

HISTORY COURSE

The History of Timekeeping

8 Chapters

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THE HISTORY OF TIMEKEEPING

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The History of Timekeeping

Course 2 · Chapter 1 · Why Timekeeping? Scope & Sources

Every day in Edinburgh, except Sundays, a gun is fired from the Castle at one o'clock. It began in the 1860s so that ships in the Firth of Forth could set their chronometers by it (check the date), and it still sounds across Princes Street today. The gun is a good place to begin a history of timekeeping, because it shows what the subject is really about: not clocks as objects, but agreement. A clock is only useful if many people trust it and set themselves by the same signal. This chapter explains why people needed to measure time, what nature offered them to start with, the main kinds of device the course will follow, and how to tell solid evidence from legend.

Why Measure Time at All?

For most of human history the need was practical rather than precise.

Farming and seasons

When to sow, when to expect floods, when to move the flocks. The need was for a calendar, not a clock.

Religion and ritual

Prayers, festivals and sacrifices had to happen at the right moment. Much of the early demand for accurate time came from priests and monasteries.

Trade, law and travel

Markets, courts, sailing and later railways all needed people in different places to agree on when something would happen.

Nature's Own Clocks

Before any device, there were three cycles that everyone could see.

Cycle	What happens	What it gave people
The day	The Earth turns once, so the Sun rises and sets	The basic unit; the position of the Sun or a shadow marks the hours
The month	The Moon runs through its phases in about 29.5 days	The first calendars; the word "month" is related to "moon"
The year	The Earth circles the Sun, giving the seasons in about 365.25 days	The farming and festival calendar

The trouble is that these three do not fit together neatly. A lunar month is not a whole number of days, and a year is not a whole number of months or days. Much of the story of calendars (Chapter 3) is a long series of compromises over this mismatch.

The awkward arithmetic

Twelve lunar months come to about 354 days, roughly eleven days short of a solar year (check the figure). A purely lunar calendar therefore drifts through the seasons, while a purely solar one ignores the Moon. Almost every calendar in history is a trade-off between the two, and the leap day and leap month are the patches.

The Main Kinds of Device

The course follows a small number of ideas through time, each solving a problem the last one left.

Device	Principle	Main weakness
Sundial	The Sun's shadow moves across a marked surface	Useless at night or under cloud, and the hours shift with the seasons
Water clock	Water flows at a steady rate, so its level marks the time	The flow varies with temperature and pressure
Mechanical clock	A falling weight released in small steps by an escapement	Poor accuracy at first; needed constant resetting

Device	Principle	Main weakness
Pendulum clock	A swinging weight keeps a steady beat	Cannot be used on a moving ship
Marine chronometer	A spring-driven watch made resistant to motion and temperature	Costly and delicate
Quartz and atomic clocks	A vibrating crystal or atom gives a very regular beat	Need coordination to stay in agreement with the Earth's slightly irregular rotation

What the Course Covers

Chapters	Theme
2–3	Shadows, water and the first calendars
4–5	The mechanical clock and the pendulum
6–7	Longitude at sea; railways, time zones and modern clocks
8	How time is kept today

> **What the course leaves out**
>
> This is an introduction for the curious, not a manual for repairers or a technical history of horology. It uses plain language and keeps mechanisms to the ideas that matter for the story. It touches only briefly on the calendars of cultures outside the main line of European and Mediterranean development, and says so where it does.

Record, Legend and Round Numbers

Three kinds of claim need different handling in a subject full of "firsts".

Record

Legend

Surviving objects, dated documents, and accounts by named people who saw the thing. These carry the most weight, but they survive unevenly.

Stories such as a single inventor producing a clock in a flash of inspiration. Real clocks emerged over generations, and "the first clock" is usually a claim about the earliest surviving evidence, not the earliest clock (check any such claim).

Round numbers

Dates like "the 14th century" or "about 1300" are honest about uncertainty. Be wary of a precise date for the start of something gradual.

A note on accuracy

Dates, names and figures in this course are given from general knowledge and flagged "check" where they are uncertain. Before quoting a date or an inventor's name elsewhere, confirm it with a museum, a specialist society or a reliable reference.

Where to See and Read More

- **Museums.** The National Museum of Scotland in Edinburgh, the Science Museum in London and the Royal Observatory at Greenwich all hold historic clocks and instruments (check current displays).
- **Public clocks.** Church towers, town halls and railway stations are part of the story, and the Castle gun is one more.
- **Specialist societies.** Clock and watch societies publish histories and guides for beginners.
- **Old sundials.** Many Scottish houses and churchyards carry one, often with a motto about time.
- **A home experiment.** A stick in the ground and a notebook make a working sundial, and the course returns to this in Chapter 2.

Exercises

EXERCISE 1

In three sentences, explain why a purely lunar calendar drifts out of step with the seasons, and name one way calendars have dealt with the problem.

→ Solution

EXERCISE 2

Sort these into record, legend or round number: (a) a dated entry in a monastery account book recording payment for a clock; (b) the story that one named man invented the clock in a single moment; (c) "mechanical clocks appeared in the later 14th century".

→ Solution

EXERCISE 3

Push a stick upright in the ground (or use a fence post) on a sunny day. Mark the end of its shadow at three times, such as 10:00, 12:00 and 14:00, and write two sentences on how the shadow's length and direction changed.

