D4.1 Natural Selection

Theme D: Continuity and Change — Ecosystems Level

Standard Level: 2 hours | Higher Level: 4 hours

Contents

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?
- What is the role of paradigm shifts in the progression of scientific knowledge?

→ Links to Other Topics

Links to Other Topics:

- **A4.1 Evolution and Speciation** — Natural selection leads to speciation; homologous structures as evidence
- **D3.1 Reproduction** — Meiosis generates variation through crossing over and independent assortment
- **D3.2 Inheritance** — Mendelian genetics provides the mechanism of heritability
- **D1.3 Mutations and Gene Editing** — Mutations create new alleles, the ultimate source of genetic variation
- **C3.2 Defence Against Disease** — Antibiotic resistance as an example of natural selection in action
- **C4.1 Populations and Communities** — Population dynamics, carrying capacity, competition
- **B4.1 Adaptation to Environment** — Structural, physiological, and behavioral adaptations
- **D4.2 Stability and Change** — Environmental changes create selection pressures
- **D4.3 Climate Change** — Novel selection pressures from changing abiotic conditions

1 D4.1.1 — Natural Selection as the Mechanism Driving Evolutionary Change

✎ Definition

Natural selection is the process by which heritable traits that enhance survival and reproduction become more common in successive generations of a population, while traits that reduce fitness become less common.

★ Key Concept

Natural selection operates as the primary mechanism of evolution:

- It acts on **existing variation** in populations
- It is a **non-random** process (unlike genetic drift)
- It leads to **adaptation** — better fit between organism and environment
- It has operated **continuously for billions of years**, producing the enormous biodiversity of life on Earth
- It is **observable in real time** in organisms with short generation times (e.g., bacteria developing antibiotic resistance)

1.1 The Paradigm Shift: Lamarckism to Darwinism

✎ Definition

A **paradigm shift** is a fundamental change in the basic assumptions and methodology of a scientific field.

The acceptance of Darwin's theory of natural selection represented a paradigm shift in biology, replacing Lamarck's theory of inheritance of acquired characteristics.

Aspect	Lamarckism (Incorrect)	Darwinism (Correct)
Variation	Acquired through use/disuse	Pre-exists in population
Mechanism	Effort creates change	Selection of existing variants
Inheritance	Acquired traits inherited	Only genetic traits inherited
Direction	Driven by need/desire	No directionality, random variation
Evidence	Intuitive but unsupported	Supported by breeding, fossils, molecular data

✍ Worked Example

The Giraffe's Neck — Two Explanations:

Lamarck's explanation (incorrect): Giraffes stretched their necks to reach high leaves. The stretched necks were inherited by offspring. Over generations, necks became longer.

Darwin's explanation (correct): Variation in neck length existed within giraffe populations. Giraffes with longer necks could access more food, survived better, and reproduced more. Alleles for longer necks increased in frequency over generations. The population evolved longer necks.

The key difference: Darwin's mechanism requires **pre-existing variation** and **differential reproduction**, not individual effort.

☞ Examiner Tip

When explaining the paradigm shift, emphasize that Darwin proposed a **testable mechanism** based on existing variation and selection, whereas Lamarck's theory made predictions that were not supported by evidence. Paradigm shifts occur when accumulating evidence cannot be explained by the old theory.

✘ Common Pitfall

Do not describe evolution as goal-directed or purposeful. Natural selection has no foresight or intention — it simply favors whatever traits happen to enhance survival and reproduction in the current environment.

2 D4.1.2 — Roles of Mutation and Sexual Reproduction in Generating Variation

★ Key Concept

Natural selection can only operate if there is **heritable variation** in traits within a population. Two main sources generate this variation:

1. **Mutation** — Creates **new alleles** (the ultimate source of all genetic novelty)
2. **Sexual reproduction** — Creates **new combinations** of existing alleles

2.1 Mutation as the Source of New Alleles

✎ Definition

A **mutation** is a random change in the DNA sequence that creates a new allele which did not previously exist in the population.

