●●●●○ **Level 4 · Science** S4.2

Genes and inheritance

How the instructions for a living thing are written, copied and passed on.

Follow the instructions of life from the cell down to the DNA, learn how they are copied and shared out, and use crosses and family trees to predict what is passed on. Then see why living things vary, how a change in a gene happens, and how people move genes between species.

YOU ARE READY FOR THIS BOOK IF

You can explain what happens when a sperm cell joins an egg cell.

One step up	S5.1 Molecules and cells
This book	**S4.2 Genes and inheritance**
One step down	S3.2 Ecosystems

Contents

S4.2.1 DNA, genes and chromosomes

S4.2.2 The structure of DNA

S4.2.3 Meiosis and sex cells

S4.2.4 Boy or girl: X and Y

S4.2.5 Dominant and recessive

S4.2.6 Family trees and genetic disorders

S4.2.7 Variation

S4.2.8 Mutation and genetic engineering

Key words, A to Z

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S4.2.1 CHAPTER 1

DNA, genes and chromosomes

Children look like their parents. What exactly is handed down from one to the other?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** A little of their blood, which mixes in the baby.
- ☐ **B** Habits and looks that the baby learns by watching.
- ☐ **C** Instructions written in a molecule called DNA, copied into every cell.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Cells, S3.1.4. It says what the nucleus does, and the chromosomes are inside it.
- Level 4, Cells, photosynthesis and respiration, S4.1.1. It shows the nucleus and the other parts of a cell in more detail.

BY THE END YOU CAN

- Put DNA, gene, chromosome, nucleus and cell in order of size
- Explain that a gene is a code for making a protein

Look at a family photo. Children often look like their parents. They are not copies of either one. Something is passed from parents to children, and it is in every cell.

Most of your cells have a nucleus. Inside the nucleus is **DNA**, a very long molecule. It holds the instructions for building and running a living thing.

The DNA is not loose. It is wound up into thread-like bundles called **chromosomes**. One chromosome is one long molecule of DNA, coiled up tightly.

TRY IT

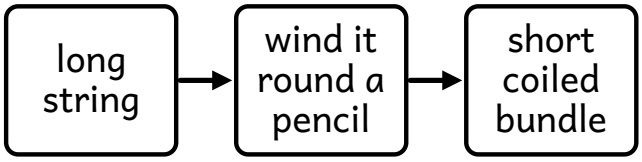
Coil a long thread

You need: a piece of string about 1 m long, a pencil or a thin stick.

1. Hold the string straight. See how long it is.
2. Tie one end to the pencil.
3. Turn the pencil to wind the string round it, close and tight.
4. Look at the pencil. Where is the string now?

What you will see: One metre of string now takes up the room of a short bundle on the pencil. That is how a chromosome holds a very long molecule of DNA in a tiny space.

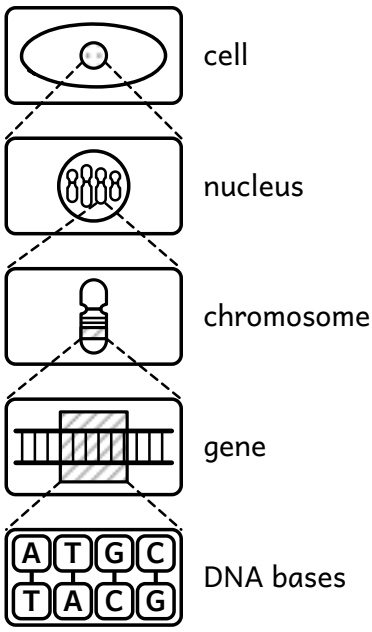
If you cannot try it, this is what happens.



The DNA of one human cell is about 2 m long if you stretch it out. The nucleus that holds it is less than 10 µm across. Coiling into chromosomes makes this possible.

Along each chromosome lie many **genes**. A gene is a section of the DNA that holds the code for making one **protein**. Proteins do much of the work in your body. They build muscle, carry oxygen in the blood and speed up reactions in cells.

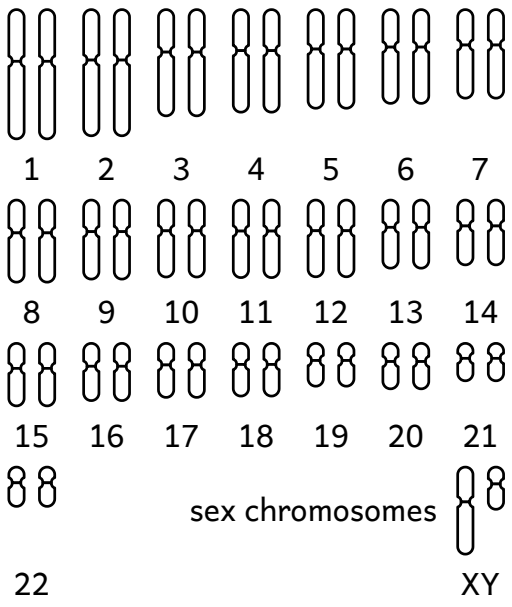
Some genes code for other molecules, but every gene in this book codes for a protein. Think of DNA as a very long recipe book. A chromosome is one volume, and a gene is one recipe.



Zoom in from the cell to the DNA bases. The panels are not to one scale. Each one is a close up of a part of the panel above.

So the order of size, from the largest, is cell, nucleus, chromosome, gene and one DNA base. A whole chromosome is one DNA molecule, so DNA is not smaller than a gene. The bases that build DNA are smaller.

Most human body cells have 46 chromosomes. They come in 23 pairs. You get one chromosome of each pair from your mother and the other from your father. Your 46 chromosomes hold about 20 000 genes.



One body cell of a man: 23 pairs, which is 46 chromosomes. Pair 1 is the longest.

WORKED EXAMPLE

A body cell of a pea plant has 7 pairs of chromosomes. How many chromosomes is that?

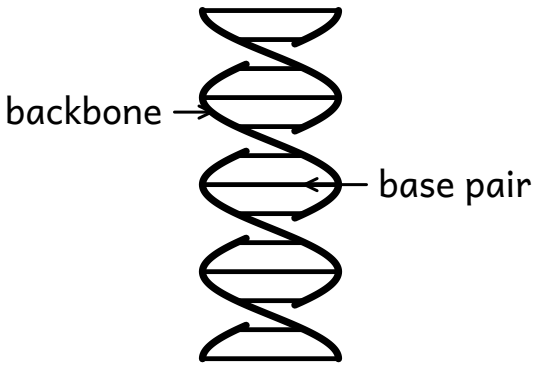
1. Each pair is made of 2 chromosomes.
2. Chromosomes = pairs × 2.
3. Chromosomes = 7 × 2 = 14.

Answer: 14 chromosomes

Living thing	Chromosomes
human	46
pea plant	14
fruit fly	8
dog	78

Chromosomes in one body cell. A dog has more than a human, so the number says nothing about how clever or complex a living thing is.

Zoom in on the DNA itself and it looks like a ladder twisted round and round. Chapter 2 shows why it has this shape.



two strands twisted

A short piece of DNA. It is far too small to see, even with a light microscope.

A WRONG IDEA MANY PEOPLE HAVE

~~One gene builds one body part, such as an eye.~~

Why it feels right: News stories speak of "the gene for" blue eyes or for height, as if one gene did the whole job.

The test that breaks it: Think of an eye. It holds many kinds of cell, and each kind needs many proteins. Each protein has its own gene.

What is true: A gene is the code for one protein. Many genes work together to build any body part.

KEY WORDS

DNA
the long molecule in cells that holds the instructions for a living thing.

chromosome
one long molecule of DNA, coiled up tightly.

gene
a section of DNA with the code for making one protein.

protein
a molecule that does work in the body, such as a muscle protein or an enzyme.

BACK TO YOUR GUESS

The answer is C: Instructions written in a molecule called DNA, copied into every cell.

Parents pass on instructions written in DNA. Almost every cell of the baby gets a copy. Blood does not pass from parent to child, and habits are learned, not inherited.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Which list puts these in order of size, largest first?

    A cell, nucleus, gene, chromosome, DNA base

    B cell, nucleus, chromosome, gene, DNA base

    C nucleus, cell, chromosome, gene, DNA base

    D DNA base, gene, chromosome, nucleus, cell

    Answer at the back of the book.

2. What is a gene?

    A A kind of protein made in the nucleus

    B Another name for a whole chromosome

    C A section of DNA with the code for making one protein

    Answer at the back of the book.

3. How many chromosomes are there in most human body cells?

    A 46 chromosomes

    B 23 chromosomes

    C 20 000 chromosomes

    Answer at the back of the book.

4. Why can about 2 m of DNA fit inside a nucleus under 10 µm across?

    A It is coiled up tightly into chromosomes.

    B The nucleus stretches to hold it.

    C The DNA is cut into small pieces and kept in the cytoplasm.

    Answer at the back of the book.

5. What does a gene give the code for?

    A A whole body part, such as an eye

    B A new chromosome

    C One protein

    D The next gene in line

    Answer at the back of the book.

6. Where are the chromosomes in a human body cell?

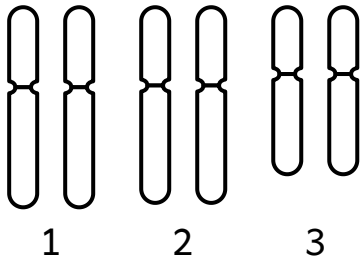
   A Spread through the cell membrane

   B In the nucleus

   C Floating loose in the cytoplasm

   Answer at the back of the book.

7. How many chromosomes are drawn in the picture of three pairs?



   Answer at the back of the book.

8. A body cell of a dog has 39 pairs of chromosomes. How many chromosomes is that?

   Answer at the back of the book.

9. A body cell of a fruit fly has 8 chromosomes. How many pairs is that?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A cell has a nucleus. The nucleus holds chromosomes. A chromosome is one coiled DNA molecule. A gene is a section of DNA that codes for one protein. Humans: 46 chromosomes, 23 pairs.

Draw: The five panels in order of size: cell, nucleus, chromosome, gene, DNA base.

S4.2.2 CHAPTER 2

The structure of DNA

> **DNA is a code with only four letters. How can four letters hold the instructions for a whole body?**

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** The four letters are used in a very long order, like the letters of a long book.
- ☐ **B** Each of the four letters is a different gene.
- ☐ **C** The letters are very large, so a few of them are enough.

IF THIS FEELS HARD, READ THIS FIRST

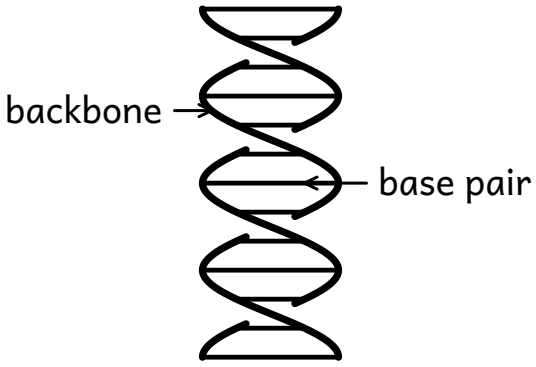
- Level 3, Cells, S3.1.4. It says what the nucleus does, and DNA is the molecule inside it.

BY THE END YOU CAN

- Describe DNA as a double helix with paired bases
- Pair A with T and C with G to complete a strand

You have seen that a gene is a code. What is the code made of? To find out, we zoom in on the DNA molecule itself.

DNA has two long strands twisted round each other. This shape is called a **double helix**. A helix is a spiral, like a spring or a spiral staircase.



two strands twisted

The double helix. The rungs are not drawn with letters here. The next pictures show them.

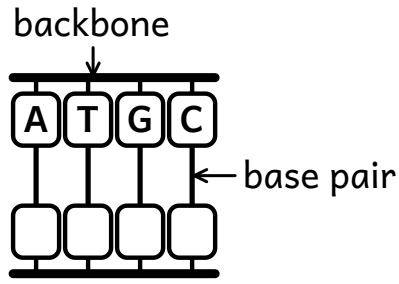
Each strand has a **backbone**. It is a chain of sugar molecules and phosphate molecules that take turns along the strand. The backbone holds the strand together.

On every sugar of the backbone sits one **base**. There are four kinds. They are called adenine, thymine, cytosine and guanine. We write them as the letters A, T, C and G.

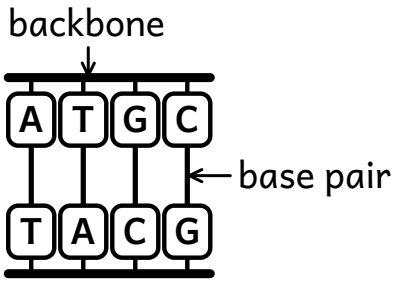
A base on one strand joins a base on the other strand. The joined pair is a **base pair**, and base pairs are the rungs of the ladder. They do not pair at random. A always pairs with T, and C always pairs with G.

DRAW IT FIRST

Build a ladder from one strand



1 One strand is given. It reads A, T, G, C. The boxes of the other strand are empty.



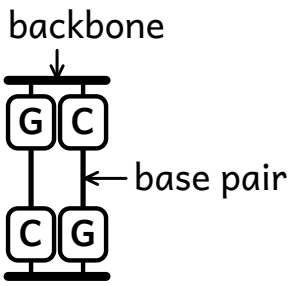
2 Fill each box with the partner of the base above it. The partner of A is T, of T is A, of G is C, and of C is G.

Base	Pairs with
A	T
T	A
C	G
G	C

The pairing rule. There is no other pair in DNA.

SEE IT THREE WAYS

As a picture



In words

Every base has one partner. G always has C opposite it, and C always has G.

In symbols

G with C, and C with G. In general, A with T and C with G.

The rule has a big result. If you know one strand, you know the other. The two strands are **complementary**: each one is the partner of the other.

WORKED EXAMPLE

One strand of DNA reads ATGC. What does the other strand read?

1. Pair each base in turn: A with T, T with A, G with C, and C with G.
2. Write the partners in the same order: T, A, C, G.
3. The other strand reads TACG.

Answer: TACG

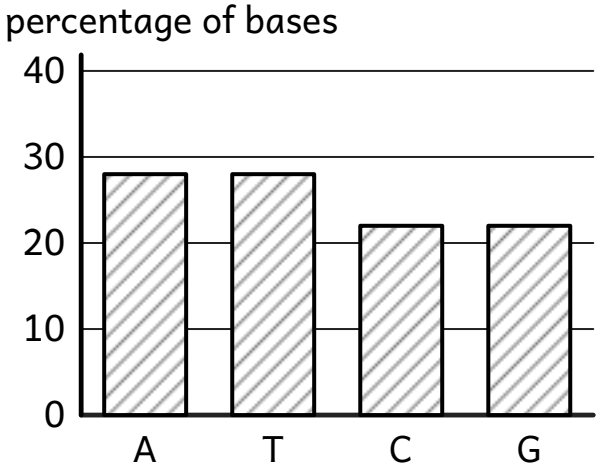
One strand can hold the bases in any order. But in a double helix, the number of A equals the number of T. The number of C equals the number of G. This is because every A has a T opposite it, and every C has a G.

