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Maxwells deamon and the second law of thermodynamics

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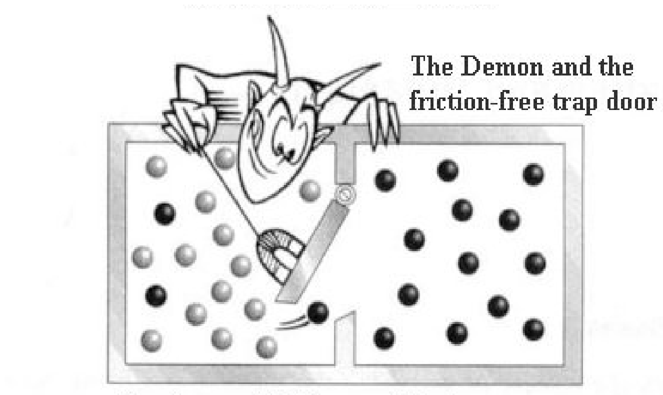
Maxwell's demon and the second law of thermodynamics

J C Maxwell (1831-1879)



Maxwell's demon (1867-)

Joakim Bergli
University of Oslo

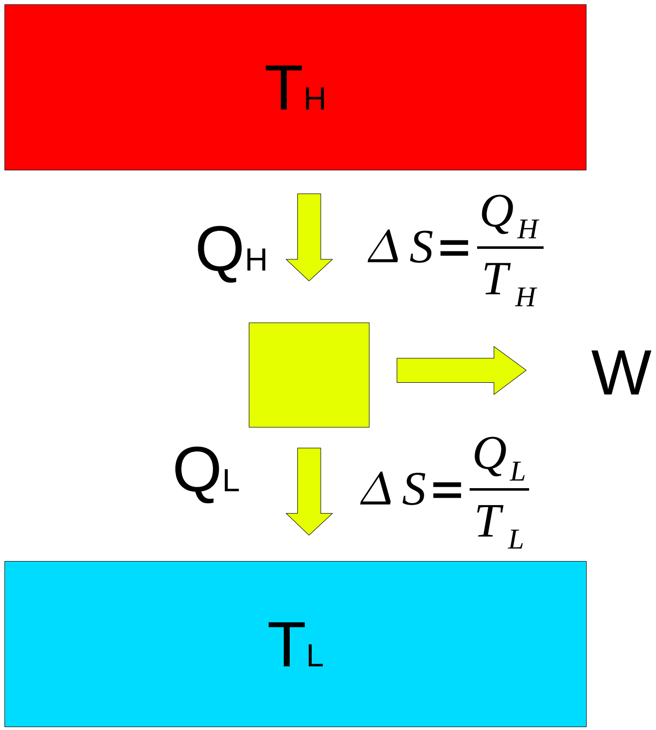
Why is it difficult to get work from heat?

Anything with a temperature has energy. This is just the energy of the motion of the atoms.

But why can we not fill the car with water, drive around and drop a piece of ice at the end??

Because the motion of atoms is disordered. There is entropy!

What is possible?
A heat engine!



Heat is taken from a high temperature reservoir. A part of this is converted to work but some part must always be released as heat to a low temperature reservoir. The amount that can be converted to work is limited by the Carnot efficiency:

$$W \leqslant \eta Q_H \qquad \eta = 1 - \frac{T_L}{T_H}$$

Entropy is taken from the high temperature bath, and the same entropy is given to the low temperature bath (so the machine does not accumulate entropy). Some heat must also go to the low temperature bath.

The laws of thermodynamics

First Law:

The total energy of the system and the environment is constant.

Second law:

Clausius:

No process is possible whose sole result is the transfer of heat from a body of lower temperature to a body of higher temperature.

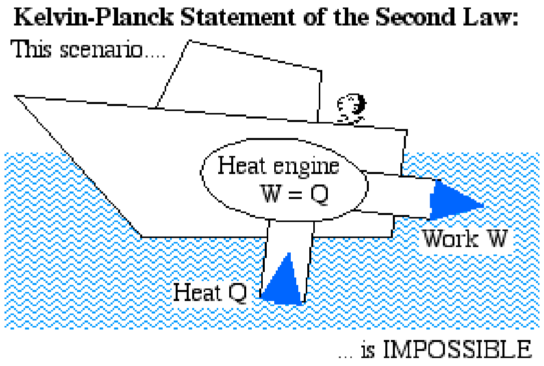
Kelvin:

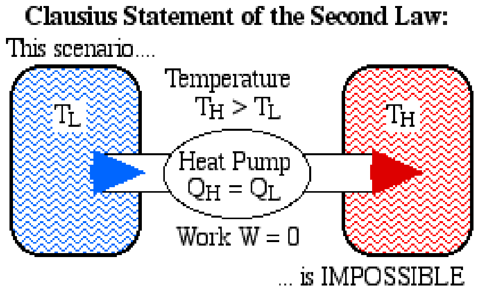
No process is possible in which the sole result is the absorption of heat from a reservoir and its complete conversion into work.

Entropy:

In a closed system the entropy will never decrease

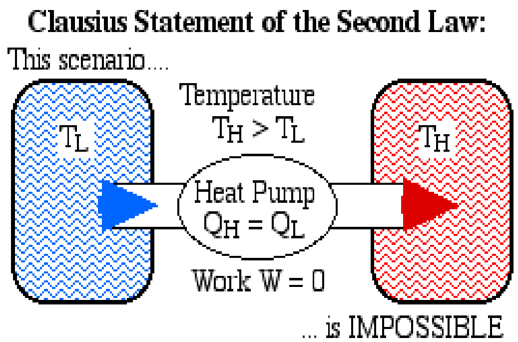
The second law in pictures

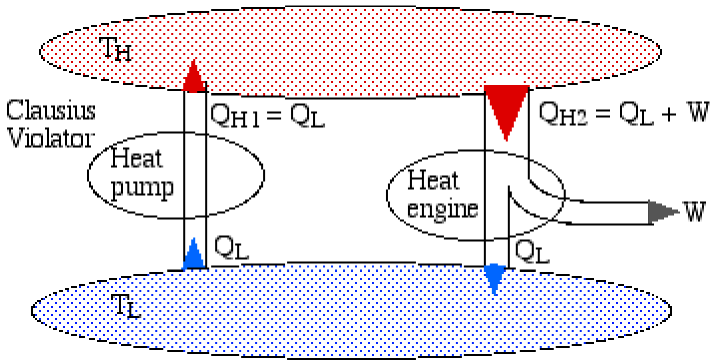


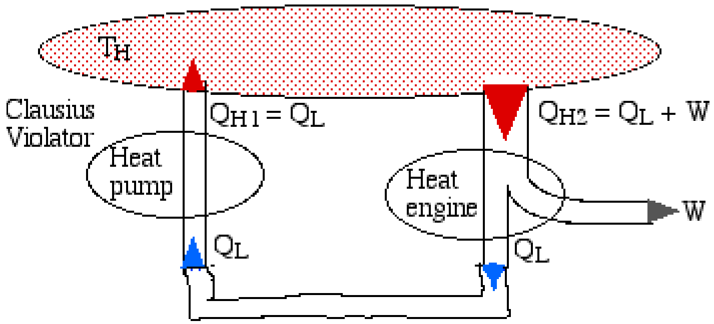


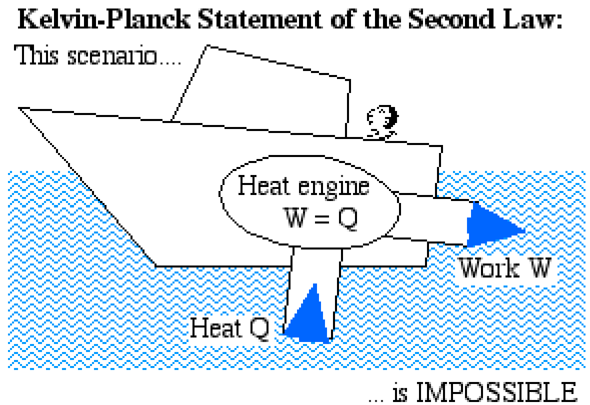
But energy is not created in any of the processes!

The two versions are indeed the same:









The second law tells us that it is impossible to extract all the energy from a heat bath.

But can we understand why?

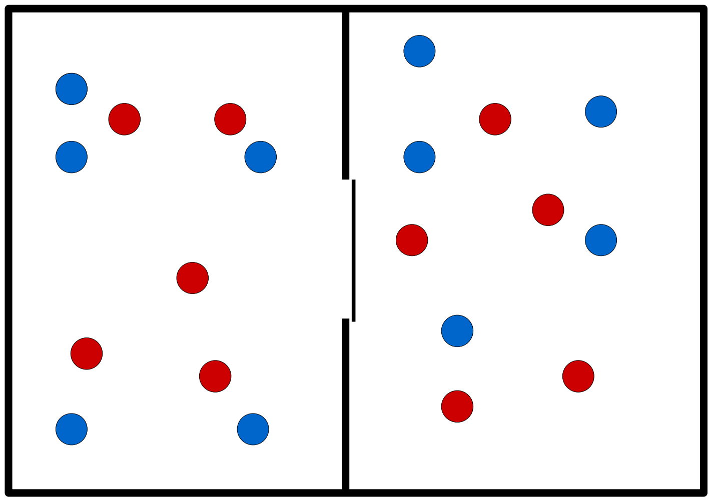
... if we conceive of **a being whose faculties are so sharpened that he can follow every molecule in its course**, such a being, whose attributes are as essentially finite as our own, would be able to do what is impossible to us.

