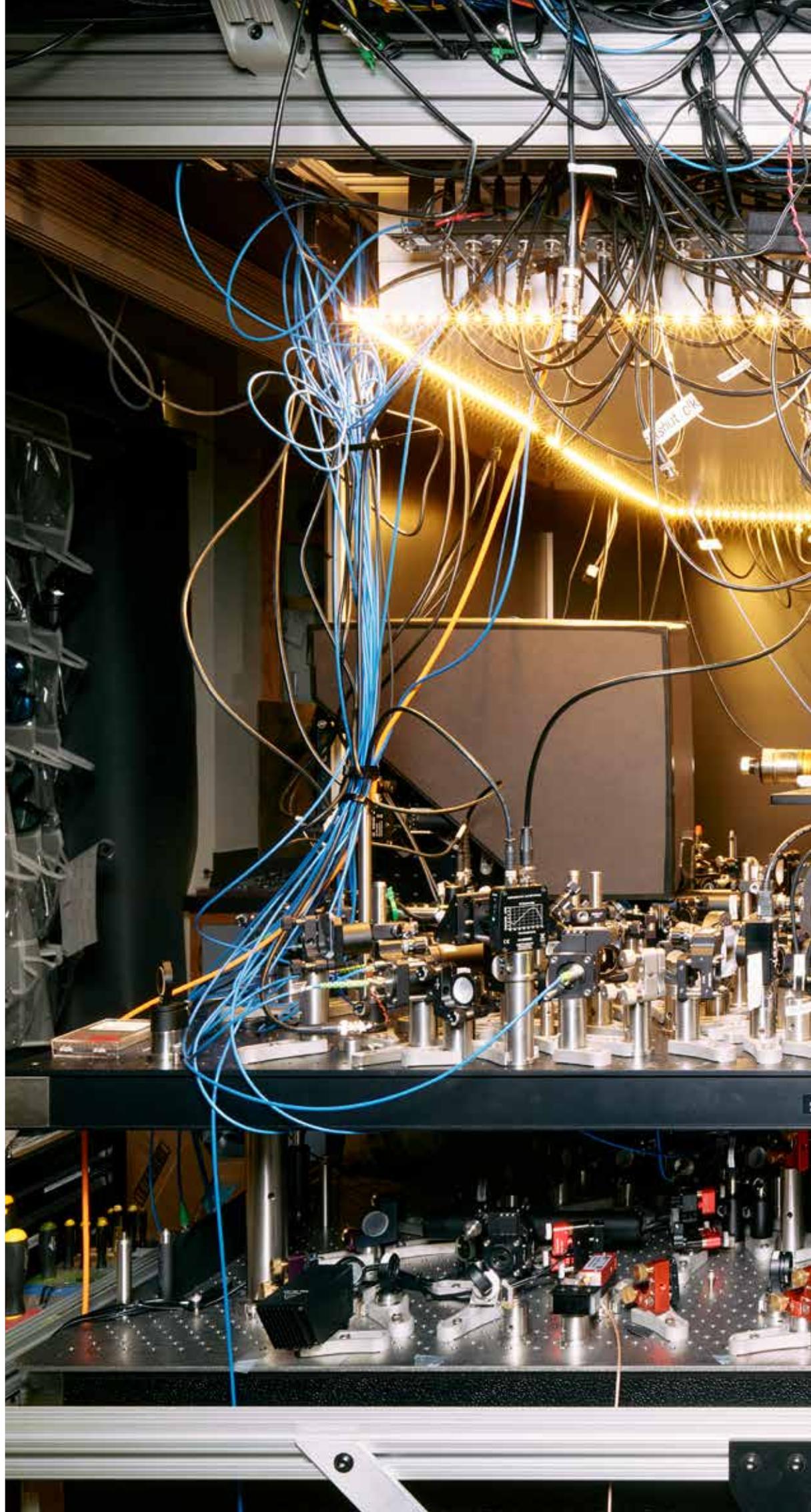


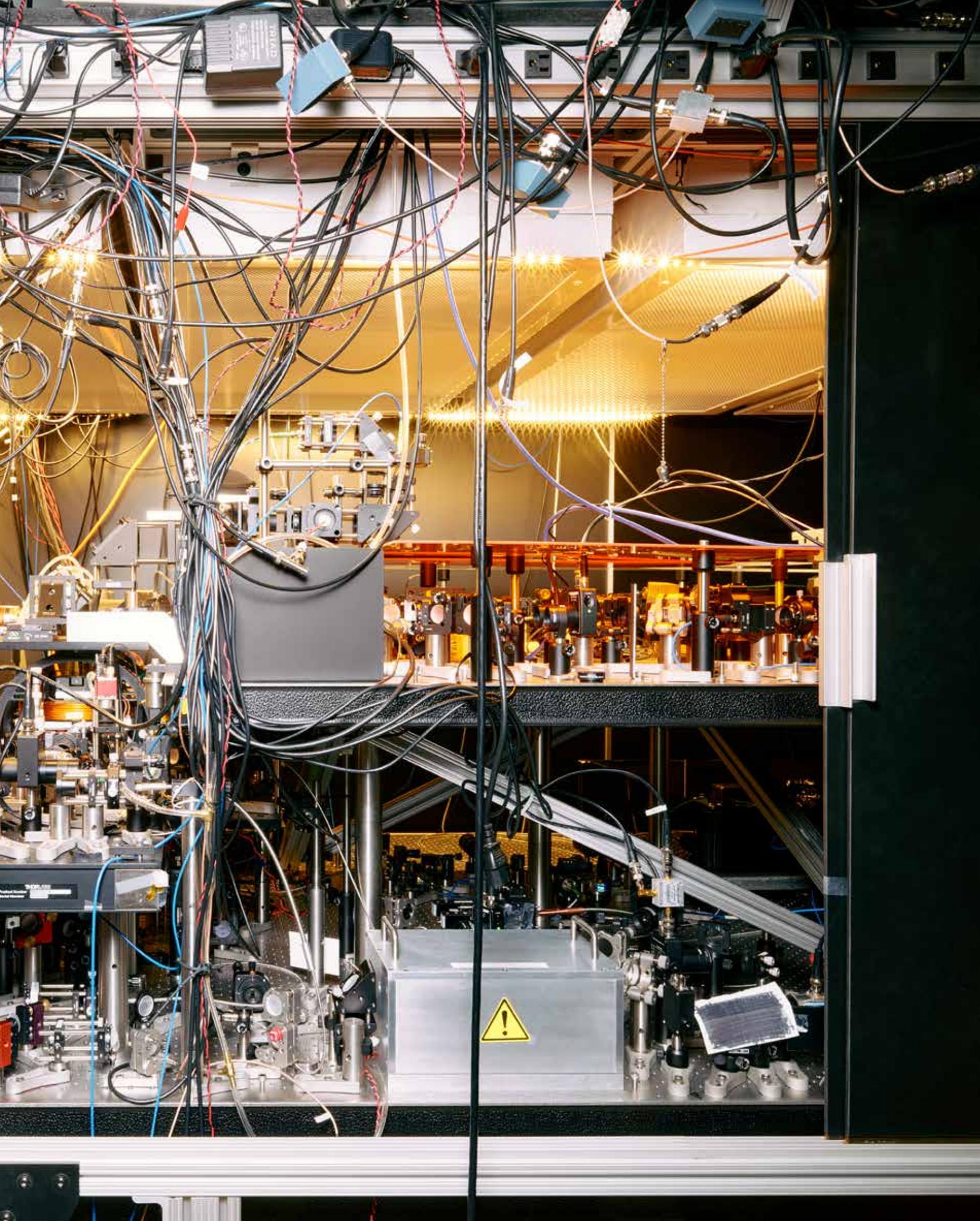
# ABOUT

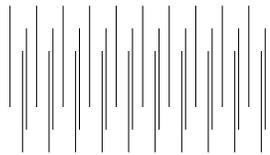
IN WINDOWLESS LABS IN COLORADO SIT THE 20 ATOMIC CLOCKS THAT A NATION SETS ITS WATCH BY. THEY ARE PRECISE TO A PICOSECOND, BUT THEY'RE BARELY KEEPING UP.

BY OLIVER ROEDER.

PHOTOGRAPHY BY JASON KOXVOLD







# CAESIUM IS A SOFT, SILVERY-GOLD METAL THAT BECOMES LIQUID WHEN STORED IN A WARM ROOM. IT IS MOSTLY FOUND IN MINERAL DEPOSITS NEAR A SMALL LAKE IN THE WILDS OF CENTRAL CANADA.

Its main commercial use is as an ingredient in drilling fluids for petroleum exploration. But thanks to quirks of chemistry and history, caesium is also the metronome of the world, the ultimate source of all modern time.

For millennia, celestial phenomena were our timekeepers and calendars, the best clockwork we had. Prehistoric tombs and monuments around the world are perfectly aligned with the sunrise on the solstice. We knew time passed because we saw things change. The Sun rose, seasons turned.

As late as the middle of the 20th century, our time remained tied to the Sun. A second was officially defined as a fraction of the solar year. But in 1967, deep in the atomic age, the 13th General Conference on Weights and Measures in Paris ruled that the second would now be defined according to vibrations of the caesium atom. Ever since, timekeeping has become the domain of physicists, extracted in sunless laboratories with precision optics, synthesised by computers and distributed by satellites.

Caesium atoms, when excited by just the right frequency, resonate, like a wineglass shattered by an opera singer. By measuring this frequency, we measure time. Atoms make for handy clockwork. They don't have mechanical parts, and they don't wear out. They are attractively standard. While sunlight and pendulums vary, every caesium atom is identical to any other. And they tick very fast.

Half a century before the first accurate measurement of a caesium clock was completed, some physicists suspected that they had already gone as far as they could when it came to