WORKED EXAMPLE

In a sample of DNA, 28% of the bases are A. What percentage of the bases are C?

1. A pairs with T, so there are as many T as A. 28% are T.
2. A and T together make 28 + 28 = 56%.
3. The rest are C and G: 100 − 56 = 44%.
4. C pairs with G, so there are as many C as G: 44 ÷ 2 = 22%.

Answer: 22%

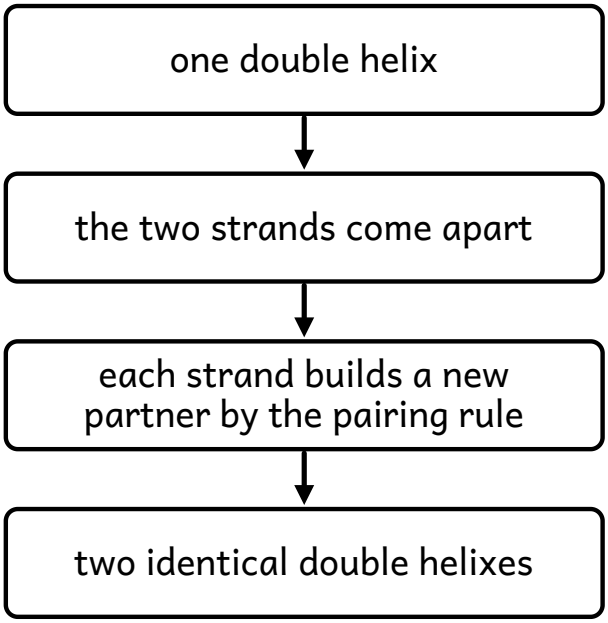


The sample of the worked example. A and T are equal. C and G are equal.

How does the order of bases make a protein? A cell reads the bases of a gene three at a time. Each group of three bases is the code for one **amino acid**. Amino acids are joined in a chain, and the chain folds to make a protein.

Four bases can make 4 × 4 × 4 = 64 different groups of three. Cells use 20 kinds of amino acid, so several groups code for the same amino acid, and a few groups mean "stop". A different order of bases makes a different protein.

The pairing rule also lets a cell copy its DNA. Before a cell divides, the two strands come apart. Each strand then builds a new partner by the rule. The result is two double helixes, each the same as the first. Each has one old strand and one new strand.



How DNA is copied before a cell divides.

TRY IT

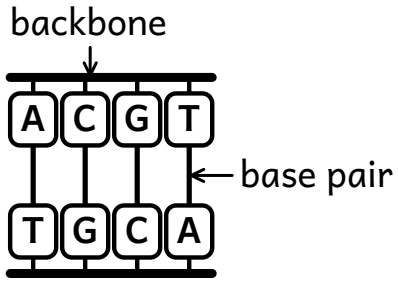
Twist a paper ladder

You need: an old sheet of paper, a pencil.

1. Tear a strip about 5 cm wide and 30 cm long from the paper. Tear it, so that you do not need scissors.
2. Draw a long line down each long edge. These are the two backbones.
3. Draw a short rung across the strip every 3 cm. At the two ends of each rung write a pair: A and T, or C and G.
4. Hold the two ends. Turn one end round and round so that the strip twists.

What you will see: The flat ladder twists into a spiral. The rungs stay straight and the backbones wind round them. A twisted ladder is the shape of a double helix.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~The two strands of DNA are exact copies of each other.~~

Why it feels right: The word "double" suggests two of the same thing.

The test that breaks it: Write one strand: ATGC. Pair each base by the rule and you get TACG. The two strands are not the same, and every base differs from the one opposite it.

What is true: The strands are complementary: each is the partner of the other. Together they hold the same information twice, in a matching form.

KEY WORDS

double helix
the shape of DNA: two strands twisted round each other.

backbone
the chain of sugar and phosphate molecules that holds a DNA strand together.

base
one of the four letters of DNA: A, T, C and G.

base pair
two bases joined across the two strands, A with T or C with G.

complementary
matching by the pairing rule. One strand is complementary to the other.

amino acid
a small molecule that is a link in the chain of a protein. Three bases code for one.

BACK TO YOUR GUESS

The answer is A: The four letters are used in a very long order, like the letters of a long book.

The four bases are used in a very long order. The order is the code. A human cell has billions of bases in a row, so four letters are more than enough.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Which pairs of bases join in DNA?

   A A with C, and T with G

   B A with A, and C with C

   C A with T, and C with G

   D A with G, and C with T

Answer at the back of the book.

2. One strand of DNA reads TTAGC. What does the other strand read?

   A AATCG

   B TTAGC

   C GGCTA

   Answer at the back of the book.

3. What is the backbone of a strand of DNA made of?

   A Bases joined end to end

   B Sugar and phosphate molecules, taking turns

   C Amino acids in a chain

   Answer at the back of the book.

4. What are the rungs of the DNA ladder?

   A Single sugar molecules

   B Whole genes

   C The chromosomes

   D Pairs of bases, one from each strand

   Answer at the back of the book.

5. Why does the pairing rule help a cell copy its DNA?

   A It makes the two strands the same as each other.

   B It cuts the DNA into short pieces.

   C Each old strand acts as the pattern for its new partner.

   Answer at the back of the book.

6. **From an earlier chapter**

   How are a gene and a chromosome related?

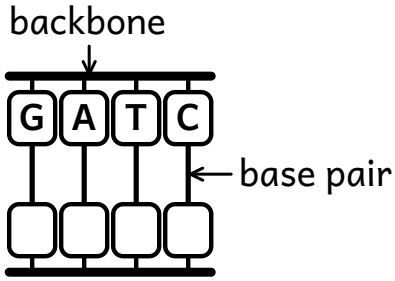
   A A chromosome is a small section of one gene.

   B A gene is a section of the DNA that makes up a chromosome.

   C They are two names for the same thing.

   Answer at the back of the book.

7. Complete the lower strand of the ladder. The strand above reads GATC. What does the lower strand read?



Answer at the back of the book.

8. In a sample of DNA, 30% of the bases are T. What percentage are G?

Answer at the back of the book.

9. A part of a gene has 90 bases. Each group of three bases codes for one amino acid. How many amino acids does this part code for?

Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

DNA is a double helix. Sugar and phosphate make each backbone. The rungs are base pairs: A with T, C with G. Three bases code for one amino acid.

Draw: A ladder with four rungs and the letters A, T, C and G on it, with the pairs matched.

S4.2.3 CHAPTER 3

Meiosis and sex cells

> **A baby has 46 chromosomes in its cells. But a sperm and an egg joined to make it. How is that possible if each parent has 46?**

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Each sex cell has all 46, and the extra ones are thrown away at fertilisation.
- ☐ **B** Each sex cell has 23 chromosomes, half the usual number, so the two make 46.
- ☐ **C** The baby takes all 46 from the mother, and the father gives none.

IF THIS FEELS HARD, READ THIS FIRST

- Level 4, Cells, photosynthesis and respiration, S4.1.4. It teaches mitosis, which this chapter compares with meiosis.
- Level 3, Growing up: puberty and reproduction, S3.4.6. It tells how a sperm and an egg join to make a new cell.

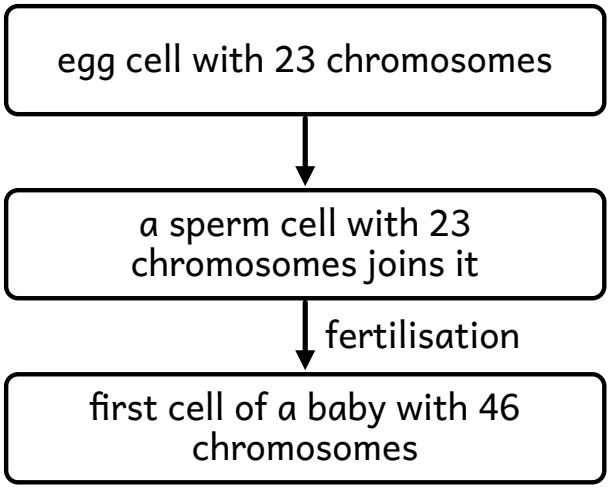
BY THE END YOU CAN

- Explain why sex cells have half the chromosomes of body cells
- Compare mitosis and meiosis

A new human begins as one cell. The cell forms when a sperm cell from the father joins an egg cell from the mother. Sperm and eggs are the **sex cells**.

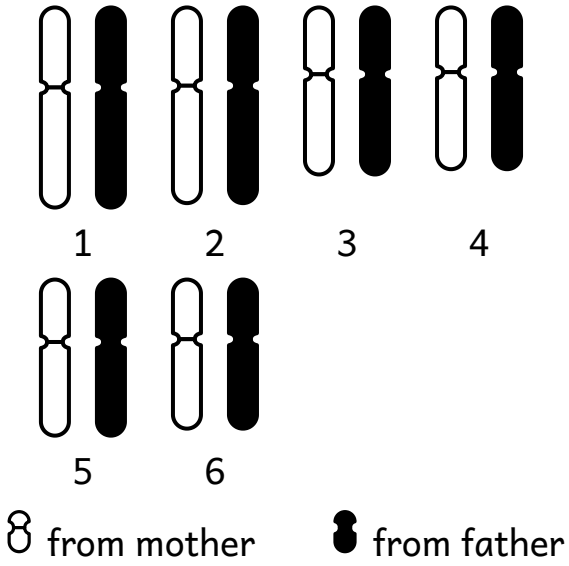
Most body cells have 46 chromosomes. Suppose a sperm and an egg each had 46. The first cell of a baby would have 92. The next generation would have 184. That cannot go on. So each sex cell has only half the usual number, which is 23.

A sex cell gets one chromosome from each of the 23 pairs. When the sperm and the egg join, the cell has 23 + 23 = 46 chromosomes. They are in 23 pairs again. This joining is called **fertilisation**.



Fertilisation restores the number of chromosomes.

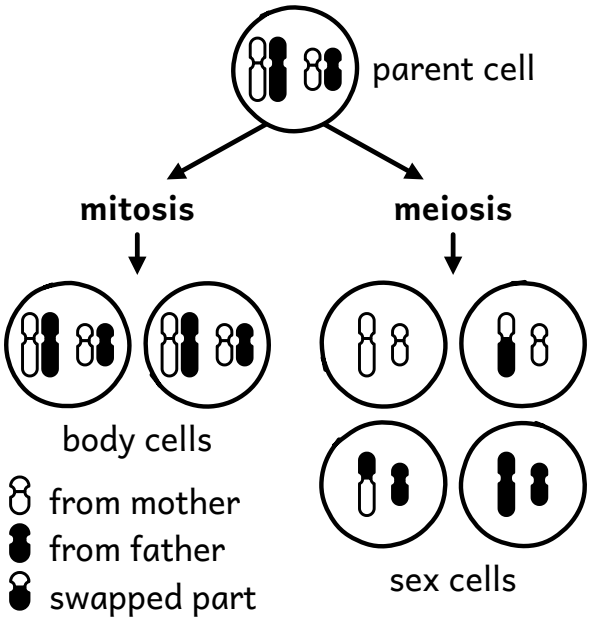
In a body cell, each pair has one chromosome from the mother and one from the father. The picture shows the mother's chromosomes in white and the father's in black.



Six of the 23 pairs. One chromosome of every pair came from each parent.

Sex cells are made by a special kind of cell division called **meiosis**. It takes place only in the sex organs: the ovaries, which make eggs, and the testes, which make sperm.

You know **mitosis** already. Mitosis makes two cells that are the same as the first. They have the same number of chromosomes and the same genes. Meiosis is different. One cell makes four cells, and each has half the chromosomes. In a man all four become sperm. In a woman only one becomes an egg, and the other three are tiny and die away.



One parent cell with four chromosomes. Mitosis keeps all four in each of two cells. Meiosis shares them out to four cells, and some parts swap first.

Two things make every sex cell different. The first is random sorting. In each pair, which chromosome goes into the sex cell is a matter of chance. The second is **crossing over**. Before the cell divides, the two chromosomes of a pair swap parts. A chromosome then holds some of the mother's DNA and some of the father's.

WORKED EXAMPLE

A cell has 3 pairs of chromosomes. How many different sex cells can random sorting make?

1. For each pair, a sex cell gets one of 2 chromosomes.
2. So there are 2 choices for pair 1, 2 for pair 2 and 2 for pair 3.
3. The number of kinds of sex cell is $2 \times 2 \times 2 = 8$.

Answer: 8 different sex cells

WORKED EXAMPLE

A human cell has 23 pairs of chromosomes. How many different sex cells can random sorting alone make?

1. Each pair gives 2 choices, and there are 23 pairs.
2. With 10 pairs we would have 2^{10} = 1 024 kinds.
3. With 23 pairs we multiply 23 twos: 2^{23} = 8 388 608.

Answer: 8 388 608 different sex cells

Pairs	Different sex cells
1	2
2	4
3	8
4	16
23	8 388 608

Each extra pair doubles the number. Crossing over adds even more kinds.

So one person can make more than 8 million different sex cells, before crossing over is counted. This is why brothers and sisters from the same parents are not the same.

Feature	Mitosis	Meiosis
Cells	2	4
Each has	46	23
Alike?	yes	no

For a human cell. Cells is how many cells one division makes. Each has is the number of chromosomes in each new cell. Mitosis is for growth and repair. Meiosis makes the sex cells, in the ovaries and testes.

TRY IT

Sort chromosomes by chance

You need: an old sheet of paper, a pencil, two cups or bowls.

1. Tear four small pieces of paper. Write L and M on the first, and L and F on the second. Write S and M on the third, and S and F on the fourth.
2. L stands for a long chromosome and S for a short one. M is from the mother and F is from the father.
3. Put the two L pieces face down in one cup. Put the two S pieces face down in the other cup.
4. Shake both cups. Pick one piece from each, without looking. Write down the two, such as LM and SF. This is one sex cell. Put the pieces back.
5. Do this 12 times. Count how many times each of the four sets of two came up.

What you will see: Usually all four sets come up, but none comes up every time. Chance decides which chromosome of each pair goes into a sex cell. With only 2 pairs there are 2 × 2 = 4 kinds. With 23 pairs there are millions.

If you cannot try it, this is what happens.

Long	Short
mother	mother
mother	father
father	mother
father	father

A WRONG IDEA MANY PEOPLE HAVE

~~Brothers and sisters get exactly the same chromosomes from their mother.~~

Why it feels right: They have the same mother and the same father, so it seems they should get the same DNA.

