

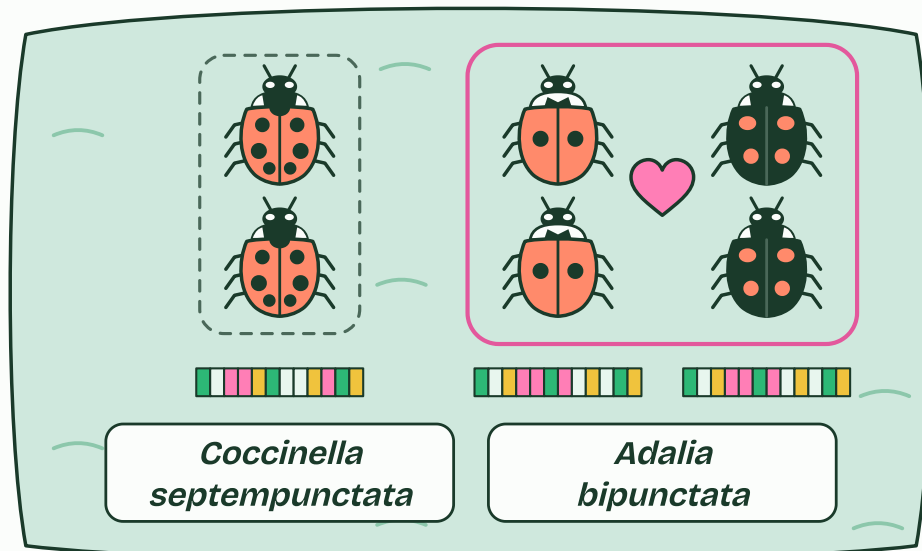
REVISION GUIDE

What makes a *species*, and how we tell them apart

Diversity of organisms

No two organisms are alike, yet we name and sort them into species. Here is how: traits, breeding, chromosomes and whole genomes, and the keys and DNA barcodes that identify what lives in a habitat.

Two species, two names



12 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-a3-1-diversity-of-organisms



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By the end you can

- ☐ Explain why variation between organisms is a defining feature of life, and how Linnaeus used shared traits to define a species A3.1.1, A3.1.2
- ☐ Name an organism with a binomial name written to the rules, and say what two species of one genus share A3.1.3
- ☐ State the biological species concept, give challenges to it, and explain why gradual speciation makes the line between populations and species arbitrary A3.1.4, A3.1.5
- ☐ Say that species differ in chromosome number, using humans (46) and chimpanzees (48), and why diploid numbers are even A3.1.6
- ☐ Classify chromosomes in a karyogram by banding, length and centromere position, and evaluate the evidence that human chromosome 2 arose from a fusion A3.1.7
- ☐ Describe a genome, how SNPs give diversity within a species, and why variation between species is much larger A3.1.8, A3.1.9
- ☐ Compare genome sizes of different groups from a database and judge whether size measures complexity A3.1.10
- ☐ Describe how whole genome sequencing has become faster and cheaper, and give current and future uses A3.1.11
- ☐ Explain why the biological species concept fails for asexual species and for bacteria that pass genes sideways A3.1.12
- ☐ Explain why parents with different chromosome numbers are unlikely to have fertile offspring A3.1.13
- ☐ Build and test a dichotomous key for local organisms A3.1.14
- ☐ Explain how DNA barcodes and environmental DNA identify the species in a habitat rapidly A3.1.15

Tick each one when you can do it without the book.

A3.1.1

A3.1.2

VARIATION AND SPECIES

01 No two beetles are *alike*, and we sort them anyway

Look along a row of beetles, or round a classroom. No two individuals are identical in every trait. Even identical twins differ, in their fingerprints, their scars and their tans. This **variation** is a defining feature of life, and it has patterns. Eight cards are enough to find them.

Shuffle the cards in the figure, then sort them by colour and by body shape. Colour pairs a round beetle with a long one every time. Body shape gives two tidy groups: every beetle in one is round and every beetle in the other is long, although inside each group the colours, sizes and spots all differ. The trait to sort by is the one that stays the same inside a group.

Patterns like these are the basis for naming and classifying organisms. In the 1700s the Swedish naturalist Carl Linnaeus sorted living things by the traits they share. To him a **species** was a group of organisms with the same body form and structure, its **morphology**. This is the **morphological species concept**. It is a **working definition**: a tool for grouping what biologists find, which can be improved or replaced.

KEY POINTS

- No two individuals are identical in every trait.
- Patterns in variation are the basis for naming and classifying organisms.
- Linnaeus grouped organisms by shared physical traits: the morphological species concept.

KEY TERMS

variation

Differences between individuals of one species, or between groups of organisms.

species

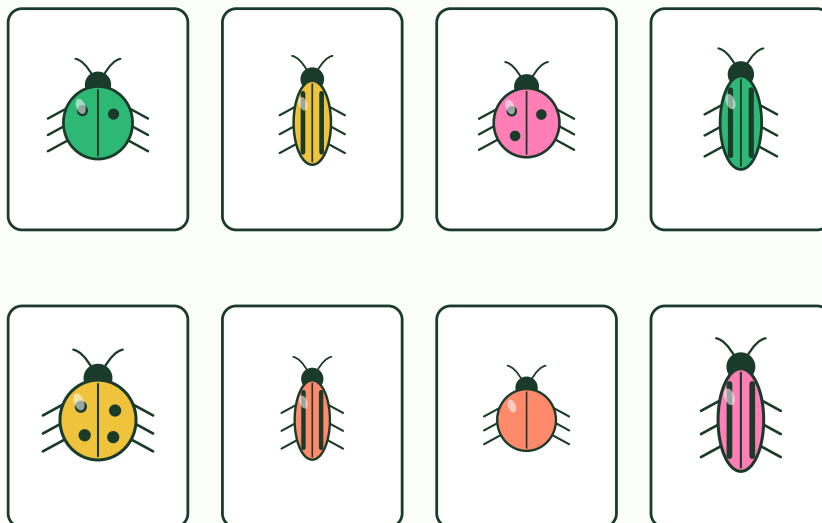
A group of organisms that share a set of traits. In the morphological species concept, the traits are the form and structure of the body.

morphology

The form and structure of an organism: its shape, its parts and how they look.

morphological species concept

The idea, used by Linnaeus, that a species is a group of organisms sharing a distinctive set of physical traits.

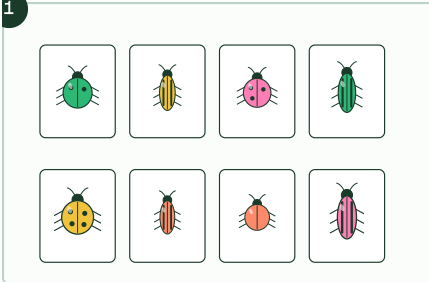


Sort the same eight cards three ways. Look at what is alike inside each group, and at what still differs.

SWITCH IT

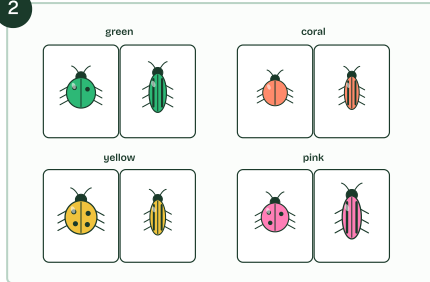
3 SETTINGS

1



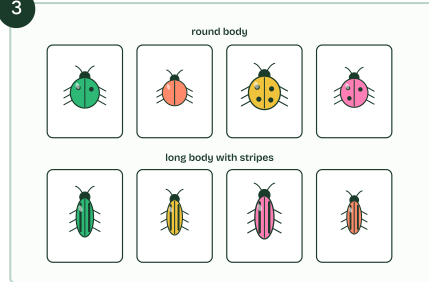
Shuffled

2



By colour

3



By body shape

WATCH OUT

Variation inside a species is not a flaw in the definition. If every member were identical, natural selection would have nothing to act on. A species is a group of *similar* organisms, never identical ones.

EXAMPLE

Some traits vary in steps, like human blood group (A, B, AB or O). Others vary smoothly, like height. Both kinds of pattern help to describe a species.

PREDICT

Identical twins share all their DNA. Are they identical in every trait?

- (A) Yes: identical DNA gives identical traits in every way
- (B) No: fingerprints, scars and tans differ even so
- (C) Yes in every physical trait, but not in behaviour

Decide before you look. Answer on page 43.

02

A3.1.3 BINOMIAL NAMING

A name with *two parts*

Common names are slippery. “Robin” means one bird in Britain and a different bird in North America, and many species have a dozen names between them. Scientists need one name that means the same thing in every language.

The answer, from Linnaeus, is the **binomial system**: every species gets a two-part name. The first part is the **genus**. The second part picks out one species within it. We are *Homo sapiens*: genus *Homo*, species *sapiens*.

Species in the same genus have similar traits. The lion (*Panthera leo*), the tiger (*P. tigris*) and the leopard (*P. pardus*) are all big cats in one genus, while the domestic cat (*Felis catus*) belongs to another. Even before you meet a name, its first word tells you what kind of organism to expect.

The rules are short. The genus has a capital letter and the species has none. The whole name is in italics when typed and underlined when handwritten. After the first full use, the genus may be shortened to its initial: *H. sapiens*.

Write it right Tap the correct way to write each name.

The human, typed in an essay

The lion

The common chimpanzee

The gut bacterium *Escherichia coli*, shortened after its first use

The fruit fly *Drosophila melanogaster*, shortened

Two of these animals share a genus. Which two?

KEY TERMS

binomial system

The system of naming each species with two parts: its genus, then its species name.

genus

A group of closely related species. The first part of a binomial name.

the lion

Panthera leo

genus

capital letter

species

lower case

one genus, similar traits

P. leo

lion

P. tigris

tiger

P. pardus

leopard

STEP BY STEP

4 STEPS

1

the lion

Panthera leo

A **binomial** name has two words, written in italics.

2

the lion

Panthera leo

genus capital letter species lower case

The first word is the **genus**, with a capital letter. The second names the **species**, in lower case.

3

the lion

Panthera leo

genus capital letter species lower case

one genus, similar traits

Panthera leo *Panthera tigris* *Panthera pardus*

lion tiger leopard

Species in one genus have **similar traits**: lion, tiger and leopard share the genus *Panthera*.

4

the lion

Panthera leo

genus capital letter species lower case

one genus, similar traits

P. leo *P. tigris* *P. pardus*

lion tiger leopard

After the first full use you may shorten the genus to its **initial**: *P. leo*.

WATCH OUT

The species name never stands alone: *leo* means nothing without its genus, because other genera have species with the same second word. And the capital belongs to the genus only: *Homo sapiens*, never *Homo Sapiens*.

REMEMBER IT**The four rules of a binomial name**

G Green	S Sloths	I Inch	A Along
Genus first with a capital letter	Species second all in lower case	Italics underlined if handwritten	Abbreviate the genus to its initial after first use

PREDICT

Two animals are named *Panthera tigris* and *Panthera onca*. What can you say about them?

- ☐ A The same species, because the first word of both names is the same
- ☐ B Different species in different genera, since the second words differ
- ☐ C Two species in one genus, so they share similar traits

Decide before you look. Answer on page 43.

03

A3.1.4 A3.1.5 THE BIOLOGICAL SPECIES CONCEPT

Can they *breed*?

Looks can mislead: males and females of one species may differ, and two species can look almost the same. Many biologists use a different test. The **biological species concept** says a species is a group of organisms that can breed and produce **fertile** offspring.

“Fertile” matters. A horse and a donkey can mate and have a healthy mule, but a mule cannot have young of its own, so horses and donkeys count as two species. The figure runs the test on imagined beetles.

No definition is the last word. Other species concepts group organisms by how alike their DNA is, or by the way of life they share. A species concept is a **working definition**, a tool that helps scientists group what they find, and it is replaced when a better tool comes along.

The breeding test has problems. Fossils cannot be tested. Populations that live far apart may never meet, so nobody knows whether they could breed. Some groups that are called separate species do have fertile young where they meet, as many oaks do. And a few species form a ring around a barrier, where each population breeds with its neighbour but the two ends of the chain do not.