J C Maxwell (1867)

To illustrate the statistical nature of the second law of thermodynamics

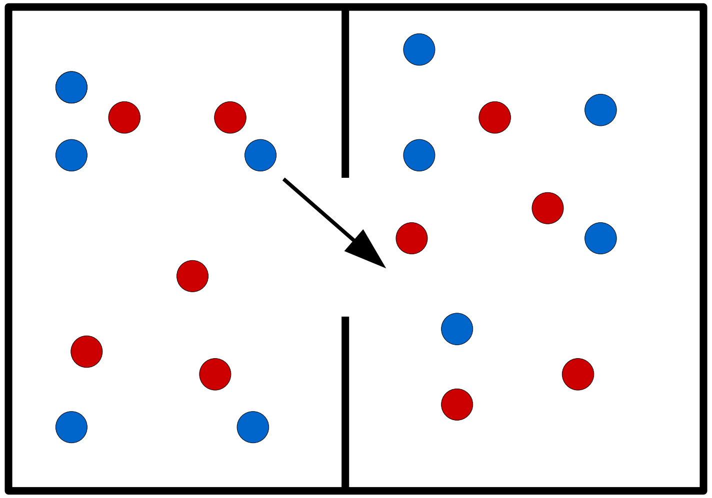
Maxwell's thought experiment

We have a container with gas. The container is divided in two parts by a wall with a small door that can be opened and closed

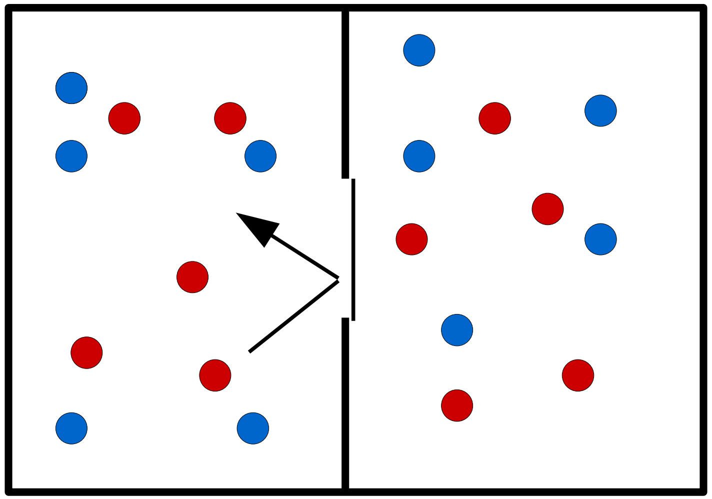


In a gas the molecules move with different velocites, the average is given by the temperature. Let us make it simple and imagine that there are some which are fast (●) and some which are slow (●).

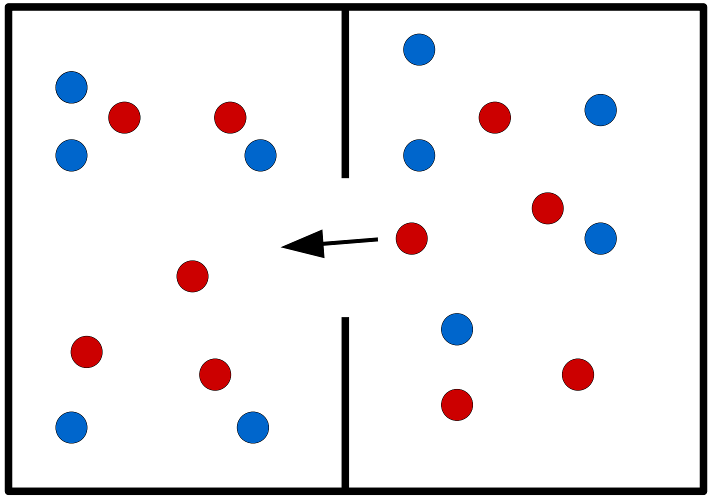
If a slow molecule comes to the door from the left we open it and let it pass through



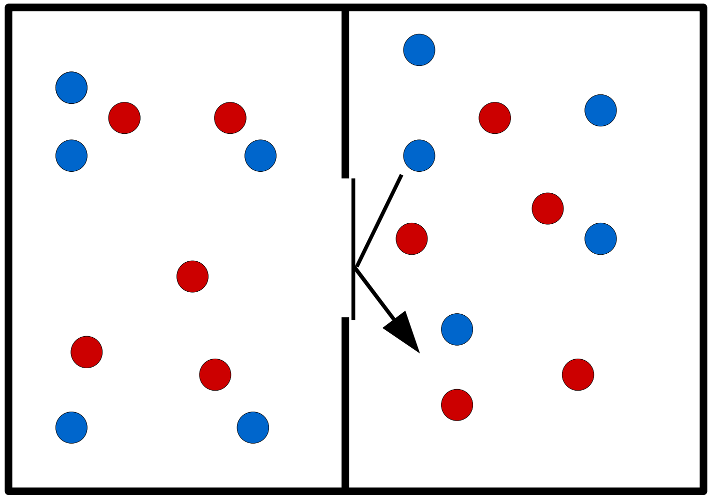
If a fast molecule comes from the left we keep the door closed



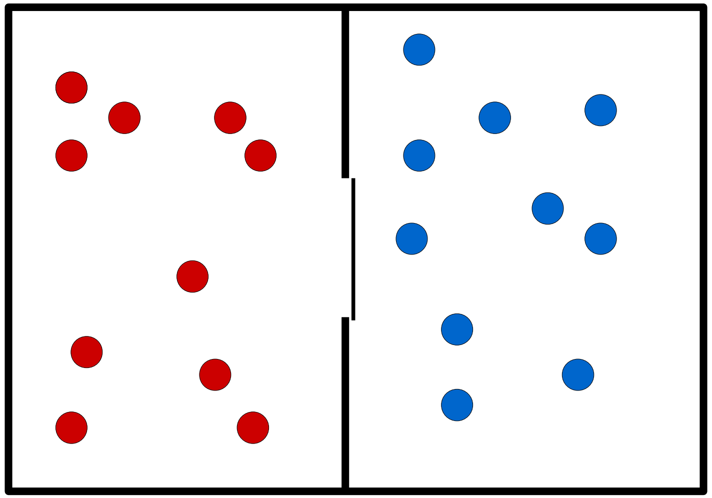
From the right we let fast molecules pass



and stop the slow

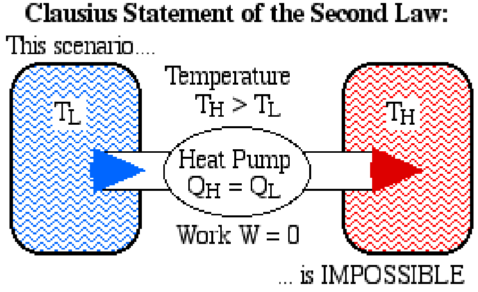


In this way we sort the molecules so that the fast are on the left and the slow on the right

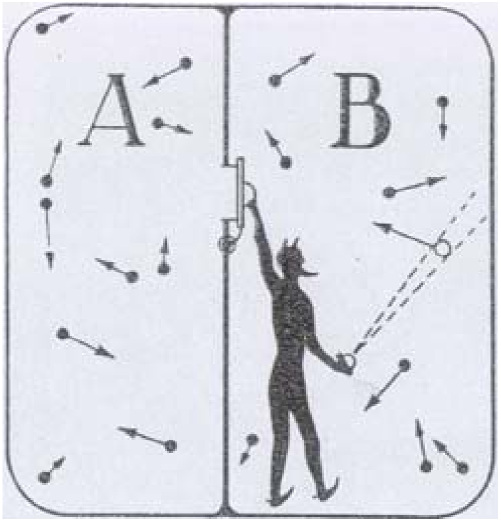


We have done the impossible!!

We created a temperature difference without any work done (The door must be without friction, we could worry about this, but it turns out not to be a problem).



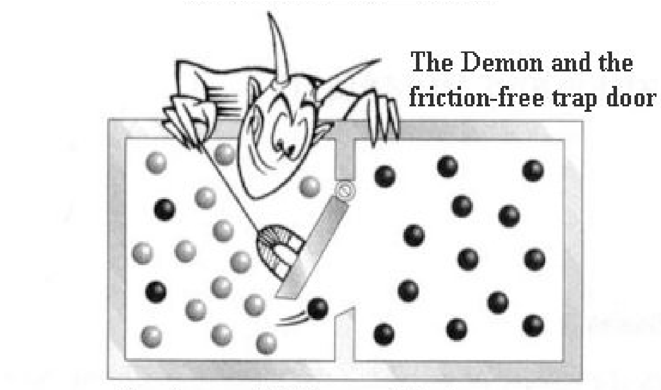
Of course it is difficult to follow the motion of molecules. Maxwell imagined the help of a very small and fast assistant, which was later called his demon. The demon can see the molecules and open or close the door.

