A BIOGRAPHY OF THE SECOND

By

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ABSTRACT

A few blinks of an eye. The time it takes a hummingbird to flap its wings 80 times. For a photon of light to travel from Los Angeles to New York and back almost 40-fold. The second has been there since the literal dawn of time, if one exists. But what defines the second? Like a pop star constantly reinventing themselves, the second has undertaken a myriad of identities, first defined as a brief moment in the daily rotation of the earth around its axis.

Today, the second is officially defined by over 9 billion oscillations of a cesium atom. Although it has changed costumes, its astronomical roots still ground the second. These definitions, these identities are projected onto it by an ever-curious, ever-demanding fan base. These fans are, of course, us – humans living in a complex, evolving society. They have been priests, farmers, scientists. Now, whatever our relationship is to one tick of the second hand, today we are beholden to this new, atomic second far beyond matters of time. Our entire technological infrastructure, from airplanes to smartphones, televisions to stock markets, driving directions to space research, would crumble without the atomic second and the 21st century horologists that build the timekeepers of the modern second: the atomic clock.

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I woke with a start at 6am to the sound of my alarm, although my body told me it was only midnight. Still jetlagged from my journey from Boston to London, I was relieved that my phone always knew the proper time, regardless of the time zone.

Even thousands of years ago, people knew that time and location were connected. In the eighteenth century, sailors learned to determine their exact longitude at sea using marine clocks. Now, atomic clocks in satellites orbiting the earth can pinpoint our location through our smartphones with exquisite accuracy, all thanks to the international standard of timekeeping: the second.

Walking sleepily down the streets of Paddington, I didn't know yet that around 12,500 miles above me, there were atomic clocks in space beaming the correct time to my phone.[i] I stopped manually setting clocks a while ago, but I couldn't quite remember when the ritual ended. A little over 150 years ago, the Royal Observatory in Greenwich was charged with keeping the correct time for all of London, including the famous St. Pancras railway station.[ii] Before then, no time zones existed. Each town operated by their own local time, until fast travel created a need for standardized time, known as "railway time." Suddenly, everyone was on the same schedule.[iii]

The atomic clocks in space that told my phone it was 6am Greenwich Mean Time (GMT) – the same time zone as Coordinated Universal Time (UTC) – are also an essential component of the Global Positioning System, or GPS, which would provide my directions for the day. I was ready to explore precisely how time and location are linked, and I had traveled overseas for this moment: to get up close and personal with one of the most advanced timekeepers in the world. I started my trek by entering the address for London St. Pancras, the first leg of my journey to the Paris Observatory.

I had decided that the best way for me to get to Paris from London would be a Eurostar train, which requires travelling a little over 31 miles through a tunnel, the majority of which stretches beneath the English Channel. For weekly commuters, it was just another week. For me, the thought of travelling under the weight of the English Channel was nothing short of terrifying. The highspeed train can travel up to 186mph, but according to their site, Eurostar only travels 100mph while in the tunnel. How long would I have to endure the anxiety of the tunnel? I began my calculations. One hundred miles per hour meant that we would travel 1.67 miles per minute. So after about 18 and a half minutes, or around 1110 seconds, we would have covered the length of the 31 mile tunnel.

I took a deep breath knowing I was on the other side of the English Channel, one step closer to finding out exactly what defined a single second of time.[iv]

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A few blinks of an eye.[v] The time it takes a hummingbird to flap its wings 80 times.[vi] For a photon of light to travel from Los Angeles to New York and back almost 40-fold. Or one hundred forty-seven feet of traveling through the Chunnel between London and Paris. The second has been there since the literal dawn of time, if one exists. But what defines the second?

Like a pop star constantly reinventing themselves, the second has undertaken a myriad of identities, first defined as a brief moment in the daily rotation of the earth around its axis.

Today, the second is officially defined by over 9 billion oscillations of a cesium atom.[vii] Although it has changed costumes, its astronomical roots still ground the second. These definitions, these identities are projected onto it by an ever-curious, ever-demanding fan base. These fans are, of course, us – humans living in a complex, evolving society. They have been priests, farmers, scientists. Now, whatever our relationship is to one tick of the second hand, today we are beholden to this new, atomic second far beyond matters of time. Our entire technological infrastructure, from airplanes to smartphones, televisions to stock markets, driving directions to space research, would crumble without the atomic second and the 21st century horologists that build the timekeepers of the modern second: the atomic clock.

