Unit 2

Life and Life Process

This unit online, with its interactives:
science-playground.com/s/10a2

Pull a handful of the slimy green threads from the edge of a pond in the monsoon, the *leu* that makes the stones slippery, and look at one thread under a microscope. It is a row of glassy cells, each with a bright green ribbon wound round inside it like the stripe on a barber's pole. That is ***Spirogyra***. In autumn, two of its threads lying side by side may join by little bridges, and the whole of one thread's living matter crawls across into the other.

Now think of a glass of water from an unsafe tap. It can carry, too small to see, the resting cysts of ***Entamoeba histolytica***, a single-celled parasite that eats its way into the wall of the human gut and causes amoebic dysentery. One alga that feeds a pond, one protozoan that makes people ill: this unit follows both through their whole lives. Then it asks two questions about every living cell. How does water get into it and out of it, and up a tree with no pump (**osmosis** and **transpiration**)? And how does a cell get energy out of its food (**intracellular respiration**)?

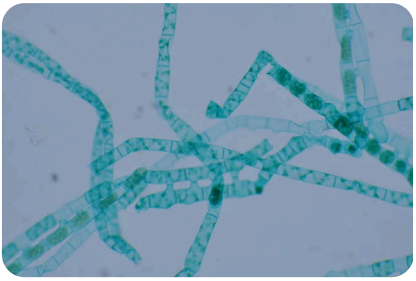


Figure 2.1 *Spirogyra conjugating, seen through a light microscope (stained). In the middle, two threads lie side by side, joined cell to cell by short tubes like the rungs of a ladder; along several threads the cells' contents have rounded off into dark, oval zygospores. By the end of section 2.1 you will know what has happened in each cell.*
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2.1 Life cycle of Spirogyra and Entamoeba

A **life cycle** is the whole series of stages an organism passes through, from one stage back to the same stage in the next generation. Both organisms here are single eukaryotic cells or chains of them, and both can reproduce without a partner. But *Spirogyra* also reproduces sexually, while *Entamoeba* never does, and *Spirogyra* lives freely while *Entamoeba* can complete its life only inside a human.

Spirogyra

Spirogyra is a green alga of fresh water: ponds, ditches, rice fields, slow streams and water tanks. Its threads float in tangled green masses near the surface, buoyed up by bubbles of the oxygen they make in sunlight, and feel slimy to the touch, so in English it is called pond silk or water silk. There are about 400 species, all built the same way.

Its body. The plant body is an unbranched **filament** (thread), a single row of cylindrical cells joined end to end. Every cell is the same: there is no root, stem or leaf, no base and no tip, and any cell can divide. So the body is a simple **thallus**, and each cell feeds, grows and divides by itself. Every cell has:

- a **cell wall** of two layers: an inner layer of **cellulose** and an outer layer of **pectin**, which swells in water into a slimy **mucilage** sheath. The slime is why the threads feel slippery and why few animals can grip them. The cross walls between cells are called **septa** (one septum).
- a thin lining of **cytoplasm** pressed against the wall, round a large central **vacuole** full of cell sap.
- one or more **chloroplasts**, the feature that names the genus (*speira*, a coil): each is a long ribbon with wavy or toothed edges, wound in a spiral (a helix) just inside the wall, from one end of the cell to the other. A cell may have one ribbon or several, according to the species.
- on each ribbon, a row of **pyrenoids**, small round bodies where the cell gathers its food into **starch**.
- a single **nucleus**, hung in the middle of the vacuole by fine strands of cytoplasm that run out to the pyrenoids, like the spokes of a wheel.

All these nuclei are **haploid** (n): the filament has one set of chromosomes.

Reproduction in Spirogyra

Spirogyra reproduces in two ways: vegetatively, by breaking into pieces, and sexually, by conjugation.

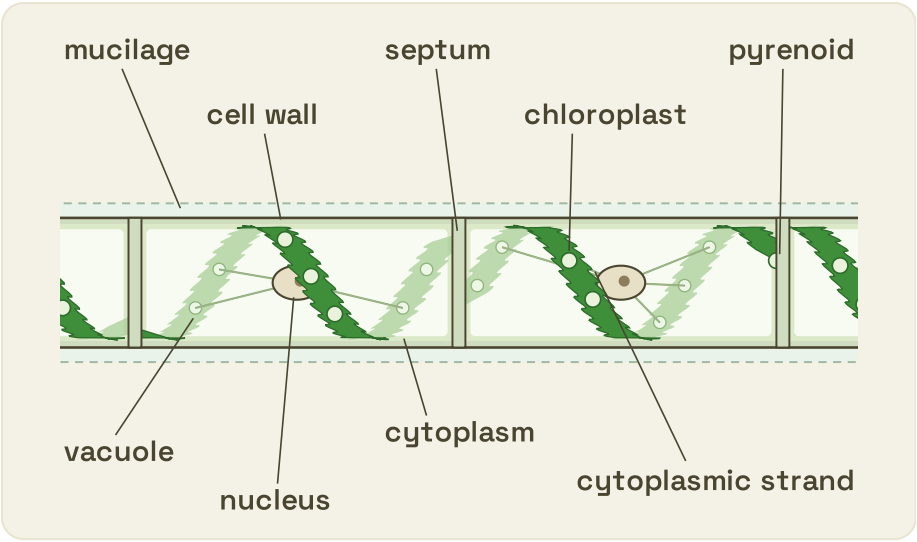


Figure 2.2 *Part of a Spirogyra filament. Each cell is a cylinder whose wall has a slimy outer layer; a ribbon-shaped chloroplast with wavy edges winds round just inside the wall, with pyrenoids along it, and the nucleus hangs in the middle of the large vacuole on strands of cytoplasm. Where the ribbon passes behind the cell it is drawn paler.*

Vegetative reproduction: fragmentation. A filament breaks easily, at a weak septum or where a cell dies, or when it is torn by moving water or animals. Every piece that has even one living cell grows into a new filament, its cells dividing by mitosis across the thread. This is how a pond fills with *Spirogyra* within weeks in warm, sunny weather.

Sexual reproduction: conjugation. At the end of the growing season, when the water cools or the nutrients run low, *Spirogyra* reproduces sexually. Two cells join by a tube and the contents of one pass into the other and fuse with them: this is **conjugation** (Latin *conjugare*, to yoke together). There are two kinds.

1. Scalariform conjugation (*scalaris*, of a ladder), between two filaments:

1. Two filaments come to lie side by side, close and parallel, held together by their mucilage.
2. Opposite cells of the two filaments each push out a small bulge, a **papilla**, towards the other.
3. The papillae meet, push the filaments slightly apart, and the wall between their tips dissolves, making an open **conjugation tube**. With a tube between each pair of facing cells, the two filaments look like a ladder; the tubes are its rungs.

4. In each joined cell, the whole protoplast (the living contents) loses water from its vacuole, shrinks away from the wall and rounds off. Each rounded protoplast is a **gamete**. Since it has no flagella and can't swim, it is called an **aplanogamete** (*a-planos*, not wandering).
5. The gametes of one filament move, by creeping like an amoeba, through the tubes into the cells of the other filament. The moving one is called the male gamete and the one that waits the female, but the two look exactly alike: they differ only in behavior. This is **physiological anisogamy**: unequal in what they do, equal in form.
6. In the receiving cell the two gametes fuse, cytoplasm with cytoplasm and nucleus with nucleus, making a **diploid** (2n) **zygote**.
7. The zygote secretes a thick wall of three layers and becomes a **zygospore**, oval and dark. At the end, one filament is a row of empty cells and the other a row of zygospores.

2. Lateral conjugation, between two neighboring cells of the same filament. It happens where one filament is alone. In one kind, a tube forms round the septum between two cells, on one side of the filament, and the contents of one cell pass through it into the other; the filament shows every second cell empty and every other cell with a zygospore. In another kind, a small hole opens in the septum itself and the gamete passes straight through.

The zygospore and its germination. Zygospores sink to the mud when the old filaments die and rot away. Their thick walls carry them through the cold or the dry season, for months if need be. When conditions improve:

1. The diploid nucleus divides by **meiosis** into four haploid nuclei.
2. Three of the four degenerate; one survives.
3. The zygospore absorbs water and swells, its outer wall layers crack open, and the inner layer grows out as a short **germ tube**, holding the one haploid nucleus.
4. The germ tube divides by mitosis, again and again, into a new filament.

So each zygospore gives just **one** new filament. The zygote is the only diploid cell in the whole life of *Spirogyra*; everything else is haploid. A life in which the adult is haploid and meiosis happens in the zygote is called **haplontic** (zygotic meiosis).

Entamoeba histolytica

Entamoeba histolytica is a single-celled parasitic protozoan (kingdom Protista), a relative of the free-living *Amoeba*. It lives in the large intestine of humans, and humans are its only important host: its whole life cycle is completed in one host, with no in-

CAREFUL

One zygospore, one filament

Meiosis normally gives four cells. In the *Spirogyra* zygospore it gives four nuclei, but three of them degenerate, so the zygospore germinates into **one** filament, not four. Compare *Mucor*, whose zygospore germinates into a sporangium full of many spores.

