HOURS, MINUTES, SECONDS

Dissecting the day

> Out of the right fob hung a great silver chain, with a wonderful kind of engine at the bottom … He put this engine to our ears, which made an incessant noise like that of a watermill, and we conjecture it is either some unknown animal, or the god that he worships; but we are more inclined to the latter opinion, because he assures us … that he seldom does anything without consulting it: he called it his oracle, and said it pointed out the time for every action of his life.
>
> – Jonathan Swift, *Gulliver's Travels*

As I approach the bottom of a long, sloping driveway just off Massachusetts Avenue, a few kilometers northwest of downtown Washington, I see that I have caught the attention of an armed guard. He advances briskly from his booth and asks in a rather serious manner if he can help me. Numerous security cameras seem to be pointed in my general direction. "I have an appointment with Dr. Matsakis up at the observatory," I explain. It turns out that I'm at the wrong driveway; I have to walk around to the left, farther up the hill. Apparently a lot of visitors to the United States Naval Observatory make the same mistake. That first driveway leads to the vice president's residence. Having no immediate business with Dick Cheney, I continue up the road. (No doubt my appearance gave me away. I suspect Mr. Cheney's visitors arrive in shiny black cars, and not on foot from the bus stop.) I wonder if the VP or his boss has ever looked through one of the observatory's many telescopes. Abraham Lincoln did. He's said to have enjoyed the view of the moon and Arcturus through the observatory's large refracting telescope.

A short walk brings me to the stately administrative building at the heart of the observatory complex. A white telescope dome rises from the west end of the building; on the roof beside it is the gold-colored "time ball" that still drops at noon each day so that ships on the Potomac can set their chronometers. The signal was no doubt more valued in 1845, when the service began, than it is in today's era of ubiquitous digital watches, radio time signals, and GPS locators.

The Time Factory

A few moments later I'm sitting down with Demetrios Matsakis, head of the observatory's Time Service department. He is dressed to the nines – gray jacket, white shirt, striped tie; if his jaw were a bit wider, he would bear a resemblance to actor Ricardo Montalbán. Matsakis has a Ph.D. in physics and worked as a radio astronomer at the observatory before being, as he puts it, "seduced by the timekeeping art." (That would seem to explain the posters of both Einstein and Stonehenge on his office wall.) He was asked to head the department about ten years ago.

When I suggest that he is the man in charge of the nation's time, Matsakis corrects me: he's in charge of the Department of Defence's time. But for most purposes, that's the same thing; many civilian applications ultimately derive their time from the USNO's clocks. Take the GPS network, for example. The satellites that make up the network depend on a set of precisely timed signals relayed between the clocks on board the satellites and the master clock here at the observatory. If the clocks are off by just a billionth of a second – one nanosecond – the system will give positions that are off by thirty centimeters.* "If you want to know where your car is, that's not too bad," says Matsakis. "But ten-nanosecond errors, twenty-nanosecond errors – the errors get bigger, and it scales right up. So that's a problem." He's not exaggerating. If you're landing the space shuttle – or even a packed 767 at O'Hare – every meter counts. Nanoseconds matter.

The master clock may be the most important machine on the site, but Matsakis explains there are nearly 100 clocks altogether. (Probably 100 on the nose "if we count the sundial," he says.) Most of them are cesium beam tube clocks: they keep time by counting the oscillations of cesium atoms, which have a natural frequency of 9,192,631,770 cycles per second. The others are called hydrogen maser clocks. They work by injecting atoms of hydrogen into a chamber called a "resonance cavity," where they oscillate with their own particular (and very stable) frequency. The technology behind the maser clocks is newer than that of the cesium clocks, and they are even more accurate. (If you want to buy one, I recommend the cesium variety. Matsakis tells me they sell for a mere $60,000 each. The maser clocks carry a $250,000 price tag.)

The challenge, however, is keeping all of these clocks in step. Each of them "has their own opinion of the time," Matsakis says. They can disagree by as much as a few nanoseconds. As the old saying goes, "A man with a watch knows what time it is. A man with two watches is never sure." Part of Matsakis's job is to develop the computer algorithms that allow the output of all those clocks to be combined into one signal that can be sent to the master clock. "The question 'What's the right algorithm?' is a subject in itself," he says. There are entire conferences devoted to working out the correct set of equations, he explains. At the time of my visit, he was organizing the Fifth International Time Scale Algorithm Symposium, which was held in Spain in early 2008. (I can't help wondering if the time-obsessed scientists paused for siesta along with the locals.)

Matsakis takes me on a tour of the USNO's various clocks, scattered among several different buildings on the observatory's grounds. All are housed in climate-controlled vaults, where the temperature is regulated to a tenth of a degree Celsius. The cesium clocks don't look like much. The squat, beige boxlike instruments resemble computer hard drives, or maybe high-end stereo amplifiers. The maser clocks are black, and a bit taller, about the size and shape of a hotel room's minibar.

There is quite a hierarchy of clocks at the observatory. "We have one 'Master Clock,' with a capital M and a capital C," Matsakis explains. "And we have other 'master clocks,' with lowercase *m*'s and *c*'s, that control their own measurement systems, and do things in parallel. They're here in case the main one breaks."

I have to ask: Has the Master Clock ever broken down?

"Oh, sure," he says. "In my ten years, it's happened twice. It seems to like to break when I'm just about to leave town. One time I was in a plane on a runway. Another time I was driving off to my son's wedding." It's not such a big deal, he assures me. "It's equipment; it can break. We have established procedures for what to do. The whole team gets together." I try to imagine a dejected, pouting "MC" being taken offline, and a bubbly, enthusiastic "mc" stepping up to the plate to fulfill the nation's precision-timekeeping needs.