world-changing theories. It was possible, the German-American physicist Albert Michelson said in an address at the University of Chicago in 1894, that "the grand underlying principles have been firmly established". What remained was the application of these principles, careful experiments rooted in the science of accurate measurement. "Our future discoveries must be looked for in the sixth place of decimals," Michelson said.

Michelson may have been right, though not for the right reasons. (He was also off by quite a few decimal places.) Modern timekeeping has improved by about an order of magnitude per decade, Moore's law for clocks. We now measure time to its quintillionth part. At this level of particularity, the latest principles of physics, and those yet to be discovered, are laid bare on tables in small rooms in otherwise unremarkable basements.

Reckoning with this new precision, the world's foremost timekeepers and clockmakers, the men and women who maintain the measure of our days, are also grappling with a fundamental question of international political importance.

How long is a second?

IN OCTOBER, I TRAVELLED TO BOULDER, Colorado, a college town outside Denver wedged in the stony corner of the country where the Great Plains meet the Rocky Mountains. On the edge of town, protected by armed guards and detection dogs, the sprawling campus of the National Institute of Standards and Technology (Nist) lies in the shadow of the Flatirons range, between a cemetery and a dental office.

Nist, a non-regulatory federal government agency, sits within the US Department of Commerce, standards and technology being important to commerce. It was founded in 1901, as the National Bureau of Standards, when there were at least eight different gallons and four different feet in common use. Its current stated mission is "to promote US innovation and industrial competitiveness by advancing measurement science".

