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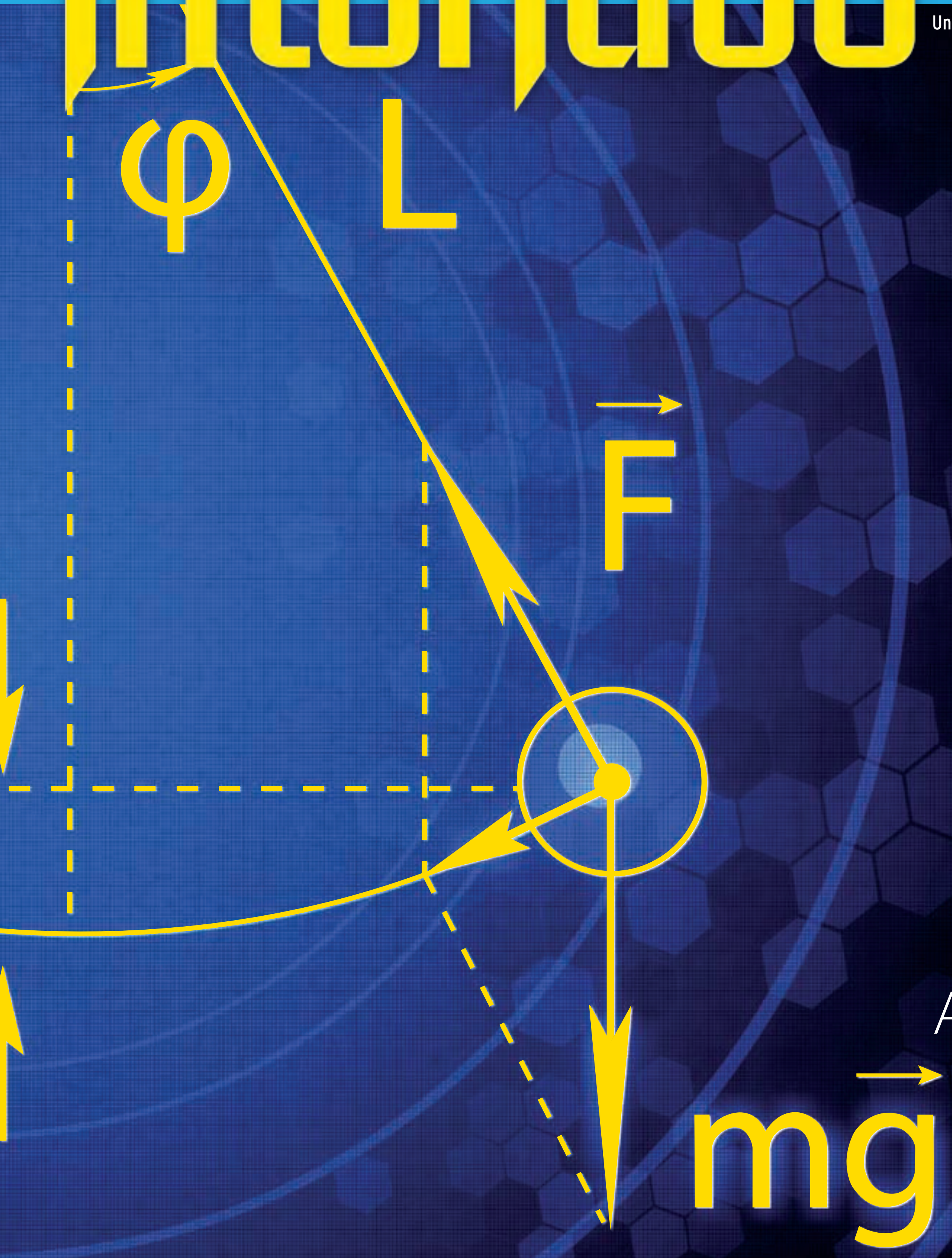