One more problem comes from how species form. **Speciation**, the splitting of one species into two or more, usually happens gradually (you saw it in A4.1). Populations that stop interbreeding grow apart a little at a time. At first they could still breed if they met, and much later they could not. There is no single day when one species becomes two, so deciding whether two populations are one species or two can be arbitrary.

KEY POINTS

- Biological species concept: organisms that can breed and produce fertile offspring.
- Competing definitions exist, and any concept is a working definition.
- Speciation is gradual, so the line between populations and species can be arbitrary.

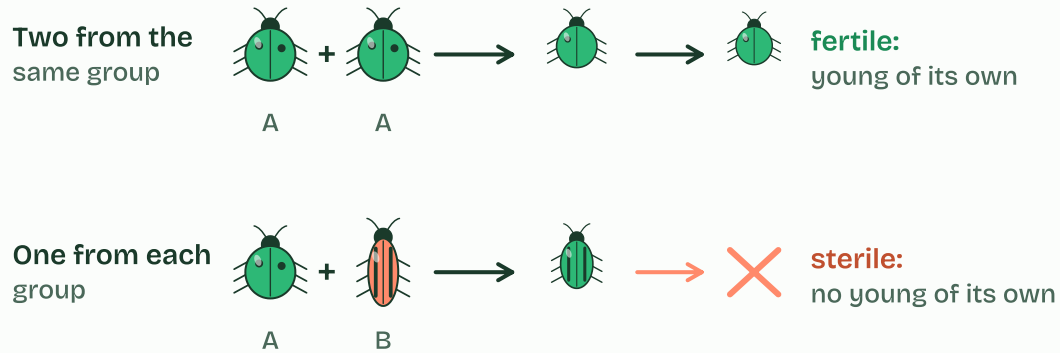
KEY TERMS

biological species concept

The idea that a species is a group of organisms that can breed with each other and produce fertile offspring.

speciation

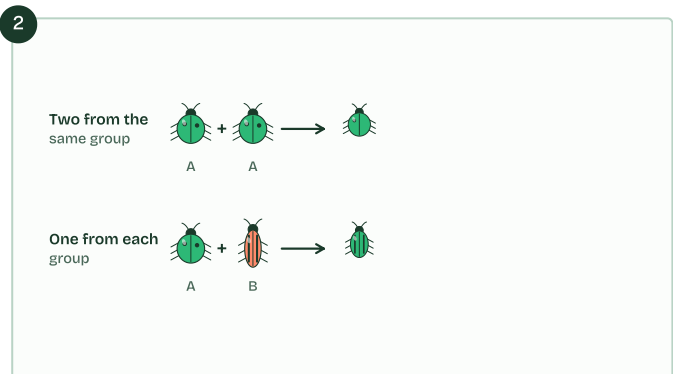
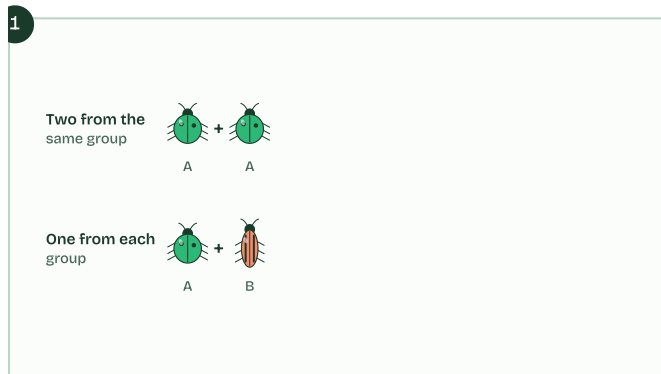
The splitting of one species into two or more.



Groups A and B: two species by this test

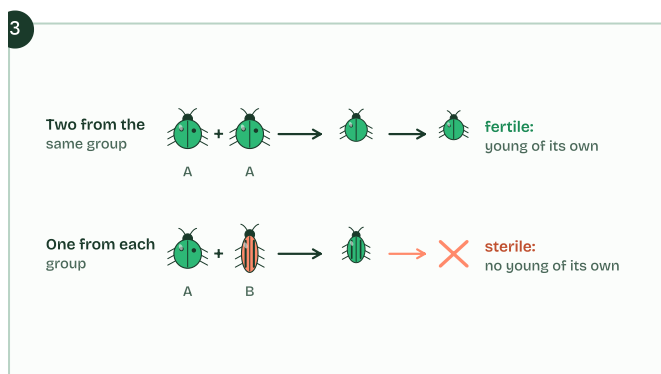
STEP BY STEP

4 STEPS

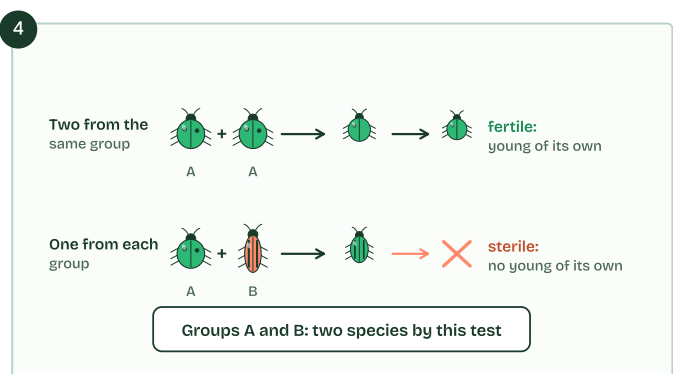


A breeding test: two beetles from the **same group**, and a pair with **one from each** (imagined beetles).

Both pairs have **young**. Mating alone does not decide it.



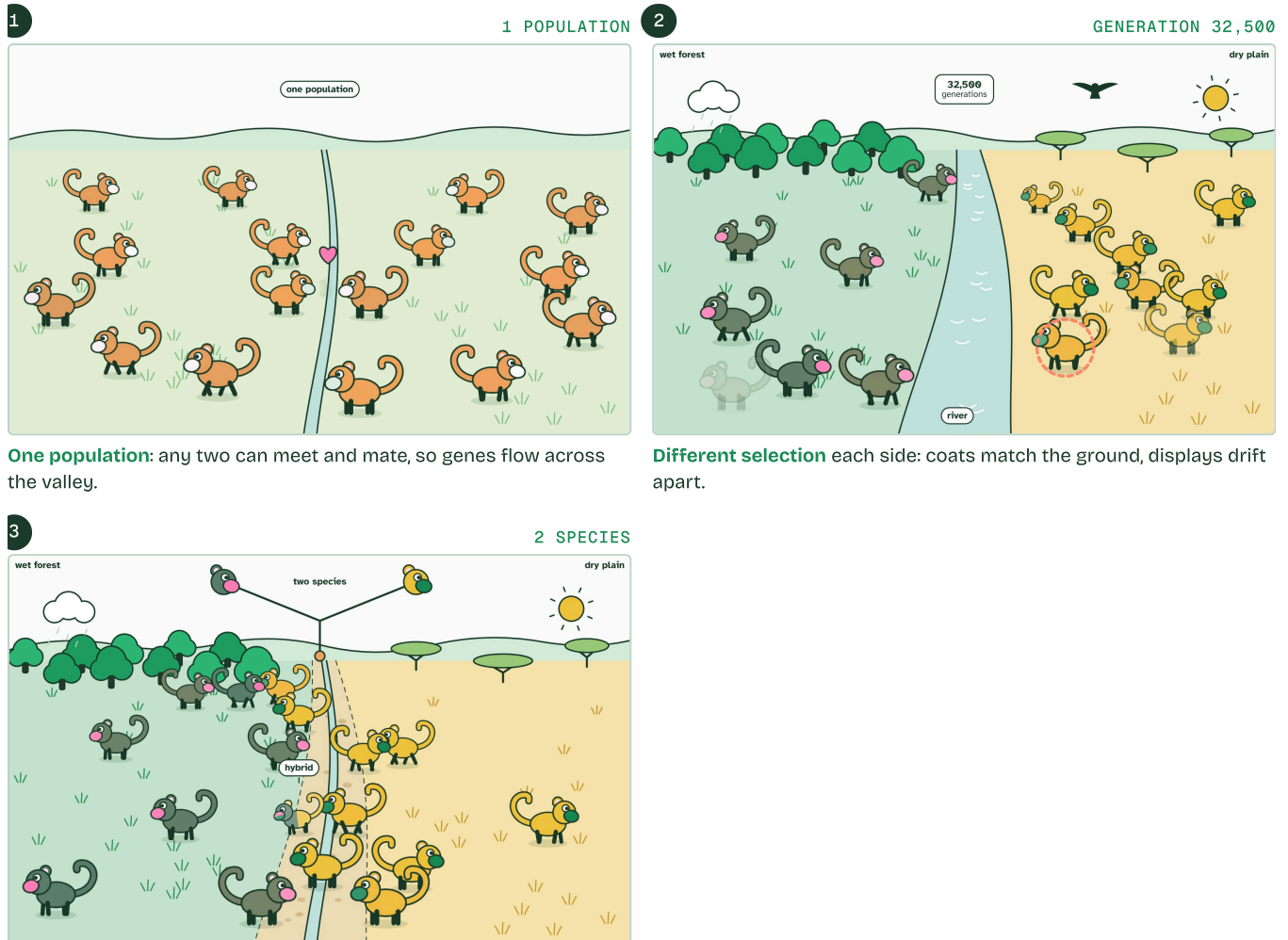
Only the first pair's young are **fertile**. The mixed pair's young cannot have young of their own.



By the biological species concept, A and B are **separate species**.

ANIMATION · WATCH IT HAPPEN: ONE POPULATION BECOMES TWO

3 MOMENTS



One population: any two can meet and mate, so genes flow across the valley.

Different selection each side: coats match the ground, displays drift apart.

Hybrids are rare, weak and often sterile, so the two never merge: **two species**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-a3-1-diversity-of-organisms#species-concept

WATCH OUT

The test is whether they *could* produce fertile offspring, not whether they do. Two populations that never meet may be one species, and two that never meet may be two. Looking at their traits and DNA is often the best that can be done.

PREDICT

Two kinds of snail live on islands 500 km apart, and none has ever crossed the sea. Can the biological species concept say whether they are one species?

- (A) Yes: they have never bred, so they must be two separate species
- (B) Yes: living on separate islands already makes them different species
- (C) Not directly: they have never met, so other evidence is needed

Decide before you look. Answer on page 43.

PREDICT

Two populations of one species stop interbreeding and slowly drift apart over a million years. On which day does one species become two?

- ☐ (A) The day they stop breeding together, because that ends gene flow
- ☐ (B) No single day: it is gradual, so the cut-off is a judgement
- ☐ (C) The day an expert first sees that their traits look different

Decide before you look. Answer on page 43.

04

A3.1.6 CHROMOSOME NUMBERS

Every species has its own *count*

A **chromosome** is a molecule of DNA wrapped up with proteins. The body cells of each species of plant or animal carry a characteristic number of them, and the numbers vary widely. A human body cell has **46** chromosomes. A chimpanzee's has **48**. Those are the only two numbers the syllabus asks you to know.

The figure adds a few more, only to show the range: a fruit fly has 8, a garden pea 14 and a dog 78. A bigger number does not mean a bigger or more advanced organism.

Look at every number: each is even. A body cell is **diploid**, with two copies of each chromosome, one inherited from each parent. The two that match are **homologous chromosomes**, so chromosomes come in pairs: 23 pairs in a human, 24 in a chimpanzee. The sex cells are **haploid**, with one from each pair: 23 in a human egg or sperm.

KEY POINTS

- Each species has a characteristic number of chromosomes: 46 in humans, 48 in chimpanzees.
- Diploid cells have an even number, because chromosomes come in homologous pairs.

KEY TERMS

chromosome

A long molecule of DNA wrapped with proteins. It carries many genes.

diploid

Having two copies of each chromosome, one from each parent.

homologous chromosomes

A matching pair of chromosomes, one from each parent, carrying the same genes in the same places.

haploid

Having one copy of each chromosome, as in a sperm or an egg.

