Cups of coffee cool, buildings crumble and stars fizzle out, physicists say, because of a strange quantum effect called “entanglement.”

Coffee cools, buildings crumble, eggs break and stars fizzle out in a universe that seems destined to degrade into a state of uniform drabness known as thermal equilibrium. The astronomer-philosopher Sir Arthur Eddington in 1927 cited the gradual dispersal of energy as evidence of an irreversible “arrow of time.”

But to the bafflement of generations of physicists, the arrow of time does not seem to follow from the underlying laws of physics, which work the same going forward in time as in reverse. By those laws, it seemed that if someone knew the paths of all the particles in the universe and flipped them around, energy would accumulate rather than disperse: Tepid coffee would spontaneously heat up, buildings would rise from their rubble and sunlight would slink back into the sun.

“In classical physics, we were struggling,” said Sandu Popescu, a professor of physics at the University of Bristol in the United Kingdom. “If I knew more, could I reverse the event, put together all the molecules of the egg that broke? Why am I relevant?”
Surely, he said, time’s arrow is not steered by human ignorance. And yet, since the birth of
thermodynamics in the 1850s, the only known approach for calculating the spread of energy was to
formulate statistical distributions of the unknown trajectories of particles, and show that, over time,
the ignorance smeared things out.

Now, physicists are unmasking a more fundamental source for the arrow of time: Energy disperses
and objects equilibrate, they say, because of the way elementary particles become intertwined when
they interact — a strange effect called “quantum entanglement.”

“Finally, we can understand why a cup of coffee equilibrates in a room,” said Tony Short, a quantum
physicist at Bristol. “Entanglement builds up between the state of the coffee cup and the state of the
room.”

A watershed paper by
Noah Linden, left, Sandu Popescu, Tony Short and Andreas Winter (not pictured) in 2009 showed
that entanglement causes objects to evolve toward equilibrium. The generality of the proof is
“extraordinarily surprising,” Popescu says. “The fact that a system reaches equilibrium is universal.”
The paper triggered further research on the role of entanglement in directing the arrow of time.

Popescu, Short and their colleagues Noah Linden and Andreas Winter reported the discovery in the
journal Physical Review E in 2009, arguing that objects reach equilibrium, or a state of uniform
energy distribution, within an infinite amount of time by becoming quantum mechanically entangled
with their surroundings. Similar results by Peter Reimann of the University of Bielefeld in Germany
appeared several months earlier in Physical Review Letters. Short and a collaborator strengthened
the argument in 2012 by showing that entanglement causes equilibration within a finite time. And,
in work that was posted on the scientific preprint site arXiv.org in February, two separate groups
have taken the next step, calculating that most physical systems equilibrate rapidly, on time scales
proportional to their size. “To show that it’s relevant to our actual physical world, the processes have
to be happening on reasonable time scales,” Short said.

The tendency of coffee — and everything else — to reach equilibrium is “very intuitive,” said Nicolas
Brunner, a quantum physicist at the University of Geneva. “But when it comes to explaining why it
happens, this is the first time it has been derived on firm grounds by considering a microscopic
theory.”
If the new line of research is correct, then the story of time’s arrow begins with the quantum mechanical idea that, deep down, nature is inherently uncertain. An elementary particle lacks definite physical properties and is defined only by probabilities of being in various states. For example, at a particular moment, a particle might have a 50 percent chance of spinning clockwise and a 50 percent chance of spinning counterclockwise. An experimentally tested theorem by the Northern Irish physicist John Bell says there is no “true” state of the particle; the probabilities are the only reality that can be ascribed to it.

Quantum uncertainty then gives rise to entanglement, the putative source of the arrow of time.

When two particles interact, they can no longer even be described by their own, independently evolving probabilities, called “pure states.” Instead, they become entangled components of a more complicated probability distribution that describes both particles together. It might dictate, for example, that the particles spin in opposite directions. The system as a whole is in a pure state, but the state of each individual particle is “mixed” with that of its acquaintance. The two could travel light-years apart, and the spin of each would remain correlated with that of the other, a feature Albert Einstein famously described as “spooky action at a distance.”

“Entanglement is in some sense the essence of quantum mechanics,” or the laws governing interactions on the subatomic scale, Brunner said. The phenomenon underlies quantum computing, quantum cryptography and quantum teleportation.

Seth Lloyd, now an MIT professor, came up with the idea that entanglement might explain the arrow of time while he was in graduate school at Cambridge University in the 1980s.
The idea that entanglement might explain the arrow of time first occurred to Seth Lloyd about 30 years ago, when he was a 23-year-old philosophy graduate student at Cambridge University with a Harvard physics degree. Lloyd realized that quantum uncertainty, and the way it spreads as particles become increasingly entangled, could replace human uncertainty in the old classical proofs as the true source of the arrow of time.

Using an obscure approach to quantum mechanics that treated units of information as its basic building blocks, Lloyd spent several years studying the evolution of particles in terms of shuffling 1s and 0s. He found that as the particles became increasingly entangled with one another, the information that originally described them (a “1” for clockwise spin and a “0” for counterclockwise, for example) would shift to describe the system of entangled particles as a whole. It was as though the particles gradually lost their individual autonomy and became pawns of the collective state. Eventually, the correlations contained all the information, and the individual particles contained none. At that point, Lloyd discovered, particles arrived at a state of equilibrium, and their states stopped changing, like coffee that has cooled to room temperature.

“What’s really going on is things are becoming more correlated with each other,” Lloyd recalls realizing. “The arrow of time is an arrow of increasing correlations.”

