REVISION GUIDE

# Same genes, *different* cells

## Gene expression

Every cell in your body carries the same genes, but a skin cell is not a nerve cell. Follow a gene to the trait it gives, switch genes on and off with transcription factors and tags on the DNA, find out why ligers are giants, test identical twins in the dry lab, and watch bacteria switch on genes for lactose only when it arrives.

9 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-d2-2-gene-expression

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## By the end you can

- [ ] Outline gene expression as transcription, translation and the function of the protein made D2.2.1
- [ ] Explain how transcription is regulated by proteins binding promoters and enhancers D2.2.2
- [ ] Explain how the rate of mRNA breakdown regulates translation D2.2.3
- [ ] Outline epigenesis, and explain why it changes phenotype but not genotype D2.2.4
- [ ] Distinguish the genome, transcriptome and proteome of a cell D2.2.5
- [ ] Explain how methylation of promoters and of histones acts as an epigenetic tag D2.2.6
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- [ ] Explain how monozygotic twin studies show the effect of the environment on gene expression D2.2.10
- [ ] Explain how a hormone and lactose change the pattern of gene expression D2.2.11

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

# 01 From gene to *trait*

D2.2.1 HL GENE EXPRESSION AND THE PHENOTYPE

A gene on its own does nothing. Its information has an effect on the organism only when the gene is **expressed**, and in most cases that takes three steps. The gene is **transcribed** into mRNA, the mRNA is **translated** into a polypeptide, and the protein that polypeptide folds into then does a job: very often as an enzyme.

Take skin and hair colour. The gene for the enzyme tyrosinase is transcribed and translated in pigment cells. Tyrosinase catalyses the first steps in turning the amino acid tyrosine into melanin, the dark pigment. A person whose tyrosinase gene codes for a non-functional enzyme makes little or no melanin: that is one form of albinism. The trait comes from the gene, but only through the protein.

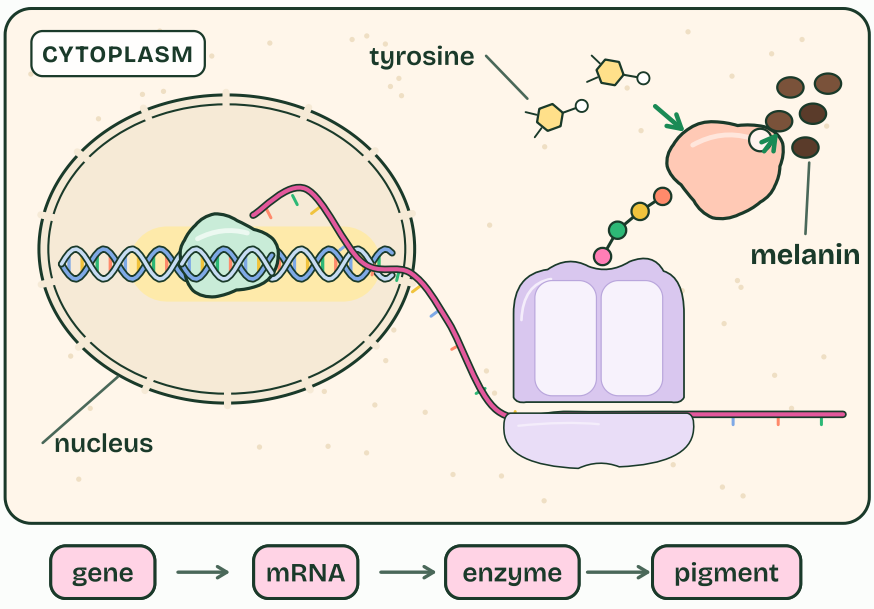
Every cell in your body has the tyrosinase gene, yet only pigment cells express it. Which genes a cell expresses, and how much, is what the rest of this guide is about.

KEY POINTS

- Gene expression: the information in a gene having an effect on the phenotype.
- Usually three stages: transcription, translation, then the protein's function.
- Cells do not express every gene they carry.

KEY TERMS

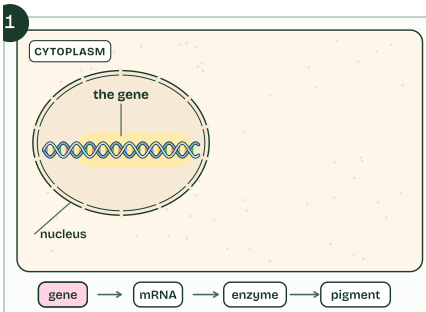
**expressed**
The process by which the information in a gene has an effect on the phenotype: usually transcription, then translation, then the function of the protein made.



STEP BY STEP

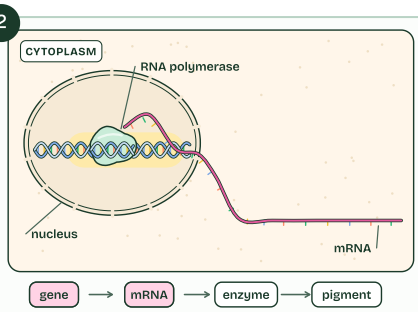
4 STEPS

1



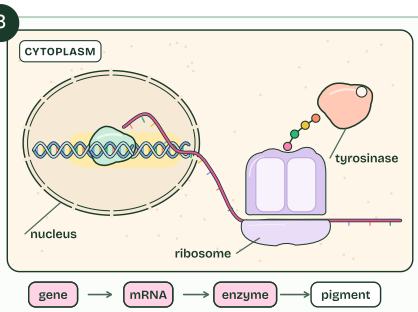

The **gene**: a length of DNA coding for the enzyme tyrosinase.

2



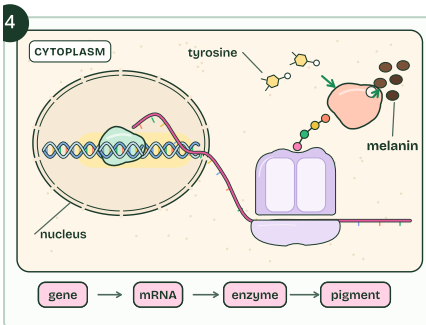

**Transcription**: RNA polymerase copies the gene into mRNA.

3




**Translation**: ribosomes make a polypeptide, which folds into the enzyme.

4

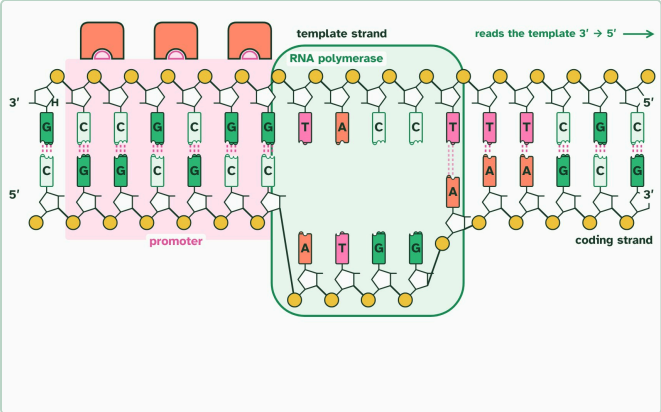



The **function**: tyrosinase turns tyrosine into melanin, the dark pigment.

ANIMATION · FROM PROMOTER TO MATURE MRNA

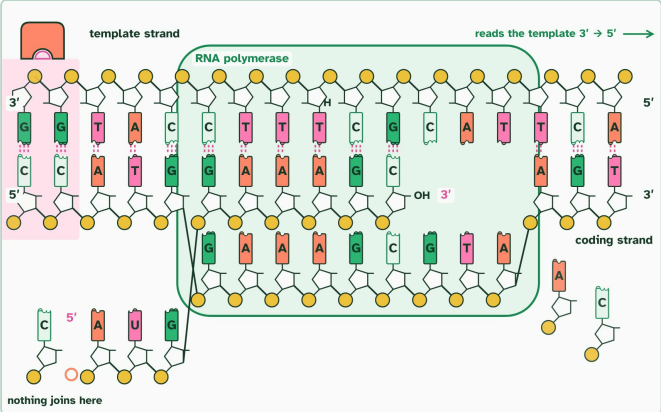
6 MOMENTS

1 STARTING



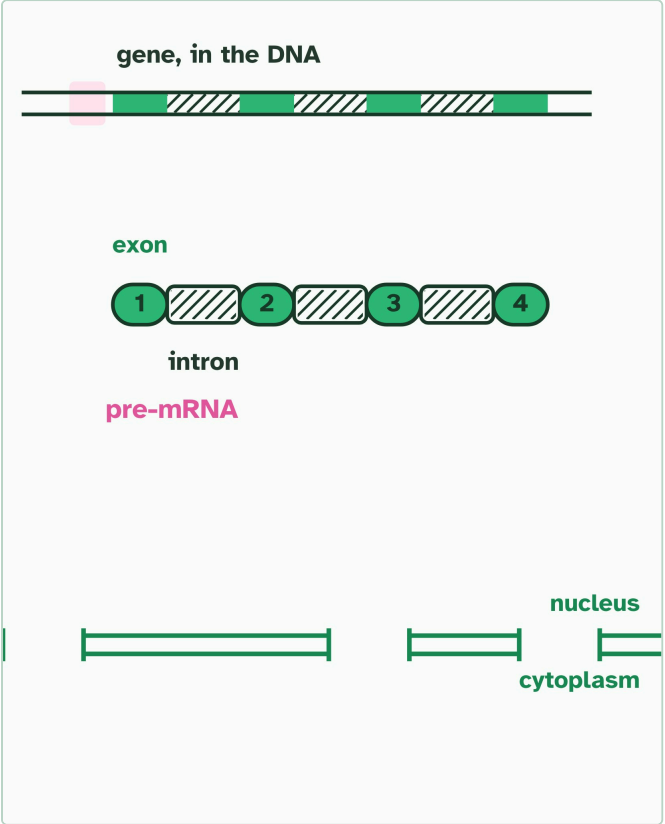

Transcription factors bind the promoter. Only then can RNA polymerase bind and begin.

