

PRIZE COURSE

How Glaciers Work

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10 Chapters | Philip Osztromok | Generated with Claude

HOW GLACIERS WORK

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How Glaciers Work 🏆

Chapter 1 · What Is a Glacier

There are no glaciers in Scotland today, but climb Ben Nevis on a clear day and you are looking at the work of one. The wide, steep-sided glens, the bowl-shaped hollows high on the mountains and the lochs that fill them were all shaped by rivers of ice that finally melted away about 11,700 years ago. Across the world the story is different: from the Alps to the Himalaya, from Iceland to Patagonia, ice is still moving downhill right now, slowly and quietly. This course explains how. Chapter 1 starts with the most basic question there is: what exactly is a glacier, and how much of it is there?

> **WHAT WAS RUN**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The numbers are round, textbook-style values, good for building intuition and not for a research paper. Where a figure is approximate or has not been checked against a source it is marked *(check)*.

A Working Definition

A **glacier** is a large, long-lived mass of ice that formed on land from compacted snow and is moving under its own weight. Each part of that sentence is doing a job:

PART OF THE DEFINITION	WHAT IT RULES OUT
Large	a patch of old snow in a shady gully (often called a snowfield or a snow patch)
Long-lived	seasonal snow and a frozen pond, which are gone within months
Formed from snow on land	sea ice and lake ice, which are frozen water and not compacted snow
Moving under its own weight	permanent ice that is stuck in place, such as a frozen cave floor

The last point is the one that makes a glacier a glacier. Ice looks like the most solid thing imaginable, yet a thick enough pile of it creeps and slides downhill, usually at a few centimetres to a few metres per day. How and why a solid can flow is the subject of How Glaciers Work 3. For now, remember that a glacier is not just a lot of ice: it is ice that *moves*.

NO SIZE LIMIT?

There is no official minimum size. Many scientists use roughly 0.01 square kilometres (about the size of one and a half football pitches) as a rule of thumb for the smallest thing worth calling a glacier *(check)*. Below that the ice is usually too thin to flow.

Snow, Firn and Ice

Fresh snow is mostly air. A snowflake is a delicate crystal and a freshly fallen snowpack is fluffy because the crystals sit loosely, with gaps in between. Over weeks, months and years the weight of newer snow on top squeezes the lower layers: the crystals break down, round off and pack together, and air is pushed out. The material goes through three recognisable stages:

STAGE	AGE (TYPICAL)	DENSITY (KG/M³)	WHAT IT IS LIKE
Fresh snow	hours to days	about 50 to 150	light, fluffy, crystals still recognisable
Firn	at least one summer, up to decades	about 400 to 830	coarse grains, like wet sugar or old packed snow; air still connected to the surface
Glacier ice	decades to hundreds of thousands of years	about 830 to 917	hard, often blue; air is sealed into separate bubbles

Firn (pronounced like "fern") is the in-between stage, from a German word meaning "last year's". It is snow that has survived at least one melt season but is not yet ice. The switch from firn to ice happens when the gaps between the grains close off and trap the air as bubbles, at a density of about 830 kg/m³. Those tiny bubbles are samples of the atmosphere from the year the snow fell, which is why ice cores are such valuable records (Chapter 2 of this course returns to this). Here is how much of each stage is air, using a short Python loop and the density of solid ice, 917 kg/m³:

```
RHO_ICE = 917                                  # kg/m3, solid ice with no air in it

stages = [("fresh snow", 100), ("settled snow", 350), ("firn", 600),
          ("bubbly glacier ice", 850), ("pure ice", RHO_ICE)]
```

```
for name, rho in stages:
    air = (1 - rho / RHO_ICE) * 100            # share of the volume that is air
    print(f"{name:19s} {rho:4d} kg/m3   {air:4.1f}% air")
# fresh snow           100 kg/m3   89.1% air
# settled snow         350 kg/m3   61.8% air
# firn                 600 kg/m3   34.6% air
# bubbly glacier ice   850 kg/m3    7.3% air
# pure ice             917 kg/m3    0.0% air
```

Fresh snow is about nine parts air to one part ice. That is why a metre of snow is such a poor guide to how much "stuff" has fallen, and why scientists measure snowfall in **water equivalent** (w.e.): the depth of water you would get if you melted it. A metre of fresh snow at 100 kg/m^3 is only about 0.1 m of water. The next snippet turns that into ice, then asks a bigger question: how long does it take to build a glacier-sized layer?

```
RHO_SNOW, RHO_ICE = 100, 917
snow = 1.0                                     # metres of fresh snow
ice = snow * RHO_SNOW / RHO_ICE
print(f"{snow:.0f} m of fresh snow squeezes into {ice:.3f} m of ice")

net = 0.5                                      # metres of water equivalent kept per ye
years = 100 * RHO_ICE / 1000 / net
print(f"At {net} m w.e. per year, 100 m of ice takes about {years:.0f} years to build")
# 1 m of fresh snow squeezes into 0.109 m of ice
# At 0.5 m w.e. per year, 100 m of ice takes about 183 years to build
```

Two lessons here. First, a glacier is built from enormous amounts of snow: roughly nine metres of fresh snow for every metre of ice. Second, the process is slow, and it only works if snow keeps *accumulating* faster than it melts. That balance is the heart of Chapter 4 (How Glaciers Work 4, "Mass Balance").

> Common mistakes
> Thinking glacier ice is frozen tap water (it is compacted snow, with bubbles and a very different texture); thinking a glacier must be white (old, dense, bubble-free ice absorbs red light and looks blue); and calling any frozen thing a glacier (a lake that freezes every winter is not one).

Where Glaciers Live

A glacier needs two things at once: snow, and temperatures low enough that the snow does not all melt in summer. That combination is found in two kinds of place. Near the poles it is cold almost everywhere, so ice lies at sea level. In lower latitudes, such as the Alps, it is cold only because the land is high. Even on the equator there are glaciers on the highest mountains, on Mount Kenya in Africa and on peaks in Ecuador and Indonesia, because air cools by roughly 6 to 7 °C for every kilometre you climb *(check)*.

REGION	EXAMPLE	WHY THERE IS ICE
Polar	Antarctica, Greenland, Svalbard	cold at sea level; ice sheets that bury whole landscapes
Mountains of mid-latitudes	the Alps (Aletsch Glacier, Switzerland), Norway's Jostedalsbreen, the Southern Alps of New Zealand	height keeps summers cool; heavy snow from the sea or the Atlantic westerlies
High Asia	Himalaya, Karakoram, Tibetan Plateau	the greatest concentration of ice outside the polar regions
Tropical mountains	Mount Kenya, the Andes of Ecuador and Peru	only the very highest summits; these small glaciers are disappearing fast
Sub-polar islands	Iceland (Vatnajökull), Patagonia, South Georgia	plenty of snow and cool summers, close to the ocean

Notice what is missing from the list: the United Kingdom. Our mountains are high enough in places (Ben Nevis is 1345 m), but our maritime climate is mild, so summer melts the snow. There are a few patches in the Cairngorms and on Ben Nevis that last many years, but none large enough to be called a glacier.

Types of glacier, by size and shape

Glaciologists sort ice masses by how they sit in the landscape. These names will appear in later chapters:

TYPE	SHAPE	EXAMPLE
Cirque glacier	small, sits in a bowl-shaped hollow high on a mountain	the hollows on Ben Nevis's north face were once filled with these

TYPE	SHAPE	EXAMPLE
Valley glacier	a long tongue of ice that follows a valley downhill	the Mer de Glace, France; Aletsch Glacier, Switzerland, the longest in the Alps at about 20 km *(check)*
Ice cap	a dome of ice covering a plateau or highland, under 50,000 km²	Vatnajökull, Iceland
Ice sheet	a continent-sized dome, over 50,000 km², that buries mountains and valleys	Greenland and Antarctica (the only two today)
Tidewater glacier	any glacier that ends in the sea, losing ice as icebergs	Perito Moreno Glacier, Argentina (which ends in a lake)

How Much Ice Is There?

About two thirds of all the fresh water on Earth is locked in ice *(check)*, and almost all of it sits in just two places. The next snippet uses round volume figures and adds a useful measure: the **sea-level equivalent**, the number of metres the global ocean would rise if that ice melted and ran into the sea.

```
RHO_ICE, RHO_WATER = 917, 1000
OCEAN_KM2 = 361.8e6                              # area of the world ocean, km2

stores = {"Antarctica": 26.5e6, "Greenland": 2.9e6, "all other glaciers": 0.158e6}   # k
total = sum(stores.values())

for name, vol in stores.items():
    rise = vol * RHO_ICE / RHO_WATER / OCEAN_KM2 * 1000     # metres of sea level if it
    print(f"{name:19s} {vol / 1e6:5.2f} million km3  {vol / total * 100:4.1f}% of the ic
# Antarctica          26.50 million km3  89.7% of the ice   67.2 m of sea level
# Greenland            2.90 million km3   9.8% of the ice    7.4 m of sea level
# all other glaciers   0.16 million km3   0.5% of the ice    0.4 m of sea level
```

Almost 90% of the world's glacier ice is in Antarctica and nearly all the rest is in Greenland. Everything else put together, every glacier in the Alps, Himalaya, Andes, Alaska and Scandinavia, is about half of one percent by volume. Yet those "other" glaciers matter far out of proportion to

their size, because they are where most people live nearby, they feed rivers, and they are shrinking fastest (Chapter 9 of this course).

WHY 67 M AND NOT THE USUAL 58 M?

The figure normally quoted for Antarctica is about 58 m of sea-level rise *(check)*. Our simple sum gives 67 m because it treats every cubic kilometre of ice as new water added to the ocean. In reality some Antarctic ice already sits below sea level, where it already displaces its own weight of sea water, and the ocean would also spread over newly flooded land. The simple model overshoots by around 15%, which is a good example of a rough number that is still useful for judging scale.

Where This Leads

You now have the starting kit: a glacier is large, long-lived, land-based, snow-made and moving; snow becomes firn and then ice as air is squeezed out; and nearly all the world's ice is locked in two ice sheets, with a small but important remainder in mountain glaciers. How Glaciers Work 2 follows a single snowflake from the sky to the bottom of an ice core, looking at how density rises, how air gets trapped and how scientists read thousands of years of climate from a stick of ice.

EXERCISE 1

Using area in million km^2 and volume in million km^3 (Antarctica 14.0 and 26.5; Greenland 1.71 and 2.9; all other glaciers 0.70 and 0.158), work out the average ice thickness of each store in metres. Which two would you call ice sheets by the definition above, and why are the "other glaciers" so much thinner on average?

View solution

EXERCISE 2

Ice has a density of 917 kg/m^3, fresh water 1000 and sea water 1025. Using Archimedes' principle (the submerged fraction equals the density of the object divided by the density of the liquid), print the percentage of an iceberg that sits below the surface in each liquid, and the height above the sea surface of an iceberg that is 100 m tall in total.

View solution

EXERCISE 3

Convert 50 m of ice into metres of water equivalent, then work out how many years it takes to build at three sites: the high Alps (1.5 m w.e. per year), a very wet maritime hill (2.0) and the dry interior of Antarctica (0.03). Predict which will take longest before you run it, and say what that suggests about the age of the ice at each place.

View solution

QUICK REFERENCE

- **Glacier:** a large, long-lived mass of ice, made from compacted snow on land, that moves under its own weight
- **Stages:** fresh snow (about 50 to 150 kg/m^3), then firn (about 400 to 830), then glacier ice (about 830 to 917)
- **Bubbles:** air is sealed into bubbles at about 830 kg/m^3, the firn-to-ice change
- **Water equivalent:** the depth of water you get by melting the snow; about 9 m of fresh snow makes 1 m of ice
- **Where:** polar regions, high mountains and a few tropical peaks; not in the UK today
- **Types:** cirque, valley, ice cap (under 50,000 km^2), ice sheet (over 50,000 km^2), tidewater
- **World ice:** about 90% in Antarctica, nearly 10% in Greenland, about 0.5% in all other glaciers

COMING NEXT

How Glaciers Work 2 follows snow as it turns into ice: compaction, density, trapped air bubbles and what ice cores tell us about the past.

How Glaciers Work

Chapter 2 · Snow Into Ice

In How Glaciers Work 1 we met the three stages of the story: fresh snow, firn and glacier ice. This chapter follows one winter's snowfall on its long journey downward. Picture a flake that lands on the Greenland ice sheet this January. By spring it has been buried by more snow. After a few decades it is a grain of firn tens of metres down. After a few centuries it has become solid ice with a tiny bubble of today's air trapped inside, and if nothing disturbs it, that bubble will still be there thousands of years from now. Scientists drill down to collect these bubbles, and that is how we know what the atmosphere was like long before anyone measured it.

> **WHAT WAS RUN**
>
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Accumulation: Where the Snow Comes From

A glacier only grows if snow arrives. The snow that sticks around through the summer is called **accumulation**, and it is measured in **water equivalent** (w.e.), the depth of water you would get by melting it, exactly as in How Glaciers Work 1. Accumulation varies enormously from place to place:

PLACE	ACCUMULATION (M W.E. PER YEAR)	WHAT IT MEANS
Central Antarctica	about 0.03 to 0.05 *(check)*	effectively a cold desert; ice is built extremely slowly
Central Greenland	about 0.2 to 0.25 *(check)*	cold, with modest snowfall; a classic ice-core site
Alps, high glacier	about 1 to 2 *(check)*	plenty of snow, but summers are warm enough to melt some

PLACE	ACCUMULATION (M W.E. PER YEAR)	WHAT IT MEANS
Maritime mountains (Norway, Patagonia, Alaska coast)	several metres *(check)*	storms off the ocean dump huge amounts of snow

Notice the odd result: the places with the least snowfall are often the best archives. A site that gets 0.03 m w.e. per year takes 33 years to add one metre of water, so a deep core from there reaches back a very long way. A site with heavy snowfall gives a detailed, year-by-year record but a shorter one. Choosing where to drill is always a trade between how far back you can see and how fine the detail is.

Compaction: Squeezing Out the Air

Once buried, snow changes in three overlapping ways. First, the grains **settle** and slide past each other into a tighter pack. Second, they **sinter**, which means the grains bond together where they touch (the same effect that turns a loose pile of ice cubes in a freezer into one lump). Third, under growing pressure the grains deform and the gaps between them shrink. In very cold places this takes a long time. Where meltwater trickles down in summer and refreezes, it fills the gaps much faster, so the same density is reached in years and not decades.

A common simplification is to say that density rises quickly near the surface, then more slowly as it approaches the density of solid ice (917 kg/m³). Real firn follows more complicated equations, but a smooth curve captures the idea. This snippet builds one: the density starts at 350 kg/m³ at the surface and approaches 917 with a "decay depth" of 35 m, which sets how quickly the change happens. The values are illustrative *(check)*, loosely chosen to resemble a cold, dry site.

```
import math
RHO_ICE, RHO_SURF, H = 917, 350, 35          # kg/m3, kg/m3, metres (decay depth)

def density(z):
    return RHO_ICE - (RHO_ICE - RHO_SURF) * math.exp(-z / H)

for z in (0, 10, 30, 50, 70, 100):
    rho = density(z)
    air = (1 - rho / RHO_ICE) * 100
    print(f"{z:4d} m   {rho:5.0f} kg/m3   {air:4.1f}% air")
```

```
z = 0
while density(z) < 830:
    z += 0.1
print(f"Density reaches 830 kg/m3 at about {z:.0f} m")
#    0 m     350 kg/m3   61.8% air
#   10 m     491 kg/m3   46.5% air
#   30 m     676 kg/m3   26.2% air
#   50 m     781 kg/m3   14.8% air
#   70 m     840 kg/m3    8.4% air
#  100 m     884 kg/m3    3.6% air
# Density reaches 830 kg/m3 at about 66 m
```

The density climbs fast in the top 30 m, then flattens out. The switch from firn to ice happens at 830 kg/m^3, which this model puts at about 66 m down. Real cold sites such as the interior of Greenland or Antarctica have a firn layer of roughly 50 to 100 m *(check)*, so the model is in the right range. In the warm, wet glaciers of the Alps or Iceland the firn layer can be just 10 to 30 m thick *(check)*, and Exercise 1 asks you to explore that.

How Old Is the Snow at Depth?

Density tells us how squeezed the snow is. The next question is how old. To answer it we need to know how much water has been stacked on top. Because deeper layers are denser, the same metre of depth holds more water at the bottom than at the top. The snippet below adds up the water equivalent down to each depth (summing slices of 10 cm) and divides by an accumulation rate of 0.25 m w.e. per year, a figure in the range of central Greenland *(check)*. It reuses the density curve from the last snippet.

```
import math
RHO_ICE, RHO_SURF, H = 917, 350, 35
ACC = 0.25                                  # m water equivalent per year

def density(z):
    return RHO_ICE - (RHO_ICE - RHO_SURF) * math.exp(-z / H)

we = 0.0                                    # water equivalent above this depth, in met
step = 0.1
z = 0.0
```

```
    marks = {10, 30, 50, 70, 100}
    while z < 100:
        we += density(z) * step / 1000
        z += step
        zr = round(z)
        if abs(z - zr) < 1e-6 and zr in marks:
            print(f"{zr:4d} m deep   {we:5.1f} m w.e. above   age {we / ACC:4.0f} years")
    #   10 m deep     4.2 m w.e. above   age   17 years
    #   30 m deep    16.1 m w.e. above   age   64 years
    #   50 m deep    30.7 m w.e. above   age  123 years
    #   70 m deep    47.0 m w.e. above   age  188 years
    #  100 m deep    73.0 m w.e. above   age  292 years
```

So at the firn-to-ice change, about 66 to 70 m down, the snow is nearly two centuries old, and that is at a site with modest snowfall. At a very dry site such as the Antarctic interior, where accumulation is ten times smaller, the same depth would be thousands of years old. This gap matters, and it leads to one of the strangest facts in ice-core science.