→ Solution

Quick Reference

- **Why measure time:** farming, ritual, trade, law and travel
- **Natural clocks:** the day, the lunar month (about 29.5 days), the year (about 365.25 days)
- **The mismatch:** the three cycles do not divide evenly, so calendars are compromises
- **Devices:** sundial, water clock, mechanical clock, pendulum clock, chronometer, quartz and atomic clocks
- **Handling sources:** separate record, legend and round numbers
- **First stops:** museums, public clocks, specialist societies

- **Check:** the date of the Castle gun, the figure for the lunar year, claims about "firsts", current museum displays

Next chapter: Sun, Shadow and Water, which covers sundials, water clocks and how the day came to be divided into hours.

The History of Timekeeping

Course 2 · Chapter 2 · Sun and Water

Before there were gears there were shadows and dripping water. For thousands of years, the two best ways to tell the time of day were to watch where the Sun's shadow fell and to measure how much water had run out of a vessel. Both were in use in the ancient Mediterranean and the Near East, both had clear weaknesses, and both left us something lasting: the habit of dividing the day into hours. This chapter follows the shadow clock, the sundial and the water clock, looks at the lesser candle and incense clocks, and explains why an "hour" did not always mean the same length of time.

Shadow Clocks and Obelisks

The simplest clock is a vertical post. As the Sun climbs, the shadow shortens; as it descends, the shadow lengthens, and its direction swings round. Tall stone obelisks in ancient Egypt are often described as serving this purpose among others (check how far this was their main use). Smaller portable shadow clocks, with a crossbar casting a shadow along a marked scale, survive from Egypt from perhaps the middle of the second millennium BC (check the date).

> **Why the hours were uneven**
>
> Many ancient systems divided the period from sunrise to sunset into a fixed number of parts, commonly twelve. Since daylight is longer in summer than in winter, a daytime hour in June was longer than one in December. These "seasonal" or "temporal" hours were common in the ancient world and for a long time afterwards (check the details by region). Equal hours, the same length all year round, took centuries to become the norm.

The Sundial

A sundial improves on the post by tilting the shadow-casting edge, the gnomon, so that it points at the celestial pole, parallel to the Earth's axis. A gnomon set at this angle gives the same shadow direction at the same time every day of the year, so one marked dial can show equal hours. Greek and Roman writers describe a range of dial forms, and the Roman writer Vitruvius,

in his work on architecture, lists several types (check). Sundials remained common long after mechanical clocks appeared, and many were used to set the early clocks.

Type	How it works	Where you may see it
Horizontal dial	A flat plate with a raised gnomon, angled for the local latitude	Gardens and parks
Vertical dial	Fixed to a wall, usually facing south	Churches, houses, castles
Equatorial dial	The dial plate is parallel to the equator, so the hour marks are evenly spaced	Modern gardens and sculptures
Portable dial	A small dial, sometimes with a compass for orientation	Museum collections

Sundial time is not clock time

A sundial shows local solar time. Because the Earth's orbit is elliptical and its axis is tilted, the Sun runs ahead of or behind a steady clock by up to roughly a quarter of an hour during the year (check the figure). This difference is called the equation of time, and good dials carry a correction table. There is also a small shift for longitude: Edinburgh's solar noon is a little behind Greenwich's.

Water Clocks

A sundial is useless at night and on a cloudy day. The water clock, called a clepsydra in Greek, answers both problems. In its simplest form, water drips from a hole in a vessel, and marks on the inside show how much time has passed as the level falls. Examples are known from ancient Egypt, where a surviving vessel from the reign of Amenhotep III is often cited (check), and the device was used in Greece and Rome, among other things to time speeches in the law courts (check).

Outflow type

Water leaves a vessel through a small hole, and the falling level is read against marks. Simple, but the flow slows as the level drops.

Inflow type

Water flows into a vessel with a float, which rises and points to the hour. Better designs

kept the supply tank topped up to give a steadier flow.

Elaborate versions

Hellenistic and later makers added gears, figures and alarms. A famous medieval example is an elaborate water clock built in China in the late eleventh century (check the date and the maker).

The main trouble with the water clock was control of the flow. Warm water is thinner than cold, and the pressure changes as the level changes, so accuracy was always limited. Good makers addressed this with constant-level tanks, but the clock needed regular checking against the Sun.

Candles, Incense and Sand

Other devices measured time by burning or flowing at a steady rate.

- **Candle clocks.** A candle marked in bands burns down at a roughly even rate. They are described in various sources, with a famous account of King Alfred using candles to measure his day, which may be partly legend (check).
- **Incense clocks.** Used in East Asia, a trail or stick of incense burns along a marked path, sometimes with threads that drop weights at set points.
- **Hourglasses.** Sand running between two glass bulbs. The device appears in records from about the fourteenth century (check), and became common at sea.

Handle "firsts" with care

It is tempting to say a particular culture invented a particular device, but the surviving evidence is patchy. A device first appearing in a surviving document or object does not show that it was not in use earlier. The safest wording is "the earliest surviving evidence" rather than "the inventor".

How the Day Got Its Hours

The division of the day into twenty-four parts is usually traced to the Egyptians, who divided the night by the rising of certain stars and the day by the Sun, and to the Greek astronomers, who later fixed equal hours for their calculations (check the details). The division into sixty minutes and sixty seconds is usually credited to the Babylonian number system, which used base sixty (check). The sixty-based system lives on in our clocks and in angles on a circle.

Exercises

EXERCISE 1

Explain in three sentences why a daytime "hour" of twelve parts between sunrise and sunset would be longer in an Edinburgh June than in an Edinburgh December.

→ Solution

EXERCISE 2

List one strength and one weakness of each of these: a sundial, an outflow water clock and a candle clock. Which would you rather rely on for timing a night watch, and why?