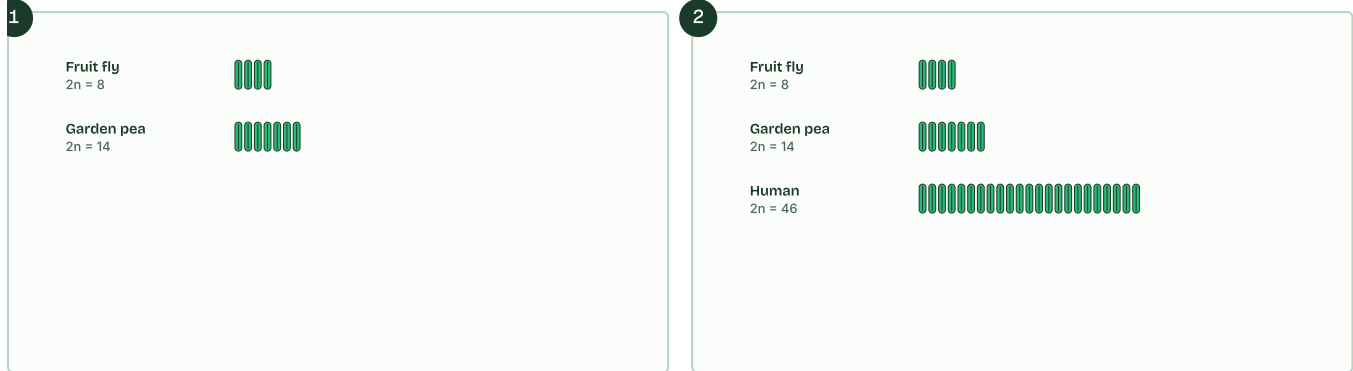
Fruit fly $2n = 8$ **Garden pea** $2n = 14$ **Human** $2n = 46$ **Chimpanzee** $2n = 48$ 

one more pair

Dog $2n = 78$ 

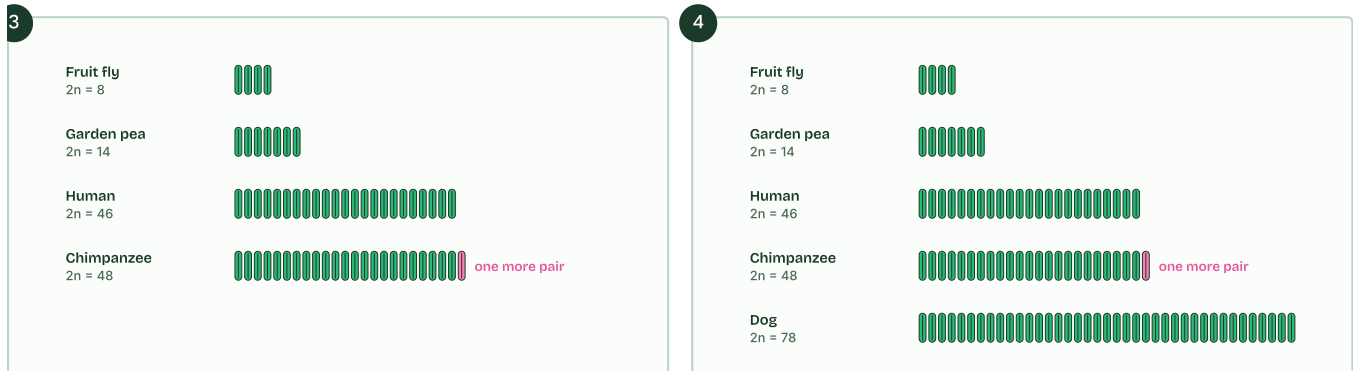
STEP BY STEP

4 STEPS



A fruit fly has 8 chromosomes in its body cells: **4 pairs**. A garden pea has 14: 7 pairs. Different species, different numbers.

A human has **46**: 23 pairs.



A chimpanzee has **48**: 24 pairs, one more pair than a human.

A dog has 78. More chromosomes does **not** mean a bigger or more complex animal. Every number is **even**, because chromosomes come in pairs.

WATCH OUT

Chromosome number is not the number of genes, and it is not the amount of DNA. A chromosome can be long or short and can carry many genes or few. A dog has more chromosomes than a human, which tells you nothing about which is the more complex.

PREDICT

Why does a diploid cell always have an even number of chromosomes?

- (A) One of each pair comes from each parent, so the total is even
- (B) A cell copies each chromosome once, so the total is always doubled up
- (C) Natural selection has removed every species with an odd number of them

Decide before you look. Answer on page 43.

05

A3.1.7 KARYOTYPING AND KARYOGRAMS

Laying out the *chromosomes*

How do biologists compare chromosomes? They make a **karyotype**: the full set of one cell's chromosomes. Photographed and arranged in pairs, the picture is a **karyogram**. The cell is stopped part-way through dividing, when the chromosomes are short and thick, and stained so dark bands show.

To arrange them, match each chromosome with its partner using three clues: its **length**, its **banding pattern** and the position of its **centromere**, the pinched point where its two arms meet. Pairs are lined up from the longest. A human karyogram has 22 numbered pairs, roughly from longest to shortest, plus two sex chromosomes: XX in a female, XY in a male. It shows the number, the sex, and any extra or missing chromosome: three copies of chromosome 21 cause Down syndrome.

Now a puzzle. Humans have 46 chromosomes, but chimpanzees, gorillas and orangutans have 48. If we share an ancestor with them, where did a pair go? The hypothesis: human chromosome 2 was made when two ape chromosomes fused end to end in an ancestor we share with chimpanzees. (The syllabus calls the two ape chromosomes 12 and 13, an older way of numbering them.)

Look at them in the second tool below. The two ape chromosomes, placed end to end, match human chromosome 2 in **length** and in **banding**. Human chromosome 2 has DNA typical of a chromosome **end** (a telomere) in the middle, where a join would be. And it carries the remains of a **second centromere**, switched off. Every other human chromosome matches one ape chromosome.

Testing a prediction. A good hypothesis predicts something that could turn out false. If two chromosomes fused, chromosome ends should be found in the middle of the new one, and that can be checked. A claim such as “it fused so that humans could think” predicts nothing anyone can check. It is not testable, however interesting. Try sorting a few statements.

Testable or not? Decide whether evidence could ever show each statement wrong.

Chromosome 2 fused so that humans could become intelligent.

Human chromosome 2 contains the remains of a second, switched-off centromere.

The best human chromosome is chromosome 1.

If two ape chromosomes fused end to end, telomere DNA should be found in the middle of the new one.

Human chromosome 2 has the same banding as two ape chromosomes placed end to end.

KEY TERMS

karyotype

The full set of chromosomes of a cell, as seen in the lab.

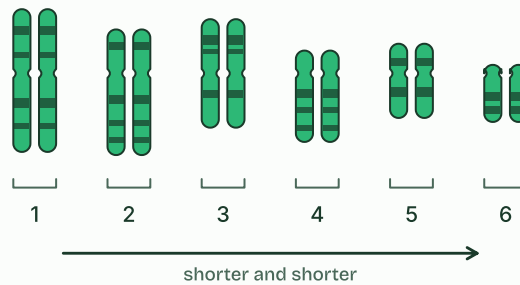
karyogram

A photograph or drawing of the chromosomes of one cell, arranged in matching pairs and ordered by size.

KEY POINTS

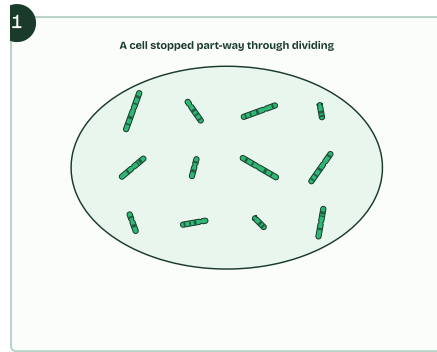
- A karyogram arranges chromosomes in pairs by length, banding pattern and centromere position.
- Human chromosome 2 matches two ape chromosomes end to end, has telomere DNA in its middle and a remnant second centromere.
- A testable hypothesis makes a prediction that evidence could contradict.

Numbered from the longest to the shortest

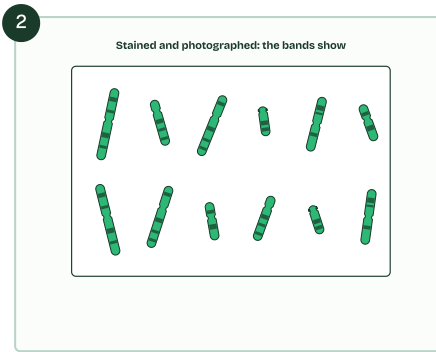


STEP BY STEP

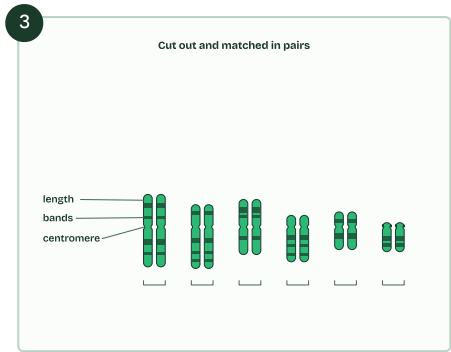
4 STEPS



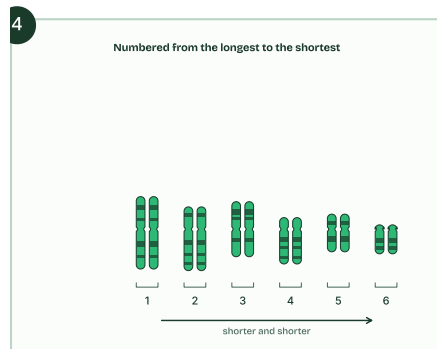
A cell is stopped part-way through **dividing**, when its chromosomes are short and thick.



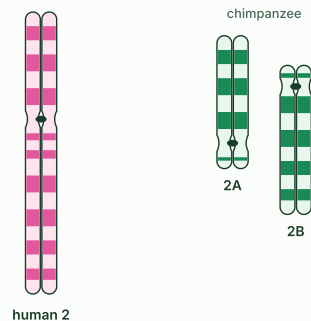
The chromosomes are **stained**, so dark bands show, and **photographed**.



Each is cut out and matched with its partner by **length**, **banding pattern** and **centromere position**.



The pairs are lined up with the centromeres in a row and numbered from the **longest**: a karyogram. (Simplified: six pairs.)



Drag each chromosome next to its partner, using length, bands and centromere position. The tool shows what matched.

STEP BY STEP

3 STEPS

1

Chromosomes from one cell

The karyogram: a pair in each place

2

Chromosomes from one cell

The karyogram: a pair in each place

a pair	a pair		

3

human 2

chimpanzee

2A

2B

Chromosomes from one cell, condensed and doubled. Pair them by **length**, **centromere position** and **bands**.

A pair matches on all three. A karyogram puts the pairs in order, **longest first**.

Human **chromosome 2** beside two chimpanzee chromosomes, 2A and 2B. Do they fit together?

human 2

chimpanzee

2A

2B

Human chromosome 2 beside two ape chromosomes. Look at the three pieces of evidence and judge how well each supports the hypothesis.

STEP BY STEP

3 STEPS

1

Chromosomes from one cell

The karyogram: a pair in each place

2

Chromosomes from one cell

The karyogram: a pair in each place

a pair	a pair		

3

human 2

chimpanzee

2A

2B

Chromosomes from one cell, condensed and doubled. Pair them by **length**, **centromere position** and **bands**.

A pair matches on all three. A karyogram puts the pairs in order, **longest first**.

Human **chromosome 2** beside two chimpanzee chromosomes, 2A and 2B. Do they fit together?

WATCH OUT

The evidence supports the hypothesis from several directions, but nobody watched the fusion. And it does not mean humans came from chimpanzees: both lines come from a shared ancestor, which was neither.

PREDICT

If two chromosomes had fused end to end, what would you expect in the middle of the new, longer chromosome?

