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# The media of high-resolution time: Temporal frequencies as infrastructural resources

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# The media of high-resolution time: Temporal frequencies as infrastructural resources

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**ABSTRACT**
This article offers a short history of the transformation of time signals into a fundamental stability around which new communication infrastructures are built. These infrastructures include the Network Time Protocol, the Global Positioning System, and high-frequency trading. This article argues that "high-resolution time" can serve as a useful analytic framework for understanding the making and appropriation of contemporary temporal standards. Contemporary temporal infrastructures—the systems of time measurement and dissemination that subtend communication infrastructures—are based on the vibrations of caesium atoms, which act as fixed points. A focus on resolution aligns an analysis with the ways that time standards are, in practice, treated as both infrastructures and texts. High-resolution time, therefore, offers an understanding of time as a scalable resource built through contingent media practices.

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In *Technics and Civilization*, Lewis Mumford writes:

> The clock, not the steam-engine, is the key-machine of the modern industrial age … The clock, moreover, is a piece of power-machinery whose "product" is seconds and minutes: by its essential nature it dissociated time from human events and helped create the belief in an independent world of mathematically measureable sequences: the special world of science. (Mumford 2010, 14–15)

Mumford's description of the productivity of the clock is perhaps more apt now than it was when he first wrote it. Today, the products of atomic clocks—their seconds and fractions of seconds—are orders of magnitude more precise, accurate, and stable than the clocks of the 1930s, when Mumford was writing (Mackenzie 2001). Unlike many other precise, accurate, and stable products, atomic seconds are also cheap and relatively easy to produce. Since 1967, atomic clocks have married the measurement of time and the broadcast of time in large, centralized timeservers. This marriage was made possible by the stability of caesium-133 atoms, which, under strict conditions, vibrate at 9,192,631,770 Hz (cycles per second). The vibrations of caesium-133—called its "resonance"—are considered an invariant of nature. Fixed points and known quantities are the fundamental features of a measurement system; by building clocks that constantly broadcast caesium's invariant resonance, we have created a time standard that is always ready at hand as both a fixed point and a known quantity.

Atomic seconds index a second transition to the one described by Mumford: They turned an "independent world of mathematically measurable sequences" into fungible resources for systems that run on precision and differentiation. Atomic clocks are so stable, in fact, that of the seven base units of measurement in the International System of units (the SI, for short—the modern iteration of the metric system), the definition of the atomic-based second is a benchmark for all but the kilogram and the kelvin. In recently proposed SI redefinitions, the second is also incorporated in the definition of these units.[1] As such, the second is poised to become nothing less than a primary unit for all other units. This is because, relative to other measurement standards, time and frequency are the most accurate and cheapest measurements to produce. As Tony Jones (2000) argues, "If you want to measure something accurately, try turning it into a time or a frequency" (141). Jones notes—and if anything, his figures are conservative—that "time can be measured a thousand times more accurately than distance and millions of times more accurately than mass and, for the same levels of accuracy, at less than 1 percent of the cost of measuring either" (141).

Through a brief history of the use of time as a fixed point in measurement standardization, an illustration of the media techniques and technologies for making atomic time, and a survey of some of the now-basic infrastructures that are based on the stability of atomic

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timekeeping, I offer "high-resolution time" as a useful way for thinking about the scalability and plasticity of atomic timekeeping. "Resolution" in this case refers to the smallest interval or increment that a technology contains. All clocks and calendars can be described in terms of their resolution. A manual wristwatch usually has a resolution of 1 second. A word-a-day calendar has a resolution of 1 day. The Global Positioning System (GPS) has a resolution of 1 nanosecond (one billionth of a second). High-resolution time joins several parts of atomic timekeeping: its creation, its upkeep, and its dissemination. The rest of this article is organized as follows: The next section addresses the history of time measurement and its ascendance as a dominant "fixed point" for measurement standards; the subsequent section documents the crafting and maintenance of high-resolution time, including its material and institutional basis. The penultimate section presents some examples of the uses of high-resolution time and its incorporation into the basic building blocks of networked infrastructures; the final section discusses some possible directions for analyzing "artificial synchronicity" and the effects of high-resolution time.

## Time as a fixed point

There is a long history of using time as a fixed point in building standardized measurement systems. In the United States, it dates to the earliest days of the Republic. On April 28, 1785, James Madison wrote to James Monroe, "Next to the inconveniency of speaking different languages, is that of using different and arbitrary weights and measures." Madison further lamented, "Do not Congress think of a remedy for these evils?" (Madison 1865, 152–153).

