



A Single-Molecule Engine

Marc W. Bockrath

Science **338**, 754 (2012);

DOI: 10.1126/science.1230530

This copy is for your personal, non-commercial use only.

If you wish to distribute this article to others, you can order high-quality copies for your colleagues, clients, or customers by [clicking here](#).

Permission to republish or repurpose articles or portions of articles can be obtained by following the guidelines [here](#).

The following resources related to this article are available online at www.sciencemag.org (this information is current as of November 25, 2012):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:

<http://www.sciencemag.org/content/338/6108/754.full.html>

A list of selected additional articles on the Science Web sites **related to this article** can be found at:

<http://www.sciencemag.org/content/338/6108/754.full.html#related>

This article **cites 4 articles**, 1 of which can be accessed free:

<http://www.sciencemag.org/content/338/6108/754.full.html#ref-list-1>

This article appears in the following **subject collections**:

Chemistry

<http://www.sciencemag.org/cgi/collection/chemistry>

CHEMISTRY

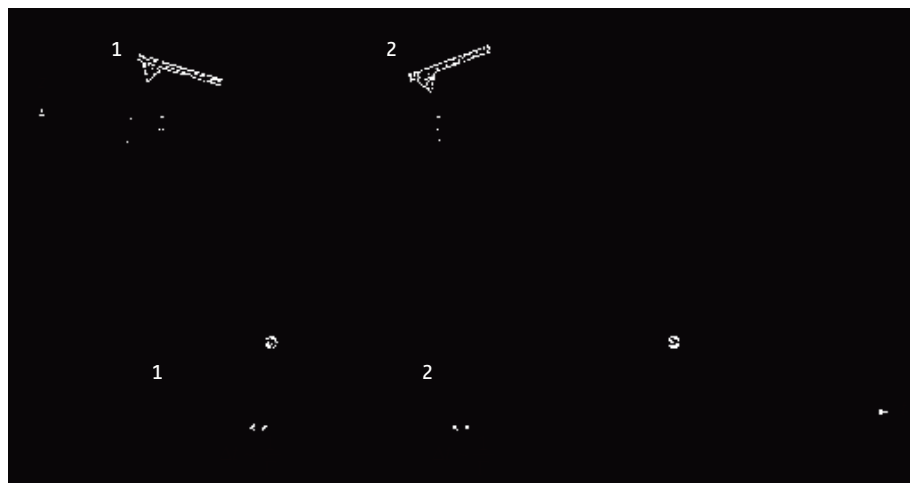
A Single-Molecule Engine

Marc W. Bockrath

A single hydrogen molecule can be used to drive the tip motion of a scanning tunneling microscope.

In physical systems, mechanical energy usually flows from the large to the small in the form of dissipation into the random thermal motion of the molecules and atoms in the system. In biology, many natural systems have evolved to reverse this trend, enabling the flow of energy from the small to the large, with examples including photosynthesis (1) or motor protein motion (2). The desire to recreate this ability in artificial systems motivates a search for strategies and concepts that enable energy harvesting from very small subsystems. On page 779 of this issue, Lotze *et al.* (3) now show how the motion of a macroscopic cantilever beam can be excited using the driven motion of only a single molecule. In this case, a single hydrogen molecule is trapped between a copper surface and a scanning tunneling microscopy tip mounted on a flexible springlike cantilever. The authors find that when a particular bias voltage between the tip and copper is applied, the electric current causes the hydrogen to switch stochastically between two different positional states and the cantilever begins to oscillate spontaneously.

Because the hydrogen molecule and the cantilever are coupled by the molecular forces between the tip and hydrogen, which act like a spring attached to the tip, the observed oscillation results from a transfer of energy between the driven motion of the hydrogen molecule and the cantilever. Although the precise nature of the two different hydrogen positional states is not yet known, in the two states (see the figure, states 1 and 2) the effective force of the hydrogen on the cantilever differs. The electric current flowing between the tip and the substrate randomly knocks the hydrogen between the two states, producing a fluctuating force on the cantilever. To extract energy from this random motion and to transfer it to the oscillator, a vital ingredient is force hysteresis—the forces when the cantilever is approaching or receding from the surface must differ. The trick to obtaining this hysteretic force is to couple the probabilities and transition rates between the two hydrogen states to



In the driver's seat. A simplified picture of the typical energy transfer cycle, showing the tip position above the copper surface z versus time t , plotted as the black curve. The red regions correspond to the trapped hydrogen molecule being in positional state 1, and the blue regions correspond to the hydrogen molecule being in positional state 2. In state 1, the attractive force between the hydrogen and the tip is stronger than in state 2. The horizontal dashed line marks the spatial location where the hydrogen molecule acquires a transitional lifetime between the two states, with 1 being the most probable state above the line and blue the most probable state below it. Once the threshold is crossed, a typical waiting time Δt on the order of the inverse transition rate Γ is required until the actual transitions occur, events marked by the filled ($1 \rightarrow 2$) and open ($2 \rightarrow 1$) circles. Because the force in the two hydrogen states differs, on average there is a net energy transfer to the cantilever during each cycle.

the cantilever position and motion, exploiting a phenomenon known as stochastic resonance (4). Lotze *et al.* accomplish this by using their finding that although the electric current randomly switches the hydrogen between the two states, the bias voltage can be tuned to a specific value so that the hydrogen positional fluctuations become highly correlated with the tip motion.