The test that breaks it: Every egg is made by meiosis. Random sorting and crossing over mean each egg differs. Two children get different sex cells from the same parent.

What is true: Each sex cell has its own mix. Brothers and sisters share many genes, but not all. The exception is identical twins, who grow from one fertilised egg.

KEY WORDS

sex cells
egg cells and sperm cells, which have half the chromosomes of a body cell.

fertilisation
the joining of a sperm cell and an egg cell to make one new cell.

meiosis
cell division that makes four different cells, each with half the chromosomes.

mitosis
cell division that makes two identical cells with the same number of chromosomes.

crossing over
the swap of parts between the two chromosomes of a pair.

BACK TO YOUR GUESS

The answer is B: Each sex cell has 23 chromosomes, half the usual number, so the two make 46.

A sex cell has only half the chromosomes of a body cell: 23. When a sperm and an egg join, the 23 and the 23 make 46 again.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. How many chromosomes does a human egg cell have?

    A 23 chromosomes

    B 46 chromosomes

    C 92 chromosomes

    Answer at the back of the book.

2. What happens at fertilisation?

    A One cell divides to make four sex cells.

    B A body cell divides to make two identical cells.

    C A sperm cell joins an egg cell to make one cell with 46 chromosomes.

    Answer at the back of the book.

3. What does one cell make when it divides by meiosis?

    A Two cells identical to it

    B Four different cells, each with half the chromosomes

    C Four identical cells, each with all the chromosomes

    Answer at the back of the book.

4. Which of these is a job of mitosis, and not of meiosis?

    A Making egg cells

    B Making new skin cells to heal a cut

    C Making sperm cells

    Answer at the back of the book.

5. Why are sex cells made by meiosis and not by mitosis?

   A Mitosis only works in plants.

   B Meiosis is a faster kind of division.

   C Mitosis would give sex cells with all the chromosomes of a body cell, and the number would double each generation.

   Answer at the back of the book.

6. What does crossing over do?

   A It joins a sperm and an egg together.

   B It copies a chromosome exactly.

   C It swaps parts between the two chromosomes of a pair, so each sex cell is different.

   Answer at the back of the book.

7. **From an earlier chapter**

   One strand of DNA reads CCGA. What does the other strand read?

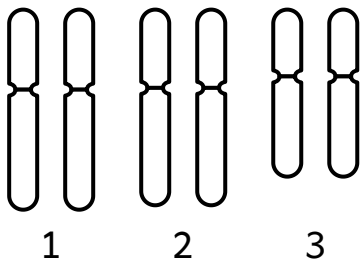
   A CCGA

   B GGCT

   C GGAC

   Answer at the back of the book.

8. The picture shows the pairs of one cell. How many chromosomes are in one sex cell made from it?



   Answer at the back of the book.

9. A cell has 4 pairs of chromosomes. How many different sex cells can random sorting make?

   Answer at the back of the book.

10. A body cell of a dog has 78 chromosomes. How many chromosomes does a dog sperm cell have?

    Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Sex cells have 23 chromosomes, half of 46. Fertilisation makes 46 again. Meiosis: 4 different cells. Mitosis: 2 identical cells. Random sorting and crossing over make the difference.

Draw: One parent cell with two arrows: mitosis to 2 cells, meiosis to 4 cells.

S4.2.4 CHAPTER 4

Boy or girl: X and Y

What decides whether a baby is a boy or a girl?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** The mother's egg decides, because the baby grows inside her.
- ☐ **B** What the mother eats during the pregnancy.
- ☐ **C** The father's sperm decides, because it carries either an X or a Y chromosome.

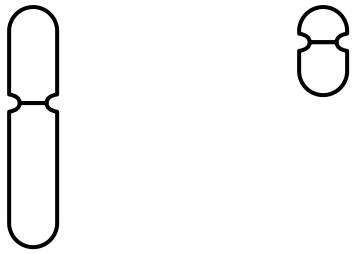
IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Statistics and chance, M3.7.6. It shows how to say how likely something is, such as 1 in 2.
- Level 3, Statistics and chance, M3.7.7. It shows how to find a chance when every outcome is equally likely.

BY THE END YOU CAN

- Use a Punnett square to show how X and Y chromosomes decide sex
- Explain why the chance of a boy or a girl is about even

Of your 23 pairs of chromosomes, 22 pairs are the same kind in everyone. They are numbered 1 to 22. The 23rd pair is the **sex chromosomes**. They are called X and Y.



X chromosome Y chromosome

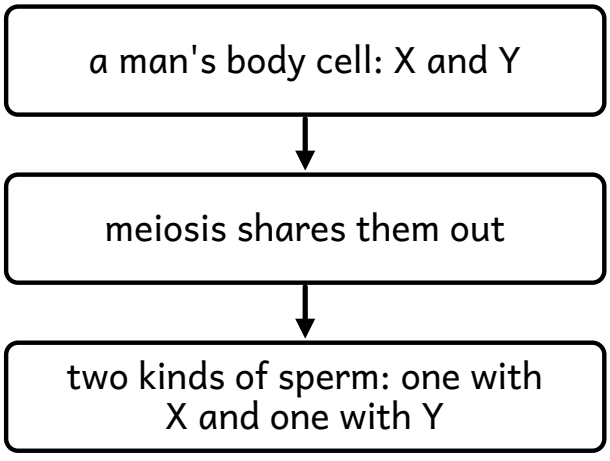
The Y chromosome is much smaller than the X chromosome and carries far fewer genes.

In most people, a pair of two X chromosomes (XX) develops as female. A pair of an X and a Y (XY) develops as male. A gene on the Y chromosome starts the changes that make a body male. Without it, the body develops as female.

Sex pair	Usually
XX	female
XY	male

Usually means develops as. This is the usual pattern. A few people have other patterns, which are described below.

Most women have two X chromosomes in each body cell. Meiosis shares them out, so every egg gets one X. In most men, a body cell has an X and a Y. Meiosis gives half of his sperm an X and half a Y.

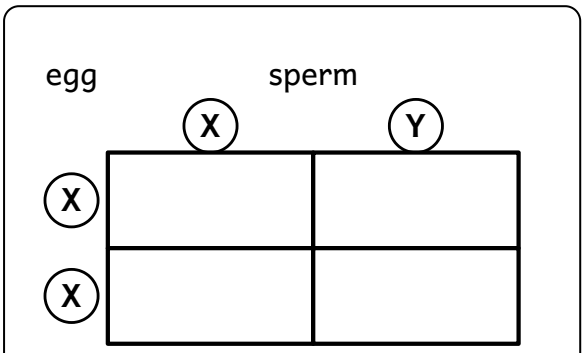


A man makes two kinds of sperm in equal numbers. A woman makes one kind of egg, with an X.

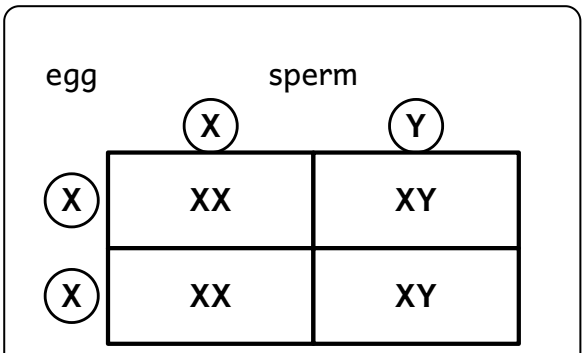
A **Punnett square** shows every way an egg and a sperm can meet. Put the egg's chromosomes down the side and the sperm's across the top. Each box is one possible child, called an **offspring**.

DRAW IT FIRST

Cross an egg with a sperm



1 Write the two eggs, X and X, down the side. Write the two kinds of sperm, X and Y, across the top.



2 Fill each box with the letter from its row and the letter from its column. Two boxes read XX and two read XY.

Two boxes read XX and two read XY. So each baby has a 1 in 2 chance of being a girl. It has a 1 in 2 chance of being a boy. The sperm decides. A sperm with an X gives a girl. A sperm with a Y gives a boy.

WORKED EXAMPLE

Use the Punnett square. What is the chance that a baby is XY?

1. The square has 4 boxes, and each is equally likely.
2. The number of boxes that read XY is 2.
3. The chance is 2 out of 4, which is 1 in 2.

Answer: 1 in 2

Each birth is a fresh chance. The sperm that wins is not affected by earlier babies. A family with three girls still has a 1 in 2 chance of a boy next time. Chance has no

memory.

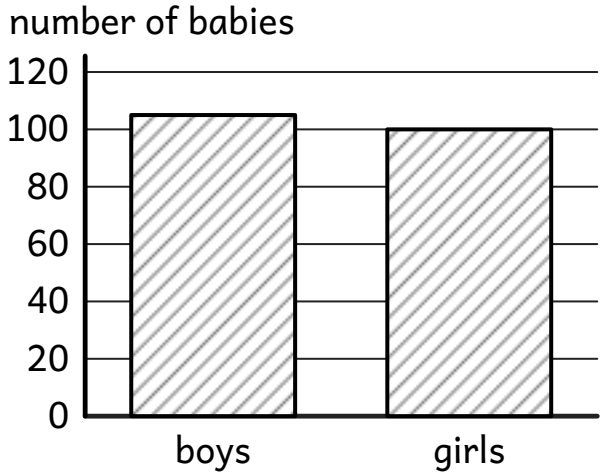
A ratio is a chance, not a promise. A family with four children may have four girls. But among very many births, the numbers come close to half and half. Across the world, slightly more boys are born than girls: about 105 boys for every 100 girls.

WORKED EXAMPLE

About 105 boys are born for every 100 girls. A region has 2 050 births in a year. About how many are boys?

1. In every group of 105 + 100 = 205 births, about 105 are boys.
2. The number of groups of 205 births is 2 050 ÷ 205 = 10.
3. About 1 050 are boys, because 10 × 105 = 1 050.

Answer: About 1 050 boys



Out of 205 births, about 105 are boys and 100 are girls. That is close to even, with a few more boys.

A few people have another pattern of sex chromosomes, such as a single X, or XXY. Some are born with a body that develops in a way that does not match the usual XX or XY pattern. This is part of the natural range of human bodies. The pages above describe the usual pattern.

TRY IT

Cross two parents with paper

You need: an old sheet of paper, a pencil, two cups or bowls.

1. Tear four small pieces of paper. Write X on two of them for the egg. Write X on the third and Y on the fourth for the sperm.
2. Put the two X pieces for the egg in one cup. Put the other two in the second cup.
3. Shake both cups. Pick one piece from each, without looking. The two together are one child, such as XY.
4. Write down boy for XY or girl for XX. Put the pieces back. Do this 20 times and count the boys and the girls.

What you will see: You may not get exactly 10 and 10. That happens only about 1 time in 6. The count is usually close to half and half, and sometimes it is not. That is what a 1 in 2 chance means for a small number of tries.

If you cannot try it, this is what happens.

Sperm	Egg	Child
X	X	XX
Y	X	XY

A WRONG IDEA MANY PEOPLE HAVE

~~The mother decides whether the baby is a boy or a girl.~~

Why it feels right: The baby grows inside the mother, so it seems that her body must decide.

The test that breaks it: Look at the Punnett square. Both eggs carry an X. Only the sperm differs, so only the sperm can change the result.

What is true: Every egg carries an X. The sperm carries an X or a Y. So the father's sperm decides.

KEY WORDS

sex chromosomes
the pair of chromosomes called X and Y.

Punnett square
a square of boxes that shows every way two parents' chromosomes or genes can combine.

offspring
a child or young one of a parent.

BACK TO YOUR GUESS

The answer is C: The father's sperm decides, because it carries either an X or a Y chromosome.

The sperm decides. Every egg carries an X chromosome, and a sperm carries either an X or a Y. Food and the mother's body do not change which one fertilises the egg.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Which sex chromosomes can one sperm cell carry?

   A Either an X or a Y

   B Always an X

   C Either an X or a Y, decided by the egg

   D Both an X and a Y

   Answer at the back of the book.

2. Which sex chromosome does every egg cell carry?

   A An X

   B Either an X or a Y

   C A Y

   Answer at the back of the book.

3. What decides whether a baby gets XX or XY?

   A Whether the mother eats well in the pregnancy

   B Whether the egg carries an X or a Y

   C Whether the sperm that joins the egg carries an X or a Y

   Answer at the back of the book.

4. A couple has three girls. What is the chance that their next baby is a boy?

   A More than 1 in 2, because a boy is due

   B 1 in 2

   C Less than 1 in 2, because this family makes girls

   Answer at the back of the book.

5. Why are about as many boys as girls born?

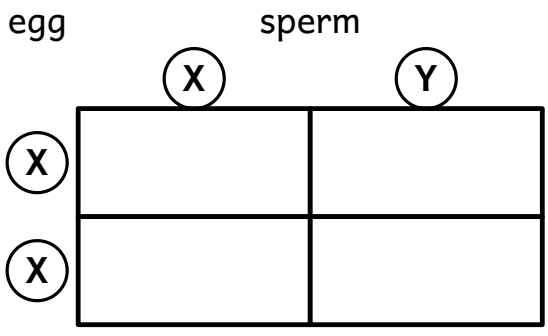
   A Every family has the same number of boys and girls.

   B Half of sperm carry an X and half carry a Y, so each baby has a 1 in 2 chance of each.

   C Nature changes the chances after each birth to balance them.

   Answer at the back of the book.

6. Look at the empty Punnett square. When it is filled in, how many of the four boxes read XX?



   A 1 box

   B 2 boxes

   C 4 boxes

   Answer at the back of the book.

7. **From an earlier chapter**

   A woman's body cell has 46 chromosomes. How many chromosomes does one of her egg cells have?

   A 46 chromosomes

   B 23 chromosomes

   C 92 chromosomes

   Answer at the back of the book.

8. Each baby has a 1 in 2 chance of being a boy. In 400 births, about how many boys do you expect?

   Answer at the back of the book.

9. About 105 boys are born for every 100 girls. A town has 410 births. About how many are boys?

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

XX usually develops as female and XY as male. Every egg carries X. A sperm carries X or Y, so the sperm decides. Each baby has about a 1 in 2 chance of each. Chance has no memory.

Draw: A Punnett square with X and X down the side, X and Y across the top, and XX, XY, XX, XY inside.

S4.2.5 CHAPTER 5

Dominant and recessive

> **A pea plant with round seeds is crossed with one with wrinkled seeds. All the offspring have round seeds. Where did "wrinkled" go?**

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** It is still there, hidden, and it can come back in a later generation.
- ☐ **B** It was lost for ever, because round always wins.
- ☐ **C** The wrinkled plant's pollen did not work.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Cells, S3.1.6. It shows how cells fit into a living thing, which helps when we talk about a cell's two copies of a gene.
- Level 3, Statistics and chance, M3.7.7. It shows how to find a chance from a count of equally likely outcomes.