Madison advocated for a proposal advanced by "ingenious and philosophical men": Take a clock that regularly beats an accurate second; measure the length of its pendulum; and use it as a standard measure of length (153). A standard length, could in turn, be used to create a standard mass (Madison suggested a "cubical piece of gold"), and a standard weight could be used, and divided into fractions, to create standard coinage. To Madison, this proposal was obviously common sense and easily reproduced, "as it is founded on the division of time, which is the same at all times and in all places, and proceeds on other data which are equally so, it would not only secure a perpetual uniformity throughout the United States, but might lead to universal standards in these matters among nations" (153). In other words, Madison and his contemporaries drew on a circulating theory of time's universality, and its instantiation, to argue that the stable mechanics of a clock could provide the basis of a potentially international system for deriving standards.

In the budding American republic, senior government officials often made standardized measurement their bailiwick. In 1790, Thomas Jefferson proposed a new decimal system of measurement based on the "seconds pendulum," but Congress and war in the Northwest Territory stalled it (Jefferson 1950; Hellman 1931). John Quincy Adams, then Secretary of State, took up the subject of standardized units in 1817. His ambivalent analysis, one of the most erudite studies on the subject of standardization for its time, ultimately concluded that standardization was futile, if only because "common people" would resort to referring measurements back to the human body—the most accessible of reference points (Adams 1821).

Measurement standardization followed a bloodier path in France, where the French Revolution interrupted similar proposals to use the seconds pendulum as the standard of length. At one hopeful moment it appeared likely that the United States, Great Britain, and France would all share a measurement system based on the seconds pendulum. However, a disagreement over where to measure the pendulum's movement stalled the plan (Alder 2002). Since differences in latitude alter a pendulum's swing, the parties needed to agree on the measurement's location. Would the observations be done in Paris, London, Jefferson's home of Monticello, or some neutral location? Before an agreement was reached, the French Commission of Weights and Measures retreated, worried that basing a unit of length on a unit of time would introduce a new level of instability into the system—in particular, as the Commission pursued a decimal division of the day, it demonstrated that the definition of "the second" was not stable enough to create a new measurement system. Instead, the French based the Metric System on a partial measurement of the circumference of the earth, a supposedly infallible "invariant of nature" (Alder 2002). While the French Revolutionary government failed in its attempts to decimalize time (and the definition of the second remained a fraction of the day), it succeeded in creating a measurement system where nearly all the units were based on a single, seemingly stable measurement. As James Madison knew, a coordinated system requires a fixed point—any fixed point. In the metric system, this point began as a sample of the earth's circumference. Fixed points create the conditions of commensurability in measurement systems and standards. They create the possibility for the production of stabilities, like the standardized time of day. Stabilities, in turn, create the possibility for communication infrastructures. While imprecision and instability are liable to intervene in these processes at any stage, the maintenance of fixed points and the production of stabilities largely ensure that our planes do not crash. Contemporary temporal infrastructures are based on atomic vibrations as fixed points and produce seconds as stabilities. They are a fragile but dependable precondition in the creation of new networked technologies.

In *Communication as Culture*, James Carey (2009) memorably writes, "The control of time allows for the coordination of activity and, therefore, effective social control" (173). Time, for Carey, was colonized by the "tentacles of commerce and politics" (172). Temporal structures for theorists like Carey bear ontological weight, as the structures are said to seep into consciousness, disciplining mind and body to the patterns of time management. But time was no longer time, Carey argues, it was "a continuation of space in another dimension" (175). Correspondingly, time became a problem of communication.[2] The co-development of atomic timekeeping and network timekeeping exemplifies the union of the measurement of time and the administration of time. This union animates the history of timekeeping, with everything from observatories, to the telegraph, time zones, and clocks entwined in a system to measure time and how to tell a population what time it is. While promoting his system of standardized time zones—"Cosmic Time," as he called it—the Canadian engineer Sandford Fleming (1889) argued that unsynchronized time posed an increasing risk to social and bureaucratic life:

> Our present system of notation … produces a degree of ambiguity which, as railways and telegraphs become greatly multiplied, will lead to complications in social and commercial affairs, to errors in chronology, to litigation in connection with succession to property, insurance, contracts, and other matters; and, in view of individual and general relationships, it will undoubtedly act as a clog to the business of life and prove an increasing hindrance to human intercourse. (348)