The Master Clock itself – I observe it from the hallway, through a window – looks like a very ordinary stack of blue, black, and gray electronic components. Dubbed NAV-18, it has a variety of knobs and buttons; a half-dozen coaxial cables, which connect it to other machinery; and several LED displays, two of which, for some reason, read "0." The third display, with a little effort, can be deciphered as Coordinated Universal Time (UTC), which replaced Greenwich Mean Time as the world's time reference in 1972.

The Master Clock's modest appearance is deceiving: this remarkable machine "talks" to the USNO's other clocks, and constantly corrects itself to best reflect their collective timekeeping output. And it does so with staggering precision. It keeps time to within one hundred picoseconds – one hundred *trillionths* of a second – over the course of each day, every day. Had it been set when the dinosaurs went extinct, 60 million years ago, it would have gained or lost no more than about two seconds.

I glance at my watch. One of us is off by fifty seconds. I'm guessing it's me.

Keeping Time by Sun, Sand, and Water

Matsakis's clocks are the culmination of thousands of years of ever-more-precise time reckoning. We have seen how ancient skywatchers learned to track the months by following the phases of the moon; tallying the sun's daily rising and setting must be an equally primitive instinct. But dividing the day itself into smaller parts is more difficult, and marks a more recent development in our history.

Every day, the sun rises in the east, climbs high in the southern sky, and sets in the west.* Someone long ago must have noticed that if you plant a stick vertically into the ground, it casts a shadow, and the motion of the shadow mirrors the motion of the sun across the sky – and so the idea of the sundial was born. That stick would evolve into the sundial's pointer, called a *gnomon*, from a Greek word meaning "to show" or "indicate." The first sundials were probably made in the middle of the fourth millennium B.C., likely in Egypt or the Near East.

The Egyptians built sundials on both large and small scales, from giant obelisks to tiny hand-held versions. The portable "shadow clock," dating from around 1500 B.C., was an ingenious yet simple affair: when the crossbar on the T-shaped device is pointed toward the sun, its shadow falls on the ruled perpendicular shaft, allowing the user to estimate the hour. The Egyptians divided the day into twenty-four hours – an idea that may have originated with the Babylonians.* The Egyptians used their sundials to track twelve hours of daylight, with twelve more hours assigned to the darkness of night. (The number twelve was surely considered to be special, as it is roughly the number of lunar cycles in the year.)

The twenty-four-hour day is a tradition that we've kept, but with one important change: the length of the Egyptian hour would have varied with the seasons; an hour in summer was longer because the day itself was longer. Today we use hours of a fixed length – and so we count quite a few more hours of daylight in summer than in winter.

By the time of the Roman Empire, sundials had become both sophisticated and common. In the first century B.C., an architect named Vitruvius could list thirteen kinds of sundials. They were placed in public squares and private courtyards. They soon became integral to Roman society, allowing people to structure their days, which could now be mapped out into hours, and the hours cut into halves and quarters.

Not everyone was pleased. "The gods confound the man who first found out how to distinguish the hours," the Roman playwright Plautus lamented in the second century B.C. "Confound him, too, who in this place set up a sundial, to cut and hack my days so wretchedly into small portions!"

There were other timekeeping devices that didn't rely on the sun. Sand clocks work pretty much like the modern hour glass: they run for a certain interval of time, after which one turns them over and the process begins again. One could also use a slow-burning candle, with regularly spaced notches marked on its side.

Another ancient timekeeping tool was the clepsydra, or water clock. A clepsydra can be as simple as a bucket with a small hole at the bottom from which water drips at a regular rate. Marks on the side of the bucket indicate intervals of time. Alternatively, water can drip into a second vessel, with its own markings to track the hours. In the law courts of ancient Rome, water clocks were used to regulate the period that each lawyer could speak. If people wanted to hear more, they would yell out "*aquam dare*" – "add water." The Roman expression for wasting time was *aquam perdere* – literally, "to lose water."

Although water clocks were used throughout the ancient world, it was in the Far East that the most sophisticated devices were built. In fact, China's mechanical water clocks predate Europe's first mechanical clocks by several centuries. The best-known and most elaborate was the so-called Heavenly Clockwork, built by a civil servant named Su Sung and begun in A.D. 1077. This remarkable machine used flowing water to turn a giant wheel at a precise, controlled rate. The wheel carried thirty-six buckets, which filled and emptied in steady succession. By the time it was completed in 1090, the clock was nearly ten meters tall and employed dozens of wheels, bells, and gongs; it was housed in a pagoda five stories high. (Sadly, when a new emperor came to power in 1094, Su Sung's clock, along with other reminders of the old regime, was dismantled and eventually forgotten. When European clocks arrived in China centuries later, they were welcomed as a "new" invention.)

All of these instruments have obvious shortcomings: sundials are useless at night and on cloudy days, sand clocks and water clocks require constant maintenance, and water can freeze in cold weather.

Church Time

In medieval Europe, the greatest demand for reliable timekeeping came from the Church. Great cathedrals and monasteries were being built across the continent, and the monks who lived within their walls followed a strict regimen of daily activities, of which scheduled prayer was the most important. Worship began with matins in the early morning and ended with vespers in late evening. (The English word for "midday," *noon*, comes from the Latin name for the midday prayer, *none*.) At night, one of the monks would have to stay awake, keeping an eye on the water clock or the sand clock. At the appointed hour, it would be his job to ring a bell, waking the others in time for morning prayer (a ritual alluded to in the children's nursery rhyme *Frère Jacques*). One can only imagine the trouble this poor monk would have been in if he fell asleep on the job.

A solution came sometime in the thirteenth century. We don't know where the discovery was made, or who should get the credit – probably a craftsman or ironsmith working somewhere in northern Europe. He may have heard stories about the magnificent water clocks used by the Chinese, or it may have been an independent discovery. Somehow, he made the breakthrough that led to a new kind of machine for measuring time.

