Physicists investigate how time moves forward

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As humans, we have a very intuitive concept of time, and of the differences between the past, present, and future. But, as scientists Edward Feng of the University of California, Berkeley, and Gavin Crooks of the Lawrence Berkeley National Laboratory point out, science does not provide a clear definition of time.

“In our everyday lives we have the sense that time flows inexorably from the past into the future; water flows downhill; mountains erode; we are born, grow old, and die; we anticipate the future but remember the past,” the scientists write in a recent study in *Physical Review Letters.* “Yet almost all of the fundamental theories of physics – classical mechanics, electrodynamics, quantum mechanics, general relativity, and so on – are symmetric with respect to time reversal.

“The only fundamental theory that picks out a preferred direction of time is the second law of thermodynamics, which asserts that the entropy of the Universe increases as time flows toward the future. This provides an orientation, or arrow of time, and it is generally believed that all other time asymmetries, such as our sense that future and past are different, are a direct consequence of this thermodynamic arrow.”

In their study, Feng and Crooks have developed a method to accurately measure “time asymmetry” (which refers to our intuitive concept of time, that the past differs from the future, in contrast with time symmetry, where there is no distinction between past and future). They began by investigating the increase in energy dissipation, or entropy, in various arrangements.

The scientists’ method of measuring time asymmetry is best explained in the context of an experiment. In the macroscopic world, where glasses of milk are spilled, time asymmetry is obvious. But on the microscopic scale, because the amount of energy involved is so small, it’s more difficult to tell that entropy is increasing, and that time is moving forward and not backward. In fact, during some intervals, entropy might actually decrease. So even though overall entropy is still increasing on average, in accordance with the second law, the direction of time is not obvious at every moment in the experiment. Further, the scientists show that even an average entropy increase does not necessarily ensure time asymmetry, but can arise in an arrangement that appears time-symmetric.

Feng and Crooks wanted their new measurement method to explain how time can move forward even at points when entropy is decreasing. To do this, they analyzed the folding and unfolding of a single RNA molecule attached to two tiny beads. By controlling the distance between one bead and an adjacent optical laser trap, the scientists could stretch and compress the RNA molecule. Initially, the RNA starts in thermal equilibrium, but, as it’s alternately stretched and compressed, the total entropy of the RNA and the surrounding bath increases on average.

“We use an ensemble, or large number, of RNA trajectories to measure the time asymmetry,” Feng explained to *PhysOrg.com*. “Using work measurements for both forward and reverse experiments, we simply plug these measurements into an expression for A, or time asymmetry, in the paper. Assuming we know the free energy change, this gives the square of the length of time's arrow.”

To measure time asymmetry in this arrangement, an observer watching the RNA’s trajectory of unfolding and folding should be able to tell if the trajectory was generated by stretching or compressing. The scientists quantify this observation in terms of the “Jensen-Shannon divergence,” a probability which gives a “0” if stretching and compressing are identical, a “1” if they are distinguishable at every moment, and some fraction of one if they overlap occasionally.

This probability, Feng and Crooks explain, can more accurately describe time asymmetry than a simple measurement of average entropy, since the average entropy is sensitive to unusual events. For example, if the RNA becomes tangled, it resists being unfolded when the beads expand. Because the tangled RNA is pulled apart very slowly, the process is essentially time-symmetric. The scientists show that a model of this process has large average dissipation, or entropy increase, but small time asymmetry, as one intuitively expects due to the slow pulling.

“The Jensen-Shannon divergence is better than the average dissipation due to its mathematical form,” Feng said. “This accounts for the rare events in a different way, which we show with the RNA molecule that can get stuck.”

Besides the theoretical interest, this research could have other applications, such as for estimating free energy differences in non-equilibrium experiments. The scientists explain that understanding the relation between time asymmetry and entropy could also be important for studying molecular motors and other kinds of biological machinery.

“While time blatantly moves forward in the macroscopic world, the direction of time becomes confusing on the scale of a single molecule,” Feng summarized. “Our definition employing the Jensen-Shannon divergence highlights this distinction. We hope this will have an impact as scientists study biological molecules and continue to perform single-molecule experiments.”

More information: Feng, Edward H. and Crooks, Gavin E. “Length of Time’s Arrow.” *Physical Review Letters* 101, 090602 (2008).