- Ⓐ A gene that makes the two chromosomes stick together for good
- Ⓑ A stretch of DNA that cannot be copied, so the cell could not divide
- Ⓒ Telomere DNA, normally found only at a chromosome's end

Decide before you look. Answer on page 43.

06

A3.1.8

A3.1.9

GENOMES WITHIN AND BETWEEN SPECIES

One genome, many *versions*

Your **genome** is all the genetic information you carry: your genes, the DNA between them, and the small loops of DNA in your mitochondria. Almost every cell in your body holds a full copy.

Two people share most of their genome: the same genes, in the same places. What differs is small and scattered. At about one place in a thousand, one base differs: a **single nucleotide polymorphism**, or SNP (said “snip”). Any two people share about 99.9% of their genome. Many SNPs lie in DNA that codes for nothing and have no known effect. Others alter a protein, or how much of it is made.

Between species the differences are far greater. Genomes differ in their overall **size**, which is the total amount of DNA, and in **base sequence**. Variation between species is much larger than variation within a species. That is why a stretch of DNA can show whose it is, and why a species can be recognised from its genome.

KEY POINTS

- A genome is all the genetic information of an organism.
- Members of one species share most of their genome; SNPs give some diversity.
- Variation between species is much larger than variation within a species.

KEY TERMS

genome

All the genetic information of an organism: its genes, the DNA between them and the DNA of its organelles.

single nucleotide polymorphism

A single base in the genome that differs between individuals of one species, found in many of them. Short form: SNP.

Within one species

Person 1
reference

A T G C C T A G G T A C G A T T C A G C

Person 2
1 differs

A T G C C T A **C** G T A C G A T T C A G C

Person 3
2 differ

A T G C C T A G G T A C **C** A T T **G** A G C

SNP: one base differs

Between two species

Species B, no. 1
8 differ

A T **C** C C **A** A **C** G **A** A **G** G A **A** T **G** A **C** C

Species B, no. 2
8 differ

A T **C** C C **A** A **C** G **A** A **G** G **T** T **G** A **C** C

STEP BY STEP

3 STEPS

1 Within one species

Person 1 reference: A T G C C T A G G T A C G A T T C A G C

Person 2 1 differs: A T G C C T A **C** G T A C G A T T C A G C

Person 3 2 differ: A T G C C T A G G T A C **C** A T T **G** A G C

2 Within one species

Person 1 reference: A T G C C T A G G T A C G A T T C A G C

Person 2 1 differs: A T G C C T A **C** G T A C G A T T C A G C

Person 3 2 differ: A T G C C T A G G T A C **C** A T T **G** A G C

SNP: one base differs

3 Within one species

Person 1 reference: A T G C C T A G G T A C G A T T C A G C

Person 2 1 differs: A T G C C T A **C** G T A C G A T T C A G C

Person 3 2 differ: A T G C C T A G G T A C **C** A T T **G** A G C

SNP: one base differs

Between two species

Species B, no. 1 6 differ: A T **C** C C A C G A G A T **G** A C

Species B, no. 2 6 differ: A T **C** C C A C G A G G T T **T** G A C

One short stretch of the genome in three people. Bases that differ from person 1 are **pink**: very few.

A difference at a single base is a **single nucleotide polymorphism**, or SNP. Together, SNPs make each person's genome their own.

The same stretch in another species: **far more** differences. (Simplified: real differences are much rarer in both cases, but the pattern holds.)

WATCH OUT

A SNP is a place in the genome where individuals differ, not a gene and not a disease. Having a SNP is normal: we all carry thousands, and many have no known effect.

PREDICT

Two unrelated people have their whole genomes read and compared. About how different are they?

- (A) About one base in ten differs, so they share only about 90%
- (B) One base in a thousand differs: they share about 99.9%
- (C) None: unrelated people of one species have identical genomes

Decide before you look. Answer on page 43.

07

A3.1.10 COMPARING GENOME SIZES

Big genome, *small* organism

A genome's size is the total amount of DNA, counted in base pairs. A bacterium such as *E. coli* has a few million. A human has about three billion. You might expect more complex organisms to need more DNA, and the figure shows why that fails.

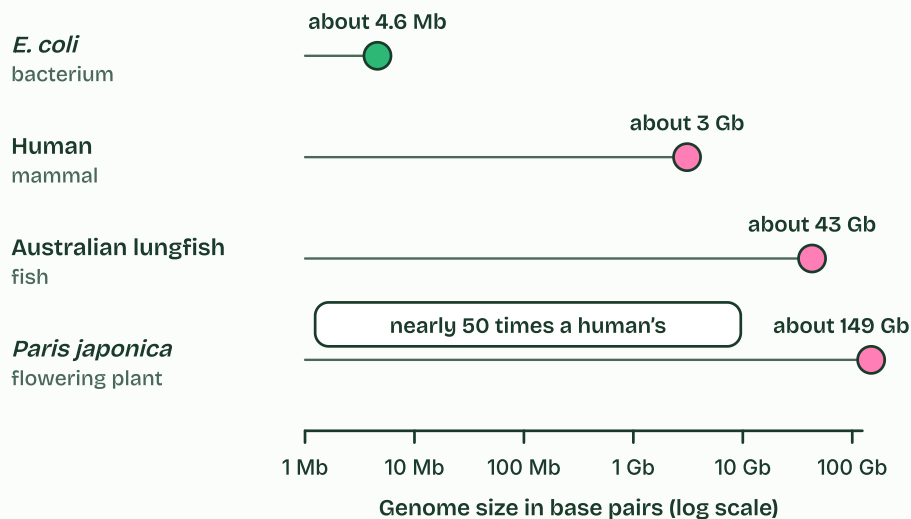
The Australian lungfish has a genome more than ten times as large as ours, and the flowering plant *Paris japonica* nearly fifty times. Neither is the most complex organism alive. Genome size is **not** a valid measure of how complex an organism is.

Why? A bigger genome does not always hold more genes. Much of the extra DNA does not code for a protein. It lies between genes, or is short sequences repeated many times. Some plants have also copied whole sets of chromosomes, which adds copies of the same genes and multiplies their DNA.

In the dry lab you will do what scientists do with a genome database: pick groups of organisms, find the genome sizes, and compare them with how complex the organisms are.

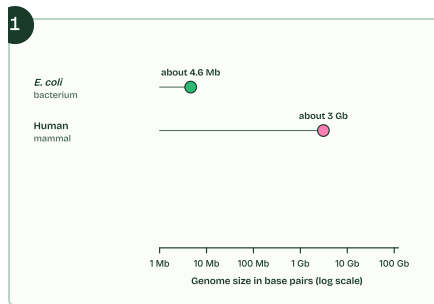
KEY POINTS

- Genome size varies enormously between groups of organisms.
- Genome size is not a measure of complexity: much DNA is non-coding or repeated.

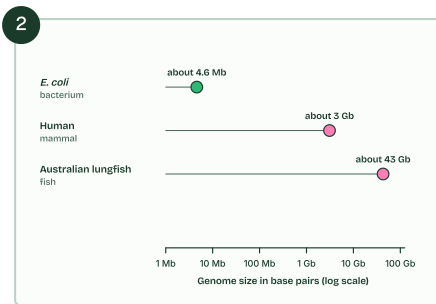


STEP BY STEP

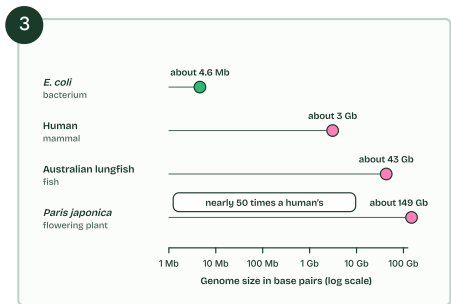
3 STEPS



A bacterium's genome is millions of base pairs. A human's is about **three billion**. (Mb is millions, Gb billions of base pairs.)

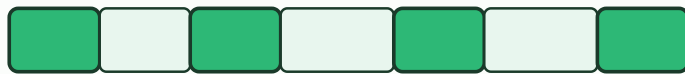


The Australian lungfish's genome is more than **ten times** a human's.



The flowering plant *Paris japonica* has one of the biggest genomes known. Size is **not** a measure of how complex an organism is.

Smaller genome



the same four genes in both

Larger genome



non-coding DNA

gene

repeated sequence

The same four genes can sit in a small genome or a large one. The difference is mostly DNA that does not code for a protein.

WATCH OUT

A bigger genome is not a more advanced one. When you see a big number, ask what the DNA is made of, and count genes if you can, not just base pairs.

PREDICT

A student says: "The organism with the biggest genome must be the most complex." Which fact shows this is wrong?

- (A) A fish and a flowering plant have genomes bigger than ours
- (B) Humans have the biggest genome of any organism measured so far, by far
- (C) Bacteria have no DNA, so size cannot be compared at all

Decide before you look. Answer on page 43.

08

A3.1.11 WHOLE GENOME SEQUENCING

Reading a *whole* genome

Whole genome sequencing reads the order of every base in an organism's genome. The first human genome took an international project more than ten years and billions of dollars. Machines have improved so much that a genome can now be read in days, for a small fraction of the cost.

Faster and cheaper sequencing matters because it brings genomes within reach of ordinary research. Today, comparing whole genomes of different species shows how closely related they are and which changes separated their lines. Genomes read from ancient remains have been compared with ours in this way.

In the future, a doctor may use a patient's own genome to choose the medicine and dose most likely to work for them: **personalised medicine**. A genome can also reveal SNPs that raise the risk of a disease, so that it can be watched for or prevented.

KEY TERMS

whole genome sequencing

Reading the order of every base in an organism's genome.

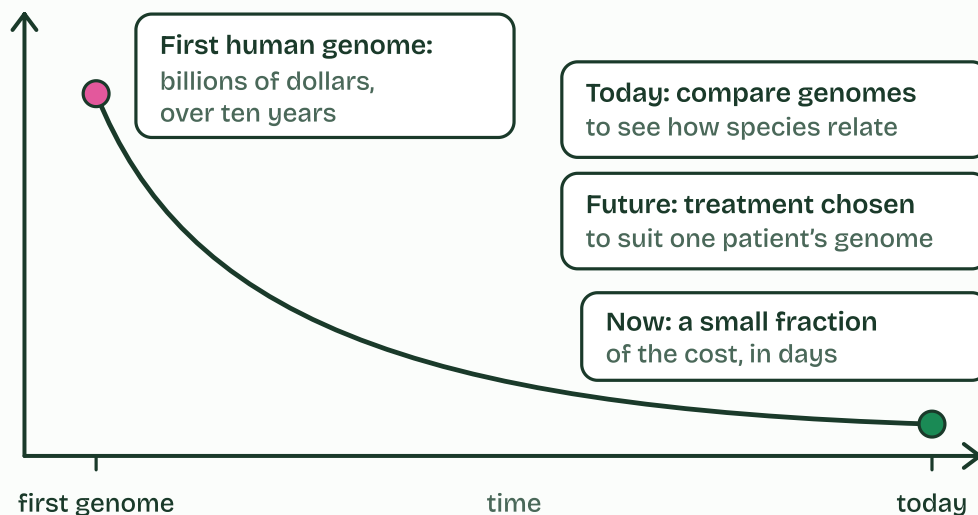
personalised medicine

Treatment chosen to suit a person's own genome.

KEY POINTS

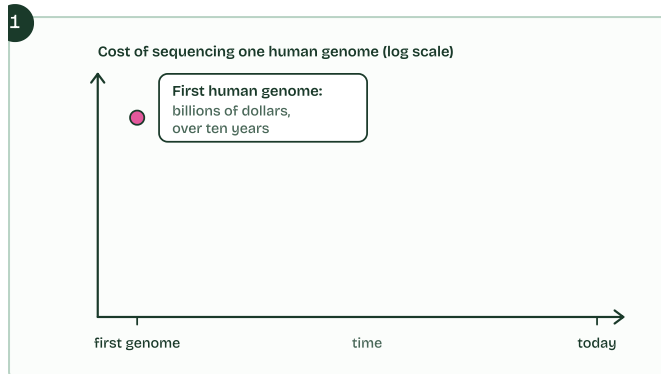
- Whole genome sequencing is getting faster and cheaper.
- Current use: research into evolutionary relationships. Future use: personalised medicine.