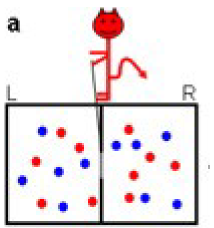


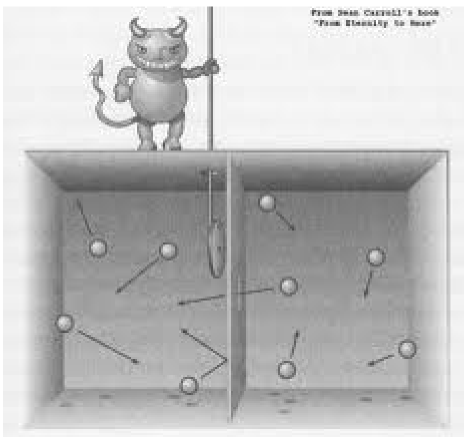
Demon:

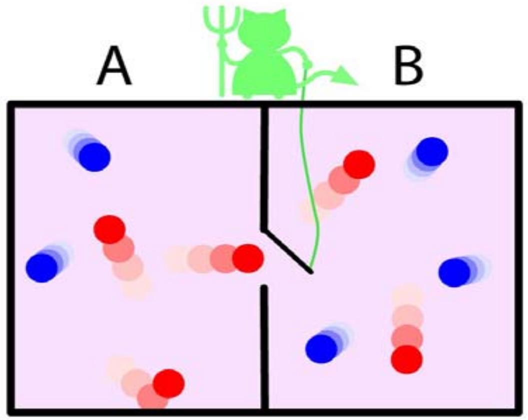
a supernatural being of Greek mythology intermediate between gods and men

Merriam-Webster dictionary







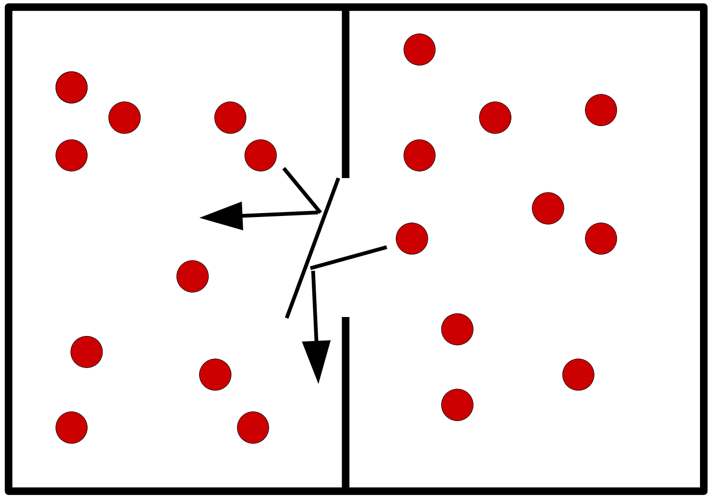


But can we build it?

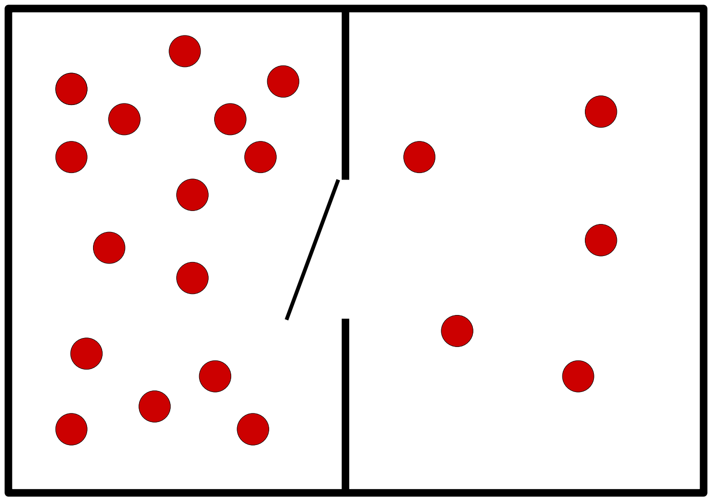
Without some mysterious demon but using the laws of physics?

A simplification: creating pressure difference instead of temperature difference

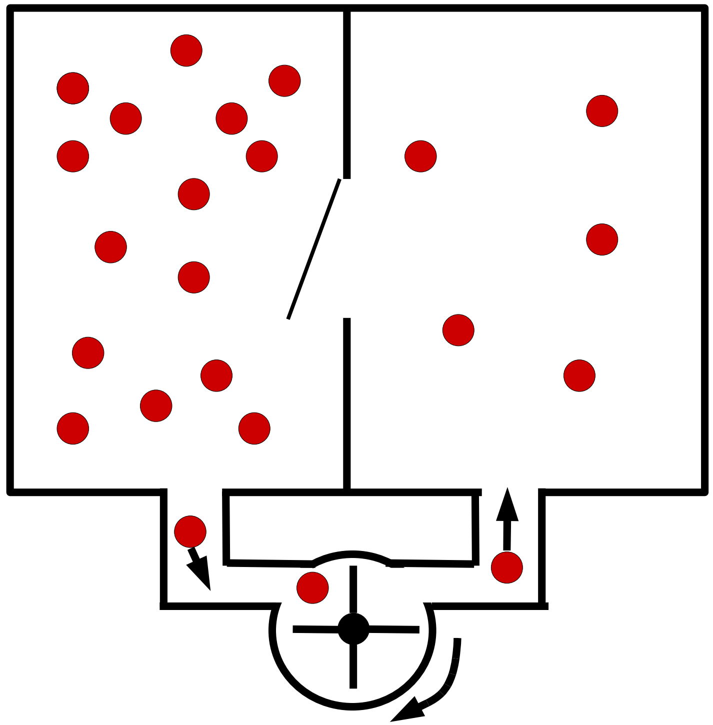
All we need is a one-way door



and get a pressure difference

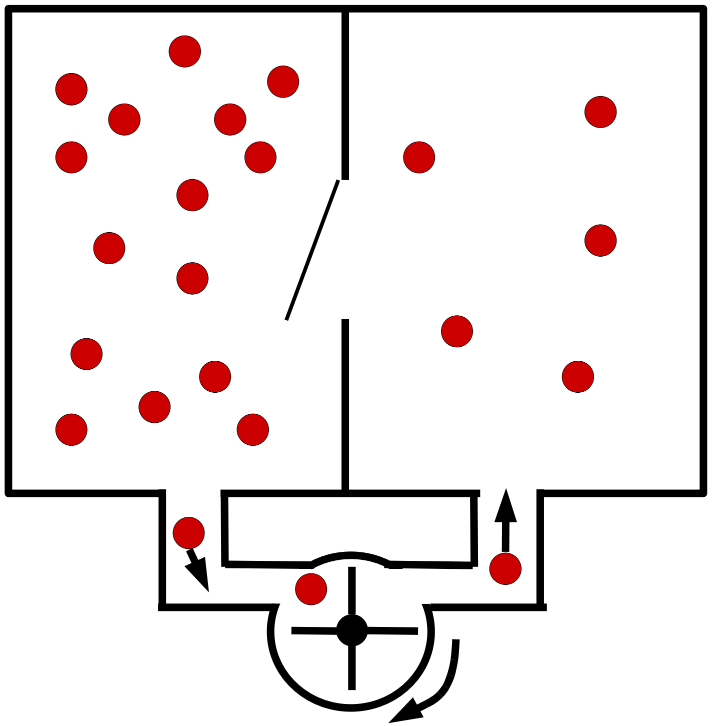


Then we attach a turbine and get work done

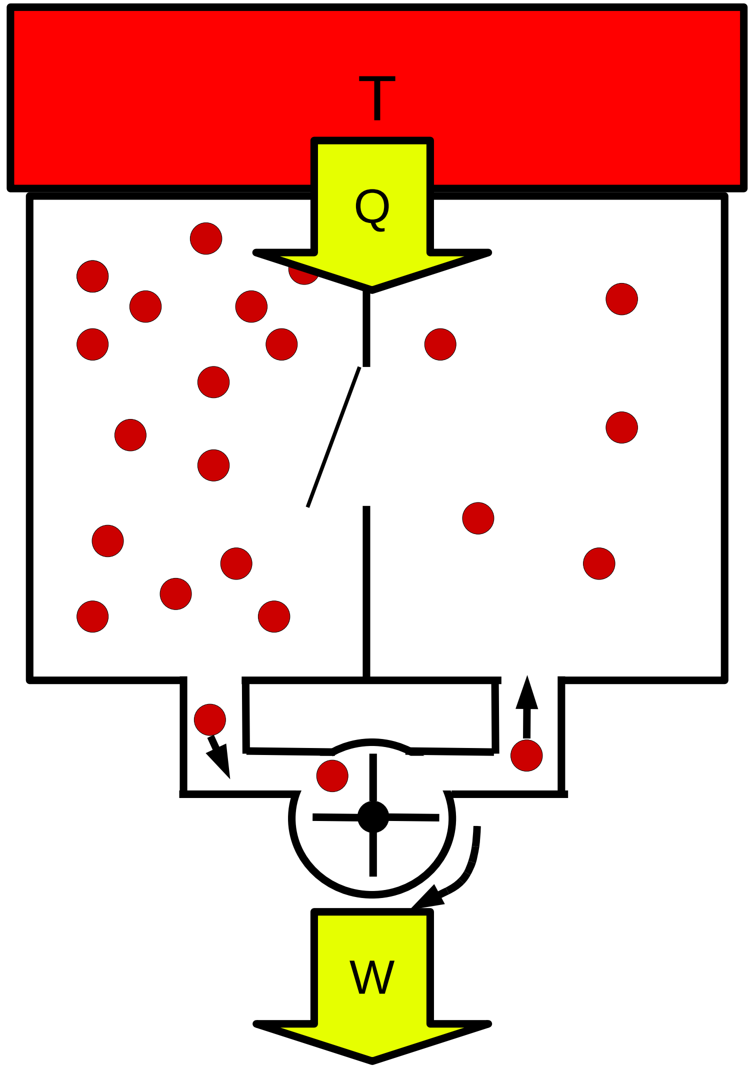


Be careful!

