UNIVERSITY OF MARYLAND


# Adventures of an Idea: the Life and Travels of Maxwell's Demon

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# A brief (and *incomplete*!) introduction to the Laws of Thermodynamics

*heat* is a form of energy … not a substance

$H_2O$

"slow"

ice, -5 °C

water, 25 °C

$H_2O$

"fast"

1. The **energy** of the universe is constant.
2. The **entropy** of the universe tends to a maximum.

Rudolf Clausius (1865)

# A brief (and *incomplete*!) introduction to the Laws of Thermodynamics

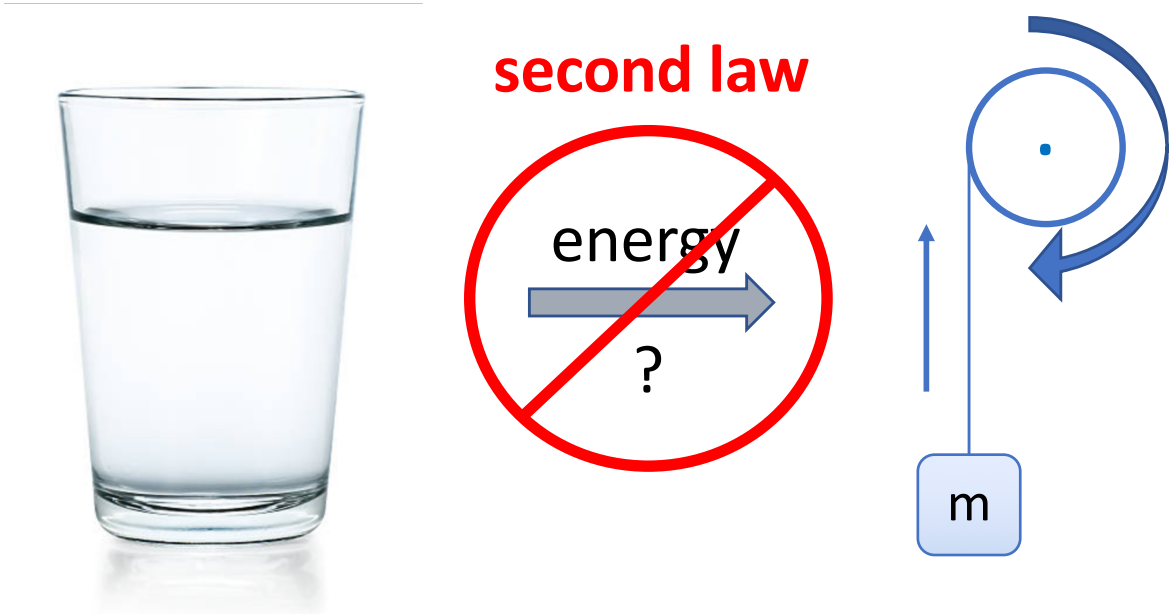
the ice melts
(of course!)

energy flows
*from* the warm water
*to* the cold ice

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

*Clausius statement of 2nd Law*

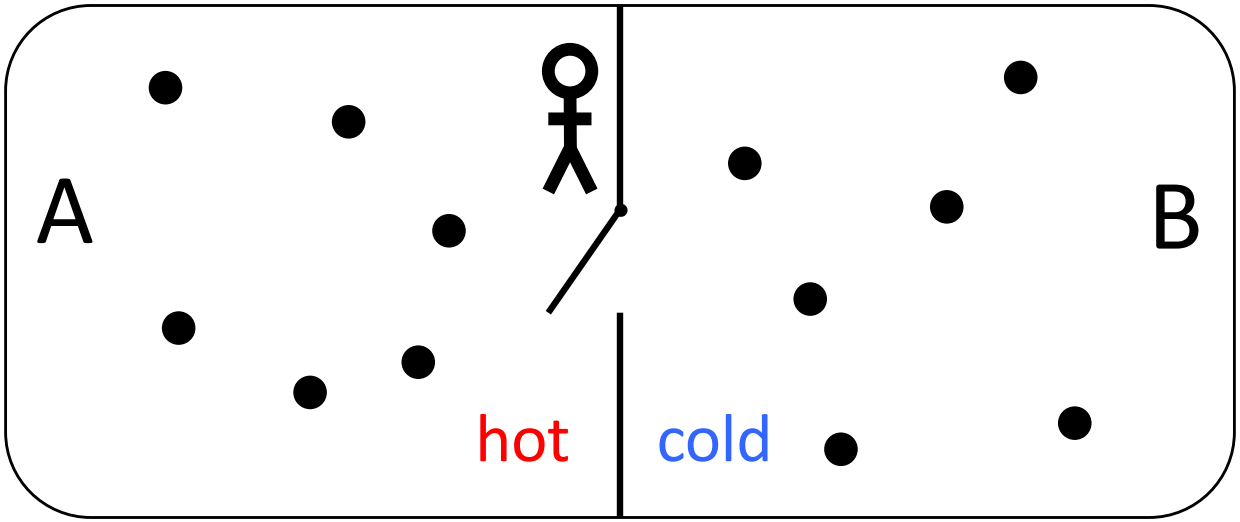
# A brief (and *incomplete*!) introduction to the Laws of Thermodynamics




No process is possible whose sole result
is the extraction of energy from one body, and
the conversion of all that energy into *work*.

*Kelvin-Planck statement of 2nd Law*

# Maxwell's demon

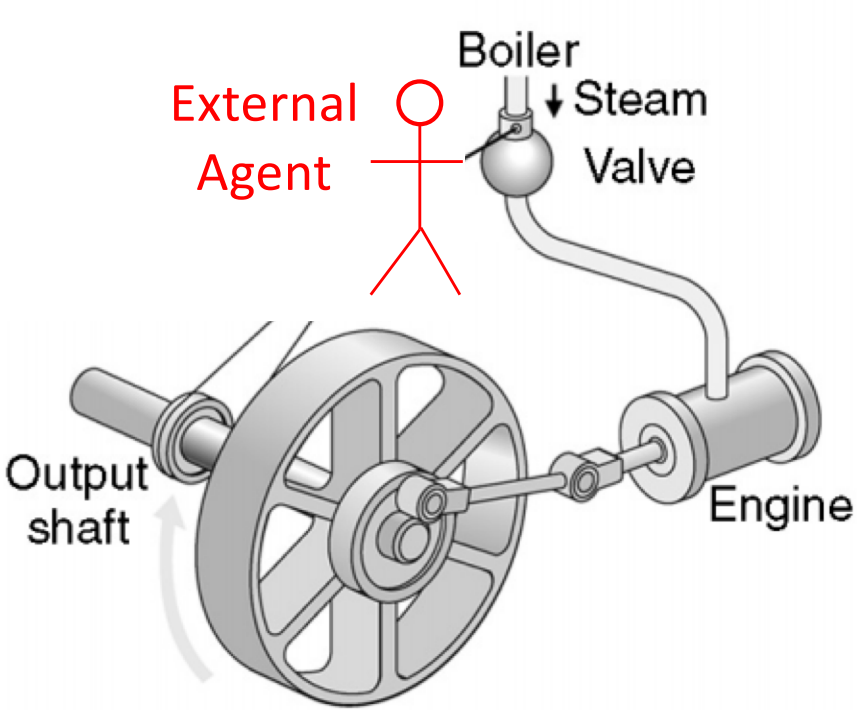



"… the energy in A is increased and that in B diminished; that is, the hot system has got hotter and the cold colder and yet no work has been done, only the intelligence of a very observant and neat-fingered being has been employed"

James Maxwell, letter to Peter Tait (1867)