Fleming and other standard time advocates were eventually heeded, and along with Coordinated Universal Time and other, civil time standards, an international system of time zones and daylight-saving time were adopted. As clocks produced ever higher resolutions of temporal signatures, telecommunications networks could transmit them—creating ever more precise and powerful temporal measurement and management infrastructures (Aveni 1989; Barnett 1998; Bartky 1989; 2000; Crary 2013; Elias 1992; Kern 1983; Thompson 1967). Using time as a fixed point is of special import. First, the measurement of time is always necessarily mediated by a measurement technology (Jespersen et al. 1999). Second, time "moves" in one direction. This means that the tools for measuring time require continuous calibration. If we weigh something with a scale, we can know its mass; a clock is, in essence, always asking "What time is it now?" But if the second is a measure of duration, what kind of duration is it measuring? The obvious answer is that the second is a fraction of an earth day (24 hours or 86,400 seconds). However, the earth's movements are slowing down and that process, too, is unfolding in an irregular way. In effect, an earth day is not a uniform measure and neither is the second. Up until the 1960s, astronomers produced time standards that were derived from the earth's movements and the length of an average day. Since the earth's movements are not uniform, year over year, they tried to mitigate the differences by using an average year instead of constant measurements. This so-called "ephemeris second," adopted in 1960, was the last, best attempt to develop a second that could include all the errors intrinsic to reliance on the earth as a timekeeper. The ephemeris second only lasted 7 years. Atomic clocks were proven possible in 1955 and by 1967 were precise and stable enough to replace ephemeris measurements in the production of seconds and standard time scales.[3] What the caesium second lacked, however, was any ongoing indexical relationship to another frequency; the ephemeris second could be checked against the earth's orbital frequency, whereas the caesium second was simply good at ticking. Prior to its ratification in 1967, the caesium second was compared to the ephemeris second and the regular movements of the moon around the earth (a handier measurement than measuring the earth's movement around the sun). These lunar observations were performed from 1956 to 1965, and were thought to provide a suitable check of the ephemeris second. The atomic-based second adopted in 1967 is consequently a representation of a synthesized "paper second" (an average of the earth's movements) and an index of terrestrial relationships to the sun and moon. This is a key moment in the history of temporal technologies, in which the practicality and precision of a lab instrument, the atomic clock, upended and redefined the technics of time—a kind of "measurement inversion."[4]

## The media of high-resolution time

Clocks, as Lewis Mumford knew, do not just "measure" time; they produce temporal resources in the form of seconds and fractions of seconds. If clocks are the producers of temporal resources, then we ought to dwell on the technical and material basis of this production.

The production of time standards is always based on an interaction between scientists and technicians working with and through instruments and media. For instance, the shift from astronomical time to physical time was marked by a change in instrumentality—the move from the telescope and the ephemeris table to the servomechanism of an atomic clock and the circulation of authoritative calculations. And time standards, like those used to set local time on networked devices, are regularly broadcast on shortwave radio and between satellites and terrestrial time servers (Parks 2005). In other words, across temporal infrastructures—from the mechanism for measuring atomic vibrations to the methods for synchronizing devices—high-resolution time is treated mediatically, as a socially maintained structure of communication (Gitelman 2006). It is not enough, however, to simply claim that standard time is a medium (who cares?). Instead, looking at the medium specificities of standardized time exposes an entanglement of measurement, human relationships to daylight, and the always-provisional techniques for making and maintaining technologies. By outlining some of these specificities here, we can perhaps better understand the relationality and intersectionality of high-resolution time as both an infrastructure and a text that is saturated in media techniques.

The simplest version of an atomic clock works much like a wristwatch. At the atomic clock's core is a quartz crystal that vibrates. These vibrations produce the seconds used in time signals just as the quartz crystal in a wristwatch signals the seconds hand to move. But, unlike a wristwatch, the constant vibrations of the quartz crystal are also repurposed in the maintenance of a near-perfect cybernetic technology. The crystal, if powered correctly, maintains a microwave resonator at a constant frequency of 9,192,631,770 Hz. To assure that the quartz does both these things, it is linked to a servomechanism that automatically adjusts the electrical input to the quartz crystal controlling the vibrations. The remainder of the clock is engineered to communicate with the servomechanism to create feedback and control. Thus, the atomic clock is made up of two basic pieces: a vibrating mechanism that produces the pulses of "seconds," and a feedback-and-control mechanism that calibrates the vibrating crystal. [5]

In 1979, Jespersen and Fitz-Randolph described the atomic clock in terms of a more familiar media apparatus, the radio:

> This whole *feedback* system operates in a continuous cycle, automatically. The process is much like carefully tuning in a radio so that the listener hears the loudest and clearest signal. When this happens, the receiver is exactly "on frequency" with the signal that is sent. In the case of the atomic clock, the caesium atoms thus provide the broadcast signal and maintain the frequency at 9, 192, 631, 770 Hz. (Jespersen and Fitz-Randolph 1979, 52)