Check 1

In scalariform conjugation, where are the zygospores formed?

a in the conjugation tubes

b in the cells of the filament that receives the gametes

c in both filaments, one in every cell

d in the mud, after the gametes are released

sect or other animal in between. Its name says what it does: *ent-* (inside, in the gut), *amoeba*, and *histolytica* (*histos*, tissue; *lysis*, dissolving), the tissue-dissolver. In some of the people it infects, it eats into the wall of the large intestine and causes **amoebic dysentery** (amoebiasis): stomach pain and frequent stools with blood and mucus. From the gut it can travel in the blood to the liver and make an **amoebic liver abscess**, a pocket of dead tissue.

It has two main forms, each with a job:

	Trophozoite	Cyst
What it is	the active, feeding, dividing form	the resting, infective form
Size	about 15–30 μm (up to 60 μm when it invades)	about 10–15 μm
Shape	irregular, changing; moves by one broad **pseudopodium** at a time	round, with a thick, smooth wall
Nuclei	one	one, then two, then four (mature)
Inside	food vacuoles, often with **red blood cells** it has eaten	a **glycogen** store and rod-shaped **chromatoid bodies** with rounded ends (food reserves) when young; both mostly used up as it matures
Survives outside the body?	no: dies within minutes to hours	yes: weeks in damp, cool places

Each nucleus is round, with a small dot, the **karyosome**, at its center, and a fine ring of chromatin under its membrane. Unlike *Amoeba*, *Entamoeba* has no contractile vacuole: it lives in the gut, where it doesn't need to pump out water.

The life cycle of Entamoeba histolytica



Figure 2.3 *A trophozoite of Entamoeba histolytica from a patient's stool, stained and seen through a light microscope. The darker round bodies inside it are red blood cells it has swallowed, the sign of the invasive form.*
Photo: CDC/ Dr. Mae Melvin; Dr. Greene, CC0

1. **Infection.** A person swallows **mature cysts**, each with four nuclei, in water or food contaminated with human feces: unboiled water, raw vegetables washed in dirty water, food handled with unwashed hands, or food that flies have walked on. A few cysts are enough. Trophozoites, if swallowed, are killed by the stomach's acid; the cyst's wall survives it.
2. **Excystation.** In the lower part of the small intestine, where the juices are alkaline, the cyst wall weakens and the four-nucleate amoeba squeezes out through a small opening. Its nuclei divide once more (4 → 8), and its cytoplasm

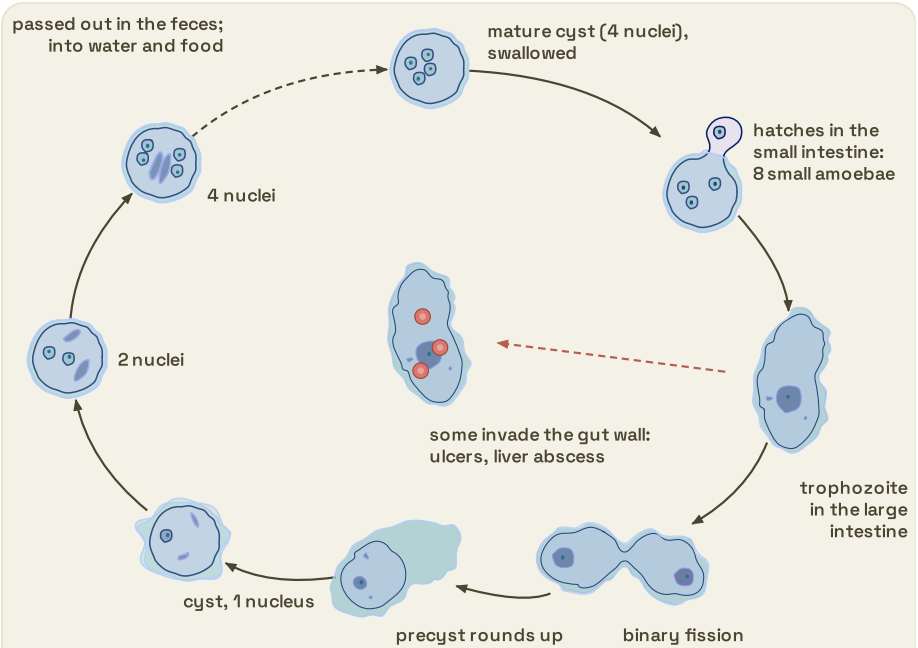
divides round them, so each cyst gives **eight small amoebae** (metacystic trophozoites).

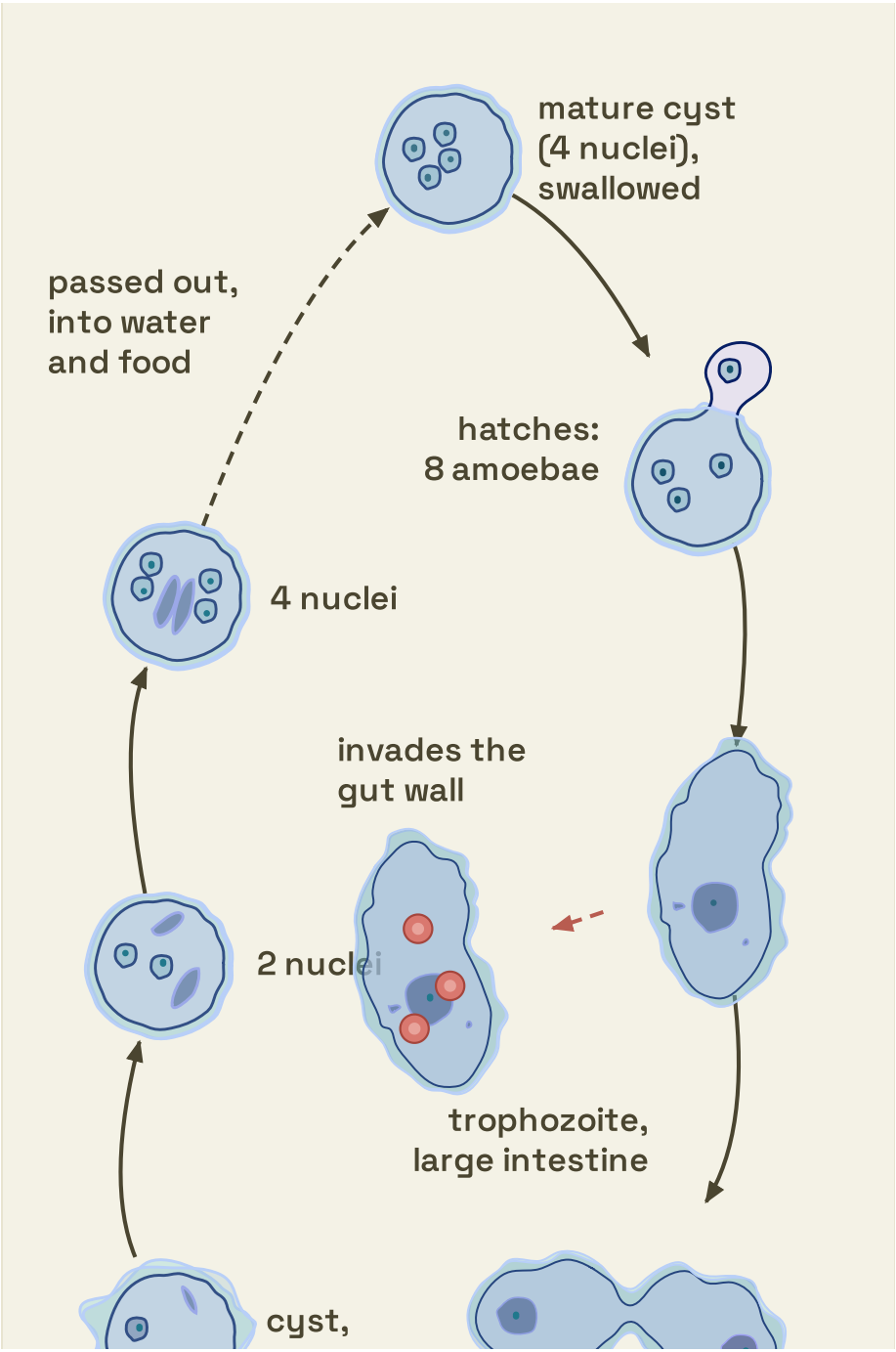
3. **Trophozoites in the large intestine.** The young amoebae are carried on into the large intestine (the colon). There they grow into trophozoites, live on bacteria and food particles in the gut, and multiply by **binary fission**, the nucleus dividing by mitosis and the cell pinching in two. In most infected people, that is all they do: they live harmlessly in the gut, and the person has no illness.
4. **Invasion (in some people).** In others, for reasons that depend on both the amoeba's strain and the person's gut, the trophozoites attack the gut lining. They kill the cells they touch, digest the tissue with enzymes, and burrow into the wall, making **flask-shaped ulcers**: a small opening that widens out underneath. They swallow red blood cells from the damaged vessels. This is amoebic dysentery. Some are carried by the blood of the portal vein to the **liver**, and rarely to the lungs or brain, where they form abscesses. These invading trophozoites can't go on to the next stage: they are a dead end for the parasite.
5. **Encystment.** As the contents of the gut move along the colon and dry out, many trophozoites in the gut's cavity stop feeding, empty their food vacuoles and round up, becoming smaller **precystic** forms. Each secretes a tough wall round itself: it is now a **cyst**, with one nucleus, a glycogen store and chromatoid bodies.
6. **Maturing of the cyst.** The nucleus divides twice by mitosis: one nucleus, then two, then **four**. The glycogen and chromatoid bodies are mostly used up. A four-nucleate cyst is mature and infective.
7. **Passing out.** Cysts leave the body in the feces, sometimes in huge numbers. Outside, they can't multiply, but they stay alive in damp soil, water and food for weeks, waiting to be swallowed by the next person.