It's
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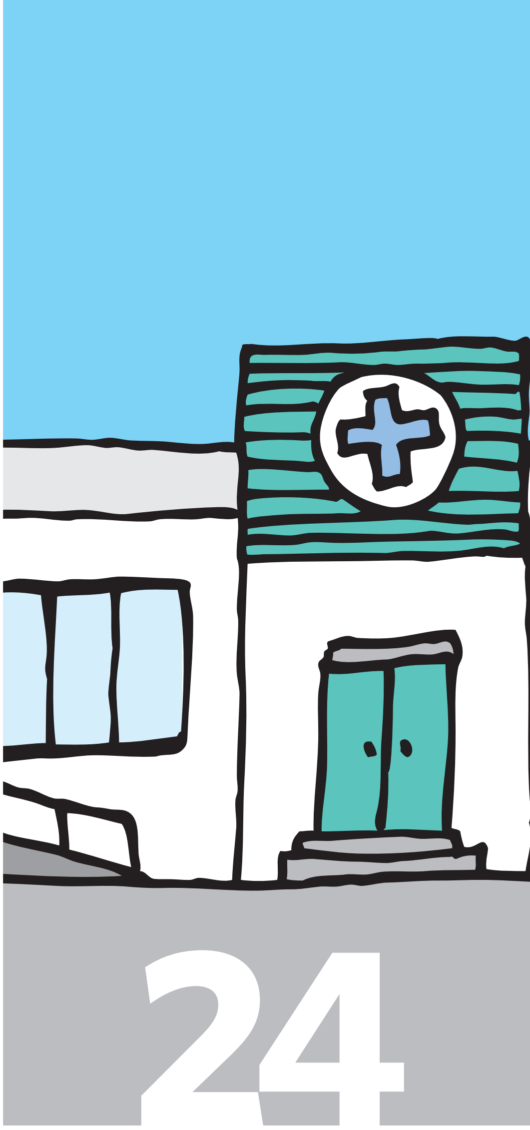
Time