Nist's remit today is impossibly broad. One handbook, plucked at random from its website, consists of 290 pages discussing the net contents of packaged goods, and notes that "packages of compressed peat moss do not have declaration of expanded volume". Another, at 344 pages, covers both "products for use in lubricating tractors" and "pressed and blown tumblers and stemware".

One of Nist's main concerns is time. It measures and distributes it for the United States, second after second, always and endlessly. Underlying this seemingly mundane task is a complex administrative bureaucracy and a sophisticated scientific apparatus. The institute claims five Nobel Prizes, one in chemistry and four in physics. In recent years, the measurement science has outpaced the bureaucracy that constrains it, and both are now working to redefine the second itself.

Nist's Boulder complex is equal parts Eisenhower-era modernism and 1990s-era shopping mall. Through the middle runs a thick, tall barrier of red stone, like a castle wall. Behind this, through long corridors plastered with research posters, Jeff Sherman and Greg Hoth work within the citadel as physicists in the Time Realization and Distribution Group.

I slipped in through a side door and past a black curtain to an unassuming white room, one of an endless string of laboratories. On a low platform, against the wall, sat a large metal frame. A large metal tube descended endways from the top and some very advanced plumbing, strung with blue wires, ingressed and egressed its base. I put on special protective goggles, tinted to the colour of the lasers inside. A small monitor periodically showed a burst of the quantum physics within.

This is a "caesium fountain", called Nist-F3, and it is the tuning fork for America's official atomic clocks, the ur-clock. It rings not sound but microwaves. The best caesium clocks count seconds to 16 decimal places of precision (dwell on that, Michelson). If Nist-F3 had been keeping time since the dinosaurs, it'd be off by less than a second. Hoth had erected a makeshift barrier around its base so he didn't accidentally trip over it, imperilling the drumbeat of a nation. "A lab with a fountain has enough problems for anybody," he said.

Under normal circumstances, atoms zip around very fast. In the fountain, lasers from six directions are fired at the wisp of caesium floating in its vacuum chamber, slowing it in a molasses of light and cooling it to very near absolute zero. (The technique won Nist a Nobel Prize in 1997.) Another laser then shoots the cold ball up the tube, like water from a fountain, hence the name.

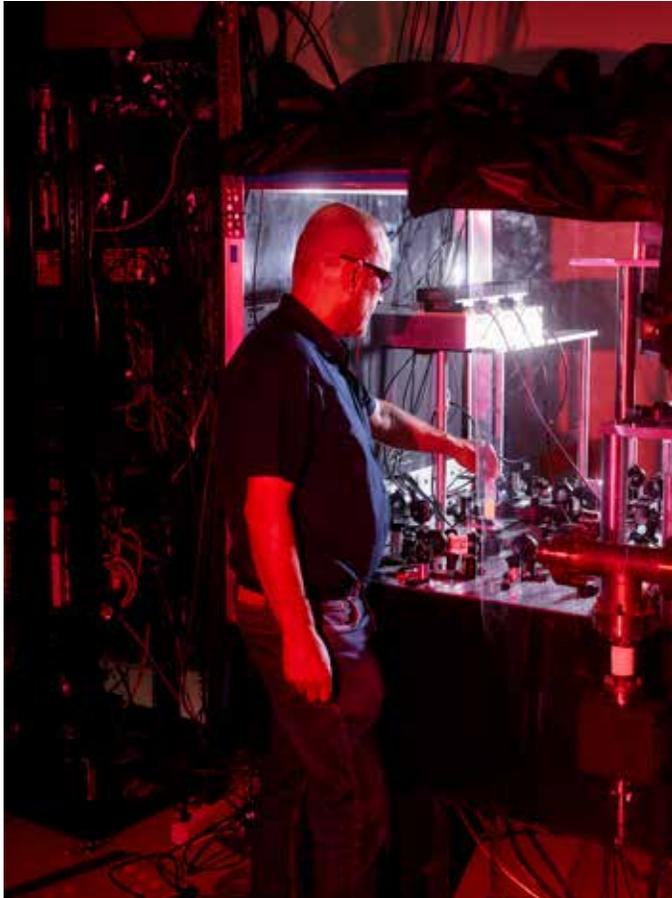
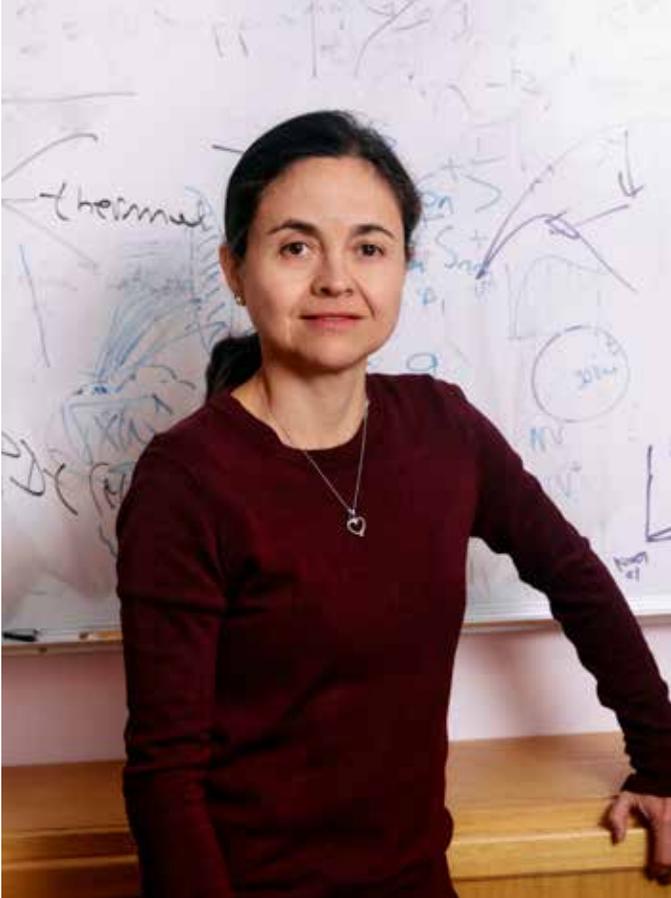
This flight buys precious time, about half a second, for the atoms to be studied. On their way up, they are blasted by microwaves. This excites some of the caesium atoms, which begin to vibrate, oscillating between two energy states at an exact, steady and very fast frequency - a quantum pendulum. The more atoms that are excited, the closer the microwave is tuned to caesium's natural resonant frequency. For now, a second is officially the "duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the caesium-133 atom".