- Mutations occur during DNA replication, from mutagens (radiation, chemicals), or spontaneously
- Most mutations are **neutral or harmful**, but some are **beneficial** in certain environments
- Mutation rate is slow (10^{-8} to 10^{-9} per base per generation) but over evolutionary time provides substantial new genetic material
- Mutations are the **only source of entirely new alleles**

2.2 Sexual Reproduction as the Source of New Combinations

Sexual reproduction does **NOT** create new alleles — it creates new **combinations** of existing alleles through three mechanisms:

1. **Crossing over** (recombination) during prophase I of meiosis
   - Homologous chromosomes exchange DNA segments
   - Creates new allele combinations on the same chromosome
2. **Independent assortment** during metaphase I of meiosis
   - Maternal and paternal chromosomes randomly distributed to gametes
   - 2^n possible combinations (where n = haploid number; in humans: $2^{23} = 8.4$ million)
3. **Random fertilization**
   - Any sperm can fertilize any egg
   - Multiplies variation from meiosis

Source	Creates New Alleles?	Creates New Combinations?	Rate
Mutation	Yes	No	Slow (10^{-8} per base)
Meiosis	No	Yes	Every gamete formation
Random fertilization	No	Yes	Every fertilization event

☞ **Examiner Tip**

When comparing mutation and sexual reproduction, be clear that:

- Mutation is the **only source of new alleles**
- Sexual reproduction is the **only source of new combinations**
- Both are essential for evolution, but they contribute different types of variation

→ **Links to Other Topics**

Link to D3.1 Reproduction: Meiosis creates gametes with genetic variation through crossing over and independent assortment. Random fertilization further increases variation.

Link to D1.3 Mutations: Mutations can be caused by replication errors, radiation, or chemicals. Only mutations in germline cells can be passed to offspring.

3 D4.1.3 — Overproduction of Offspring and Competition for Resources

★ Key Concept

Organisms produce far more offspring than can possibly survive to reproductive age. This **overproduction** leads to **competition for resources**, creating the conditions for natural selection to operate.

✎ Definition

Carrying capacity is the maximum population size that an environment can sustainably support with available resources.

3.1 Examples of Overproduction

Species	Offspring Produced	Typical Survivors to Reproduction
Codfish	5 million eggs	∼2 (replacement rate)
Oak tree	10,000 acorns/lifetime	∼1–2 reach maturity
Salmon	Thousands of eggs	∼2
Human (historically)	6–8 children	∼2–4 survived to adulthood

3.2 Intraspecific vs. Interspecific Competition

Type	Intraspecific Competition	Interspecific Competition
Definition	Competition **within** a species	Competition **between** different species
Intensity	Most intense (identical needs)	Less intense (unless niches overlap)
Examples	Male deer competing for territory; oak seedlings competing for light	Different bird species competing for insects
Evolutionary impact	Drives natural selection most powerfully	Can lead to niche differentiation

✘ Common Pitfall

Students often confuse **intra**specific (within a species) and **inter**specific (between species) competition. Remember: **intra** = internal/within; **inter** = international/between.

✏ Diagram Required

Connection to Natural Selection:

Overproduction → Competition for limited resources → Not all survive equally → Differential survival and reproduction → **Natural Selection**

This creates the "struggle for existence" that Darwin described as essential for natural selection.

4 D4.1.4 — Abiotic Factors as Selection Pressures

✎ Definition

Abiotic factors are non-living environmental factors (physical and chemical) that influence which individuals survive and reproduce.

★ Key Concept

Abiotic selection pressures include:

- **Temperature** — Extreme heat or cold selects for tolerance adaptations
- **Water availability** — Drought or flooding conditions
- **Salinity** — Salt concentration in soil or water
- **pH** — Acidity or alkalinity of environment
- **Light availability** — Affects photosynthetic organisms
- **Oxygen availability** — Low oxygen in water or at high altitude
- **Natural disasters** — Fires, floods, hurricanes, volcanic eruptions
- **Soil nutrients** — Nitrogen, phosphorus, minerals

4.1 How Abiotic Factors Act as Selection Pressures

1. Individuals **vary** in tolerance to abiotic factors (genetic variation)
2. Those with alleles conferring greater tolerance **survive better**
3. Survivors **reproduce more**, passing tolerance alleles to offspring
4. Over generations, population becomes **better adapted** to abiotic conditions

Abiotic Factor	Selection Pressure	Example Adaptation
Cold temperature	Kills cold-sensitive individuals	Antifreeze proteins, thick fur
Drought	Kills individuals losing too much water	Deep roots, waxy cuticle, CAM photosynthesis
High salinity	Disrupts osmotic balance	Salt excretion glands, salt-tolerant enzymes
Low light	Limits photosynthesis	Large thin leaves, shade-tolerant pigments
Air pollution	Changed background color (peppered moths)	Melanic coloration for camouflage

✍ Worked Example

Peppered Moths and Industrial Pollution:
Before the Industrial Revolution, light-colored peppered moths (*Biston betularia*) were well camouflaged on lichen-covered tree bark. Dark (melanic) moths were rare (∼2%). During industrialization, air pollution killed lichens and darkened tree bark with soot. This **abiotic change** created a new selection pressure:

- Dark moths became better camouflaged, avoiding predation
- Light moths became more visible to predators
- Dark moth frequency increased to ∼95% in polluted areas

After pollution controls (Clean Air Acts), the pattern reversed. This demonstrates natural selection responding to changing abiotic conditions.