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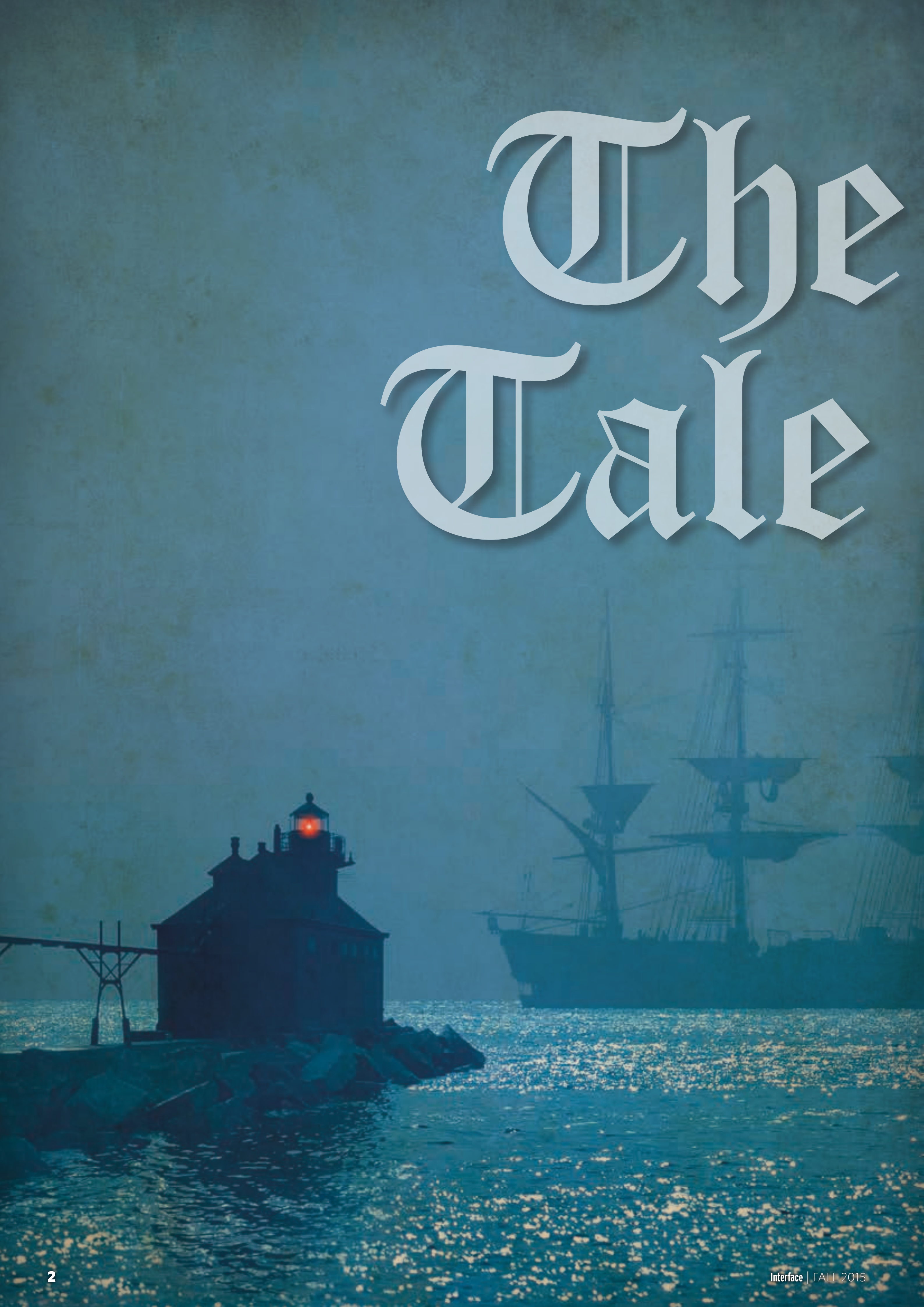
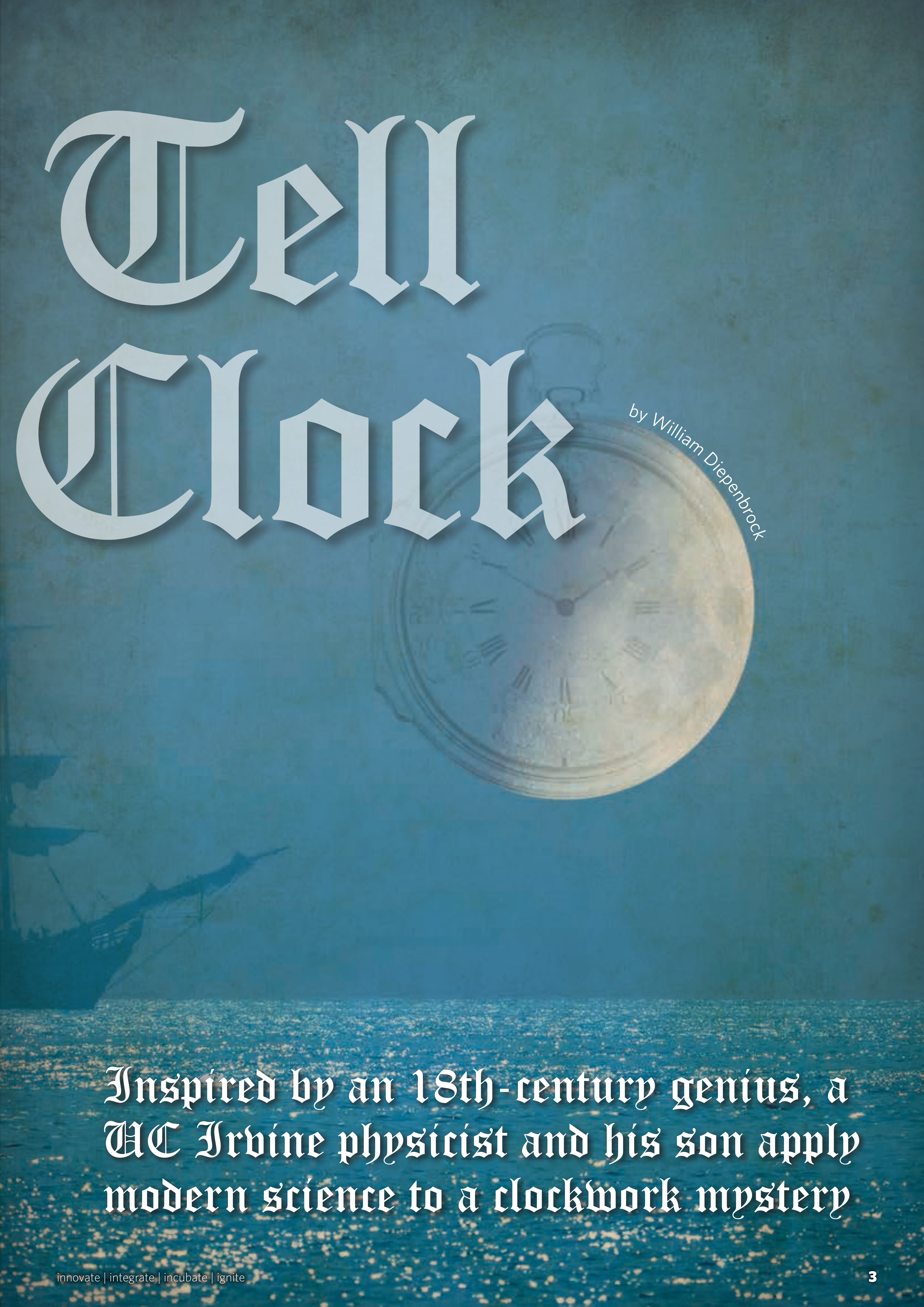
On the cover: *A physicist and his engineering-student son use modern technology to build a delicate timing tool, proving (and updating) an 18th-century genius's theories*