So there is no sexual reproduction in the life of *Entamoeba*: it multiplies only asexually, by binary fission of the trophozoites and by the division of the cyst's nuclei (one cyst giving eight amoebae). The trophozoite is the form that does harm; the cyst is the form that spreads.

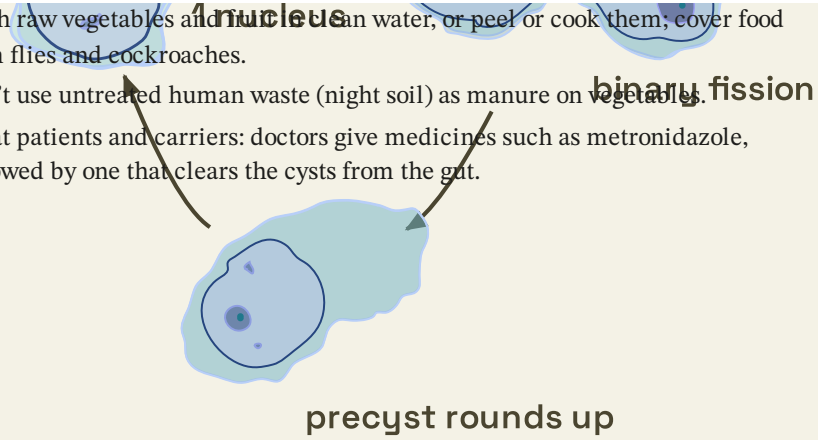
Prevention. Since the cyst spreads the disease, the way to stop it is to keep human feces away from what people eat and drink:

- Drink boiled, filtered or treated water. **Boiling** kills cysts; the chlorine in ordinary tap water does not reliably kill them.
- Wash hands with soap after using the toilet and before cooking or eating.
- Use toilets, and keep them away from wells and water sources.


passed out in the feces;
into water and food
mature cyst (4 nuclei),
swallowed
hatches in the
small intestine:
8 small amoebae
4 nuclei
2 nuclei
some invade the gut wall:
ulcers, liver abscess
trophozoite
in the large
intestine
cyst, 1 nucleus
precyst rounds up
binary fission


mature cyst
(4 nuclei),
swallowed
passed out,
into water
and food
hatches:
8 amoebae
4 nuclei
invades the
gut wall
2 nuclei
trophozoite,
large intestine
cyst,

- Wash raw vegetables and fruit in clean water, or peel or cook them; cover food from flies and cockroaches.
- Don't use untreated human waste (night soil) as manure on vegetables.
- Treat patients and carriers: doctors give medicines such as metronidazole, followed by one that clears the cysts from the gut.



Entamoeba: after Mariana Ruiz Villarreal (LadyofHats), Public domain, via Wikimedia Commons

Figure 2.4 *The life cycle of Entamoeba histolytica, completed in one host. Mature cysts with four nuclei are swallowed; each releases an amoeba that becomes eight small trophozoites; trophozoites multiply by binary fission in the large intestine; some invade the wall, while others round up into cysts, whose nucleus divides into two and then four; the cysts pass out in the feces. Only the cyst can infect.*

CAREFUL

A person can spread it without being ill

Most people infected with *E. histolytica* have no symptoms at all, yet they pass cysts in their stools, sometimes millions a day. These **carriers** (cyst passers), often food handlers who don't know they are infected, are the main source of new infections. A person ill with dysentery passes mostly trophozoites, which die outside the body, so is less infectious than a healthy-looking carrier.

DID YOU KNOW?

Two amoebae that look the same

Under a microscope, the cysts of *Entamoeba histolytica* look exactly like those of ***Entamoeba dispar***, a harmless amoeba of the human gut, and the two were thought to be one species until DNA tests separated them in 1993. Many of the people whose stool tests show "*E. histolytica* cysts" in fact carry the harmless *E. dispar*. Only special tests (for its proteins or its DNA) can tell them apart, which is why a good laboratory reports "*E. histolytica/E. dispar*" when it sees cysts alone.

A STORY FROM SCIENCE

The doctor who found the amoeba

In 1873 a young farmer from near Arkhangelsk, in the far north of Russia, came to a hospital in St Petersburg with dysentery that would not stop. The doctor, **Fedor Lösch**, looked at his stools under a microscope and saw large amoebae, many of them full of red blood cells. To test whether they caused the disease, he put the patient's stools into the rectum of four dogs; one developed ulcers in its colon, full of the same amoebae. Lösch published his findings in 1875. It was the first time an amoeba was linked with a human disease, though Lösch himself wasn't sure it was the cause. In 1903 the German zoologist **Fritz Schaudinn** told the harmful amoeba apart from a harmless one and named it *Entamoeba histolytica*.

Check 2

How many trophozoites does one mature cyst of *Entamoeba* finally give?

a 1
b 4
c 8
d 16

2.2 Osmosis and transpiration process

Water is about 70 to 90 percent of a living cell, and every cell is always taking water in or losing it. Two processes control this: osmosis, by which water moves into and out of cells, and transpiration, by which a plant loses water from its leaves and so draws more up from the soil.

Osmosis

Put a dried raisin in a cup of water overnight and it swells up plump again. Sprinkle salt on slices of cucumber for *achar*, and in a few minutes they sit in a puddle of their own water. In both, water has crossed the skins of living cells, in opposite directions. Why?

First, **diffusion**: the molecules of a liquid or gas are always moving at random, so any substance spreads from where it is more concentrated to where it is less concentrated, until it is evenly spread. A drop of ink in water spreads this way.

Now separate two solutions by a **semipermeable membrane**: a sheet with pores that let small water molecules through but not larger dissolved molecules such as sugar. Cellophane, the skin inside an egg's shell and the membrane of every living cell behave like this (a cell membrane is better called **selectively permeable**, since it also lets some solutes through and controls which). The sugar can't cross, so only the water can even things out. Water molecules keep crossing the membrane both ways, but the solution with more sugar dissolved in it has a lower concentration of water. More water molecules cross each second from the side with more water (less solute) to the side with less water (more solute) than come back, and the more concentrated solution gains water.

Osmosis is the movement of water (the solvent) through a semipermeable membrane, from a less concentrated solution (or pure water) to a more concentrated solution. In other words, water moves from where there is more water to where there is less.

Notice the two differences from ordinary diffusion: osmosis needs a membrane, and it is the water, not the solute, that moves.

The solution outside a cell is described by comparing it with the cell sap inside:

- A **hypotonic** solution is less concentrated than the cell sap (pure water is the extreme). Water enters the cell: **endosmosis**.
- An **isotonic** solution has the same concentration as the cell sap. Water enters and leaves equally, so there is no net movement.
- A **hypertonic** solution is more concentrated than the cell sap. Water leaves the cell: **exosmosis**.

In a plant cell, water entering by endosmosis fills the vacuole and presses the cytoplasm hard against the cell wall, which, being strong, presses back, like a football's leather round its bladder. The cell is firm, **turgid**; the pressure is the **turgor pressure**. In a hypertonic solution the cell loses water from its vacuole, which shrinks; the

cytoplasm pulls away from the wall, first at the corners and then all round, and the cell is **plasmolyzed**. This shrinking of the protoplast away from the wall is **plasmolysis**. Put a plasmolyzed cell back into water soon enough and it swells back: **deplasmolysis**. Left too long, it dies.

In an animal cell, with no wall, there is nothing to stop it. A red blood cell in pure water swells until it bursts (**hemolysis**); in strong salt water it shrinks and wrinkles (**crenation**). That is why the blood plasma is kept isotonic with the cells, and why a drip given in a hospital is **normal saline**, 0.9% sodium chloride, isotonic with blood, never plain water.

Demonstration: the potato osmometer

An **osmometer** shows osmosis happening and measures it. A potato's living cells make a good one.