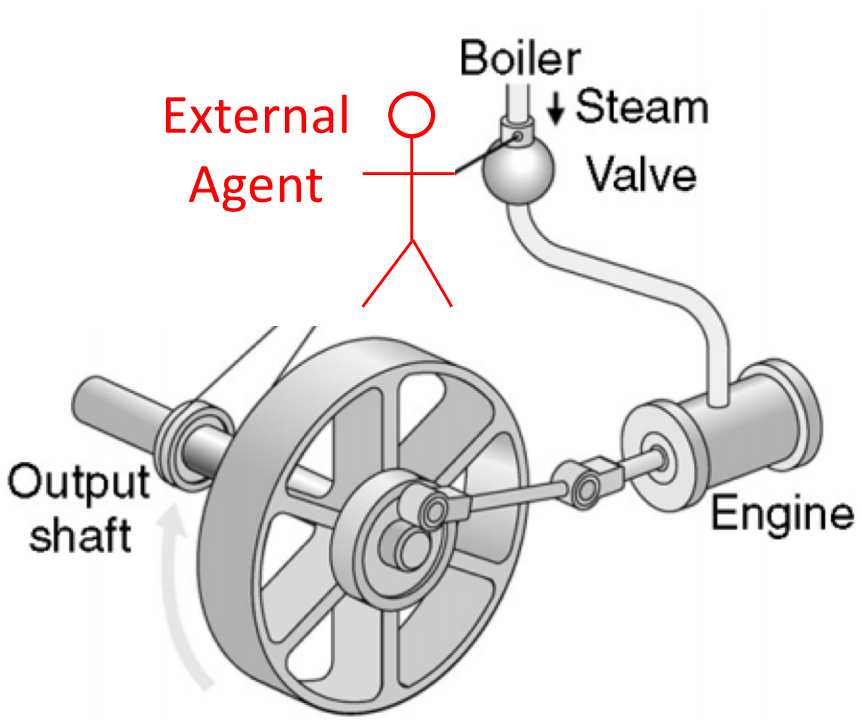
# Feedback control

The problem with steam engines …

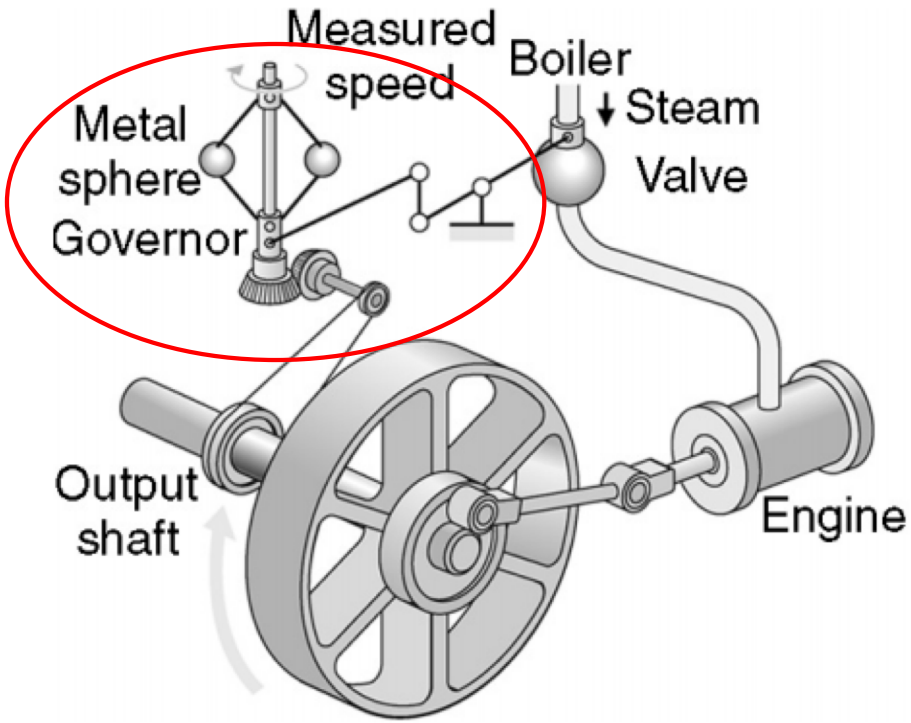


# Feedback control

*non-autonomous*



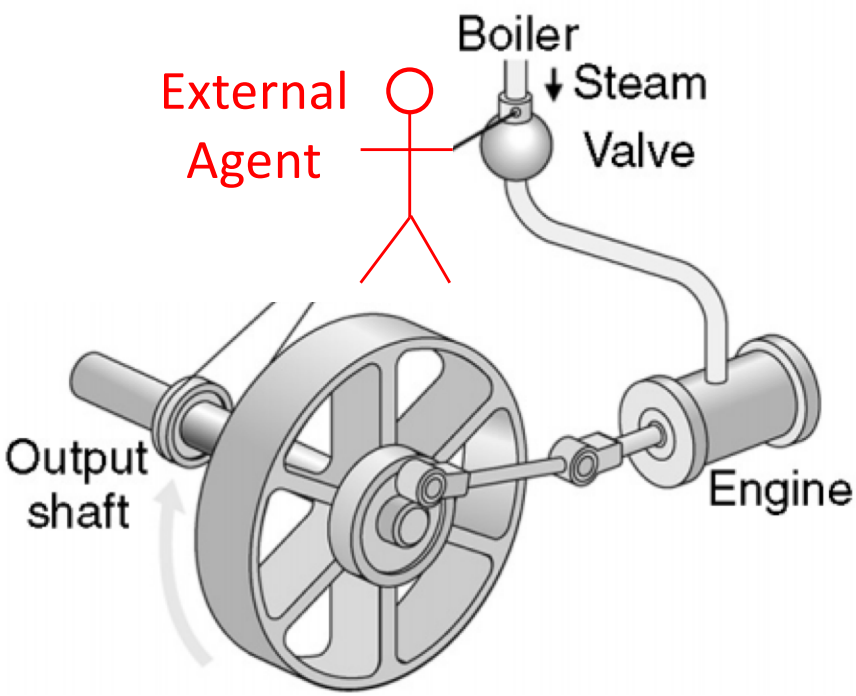

*autonomous*




James Watt (1788)

# Feedback control

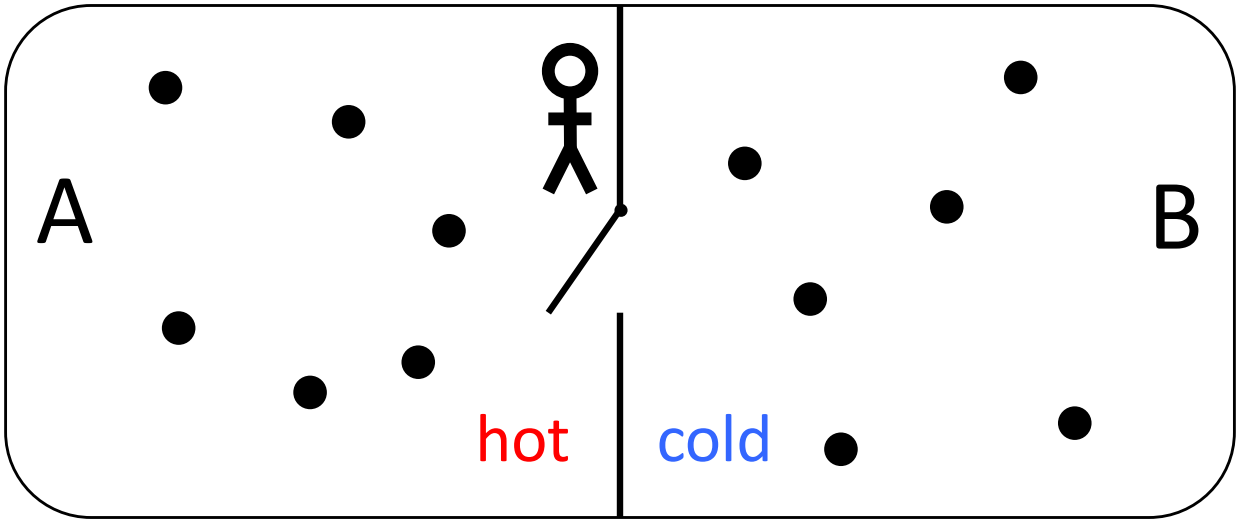
*non-autonomous*




*autonomous*

Science Museum (London)

