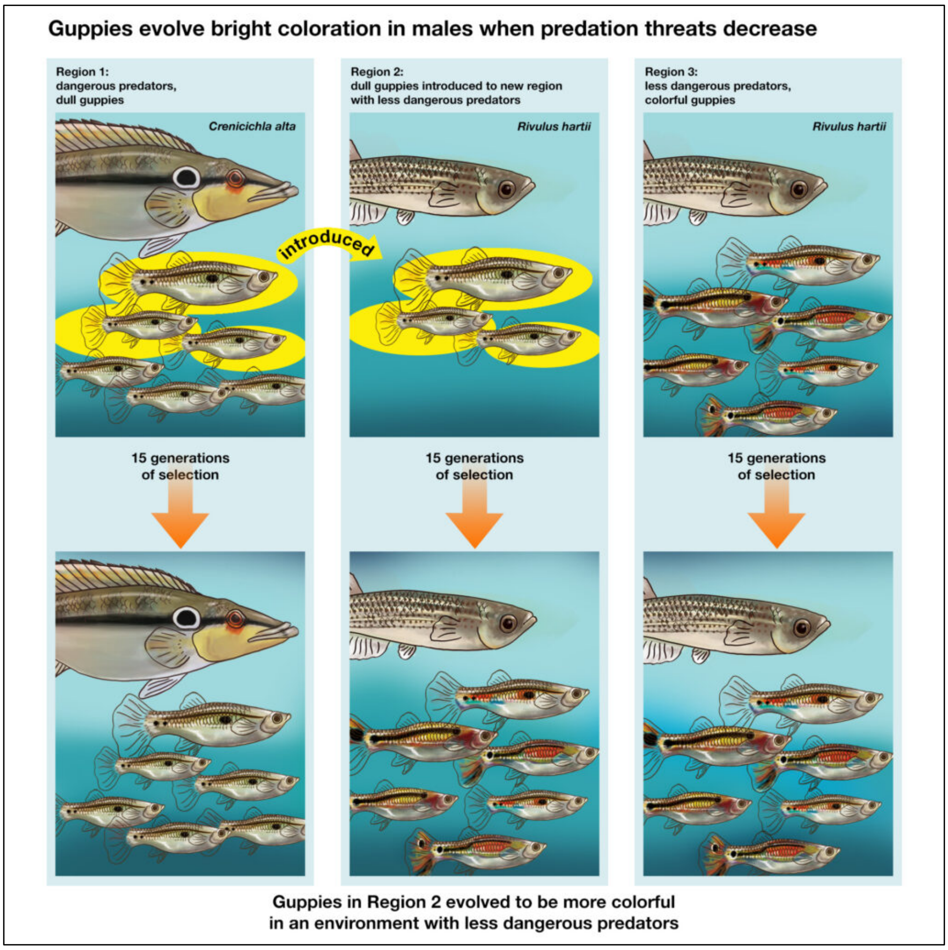

Figure 1: sexual selection of colorful males in guppies (Evolution).

Additional higher level

D4.1.9—Concept of the gene pool
A gene pool consists of all the genes and their different alleles, present in a population.

A **gene pool** consists of all the genes and their different alleles present in a population *or* species.

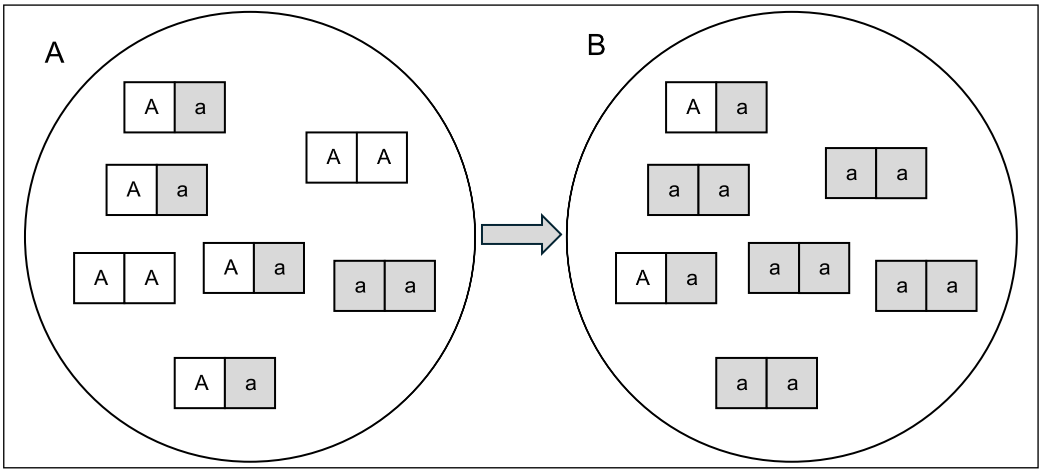

Figure 2: (a) gene pool before natural selection (b) gene pool after natural selection.