Figure 2.5 *Cells of a red onion's skin starting to plasmolyze. The purple is the pigment in each cell's vacuole; as the cell loses water, the vacuole shrinks and the protoplast begins to pull away from the cell wall, here only in places. The two small guard cells at the upper left are a stoma.*
Photo: Trương Minh Khải, CC BY 4.0

How much water moves?

How fast and how much water moves depends on the difference in concentration across the membrane. A neat way to measure it is to weigh pieces of potato before and after they soak in solutions of different strengths. The percentage change in mass is

$$\text{percentage change in mass} = \frac{\text{final mass} - \text{initial mas}}{\text{initial mass}}$$

A gain means water went in (the solution was hypotonic to the potato's cells); a loss means water came out (hypertonic). Where the line crosses zero, the solution is isotonic with the cell sap.

> CAREFUL
> **Osmosis or diffusion?**
>
> In an exam answer, osmosis must have three things: **water** (the solvent) moving, through a **semipermeable membrane**, from the **less** concentrated solution to the **more** concentrated one. A common slip is "from higher concentration to lower concentration": that describes the solute in diffusion. Say "from a dilute solution to a concentrated solution", or "from higher water concentration to lower water concentration", and you can't be marked wrong.

Check 3

A plant cell is placed in a solution more concentrated than its cell sap. What happens?

a water enters and the cell becomes turgid
b water leaves the cell and its protoplast shrinks from the wall
c salt enters and the cell bursts
d nothing, because the cell wall stops osmosis

We use percentage change, not the change in grams, because the strips don't start with exactly the same mass: a percentage compares them fairly.

Importance of osmosis

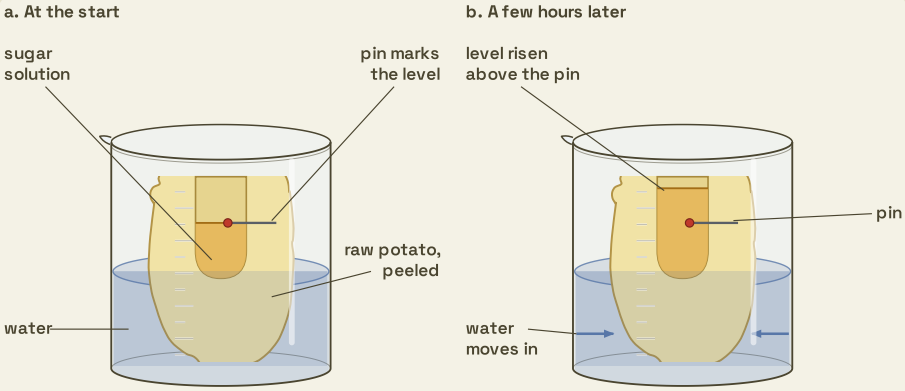
In plants:

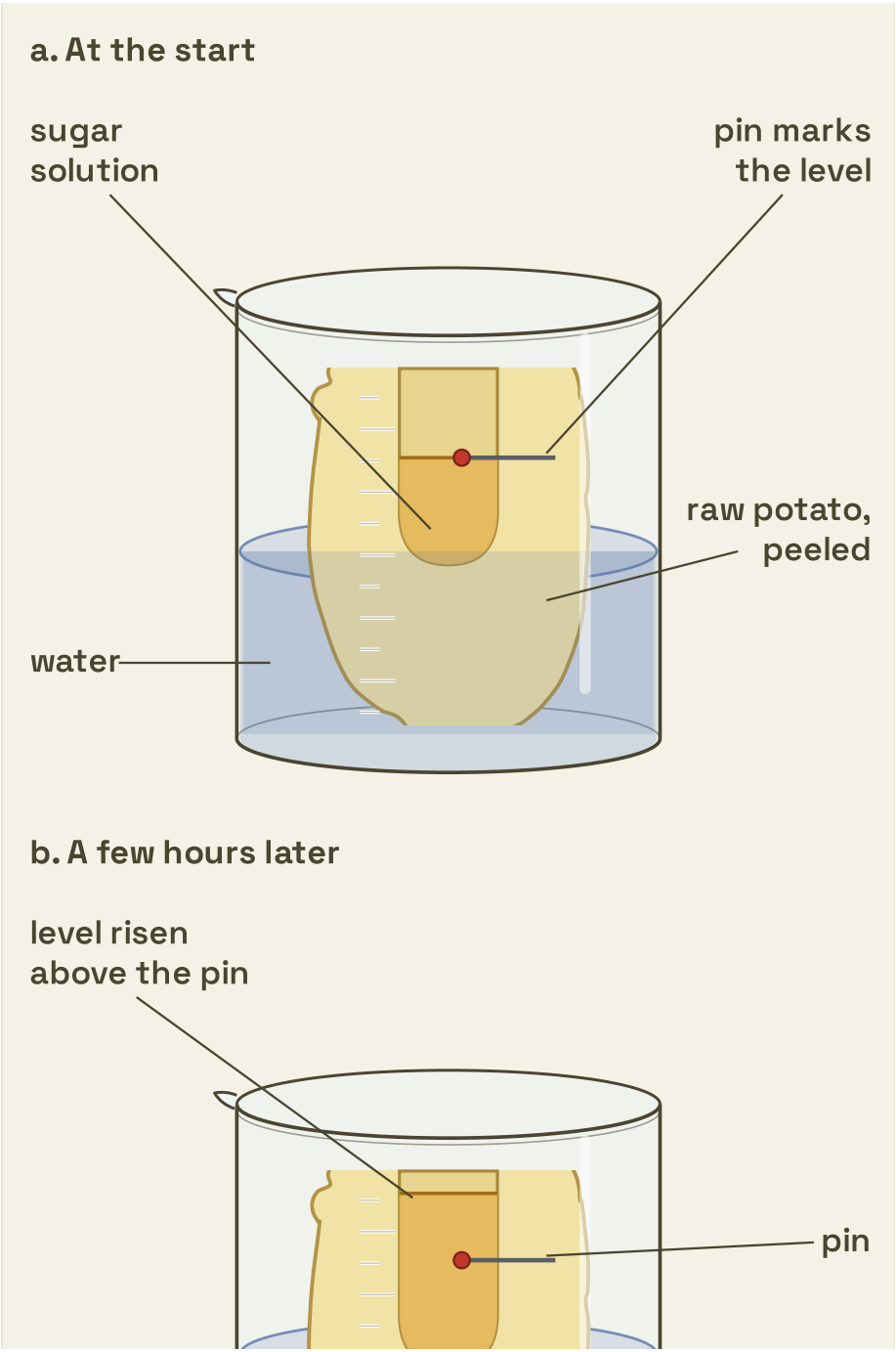
1. **Absorption of water.** The root hairs' cell sap is more concentrated than the soil water, so water enters them by osmosis, and passes from cell to cell across the root to the xylem.
2. **Turgidity and support.** Turgid cells keep soft stems, leaves and flowers firm and spread out; a herb such as spinach or mustard has little wood to hold it up. When a plant loses more water than it takes in, its cells lose turgor and it **wilts**.
3. **Opening and closing of stomata.** The two guard cells of a stoma open it when they take in water by osmosis and swell, and close it when they lose water.
4. **Movements** such as the drooping of a touch-me-not (*lajjawati*, *Mimosa*) leaf when it is touched: cells at the base of each leaf stalk lose water suddenly.

In animals, water is absorbed from the large intestine into the blood, and taken back from the kidney's tubules, by osmosis, and the body's fluids are kept isotonic with its cells.

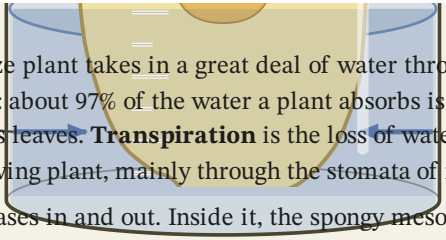
In daily life:

- Salt in *achar* and salted fish, and sugar in jam and *murabba*, draw water out of any bacteria or molds that land on them by osmosis, so they can't grow: the food keeps.
- Too much fertilizer near a plant's roots makes the soil water hypertonic: water leaves the roots and the plant wilts ("fertilizer burn"). Salt sprinkled on weeds kills them the same way.
- Sea water can't quench thirst: it is more concentrated than our body fluids, so drinking it draws water out of the cells.


a. At the start
sugar solution
pin marks the level
raw potato, peeled
water
b. A few hours later
level risen above the pin
pin
water moves in


a. At the start
sugar solution
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raw potato, peeled
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b. A few hours later
level risen above the pin
pin

Transpiration



A sunflower or a maize plant takes in a great deal of water through its roots, but uses only a small part of it: about 97% of the water a plant absorbs is lost into the air as vapor, mostly through its leaves. **Transpiration** is the loss of water as water vapor from the aerial parts of a living plant, mainly through the stomata of its leaves.