Air Bubbles: Samples of an Old Atmosphere

Throughout the firn the pore spaces are still connected to the surface, so air can move through them and mix with the atmosphere above. Only at about 830 kg/m³ do the pores pinch off into separate bubbles. This is called **close-off**. From then on, each bubble is sealed with whatever air was around at that moment.

> **THE AIR IS YOUNGER THAN THE ICE**
>
> By the time bubbles close off, the surrounding ice is already around 190 years old in our model, but the air in the bubbles is only as old as the moment of closing. In practice the air is younger than the ice around it by a gap that scientists call the **age difference**. It is about a century at cold, moderately snowy sites and can be thousands of years at the driest ones *(check)*. Researchers have to correct for it when they compare air data with temperature data from the ice, otherwise the two records would be out of step.

Reading the Layers

In places where snow falls in distinct seasons, each year leaves a visible or chemical layer: summer snow differs from winter snow in dust, in the shape of the grains and in chemical traces. Counting these annual layers works like counting tree rings. But layers do not stay the same thickness. As the ice sheet flows outward, the ice at depth is stretched sideways and squeezed thinner. A simple model is that the thickness of a layer shrinks in proportion to how much ice lies below it, so the layers are thickest at the surface and shrink to almost nothing at the bed. The next snippet runs that model for an ice sheet 3000 m thick, with 0.27 m of ice added at the surface each year.

```
import math
A_ICE = 0.27                                # m of ice added per year at the surface
THICK = 3000                                # m, thickness of the ice sheet

print("depth   layer thickness   age")
for depth in (0, 1000, 2000, 2800, 2950):
    frac = (THICK - depth) / THICK          # simple model: layers thin in proportion t
    layer_mm = A_ICE * frac * 1000
    age = max(0.0, -(THICK / A_ICE) * math.log(frac))
    print(f"{depth:5d} m   {layer_mm:6.0f} mm/yr   {age:7.0f} years")
# depth   layer thickness   age
#     0 m      270 mm/yr         0 years
#  1000 m      180 mm/yr      4505 years
#  2000 m       90 mm/yr     12207 years
#  2800 m       18 mm/yr     30089 years
#  2950 m        5 mm/yr     45493 years
```

The top third of the ice holds about 4,500 years. The bottom 200 m holds well over 15,000 years, squashed into layers a few centimetres thick or less. This simple model (a simplified version of what glaciologists call the Nye model) says the ice gets older ever more steeply near the bed. Real ice sheets are more complicated, and the oldest, deepest ice can be folded or mixed up where it flows over bumpy rock, but the pattern of thinning layers is real. That is why scientists hunt for places where the ice is thick, flat and slow-moving, so the deepest layers stay in order.

What the Bubbles and Ice Reveal

The ice itself holds clues as well. The ratio of two forms (isotopes) of oxygen in the water molecules tells us how cold it was when the snow fell: colder snow is "lighter". Dust and ash show how windy and dry the world was and when volcanoes erupted. And the bubbles give a direct record of the gases in the atmosphere, including carbon dioxide and methane. Antarctic cores have given a continuous record of the air back roughly 800,000 years *(check)*, and in that whole span the carbon dioxide level never went above about 300 parts per million until the industrial era *(check)*. Here is a small snippet comparing three rounded values:

```
# Carbon dioxide in trapped air, parts per million (rounded; check)
record = [("last ice age, about 20,000 years ago", 190),
          ("just before industry, about 1750", 280),
          ("today (recent years)", 420)]

base = record[0][1]
for label, ppm in record:
    change = (ppm / base - 1) * 100
    print(f"{label:38s} {ppm:3d} ppm   {change:+4.0f}% vs ice age")

rise = record[2][1] - record[1][1]
print(f"Rise since 1750: {rise} ppm, which is {rise / (record[1][1] - base):.1f} times t
# last ice age, about 20,000 years ago   190 ppm     +0% vs ice age
# just before industry, about 1750       280 ppm    +47% vs ice age
# today (recent years)                   420 ppm   +121% vs ice age
# Rise since 1750: 140 ppm, which is 1.6 times the whole ice-age-to-1750 rise
```

The whole swing from the depths of the last ice age to the eve of industry was about 90 ppm over some 18,000 years. The rise since then is about 140 ppm in under 300 years. Ice cores did not create that observation, but they are what makes it possible: without a baseline of old air, we would have no way to say what "natural" looks like. Chapter 8 (How Glaciers Work 8, "Ice Ages") picks up the ice-age half of this story.

> Common mistakes
> Thinking the ice at depth is simply "old snow in layers" that stays the same thickness (it thins a lot); assuming the air in a bubble is the same age as the ice around it (it is younger); and assuming more snowfall always gives the longest record (it gives the finest detail, but dry sites reach back further per metre of ice).

EXERCISE 1

The density curve can be rearranged to give the depth of the firn-to-ice change directly. Using the same shape as in the chapter, compute that depth at three sites: a cold dry interior (surface density 350, decay depth 35 m), a cool maritime glacier (450, 15 m) and a wet temperate glacier (500, 8 m). Say in one sentence why the warm, wet site closes off so much sooner.

View solution

EXERCISE 2

Using the layer-thinning model (3000 m of ice, 0.27 m of ice added per year), print how many years one metre of core holds at depths of 0, 1000, 2000 and 2800 m. Then find the depth at which annual layers are only 1 mm thick, and say how far above the bed that is.

View solution

EXERCISE 3

Using 190 ppm (about 20,000 years ago), 280 ppm (1750) and 420 ppm (today), work out the average rise in carbon dioxide per year in each period (take 18,250 years for the first and 275 for the second) and how many times faster the recent rise is. Predict the ratio roughly before running it.

View solution

QUICK REFERENCE

- **Accumulation:** snow that survives the summer, measured in metres of water equivalent per year; from about 0.03 in central Antarctica to several metres in maritime mountains *(check)*
- **Compaction:** settling, sintering and pressure squeeze out air; meltwater refreezing speeds it up
- **Close-off:** at about 830 kg/m^3 the pores seal into bubbles; firn thickness is roughly 50 to 100 m at cold sites and 10 to 30 m at wet ones *(check)*
- **Age difference:** air in a bubble is younger than the ice around it
- **Layer thinning:** annual layers get thinner with depth, so the oldest ice is the most squashed
- **Ice-core clues:** isotopes (temperature), dust and ash, and bubbles (gases such as carbon dioxide and methane)

- **Trade-off:** snowy sites give fine detail over a short record; dry sites give a long record with coarse detail

COMING NEXT

How Glaciers Work 3 asks the question hidden in all of this: if ice is a solid, how does a glacier flow? Internal deformation, sliding over the bed, and how fast ice really moves.

How Glaciers Work

Chapter 3 · How Ice Flows

How Glaciers Work 2 ended with a puzzle. Snow turns into ice, and ice is a hard, brittle solid: tap it with a hammer and it shatters. Yet the layers we counted in the ice sheet were being carried outward, and valley glaciers move boulders and bury villages' old paths over the centuries. How can a solid flow? The answer is that ice is a solid made of crystals, and crystals can deform slowly under a steady load, given enough time. This chapter works out how much load, how fast the deformation is, and how a second process, sliding over the ground, can add to it.

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The Push That Makes Ice Move

A glacier sits on a slope, so gravity pulls it downhill. The weight of the ice presses on the bed, and the part of that weight that acts along the slope tries to shear the ice, sliding the top over the bottom, like pushing the top of a deck of cards sideways. That sideways force per unit area is the **basal shear stress**, and a standard approximation for it is:

```
# basal shear stress = ice density x gravity x thickness x sin(surface slope)
tau = rho * g * h * sin(slope)
```

Stress is measured in pascals (Pa); a kilopascal (kPa) is 1,000 Pa. Using 917 kg/m^3 for the density of ice, 9.81 m/s^2 for gravity and a gentle 5 degree slope, this snippet shows how the stress grows with thickness:

```python
import math
RHO, G = 917, 9.81            # kg/m3, m/s2
SLOPE = 5                     # degrees

print("thickness   basal shear stress")
for h in (20, 50, 100, 200, 500, 1000):
    tau = RHO * G * h * math.sin(math.radians(SLOPE))
    print(f"{h:6d} m   {tau / 1000:6.0f} kPa")
# thickness   basal shear stress
#     20 m       16 kPa
#     50 m       39 kPa
#    100 m       78 kPa
#    200 m      157 kPa
#    500 m      392 kPa
#   1000 m      784 kPa
```

The stress is simply proportional to thickness: ten times thicker ice, ten times the stress. In practice, real glaciers adjust their shape until the basal stress settles at roughly 50 to 150 kPa *(check)*. A thick glacier therefore has a gentle surface slope, and a thin one can be steep, which is why the 1,000 m figure above (for a 5 degree slope) is unrealistic: a kilometre of ice would flatten its own surface until the stress came down. Exercise 1 explores that.

Internal Deformation: Crystals Creeping

Ice is made of crystals, and each crystal is built from layers of molecules that can slip over one another, a little like sheets of paper in a ream. Under stress the layers slip, very slowly, and the crystals also grow, shrink and rotate to line up with the flow. None of this happens fast, but it never stops while the stress is there. This steady, slow change of shape is called **creep**, and the glacier's total shape change from it is called **internal deformation**.

Laboratory tests and field measurements gave a simple rule that is now known as **Glen's flow law**: the rate at which ice deforms is proportional to the stress raised to the power 3 ($n = 3$). The cube has big consequences. Double the stress and the ice deforms eight times faster. Combined with the formula above, which makes stress depend on thickness and slope, it gives a speed at the glacier surface for a slab that is frozen to its bed:

```python
import math
RHO, G = 917, 9.81
SEC_YEAR = 3.156e7
A = 2.4e-24                    # Pa^-3 s^-1, ice at 0 C (check)
N = 3
SLOPE = math.radians(5)

def surface_speed(h):
    """Speed at the top of a slab of thickness h that only deforms (no sliding), in m per
    u = 2 * A / (N + 1) * (RHO * G * math.sin(SLOPE)) ** N * h ** (N + 1)
    return u * SEC_YEAR

for h in (50, 100, 200, 400):
    print(f"h = {h:3d} m   surface speed {surface_speed(h):8.2f} m/yr")
print(f"Doubling the thickness multiplies the speed by {surface_speed(200) / surface_spe
# h =  50 m   surface speed     0.11 m/yr
# h = 100 m   surface speed     1.83 m/yr
# h = 200 m   surface speed    29.20 m/yr
# h = 400 m   surface speed   467.26 m/yr
# Doubling the thickness multiplies the speed by 16
```

The speed grows with thickness to the power 4 (one power of 3 from the stress, one more because a thicker slab has more ice that is able to shear), so doubling the thickness makes the glacier 16 times faster. This is the main reason big glaciers move far faster than small ones. The 400 m result is above any plausible real glacier on a frozen bed, since real glaciers also change their slope to reduce the stress, but it shows how steeply the speed rises.

Temperature Changes Everything

The constant *A* in the snippet is a measure of how soft the ice is, and it depends strongly on temperature. Ice near its melting point is many times softer than ice at minus 20 °C. Here are three rounded values and what they do to a 200 m thick glacier:

```python
import math
RHO, G, SEC_YEAR, N = 917, 9.81, 3.156e7, 3
SLOPE = math.radians(5)
```

```
H = 200
A_TABLE = {0: 2.4e-24, -10: 3.5e-25, -20: 1.2e-25}   # Pa^-3 s^-1, rounded (check)

for temp, A in A_TABLE.items():
    u = 2 * A / (N + 1) * (RHO * G * math.sin(SLOPE)) ** N * H ** (N + 1) * SEC_YEAR
    print(f"{temp:4d} C   A = {A:.1e}   surface speed {u:6.2f} m/yr")
#    0 C   A = 2.4e-24   surface speed  29.20 m/yr
#  -10 C   A = 3.5e-25   surface speed   4.26 m/yr
#  -20 C   A = 1.2e-25   surface speed   1.46 m/yr
```

Going from 0 °C to minus 20 °C slows the deformation by a factor of about 20. That is why the deep, cold ice of the Antarctic interior creeps along so slowly, while a "temperate" glacier (ice at the melting point throughout, typical of the Alps, Norway or Iceland) flows readily. Glaciologists call a glacier **cold-based** if its bed is below freezing and **warm-based** if it is at the melting point. The difference decides whether the second kind of motion is possible.

Basal Sliding: Riding on Water

If the base of the glacier is at the melting point, a thin film of meltwater can form between ice and rock, and the whole glacier can slide over its bed. Sliding is not the same as creep: the ice moves as a block, with little change of shape. The water pressure matters more than the amount of water: high water pressure partly floats the ice and reduces friction, so a glacier often speeds up when water arrives suddenly, such as at the start of the melt season or after heavy rain. Sliding can also happen over soft, wet sediment, which can deform itself under the ice.

Our snippet below adds a uniform sliding speed of 30 m/yr to the deformation profile of a 200 m thick glacier. It prints how fast the ice moves at different heights above the bed:

```
import math
RHO, G, SEC_YEAR, N = 917, 9.81, 3.156e7, 3
A, H = 2.4e-24, 200
SLOPE = math.radians(5)

def speed_at(height_above_bed, sliding):
    """Deformation speed at a height above the bed plus a uniform sliding speed (m/yr)."
    k = 2 * A / (N + 1) * (RHO * G * math.sin(SLOPE)) ** N * SEC_YEAR
    depth_part = H ** (N + 1) - (H - height_above_bed) ** (N + 1)
```

```
    return k * depth_part + sliding

print("height above bed   frozen bed   sliding bed (+30 m/yr)")
for z in (0, 50, 100, 150, 200):
    print(f"{z:10d} m   {speed_at(z, 0):8.1f}      {speed_at(z, 30):8.1f}")
top0, top30 = speed_at(H, 0), speed_at(H, 30)
print(f"Sliding supplies {30 / top30 * 100:.0f}% of the surface speed")
print(f"Time to travel 5 km: {5000 / top0:.0f} yr frozen, {5000 / top30:.0f} yr sliding")
# height above bed   frozen bed   sliding bed (+30 m/yr)
#          0 m        0.0          30.0
#         50 m       20.0          50.0
#        100 m       27.4          57.4
#        150 m       29.1          59.1
#        200 m       29.2          59.2
# Sliding supplies 51% of the surface speed
# Time to travel 5 km: 171 yr frozen, 84 yr sliding
```

Look at the left-hand column: on a frozen bed the ice at the base does not move at all, and almost all of the speed is gained in the lowest half of the glacier, because that is where the stress is concentrated. The surface ice moves almost like a raft carried by the ice beneath it. The right-hand column shows the same shape shifted by the sliding speed. Here, sliding doubles the speed and halves the time for the ice to travel 5 km.

Deformation and Sliding Compared

	INTERNAL DEFORMATION	BASAL SLIDING
What moves	ice changes shape, with the top moving fastest	the whole glacier slips over its bed
Needs	only ice, stress and time	a bed at the melting point, with water
Depends on	thickness, slope and ice temperature (stress cubed)	water pressure, bed roughness, soft sediment
Behaviour	steady, changes slowly	can speed up in hours or days
Typical in	cold polar ice, thin cold glaciers	temperate valley glaciers, fast ice streams

How Fast Is Fast?

Glacier speeds span an enormous range. Some rounded examples, all *(check)*:

WHERE	TYPICAL SPEED	WHY
Antarctic interior	a few metres per year	cold ice, low slope, frozen bed
Alpine valley glaciers (Switzerland, Austria)	about 10 to 100 m per year	temperate ice, some sliding
Scottish Highlands, last ice age	probably tens of metres per year	a thick, temperate ice cap, inferred from landforms
Greenland outlet glacier (Jakobshavn Isbrae)	around 40 m per day at its fastest	a deep, narrow channel and sliding
Antarctic ice streams (Pine Island)	several kilometres per year	soft, wet bed and thick ice
Surging glaciers (Alaska, Svalbard, Pamirs)	tens of metres per day for months, then quiet for decades	sudden changes in water at the bed

A fast glacier is usually a glacier sliding on a wet bed, not one deforming faster. Because sliding responds to water, speeds are not constant: many Alpine glaciers speed up in early summer when meltwater first reaches the bed, and slow again later when the water drains through efficient channels. This also means a glacier is not just a "slow river": its speed depends on what is happening at the bed, which scientists can only measure indirectly, with boreholes, seismic signals or satellites.

Common mistakes

Thinking glacier ice is a liquid or is "melting and refreezing" as it moves (it deforms as a solid, though pressure melting has a small role at the bed); assuming a steeper slope alone explains fast glaciers (thickness and the state of the bed matter as much); and assuming glaciers move at one steady speed (sliding changes with the seasons and the water supply).

EXERCISE 1

Real glaciers settle at a basal shear stress of about 100 kPa. Rearrange the stress formula to find the surface slope that gives exactly 100 kPa for ice 50, 100, 200, 400 and 1000 m thick. Say what happens to the slope as the ice gets thicker, and why that fits what you know about big ice sheets.

View solution

EXERCISE 2

For a 200 m thick deforming glacier at 0 °C, print the surface speed for slopes of 2, 5 and 10 degrees. Before you run it, predict roughly how many times faster the 10 degree glacier is than the 5 degree one, using the cube in Glen's law.

View solution

EXERCISE 3

A glacier deforms at 29.2 m per year. Suppose its bed starts to slide at 30, 300 and 3000 m per year. For each case print the total speed per year and per day, the share of the motion that comes from sliding, and how long the ice takes to travel 5 km. At what point does deformation become a minor part of the story?