BY THE END YOU CAN

- Use the words allele, dominant, recessive, genotype and phenotype correctly
- Predict offspring ratios with a Punnett square

You have two copies of most genes. A man has one X and one Y, so he has only one copy of the genes on each of them. One copy is on the chromosome you got from your mother, and one is on the chromosome you got from your father. The two copies are not always the same.

Different versions of one gene are called **alleles**. In the 1800s a monk named Gregor Mendel grew thousands of pea plants and counted what they made. The

seed shape of a pea plant has two alleles. One makes round seeds and one makes wrinkled seeds.

We write alleles as letters. R is the allele for round seeds and r is the allele for wrinkled seeds. A pea plant has two alleles, so its pair of letters is RR, Rr or rr.

Mendel found that a seed with Rr is round. One copy of R is enough. We say that R is **dominant** and r is **recessive**. A dominant allele shows its effect when there is one copy or two. A recessive allele shows only when there are two copies and no dominant allele.

The pair of alleles a plant has is its **genotype**, such as Rr. What you can see is its **phenotype**, such as round seeds.

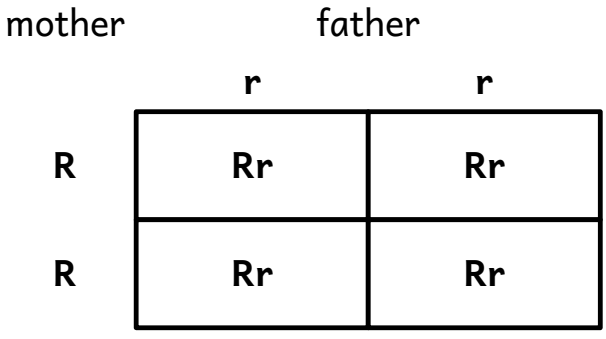
Seed shape belongs to the seed itself. The seeds on a plant are its offspring, so each seed has its own genotype. A round plant means a plant grown from a round seed.

Genotype	Phenotype
RR	round seeds
Rr	round seeds
rr	wrinkled seeds

Two genotypes, RR and Rr, give the same phenotype. Only rr gives wrinkled seeds.

RR and rr are **homozygous**: the two alleles are the same. Rr is **heterozygous**: the two alleles are different. An Rr seed is round, but it carries r. The plant that grows from it can pass r on to its offspring.

Now we predict. First, cross a plant with two R alleles and a plant with two r alleles. Each parent can give only one kind of allele, so every offspring gets one R and one r.



Every offspring is Rr, so every seed is round. The wrinkled allele is hidden, but not lost.

Next, cross two of these Rr plants. Each parent gives R or r with an equal chance. The square shows the four ways the alleles can meet.

DRAW IT FIRST

Cross two Rr plants

mother / father

	R	r
R		
r		

1 Write the mother's alleles, R and r, down the side. Write the father's alleles, R and r, across the top.

mother / father

	R	r
R	RR	Rr
r	Rr	rr

2 Fill each box with the two alleles that meet there. The boxes read RR, Rr, Rr and rr.

mother / father

	R	r
R	RR	Rr
r	Rr	rr

wrinkled seeds

3 Hatch the box that shows the recessive phenotype. Only rr has wrinkled seeds.

WORKED EXAMPLE

Two Rr pea plants are crossed. What is the ratio of round seeds to wrinkled seeds among their offspring?

1. The square has 4 boxes. 1 reads RR, 2 read Rr and 1 reads rr.
2. Round seeds are RR and Rr, so 3 boxes are round.
3. Wrinkled seeds are rr, so 1 box is wrinkled.
4. The ratio of round to wrinkled is 3 : 1.

Answer: 3 : 1

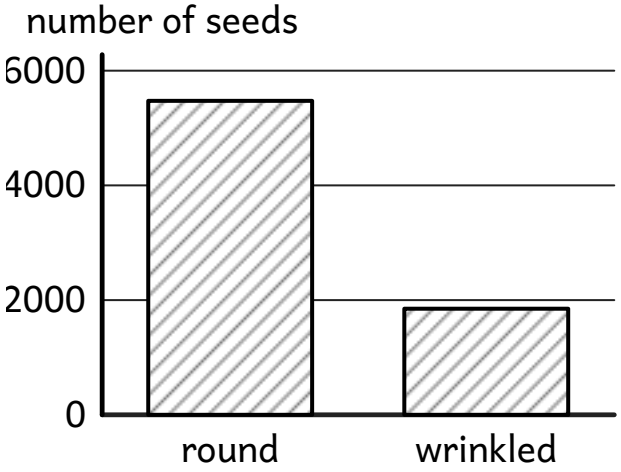
The ratio of genotypes is 1 RR : 2 Rr : 1 rr. The ratio of phenotypes is 3 round : 1 wrinkled. Three quarters of the offspring are round and one quarter are wrinkled. A ratio is a chance for each seed. It is not a promise for one pod.

WORKED EXAMPLE

Mendel counted the seeds of the second generation. He found 5 474 round seeds and 1 850 wrinkled seeds. How many round seeds were there for every wrinkled seed? Give the answer to one decimal place.

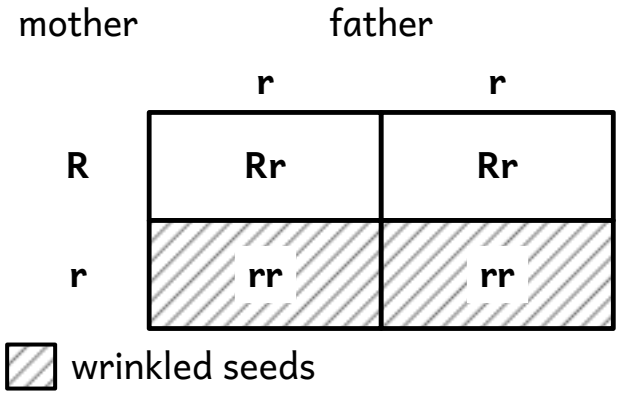
1. Divide the round seeds by the wrinkled seeds.
2. 5 474 ÷ 1 850 = 2.96 to two decimal places.
3. To one decimal place this is 3.0, so there were about 3 round seeds for each wrinkled seed.

Answer: 3.0



Mendel counted every seed of the second generation. The result is close to 3 : 1, but it is not exactly 3 : 1. Chance seldom gives an exact ratio.

How can you tell if a round plant is RR or Rr? You cannot tell by looking. Cross it with a wrinkled plant, which is always rr. If the round plant is RR, every seed is round. If it is Rr, about half the seeds are wrinkled.



Rr crossed with rr. Half of the boxes are Rr and round. Half are rr and wrinkled. The ratio is 1 : 1.

People have genes in pairs too, and some features follow this pattern. In some families, extra fingers or toes are caused by a dominant allele. This feature is rare, so dominant does not mean common.

Be careful with other examples. Eye colour, tongue rolling and earlobe shape are often taught as single gene features. They are not. Several genes and other things affect them. This is a well known myth.

TRY IT

Fold *a* Punnett square

You need: *a*n old sheet of paper, *a* pencil.

1. Fold the paper in half, then in half *a*gain the other w*a*y. Open it. You have four boxes. Draw over the fold lines.
2. Write R *a*nd r *a*cross the top for the f*a*ther. Write R *a*nd r down the side for the mother.
3. In e*a*ch box write the letter from its column *a*nd the letter from its row. Write the c*a*pit*a*l letter first.
4. Count the boxes of e*a*ch genotype. Colour in the rr box.

What you will see: The boxes read RR, Rr, Rr *a*nd rr. One box in four is rr. The coloured box is the plant with wrinkled seeds.

If you cannot try it, this is what happens.

Genotype	Boxes
RR	1
Rr	2
rr	1

A WRONG IDEA MANY PEOPLE HAVE

~~A dominant allele is the one that most people have, or the stronger one.~~

Why it feels right: In everyday speech, "dominant" means winning or strong.

The test that breaks it: In some families the allele for extra fingers is dominant, yet very few people have it. A dominant allele only needs one copy to show.

What is true: Dominant means that one copy is enough to show. It says nothing about how common, strong or healthy the allele is. A recessive allele is not weaker. It is hidden when a dominant allele is present.

KEY WORDS

allele
one version of a gene.

dominant
an allele that shows its effect when there is one copy or two.

recessive
an allele that shows only when there are two copies and no dominant allele.

genotype
the pair of alleles an organism has, such as Rr.

phenotype
what you can see or measure, such as round seeds.

homozygous
having two of the same allele, such as RR or rr.

heterozygous
having two different alleles, such as Rr.

BACK TO YOUR GUESS

The answer is A: It is still there, hidden, and it can come back in a later generation.

The wrinkled allele is still there. It is hidden by the round allele. When two of these offspring are crossed, about 1 in 4 of their seeds are wrinkled again.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. A pea seed has the genotype Rr. R is dominant. What shape is the seed?

   A Wrinkled

   B Half round and half wrinkled, a blend of the two

   C Round

Answer at the back of the book.

2. Which of these plants is heterozygous?

   A Rr

   B RR

   C rr

   Answer at the back of the book.

3. Two Rr plants are crossed. What chance does each seed have of being wrinkled?

   A 1 in 4

   B 1 in 2

   C 3 in 4

   D None, because round is dominant

   Answer at the back of the book.

4. What does "recessive" mean?

   A An allele that is rare

   B An allele that disappears when a dominant allele is present

   C An allele that shows only when there is no dominant allele with it

   D An allele that is weaker or harmful

   Answer at the back of the book.

5. A round seeded plant is crossed with a wrinkled plant. About half of the seeds are wrinkled. What is the genotype of the round plant?

   A RR

   B rr

   C Rr

   Answer at the back of the book.

6. Which of these is a phenotype?

   A The letters Rr

   B Round seeds

   C The pair of alleles in a cell

   Answer at the back of the book.

7. Which statement about eye colour is true?

   A Eye colour is decided by one gene, and brown is dominant.

   B Several genes help decide eye colour, so it does not follow a plain dominant and recessive pattern.

   C Eye colour comes only from the mother.

   Answer at the back of the book.

8. **From an earlier chapter**

   Each baby has a 1 in 2 chance of being a girl. How many of the four boxes in the Punnett square for an XX mother and XY father read XX?

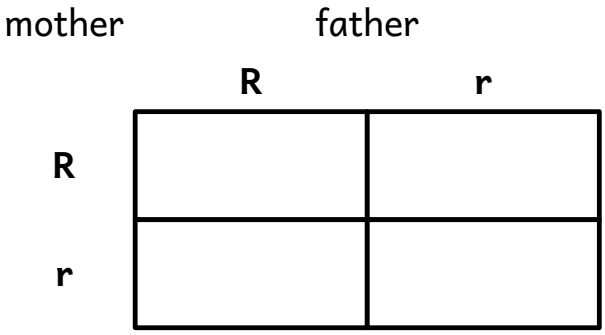
   A 1 box

   B 2 boxes

   C 4 boxes

   Answer at the back of the book.

9. Look at the empty square for two Rr plants. When it is filled in, how many boxes read Rr?



   Answer at the back of the book.

10. Two Rr plants are crossed and give 120 seeds. About how many are wrinkled?

    Answer at the back of the book.

11. An Rr plant is crossed with an rr plant and gives 80 seeds. About how many are round?

    Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Alleles are versions of a gene. A dominant allele shows with one copy. A recessive allele needs two. Genotype is the alleles, phenotype is what you see. Rr × Rr gives 3 round : 1 wrinkled.

Draw: A Punnett square for Rr × Rr, with the four boxes filled in and rr hatched.

S4.2.6 CHAPTER 6

Family trees and genetic disorders

> **Two healthy parents have a child with cystic fibrosis. How can that happen?**

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** The child caught the condition from the mother during the pregnancy.
- ☐ **B** Both parents carry one copy of a hidden allele, and the child got a copy from each.
- ☐ **C** One parent must have hidden the condition.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Body systems, S3.3.6. It says what red blood cells do, which helps with sickle cell disease.
- Level 3, Body systems, S3.3.5. It shows how the lungs work, which helps with cystic fibrosis.

BY THE END YOU CAN

- Read a family tree to find who carries an allele
- Explain how sickle cell disease and cystic fibrosis are inherited

Some conditions run in families. Some are caused by a change in a gene or a chromosome. They are called **genetic disorders**. Doctors draw a **family tree** to follow an allele from one generation to the next.

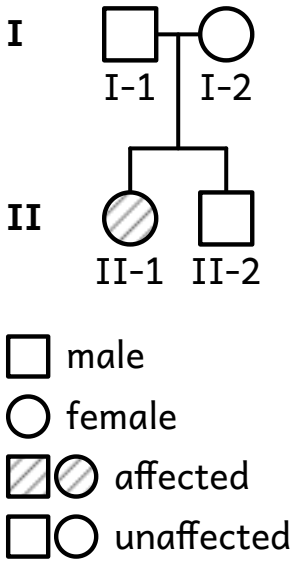
In a family tree, a square stands for a male and a circle for a female. A line joins a couple, and a line down from it leads to their children. A person with the condition is hatched all over. A person with one copy of the allele and no signs is hatched on

one half, and is a **carrier**. A tree hatches half a symbol only when a test has shown that the person is a carrier. A plain symbol means no signs of the condition, and the person may still be a carrier.

Cystic fibrosis is caused by a recessive allele. The gene makes a protein in the membranes of cells. Without it, the body makes thick, sticky mucus that clogs the lungs and the gut. People with the condition can have trouble breathing, many chest infections, and trouble digesting food. Doctors and health workers can help manage it.

We write the usual allele as F and the cystic fibrosis allele as f. FF is not affected. Ff is a carrier and is healthy. Only ff has cystic fibrosis. A carrier is a person with one copy of a recessive allele and one copy of the dominant allele.

Now look at a family tree. The daughter has cystic fibrosis. Her parents and her brother do not.



The daughter has cystic fibrosis. Her parents and her brother do not.

Reason it out. The daughter has the condition, so her genotype is ff. She got one f from each parent. Her parents are healthy, so each also has an F. So both parents are Ff, and both are carriers. Her brother is healthy, so he is FF or Ff. The tree cannot tell us which.

A rule follows. Two healthy parents may have a child with a condition like this. Suppose one gene on one of the 22 numbered pairs causes it, and the child got the allele from both parents. Then the allele must be recessive, and both parents must be carriers. Rarely, one of the two copies in the child is new, from a mutation in an

egg or a sperm. Then only one parent is a carrier. Many carriers never know it until a child is born with the condition.