A leaf is built to let gases in and out. Inside it, the spongy mesophyll cells are loosely

Potato: ZooFari, Wikimedia Commons, public domain

Figure 2.6 *The potato osmometer. a. At the start, a hollowed raw potato holding sugar solution stands in a beaker of water, a pin marking the level. b. A few hours later the level has risen above the pin: water has moved from the beaker through the potato's living cells into the sugar solution.*

packed, with large **air spaces** between them, which open to the outside air through the **stomata** (one **stoma**), pores each between two kidney-shaped **guard cells**. The walls of the mesophyll cells are always wet. Water evaporates from them into the air spaces, so the air inside the leaf is nearly saturated with water vapor; when the stomata are open, the vapor diffuses out into the drier air outside.

There are three kinds of transpiration, by where the water leaves:

Kind	Through	Share of the water lost
Stomatal transpiration	the stomata of leaves and young stems	about 90%
Cuticular transpiration	the waxy cuticle covering the leaves and stems	about 5–10% (more in shade plants with a thin cuticle)
Lenticular transpiration	the lenticels, small pores in the bark of woody stems and fruits	well under 1%

How transpiration pulls water up. As water evaporates from a leaf's cells, they draw water from the cells next to them, and those from the xylem in the leaf's veins. The xylem is a set of continuous, very thin tubes from the root to the leaf, full of water, and water molecules cling to one another (**cohesion**) and to the walls of the tubes (**adhesion**). So the loss at the top pulls the whole thread of water up behind it, like drinking through a straw. This **transpiration pull** lifts water and the minerals dissolved in it to the top of the tallest trees: over 110 m in California's coast redwoods. Root pressure, the push from osmosis in the roots, lifts water only a few meters at most.

WORKED EXAMPLE

Finding the cell sap's concentration

Prakriti cut five equal strips of potato, weighed each, and left them for an hour in sugar solutions of different strengths. Then she dried their surfaces and weighed them again.

Sugar solution (mol/L)	0	0.2	0.4	0.6	0.8
Mass at start (g)	2.50	2.40	2.60	2.50	2.40
Mass after an hour (g)	2.95	2.57	2.52	2.20	1.92

a. Find the percentage change in mass of each strip. b. Plot it against the concentration and find the concentration that is isotonic with the potato's cell sap.

Answer

a. Percentage change = (final − initial) ÷ initial × 100%:

- 0 mol/L: (2.95 − 2.50) ÷ 2.50 × 100% = **+18%**
- 0.2 mol/L: (2.57 − 2.40) ÷ 2.40 × 100% = **+7.1%**
- 0.4 mol/L: (2.52 − 2.60) ÷ 2.60 × 100% = **−3.1%**
- 0.6 mol/L: (2.20 − 2.50) ÷ 2.50 × 100% = **−12%**
- 0.8 mol/L: (1.92 − 2.40) ÷ 2.40 × 100% = **−20%**

b. The change goes from +7.1% at 0.2 mol/L to −3.1% at 0.4 mol/L, so it crosses zero between them. Reading along the straight line between those two points: 0.2 + 0.2 × 7.1 ÷ (7.1 + 3.1) = 0.2 + 0.14 = **about 0.34 mol/L**. A sugar solution of about 0.34 mol/L is isotonic with the potato's cell sap: in it, a strip would neither gain nor lose water.

Factors affecting transpiration

Factor	Effect on transpiration	Why
Light	faster in light	stomata open in light (for photosynthesis) and mostly close in the dark; light also warms the leaf
Temperature	faster when warmer	water evaporates faster, and warm air can hold more vapor

DID YOU KNOW?

How hard does osmosis push?

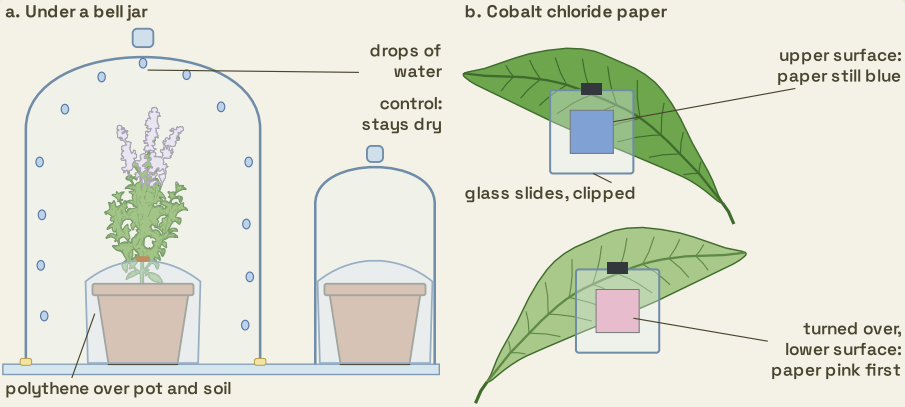
If a membrane separates pure water from a solution, water flows in until a pressure on the solution's side stops it. This pressure is the **osmotic pressure**. For a dilute solution, the Dutch chemist Jacobus van 't Hoff found in 1886 that it follows the same rule as a gas, $\pi = cRT$: c is the concentration of dissolved particles in mol/m³, $R = 8.314$ J/(mol K), and T the temperature in kelvin. For a 0.3 mol/L sugar solution (300 mol/m³) at 27 °C (300 K): $\pi = 300 \times 8.314 \times 300 \approx 750{,}000$ Pa, about **7.4 times the pressure of the air**. That is enough to hold up a column of water about 76 m tall. It was for this work that van 't Hoff received the first Nobel Prize in Chemistry, in 1901.

Factor	Effect on transpiration	Why
Humidity	slower in humid air	the difference between the wet air inside the leaf and the air outside is smaller
Wind	faster in wind (up to a point)	moving air sweeps away the vapor around the leaf; a strong wind may close the stomata
Water in the soil	slower when the soil is dry	the plant loses turgor and its stomata close to save water
The leaf itself	slower with fewer or sunken stomata, a thick cuticle, hairs, small or rolled leaves, or spines	less surface and less open pore area

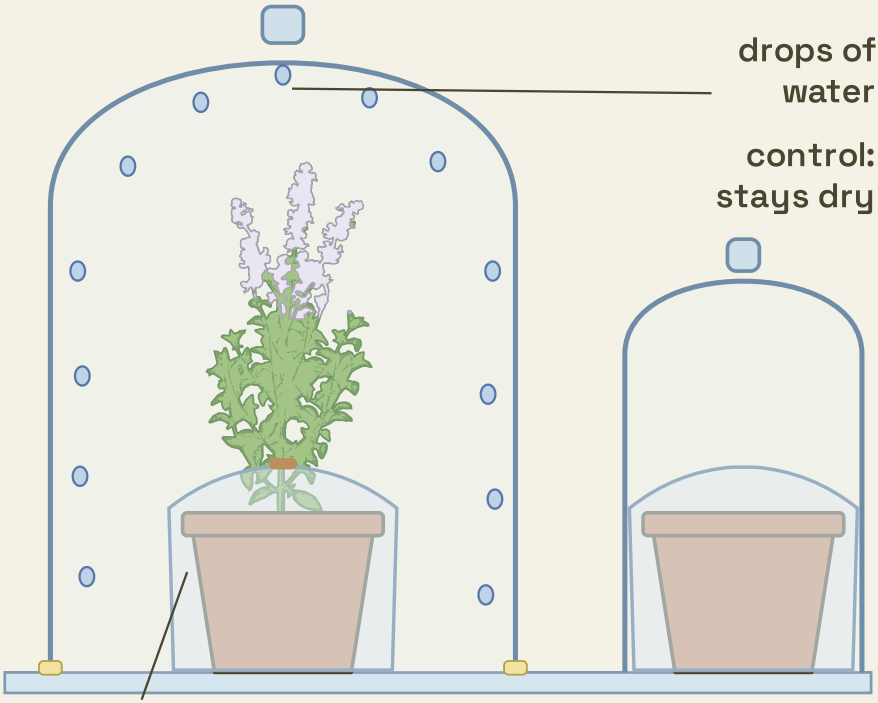
The rate of transpiration is measured with a **potometer** (*poton*, drink): a leafy shoot is fixed, airtight, into a water-filled tube that ends in a thin glass tube with a scale. A small air bubble is let into the thin tube, and as the shoot takes up water, the bubble moves along the scale. Strictly, a potometer measures how fast the shoot **takes up** water, not how fast it loses it, but nearly all the water taken up is transpired, so the two are almost the same.

Importance of transpiration

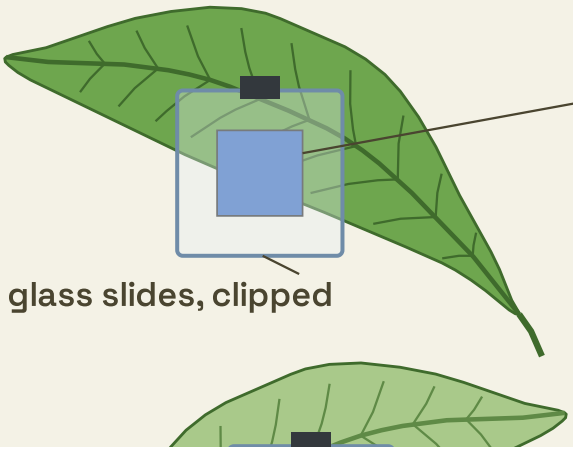
1. **It lifts water and minerals.** The transpiration pull draws water from the roots to the topmost leaves, and with it the minerals the roots absorb, without any pump.