2 5′ → 3′



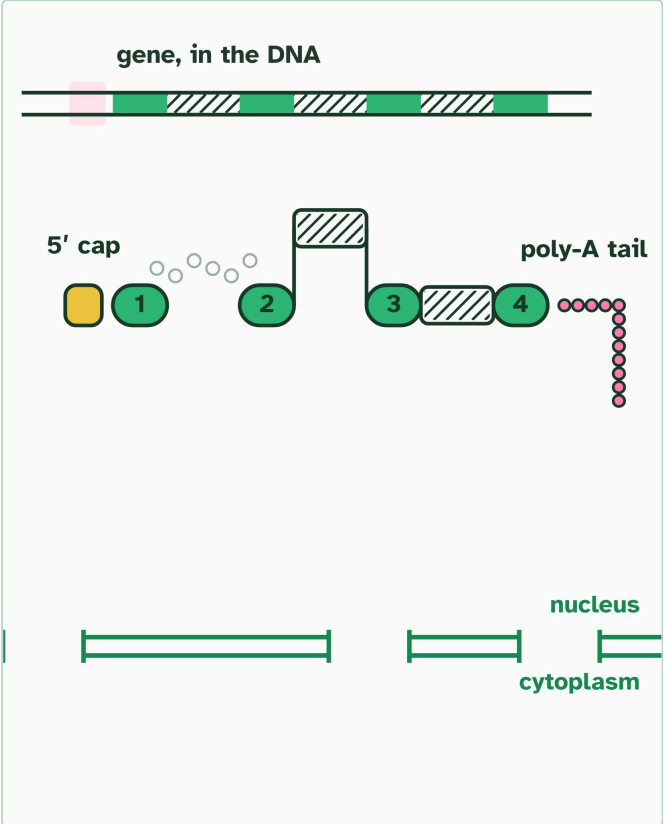

The RNA grows 5′ to 3′: every new nucleotide joins its 3′ end.

3 PRE-MRNA



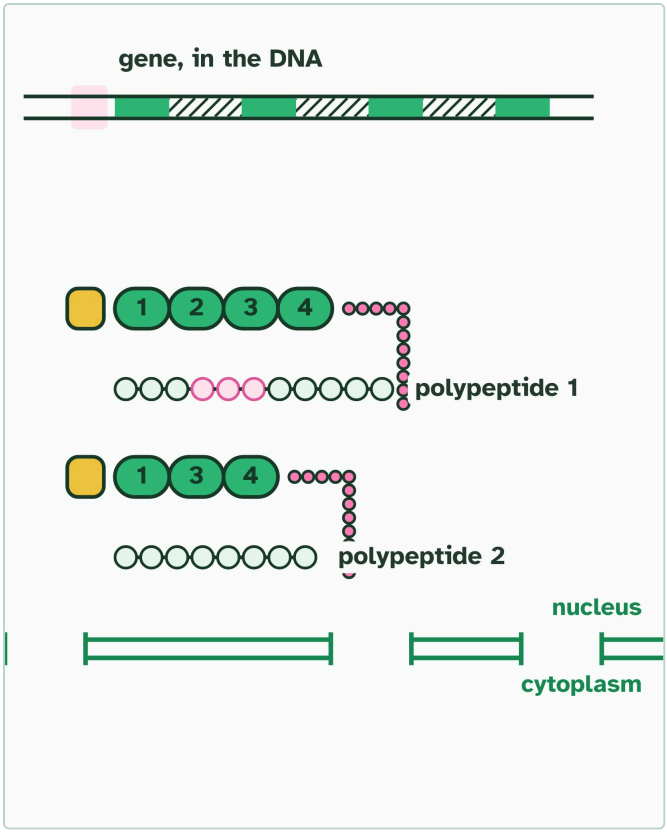

In a eukaryote the first RNA is pre-mRNA: exons, with introns between them.

4 PROCESSING



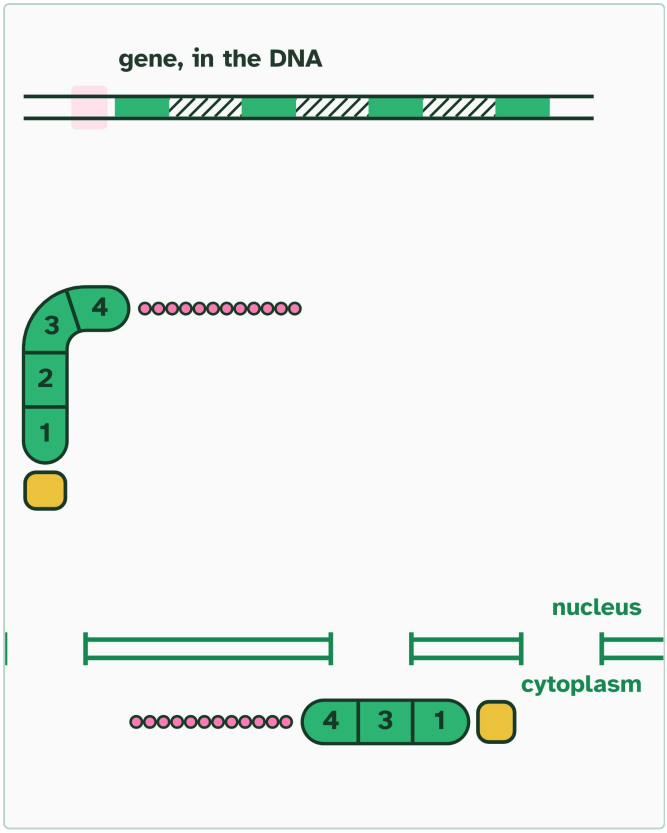

A 5′ cap and a poly-A tail are added. The introns are cut out and the exons spliced together.

5 MATURE MRNA




Spliced another way, the same gene gives a different polypeptide.

6 MATURE MRNA




Capped, tailed and spliced, the mature mRNA leaves the nucleus.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d2-2-gene-expression#expression

WATCH OUT

A gene does not code for a trait directly. It codes for a polypeptide, and the trait comes from what that protein does.

PREDICT

**A mutation stops a pigment cell's tyrosinase from working, but the cell still makes plenty of tyrosinase mRNA. What happens to the colour of the skin around it?**

(A) It stays dark, because the gene is still being transcribed into plenty of mRNA

(B) It goes pale, because the protein made from that mRNA cannot make melanin

(C) It goes darker, because the cell makes more mRNA to make up for the faulty enzyme

Decide before you look. Answer on page 30.

D2.2.2 HL REGULATION OF TRANSCRIPTION

# 02 Switches on the *DNA*

Most gene expression is controlled at the first step: whether the gene is transcribed, and how fast. The control is done by proteins that bind to particular base sequences in the DNA, each protein recognising its own sequence.

The **promoter** is a sequence just before the gene, where RNA polymerase binds to start transcription. In eukaryotes RNA polymerase cannot bind on its own. It needs **transcription factors**, proteins that bind at the promoter first and help RNA polymerase attach.

Further away, sometimes thousands of bases from the gene, are **enhancers**. Activator proteins that bind an enhancer increase the rate of transcription: the DNA folds round so the activator touches the proteins at the promoter. Other proteins, repressors, bind DNA and reduce transcription or stop it. A cell's pattern of expression depends on which of these proteins it makes.

KEY POINTS

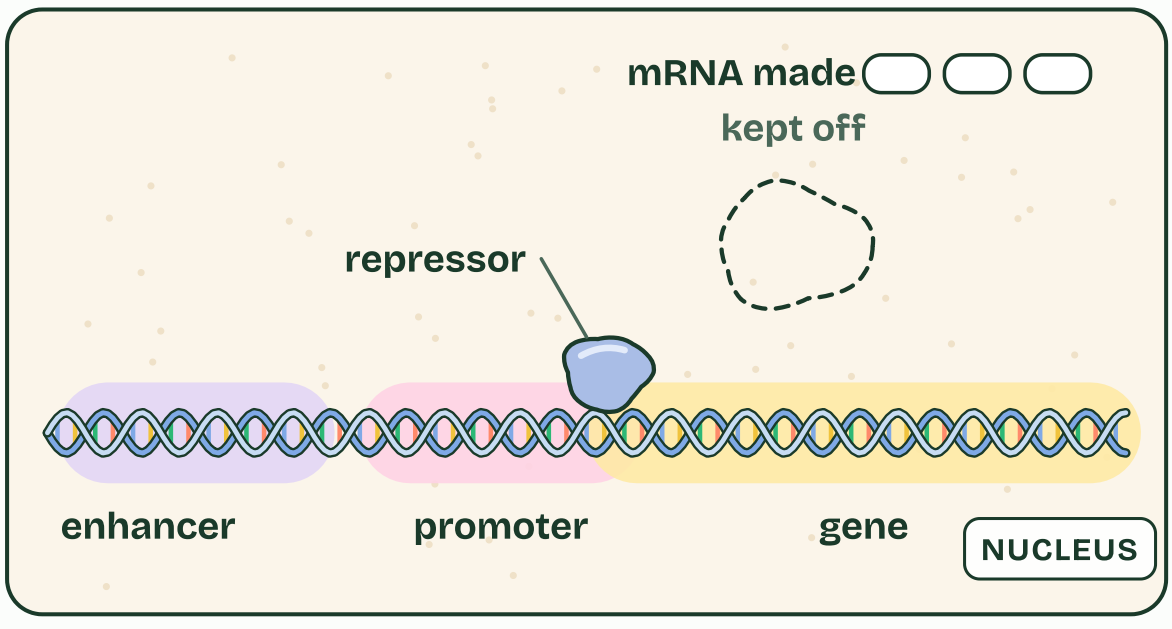
- Proteins that bind specific base sequences regulate transcription.
- Promoter: where RNA polymerase binds, with the help of transcription factors.
- Enhancer: a distant sequence where activators bind and increase transcription.
- Repressors bind DNA and decrease transcription.

KEY TERMS

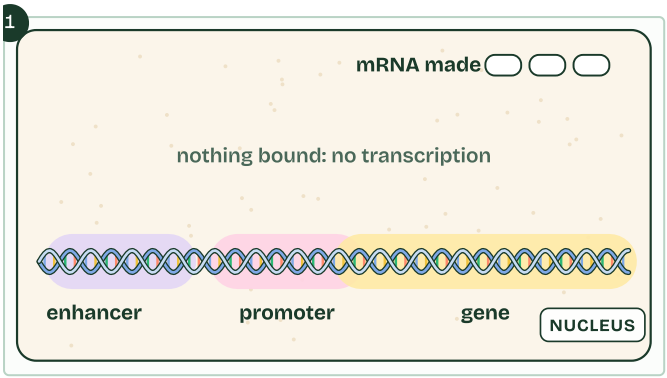
**promoter**
A sequence of DNA just before a gene where RNA polymerase binds to start transcription. It is not transcribed itself.

**transcription factors**
Proteins that bind to specific DNA sequences, such as promoters and enhancers, and so increase or decrease the transcription of a gene.