View solution

QUICK REFERENCE

- **Basal shear stress:** ice density x gravity x thickness x sin(slope); glaciers settle at roughly 50 to 150 kPa *(check)*
- **Creep:** ice crystals slip and rotate slowly under steady stress; the sum of this is internal deformation
- **Glen's flow law:** deformation rate goes as stress cubed (n = 3); surface speed goes as thickness to the power 4
- **Temperature:** ice at 0 °C is about 20 times softer than at minus 20 °C *(check)*
- **Cold-based vs warm-based:** bed below or at the melting point; only warm-based glaciers can slide
- **Basal sliding:** the glacier slips over its bed on a film of water; water pressure controls it, and speeds can change in hours
- **Speeds:** a few metres a year in the Antarctic interior; tens of metres a year in the Alps; tens of metres a day in the fastest outlets and surges *(check)*

COMING NEXT

How Glaciers Work 4 asks what decides whether a glacier grows or shrinks: the balance between snow gained at the top and ice lost at the bottom, the equilibrium line, and why a glacier can retreat even while it keeps flowing.

How Glaciers Work

Chapter 4 · Mass Balance

How Glaciers Work 3 showed how ice moves: it deforms under its own weight and, on a wet bed, slides. Movement is only half the story. The ice that flows down a valley has to come from somewhere, and ice that reaches the bottom has to go somewhere. A glacier is a moving conveyor belt with a supply at the top and a loss at the bottom, and whether it grows or shrinks depends on the budget between the two. This is why a glacier can retreat up its valley while its ice keeps flowing downhill the whole time. This chapter builds that budget in a few lines of Python, then uses it to see what a warmer climate does and why the answer arrives so slowly.

> **WHAT WAS RUN**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The glacier here is a made-up toy valley glacier with round numbers, built to show the logic of the budget, so the figures are good for intuition and not for research. Where a figure is approximate or has not been checked against a source it is marked *(check)*.

The Glacier's Budget

Glaciologists treat a glacier like a bank account. Snow, and sometimes rain that freezes, adds to it: that is **accumulation**. Melting, plus sublimation (ice turning straight to vapour), plus calving (chunks breaking off into a lake or the sea) take away from it: that is **ablation**. The balance at the end of the year is the **mass balance**:

```
# mass balance for a year = accumulation - ablation\nbalance = accumulation - ablation
```

Ice and snow have different densities (How Glaciers Work 2 covered that), so mass balance is measured in **metres of water equivalent**, written m w.e. It means "if everything gained or lost were melted, how deep would that layer of water be?" One metre w.e. is about 1.09 m of solid ice, because ice is roughly 917 kg/m³ and water 1,000 kg/m³. Scientists measure it on the glacier

with stakes drilled into the ice, which show how much surface has been lost, and with pits dug in the snow to find how much has been gained. The longest continuous records, such as Storglaciären in Sweden, run back to the 1940s *(check)*, and one year of the budget is counted from one autumn to the next (a "balance year"), not from January.

Two Zones and the Line Between Them

Temperature falls with height, and snowfall tends to rise with it. So the top of a glacier gains more snow than it melts, and the bottom melts more than it gains. The glacier divides in two:

- The **accumulation zone** at the top, where the year's balance is positive and some snow survives the summer.
- The **ablation zone** at the bottom, where the balance is negative and the previous winter's snow melts away, leaving bare ice by late summer.

The boundary where the balance is exactly zero is the **equilibrium line**, and its height is the **equilibrium line altitude**, or **ELA**. Ice flows from the accumulation zone, across the line, into the ablation zone, which is how the ice from How Glaciers Work 3 keeps the bottom of the glacier supplied. The ratio of the accumulation area to the whole glacier is the **accumulation area ratio** (AAR). A glacier in balance often has an AAR of about 0.5 to 0.7 *(check)*.

Here is a toy glacier, 9 km² in total, divided into 100 m bands of height with the area of each. Near the ELA the balance rises by 0.7 m w.e. for every 100 m of height *(check)*: that rate is the **balance gradient**. The first snippet asks what the glacier's average balance and AAR would be if the ELA sat at four different heights:

```
# Toy valley glacier: area (km2) in 100 m elevation bands, mass balance in m water equiv
BANDS = [(2900, 0.4), (2800, 0.7), (2700, 1.0), (2600, 1.3), (2500, 1.5),
         (2400, 1.4), (2300, 1.1), (2200, 0.8), (2100, 0.5), (2000, 0.3)]   # (band mid
GRAD = 0.007          # m w.e. per year per metre of elevation (7 m per 1000 m) (check)

def balance(z, ela):
    return GRAD * (z - ela)

def totals(ela):
    area = sum(a for _, a in BANDS)
    net = sum(balance(z, ela) * a for z, a in BANDS)          # km2 x m = 0.001 km3 w.e.
    acc_area = sum(a for z, a in BANDS if z > ela)
```

```
    return area, net / area, acc_area / area

for ela in (2300, 2400, 2500, 2600):
    area, b, aar = totals(ela)
    print(f"ELA {ela} m   specific balance {b:+.2f} m w.e./yr   accumulation area {aar *
# ELA 2300 m   specific balance +1.21 m w.e./yr   accumulation area  70%
# ELA 2400 m   specific balance +0.51 m w.e./yr   accumulation area  54%
# ELA 2500 m   specific balance -0.19 m w.e./yr   accumulation area  38%
# ELA 2600 m   specific balance -0.89 m w.e./yr   accumulation area  23%
```

The pattern is clear. An ELA of 2,300 m gives a healthy surplus over most of the glacier. At 2,600 m the accumulation zone has shrunk to under a quarter of the area, and the glacier loses almost a metre of water a year, averaged over its whole surface. Notice that the balance goes from positive to negative somewhere between 2,400 m and 2,500 m. That is the ELA at which this glacier would be in balance, and the next snippet finds it exactly.

Finding the Steady State

A glacier is in a **steady state** when the total gain equals the total loss, so the net balance is zero.

range, test the middle, and keep whichever half still contains the answer. Forty halvings is far more precision than the data deserves, but it costs nothing:

```
# Find the ELA that gives zero balance (the "steady state" ELA) by bisection
BANDS = [(2900, 0.4), (2800, 0.7), (2700, 1.0), (2600, 1.3), (2500, 1.5),
         (2400, 1.4), (2300, 1.1), (2200, 0.8), (2100, 0.5), (2000, 0.3)]
GRAD = 0.007

def net(ela):
    return sum(GRAD * (z - ela) * a for z, a in BANDS)

lo, hi = 1500, 3500
for _ in range(40):
    mid = (lo + hi) / 2
    if net(mid) > 0:
        lo = mid          # still gaining mass, so the balance line can sit higher
    else:
```

```
        hi = mid
print(f"Steady-state ELA = {mid:.0f} m")
area = sum(a for _, a in BANDS)
aar = sum(a for z, a in BANDS if z > mid) / area
print(f"Accumulation area ratio there = {aar:.2f}")
# Steady-state ELA = 2472 m
# Accumulation area ratio there = 0.54
```

So this glacier is balanced when the ELA sits at about 2,472 m, with a little over half the glacier in the accumulation zone. The other numbers in this chapter are measured from that steady state.

What Warming Does

The air cools by about 6.5 °C for every kilometre you climb *(check)*, which is called the lapse rate. If the climate warms by 1 °C, the freezing level, and with it the ELA, climbs by roughly 1 ÷ 0.0065, about 154 m. This is a rough rule, since snowfall and cloud change too, but it is a useful first guess:

```
BANDS = [(2900, 0.4), (2800, 0.7), (2700, 1.0), (2600, 1.3), (2500, 1.5),
         (2400, 1.4), (2300, 1.1), (2200, 0.8), (2100, 0.5), (2000, 0.3)]
GRAD = 0.007
LAPSE = 6.5 / 1000      # degrees C lost per metre of height (check)
ELA_STEADY = 2472       # steady-state ELA found above

def specific_balance(ela):
    area = sum(a for _, a in BANDS)
    return sum(GRAD * (z - ela) * a for z, a in BANDS) / area

# Warming moves the ELA up: a rough rule is that the ELA rises by (warming / lapse rate)
for warming in (0, 0.5, 1, 2, 3):
    ela = ELA_STEADY + warming / LAPSE
    b = specific_balance(ela)
    print(f"+{warming:.1f} C   ELA {ela:5.0f} m   specific balance {b:+.2f} m w.e./yr")
# +0.0 C   ELA  2472 m   specific balance +0.00 m w.e./yr
# +0.5 C   ELA  2549 m   specific balance -0.54 m w.e./yr
# +1.0 C   ELA  2626 m   specific balance -1.08 m w.e./yr
# +2.0 C   ELA  2780 m   specific balance -2.15 m w.e./yr
```

```
# +3.0 C   ELA  2934 m   specific balance -3.23 m w.e./yr
```

Half a degree is already enough to push the glacier from balance into steady loss, and each extra degree costs a bit more than a metre of water a year, averaged over the whole glacier. A balance of minus 1 m w.e. on a 9 km² glacier is 9 million cubic metres of water leaving the ice each year, roughly three and a half thousand Olympic swimming pools *(check)*. And the damage is lopsided: a rising ELA removes area from the accumulation zone, which is the part that feeds the glacier, so each step of warming makes the next step harder to survive.

Advance and Retreat: The Slow Response

A change in the balance does not move the snout (the lowest end of the glacier) straight away. When the balance turns negative, the whole glacier thins first. Only when the ice at the lower end gets thin enough that the ice flowing in cannot replace what melts does the snout pull back, and in a large glacier that takes years or decades. The time needed to settle into a new shape is the **response time**, and for valley glaciers it is typically a few decades to a few hundred years *(check)*.

The next snippet is a crude one-box model of that. Each year it adds the balance times the area to the ice volume, and then works out a new area from a standard scaling rule that says volume grows faster than area *(check)*. As the glacier loses its low-lying tongue, its average height rises, which brings the balance back towards zero. The model starts in balance, then adds 1 °C of warming from year 10 and holds it there:

```
# A one-box glacier: ice volume changes each year by (specific balance x area)
GAMMA, C = 1.375, 0.034          # volume-area scaling V = C x A^GAMMA, km3 and km2 (ch
GRAD, LAPSE = 0.007, 6.5 / 1000  # m w.e./yr per m ; degrees C per m (check)
ICE_DENSITY = 0.917              # relative to water
ELA_STEADY, AREA0 = 2472, 9.0    # start in balance

area = AREA0
volume = C * area ** GAMMA
print(" year   ELA   area km2   volume km3   balance m w.e./yr")
for year in range(0, 201):
    ela = ELA_STEADY + (1.0 / LAPSE if year >= 10 else 0)     # +1 C from year 10, then
    mean_z = ELA_STEADY + (AREA0 - area) * 25                  # losing the low tongue r
```

```
    b = GRAD * (mean_z - ela)
    if year % 20 == 0 or year == 10:
        print(f"{year:5d}  {ela:5.0f}  {area:8.2f}  {volume:10.3f}   {b:+10.2f}")
    volume = max(volume + b * area / 1000 / ICE_DENSITY, 0.0)  # m w.e. x km2 = 0.001 km
    area = (volume / C) ** (1 / GAMMA)
#  year   ELA   area km2   volume km3   balance m w.e./yr
#     0   2472      9.00       0.698        +0.00
#    10   2626      9.00       0.698        -1.08
#    20   2626      8.10       0.604        -0.92
#    40   2626      6.78       0.473        -0.69
#    60   2626      5.88       0.389        -0.53
#    80   2626      5.23       0.331        -0.42
#   100   2626      4.75       0.290        -0.33
#   120   2626      4.39       0.260        -0.27
#   140   2626      4.11       0.237        -0.22
#   160   2626      3.88       0.219        -0.18
#   180   2626      3.70       0.206        -0.15
#   200   2626      3.56       0.195        -0.12
```

Several things show up. At first the balance is a harsh minus 1.08 m w.e. a year. As the glacier loses area, it loses its lowest, hungriest part, and the loss rate falls: the balance recovers to minus 0.33 after a century. The glacier is still shrinking at year 200, when it holds only about 40% of its starting area and is nowhere near its new steady state. A glacier that has been shocked by warming keeps retreating for generations even if the temperature stops rising. Alpine glaciers are still shrinking after the Little Ice Age ended around 1850 *(check)*, and that is one reason why.

Balance and the Snout Compared

MASS BALANCE (THE BUDGET)	WHAT THE GLACIER DOES
positive for many years	thickens, and the snout eventually advances
about zero	holds its shape; ice still flows, but the snout stays put
negative	thins, then the snout retreats up the valley
very negative for decades	breaks into disconnected patches, then disappears

A retreating glacier is not flowing backwards. The ice in it is still moving downhill, as How Glaciers Work 3 showed. The snout pulls back because ice is melting at the end faster than it arrives. Picture an escalator moving upwards while you walk down it a little too slowly: you move backwards relative to the floor even though your feet are always stepping forward.

Real Glaciers: Not Just Temperature

Temperature matters, but snow matters as much. A glacier's budget also depends on how much snow falls on it, how much sun reaches it, how dirty the surface is, and whether the lower end sits in a lake or the sea. Some rounded examples, all *(check)*:

WHERE	WHAT HAPPENED	WHY IT MATTERS
Swiss Alps (Rhône Glacier, Aletsch)	long retreat since about 1850, speeding up in recent decades	a standard example of an ELA that has risen above much of the ice
Franz Josef Glacier, New Zealand	advanced in the 1990s and early 2000s, then retreated fast	heavy snowfall can beat modest warming for a while
Scottish Highlands, about 12,900 to 11,700 years ago	small glaciers re-formed in the corries after the ice sheet had gone	a cold snap lowered the ELA enough for ice to grow again, as landforms show
Kilimanjaro, Tanzania	lost most of its ice cover in the last century	a tropical case where dry air and sunshine matter as well as warmth
Tidewater glaciers (Alaska, Greenland)	retreat in sudden steps	ice lost by calving into water is not set by melt alone

The last row is a warning that the simple budget has limits. If a glacier ends in deep water, the speed with which icebergs break away matters as much as the melt, and the behaviour can be much less smooth than our one-box model suggests. How Glaciers Work 7 looks at that in detail.

> Common mistakes
> Thinking a retreating glacier is flowing backwards (the ice still moves downhill; the snout retreats because melting wins); expecting the snout to react the same year the climate changes (response times run from decades to centuries); and treating a single bad summer as a trend (mass balance is judged over many years, and a glacier can gain mass in one year and lose it in the next).

EXERCISE 1

Using the toy glacier from this chapter, print the accumulation area ratio and the average balance for ELAs from 2,050 m to 2,950 m in steps of 100 m. Then interpolate between the two table rows where the balance changes sign, to estimate the ELA where it is zero. Does it agree with the value the bisection snippet found?

View solution

EXERCISE 2

Compare two climates for the same 9 km² glacier. A maritime climate has a steep balance gradient of 0.010 m w.e. per year per metre, and a continental climate a gentle gradient of 0.003. Find the steady-state ELA for each, then raise the ELA by the 1 °C rule and print the new average balance. Which glacier is more sensitive to warming, and by roughly what factor?

View solution

EXERCISE 3

Adapt the one-box model so that the climate warms by 1 °C from year 10 to year 60, and then returns to the original climate. Run it for 300 years and print the area every 25 years. Does the glacier recover its original size, and is the recovery faster or slower than the retreat was? Say why in one sentence.

View solution

QUICK REFERENCE

- **Mass balance:** accumulation minus ablation over a balance year, in metres of water equivalent (m w.e.); 1 m w.e. is about 1.09 m of ice
- **Ablation:** loss by melting, sublimation and calving
- **Accumulation zone and ablation zone:** the upper part with positive balance and the lower part with negative balance
- **Equilibrium line (ELA):** the height where the balance is zero; the AAR is the share of the glacier above it, often about 0.5 to 0.7 for a balanced glacier *(check)*
- **Warming:** raises the ELA by roughly 150 m per degree Celsius *(check)*, shrinking the accumulation zone

- **Response time:** decades to centuries for valley glaciers *(check)*; a glacier keeps retreating after the climate stops changing
- **Advance and retreat:** the snout moves because of the budget, not because ice flows backwards

COMING NEXT

How Glaciers Work 5 returns to the ice itself and asks what happens when it flows over a bump or a steep step. Ice bends slowly, but it also cracks, and the crevasses and icefalls that result are among the glacier's most visible and dangerous features.

How Glaciers Work

Chapter 5 · Crevasses and Icefalls

How Glaciers Work 4 treated the glacier as a conveyor belt with a budget: snow arrives at the top, ice flows down, and melting takes it away at the bottom. The ice in that conveyor was assumed to flow smoothly. Real glaciers do not always oblige. Where the valley steepens, narrows or bends, the ice is stretched faster than it can flow, and it does what any solid does when pulled too hard: it cracks. The cracks are **crevasses**, and where a whole glacier tumbles over a steep step the result is a chaotic maze of cracks and towers called an **icefall**. This chapter asks why ice flows in one place and breaks in another, how deep the cracks go, and why water makes them much worse.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The numbers describe a toy glacier with round values and are built to show the logic, so they are good for intuition and not for research or for judging a real crevasse. Where a figure is approximate or has not been checked against a source it is marked *(check)*.

Two Ways to Respond to a Pull

How Glaciers Work 3 showed that ice behaves like a very thick liquid when it is loaded slowly: its crystals slide past each other and the ice *flows*. Scientists call that **ductile** behaviour, the same way a lump of warm toffee stretches rather than snaps. But pull the toffee quickly, or chill it, and it snaps with a clean break. That is **brittle** behaviour, and ice has both modes. The difference is not temperature alone. It is the *rate* of pulling compared with how fast the ice can relax by flowing.