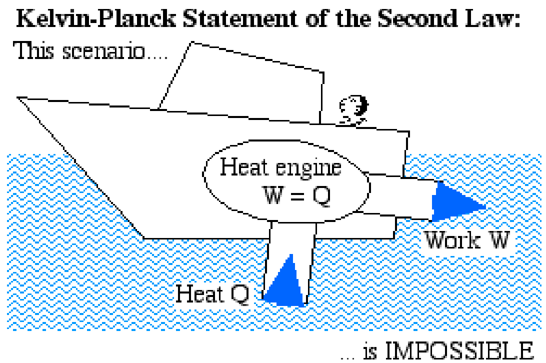
In this process the gas expands and will cool down



The energy must come from somewhere. We must connect our gas to a reservoir to keep the temperature. The energy comes from the reservoir.

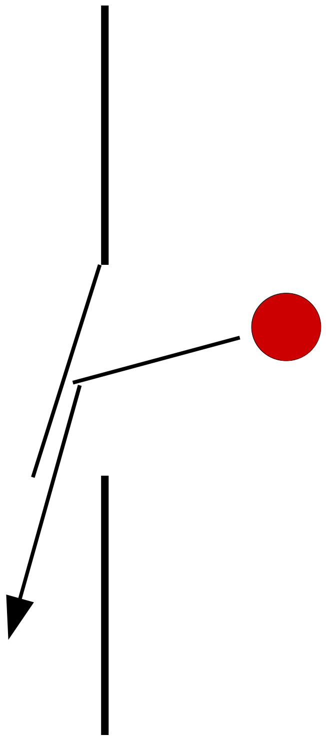


And what we have is actually this:

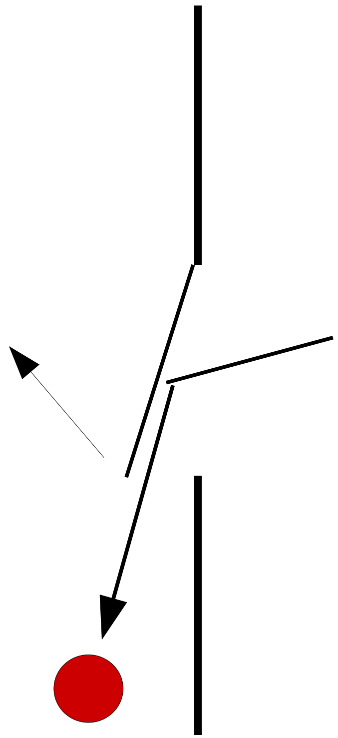


Will it work?

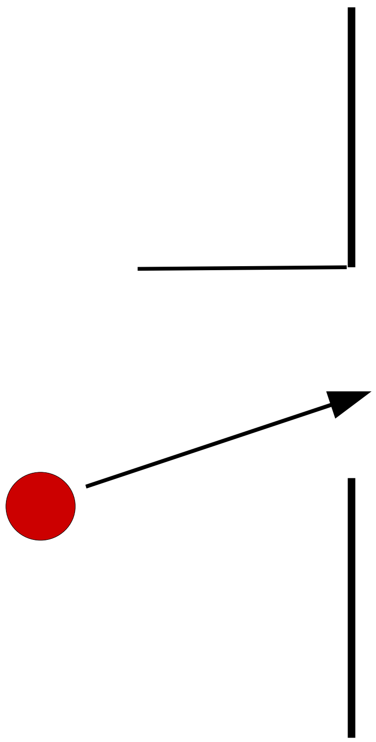
What happens when a molecule strikes the door?



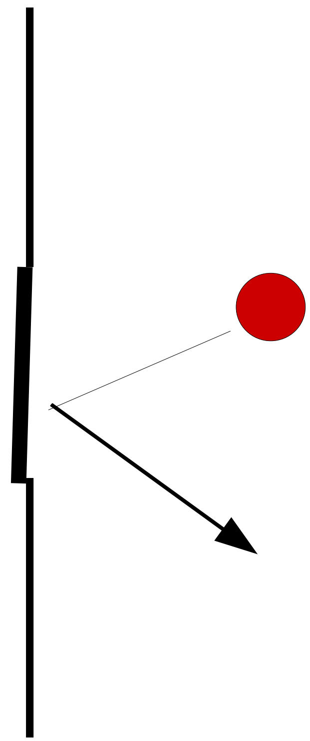
The door will get energy!



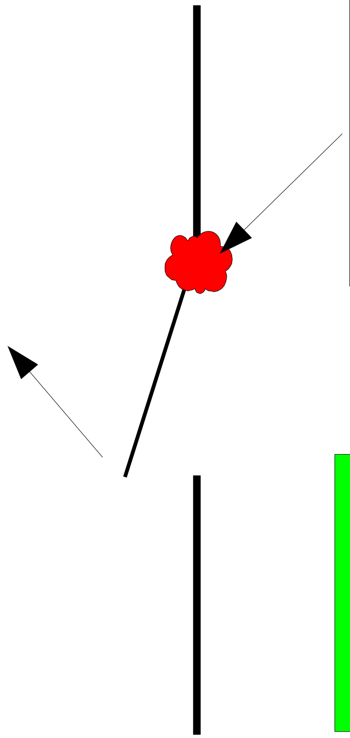
This is not good, it will swing open and close, and particles can go the wrong way



It could help to make the door heavy, but then it will not open



But what about friction?
The door should stop moving

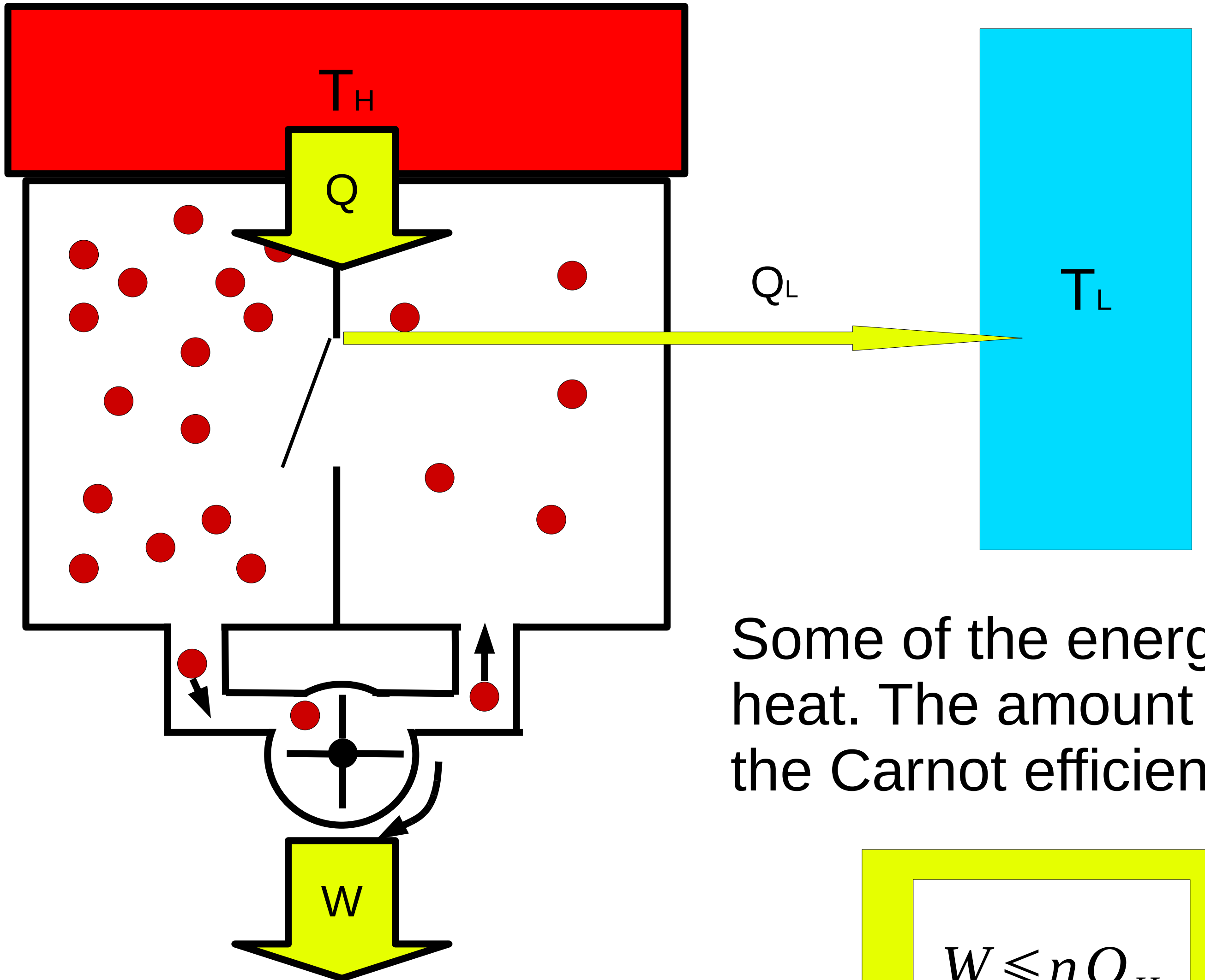


Everything will heat up until it has the same temperature as the gas. Then, on average, the door will hit the molecules as much as the molecules hit the door.