As complex as an instant on Earth, the biography of a second is much more than a glimpse into the history of timekeeping. The evolution of the second and how we define it as a civilization reflects a deep and complex history of our societal yearnings, our technological advances, and our ability to navigate the world – both figuratively and literally. I ride several trains in this story as I navigate the history of how we progressed to our current definition of the second. I conquered my fear of the English Channel to meet a couple of the scientists interested in reinventing its identity once again, with their cutting edge optical atomic clock technology. But first, let me start at the beginning, before the concept of a second was even born.

* * *

Sara Schechner leads me past stacks of historical treasure on old bookshelves to a hidden office above Harvard University's collection of historical scientific instruments. She is the museum's curator, and it is no surprise that the path of historical goods and trinkets continue into her private office. A large grandfather clock towers over a small table, displaying the familiar hour, minute and second hands, sharing the clockface with an astronomical display of celestial objects. Its grand size contrasts Schechner's analog wristwatch, whose clockface also shares an astronomical component: the phases of the moon. Besides their size, there is another striking difference between the two timekeepers – what makes them tick. The grandfather clock boasts a large pendulum, weightily hanging inside of a clear, vacuum-sealed chamber. In the case of a pendulum clock, conceptualized by Galileo[viii] and first patented by Huygens in 1657,[ix] the frequency of the swing is one. One heavy swing to the right is equal to one second. A swing back to the left, and the second hand jolts one second more around the 360-degree clockface. In contrast, Schechner's watch contains a tiny tuning fork made of quartz. When hit with a jolt of electricity through a small battery, the crystal oscillates, or vibrates 32,768 times in one second,[x] for each of the 60 ticks around the face of the watch. These are just two ways to track time, but I'm here to learn about how we kept time thousands of years ago, beginning with the ancient Babylonians and Egyptians.

Standing in the Nile Valley, watchers of the night sky 5000 years ago would have observed the same pattern we can still see today: stars rising in the east, rotating around a celestial north pole, and setting in the west. Thirty-six bright stars rise throughout the year in 10-day intervals, referred to as the decans for the number 10. "Egyptians at this period knew there were 365 days a year," Schechner says, and they used a bureaucratic system of 10-day weeks – 36 weeks in the year with 5 days added on.

The passage of time is not exactly subtle. As our bright sun moves across the sky and disappears behind the horizon, it takes with it the colors of daytime, shifting the sounds of nature. The daily cycles turn into seasonal ones as daylight gets shorter and rains pound fiercer. As communities integrated agriculture and worship into their daily lives, they became more interested in organizing the passage of time. "The first people who had a sense of time for a *precision purpose* were astronomers and priests," Schechner says. "They were interested, from the astronomical side, in knowing more about the cosmos and the calendar."

The yearly calendar cycle was important to structuring life, especially around agricultural systems. Tracking the year helped inform ancient societies when to plant, when to harvest and when to hold religious festivals. "The most important of [the decans] was the star Sirius," Schechner says, because at the time of this system, "Sirius would rise right before the sun in the sky and soon after, the Nile would flood."

The Egyptian 10-day system was eventually replaced by a seven-day week during the rise of the ancient Greeks – just one example of how bureaucracy has been responsible for how we define time, from eons to years to weeks to days to hours to seconds. Many terms that reference time were created and dissolved in parallel to the rise and fall of empires, while others solidified over centuries. The original definition of a second was, simply put, a division of the hour. It was the Babylonian base-60 numbering system that divided the hours, giving us the second: 60 minutiae in an hour, and secondarily, 60 seconds in one minute.[xi] But in antiquity, the hours weren't fixed in length like they are today. Instead, ancient Egyptians cut up the hours of daylight and nighttime into the same number throughout the year – the number 12, based on the decans – such that hours would be longer in the summer and shorter in the winter. "I kind of think of it just like sponges – it's like you have a sponge and it can be swollen or shrink up, but it's still a unit of a sponge, made up of these components," Schechner says. With longer and shorter hours, this also meant longer and shorter minutes and seconds. The second of summer and the second of winter did not tick rhythmically on a clock like they do today, rather were variable. The second was still just a concept, an inconsequential unit of time. But before the second hand could be added to a clock, clockfaces themselves first had to be invented, and the precursor to the clockface was the mechanical clock.