The rate at which ice creeps under stress follows Glen's flow law from How Glaciers Work 3: the strain rate grows as the cube of the stress. That cube matters. Double the stress and the ice can relax eight times faster, but only up to a point. Pull faster than it can relax and the stress keeps building until the ice reaches its tensile strength, which is roughly 100 kPa for glacier ice *(check)*, the pressure of about ten metres of water in a tube. At that point it fractures. The first snippet compares the speed at which ice can creep under tension with the rate at which four different places are being stretched:

```
# How fast can ice flow its way out of a stretch? Creep rate under tension (Glen's law, r
A = 2.4e-24                  # flow constant for ice at 0 C, Pa^-3 s^-1 (check)
YEAR = 365.25 * 24 * 3600    # seconds in a year

def creep_rate(stress_kpa):
    return A * (stress_kpa * 1000) ** 3 * YEAR      # strain per year

for s in (50, 100, 150, 200):
    print(f"tension {s:3d} kPa   ice can relax at {creep_rate(s):.3f} per year")

limit = creep_rate(100)       # a rough tensile stress at which ice cracks (check)
print()
SITES = [("steady valley section", 0.001), ("gentle bend", 0.02), ("approaching a step",
         ("on an icefall", 0.50)]
for name, rate in SITES:
    verdict = "cracks (brittle)" if rate > limit else "flows (ductile)"
    print(f"{name:22s} stretching {rate:.3f} per year   {verdict}")
# tension  50 kPa   ice can relax at 0.009 per year
# tension 100 kPa   ice can relax at 0.076 per year
# tension 150 kPa   ice can relax at 0.256 per year
# tension 200 kPa   ice can relax at 0.606 per year
#
# steady valley section  stretching 0.001 per year   flows (ductile)
# gentle bend            stretching 0.020 per year   flows (ductile)
# approaching a step     stretching 0.150 per year   cracks (brittle)
# on an icefall          stretching 0.500 per year   cracks (brittle)
```

At 100 kPa the ice can relax by about 0.076 (7.6%) per year. A valley stretching the ice at 0.001 per year, or even a bend at 0.02, is well inside that: the ice simply flows a little faster. Near the lip of a steep step it is being pulled at 0.15 per year, twice the limit, and on the icefall itself at 0.5 per year, more than six times. Flow cannot keep up, so the ice breaks. The "strain" here means how much a piece of ice stretches as a fraction of its original length: a strain of 0.15 per year means a 100 m stretch of glacier is pulled about 15 m longer each year.

How Deep Does a Crevasse Go?

A crevasse does not run all the way down. Ice at depth is squeezed by the weight of the ice above it, and that squeeze closes the crack. Think of a crack in a thick sponge under a heavy weight: the pull opens it near the top, the pressure shuts it lower down. The depth at which the two balance gives the crevasse depth. The glaciologist John Nye worked out a simple rule for it in the 1950s *(check)*. A crevasse in dry ice reaches a depth of:

```
# d = (2 / (density x gravity)) x (strain rate / A) ** (1 / 3)
```

where A is the same flow constant as before. Because of the cube root, a large change in strain rate makes only a modest change in depth. Here it is as code, for a range of strain rates from a quiet glacier to an icefall:

```
# Nye's rule of thumb: how deep does a dry crevasse reach for a given strain rate?
A = 2.4e-24                  # Pa^-3 s^-1 (check)
RHO_ICE, G = 917, 9.81
YEAR = 365.25 * 24 * 3600

def nye_depth(strain_per_year):
    rate = strain_per_year / YEAR                    # convert to per second
    return 2 / (RHO_ICE * G) * (rate / A) ** (1 / 3)    # metres

print(" strain per year   crevasse depth")
for e in (0.01, 0.02, 0.05, 0.10, 0.20, 0.50):
    print(f"{e:15.2f}   {nye_depth(e):10.1f} m")
#  strain per year   crevasse depth
#             0.01         11.3 m
#             0.02         14.3 m
#             0.05         19.4 m
#             0.10         24.4 m
#             0.20         30.7 m
#             0.50         41.7 m
```

Fifty times more stretching (from 0.01 to 0.5 per year) makes the crack only about four times deeper. The depths are typical of what climbers report for dry crevasses: tens of metres, and

rarely beyond 40 or 50 m in a cold glacier *(check)*. That is deep enough to be lethal long before the bottom is visible.

Water Makes Crevasses Deeper

Nye's rule assumes an empty crack. A crevasse holding meltwater changes the sums, because water is denser than ice (1,000 versus 917 kg/m^3). Water pressing outwards on the walls of the crack pushes the crevasse downward, and the deeper the water, the greater the pressure at the bottom. A common formula adds a term for the water depth: the crevasse depth is the dry depth plus 1.09 times the depth of water in it *(check)*. The next snippet applies it with the same 100 kPa pull:

```
# Dry versus water-filled crevasses: d = R / (rho_ice g) + (rho_water / rho_ice) x water
RHO_ICE, RHO_W, G = 917, 1000, 9.81
R = 100_000                  # tensile stress pulling the walls apart, Pa (check)

dry = R / (RHO_ICE * G)
print(f"Dry crevasse: {dry:.1f} m deep")
print(" water depth   crevasse depth   times deeper than dry")
for water in (0, 5, 10, 20, 40):
    d = dry + (RHO_W / RHO_ICE) * water
    print(f"{water:9d} m   {d:11.1f} m   {d / dry:14.1f}")
# Dry crevasse: 11.1 m deep
#  water depth   crevasse depth   times deeper than dry
#          0 m          11.1 m             1.0
#          5 m          16.6 m             1.5
#         10 m          22.0 m             2.0
#         20 m          32.9 m             3.0
#         40 m          54.7 m             4.9
```

With 20 m of water in it, a crevasse that would have been 11 m deep reaches almost 33 m, three times the dry depth. In nature a water-filled crevasse is likely to keep going: as the crack deepens it can hold more water and push deeper still, and that runaway can open a pathway through the whole thickness of cold ice *(check)*. This is one way that meltwater from the glacier's surface reaches the bed, where it lubricates the sliding that How Glaciers Work 3 described and

speeds the glacier up. It is also how the huge ice shelves in Antarctica can crack apart, a theme for How Glaciers Work 7.

Which Way Do the Cracks Run?

Cracks open at right angles to the direction of the strongest pull, so the pattern of crevasses is a map of how the ice is being stretched. That is what lets a trained eye read the glacier from the air:

TYPE OF CREVASSE	WHERE IT FORMS	WHAT STRETCHES THE ICE
Transverse	across the glacier, usually where the slope steepens	the ice speeds up and is pulled apart along the flow
Longitudinal	along the glacier, where a valley widens	the ice spreads out sideways as it leaves a narrow section
Marginal	at the glacier edge, angled up-glacier by about 45 degrees	the centre moves faster than the edge, which drags on the valley wall
Splaying or radial	fanning out near the snout of a spreading lobe	ice spreads out in every direction as it leaves a confined valley
Bergschrund	at the very top, between the moving ice and the rock wall	the glacier pulls away from its headwall, which does not move

Inside an Icefall

Crevasses can also close. When ice slows down, such as at the bottom of a steep step, it is squeezed together, and cracks that opened upstream are pressed shut or sheared into bands. The snippet below treats an icefall as a stretch of glacier whose speed changes from point to point, and asks which parts are stretched, which are squeezed, and how deep the cracks are likely to be:

```
# A toy icefall: ice speed (m/yr) at points every 100 m down a glacier
A, RHO_ICE, G = 2.4e-24, 917, 9.81
YEAR = 365.25 * 24 * 3600
```

```
LIMIT = A * 100_000 ** 3 * YEAR        # strain rate at which ice cracks under 100 kPa (
SPEED = [40, 42, 45, 55, 100, 220, 260, 150, 80, 60, 55, 54]   # m/yr at 0, 100, 200 ...

print("segment (m)   strain/yr   state")
for i in range(len(SPEED) - 1):
    strain = (SPEED[i + 1] - SPEED[i]) / 100      # change in speed over 100 m, per year
    if strain > LIMIT:
        depth = 2 / (RHO_ICE * G) * (strain / YEAR / A) ** (1 / 3)
        state = f"crevasses, about {depth:.0f} m deep"
    elif strain < 0:
        state = "squeezed, crevasses close"
    else:
        state = "intact"
    print(f"{i * 100:4d}-{(i + 1) * 100:<5d}   {strain:+8.2f}   {state}")
# segment (m)   strain/yr   state
#    0-100        +0.02   intact
#  100-200        +0.03   intact
#  200-300        +0.10   crevasses, about 24 m deep
#  300-400        +0.45   crevasses, about 40 m deep
#  400-500        +1.20   crevasses, about 56 m deep
#  500-600        +0.40   crevasses, about 39 m deep
#  600-700        -1.10   squeezed, crevasses close
#  700-800        -0.70   squeezed, crevasses close
#  800-900        -0.20   squeezed, crevasses close
#  900-1000       -0.05   squeezed, crevasses close
# 1000-1100       -0.01   squeezed, crevasses close
```

The ice speeds up from 45 to 260 m/yr between the 200 m and 600 m marks, just 400 m of glacier. The strain rate peaks at 1.20 per year, about sixteen times the cracking limit, between 400 and 500 m, and Nye's rule puts crevasses there at 56 m. Below that point the ice slows down again, so it is squeezed and the cracks close, leaving the deformed, broken surface that climbers meet at the bottom. Within the broken zone the cracks cross in both directions and slice the ice into blocks and walls. A tall, free-standing block of ice between crevasses, or hanging on the lip of a step, is called a **serac**, from a Swiss French word for a kind of cheese the blocks resemble *(check)*. Seracs can topple without warning, and on a warm day or after a cold night the ice may break under its own weight.

Hazards, and Real Places

Crevasses are one of the main dangers of travelling on glaciers, and most of what is known about them comes from people who have had to cross them. The danger comes from the fact that they are often hidden: a bridge of snow can cover the crack and look just like the surface around it. Seracs are an even greater hazard on steep routes, because a collapse can send ice avalanches down the slope. Some examples, all rounded and all *(check)*:

WHERE	WHAT HAPPENS	WHY IT MATTERS
Khumbu Icefall, Nepal	the glacier drops about 600 m and moves roughly a metre a day *(check)*	the route to Everest from the south has to be remade through shifting seracs every season, and a serac avalanche killed 16 guides in 2014 *(check)*
Géant Icefall, Mont Blanc massif, France and Italy	a steep tumble of seracs above a popular glacier route	climbers and skiers plan around the time of day, since the ice is more stable when cold
Marmolada, Italian Dolomites, 2022	a serac and glacier section collapsed on a hot summer day, killing 11 people *(check)*	heat and meltwater make ice that looks solid unreliable, even on a glacier
Brunt Ice Shelf, Antarctica (British station Halley)	large cracks opened in the ice shelf, and the station was moved inland in 2016 and 2017 *(check)*	crevasses are not just a mountain hazard: they decide where research stations can be built
Scottish Highlands	no active glaciers today, but buried snow bridges and cornices cause serious accidents in winter	a good reminder that these ideas, brittle snow and ice with a weak layer beneath, apply to hillwalkers as well as polar crews

People who travel on glaciers deal with the risk using ropes, with a team tied together so one person can arrest the fall of another, and by choosing times and routes with care. They keep away from the area under seracs, and travel early in the morning, when the snow bridges are frozen hard and strongest. None of this makes a crevasse safe. It makes a fall survivable and shortens the time that anyone spends under hanging ice.

Common mistakes

Assuming a glacier is either "solid" or "liquid" (ice does both, depending on how quickly it is loaded); thinking crevasses go all the way to the bed (the weight of the ice closes them at depth, unless water is helping); and believing a flat white surface is a safe one (snow bridges hide crevasses, which is why travel on a glacier needs a rope even where the ground looks gentle).

EXERCISE 1

Rearrange Nye's rule so it gives the strain rate needed to open a crevasse of a given depth. Print the strain rate for dry crevasses 10, 20, 30 and 50 m deep, and check each answer by passing it back into the depth function. How much more stretching does a 20 m crevasse need than a 10 m one, and why does that follow from the formula?

View solution

EXERCISE 2

Using the water-depth formula, find how much water a crevasse needs to reach 50 m when the tension is 50, 100 and 150 kPa. Print the dry depth for each and the water depth needed. Does a stronger pull make the water more or less important?

View solution

EXERCISE 3

Take the speed-up from 40 to 260 m/yr and spread it over a stretch of glacier of varying length: 200, 500, 1,000, 2,000, 3,000 and 4,000 m. For each, print the strain rate and whether the ice would crack, using the 100 kPa limit. Then use a loop to find the shortest stretch in whole hundreds of metres that avoids cracking. What does this tell you about where icefalls form?

View solution

QUICK REFERENCE

- **Ductile and brittle:** ice flows when pulled slowly and cracks when pulled faster than it can relax; tensile strength is about 100 kPa *(check)*
- **Crevasse:** a crack opened by stretching; it runs at right angles to the strongest pull
- **Depth:** Nye's rule gives about 10 to 40 m for dry crevasses, depending on the strain rate *(check)*; the depth rises with the cube root of the rate
- **Water:** a crevasse holding water goes much deeper and can reach the bed
- **Crevasse types:** transverse, longitudinal, marginal, splaying, and the bergschrund at the head of the glacier

- **Icefall:** a steep step where fast stretching breaks the ice into crevasses and seracs; below it the ice is squeezed and cracks close
- **Serac:** a tall block of ice between crevasses, liable to collapse without warning
- **Hazards:** hidden snow bridges and falling seracs; use ropes, avoid the area under seracs, travel when it is cold

COMING NEXT

How Glaciers Work 6 looks at what a moving glacier does to the land beneath it. Ice that can crack and flow can also grind, pluck and carry rock, and it leaves behind the valleys, lakes and boulders that tell us where glaciers used to be, including those left across the British hills.

How Glaciers Work

Chapter 6 · Carving the Land

How Glaciers Work 5 ended with ice that can both flow and crack. A glacier that can do both is a powerful tool, and it is pushing against rock. The ice flows over its bed, grips stones, drags them along and breaks off more, and over thousands of years it reshapes the valley that holds it. When the ice melts, the shape of the land is the evidence: a wide, steep-sided valley with a flat floor, a bowl-shaped hollow high on a mountain, a long finger of sea running between cliffs, a ridge of rubble across a plain, a boulder sitting where no boulder should be. This chapter explains how each one is made and uses small calculations to show how fast, how deep and how far.

> **WHAT WAS RUN**
>
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Two Ways Ice Wears Rock Away

A glacier erodes its bed in two main ways. The first is **abrasion**: rock fragments frozen into the base of the ice act like sandpaper on the bed beneath, grinding it smooth and leaving fine rock flour that turns glacial streams a milky grey-green. Larger stones leave scratches called **striations**, which point in the direction the ice was moving. The second is **plucking**, sometimes called quarrying. Meltwater seeps into cracks in the bedrock and refreezes; the ice grips the loosened block and pulls it away as the glacier moves on. Plucking works best on well-jointed rock and tends to leave a steep, jagged face on the downstream side of a rock step, while abrasion smooths the upstream side.

Both processes need the ice to *slide* over its bed, which brings back the basal sliding of How Glaciers Work 3. A glacier frozen to its bed barely erodes, and that is why cold, slow ice on high ground can protect the landscape beneath it for a very long time. Some studies suggest the erosion rate grows faster than the sliding speed, roughly as the square of it *(check)*. The next snippet uses that rule with deliberately round constants:

```python
# Erosion rate grows faster than sliding speed: e = K * u ** L (toy constants, check)
K, L = 1e-4, 2.0          # e in mm per year when the sliding speed u is in m per year

print(" sliding speed   erosion rate   rock removed in 10,000 years")
for u in (10, 50, 100, 200, 500):
    e = K * u ** L                    # mm per year
    metres = e * 10_000 / 1000        # mm over 10,000 years, converted to metres
    print(f"{u:9d} m/yr   {e:8.2f} mm/yr   {metres:12.1f} m")
#  sliding speed   erosion rate   rock removed in 10,000 years
#         10 m/yr       0.01 mm/yr            0.1 m
#         50 m/yr       0.25 mm/yr            2.5 m
#        100 m/yr       1.00 mm/yr           10.0 m
#        200 m/yr       4.00 mm/yr           40.0 m
#        500 m/yr      25.00 mm/yr          250.0 m
```

A glacier sliding at 100 m/yr removes 10 m of rock in 10,000 years. A fast one at 500 m/yr, five times quicker, removes 250 m, twenty-five times as much. That square is the heart of the matter: the fast, thick glaciers in the steepest, wettest mountains do most of the carving, and a slow glacier on a plateau does very little. Real rates vary widely, from a fraction of a millimetre to several millimetres a year *(check)*, but the pattern, small differences in speed giving large differences in erosion, shows up in the landscape.

From V to U

A river cuts downwards, so a river valley is usually V-shaped: steep sides that meet at a narrow floor. A glacier is different. It is a thick, wide body of ice that fills the valley and presses on the floor *and* both walls, so it widens and deepens the valley at the same time. The result is a **U-shaped valley**: steep sides, a broad, flat or gently rounded floor, and walls that curve smoothly into it. A convenient way to describe the shape is a power law: the height of the valley floor above its lowest point is H times (distance from the centre divided by half-width) raised to the power b. A V-shape has b close to 1, a U-shape has b near 2 or more *(check)*. The snippet below draws both valleys with the same rim height and width and compares the amount of space each one holds:

```python
# Cross-sections of a river-cut V and a glacier-cut U: floor height = H * (|x| / W) ** b
H, W = 600, 1000          # rim height above the lowest point (m) and half-width (m)

def height(x, b):
    return H * (abs(x) / W) ** b

print("   x (m)    V-valley (b=1)    U-valley (b=2)")
for x in (0, 200, 400, 600, 800, 1000):
    print(f"{x:7d}   {height(x, 1):10.0f} m   {height(x, 2):10.0f} m")

def area(b):                          # rock removed below the rims, summed in 1 m slice
    return sum(H - height(x, b) for x in range(-W, W))

print(f"Cross-section area, V: {area(1):,.0f} m2   U: {area(2):,.0f} m2   U / V = {area(
#    x (m)    V-valley (b=1)    U-valley (b=2)
#       0            0 m            0 m
#     200          120 m           24 m
#     400          240 m           96 m
#     600          360 m          216 m
#     800          480 m          384 m
#    1000          600 m          600 m
# Cross-section area, V: 600,000 m2   U: 800,000 m2   U / V = 1.33
```

Read a row across: 400 m from the centre line the V-valley has already climbed 240 m, whereas the U-valley has climbed only 96 m. The U-valley has a wide, level floor and then walls that rise steeply near the rim, which is why Alpine farmers put their villages and fields on the floor of such valleys. For the same rim height and width, the U-valley holds a third more space (an area ratio of 1.33): the glacier has removed a third more rock than a river would have. A U-shaped valley is often one of the first things geologists look for when deciding if a region was ever glaciated.