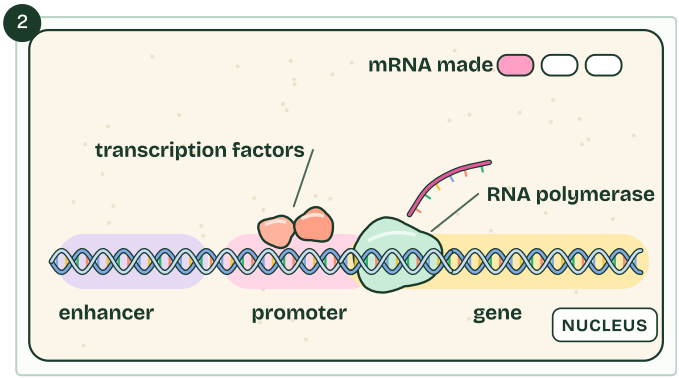
**enhancers**
A DNA sequence, often far from the gene it affects, where activator proteins bind to increase the rate of transcription of that gene.



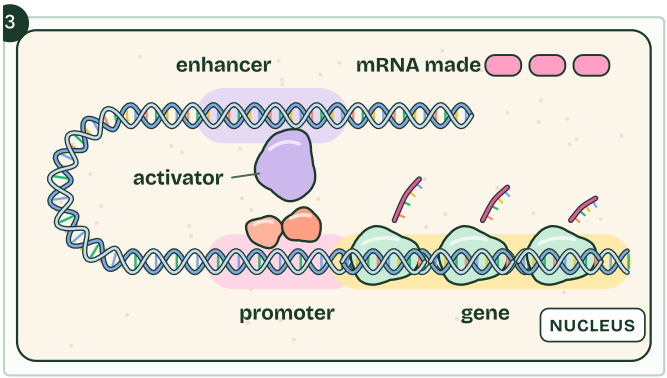
STEP BY STEP
4 STEPS



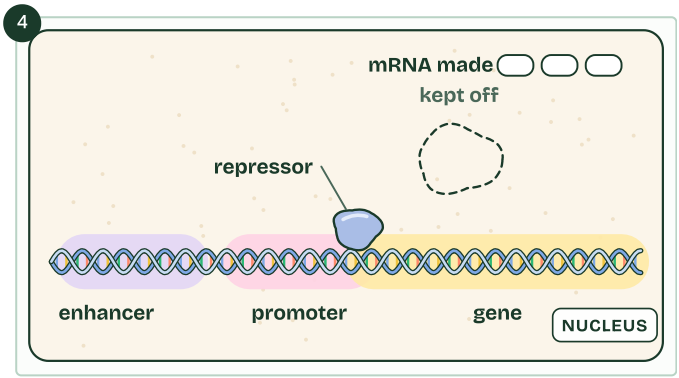

A gene with its **promoter**, and an **enhancer** further along the DNA.




**Transcription factors** bind the promoter and RNA polymerase joins them.




An **activator** binds the enhancer and helps: far more mRNA.




A **repressor** binds near the promoter: RNA polymerase is kept off.

WATCH OUT

A promoter is DNA, not a protein. The promoter and the enhancer are sequences; transcription factors, activators and repressors are the proteins that bind to them.

PREDICT

**A cell stops making one activator protein. What happens to a gene whose enhancer that activator binds?**

(A) It stops being transcribed at all, as the activator is needed to make its mRNA

(B) It is transcribed more slowly, as long as its promoter can still be bound

(C) It is transcribed faster, because RNA polymerase is no longer held at the enhancer

Decide before you look. Answer on page 30.

# 03 One genome, many *cells*

D2.2.5 HL GENOME, TRANSCRIPTOME AND PROTEOME

The **genome** is all of a cell's DNA, every gene included. In one person, nearly every cell has the same genome. What differs is what each cell does with it.

The **transcriptome** is all the RNA a cell has transcribed at a given time, and the **proteome** is all the proteins it has made. No cell expresses all of its genes. A beta cell in the pancreas transcribes the insulin gene; a red blood cell precursor transcribes the haemoglobin genes instead; neither transcribes the gene for rhodopsin, the light-absorbing pigment of the eye. Some genes, those for respiration enzymes or RNA polymerase, are on in almost every cell.

The pattern of expression is what makes a cell what it is. A cell differentiates by switching on some genes and leaving others off, so its transcriptome and proteome, unlike its genome, are its own. The transcriptome also changes from hour to hour as the cell responds to its surroundings.

KEY POINTS

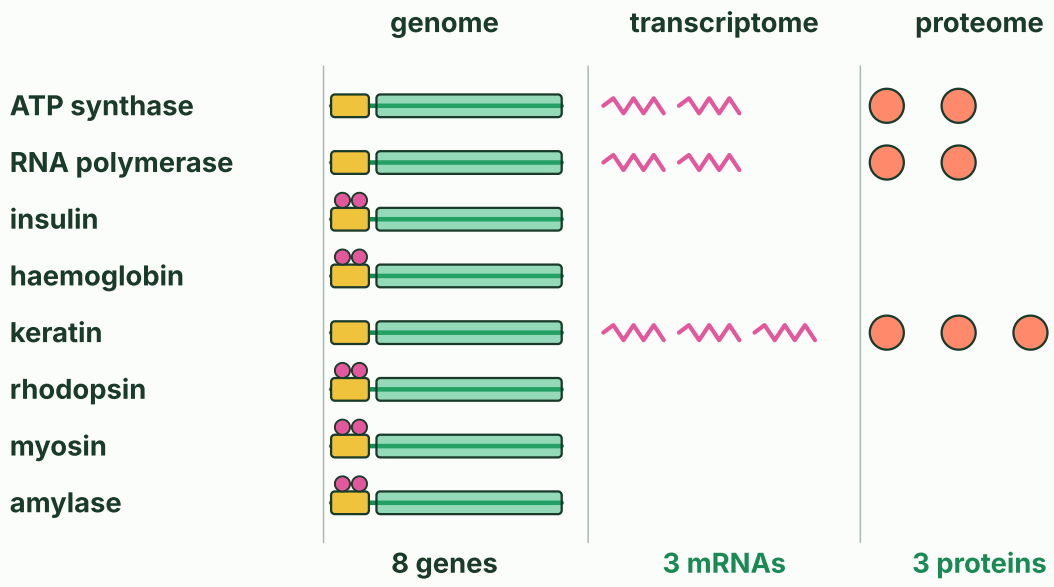
- Genome: all the DNA. The same in nearly every cell of one organism.
- Transcriptome: all the RNA transcribed. Proteome: all the proteins made.
- No cell expresses all its genes; the pattern decides how it differentiates.

KEY TERMS

**genome**
The whole of the genetic information of an organism or cell: all of its DNA.

**transcriptome**
All the RNA molecules transcribed in a cell at a particular time.

**proteome**
All the proteins made by a cell, a tissue or an organism at a particular time.

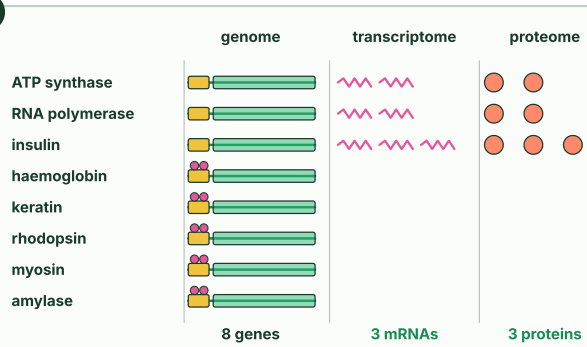



The same eight genes in three kinds of cell. Choose a cell and read its transcriptome and proteome, then tap the genes to find the patterns.

STEP BY STEP

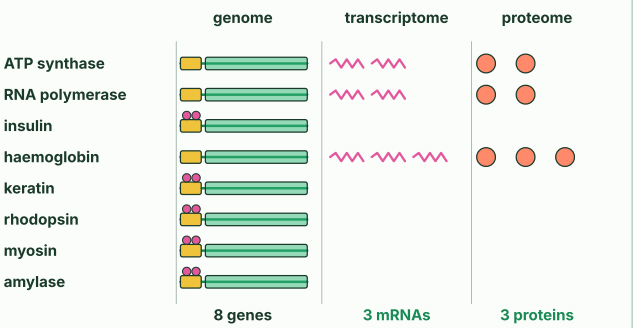
3 STEPS

1



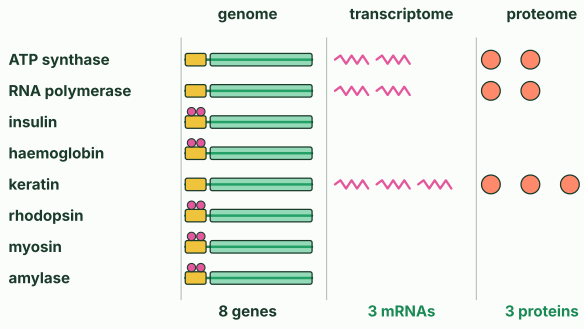

A **beta cell** of the pancreas: the same eight genes as every other cell, but it transcribes only three, insulin among them.

2




A **red blood cell precursor**: the same genome, a different transcriptome. Haemoglobin is on, insulin is off.

3




A **skin cell**: keratin on. The genes every cell needs are on in all three; the genes that are off carry methyl tags on their promoter.

WATCH OUT

A skin cell has the insulin gene. Cells differ in which genes they express, not in which genes they have.

PREDICT

**Which of these is likely to be the most alike in a skin cell and a beta cell from the same person?**

(A) Their genomes, since nearly every cell in one body carries the same DNA

(B) Their transcriptomes, since both of them transcribe the genes every cell needs

(C) Their proteomes, since both cells make the same enzymes for respiration

Decide before you look. Answer on page 30.

# 04 How long a message *lasts*

D2.2.3 HL DEGRADATION OF MRNA

Transcription is not the only control. Once an mRNA reaches the cytoplasm, ribosomes translate it again and again, until it is broken down by enzymes called **nucleases**. The longer an mRNA survives, the more protein is made from it.

In human cells an mRNA may last from minutes to days before nucleases break it down. The mRNAs for proteins that must be switched off quickly, such as some transcription factors and signals between cells, last only minutes, so the protein stops being made soon after the gene is switched off. The mRNA for globin, in a red blood cell precursor, lasts a day or more, so a great deal of haemoglobin is made from each one.