The Tale





Tell Clock

by William Diepenbrock

Inspired by an 18th-century genius, a UC Irvine physicist and his son apply modern science to a clockwork mystery

This is the tale of how the centuries-old ravings of a mad genius inspired a UC Irvine physicist and his son to craft a novel device so sensitive it can potentially measure the impact of the moon's orbit or the Earth's revolution on the intricate mechanisms of a mechanical clock.

Like the creators of many such breakthroughs, they made it in their garage.

"It's really a unique project because we are using modern technology to try to unravel the secrets of cutting-edge, 18th-century technology – technology that we still don't fully understand," says UCI experimental physicist and Calit2 affiliate David Kirkby. "It's a fascinating intellectual challenge."

"We've both pushed the limits of what we've done before," adds Dylan Kirkby, an electrical engineering student at Cal Poly San Luis Obispo. "I think we've both learned a lot."

The Kirkbys launched their effort in 2013 after David's uncle, a British clockmaker, complained about the lack of tools precise enough to continuously monitor the accuracy of pendulum clocks – the standard for clockmaking from the late 1600s until the early 1900s.

They knew it would be a challenge, but they never guessed the hidden rewards tackling the clockwork mystery would bring.

RAVINGS OF A MAD GENIUS

Among the greatest of the early clockmakers was John Harrison, a cabinet maker by trade, who helped Britain solve the problem of measuring longitude – at that time, a life-and-death issue for the British Navy – by inventing a hyperaccurate sea watch in the mid-1700s.

Near the end of Harrison's life, after a series of frustrating battles with authorities who often discounted his theories, the genius made the fantastic claim that he could create a pendulum clock that would be accurate to a second over 100 days using a design discounted by all common practice.

Where other clockmakers created designs to limit the impact of humidity, barometric pressure and temperature, Harrison's design embraced them. Where conventional practice favored small pendulum arcs, Harrison advocated larger arcs.