Tributary glaciers add a twist. A small glacier feeding a big one carves a shallower valley, because it has less ice, so when the ice melts the side valley is left hanging high above the main one. Water drops out of it as a **hanging valley** waterfall. Yosemite's Bridalveil Fall, in California, is a famous example, and so are many waterfalls in the Lake District and Snowdonia *(check)*.

Cirques, Arêtes and Horns

At the top of a glacier, where snow piles up and turns to ice, the ice does not flow straight down. It slumps and rotates in a hollow, grinding the rock at the back and the floor and plucking the headwall, which retreats. The hollow becomes an armchair-shaped basin with a steep back wall, a rounded floor and a lip at the front, called a **cirque**. The name comes from French; the Welsh say *cwm*, the Scots *corrie* and the Alpine Germans *Kar*. Many British cirques now hold small lakes: Cwm Idwal in Snowdonia, which Charles Darwin visited in 1842 and recognised as glacial *(check)*, and Red Tarn below Helvellyn.

When two cirques cut into opposite sides of a mountain ridge, the ridge between them is whittled into a knife-edge called an **arête**: Striding Edge on Helvellyn is one, and Crib Goch on Snowdon is another. Where three or more cirques eat into a peak from different sides, what is left is a sharp, pyramid-shaped summit called a **horn**. The Matterhorn is the textbook case. None of these three shapes was carved by the ice that sits on it; they are the places where ice has *removed* the rock around them.

Fjords and the Floating Limit

A **fjord** is a U-shaped valley whose floor has been carved below sea level and then flooded when the ice melted. Some are astonishingly deep. A glacier can keep cutting its bed down only as long as it presses hard on it. Ice is a little less dense than seawater (917 kg/m³ versus about 1,028), so once the bed is deep enough the ice would float, and the grip on the bed fades. That sets a limit: the deepest the bed can be scoured is about 89% of the ice thickness *(check)*. The next snippet applies the limit, and runs it in reverse on some real fjords:

```
# A glacier can scour its bed below sea level until the ice would float: depth = H * rho_
RHO_ICE, RHO_SEA = 917, 1028

def max_depth(thickness):
    return thickness * RHO_ICE / RHO_SEA

print(" ice thickness   deepest bed it can scour")
for h in (300, 500, 1000, 1500, 2000):
    print(f"{h:9d} m   {max_depth(h):12.0f} m")

print()
FJORDS = [("Milford Sound, New Zealand", 265), ("Hardangerfjord, Norway", 860), ("Sognef
for name, depth in FJORDS:
    need = depth * RHO_SEA / RHO_ICE          # ice thickness needed to carve that depth
```

```
    print(f"{name:27s} {depth:5d} m deep   ice at least {need:5.0f} m thick")
# ice thickness   deepest bed it can scour
#       300 m            268 m
#       500 m            446 m
#      1000 m            892 m
#      1500 m           1338 m
#      2000 m           1784 m
#
# Milford Sound, New Zealand    265 m deep   ice at least   297 m thick
# Hardangerfjord, Norway        860 m deep   ice at least   964 m thick
# Sognefjord, Norway           1308 m deep   ice at least  1466 m thick
```

Ice 1,500 m thick can carve to about 1,340 m below sea level, so Norway's Sognefjord at roughly 1,300 m *(check)* implies ice at least 1,470 m thick sitting in that valley, in line with the thick Scandinavian ice sheet of the last ice age. Milford Sound in New Zealand, at about 265 m *(check)*, needed only 300 m of ice. Fjords are also often shallow at the mouth, where a rock lip (a **threshold**) was left as the ice thinned and spread out, so the deepest water is inland. Scotland has its own examples, such as Loch Etive and Loch Torridon, sea lochs that are fjords in everything but name *(check)*.

Dropping the Load: Moraines

Everything the glacier carries has to go somewhere. The ice carries rock on top, inside and underneath, and the material that melts out is a jumble of boulders, gravel, sand and clay called **till**. Unlike river deposits, till is unsorted: a boulder the size of a car can lie beside a pinch of clay. Piled up, it forms a **moraine**, and the position of the moraine records where the ice stood:

MORAINE TYPE	WHERE IT FORMS	WHAT IT TELLS YOU
Lateral	a ridge along each side of the glacier, fed by rockfall from the valley walls	how wide and how thick the glacier once was
Medial	a dark stripe down the middle, where two glaciers meet and their lateral moraines merge	that a glacier has tributaries
Terminal (end)	a ridge across the valley at the furthest point the ice reached	the maximum advance

MORAINE TYPE	WHERE IT FORMS	WHAT IT TELLS YOU
Recessional	a series of smaller ridges up-valley of the terminal moraine	pauses during the retreat
Ground moraine	a blanket of till under the glacier, left as it melts	much of the gentle, lumpy relief of lowland areas

A terminal moraine builds only while the snout sits still, with the speed of the ice flowing in balanced by the melting at the front, as in How Glaciers Work 4. The longer the glacier holds its position, the bigger the ridge. Using the snout of a medium valley glacier with rounded numbers:

```
# How big a moraine ridge does a stationary glacier build? Debris arrives at the snout a
SPEED, THICK, WIDTH = 50, 100, 500      # snout ice speed (m/yr), thickness (m), width (
DEBRIS = 0.002                           # debris as a fraction of the ice volume (0.2 p
RIDGE_AREA = 600                         # cross-section of the ridge in m2 (about 20 m

flux = SPEED * THICK * WIDTH             # m3 of ice reaching the snout per year
supply = flux * DEBRIS                   # m3 of rock per year
print(f"Ice flux {flux:,} m3/yr carries {supply:,.0f} m3/yr of debris")
print(" years at the snout   moraine volume   ridge length")
for years in (10, 50, 100, 500):
    volume = supply * years
    print(f"{years:12d}   {volume:15,.0f} m3   {volume / RIDGE_AREA:8,.0f} m")
# Ice flux 2,500,000 m3/yr carries 5,000 m3/yr of debris
#  years at the snout   moraine volume   ridge length
#           10            50,000 m3         83 m
#           50           250,000 m3        417 m
#          100           500,000 m3        833 m
#          500         2,500,000 m3      4,167 m
```

Even with debris making up only 0.2% of the ice, a hundred years at one spot builds a ridge of about 830 m, a large and obvious feature. Five hundred years builds one over 4 km long. This is why the great terminal moraines of the last ice age are so imposing: Long Island in New York is a pair of them *(check)*, and the Baltic coast of northern Europe has long belts of them. Meltwater also leaves its own work: long sinuous ridges of sand and gravel called **eskers**, left by rivers that

flowed inside or under the ice, and streamlined, whale-backed hills called **drumlins**, moulded under moving ice and pointing along the flow. Drumlins are plentiful in the Strangford Lough area of Northern Ireland and in the Eden Valley in Cumbria *(check)*.

Erratics: Boulders Out of Place

A boulder carried by ice and dropped far from its source is an **erratic**. It sits on rock of a different kind, so it is clearly a stranger. On the limestone pavement above Ingleton and Austwick in the Yorkshire Dales, the Norber erratics are grey Silurian greywacke boulders perched on pale limestone pedestals, because the boulders shield the rock beneath them from rain while the open limestone is dissolved away *(check)*. Shap granite from Cumbria has been found in Yorkshire, Lancashire and as far as the east coast, and boulders from Norway have turned up in East Anglia *(check)*. How long does a journey like that take?

```
# How long does it take ice to carry a boulder (an erratic) a given distance?
print(" distance   at 20 m/yr   at 50 m/yr   at 100 m/yr")
for km in (10, 50, 100, 300):
    row = [km * 1000 / speed for speed in (20, 50, 100)]
    print(f"{km:6d} km   {row[0]:6,.0f} yr   {row[1]:6,.0f} yr   {row[2]:7,.0f} yr")
#  distance   at 20 m/yr   at 50 m/yr   at 100 m/yr
#     10 km      500 yr      200 yr       100 yr
#     50 km    2,500 yr    1,000 yr       500 yr
#    100 km    5,000 yr    2,000 yr     1,000 yr
#    300 km   15,000 yr    6,000 yr     3,000 yr
```

A boulder carried 100 km at an average of 50 m/yr needs 2,000 years, a tiny slice of an ice age that ran for tens of thousands of years. These are lower limits on the time (ice rarely flows at a constant speed for so long, and a boulder spends long periods stuck in the ice) but they show why such journeys are completely plausible. In the 1830s and 1840s, Louis Agassiz argued that erratics and U-shaped valleys showed Europe had once been covered by a great ice sheet, an idea first resisted and then accepted, and the foundation of How Glaciers Work 8.

Reading a Landscape

Putting the clues together lets you work out what was here before:

LANDFORM	MADE BY	WHERE TO SEE ONE
U-shaped valley	ice filling and widening a river valley	Glen Coe, Scotland; Nant Ffrancon, Wales; Yosemite Valley, USA *(check)*
Hanging valley	a small tributary glacier cutting less deeply than the main one	Bridalveil Fall, California; waterfalls along many Lake District valleys
Cirque, cwm, corrie	ice rotating and plucking at the head of a glacier	Cwm Idwal, Wales; Red Tarn, England
Arête and horn	two or more cirques cutting back into a ridge or peak	Striding Edge, England; the Matterhorn, Switzerland and Italy
Fjord	a glacier cutting below sea level, later flooded	Sognefjord, Norway; Milford Sound, New Zealand; Loch Etive, Scotland
Moraine	till dumped at the edge or snout of the ice	Long Island, USA; ridges across the Baltic coast *(check)*
Drumlin	till moulded under moving ice	Strangford Lough, Northern Ireland; the Eden Valley, England *(check)*
Erratic	a boulder carried and dropped by ice	Norber, Yorkshire Dales; Shap granite boulders across northern England *(check)*

Common mistakes

Thinking a glacier is a bulldozer that pushes everything aside (it also grinds, plucks and carries rock inside and under itself); assuming all glaciers erode equally (a cold glacier frozen to its bed can leave the landscape almost untouched); thinking every valley with a stream in it was cut by the stream (the stream is often far too small, the valley having been shaped by ice); and confusing a drumlin with a moraine (a drumlin is moulded under the ice, a moraine is dumped at its edge).

EXERCISE 1

Using the erosion rule e = K × u^2, with K = 1e-4 (mm per year, with u in m/yr), find how long a glacier needs to remove 50 m of rock when sliding at 10, 20, 50, 100 and 200 m/yr. Print the erosion rate and the time in years for each, and then the ratio of the erosion rates for 200 and 20 m/yr. Why is that ratio not 10?

View solution

EXERCISE 2

Rearrange the valley-shape formula to find the exponent b from one measurement: b = log(h / H) / log(x / W). Three valleys, each with H = 600 m and W = 1,000 m, have a floor height at x = 500 m of 280, 150 and 100 m. Print b for each, and label it V-shaped if b is below 1.5 and U-shaped otherwise. Which valley is the most clearly glacial?

View solution

EXERCISE 3

A terminal moraine ridge is 1,500 m long with a cross-section of 600 m^2. Using the snout in the moraine snippet (50 m/yr, 100 m thick, 500 m wide), work out how many years the glacier must have held its position if debris made up 0.1, 0.2 and 0.5% of the ice. What does that tell you about how confidently a ridge can be turned into a date?

View solution

QUICK REFERENCE

- **Abrasion and plucking:** rock in the ice grinds the bed smooth; ice freezes onto loosened blocks and pulls them away
- **Erosion rate:** grows faster than sliding speed, roughly as its square *(check)*; frozen-bed glaciers erode very little
- **U-shaped valley:** ice widens and deepens a valley together; floor height follows H (x / W)^b with b near 2 or more, against b near 1 for a river V
- **Cirque, arête, horn:** a hollow at the head of a glacier, the ridge between two of them, and the peak left by three or more
- **Fjord:** a glaciated valley cut below sea level; the deepest bed is about 89% of the ice thickness *(check)*
- **Moraine:** unsorted till dumped at the sides, centre or snout of the ice; the terminal moraine marks the maximum advance
- **Erratic:** a boulder of foreign rock left by melting ice, often carried for hundreds or thousands of years
- **Drumlins and eskers:** hills moulded under the ice and ridges left by tunnels of meltwater

COMING NEXT

How Glaciers Work 7 moves from valley glaciers to the giants. Greenland and Antarctica hold nearly all of the world's glacier ice, flow out in rivers of ice and shelves that float on the sea, and break up into icebergs in a process called calving, with consequences for sea level.

How Glaciers Work

Chapter 7 · Ice Sheets and Ice Shelves

How Glaciers Work 6 followed valley glaciers as they carved their landscapes. Valley glaciers are the small end of the story. Two bodies of ice, Greenland and Antarctica, hold nearly all of the world's glacier ice, and they are so large that they bury entire mountain ranges and make their own weather. An ice sheet is a glacier on a continental scale, and its edges are where things get dramatic: ice runs out to sea, floats, and breaks into icebergs. This chapter looks at how the ice sheets are built, what an ice shelf is, why calving happens, and how to turn a mass of ice into a number for sea level. All the calculations are small and run in plain Python.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The numbers use rounded volumes and rates, so they are good for intuition and not for research. Where a figure is approximate or has not been checked against a source it is marked *(check)*.

Two Ice Sheets, Two Different Worlds

A glacier is called an **ice sheet** when it covers more than 50,000 km² and is not controlled by the land beneath it *(check)*. The ice is so thick that it flows outwards from a central dome under its own weight, in every direction, regardless of the shape of the rock below. Only two exist today. They are very different:

	GREENLAND	ANTARCTICA
Area of ice	about 1.7 million km², roughly seven times the area of the United Kingdom *(check)*	about 14 million km², larger than Europe *(check)*
Greatest thickness	over 3 km *(check)*	over 4.7 km *(check)*
Volume	about 2.9 million km³ *(check)*	about 26.5 million km³ *(check)*
Surface climate	cold at the top, but summers are warm enough for widespread melting at the edges	so cold that almost no surface melt occurs; ice is lost mainly where it meets the ocean

	GREENLAND	ANTARCTICA
Main ice loss	about half surface meltwater, half icebergs *(check)*	mostly calving and melting from underneath floating shelves
Bed	a bowl of land, with the rim mountainous and the middle low in places	East Antarctica rests mostly on land above sea level; much of West Antarctica sits below sea level

Antarctica is the larger of the two by almost a factor of ten, and holds around 90% of the world's ice *(check)*. It is a good moment to see what that means in sea level. The snippet below converts an ice volume to metres of sea level by melting it, dividing by the area of the oceans and spreading the water evenly:

```
# How much sea level is locked up in the ice sheets? Ice volume -> water volume -> sprea
OCEAN_AREA = 3.61e14               # m2, about 361 million km2 (check)
RHO_ICE, RHO_WATER = 917, 1000     # kg per m3

def sea_level_m(volume_km3):
    water_m3 = volume_km3 * 1e9 * RHO_ICE / RHO_WATER    # 1 km3 = 1e9 m3; meltwater is 
    return water_m3 / OCEAN_AREA

ICE = [("Mountain glaciers", 0.16e6), ("Greenland", 2.9e6), ("Antarctica", 26.5e6)]   # 
print(" ice body             volume (km3)   sea level if all melted")
for name, v in ICE:
    print(f"{name:18s} {v:14,.0f}   {sea_level_m(v):8.1f} m")
#  ice body             volume (km3)   sea level if all melted
# Mountain glaciers         160,000        0.4 m
# Greenland               2,900,000        7.4 m
# Antarctica             26,500,000       67.3 m
```

Greenland alone is about 7.4 m, the height of a two-storey house, and Antarctica is nine times more. The calculation gives 67 m for Antarctica, but the figure normally quoted is about 58 m *(check)*. The difference is the lesson: ice that is already below sea level, resting on a bed that is under the ocean, has already pushed its weight of water aside, so its melting raises the ocean by less than its volume suggests. Counting only the ice that sits above the point where it would float gives the smaller number. Mountain glaciers, with a mere 0.4 m, are small by comparison,

but they are much more exposed and are shrinking fast, which is why they matter so much in How Glaciers Work 9.

The UK is a useful reminder that ice sheets come and go. During the last ice age, an ice sheet covered most of Scotland, northern England, Wales and Ireland, up to a kilometre or more thick in places *(check)*, and carved much of what How Glaciers Work 6 described. The British Antarctic Survey, based in Cambridge, runs research stations on the Antarctic Peninsula and on the Brunt Ice Shelf, where the ice is studied close up.