→ Links to Other Topics

Link to D4.3 Climate Change: Global warming, ocean acidification, and changing rainfall patterns are creating novel abiotic selection pressures. Populations with greater genetic diversity have more potential to adapt.
Link to B4.1 Adaptation to Environment: Organisms show structural, physiological, and behavioral adaptations to abiotic conditions in their environment.

5 D4.1.5 — Differences in Adaptation, Survival and Reproduction as the Basis for Natural Selection

✎ Definition

Fitness in biology refers to the reproductive success of an individual relative to others in the population — specifically, the heritable factors that influence survival to reproductive age and reproductive output within a specific ecological niche.

✘ Common Pitfall

Fitness does **NOT** mean physical strength, health, or athletic ability! This is a common misconception. Biological fitness is about **passing genes to the next generation**, not about being physically strong.

5.1 Components of Fitness

1. **Survival to reproductive age** — Must live long enough to reproduce
2. **Reproductive output** — Number of offspring produced
3. **Offspring viability** — Offspring must survive and reproduce themselves

★ Key Concept

Key characteristics of fitness:

- Fitness is **relative** (compared to other individuals in the population)
- Fitness is **environment-specific** (what is fit in one environment may be unfit in another)
- Fitness is about **genes passed on**, not individual survival
- Greater fitness = higher **probability** of passing on genes, not a guarantee

✍ Worked Example

Question: Who has higher biological fitness — a bodybuilder with no children, or a physically frail person with 6 surviving children who reproduce?

Answer: The frail person with 6 children has **much higher fitness**. Despite being physically weaker, they have successfully passed their genes to the next generation. The bodybuilder, regardless of physical strength, has **zero fitness** because no genes were passed on. Fitness is measured by reproductive success, not physical condition.

5.2 Types of Adaptations

✎ **Definition**

An **adaptation** is a heritable trait that enhances fitness in a particular environment. Adaptations result from past natural selection.

Adaptation Type	Definition	Examples
Structural	Physical features of organism	Camouflage, thick fur, streamlined body
Physiological	Internal biochemical/metabolic processes	Antifreeze proteins, venom production, C4 photosynthesis
Behavioral	Actions that enhance survival/reproduction	Migration, hibernation, courtship rituals

☞ **Examiner Tip**

When defining fitness in an exam, always emphasize:

1. It is about **reproductive success**
2. It is **relative** to other individuals
3. It is measured in a **specific environment**

Never define fitness as "strength" or "health."

6 D4.1.6 — Requirement that Traits are Heritable for Evolutionary Change

★ Key Concept

For natural selection to cause evolutionary change, traits **must be heritable** — encoded in DNA and passed from parents to offspring through gametes. Acquired traits cannot contribute to evolutionary change.

Aspect	Heritable Traits	Acquired Traits
Encoded in DNA?	Yes	No
In gametes?	Yes	No
Inherited by offspring?	Yes	No
Can lead to evolution?	Yes	No
Examples	Eye color, blood type, disease susceptibility	Muscles from exercise, scars, tattoos, learned behaviors

6.1 Why Heritability is Required

1. Natural selection favors individuals with advantageous traits
2. These individuals survive better and/or reproduce more
3. **If traits are heritable** → offspring inherit advantageous traits → traits become more common
4. **If traits are acquired** → offspring don't inherit them → no change in population

✍ Worked Example

The Tattoo Analogy:
Imagine a person gets a tattoo that makes them more attractive to potential mates, increasing their reproductive success. Will their children be born with this tattoo?
No. The tattoo is an **acquired trait** — it is not encoded in DNA. The genes in the gametes are unchanged by the tattoo. Each generation would need to acquire the tattoo independently.
This illustrates why acquired traits cannot lead to evolutionary change: they do not change the DNA sequence in gametes, so they cannot be passed to offspring.