His designs were dismissed, even derided, as the ravings of a madman.

More than200 years ticked by before the clockmaker's vision would be given shape.

In 1975, amateur clockmaker and Harrison enthusiast Martin Burgess began building a clock with modern materials based on Harrison's designs as a way of proving his claim. In 2009, the clock was completed and, earlier this year, it was tracked for 100 days at the Royal Observatory at Greenwich.

The stunning result: accurate to within five-eighths of a second.

THE STAGE IS SET

The experiment appeared to vindicate Harrison's theories, but it also posed new conundrums for England's leading makers of mechanical clocks: Why was the Burgess clock so accurate? Could the results be replicated on a broader scale?

To find out, the clockmakers want to build a covey of clocks based on Harrison's designs beefed up with improvements made possible by today's more accurate manufacturing standards and materials. But first, they need a delicate timing tool that can show how and why they work.

"They can build these fantastically small gears using fantastically large machines but really don't have the expertise in modern electronics or software to measure their accuracy," David said.

In the Burgess experiment, horologists checked the clock's accuracy once a day by calling Britain's national speaking clock. A commercial electronic measuring system provided added information, but neither system could show tiny fluctuations in clock performance.

Enter the Kirkbys.

ACCURATE TO MICROSECONDS

Their timing tool constantly tracks a clock's accuracy in millionths of seconds and the arc of the pendulum in hundredths of a degree while simultaneously tracking air temperature, humidity, barometric pressure – even the subtle pull of the moon's 27-day trip around the Earth and the Earth's 365-day voyage around the sun.

So, how did they do it?

First, they mounted a simple pendulum clock to the wall of their Irvine garage. The clock's metal mechanism – exposed directly to the environment – includes four gear wheels, the pendulum and a 13-pound lead weight.

Next, they designed a circuit board to route clock and environmental measurements to a custom-crafted software program that presents and analyzes the data. It's a tried-and-true technique for the senior Kirkby.

In their garage, David Kirkby and his son Dylan designed and built a system to measure tiny fluctuations in a clock's performance.

"I have experience with these kinds of designs from my background in particle physics," he says. "It's a branch of physics where we can't buy our equipment off the shelf; we have to make it. So we design a lot of electronics and software. Only now, instead of tracking galaxies, I'm measuring the movement of a clock."

Dylan assembled the circuit board – an effort that involved more than 100 parts and about three days to complete. One microchip is so tiny, the Kirkbys had to warm its pins in a pancake pan so they could attach it to the board.

The board is fed by meteorological sensors, a GPS antenna mounted on the roof of the family home to ensure a constant stream of accurate time measurements, and an infrared beam that targets a thin titanium comb attached to the bottom of the pendulum.

> **"They can build these fantastically small gears using fantastically large machines but really don't have the expertise in modern electronics or software to measure their accuracy."**

NOVEL APPROACH

The heart of the tool is the infrared beam, which rests in a small aluminum block on its own shelf below the clock.

"What's really novel about this is that the infrared beam is very deep in there and shoots through a very narrow hole, so it's very tightly focused, and therefore not affected by changes in ambient lighting. If you could see it, it would look like a light saber," David says.

As the pendulum swings, six teeth on a comb break the light.

"The design of the comb is such that the beam gets broken and unbroken many times on each swing," says David. "That generates a lot of information. From one end to the other, that's not only telling us when it passes, but how fast it passes and, indirectly, how far it swings."

A shorter, seventh tooth designed by Dylan tracks changes in pendulum length as small as one ten-thousandth of an inch in response to changing temperatures.

"That's something nobody's done before," Dylan says.

After gathering data on and off for more than a year, the Kirkbys learned some basic truths.