It will never work! The thermal fluctuations of the door will make it open too much of the time. A one way door is not possible.

We have to remove the extra heat!

But this is a heat engine!

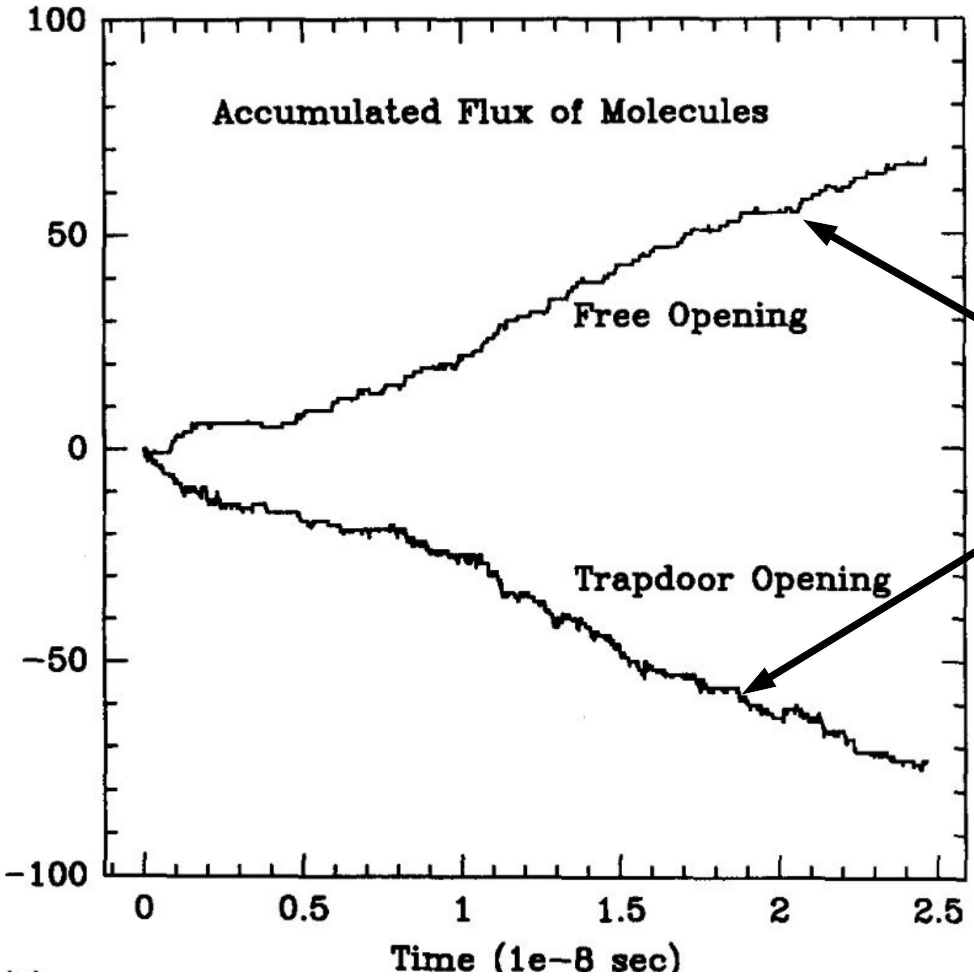


Some of the energy is given away as heat. The amount of work is limited by the Carnot efficiency

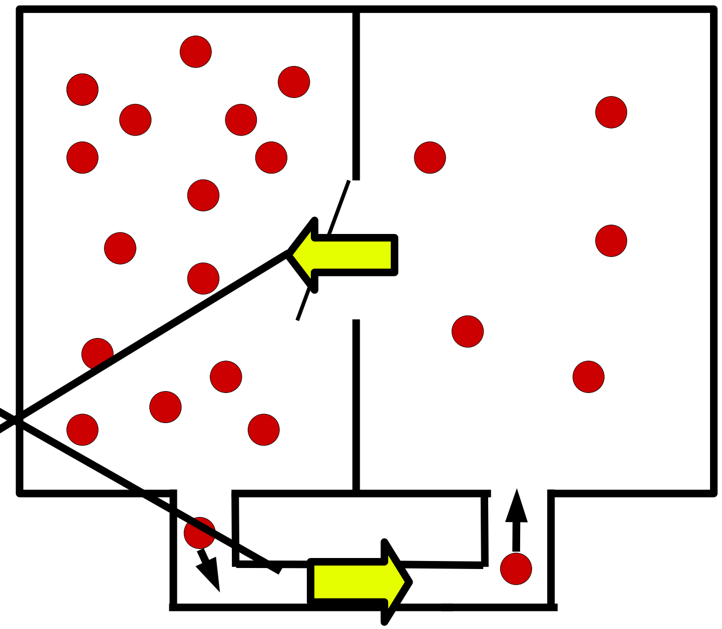
$$W \leqslant \eta Q_H$$

$$\eta = 1 - \frac{T_L}{T_H}$$

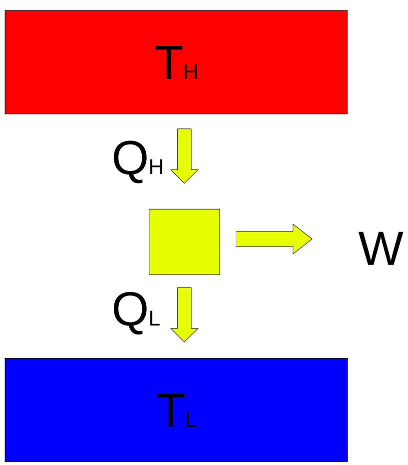
One way door with cooling



P. A. Skordos and W. H. Zurek, Am. J. Phys. 60, 876 (1992)



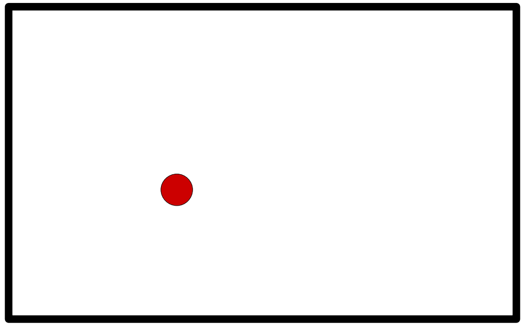
This is just a normal heat engine!



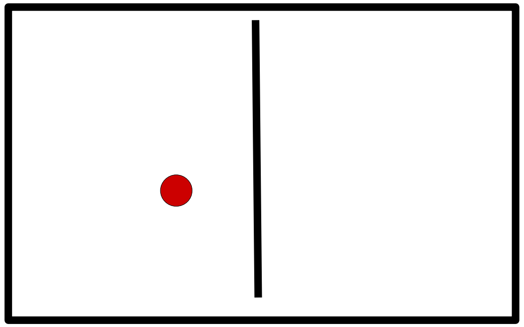
We need a more clever device
(but still keeping the laws of physics)