The crucial invention is known as the "escapement." An escapement is a device that regulates what would otherwise be a continuous movement, such as the rotation of a wheel pulled by a falling weight. At regular intervals, the escapement engages, and then disengages, the rotating wheel. This slows the wheel down and, more crucially, makes it rotate at a uniform rate. The wheel, in turn, can be geared to a mechanism for striking a bell at a particular hour. "The tick-tock of the clock's escapement," as historian Daniel Boorstin has put it, "would become the voice of time."

And while the length of an "hour" read off a sundial changed with the seasons, the hour measured by a mechanical clock remained fixed. An hour in summer and an hour in winter were now the same. The creation of "equal hours," says Boorstin, was one of the great revolutions in human experience: "Here was man's declaration of independence from the sun, new proof of his mastery over himself and his surroundings. Only later would it be revealed that he had accomplished this mastery by putting himself under the dominion of a machine with imperious demands all its own." Timekeeping had become divorced from the motion of the heavens – or nearly so. At this stage, the sundial remained the most reliable timekeeper; a clock would have to be reset from time to time, perhaps daily, as it drifted from the "true" hour given by the sundial.

These early clocks ticked because of the regular motion of the escapement, but at first they had no “hands”; it was only the bell that indicated the time. Our word *clock* comes from the French word for “bell,” *cloche* (German *Glocke*, Middle English *clok*) – although the same word could just as easily apply to a water clock or sand clock. Similarly, the Latin word *horologium* could apply to any kind of timekeeping device.

Although we can’t say who invented the mechanical clock, or precisely when, we can be sure such clocks existed in the final decades of the thirteenth century. Records show that a fully automated, weight-driven clock was installed at Dunstable Priory in Bedfordshire, England, in 1283. Within a few decades, most cathedrals and monasteries – at least those that could afford it – likely had such a device.

The Iron Voice of Salisbury

To say that the small English city of Salisbury is charming is like saying the pyramids are old or the Great Wall of China is long. Its medieval streets are lined with wonderfully preserved half-timbered houses, and the market square bustles on Tuesday and Saturday mornings as it has for seven hundred years. Thirsty visitors in need of a pint can duck into any number of creaky, low-ceilinged pubs with typical English names (the Old Ale House, the King’s Head), very English names (the Coach and Horses, the Wig and Quill), or uniquely English names (the Haunch of Venison). But the real attraction in Salisbury is the magnificent thirteenth-century cathedral and the tranquil green space – the “close” – that surrounds it. In his *Notes from a Small Island*, writer Bill Bryson declares, “There is no doubt in my mind that Salisbury Cathedral is the single most beautiful structure in England and the Close around it the most beautiful space.” No wonder John Constable set up his easel across the river to capture the serene grandeur of the cathedral and the surrounding meadows.

Salisbury Cathedral boasts many records: its towering spire, at 123 meters, is the tallest in Britain; its close is the largest. Its chapter house contains one of just four surviving original copies of the Magna Carta. It also houses what is very likely the world's oldest working clock. The machine was built in the late 1300s and was originally housed in the cathedral's bell tower; when the tower was demolished in the eighteenth century, the medieval clock was put in storage and forgotten. It was rediscovered in the early twentieth century and, after some refurbishment, was placed at ground level in the north aisle, not far from the cathedral's grand western entrance, where it stands today.

On a recent visit, I met with John Plaister, whose title is as English as the city: he's the Clock-keeper to the Dean and Chapter of Salisbury Cathedral. As we listened to the clock's hypnotic tick-tocking, Plaister explained the significance of the machine's many parts. The most visible components are the vertical, geared wheels with their iron teeth. As Plaister points out, the gears turn by the power of gravity: two stone weights hang from pulleys behind the clock; as the weights fall, they pull on ropes that unwind from a pair of horizontal wooden cylinders, turning two of the geared wheels. (One of them controls the so-called time-train; the other, the clock's striking mechanism.) When the weights reach the floor, the clock has to be "wound": the weights are hoisted back up, using a pair of iron wheels that resemble a car's steering wheel.

The most important part of the clock – probably unnoticed by most visitors – is the escapement itself. It consists of two critical components: a vertical shaft known as a "verge," and a horizontal iron bar that swings back and forth, called a "foliot." Two small weights that hang from the ends of the foliot control the rate at which the clock ticks. "Of course, a clock working for more than six hundred years has had to have some replacements," Plaister says with a plummy West Country accent. "But the majority of the clock is original."

I'm struck by how little the machine resembles what we think of as a "clock." Like all such early devices, it has no hands and indeed no "face"; only the bell (now removed) would have announced the hour. The entire mechanism is housed in a cube-shaped iron frame, a bit more than a meter on a side; one can peer straight through it.

The Salisbury clock, like all mechanical clocks of that era, was not particularly accurate, easily gaining or losing as much as fifteen minutes over the course of a day. A good Roman sundial could have done the job just as well – on sunny days, at least. "When this clock was made, an hour was only divided into four equal quarters," Plaister says. "Minutes hadn't arrived yet." Not like today, where "we all tear about … with our modern watches, to the second," he says. "They tore about to the nearest quarter or the nearest hour."

Plaister explains that although the clock's exact origins are unknown, the cathedral's records show that a man was paid to wind the clock as early as 1386. "I've no fear to say it's the oldest working clock in England," he says. "I wouldn't like to put my hand on my heart and say it couldn't be challenged, somewhere in the world. But I think it's got a good head start."

Just sixty kilometers to the west of Salisbury, about halfway between Shepton Mallet and Cheddar, sits the tiny cathedral city of Wells. It too has a medieval clock; in fact, its clock may have been designed by the same man who built the Salisbury machine. And yet the two clocks could hardly be more different.