Rivers of Ice: Ice Streams and Outlet Glaciers

An ice sheet does not drain evenly. Most of the interior moves very slowly, at a few metres a year, frozen to the bed in many places. Near the coast the ice funnels into fast channels. In Greenland these are **outlet glaciers**, squeezed between mountains. In Antarctica they are **ice streams**, rivers of ice bounded on both sides by slower ice rather than by rock, running at hundreds of metres a year *(check)*. Basal sliding and soft, wet sediment at the base (How Glaciers Work 3) explain how they move so fast. Jakobshavn Isbræ (Sermeq Kujalleq) in west Greenland has been clocked at over 17 km a year in recent years *(check)*, among the fastest glaciers on Earth. The fast channels carry most of the ice out to the edge, so changes in them can matter more for sea level than changes anywhere else on the sheet.

Ice Shelves: Ice That Floats

When an ice stream reaches the coast it can keep going. The ice slides off the land and spreads over the sea as a **floating ice shelf**, a thick, flat slab fed from the land behind it and, in places, thickened from below by sea water freezing on. The line where the ice leaves the bed and starts to float is the **grounding line**. Antarctic shelves are enormous: the Ross Ice Shelf is about the size of France *(check)*, and the Filchner-Ronne Ice Shelf is nearly as large *(check)*. Greenland has a few, much smaller. Because ice is slightly less dense than seawater, a shelf floats with most of its thickness underwater. Archimedes' principle makes it easy to work out how much:

```
# An ice shelf floats: how much of it sticks out of the sea? (Archimedes: ice displaces
RHO_ICE, RHO_SEA = 917, 1028
above_fraction = 1 - RHO_ICE / RHO_SEA
print(f"Fraction of floating ice above the sea: {above_fraction:.1%}")
```

```
print(" shelf thickness   above the sea   below the sea")
for h in (100, 300, 500, 1000):
    above = h * above_fraction
    print(f"{h:11d} m   {above:9.0f} m   {h - above:11.0f} m")
# Fraction of floating ice above the sea: 10.8%
#  shelf thickness   above the sea   below the sea
#          100 m          11 m            89 m
#          300 m          32 m           268 m
#          500 m          54 m           446 m
#         1000 m         108 m           892 m
```

Only about a tenth of a floating shelf sticks out of the sea. A 300 m shelf has a cliff of 32 m above the water and 268 m under it, and the proportion is the same for an iceberg, which is where the saying "tip of the iceberg" comes from. This has a surprising consequence for sea level: floating ice, when it melts, adds almost nothing to the ocean because it already displaces its own weight of water. (The small difference between fresh meltwater and salt water is usually ignored *(check)*.) That is why a drink with ice cubes does not overflow when they melt. It is also why the ice shelves themselves are not the main contributors to sea level; ice on land is.

Why Shelves Matter: Buttressing

If shelves do not raise the sea, why do scientists watch them so closely? Because shelves act as a **buttress**. They are pinned by coastlines, islands and shallow banks, and so they hold back the ice stream behind them, in the way a flying buttress props up a cathedral wall. When a shelf thins or breaks up, the ice behind it speeds up and delivers more ice to the ocean, which *does* raise sea level. In 2002 the Larsen B shelf on the Antarctic Peninsula broke up within weeks, and the glaciers behind it sped up several times over in the following months and years *(check)*. Larsen C lost an iceberg called A68 in July 2017, about 5,800 km², roughly four times the size of Greater London *(check)*, and shelves in the Amundsen Sea are thinning from below as warmer ocean water reaches under them *(check)*.

The Brunt Ice Shelf, home to the British Halley research station, is a UK example. The station, a set of modules on skis built to be moved, was relocated inland between 2016 and 2017 after a huge crack began to open in the ice, and a large iceberg, A81, finally broke away from the shelf

in January 2023 *(check)*. A research station that has to be towed away from a growing crack is a vivid demonstration that the shelf edge is a living, moving thing.

Calving: How Icebergs Are Born

Calving is the breaking off of ice at a glacier's front, where the ice ends at the sea or a lake. The ice is under stress at its front (How Glaciers Work 5), crevasses open, and eventually a block breaks off under its own weight, helped by melt at the waterline, wave action and the pull of the water. Calving is why a glacier front can stay put, advance or retreat even though the ice behind it is always moving forward. As with the mass balance in How Glaciers Work 4, it comes down to a sum: the front advances at the speed the ice flows to it, less whatever is lost to icebergs.

```
# A calving glacier front: it moves forward with the ice speed and backward with calving
SPEED = 8.0                          # km per year of ice flowing to the front (toy valu
CALVING = [7.0, 8.0, 9.0, 10.0]      # km per year of ice lost to icebergs

print(" calving (km/yr)   front position after 1, 5 and 10 years (km, + = advance)")
for c in CALVING:
    net = SPEED - c
    print(f"{c:10.1f}        {net * 1:+6.1f}  {net * 5:+6.1f}  {net * 10:+6.1f}")
#  calving (km/yr)   front position after 1, 5 and 10 years (km, + = advance)
#         7.0          +1.0    +5.0   +10.0
#         8.0          +0.0    +0.0    +0.0
#         9.0          -1.0    -5.0   -10.0
#        10.0          -2.0   -10.0   -20.0
```

If calving is 7 km a year and the ice arrives at 8 km a year, the front advances by 1 km a year and 10 km in a decade. When calving matches the ice speed, the front sits still, even though the ice is racing past at 8 km a year. At 10 km a year the front retreats 20 km in a decade. A small rise in calving, from 8 to 10 km a year, is enough to turn a stable front into a rapid retreat. The reverse also holds, so a front that has retreated can regrow if calving drops. The numbers here are toy values, but they show how sensitive fronts are.

Counting Sea Level in Gigatonnes

Scientists measure the ice sheets from satellites, which weigh the ice through changes in gravity or measure its height with lasers and radar, and report the answer in **gigatonnes** (Gt): billions of tonnes. A tonne of water is a cubic metre, so a gigatonne is a cubic kilometre of water. The conversion to sea level is a one-liner, and the result is easy to remember:

```
# Mass losses are quoted in gigatonnes (Gt) a year. How much sea level is that?
OCEAN_AREA = 3.61e14                    # m2 (check)
GT_PER_MM = OCEAN_AREA * 0.001 / 1e9    # 1 mm of ocean = this many m3 of water = this m
print(f"1 mm of sea level = {GT_PER_MM:.0f} Gt of water")

LOSS = [("Greenland", 270), ("Antarctica", 150)]    # Gt per year, round recent-decade v
print(" ice sheet     loss (Gt/yr)   sea level (mm/yr)   years to add 10 cm   years to ad
for name, gt in LOSS:
    mm = gt / GT_PER_MM
    print(f"{name:11s} {gt:9d}   {mm:14.2f}   {100 / mm:16.0f}   {1000 / mm:14.0f}")
# 1 mm of sea level = 361 Gt of water
#  ice sheet     loss (Gt/yr)   sea level (mm/yr)   years to add 10 cm   years to add 1 m
# Greenland         270             0.75                134             1337
# Antarctica        150             0.42                241             2407
```

Every 361 Gt of melted ice raises the sea by about 1 mm. At the recent rates, taken from the broad range of published estimates *(check)*, Greenland's 270 Gt a year adds 0.75 mm to the sea each year and Antarctica's 150 Gt adds 0.42 mm. That sounds small, but the 1,337 and 2,407 years to a metre assume nothing changes, and the loss rate has been rising, with the sheets losing several times more than in the 1990s *(check)*. A rise of a metre would put much of the coast of low-lying countries such as Bangladesh and the Netherlands at risk *(check)*. Sea level also rises from the warming of the water itself and from mountain glaciers, so the ice sheets are only part of the total.

The Tipping Question

Parts of West Antarctica, such as the Thwaites Glacier, rest on a bed that slopes downwards *inland*, below sea level. Where the bed deepens as you go inland, a retreating grounding line meets thicker ice, which flows out faster, which pushes the line back further. That feedback loop is called **marine ice sheet instability**, and whether parts of West Antarctica have already

crossed the threshold into a self-sustaining retreat is an active research question *(check)*. It is a good example of why ice sheets are hard to forecast: the physics is known, but the timing depends on details of the bed and of the ocean. How Glaciers Work 9 looks at how it is monitored, and How Glaciers Work 10 at how to read the risk without alarm or false comfort.

Common mistakes

Thinking that melting sea ice or ice shelves raises sea level the way melting land ice does (floating ice already displaces its own weight; the effect comes from ice on land, and from shelves only through the buttressing they give up); mixing up an ice sheet (more than 50,000 km^2, continental) with an ice shelf (the floating part); quoting sea level equivalents without saying whether the ice below sea level is counted; and picturing calving as a sudden one-off event, when it is a steady process that can speed up or slow down.

EXERCISE 1

Using the sea level function from the first snippet (ocean area 3.61e14 m^2, ice density 917 kg/m^3), print the sea level rise if 1, 5 and 10% of Greenland (2.9 million km^3) and of Antarctica (26.5 million km^3) melt. Then print the share of Greenland that would have to melt to raise the sea by 1 m. Which result surprises you most?

View solution

EXERCISE 2

Run the shelf calculation in reverse. For ice cliffs standing 10, 20 and 50 m above the sea, print the total shelf thickness and the depth below the water. Then say how thick a shelf must be if its cliff is 25 m high. Why can you not work out the thickness of a floating shelf from its cliff without some knowledge of the ice density?

View solution

EXERCISE 3

A calving front receives ice at a steady 8 km per year. For the first five years calving removes 8 km a year, and from year 6 it rises to 10 km a year. Print the calving rate and the front position (km from the starting line) for each of the ten years, and the first year in which the front is 5 km or more behind where it started. What does this say about how long it takes to notice a change in calving?

View solution

QUICK REFERENCE

- **Ice sheet:** a continental glacier of more than 50,000 km^2 that flows outwards from a dome; only Greenland and Antarctica exist today
- **Sea level equivalents:** about 0.4 m for mountain glaciers, 7.4 m for Greenland, and about 58 m for Antarctica once ice already below sea level is discounted *(check)*
- **Ice streams and outlet glaciers:** fast channels that carry most of the ice from the interior to the coast
- **Ice shelf:** floating ice fed from land; about 10.8% of its thickness sits above the water, and its melting hardly changes sea level
- **Buttressing:** shelves hold back the ice behind them, so a collapsing shelf lets land ice speed up
- **Calving:** front advance per year equals the ice speed minus the calving rate
- **Gigatonnes:** 361 Gt of ice lost is about 1 mm of sea level *(check)*
- **Marine ice sheet instability:** a retreating grounding line on a bed that deepens inland can keep retreating by itself *(check)*

COMING NEXT

How Glaciers Work 8 goes back in time. Ice sheets have grown and shrunk many times in the last two and a half million years, driven by small, regular changes in Earth's orbit called Milankovitch cycles, and the evidence for the ice ages is written in rocks, in the sea floor and in the ice cores of How Glaciers Work 2.

How Glaciers Work

Chapter 8 · Ice Ages

How Glaciers Work 7 ended by saying that ice sheets have grown and shrunk many times. The ice sheets we have today, Greenland and Antarctica, are what is left of a much larger world of ice. In the last two and a half million years, ice sheets have swollen across Canada, northern Europe and the British Isles, held back the sea by well over a hundred metres, and then melted away, over and over. This chapter explains the slow clock behind that rhythm, how long each phase lasted, and how we know any of it happened. The calculations are small and run in plain Python.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The curves here are toys that show how the ideas work, not climate models, and the numbers are rounded. Where a figure is approximate or has not been checked against a source it is marked *(check)*.

What an Ice Age Actually Is

The words are used loosely, so it helps to separate three levels. An **ice age** in the strict sense is a long period, millions of years, when there are permanent ice sheets at the poles. By that definition we are *in* an ice age now, because Greenland and Antarctica are still covered. Within an ice age, the climate swings between **glacial periods**, when ice sheets spread far over the continents, and warmer **interglacial periods**, when they shrink back. When people say "the Ice Age" they mean the most recent glacial period, which ended around 11,700 years ago *(check)*. We live in an interglacial called the Holocene.

	ICE AGE (LONG SENSE)	GLACIAL PERIOD	INTERGLACIAL
Length	millions of years	roughly 80,000 to 100,000 years *(check)*	roughly 10,000 to 30,000 years *(check)*
Ice	permanent ice sheets exist at the poles	sheets also cover Canada, Scandinavia and the British Isles	sheets retreat to Greenland and Antarctica, as now

	ICE AGE (LONG SENSE)	GLACIAL PERIOD	INTERGLACIAL
Sea level	depends on the phase	about 120 to 130 m lower than today at the peak *(check)*	close to today's level
Example	the last 2.6 million years *(check)*	the last glacial maximum, about 20,000 years ago *(check)*	the Holocene, from about 11,700 years ago

The last glacial period was no short winter. At its peak, around 20,000 years ago, ice covered most of Scotland, much of northern England, Wales and Ireland, and the North Sea floor between Britain and the Continent was dry land that people and mammoths could walk over *(check)*. A tundra landscape lay south of the ice, and the Thames ran through a land much colder than the one we know.

The Slow Clock: Milankovitch Cycles

What switches ice sheets on and off? The sun's output hardly changes. What changes is *where* and *when* its energy lands on Earth. The Serbian scientist Milutin Milankovitch worked out in the early twentieth century that three small, regular changes in Earth's orbit add up to a pacemaker for the ice ages. The three are:

CYCLE	WHAT CHANGES	PERIOD	EFFECT
Eccentricity	the orbit stretches from nearly circular to slightly oval	about 100,000 years (and 400,000) *(check)*	changes the total sunlight over the year only slightly, but changes how strong the other two cycles can be
Tilt (obliquity)	Earth's axis leans between about 22.1° and 24.5° *(check)*	about 41,000 years	more tilt means stronger seasons, with warmer summers and colder winters at high latitudes
Wobble (precession)	the axis slowly circles, like a spinning top, changing which season falls nearest the sun	about 23,000 years (19,000 to 26,000) *(check)*	decides whether northern summer happens when Earth is close to or far from the sun

The cycles hardly change the yearly total of sunshine. They change how it is shared between seasons and latitudes. And the key place is the far north, because that is where the big continents sit. If summers at around 65°N are cool, winter snow does not completely melt, snow accumulates year after year (How Glaciers Work 2 and 4), and an ice sheet begins to grow. If

those summers are warm, the snow goes. The three cycles run at different speeds, so their effects add together and cancel each other out in a changing pattern. The snippet below adds the three as plain cosine waves to make a toy "summer sunshine" curve, and prints it against time:

```
import math

# Three orbital cycles (periods in thousands of years) added together as a toy summer-su
CYCLES = [("Eccentricity", 100, 1.0), ("Tilt (obliquity)", 41, 1.0), ("Wobble (precessio
print(" cycle                 period (kyr)")
for name, p, a in CYCLES:
    print(f"{name:20s} {p:10d}")

def sunshine(t_kyr):
    return sum(a * math.cos(2 * math.pi * t_kyr / p) for _, p, a in CYCLES)

print(" time (kyr ago)   toy sunshine   bar")
for t in range(0, 201, 10):
    s = sunshine(-t)
    print(f"{t:10d}   {s:12.2f}   {'#' * round((s + 3) * 6)}")
# cycle                 period (kyr)
# Eccentricity                100
# Tilt (obliquity)             41
# Wobble (precession)          23
#  time (kyr ago)   toy sunshine   bar
#           0           3.00   ######################################
#          10          -0.07   ##################
#          20          -0.01   ##################
#          30          -0.76   #############
#          40           0.11   ###################
#          50          -0.35   ################
#          60          -2.56   ###
#          70           0.39   ####################
#          80           0.27   ####################
#          90           2.00   ################################
#         100          -0.50   ##############
#         110           0.60   ######################
#         120           1.41   ##########################
#         130          -0.41   ################
#         140          -0.81   #############
#         150          -2.53   ###
#         160           0.97   ########################
#         170          -0.48   ##############
```

```
#        180          -0.00   ##################
#        190           0.08   ##################
#        200           1.39   ##########################
```

The curve is irregular because three waves with different lengths seldom line up. It has deep lows (-2.56 at 60 kyr, -2.53 at 150 kyr) when all three are pushing the same way, and high peaks (2.00 at 90 kyr) when they are in step the other way. In the real climate, a run of cool northern summers lets ice build, and a peak melts it. The toy gives all three cycles the same strength, which is not true of the real thing, but it shows the main idea: no single cycle explains the pattern; their combination does.

THE 100,000-YEAR PUZZLE

The ice record of the last million years has big swings roughly every 100,000 years, but the sunshine change from the 100,000-year eccentricity cycle is the weakest of the three. Before about a million years ago the main beat was the 41,000-year tilt cycle *(check)*. Why the beat changed is an open question. Feedbacks inside the climate system, such as ice sheets reflecting sunlight, carbon dioxide leaving the air as the oceans cool, and the bedrock sinking under the ice, must amplify the small push from the orbit.

Counting the Peaks

How often does a strong peak arrive? The snippet below goes through the toy curve and records each time it reaches a local maximum above a threshold, then prints the gaps between the peaks:

```
import math

# Same cycles as before; count how many warm peaks (maxima) the toy curve has in 400 thou
def sunshine(t):
    return sum(math.cos(2 * math.pi * t / p) for p in (100, 41, 23))
peaks = []
for t in range(1, 400):
    if sunshine(t) > sunshine(t - 1) and sunshine(t) > sunshine(t + 1) and sunshine(t) >
        peaks.append(t)
print("Strong peaks (kyr from now):", peaks)
```

```
print("Gaps between them (kyr):", [b - a for a, b in zip(peaks, peaks[1:])])
# Strong peaks (kyr from now): [90, 116, 206, 297, 323, 369]
# Gaps between them (kyr): [26, 90, 91, 26, 46]
```

The gaps are 26, 90, 91, 26 and 46 thousand years. They are not regular, but the larger gaps cluster near 90 to 100 thousand years, echoing the rhythm of the real glacial cycles *(check)*. A pattern that is the sum of simple rhythms looks complicated, but it is predictable, which is why scientists can say with some confidence what the orbit will do over the next hundred thousand years *(check)*.