The hysteresis is then provided by the stochastic nature of the transition between the hydrogen states itself (see the figure). The tip position z is plotted as a function of time t by the sinusoidal curve. Here, starting at the arrow, the hydrogen molecule is in state 1, and when the tip crosses the spatial threshold shown by the horizontal dashed line, the probability of transition to state 2 turns on in the form of a nonzero transition rate Γ to state 2 and corresponding finite lifetime $\Delta t \sim 1/\Gamma$ for state 1. The transition typically must wait for this lifetime to happen; the event is plotted as the filled circle. The hydrogen molecule is then in state 2, corresponding to the blue region under the curve. Meanwhile, the cantilever continues its descent, finally reaching its minimum and turning

around and moving upward. When the cantilever crosses the threshold again, state 2 now has a finite lifetime and again the transition takes on the order of this lifetime to occur. The hydrogen molecule makes its transition back to state 1 at the open circle. Meanwhile, the cantilever continues its upward motion, eventually turning around and continuing the cycle, corresponding to the red shaded region. In this way, although the hydrogen motion is probabilistic, on average a hysteretic force is applied to the cantilever. If it can be arranged for the force in state 2 to be less than that in state 1—as it is in the reported experiment—on average, with each cycle of motion the hydrogen will deliver a net downward impulse to the oscillator.

In reality, the spatial threshold for changing the transition probabilities between the two states is not sharp in space but smooth. Nevertheless, the detailed calculations by Lotze *et al.* show that the results are similar and account very well for their data. Another important aspect is that the energy delivered in each cycle is very small, ~ 10 meV. However, because it is delivered at the resonance frequency, and the intrinsic frictional losses

Department of Physics and Astronomy, University of California, Riverside, Riverside, CA 92521, USA. E-mail: marc.bockrath@ucr.edu

within the cantilever per cycle are smaller than the energy of each energy transfer, the energy from many cycles can build up enough to produce appreciable motion of the cantilever, limited ultimately by nonlinearities present in the system.

Being able to direct energy from the small to the large is an important ability if, for example, one wants to harvest chemical or other forms of energy toward powering func-

tional nanostructures. The work of Lotze *et al.* is an intriguing demonstration of how this can work in a synthetic structure. Although the elegance and efficiency of biological systems in this regard may provide inspiration, the initial step taken by this experiment provides a strong direction for further research, toward controlling and directing large-scale motion from nanoscale or even single-molecule energy sources.

References

1. Y.-C. Cheng, G. R. Fleming, *Annu. Rev. Phys. Chem.* **60**, 241 (2009).
2. A. Gennerich, R. D. Vale, *Curr. Opin. Cell Biol.* **21**, 59 (2009).
3. C. Lotze, M. Corso, K. J. Franke, F. von Oppen, J. I. Pascual, *Science* **338**, 779 (2012).
4. L. Gammitoni, P. Hänggi, P. Jung, F. Marchesoni, *Rev. Mod. Phys.* **70**, 223 (1998).

10.1126/science.1230530

CLIMATE CHANGE

Constraining Cloud Feedbacks

Karen M. Shell

Despite decades of improvements in computer models of Earth's climate, estimates of the climate sensitivity—the change in global average surface air temperature in response to a doubling of carbon dioxide concentration—remain uncertain (1). Much of the uncertainty results from radiative feedbacks that amplify or dampen climate changes. Particular attention has been given to the cloud feedback. Global warming is expected to change the cloud cover, but these changes and their effects on global temperature are very difficult to predict. On page 792 of this issue, Fasullo and Trenberth (2) present an observational test of the cloud feedback based on satellite measurements of relative humidity (RH) in cloud-free subtropical regions. The authors focus on environmental conditions that are easier to observe than the cloud properties themselves.

Clouds cool the climate by reflecting incoming sunlight back to space, but they also warm the climate by absorbing upwelling terrestrial radiation from the surface. Their net effect is to cool the planet, but changes in clouds in response to global warming may increase or reduce this cooling. Climate models do not agree on the spatial patterns of cloud changes or their net radiative effects, and the cloud feedback is responsible for most of the uncertainty in climate sensitivity in model studies (3–5). Observational data are needed to resolve these issues.

Global, reliable satellite data are available for only a few decades, too short a time to directly observe century-scale feedbacks.

Thus, determining the climate sensitivity from observations requires two nontrivial steps. First, the relation between short-term (seasonal, interannual, or decadal) and long-term feedbacks needs to be determined

A simple diagnostic circumvents the need for measuring cloud properties, helping to improve climate sensitivity estimates.

using models. Second, modeled short-term feedbacks must be compared to observations to test the models.

If similar processes control both short-term and long-term feedbacks—for example, cloud cover increases or decreases in a predictable manner in response to temperature increases—then these short-term observations can perhaps be used as proxies for longer-term changes. However, short-term and long-term cloud feedbacks do not appear to be correlated in models (6). Thus, the first step is not only difficult but may even be impossible, if short-term observations are not a guide to long-term changes.

Regarding the second step, one reason for the

Linking relative humidity to cloud feedbacks. Water vapor (in cm) (A), cloud fraction (B), and reflected solar radiation (in W/m²) (C) for July 2012. Black regions in the water vapor plot indicate missing data, often due to high cloud coverage. Regions with high cloud fraction and reflected solar radiation generally coincide with high amounts of water vapor. Note in particular the subtropical regions with low reflected solar radiation. Fasullo and Trenberth use the correlations of these three fields to relate relative humidity changes to reflected solar radiation changes and, hence, cloud feedbacks.



College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA. E-mail: kshell@coas.oregonstate.edu