Armed with this frequency, calibrated and re-calibrated, Nist-F3 keeps a larger ensemble of workhorse atomic clocks, called caesium beams and hydrogen masers (like lasers but for microwaves), on key. The masers sit behind five layers of magnetic and thermal shielding and two layers of vacuum. For climate control, they are stored in converted chicken-egg incubators - "given a paint job and tripled in price and sold to the government", Sherman said. One of these incubators was called Elvis and another George. The clocks inside cost hundreds of thousands of dollars. If you could see them, they would glow pink like a neon sign.

Sherman likened the process of measuring time this way to a playground game. You give a child a push on a swing and then close your eyes. You try to guess when the child has returned, and give her another push. You don't want to crash into the child, or miss her completely. But time it right, and the game keeps going smoothly, the pendulum keeps swinging regularly. The caesium fountain ensures that America's official clocks are ticking along.

"LET THERE BE LIGHTS IN THE FIRMAMENT of the heaven to divide the day from the night," God said. "And let them be for signs, and for seasons, and for days, and years."







OPENING PAGES:  
AN EXPERIMENT AT JILA  
THAT CAN TRAP AND  
MANIPULATE SINGLE  
ATOMS. THEIR QUANTUM  
PROPERTIES COULD  
LEAD TO BETTER CLOCKS

PREVIOUS PAGE:  
ANDREW LUDLOW AND HIS  
YTTERBIUM OPTICAL CLOCK

OPPOSITE, (CLOCKWISE  
FROM TOP LEFT): ANA  
MARIA REY IN HER OFFICE  
AT JILA; A VACUUM SYSTEM  
IN NIST'S OPTICAL CLOCK  
LAB; JEFF SHERMAN  
WEARING HIS PROTECTIVE  
LASER GOGGLES IN THE  
NIST LABS; THE LASER MAZE  
OF A MODERN CAESIUM  
FOUNTAIN; VLADISLAV  
GERGINOV WORKING ON  
NIST-F4; HARDWARE IN THE  
'TIME LAB' CALCULATES  
THE OFFICIAL US TIME

OVERLEAF: GRADUATE  
STUDENT RESEARCHER  
TRISTAN ROJO AT WORK  
IN A CLOCK LAB



Timekeeping started in the heavens, with days and years. We awake, we sleep, we harvest and so on. Holidays marking the winter and summer solstices, the shortest and longest days of the year, are “nearly universal”, writes the historian Ken Mondschein in *On Time*. Our old timekeepers, places like Newgrange and Stonehenge, testify to this.

“As soon as you get larger than a big family group, you start to have a need for co-ordination,” Chad Orzel told me. “You don’t want people to be just hanging around for ever, so you start to subdivide the day more and more.” Orzel did his PhD research at a Nist office in Maryland, where he had to cut through the clock lab to get to the coffee room. He’s now a physics professor at Union College and author of *A Brief History of Timekeeping*.

For Orzel, the history of time is a history of marking it more accurately and distributing it more publicly. In many cultures, time was long the purview of a religious elite, who maintained it in temples, ensuring the proper time for prayer and observance. Then there were public sundials in Greece and Rome. They beat drums and sounded trumpets on the hour. Then cathedral clocks went up in Europe. Medieval clocks had no minute hand; they weren’t accurate enough. Mechanical clocks and watches brought individual time into people’s homes. The obvious demands of railroad companies – usable schedules, not crashing – accelerated standardised time.

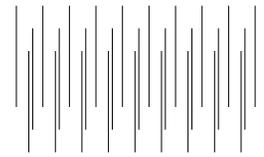
Throughout, time underpinned science and technology. A fundamental problem facing the seafaring nations of the 18th century, for example, was determining ships’ longitude, their distance east and west from the Greenwich meridian. In 1714, parliament offered a prize of £20,000 (millions of pounds today) for anyone who could determine longitude to within half a degree. The prize motivated clockmakers above all, because to know time is to know place. GPS works today because its satellites have atomic clocks onboard.

As late as the second world war, Londoners could hire a woman named Ruth Belville. Once a week, Belville set her family’s pocket chronometer at the Royal Observatory in Greenwich. She then visited her clients around the city, telling them what time it was, and they would set their own clocks. The Belvilles had operated this service since 1836. Now Nist servers respond to more than 100 billion requests a day for the time, synchronising between a quarter and half of all machines connected to the internet.

To keep time with a clock is already to abstract it. A clock is a model of the change that we’re actually interested in. The atomic clock, which forever ripped time from its solar embrace, is the ultimate abstraction.

Financial firms, stock exchanges, defence contractors, telecoms and others pay more than \$1,000 per month for certification of the accuracy of their clocks within a handful of nanoseconds, via a GPS antenna. For another \$345 a month, Nist will throw in a rubidium oscillator, a tiny atomic clock. The institute can also deliver high-fidelity time to customers via geostationary satellites, in the event of a GPS failure, or optical fibre. Clocks are the technology that enables all others.