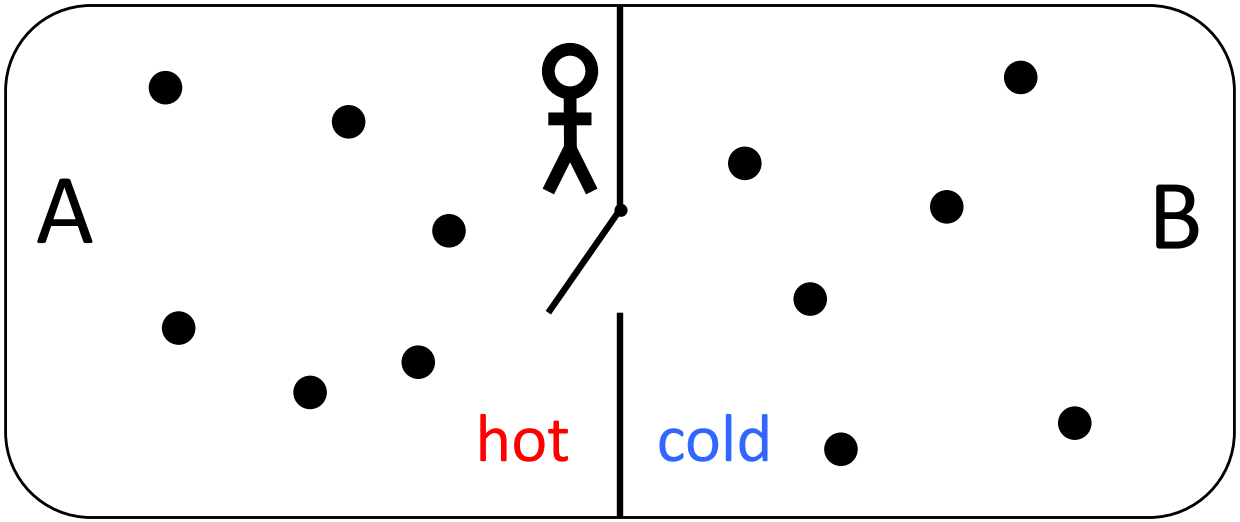
# Maxwell's demon




*non-autonomous*

Maxwell's demon performs feedback control at the molecular level.

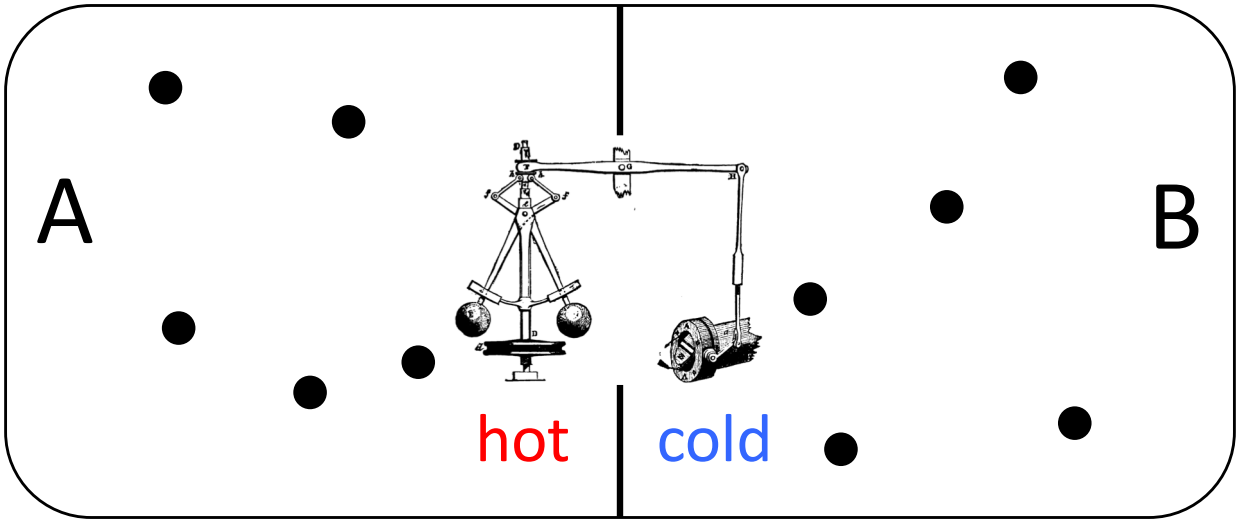
# Maxwell's demon




*non-autonomous*

*idea*: replace the external agent / demon by a mechanical gadget.

# Maxwell's demon

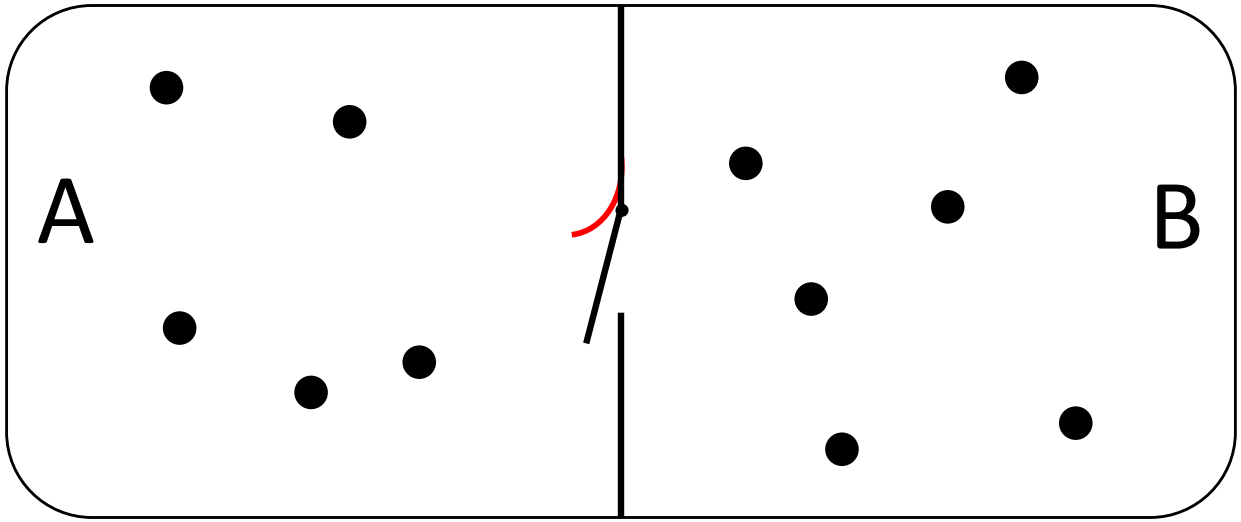



*autonomous*

*idea*: replace the external agent / demon by a mechanical gadget.

*Is a mechanical Maxwell demon possible?*

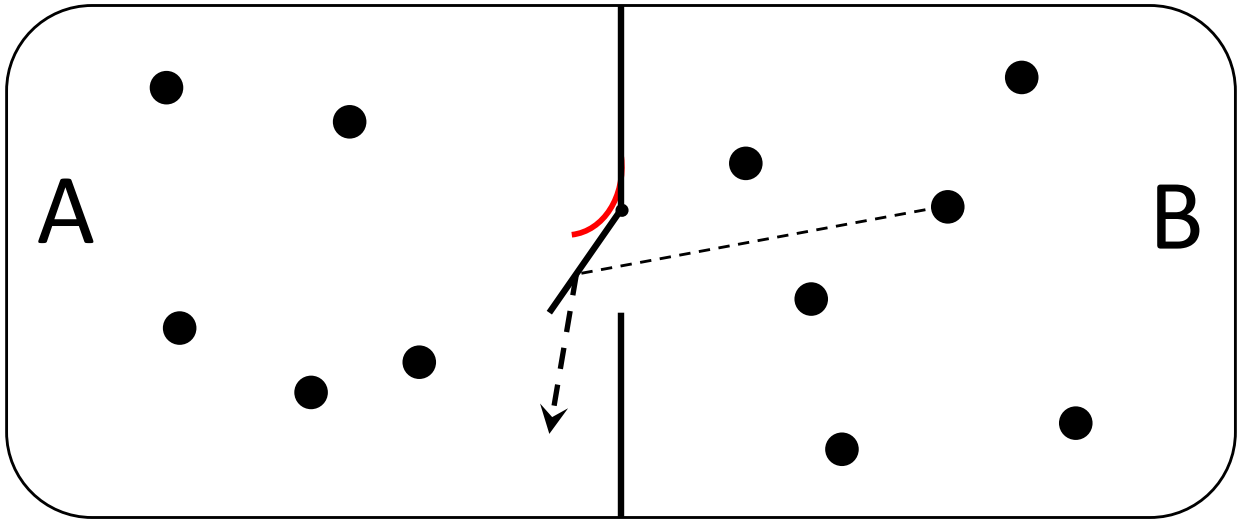
# Smoluchowski's trapdoor




Marian Smoluchowski (1912)

