Natural Science | Oct 28, 2026 | 5 min read | By Bryan White

Information Engines in Complex Fluids: How a Colloidal Maxwell's Demon Extracts Work from Hidden Environmental Memory

Thermodynamics * Statistical Mechanics * Information Physics

1. Executive Summary: Tapping Non-Markovian Memory in Stochastic Information Engines

In 1867, Scottish physicist James Clerk Maxwell proposed a famous thought experiment testing the statistical foundations of the Second Law of Thermodynamics : if a microscopic observer -- later dubbed Maxwell's demon by Lord Kelvin -- could track the individual thermal velocities of gas molecules and selectively open a frictionless trapdoor between two chambers, it could sort fast and slow particles to create a temperature gradient without performing mechanical work. Over the following century, Leo Szilard (1929), Rolf Landauer (1961), and Charles Bennett (1982) resolved this paradox by demonstrating that Shannon information is physically coupled to thermodynamic entropy [2, 4] . Acquiring, storing, and erasing one bit of measurement information in a thermal bath at temperature T requires a minimum heat dissipation of k B T ln 2 (approximately 2.87 x 10 −21 J at 298 K), where k B is the Boltzmann constant [2] .

Until recently, almost all experimental realizations of colloidal and nanoscale information engines -- whether using optically trapped microspheres, single-electron boxes, or biomolecular rotary motors -- were analyzed under a strict Markovian (memoryless) bath assumption [3, 4] . In a purely viscous Newtonian solvent such as water, solvent molecules collide and relax on picosecond timescales (τ bath ∼ 10 −12 s), meaning any energy or information transferred from a colloidal particle to its surroundings dissipates almost instantaneously. In a landmark October 2026 study published in Nature Physics , Lokesh Muruga, Felix Ginot, Sarah A. M. Loos, and Clemens Bechinger at the University of Konstanz and the Max Planck Institute for Dynamics and Self-Organization demonstrated that when an information engine operates inside a viscoelastic, non-Markovian complex fluid , the surrounding medium stores temporal correlations in unobserved (“hidden”) degrees of freedom [1] . By implementing a time-delayed double-measurement feedback protocol that exploits information backflow from the fluid network, the researchers extracted up to three times more work than a standard single-measurement Markovian protocol -- and in specific feedback regimes extracted work exceeding the equilibrium elastic energy stored in the observable particle trap itself [1] .

2. Colloidal Optical Tweezers in a Viscoelastic Micellar Bath

To construct a laboratory Maxwell's demon capable of probing environmental memory, Bechinger's team suspended a micrometer-scale silica colloid (radius R ~ 1.36 um) inside an entangled wormlike micellar solution (equimolar cetylpyridinium chloride and sodium salicylate in water) and confined the particle within a harmonic

potential U (x) = ½κ(x − x 0) [2] generated by a piezoelectrically steerable laser optical trap of stiffness κ [1] . Unlike pure water, which behaves as a memoryless viscous bath, the entangled micellar polymers form a transient viscoelastic network with a stress-relaxation time τ m on the order of seconds -- comparable to the characteristic relaxation time τ κ = gamma/κ of the optically trapped colloid itself [1] .

Mathematically, the stochastic trajectory x (t) of the visible colloidal bead cannot be described by a memoryless Langevin equation. Instead, it obeys a generalized Langevin equation with a finite-time friction memory kernel Γ(t − t'), which can be mapped onto a coupled system in which the observable particle coordinate x (t) interacts elastically with one or more hidden bath coordinates h (t) representing the local deformation of the surrounding micellar cage [1, 5] . When a thermal fluctuation pushes the glass bead in one direction, the bead strains the invisible micellar network; as the network relaxes over seconds, it exerts a delayed restoring force back onto the bead, imprinting a multi-second physical memory of the particle's past trajectory into the fluid.

| Thermodynamic / Engine Parameter | | Markovian Viscous Bath (Water) | | Non-Markovian Viscoelastic Bath (Micellar Fluid) | | Physical & Information-Thermodynamic Consequence |

| Bath Relaxation Time (τ m) | | ∼10 −12 s (τ m ≪ τ κ) | | ∼1-5 s (τ m ~ τ κ) | | Viscoelastic network retains strain history across feedback cycles [1] |

| Governing Stochastic Dynamics | | Memoryless Langevin (white thermal noise) | | Generalized Langevin / coupled hidden coordinate h (t) | | Past particle displacements remain correlated with hidden bath states [1, 5] |

| Optimal Feedback Protocol | | Single instantaneous position measurement x (t 0) | | Time-delayed double measurement (x (t −1), x (t 0)) | | Velocity-like difference reconstructs hidden micellar strain state [1] |

| Maximum Extracted Work (− W) | | Bounded by ½ k B T (observable potential energy) | | Up to ∼3x higher; can exceed ½κ⟨ x [2] ⟩ | | Taps non-equilibrium elastic energy stored in hidden degrees of freedom [1] |

| Second Law Generalized Bound | | −⟨ W ⟩ <= k B T ⟨ I obs ⟩ | | −⟨ W ⟩ <= Delta F eff + k B T ⟨ I obs+hidden ⟩ | | Preserves Second Law when mutual information with bath memory is counted [1, 4] |

3. The Time-Delayed Double-Measurement Protocol and Information Backflow

In a classical colloidal information engine operating in a memoryless fluid, the demon measures the particle's position x 0 = x (t 0) when a random thermal fluctuation carries it away from the trap center. The feedback controller then instantaneously shifts the laser trap center x trap to the particle's measured position, reducing the trap potential energy to zero and extracting work − W = ½κ x 0 [2] without doing mechanical work against the particle [3, 4] .