→ Solution

EXERCISE 3

Make a simple water clock: pierce a small hole near the bottom of a plastic cup, hold it over a bowl and fill it with water, and record how much has run out at 30-second intervals. Write two sentences on whether the flow stayed steady.

→ Solution

Quick Reference

- **Shadow clock:** a post or bar whose shadow length and direction mark the hour
- **Seasonal hours:** daylight split into twelve parts, so longer in summer

- **Sundial:** gnomon parallel to the Earth's axis, giving equal hours
- **Equation of time:** sun time differs from clock time by up to about a quarter of an hour
- **Water clock:** clepsydra; steady flow was the main problem
- **Other timers:** candles, incense, hourglasses
- **Base sixty:** the Babylonian number system lies behind minutes and seconds
- **Check:** early dates, the obelisk purpose, named makers and the account of King Alfred

Next chapter: Calendars, which covers lunar and solar years, the Roman and Julian calendars and the Gregorian reform.

The History of Timekeeping

Course 2 · Chapter 3 · Calendars

In September 1752, the British Isles and their American colonies went to bed on Wednesday 2 September and woke on Thursday 14 September. Eleven days had been removed from the calendar, and the tale of rioters crying "give us our eleven days" has been told ever since, although historians doubt that there were real riots over it (check). Scotland, for its part, had already moved the start of the year to 1 January in 1600 (check), a century and a half before England. This chapter explains why calendars need such repairs, follows the main steps from the Egyptian and Roman calendars to the Julian reform, and shows how and why the Gregorian calendar replaced it.

Three Kinds of Calendar

As Chapter 1 showed, the Moon and the Sun do not fit together neatly. Calendars choose one of three ways of dealing with this.

Lunar

Months follow the Moon, and the year is twelve of them, about 354 days. The seasons drift. The Islamic calendar is the best-known example still in use.

Solar

The year follows the seasons, and months are only a convenient division. The modern civil calendar is of this kind.

Lunisolar

Months follow the Moon but an extra month is added every few years to keep in step with the seasons. The Hebrew calendar and the traditional Chinese calendar work this way (check the details).

From Egypt to Rome

The ancient Egyptians are often credited with a civil calendar of twelve months of thirty days plus five extra days, making 365 (check). It had no leap day, so it slowly slid against the true solar year, by about one day every four years.

The early Roman calendar had a short year, traditionally said to have started in March, with an unreliable system of added months managed by priests. The officials who controlled the insertions could and did use them for political ends, extending or shortening the term of a magistrate (check). By the time of Julius Caesar the calendar had slipped badly out of step with the seasons.

> **The Julian reform**
>
> In 46 BC, Julius Caesar, advised by astronomers including Sosigenes of Alexandria, introduced a solar calendar of 365 days with an extra day every fourth year (check the details). The year of transition was exceptionally long, sometimes called the "year of confusion" (check). The Julian calendar took the year as 365.25 days. This was close, but about eleven minutes too long (check the figure), and over centuries the error added up.

Why the Julian Calendar Drifted

The true solar year, from one spring equinox to the next, is nearer 365.2422 days. The Julian calendar's extra 0.0078 days a year amounts to about one day in 128 years. By the sixteenth century the equinox had slipped about ten days from where the Church fathers had placed it in the fourth century (check). That mattered because the date of Easter was tied to the spring equinox, and Easter was drifting later into the year.

The Gregorian Reform

Pope Gregory XIII issued a bull in 1582 reforming the calendar (check the date). The main changes were these.

Change	What it did
Skipping ten days	In the countries that adopted it first, 4 October 1582 was followed by 15 October (check)

Change	What it did
New leap rule	A year divisible by 4 is a leap year, except century years, which must also be divisible by 400
Result	An average year of 365.2425 days, off by about a day in three thousand years or so (check)
Easter	The rules for calculating Easter were adjusted to match

Under the new rule, 1900 was not a leap year but 2000 was.

> **Politics, not astronomy, set the pace**
>
> The reform was issued by a Pope, so Protestant countries were slow to accept it. Britain and its colonies switched only in 1752, when the gap had grown to eleven days. Russia changed after its revolution in 1918, and Greece in 1923 (check the dates). For a long period, travellers crossing Europe could find the date changed at a border.

Other Quirks We Still Live With

- **Month names.** September to December are named for the numbers seven to ten, a leftover from when the Roman year began in March (check).
- **July and August.** Named for Julius Caesar and Augustus, who gave their names to months (check).
- **The seven-day week.** It does not match any astronomical cycle exactly, and comes from older traditions whose details are debated (check).
- **The new year.** In Britain, the legal year began on 25 March until 1752 in England, and on 1 January in Scotland from 1600 (check).

> **Reading old dates**
>
> Documents from the period of change may carry two years, such as "1688/9", or be marked "Old Style" or "New Style". When using old records, always check which calendar the writer was using before comparing dates, since the same event can carry two different dates.

Exercises

EXERCISE 1

State the Gregorian leap-year rule, and use it to decide whether each of these was or will be a leap year: 1600, 1700, 1900, 2000, 2024, 2100.

→ Solution

EXERCISE 2

If the Julian calendar gains one day every 128 years, roughly how many days of error would build up between 325 and 1582? Compare your answer with the ten days that the 1582 reform removed.

→ Solution

EXERCISE 3

Pick a historical event dated in a book or museum label and find out whether its date is given in the Old Style or New Style. Write two sentences on what you found and how the two dates differ.