Cost of sequencing one human genome (log scale)

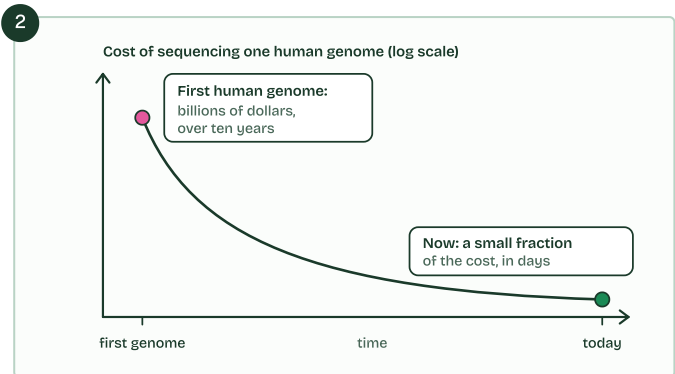


STEP BY STEP

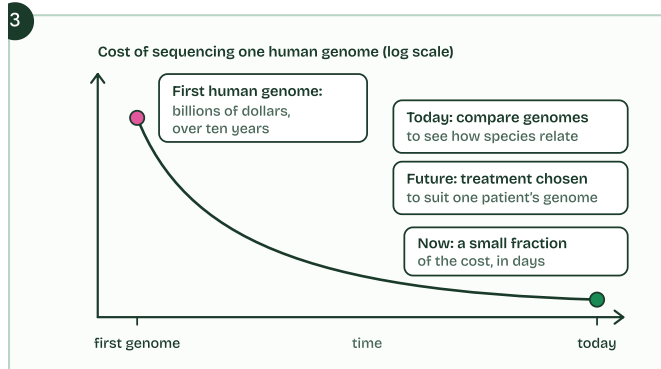
3 STEPS



The first human genome was a huge international effort: **years** of work and **billions** of dollars.



Sequencing machines improved, and the cost and the time **fell steeply**. (The shape is drawn to show the trend, not exact values.)



Cheap, fast genomes bring uses within reach: **comparing species** now, and **personalised medicine** in the future.

WATCH OUT

A genome is a text, not an explanation. Reading every base does not tell you what every gene does, and a genome does not fix your future: many traits depend on the environment too. It also raises questions of privacy. Who should be allowed to see yours?

PREDICT

How has the cost of sequencing a human genome changed since the first one was done?

- (A) It has hardly changed: sequencing is still a huge, slow project
- (B) It has risen, because genomes now need much dearer machines
- (C) It has fallen steeply, and sequencing has become far faster

Decide before you look. Answer on page 44.

09

A3.1.12 HL ASEQUAL SPECIES AND HORIZONTAL GENE TRANSFER

When the species rule *breaks*

The biological species concept needs breeding. But a great many organisms never breed with a partner. A bacterium reproduces by splitting in two, and each new cell is a copy of the first. There are no matings to watch and no offspring that are anything but clones, so the question “can they produce fertile offspring?” has no answer. Some plants, fungi and animals reproduce asexually too. Biologists group these organisms in other ways: by shape and structure, by how they get their energy and, increasingly, by how alike their DNA is.

Bacteria add a second problem. Genes normally pass down from parent to offspring. In **horizontal gene transfer** they pass sideways, between cells that are already alive. In **conjugation** two bacteria touch and a copy of a **plasmid** passes across. Cells can also take up DNA from their surroundings or receive it from a virus. A gene can even cross from one species to another, which is one reason antibiotic resistance spreads so fast.

A species concept that assumes genes stay inside one species' gene pool breaks down when genes jump between species, so it does not work well for these organisms.

KEY POINTS

- The biological species concept fits poorly where organisms reproduce asexually.
- Horizontal gene transfer moves genes between species, so gene pools are not closed.

KEY TERMS

horizontal gene transfer

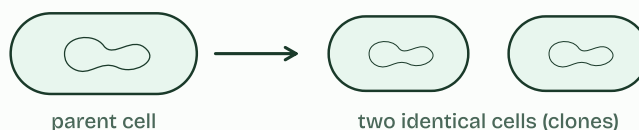
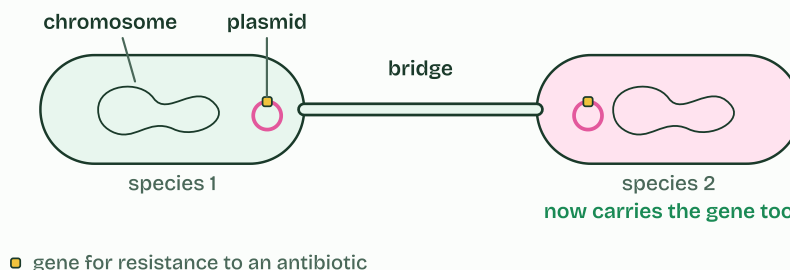
The passing of genes between living organisms that are not parent and offspring, with no reproduction.

conjugation

Bacteria in contact passing a copy of a plasmid from one cell to another.

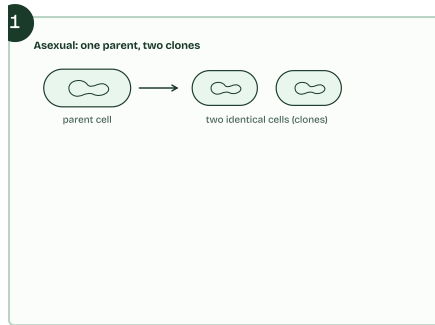
plasmid

A small ring of DNA in a bacterium, separate from its main chromosome.

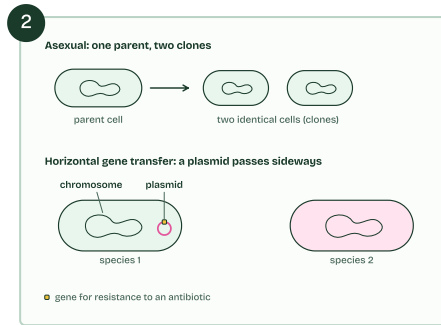
Asexual: one parent, two clones**Horizontal gene transfer: a plasmid passes sideways**

STEP BY STEP

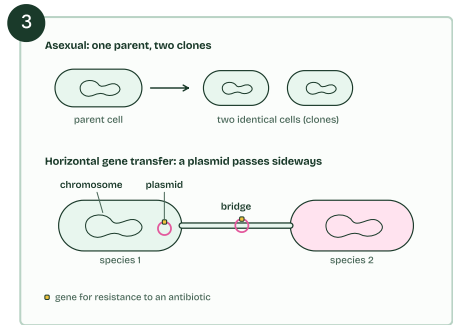
4 STEPS



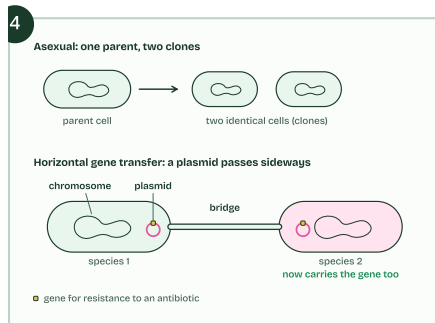
A bacterium reproduces by **copying itself**: two identical cells, with no partner and nothing to test.



Two bacteria of **different species**. One carries a **plasmid**, a small ring of DNA, with a gene on it.



The cells touch and a bridge forms. A **copy** of the plasmid passes across.



The second species now has the gene. No new cell was made: the gene moved **sideways**.

WATCH OUT

Horizontal gene transfer is not reproduction: no new cell is made. And asexual does not mean unclassifiable. Bacteria and other asexual organisms still fall into recognisable groups, just not groups defined by breeding.

REMEMBER IT**Where the species concept struggles**

F Five	A Apes	H Hug	G Grumpy	A Aunts	H Happily
Fossils no breeding test is possible	Apart populations that never meet	Hybrids some different species have fertile young	Gradual no single day when one species becomes two	Asexual no partners to breed with	Horizontal transfer genes jump between species

PREDICT

A bacterium carries a plasmid with an antibiotic-resistance gene. It touches a bacterium of a different species. What can happen?

- Ⓐ Nothing can happen, because genes pass only from parent to offspring
- Ⓑ A copy of the plasmid can pass across with no cell dividing
- Ⓒ The two cells fuse into one new cell, which then divides in two

Decide before you look. Answer on page 44.

10

A3.1.13 HL CHROMOSOME NUMBER AS A SHARED TRAIT

The number that has to *match*

Chromosome number is a trait that members of a species share, as their body form and their DNA are. It matters most when two species mate. Each parent gives a set of chromosomes to the offspring, and at meiosis every chromosome must find a partner before the sets can be shared out into gametes.

If the parents have the same number and similar chromosomes, they pair cleanly, like the matching pair in the figure. If the numbers differ, the hybrid has chromosomes with no equal partner. When these are shared out, some gametes receive part of the genome twice and part of it not at all. Gametes like that rarely work, so **cross-breeding between closely related species is unlikely to produce fertile offspring when their chromosome numbers differ**.

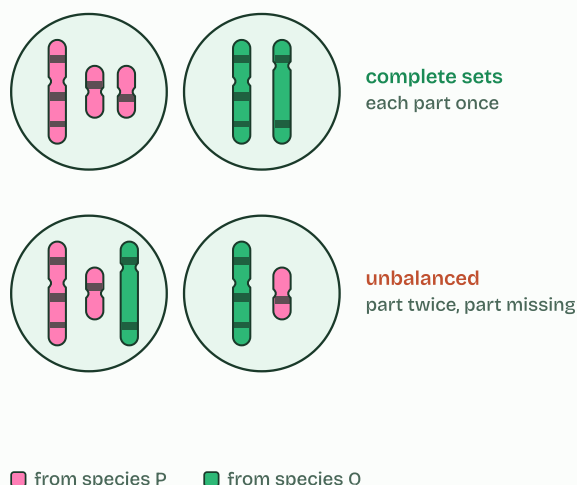
The mule shows it (you met it in A4.1). A horse gamete has 32 chromosomes and a donkey gamete 31, so a mule has 63, an odd number, and not every chromosome can have a partner. A mule is healthy but sterile. It is also why different chromosome numbers, such as 46 in humans and 48 in chimpanzees, are one sign that two groups are separate species.

Notice the word *unlikely*. Some closely related species with different numbers do produce fertile young, and equal numbers do not guarantee fertility. It is a strong pattern, not a law.

KEY POINTS

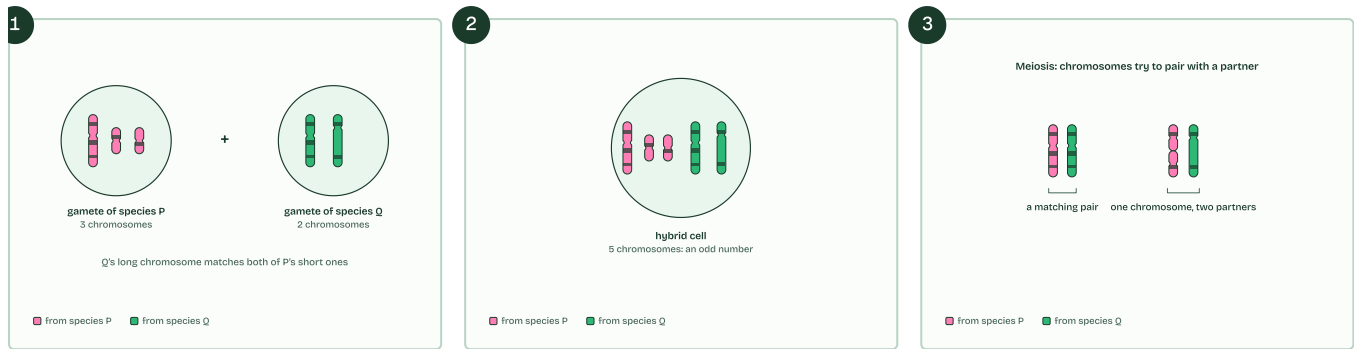
- Chromosome number is a trait shared within a species.
- Hybrids of parents with different numbers have chromosomes with no partner, so they are usually sterile.