DRAW IT FIRST

Cross two carriers

mother / father

	F	f
F		
f		

1 Write the mother's alleles, F and f, down the side. Write the father's alleles, F and f, across the top.

mother / father

	F	f
F	FF	Ff
f	Ff	ff

2 Fill each box. The boxes read FF, Ff, Ff and ff.

mother / father

	F	f
F	FF	Ff
f	Ff	ff

cystic fibrosis

3 Hatch the box with the condition. Only ff has cystic fibrosis.

WORKED EXAMPLE

Both parents are carriers of cystic fibrosis. What is the chance that a child has the condition, is a carrier, or is not a carrier?

1. Each parent gives F or f, so the square has 4 boxes. They read FF, Ff, Ff and ff.
2. Boxes that read ff, so the child has the condition: 1.
3. Boxes that read Ff, so the child is a carrier: 2.
4. Boxes that read FF, so the child is not a carrier: 1.
5. So ff is 1 out of 4, which is 1 in 4. Ff is 2 out of 4, which is 1 in 2. FF is 1 out of 4, which is 1 in 4.

Answer: Cystic fibrosis 1 in 4, carrier 1 in 2, not a carrier 1 in 4

The chance is for each child, and each child is a fresh chance. Two carriers can have four healthy children, or two children with the condition. The ratio is a chance, not a promise.

Sickle cell disease is also caused by a recessive allele. The gene makes part of haemoglobin, the protein in red blood cells that carries oxygen. We write the usual allele as H and the sickle allele as h.

A person with hh makes a different haemoglobin. Their red blood cells can bend into a curved, sickle shape. These cells can block small blood vessels and cause pain. They also break easily, which can cause tiredness, and they raise the risk of infection. Doctors and health workers can help manage it.

Alleles	Result
HH	no disease
Hh	carrier
hh	disease

Sickle cell disease needs two copies of h. A person with Hh is a carrier and is usually healthy.

The sickle allele is common in some parts of the world. The reason is malaria. Malaria is a disease caused by a tiny parasite, which mosquito bites pass to people.

A carrier, with one h and one H, is less likely to become severely ill with malaria than a person with HH.

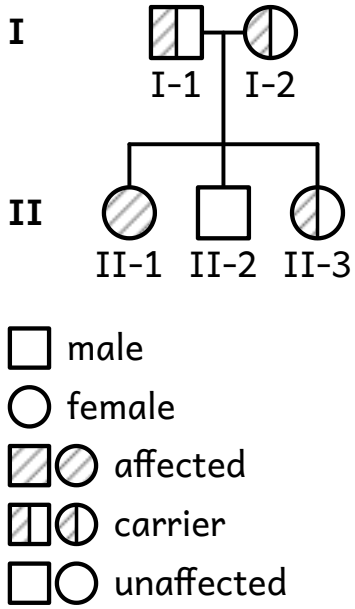
So in places where malaria is common, carriers were more likely to survive and to have children. The allele stayed common there. Two copies cause the disease, so the allele does not spread to everyone. The result is a balance.

WORKED EXAMPLE

A man is a carrier of cystic fibrosis. His partner has cystic fibrosis. What is the chance that their child has it?

1. The man is Ff. His partner is ff, so she can give only f.
2. The four boxes read Ff, ff, Ff and ff. Boxes that read ff: 2.
3. The chance is 2 out of 4, which is 1 in 2.

Answer: 1 in 2



Sickle cell disease in one family. Tests show that both parents are carriers, Hh. II-1 has hh and II-3 is a carrier, Hh. II-2 has no signs, so he is HH or Hh. Only a test can tell which.

TRY IT

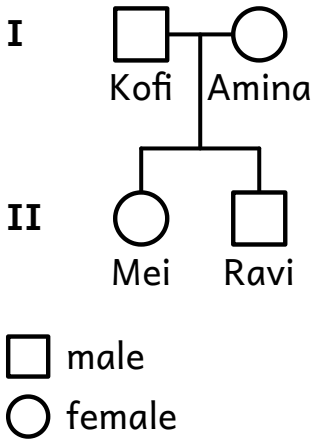
Draw your family tree

You need: an old sheet of paper, a pencil.

1. Draw a square for each male and a circle for each female in your family. Put the oldest generation at the top.
2. Join each couple with a line. Draw a line down from it to the children of the couple.
3. Write a name under each symbol. Write "I" beside the top row, "II" beside the next row, and so on.
4. Look at your tree. Which people are in the same generation as you?

What you will see: A family tree shows who is related to whom. Doctors add shading to show who has a condition and who is a carrier. Draw only names for now. Do not write a person's health on a tree without their wish.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~Cystic fibrosis and sickle cell disease can be caught from another person.~~

Why it feels right: Many illnesses are caused by germs that spread, so any illness may seem catchable.

The test that breaks it: Look at the family tree. The condition follows the alleles a child receives from their parents. No germ is involved, and touching or living with a person with the condition cannot pass it on.

What is true: These conditions are inherited. A child is born with the alleles. They are not infections, and nobody is to blame.

KEY WORDS

carrier
a person with one copy of a recessive allele. A carrier usually has no signs and can pass the allele on.

genetic disorder
a condition caused by a change in a gene or a chromosome. Many are passed on from parents to children.

family tree
a drawing that shows how people are related, and who has a condition.

BACK TO YOUR GUESS

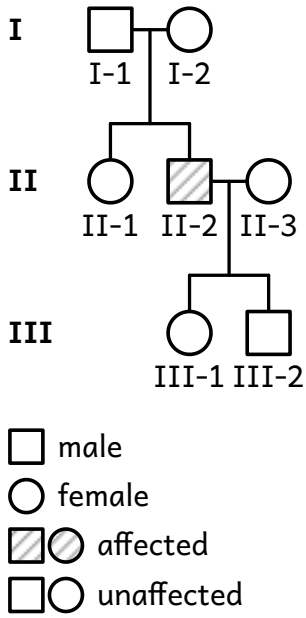
The answer is B: Both parents carry one copy of a hidden allele, and the child got a copy from each.

Cystic fibrosis is caused by a recessive allele. A parent with one copy is healthy, but can pass the copy on. A child who gets a copy from each parent has the condition.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. In the picture, II-2 has cystic fibrosis. His partner, II-3, and their two children have no signs of it. What are the genotypes of the two children?



   A One Ff and one ff

   B Both Ff

   C Both FF

   Answer at the back of the book.

2. What is a carrier?

   A A person with one recessive allele and one dominant allele

   B A person with two copies of the recessive allele

   C A person who can pass the condition on by touch

   Answer at the back of the book.

3. Two carriers of cystic fibrosis have a child. What is the chance that the child has cystic fibrosis?

   A 1 in 2

   B 3 in 4

   C 1 in 4

   D None, because both parents are healthy

   Answer at the back of the book.

4. Why is the sickle cell allele common in places where malaria is common?

   A Malaria causes the allele to form in the blood.

   B Carriers are less likely to become severely ill with malaria, so they live to pass the allele on.

   C The allele is dominant, so it spreads more than other alleles.

   Answer at the back of the book.

5. A man with sickle cell disease (hh) has children with a woman with the genotype HH. What is true of their children?

   A All of them are carriers.

   B Half of them have sickle cell disease.

   C None of them has the sickle allele.

   Answer at the back of the book.

6. Two healthy parents have a child with a genetic disorder caused by one gene on one of the 22 numbered pairs. The child has two copies of the allele, one from each parent. What does this tell us about the allele?

   A It is dominant.

   B It is recessive, and both parents are carriers.

   C It is on the X chromosome, so only the mother carries it.

   Answer at the back of the book.

7. **From an earlier chapter**

   Two plants are crossed, Tt with tt. T is the dominant allele for tall and t is for short. What is the chance of a short offspring?

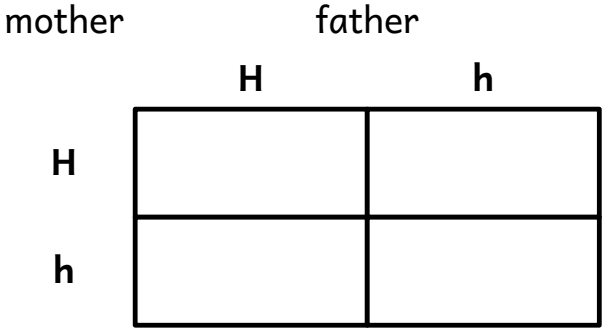
   A 1 in 4

   B 1 in 2

   C 3 in 4

   Answer at the back of the book.

8. Look at the empty square for a carrier mother and a carrier father of sickle cell disease. How many boxes will read Hh when it is filled in?



Answer at the back of the book.

9. Among 400 children whose parents are both carriers of cystic fibrosis, about how many are expected to have the condition?

Answer at the back of the book.

10. Many couples are each a carrier (Ff) and a person with cystic fibrosis (ff). They have 120 children in all. About how many have the condition?

Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Carriers have one copy of a recessive allele and are usually healthy. Two carriers: 1 in 4 affected, 1 in 2 carriers, 1 in 4 not carriers. Squares are males, circles are females.

Draw: A family tree of two carrier parents and their children, with the Punnett square beside it.

S4.2.7 CHAPTER 7

Variation

Why are no two people exactly alike, even in one family?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Only because of the different food and places they grow up in.
- ☐ **B** Only because of the genes they got from their parents.
- ☐ **C** Because of both: their genes and the surroundings in which they live and grow.

IF THIS FEELS HARD, READ THIS FIRST

- Level 2, Tables and charts, M2.7.1. It teaches how to count data in a tally and a frequency table.
- Level 2, Tables and charts, M2.7.3. It shows how to draw and read a bar chart, the step before a histogram.

BY THE END YOU CAN

- Sort features into ones caused by genes, surroundings or both
- Collect hand spans from family and friends and plot a histogram

Look at the people in one family. They have things in common, but no two are exactly alike. The differences between living things of the same kind are called **variation**.

Variation has two causes. Some features come from genes: they are inherited. Some come from the **environment**, which means the surroundings and everything that happens to a living thing. Many features come from both.

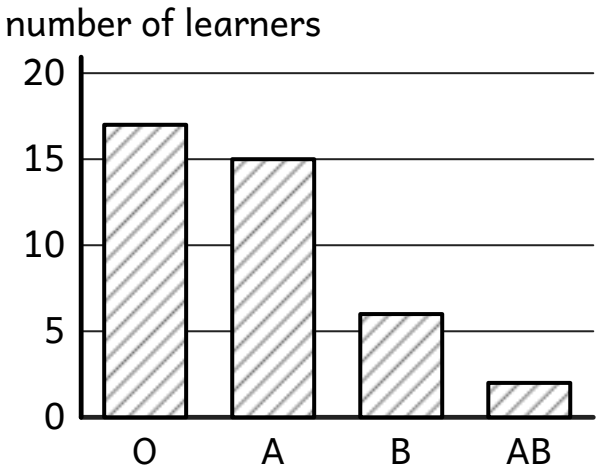
Feature	Cause
blood group	genes
scar	environment
language	environment
height	both
body mass	both

Environment means the surroundings and what happens to a person. Language here means the language a person speaks. Genes decide your blood group, and a scar comes from an injury.

Take height. Your genes set a range for how tall you can grow. Food, health and sleep decide where in that range you end up. Take body mass. Genes affect it, and so do the food you eat and the exercise you take.

Identical twins give us a clue. They start from one fertilised egg, so they have almost exactly the same DNA. When identical twins differ, for example in mass, the cause is mostly the environment.

There are two kinds of variation. Some features fall into separate groups, with nothing in between. Your blood group is A, B, AB or O. This is **discontinuous variation**. Other features can take any value in a range. Height, mass and hand span are like this. This is **continuous variation**.



Example numbers for a class of 40. The shares of each group differ from place to place. Separate groups give separate bars with gaps. Each learner is in exactly one group.

For continuous variation we use a **histogram**. We split the range into classes of equal width. We count how many values fall in each class. This count is the **frequency**. The bars touch, because the end of one class is the start of the next.

A value on a boundary goes in the higher class. So 20.0 cm goes in the class from 20 to 22 cm, and not in 18 to 20 cm. Here are the hand spans of 30 people. A span is the distance from the tip of the thumb to the tip of the little finger. The hand is spread wide.

cm	cm	cm	cm
15.2	15.8	16.4	16.9
17.1	17.5	17.8	18.0
18.3	18.6	18.9	19.0
19.2	19.4	19.5	19.7
19.9	20.0	20.2	20.4
20.6	20.9	21.1	21.3
21.8	22.0	22.4	22.7
23.1	23.6		

The hand spans of 30 people, in cm. Read across each row.

WORKED EXAMPLE

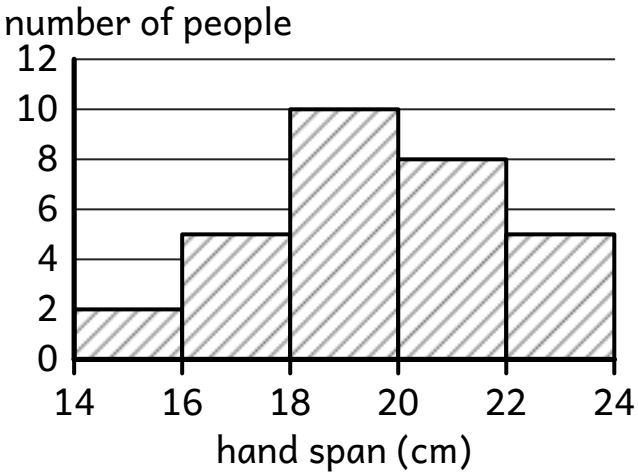
The table shows 30 hand spans in cm. How many are in the class from 18 to 20 cm?

1. The class 18 to 20 cm includes 18.0 and every value up to, but not including, 20.0.
2. They are 18.0, 18.3, 18.6, 18.9, 19.0, 19.2, 19.4, 19.5, 19.7 and 19.9.
3. There are 10 values in the class.

Answer: 10 people

Class (cm)	People
14 to 16	2
16 to 18	5
18 to 20	10
20 to 22	8
22 to 24	5

The frequency of each class. All five classes are 2 cm wide.



Most hand spans are near the middle. Fewer are very small or very large. This is a common shape for continuous variation.

WORKED EXAMPLE

Use the histogram. How many of the 30 people have a hand span of 20 cm or more?

1. Spans of 20 cm or more are in the classes 20 to 22 cm and 22 to 24 cm.
2. Read the bars. The class 20 to 22 cm has a bar of height 8.
3. The class 22 to 24 cm has a bar of height 5.
4. The number of people is 8 + 5 = 13.

Answer: 13 people

A histogram looks like a bar chart, but there are two differences. Its bars touch. Its horizontal axis is a number line, so the classes have no gaps. In this book the

classes are of equal width, so the height of each bar is the frequency. A bar chart for separate groups has gaps between its bars.