→ Solution

Quick Reference

- **Calendar types:** lunar, solar and lunisolar
- **Julian (46 BC):** 365 days plus a leap day every fourth year; year taken as 365.25 days
- **True year:** about 365.2422 days, so the Julian calendar gained a day in about 128 years
- **Gregorian (1582):** ten days dropped; century years leap only if divisible by 400
- **Britain:** changed in 1752, removing eleven days; Scotland moved New Year to 1 January in 1600

- **Old Style / New Style:** always check which one a source uses
- **Check:** reform dates, the Egyptian and Roman details, named advisers, adoption dates by country

Next chapter: The Mechanical Clock, which covers the escapement, the first tower clocks and the monastic need for bells.

The History of Timekeeping

Course 2 · Chapter 4 · The Mechanical Clock

The word "clock" comes from the same root as the French cloche and the Latin clocca, a bell (check the derivation). That is a clue to what the first mechanical clocks were for. They did not, at first, have faces or hands. They struck a bell, to call monks to prayer or townspeople to work, and the sound mattered more than the sight. This chapter follows the invention that made them possible, the escapement, describes how the earliest clocks worked, and traces their spread from monasteries to town squares and, in time, to the home.

The Problem to Solve

A falling weight, pulling on a rope wound round a drum, can drive a train of gears. The difficulty is that a weight simply falls: left to itself it would drop to the floor in a rush. To make a clock, the energy has to be released in small, equal steps. The device that does this is the escapement.

The key idea

An escapement lets a toothed wheel advance one tooth at a time, each time with a small "tick", while a regulating part swings back and forth to control the pace. The invention of the escapement, probably in Europe in the late thirteenth century, is the point at which the mechanical clock becomes possible (check the date and place). Nobody knows who devised it, and any named inventor is a legend or a guess (check).

The Verge and Foliot

The earliest known escapement is the verge, sometimes with a balance bar called a foliot.

The crown wheel

A wheel with pointed teeth, turned by the falling weight through a train of gears.

The verge

A vertical rod with two small flags, the pallets, set at an angle so that one tooth is caught as another is released.

The foliot

A horizontal bar fixed to the top of the verge, with small weights at each end. Moving the weights in or out changes how fast it swings and so how fast the clock runs.

The weakness was that the foliot had no natural rhythm of its own. Its speed depended on the force driving the clock, and so on friction and on the state of the gears. These clocks were commonly out by a quarter of an hour or more a day (check the figure), and keepers set them against a sundial at noon.

Early Clocks in Records

Place and period	What the record shows
Italy and England, late 13th century	Documents suggest early clocks, often in religious houses; it is not always clear what kind of device they were (check)
Milan, around the 1330s	A public striking clock is mentioned (check)
Salisbury Cathedral, 1386	A clock with a verge escapement and no dial, often cited as the oldest working example in England (check the details)
Padua, around 1360s	An astronomical clock made by Giovanni de Dondi, with a display of the planets (check)
Wells and Exeter, 14th century	Cathedral clocks with astronomical dials, parts of which survive (check)

What "oldest" means

Claims that a clock is "the oldest in the world" usually depend on a definition: oldest working, oldest surviving in its original form, or oldest with a documented date. Most old clocks have been repaired, converted or had parts replaced over centuries. When you see a claim of this kind, ask which definition is being used.

Clocks in the Town

By the fourteenth and fifteenth centuries, cities across Europe were building public clocks, and the reasons were not only religious. A town clock was a matter of civic pride and of civic order.

- **Working hours.** A bell told craftsmen and market traders when to start and stop, and employers and workers sometimes quarrelled over whose time it measured (check).
- **Markets and courts.** A public time made it possible to fix the opening and closing of a market or the hour of a hearing.
- **Prestige.** Towns competed to have the grandest clock, with moving figures, astronomical dials and processions of statues. Prague's astronomical clock, begun around 1410, is a famous example (check).
- **Standard hours.** As clocks spread, equal hours of the same length all year round replaced the seasonal hours of Chapter 2 in daily life.

> **Dials came later than bells**
>
> Many early clocks had no dial at all and simply struck the hours. Dials and hands, and the hour hand in particular, became common in the following centuries, and the minute hand only became useful once clocks were accurate enough to justify it, which took the pendulum (Chapter 5).

Springs and Smaller Clocks

A weight-driven clock must be fixed in one place and needs a tall case or tower to give the weight room to fall. The coiled spring, in use by the fifteenth century (check), made smaller, portable clocks possible, and in time watches. The early spring-driven clocks had a problem of their own: a spring pulls harder when fully wound than when nearly run down, so the clock sped up and slowed down. A cone-shaped pulley called a fusee, which evened out the pull, was the answer (check the date). Nuremberg in Germany was known for its early small portable timepieces (check).

Exercises

EXERCISE 1

In four sentences, explain what an escapement does and why a falling weight alone cannot run a clock.

→ Solution

EXERCISE 2

Imagine you are a cathedral official in the fourteenth century deciding whether to buy a mechanical clock. List three arguments in favour and two against, using what you know of the alternatives (sundials, water clocks, candles).

→ Solution

EXERCISE 3

Find a public clock near you (a church, a town hall or a station). Note whether it has a dial, a bell or both, and write two sentences on what you can find out about its age and whether it is the original mechanism.