The Szilard engine

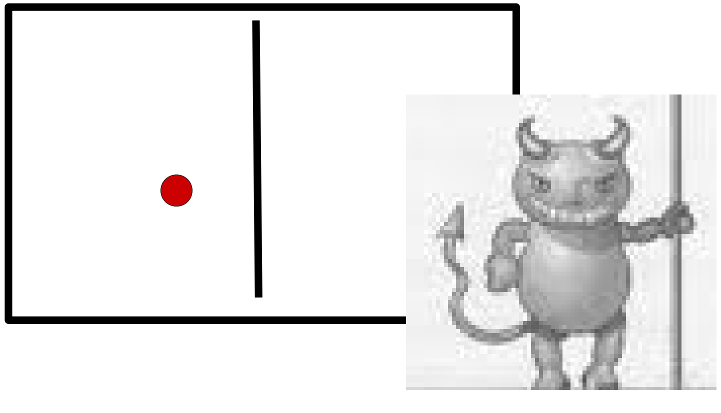
A container with only one molecule



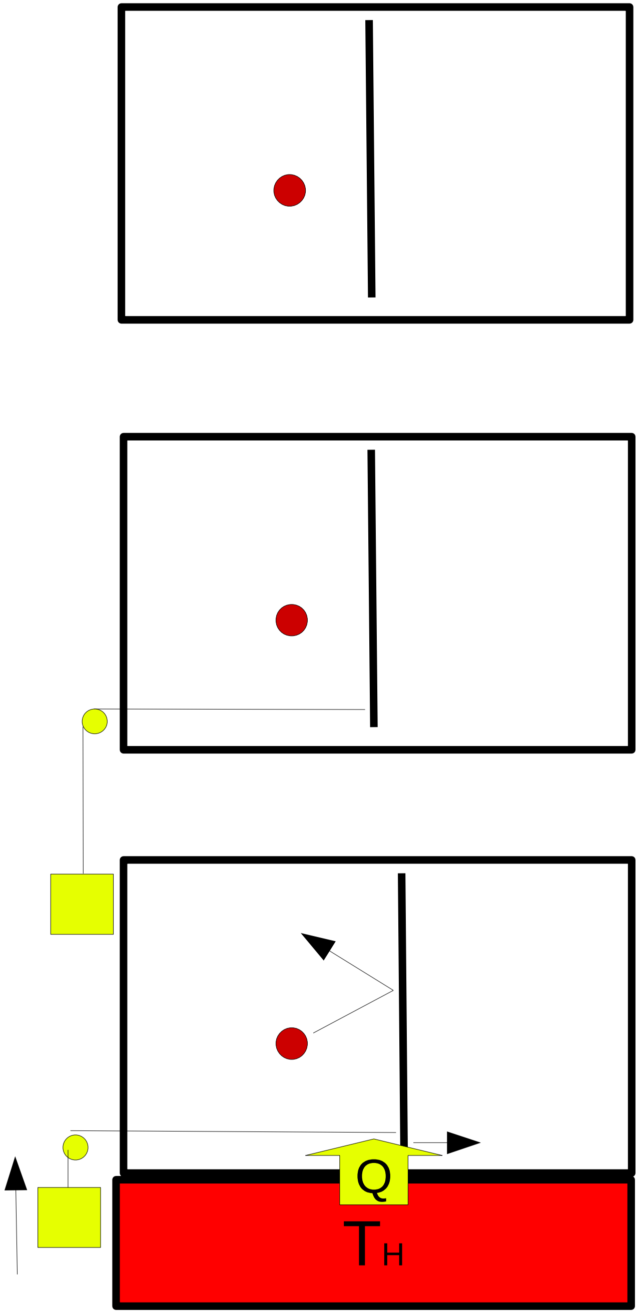
Insert a partition in the middle



Measure on which side the molecule is (this is the work of the demon)



Molecule on left

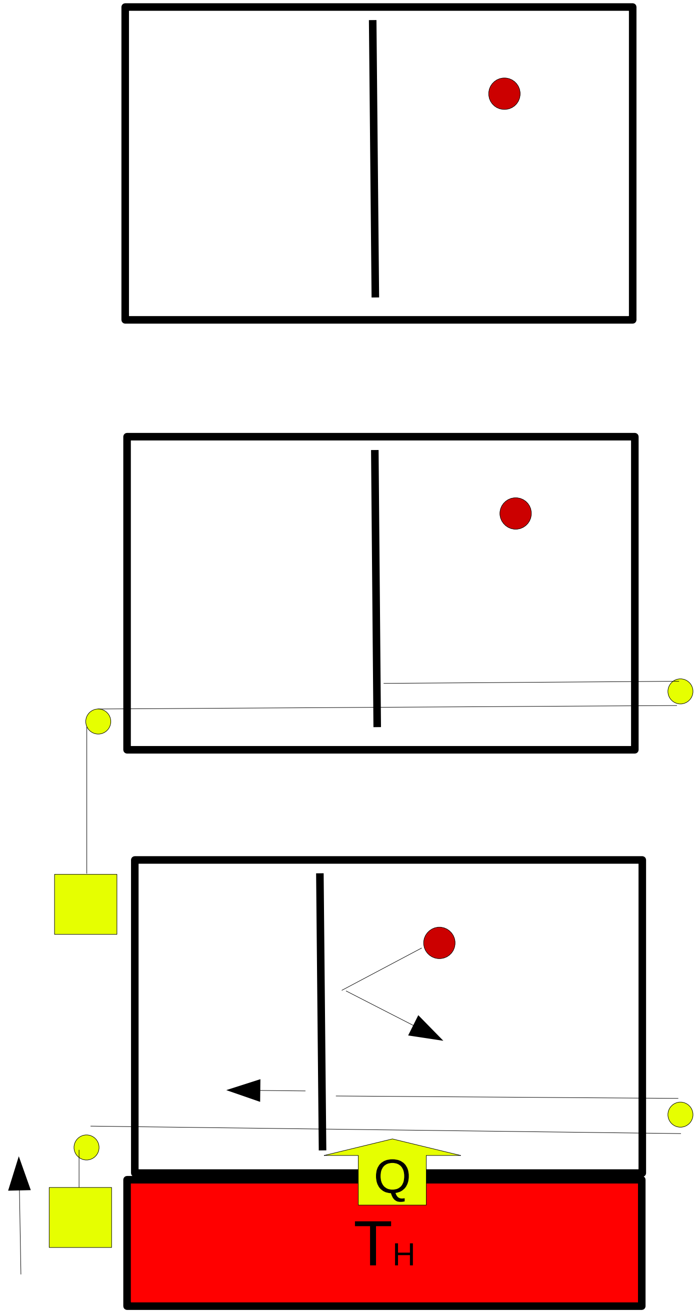


The demon knows on which side the molecule is

It attaches the weight depending on which side the molecule is on

The gas expands and lifts the weight. Note that the expanding gas will cool if we do not attach it to a reservoir.

Molecule on right



The amount of work is $W = kT \ln 2$

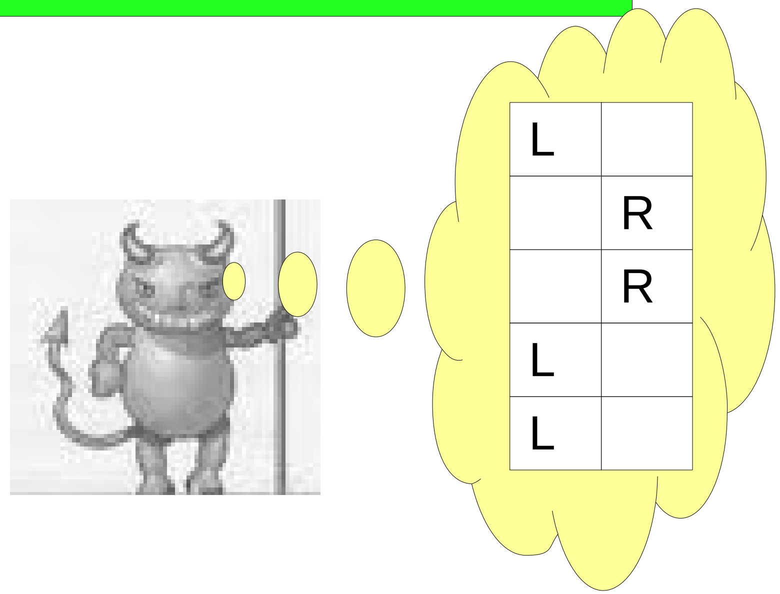
The net result

- Our engine came back to the same state.
- Energy was transferred from the heat bath to the gas
- The weight was lifted.

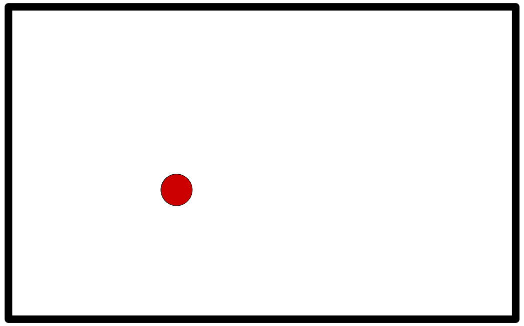
No process is possible in which the sole result is the absorption of heat from a reservoir and its complete conversion into work.

But what about the demon?

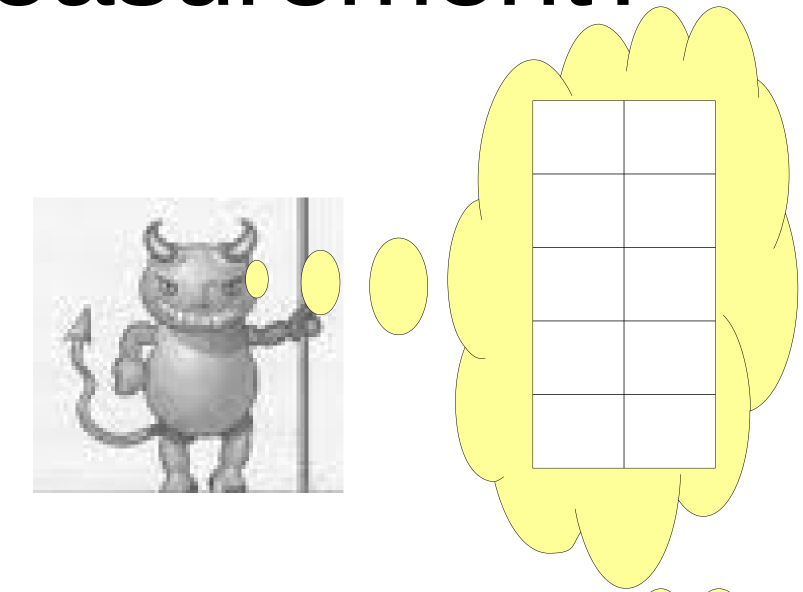
The demon is not back to the original state, it still knows which side the molecule was on. It has gained information. For some time it may work, but if we run for a long time, it will run out of memory!

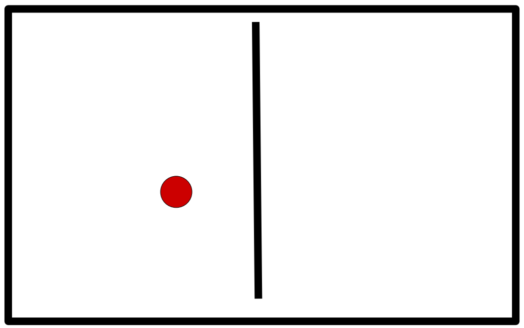


What happens in measurement?