In Orzel’s office in Schenectady, New York, an antique high-precision balance, used for measuring weights, sat in a wooden case behind him. “It doesn’t really work any more,” he said. “But it looks kind of cool.”



## ON OCTOBER 31, CLOCKS IN THE US DEVIATED FROM UTC BY JUST 1.3, A BILLIONTH OF A SECOND

IN THE US, BY FEDERAL LAW, THE OFFICIAL time is Coordinated Universal Time, known as UTC, as “interpreted or modified ... by the Secretary of Commerce in coordination with the Secretary of the Navy”. The Secretary of Commerce delegates its timekeeping authority to Nist, which in turn maintains a time scale called UTC(Nist), the official American time. You can see it, and how far deviated your clock is from it, at [time.gov](http://time.gov).

UTC itself, the spiritual successor of Greenwich Mean Time, is maintained by the International Bureau of Weights and Measures (BIPM, from the French), still headquartered in a Paris suburb. But UTC is a “paper” time scale. It has no live display or signal, and only exists as a weighted average of times submitted by dozens of labs around the world, calculated in retrospect. Once a month, BIPM publishes a document called Circular T, recording and comparing the performance of its contributing labs. On October 31, for example, the clocks in Bratislava ran 94 nanoseconds fast while those in Bucharest were 485 nanoseconds slow. The American clocks deviated from UTC by just 1.3, a billionth of a second.

In Newton’s physics, one big clock – God’s clock – ticks for the whole universe. In Einstein’s physics, the big clock has exploded. We each carry our own little clock, which ticks differently depending on where we are and where we’re going. Special relativity taught us that the faster we go, the slower our clock ticks. General relativity taught us that our location matters, and that gravity itself slows time.

In the room where Nist-F3 lives, there is a survey marker embedded in the floor, the

type of thing more often found outdoors, along property boundaries or on mountaintops. It was put there by the National Oceanic and Atmospheric Administration, which has an office next door and came in armed with gravimeters to measure the precise gravitational field. When distributing hyperaccurate time, you have to know how high up you are, or, rather, how far you are from the centre of the Earth.

There are some 20 atomic clocks playing in the Boulder ensemble. Their signals flow into another unassuming white room, smaller than the first, called the Time Lab. One wall is lined with racks packed with electronic components – “auxiliary output generator”, “doubler”, “distribution amplifier” – and another with cardboard boxes, tools and spare parts.

Redundancy is the state religion here. The clocks’ signals pour in via wires from around this building, snaking down through the ceiling. Some in orange tubes come from clocks quarantined in another building. Two instruments measure them all, and another two do it again. Five computers digest this data. Two computers calculate the ensemble’s average, via a special weighting algorithm. Clocks that perform well are promoted and those that perform poorly are demoted or excised. The whole system is air-gapped from any external network, and runs bespoke code unreliant on any entity outside the citadel. The entire process is replicated in another building.

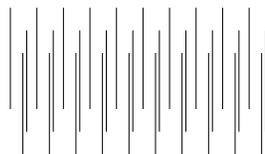
Every second – *the second* – tiny green lights blink on the rack. At the same time, give or take a few nanoseconds, on racks in the UK or Argentina or Japan, similar lights blink. Every 12 minutes, the system beeps as it adjusts particular clocks to the millionth of a millionth of a second. Just then, the system beeps. Finally – anticlimactically and beautifully – a small red display ticks its official realisation of UTC time. At that particular moment, it read 17:36:55.

Despite their picosecond precision, very few of the scientists at Nist wear watches. When asked why, Sherman recalled the words of an old colleague: “It pays not to obsess about these things.”

**SO, HOW LONG IS A SECOND? A NEWER** generation of atomic clocks, called optical lattices, replaces microwaves with waves from the visible spectrum, which have a much higher frequency, dividing measured time into finer segments still. They count ripples of light, a million billion per second. They can do this thanks to optical “frequency combs”, specialised lasers that act like “rulers for light” and allow these ungodly blazing frequencies to be measured with standard electronics. (This won Nist a Nobel Prize in 2005.) Light, after all, is how we communicate with the microscopic world. We see colour because atoms emit light.

Optical clocks ditch caesium for other elements with similar oscillatory properties, including ytterbium, strontium or aluminium ions, but the basic principle is the same, measuring the resonant frequency of excitable atoms. Ytterbium, for example, is a rare-earth metal. In significant quantity, like caesium, it is soft and silvery.

Optical clocks are 100 times better than their microwave forebears and we’re now looking at the 18th decimal place. For scale, here’s pi to the 18th decimal place: 3.141 592 653 589 793 238. These



## **VERY FEW NIST SCIENTISTS WEAR WATCHES. ‘IT PAYS NOT TO OBSESS ABOUT THESE THINGS’**

clocks would lose less than a second over the age of the universe. An optical clock is so precise that if you lifted one a centimetre off the ground, it would detect the gravitational dilation foretold by Einsteinian relativity. An optical clock is so precise that it has outgrown the very definition of a second. “The scientific motivations to change the definition are very clear,” Hoth said.

Elizabeth Donley and I met in a cramped Nist conference room, governmentally drab save the Halloween decorations. Donley’s professional title is unmatched. She is chief of the Time and Frequency Division, and has been for six years. In that capacity, she represents Nist and therefore the US in a byzantine series of organisations, committees, subcommittees, meetings, conferences, memos, papers and proposals that will ultimately redefine the second. “We’re hitting a limit where we can’t just talk about time any more, we have to talk about *space-time*,” Donley said.