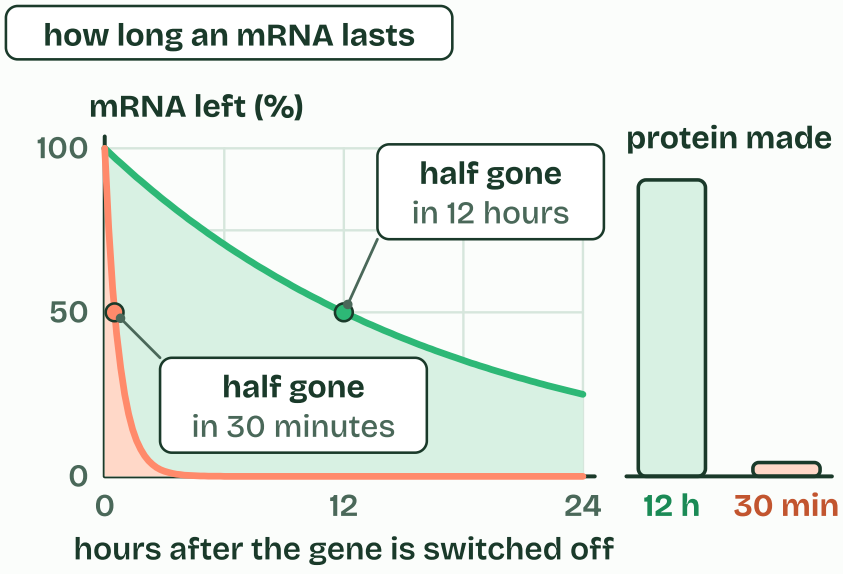
A cell can change the lifetime of an mRNA, protecting it or marking it to be broken down sooner. That is a second way of regulating how much of a protein is made: control of translation, by control of degradation. (The cap and tail added to mRNA after transcription, in D1.2, are part of what protects it.)

KEY POINTS

- mRNA is translated until nucleases break it down.
- In human cells mRNA lasts from minutes to days.
- Controlling how fast mRNA is broken down regulates translation.

KEY TERMS

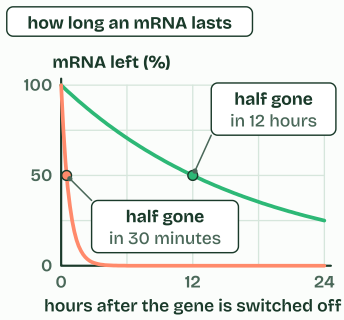
**nucleases**
Enzymes that break down nucleic acids. Nucleases in the cytoplasm break down mRNA, ending its translation.



STEP BY STEP

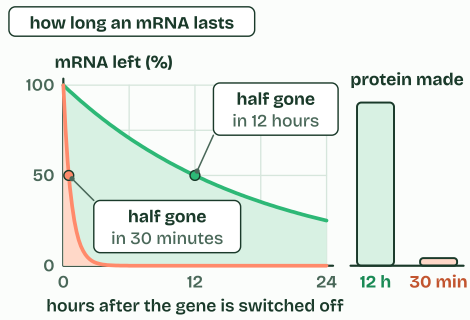
2 STEPS

1




After the gene is switched off, one **mRNA** is half gone in 30 minutes, the other only after 12 hours.

2

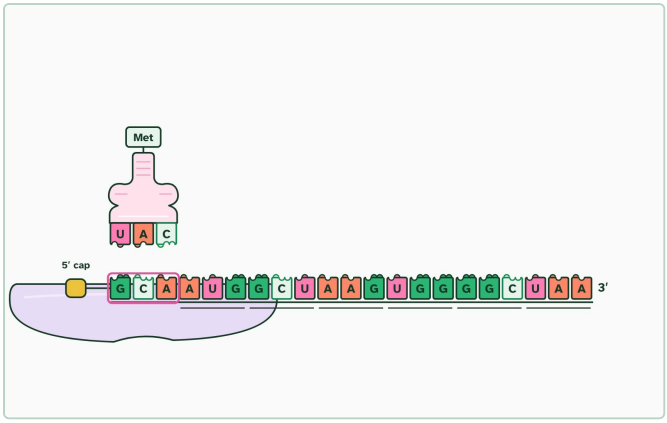



Protein is made the whole time an mRNA lasts: far more from the **long-lived** one.

ANIMATION · START, THEN A, P AND E

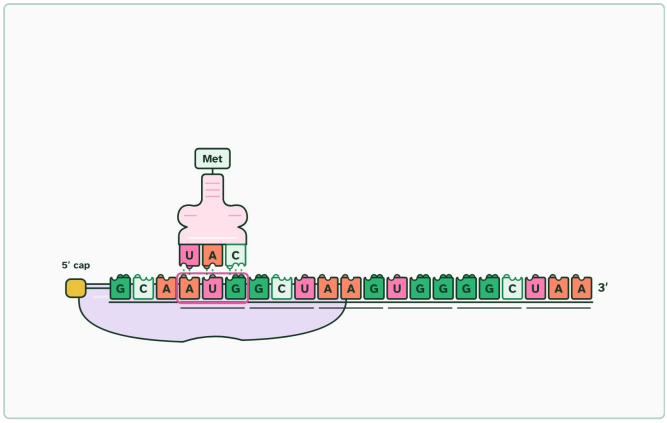
6 MOMENTS

1 SMALL SUBUNIT AT THE 5′ END



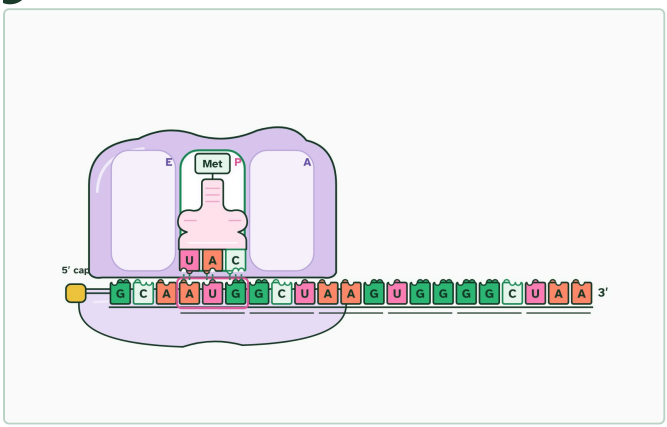

The small subunit attaches to the mRNA at its 5′ end.

2 UNDER THE SUBUNIT: AUG



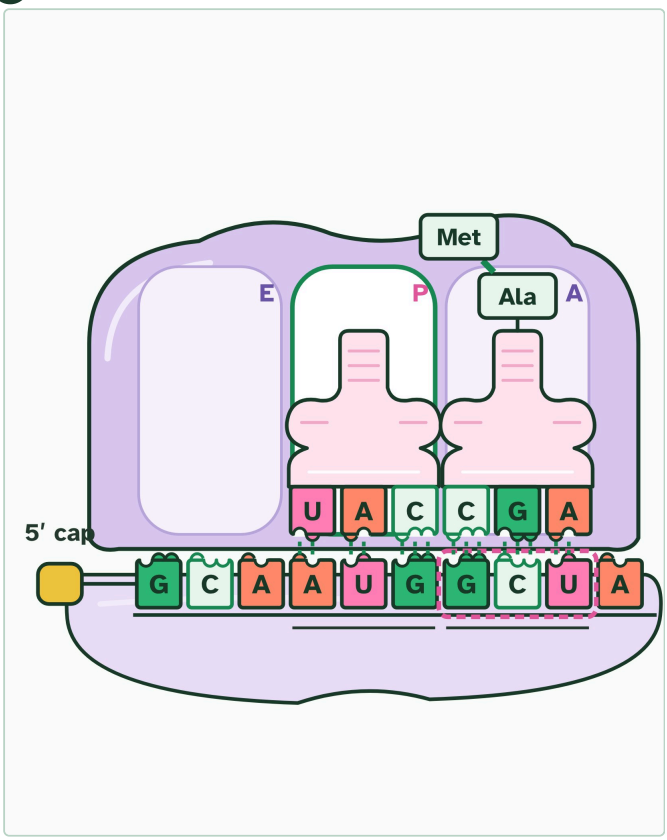

It moves towards the 3′ end until it reaches the start codon, AUG. The initiator tRNA pairs with it.

3 CODON 1: AUG, MET, P SITE



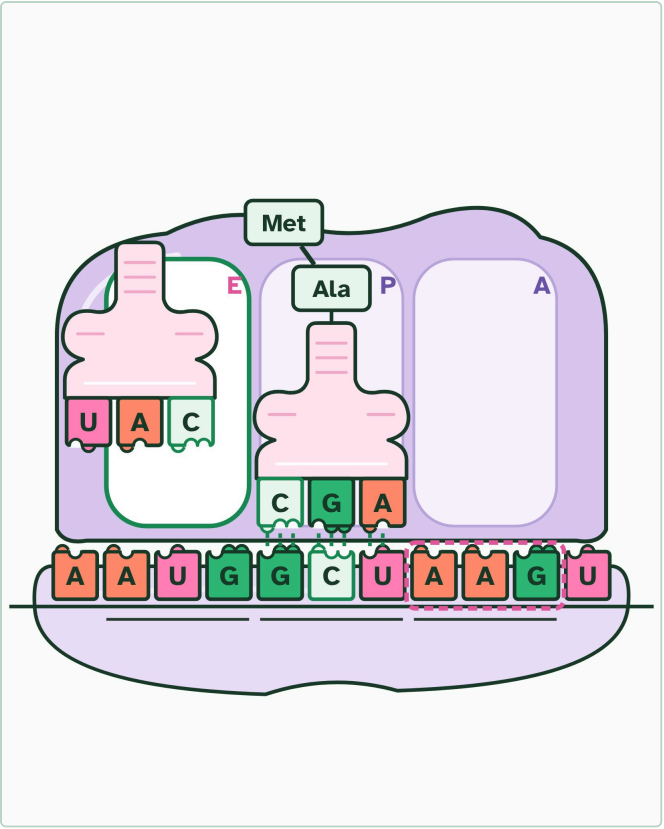

The large subunit joins. The initiator tRNA sits in the P site.

4 CODON 2: GCU, ALA, A SITE



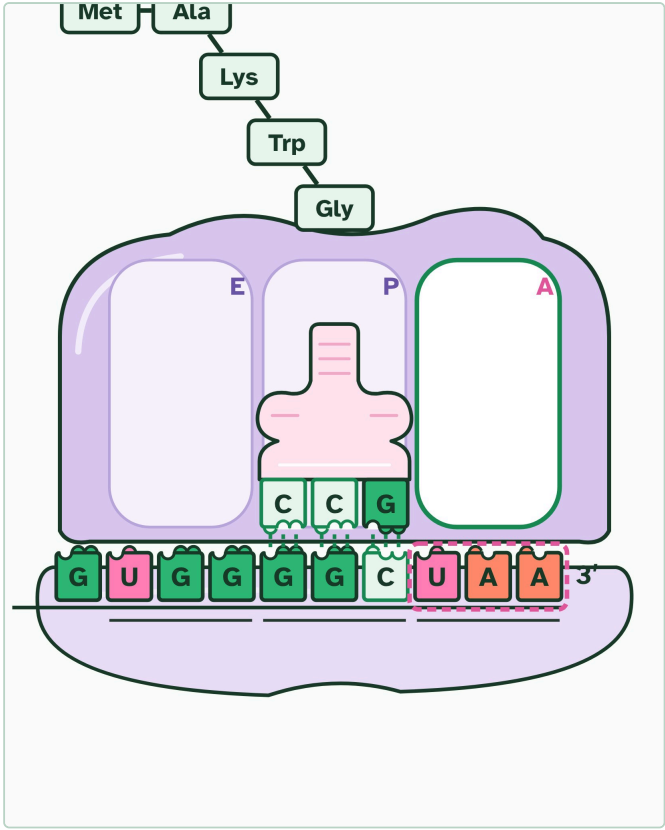

Another tRNA arrives in the A site. A peptide bond joins methionine to its amino acid.