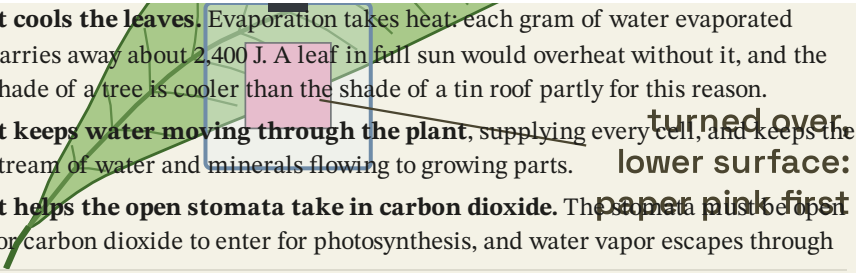

a. Under a bell jar
drops of water
control: stays dry
polythene over pot and soil
b. Cobalt chloride paper
upper surface: paper still blue
glass slides, clipped
turned over, lower surface: paper pink first

a. Under a bell jar



b. Cobalt chloride paper





2. **It cools the leaves.** Evaporation takes heat: each gram of water evaporated carries away about 2,400 J. A leaf in full sun would overheat without it, and the shade of a tree is cooler than the shade of a tin roof partly for this reason.
3. **It keeps water moving through the plant**, supplying every cell, and keeps the stream of water and minerals flowing to growing parts.
4. **It helps the open stomata take in carbon dioxide.** The stomata must be open for carbon dioxide to enter for photosynthesis, and water vapor escapes through the same pores.
5. **It brings rain.** Forests return huge amounts of water to the air: a large oak tree can transpire about 150,000 liters in a year. Much of the rain over a large forest, such as the Amazon, is water that the forest's own trees transpired.

Basil: F. M. Blanco, Flora de Filipinas (1880s), public domain
Mango leaf: traced from W. H. Fitch's plate in Curtis's Botanical Magazine (public domain)

Figure 2.7 *Two ways to show transpiration. a. A potted plant under a bell jar, its pot and soil wrapped in polythene so that no water evaporates from them: drops of water collect on the inside of the jar. b. Cobalt chloride paper, blue when dry, held against both surfaces of a leaf between two glass slides: the paper on the lower surface, which has more stomata, turns pink first.*

WORKED EXAMPLE

A bubble in a potometer

In a potometer, the air bubble moves 42 mm along a thin tube of internal radius 0.5 mm in 6 minutes. Find the volume of water taken up per minute.

Answer

The water taken up fills a cylinder of the tube, as long as the distance the bubble moved:

$$V = \pi r^2 d = 3.14 \times (0.5\ \text{mm})^2 \times 42\ \text{mm} = 3.14 \times 0.25 \times 42 = 33\ \text{mm}^3$$

Rate $= 33\ \text{mm}^3 \div 6\ \text{min} =$ **5.5 mm³ per minute** (0.0055 mL per minute).

But transpiration also has a cost: in hot, dry weather a plant may lose water faster than its roots can take it in, and then it wilts, its stomata close, photosynthesis slows, and if the loss goes on, it dies. Farmers water crops, and gardeners transplant seedlings in the evening and shade them, to reduce the loss. Because it is both useful and harmful, transpiration has been called a **necessary evil**.

DID YOU KNOW?

Drops that are not transpiration

On a cool morning, grass and taro leaves often carry drops of water along their edges. These are pushed out as liquid, by root pressure, through pores at the leaf's edge, at night when the air is too humid to transpire: **guttation**. It is not transpiration, which is always the loss of water as **vapor**.

Check 4

In which conditions does a plant transpire fastest?

a cool, humid, still air, at night
b cool, dry air, at night
c warm, dry, windy air, in sunlight
d warm, humid, still air, in sunlight

2.3 Intracellular respiration

You eat dal bhat at noon, and at three in the afternoon you are running a race. The energy for the race was in the rice's starch, which your gut broke down into glucose and your blood carried to the muscles. But glucose is not energy you can use. Every cell has to break its food down to release the energy in it, and it does so inside itself, all the time.

Introduction

Intracellular respiration (also called **cellular respiration** or **tissue respiration**) is the process by which food, mainly glucose, is broken down **inside living cells**, step by step, by enzymes, to release the energy stored in it. The energy is caught in a molecule called **ATP** (adenosine triphosphate), which the cell then uses for its work.

It is "intracellular" (inside the cell) to tell it apart from **external respiration**, or breathing, which only exchanges gases between the body and the air in the lungs. Breathing supplies the oxygen and removes the carbon dioxide; the respiration itself happens in every living cell, of every plant, animal, fungus and microbe, day and night.

ATP, the energy currency. ATP is made from ADP (adenosine diphosphate) and phosphate, using energy released from food; when the cell needs energy, it splits ATP back into ADP and phosphate, and the energy released does work:

$$\text{ADP} + \text{phosphate} + \text{energy (from food)} \rightleftharpoons \text{ATP} + \text{water}$$

CAREFUL

Respiration is not burning

Glucose burned in a flame and glucose respired in a cell give the same products, carbon dioxide and water, and the same total energy. But burning releases it all at once, as heat and light, at hundreds of degrees. Respiration releases it in dozens of small steps, each controlled by its own enzyme, at body temperature, and catches a large part of it in ATP instead of losing it all as heat. So respiration is often called a slow, controlled **oxidation** of food, never a burning.

Each ATP carries a small, standard amount of energy, about 30.5 kJ per mole under the standard conditions chemists use, the right size for one job: one pull of a muscle protein, one link in a protein chain, one turn of a pump in the membrane. That is why ATP is called the cell's energy currency: glucose is a large note, and ATP the small change the cell can spend anywhere.

Intracellular respiration is of two kinds: **aerobic**, which uses oxygen, and **anaerobic**, which doesn't.

Aerobic respiration

In **aerobic respiration**, glucose is broken down completely, using oxygen, into carbon dioxide and water:

$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{energy (about 2,870 kJ per mole of glucose)}$$

It happens in three stages, in two places in the cell:

1. **Glycolysis** (*glykys*, sweet; *lysis*, splitting), in the **cytoplasm**. Each glucose molecule (6 carbon atoms) is split, in ten steps, into two molecules of **pyruvic acid** (pyruvate, 3 carbons each). This needs no oxygen. It gives a net gain of **2 ATP**, and hydrogen atoms are taken off the food and carried away by a carrier molecule, NAD (as NADH).
2. **The Krebs cycle**, in the **matrix** of the mitochondria. Each pyruvic acid enters a mitochondrion, loses one carbon as carbon dioxide (forming acetyl coenzyme A), and the rest goes round a cycle of reactions that takes it apart completely: all its carbon leaves as **carbon dioxide**, and its hydrogen is handed to the carriers NAD and FAD. It gives **2 ATP** per glucose.
3. **The electron transport chain** (oxidative phosphorylation), on the **inner membrane** of the mitochondria, its folds the **cristae**. The carriers hand over their hydrogen; its electrons pass along a chain of proteins in the membrane, and the energy they give up is used to make most of the ATP. At the end of the chain,

oxygen takes the electrons and combines with hydrogen to form **water**. Without oxygen at the end, the whole chain stops.

So the carbon dioxide you breathe out comes from the Krebs cycle, and the oxygen you breathe in ends up in water. Because most of the ATP is made in the mitochondria, they are called the **powerhouses of the cell**; cells that work hard, such as heart muscle cells and sperm, are packed with them.

Anaerobic respiration

When there is no oxygen, or not enough, glycolysis can still go on: it doesn't need oxygen. But the cell must get rid of the pyruvic acid and free its carriers for more glycolysis, so it turns the pyruvic acid into something else. This is **anaerobic respiration** (*an-*, without; *aer*, air), the breakdown of food without oxygen. Its products still hold most of the food's energy, and it gives only the **2 ATP** of glycolysis per glucose.