✘ Common Pitfall

Individuals do not evolve! This is a critical distinction:

- **Individuals** are selected (survive and reproduce differentially)
- **Populations** evolve (allele frequencies change over generations)

An individual's genotype is fixed from fertilization to death. Evolution happens at the population level over multiple generations.

→ Links to Other Topics

Link to D1.3 Mutations: Mutations change the DNA sequence, creating new heritable alleles. Only mutations in germline cells (cells that produce gametes) can be inherited.
Link to D3.2 Inheritance: Mendelian genetics describes how heritable traits are passed from parents to offspring through the segregation and independent assortment of alleles.

7 D4.1.7 — Sexual Selection as a Selection Pressure

✎ Definition

Sexual selection is a form of natural selection that acts on traits affecting **mating success**, rather than survival. It can favor traits that reduce survival but increase mating success.

7.1 Two Forms of Sexual Selection

Type	Intersexual Selection (Mate Choice)	Intrasexual Selection (Competition)
Mechanism	One sex (usually females) chooses mates	One sex (usually males) competes for mates
Traits favored	Bright colors, displays, ornaments	Large size, weapons, aggression
Examples	Peacock tail, bird of paradise plumage, guppy spots	Deer antlers, elephant seal size, lion manes
Memory aid	"Choice" — between sexes	"Competition" — within a sex

★ Key Concept

Why females are typically choosy:

- Greater investment in offspring (eggs are larger and more costly than sperm)
- Fewer total offspring possible (limited by egg production, pregnancy)
- Must choose wisely to maximize offspring quality

Why males typically compete:

- Lower investment per offspring (sperm are cheap to produce)
- Reproductive success limited by access to females
- High variance in male success (some mate many times, others never)

7.2 Sexual Dimorphism

✎ Definition

Sexual dimorphism refers to phenotypic differences between males and females of the same species, often resulting from sexual selection.

Examples include: male lions with manes; male peacocks with elaborate tails; male elephant seals 3× the size of females.

7.3 Conflict Between Sexual and Natural Selection

★ Key Concept

Sexual selection can favor traits that **reduce survival** but **increase mating success**:

- **Peacock tail:** Attracts females (sexual selection favors) BUT makes flying difficult and attracts predators (natural selection opposes)
- **Bright coloration:** Attractive to females BUT visible to predators
- The actual trait represents a **balance** between sexual selection and natural selection

✏ Diagram Required

Conflicting Selection Pressures:

Male trait (e.g., bright coloration)

↓

Sexual Selection	**Natural Selection**
(mate attraction)	(survival)
↓	↓
Favors MORE color	Favors LESS color

↓

Actual phenotype = Balance between opposing pressures

8 D4.1.8 — Modelling of Sexual and Natural Selection (Endler's Guppy Experiments)

★ Key Concept

John Endler's experiments with Trinidadian guppies (*Poecilia reticulata*) demonstrate the balance between sexual selection and natural selection in action. These experiments provide direct, observable evidence of evolution.

8.1 Experimental Design

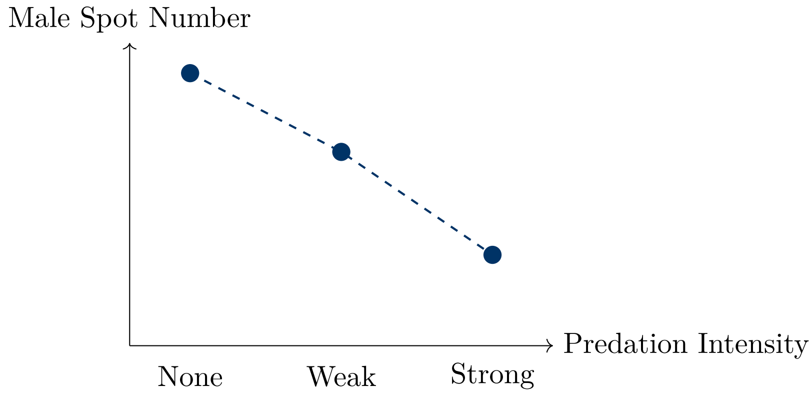
- **Independent variable:** Predation pressure (none, weak, strong)
- **Dependent variable:** Number and size of colored spots on male guppies
- **Predators used:**
  - None (laboratory greenhouse pools)
  - Weak: *Rivulus hartii* (small fish, eats only baby guppies)
  - Strong: *Crenicichla alta* (pike cichlid, eats adult guppies)
- **Duration:** Multiple generations to allow evolution

8.2 Key Findings

Predation Level	Male Coloration	Interpretation
No predation	Many colorful spots	Sexual selection dominates; females choose colorful males with no predator cost
Weak predation	Moderate coloration	Slight natural selection pressure; sexual selection still prominent
Strong predation	Significantly fewer spots	Natural selection dominates; colorful males eaten more often

✏ Diagram Required

Graphical Representation:



Pattern: Negative correlation between predation intensity and male coloration. As predation increases, natural selection against visibility outweighs sexual selection for attractiveness.