How Much Ice, How Much Sea

At the peak of the last glacial period, global sea level was about 120 to 130 m below today's *(check)*. That water had not vanished. It was locked up in the ice sheets, and How Glaciers Work 7 gave the tool to turn a sea level into an ice volume. The snippet runs it backwards: for a given fall in sea level, how much extra ice must there have been?

```
# Ice volume needed for a given sea level fall, using the same ocean area and ice density
OCEAN_AREA = 3.61e14           # m2 (check)
RHO_ICE, RHO_WATER = 917, 1000

def ice_km3(drop_m):
    water_m3 = drop_m * OCEAN_AREA
    return water_m3 * RHO_WATER / RHO_ICE / 1e9

print(" sea level fall (m)   extra ice (million km3)   times today's Greenland")
for drop in (20, 60, 120, 130):
    v = ice_km3(drop)
    print(f"{drop:14d}   {v / 1e6:18.1f}   {v / 2.9e6:20.1f}")
#  sea level fall (m)   extra ice (million km3)   times today's Greenland
#                  20                  7.9                   2.7
#                  60                 23.6                   8.1
#                 120                 47.2                  16.3
#                 130                 51.2                  17.6
```

A fall of 120 m needs about 47 million km³ of extra ice, sixteen Greenlands. Most of it sat in the great North American and Eurasian ice sheets, which have mostly gone, and the rest was a larger Antarctica and Greenland *(check)*. This is also why the loss of the ice sheets that remain matters: the last time the ice melted, the sea rose by well over a hundred metres in about ten thousand years, at an average of more than a metre a century *(check)*. The sea also rose in bursts, the fastest of which, called meltwater pulses, may have added several metres in a few centuries *(check)*.

The Evidence: How We Know

Nobody was there, so how can we be sure? Evidence comes from several independent sources that tell the same story, and the agreement between them is what makes the case strong:

EVIDENCE	WHERE IT IS FOUND	WHAT IT SHOWS
Landforms	U-shaped valleys, cirques, moraines, erratics (How Glaciers Work 6)	where ice once reached; in Britain, moraines mark the southern edge of the ice sheet at roughly the line from Wales to East Anglia *(check)*
Ice cores	Greenland and Antarctica (How Glaciers Work 2)	temperature through the oxygen isotopes in the ice, and past air in the trapped bubbles; the Antarctic cores reach back about 800,000 years *(check)*
Sea floor mud	cores from ocean sediments	shells of tiny creatures whose chemistry records global ice volume over millions of years
Old shorelines	coral terraces, raised beaches	past sea levels, both high and low
Pollen and fossils	peat bogs and lake mud	which plants and animals lived where, and so how cold it was

The ice core story deserves a closer look, because it gives the clearest temperature record. Water molecules with the lighter oxygen isotope (oxygen-16) evaporate and fall as snow more easily than ones with the heavier oxygen-18, and the contrast grows as the air gets colder. So colder snow has a lower proportion of oxygen-18, written **$\delta^{18}O$** (delta-O-18) and quoted in parts per thousand, or "per mil". The snippet below turns $\delta^{18}O$ into a temperature using a toy slope:

```
# Ice-core temperature from the oxygen isotope ratio (delta-18O, in per mil). Toy slope:
```

```
SLOPE = 0.67
SAMPLES = [("Recent ice (interglacial)", -35.0), ("Mid-way", -38.0), ("Last glacial maxi
base = SAMPLES[0][1]
print(" sample                      d18O (per mil)   temperature vs recent (C)")
for name, d in SAMPLES:
    print(f"{name:26s} {d:10.1f}   {(d - base) / SLOPE:+16.1f}")
#  sample                      d18O (per mil)   temperature vs recent (C)
# Recent ice (interglacial)       -35.0              +0.0
# Mid-way                         -38.0              -4.5
# Last glacial maximum ice        -41.0              -9.0
```

A drop of 6 per mil on this toy scale gives -9 °C, which is in the range of the real change at the Greenland summit between the last glacial maximum and now *(check)*. The numbers here are illustrative: real $\delta^{18}O$ values depend on the site, and the slope has to be calibrated for each place. Even so, the principle is the same and it shows how a chemical measurement on a piece of ice becomes a thermometer. Together with the dust and the trapped carbon dioxide, the cores show carbon dioxide and temperature rising and falling together across the glacial cycles *(check)*.

Common mistakes

Treating "ice age" as a single cold spell that ended (we are in an ice age in the long sense, in an interglacial); saying the ice ages were caused by changes in the sun (the cause is the shape and tilt of the orbit, which changes how sunlight is shared, not its total); expecting one orbital cycle to explain the whole record (the combination matters, plus feedbacks); and assuming a Milankovitch cycle will cause rapid change in a human lifetime (they work over thousands of years, so they do not explain the warming of the last century, which is the subject of How Glaciers Work 9).

EXERCISE 1

Write a function that finds the peaks of a sum of cosines with a threshold of 1.0 over 400 kyr. Run it twice: once with only the tilt (41) and wobble (23) cycles, and once with all three cycles. For each case print the number of peaks, the average gap and the first five peaks. What does the 100,000-year cycle change, and what does it leave alone?

View solution

EXERCISE 2

Using the ice volume function, print the extra ice needed for sea level falls of 50, 90 and 140 m. Then spread each volume over an area about the size of Canada (roughly 10 million km^2) and print the average thickness. Is the result thick enough to be believable, and what does it say about where the ice must have been?

View solution

EXERCISE 3

Starting from a recent $\delta^{18}O$ of -35 per mil, convert samples at -36, -39, -42 and -44 per mil to temperature changes using two different slopes, 0.67 and 0.50 per mil per °C. Print both results and the gap between them. What does the growing gap tell you about the uncertainty of an ice-core thermometer?

View solution

QUICK REFERENCE

- **Ice age (long sense):** a period with permanent polar ice sheets; we are in one now, in an interglacial
- **Glacial and interglacial:** cold phases of about 80,000 to 100,000 years and warm phases of about 10,000 to 30,000 *(check)*
- **Milankovitch cycles:** eccentricity (about 100,000 years), tilt (about 41,000) and wobble (about 23,000); they change the sharing of sunlight, not its total
- **Why northern summers matter:** cool summers at around 65°N let snow survive and ice sheets grow
- **Feedbacks:** ice reflectivity, carbon dioxide and sinking bedrock amplify the small orbital push
- **Last glacial maximum:** about 20,000 years ago, sea level 120 to 130 m lower, about 47 million km^3 of extra ice for 120 m *(check)*
- **Evidence:** landforms, ice cores, sea floor mud, old shorelines, pollen and fossils, all agreeing
- **$\delta^{18}O$:** less oxygen-18 in snow means colder air; the slope must be calibrated for each site

COMING NEXT

How Glaciers Work 9 returns to the present. The orbit does not explain the retreat of glaciers over the last century, so the chapter looks at what has been observed, what meltwater means for water supply

from the Alps to the Himalayas, and how scientists monitor glaciers with stakes, satellites and lasers.

How Glaciers Work

Chapter 9 · Climate Today

How Glaciers Work 8 ended with a warning: the slow orbital clock explains the ice ages, but it works over thousands of years, so it cannot explain what glaciers have done in the last hundred. This chapter comes back to the present. It covers what has been observed, how the loss is measured, why meltwater matters to the people who live downstream, and how a glacier's story can be turned into numbers. The calculations are small and run in plain Python.

> **WHAT WAS RUN**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The data are made up to show the method, and the models are toys, not forecasts. Where a figure is approximate or has not been checked against a source it is marked *(check)*.

What Has Been Observed

Almost everywhere that glaciers are measured, they are losing more than they gain. Since the nineteenth century, when the first maps and photographs were made, most mountain glaciers have shortened, and the rate has risen since about 1990 *(check)*. Taken together, the world's glaciers outside the two big ice sheets lost roughly 270 billion tonnes of ice a year between 2000 and 2019 *(check)*. That is about 270 cubic kilometres of water every year, enough to fill Loch Ness (about 7.5 km^3) more than thirty times *(check)*.

The loss is uneven. Some glaciers in the Karakoram, in the high mountains of Asia, were close to balance for years, a puzzle that is still debated *(check)*. Glaciers in the Alps, the Andes, Alaska and Iceland have lost a lot. In a very hot summer such as 2022 the Alps lost several per cent of their remaining ice in a single year *(check)*. Many small glaciers have disappeared completely, and there are no glaciers left in the British Isles, whose last ones vanished at the end of the last glacial period; only a few snow patches on the Scottish hills survive into some summers *(check)*.

REGION	PATTERN	WHY IT MATTERS
Alps	strong retreat, small glaciers vanishing	summer river flow, hydropower, tourism

REGION	PATTERN	WHY IT MATTERS
Andes	fast loss in the tropics, where glaciers are small and high	dry-season water for cities such as La Paz and Lima *(check)*
High mountains of Asia	mixed, with loss in the Himalaya and some stable areas in the Karakoram *(check)*	the headwaters of rivers that serve hundreds of millions of people
Alaska and Arctic Canada	among the largest total losses	a big share of today's glacier contribution to sea level *(check)*
Iceland and Scandinavia	steady retreat; small glaciers vanishing	local rivers and hydropower; Iceland has held a funeral for a lost glacier, Okjokull *(check)*

Measuring a Glacier With Stakes

The oldest and most direct method is the one from How Glaciers Work 4: push stakes into the ice, read them once or twice a year, dig snow pits to measure what has accumulated, and add it all up. The result is the **annual mass balance**, written in metres of water equivalent (m w.e.), which makes snow, firn and ice comparable. The snippet below takes ten years of made-up balances for a small glacier of 5 km² and accumulates them:

```
# Annual mass balance of a toy glacier, stake measurements in metres of water equivalent
AREA_KM2 = 5.0
BALANCE = [-0.4, -0.9, -0.6, -1.2, -0.3, -1.4, -0.8, -1.1, -0.5, -1.3]
RHO_ICE, RHO_WATER = 917, 1000
total = 0.0
print(" year   balance (m w.e.)   cumulative (m w.e.)   volume lost (million m3 water)")
for i, b in enumerate(BALANCE, start=1):
    total += b
    vol = total * AREA_KM2 * 1e6 / 1e6
    print(f"{i:5d}   {b:14.1f}   {total:17.1f}   {vol:24.1f}")
thin = total * RHO_WATER / RHO_ICE
print(f"Average thinning over 10 years: {thin:.1f} m of ice, {thin / 10:.2f} m a year")
#  year   balance (m w.e.)   cumulative (m w.e.)   volume lost (million m3 water)
#     1             -0.4               -0.4                     -2.0
#     2             -0.9               -1.3                     -6.5
#     3             -0.6               -1.9                     -9.5
#     4             -1.2               -3.1                    -15.5
#     5             -0.3               -3.4                    -17.0
```

```
#     6            -1.4               -4.8                    -24.0
#     7            -0.8               -5.6                    -28.0
#     8            -1.1               -6.7                    -33.5
#     9            -0.5               -7.2                    -36.0
#    10            -1.3               -8.5                    -42.5
# Average thinning over 10 years: -9.3 m of ice, -0.93 m a year
```

A glacier that loses 0.85 m w.e. a year on average sounds modest, but it is a constant loss: after ten years the glacier has thinned by about 9 m of ice and lost 42.5 million m³ of water, about 17,000 Olympic swimming pools *(check)*. Note the last line: water is denser than ice, so a metre of water equivalent is a little more than a metre of ice. One bad year, such as -1.4 m w.e. in year 6, can undo several good ones. Some European glaciers have had stake records running for decades, and a few reference glaciers have been measured every year since the middle of the twentieth century *(check)*. These long records are very valuable because they let scientists separate a trend from a bad summer.

Measuring From Above: The Geodetic Method

Stakes only measure a few points, and glaciers are big. Another approach is to survey the whole surface twice and subtract. Aerial photographs and satellite images are turned into **digital elevation models** (DEMs), grids of heights. Subtracting an old DEM from a new one gives the thickness change in every cell. The average change times the area gives a volume, and the volume times an assumed density gives a mass. The snippet uses a tiny 4 by 4 grid in place of the thousands of cells in a real model:

```
# Geodetic method: subtract an old height map from a new one to find the volume and mass
CELL = 100                # each grid cell is 100 m x 100 m
OLD = [[2010, 2040, 2075, 2110], [1985, 2015, 2050, 2090], [1960, 1990, 2025, 2065], [194
NEW = [[2008, 2038, 2074, 2109], [1979, 2008, 2045, 2087], [1951, 1981, 2017, 2060], [193
RHO = 850                 # kg/m3, usual density assumed for a mix of ice, firn and snow
diffs = [n - o for row_o, row_n in zip(OLD, NEW) for o, n in zip(row_o, row_n)]
mean_dh = sum(diffs) / len(diffs)
area = len(diffs) * CELL * CELL
vol = mean_dh * area
mass_t = vol * RHO / 1000
print(f"Cells: {len(diffs)}   area: {area / 1e6:.2f} km2")
```

```
print(f"Mean height change: {mean_dh:.2f} m   (largest loss {min(diffs)} m, smallest {ma
print(f"Volume change: {vol:,.0f} m3   mass change: {mass_t:,.0f} tonnes")
# Cells: 16   area: 0.16 km2
# Mean height change: -6.12 m   (largest loss -12 m, smallest -1 m)
# Volume change: -980,000 m3   mass change: -833,000 tonnes
```

The 16 cells lost 6.12 m on average, or about 833,000 tonnes, and the density is the weak link. The value of 850 kg/m^3 is a convention for ice, firn and snow together, and a different assumption changes the answer by several per cent (Exercise 3). A strength of the geodetic method is that it covers the whole glacier, and a weakness is that it gives the change over several years rather than for each one. Satellites add two other tools. Laser altimeters such as ICESat-2 measure the height of the surface from orbit *(check)*, and gravity satellites such as GRACE detect the tiny change in Earth's pull when large masses of ice are lost *(check)*.

METHOD	WHAT IT MEASURES	STRENGTH	WEAKNESS
Stakes and pits	mass balance at points	direct, yearly, very precise	few glaciers, hard, risky work
Photos and DEMs	height change of the whole surface	covers whole glaciers and whole regions	multi-year; needs a density assumption
Laser altimetry	surface height from orbit	global coverage, repeated passes	narrow tracks; clouds and steep slopes cause gaps
Gravity satellites	total mass change of a region	direct measure of mass, not height	coarse resolution; cannot separate single glaciers
Terminus mapping	length and area change	cheap, goes back centuries from old maps and paintings	length changes lag behind mass changes

The methods check each other. When stakes, DEMs and satellites all show the same pattern, as they do for most regions, confidence is high. When they disagree, it usually points to a bias in one of them, such as a wrong density or debris cover hiding the ice, and that is how the methods improve.

Meltwater and Water Supply

A glacier is a reservoir that is filled in winter and emptied in summer, and in dry or hot years it releases its stored ice as well. That is why glacier-fed rivers keep flowing when rain-fed ones fall: the Indus, the Ganges and the Brahmaputra in South Asia, the rivers of the Andes and the Rhône and the Rhine in Europe all get meltwater in the dry or hot months *(check)*. The share varies. Close to the mountains, the glacier contribution can be most of the flow in late summer, but far downstream, rain and snowmelt from lower ground dominate, and the glacier share can be small *(check)*.

A shrinking glacier tells an unusual story. At first it releases *more* water, because more of the ice is melting each year. Later, when the glacier has become small, it has less ice to melt and the flow falls below where it started. The turning point is called **peak water**. The snippet below is a toy model of it: the glacier loses 2% of its remaining area a year, while melt per square kilometre rises steadily with warming.

```
# Toy "peak water": a shrinking glacier whose melt per square kilometre keeps rising as t
AREA0 = 100.0             # km2
SHRINK = 0.02             # fraction of the remaining area lost each year
MELT0, RISE = 1.2, 0.04   # m w.e. of melt per year at the start, and its rise each year
best = (0, 0.0)
print(" year   area (km2)   melt per km2 (m)   meltwater (million m3)")
for yr in range(0, 101):
    area = AREA0 * (1 - SHRINK) ** yr
    melt = MELT0 + RISE * yr
    water = area * melt          # km2 * m = million m3
    if water > best[1]:
        best = (yr, water)
    if yr % 10 == 0:
        print(f"{yr:5d}   {area:9.1f}   {melt:15.2f}   {water:18.1f}")
print(f"Peak meltwater in year {best[0]}: {best[1]:.1f} million m3")
#  year   area (km2)   melt per km2 (m)   meltwater (million m3)
#     0       100.0              1.20                120.0
#    10        81.7              1.60                130.7
#    20        66.8              2.00                133.5
#    30        54.5              2.40                130.9
#    40        44.6              2.80                124.8
#    50        36.4              3.20                116.5
#    60        29.8              3.60                107.1
#    70        24.3              4.00                 97.2
#    80        19.9              4.40                 87.4
#    90        16.2              4.80                 77.9
#   100        13.3              5.20                 69.0
```

```
# Peak meltwater in year 19: 133.5 million m3
```

The meltwater rises from 120 to a maximum of 133.5 million m^3 around year 19, then falls to 69.0 million m^3 by year 100, 57% of the start. A river that depends on the glacier would see this as extra water for a generation, followed by a long decline. In reality, peak water has already passed in many small basins, and in others, especially those with large glaciers, it is expected later in the century *(check)*. The timing depends on the size of the glacier, so a region of large glaciers can see more water for decades, while a region of small ones has already begun to lose it *(check)*.

> **NOT JUST WATER SUPPLY**
>
> Meltwater has other effects. It feeds **glacial lakes**, held back by moraines or ice, which can burst; this is the subject of How Glaciers Work 10. And it reaches the sea. Glaciers outside the ice sheets are a small store compared with Greenland and Antarctica, but because they are melting fast they have supplied a large share of recent sea level rise, perhaps a fifth to a quarter *(check)*.