"The next big time discipline keeper is the Catholic Church and in the monasteries around the seventh century," Schechner says. Specifically, the Benedictine Rule relied on being able to strictly keep track of hours throughout the day. In essence, Schechner argues, "The invention of the mechanical clock comes out of this system as an alarm clock to wake up monks to do what they need to do." Monastery clocks were a step forward but were still ancestors of today's second. But the next evolution of the global society is what truly motivated the rise of the second to a necessary element of the human experience.

* * *

I had just visited a year or so before, but I hadn't noticed anything special about a large, nondescript machine in the far back corner of the Clockmakers' Museum on the third floor of London's Science Museum. Anna Rolls, curator, leads me back to the time keeping contraption, tucked away from the rest. This is one of the earliest known mechanical clocks, with no recognizable clockface. Clocks were generally heard more than seen, Rolls explains. "Early timekeepers didn't have any dials on them," she says. They told time by ringing the bells, like those in the monasteries indicating prayer time. The word clock is derived from the Latin word for bell. "You also have the French word *closch* and the Swedish word *clocken*, which both mean bell," Rolls says. Pointing to my watch, she continues: "On the other hand, your watch is that visual thing that you're looking at, you're watching."

In the 17th century, Christiaan Huygens was the first to patent the pendulum clock, like the one in Sara Schechner's office, and the many on display here in the museum. Until Huygens, clocks were only reliable within about 15 minutes per day, but with the advent of the pendulum clock, the timekeeper was reliable to within 10-15 *seconds* per day.[xii] Within a century, pendulum clocks would be everywhere: railway stations, work factories, and private homes. The bursting industrial revolution increased commerce, including the buying and selling goods overseas. But none of the early precision mechanical timepieces could solve the biggest timekeeping problem facing the increasing global ambitions of European powers: the problem of calculating longitude.

The 18th century and the story of the marine chronometer propelled the second to become the most important unit of time. Most people were still only concerned with hours and minutes, but the quest to determine longitude marked the beginning of an important connection between precise time and geographical location.

If you picture the earth as a 360-degree sphere and divide that by the 24 hours in the day, every 15 degrees of longitude traveled is equal to a one-hour time difference. Being off of your perceived location by only a couple of hundred feet, equal to just a few seconds, could spell shipwreck. Astronomical methods to find precise longitude hadn't been full developed yet. The difference between your local time (found easily by the sun) and a reference time could help you calculate longitude, but this required a method for carrying time with you to sea. Embarking without the ability to find longitude became a risky business.

It was a dark and stormy night in October 1707, when Admiral Sir Cloudesley Shovell, a commander with the British Royal Navy, was trying to navigate a fleet of warships home. Without a reliable method of finding longitude, Shovell led the fleet into the rocks of the Scilly Isles, just southwest of Great Britain. It was a disastrous evening. Four ships and 2000 lives were lost. Seven years later, in 1714, the Office of the Admiralty and Marine Affairs, on behalf of Queen Anne, established the Board of Longitude. The Longitude Act of 1714 offered a Queen's ransom to the person who could establish a reliable method of finding longitude to within half a degree.[xiii]

King Charles II had established the Royal Greenwich Observatory for this purpose nearly 40 years before,[xiv] but had not cracked the problem. Astronomical methods of finding longitude meant years and years of tediously charting celestial patterns. The other method was carrying time on board a ship to compare its local time to the clock's reference time. The only timekeeper accurate enough to even come close to the accuracy needed to find longitude at the time was the pendulum clock. “The pendulum works brilliantly when it's rooted to the ground and doesn't move,” Rolls says. “You put it on a boat – it's completely useless.”