→ Solution

Quick Reference

- **Clock and bell:** early clocks struck bells; many had no dial
- **Driving force:** a falling weight (later a coiled spring)
- **Escapement:** releases the energy in small, equal steps
- **Verge and foliot:** the first escapement; simple, but poor accuracy
- **Early examples:** Salisbury (1386), Milan, Padua, Prague
- **Spring and fusee:** allowed smaller clocks; the fusee evened out the pull
- **Equal hours:** spread with the public clock

- **Check:** the date of the escapement, "oldest" claims, the dates and details of the named clocks

Next chapter: The Pendulum and Precision, which covers Galileo, Huygens, the anchor escapement and the clockmakers of Britain.

The History of Timekeeping

Course 2 · Chapter 5 · Pendulum and Precision

A well-known story says that a young Galileo, sitting in the cathedral at Pisa, watched a lamp swinging from the ceiling and timed its swings against his own pulse, noticing that they took the same time whether the swing was wide or narrow (check; the tale is probably embroidered). Whatever the truth of the story, the idea behind it changed timekeeping. A pendulum has a natural rhythm of its own, set by its length. Harnessing that rhythm took the best clocks from losing a quarter of an hour a day to losing a few seconds. This chapter follows that leap in accuracy, and the people and the mechanisms that brought it about.

The Idea of the Pendulum

A weight on a string or rod swings back and forth at a rate that depends almost entirely on its length, not on its weight or, for small swings, on how far it swings. This property, called isochronism, is only approximately true, but for small swings it is true enough to be very useful (check the details of the physics).

The pendulum rule

The time of one swing grows with the square root of the length. A pendulum about one metre long takes roughly one second to swing from one side to the other (check), which is why the "seconds pendulum" became a standard idea. A shorter pendulum swings faster; a longer one more slowly. To adjust a pendulum clock, you move the bob up or down.

Huygens and the First Pendulum Clock

Galileo studied the pendulum and, late in life, is said to have designed a clock using one, but the first working pendulum clock is credited to the Dutch scientist Christiaan Huygens, who built one around 1656 and published a description soon after (check the dates). Huygens' early clocks were reported to keep time to within about a minute a day, and later versions did better (check the figure). It was an enormous improvement on the verge and foliot of Chapter 4. Huygens also worked out the mathematics of the pendulum in detail, in a book published in 1673 (check).

Stage	Typical accuracy	Notes
Verge and foliot	Perhaps a quarter of an hour a day or worse	Set against a sundial
Early pendulum clocks	About a minute a day	Wide swings; verge escapement
Anchor escapement and long case	A few seconds a day	Narrow swings; seconds pendulum
Best observatory clocks	A fraction of a second a day	Temperature-compensated pendulums

All figures are rough guides only (check).

The Anchor Escapement and the Long-Case Clock

The early pendulum clocks still used the verge escapement, which forced the pendulum to swing through a wide arc, undermining the accuracy gain. In England in the later seventeenth century, an escapement shaped like a ship's anchor, now called the anchor or recoil escapement, was introduced, and the credit is often given to the English clockmaker William Clement or to Robert Hooke, though the matter is disputed (check). It let the pendulum swing through a small arc, where the rule of isochronism holds best.

A small arc allows a long pendulum, and a long pendulum needs a tall case. The result was the long-case clock, the grandfather clock of the popular name, which became a status piece of the British home. The name "grandfather clock" itself is said to come from a nineteenth-century American song (check).

Weights

Two or three weights hang inside the case, driving the movement and the striking. Long-case clocks run for a day, eight days or a month between windings.

Bob and rod

The pendulum hangs from a thin spring at the top. A nut under the bob lets the owner adjust the rate with a turn of the key.

Dial and hands

With the accuracy came the minute hand, and then the seconds hand, as clocks became precise enough to make them worth reading.

Fighting the Weather

A metal pendulum rod lengthens a little in warm weather and shortens in cold, so a clock runs slow in summer and fast in winter. The best makers devised compensation to cancel this. Two famous designs are the mercury pendulum, in which the expansion of liquid mercury balances the rod, and the gridiron, which uses rods of different metals (check the makers and dates). Changes in air pressure and humidity also have an effect, and observatory clocks were sometimes kept in sealed chambers.

> **Why accuracy mattered**
>
> Better clocks did not simply make life tidier. Astronomers needed them to time the passage of stars across the sky, and navigators needed them to find a ship's position at sea. The question of longitude, in Chapter 6, is where accurate timekeeping changed history most plainly.

Clockmakers in Britain

From the seventeenth century, London was one of the leading centres of clockmaking, and the Worshipful Company of Clockmakers received its charter in 1631 (check the date). Names such as Thomas Tompion and George Graham are often cited among the finest makers of the following century (check). Edinburgh had its own guild of craftsmen, and clockmakers in Scotland made long-case clocks that survive in museums and houses (check the guild details).

> **Who invented what**
>
> Disputes over priority were common in the age of the pendulum clock, with Hooke, Huygens and others each claiming credit for various devices. Historians still weigh the evidence, so treat any single-name attribution in popular accounts with caution.

Exercises

EXERCISE 1

A pendulum clock runs 30 seconds fast each day. Should you raise or lower the bob, and why? Explain in three sentences.

→ Solution

EXERCISE 2

Explain why a long-case clock is tall, and why a pendulum clock cannot easily be used on a ship.

→ Solution

EXERCISE 3

Make a pendulum from a string and a small weight. Time 20 swings with a short string and with one twice as long, and write two sentences on how the timing changed.