A spring-loaded trapdoor prevents particles from passing from A to B …

# Smoluchowski's trapdoor

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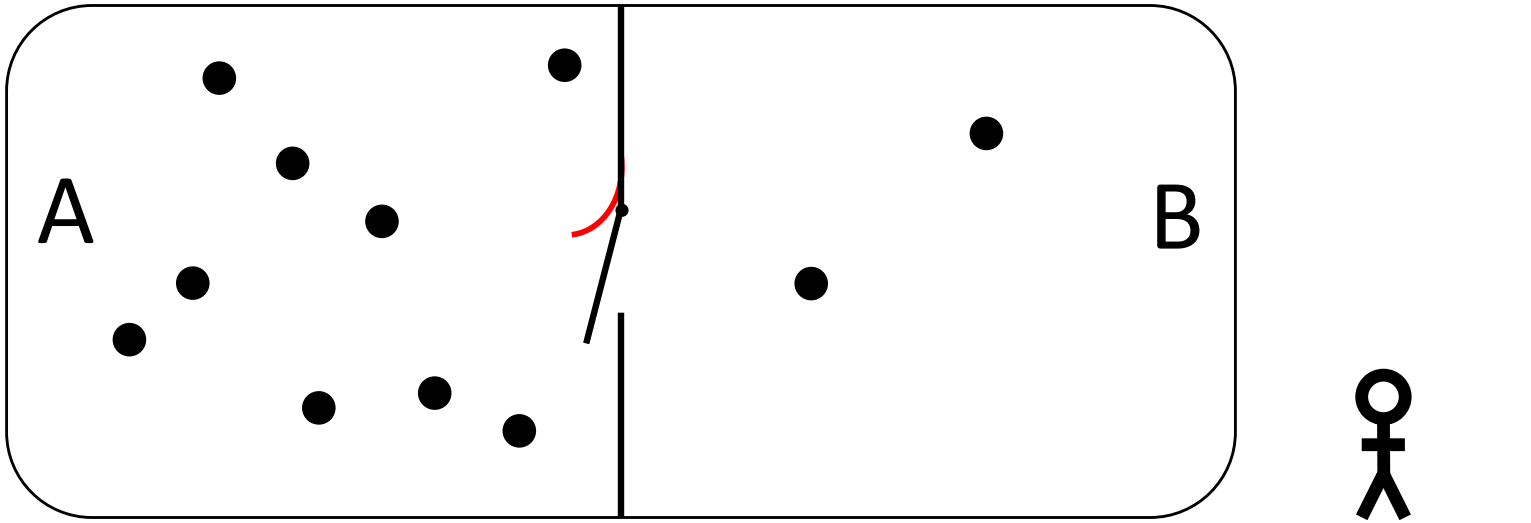
A spring-loaded trapdoor prevents particles from passing from A to B, but occasionally permits a particle to pass from B to A ...

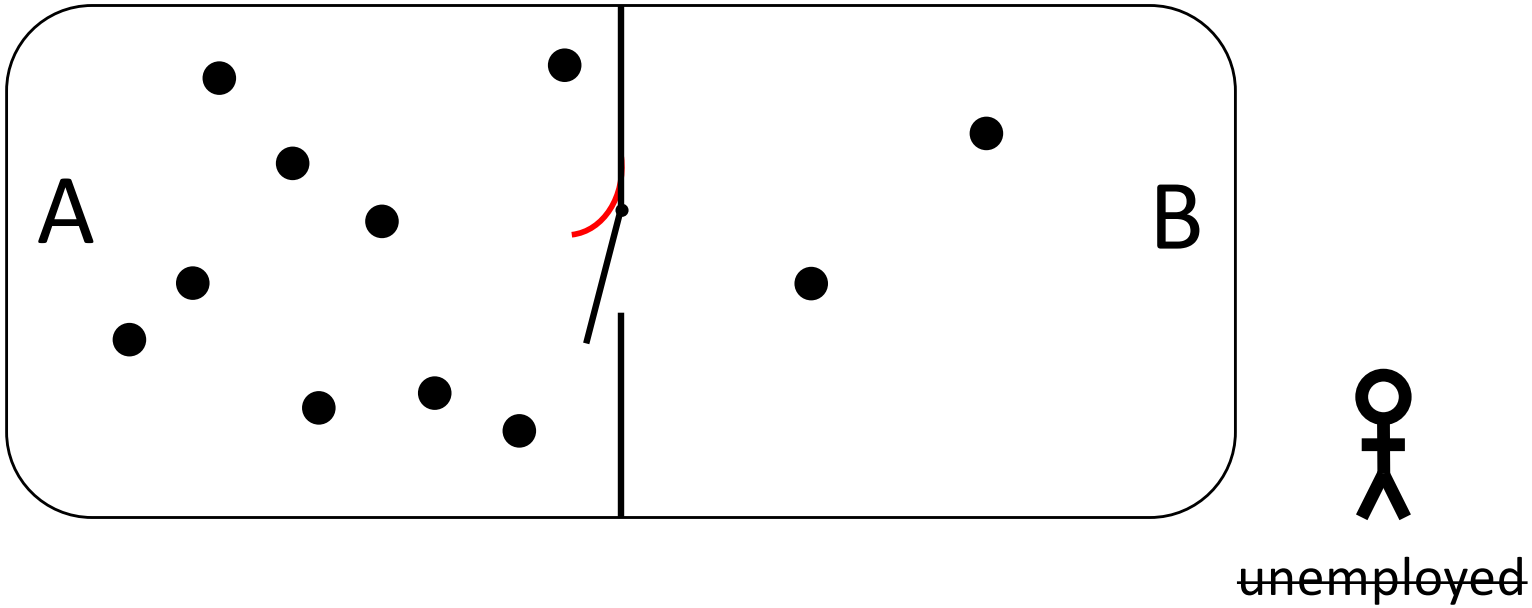
# Smoluchowski's trapdoor




Marian Smoluchowski (1912)

A spring-loaded trapdoor prevents particles from passing from A to B, but occasionally permits a particle to pass from B to A, thereby creating a pressure difference.

# Smoluchowski's trapdoor




~~unemployed~~

Marian Smoluchowski (1912)