An 18th century clockmaker, just 21 years old, but already an expert, stepped up to the task. The second rose to fame alongside John Harrison, whose first marine timekeeper, H1, was put to trial in 1736.[xv] It would take three more tries and almost 30 years before Harrison, with some help along the way, completed his fourth chronometer. H4 boasted a dramatically different look than the first three clocks. H4 was most similar to a large pocketwatch and used a balance wheel – a coiled spring attached to a small weight. The balance wheel was not a new invention, but Harrison, with the help of John Jeffreys, improved its accuracy with a redesign of the coil and spring mechanism. The H4 mechanism was larger than a typical watch so that the spring mechanism could coil five times per second, more oscillations than a pocketwatch, which made it more consistent and reliable. He also added a bi-metal part that compensated for temperature changes. In 1761, Harrison’s son set sail for Jamaica and completed a successful trial of H4. But it wasn’t enough for the commissioners of the Board of Longitude, who decided that more testing was needed to declare a victory. By the time H4 set sail on its second trial to Barbados in 1764, Neville Maskelyne, Astronomer Royal, had already sailed a competing trial less than a year earlier to assess two lunar astronomical methods of finding longitude.[xvi]

Despite Maskelyne’s great strides in calculating longitude based on the moon and the stars, Harrison’s chronometer won the trials. Over the course of his work, Harrison was awarded over twenty thousand pounds, more than one million dollars in today’s currency. H4 kept time accurately to within a few seconds per month, blowing the initial requirement of one second per day out of the water. The Clockmakers’ Museum holds the original H1 and H2 chronometers as well as the H5. But it was H4 that changed the course of history. The museum boasts a convincing replica, but the original is less than ten miles away, at (just about) zero degrees longitude, in the Greenwich Observatory, where Maskelyne reigned from the middle of the 18th to the early 19th century.[xvii]

The two men and their methods reflected an ongoing conflict between humans increasing authority over time through mechanization, and astronomical time, imperfect in its very nature. Even Greenwich Observatory, the location from which every time zone counts either up or down (EST in the US for example is GMT-5), no longer provides the world’s time through observations of planetary bodies. In 1972, Universal Coordinated Time, a compromise between the atomic and astronomical timescales, replaced GMT as the world standard for time.

* * *

Atoms are the elements that make up everything in the Universe, from our bodies to the air we breathe to the ground we walk on to all of the stars in the sky. Besides a few quantum quirks, atoms are consistent in their behavior, making them ideal “pendulums” for a super reliable clock. Even before first official definition of a second in 1952 based on astronomical time, scientists were working on building atomic clocks.

Over a decade earlier, World War II swept most of the globe. As with the first world war, new and improved technologies were imperative to defense strategies. Radar technology, for example, could locate enemies at a distance by sending out radio waves that created an image based on where the waves landed before bouncing back. Radio waves send long waves at low frequencies, but shorter more frequent wavelengths, like those in the microwave part of the electromagnetic spectrum, can travel farther and pick up more detail. During WWII, microwave technology developments led not only to improved radar images, but also the microwave oven and the atomic clock.[xviii]

An atomic clock has the same basic components of a mechanical clock: an oscillator and something to count the number of oscillations. The atom itself is the clock's oscillator – the pendulum of the atomic clock. The oscillations actually come from the atom's electrons, which are bombarded with lasers at a particular frequency, forcing the electrons to jump between two different energy levels. For a cesium clock, this transition of electrons between energy levels occurs 9,192,631,770 times in one second. Nine billion oscillations, or Hertz, falls in the microwave range of the electromagnetic spectrum. The new microwave radar technology developed during the war was what ultimately allowed scientists to count the atomic frequency. The atomic clock, or "cosmic pendulum", as a post-war New York Times article referred to it, was developed over the next two decades.[xix]

It started with an ammonia atom in 1949 by scientists at the US National Bureau of Standards, but by 1955, just one year before second would be redefined based on another astronomical model, the National Physics Laboratory in London demonstrated the first cesium atomic clock. In 1967, the second was redefined once more, this time based on the cesium atom, creating an international atomic timescale.[xx]

* * *

Global societies are tied together by a number of logistics, from trade deals to culture, and timescales play a big part in that systematization. Universal Time (UT) is centered around our universal experience of the rotation of the earth, while International Atomic Time (TAI) is based on the continuous "ticking" of an array of atomic clocks. As our timekeepers became more and more precise, scientists realized that the rotation of the earth varied by seconds or even minutes on a daily basis. Much like in ancient times, when the length of a second changed with the seasons, a second based on a Universal Timescale would be variable – at a much, much smaller scale, but inconsistent none-the-less.[xxi]

