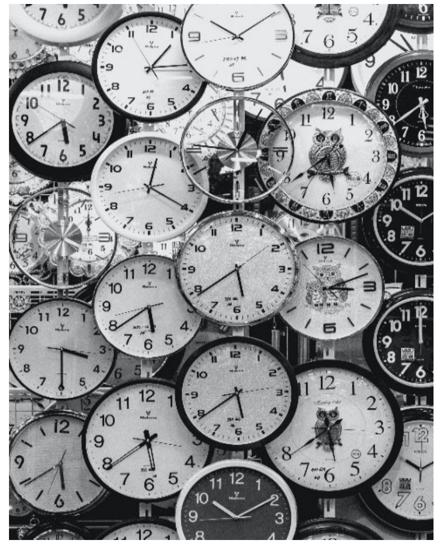
The Quantum Leap
December 22, 2022

Does Anybody Really Know What Time It Is?



When Robert Lamm wrote that first hit song for the band Chicago in 1969, he was likely referring to the pressure that time places on society, not the technological advances dependent on precise time keeping. It's a crucially important and prescient question that enables modern technology in ways most people are unaware. Why am I featuring this in a "Quantum Leap" blog? If we can now readily obtain the "official" time by syncing our cell phone with GPS satellites or our computer with an atomic clock with accuracy to within one second per 60 million years, why do we need to measure time more accurately than that? Keep reading and I hope you'll understand.

How do Clocks Work?

"Time" is not some absolute and discrete "thing", it's a somewhat arbitrary convention that society agrees to agree on. [It's also "relative" as in Einstein's theory, which essentially means that time can differ based on conditions of the measurer]. In the very early days, it was measured by the earth's rotation, with a day being defined as one rotation. Ancient Egyptians defined a second by dividing the day by 24 into hours, then by 60 into minutes and then again by 60 into seconds (rooted in night cycles and decans), so a second was 1/86,400th of a day. In other words, our current "second" is a man-made construct. In this section I want to explain a bit of the history on the evolution of clocks so that you have a fundamental understanding of how time is measured. The subsequent sections will explain why accuracy and precision of time measurement is so important and enabling, along with listing some of the companies in this field.

Clocks work by counting a periodic event with a known frequency. In the above example, it is the daily rotation of the earth. When grandfather clocks were the standard time-keeping devices, they worked by having a pendulum swing back and forth with its gears counting the swings. The arm of the pendulum in that grandfather clock is typically adjusted to make each half-swing one second. One "cycle" per second is known as 1 Hertz (Hz).

When electronic wrist watches were developed, they used a piece of quartz which vibrates at a certain frequency (32,768 Hz) so in this case a "second" is measured as 32,768 vibrations. The higher the base frequency, generally the more accurate the clock. For example, if that grandfather clock is off by 0.1 Hz, it will be off by one second in ten. If the quartz wristwatch is off by 0.1 Hz, it will be off by one second out of 327,689 or roughly 0.26 seconds per day.

Around 70 years ago, scientists realized that atoms could be used as clocks. When certain atoms are exposed to specific energies (e.g., microwave frequencies) the outer electrons transition between orbits. Specifically, the electron jumps to a higher energy orbit (or takes a "quantum leap") and the time it takes to return to the original lower energy state is the measurement frequency, hence the "quantum" connection. Since 1967, The International System of Units (SI) has defined the "second" as the period equal to 9,192,631,770 cycles of the radiation transition of Cesium-133. Cesium oscillators, such as the atomic clock maintained by NIST in Boulder, CO (UTC(NIST)), is accurate to within 0.03 nanoseconds per day. The SI aggregates the data of more than 400 atomic clocks operated by over 80 laboratories around the world, averaging their "time" to create the world's "official" time known as UTC.

Why Do We Need Such Precision Regarding Time?

GPS satellites are a relatively ubiquitous technology and while the name refers to their role in positioning, it is their role as timekeepers that is most relevant to this post and many systems use GPS to derive their time. Specifically, each satellite has an onboard atomic clock, and the signals it beams down to your GPS receiver utilizes the precision of that clock to enable the GPS receiver to triangulate signals and determine position (as well as transmitted time).

In January of 2016, the US Air Force took one of the many satellites in the US GPS constellation offline, and an incorrect time stamp was accidentally uploaded to several other GPS satellites leading to a **thirteen-millionths** of a second error in their time – less time than it takes the sound of a bullet to leave the chamber. It caused global telecommunications networks to begin to fail, BBC digital radio was out for two days, electrical power grids began to malfunction and even police and fire EMS radio equipment in the US and Canada stopped functioning. This 13-mircosecond error in GPS clocks wreaked havoc on our modern world.