The Wells clock has a magnificent face, with elaborate paintings of the earth, moon, sun, and stars – a colorful fourteenth-century model of the known cosmos (and one of the few surviving renderings of a geocentric – that is, pre-Copernican – world view). The clock has an hour hand that moves along a twenty-four-hour dial; the minute hand is believed to have been added in the sixteenth century.

Along with the time of day, the Wells clock displays the day of the lunar month and the phase of the moon. It also puts on a show: above the dials, a miniature medieval tournament springs to life every quarter-hour, with four tiny knights on horseback galloping in a circle – two in each direction. As the warriors spin around, one of the knights always knocks his opponent flat on his back, only to see him propped up again a few seconds later, ready for another confrontation. Over the centuries he's been knocked down some 53 million times. "We always say he should have learned to duck by now," observes Frances Neale, the cathedral's archivist. "But he never has."

These clocks were revolutionary for their day – but more advances were in store. True "striking" clocks – ringing the hours from one through twelve – were in place by the middle of the fourteenth century.

For the first time in history, anyone within earshot could know the time. Clockmakers began to give their machines dials and hands – actually just one hand, at first, to show the hour; that was all that the accuracy of these early machines justified.

But clocks were becoming ever more reliable, more accurate, and more sophisticated. A few of them were dazzling showpieces that would have been a focal point for an entire city, such as the great astronomical clocks that appeared in Strasbourg, Prague, Copenhagen, and other European centers.

Before long, clocks were ringing out from courthouses and town halls, and later from banks and businesses. Wealthy citizens began to keep clocks in their homes. Miniaturization came quickly: clocks powered by tightly wound springs rather than falling weights allowed for greater portability; the first pocket watches appeared in the early 1500s. Less than a century later, Elizabeth I wore a watch on her finger. (It even had a tiny alarm – a small prong would extend and scratch her finger at the appointed hour.) Clock time was beginning to be ubiquitous.

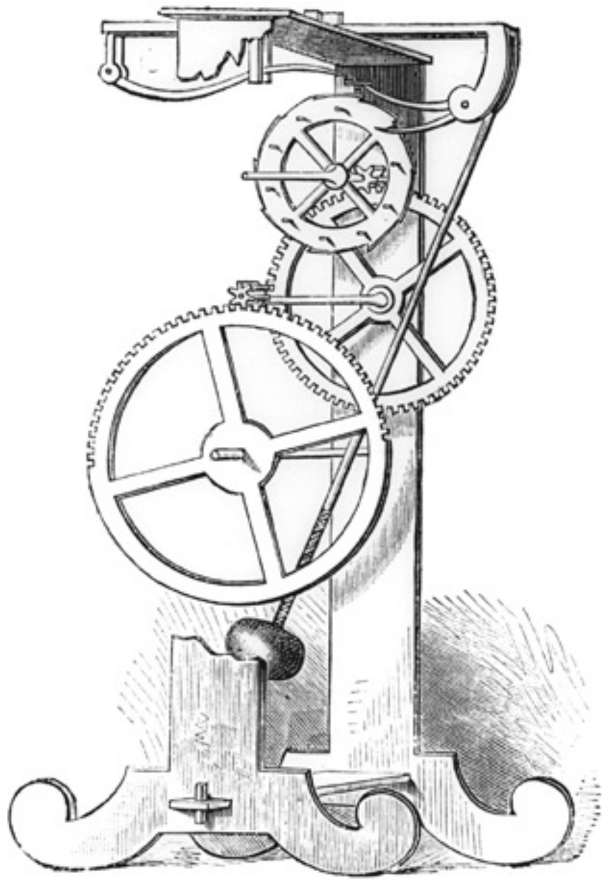
The Value of Time

Much has been written on the role of the clock in ushering in a new, more hurried way of life. Certainly the proliferation of public clocks made time more visible; at the very least, people must have begun to think of time as something that kept passing – something that unfolded relentlessly as hour followed hour. And yet the pace of life was surely on the rise even in medieval times, before the first mechanical clocks appeared on the scene. The new technology may have simply been the latest means of satisfying a well-established urge. The development of mechanical clocks "was more a consequence than a cause of the sense of urgency that arose in the Middle Ages and Renaissance," argues historian Sara Schechner. "Clocks were seen as tools to aid the administration of civic life and their bells were used to synchronize work schedules, but the same roles were given to sundials, sandglasses, and calendars."

Indeed, the quantization of time may have been part of a larger trend of assigning numbers to previously uncounted (or poorly counted) entities – what historian Alfred Crosby has called the "quantitative revolution." Anthropologist Anthony Aveni points out that perspective painting, double-entry bookkeeping, polyphonic music, monetary standards, and a new precision in weights and measures all appeared on the scene at roughly the same time. "In a relatively brief span of years around 1300," he writes, "virtually everything in the Western world became an essence to which a number could be assigned – a sea change in the very perception of reality."

Time – now a measurable quantity – was beginning to be seen as a commodity to be valued. Although the phrase "time is money" had yet to be popularized by Benjamin Franklin, time was already being treated as such.* Wasting time was seen as not only foolish but sinful. A seventeenth-century Puritan clergyman named Richard Baxter put it this way: "To redeem time is to see that we cast none of it away in vain, but use every minute of it as a most precious thing … Consider also how unrecoverable Time is when it's past. Take it now or it's lost forever. All the men on earth, with all their power, and all their wit, are not able to recall one minute that is gone."

The 1600s brought a new kind of timekeeper – a clock regulated by a swinging pendulum rather than a verge and foliot. One of the first to consider such a mechanism was the Italian astronomer and mathematician Galileo Galilei (1564-1642). Galileo had noticed the regularity of a swinging pendulum – he may have been inspired by the sight of a gently swaying lamp hanging from the ceiling of the cathedral in Pisa – and he even drew up plans for a pendulum clock in the final years of his life. But the first such clocks were built in the Netherlands in the 1650s, based on a design by the Dutch astronomer Christiaan Huygens (1629-95).