5 CODON 3: AAG, LYS, A SITE




The ribosome moves one codon. The empty tRNA leaves from the E site; the chain's tRNA is now in P.

6 CODON 6: UAA, STOP, A SITE




At the stop codon the chain is released and the subunits come apart.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d2-2-gene-expression#mrna

PREDICT

**Two genes are transcribed at the same rate, but one gene's mRNA lasts ten times longer. What is the result?**

(A) Both proteins are made in the same amounts, since transcription sets the amount

(B) Much more of the protein from the longer-lasting mRNA, read for longer

(C) Less of the protein from the longer-lasting mRNA, since it is read more slowly

Decide before you look. Answer on page 30.

# 05 Tags, not *changes*

D2.2.4 HL D2.2.6 HL EPIGENESIS; METHYLATION OF THE PROMOTER AND HISTONES

A zygote is one undifferentiated cell. As it divides into an embryo, its descendants become different kinds of cell, each with its own pattern of gene expression. This development of patterns of differentiation is **epigenesis**. The base sequence of the DNA does not change: the cells differ in phenotype, not in genotype.

The patterns are held in place by chemical **epigenetic tags** added to the DNA and the proteins around it. Two of the commonest are methyl groups:

**Methylation of the promoter.** Methyl groups can be added to cytosine bases in a gene's promoter. A methylated promoter represses transcription, so the gene downstream is not expressed.

**Methylation of histones.** DNA is wound round histone proteins in nucleosomes, and methyl groups can be added to amino acids in the histone tails. Depending on which amino acid is tagged, this can repress transcription or activate it. Acetyl groups on histones, another kind of tag, loosen the nucleosomes and make transcription easier. (How each tag does this is beyond the course.)

KEY POINTS

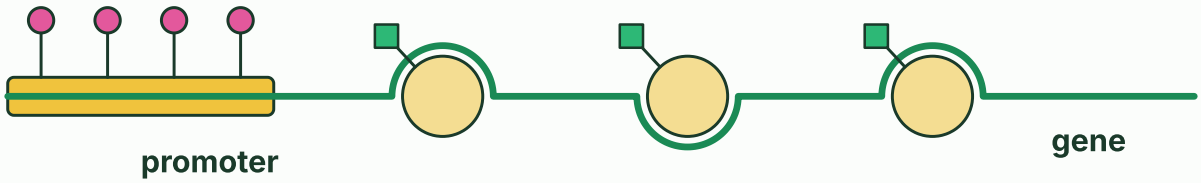
- Epigenesis: the development of patterns of differentiation in a multicellular organism.
- Epigenetic changes alter phenotype, never the DNA base sequence (genotype).
- Methylated cytosines in a promoter repress transcription of the gene.
- Methylated histones can repress or activate transcription.

KEY TERMS

**epigenesis**
The development of patterns of differentiation in the cells of a multicellular organism, as different genes are switched on and off. The DNA base sequence does not change.

**epigenetic tags**
Chemical groups added to DNA or to histone proteins that change whether genes are expressed, without changing the base sequence.

RNA polymerase cannot bind the promoter



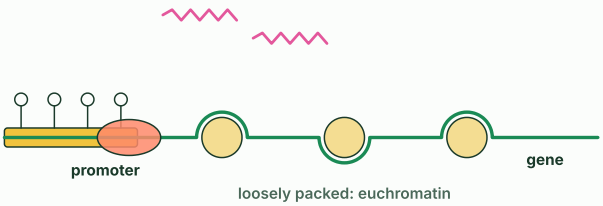

loosely packed: euchromatin

One gene, its promoter and three nucleosomes. Add methyl and acetyl tags, watch the transcription, and check the base sequence each time.

STEP BY STEP

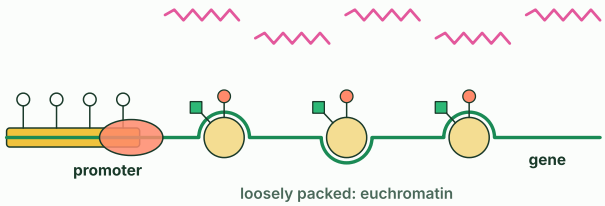
3 STEPS

1



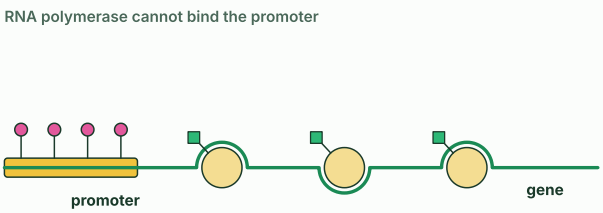

A gene with no tags: its promoter and three **nucleosomes**. It is transcribed a little.

2




**Acetyl** and activating **methyl** tags on the histone tails loosen the nucleosomes: more mRNA.

3




Methyl tags on the promoter's cytosines: RNA polymerase cannot bind and the gene is **off**. The base sequence has not changed.

WATCH OUT

Methylation does not change a cytosine into a different base. A methylated C still pairs with G, and the sequence reads exactly as before.

PREDICT

**A gene's promoter is heavily methylated, but the histones around the gene carry acetyl tags. Is the gene expressed?**

(A) Yes, since acetyl tags on the histones always override any methyl tags

(B) No, since the methylated promoter represses transcription of the gene

(C) Yes, but only at a slower rate, as the two kinds of tag cancel each other out

Decide before you look. Answer on page 30.

# 06 Tags that are *passed on*

D2.2.7 HL EPIGENETIC INHERITANCE

When a liver cell divides, both daughter cells are liver cells. Their pattern of gene expression is inherited, though no gene has changed. This works because epigenetic tags can stay in place through cell division: when the DNA is replicated, enzymes add methyl groups to the new strand where the old strand has them, so the pattern is copied with the DNA.

This is **epigenetic inheritance**: a change in phenotype passed on to daughter cells, or sometimes to offspring, without any change in the nucleotide sequence. It happens when tags such as DNA methylation or histone modifications remain in place during mitosis or meiosis.

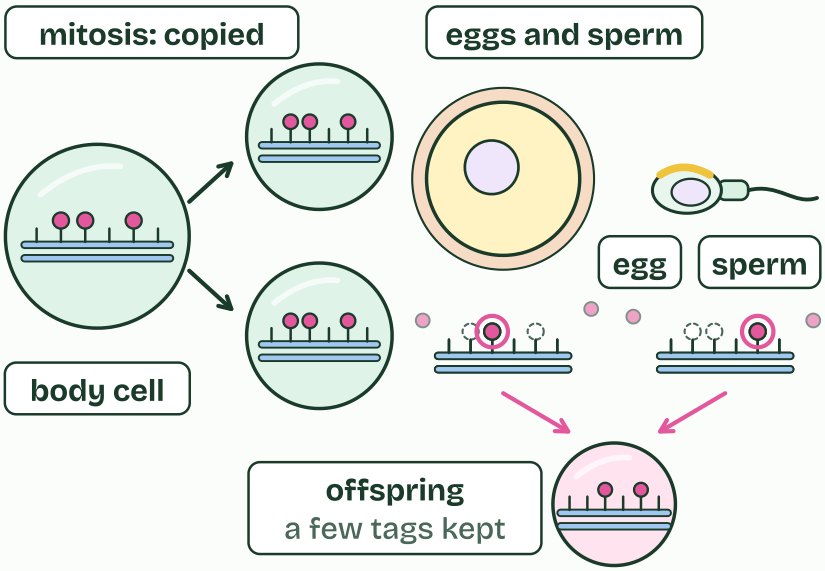
Passing tags on to offspring is less common, because most tags are removed when eggs and sperm are made (the next chapter). But some survive. In plants, which have no separate germ line, tags laid down in response to stress can be passed on through seeds.

KEY POINTS

- Tags copied with the DNA keep a cell's pattern of expression through mitosis.
- Epigenetic inheritance: phenotype passed on with no change to the DNA sequence.
- Tags that remain through meiosis can pass to offspring.

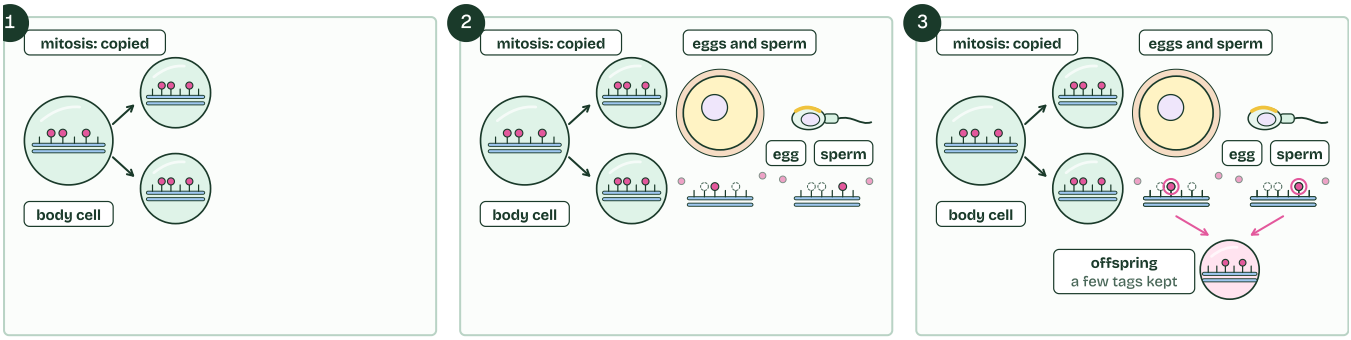
KEY TERMS

**epigenetic inheritance**
Changes in gene expression passed on to daughter cells or to offspring without any change in the DNA base sequence.