In the atomic clock, the caesium atom enters the process as the grist for the feedback mechanism. Caesium-133 shifts its energy states in an almost perfectly predictable manner. Harnessing of this predictability enabled an improvement over mechanical clocks that depended on precisely measured pendulums or finely cut crystals (Jesperson et al. 1999). Moreover, caesium is not expensive. Though rare, the largest deposit of caesium in the world is in the Tanco Mine at Bernic Lake in Manitoba, Canada, and Canada is by far the world's largest producer of the element. At current rates of mining (anywhere from 5,000 to 10,000 kg per year), worldwide reserves of caesium would last thousands of years. Pure caesium is hazardous and one form of the element, a reactor by-product, is considered a potential ingredient in so-called "dirty bombs." But as Butterman, Brooks, and Reese write in a Mineral Commodity Profile for the U.S. Geological Survey, most of cesium's compounds are considered to be "innocuous." The authors also note that "Because the potential supply is vast compared with foreseen demand and most of it is located in a politically stable environment, no supply disruptions seem likely" (Butterman, Brooks, and Reese 2005, 8). As a result, we have nested stabilities: The atomic clock is engineered to produce stable signals from a stable element, and it relies on a material that is amply available in a politically stable country.

To become the stable basis of contemporary information infrastructures, it was not enough for atomic clocks to offer newfound precision; precision had to be allied with a distribution network. There are many time scales in use in different kinds of operations. Two "broadcast time" scales are used in most civil operations: GPS (Global Positioning System) time (also called International Atomic Time) and Coordinated Universal Time (UTC). Both GPS time and UTC are "paper" clocks, meaning that they do not originate from a single device. Instead, they are calculated through a weighted synthesis of more than 300 atomic clocks in laboratories worldwide. This process of weighting is at the heart of universal timekeeping. In fact, the time provided by our computers, telephones, and GPS systems is itself an approximation, which is later adjusted using a document called *Circular T* (Figure 1). Every month, *Circular T* retrospectively provides laboratories with a weighted, calculated value for UTC and International Atomic Time for a given month. *Circular T* also includes the local realizations of these time scales and the local uncertainties of these calculations. To simplify this: Even the most precise clock readings available to everyday civil operations are, in the final measure, susceptible to revision by a memo. *Circular T* includes the standard features of the memo: a header, date (including time in UTC), and contact information for the Bureau International des Poids et Mesures (BIPM), the body responsible for maintaining the metric system. It also includes an ISSN (International Standard Serial Number), a sign of its status as a tool of

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1 - Coordinated Universal Time UTC and its local realizations UTC(k). Computed values of [UTC-UTC(k)]
and uncertainties valid for the period of this Circular.
From 2015 July 1, 0h UTC, TAI-UTC = 36 s.

| Date 2015 0h UTC | NOV 28 | DEC 3 | DEC 8 | DEC 13 | DEC 18 | DEC 23 | DEC 28 | Uncertainty/ns | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MJD | 57354 | 57359 | 57364 | 57369 | 57374 | 57379 | 57384 | uA | uB | u | |
| Laboratory k | | | | [UTC-UTC(k)]/ns | | | | | | | |
| AOS (Borowiec) | -2.3 | -2.4 | -2.9 | -2.5 | -3.2 | -2.8 | -2.0 | 0.7 | 5.0 | 5.1 | |
| APL (Laurel) | 2.6 | 2.7 | 3.1 | 2.1 | 1.9 | 1.3 | 0.1 | 0.3 | 4.9 | 4.9 | |
| AUS (Sydney) | -328.6 | -308.8 | -288.9 | -268.2 | -247.2 | -232.0 | -207.5 | 0.3 | 5.0 | 5.1 | |
| BEV (Wien) | 32.5 | 16.1 | 16.5 | 16.3 | 10.0 | 8.7 | 10.3 | 0.7 | 3.1 | 3.1 | |
| BIM (Sofiya) | 3050.9 | 3080.9 | 3114.4 | 3127.2 | 3167.3 | 3184.6 | 3206.9 | 1.5 | 7.0 | 7.2 | |
| BIRM (Beijing) | -263.4 | -263.9 | 1.8 | -14.6 | -19.0 | -25.0 | -30.9 | 1.5 | 20.0 | 20.1 | (1) |
| BY (Minsk) | -4.5 | -2.7 | -3.7 | -1.1 | 1.7 | 4.8 | 7.4 | 1.5 | 7.0 | 7.2 | |
| CAO (Cagliari) | -9444.9 | -9563.4 | -9683.0 | -9787.4 | -9897.4 | -10005.7 | -10117.0 | 8.0 | 7.0 | 10.7 | |
| CH (Bern-Wabern) | 1.5 | -2.1 | 1.1 | 2.3 | 1.7 | 3.7 | 6.4 | 0.3 | 1.2 | 1.3 | |
| CNM (Queretaro) | -2.4 | -1.8 | 5.5 | 0.3 | -0.4 | -1.7 | -0.4 | 3.0 | 5.0 | 5.8 | |

**Figure 1.** Excerpt from *Circular T*, January 2016.

standardization, akin to other media standards like those for cataloguing and indexing periodicals. *Circular T* also specifies that, as of July 2015, Coordinated Universal Time and GPS time (atomic time) diverge by 37 seconds. UTC and GPS times diverge because the earth does not conform to the perfect stability of atomic timekeeping. To bring civil time back in line with solar time—with noon as the middle of the day—a new second is inserted into the time stream. These seconds are "leap seconds" and they have been inserted 27 times since 1972 (McCarthy and Seidelmann 2009).