TRY IT

Measure hand spans

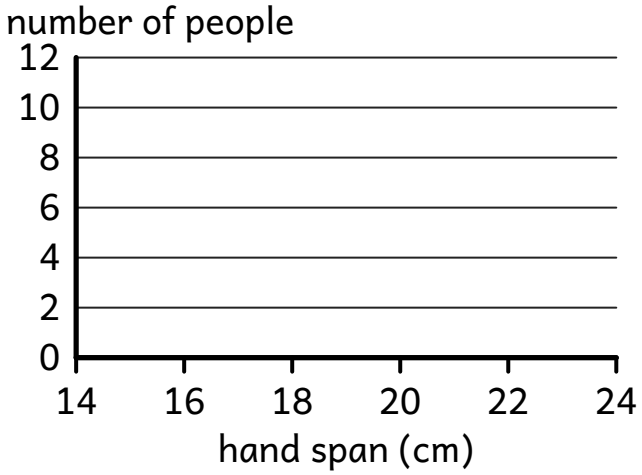
You need: a ruler, or a strip of paper marked in centimetres, a pencil, an old sheet of paper, family and friends, at least 15 if you can.

Be safe: Measure only people who agree. Do not touch anyone's hand without being asked. Keep the pencil away from faces.

1. Ask each person first. Only measure people who agree.
2. Ask a person to spread one hand flat on the paper, with the fingers wide. Put a dot at the tip of the thumb and a dot at the tip of the little finger.
3. Measure between the dots, to the nearest 0.5 cm. Use the same hand for everyone. Write the numbers in a list.
4. Choose classes of equal width, such as 2 cm. Count how many spans fall in each class. Draw the bars so that they touch.

What you will see: Most spans fall near the middle, with fewer at both ends. If your numbers differ, that is variation too. Adults and children have different ranges, so a mixed group gives a wider spread.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~Your genes decide everything about you.~~

Why it feels right: We say that a feature "runs in the family", so it can seem that nothing else matters.

The test that breaks it: Identical twins have almost the same genes. Yet they can differ in mass, in scars and in the language they speak. Those differences come from the environment.

What is true: Genes decide a great deal. But for many features, genes and the environment work together. Some features, such as a scar, have nothing to do with genes.

KEY WORDS

variation
the differences between living things of the same kind.

environment
the surroundings of a living thing and everything that happens to it.

continuous variation
variation in which a feature can take any value in a range, such as height.

discontinuous variation
variation in which a feature falls into separate groups, such as blood group.

histogram
a chart for continuous data, with bars that touch. With classes of equal width, the height of a bar is its frequency.

frequency
the number of values that fall in a class.

BACK TO YOUR GUESS

The answer is C: Because of both: their genes and the surroundings in which they live and grow.

Both. Genes give a person their starting point. Food, health, learning and chance then add to it. For many features, the two work together.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Which feature is caused by the environment and not by genes?

   A Blood group

   B A scar on the knee

   C The shape of the fingers

   Answer at the back of the book.

2. Which feature is caused by both genes and the environment?

   A Height

   B Blood group

   C The language a person speaks

   Answer at the back of the book.

3. Two identical twins are different in body mass. What is the most likely cause?

   A They have very different genes.

   B Chance in the Punnett square.

   C One of them is a carrier.

   D The environment, such as food and exercise

   Answer at the back of the book.

4. Blood group can be A, B, AB or O, and nothing in between. What kind of variation is this?

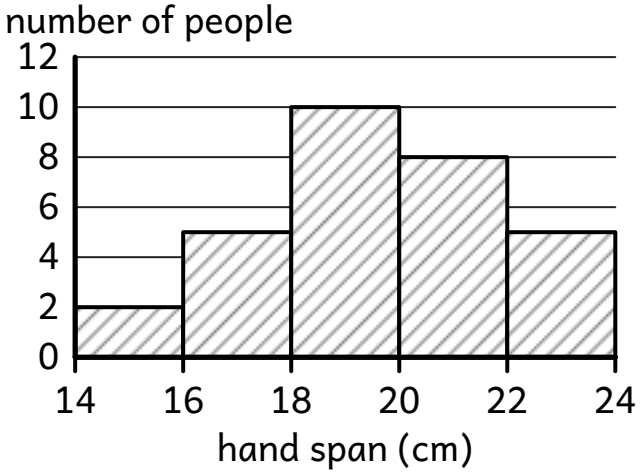
   A Discontinuous variation

   B Continuous variation

   C No variation, because it is inherited

   Answer at the back of the book.

5. Look at the histogram. In which class is the tallest bar?



A 16 to 18 cm

B 20 to 22 cm

C 18 to 20 cm

Answer at the back of the book.

6. Why do the bars of a histogram of hand spans touch?

A To save space on the page

B Hand span can take any value in a range, so one class begins where the last ends.

C Because each bar is a different feature

Answer at the back of the book.

7. **From an earlier chapter**

Two carriers of sickle cell disease have a child. What is the chance that the child is also a carrier?

A 1 in 4

B None, because both parents are healthy

C 1 in 2

Answer at the back of the book.

8. Hand spans from 12 cm to 24 cm are put in 6 classes of equal width. How wide is each class?

   Answer at the back of the book.

9. The classes of a hand span histogram start at 14 cm and are 2 cm wide. In which class is a hand span of 17.3 cm? Write the class as two numbers.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Variation comes from genes, the environment, or both. Blood group falls in separate groups. Height can take any value in a range. A histogram has touching bars. With classes of equal width, the height of a bar is its frequency.

Draw: A histogram of hand spans with classes of 2 cm and touching bars, with both axes named.

S4.2.8 CHAPTER 8

Mutation and genetic engineering

Bacteria can make human insulin. How can a tiny bacterium make a human protein?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** People put the human gene for insulin into the bacterium, and the bacterium reads it.
- ☐ **B** The bacterium eats human cells and keeps their insulin.
- ☐ **C** The bacterium turns into a human cell.

IF THIS FEELS HARD, READ THIS FIRST

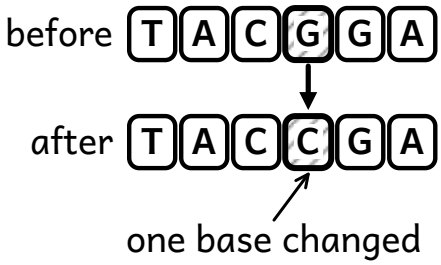
- Level 4, Cells, photosynthesis and respiration, S4.1.4. DNA is copied before a cell divides, and most mutations are mistakes made in that copying.
- Level 4, Cells, photosynthesis and respiration, S4.1.5. It explains enzymes, the proteins that are used as scissors to cut DNA.
- Level 2, How plants grow, S2.1.7. It shows how seeds and pollen spread, which matters for the risks of modified crops.

BY THE END YOU CAN

- Explain how a mutation can change a gene and its protein
- Weigh up the benefits and risks of genetically modified crops

A gene is a code of bases. What happens if the code changes? A change in the order of the bases in DNA is called a **mutation**.

Mutations happen by chance. A cell can make a mistake when it copies its DNA. Ultraviolet light, other radiation and some chemicals can also damage DNA. Cells repair most of the damage, but not all.



A mutation of one base. The fourth base changed from G to C.

Remember that a cell reads bases three at a time. Each group of three codes for one amino acid. In the picture the groups are TAC GGA before and TAC CGA after. One group changed.

WORKED EXAMPLE

Compare the strands TACGGA and TACCGA. In which position do they first differ, and in which group of three bases is the change?

1. Compare the two strands base by base.
2. They first differ at position 4.
3. Positions 1 to 3 are group 1, and positions 4 to 6 are group 2.
4. The change is in group 2.

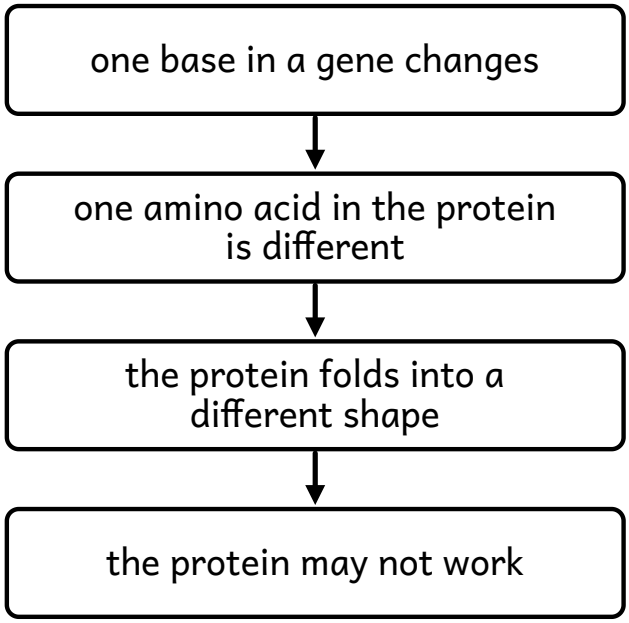
Answer: Position 4, in group 2

What does a changed group do? That depends on the mutation, and there are three main cases.

First, most mutations have no effect. Several groups of three code for the same amino acid, so the protein stays the same. Only a small part of human DNA codes for proteins at all, so many mutations fall outside genes.

Second, some mutations change an amino acid. A protein folds into a shape, and its shape gives it its job. A different amino acid can change the shape, so the protein may do its job badly or not at all. In sickle cell disease, one base change in the haemoglobin gene means that one amino acid is different.

Third, a few mutations help. A changed protein may work better, or do something new. New alleles begin as mutations, and helpful ones can spread through a species over many generations.



How a mutation can change a protein. Each step may not happen.

A mutation in a body cell, such as a skin cell, stays in that cell and the cells that come from it. It is not passed to children. A mutation in an egg or a sperm can be passed on, and then every cell of the child has it. An extra or a missing base shifts every group after it, and this often has a bigger effect than a swap.

TRY IT

Change a code written in threes

You need: an old sheet of paper, a pencil.

1. Write THE CAT SAT. Each word has three letters, like a group of three bases.
2. Change one letter: write THE CAR SAT. Read it. One word changed, and the rest is still clear.
3. Now write THECATSAT, with no gaps. Put an extra letter X after THE. Write the letters again, in groups of three, from the start.
4. Read the groups. How many words are wrong now?

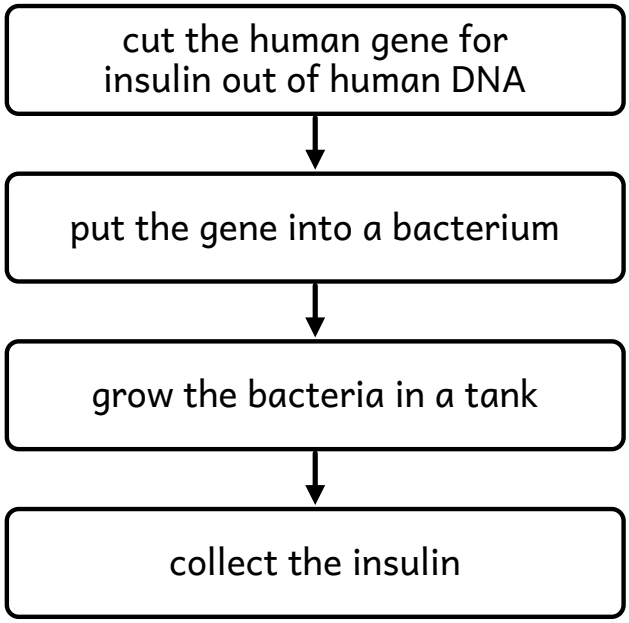
What you will see: A change of one letter damaged one word. An extra letter shifted every group after it, so every word after the change was wrong. This is why an extra or missing base can be so serious.

If you cannot try it, this is what happens.

Change	Words
none	THE CAT SAT
one swapped	THE CAR SAT
one added	THE XCA TSA T

People can also change the DNA of a living thing on purpose. **Genetic engineering** means taking a gene from one living thing and putting it into another. It works because every living thing reads the DNA code in the same way.

Insulin is a protein that helps to control the level of sugar in the blood. Some people's bodies do not make enough of it. Today, most insulin that people use is made by engineered bacteria or yeast. Here we follow the bacteria. The human gene for insulin is cut out of human DNA with enzymes that act as scissors. It is put into a bacterium, and the bacterium reads it and makes insulin.



Cut, insert, grow. The bacteria divide quickly, so one engineered cell becomes very many.

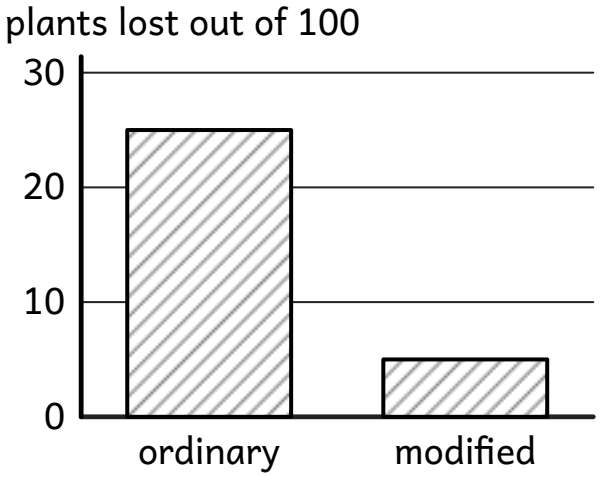
Crops can be engineered too. A gene may be added to a plant for a new feature. The plant may resist a pest insect, survive with little water, or have more vitamins in its grain. Such a plant is **genetically modified**, or GM.

WORKED EXAMPLE

In one example trial, pests destroyed 25 of every 100 plants of an ordinary crop. They destroyed 5 of every 100 plants of a modified crop. How many fewer plants out of 100 were lost with the modified crop?

1. Of every 100 plants, the ordinary crop lost 25.
2. Of every 100 plants, the modified crop lost 5.
3. The difference is 25 − 5 = 20 plants.
4. Check: the modified crop kept 100 − 5 = 95 plants. The ordinary crop kept 100 − 25 = 75. So 95 − 75 = 20.

Answer: Out of every 100 plants, 20 fewer are lost.



Example numbers for one trial of one modified crop. Another trial or another crop may give a different result.

Is a modified crop a good idea? A fair answer weighs the benefits against the risks. The result can differ for each new crop and each place, so each one is judged on its own.

Benefit	Risk
more food	wild plants
less spray	insects
vitamins	seed control
drought	unknowns

Read across the rows. Each one is explained in the text. Drought means a crop that lasts through a dry spell, and unknowns means long term effects that are not yet known.