STEP BY STEP

3 STEPS




**Mitosis**: the methyl tags are copied with the DNA, so both daughter cells keep the pattern.

Making **eggs and sperm**: most tags are removed.

But not all: a few tags stay on, and pass to the offspring.

PREDICT

**A drug stops a cell copying methyl tags onto the new DNA strand when it replicates. What happens over several divisions?**

(A) The DNA base sequence slowly changes, so the cells pick up new mutations

(B) The tags are diluted, and genes that were switched off can switch on again

(C) Nothing changes, because the old strand keeps the tags for each daughter cell

Decide before you look. Answer on page 30.

# 07 Wiped clean, *nearly*

D2.2.9 HL REMOVAL OF MOST BUT NOT ALL TAGS FROM EGG AND SPERM

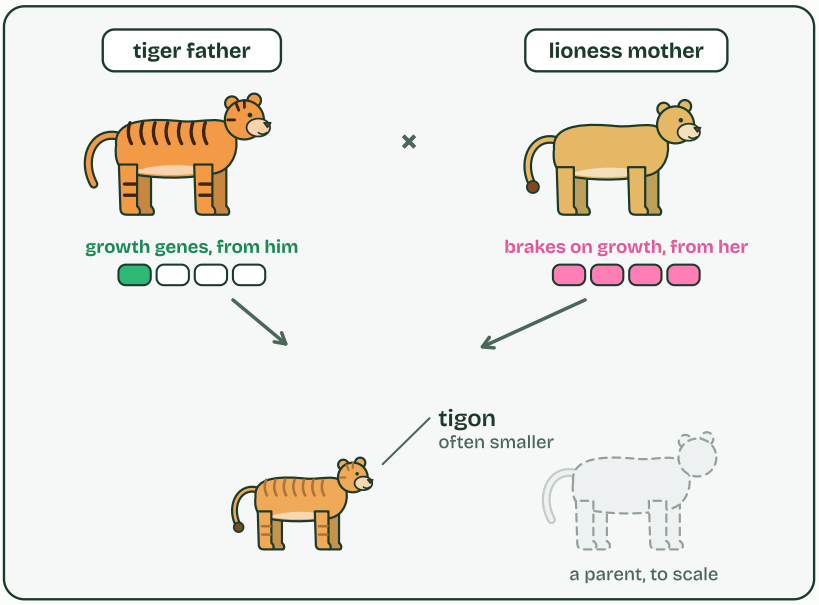
As eggs and sperm are made, and again just after fertilisation, most epigenetic tags are removed. This resets the genome, so the zygote can give rise to every kind of cell, not just the kinds its parents' gamete-making cells were.

Most, but not all. Some genes keep tags that depend on which parent they came from, so a gene can be switched off in the copy from the mother and on in the copy from the father, or the other way round. Many of these genes control growth before birth.

Lions and tigers show what happens when the two parents' tags do not match. A cross between a male lion and a female tiger, a **liger**, grows larger than either parent. The reverse cross, a male tiger and a female lion, gives a **tigon**, usually no larger than its parents and often smaller. The genes are the same mix in both; what differs is which parent each set of tags came from. One explanation: in lions, the father's genes for growth before birth are left strongly switched on and the lioness's tags hold growth back; in tigers both are weaker. A liger gets the lion's growth genes with no lioness's brake, and grows on.

KEY POINTS

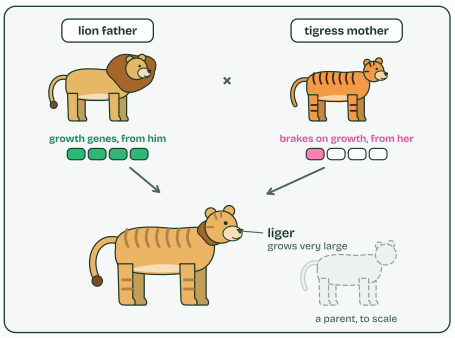
- Most epigenetic tags are removed from eggs and sperm, so the zygote starts afresh.
- Some remain, and differ with the parent they came from.
- Ligers (lion father) are larger than tigons (tiger father): the tags, not the genes, differ.



STEP BY STEP

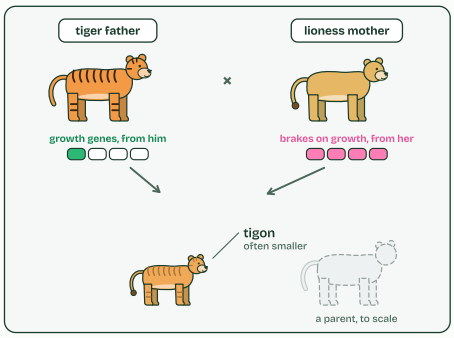
2 STEPS

1




A **liger**: strongly active growth genes from the lion father, weak brakes from the tigress. It grows very large.

2




A **tigon**: weaker growth genes from the tiger father, strong brakes from the lioness. It is often smaller.

WATCH OUT

A liger and a tigon both get half their genes from a lion and half from a tiger. If the genes alone set their size, they would be the same size.

PREDICT

**Why does the zygote need most of the tags in the egg and sperm to be removed?**

(A) So that the base sequence of its DNA can be checked and repaired before it divides

(B) So that its descendants can switch on whichever genes each kind of cell needs

(C) So that the genes from the mother and the father end up with exactly matching tags

Decide before you look. Answer on page 30.

# 08 The environment leaves *marks*

D2.2.8 HL D2.2.10 HL ENVIRONMENTAL EFFECTS; MONOZYGOTIC TWIN STUDIES

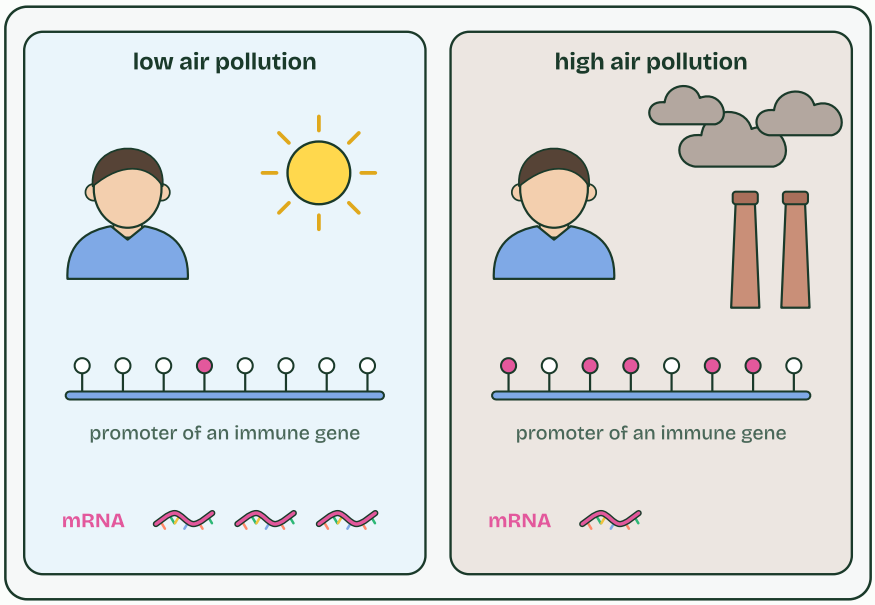
Epigenetic tags are not fixed. Diet, stress, smoking, temperature and pollution can all add or remove them, so the environment can change which genes a cell expresses.

**Air pollution** is one example. Children who breathe more air pollution, from traffic and burning fuels, have been found to have more methyl tags on the promoter of an immune-system gene in their blood cells, and to express it less. Methyl tags elsewhere in the genome change with exposure too. Tags changed in this way can last, which is one way the environment early in life may affect health years later.

**Monozygotic twins** come from one zygote, so they have the same DNA base sequence. Any difference between them in gene expression must come from the environment (or from chance). Studies of twins find that their methyl tags are very alike when they are young and grow more different with age, and more so in twins who have lived apart and led different lives. Twin studies are how the effects of the environment on gene expression can be separated from the effects of genes.

KEY POINTS

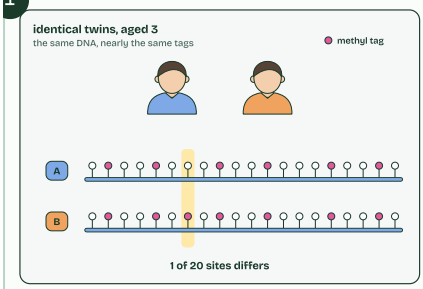
- The environment can change gene expression by adding or removing tags.
- Air pollution alters methyl tags on DNA.
- Identical twins share their DNA; differences in their tags come from the environment.



STEP BY STEP

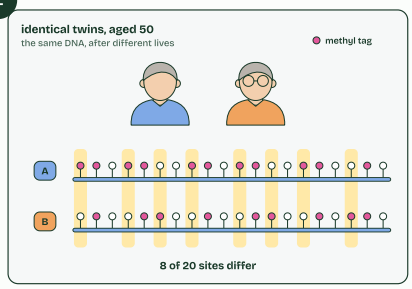
3 STEPS

1



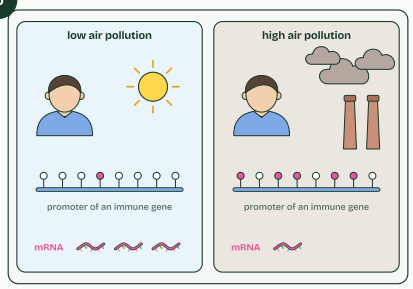

Identical twins aged 3: the same DNA and nearly the same **methyl tags**.

2




The same twins aged 50, after different lives: many sites now differ.

3




**Air pollution**: more methyl tags on an immune gene's promoter, and less of its mRNA.

WATCH OUT

Identical twins who differ in a trait have not had their genes changed by their lives. Their base sequences are still the same; their tags, and so their expression, differ.

PREDICT

**Why are identical twins, rather than non-identical twins, used to study the effect of the environment on gene expression?**

(A) Because identical twins always grow up in the same home, eating the same food

(B) Because identical twins share all their DNA, so genes cannot explain any difference

(C) Because identical twins have no epigenetic tags until they leave their shared home

Decide before you look. Answer on page 30.

TRY IT

The dry lab at the end of the guide lets you test twin pairs of different ages, together and apart, and children breathing low and high air pollution. Predict the patterns first.

# 09 Signals from *outside*

D2.2.11 HL EXTERNAL FACTORS AND THE PATTERN OF GENE EXPRESSION

Cells change their pattern of gene expression in response to what reaches them from outside. Two examples: a hormone in an animal, and a food molecule in a bacterium.