From Ice Loss to Sea Level

How Glaciers Work 7 used a sea level to find an ice volume. The snippet below runs the other way. A mass loss in gigatonnes (1 Gt is a billion tonnes, which is one cubic kilometre of water) is spread over the ocean to give the rise in millimetres:

```
# Convert glacier mass loss in gigatonnes (Gt) a year to sea level rise, using the same
OCEAN_AREA = 3.61e14       # m2 (check)
def mm_per_year(gt):
    water_m3 = gt * 1e12 / 1000        # 1 Gt = 1e12 kg = 1e9 m3 of water
    return water_m3 / OCEAN_AREA * 1000
print(" mass loss (Gt a year)   sea level (mm a year)   over 50 years (mm)")
for gt in (100, 270, 400):
    mm = mm_per_year(gt)
    print(f"{gt:19d}   {mm:19.2f}   {mm * 50:17.0f}")
#  mass loss (Gt a year)   sea level (mm a year)   over 50 years (mm)
#                 100                  0.28                 14
#                 270                  0.75                 37
```

```
#               400               1.11               55
```

A loss of 270 Gt a year is only about 0.75 mm of sea level a year, and 37 mm over 50 years. This looks small, but it adds to what the ice sheets, and the warming of the ocean itself, add. The sum of all sources is several millimetres a year, and a few millimetres a year is a few centimetres in a decade *(check)*. The small mountain glaciers are never going to raise the sea by metres, because there is not enough ice. If all of them melted, the sea would rise by about a third of a metre *(check)*, in comparison with about 7 m for Greenland (How Glaciers Work 7).

Common mistakes

Treating one year as a trend (a snowy winter can give a good year inside a long decline); confusing the glacier's length with its mass (the front may retreat for years after the mass balance has turned); assuming all glaciers behave alike (the Karakoram and Alaska differ); forgetting that more meltwater now can mean less later (peak water); mixing up metres of ice with metres of water equivalent; and blaming the orbit, which changes over thousands of years, for a change that has happened in decades (How Glaciers Work 8).

EXERCISE 1

Using the ten stake years from the chapter, work out the average yearly loss in metres of ice. Then print how long a glacier 20, 40 and 80 m thick would last if it lost ice at that average rate. Finally, print how long a 40 m glacier would last if every year were as bad as the worst year in the record. What does the difference tell you about using the average for a forecast?

View solution

EXERCISE 2

Run the peak water model for three shrink rates, 1%, 2% and 4% a year, keeping the same starting melt and the same rise. For each, print the year of peak water, the peak itself, the meltwater in year 100 and that as a percentage of the start. What does it mean when the peak year is 0, and which glacier would still be giving more water than it did at the start after a century?

View solution

EXERCISE 3

Using the two height grids from the chapter, print the mean height change for each of the four rows together with the mean old height of the row. Then print the total mass change with an assumed density of 850 and of 900 kg/m^3, and the percentage difference between them. Which part of the glacier thinned most, and how much does the density assumption matter?

View solution

QUICK REFERENCE

- **Observed loss:** most glaciers outside the ice sheets are shrinking, about 270 Gt a year in 2000 to 2019 *(check)*, with large regional differences
- **Mass balance:** measured with stakes and pits in m w.e.; one bad year can undo several good ones
- **Geodetic method:** subtract an old DEM from a new one; mean change times area times density gives mass
- **Satellites:** laser altimeters measure height, gravity satellites measure total mass
- **Methods check each other:** disagreement points to a bias such as density or debris cover
- **Peak water:** a shrinking glacier first releases more water, then less than before
- **Gt to sea level:** about 361 Gt of water is 1 mm of sea level *(check)*, so 270 Gt a year is about 0.75 mm a year
- **Length lags mass:** the front can keep retreating after the mass balance has improved

COMING NEXT

How Glaciers Work 10 is the last chapter. It is about living with glaciers: how to travel on them safely, what dangers glacial lakes and collapsing ice bring, what to watch for, and a recap of the whole course.

How Glaciers Work

Chapter 10 · Living With Glaciers

How Glaciers Work 9 measured glaciers from a safe distance, with satellites and spreadsheets. This last chapter is about the people who live near them, work on them or walk across them. A glacier is a beautiful and useful neighbour, and it is also a moving, cracking, melting landscape. Almost every hazard in this chapter comes from something you already know: ice that flows (How Glaciers Work 3), crevasses and icefalls (How Glaciers Work 5), and meltwater (How Glaciers Work 9). The snippets are short and run in plain Python.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The numbers are made up to show the method, and this chapter is an introduction, not a safety manual: nobody should travel on a glacier because of a course, and a real trip needs training, equipment and, for beginners, a qualified guide. Where a figure is approximate or has not been checked against a source it is marked *(check)*.

Travelling on a Glacier

The main danger for a walker is the crevasse, and the main reason it is dangerous is that it can be hidden. A winter snowfall can bridge a crevasse with a layer of snow that looks like the rest of the surface. The bridge is strongest in the cold early morning, when it is frozen hard, and weakest in the warm afternoon *(check)*. This is why mountain guides start early and finish early. The standard answer to the risk has several parts that work together:

PRECAUTION	WHAT IT DOES	WHY IT WORKS
Rope team	people travel roped together with a few metres of rope between them	if one person falls into a crevasse, the others hold the rope
Harness and crampons	attach people to the rope and grip the ice	a fall on bare ice is hard to stop without crampons and an axe
Early start	cross the glacier while it is still frozen	snow bridges and stream crossings are safest before the sun has warmed them

PRECAUTION	WHAT IT DOES	WHY IT WORKS
Route choice	avoid icefalls, steep seracs and the paths of avalanches	the best fix for a hazard is not to be under it
Rescue skills	practise pulling a person out with pulleys and anchors	a rescue has to work in minutes, with cold hands, and cannot be learned on the day
Weather and conditions	check the forecast, the freezing level and recent snow	fog hides crevasses, and a warm night means soft snow in the morning *(check)*

The same logic works for water. A glacier stream is small and gentle in the cold of the morning and then, as the sun melts more ice, it swells through the day and peaks in the late afternoon or evening *(check)*. The snippet below uses a made-up daily cycle, a base flow of 2 m^3/s plus a daytime bump that peaks at midday, and marks the two-hourly crossing times when the flow is under a limit of 3 m^3/s:

```
# Plan a stream crossing: glacier meltwater peaks in the afternoon, so when is the strea
import math
def flow(hour):
    return 2.0 + 3.0 * max(0.0, math.sin(math.pi * (hour - 6) / 12))
LIMIT = 3.0
print("hour   flow (m3/s)   crossing")
for h in range(0, 24, 2):
    print(f"{h:02d}:00   {flow(h):9.2f}     {'OK' if flow(h) <= LIMIT else 'too high'}")
# hour   flow (m3/s)   crossing
# 00:00        2.00     OK
# 02:00        2.00     OK
# 04:00        2.00     OK
# 06:00        2.00     OK
# 08:00        3.50     too high
# 10:00        4.60     too high
# 12:00        5.00     too high
# 14:00        4.60     too high
# 16:00        3.50     too high
# 18:00        2.00     OK
# 20:00        2.00     OK
# 22:00        2.00     OK
```

The flow is at its base value until 06:00, climbs to 5.0 m³/s at 12:00 and drops again by evening. A walker who reaches the stream at 10:00 faces more than twice the flow of one who arrives at 06:00. Real streams peak later than midday, because the water takes time to run through and under the ice, but the lesson is the same: the time of day is part of the route. The Alps are among the most visited glacier regions in the world, with tens of thousands of people on the ice every summer, and most of them go in guided groups that leave before dawn *(check)*.

Choosing a Route by Hazard

A route is a trade-off. The short way is rarely the safe way, and hazards are not equally bad, so the useful question is how likely the hazard is and how bad the result would be. The snippet scores three made-up route options on four hazards, with weights that make an icefall (collapse without warning) and a lake (a big, sudden flood) count for more than a steep slope:

```
# Score three route options by adding up weighted hazards (1 = low, 5 = high)
WEIGHTS = {"crevasses": 3, "icefall": 5, "lake": 4, "slope": 2}
ROUTES = {
    "Valley glacier, early start": {"crevasses": 3, "icefall": 1, "lake": 1, "slope": 1}
    "Short cut under the icefall": {"crevasses": 2, "icefall": 5, "lake": 1, "slope": 3}
    "Moraine rim above the lake":  {"crevasses": 1, "icefall": 1, "lake": 4, "slope": 4}
}
for name, hz in sorted(ROUTES.items(), key=lambda kv: sum(WEIGHTS[k] * v for k, v in kv[
    score = sum(WEIGHTS[k] * v for k, v in hz.items())
    print(f"{score:3d}  {name}")
#  20  Valley glacier, early start
#  32  Moraine rim above the lake
#  41  Short cut under the icefall
```

The early-start route on the valley glacier scores 20 and the short cut under the icefall scores 41, twice as bad. Note that the safest route is not hazard-free: it still has crevasses (score 3), which is why it is done roped and in the early morning. The numbers are not magic, since a different set of weights could change the order. What the exercise does is force you to write down what you are afraid of and how much, which is the first step of any risk assessment.

Glacial Lakes and Outburst Floods

When a glacier retreats, it often leaves a hollow in the rock that fills with meltwater, held in place by a dam of moraine (How Glaciers Work 6) or by the ice itself. These **proglacial lakes** have grown in number and size in most mountain regions as glaciers have retreated *(check)*. If the dam fails, because the moraine is breached by a wave or the ice dam floats or the lake overflows, the lake can empty in hours or days. The result is a **glacial lake outburst flood**, or GLOF. What starts the failure is often something above the lake, such as an avalanche of rock or ice falling into the water and making a wave that overtops the dam *(check)*.

These events are rare but severe. A flood from a lake above the Peruvian city of Huaraz in 1941 killed thousands of people *(check)*, and Himalayan floods have destroyed bridges, roads and hydropower stations far from the lake *(check)*. In Iceland, floods called *jökulhlaups* come from lakes under the ice, often driven by volcanic heat, and are watched closely *(check)*. The size of the danger depends on the volume of water, how fast it drains, and how far and how steep the valley is below. The snippet works out the first two for a small lake, and the time a flood would take to reach villages downstream:

```
# A glacial lake outburst: how big is the lake, and how long does the flood take to arri
AREA_KM2, DEPTH_M = 0.8, 25
lake = AREA_KM2 * 1e6 * DEPTH_M
print(f"Lake volume: {lake / 1e6:.0f} million m3 = {lake / 2500:,.0f} Olympic pools")
for hours in (1, 6, 24):
    q = lake / (hours * 3600)
    print(f"Drains in {hours:2d} h: average {q:9,.0f} m3/s")
SPEED = 6
print("Warning time before the flood front arrives (6 m/s):")
for km in (4, 12, 30):
    print(f"  {km:3d} km downstream: {km * 1000 / SPEED / 60:5.1f} min")
# Lake volume: 20 million m3 = 8,000 Olympic pools
# Drains in  1 h: average     5,556 m3/s
# Drains in  6 h: average       926 m3/s
# Drains in 24 h: average       231 m3/s
# Warning time before the flood front arrives (6 m/s):
#     4 km downstream:  11.1 min
#    12 km downstream:  33.3 min
#    30 km downstream:  83.3 min
```

The lake holds 20 million m^3, about 8,000 Olympic pools. If it drained over a day, the average flow would be 231 m^3/s, which is about the flow of a big river and could be survived in a wide valley. If it drained in an hour, the average flow would be 5,556 m^3/s, many times the flow of a big river *(check)*, and a narrow valley would be turned into a torrent carrying boulders. A flood front at 6 m/s (about 22 km/h) would reach a village 4 km below the lake in 11 minutes, which is barely time to leave a house. That is why warning systems, escape routes and land-use rules matter so much downstream, and why a village 30 km away has a much better chance than a hamlet that is 4 km away.

WAY OF REDUCING THE RISK	EXAMPLE	STRENGTH	WEAKNESS
Lower the lake	dig a channel or pump or siphon water out to reduce the level	removes part of the danger permanently	costly, remote, and the work itself is dangerous *(check)*
Early warning	level sensors, cameras and sirens linked to downstream villages	saves lives even when the flood cannot be stopped	needs power, signal and regular maintenance in a harsh place *(check)*
Land-use planning	no houses, schools or power stations on the flood path	cheap and permanent	people live there already, and valley floors are the best farmland
Mapping and monitoring	satellite surveys of lake area, dam condition and slopes above	finds the dangerous lakes before they fail	there are thousands of lakes, and few can be inspected on the ground *(check)*

What to Watch

A lot of glacier safety is about noticing change. The signs listed below are what mountain communities, guides and scientists look for, and several of them are things you could measure with the methods of How Glaciers Work 9:

- **A growing lake:** a lake that has doubled in area in a few years, or one that sits right under a steep glacier front or unstable slope
- **A rising level:** a lake that rises quickly and at a steady rate is more worrying than one that rises slowly and then falls, which is why monitoring looks at the rate as well as the level (Exercise 3)

- **Unstable slopes:** as ice retreats and permafrost warms, the rock above can lose its support and fall *(check)*
- **A change in the stream:** a river that suddenly turns muddy, rises with no rain, or falls away abruptly can mean something is moving or blocked upstream
- **Sounds and cracks:** new crevasses, groaning ice and falling stones are all signs to leave, quickly and by the way you came
- **A warm spell:** a hot, rainless week, or rain on snow, increases melt, softens snow bridges and raises streams *(check)*

Common mistakes

Trusting a snow-covered surface because it looks the same as the rest; leaving a crossing until the afternoon; using the shortest route rather than the safest; camping or building on the path of a flood because it is flat and sheltered; assuming that a lake which has been stable for years is safe for ever; relying on an alarm that nobody has tested; and treating a course, or a book, as a substitute for training and a guide.

EXERCISE 1

The lake in the chapter has an area of 0.8 km² and a mean depth of 25 m. Three villages lie 4, 12 and 30 km downstream. Print the lake volume, then for flood-front speeds of 3, 6 and 10 m/s print how many minutes each village has before the flood arrives. How much warning does the nearest village get in the fastest case, and what does that say about where to put a siren?

View solution

EXERCISE 2

Using the daily stream-flow model from the chapter, print the peak flow and the hour it happens. Then, for three limits (2.5, 3.5 and 4.5 m³/s), print how many hours of the day the flow is under the limit, and how many of those hours fall between 06:00 and 20:00. What happens to the safe daytime window when the limit is low?

View solution

EXERCISE 3

A lake level sensor gives one reading a day, in metres above the usual level: 0.0, 0.1, 0.2, 0.3, 0.4, 0.7, 1.2, 1.9, 2.8. Write a loop that prints the level, the average rise per day over the last three readings, and a status: WARN at 1.0 m, ALARM at 2.0 m, and ALARM as well if the rate of rise reaches 0.6 m a day. On which day does the rate trigger the alarm, and would the level alone have raised it on the same day?

View solution

QUICK REFERENCE

- **Crevasses can be hidden:** snow bridges are strongest in the cold morning and weakest in the warm afternoon *(check)*
- **Travel precautions:** rope team, harness, crampons, early start, route choice, rescue practice
- **Streams peak with the sun:** the time of day is part of the route
- **Risk scoring:** weight hazards by how bad they are, and write down what you are afraid of
- **GLOF:** a glacial lake outburst flood, when a moraine or ice dam fails and the lake empties in hours or days
- **Flood arrival time:** distance divided by speed, so a village 4 km away at 6 m/s has about 11 minutes
- **Reducing risk:** lower the lake, early warning, land-use planning, mapping and monitoring
- **Watch:** growing lakes, rising levels and their rate, unstable slopes, changes in streams, new cracks, warm spells

Course Complete

That is all ten chapters. Here is the whole course in one pass, with the idea that each chapter added:

CHAPTER	BIG IDEA
1 What Is a Glacier	a glacier is ice that is thick enough to flow, formed where more snow falls than melts
2 Snow Into Ice	snow is compressed through firn into ice, trapping air bubbles that record old atmospheres
3 How Ice Flows	ice moves by deforming internally and by sliding on its bed

CHAPTER	BIG IDEA
4 Mass Balance	the budget of accumulation and ablation decides whether a glacier advances or retreats
5 Crevasses and Icefalls	ice cracks where the stress is high and the flow is fast
6 Carving the Land	glaciers shape valleys, fjords and moraines, and leave erratics behind
7 Ice Sheets and Ice Shelves	the two big ice sheets hold most of the ice and the most sea level
8 Ice Ages	slow orbital cycles pace the glacial and interglacial periods
9 Climate Today	glaciers are measured by stakes, maps and satellites, and most are losing mass
10 Living With Glaciers	the same physics makes hazards and water supplies, so watch, plan and respect them

Looking back, one theme runs through the chapters: a glacier is a balance. Snow comes in at the top, ice goes out at the bottom, and the shape, the flow, the crevasses, the valley and the water supply all follow from how that balance is struck. When the balance changes, as it has between the ice ages and as it has in recent decades, everything else changes with it, and the changes are measured, in the end, with the same few ideas you have used in these exercises: areas, thicknesses, densities, rates and a bit of arithmetic.

WHERE TO GO FROM HERE

If this course has interested you, there are good ways to carry on. Fieldwork courses, such as a mountain skills or avalanche awareness course, teach the practical side. Courses on climate, oceans, and landscape and rivers give the wider picture of how ice fits in with the rest of the Earth, and mapping and data courses, using free satellite images and open glacier datasets, let you do your own measurements. Maybe the best next step is a visit: a guided walk to the edge of a glacier in the Alps, Norway or Iceland shows you everything in this course at once.