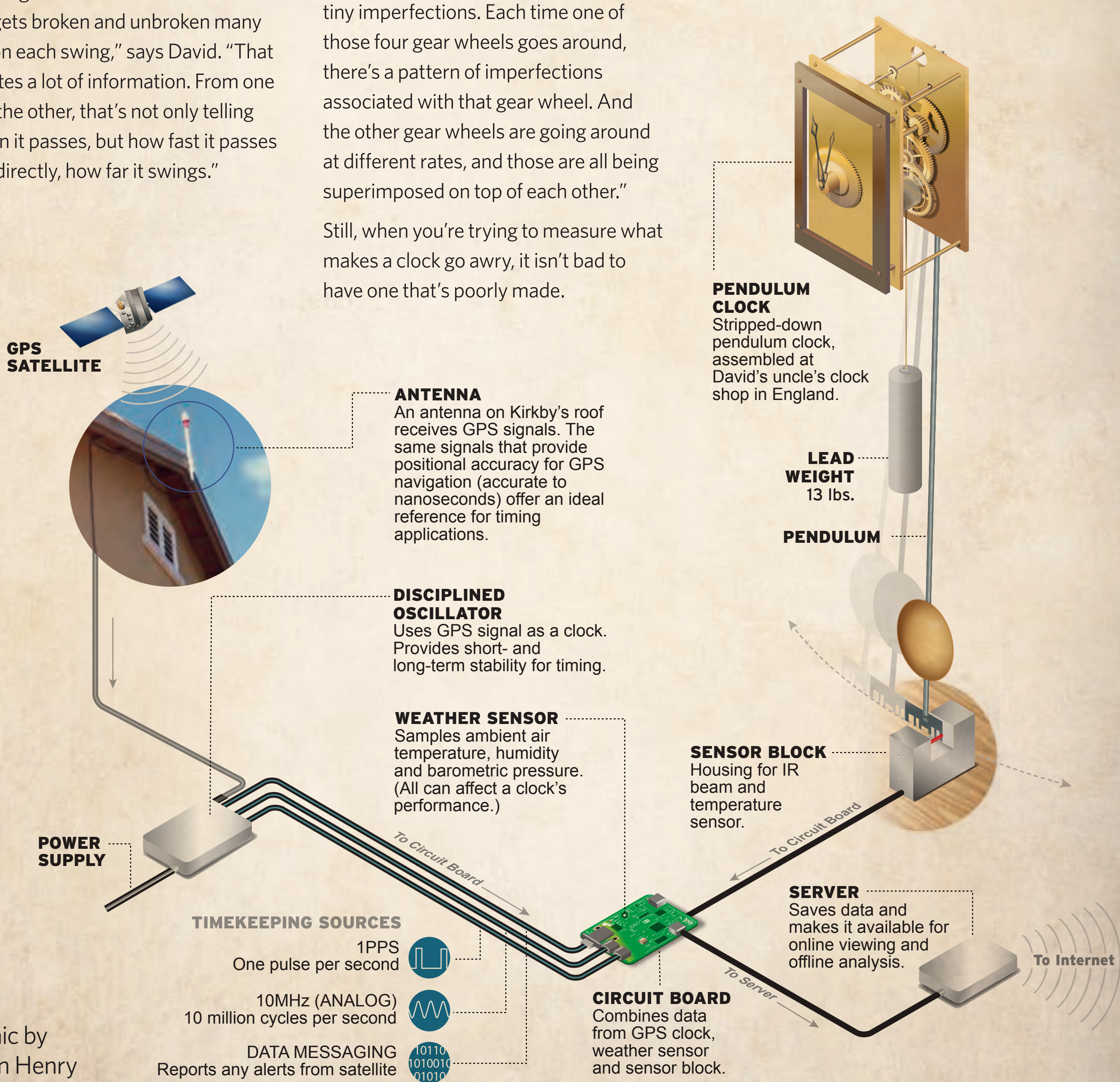
"One of the first things we learned is this clock isn't very well made," David says. "Every tick is different because the gears are hand-cut. Each tooth has tiny imperfections. Each time one of those four gear wheels goes around, there's a pattern of imperfections associated with that gear wheel. And the other gear wheels are going around at different rates, and those are all being superimposed on top of each other."