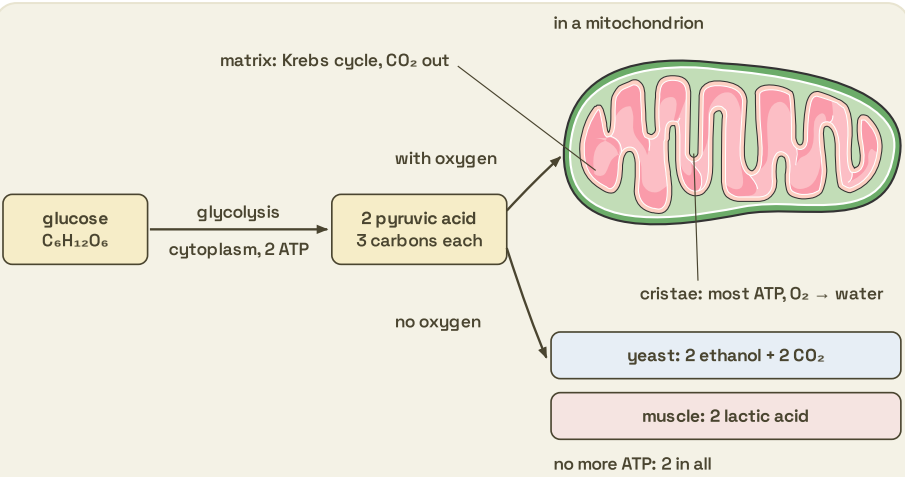
In yeast (and in plant roots in waterlogged soil), pyruvic acid becomes **ethanol** (alcohol) and carbon dioxide. This is **alcoholic fermentation**:

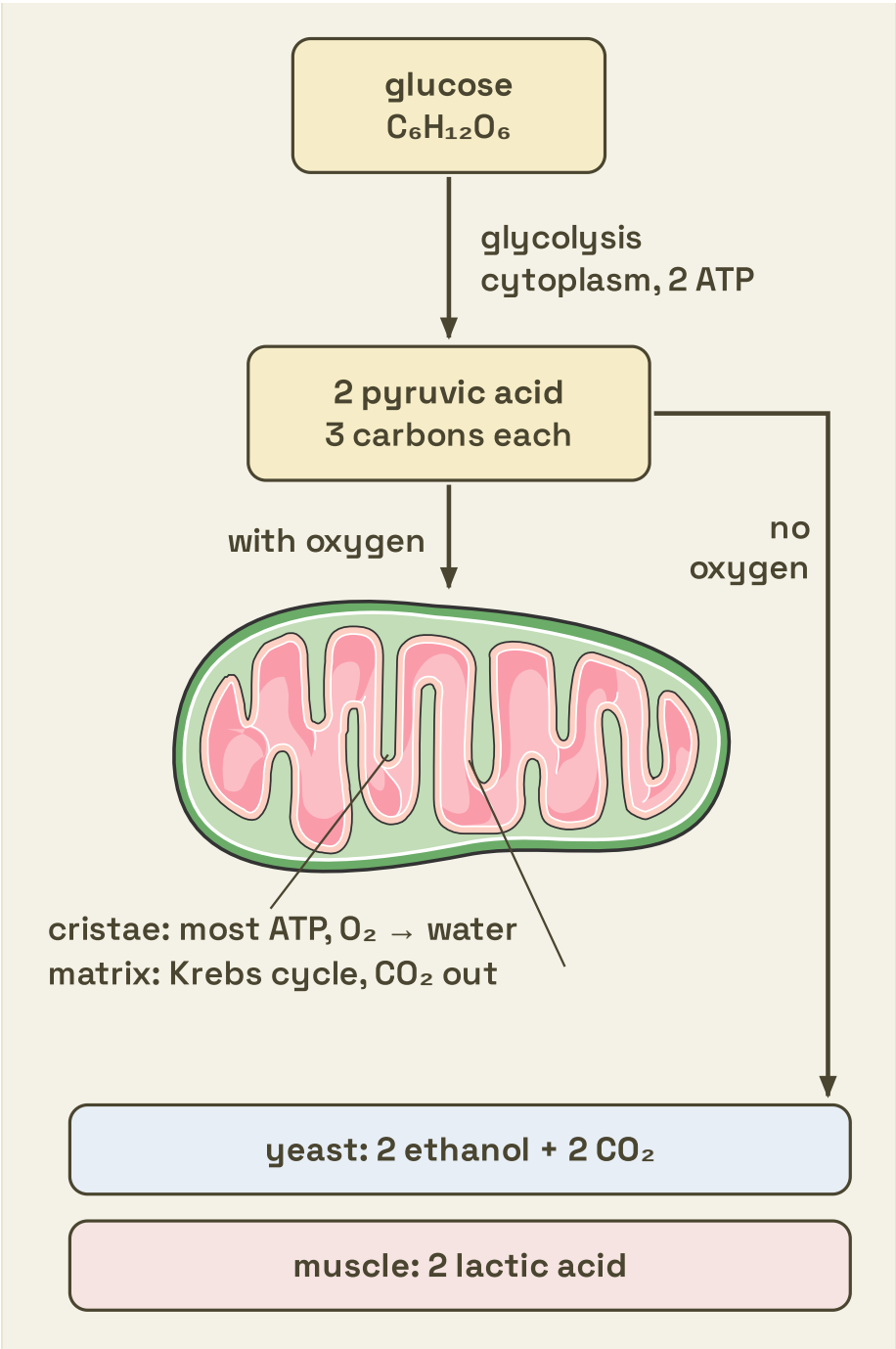
$$C_6H_{12}O_6 \longrightarrow 2\,C_2H_5OH + 2\,CO_2 + \text{energy (2 ATP)}$$

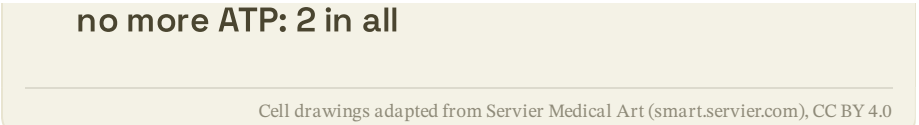
In our muscles during hard exercise, when the blood can't bring oxygen fast enough, and in lactic acid bacteria, pyruvic acid becomes **lactic acid**. This is **lactic acid fermentation**:

$$C_6H_{12}O_6 \longrightarrow 2\,C_3H_6O_3 + \text{energy (2 ATP)}$$

Some microbes live only without oxygen, which is poison to them: those in the mud of a gobar gas plant, which turn dung into methane, are among them, and *Entamoeba* itself lives where there is very little oxygen.


in a mitochondrion
matrix: Krebs cycle, CO_2 out
with oxygen
glucose
$C_6H_{12}O_6$
glycolysis
cytoplasm, 2 ATP
2 pyruvic acid
3 carbons each
cristae: most ATP, O_2 → water
no oxygen
yeast: 2 ethanol + 2 CO_2
muscle: 2 lactic acid
no more ATP: 2 in all


glucose
$C_6H_{12}O_6$
glycolysis
cytoplasm, 2 ATP
2 pyruvic acid
3 carbons each
with oxygen
no
oxygen
cristae: most ATP, O_2 → water
matrix: Krebs cycle, CO_2 out
yeast: 2 ethanol + 2 CO_2
muscle: 2 lactic acid



Cell drawings adapted from Servier Medical Art (smart.servier.com), CC BY 4.0

Figure 2.8 *Where glucose goes in a cell. Glycolysis in the cytoplasm splits it into two pyruvic acid, making 2 ATP. With oxygen, pyruvic acid enters a mitochondrion: the Krebs cycle in the matrix releases carbon dioxide, and the electron transport chain on the cristae makes most of the ATP, oxygen becoming water. Without oxygen, pyruvic acid becomes lactic acid (in muscle) or ethanol and carbon dioxide (in yeast), and no more ATP is made.*

CAREFUL

38 ATP or about 30?

Many books say aerobic respiration makes **38 ATP** from one glucose molecule (2 in glycolysis, 2 in the Krebs cycle and 34 from the electron transport chain), or 36 in some cells. That count assumed each NADH gives exactly 3 ATP and each $FADH_2$ 2. Measurements since the 1990s show they give about 2.5 and 1.5, and some energy is spent moving materials into the mitochondria, so the real yield is **about 30 to 32 ATP**. In an exam that asks for the number, write 38 ATP (the figure in most question papers), and if there is room, add "about 30–32 by modern measurements": that answer is right either way.

CAREFUL

Lactic acid and the next day's soreness

A sprint makes lactic acid in the muscles, and the burning feeling during hard effort comes with it. But the aching muscles you feel a day or two after unusual exercise are not caused by lactic acid: it is cleared from the muscles within an hour or so of stopping, much of it carried by the blood to the liver and heart, which use it. The later soreness comes from tiny injuries to the muscle fibers, which heal in a few days.

WORKED EXAMPLE

How much energy is caught?

One mole of glucose releases about 2,870 kJ in aerobic respiration, and making one mole of ATP stores about 30.5 kJ. a. Taking 38 ATP per glucose, what percentage of the energy is stored in ATP? b. What happens to the rest? c. How many moles of glucose must yeast ferment to make as much ATP as aerobic respiration makes from one mole?

Answer

a. Energy stored $= 38 \times 30.5$ kJ $= 1{,}159$ kJ. Percentage $= 1{,}159 \div 2{,}870 \times 100\% \approx$ **40%**. (With about 32 ATP, $32 \times 30.5 \div 2{,}870 \times 100\% \approx 34\%$.)

b. The rest, about 60%, is released as **heat**. That heat is not wasted in a mammal or bird: it keeps the body warm.

c. Fermentation gives 2 ATP per glucose, aerobic respiration 38. So yeast must ferment $38 \div 2 =$ **19 moles of glucose** to make as much ATP as one mole respired aerobically. (With 32 ATP, 16 moles.) That is why yeast in dough or a jaand pot uses up sugar so fast.