In practice, the insertion of a leap second requires a manual (literally, by hand) switching of the national time servers around the globe. These insertions are now extremely controversial and may be eliminated in the near future, at which point civil time will be completely disarticulated from the sun. In theory, the steady divergence of civil and solar time would mean that noon could, theoretically, coincide with a pitch-black sky. The risks of keeping the leap seconds are also stark: Manual intervention in the time service could have unpredictable results. On the one hand, an increasing number of networks are tied into services like the Network Time Protocol, and, on the other, programming computers to deal with leap seconds is complex. For instance, the entire nuclear deterrent system in the United States is supposedly turned to a "special mode" for 1 hour before and after each leap second, which costs in the range of "two-digit million dollars" (Kamp 2011, 47). Consequently, the cost of reprogramming computers and networks and the cost of unforeseen physical, financial, or military disaster make leap seconds an increasingly untenable practice.

As an infrastructure of infrastructures, the measurement and broadcast of time are uniquely powerful. It would be a mistake, however, to take the measurement of time for granted or to consider it the mere transduction of a natural invariant into a technical apparatus. Instead, to grasp the contingency of contemporary temporal infrastructures, it is necessary to consider the material and social protocols that make high-resolution time possible: the atoms, the clocks, the memos, and the hands that insert leap seconds into the time stream. Steven Jackson has eloquently described the practices of maintenance and repair in contemporary information systems as "the subtle acts of care by which order and meaning in complex sociotechnical systems are maintained and transformed, human value is preserved and extended, and the complicated work of fitting to the varied circumstances of organizations, systems, and lives is accomplished" (Jackson 2014, 222). In the case of time standards, the high resolution of atomic-based times is a result of precisely these "subtle acts of care" that establish, maintain, and reproduce meaning and stability. While the importance of temporal infrastructures is hard to overstate, it is equally necessary to highlight the ways that stability is established through practices like "tuning" an atomic clock, accessing a stable supply of caesium, writing and distributing a memo, and manually adjusting a clock.

## The uses of high-resolution time

The rise of atomic timekeeping illustrates how the easy reproducibility and cost-effective precision of caesium-133 has transformed it into an unimpeachable and irresistibly plastic resource. It also enabled new practices of transduction and transformation, as formerly nontemporal forms of measurement were turned into times and frequencies. This transformation highlights the mediating role that time and frequency play in building knowledge infrastructures and the criticality of maintaining temporal standards. Infrastructures are "pervasive enabling resources in network form" (Bowker et al. 2010, 98) and exist as sets of protocols, conditions, and forms for enabling other kinds of activities; as such, all infrastructures are by definition relational (Bowker and Star 1999; Star and Ruhleder 1996). Time measurement and time broadcast simply tend to hold more relations together than other forms of enabling infrastructures.

Temporal measurement and broadcast did not become an infrastructure of infrastructures on their own; instead, a long, patterned appropriation of temporal infrastructures articulated previously unconnected phenomena to the exchange of precise temporal epochs. These uses of high-resolution time are often cited when describing the basic scaffolding of networked communication and computation. But to become scaffolding, temporal measurement had to undergo a process of infrastructuring (Bowker et al. 2010; Hughes 1983; 1989; Scott 1998). Atomic time is a direct result of a redefinition of time in the metric system, which is itself a basic infrastructure for nearly every technical and scientific measurement in the world. The signatories to the Metre Convention make up 98% of the world's economy, and as a result, the system is the lingua franca of international trade, science, and measurement and represents what Fischer and Ullrich call a "global measurement quality infrastructure" (2016, 4). The Network Time Protocol, the Global Positioning System, and high-frequency trading are all phenomena that rely on the infrastructured operation of high-resolution time. They draw, to varying degrees, off of the long-term stability of atomic timekeeping and the fact that greater resolution enables greater granularity and the distinction of difference.