Galileo showed how a pendulum could be used for precision timekeeping. This diagram was likely drawn by his son, Vincenzio, *c*. 1641. *(Science Photo Library)*

By the end of the century, the accuracy of pendulum clocks had improved dramatically, with a typical daily error falling from fifteen minutes to as little as fifteen seconds. By now, most clocks and watches had a minute hand, and the second hand would soon follow. Clocks had finally become more useful than sundials. It may not be a coincidence that, by the 1660s, the word “punctual” had come into common usage.

Trouble at Sea: The Longitude Problem

One of the greatest pressures for accurate timekeeping came from ship captains. Successful navigation required an accurate measure of both latitude and longitude, the two coordinates that mark any given location. Latitude, the distance north or south of the equator, can be read off a sextant – for example, by measuring the height of Polaris (the North Star) above the horizon. But there was no easy way to determine one's longitude, the distance traveled east or west. Countries like Britain depended on shipping and trade, and mistakes at sea were costing ships, cargo – and hundreds of lives. The problem attracted some of Europe's brightest minds, as geographers, astronomers, and craftsmen struggled to find an answer. It was also the prime motivation behind the founding of the Royal Observatory at Greenwich in 1675. (Charles II appointed John Flamsteed as the first Astronomer Royal, charging him to "apply himself with the most exact care and diligence to the rectifying of the tables of the motions of the heavens, and the places of the fixed stars, so as to find out the so much desired longitude of places for the perfecting of the art of navigation.")

In principle, longitude can be calculated – *if* you know the time difference between your current location and your home port. Suppose, for example, that you set sail from London, heading through the English Channel and out into the Atlantic. A few days later, you know you're several hundred kilometers west of England – but exactly how far have you traveled? If you knew the time back at London, then – with a little math – you can work out your longitude. Let's say you know that it's 1:00 p.m. back home in London. But from tracking the sun as it crosses the sky, you can see that your own local time is 12:00 noon. In twenty-four hours, the earth turns through 360 degrees of longitude. That means that in one hour, the earth turns through 15 degrees. Turning that around, each one-hour time difference corresponds to 15 degrees of longitude. So you must be located 15 degrees west of London.

The problem, then, boils down to knowing the time back at the home port. A good pendulum clock, set prior to departure, would do the trick, but a pendulum clock would be useless on the rolling deck of a ship. And the various portable clocks and watches that were in use at that time were hopelessly inaccurate. What was needed was a timekeeping device that was both accurate and portable – one that could cope with changes in temperature, and keep working even on a rough sea voyage.

The quest for a method of determining longitude at sea became a top priority for governments of the day. In 1714, the British parliament, through the newly established Board of Longitude, offered a prize of

£20,000 – equivalent to more than $10 million today – to anyone who could solve the longitude problem.

One man who took the challenge seriously was an Englishman named John Harrison (1693-1776). Born in Yorkshire, with no formal education, Harrison devoted his life to the problem of precision timekeeping.* His four great machines – timepieces that he labored over for decades – now form the centerpiece of the gallery that bears his name in the museum at the Greenwich Observatory, just outside London.

The first three timepieces – known as H1, H2, and H3 – are hardly what we would consider "portable"; each is roughly the size of a car's engine. Weighing in at thirty-five kilograms, H1 is intimidating in its complexity. In front, it has an oval-shaped brass plate, with four large dials displaying the time. Behind that, the clock's inner workings are exposed – dozens of brass wheels and gears, and what seems like hundreds of shiny brass rods of various lengths, sticking out of the machine at odd angles. The clock still functions: its many parts slide back and forth, or spin around, as the spring-driven mechanism hums along. At sea, it kept time to about ten seconds per day – not bad, but Harrison believed he could do better.

Harrison was sure that H2 – just as big and complex – was flawed; he never even tested it. Instead he put his hopes in H3, which he believed would be his masterpiece. The third machine is an astonishing achievement. It has 753 separate parts. One of them, called a "bi-metallic strip," was a crucial breakthrough: by using a thin strip of brass attached to a parallel, thin strip of steel, the clock's escapement could compensate perfectly for changes in temperature. H3 was slightly smaller than H1 and H2; even so, it stood 60 centimeters high and weighed nearly 30 kilograms. For nearly two decades, Harrison built and rebuilt this third machine. But he could never get it quite right.

"Poor old Harrison spent nineteen years of his life trying to persuade it to keep stable time," says Jonathan Betts, Curator of Horology at the museum. "And he never achieved satisfaction. In later years he could only describe it through gritted teeth as 'my curious third machine.' It must have been a great disappointment to him."

Harrison's frustration may be reflected in the words he inscribed on each of his machines. The inscription on H2, engraved in large, ornate letters, reads, “Made for His Majesty George II.” The frontispiece of H3 says simply, “John Harrison.”

With H3 seeming to be a dead end, Harrison tried a radically new approach. He drew up plans for a small pocket watch, and commissioned a friend to build it for him. He wanted to use it to test the accuracy of his larger clocks. Most watches of Harrison’s day were just about useless as precision timekeepers. But as Harrison reflected on the design of the new pocket watch, he began to think that an accurate watch could, in fact, be made.

Harrison had finally started to think small – and it paid off. The result is the remarkable machine known as H4. The difference between it and its predecessors is like night and day. While his first three clocks were enormous, H4 is just twelve centimeters across – about the size of a dessert plate – and weighs only one and a half kilograms. In its polished silver case, it looks like a slightly larger version of an ordinary pocket watch. But H4 was anything but ordinary. With its jeweled pivots crafted from rubies and diamonds, the watch’s innards were virtually frictionless. During sea trials, it lost only five seconds over two and a half months. It was the best watch the world had ever seen.