The first attempt to standardize the second, to give it its first "official" identity, didn't come until 1952, when an international group of scientists agreed that the second based on the year would be more consistent than a second defined by the earth's rotation. The second became part of ephemeris time, an astronomical timescale calculated based on the moon and stars instead of the rotation of Earth. Similar to 18th century astronomical optimism, this adjustment was more compelling in theory than in practice; only a few years later a wobbly Earth axis forced another redefinition of the second. Instead of the earth's yearly orbit calculated with respect to the stars (the sidereal year), the ephemeris second would be calculated using the earth's yearly orbit based on the seasons, for example one summer solstice to the next. This is called the tropical year, and it is about 20 minutes shorter than the sidereal year.[xxii]

The idea was to define an official second for UTC (Coordinated Universal Time) that was pretty much the same length as the astronomical second of Universal Time (UT, or more specifically, a corrected universal timescale called UT1). The UT1 timescale represents the day as we know it, a day in which the sun is at its highest point at midday, pretty close to noon for most places. Ephemeris time based on the tropical year was closer to UT1 than sidereal time, but since our celestial bodies prove to be imperfect (sorry Aristotle), in order to create a standard for UTC, we still had to find a more perfect second: the atomic second.

* * *

And we did. But for all of its glory and consistency, the atomic second was, and still is, based on the length of the ephemeris second. In retrospect, scientists have referred to ephemeris time as “doomed from the start.”[xxiii] This measurement of the ephemeris second, based on the moon’s position relative to the stars, was done over a long period of time, during which the rotation of the earth was slowing down, and the length of the day was getting longer. So scientists did find a more reliable second with the atomic second, which now rules the International Atomic Timescale (TAI), but since it was still arbitrarily based on the length of ephemeris time (which was off from the start), it would quickly get ahead of the daily astronomical timescale that we had been aiming to reproduce all along.[xxiv]

Instead of redefining the length of the atomic second, which would cause a plethora of scientific complications, leap seconds are now added once every couple of years to atomic time to keep it within .9 seconds of UT1. This is similar to the leap year, where every four years a day is added to February. Just like the leap year, which causes all kinds of issues for computer software, the leap second comes with its own set of complications.

The biggest issue is the connection between timekeeping and location mapping. "Any system that depended on navigation had troubles with the leap second," says Judah Levine, a physicist in the Time and Frequency division at the National Institute of Standards and Technology (NIST). That includes GPS, which relies on calculating the speed between two times, and now runs on its own timescale. You can’t calculate speed when a clock is stopped, Levine says. And GPS isn’t the only timescale to have broken free from atomic and astronomical time – individual companies that don’t want to deal with leap seconds are creating their own timescales outside of international standardized timescales, like Google, Microsoft, and Linux. "The price of leap seconds is a proliferation of these private timescales, which are not standard," Levine says.

In his line of work, which deals with atomic time, Levine believes the leap second causes more problems than it fixes. "There's a whole community that says ‘enough, the problems of leap seconds are now serious enough that it's time to stop doing leap seconds,’" Levine says. "On the other hand, there are people who say 'well it doesn't matter whether or not it's a big deal – it’s the principle of the matter; it's the wrong thing to do because time has been linked to astronomy forever and ever and ever and ever and ever, and unhooking time from astronomy is fundamentally the wrong thing to do."

But the discussion of the leap second is still ongoing, and for all practical purposes, is a stalemate, Levine says. "There has been no clear solution that makes everybody happy, or at least makes everybody equally unhappy."

* * *

After arriving at the Paris Observatory and a quick lesson in quantum physics from physicist and atomic clock builder Jérôme Lodewyck, we walk across the beautiful observatory grounds, past an old meridian line etched in the sidewalks, and stop at a small stone building. The overall effect is very quaint, belying the technological marvels inside. We traverse down a staircase, winding around and then a straight shot down several more staircases, finally arriving at the laboratories deep underground.