✍ Worked Example

Question: Predict what would happen to male guppy coloration if predators were removed from a high-predation population.

Answer: Male coloration would **increase** over subsequent generations. With predators removed, natural selection against bright colors would no longer operate. Sexual selection (female preference for colorful males) would dominate, and alleles for brighter coloration would increase in frequency. This is exactly what Endler observed in his experiments.

☞ Examiner Tip

When interpreting Endler's data:

1. Identify **both** types of selection (sexual AND natural)
2. Explain the **mechanism** (how predation changes allele frequencies)
3. Recognize this as **evidence for evolution** (observable change in allele frequencies)

4. Note that spots don't disappear completely — there is a **balance** between opposing selection pressures

Higher Level Content

☆ AHL Content

The following content (D4.1.9 – D4.1.15) is for **Higher Level students only**. It covers population genetics concepts including gene pools, allele frequencies, Hardy-Weinberg equilibrium, types of selection, and artificial selection.

9 D4.1.9 — Concept of the Gene Pool [HL]

✎ Definition

The **gene pool** is all the genes and their different alleles present in an interbreeding population at a given time.

★ Key Concept

For a diploid population of N individuals:

- The gene pool contains $2N$ copies of each gene
- Includes all alleles for all genes (both common and rare)
- Represents the total genetic diversity of the population

9.1 Gene Pool Size vs. Population Size

✘ Common Pitfall

A large population can have a small gene pool! Gene pool "size" refers to **genetic diversity**, not number of individuals.

Population Type	Individuals	Genetic Diversity	Gene Pool Size
Cheetahs (bottleneck)	Thousands	Very low	Small
Crop monoculture	Millions	Zero (clones)	Very small
Healthy wild population	Large	High	Large

✍ Worked Example

Calculating Allele Frequencies from a Gene Pool:
Population of 5 diploid individuals with genotypes: PP, Pp, pp, pp, pp
Step 1: Count alleles

- P alleles: $2 + 1 + 0 + 0 + 0 = 3$
- p alleles: $0 + 1 + 2 + 2 + 2 = 7$
- Total alleles: 10 (because $5 \times 2 = 10$ for diploid organisms)

Step 2: Calculate frequencies

- Frequency of P $= 3/10 = 0.3$ (or 30%)
- Frequency of p $= 7/10 = 0.7$ (or 70%)
- Check: $0.3 + 0.7 = 1.0$ ✓

10 D4.1.10 — Allele Frequencies of Geographically Isolated Populations [HL]

✎ Definition

Allele frequency is the proportion of a particular allele among all alleles for that gene in a population. It is expressed as a decimal (0 to 1) or percentage (0% to 100%).

★ Key Concept

Allele frequencies can vary dramatically between geographically isolated populations due to:

- Different selection pressures in different environments
- Genetic drift (random changes, especially in small populations)
- Founder effects (small number of colonizers)
- Historical bottlenecks

10.1 Example: Sickle Cell Allele (HbS)

Region	HbS Frequency	Explanation
Sub-Saharan Africa	10–40%	Heterozygotes resistant to malaria (balancing selection)
Northern Europe	<1%	No malaria; HbS only causes disease (negative selection)
Mediterranean	5–15%	Historical malaria presence

☞ **Examiner Tip**

The sickle cell example demonstrates **heterozygote advantage**: HbA/HbS heterozygotes have higher fitness in malaria-endemic regions because they are resistant to malaria but do not suffer from sickle cell disease. This maintains both alleles in the population at intermediate frequencies.

11 D4.1.11 — Changes in Allele Frequency as a Consequence of Natural Selection [HL]

✎ **Definition**

Neo-Darwinism (the Modern Synthesis) combines Darwin's theory of natural selection with Mendelian genetics. It defines evolution as a **change in allele frequencies in a gene pool over time**.