But *it doesn't work !*

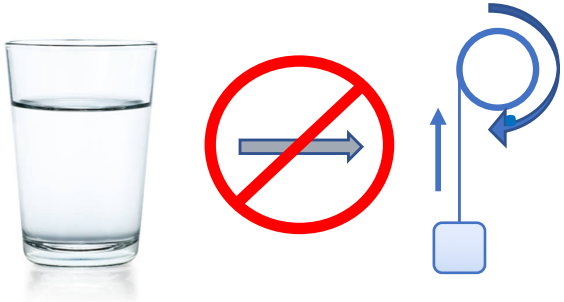
# Recall: statements of the Second Law

**Entropy** must increase.

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

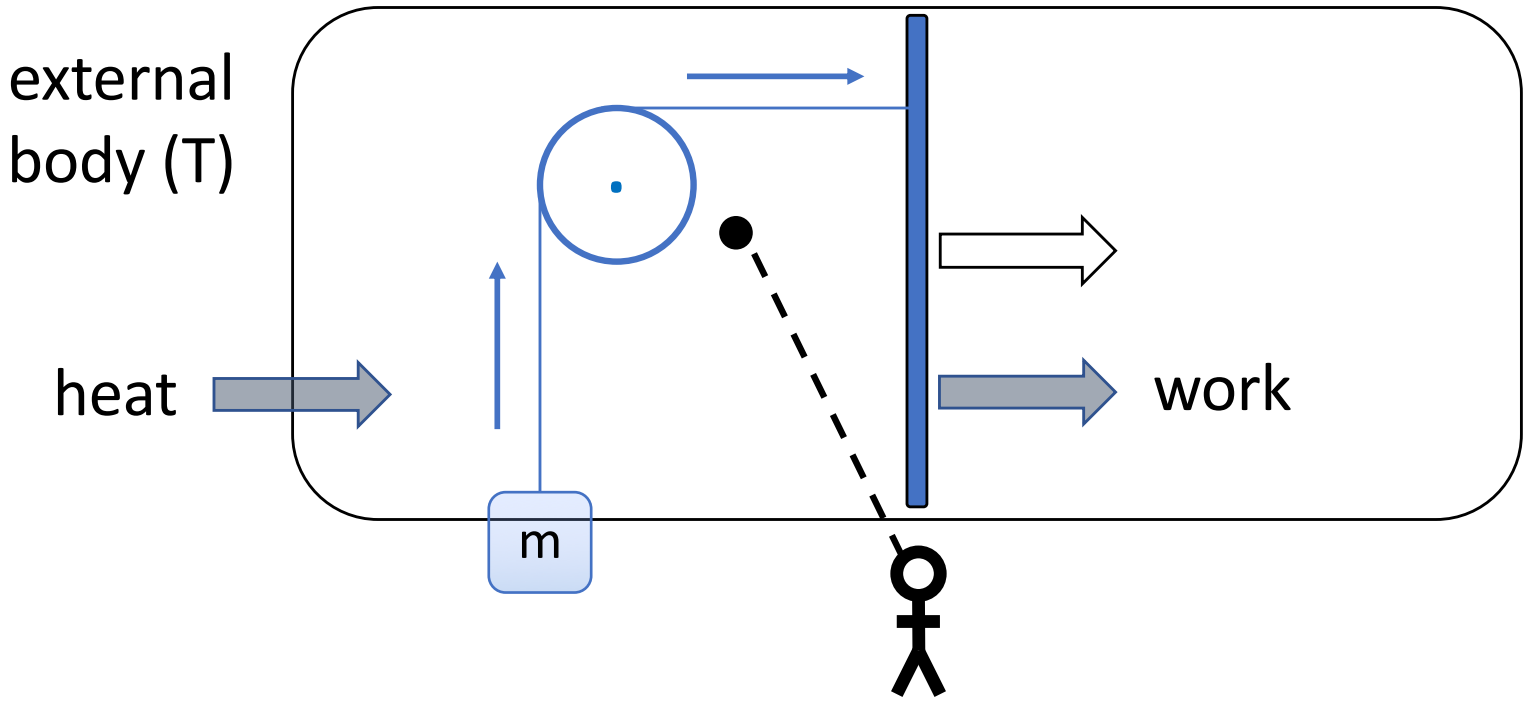
*Clausius statement*

No process is possible whose sole result is the extraction of energy from one body, and the conversion of all that energy into *work*.



*Kelvin-Planck statement*

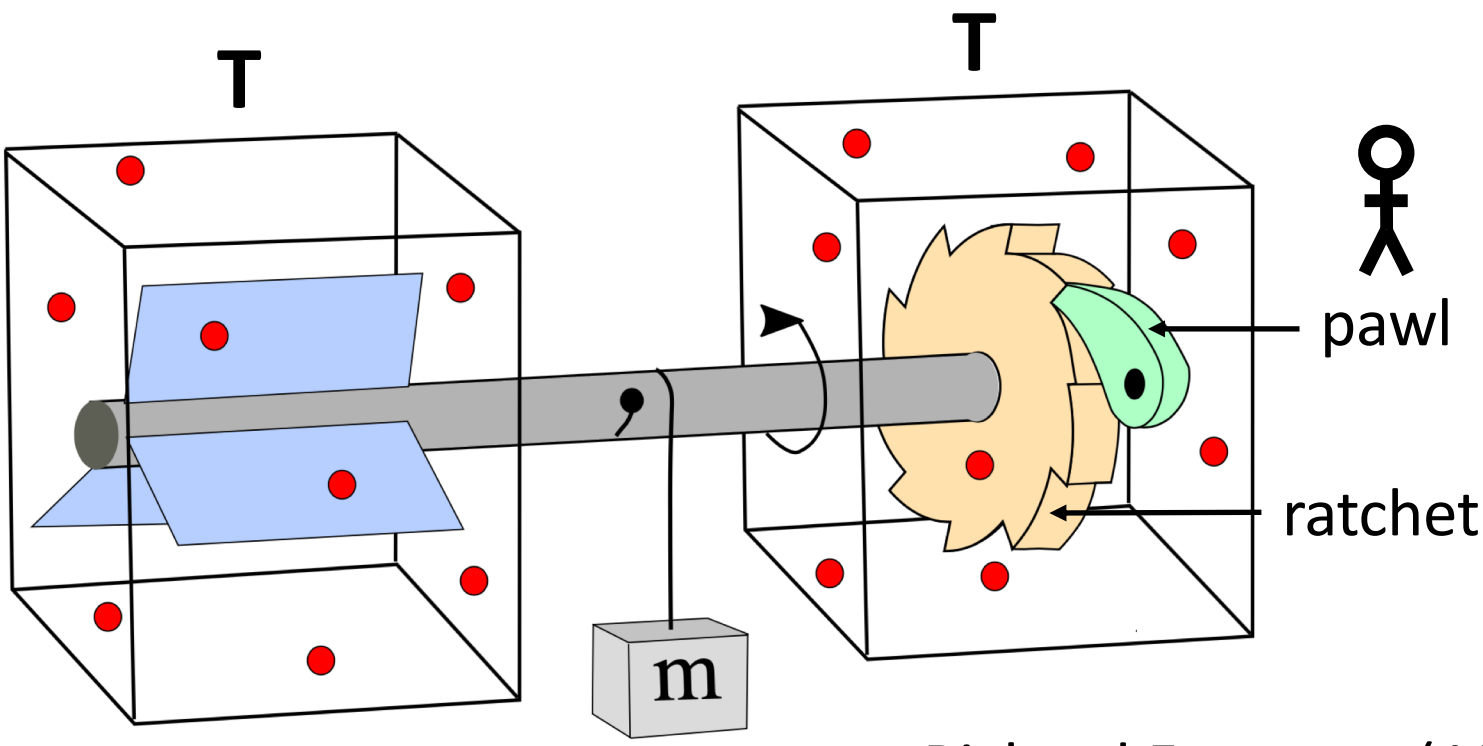
# Szilard's engine




"The objective of the investigation is to find the conditions which apparently allow the construction of a perpetual-motion machine of the second kind, if one permits an intelligent being to intervene in a thermodynamic system."

Leo Szilard (1929)

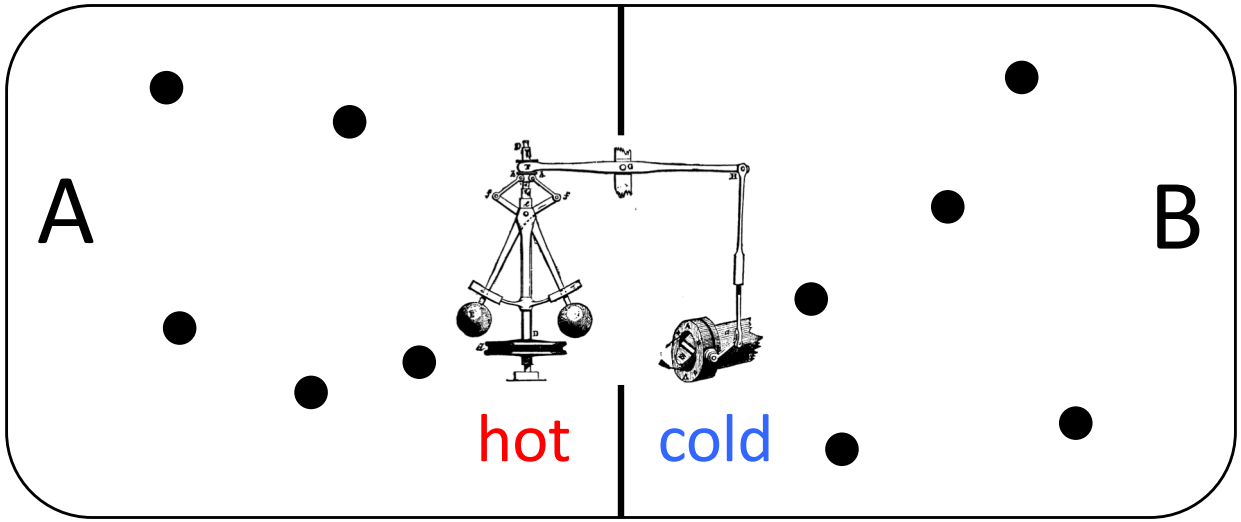
# Feynman's ratchet and pawl




Richard Feynman (1963)