The idea, presented in his 1988 doctoral thesis, fell on deaf ears. When he submitted it to a journal, he was told that there was “no physics in this paper.” Quantum information theory “was profoundly unpopular” at the time, Lloyd said, and questions about time’s arrow “were for crackpots and Nobel laureates who have gone soft in the head,” he remembers one physicist telling him.

“I was darn close to driving a taxicab,” Lloyd said.

Advances in quantum computing have since turned quantum information theory into one of the most active branches of physics. Lloyd is now a professor at the Massachusetts Institute of Technology, recognized as one of the founders of the discipline, and his overlooked idea has resurfaced in a stronger form in the hands of the Bristol physicists. The newer proofs are more general, researchers say, and hold for virtually any quantum system.

“When Lloyd proposed the idea in his thesis, the world was not ready,” said Renato Renner, head of the Institute for Theoretical Physics at ETH Zurich. “No one understood it. Sometimes you have to have the idea at the right time.”
coffee are correlated with air particles; the coffee has reached thermal equilibrium.

In 2009, the Bristol group’s proof resonated with quantum information theorists, opening up new uses for their techniques. It showed that as objects interact with their surroundings — as the particles in a cup of coffee collide with the air, for example — information about their properties “leaks out and becomes smeared over the entire environment,” Popescu explained. This local information loss causes the state of the coffee to stagnate even as the pure state of the entire room continues to evolve. Except for rare, random fluctuations, he said, “its state stops changing in time.”

Consequently, a tepid cup of coffee does not spontaneously warm up. In principle, as the pure state of the room evolves, the coffee could suddenly become unmixed from the air and enter a pure state of its own. But there are so many more mixed states than pure states available to the coffee that this practically never happens — one would have to outlive the universe to witness it. This statistical unlikelihood gives time’s arrow the appearance of irreversibility. “Essentially entanglement opens a very large space for you,” Popescu said. “It’s like you are at the park and you start next to the gate, far from equilibrium. Then you enter and you have this enormous place and you get lost in it. And you never come back to the gate.”

In the new story of the arrow of time, it is the loss of information through quantum entanglement, rather than a subjective lack of human knowledge, that drives a cup of coffee into equilibrium with the surrounding room. The room eventually equilibrates with the outside environment, and the environment drifts even more slowly toward equilibrium with the rest of the universe. The giants of 19th century thermodynamics viewed this process as a gradual dispersal of energy that increases the overall entropy, or disorder, of the universe. Today, Lloyd, Popescu and others in their field see the arrow of time differently. In their view, information becomes increasingly diffuse, but it never disappears completely. So, they assert, although entropy increases locally, the overall entropy of the universe stays constant at zero.

“The universe as a whole is in a pure state,” Lloyd said. “But individual pieces of it, because they are entangled with the rest of the universe, are in mixtures.”

One aspect of time’s arrow remains unsolved. “There is nothing in these works to say why you started at the gate,” Popescu said, referring to the park analogy. “In other words, they don’t explain why the initial state of the universe was far from equilibrium.” He said this is a question about the nature of the Big Bang.

Despite the recent progress in calculating equilibration time scales, the new approach has yet to make headway as a tool for parsing the thermodynamic properties of specific things, like coffee, glass or exotic states of matter. (Several traditional thermodynamicists reported being only vaguely aware of the new approach.) “The thing is to find the criteria for which things behave like window glass and which things behave like a cup of tea,” Renner said. “I would see the new papers as a step in this direction, but much more needs to be done.”

Some researchers expressed doubt that this abstract approach to thermodynamics will ever be up to the task of addressing the “hard nitty-gritty of how specific observables behave,” as Lloyd put it. But the conceptual advance and new mathematical formalism is already helping researchers address theoretical questions about thermodynamics, such as the fundamental limits of quantum computers and even the ultimate fate of the universe.

“We’ve been thinking more and more about what we can do with quantum machines,” said Paul Skrzypczyk of the Institute of Photonic Sciences in Barcelona. “Given that a system is not yet at equilibrium, we want to get work out of it. How much useful work can we extract? How can I
intervene to do something interesting?”

Sean Carroll, a theoretical cosmologist at the California Institute of Technology, is employing the new formalism in his latest work on time’s arrow in cosmology. “I’m interested in the ultra-long-term fate of cosmological space-times,” said Carroll, author of “From Eternity to Here: The Quest for the Ultimate Theory of Time.” “That’s a situation where we don’t really know all of the relevant laws of physics, so it makes sense to think on a very abstract level, which is why I found this basic quantum-mechanical treatment useful.”

Twenty-six years after Lloyd’s big idea about time’s arrow fell flat, he is pleased to be witnessing its rise and has been applying the ideas in recent work on the black hole information paradox. “I think now the consensus would be that there is physics in this,” he said.

Not to mention a bit of philosophy.

According to the scientists, our ability to remember the past but not the future, another historically confounding manifestation of time’s arrow, can also be understood as a buildup of correlations between interacting particles. When you read a message on a piece of paper, your brain becomes correlated with it through the photons that reach your eyes. Only from that moment on will you be capable of remembering what the message says. As Lloyd put it: “The present can be defined by the process of becoming correlated with our surroundings.”

The backdrop for the steady growth of entanglement throughout the universe is, of course, time itself. The physicists stress that despite great advances in understanding how changes in time occur, they have made no progress in uncovering the nature of time itself or why it seems different (both perceptually and in the equations of quantum mechanics) than the three dimensions of space. Popescu calls this “one of the greatest unknowns in physics.”

“We can discuss the fact that an hour ago, our brains were in a state that was correlated with fewer things,” he said. “But our perception that time is flowing — that is a different matter altogether. Most probably, we will need a further revolution in physics that will tell us about that.”

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