→ Solution

Quick Reference

- **Pendulum:** swing time depends on length; small swings are nearly equal in time
- **Huygens:** first working pendulum clock, around 1656
- **Seconds pendulum:** about one metre long, one second per swing
- **Anchor escapement:** small arc, better accuracy, tall case
- **Accuracy:** from minutes a day to seconds a day
- **Temperature:** compensated by mercury or gridiron pendulums
- **Guilds:** London Clockmakers' Company, 1631

- **Check:** the Galileo story, dates and attributions, accuracy figures and the origin of the name

Next chapter: Longitude and the Marine Chronometer, which covers why finding a ship's position needed an accurate clock, and the story of John Harrison.

The History of Timekeeping

Course 2 · Chapter 6 · Longitude at Sea

On the night of 22 October 1707, a British fleet returning from the Mediterranean ran onto the rocks off the Isles of Scilly, and well over a thousand sailors are reported to have died (check the date and the toll). The admiral and his officers had misjudged their position. They knew how far north they were, but not how far east or west. The disaster is often cited as one reason Parliament took the problem of longitude seriously. This chapter explains why finding longitude is a problem about time, follows the competing solutions, and tells the story of the clockmaker who built the machines that solved it.

Latitude Is Easy, Longitude Is Hard

A navigator can find latitude, the distance north or south of the equator, by measuring the height of the Sun at noon or of the Pole Star at night. Longitude, the distance east or west, has no fixed reference in the sky, because the Earth turns beneath it.

Longitude is time

The Earth turns through 360 degrees in 24 hours, which is 15 degrees every hour. If a navigator knows the time at a reference place, such as Greenwich, and can find local noon by the Sun, the difference in time gives the distance in longitude. One hour's difference is 15 degrees, and at Edinburgh's latitude that is a little over 900 kilometres (check the figure). The difficulty was keeping accurate time through months at sea.

Time error	Longitude error	Distance at the equator
4 seconds	1 minute of arc	About 1.9 km
1 minute	15 minutes of arc	About 28 km
4 minutes	1 degree	About 111 km

These are approximate figures (check).

The Prize and the Board

In 1714 the British Parliament passed the Longitude Act, offering rewards, the largest of £20,000 (a vast sum then; check), for a method of finding longitude at sea to a stated accuracy, and set up the Board of Longitude to judge the claims (check the details). Many proposals came in, some from cranks, but the serious contenders fell into two groups.

The astronomical method

Use the Moon's position against the stars as a kind of clock face in the sky. Accurate tables and instruments were needed, and the sums were long and tiring at sea. The method of "lunar distances" was developed in the eighteenth century and used for decades (check).

The clock method

Carry a clock set to home time and compare it with local noon. Simple in principle, but a pendulum clock cannot work on a pitching ship, and ordinary watches were not good enough.

Other schemes

Proposals included signal ships, firing guns and even a wounded-dog scheme based on a "sympathetic powder", which is best treated as a curiosity (check).

John Harrison

John Harrison, a self-taught carpenter and clockmaker from Yorkshire (check), devoted decades to the clock method. His story is often told as a battle of a lone craftsman against the scientific establishment, which is partly true but oversimplified (check).

Instrument	Date (approx.)	Notes
H1	1730s	A large brass clock with linked balances; tested on a voyage to Lisbon and back (check)

Instrument	Date (approx.)	Notes
H2 and H3	1740s to 1750s	Refinements; H3 took many years and introduced ideas that later proved useful (check)
H4	1759	A large pocket watch, far smaller than the earlier models, tested on a voyage to the West Indies in the early 1760s (check)

H4 lost only a few seconds over a long voyage, well within the terms of the Act, but the Board was cautious and demanded further trials and copies, and Harrison received his payments in stages, with the final award coming only after the intervention of the king (check). The instruments can be seen at the Royal Observatory in Greenwich (check current displays).

> **Why it was so hard**
>
> A sea clock had to cope with a ship's motion, with changes in temperature from the tropics to the north Atlantic, with changing lubrication as oil thickened or thinned, and with months of running without repair. Harrison's answers included bearings that needed no oil, parts of different metals that cancelled each other's expansion, and a very different kind of balance from the pendulum.

From Prototype to Standard Equipment

Harrison's work showed that the clock method was possible but expensive. Other makers, among them Thomas Earnshaw and John Arnold in England, simplified the design in the later eighteenth century, making chronometers that could be produced in larger numbers at lower cost (check). By the early nineteenth century, a chronometer was standard on Royal Navy ships and on many merchant vessels. Captain James Cook took such timekeepers on his later voyages, and reported well of them (check).

The lunar distance method faded as chronometers became cheaper. A ship might carry several, and compare them to catch one that had gone astray.

> **A tidy tale**

The story of Harrison the underdog is attractive, and it has been told in books and television. Recent historians point out that the Board included supporters as well as sceptics, that the astronomical method also worked, and that the awards were more complex than "the prize" suggests. Read popular versions with that in mind.

Exercises

EXERCISE 1

A navigator finds local noon at the moment the chronometer, set to Greenwich time, reads 15:00. How far east or west of Greenwich is the ship, and in which direction? Explain your reasoning.

→ Solution

EXERCISE 2

A chronometer loses 3 seconds a day. After a voyage of 60 days with no correction, how large is the time error, and roughly how far off in longitude would it put the ship at the equator?

→ Solution

EXERCISE 3

Make a list of four problems a clock faces at sea and, for each, one idea (ancient or modern) that might overcome it. Then write two sentences on which problem you think was the hardest.