In spite of the success of H4, the Board of Longitude waffled; as Betts puts it, they kept “moving the goalposts” for awarding the prize, and gave Harrison only a series of small payments. Only after he appealed directly to the new king, George III, was he finally paid in full.* He died three years later.

John Harrison’s ultra-precise marine chronometer, known simply as “H4.” *(© National Maritime Museum, Greenwich, London)*

Harrison’s story is a remarkable one, even if he is only just beginning to get the recognition he deserves. “Harrison is the father of the precision watch,” says Betts. “It was only after H4 that people began to recognize that we can have accurate time in our pockets and on our wrists.”

In the final decades of the eighteenth century, Britain was in the midst of a sweeping transformation – we now call it the Industrial Revolution – and much of that change would have been unthinkable without precision timekeeping.

Steam power – mainly derived from coal – led to a boom in manufacturing. People began to work in factories; goods were soon moving by steamship and locomotive. By the late nineteenth century, the telegraph and the telephone carried information across vast distances in an instant. All of these developments led to a more scheduled world. Even in the early years of this transformation, the new tools of industry were changing the way people went about their lives. The role of the clock was becoming paramount. As historian of science G.J. Whitrow writes,

> Steam power was the driving force of the industrial revolution. Although the old cottage-based handloom weavers often had to work very hard for a living, they could at least work when they liked, but factory workers had to work whenever the steam power was on. This compelled people to be punctual, not just to the hour but to the minute.

The steam engine may be the symbol of this period of profound change, but it was the clock that made it all possible. As historian Lewis Mumford observed, “The clock, not the steam engine, is the key machine of the modern industrial age.”

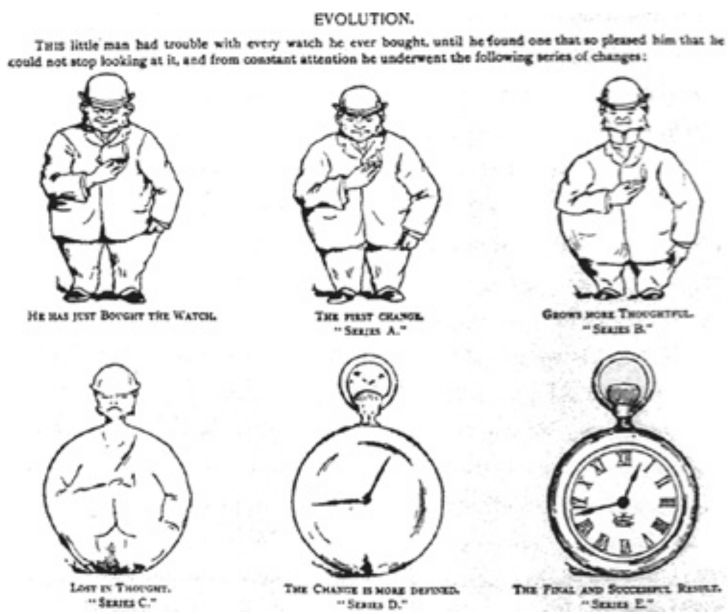
The effect on society was profound, and was felt in the workplace most of all. The clock now declared, unambiguously, how much time one owed to one’s employer and how much time was truly one’s own. By the start of the twentieth century, work and leisure were thoroughly separated.

Trouble with the Trains: The Time Zone Problem

Time, however, remained a *local* affair. In the early 1800s, different cities kept different local times. In England, even though clocks and watches were commonplace, it was still the sun that regulated their use: it was noon when the sun reached its highest point in the sky, and this, naturally, varied from one town to the next. Even if the difference between neighboring towns was negligible, it added up. There was nearly a half-hour difference between Dover in the east and Penzance in the west; a twenty-minute difference separated London and Bristol. In North America, the differences were vastly greater. When it was noon in Chicago, for example, it was 12:30 in Pittsburgh, 12:55 in New York, and 1:08 in Boston.

In the age of the horse-drawn stagecoach, when it took several days to travel from one city to another, that time difference hardly mattered. But with the growth of the railways in the 1800s, people began to move much faster, and the world began to appear smaller. The German writer and poet Heinrich Heine, writing from Paris, mused on his shrinking continent in 1843:

> What changes must now occur, in our way of looking at things, in our notions! … Space is killed by the railways, and we are left with time alone … Now you can travel to Orléans in four and a half hours, and it takes no longer to get to Rouen. Just imagine what will happen when the lines to Belgium and Germany are connected up with their railways! I feel as if the mountains and forests of all countries were advancing on Paris. Even now, I can smell the German linden trees; the North Sea's breakers are rolling against my door.



Man and machine gradually merge in this advertisement for the Waterbury Watch Company, 1883. *(Library of Congress)*

Because of the problem of time, however, achieving this "connectedness" would not be easy. The variation among local times was beginning to cause significant confusion. An explanatory note in a British timetable for the Great Western Railway, from 1841, is typical:

> *London time is kept at all stations on the railway, which is about 4 minutes earlier than Reading time; 51/2 minutes before Stevenson time; 71/2 minutes before Cirencester time; 8 minutes before Chippenham time; and 14 minutes before Bridgewater time.*

Britain took the first step: in 1847, all of the nation's railways began to set their schedules by Greenwich Mean Time (GMT) – the "mean solar time" observed at Greenwich.* Many Britons got their first taste of the new system in 1851, when the Great Exhibition was held in London. More than 6 million people traveled – mainly by train – to the capital that year. In 1880, GMT was adopted as the legal standard for the nation.

In North America, the situation was more complex. The railway companies started to use a number of small, regional time zones. By the 1870s, there were at least eighty of these railway zones in use across the continent. Train schedules started to read like technical manuals, as inter-city trains wound their way through a hodgepodge of local time zones.