D4.1.10—Allele frequencies of geographically isolated populations
Application of skills: Students should use databases to search allele frequencies. Use at least one human example.

Species may exist in different geographically isolated environments and thus individuals may belong to different populations. Despite belonging to the same species, these populations have distinct gene pools with different allele frequencies. For example, the lactose tolerance allele in humans exists in different frequencies across the many human populations on earth (people living in certain continents or regions are more likely to be lactose intolerant than others).

D4.1.11—Changes in allele frequency in the gene pool as a consequence of natural selection between individuals according to differences in their heritable traits
Darwin developed the theory of evolution by natural selection. Biologists subsequently integrated genetics with natural selection in what is now known as neo-Darwinism.

Darwin developed the theory of evolution by natural selection but was unable to fully explain all its details (DNA was not yet even known back then), but biologists subsequently integrated new discoveries in genetics with natural selection to emerge with what is now known as **neo-Darwinism**. Essentially, natural selection increases the frequency of beneficial alleles and reduces that of harmful ones within the gene pool.

D4.1.12—Differences between directional, disruptive and stabilizing selection

Students should be aware that all three types result in a change in allele frequency.

Natural selection on traits controlled by a single gene changes frequency of its alleles, but with **polygenic traits** (characteristics controlled by multiple genes), natural selection affects the distribution of phenotypes in three main ways:

1. **Stabilizing selection**: the intermediate phenotype is chosen as the population stabilizes on a single trait, which decreases genetic diversity due to homogeneity.
   - (i.e. human birth weight is a type of stabilizing selection since large babies caused pregnancy complications and light babies were less likely to survive, so the phenotype stabilized in the middle at around 7lb)
2. **Directional selection**: one of two phenotypic extremes within the spectrum is selected for, causing the allele frequency to continuously shift towards one 'direction'. This usually occurs in highly changeable environments or when a new allele develops (due to mutation) and overpowers all others due to its benefits.
   - (i.e. during the industrial revolution, air pollution caused tree bark to turn into a black color, so black peppered moths were more likely to survive than white ones due to camouflage)
3. **Disruptive (diversifying) selection**: when two extreme/divergent phenotypes are favored over intermediate ones, increasing genetic diversity and heterogeneity.
   - (i.e. big male elephants can mate by brute force and small ones can sneak into the big males' territory and mate whereas medium-sized elephants are too big to sneak in and too small to overtake the large elephants in a battle)

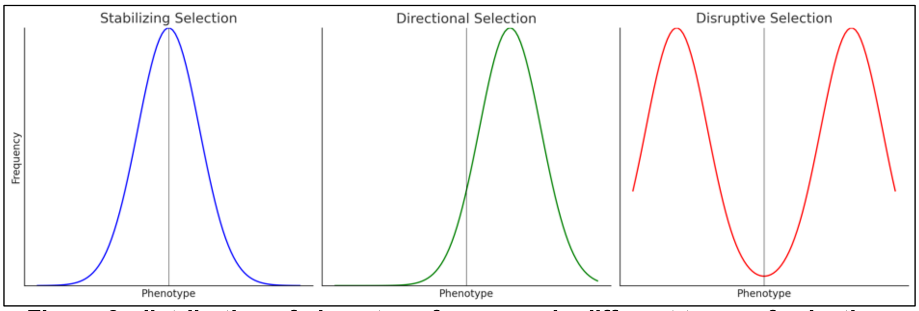

Figure 3: distribution of phenotype frequency in different types of selection.

D4.1.14—Hardy–Weinberg conditions that must be maintained for a population to be in genetic equilibrium

Students should understand that if genotype frequencies in a population do not fit the Hardy–Weinberg equation, this indicates that one or more of the conditions is not being met, for example mating is non-random or survival rates vary between genotypes.