→ Solution

Quick Reference

- **Latitude:** found from the Sun or Pole Star

- **Longitude:** a time difference; 15 degrees per hour
- **1707:** the Scilly disaster, a spur to action
- **1714:** the Longitude Act and the Board of Longitude
- **Two methods:** lunar distances and the chronometer
- **Harrison:** H1 to H4, a lifetime's work
- **Later makers:** Arnold and Earnshaw made chronometers affordable
- **Check:** the disaster details, prize amounts, dates of the instruments and the trials, the lunar method's timeline

Next chapter: Railways, Time Zones and the Modern Clock, which covers railway time, Greenwich, standard time zones and the quartz and atomic clocks.

The History of Timekeeping

Course 2 · Chapter 7 · Railways, Time Zones and the Modern Clock

Until the nineteenth century, noon was where the Sun said it was. Because the Sun reaches its highest point a little later as you go west, local noon in Edinburgh came about twelve and a half minutes after noon in London (check the figure), and every town kept its own time. That was no trouble when the fastest way to travel was a horse. When railways arrived, running a timetable across a country of many local times became a puzzle that only a single shared time could solve. This chapter follows that change, the creation of time zones, and the arrival of the quartz and atomic clocks that now stand behind every phone.

Local Time and the Railway Problem

Under local mean time, a town set its public clock by the Sun, or by a sundial adjusted for the equation of time (Chapter 2). A traveller going from Edinburgh to London would find their watch wrong on arrival by a few minutes, which mattered little before the train.

Timetables

A timetable showing the same departure for every station had to say whose time it used. Some early timetables listed several, which confused passengers.

Safety

Trains on single lines, running to different clocks, risked collision. Accurate shared time was a safety matter and not just a convenience.

Cost

Missed connections and arguments between companies were expensive, which gave the railways a strong reason to agree.

Railway Time in Britain

The Great Western Railway is generally credited with adopting London time along its line from 1840, and other railways followed over the next few years (check the dates). The telegraph, which ran alongside the tracks, allowed a time signal to be sent from Greenwich to stations

across the network (check). By the late 1840s most British railways ran on "railway time", which was Greenwich Mean Time, and by 1855 the great majority of public clocks had followed (check).

The law catches up

Railway time was convenient but had no legal force at first, and some towns resisted, notably those that had their own tradition of time. In 1880 a law made Greenwich Mean Time the legal time throughout Great Britain (check the date and wording). Edinburgh's clocks therefore moved a few minutes from the Sun's time to London's, and a city that had set its clocks by the Sun for centuries now set them by Greenwich.

Time Zones and the Prime Meridian

Large countries faced the problem on a bigger scale. The United States and Canada had dozens of local railway times in the 1870s, and the railways there agreed on a system of time zones in 1883 (check). The proposal of a worldwide system of zones is often linked to the Canadian railway engineer Sandford Fleming, who campaigned for it (check).

Step	What happened
1884	The International Meridian Conference in Washington chose the meridian through Greenwich as the world's prime meridian (check the vote and the details)
Zone system	The world divided into zones about 15 degrees wide, an hour apart, though real zones follow borders and politics
Adoption	Countries took up standard time over the following decades, at different speeds
Date line	A line roughly opposite Greenwich where the calendar date changes by a day

Daylight saving

The summer shift of the clocks was introduced in Britain in 1916 during the First World War to save fuel (check). The idea is often credited to William Willett, a builder, who proposed it in 1907 (check). Scotland's long summer evenings and dark winter mornings have made the topic a recurring argument ever since.

Quartz and Atomic Clocks

The twentieth century changed the foundation of timekeeping. Previously, the Earth's rotation was the standard and clocks were checked against the stars. Two new technologies took over as the reference.

- **Quartz.** A small crystal of quartz vibrates at a very steady frequency when an electric current passes through it. Quartz clocks were developed in the 1920s and 1930s (check), and became cheap enough for wristwatches from the 1960s and 1970s (check). A good quartz watch is accurate to a few seconds a month.
- **Atomic clocks.** Atoms of certain elements, such as caesium, absorb and emit radiation at an extremely precise frequency. The first practical caesium clock was built in England in the 1950s (check), and in 1967 the second was defined by caesium's frequency rather than by the Earth's turning (check). The best modern atomic clocks lose or gain about a second in many millions of years or better (check).

> **The Earth is not a perfect clock**
>
> Atomic time proved steadier than the Earth, whose rotation slows slightly and varies from year to year. To keep civil time in step with the Sun, an extra "leap second" is occasionally added to the official time scale. This is the topic of Chapter 8.

Exercises

EXERCISE 1

Edinburgh is about 3 degrees west of Greenwich. Using 4 minutes of time per degree, work out how far Edinburgh's local solar time was behind Greenwich Mean Time, and explain why this mattered for railways.

→ Solution

EXERCISE 2

A train leaves London at 09:00 and takes 8 hours to reach a city 30 degrees west. The traveller's watch is still on London time. What does a local clock, running on solar time,

read when they arrive?

→ Solution

EXERCISE 3

List the three main drivers (technology, safety and money) that pushed Britain to a single time, and for each give one sentence on how it applied. Then write one sentence on whether you think a law was necessary.

→ Solution

Quick Reference

- **Local time:** each town kept the Sun's time; 4 minutes per degree of longitude
- **Railway time:** London time spread along the railways from the 1840s
- **Law:** Greenwich Mean Time made legal in Great Britain in 1880
- **Zones:** 1884 meridian conference; zones about 15 degrees wide
- **Daylight saving:** introduced in 1916
- **Quartz:** a vibrating crystal; cheap and accurate
- **Atomic:** the second defined by caesium in 1967
- **Check:** dates of adoption, the conference details, named campaigners, accuracy claims

Next chapter: Capstone: Time Today, which covers how time is kept now, leap seconds, satellite navigation and the story as a whole.