The discussions began to heat up some eight years ago, and in 2020 the Consultative Committee for Time and Frequency – deep within a hierarchy underlying the BIPM – formed a task force, itself divided into three subgroups, to address the problem. It will present a resolution to the General Conference on Weights and Measures, the ultimate authority over the International Committee for Weights and Measures, which approves such things every four years, just like the Olympics. They next meet in 2026.

“It is a little bit political,” Donley said.

There is no debate that the second should be redefined. The question is *as what*. It is a weighty issue, especially because the second is the most fundamental of our fundamental units. In addition

to the second, BIPM co-ordinates the definitions of six other base entries in the International Systems of Units, or SI. They are the ampere (current), candela (luminosity), kelvin (temperature), kilogram (mass), metre (length) and mole (amount). Five of these depend, in turn, on the second. A metre, for example, is the distance travelled by light in a vacuum during a tiny fraction of a second. A new second will mean five other new units too. “Two sentences can turn into a laboratory and 50 years of iterative work,” Sherman had said of the current definition of a second. “So, ‘simple’ sort of never is.”

The task force was due to meet in November to discuss its progress, and Donley was deep in preparation. It is faced with eight mandatory criteria and seven “ancillary conditions”. For example, the new definition must improve accuracy, be reliably achievable and provide continuity after the caesium era. There are two options for redefinition left on the table, Donley explained:

1. A definition based on a single optical-clock species, likely strontium or ytterbium, but other candidates include aluminium, calcium, mercury and rubidium.
2. A definition based on a (possibly evolving) weighted average of more than one of the elements above.

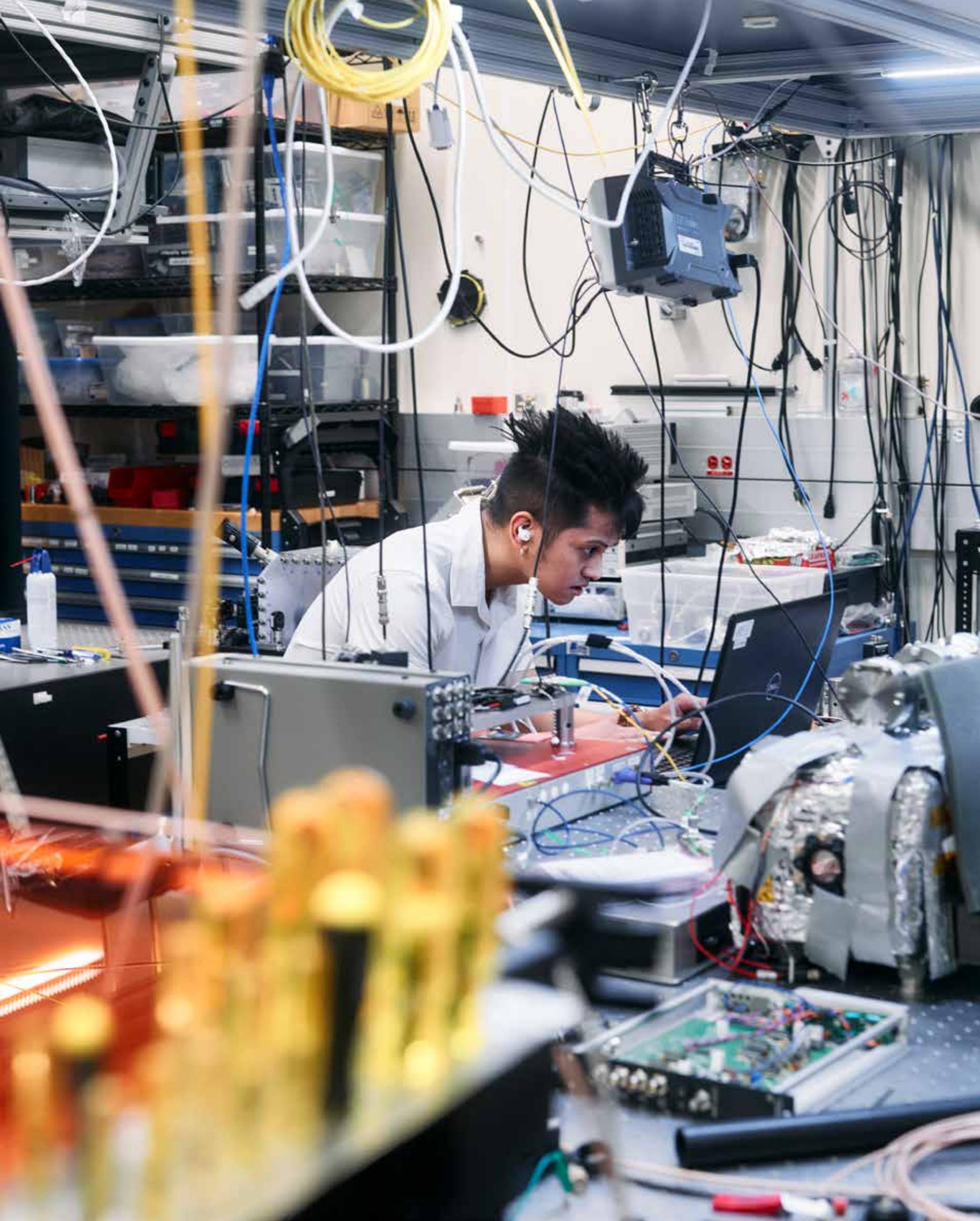
Option 1 is straightforward and would deliver an elegant definition, but it would require broad international consensus around one element. Option 2 is flexible and powerful but more complex; its definition would be lengthy, involved and perhaps difficult to convey to users. Parsimony might be nice when defining the fundamental unit.