The clock on my computer's desktop reads 1:35:16. If I disconnected it from the Internet, it might lose 1 or 2 seconds today and 10 to 30 seconds by the end of the week. This will probably not gravely affect my life. When David Mills (1991) first introduced the Network Time Protocol (NTP), he made it clear that such protocols are not designed for everyday use but for more complex operations (which, of course, come to bear on everyday life). He recognized then that "Accurate, reliable time is necessary for financial and legal transactions, transportation and distribution systems and many other applications involving widely distributed resources" (1482). Mills knew that two interwoven questions could encapsulate late-20th-century concerns about synchronized time. So he asked: "How do hosts in a large, dispersed networking community know what time it is? How accurate are their clocks?" (1482). NTP was one of the first Internet Protocols, and Mills's own answer to his question "How accurate are their clocks?" illustrates the relatively small amount of concern for synchronous timekeeping in the early 1990s. In a survey of the Internet's 94,260 servers in the late 1980s, he found, "About half of the replies had errors greater than 2 [minutes], while 10% had errors greater than 4 [hours]. A few had errors over two weeks" (1482). While Mills's concerns about clock accuracy persist, hosts in a networking community now "know" what time it is because of protocols like NTP, and a near flawless clock accuracy is taken for granted. In the years since the creation of the Network Time Protocol, the list of systems, industries, and occupations that rely on networked, coordinated time has expanded exponentially. Protocols like NTP made this possible by creating highly precise conditions of synchronicity. For instance, in the case of the Global Positioning System, a miscalculation of a nanosecond (one billionth of 1 second) is equivalent to at least 12 inches in mapped space. The loss or gain of a full second, then, is equivalent to a mislocation of at least a billion feet, or 7.6 times the circumference of the earth, or 80% of the distance to the moon (Logsdon 1995).

Finance capital is similarly reliant on the measurement and differentiation of thin slices of time and on a network suffused with temporal contingency. Automated arbitrage is nearing the speed of light, with thousands of electronic trades occurring each second. In automated arbitrage, buying and selling financial products in tiny fractions of a second can yield substantial profits, which accumulate through additions of many fractions of a cent instead of larger gains over longer periods of time. While trades regularly occur in microseconds, one latency management group predicts future trades could occur in picoseconds (one trillionth of a second) with reduction of latency in fiber-optic networks: "In high-frequency trading, light propagation delays are, in many cases, the largest limiting factor preventing traders from immediately exploiting arbitrage opportunities" (Paulson 2011, 19). High-frequency trading depends on a complex material apparatus that extends from the location of bodies, to terminals, to buildings, and to fiber-optic nodes. What is particularly noteworthy is that each morning, the entire system is resynchronized to atomic clocks (MacKenzie 2008). Atomic synchronicity, in other words, subtends the entire assemblage of high-frequency trading.

We have inherited the truism, from Marx, that the duration of a transaction—the process of transforming commodities into money—was a major source of loss: "Quite different is the time which generally passes before the commodity makes its transition into money; or the time during which it remains a *commodity*, only a potential but not a real value. This is pure loss" (Marx 1973, 534–535, emphasis in original). The physical conditions of transforming commodities into money have changed but this dynamic has not. The speed of light is merely the newest obstacle for reducing the "pure loss" of monetization. What Marx described as pure loss corresponds to what we call "latency," the realm of untapped potentials. The speed of light became a constraint on monetization only when the precise measurement of microseconds became a stable component of the infrastructures of finance.

James Carey (2009) saw the creation of new futures markets as a direct result of the building of the American telegraph network and the coordination of temporal epochs. Carey writes, "In a certain sense the telegraph invented the future as a new zone of uncertainty and a new region of practical action" (168–71). The expansion of coordinated time and the greater resolution of new time systems have further expanded the possibilities of mining value from temporal difference. But the speed of trading is also a liability. Speedy, high-frequency trading exacerbated the so-called "Flash Crash" of 2010. When, on May 6, overall stock prices fell 5% and prices fluctuated wildly, it became clear that high-frequency trading surpassed human capacities to observe market fluctuations. The Flash Crash uncovered the fragility and limits of the temporal infrastructure that undergirds our economy.

Two problems have plagued those who have tried to keep a long-term record of time: Every clock eventually becomes less accurate,[6] and the earth is an unpredictable timekeeper. In response, scientists and standards bodies have advanced the development of ever more accurate clocks, and the replacement of the earth as a primary timekeeper. Atomic time appeared, first, as an unprecedentedly precise and stable solution to the problem of time keeping but, in a short period, ascended from a secondary check on astronomical time to the primary condition for the operation of networked systems.

## Conclusion

At its most basic level, pure sensory simultaneity is now understood to be an impossible achievement—because of communication lags, certainly, but more to the point, because of the Special Theory of Relativity. In his seminal paper "On the Electrodynamics of Moving Bodies," Albert Einstein (1952) defines simultaneous events in terms of everyday phenomena:

> If, for instance, I say, "That train arrives here at 7 o'clock," I mean something like this: "The pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events." (39)

Simultaneity is, in other words, felt but always illusory. With simultaneity, we are always dealing with a social construction of a sense of timeliness (Sharma 2014), which may be a useful concept for theories of modernity but is shaky ground on which to build an understanding of time and infrastructure (Galison 2003). Temporal infrastructures enable artificial synchronicity in systems that are very good at time reckoning and coordinating their reckoning by correcting for entropy, gravity, and movement. The atomic second, at the heart of temporal infrastructures, is a mediatic recording protocol for transforming constant energy into stable ticks; broadcast time standards like Coordinated Universal Time are, correspondingly, media transmission standards for disseminating authoritative time across space. Theorizing measurements and protocols as communication problems opens them up to being denaturalized and potentially revised.