**A hormone: oestrogen.** Oestrogen is a steroid, so it passes through the cell membrane. Inside target cells, such as those lining the uterus, it binds a receptor protein. The hormone and receptor together act as a transcription factor: they bind to particular sequences in the DNA and increase the transcription of the genes nearby, which make the cells grow and divide. Cells with no oestrogen receptor do not respond.

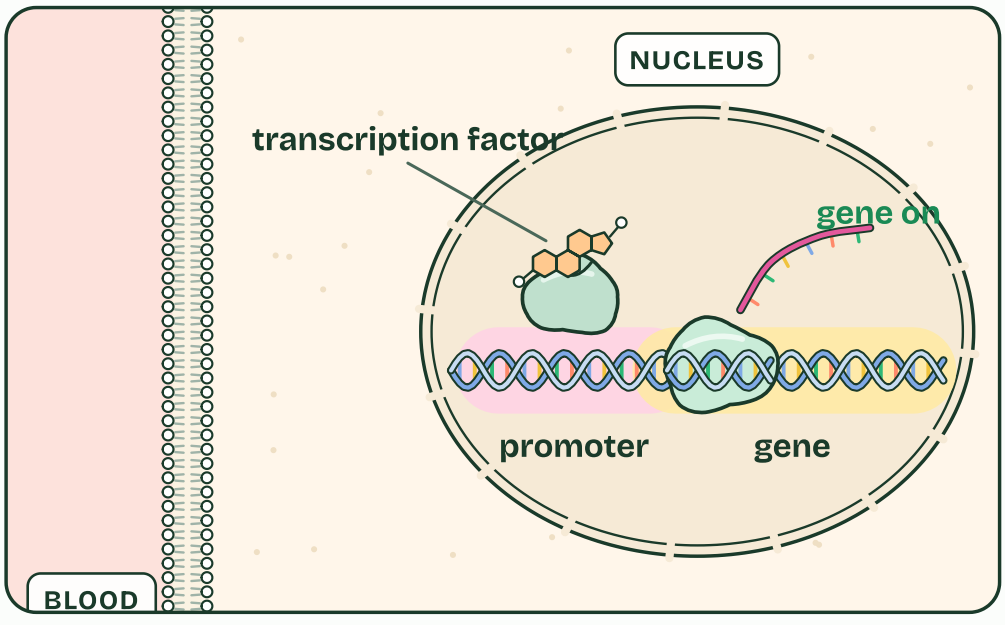
**A biochemical: lactose in *E. coli*.** The genes for taking in and digesting lactose sit together in the **lac operon**, transcribed together from one promoter. A regulatory gene makes a **repressor** protein that binds the **operator**, a sequence between the promoter and the genes, so RNA polymerase cannot transcribe them. When lactose is present, a form of it binds the repressor and changes its shape, so it lets go of the operator. The genes are transcribed and the enzymes made. When the lactose is used up, the repressor binds again. The bacterium makes the enzymes only when they are needed.

KEY POINTS

- Oestrogen binds a receptor inside its target cells; together they act as a transcription factor.
- lac operon: a repressor binds the operator and blocks transcription.
- Lactose binds the repressor so it lets go: the genes are expressed only when lactose is present.

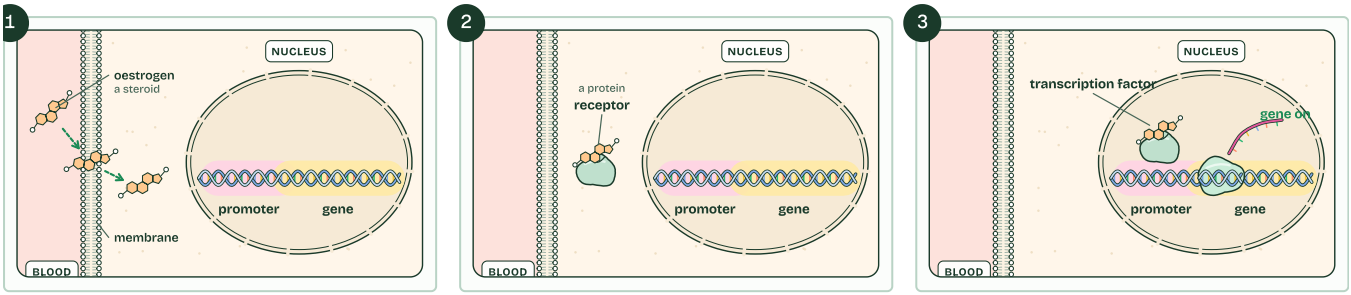
KEY TERMS

**lac operon**
A group of bacterial genes transcribed together from one promoter, and controlled together by one operator.



STEP BY STEP

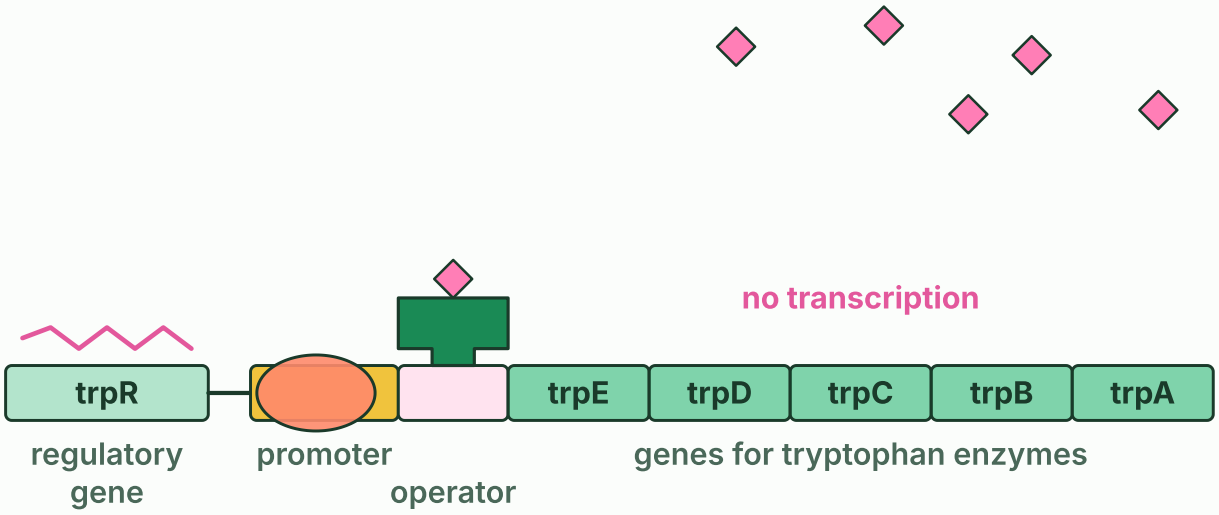
3 STEPS




**Oestrogen**, a steroid, passes through the cell membrane.

It binds a **receptor** protein inside the cell.

Together they act as a **transcription factor**: they bind DNA and switch the gene on.

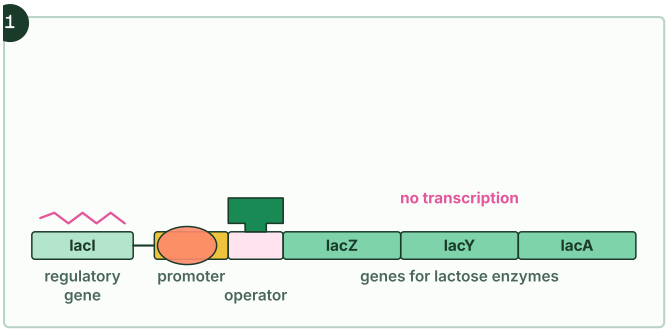



The lac operon, and the trp operon for comparison. Add lactose or tryptophan, mutate the regulatory gene or the operator, and watch the repressor.

STEP BY STEP

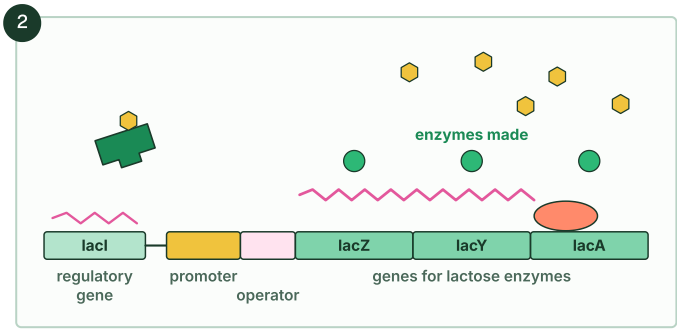
3 STEPS

1



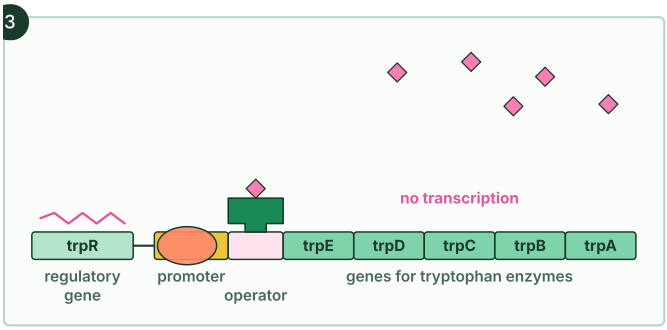

The **lac operon** with no lactose: the **repressor** sits on the **operator**, and RNA polymerase cannot transcribe the genes.

2




Lactose arrives and binds the repressor, which lets go of the operator: the genes are transcribed and the enzymes made.

3




The **trp operon** with tryptophan: tryptophan activates its repressor, which binds the operator and switches the genes off.

REMEMBER IT

### Four parts of an operon

| R | P | O | G |
|---|---|---|---|
| R | P | O | G |
| **Regulatory gene** | **Promoter** | **Operator** | **Genes** |
| makes the repressor | RNA polymerase binds | the repressor binds | transcribed together |

PREDICT

**A mutation changes the lac operator so that the repressor can no longer bind to it. What happens when there is no lactose?**

(A) The genes are off, because without lactose RNA polymerase cannot bind the promoter

(B) The genes are transcribed anyway, and the enzymes are made with nothing to digest

(C) The repressor binds the promoter instead, which keeps the genes switched off

Decide before you look. Answer on page 31.

# Key terms

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

**enhancers** 02
A DNA sequence, often far from the gene it affects, where activator proteins bind to increase the rate of transcription of that gene.

**epigenesis** 05
The development of patterns of differentiation in the cells of a multicellular organism, as different genes are switched on and off. The DNA base sequence does not change.

**epigenetic inheritance** 06
Changes in gene expression passed on to daughter cells or to offspring without any change in the DNA base sequence.