Two ways the chromosomes can be shared out



STEP BY STEP

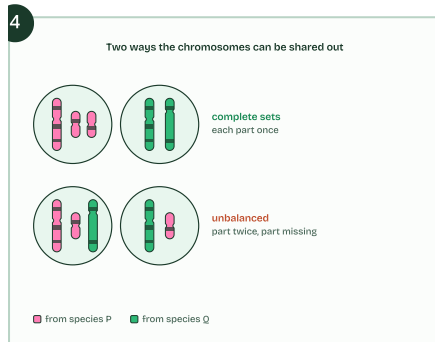
4 STEPS



Two **imagined** species. Q has one long chromosome where P has two short ones, so they have different chromosome numbers.

A hybrid gets **both sets**: five chromosomes, an odd number. One cannot have an equal partner.

At meiosis each chromosome looks for its match. Two pair neatly, but the long one is left matching **two** at once.



Some ways of sharing them out give complete sets. Others give a gamete with part of the genome **twice** and part **missing**. With many such mismatches, most gametes fail.

WATCH OUT

A hybrid's chromosome number is the sum of the two *gametes*, not of the two parents' body cells: $32 + 31 = 63$ for the mule, not $64 + 62$.

PREDICT

A hybrid cell has 63 chromosomes. Could every one of them have an equal partner at meiosis?

- (A) No: with an odd number, at least one has no partner
- (B) Yes: parents with similar bodies always have chromosomes that pair up
- (C) Yes: meiosis can make a partner for a lone chromosome by copying it

Decide before you look. Answer on page 44.

11

A3.1.14 HL DICHOTOMOUS KEYS

Building a *key*

To name an organism you have not met, use a **dichotomous key**.

“Dichotomous” means divided in two. At every step you choose between two statements, or answer a yes or no question, and each choice sends you to the next step or to a name. Follow the right path and you finish at one organism and no other.

A key is only as good as its questions. Use features that are easy to see, that mean the same to anyone, and that do not change as the organism grows or with the season: the number of legs on an animal, or a leaf edge that is toothed or smooth. Avoid size, colour and behaviour. A leaf is green in summer and red in autumn, and a young animal is smaller than an adult.

A key can be drawn as a branching chart, as in the figure, or written as numbered pairs of statements, with the same result.

To build your own, choose six to ten local organisms, such as the leaves of trees in your school grounds. List what tells them apart, find one feature that splits the set into two groups, then split each group again until every organism is alone. Then test the key on someone who does not know the answers. If an organism ends in the wrong place, or two end together, the key needs fixing. The two tools below let you practise on a card set of garden animals: build a key for them and test it, then use a key we give you.

KEY TERMS

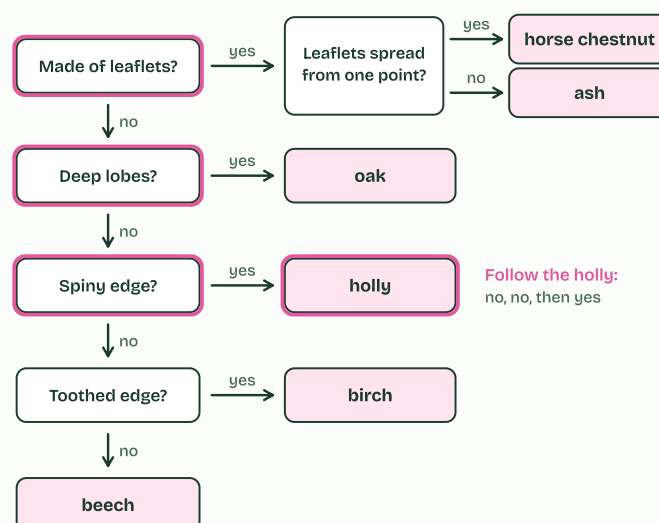
dichotomous key

A tool for identifying organisms: a series of choices between two statements, each leading to the next choice or to a name.

KEY POINTS

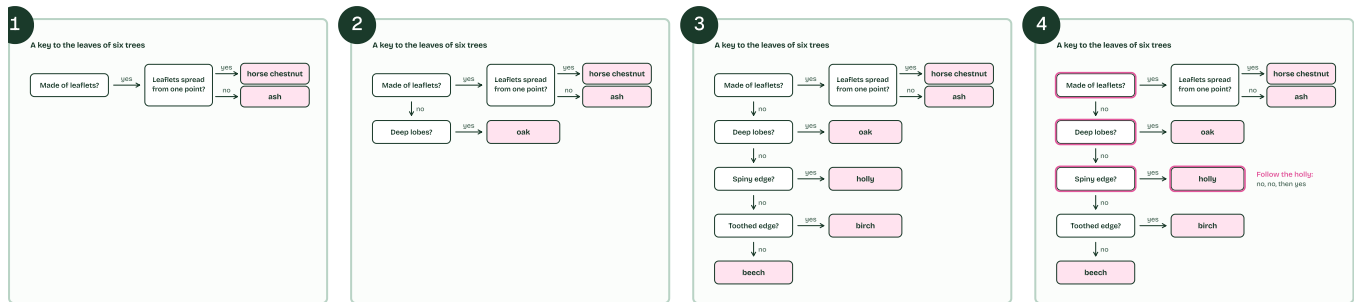
- A dichotomous key uses paired choices that lead to one name.
- Choose features that are visible, countable and do not change.
- Test a key on someone else, then fix it where it fails.

A key to the leaves of six trees



STEP BY STEP

4 STEPS

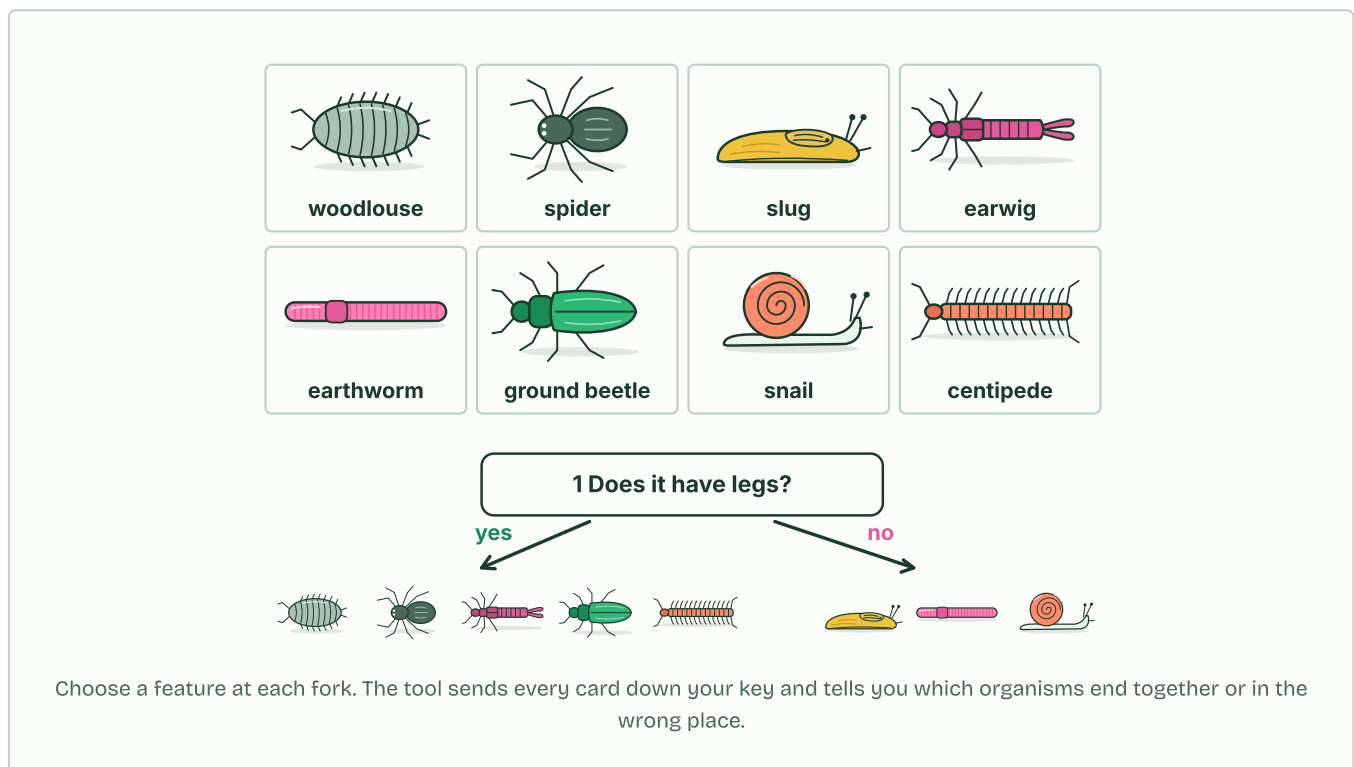


Every step is a question with **two** answers. A leaf made of leaflets leads to one more question, and then to horse chestnut or ash.

A leaf in one piece leads to the next question. **Deep lobes:** oak.

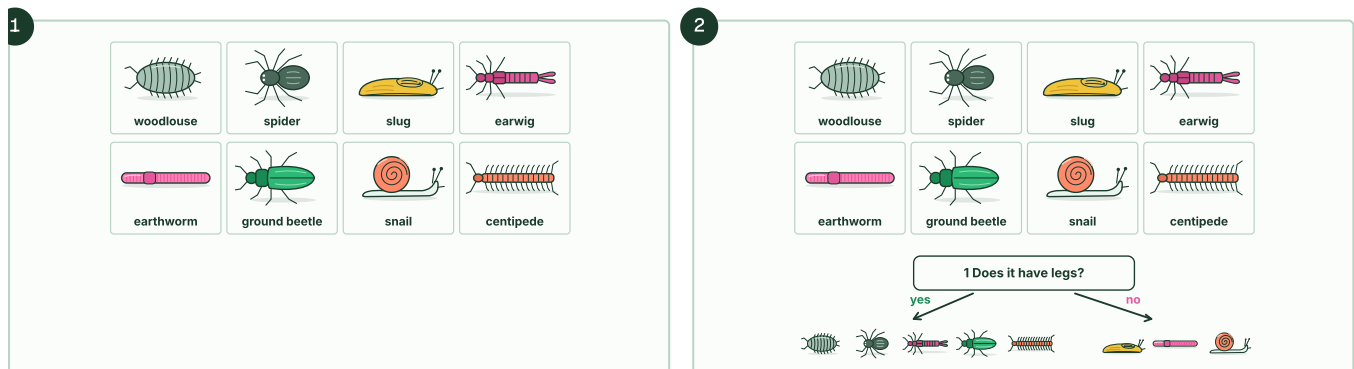
Each remaining question uses an **edge** that is easy to see: spiny, toothed, or neither. Every leaf reaches exactly one name.

Check a key by following one leaf through it: holly is **no** to leaflets, **no** to deep lobes and **yes** to a spiny edge.