High-resolution time is not without its instabilities. Zoom in close enough on high-resolution time and it reveals a fundamental conflict between lives lived according to cycles of day and night, and the physical constants of atoms. The problem of leap seconds and the conversion of all base units to standards of time expose the fact that the stabilization of the second has directly altered the administration of both synchronicity and measurement. In each, the second has hardened and become less apparently susceptible to revision. This has consequences for how we conceive of physical infrastructures, as they too begin to take on a hardened appearance. Leap seconds make this clear in the way they threaten the stability of coordinated time and, more importantly, how they are figured as threats to order.

I have suggested that high-resolution time may serve as a useful analytic for thinking through the imbrications of temporal measurement, transmission, and infrastructuring. It reframes time as a media technique that is crafted, maintained, repaired, and shared. In this article I also offer an outline of the history, making, and use of high-resolution time to invite further explorations of the ways time is measured, shared, and appropriated as an infrastructuring tool and a media text.

## Notes

1. Approved in 2011, Resolution 1 of the Bureau International des Poids et Mesures (one of the bodies responsible for the International System of Units) describes the redefinitions of the base units in terms of the "invariants of nature," among which the second, and by extension the resonance of the caesium-133 atom, will be primary. The resolution is available at http://www.bipm.org/en/si/new_si/what.html
2. Even if we follow Carey's observation that temporal standards enacted an expansion of spatial control, this was not a clean process. Instead, these expansions were uneven and invested large-scale infrastructures with new instabilities that in some cases did not manifest for decades. For instance, at the peak of its empire, the 0° meridian located in Greenwich placed Britain at the center of a global time

standard. But by placing the International Date Line in the far-away Pacific Ocean, the British Empire paved the way for East Asian stock markets to exert greater influence on financial events in the late 20th century, since they are the first markets to open each morning (Sturken 2004). Today, as atomic timekeeping replaces previous time standards, the centrality of the U.S. Naval Observatory overtakes the historical home of astronomical timekeeping in Greenwich, UK—wiping away another residual artifact of British Imperial control over space and time.

3. Through the 1950s and 1960s, astronomers could compare their calculations of celestial movements against an atomic clock, which up to this point was simply a very accurate check on their manual calculations.
4. "Measurement inversion" is an intentional play on Geoffrey Bowker's (1994) conceptual approach to studying infrastructure through inversion.
5. There are many kinds of atomic clock available today. This description is a simplification of the original atomic clocks developed in the 1950s and 1960s.
6. "Accuracy" is how closely a clock is aligned to time standards, while "precision" is how granular the time reading is, and "stability" is how well a specific clock can maintain its accuracy.

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## References

Adams, J. Q. 1821. *Report of the Secretary of State, upon weights and measures*. Washington, DC: Gales & Seaton.

Alder, K. 2002. *The measure of all things*. New York, NY: Free Press.

Aveni, A. F. 1989. *Empires of time: Calendars, clocks, and cultures*. New York, NY: Basic Books.

Barnett, J. E. 1998. *Time's pendulum: The quest to capture time—from sundials to atomic clocks*. New York, NY: Plenum Trade.

Bartky, I. R. 1989. The adoption of Standard Time. *Technology and Culture* 30:25–56.

Bartky, I. R. 2000. *Selling the true time: Nineteenth-century timekeeping in America*. Stanford, CA: Stanford University Press.

Bowker, G. C. 1994. *Science on the run: Information management and industrial geophysics at Schlumberger, 1920–1940*. Cambridge, MA: MIT Press.

Bowker, G. C., and S. L. Star. 1999. *Sorting things out: Classification and its consequences*. Cambridge, MA: MIT Press.

Bowker, G. C., K. Baker, F. Millerand, and D. Ribes. 2010. Toward information infrastructure studies: Ways of knowing in a networked environment. In *International handbook of Internet research*, ed. J. Hunsinger, L. Klastrup, and M. M. Allen, 97–117. Dordrecht, The Netherlands: Springer.

Butterman, W. C., W. E. Brooks, and R. G. Reese. 2005. Cesium. *Mineral Commodity Profiles report 2004-1432*. Reston, VA: U.S. Geological Survey. https://pubs.usgs.gov/of/2004/1432

Carey, J. W. [1989] 2009. *Communication as culture: Essays on media and society*. 2nd ed. New York, NY: Routledge.