WORKED EXAMPLE

Ethanol from sugar

How much ethanol and carbon dioxide does yeast make by fermenting 90 g of glucose? (C = 12, H = 1, O = 16)

Answer

Molar masses: $C_6H_{12}O_6 = 6 \times 12 + 12 \times 1 + 6 \times 16 =$ **180 g/mol**; $C_2H_5OH = 2 \times 12 + 6 \times 1 + 16 =$ **46 g/mol**; $CO_2 = 12 + 2 \times 16 =$ **44 g/mol**.

From the equation, 180 g of glucose gives $2 \times 46 = 92$ g of ethanol and $2 \times 44 = 88$ g of carbon dioxide.

90 g is half of 180 g, so it gives **46 g of ethanol** and **44 g of carbon dioxide**. (Check: 46 + 44 = 90 g. No mass is lost.)

Advantages of intracellular respiration

Respiration is not something a cell can do without: it is how every cell gets its energy. Its advantages, or importance, are:

1. **It releases energy for every life process.** The ATP it makes powers muscle contraction, the beating of the heart, nerve impulses, the active transport of

substances across membranes, cell division and growth, the building of proteins, fats and DNA, and the making of milk, hormones and enzymes.

2. **It releases energy in small, usable steps.** Because the energy comes out a little at a time and is caught in ATP, the cell isn't damaged by heat, and the energy can be carried to wherever it is needed and spent in small amounts.
3. **It keeps the body warm.** The energy not caught in ATP is released as heat, which keeps the body of birds and mammals at a steady temperature, about 37 °C in humans.
4. **It provides building materials.** Its intermediate products (pyruvic acid, the acids of the Krebs cycle) are the starting points for making amino acids, fats and other substances the cell needs.
5. **It makes carbon dioxide**, which green plants use in photosynthesis, so respiration and photosynthesis together keep oxygen and carbon dioxide cycling through living things and the air.
6. **It can work with or without oxygen.** Glycolysis works without oxygen, so cells can survive a short shortage (a sprint, a flooded root), and some organisms live where there is none.
7. **Its anaerobic form is useful to people.** Yeast's fermentation raises bread and makes alcohol and the starter cultures of *jaand* and *chhyang*; lactic acid bacteria turn milk into *dahi* and mustard leaves into *gundruk*; microbes in a gobar gas plant make methane for cooking.

And aerobic respiration has two advantages over anaerobic: it releases far more energy from the same food (about 15 to 19 times as much ATP), and its products, carbon dioxide and water, are harmless, while ethanol and lactic acid are harmful if they build up.

Check 5

In which part of the cell is most ATP made in aerobic respiration?

a the cytoplasm, in glycolysis
b the nucleus
c the inner membrane (cristae) of the mitochondria
d the ribosomes

IN SHORT

- *Spirogyra* is a haploid, unbranched, filamentous green alga of fresh water: cells with a two-layered wall (cellulose and mucilaginous pectin), spiral, ribbon-like chloroplasts with pyrenoids, and a nucleus hung by strands in a large vacuole. It reproduces **vegetatively** by fragmentation and **sexually** by **conjugation**: **scalariform** (between two filaments, a ladder of conjugation tubes) or **lateral** (between neighboring cells of one filament). The gametes are alike in form but one moves (physiological anisogamy). The diploid **zygospore** undergoes **meiosis** on germination; three of the four nuclei degenerate and one new filament grows.
- *Entamoeba histolytica* is a protozoan parasite of the human large intestine, completing its life in one host. The **mature four-nucleate cyst** is swallowed in contaminated food or water; **excystation** in the small intestine gives **eight** small amoebae; **trophozoites** multiply by **binary fission** in the large intestine, some invading the wall (amoebic dysentery, liver abscess); others **encyst**, the cyst's nucleus dividing to two and then four; cysts pass out in the feces. No sexual reproduction. Prevented by safe water, toilets and handwashing.
- **Osmosis** is the movement of water through a semipermeable membrane from a less concentrated to a more concentrated solution. In **hypotonic** solutions cells gain water (turgid); in **hypertonic** ones they lose it (plasmolysis in plant cells); in **isotonic** ones there is no net change. Percentage change in mass = (final − initial) ÷ initial × 100%. Osmosis absorbs water in roots, keeps cells turgid, opens stomata, and preserves food in salt and sugar.
- **Transpiration** is the loss of water vapor from a plant's aerial parts: stomatal (about 90%), cuticular and lenticular. It is shown by the bell jar (pot sealed) and by cobalt chloride paper (blue → pink, faster on the lower surface); it is faster in light, warmth, dry air and wind. It pulls water and minerals up the xylem and cools the leaves, but causes wilting when water is short: a necessary evil.
- **Intracellular respiration** is the stepwise, enzyme-controlled breakdown of food inside cells, releasing energy as ATP. **Aerobic**: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy, through glycolysis (cytoplasm), the Krebs cycle (matrix) and the electron transport chain (cristae); 38 ATP in most books, about 30–32 today. **Anaerobic**: glycolysis then fermentation, to ethanol + CO_2 (yeast) or lactic acid (muscle), 2 ATP. Respiration powers every life process, keeps the

> body warm, gives building materials and CO_2 for photosynthesis, and in its anaerobic form makes bread, alcohol and curd.

Exercise

1. Choose the correct option

a. The chloroplast of *Spirogyra* is:

- **a** cup-shaped
- **b** star-shaped
- **c** ribbon-shaped and spiral
- **d** a network

b. Conjugation between two adjacent cells of the same filament of *Spirogyra* is called:

- **a** scalariform conjugation
- **b** lateral conjugation
- **c** fragmentation
- **d** binary fission

c. The infective stage of *Entamoeba histolytica* is the:

- **a** trophozoite
- **b** precystic form
- **c** uninucleate cyst
- **d** tetranucleate (four-nucleate) cyst

d. A red blood cell placed in distilled water:

- **a** shrinks
- **b** stays the same
- **c** swells and bursts
- **d** becomes plasmolyzed

e. Which of these shows that osmosis needs living cells?

- **a** a raw potato osmometer
- **b** a boiled potato osmometer used as a control
- **c** a bell jar over a plant
- **d** cobalt chloride paper

f. The end products of aerobic respiration are:

- **a** glucose and oxygen
- **b** ethanol and carbon dioxide
- **c** lactic acid and water
- **d** carbon dioxide and water

2. Give reasons

a. *Spirogyra* feels slimy to touch.

b. Conjugation in *Spirogyra* is called physiological anisogamy.

c. Drinking unboiled water can cause amoebic dysentery.

d. The pot and soil are covered with polythene in the bell jar experiment on transpiration.

e. Transpiration is called a necessary evil.

f. Mitochondria are called the powerhouses of the cell.

3. Differentiate between

i. Scalariform conjugation and lateral conjugation

ii. Osmosis and diffusion

iii. Aerobic and anaerobic respiration

4. Answer the following questions

a. Describe scalariform conjugation in *Spirogyra* and the germination of its zygospore, with diagrams.

b. Describe the life cycle of *Entamoeba histolytica* with a diagram. How can amoebic dysentery be prevented?

c. Define osmosis. Describe an experiment to demonstrate osmosis using a potato.

d. What is transpiration? Describe an experiment to show that leaves lose water vapor, and that more is lost from the lower surface.

e. What is intracellular respiration? Explain aerobic respiration with its stages and equation, and write any four advantages of respiration.

5. Numerical problems

a. A potato strip weighing 3.20 g is left in a sugar solution for an hour and then weighs 2.88 g. Find the percentage change in its mass. Was the solution hypotonic, isotonic or hypertonic to the potato cells?

b. Beetroot discs of equal mass were left in salt solutions. Their percentage changes in mass were: 0.1 mol/L, +6%; 0.2 mol/L, +2%; 0.3 mol/L, −2%; 0.4 mol/L, −6%. Find the concentration isotonic with the beetroot cells.

c. In a potometer the air bubble moves 60 mm in 5 minutes along a tube whose cross-sectional area is 1.0 mm^2. When a fan blows on the shoot, it moves 60 mm in 3 minutes. Find the rate of water uptake in each case, and explain the difference.

d. A mango tree loses about 120 liters of water a day by transpiration. If 90% of this is lost through stomata, how much is lost through the stomata in a 30-day month? About how much water must the tree absorb each day, if 97% of what it absorbs is transpired?

e. One mole of glucose (180 g) gives about 2,870 kJ in aerobic respiration, and one mole of ATP stores 30.5 kJ. a. How much energy is stored in ATP from 360 g of glucose, at 38 ATP per glucose? b. How many moles of ATP would 360 g of glucose give in anaerobic respiration?

Found a mistake? Please tell us.