The benefits can be large. A crop that resists a pest can give more food from the same land, and farmers need fewer sprays against insects. A crop with more vitamins can help people whose diet lacks them. A crop that lasts in drought can still grow when rain is short.

The risks need care. Pollen can carry a new gene to wild plants of the same kind. The effect on wild plants and on insects may not be known. Some seed may be controlled by its maker. A farmer may not be allowed to save seed and plant it again. Some long term effects may not show for many years.

Pests can also become resistant to a crop over many generations. Large reviews by science bodies have found that the GM foods now sold are as safe to eat as other foods. Each new crop is tested before it is grown.

To weigh a case, ask questions. Who gains, and who could be harmed? What does the evidence show? Has it been tested, and by whom? Can the risks be reduced? Two careful people can weigh the same facts and reach different answers.

A WRONG IDEA MANY PEOPLE HAVE

~~Every mutation is harmful.~~

Why it feels right: The word sounds frightening, and we hear most about mutations that cause disease.

The test that breaks it: Compare the strands before and after a base changes. If the new group codes for the same amino acid, the protein is the same. Many mutations are like this, or fall outside genes.

What is true: Most mutations have no effect. Some are harmful and a few help. Mutations are also the source of new alleles, and so of the variation that we see in living things.

KEY WORDS

mutation
a change in the order of the bases in DNA.

genetic engineering
moving a gene from one living thing into another.

genetically modified
having a gene that was added by genetic engineering. GM is short for it.

BACK TO YOUR GUESS

The answer is A: People put the human gene for insulin into the bacterium, and the bacterium reads it.

People cut out the human gene for insulin and put it into bacteria. All living things read the DNA code in the same way, so the bacteria make insulin from it.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. What is a mutation?

   A A change in the order of bases in DNA

   B A change that always causes a disease

   C A gene moved from one living thing into another

   Answer at the back of the book.

2. Why can a change in one base change a protein?

   A The whole gene is deleted whenever one base changes.

   B Proteins are made of bases, so a base change changes the protein directly.

   C The group of three bases changes, so a different amino acid may be added.

   Answer at the back of the book.

3. Which mutation can be passed on to a child?

   A A mutation in a skin cell

   B A mutation in a sperm cell or an egg cell

   C Any mutation, in any cell

   Answer at the back of the book.

4. Which thing is put into a bacterium to make it produce human insulin?

   A The human gene for insulin

   B A whole human cell

   C Insulin itself

   D A whole human chromosome

   Answer at the back of the book.

5. Why can a bacterium read a human gene?

   A All living things use the same DNA code.

   B The bacterium changes the gene so that it fits.

   C A bacterium is really a very small human cell.

   Answer at the back of the book.

6. Which is a possible benefit of a crop that resists a pest insect?

   A The crop grows well in a drought.

   B Fewer sprays are needed against the insect.

   C The crop is certain to be safe for every wild plant and insect.

   Answer at the back of the book.

7. Which is a possible risk of a modified crop?

   A Pollen may carry the new gene to wild plants of the same kind.

   B The crop becomes a different species of living thing.

   C Eating it puts the new gene into the cells of the person who eats it.

   Answer at the back of the book.

8. **From an earlier chapter**

   Which chart suits hand span data, which is continuous?

   A A bar chart with gaps between the bars

   B A histogram, with bars that touch

   C A family tree

   Answer at the back of the book.

9. The strand TACGGA changes to TACCGA. At which position does the change happen? Count from 1.

   Answer at the back of the book.

10. In a trial, 30 of every 100 plants of an ordinary crop are lost to pests. 6 of every 100 plants of a modified crop are lost. How many fewer plants out of 100 are lost with the modified crop?

    Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A mutation changes the order of bases. Most do nothing, some change a protein, a few help. Genetic engineering moves a gene between species: cut, insert, grow. Weigh benefits against risks.

Draw: Three boxes: cut the gene, insert it, grow the cells, with one benefit and one risk written beside them.

Key words, A to Z

Every key word in this book, what it means, and the chapter that teaches it.

allele
one version of a gene. S4.2.5

amino acid
a small molecule that is a link in the chain of a protein. Three bases code for one. S4.2.2

backbone
the chain of sugar and phosphate molecules that holds a DNA strand together. S4.2.2

base
one of the four letters of DNA: A, T, C and G. S4.2.2

base pair
two bases joined across the two strands, A with T or C with G. S4.2.2

carrier
a person with one copy of a recessive allele. A carrier usually has no signs and can pass the allele on. S4.2.6

chromosome
one long molecule of DNA, coiled up tightly. S4.2.1

complementary
matching by the pairing rule. One strand is complementary to the other. S4.2.2

continuous variation
variation in which a feature can take any value in a range, such as height. S4.2.7

crossing over
the swap of parts between the two chromosomes of a pair. S4.2.3

discontinuous variation
variation in which a feature falls into separate groups, such as blood group. S4.2.7

DNA
the long molecule in cells that holds the instructions for a living thing. S4.2.1

dominant
an allele that shows its effect when there is one copy or two. S4.2.5

double helix

the shape of DNA: two strands twisted round each other. S4.2.2

environment
the surroundings of a living thing and everything that happens to it. S4.2.7

family tree
a drawing that shows how people are related, and who has a condition. S4.2.6

fertilisation
the joining of a sperm cell and an egg cell to make one new cell. S4.2.3

frequency
the number of values that fall in a class. S4.2.7

gene
a section of DNA with the code for making one protein. S4.2.1

genetic disorder
a condition caused by a change in a gene or a chromosome. Many are passed on from parents to children. S4.2.6

genetic engineering
moving a gene from one living thing into another. S4.2.8

genetically modified
having a gene that was added by genetic engineering. GM is short for it. S4.2.8

genotype
the pair of alleles an organism has, such as Rr. S4.2.5

heterozygous
having two different alleles, such as Rr. S4.2.5

histogram
a chart for continuous data, with bars that touch. With classes of equal width, the height of a bar is its frequency. S4.2.7

homozygous
having two of the same allele, such as RR or rr. S4.2.5

meiosis
cell division that makes four different cells, each with half the chromosomes. S4.2.3

mitosis
cell division that makes two identical cells with the same number of chromosomes. S4.2.3

mutation

a change in the order of the bases in DNA. S4.2.8

offspring
a child or young one of a parent. S4.2.4

phenotype
what you can see or measure, such as round seeds. S4.2.5

protein
a molecule that does work in the body, such as a muscle protein or an enzyme. S4.2.1

Punnett square
a square of boxes that shows every way two parents' chromosomes or genes can combine. S4.2.4

recessive
an allele that shows only when there are two copies and no dominant allele. S4.2.5

sex cells
egg cells and sperm cells, which have half the chromosomes of a body cell. S4.2.3

sex chromosomes
the pair of chromosomes called X and Y. S4.2.4

variation
the differences between living things of the same kind. S4.2.7

Answers

S4.2.1. DNA, genes and chromosomes

1. **cell, nucleus, chromosome, gene, DNA base**

   A cell holds a nucleus. The nucleus holds chromosomes. A chromosome holds many genes. A gene is made of many DNA bases.

   - **If you chose A:** A gene is a section of a chromosome, so a chromosome is larger than a gene.
   - **If you chose C:** The nucleus is inside the cell, so the cell is larger.
   - **If you chose D:** That list is right but turned round. It starts with the smallest, and the question asks for the largest first.

2. **A section of DNA with the code for making one protein**

   A gene is a short section of a DNA molecule. Its order of bases is the code for one protein.

   - **If you chose A:** A gene is not a protein. It is the code for one. The protein is made from the code.
   - **If you chose B:** A chromosome holds many genes, about 20 000 in a whole human cell.

3. **46 chromosomes**

   There are 23 pairs of chromosomes and each pair has 2. So 23 × 2 = 46.

   - **If you chose B:** There are 23 pairs. Each pair has 2 chromosomes, so you need to double.
   - **If you chose C:** About 20 000 is the number of genes, not chromosomes. A chromosome holds many genes.

4. **It is coiled up tightly into chromosomes.**

   A long thread coils into a small bundle, like the string on the pencil. A chromosome is one DNA molecule coiled up.

   - **If you chose B:** The nucleus stays tiny. The DNA is what changes shape: it is coiled.
   - **If you chose C:** The DNA is kept in the nucleus, in 46 long pieces called chromosomes, each one coiled up.

5. **One protein**

   The order of bases in a gene tells the cell how to make one protein. Many genes together build a body part.

   - **If you chose A:** Body parts are built from many proteins, so many genes work together on one part.
   - **If you chose B:** Chromosomes are long DNA molecules. They are not made from the code in one gene.
   - **If you chose D:** Each gene has its own job. Its code makes one protein.

6. **In the nucleus**

   The nucleus is the control centre of the cell. It holds the chromosomes, and the chromosomes hold the DNA.

   - **If you chose A:** The membrane is the thin skin of the cell. It holds no chromosomes.
   - **If you chose C:** In a human cell the cytoplasm holds the other parts. The chromosomes stay in the nucleus. Go to S3.1.4.

7. **6 chromosomes**

   There are 3 pairs. Each pair has 2 chromosomes, so 3 × 2 = 6.

8. **78 chromosomes**

   Each pair has 2 chromosomes. 39 × 2 = 78.

9. **4 pairs**

   Chromosomes come in pairs of 2. 8 ÷ 2 = 4.

S4.2.2. The structure of DNA

1. **A with T, and C with G**

   The pairing rule is the same in every living thing: A with T, and C with G.

   - **If you chose A:** That swaps the partners. In DNA, A pairs with T, and C pairs with G.
   - **If you chose B:** A base pairs with a different base across the two strands, never with its own kind.
   - **If you chose D:** Those pairs do not form. A needs T, and C needs G.

2. **AATCG**

   T pairs with A, T with A, A with T, G with C, and C with G. So the partner strand is AATCG.

   - **If you chose B:** That is a copy of the strand you were given. The partner strand has the matching base at each place, not the same one.
   - **If you chose C:** You paired A with C and T with G. The rule is A with T, and C with G.

3. **Sugar and phosphate molecules, taking turns**

   Each strand has a backbone of sugar and phosphate. A base is attached to each sugar.

   - **If you chose A:** The bases hang off the backbone and meet the bases of the other strand. They are not the backbone.
   - **If you chose C:** Amino acids make proteins. DNA is a different molecule, with sugar and phosphate in the backbone.

4. **Pairs of bases, one from each strand**

   Each rung is one base pair: a base on one strand joined to its partner on the other.

   - **If you chose A:** Sugars are part of the backbone, the sides of the ladder, not the rungs.
   - **If you chose B:** A gene is a long section of DNA with many rungs. A single rung is only one base pair.
   - **If you chose C:** A chromosome is a whole DNA molecule, ladder and all. A rung is one small part of it. Go to S4.2.1.

5. **Each old strand acts as the pattern for its new partner.**

   When the strands come apart, each one tells the cell which bases to add. That gives two identical double helixes.

   - **If you chose A:** The strands are partners, not copies. The rule gives each base its matching base.
   - **If you chose B:** The rule does not cut anything. It says which base goes opposite which.

6. **A gene is a section of the DNA that makes up a chromosome.**

   A chromosome is one long DNA molecule, and a gene is one section of it with the code for one protein.

   - **If you chose A:** It is the other way round. A gene is a section of the DNA of a chromosome. Go to S4.2.1.
   - **If you chose C:** A chromosome is a whole coiled DNA molecule with many genes. A gene is just one section. Go to S4.2.1.

7. **CTAG**

   G pairs with C, A with T, T with A, and C with G. So the lower strand reads CTAG.

8. **20%**

   T pairs with A, so 30% are A as well. A and T make 60%. The other 40% are C and G in equal shares, so G is 20%.

9. **30 amino acids**

   Three bases make one group, so 90 ÷ 3 = 30 groups. Each group is one amino acid.

S4.2.3. Meiosis and sex cells

1. **23 chromosomes**

   A body cell has 46 chromosomes, and a sex cell has half. 46 ÷ 2 = 23.

   - **If you chose B:** That is the number in most body cells. A sex cell has half of it.
   - **If you chose C:** That would be the number if two body cells joined, and cells would double each generation.

2. **A sperm cell joins an egg cell to make one cell with 46 chromosomes.**

   The sperm brings 23 chromosomes and the egg brings 23. Together they make 23 + 23 = 46.

   - **If you chose A:** That is meiosis, which makes sex cells before fertilisation.
   - **If you chose B:** That is mitosis, which is used for growth and repair. Go to S4.1.4.

3. **Four different cells, each with half the chromosomes**

   Meiosis makes four cells, each with one chromosome from each pair, and no two are the same.

   - **If you chose A:** That is mitosis. Meiosis makes more cells, with half the chromosomes, and they are all different.
   - **If you chose C:** Meiosis shares the chromosomes out, so each cell gets half. Random sorting and crossing over make them all different.

4. **Making new skin cells to heal a cut**

   Mitosis makes identical body cells for growth and repair. Meiosis only makes sex cells.

   - **If you chose A:** Egg cells are sex cells, and sex cells are made by meiosis.
   - **If you chose C:** Sperm cells are sex cells, and sex cells are made by meiosis.

5. **Mitosis would give sex cells with all the chromosomes of a body cell, and the number would double each generation.**

   Meiosis halves the number, so fertilisation brings it back to the number of a body cell and not to double that.

   - **If you chose A:** Mitosis works in animals too. It is how your body grows and heals. Go to S4.1.4.
   - **If you chose B:** Speed is not the reason. The reason is the number of chromosomes.

6. **It swaps parts between the two chromosomes of a pair, so each sex cell is different.**

   After a swap, a chromosome holds DNA from both parents. That is one reason why no two sex cells are the same.

   - **If you chose A:** That is fertilisation. Crossing over happens inside one cell, before it divides.
   - **If you chose B:** It does the opposite: parts of two chromosomes swap, so the new chromosomes are not exact copies.

7. **GGCT**

   C pairs with G, C with G, G with C, and A with T. The partner reads GGCT.

   - **If you chose A:** That is the same strand. The partner has the matching base at each place. Go to S4.2.2.
   - **If you chose C:** You paired the first three correctly, but A pairs with T, not with C. Go to S4.2.2.

8. **3 chromosomes**

   A sex cell gets one chromosome from each pair. There are 3 pairs, so a sex cell has 3.

9. **16 different sex cells**

   Each pair gives 2 choices. 2 × 2 × 2 × 2 = 16.

10. **39 chromosomes**

    A sex cell has half the chromosomes of a body cell. 78 ÷ 2 = 39.

S4.2.4. Boy or girl: X and Y

1. **Either an X or a Y**

   A man's body cell has an X and a Y. Meiosis gives one to each sperm, so half the sperm carry X and half carry Y.