Option 2 is based on a paper by Jérôme Lodewyck, of the French metrology group Syrte. “It’s several pages long and it’s very abstract, so a lot of people are not comfortable with it,” Donley said. But Lodewyck and that option’s backers value mutability and optimality over simplicity. “A system of units is not for the beauty of it,” Lodewyck told me. And he was undeterred by a few pages of maths. “The concept of ‘average’ is everywhere in our everyday lives. Scientists, they master it very well.”

Politicising this further, labs around the world have their own pet clocks and preferences. Nist excels in ytterbium and aluminium ion, for example, but would need to get up to speed on strontium. But by all accounts, the process has thus far been civil. “The community is pretty well behaved and pretty conservative, and no one’s in a rush,” Sherman said.

According to a roadmap published this year by Donley and the task force, the redefinition will be proposed in 2026 and executed in 2030. The slow bureaucracy of time seemed to weigh on Donley. She planned to step down as time chief in a couple months, and return to more practical timekeeping work. “We have to keep producing seconds, one after the other,” Donley said. “You do it, and then they want another one.”

**ELSEWHERE IN BOULDER, OTHER** clockmakers are building not atomic but nuclear clocks, driven by nuclei, the cores of atoms. Nuclei are more protected, less susceptible to the noisy environment around them and possibly easier to make portable. A paper describing the workings of a nuclear clock using thorium was published on the cover of *Nature* in September. Nist announced



that the research could lead to more accurate GPS and faster internet speeds.

One of the paper's authors, the nuclear physicist Jun Ye, greeted me in his office at JILA, a collaboration between NIST and the University of Colorado Boulder, once known as the Joint Institute for Laboratory Astrophysics and founded during the American "space race" with the Soviet Union. I was running about a trillion nanoseconds late, having struggled to find campus parking.

A move from the 16th to the 18th decimal place, the possible adoption of nuclear clocks and a redefinition of the second will have no appreciable impact on our daily schedules. We won't sleep in longer or get any younger. But the mundane act of measuring time may help uncover basic truths about our universe.

"Human beings are really good at building scopes, whether it's microscopes or telescopes," Ye told me. For him, clocks are both. Ye spoke romantically about what timepieces could do, zooming in his mind through powers of 10. He imagined an array of interlinked clocks in outer space that could detect gravitational waves, or echoes of the Big Bang. He imagined them exploring dark matter, about which we are woefully ignorant, but some sensitive instruments might help. He imagined unifying quantum physics and gravity, and atoms in superposition. ("In lay language," he said as I nodded, "that's because they are not part of any eigenstates of a particular Hamiltonian.") And we may discover that the fundamental constants of our universe are not constant after all. "We're knocking on the front door of nature's secrets," Ye said.

Downstairs, JILA graduate students milled around dark labs. Some workspaces looked like engine rooms of spaceships, and others looked like the cockpits. Three rough branches of quantum science - computing, simulation and clocks - are hopelessly intertwined here. Two students, Alec Cao and Theo Lukin Yelin, manipulated individual atoms with optical "tweezers". I saw the atoms on a screen, levitated in a light field, arranged like footballers in a disciplined formation. They were attempting to simulate real-world materials one atom at a time. The pair were also authors on a paper published that month in *Nature*, titled "Multi-qubit gates and Schrödinger cat states in an optical clock".

The most fundamental scientific questions are sometimes answered at billion-dollar particle colliders by thousands of scientists. Clocks and their hyper-precision provide a cheaper route to discovery. "We have an experiment on a tabletop that probes a lot of fundamental physics," grad student Tian Ooi told me. It's an attractive prospect. In the hallway, someone had posted an edit of the "distracted boyfriend" meme: Ye looks away from a strontium clock and ogles a thorium clock.

Upstairs at JILA, in a rare room with sunlight, the theorist Ana Maria Rey sat beneath a whiteboard dense with layers of mathematics. Her job is a sort of micro-scale sociology. The behaviour of one atom, she noted, is not the same as the behaviour of many atoms. She saw the lab work downstairs - the clocks, the simulation - as pointing toward a number of physics' holy grails, among them room-temperature superconductors. Rey also mentioned emulating a black hole in the laboratory. "It's kind of a dream," she said.



ELIZABETH DONLEY, NIST TIME AND FREQUENCY DIVISION CHIEF

These new clocks promise earthbound uses as well, especially if they're mobile, moving through the space part of space-time. One obvious use is geodesy, the science of measuring the Earth's shape, orientation and gravity. If a fancy clock were buckled in the backseat and driven around, it would generate incredibly detailed topography simply by telling time.

Ye's current professional goal is getting 1,000 atoms to live in harmony with one another. This has informed his broader worldview about humankind. "I'm not a philosopher," Ye said. "But sometimes I ask, 'What is the meaning of life?'"

**SAM BARON IS A PHILOSOPHER, AT THE University of Melbourne, and I reached him one night over video chat. "Here's something that might be kind of neat," he told me. "The work I have done is about whether or not time exists at all."**

Baron, it turned out, believes it does not. I did find this neat, if troubling. He granted that it was a contentious notion, though not one without precedent. Kant believed that time does not exist in the world, but rather is a projection we add to it. In versions of Buddhist thought, time is an illusion and a timeless consciousness is real. Even Einstein, who was deeply influenced by philosophy, might agree to an extent, given that relativity itself downgrades time massively from Newton's universal container.

What does exist, for Baron, is *change*. Things change and we measure them changing. At best, "time" is a label that we place on changing systems (like ringing atoms) but itself adds nothing to our discussion of reality. "Time" is a useful fiction.