An atomic clock looks nothing like what you picture when you imagine a typical clock. It's a machine made from a network of wires and lasers and mirrors that help direct the laser energy towards a chamber that hold atoms. Another part of the clock helps count the "ticks" of the atom. The particular clock I'm visiting is an optical clock – which means its frequency operates in the visible part of the electromagnetic spectrum versus the microwave part of the spectrum. Similar to how the first cesium atomic clock required the Nobel prize-winning microwave atomic resonance measurement technology, the optical atomic clock would not be possible without the optical frequency comb, the winning technology of the 2005 Nobel Prize in Physics.[xxv] The optical frequency comb is a counting device that measures frequencies or wavelengths of light over time – named for the spikes of wavelengths that look like the teeth of a comb.[xxvi]

Before this technology, scientists weren't able to accurately measure frequencies in the optical range of the electromagnetic spectrum, which means optical atomic clocks only existed in theory. But just like Harrison improved the reliability of the pocketwatch by increasing the frequency of its oscillator (the balance spring) for the marine chronometer, increasing the frequency of atomic clocks from the microwave to the optical range of the electromagnetic spectrum created a more reliable atomic clock.

Since 1967, the second has been defined by the cesium atom, which resonates in the microwave range, but atoms like mercury, aluminum, strontium and ytterbium all resonate in the optical range. "For the moment, the definition is based on one atom: cesium," says Pacôme Delva, another physicist working at the Paris Observatory. So if you want to use another type of atom, he says, you need to compare the ratios of the new atoms to the cesium atom. Delva was involved with a European project from 2013-2016 that did just that. The project, International Timescales with Optical Clocks (ITOC), was a collaboration between major metrology institutes in Europe and published an array of research on optical atomic clocks, including strontium, ytterbium, calcium, mercury, and aluminum clocks.

Among optical clocks and the various atoms that can be used, there are two types: the lattice clock and the trapped ion clock. The Paris Observatory and the National Physics Laboratory (NPL) in London have both. A trapped ion clock traps a single, charged atom using a weak electric field. "This is good because it causes very little disturbance to the atom's internal energy levels, and hence very little disturbance to the frequency of the clock," Rachel Godun, from the NPL writes in an e-mail interview. The downside to ion clocks is a weak signal muddied even further by noise. On the other hand, lattice clocks use neutral atoms, which output a strong signal. "But, to trap neutral atoms," Godun says, "you need much stronger electric fields that actually disturb the atomic energy levels that you're relying on for the clock." This can make the frequency unreliable. The pros and cons of each type of optical clock are the inverse of the other, and no clear frontrunner has emerged in a hypothetical showdown. One thing they have in common, is they are both complex machines, difficult to assemble and generate a reliable tick.

The tedious process of building an optical clock might take months, Lodewyck says. When building a new clock, it's especially important to get it as precise as possible. And after that, "You have to face the truth," he says. "You have to check if your clock is actually working according to specification. And for this you need two clocks built with the same atoms, and possibly built by completely different teams so that you don't reproduce the same mistakes." Comparing clocks to make sure they operate consistently is a critical leg on the journey of a redefinition of the second using optical clocks. "Although optical clocks have been shown to perform two orders of magnitude better than cesium, it's important that optical clocks around the world agree with each other," Godun says.

But if an optical atomic clock is to redefine the second in the future, which type of optical clock will be best? And which atom on the periodic table will be used for the new second? In the basement of the building that houses Lodewyck's optical atomic clock, he draws a web of atoms on a whiteboard for me to illustrate a proposal for the redefinition of a second that's inclusive of all of the options. Cesium, the current standard, is at the center of the web, with lines reaching out to an array of other atoms: rubidium, strontium, strontium ion, ytterbium, multiple ytterbium ions, mercury, mercury ion, and aluminum ion. Lodewyck says a redefinition is still some years away, but most of the scientists I've spoken with agree – it is inevitable.