★ **Key Concept**

This definition of evolution is powerful because it is:

- **Quantifiable** — allele frequencies can be measured
- **Precise** — not just "change in species"
- **Detectable** — can identify evolution even when phenotypes haven't obviously changed

11.1 Mechanism: How Natural Selection Changes Allele Frequencies

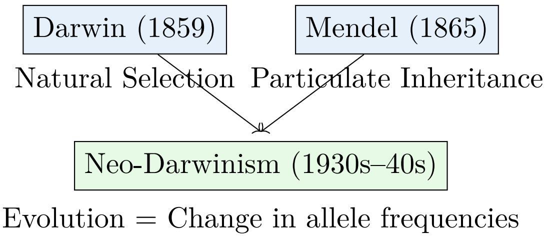
1. **Variation exists** — Different alleles present in population
2. **Phenotypic differences** — Alleles cause phenotypic differences affecting survival/reproduction
3. **Differential survival/reproduction** — Some phenotypes more successful
4. **Differential gene transmission** — Successful individuals pass more alleles to offspring

5. **Allele frequency change** — Favored alleles become more common

6. **Population evolves** — Gene pool composition changes

✏ Diagram Required

Neo-Darwinism Synthesis:



Darwin knew inheritance was needed but didn't know the mechanism. Mendel discovered genes but his work wasn't widely known until 1900. The integration of both theories created modern evolutionary biology.

☞ Examiner Tip

A change in allele frequencies **is** evolution, even if:

- No new species has developed
- No obvious phenotypic change is visible
- The change is small

This is a more nuanced understanding of evolution than simply "new species forming."

12 D4.1.12 — Differences Between Directional, Disruptive and Stabilizing Selection [HL]

★ Key Concept

All three types of selection change allele frequencies (i.e., cause evolution), but they affect variation in different ways and produce different patterns of change.

12.1 Comparison of Selection Types

Aspect	Stabilizing	Directional	Disruptive
Favored phenotype	Intermediate	One extreme	Both extremes
Effect on mean	No change	Shifts	No change (or splits)
Effect on variation	Decreases	May decrease	Increases
Distribution shape	Narrower bell curve	Shifted bell curve	Bimodal (two peaks)
Commonness	Most common	Common	Least common
Typical scenario	Stable environment	Environmental change	Heterogeneous environment
Example	Human birth weight	Antibiotic resistance	African seed-crackers

✏ Diagram Required

Graphical Representation of Selection Types:
Stabilizing Selection:

- Middle phenotype favored; extremes selected against
- Bell curve becomes **narrower** (reduced variance)
- Mean stays the same
- Example: Human birth weight — intermediate weight has highest survival

Directional Selection:

- One extreme phenotype favored
- Bell curve **shifts** toward favored extreme
- Mean changes
- Example: Bacteria becoming antibiotic resistant — resistance increases over time

Disruptive Selection:

- Both extremes favored; middle selected against
- Bell curve becomes **bimodal** (two peaks)
- Variation increases
- Example: African seed-cracker finches — small beaks for soft seeds, large beaks for hard seeds

✍ **Worked Example**

Why is human birth weight an example of stabilizing selection?

- Intermediate birth weight (3–4 kg) has the **highest survival rate**
- **Very low birth weight:** Babies are underdeveloped, with higher mortality
- **Very high birth weight:** Difficult delivery, higher mortality for both mother and baby
- Selection **favors the intermediate** and **removes extremes**
- Result: Birth weight distribution is narrower than it would be without selection

✘ **Common Pitfall**

Even stabilizing selection causes evolution! Although the mean doesn't change, allele frequencies for extreme phenotypes decrease. All three types of selection change allele frequencies.

13 D4.1.13 — Hardy-Weinberg Equation [HL]

✦ **Formula / Equation**

The Hardy-Weinberg Equations:
Allele frequencies:

$$p + q = 1$$

Genotype frequencies:

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

Where:

- p = frequency of dominant allele (e.g., A)
- q = frequency of recessive allele (e.g., a)
- p^2 = frequency of homozygous dominant (AA)
- $2pq$ = frequency of heterozygotes (Aa)
- q^2 = frequency of homozygous recessive (aa)

★ Key Concept

Critical distinction:

- p and q are **allele frequencies** (proportion of alleles)
- p^2, $2pq$, and q^2 are **genotype frequencies** (proportion of individuals)

13.1 Problem-Solving Strategy

1. **Identify what you know:** Usually q^2 (frequency of homozygous recessive phenotype)
2. **Calculate q:** Take the square root of q^2
3. **Calculate p:** Use $p = 1 - q$
4. **Calculate carrier frequency:** Use $2pq$
5. **Check:** Ensure $p + q = 1$ and $p^2 + 2pq + q^2 = 1$