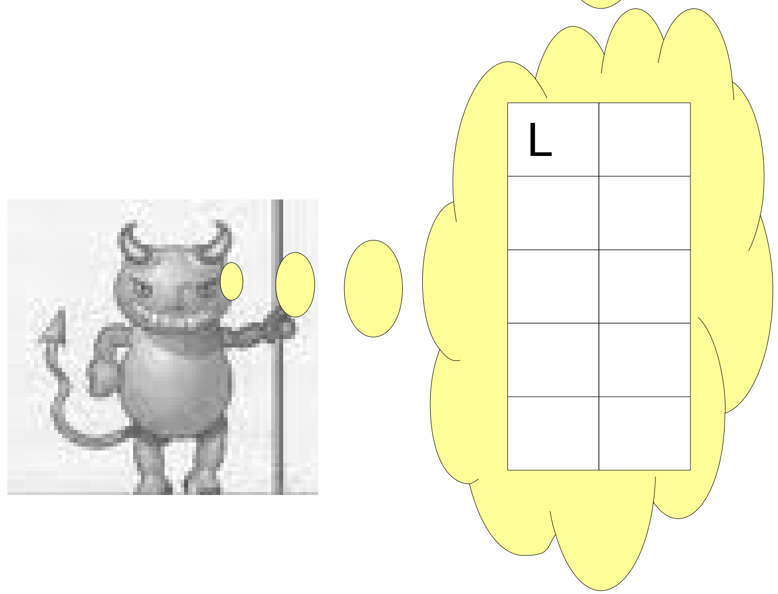


$$S = k \ln \Omega$$





$$S = k \ln \frac{\Omega}{2}$$



$$\Delta S = -k \ln 2$$

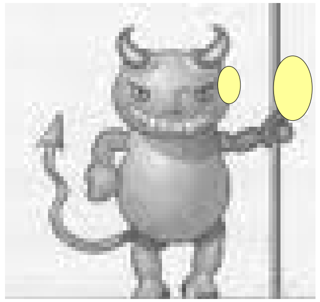
The entropy decreases and the demon gets information

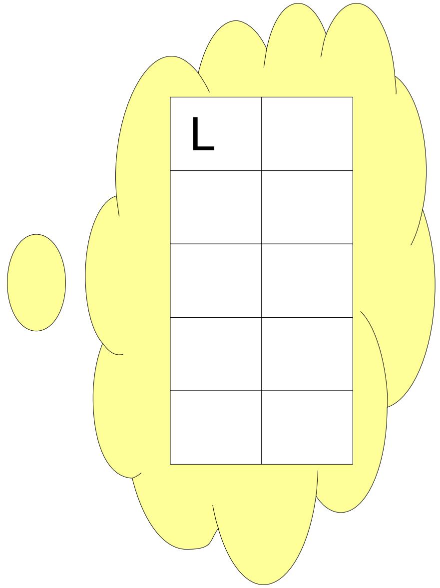
Claude Shannon (1916-2001)

Shannon information

If the memory has different states *i* and the probability of each is p_i the information is:

$$S = -k \sum_i p_i \ln p_i$$





In our case we both sides (L and R) are equally probable: $p_L = p_R = \frac{1}{2}$

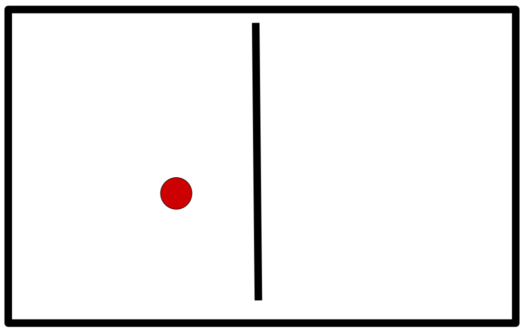
Which gives $$S = k \ln 2$$

The increase in the information is exactly equal to the decrease of entropy in the gas!

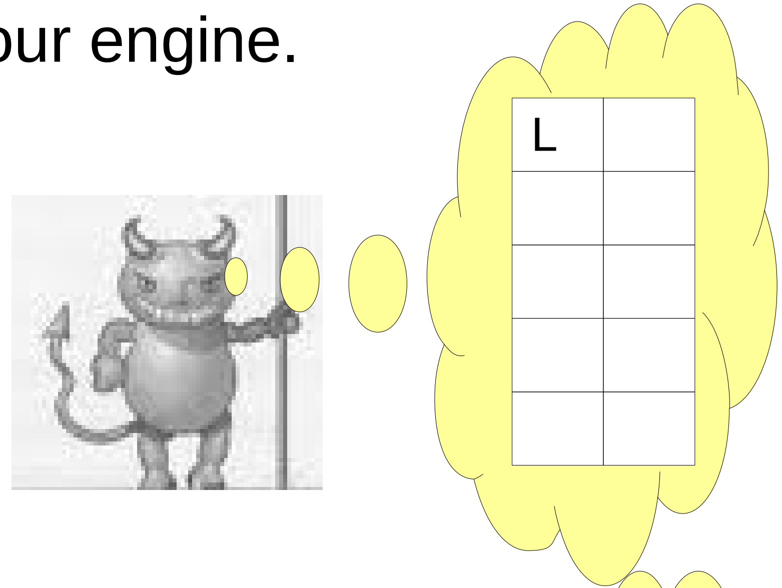
Landauers principle:
Forgetting is not for free

We can imagine the memory similar to our engine.

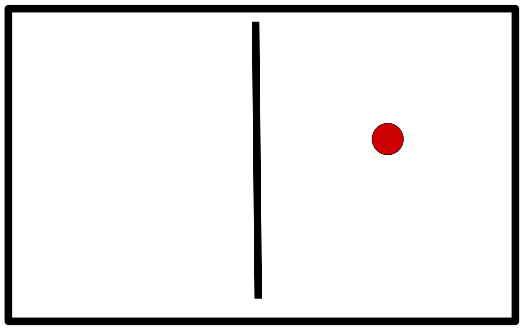
L state



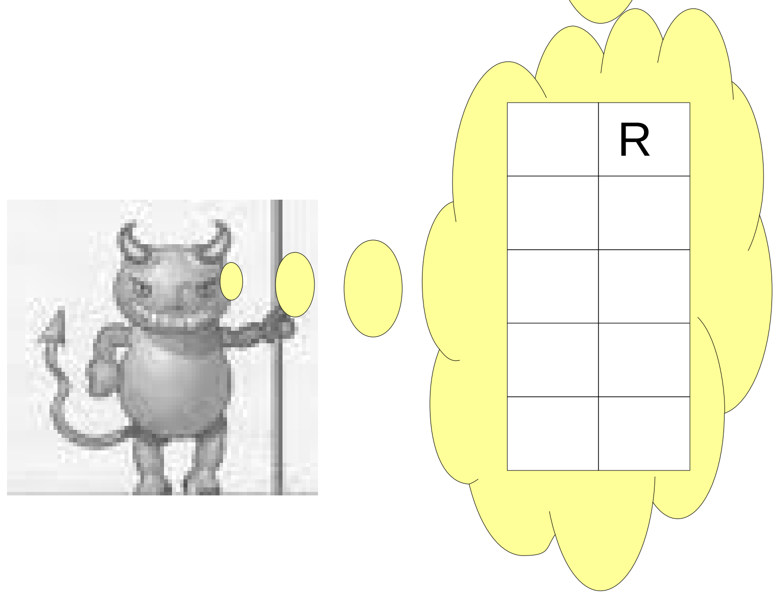
Molecule on left
means demon
remembers left