An engineer named Sandford Fleming (1827-1915) had the logical answer. Born in Scotland and raised in Canada, Fleming proposed a system for standardizing time around the globe. In 1879, he suggested that the world should be divided into twenty-four equal zones of Standard Time, each spanning fifteen degrees of longitude. Clocks in each zone would keep the same time – namely, mean solar time at the central meridian of the zone. Each zone would be exactly one hour ahead of, or behind, the neighboring zone. Critics dismissed the idea as utopian, but Fleming persisted, promoting the plan at one conference after another, year after year.

For the system to work, there would have to be a "starting point" for measuring time – a Prime Meridian from which the other zones could be referred. Naturally, each country wanted the honor of having the Prime Meridian on its own soil. Britain, however, had a clear head start: the observatory at Greenwich housed the most sophisticated telescopes and clocks, and already served as the time standard for most of the world's shipping. After much debate, the international community recognized Greenwich as the Prime Meridian. Fleming's proposal for Standard Time was adopted by delegates to the International Prime Meridian Conference in Washington in 1884.* (The French nonetheless managed to avoid mentioning Greenwich in any of their official documents. In 1898, French time was officially defined as "Paris mean time, retarded by nine minutes and twenty-one seconds" – which, as writer Clark Blaise has put it, just happens to be "identical to that of a certain leafy London suburb.")

We now take Standard Time for granted: when we fly into a new time zone, we adjust our watches by however many hours the pilot tells us to.

In general, we remain oblivious to the chaos that would prevail without such a system. But the implications of Standard Time are profound. It has even played a role in forging national identities, according to historian Michael O'Malley of George Mason University in Virginia, and the author of *Keeping Watch: A History of American Time*. One result of Standard Time, O'Malley told me, is a kind of "vertical bond" connecting towns and cities that are thousands of kilometers apart – but that just happen to lie, more or less, on a north-south line. "It puts me in a community with people in Atlanta – people I have nothing in common with, except that we're getting up at exactly the same time," he says. "Sunrise in Atlanta is at a very different time than sunrise here." Today, a teacher in Maine, a lawyer in Baltimore, and a shop clerk in Florida all start their working day at the same time, and, if they happen to be fans of Conan O'Brien or David Letterman, they'll switch their TVs on at exactly the same time in the evening. This kind of synchrony, O'Malley notes, is felt even more acutely during major television events such as the Super Bowl, when, during the commercial breaks – as the utility companies are well aware – a million toilets are likely to flush at the same time.

Just as Standard Time was taking hold, the machines that we use to read the time moved one step closer to us: we started to wear them. At first, wristwatches were regarded as jewelry and were worn mostly by women. That changed during the First World War, when soldiers started wearing them in the trenches. We have been wearing these intimate timepieces ever since.*

In the late 1920s, the invention of the quartz oscillator allowed for precise timekeeping beyond the capability of even the best mechanical clocks. Scientists found that when certain kinds of crystals are subjected to an electric charge, they vibrate – and the frequency of the vibration can be controlled by adjusting the size of the crystal. Those vibrations can in turn be used to control an integrated circuit – essentially a series of tiny electric switches – which can power a display, either analog or digital. (In the latter variety, there are no moving parts.) The first reliable quartz clocks were developed in the 1940s. The best of them could keep time to 1/10,000 of a second per year – a staggering leap forward from even the best mechanical timekeeper. The first quartz wristwatches appeared in the late 1960s; even the dollar-store variety can easily keep time to about a second per day. The vast majority of today's clocks and watches make use of this tiny device, one of the miracles of twentieth-century engineering.

Living on Atomic Time

Another kind of oscillator, making use of the natural frequencies of vibrating atoms, proved even more accurate. The first atomic clock was built in 1948, using molecules of ammonia. A few years later, scientists discovered how to use atoms of cesium to build an even more effective timekeeper. In a cesium clock, atoms are held in a special cavity and bombarded with microwave radiation. That radiation causes the atoms to flip back and forth between two energy states, and the rate of that flipping remains extremely stable. Cesium clocks can now be found in leading research laboratories around the world – including the U.S. Naval Observatory, where Dr. Matsakis is justifiably proud of his flock of exquisite timekeepers.

Thanks to atomic clocks, we now measure time with a precision that is actually better than that of the natural cycles that inspired them. We once used sundials to check the accuracy of our clocks, but now it is the other way around: these ultra-precise clocks can actually reveal the irregularities in the earth's rotation. ("The earth is a lousy clock," as Matsakis puts it.) As a result, in 1967, the international definition of the second was changed. Previously, it had been linked to solar time: the second was simply 1/86,400 of the mean solar day. But if the day itself is known to vary in length, that definition is flawed. Today the second is defined as the duration of 9,192,631,770 vibrations of a particular isotope of cesium.

New technologies hold the promise of even more precise timekeeping in the future. Devices known as atomic fountain clocks and ion trap clocks, developed over the last few years, are one hope. Matsakis's colleagues at the USNO are developing a fountain clock that will use atoms of rubidium. When the technology is perfected, he says, such clocks will be 50 to 100 times better than the current crop of atomic clocks.

Another route is to take advantage of elements that oscillate at even higher frequencies. Strontium, for example, resonates at a frequency of 429,228,004,229,952 cycles per second (that's 429 *trillion*). Researchers at the University of Tokyo have recently claimed to be able to construct an "optical lattice clock" using strontium that can keep time with an accuracy of 1 part in 10^{18} – that is, one part in 1,000 trillion. Such a clock would be accurate to 1 second in 30 billion years.

Atomic time is determined not by any one clock or any one observatory, but rather by a global network of such clocks. Labs from around the world feed the signals from their atomic clocks to an office at the International Bureau of Weights and Measures just outside Paris, where computers work out a kind of weighted average of those times. (The USNO's contribution makes up about 40 per cent of that average.) The result, as mentioned, is Coordinated Universal Time.