In Baron's view, the Einsteinian explosion of our understanding of time (or whatever), which happened not all that long ago, is just the beginning of a reorganisation of our thinking. Baron's great lament is that philosophers and physicists don't speak to one another any more, as the fields have specialised beyond recognition. He pointed out physics' failure to come to grips with string theory or quantum gravity, despite in the latter case a century of effort. He suspected philosophers could help.

"There's a deep hostility toward philosophy," Baron said. "Let's all get in the same room and talk about what the fuck is going on with physics."

Some of the physicists I spoke to grappled with similar questions. One of Bijunath Patla's jobs is telling time on the Moon, where, thanks to relativity, clocks tick about 56 microseconds per day faster than on Earth. He is a theorist at NIST, and on a wall of his otherwise unadorned office hung a portrait of Einstein. It used to hang on a different wall, but it once fell off and hit Patla in the head, a post-Newtonian story too good to make up.

"If the universe was empty, is there a relevance for time?" Patla asked me. "Because nothing changes. So when does the universe start to change? Let's put one electron. If you wait a long time, the electron might change its spin. It would be billions of years, but a notion of time starts to emerge in this construction."

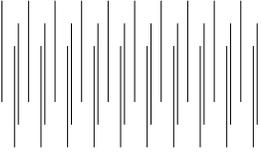
For Emily Thomas, a philosopher at Durham University, time is real and political, and the questions that we ask about it are reflections of the era. Newton's idea of God's time was "very obviously a product of 17th-century Britain". Later, with the invention of photography and cinema, time could be laid out in space. It became natural to think of the past, present and future all existing, all spread out on a table. "But what was built into that was a politically questionable, racist, sexist notion of progress, that the future is better than the past," Thomas said.

And now we are inventing the concept of millionths of millionths of millionths of seconds, a reflection, perhaps, of our own technocratic era.

As for its existence? "I just find it impossible to get past my own experience of living in time," she said.

**BACK IN THE NIST CITADEL, WHERE TIME** certainly seemed to exist, Andrew Ludlow and his students minded their two ytterbium optical clocks. These machines, named Yb-1 and Yb-2, may be the most accurate clocks in the world, and therefore a bargain at an estimated \$1mn each. The first one became so good that they built a second one just to measure how good it was. Each clock is now a sort of Ship of Theseus, having been tinkered with and improved for a decade or more. If ytterbium is part of the new definition, these machines could play a leading role in official timekeeping.

These clocks sit on tables within metal frames, with elements set on various tiers, like futuristic model train sets. Many of these elements are precision optics, creating mazes for the lasers that bend and bounce through them: mirrors, lenses, filters, splitters, samplers. Wires flow in heavy waterfalls from above and snake in streams throughout. In dedicated rooms nearby, highly coherent lasers are generated, and routed into the clocks via fibre optics, hair-width strings



# ADOPTING NUCLEAR CLOCKS MAY UNCOVER BASIC TRUTHS ABOUT OUR UNIVERSE

of glass. Five different colours run through this clock. “No single laser can do everything you need,” Ludlow said.

“Go ahead and turn the atomic-beam shutter on,” he instructed a student - not words uttered in every federal government office. Ludlow has been in the time game for more than 20 years, and sits on one of the redefinition committees. The administrative details have been just as challenging as the science. The international bureaucracy means he is often in timekeeping meetings in the middle of the night.

The strontiumists at JILA and the ytterbiumites at NIST compose a small community and maintain a friendly rivalry, even including an inter-element football game. Ludlow didn’t mention who won. Perhaps no surprise, then, that he favours Option 2, the evolving weighted average. It is a living, breathing thing. “Nature has given us at least a dozen good, interesting possibilities,” he said. “Right now there is no clear choice for what the right clock is.”

In the spring of 2020, a small group of unsung essential workers including Vladislav Gerginov roamed the lonely halls of NIST. During the height of the pandemic, when the experience of time became deeply distorted, the Time Group were the only people allowed in the building. This was the real deep state at work. “The time scale can’t stop,” Gerginov told me.

For nearly five years, Gerginov has been working on NIST-F4, a newer caesium fountain that is nearing certification as the “primary frequency

standard”, the official American realisation of the second in the remainder of the caesium era. Its room is bigger, its metal tube taller, its seconds purer.

We donned our goggles as Gerginov, a veteran of the time wars, recalled past laser burns. (“It’s not pleasant,” he said.) He removed black curtains and clear plastic dust protectors from his beloved fountain, revealing the quantum clockwork and green laser light. The curtains protected us from the machine, but also the machine from us. Everything can disturb its perfection - room lights, engines in the car park, the position of a wire, the black-body radiation we all emit just by standing around.

Gerginov’s days are spent wading through the minutiae of tiny decimal places, fixing, waiting, fixing, waiting. “Identifying problems in the 16th digit takes weeks,” he said. “You have to be very slow, very conservative.”

Would he be sad at the end of caesium’s reign, when some new element becomes the primary oscillating dictator of our days? “There’s no rush, there are a lot of things that have to happen first,” he said. “I’m not worried at all about it.”

I wondered what lessons a person learns after years in a windowless lab, in a secure federal facility, accompanied by nothing but laser light, the hum of fine machinery and the near-perfectly measured passage of time, which may or may not exist.

“Patience,” Gerginov said. “Patience.” 

.....  
*Oliver Roeder is the FT’s US senior data journalist*



**ROSEBERYS**  
LONDON

**The Collection of  
Mary and Alan Hobart,  
Founders of Pym's Gallery**

Tuesday 26 November

*Including pieces by Leonard Baskin,  
Angelo Lelii and Sir William Orpen.*



VIEW CATALOGUE

+44 (0)20 8761 2522  
williamsummerfield@roseberys.co.uk  
[www.roseberys.co.uk](http://www.roseberys.co.uk)