Maxwell's demons may drive some biological systems

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(PhysOrg.com) -- According to the second law of thermodynamics, entropy always increases. For example, two bodies of different temperatures, when brought into contact, will eventually mix together to result in a uniform temperature.

But, as the physicist James Clerk Maxwell famously suggested in 1871, what would happen if a theoretical demon could stand at a doorway between the two bodies, and only allow high-temperature particles to pass through one way, and only low-temperature particles to pass through the other? The tiny doorman would prevent the two temperatures from mixing, and theoretically prevent entropy. Of course, the demon would use energy to do this job, thus creating entropy itself, and so the second law would not be violated.

While Maxwell's demon was originally considered a thought experiment, similar mechanisms have been discovered for various applications. One example is a Ranque-Hilsch vortex tube, which is a pneumatic device that separates hot and cold air by spinning hot and cold molecules in different directions.

Now, a recent study shows that a similar mechanism may drive a motor switch in the bacteria *Escherichia coli*, and may be responsible for many other signaling systems in biology. Researcher Yuhai Tu at IBM's T.J. Watson Research Center in Yorktown Heights, New York, explains how *E. coli*'s Maxwell's demons work in a recent issue of the *Proceedings of the National Academy of Sciences.*

“There are two related contributions made in this paper,” Tu told *PhysOrg.com.* “First, a general non-equilibrium mechanism for making a highly sensitive switch (i.e., how Maxwell's demons can be used to increase sensitivity). Second, a general result on dwell-time statistics (how long a system should stay in a given state before it switches to other states). This result can be used as a diagnostic tool to detect the existence of these demons (or non-equilibrium effects) in an unknown system.”

The bacterium contains flagellar motors that drive its motion. A flagellar motor has a switch (a shift gear) whose job is to sense the concentration of a regulator called CheY-P, and then control the rotational direction of the motor to be either clockwise (CW) or counterclockwise (CCW), accordingly.

“The purpose of the CW and CCW switch is to control the motion of the cell,” Tu said. “The CheY-P level is the signal (red/yellow/green light) which affects the switch (stop/slow/move). In a very loose sense, CCW results in movement and CW results in switching direction. The bacterium cell needs to control these two types of motions to navigate towards (away from) favorable (toxic) environments.”

Conventionally, the switching mechanism was thought to operate in equilibrium, where the switch changes between clockwise and counterclockwise motor rotations in a balanced way. An earlier experiment showed that the time interval a flagllear motor spends in a given state (either clockwise or counterclockwise) follows a peaked distribution. Based on Tu’s work, this peaked interval time distribution indicates that the switch operates out of equilibrium.

In order to achieve this fast and accurate switching, the switch must be extremely sensitive to the CheY-P concentration. In the non-equilibrium model, Tu shows that this high sensitivity can be explained by the presence of two Maxwell’s demons, which act as the switch’s sensors for the CheY-P.

"The easiest way to explain the work of these two Maxwell's demons is that they are two coincidence counters," he said. "Each switch can have up to 34 CheY-P regulators bind to it. One of the demons will count the number of bound CheY-P, and if the number is greater than some threshold, say 22, it will switch the motor from CCW to CW; another demon works the opposite way with a low threshold, say 12. If the number of CheY-P bound is less than 12, this demon will switch the motor from CW to CCW."

These "demons" consume energy to do their work, in accordance with the second law of thermodynamics. The more energy the demons use, the more sensitive the switch is. Tu determined the exact amount of energy used per switch cycle, and discovered that it is roughly equal to the work done by one or two protons moving through the membrane near the flagellar motor. Based on this finding, he predicts that the switch may be powered by protons passing through the membrane. This possibility would agree with earlier observations that the average switching frequency depends on the proton flux.

As Tu explains, viewing the flagellar motor switch in the framework of a non-equilibrium model could help scientists understand the switching mechanism as an integrated part of the motor system. In biology, many systems operate out of equilibrium, and Tu's model could help scientists detect interesting non-equilibrium effects. Besides the flagellar motor, he predicts that a similar non-equilibrium mechanism, driven by Maxwell's demons, could be responsible for a variety of other cellular processes.

More information: Tu, Yuhai. "The nonequilibrium mechanism for ultrasensitivity in a biological switch: Sensing by Maxwell's demons." *PNAS,* August 19, 2008, vol. 105, no. 33, 11737-11741.