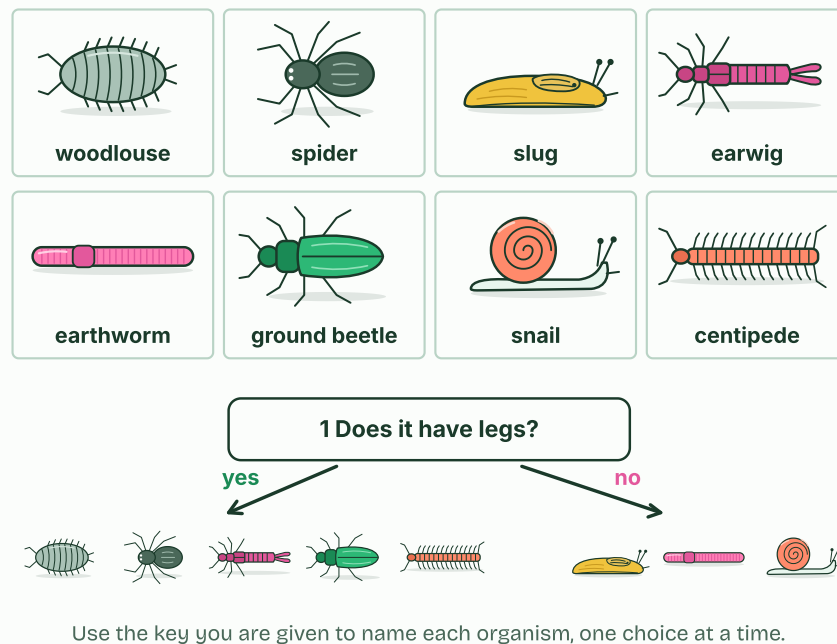
STEP BY STEP

2 STEPS



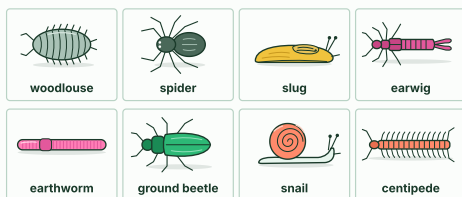
Eight animals from leaf litter and soil. A **dichotomous key** tells them apart with questions that each have two answers.

Each question **splits** the group in two; the next question splits each part again, until each animal is alone with its name.



STEP BY STEP

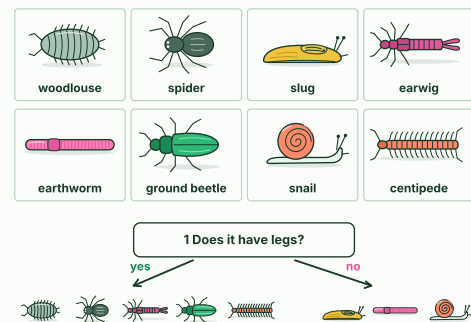
1



Eight animals from leaf litter and soil. A **dichotomous key** tells them apart with questions that each have two answers.

2 STEPS

2



Each question **splits** the group in two; the next question splits each part again, until each animal is alone with its name.

THE SAME KEY, AS NUMBERED STATEMENTS

1a Leaf made of separate leaflets: go to 2. **1b** Leaf in one piece: go to 3. **2a** Leaflets spread from one point: horse chestnut. **2b** Leaflets in pairs along a stalk: ash. **3a** Edge deeply lobed: oak. **3b** Edge not deeply lobed: go to 4. And so on.

WATCH OUT

Never harm what you study. Photograph organisms, take only a leaf from a plant that has many, and put animals back where you found them. Never taste or touch a plant or fungus you cannot name.

PREDICT

Which feature is best for a key that tells the leaves of different trees apart?

- (A) Colour, because every leaf looks different at a glance
- (B) Size, because it is the easiest thing to measure
- (C) Whether the edge is toothed or smooth

Decide before you look. Answer on page 44.

12

A3.1.15 HL DNA BARCODES AND ENVIRONMENTAL DNA

Barcodes from the *soil*

How many species live in a pond? Netting them all takes weeks, and shy or tiny ones are missed. But every animal leaves traces of itself in the water: skin cells, mucus, droppings. **Environmental DNA** (eDNA) is the DNA collected from a sample of water, soil or air, not from an animal you have caught.

To tell whose DNA it is, scientists read a **DNA barcode**: a short stretch of DNA, a few hundred base pairs long, that is alike in members of one species and different between species. A good barcode has two ends that are the same in every species, so one pair of primers works on all of them, and a middle that varies. For animals it is usually part of a mitochondrial gene, for bacteria a ribosomal RNA gene, and plants use other genes.

The steps are always the same: collect a sample, extract the DNA, make millions of copies of the barcode region with PCR, read their sequences, and match each sequence against a **reference library** of barcodes from known species. Out comes a list of the species present, in a few days, including ones nobody saw.

Because it is so quick, barcoding with eDNA lets the biodiversity of a habitat be investigated rapidly.

KEY TERMS

Environmental DNA

DNA taken from a sample of water, soil or air, shed by the organisms that live there, instead of from an organism that has been caught.

DNA barcode

A short stretch of DNA that is very alike within a species and different between species, used to identify it.

KEY POINTS

- A barcode is a short, variable stretch of DNA flanked by sequences shared by all species.
- eDNA plus barcodes gives a rapid species list for a habitat.



Reference library: one barcode for each species

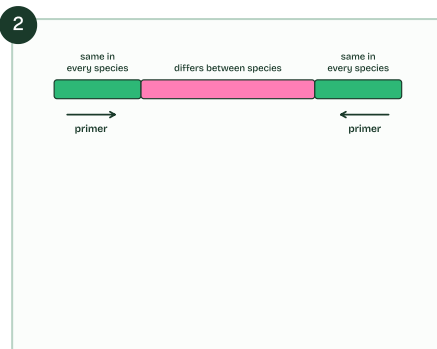
Species A	flank	A	T	G	C	C	T	A	G	G	T	A	C	flank
Species B	flank	A	T	G	C	G	T	A	G	C	T	A	C	flank
Species C	flank	A	T	C	C	G	T	A	G	G	T	T	C	flank
Species D	flank	T	T	G	C	C	A	A	G	G	A	A	G	flank
identical: it matches species D														
Sample	flank	T	T	G	C	C	A	A	G	G	A	A	G	flank

STEP BY STEP

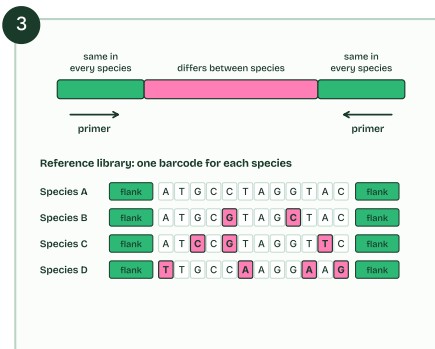
4 STEPS



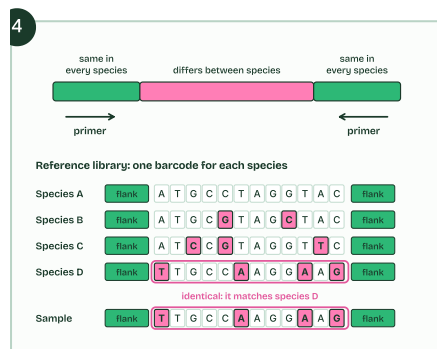
A barcode is a short stretch of DNA with **two ends the same in every species** and a **middle that differs** between species.



Because the ends match everywhere, one pair of **primers** can copy the barcode from any species in a mixed sample.



Each species in the reference library has its own barcode. Pink marks where a barcode differs from species A. (Letters invented.)

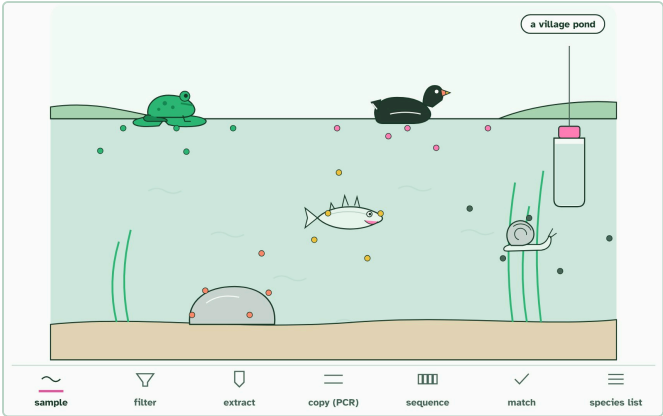


A barcode read from a sample is **matched** against the library. Here it is identical to one species' barcode.

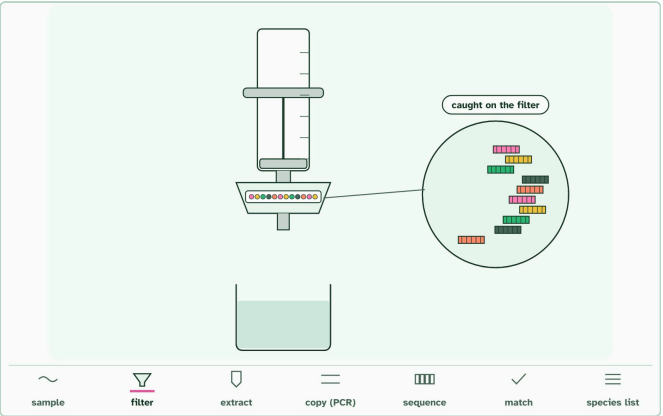
ANIMATION · WATCH IT HAPPEN: A SAMPLE BECOMES A SPECIES LIST

7 MOMENTS

1 1 OF 7: SAMPLE 2 2 OF 7: FILTER

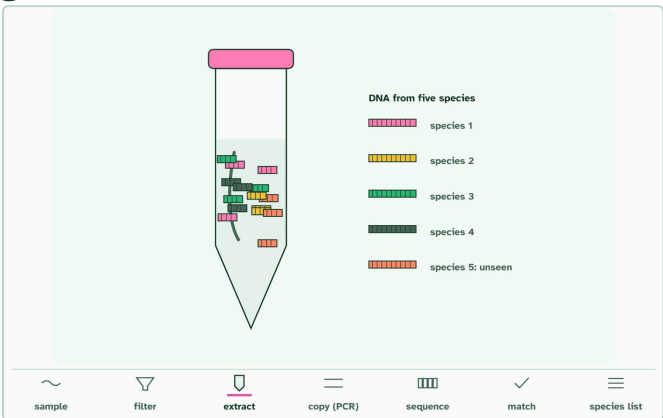


Collect a sample: a bottle of pond water. The DNA in it is **environmental DNA** (eDNA).

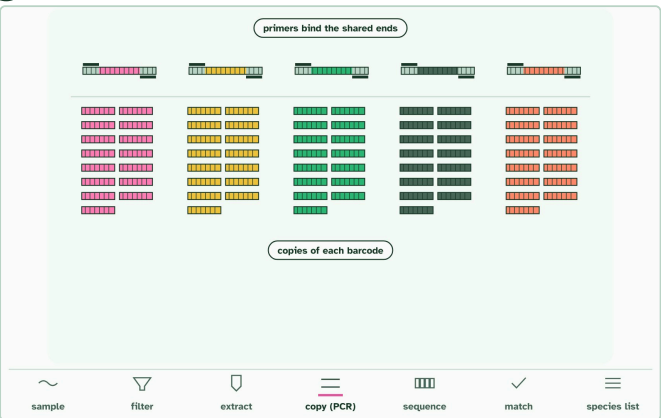


Push the water through a fine filter. Cells and DNA from every species are caught on it.

3 3 OF 7: EXTRACT 4 CYCLE 5: 32 COPIES EACH

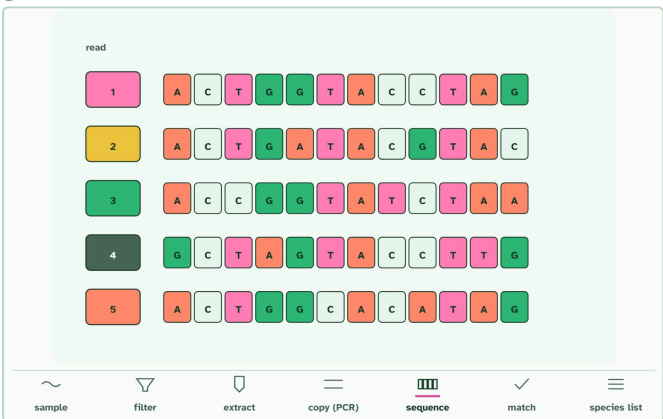


Extract the DNA from the filter: a mixture from every species living there.



PCR copies one short stretch, the **barcode**, from every species at once. The primers fit ends that all of them share; the barcode between them differs.