The History of Timekeeping

Course 2 · Chapter 8 · Capstone: Time Today

The Edinburgh gun that began this course is still fired every day at one o'clock, but nobody now sets a watch by it. Your phone knows the time to a fraction of a second without being asked, and so does the cash machine, the railway signal and the trading floor. This closing chapter explains how that agreement is kept, why the world sometimes adds a second to its clocks, how satellites and networks spread the time, and what the whole story from shadow to atom tells us about how people agree on things.

Who Keeps the Time?

No single clock keeps the world's time. Instead, many national laboratories run atomic clocks, and their readings are combined into an international average.

International Atomic Time (TAI)

A steady scale made by combining a large number of atomic clocks around the world. It counts seconds and does not follow the Earth.

Coordinated Universal Time (UTC)

The civil time used worldwide. It runs at the same rate as atomic time but is kept within a second of the Earth's rotation by occasional adjustments (check the details).

Local time

UTC plus or minus a whole number of hours (sometimes half or quarter hours) set by each country, plus daylight saving where used. In Britain this is Greenwich Mean Time in winter and British Summer Time in summer.

In the United Kingdom, the National Physical Laboratory keeps national time and contributes to the international average (check). The International Bureau of Weights and Measures near Paris combines the data from laboratories around the world (check).

The Leap Second

The Earth's rotation is slightly irregular and slowing over long periods, so a day is not exactly 86,400 atomic seconds. To keep UTC close to the position of the Sun, an extra second was occasionally added at the end of 30 June or 31 December, starting in 1972 (check). There have been about twenty-seven such additions (check the count).

A debate about the leap second

Leap seconds are a nuisance for computers, because a minute with 61 seconds breaks many assumptions, and several outages have been blamed on them (check). Metrologists have voted to phase out leap seconds in the future, allowing UTC to drift further from the Sun's time, with the details and date still to be settled (check the current position). The question echoes the debates of earlier centuries: how much should the clock bend to the sky, and how much should the sky bend to the clock?

Spreading the Time

Method	How it works	Typical accuracy
Radio time signals	Broadcast from a national laboratory to radio-controlled clocks	Around a millisecond or better (check)
Internet time (NTP)	Computers ask servers for the time and correct for the delay	Milliseconds to tens of milliseconds (check)
Satellite navigation	Each satellite carries atomic clocks and broadcasts its time	Tens of nanoseconds, in the best cases (check)
Fibre links	Time and frequency sent along dedicated optical fibres between laboratories	Even better than satellites over short distances (check)

Longitude, completed

Chapter 6 showed that finding position at sea depends on time. Satellite navigation completes that story: a receiver works out its position by comparing the tiny differences in the time signals arriving from several satellites. A time error of a microsecond is a position

error of hundreds of metres, since radio signals travel about 300 metres in a microsecond (check). The chronometer problem has become a problem of nanoseconds.

What Depends on Exact Time Now

- **Financial trading.** Transactions must be time-stamped to fractions of a second to settle disputes and meet regulation.
- **Power grids.** The timing of alternating current across a network must be coordinated.
- **Mobile networks.** Base stations need shared time to avoid interfering with each other.
- **Science.** Astronomers combine telescopes across continents, and physicists test their theories with ever more precise clocks.

The Story as a Whole

Looking back across the course, a few patterns stand out.

Theme	Where it appeared
Each device fixed a weakness of the last	Sundial to water clock; verge to pendulum; pendulum to chronometer
Demand drove precision	Prayer, markets, navigation, railways, computing
Agreement mattered more than accuracy	Railway time; time zones; the Gregorian reform
Politics shaped the calendar	The Roman priests; the papal bull; the 1752 change
Legends cluster around "firsts"	Galileo's lamp; the lone inventor of the clock; the Harrison underdog tale

Reading a claim about time

When you meet a claim such as "the oldest clock", "the first accurate watch" or "the day the calendar lost eleven days", ask four questions. Which definition is being used? What is the earliest surviving evidence? Is a legend filling a gap? And which calendar and time

standard was the writer using? These four checks will serve you well in the later history of any invention.

Exercises

EXERCISE 1

In four sentences, explain the difference between atomic time, UTC and local time, and say why a leap second is needed.

→ Solution

EXERCISE 2

A satellite navigation receiver has a clock error of 2 microseconds. Using the figure of about 300 metres per microsecond, estimate the position error. Then say why the satellites carry atomic clocks while receivers do not.

→ Solution

EXERCISE 3

Choose any three of the eight chapters and write one sentence each on what problem the chapter's main idea solved and what new problem it left. Then write two sentences on which advance you think mattered most.

→ Solution

Course complete

You have followed timekeeping from a stick in the ground to a clock that would lose less than a second in the age of the universe (check). The next time you glance at a phone, or hear the one o'clock gun from Edinburgh Castle, you are looking at the end of a very long chain of agreements.

Quick Reference

- **TAI:** steady atomic scale
- **UTC:** atomic rate, kept near the Sun by leap seconds
- **Local time:** UTC plus a zone offset and any daylight saving
- **Leap seconds:** added since 1972; being phased out
- **Distribution:** radio, internet, satellite and fibre
- **One microsecond:** about 300 metres of signal travel
- **Pattern:** each device fixed a weakness; agreement mattered as much as accuracy
- **Check:** the leap second count and future, accuracy figures, the organisations' roles