**epigenetic tags** 05
Chemical groups added to DNA or to histone proteins that change whether genes are expressed, without changing the base sequence.

**expressed** 01
The process by which the information in a gene has an effect on the phenotype: usually transcription, then translation, then the function of the protein made.

**genome** 03
The whole of the genetic information of an organism or cell: all of its DNA.

**lac operon** 09
A group of bacterial genes transcribed together from one promoter, and controlled together by one operator.

**nucleases** 04
Enzymes that break down nucleic acids. Nucleases in the cytoplasm break down mRNA, ending its translation.

**promoter** 02
A sequence of DNA just before a gene where RNA polymerase binds to start transcription. It is not transcribed itself.

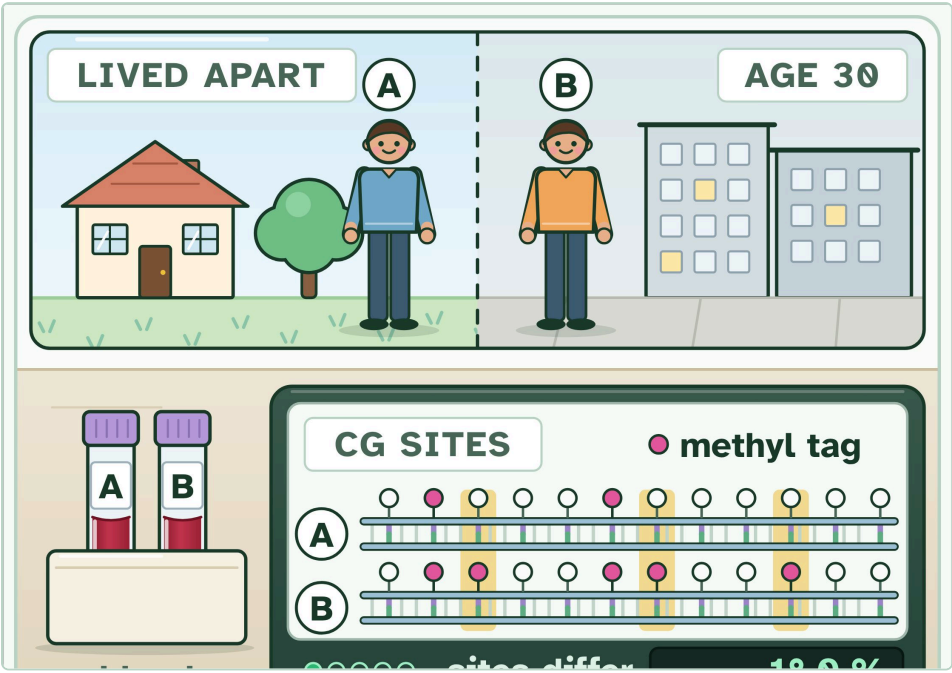
**proteome** 03
All the proteins made by a cell, a tissue or an organism at a particular time.

**transcription factors** 02
Proteins that bind to specific DNA sequences, such as promoters and enhancers, and so increase or decrease the transcription of a gene.

**transcriptome** 03
All the RNA molecules transcribed in a cell at a particular time.

# Dry lab: *Twins and tags*

Identical twins share every base of their DNA. Test their methyl tags at different ages, for twins who grew up together and twins who lived apart, then compare children breathing low and high air pollution.




Run it online: change the variables, run the trials, and the table and graph fill in as you go. `biologybybradford.com/guides/ib-biology-d2-2-gene-expression#lab`

### Your question

Do the methyl tags of identical twins grow more different as they age, and more so if they live apart? Does air pollution change the tags on one immune-system gene? Make a prediction for each before you test.

### What you can change

For the twins, their age and whether they lived most of their lives together or apart. For the children, how much air pollution they live with. Each Test is a new sample of five, so testing again is how you repeat.

### What to record

For each pair, the percentage of tested sites where the twins differ; for each child, the percentage of promoter sites methylated. Then the mean for each group. The results are invented to show the method, following the patterns of the real studies.

### Find out

- **Twins and age.** Test at least five pairs at each age who lived together. How does the percentage of differing sites change as the twins get older?
- **Together or apart.** At 15, 30 and 50, test five pairs who lived apart. Is the difference between together and apart bigger in older twins?
- **Air pollution.** Test ten children from each level of air pollution. Is the promoter more methylated where pollution is high, and by how much?
- **How sure?** Look at the spread in each group. Do the ranges overlap? Test more until you can say whether a difference is real.
- **Back to the genes.** Using your results, explain how the environment can change the expression of a gene without changing its base sequence.

### Record

- For each pair or child: the group and the percentage. The table fills as you test, and the graph shows every point with the group's mean as a bar.
- A mean for each group, and the range.
- What the data show, and what they cannot show on their own: the twins' base sequences are the same throughout, and a link with pollution is not yet proof that pollution causes the tags.
- Download the CSV to keep your table and plot your own graph.

**Your question**Do the methyl tags of identical twins grow more different as they age, and more so if they live apart? Does air pollution change the tags on one immune-system gene? Make a prediction for each before you test.**What you can change**For the twins, their age and whether they lived most of their lives together or apart. For the children, how much air pollution they live with. Each Test is a new sample of five, so testing again is how you repeat.**What to record**For each pair, the percentage of tested sites where the twins differ; for each child, the percentage of promoter sites methylated. Then the mean for each group. The results are invented to show the method, following the patterns of the real studies.

Back to the genes

Using your results, explain how the environment can change the expression of a gene without changing its base sequence.

## QUESTIONS ON THE LAB

QUESTION 1

**Twin pairs aged 3 differ at about 3 percent of sites, and pairs aged 50 at about 15 percent. What best explains the change?**

(A) Their DNA base sequences have drifted apart as they aged, through mutations

(B) Different experiences over the years added and removed different methyl tags

(C) The older twins' cells have stopped copying methyl tags when they divide

Answer on page 31.

QUESTION 2

**Why does testing identical twins, rather than any two people of the same age, make the effect of the environment clear?**

(A) Identical twins have fewer methyl tags, so any change is far easier to see

(B) Their DNA is the same, so a difference in tags cannot come from different genes

(C) Identical twins always share an environment, so only their genes can differ

Answer on page 31.

QUESTION 3

**Children in high air pollution have more methylation of the immune gene's promoter. What would you expect of the gene's expression?**

(A) Higher, because the methyl groups attract more RNA polymerase to the gene

(B) Lower, because methylation of a promoter represses transcription of its gene

(C) Unchanged, because methyl tags on a promoter have no effect on transcription

Answer on page 31.

## Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on D2.2 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=D2.2&level=HL&paper=quiz&marks=15&src=ep

# Answers

## PREDICTIONS IN THE CHAPTERS

**01** A mutation stops a pigment cell's tyrosinase from working, but the cell still makes plenty of tyrosinase mRNA. What happens to the colour of the skin around it?

B **It goes pale, because the protein made from that mRNA cannot make melanin**

Pale. Transcription and translation still happen, but the trait depends on the protein's function, and a non-functional enzyme makes no melanin. Expression is not finished until the protein does its job.

**02** A cell stops making one activator protein. What happens to a gene whose enhancer that activator binds?

B **It is transcribed more slowly, as long as its promoter can still be bound**

More slowly. The activator raises the rate of transcription, but transcription factors and RNA polymerase can still bind the promoter without it. Lose the transcription factors that bind the promoter and the gene stops altogether.

**03** Which of these is likely to be the most alike in a skin cell and a beta cell from the same person?

A **Their genomes, since nearly every cell in one body carries the same DNA**

Their genomes, which are the same. They share part of their transcriptomes and proteomes (the genes every cell needs), but each also expresses genes the other does not: keratin in one, insulin in the other.

**04** Two genes are transcribed at the same rate, but one gene's mRNA lasts ten times longer. What is the result?

B **Much more of the protein from the longer-lasting mRNA, read for longer**

More protein from the longer-lasting mRNA: each molecule is translated many more times before it is broken down. It also means that protein keeps being made for longer after the gene is switched off.

**05** A gene's promoter is heavily methylated, but the histones around the gene carry acetyl tags. Is the gene expressed?

B **No, since the methylated promoter represses transcription of the gene**

No. Methylation of the cytosines in a promoter represses transcription of the gene downstream, however loose the nucleosomes are. Try it in the tool.

**06** A drug stops a cell copying methyl tags onto the new DNA strand when it replicates. What happens over several divisions?

B **The tags are diluted, and genes that were switched off can switch on again**

Each division leaves one strand untagged, so after a few divisions most of the DNA has no methyl tags and genes that were held off can be expressed. The base sequence is unchanged throughout.

**07** Why does the zygote need most of the tags in the egg and sperm to be removed?

B **So that its descendants can switch on whichever genes each kind of cell needs**

The zygote must be able to produce every kind of cell. Tags left from the gamete-making cells would hold some genes off that a nerve, muscle or liver cell will need. Removing them resets the pattern; the few that stay are why the parent of origin can matter.

**08** Why are identical twins, rather than non-identical twins, used to study the effect of the environment on gene expression?

B **Because identical twins share all their DNA, so genes cannot explain any difference**

They share the same base sequence, so a difference in their tags or their expression cannot be put down to different genes. Non-identical twins share only about half their alleles, so a difference between them could be genetic.

**09** A mutation changes the lac operator so that the repressor can no longer bind to it. What happens when there is no lactose?

B **The genes are transcribed anyway, and the enzymes are made with nothing to digest**

With nothing to block it, RNA polymerase transcribes the genes all the time, lactose or not. The cell wastes energy and amino acids on enzymes it cannot use. Try it in the tool, then try the trp operon, which works the other way round.

## QUESTIONS ON THE DRY LAB

**Q1** Twin pairs aged 3 differ at about 3 percent of sites, and pairs aged 50 at about 15 percent. What best explains the change?

B **Different experiences over the years added and removed different methyl tags**

The twins began with the same DNA and nearly the same tags. Over decades, different diets, habits, illnesses and surroundings add and remove tags, so their methylation, and their gene expression, drift apart. Twins who lived apart drift further.

**Q2** Why does testing identical twins, rather than any two people of the same age, make the effect of the environment clear?

B **Their DNA is the same, so a difference in tags cannot come from different genes**

Two unrelated people differ in millions of bases, and some of those differences affect methylation. Identical twins share their base sequence, so differences in their tags must come from the environment, or from chance.

**Q3** Children in high air pollution have more methylation of the immune gene's promoter. What would you expect of the gene's expression?

B **Lower, because methylation of a promoter represses transcription of its gene**

Lower. Methylated cytosines in a promoter repress transcription. In the real study the gene was expressed less in the children with more methylation, and the immune cells it makes worked less well.

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

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