Crary, J. 2013. *24/7: Late capitalism and the ends of sleep*. New York, NY: Verso.

Einstein, A. 1952. On the electrodynamics of moving bodies. In *The principle of relativity: A collection of original memoirs on the special and general theory of relativity*, ed. H. A. Lorentz, A. Einstein, H. Minkowski, and H. Weyl, 37–65. New York, NY: Dover.

Elias, N. 1992. *Time: An essay*, trans. E. Jephcott. Oxford, UK: Blackwell.

Fleming, S. 1889. *Time-reckoning for the twentieth century*. Washington, DC: Smithsonian.

Fischer, J., and J. Ullrich. 2016. The new system of units. *Nature Physics* 12 (1):4–7.

Galison, P. 2003. *Einstein's clocks and Poincaré's maps: Empires of time*. New York, NY: W. W. Norton.

Gitelman, L. 2006. *Always already new: Media, history and the data of culture*. Cambridge, MA: The MIT Press.

Hellman, C. D. 1931. Jefferson's efforts towards the decimalization of United States weights and measures. *Isis* 16 (2):266–314.

Hughes, T. P. 1983. *Networks of power: Electrification in Western society, 1880–1930*. Baltimore, MD: John Hopkins University Press.

Hughes, T. P. 1989. Evolution of large technological systems. In *The social construction of technological systems: New directions in the sociology and history of technology*, ed. W. E. Bijker, T. P. Hughes, and T. J. Pinch, 51–82. Cambridge, M.A.: MIT Press.

Jackson, S. 2014. Rethinking repair. In *Media technologies: Essays on communication, materiality, and society*, eds. T. Gillespie, P. Boczkowski, and K. Foot, 221–39. Cambridge, MA: MIT Press.

Jefferson, T. 1950. *The papers of Thomas Jefferson Vol 16*, ed. J. P. Boyd. Princeton, NJ: Princeton University Press.

Jespersen, J., and J. Fitz-Randolph. 1979. *Time & clocks for the space age*. New York, NY: Atheneum.

Jespersen, J., J. Fitz-Randolph, J. Robb, and D. Miner. 1999. *From sundials to atomic clocks: Understanding time and frequency*. Washington, DC: U.S. Department of Commerce, National Institute of Standards and Technology.

Jones, T. 2000. *Splitting the second: The story of atomic time*. Philadelphia, PA: Institute of Physics.

Kamp, P. H. 2011. The one-second war. *Communications of the ACM* 54 (5):44–48.

Kern, S. 1983. *The culture of time and space, 1880–1918*. Cambridge, MA: Harvard University Press.

Logsdon, T. 1995. *Understanding the Navstar: GPS, GIS, and IVHS*, 2nd ed. New York, NY: Van Nostrand Reinhold.

Mackenzie, A. 2001. The technicity of time: From 1.00 oscillations/sec to 9,192,631,770 Hz. *Time & Society* 10 (2–3):235–57.

MacKenzie, D. 2008. *Material markets: How economic agents are constructed*. Oxford, UK: Oxford University Press.

Madison, J. 1865. *Letters and other writings of James Madison: Fourth president of the United States*. Philadelphia, PA: J. B. Lippincott.

Marx, K. 1973. *Grundrisse*, trans. M. Nicolaus. London, UK: Penguin.

McCarthy, D. D., and P. K. Seidelmann. 2009. *Time: From earth rotation to atomic physics*. Weinheim, Germany: Wiley-VCH.

Mills, D. L. 1991. Internet time synchronization: The Network Time Protocol. *IEEE Transactions on Communications* 39 (10):1482–93.

Mumford, L. 2010. *Technics and civilization*. Chicago, IL: University of Chicago Press.

Parks, L. 2005. *Cultures in orbit: Satellites and the televisual*. Durham, NC: Duke University Press.

Paulson, L. D. 2011. Some users find the speed of light too slow for their networks. *Computer* 44 (4):18–21.

Scott, J. C. 1998. *Seeing like a state: How certain schemes to improve the human condition have failed*. New Haven, CT: Yale University Press.

Sharma, S. 2014. *In the meantime: Temporality and cultural politics*. Durham, NC: Duke University Press.

Star, S. L., and K. Ruhleder. 1996. Steps toward an ecology of infrastructure: Design and access for large information spaces. *Information Systems Research* 7 (1):111–34.

Sturken, M. 2004. Mobilities of time and space: Technologies of the modern and the postmodern. In *Technological visions: The hopes and fears that shape new technologies*, ed. M. Sturken M, D. Thomas D, and S. Ball-Rokeach, 71–89. Philadelphia, PA: Temple University Press.

Thompson, E. P. 1967. Time, work-discipline, and industrial capitalism. *Past and Present* 3 (8):56–97.