Straightening Out Mind-Bending Measurements

Measuring time and space on the atomic scale requires quantum rulers and clocks. Gambini and Pullin are up to the challenge.

by MIKE PERRICONE

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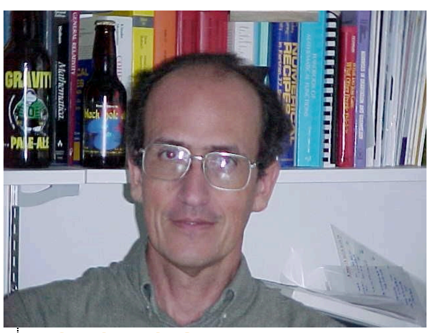
FQXi Awardees: Rodolfo Gambini, University of the Republic, Uruguay,& Jorge Pullin, Louisiana State University September 14, 2007

During tumultuous economic times in Argentina, Jorge Pullin's Buenos Aires high school had few resources. The library was a cabinet with a few dozen old books. Science classes were undemanding and uninspiring. A course in radio and TV repair was as close as he got to a laboratory.

And an accounting class provided what passed for intellectual fulfillment. "I learned how to keep accounting books adjusted for inflation, which was running at thousands of percent in Argentina at that time," Pullin recalls. One day's dollars were the next day's pennies.

But perhaps that early challenge of tracking a mind-bending phenomenon served Pullin better than he realized.



RODOLFO GAMBINI
University of the Republic, Uruguay

Now holding the Horace Hearne Chair in Theoretical Physics at Louisiana State University in Baton Rouge, and co-directing the Horace Hearne Institute for Theoretical Physics, Pullin has embarked on a long-term quest to measure mind-bending phenomena of the quantum world. With his collaborator of nearly 20 years, Rodolfo Gambini of Uruguay's University of the Republic in Montevideo, Pullin seeks accurate measurements at subatomic scales.

Start With an Itty-Bitty Ruler...

This task is easier said than done. Quantum-level distances are smaller than an atomic nucleus (10^{-15} m), while quantum-associated time increments shrink below 10^{-23} seconds, the time it takes light (traveling at the "speed of light," or 3×10^{8} meters per second) to move completely past an atomic nucleus.

Further, the Heisenberg uncertainty principle states that at the quantum level, we cannot accurately measure a particle's position and its momentum simultaneously, so scientists often use probabilities in their quantum calculations instead. But how does a ruler measure the probability of an outcome? How can a clock adapt to quantum fluctuations such as the slowing down of time experienced by particles approaching the speed of light?

It is here that Gambini and Pullin hope to apply a semblance of order. Their project, "Relational Physics With Real Rods And Clocks, And The Measurement Problem Of Quantum Mechanics," received an FQXi grant worth US$65,530.

Gambini and Pullin begin by considering the quantum world and the "real world" as indivisible. "Our view is that there is only one 'world' and it is quantum in nature," says Pullin.

Or, as Gambini, who achieved the first degree in physics ever awarded in Uruguay, says, "classical behavior observed at a macroscopic level must be understood in terms of quantum mechanics."

According to Pullin, "one can probe this world at different scales and see different behaviors." For example, "In everyday scales, one has enormous numbers of systems and subsystems interacting constantly. This limits the types of behaviors that one can see."

Not so at the quantum level.

"There, one is dealing with a limited number of systems, and their interactions have considerably more freedom," says Pullin. "One sees behaviors that one would never see in everyday life. Many of these behaviors significantly contradict our intuition, which is conditioned by our status as macroscopic observers. This makes quantum mechanics quite difficult to visualize."

At Least We Can Visualize Aristotle's Pear

A quantum conception of time is especially difficult to imagine. Like the Greek philosopher Aristotle, we associate time with change. In a famous example of a ripening pear, Aristotle compared the different states of a system with the revolutions of the earth on its axis: as each new day evolved, the pear changed.

JORGE PULLIN
Louisiana State University

Two thousand years later, Sir Isaac Newton's theory of gravity regarded time as absolute, says Ahbay Ashtekar, the Eberly Professor of Physics and Director of the Institute for Gravitational Physics and Geometry at Penn State.

Ashtekar is the author of *New Perspectives on Canonical Gravity* (1988), which inspired Pullin to work in the area of quantum gravity.

"One of Newton's fundamental postulates of dynamics asserted that there is an absolute time, ticking away independently of physical systems," says Ashtekar. "By now, we are so used to this notion [of absolute time] that it seems almost second nature to us."

But Ashtekar points to the German philosopher and mathematician Gottfried Liebniz, Newton's contemporary and frequent adversary, who argued for a relational concept of time: One physical system serves as the clock to measure the other system.

> One simply cannot 'just go buy a better clock' indefinitely. Nature puts limits on how accurate clocks…can be.
>
> *- Jorge Pullin*

In the twentieth century, Einstein's theory of General Relativity affirmed the relational nature of time. Yet scientific observations of quantum happenings remain associated with absolute, objective time.