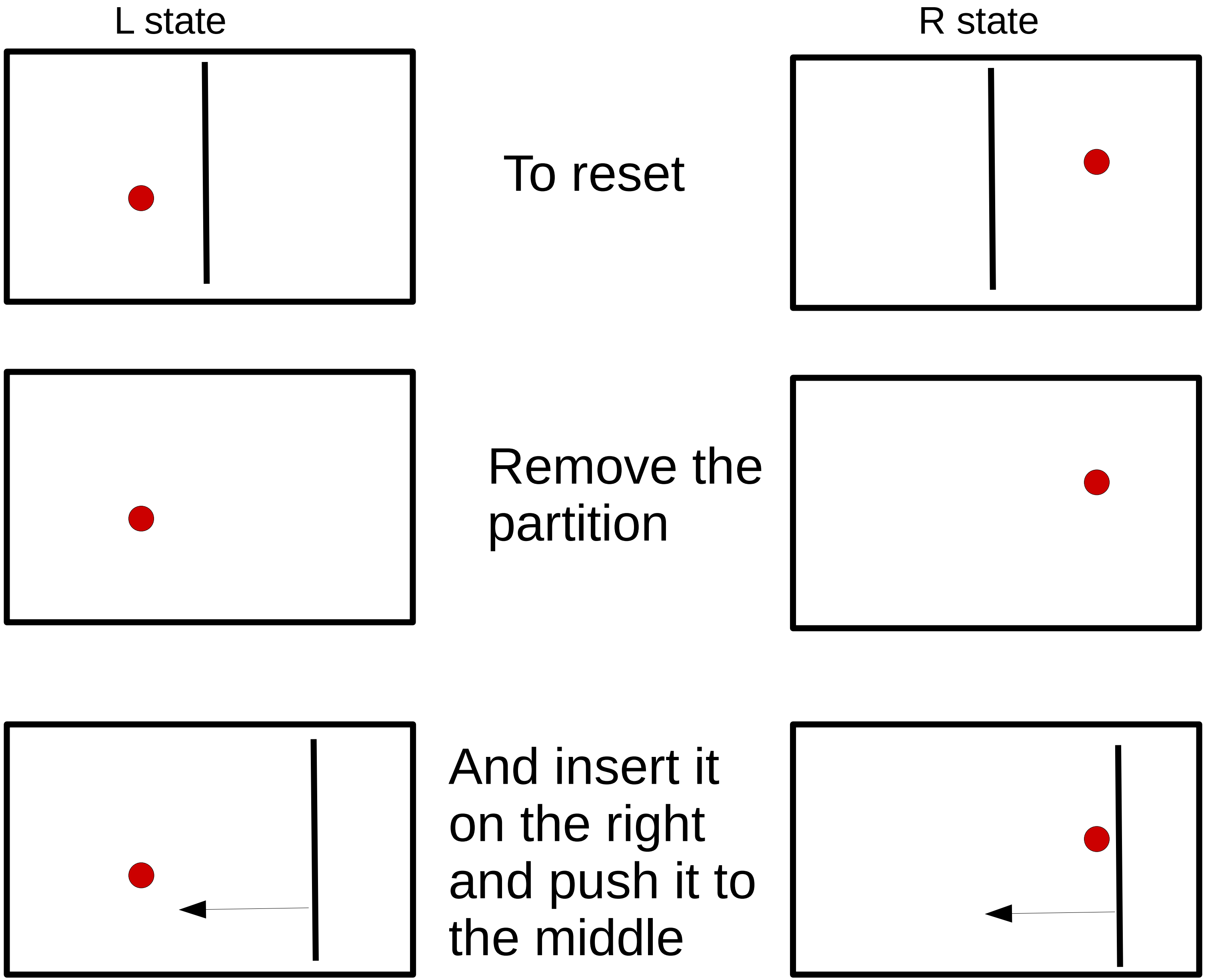
R state

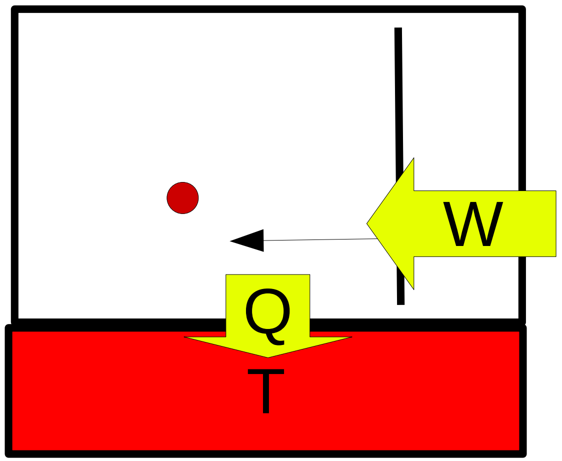


Molecule on right
means demon
remembers right



Forgetting means resetting the memory to a fixed state (let us say L)





But now we are compressing the gas. This takes work, and heat has to be given to the bath for the gas not to heat up.

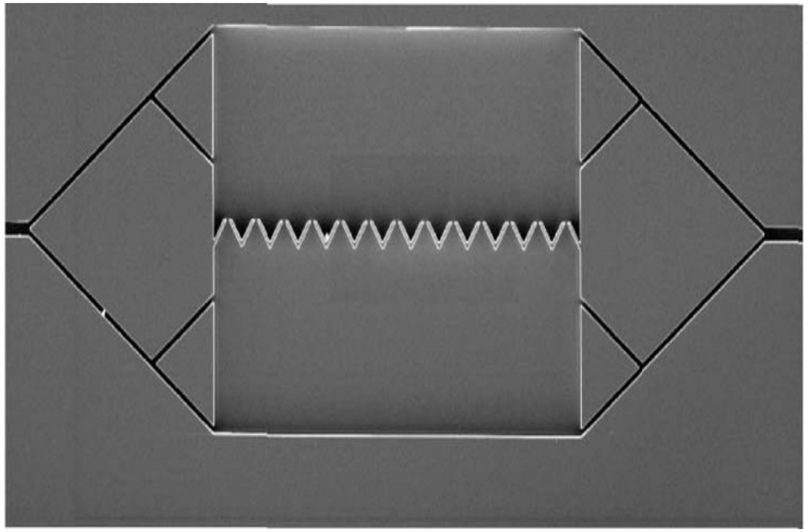
How much work is needed?

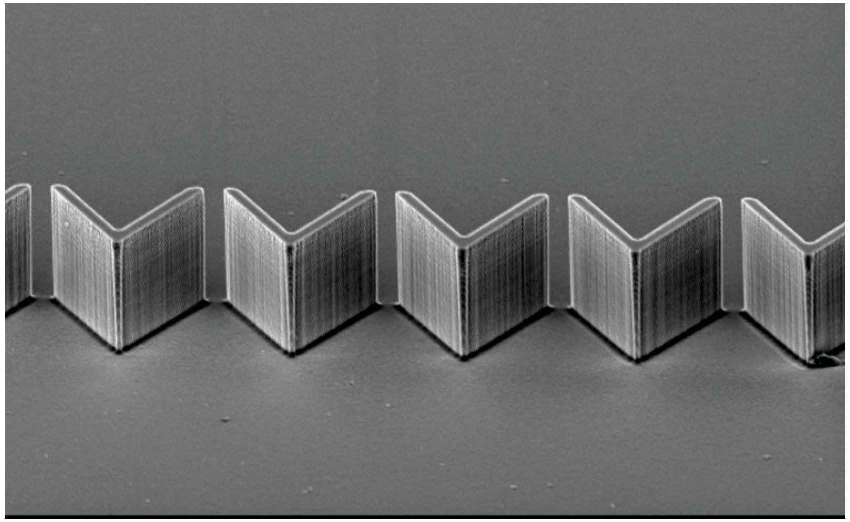
$$W = kT \ln 2$$

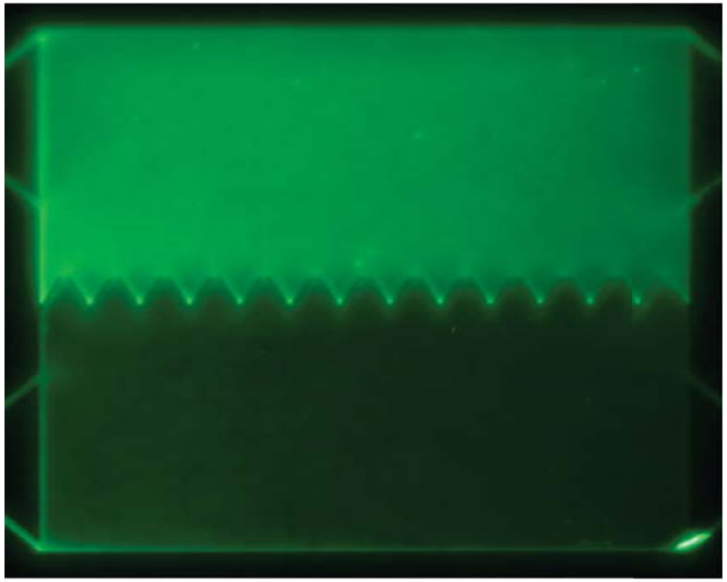
This is exactly the same amount of work as the Szilard engine produced in one cycle.

Our engine produces no work at all after resetting the memory!

A real experiment





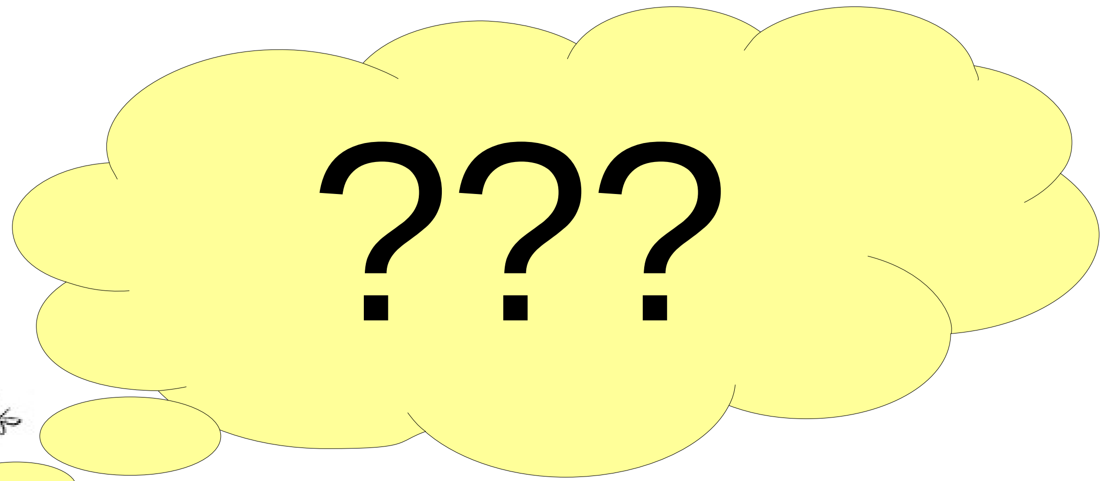


These particles are bacteria.
They do not move from thermal motion, they swim.

And they use energy!

P. Galajda, JOURNAL OF BACTERIOLOGY, Dec. 2007, p. 8704–8707

Thank you for your attention



And now you have to make your own thought experiments!