✍ Worked Example

Cystic Fibrosis Carrier Frequency:
Cystic fibrosis is an autosomal recessive disease affecting about 1 in 3,500 people. What proportion of the population are carriers?
Solution:

1. $q^2 = 1/3500 = 0.000286$ (frequency of affected individuals, genotype cc)
2. $q = \sqrt{0.000286} = 0.0169$ (frequency of recessive allele c)
3. $p = 1 - 0.0169 = 0.9831$ (frequency of normal allele C)
4. Carrier frequency $= 2pq = 2 \times 0.9831 \times 0.0169 = 0.0332$

Answer: About 3.3% or **1 in 30** people are carriers of the CF allele. This is much higher than the disease frequency (1 in 3,500)!

☞ Examiner Tip

Always show your working in Hardy-Weinberg calculations:

1. State the formula you are using
2. Substitute values
3. Calculate step by step
4. Check your answer (do frequencies sum to 1?)

Common error: Confusing p with p^2. The allele frequency is NOT the genotype frequency!

14 D4.1.14 — Hardy-Weinberg Conditions for Genetic Equilibrium [HL]

✎ Definition

Genetic equilibrium is a state where allele frequencies remain constant from generation to generation — i.e., no evolution is occurring.

★ Key Concept

For Hardy-Weinberg equilibrium, **ALL FIVE** conditions must be met:

1. **No mutations** — No new alleles created
2. **Random mating** — No mate choice, inbreeding, or assortative mating
3. **No gene flow** — No immigration or emigration
4. **Large population size** — No genetic drift
5. **No natural selection** — All genotypes have equal fitness

Condition	Reality in Nature	Effect When Violated
No mutations	Mutations always occur ($\sim 10^{-9}$/base/gen)	New alleles introduced
Random mating	Mate choice is common	Genotype frequencies change
No gene flow	Migration happens	Alleles added/removed
Infinite population	All populations finite	Random drift occurs
No selection	Fitness varies	Allele frequencies shift

★ Key Concept

Key Insight: These conditions are almost **never all met** in natural populations. Therefore, real populations are almost always evolving to some degree.
Hardy-Weinberg serves as a **null hypothesis**: if observed frequencies match H-W predictions, the population may be in equilibrium. If they don't match, evolutionary forces are acting.

✍ Worked Example

Question: A population of bacteria shows rapidly increasing frequency of antibiotic resistance alleles. Which Hardy-Weinberg condition is being violated?
Answer: The "no natural selection" condition is violated. Antibiotic use creates a strong selection pressure: resistant bacteria survive and reproduce while susceptible bacteria die. This causes directional selection, increasing the frequency of resistance alleles.

☞ **Examiner Tip**

Memorize all five conditions. A common exam question asks you to list them or explain why H-W equilibrium is rare. Remember: if **any one** condition is violated, the population is evolving.

15 D4.1.15 — Artificial Selection by Deliberate Choice of Traits [HL]

✎ **Definition**

Artificial selection (selective breeding) is selection for desired traits by humans, who deliberately choose which individuals reproduce.

15.1 Comparison: Artificial vs. Natural Selection

Aspect	Natural Selection	Artificial Selection
Selective agent	Environment, predators, disease	Humans
Traits favored	Enhance survival & reproduction	Useful or desirable to humans
Speed	Usually slow (many generations)	Can be very rapid
Direction	No predetermined goal	Directed toward specific goal
Fitness effect	Increases fitness in nature	May decrease fitness in nature
Example	Antibiotic resistance, camouflage	Dog breeds, crop varieties

15.2 Examples of Artificial Selection

- **Dogs:** All breeds from wolf ancestors in ∼15,000 years (Chihuahua to Great Dane)
- **Crops:** Wild *Brassica oleracea* gave rise to broccoli, cauliflower, kale, cabbage, Brussels sprouts
- **Corn:** Domesticated from teosinte (tiny, few kernels) to modern corn (large, many kernels)
- **Cattle:** Dairy cows selected for milk; beef cattle for muscle mass

✘ Common Pitfall

Antibiotic resistance is NATURAL selection, not artificial selection!
Common misconception: Students think antibiotic resistance is artificial selection because humans use antibiotics.
Correct understanding:

- Humans do NOT choose which bacteria survive
- Humans do NOT breed bacteria for resistance
- The environment (antibiotics) selects for resistance
- It is an **unintended consequence**, not deliberate breeding

Therefore, antibiotic resistance is natural selection, even though humans created the selective pressure.