Still, when you're trying to measure what makes a clock go awry, it isn't bad to have one that's poorly made.

BIG DATA

On that front, the Kirkbys' two-bit timepiece has been a data bonanza, generating so much information that some subtler influences – such as changes in gravity – are harder to see.

That's why they've launched a second stage to the experiment. This month, they will send their sensor array, circuit board and software suite to David's uncle in England. The tool will be attached to a far more accurate clock to begin a more sensitive round of studies, with the expectation that its sensitivity



Graphic by Sharon Henry

and analysis of subtle environmental impacts will clarify why Harrison's design works so well.

If the tool proves itself, it will become part of the next stage of the Harrison saga.

"The clockmakers have a design for a super-Burgess clock," David says. "Ideally, they would like to build several of these to prove to the world that the textbooks are all wrong on how to build an accurate pendulum clock."

"That way, they can let the data do the talking," adds Dylan.

RICH REWARD

The triumph of the British clockmakers, however, will remain secondary to the Kirkbys' reward for their sleuthing. That's because, for them, the project hasn't been about starting a business, selling timing tools to clockmakers or proving Harrison right. They showed that when they posted their ideas to the web.

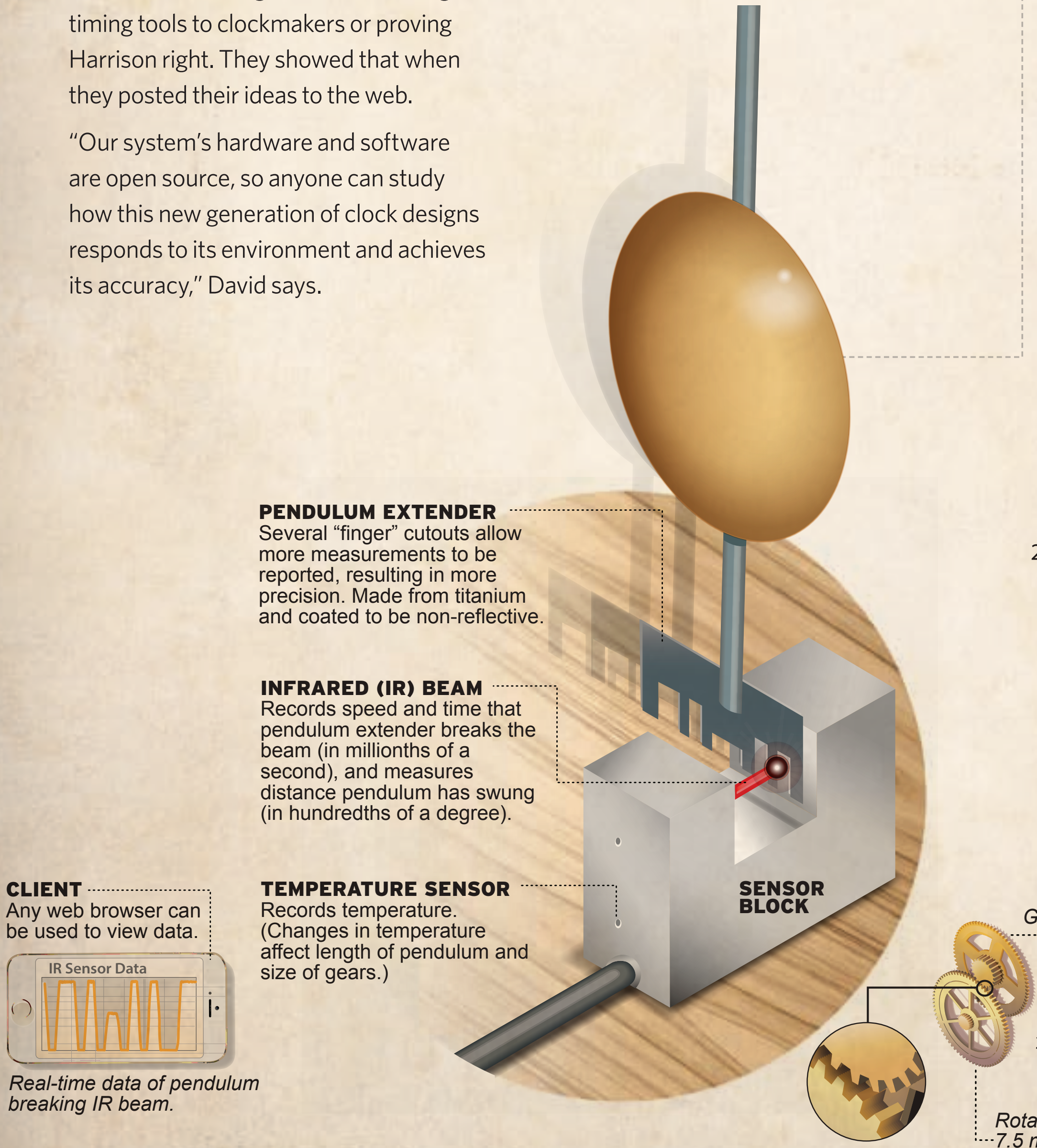
"Our system's hardware and software are open source, so anyone can study how this new generation of clock designs responds to its environment and achieves its accuracy," David says.