"While unifying General Relativity with quantum physics," says Ashtekar, "one has to transcend this limitation, and formulate quantum physics in terms of relational time, incorporating clocks into a larger physical system. This becomes essential in quantum cosmology, since the universe is a closed system: There is no external physical clock ticking away!"

Measuring the Ruler, Timing the Clock

Gambini and Pullin are attempting to address this fundamental issue.

"They treat clocks and rods as quantum subsystems, which are subject to fundamental quantum uncertainties, and which must inevitably interact with the environment," says Ashtekar.

Pullin explains that measuring a system means interfering with that system, by exchanging energy. An infinitely accurate measurement would involve an infinite amount of energy. Accounting for gravity at the quantum level further complicates the issue: energy is equivalent to mass, and mass warps space-time. So the greater the accuracy of the measurement, the greater the warping of space-time.

"One simply cannot 'just go buy a better clock' indefinitely," Pullin says. "Nature puts limits on how accurate clocks and rulers can be."

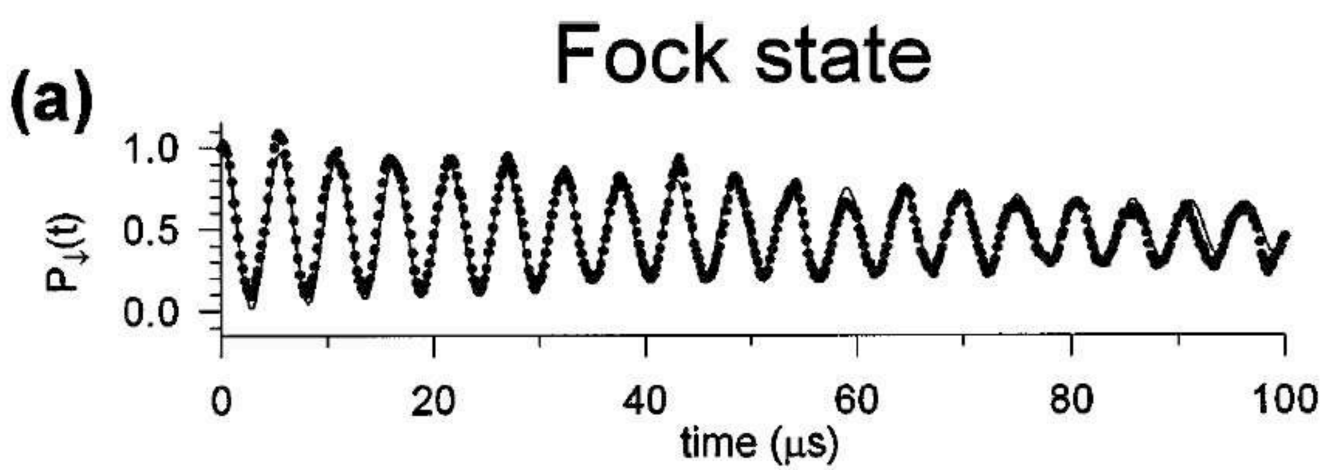
In a quantum system, Gambini and Pullin theorize that after eliminating all other sources of error and inaccuracy, one still needs to consider clocks and rods that incorporate quantum fluctuations. While these clocks and rods would not be arbitrarily exact, they would produce greater accuracy than any others in observing and predicting quantum behavior.

One of the distinctive properties of the quantum world is quantum coherence or "unitarity." Because the quantum world allows more freedom for systems to develop without interacting with other systems, their evolutions are particularly pristine; at the macroscopic level, this can produce startling effects such as laser beams and superconductivity. But the mathematical description of these evolutions only looks pristine if one casts them in terms of a perfect clock. If one uses realistic clocks, quantum coherence is imperfect.

This loss of unitarity may allow us to better understand the passage from quantum to classical behavior, significantly impacting experiments in the medium-term future, Gambini and Pullin think. Ashtekar seems to agree. "Not only will this research be directly useful to quantum gravity – particularly quantum cosmology – but it could also shed new light on the old `interpretation problem' of quantum mechanics," that is, selecting the most effective version of the quantum mechanical worldview for a particular case.

That's why Gambini envisions the project as helping to establish a systematic description of the world that "encompasses the quantum theory in a natural way." Such a system or "ontology," he says, would "radically change the predominant perspective on the world."

So, if they succeed, it seems Gambini and Pullin would produce a mind-bending phenomenon of their own.



NOT WHAT IT SOUNDS LIKE A Rabi oscillation, in which a Rubidium atom is coupled with a resonant cavity, can be interpreted as the rubidium atom providing an imperfect clock for the experiment.
Data Credit: Meekhof et al., PRL 76, 1796 (1996); Interpretation of the experiment: Bonifacio et al, PRA 61, 053802 (2000)