* * *

Even though I used it on my smartphone to navigate to his location, when I was speaking with Pacôme Delva at the Paris Observatory, I realized just how little I knew about GPS and other Global Navigation Systems like Galileo, the European version of GPS. Not to be confused with the NASA Galileo spacecraft that launched in 1989 to explore Jupiter and its moon, Europe's Galileo is comprised of over 20 satellites in orbit and counting. While the American GPS program first launched in the late '70s,[xxvii] Galileo didn't launch their first operational satellite until 2011. But in 2014, a launch of two Galileo satellites failed, after a helium line placed to closely to a fuel line froze the fuel supply, causing them to settle in elliptical orbits, rising and falling around 5200 miles two times a day.[xxviii]

The launch was a setback, and the ESA delayed the next scheduled Galileo launch to test the rogue satellites. At some point, they wanted to shut them down because they were in the wrong orbit, Delva said. But with misfortune came a silver lining for physicists like Delva – both satellites had high precision atomic clocks on board and were orbiting the earth at varying altitudes – a perfect opportunity to measure time shifts in relation to the clocks' distance from a gravity well (Earth), and test Einstein's theory of relativity in space with a degree of accuracy never measured before.[xxix] Delva and his collaborators confirmed that the theory holds. Even in space, clocks tick faster the farther away they are from a source of gravity.

Closed to the public since 2018 for renovations, I am one of the lucky few to stand on the rooftop of the Paris Observatory. Relativity aside, from my vantage point, time seems to slow down as I take in Paris. I can see out at least two miles all around me. Looking up, I imagine all of the global navigation satellites over two miles above me in space, circling Earth. Somewhere up there, three satellites are sending the time from their atomic clocks down to GPS receivers like my phone, which from my pocket was calculating my position based on the distance between the satellites and their known locations. But I don't need to look at it to know exactly where I am, my favorite city stretched out before me.

* * *

Back in the United States, I speak with another scientist, Andrew Ludlow, a physicist at NIST in the Time and Frequency division, about the benefits of atomic clocks and pushing the limits of time and technology with the optical clocks. "There's structure in the electrons that's been given to us by nature," Ludlow says. Like the structure given to us by the rotation and orbit of our great planet around our Sun, except that the structure of electrons is unimpeded by astronomical forces. But even still, capturing time inside of atoms is subject to an array of natural phenomena that might disturb the ticking of an atomic clock. This is what Lodewyck was talking about when describing the difficulties in building one of these intricate machines. There are still so many scientific complexities to overcome. "There might be an outside electric field that might stretch the electron cloud, or infrared radiation that changes the energy level structure of the atom," Ludlow says.

Because of their calculated reliability, atomic clocks are usually touted as the most "accurate" clocks that exist, like the aluminum ion clock at NIST that has the most impressive numbers of any clock yet. But I've discovered that accuracy is a bit of a misnomer. "One of the reasons why it's not appropriate really to consider accuracy is because it's really just a researcher's best estimate of all of these factors," Ludlow says. "And at some point, it's a leap of faith to say, 'I haven't made a mistake. I haven't forgotten about anything. This really should be how good the clock is. I haven't proven it, but this is what I think.'"

Ludlow says that scientists refer instead to systematic uncertainty, or a clock's reliability over a period of time. "We might say that if we start a cesium clock and let it run for 100 million years, that it will have accurately kept time out to a second over that period, whereas these optical clocks are right now about 100 times better, so that you could in principle, let it run for about the age of the universe about 10 billion years, and it would have only accumulated perhaps one second of error in that measurement of that epic," he says.

* * *

The way we've kept time has been constructed by society as far back as the Babylonians, and up until this very day. We first captured the second as a fleeting moment in our day, only to find that the tug of the Moon has been slowing Earth's daily rotation. We captured the second as a moment of our journey around the Sun, only to find that we don't orbit at a steady speed. Most recently, we've captured the perfect second in the atom, only to find that time is still subject to our own uncertainty.

The second is a tiny fraction of time that has been caught up in humans' technological innovations and efforts to organize life and society, first through observation of the stars, then with mechanical timekeeping and now with atomic clocks. Even the stars and moons and planets that gave us our first sense of measuring time are all made up of millions of tiny atoms, atoms which are now helping us tell the time in ways the ancient Babylonians or even Harrison likely could not fathom. Whether it was the stars that helped us find our place in the solar system, the chronometer that helped us find our way at sea, or the atomic clocks that tell our phones exactly where we are, at its heart, the second still beats to the tune of the universe and helps us to find our place within it.

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