But that is not the end of the story. Our clocks have also revealed that the earth itself is slowing down, spinning ever-so-slightly slower from year to year. The effect is due to tidal friction, a friction-like force resulting from the unequal pulling of the moon (and to a lesser extent the sun) on the earth and its oceans, as though a giant brake were being applied to our spinning planet. (In fact, the day is getting longer by just a bit less than one second, on average, per year. At the time of the dinosaurs, a "day" was probably around twenty-three hours long.) Left to their own devices, our atomic clocks will eventually disagree significantly with solar time. The solution is to add, from time to time, a "leap second." Leap seconds are inserted into UTC at the end of June or the end of December as needed, to keep atomic time in sync with the earth's rotation (that is, in sync with mean solar time). Without these corrections, the sun would be overhead at midnight rather than noon after a few thousand years. Since their introduction in 1972, leap seconds have been added twenty-three times.

Not everyone is happy with the leap-second system. There is always a chance that someone will make a mistake – a computer programmer will forget to implement the leap second (or input it incorrectly), and crucial clocks will go awry. What difference could a second make? In today's world, quite a bit. As we've seen, GPS systems depend on signals from atomic clocks; at the latitude of Washington, Matsakis says, a one-second error would lead to a position that's off by a thousand feet (about three hundred meters). "Do you want to have a plane crash because it thinks it's a thousand feet off from where it is?" Matsakis asks.

What is the alternative to leap seconds? One could simply try to live without them – that is, to let atomic time and solar time gradually drift apart. Before long, in that scenario, astronomers would find it hard to do their jobs: aiming your telescope in the right direction requires knowing the time with respect to the earth's rotation; if you're off by just a few seconds, the object you want to study won't even be within the telescope's field of view. Astronomers would no doubt find ways to correct for this – but as the discrepancy built up, even ordinary citizens would begin to feel the tension. Would New Yorkers really want their midwinter sun to rise only at 10 a.m.? One option would be to let the seconds accumulate until they add up to a full hour – which would take about six hundred years. Then one could add a leap hour – something we're already used to doing, thanks to Daylight Saving Time. Critics say such a move would amount to little more than shelving the problem for a few hundred years, passing the buck to the citizens of the twenty-seventh century. (The international body that decides such matters, the International Telecommunication Union, met in Geneva in 2005 to consider the issue. Their conclusion: "More time is required to build a consensus.")

The issue at the heart of such arguments is one that goes back to the Middle Ages: Do we read time *from* nature, by looking up at the position of the sun and stars? Or do we impose time *on* nature, looking down at our mechanical timepieces? So far we have always managed to find a delicate balance between these conflicting urges.

Atomic clocks are very impressive in an intellectual sort of way, and we certainly rely on them every day for more activities than we are ever likely to realize. But my favorite timepiece is still the trusty medieval clock in Salisbury Cathedral – a clock that has stood its ground for more than six hundred years, bearing witness to all the highs and lows of

English history from the fourteenth century until today. When John Plaister, the clock-keeper, recounts that history, his words reveal the depth of his passion for both clock and country. “My goodness, the Black Death, civil war in England – the country split between north and south, the Wars of the Roses …” As he runs through the milestones in the clock’s life, I think of its methodical tick-tock, tick-tock: a soft but persistent voice, oblivious to war and peace, famine and plenty, revolution and empire. For most of those centuries, the clock was up in the belfry. Perhaps it was safer up there. “It’s seen Oliver Cromwell come charging about – and luckily it was too far up the tower for him to get involved,” Plaister rhapsodizes. “It’s seen poor Queen Elizabeth the First’s ships chased ’round the English Channel. And it was ticking when the *Mary Rose* was sunk. And more recently – and more exciting to the children of England – it was ticking in this cathedral when Guy Fawkes attempted to blow Parliament up. So it has really had an incredible history.” Plaister pauses. “And I wonder what its makers would have said if, at that time, we had told them that this clock would see a man on the moon. I’m sure they would have thought that we’d lost our marbles.”

---

* Light travels at about 300,000 kilometers per second. In one nanosecond it travels one billionth of that distance – 30 centimeters, or approximately one foot.

* At least for observers in the northern hemisphere. For those in the southern hemisphere, the sun still moves from east to west, but in an arc across the *northern* sky.

* The Babylonians used a sexagesimal counting system – a place-value system like ours, but with a base of 60 rather than 10. (60 is convenient because it divides evenly by so many other numbers: 2, 3, 4, 5, 6, 10, 12, 20, and 30.) Our divisions of the day into 24 hours ($2 \times 12 = 24$), of hours into 60 minutes, and of minutes into 60 seconds, reflects the influence of the sexagesimal system, as does our division of a circle into 360 degrees ($6 \times 60 = 360$).

* The phrase appeared in Franklin’s *Advice to a Young Tradesman* (1748). However, the sentiment is much older. In ancient Greece, an orator named Antiphon declared that “the most costly outlay is time.”

* Harrison’s quest is detailed in Dava Sobel’s popular book *Longitude* (1995).

* In the end, Harrison was paid by Parliament, at the king’s insistence. The Board of Longitude

never actually awarded its prize to anyone.

* A sundial gives “solar time.” What we strive to duplicate with our clocks is “mean solar time” – the time that a sundial *would* show if the sun moved at a uniform rate across the sky at all times throughout the year.

* It is worth mentioning that the new system was a Western creation. At the conference, there was only one representative from Africa and two from Asia (from Japan and Turkey – which were also the only non-Christian nations involved).

* A few years ago I would have written that “many of us feel naked without a watch on,” or words to that effect – but that may no longer be true. There may now be a trend toward dispensing with the wristwatch altogether, as it is rendered redundant by the LCD clocks on our cell phones. Indeed, it is now the cell phone that many of us feel naked without.