But *it doesn't work !*

# Maxwell's demon

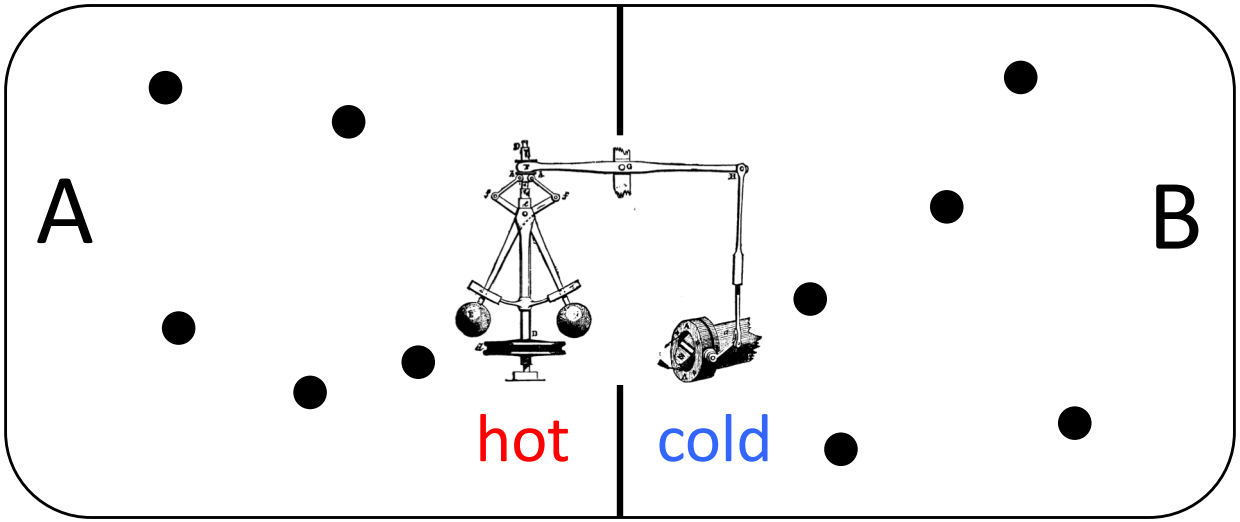



*Is a mechanical Maxwell demon possible?*

Smoluchowski, Feynman : **no!**

A mechanical demon would cause entropy to *decrease*.

# Maxwell's demon



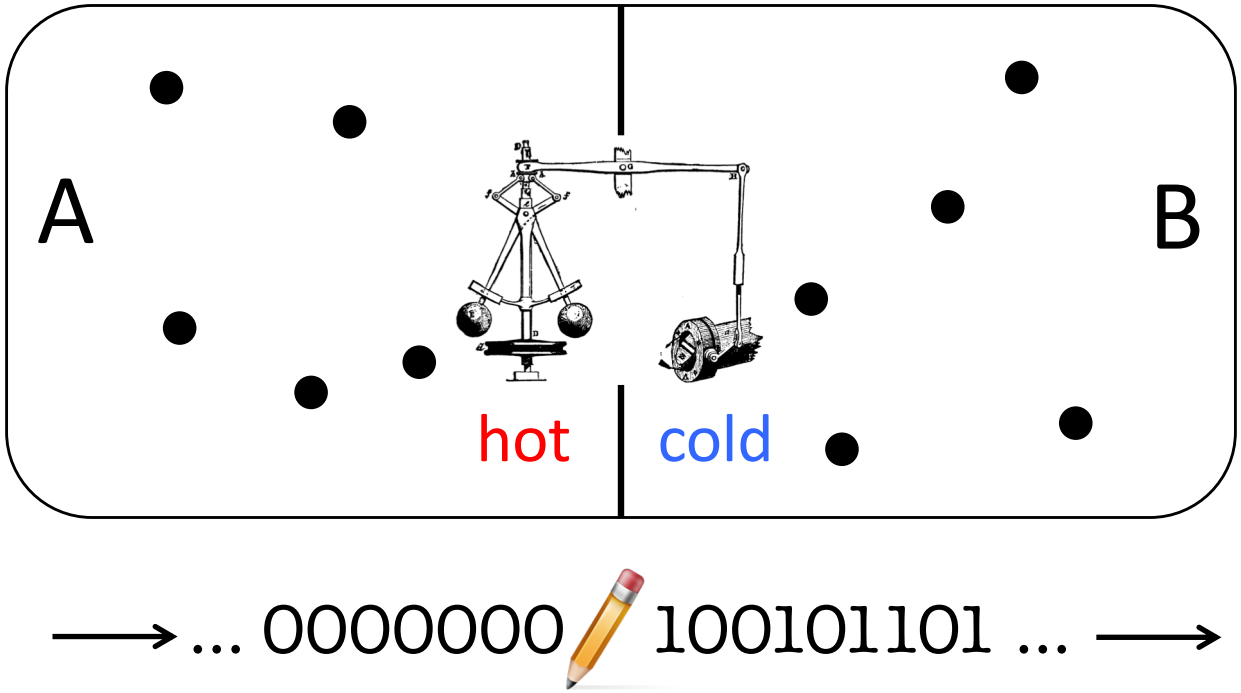

*Is a mechanical Maxwell demon possible?*

R. Landauer, *IBM J Res Dev* (1961)

O. Penrose, *Foundations of Statistical Mechanics* (1970) **yes, *but* …**

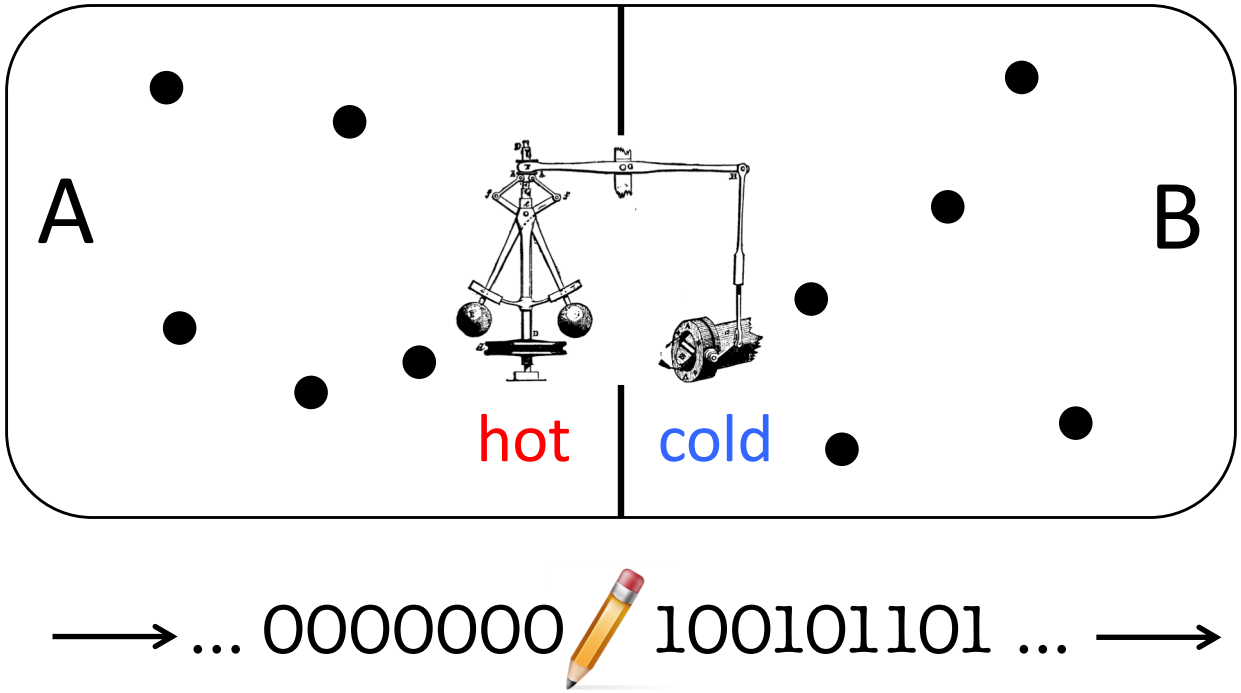
C.H. Bennett, *Int J Theor Physics* (1982)

# Mechanical Maxwell's demon




The device gathers *information*, creating a record in some physical system, such as a computer's memory.