To help illustrate why accurate timekeeping is so important, imagine that you oversee a train tunnel that brings goods in and out of a city. If the trains that run on the tracks are accurate to within 5 minutes of their schedule, that means you must allow a 10-minute window for that train to have access to the tunnel (+/- the five minutes) and therefore you can only schedule 6 trains per hour to use the tunnel. If those trains were more accurate and arrived within 2 minutes of their schedule, you could schedule 15 trains per hour (60 minutes divided by the 4-minute window). So, the throughput of the tunnel is directly proportional to the accuracy of the trains.

This same concept impacts many critical infrastructure elements of our modern society, including:

- Stock exchanges
- Power grids
- Telecommunications systems
- Computer networks
- Defense applications (e.g., ballistics accuracy, navigation without GPS, etc.)

Stock exchanges are increasingly driven by high-frequency computer trading and keeping the exchanges fair and equitable under such conditions is a core concern of regulators. All trades are required to maintain timestamps because cutting in line, known as "front running," is illegal. FINRA, the regulatory body that governs domestic exchanges, maintains "clock synchronization" requirements relative to UTC(NIST). The more precise this requirement, the more trading volume the exchanges can accommodate. The US power grid consists of more than 360,000 miles of transmission lines connecting to about 7,000 power plants, all of which must be synchronized and monitored. Monitoring for faults is one of the core attributes requiring accurate time measurement. Faults in transmission lines are measured at both ends of a given line by synchronized clocks, which can then determine which transmission tower is the source of the fault. Given the broad interdependence of the energy grid and its many power plants, any faults in the system can affect the broader grid unless resolved quickly and accurate clocks help pinpoint the faults in real-time. The current telecommunications system is a two-way transmission medium and maximizing the throughput of data is important both for user experience and for profit. Fitting more bandwidth within a given transmission line means the telecom can earn more money on it. In fact, there is talk that the next generation of cellular protocol (i.e., "6G") will require each cell tower to maintain an internal atomic clock to optimize bandwidth/throughput. This throughput concept also applies to dispersed networks (i.e., the Internet, the Metaverse, etc.). For example, Google Spanner is a worldwide database designed to operate seamlessly across hundreds of datacenters, millions of machines and trillions of lines of information. Precise timing is vital for seamless handing off between locations and to eliminate drag, but also to ensure that nobody is writing to a given byte at the same time someone is reading that byte. Google achieved this global no-latency network by using their own atomic clocks to create a proprietary time protocol (TrueTime API). Similarly, Meta has utilized atomic clocks in their Metaverse to ensure minimal latency, among other important features.

Time is Money

You undoubtedly have heard the cliché that "time is money". Here are two examples of how this can be literally true, especially as it relates to US defense initiatives:

- In January of this year, Frequency Electronics was awarded a contract worth up to **$20.2 million** for the development of a Mercury Ion Atomic Clock for applications in various US Naval platforms.
- In December 2021, Vescent Photonics was awarded a contract worth up to **$16.2 million** to develop portable atomic clocks for the Office of Naval Research (ONR) Compact Rubidium Optical Clock (CROC) program.

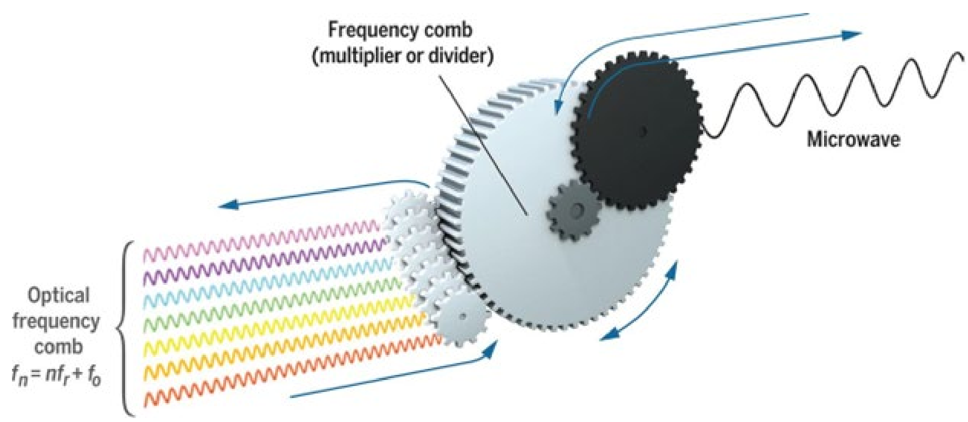
These are just two examples of such programs, highlighting the increasing importance of exquisitely accurate, field-deployable atomic clocks. A report released earlier this month suggests that the overall size of the atomic clock market will exceed $740 million by 2028. The Vescent deal cited above is being fulfilled in partnership with Infleqtion, Octave Photonics and NIST. The group aims to improve upon existing commercial atomic clocks by interrogating a two-photon optical clock transition in a warm vapor of rubidium (Rb) atoms. As Scott Davis, CEO of Vescent told me, "Exploiting the frequencies of quantized atomic energy levels to define the second, i.e., atomic clocks, has changed the world. These historically have used microwave transitions (lower energy). After the advent of the optical frequency comb, quantized transition at optical frequencies can be utilized. This represents an orders of magnitude step in performance. Vescent manufactures combs designed, for the first time, to leave the lab. This is enabling a next generation of deployed, higher performing, optical atomic clocks." The CROC program is likely the first of many similar programs where Vescent will apply its technologies.