No, for the Kirkbys, the reward lies in a two-year journey taken side by side in a sweltering garage, soldering circuit boards, checking lines of code and persistently winding a cranky clock.

"It's been fun to work together," says Dylan. "It's been a great learning experience for me. I'm pretty gung-ho – let's get in there, just slap it all down – and Dad is more 'no, you've got to build a test program.' He's definitely more methodical, and I picked that up a little bit, which is probably a good thing."

For David, the experience has added a new dimension to his relationship with Dylan.

"This has been a unique experience for me, working with my son as a colleague and learning from each other," he says.



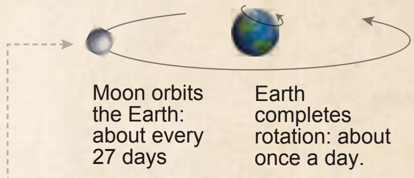
UNLOCKING VISUAL DATA

Kirkby's timing tool is precise enough to record subtle effects of gravity, weather and mechanical imperfections on a clock's performance.

Data is delivered in a visual format and can be viewed in real time or as historical graphs.

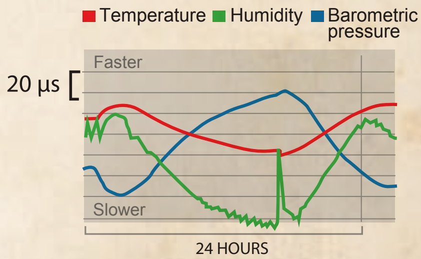
GRAVITATIONAL INFLUENCE

Clock runs faster and slower on one-day and four-week cycles. Because faster times are balanced by equal slower times, there is no change at the end of a cycle.



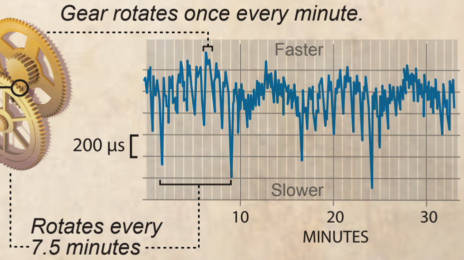
ENVIRONMENTAL INFLUENCE

Effects of weather on clock performance



MECHANICAL INFLUENCE

Each gear has its own fingerprint. Data for two gears (gear train) show time variations for each tooth in the gears.



Under the direction of Professor G.P. Li, Calit2@UCI develops IoT technology-based innovations in a multidisciplinary research environment. By integrating academic research with industry experience, the institute seeks to benefit society, incubate new technology companies and ignite economic development. Calit2 focuses on the digital transformation of healthcare, energy, the environment and culture.

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