Genetic equilibrium is a condition in which the allele frequency within a gene pool does not change across generations, satisfying the following conditions:

- no mutations
- no gene flow (individuals do not enter or exit the population)
- random mating (individuals do not favor some characteristics over others)
- no natural selection

This state of equilibrium can be attributed either to the entire genome or to one specific allele. If we look at the entire genome, then these conditions have to be met for every allele, but we look at only one single allele then these criteria have to be met for only that one single allele.

The **Hardy-Weinberg Principle of Equilibrium** states that allele frequencies are inherently stable as long as no evolutionary force is acting on them. While some genes *may* be at equilibrium, is it highly unlikely (almost impossible) for a population to have *all* of its genes at equilibrium. Even though no population on earth satisfies the Hardy-Weinberg equilibrium, it provides a baseline to which we can compare actual populations to in order to detect how evolutionary forces are acting on the population's gene pool. For example, when conducting a chi-square test, expected frequencies at equilibrium can be compared to actual observed frequences to quantify the degree to which the population's alleles are deviated away from equilibrium.

D4.1.13—Hardy–Weinberg equation and calculations of allele or genotype frequencies

Use *p* and *q* to denote the two allele frequencies. Students should understand that p + q = 1 so genotype frequencies are predicted by the Hardy–Weinberg equation: $p^2 + 2pq + q^2 = 1$.
If one of the genotype frequencies is known, the allele frequencies can be calculated using the same equations.

Suppose a gene has two alleles only, *p* and *q*. The allele frequencies of both p and q add up to 1 (100%).

$$\text{Allele frequency} = \frac{\text{number of a specific allele within the population}}{\text{total number of alleles at that locus in the population}}$$

If an individual is homozygous for the allele, the allele is counted twice (number of individuals with allele ≠ allele frequency).

Not only does allele frequency interest biologists, but **genetic frequency** as well, which describes the frequency of a specific genotype (combination of alleles i.e. homozygous pp/qq or heterozygous pq) within a population. This can be calculated through the following equation:

$$p^2 + 2pq + q^2 = 1$$

- p^2 = frequency of individuals who are pp homozygous
- 2pq = frequency of individuals who are pq heterozygous
- q^2 = frequency of individuals who are qq homozygous

$$\text{Geneotype frequency} = \frac{\text{number of individuals with a specific allele combination}}{\text{total number of individuals in the population}}$$

D4.1.15—Artificial selection by deliberate choice of traits
Artificial selection is carried out in crop plants and domesticated animals by choosing individuals for breeding that have desirable traits. Unintended consequences of human actions, such as the evolution of resistance in bacteria when an antibiotic is used, are due to natural rather than artificial selection.
Artificial selection is essentially natural selection but instead of selecting the traits that make the species more adapted to its environment, humans deliberately select for traits most beneficial to them (i.e. domesticating faster horses or more weather-resistant crops). This has been used as evidence for evolution as it can show the gradual evolutionary change much faster than what is observed in nature.

Linking questions

• How do intraspecific interactions differ from interspecific interactions?

• What mechanisms minimize competition?

Review questions

SL and HL

- Define natural selection. [1]
- Explain how the conditions necessary to bringing about natural selection are achieved. [3]
- Outline how intraspecific competition and cooperation contributes to evolutionary change through natural selection. [3]
- Outline the significance of John Endler's experiments in understanding natural selection. [3]
- Distinguish between the two types of selection pressures that promote natural selection. [4]
- Explain how the concept of "survival of the fittest" can be misleading when applied to natural selection. [5]
- Discuss how and why sexual selection may counterintuitively select for traits that do not make the individual more adapted to the environment. [6]
- Discuss the importance of balancing between reproductive and survivability in improving the adaptability of a species to its environment. [7]

Additional higher level

- Distinguish between allele and genotype frequency. [1]
- Predict a Hardy-Weinberg genotype frequency equation for a gene consisting of three alleles. [1]
- Explain the role of the three types of natural selection. [6]

References

Ann Clark, Mary, et al. *Biology 2e*. E-book, OpenStax, 2018, https://openstax.org/books/biology-2e/pages/1-introduction. OpenStax.

Experiments. evolution.berkeley.edu/lines-of-evidence/experiments.

Gordon Betts, J., et al. *Anatomy and Physiology 2e*. E-book, OpenStax, 2022, https://openstax.org/books/anatomy-and-physiology-2e/pages/1-introduction. OpenStax.

Turner, Bryan M. “Epigenetic responses to environmental change and their evolutionary implications.” *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* vol. 364,1534 (2009): 3403-18. doi:10.1098/rstb.2009.0125.