# Mechanical Maxwell's demon




The device gathers *information*, creating a record in some physical system, such as a computer's memory. This act of writing increases the *information entropy* of the memory …

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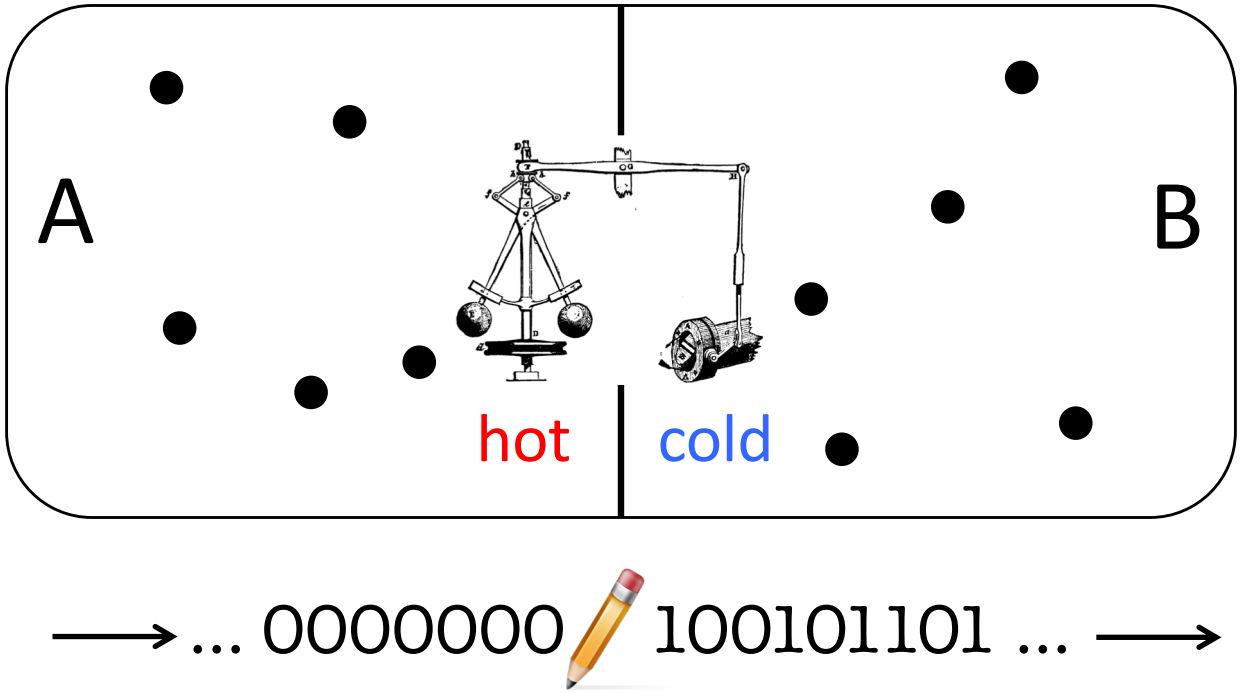
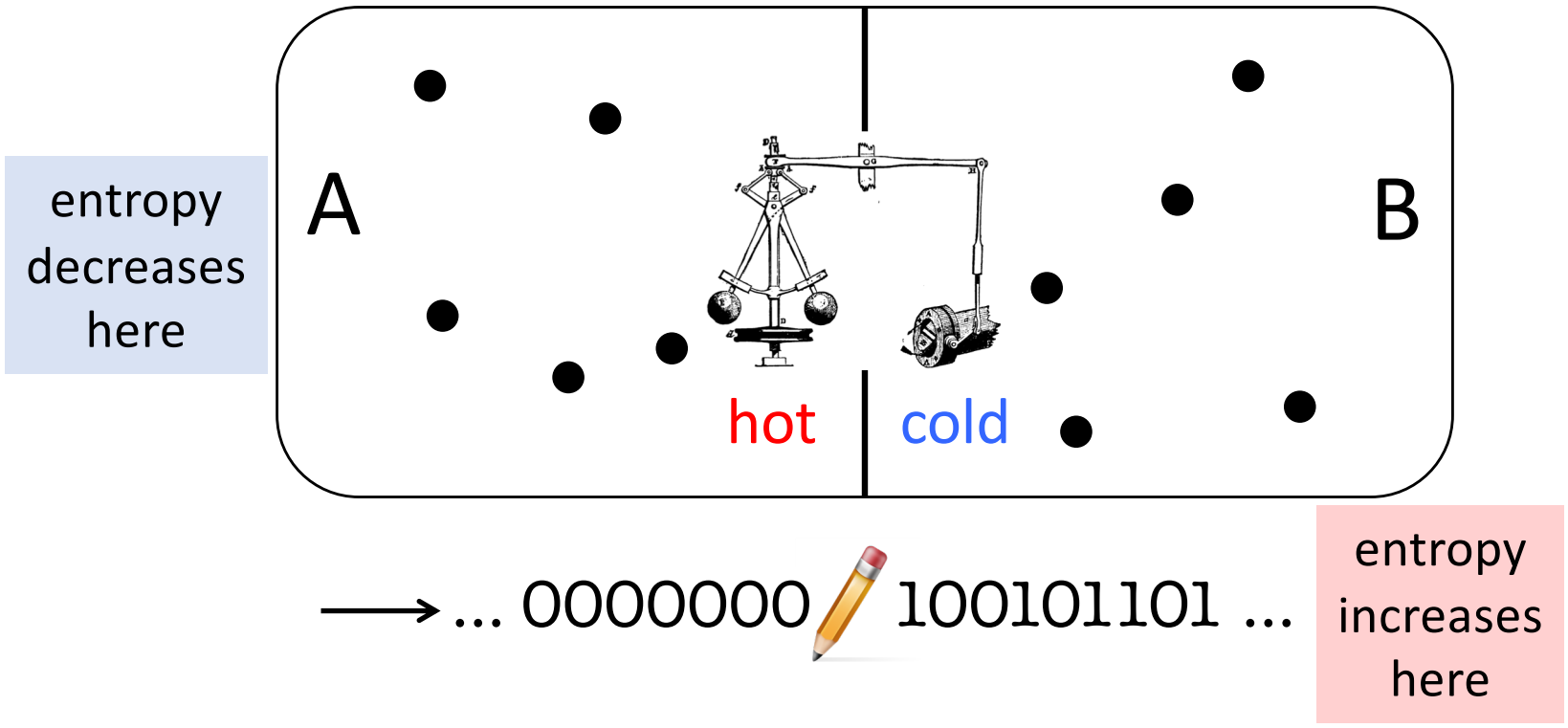



The device gathers *information*, creating a record in some physical system, such as a computer's memory. This act of writing increases the *information entropy* of the memory … which can compensate for the decrease of *thermodynamic entropy* caused by the mechanical demon.