→ Links to Other Topics

Link to C3.2 Defence Against Disease: Antibiotic resistance evolves through natural selection when bacteria are exposed to antibiotics. Resistant individuals survive and reproduce, increasing the frequency of resistance alleles in the population.
Link to A4.1 Evolution: Artificial selection demonstrates that heritable variation exists and can be selected, providing evidence for evolution by natural selection.

16 Diagram Practice

Use these spaces to practice drawing essential diagrams for this topic. Drawing from memory strengthens recall and exam readiness.

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17 Common Pitfalls and Examiner Tips

17.1 Key Misconceptions to Avoid

✘ Common Pitfall

"Individuals evolve."

Correction: Populations evolve, not individuals. An individual's genotype is fixed from birth. Evolution is change in allele frequencies across a population over generations.

✘ Common Pitfall

"Evolution is goal-directed or purposeful."

Correction: Natural selection has no foresight. It simply favors whatever traits happen to enhance survival and reproduction **now**. There is no planning for future environments.

✘ Common Pitfall

"Fitness means physical strength."

Correction: Biological fitness = **reproductive success**. A weak individual with many offspring has higher fitness than a strong individual with none.

✘ Common Pitfall

"Acquired traits can be inherited."

Correction: Only traits encoded in DNA (heritable traits) can be passed to offspring. Muscles from exercise, scars, and learned behaviors are not inherited.

✘ Common Pitfall

"Natural selection and sexual selection are the same thing."

Correction: Sexual selection can favor traits that **reduce survival** but increase mating success. The peacock's tail is disadvantageous for survival but advantageous for mating.

✘ Common Pitfall

[HL] **"Large population = large gene pool."**

Correction: Gene pool size refers to genetic **diversity**, not number of individuals. A large population can have low diversity (e.g., cheetahs after a bottleneck).

✘ Common Pitfall

[HL] **"Antibiotic resistance is artificial selection."**

Correction: Antibiotic resistance is **natural selection**. Humans don't choose which bacteria reproduce — the environment (antibiotics) does the selecting.

17.2 Examiner Tips for High Marks

☞ **Examiner Tip**

Defining natural selection: Always include:

1. Heritable variation exists
2. Differential survival **and** reproduction
3. Change in allele frequencies over generations

☞ **Examiner Tip**

Explaining examples: Use the complete mechanism:

1. Describe the variation in the population
2. Identify the selection pressure
3. Explain which phenotype has higher fitness and why
4. State that alleles for the favored trait increase in frequency
5. Conclude that the population evolves

☞ **Examiner Tip**

[HL] Hardy-Weinberg calculations:

1. Always show your working
2. State which formula you are using
3. Check that $p + q = 1$ and $p^2 + 2pq + q^2 = 1$
4. Don't confuse allele frequency (p, q) with genotype frequency (p^2, $2pq$, q^2)
5. Remember: you usually start with q^2 (homozygous recessive phenotype)

☞ **Examiner Tip**

[HL] Types of selection: When identifying the type:

- **Stabilizing:** Mean unchanged, variance decreases (narrower curve)
- **Directional:** Mean shifts in one direction
- **Disruptive:** Two peaks form (bimodal distribution)

18 Summary: Four Requirements for Natural Selection

★ Key Concept

For natural selection to occur, **all four** conditions must be present:

1. **Variation** — Individuals in the population differ in their traits
2. **Heritability** — The variation has a genetic basis (encoded in DNA)
3. **Overproduction** — More offspring are produced than can survive
4. **Differential fitness** — Some variants survive and reproduce better than others

Memory aid: VHOD — Variation, Heritability, Overproduction, Differential fitness
When all four are present, allele frequencies change over generations = **evolution by natural selection**.

→ Links to Other Topics

Final Topic Connections:

- **A4.1 Evolution and Speciation:** Natural selection is the mechanism; speciation is the long-term outcome
- **D1.3 Mutations:** Provide the raw material (new alleles) for selection
- **D3.1 Reproduction:** Sexual reproduction shuffles alleles; meiosis generates variation
- **C3.2 Defence Against Disease:** Antibiotic resistance demonstrates natural selection in real time
- **D4.2 and D4.3:** Environmental changes and climate change create new selection pressures