Because a Markovian bath has no memory, measuring the particle's position at earlier times (t −1 < t 0) yields zero additional mutual information about the future evolution of the system once x (t 0) is known.

In the viscoelastic fluid studied by Muruga et al., however, the demon cannot directly image the transparent micellar polymers -- their configuration h (t) is a hidden variable [1] . If the feedback controller relies only on a single snapshot x (t 0), it remains blind to whether the hidden micellar network is currently stretched in the same direction as the bead or pulling against it. To overcome this limitation without directly measuring the bath, the Konstanz-Max Planck team introduced a time-delayed double-measurement protocol : the demon records the particle position at two times separated by a delay Delta t = t 0 − t −1 , and adjusts the feedback trap shift as a linear combination of both measurements [1] :

x shift = alpha 0 x (t 0) + alpha 1 x (t −1)

Because the trajectory displacement between t −1 and t 0 reflects the restoring force exerted by the deformed micellar network, the two-point measurement acts as a dynamical observer that decodes information backflow from the hidden bath degrees of freedom into the visible particle coordinate [1] . When the delay Delta t is tuned to match the viscoelastic memory timescale τ m , the demon infers the instantaneous strain of the hidden micellar cage and positions the optical trap so that the relaxing viscoelastic network actively pushes the colloid toward the new trap minimum, transferring stored bath elastic energy into harvestable work [1] .

4. Exceeding Observable Energy Bounds Without Violating the Second Law

A striking quantitative finding of the experiment is that under optimized two-time feedback weights (alpha 0 , alpha 1), the average work extracted per cycle not only increases by up to a factor of three relative to memoryless protocols, but can also exceed the total thermal potential energy ½κ⟨ x [2] ⟩ = ½ k B T stored in the observable optical trap degree of freedom [1] . Naively, an observer monitoring only the visible silica bead might conclude that the engine is extracting more work than the energy available in the system, seemingly violating the generalized Second Law of Stochastic Thermodynamics [1, 4] .

Muruga, Ginot, Loos, and Bechinger show that thermodynamic consistency is fully preserved once the hidden viscoelastic degrees of freedom and the full trajectory mutual information are accounted for [1] . Under the Sagawa-Ueda generalized Second Law for feedback-controlled systems, the extractable work −⟨ W ⟩ is bounded by the free-energy change Delta F plus the mutual information I acquired by the measurement apparatus [3, 4] :

−⟨ W ⟩ <= −Delta F + k B T ⟨ I ⟩

In a non-Markovian medium, past fluctuations have already invested thermal energy into straining the hidden micellar network prior to t 0 . The double-measurement protocol acquires higher mutual information ⟨ I 2 ⟩ > ⟨ I 1 ⟩ by capturing the cross-correlations between x (t −1), x (t 0), and the hidden coordinate h (t 0) [1] . Accounting for the Landauer thermodynamic

cost of storing and erasing two correlated measurements in the external controller's memory register (at least k B T ⟨ I 2 ⟩), total entropy production across the composite system -- colloid, viscoelastic bath, and measurement demon -- remains strictly non-negative (Delta S tot >= 0) [1, 2] .

5. Implications for Cellular Biophysics and Nanoscale Autonomous Machines

Beyond resolving a fundamental question in non-equilibrium statistical mechanics , the demonstration that environmental memory is an exploitable thermodynamic resource carries direct implications for intracellular biophysics and synthetic nanorobotics [1, 5] . Living cells do not operate in dilute, memoryless aqueous solutions: the eukaryotic cytoplasm and cytoskeleton form a crowded, viscoelastic, and actively remodeling polymer gel whose relaxation timescales (milliseconds to seconds) overlap directly with the conformational stepping cycles of molecular motors such as kinesin, dynein, myosin, and F o F 1 - ATP synthase [1, 3] .

Biochemical signaling cascades and mechanosensitive enzyme complexes naturally integrate conformational history across multiple phosphorylation or allosteric binding steps -- functioning as autonomous molecular feedback sensors embedded in a non-Markovian medium [1, 4] . By proving experimentally that multi-time sensing protocols can harvest energy stored in hidden environmental correlations, the Konstanz-Max Planck study establishes quantitative design rules for synthetic microrobots, colloidal heat engines, and neuromorphic computing elements operating in complex biological and soft-matter fluids [1, 5] .

References & Primary Sources

* [1] Muruga, L., Ginot, F., Loos, S. A. M., & Bechinger, C. (2026). The extraction of work from hidden degrees of freedom. Nature Physics. -- https://doi.org/10.1038/s41567-026-03442-w

* [2] Landauer, R. (1961). Irreversibility and heat generation in the computing process. IBM Journal of Research and Development, 5(3), 183-191. -- https://doi.org/10.1147/rd.53.0183

* [3] Toyabe, S., Sagawa, T., Ueda, M., Muneyuki, E., & Sano, M. (2010). Experimental demonstration of information-to-energy conversion and validation of the generalized Jarzynski equality. Nature Physics, 6(12), 988-992. -- https://doi.org/10.1038/nphys1821

* [4] Parrondo, J. M. R., Horowitz, J. M., & Sagawa, T. (2015). Thermodynamics of information. Nature Physics, 11(2), 131-139. -- https://doi.org/10.1038/nphys3230

* [5] Loos, S. A. M., & Klapp, S. H. L. (2020). Irreversibility, heat and information flows induced by non-reciprocal interactions. New Journal of Physics, 22(12), 123051. -- https://doi.org/10.1088/1367-2630/abcc1e