   - **If you chose B:** Every egg carries an X, but a man's sperm come in two kinds, X and Y.
   - **If you chose C:** The sperm already carries its X or Y before it meets the egg.
   - **If you chose D:** A sex cell gets only one chromosome of each pair, so a sperm carries one sex chromosome. Go to S4.2.3.

2. **An X**

   A woman's body cells usually have two X chromosomes. Whichever one goes into an egg, it is an X.

   - **If you chose B:** That is true for sperm. A woman has two X chromosomes, so every egg gets an X.
   - **If you chose C:** A woman usually has no Y chromosome, so her eggs carry an X.

3. **Whether the sperm that joins the egg carries an X or a Y**

   The egg always gives an X. An X sperm makes XX and a Y sperm makes XY.

   - **If you chose A:** Food matters for health, but it does not change which sperm joins the egg.
   - **If you chose B:** Every egg carries an X, so the egg cannot make the difference.

4. **1 in 2**

   Each pregnancy is a fresh chance. The sperm is X or Y with equal chance, so the chance of a boy is still 1 in 2.

   - **If you chose A:** Chance has no memory. Earlier babies do not change which sperm wins.
   - **If you chose C:** The father's sperm are half X and half Y whatever has happened before.

5. **Half of sperm carry an X and half carry a Y, so each baby has a 1 in 2 chance of each.**

   A man makes X and Y sperm in equal numbers. So each baby has about a 1 in 2 chance of being a boy or a girl.

   - **If you chose A:** Many families have more of one than the other. Only among very many births do the numbers come close.
   - **If you chose C:** Chance has no memory. It stays about 1 in 2 for every baby.

6. **2 boxes**

   The two X sperm boxes read XX, one in each row. The two Y sperm boxes read XY.

   - **If you chose A:** Both eggs carry an X, so each of them gives XX with an X sperm. That makes two boxes.
   - **If you chose C:** Half of the sperm carry a Y, so half of the boxes read XY.

7. **23 chromosomes**

   Meiosis gives each sex cell one chromosome from each pair, so half of 46. 46 ÷ 2 = 23.

   - **If you chose A:** That is the number in a body cell. Meiosis halves it for sex cells. Go to S4.2.3.
   - **If you chose C:** Cells cannot have double the number, or it would double again each generation. Go to S4.2.3.

8. **About 200 boys**

   A chance of 1 in 2 means half. 400 ÷ 2 = 200. The real number will be near 200, but not exactly 200.

9. **About 210 boys**

   Each group of 105 + 100 = 205 births has about 105 boys. 410 ÷ 205 = 2 groups, and 2 × 105 = 210.

S4.2.5. Dominant and recessive

1. **Round**

   R is dominant, so one copy is enough, and the seed is round.

   - **If you chose A:** A wrinkled seed needs two copies of r. This seed has one R, and R is dominant, so the seed is round.
   - **If you chose B:** Alleles do not blend. One R is enough, so the whole seed is round.

2. **Rr**

   Hetero means different. Rr has two different alleles. RR and rr each have two the same.

   - **If you chose B:** RR has two alleles that are the same. That is homozygous.
   - **If you chose C:** rr has two alleles that are the same. That is homozygous too.

3. **1 in 4**

   Only one box of four reads rr, so the chance of a wrinkled seed is 1 in 4.

   - **If you chose B:** That is the chance when Rr is crossed with rr. Here only one box in four is rr.
   - **If you chose C:** Three in four is the chance of a round seed. Wrinkled is the box with rr, one in four.
   - **If you chose D:** Both parents carry r. Each can pass it on, and a seed that gets r from both is rr.

4. **An allele that shows only when there is no dominant allele with it**

   A recessive allele has an effect only when the genotype has two copies of it.

   - **If you chose A:** Recessive is about how an allele shows, not how many people have it. Some recessive alleles are common.
   - **If you chose B:** It does not disappear. It is still in the cell, and it can be passed on to the next generation.
   - **If you chose D:** Recessive does not mean weak or harmful. A recessive allele can code for a perfectly good protein.

5. **Rr**

   About half wrinkled means about half the seeds got r from the round plant. So the plant has one r, and it is Rr.

   - **If you chose A:** An RR plant gives an R to every seed. Every seed would be round.
   - **If you chose B:** An rr plant has wrinkled seeds. This plant has round seeds, so it has at least one R.

6. **Round seeds**

   A phenotype is what you can see or measure. Round seeds are seen. The alleles are not.

   - **If you chose A:** The letters give the genotype, the alleles in the cell. A phenotype is what you can see.
   - **If you chose C:** That is the genotype. A phenotype is the feature that results from it.

7. **Several genes help decide eye colour, so it does not follow a plain dominant and recessive pattern.**

   Many features, such as eye colour, depend on several genes together. A one gene pattern, like Mendel's peas, applies only to a feature that one gene decides.

   - **If you chose A:** This is a myth from old school books. Eye colour is affected by several genes.
   - **If you chose C:** Both parents give genes for eye colour. The genes are on chromosomes that come from each parent.

8. **2 boxes**

   Two boxes read XX and two read XY. So the chance of a girl is 2 out of 4, which is 1 in 2.

   - **If you chose A:** Both eggs carry an X, so the two boxes with an X sperm both read XX. Go to S4.2.4.
   - **If you chose C:** The Y sperm gives XY, so only the X sperm boxes read XX. Go to S4.2.4.

9. **2 boxes**

   The mother's R meets the father's r, and the mother's r meets the father's R. Two boxes read Rr.

10. **About 30 seeds**

    One box in four is rr, so one seed in four is wrinkled. 120 ÷ 4 = 30.

11. **About 40 seeds**

    Two boxes in four read Rr, which is round. That is half. 80 ÷ 2 = 40.

S4.2.6. Family trees and genetic disorders

1. **Both Ff**

   II-2 has cystic fibrosis, so he is ff and gives each child an f. Each child is healthy, so each also has an F. Both children are Ff, carriers.

   - **If you chose A:** A child with ff would have cystic fibrosis. Both children here have no signs of it.
   - **If you chose C:** II-2 is ff, so every child gets an f from him. No child can be FF.

2. **A person with one recessive allele and one dominant allele**

   A carrier has the genotype Ff or Hh. The dominant allele hides the recessive one, so a carrier is usually healthy. They can pass the recessive allele on.

   - **If you chose B:** That person has the condition. A carrier has only one copy.
   - **If you chose C:** Genetic disorders are not infections. They are passed on only in the sex cells, as alleles.

3. **1 in 4**

   Only one of the four boxes reads ff. So the chance is 1 in 4 for each child.

   - **If you chose A:** That is the chance of a carrier child. Only one box in four reads ff. Go to S4.2.5.
   - **If you chose B:** Three in four is the chance that the child does not have the condition.
   - **If you chose D:** Both parents can pass on f. A child who gets f from each has the condition.

4. **Carriers are less likely to become severely ill with malaria, so they live to pass the allele on.**

   One copy of the sickle allele gives some protection from severe malaria. Carriers did better where malaria is common, and the allele stayed common there.

   - **If you chose A:** Malaria is spread by mosquitoes and it does not change a gene.
   - **If you chose C:** The sickle allele is recessive. And dominant never means that an allele spreads. Go to S4.2.5.

5. **All of them are carriers.**

   The father gives h and the mother gives H. Every child is Hh, which is a carrier.

   - **If you chose B:** To have the disease a child needs h from both parents. The mother has only H, so no child has hh.
   - **If you chose C:** The father has only h to give, so every child gets one h.

6. **It is recessive, and both parents are carriers.**

   The child must have two copies, one from each parent. Both parents are healthy, so the allele is hidden in them: it is recessive.

   - **If you chose A:** A dominant allele shows in anyone who has one copy. Healthy parents would not have it.
   - **If you chose C:** The question says the gene is on one of the 22 numbered pairs, and the child got a copy from each parent. So both parents carry it.

7. **1 in 2**

   Two of the four boxes read tt, which is short. So the chance is 2 out of 4, which is 1 in 2.

   - **If you chose A:** That is the chance when two Tt plants are crossed. Here the square has two boxes of tt. Go to S4.2.5.
   - **If you chose C:** Three in four is the chance of a tall plant when two Tt plants are crossed, not this cross. Go to S4.2.5.

8. **2 boxes**

   The mother's H meets the father's h, and the mother's h meets the father's H. Two boxes read Hh, so the chance of a carrier child is 1 in 2.

9. **About 100 children**

   One child in four has ff. 400 ÷ 4 = 100. The real number will be near 100, but not exactly 100.

10. **About 60 children**

    Two of the four boxes read ff, so half of the children have the condition. 120 ÷ 2 = 60.

S4.2.7. Variation

1. **A scar on the knee**

   A scar is caused by an injury, and so by the environment. No gene makes it.

   - **If you chose A:** Blood group is inherited. The environment does not change it.
   - **If you chose C:** The basic shape of a finger is inherited. An injury can change it, but the shape starts with genes.

2. **Height**

   Genes set a range for how tall a person can be. Food, health and sleep decide where in the range they end up.

   - **If you chose B:** Blood group depends on genes only. Food and health do not change it.
   - **If you chose C:** A person learns the language they hear. That is the environment, not genes.

3. **The environment, such as food and exercise**

   The twins have almost the same genes, so a difference between them is most likely caused by surroundings.

   - **If you chose A:** Identical twins have almost exactly the same DNA, so genes are not the likely cause.
   - **If you chose B:** A Punnett square predicts how genes pass from parents. The twins have the same genes already. Go to S4.2.5.
   - **If you chose C:** A carrier has a recessive allele that is hidden. It does not change body mass. Go to S4.2.6.

4. **Discontinuous variation**

   The groups are separate, with nothing in between. This is discontinuous variation.

   - **If you chose B:** Continuous variation means any value in a range, such as height. Blood group falls in separate groups.
   - **If you chose C:** Inherited features can vary between people. People have different blood groups, so there is variation.

5. **18 to 20 cm**

   The bar for 18 to 20 cm reaches 10, which is more than any other bar.

   - **If you chose A:** That bar reaches 5. Look for the bar that reaches the highest.
   - **If you chose B:** That bar reaches 8. One bar is higher.

6. **Hand span can take any value in a range, so one class begins where the last ends.**

   There is no gap between 19.9 cm and 20.0 cm, so the bars have no gap either.

   - **If you chose A:** Space is not the reason. The reason is about the numbers.
   - **If you chose C:** Every bar is the same feature, hand span. Each bar is a class of values of it.

7. **1 in 2**

   Two of the four boxes read Hh. So the chance is 2 out of 4, which is 1 in 2.

   - **If you chose A:** That is the chance of the disease. Two boxes of four read Hh, the carrier. Go to S4.2.6.
   - **If you chose B:** Both parents can pass on h. A child who gets one H and one h is a carrier. Go to S4.2.6.

8. **2 cm**

   The range is 24 − 12 = 12 cm. Six equal classes share it, so each is 12 ÷ 6 = 2 cm wide.

9. **16 to 18 cm**

   17.3 is more than 16 and less than 18, so it is in the class from 16 to 18 cm.

S4.2.8. Mutation and genetic engineering

1. **A change in the order of bases in DNA**

   A mutation changes the order of the bases of a gene. It may be a swap, an extra base or a missing base.

   - **If you chose B:** Most mutations have no effect. Some cause disease, and a few help.
   - **If you chose C:** That is genetic engineering, which people do on purpose. A mutation is a change in the base order.

2. **The group of three bases changes, so a different amino acid may be added.**

   Each group of three codes for one amino acid. A different amino acid can change the shape of the protein, and its job.

   - **If you chose A:** One base changing does not delete the gene. It changes one group of three.
   - **If you chose B:** Proteins are made of amino acids, not bases. The bases are the code for the amino acids. Go to S4.2.2.

3. **A mutation in a sperm cell or an egg cell**

   A child grows from a fertilised egg, made from a sperm and an egg. A mutation in one of them is in the child's first cell, and so in all the cells that come from it.

   - **If you chose A:** A skin cell is a body cell. Its mutation stays in that cell and the cells that come from it.
   - **If you chose C:** Only the sex cells, the egg and the sperm, pass DNA to a child. Go to S4.2.3.

4. **The human gene for insulin**

   A gene is the code for one protein. When the human insulin gene is in a bacterium, the bacterium reads it and makes insulin.

   - **If you chose B:** Only the gene is needed. A whole cell would not work inside a bacterium.
   - **If you chose C:** The bacterium must make the insulin. What goes in is the gene, which holds the code to make it.
   - **If you chose D:** A chromosome holds thousands of genes. Only the one gene for insulin is cut out and used. Go to S4.2.1.

5. **All living things use the same DNA code.**

   The same groups of three bases code for the same amino acids in bacteria, plants and people.

   - **If you chose B:** The bacterium does not change the gene. It reads the code, because the code is shared.
   - **If you chose C:** A bacterium is a different kind of cell. It reads the same DNA code, which is why the gene works in it.

6. **Fewer sprays are needed against the insect.**

   If the crop resists the pest, the farmer needs to spray less. That is one benefit, and it has to be weighed against the risks.

   - **If you chose A:** Drought needs a different gene. Resisting a pest does nothing about water.
   - **If you chose C:** Nobody can promise this. The effect on wild plants and insects is one of the risks that people test.

7. **Pollen may carry the new gene to wild plants of the same kind.**

   If wild plants get the gene, they may change in ways that nobody planned. This is one of the risks that people study.

   - **If you chose B:** Adding one gene does not make a new species. The plant is still the same kind of plant.
   - **If you chose C:** Every food has genes, modified or not, and digestion breaks them down. This is not a risk.

8. **A histogram, with bars that touch**

   Continuous data fall in classes with no gaps between them. A histogram shows this.

   - **If you chose A:** Bars with gaps suit separate groups, such as blood groups. Hand spans run on in a range. Go to S4.2.7.
   - **If you chose C:** A family tree shows who is related. It does not show how many fall in each class of a measurement. Go to S4.2.6.

9. **Position 4**

   The first three bases match. The fourth is G before and C after.

10. **Out of every 100 plants, 24 fewer are lost.**

    The difference is 30 − 6 = 24.

About this book

For learners who can follow a written argument and have met cells and the idea that babies come from a sperm and an egg. In many schools this fits learners of about 14 to 16, and older learners can use it as a reference. Each chapter takes two or three short sessions. A learner can work alone: every exercise has its answer and the reason for it. The Try it activities use paper, string and a ruler. Nothing is heated and nothing is tasted. Two chapters name real inherited conditions and talk about sex and families. They give facts calmly and judge no one. For the chapter on hand spans, the learner measures family and friends, so ask each person first.

Written and drawn by attnom. Edition 1.0, 2026-11-12.

This book is free. You may read it, print it, copy it and share it with anyone.

The newest copy is at https://attnom.com/academy/genes-and-inheritance.