5 5 OF 7: SEQUENCE 6 6 OF 7: MATCH



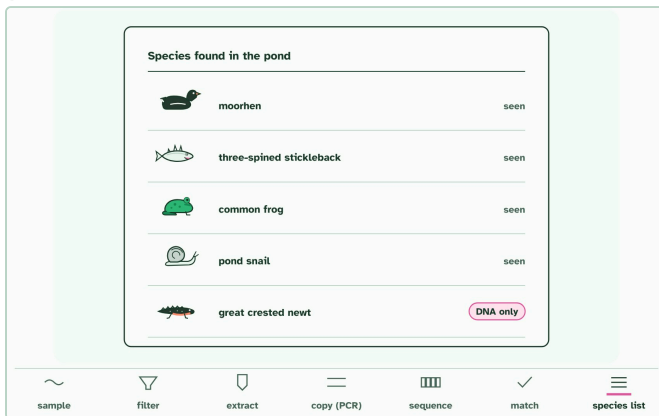
Sequence the copies: each read is one barcode's base sequence.



Match each read to a reference library of barcodes from identified species.

7

7 OF 7: SPECIES LIST



A list of the species present, from one bottle of water, much faster than searching and trapping. One of them nobody saw.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-a3-1-diversity-of-organisms#barcodes

WATCH OUT

eDNA tells you what has left DNA there, not how many, and not that it still lives there. And it can only name species that are in the reference library: a species missing from it gives no match.

REMEMBER IT**Steps of an eDNA survey****PREDICT**

A water sample from a pond is barcoded and matched.

What can the result tell you?

- (A) Exactly how many individuals of each species live there
- (B) Which listed species have left DNA in the water
- (C) The age and the sex of each animal that left DNA

Decide before you look. Answer on page 44.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

binomial system 02

The system of naming each species with two parts: its genus, then its species name.

biological species concept 03

The idea that a species is a group of organisms that can breed with each other and produce fertile offspring.

chromosome 04

A long molecule of DNA wrapped with proteins. It carries many genes.

conjugation 09

Bacteria in contact passing a copy of a plasmid from one cell to another.

dichotomous key 11

A tool for identifying organisms: a series of choices between two statements, each leading to the next choice or to a name.

diploid 04

Having two copies of each chromosome, one from each parent.

DNA barcode 12

A short stretch of DNA that is very alike within a species and different between species, used to identify it.

Environmental DNA 12

DNA taken from a sample of water, soil or air, shed by the organisms that live there, instead of from an organism that has been caught.

genome 06

All the genetic information of an organism: its genes, the DNA between them and the DNA of its organelles.

genus 02

A group of closely related species. The first part of a binomial name.

haploid 04

Having one copy of each chromosome, as in a sperm or an egg.

homologous chromosomes 04

A matching pair of chromosomes, one from each parent, carrying the same genes in the same places.

horizontal gene transfer 09

The passing of genes between living organisms that are not parent and offspring, with no reproduction.

karyogram 05

A photograph or drawing of the chromosomes of one cell, arranged in matching pairs and ordered by size.

karyotype 05

The full set of chromosomes of a cell, as seen in the lab.

morphological species concept 01

The idea, used by Linnaeus, that a species is a group of organisms sharing a distinctive set of physical traits.

morphology 01

The form and structure of an organism: its shape, its parts and how they look.

personalised medicine 08

Treatment chosen to suit a person's own genome.

plasmid 09

A small ring of DNA in a bacterium, separate from its main chromosome.

single nucleotide polymorphism 06

A single base in the genome that differs between individuals of one species, found in many of them. Short form: SNP.

speciation 03

The splitting of one species into two or more.

species 01

A group of organisms that share a set of traits. In the morphological species concept, the traits are the form and structure of the body.

variation 01

Differences between individuals of one species, or between groups of organisms.

whole genome sequencing 08

Reading the order of every base in an organism's genome.

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Dry lab: *Genome size explorer*

Look up twenty organisms from a genome database, plot genome size against group and gene count, and decide whether a bigger genome means a more complex organism.

The database: genome sizes

organism	group	Mb	genes
Australian lungfish	vertebrates	?	?
axolotl	vertebrates	?	?
baker's yeast	single-celled	?	?
bread wheat	plants	?	?
chicken	vertebrates	?	?
E. coli	bacteria	?	?
and fourteen more			

ale)

100,000



Run it online: change the variables, run the trials, and the table and graph fill in as you go. biologybybradford.com/guides/ib-biology-a3-1-diversity-of-organisms#lab

Your question

Does a bigger genome mean a more complex organism, or even more genes? What does the pattern look like inside one group, and between groups?

What you can change

Which organisms you look up (twenty are in the database, in five groups), whether the graph plots genome size against group or against gene count, and which two organisms you compare side by side.

What to record

For each organism you look up: its group, genome size and gene count. After at least ten, note the pattern, the organisms that break it, and your judgement on the four statements. Write a one-sentence conclusion that names two organisms as evidence.

Find out

- **Which group has the biggest genomes?** Look up at least ten organisms, with some from every group, and plot genome size against group. Do the groups with the biggest genomes hold the organisms you would call the most complex?
- **Does a bigger genome mean more genes?** Switch the graph to gene count. Find two organisms with about the same number of genes but genomes of very different size.
- **How much can one group vary?** Pick the group with the widest spread. Name its smallest and its largest genome, and say roughly how many times bigger one is than the other.
- **Compare two.** Choose any two organisms and compare them side by side. Which is more complex, and which has the bigger genome? Do the two answers agree?
- **Draw a conclusion.** Judge the four statements the lab gives you once you have looked up ten organisms, then write one sentence on whether genome size is a good measure of complexity, naming at least two organisms as evidence.

Record

- For every organism you look up: its group, its genome size and its gene count, with units. Genome sizes are in millions of base pairs (Mb), and 1,000 Mb is 1 Gb.
- Treat the gene counts as approximate: they are estimates, and they change as genomes are studied further. Some organisms have no gene count in the table.
- The groups are in a rough order of complexity, and that order is arguable. Say where you would change it.
- Download the results of your look-ups and plot your own graph, with axes labelled and a title. Use a log scale for genome size and say why.

QUESTIONS ON THE LAB

QUESTION 1

A nematode worm and a mouse have about the same number of genes, around 20,000. The worm's genome is about 100 million base pairs. What do you expect of the mouse's?

- (A) About the same size, since the number of genes is the same
- (B) Smaller, because a mouse is a more compact kind of animal
- (C) Much larger, with far more DNA that is not genes

Answer on page 44.

QUESTION 2

You compare the plants in the table, from thale cress to *Paris japonica*. How much do their genome sizes vary?

- (A) Hardly at all: they are all plants, so they have much the same genome
- (B) Enormously: the largest is about a thousand times the smallest
- (C) By about twofold, as closely related species of one genus might differ

Answer on page 44.

QUESTION 3

The lab shows a fish and plants with genomes much bigger than a human's. What can you conclude?

- (A) Genome size on its own does not measure complexity
- (B) The fish and the plants are more complex than a human
- (C) The human genome must have been measured wrongly

Answer on page 44.



Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on A3.1 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

[biologybybradford.com/exam-maker/sit?
topics=A3.1&level=HL&paper=quiz&marks=15&src=ep](https://biologybybradford.com/exam-maker/sit?topics=A3.1&level=HL&paper=quiz&marks=15&src=ep)

Answers

PREDICTIONS IN THE CHAPTERS

01 Identical twins share all their DNA. Are they identical in every trait?

B No: fingerprints, scars and tans differ even so

No. Twins share their DNA, but traits are shaped by the environment too: a scar or a tan is picked up during life, and even fingerprints differ. Organisms are never alike in every trait, even when their genes match.

02 Two animals are named *Panthera tigris* and *Panthera onca*. What can you say about them?

C Two species in one genus, so they share similar traits

Two species in one genus. The genus is the same (*Panthera*) and the species names differ (*tigris*, the tiger, and *onca*, the jaguar), so they are separate species that share similar traits.

03 Two kinds of snail live on islands 500 km apart, and none has ever crossed the sea. Can the biological species concept say whether they are one species?

C Not directly: they have never met, so other evidence is needed

Not directly. The test asks whether they could breed and have fertile young, and that has never been tried. Scientists use other evidence: how alike the snails' bodies and DNA are, and how long ago the islands were separated. Never having bred is not the same as being unable to.

03 Two populations of one species stop interbreeding and slowly drift apart over a million years. On which day does one species become two?

B No single day: it is gradual, so the cut-off is a judgement

On no single day. The populations grow apart a little each generation, so the point where they count as two species is a judgement, and experts can reasonably disagree. That is why the line between populations and species can be arbitrary.

04 Why does a diploid cell always have an even number of chromosomes?

A One of each pair comes from each parent, so the total is even

Each parent supplies one chromosome of every kind, so the chromosomes match up in pairs. Two sets always make an even number: $23 + 23 = 46$ in a human, $24 + 24 = 48$ in a chimpanzee.

05 If two chromosomes had fused end to end, what would you expect in the middle of the new, longer chromosome?

C Telomere DNA, normally found only at a chromosome's end

Telomere DNA. Telomeres cap the ends of chromosomes, so two chromosomes joined end to end would leave two caps in the middle. Human chromosome 2 has such a stretch exactly where the join would be.

06 Two unrelated people have their whole genomes read and compared. About how different are they?

B One base in a thousand differs: they share about 99.9%

About one base in a thousand. Humans share nearly all of their genome, and the small differences, mostly SNPs, are what make each genome unique. Between species the differences are far larger.

07 A student says: "The organism with the biggest genome must be the most complex." Which fact shows this is wrong?

A A fish and a flowering plant have genomes bigger than ours

A fish and a flowering plant have genomes bigger than ours, and neither is more complex than a human. If size measured complexity, a lungfish would beat a mammal. The extra DNA is mostly non-coding or repeated.

08 How has the cost of sequencing a human genome changed since the first one was done?

C It has fallen steeply, and sequencing has become far faster

It has fallen steeply, and the time has fallen too, from years to days. That is why genome sequencing has moved from a few big projects to something used across research and medicine.

09 A bacterium carries a plasmid with an antibiotic-resistance gene. It touches a bacterium of a different species. What can happen?

B A copy of the plasmid can pass across with no cell dividing

A copy of the plasmid can pass across. This is horizontal gene transfer: the second bacterium now has the gene without being anyone's offspring, and the gene has crossed a species line.

10 A hybrid cell has 63 chromosomes. Could every one of them have an equal partner at meiosis?

A No: with an odd number, at least one has no partner

No. An odd number of chromosomes cannot all form pairs, so at least one has no partner. When the unpaired chromosomes are shared out, gametes tend to be unbalanced, which is why the mule is sterile.

11 Which feature is best for a key that tells the leaves of different trees apart?

C Whether the edge is toothed or smooth

The edge. It is easy to see and does not change much with the season or the leaf's age. Colour changes through the year, and size depends on the age of the leaf and the tree's conditions, so neither makes a reliable question.

12 A water sample from a pond is barcoded and matched. What can the result tell you?

B Which listed species have left DNA in the water

Which species in the reference library have left DNA in the water. It does not give numbers or ages, and it cannot name a species the library lacks, but it can be done quickly from one bottle of water.

QUESTIONS ON THE DRY LAB

Q1 A nematode worm and a mouse have about the same number of genes, around 20,000. The worm's genome is about 100 million base pairs. What do you expect of the mouse's?

C Much larger, with far more DNA that is not genes

Much larger: about 2,700 million base pairs, some 27 times the worm's, for about the same number of genes. Most of the difference is DNA that does not code for a protein, including long stretches between genes and repeated sequences. Look both up and see.

Q2 You compare the plants in the table, from thale cress to *Paris japonica*. How much do their genome sizes vary?

B Enormously: the largest is about a thousand times the smallest

Enormously. Thale cress has a genome of about 135 million base pairs and *Paris japonica* about 149,000 million: roughly a thousand times larger, in the same group of organisms. Genome size varies as much inside one group as between groups, which is why it is a poor guide to complexity.

Q3 The lab shows a fish and plants with genomes much bigger than a human's. What can you conclude?

A Genome size on its own does not measure complexity

Genome size alone does not measure complexity. If it did, the fish and the plants would be more complex than we are. Size tells you the total amount of DNA, not how many genes there are, how they are used or how complicated the organism is.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.