Can we Create Even More Precise Clocks?

The short answer is yes, by using "quantum" clocks versus existing atomic clocks. As the quantum information industry continues to advance, developments have broad benefits across the industry. As Jun Ye, a Fellow at both NIST and JILA and recently named member of President Biden's National Quantum Initiative Advisory Committee noted to me, he is working on "experimental atomic clocks which explore the new measurement frontier based on quantum science. From this perspective quantum [optical] atomic clocks and quantum information processing are connected through shared intellectual development and technological advances."

Current atomic clocks operate with a frequency measured in the microwave range and an accuracy that, on its face, seems incredibly high (one second drift in 60-100 million years). Optical atomic clocks, which operate at frequencies 100,000 faster than existing atomic clocks, have been a theoretical possibility for many years, but oscillating that fast was too much for existing "counters" to measure accurately. Two advances in quantum technologies have recently changed that: 1) The development of frequency combs; and 2) Laser trapping techniques to cool atoms. The increase in accuracy that recently developed optical clocks can achieve are orders of magnitude better than todays best atomic clocks. While the previously mentioned UTC(NIST) clock operates to within one second of accuracy over 100 million years, **optical clocks can operate with accuracy to within one second over the life of the universe (13 billion years)!**

The following graphic helps display the way frequency combs act like a gear between the ultrafast optical frequencies and the microwave frequencies, which can be counted by current detectors.



In addition to the creation of frequency combs (2005 Nobel Prize in physics), controlling atoms used for measuring frequency transitions is also vital in increasing the accuracy of underlying clocks (the movements of the atoms lead to doppler effects, similar to what you hear as a speeding car goes by, reducing precision of measurement) so "laser cooling" helps push accuracy up. Companies like Infleqtion (f/k/a ColdQuanta) are leveraging their broad capabilities in cold atom science to contribute to improved clocks, with the challenge now being to move these optical atomic clocks out of the lab and into the field. As Max Perez, VP of Research and Security Solutions at Infleqtion told me, "It's important to get noise out of the system so you can achieve long-term stability…the challenge has been that the laser systems required for cold-atom clocks have been expensive and complicated. The lasers need to be highly tuned with very specific and narrow line widths…and a big part of what we are doing is bringing down the cost and size by leveraging our various technologies."

Early atomic clocks were room-sized and much less accurate than today. As is common with many technologies, science has been able to improve the accuracy and decrease the size (and cost) of atomic clocks. In fact, today it is possible to compact certain atomic clocks into a microchip. The example to the right is only 35g and is less than 17cm^3 in volume. Photonic clocks are earlier in their evolution and progress is being made to move these out of the lab and into the field (with the aim to also bring them down to chip-scale via photonically integrated circuits).

The following highlights some of the companies manufacturing atomic clocks and/or the components that are used to create them:

Conclusion

The surging attention and resources dedicated to quantum mechanics has yielded amazing technological advances. Much the Quantum Leap blog has focused on applications in Quantum Computing (QC), but other related technologies are also pushing the frontiers of technology and knowledge. More accurate clocks, leveraging certain advances developed for broader quantum information sciences, are already beginning to have practical applications beyond QC including fundamental advances in physics, more accurate sensors and more precise time keeping. As Jun Ye further noted "Atomic clocks…represent some of the most exquisitely sensitive and accurate scientific instruments that humankind has built to explore the unknows of nature." It's an exciting time to be following quantum science and I look forward to tracking and reporting on evolving breakthroughs.

Disclosure*: The author does not have any business relationship with any company mentioned in this post. The views expressed herein are solely the views of the author and are not necessarily* *the views of Corporate Fuel Partners or any of its affiliates. Views are not intended to provide, and should not be relied upon for, investment advice.*

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