# Mechanical Maxwell's demon

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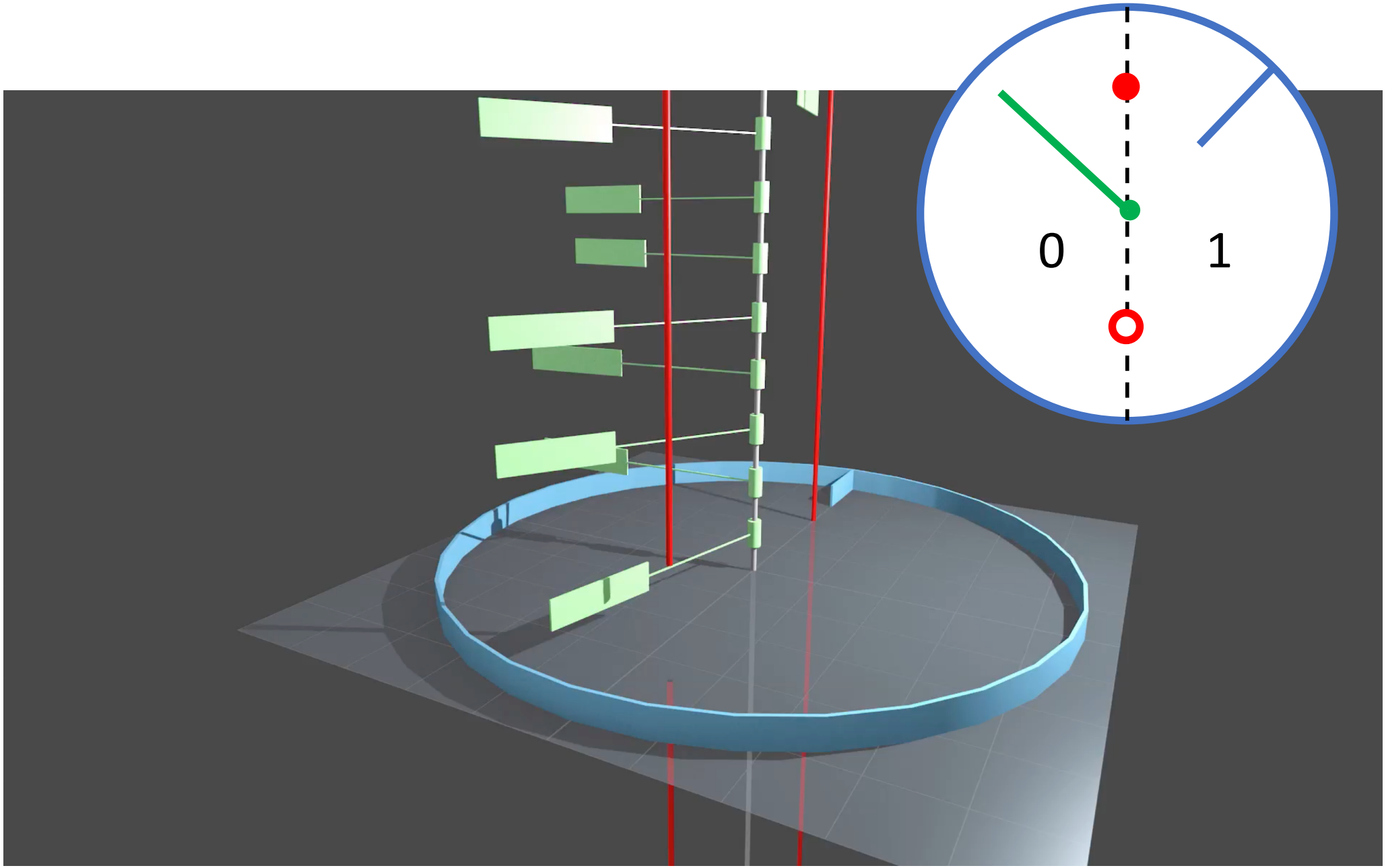
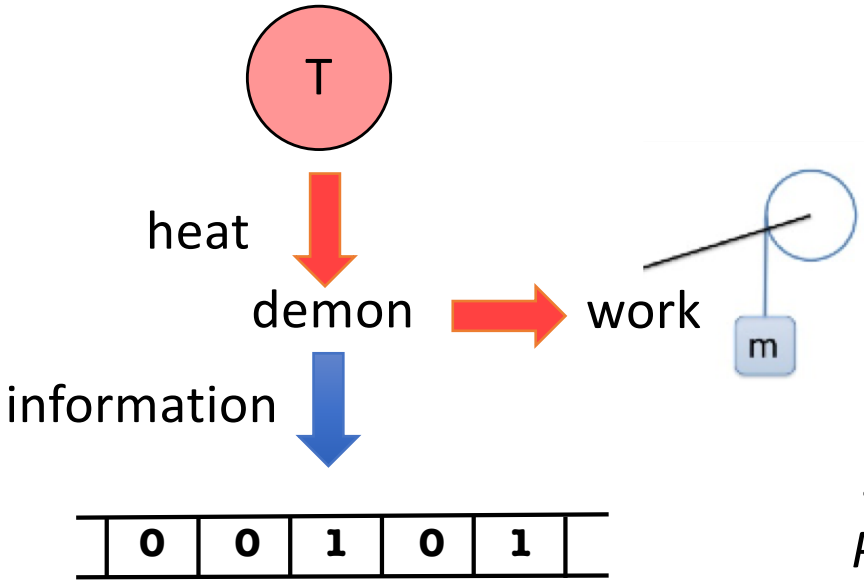



Z. Lu, D. Mandal, C.J., *Physics Today* (2014)

# *Information is Physical*[*]




S. Deffner & C.J.,
*Phys Rev X* (2013)

- A blank memory is a thermodynamic resource.

... OOOOOOO ... ~ 

[*] R. Landauer, *Physics Today* (1991)

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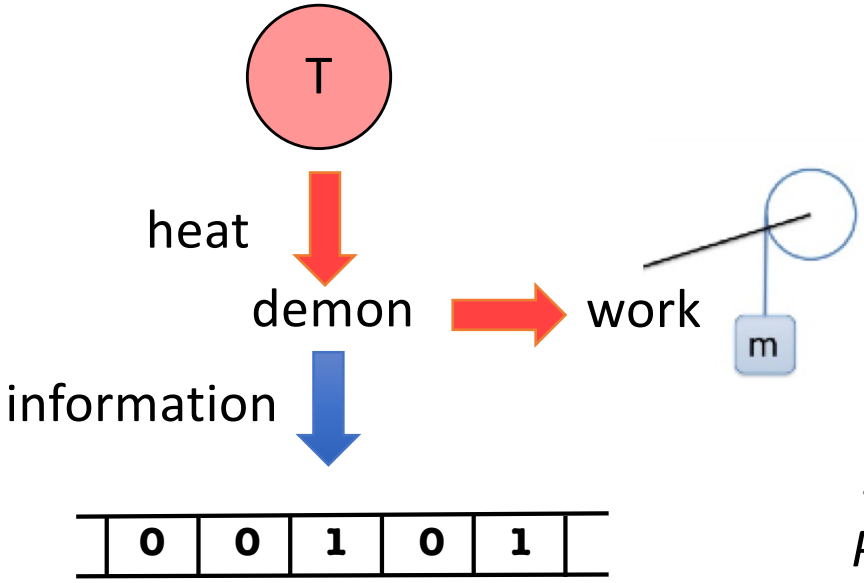


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... 1001011 ... ~ 

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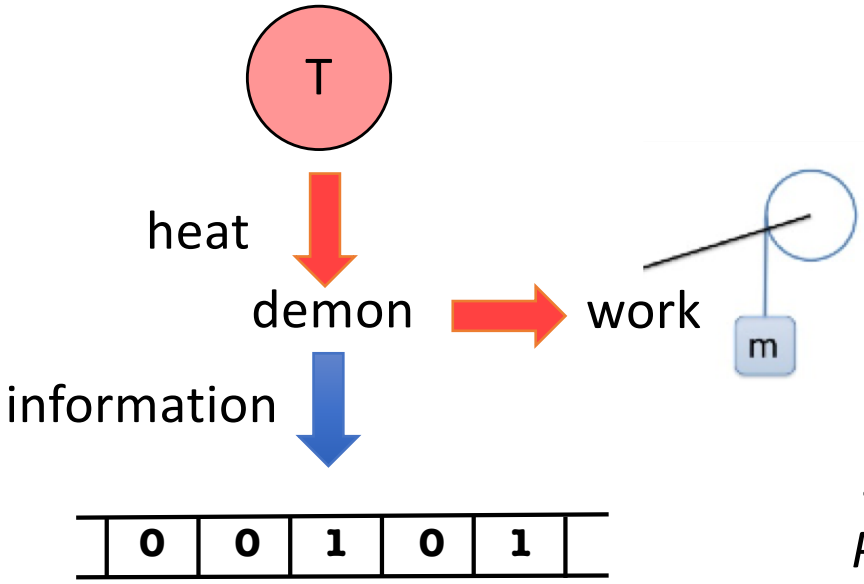


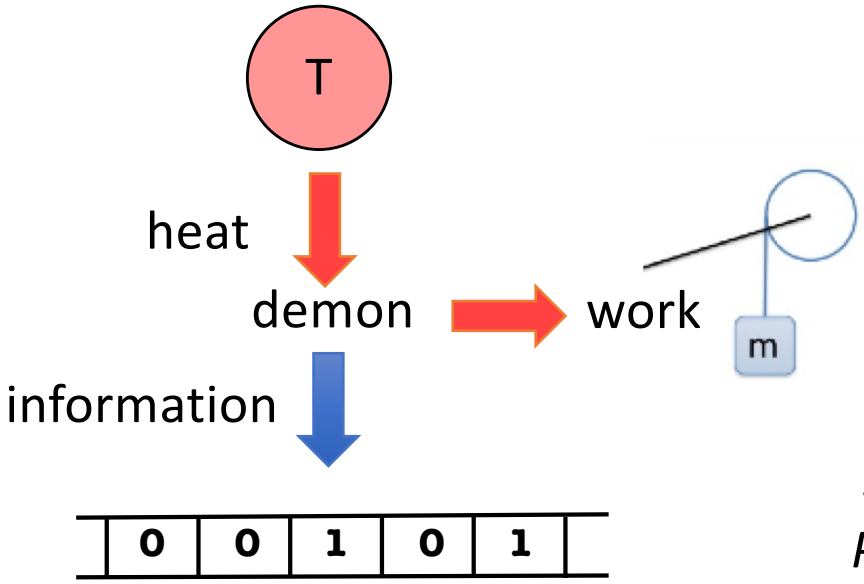

S. Deffner & C.J.,
*Phys Rev X* (2013)

- A blank memory is a thermodynamic resource.

- The erasure of memory carries a thermodynamic cost.
  *Landauer's principle* : $k_B T \ln(2)$ per bit

[*] R. Landauer, *Physics Today* (1991)

# *Information is Physical**



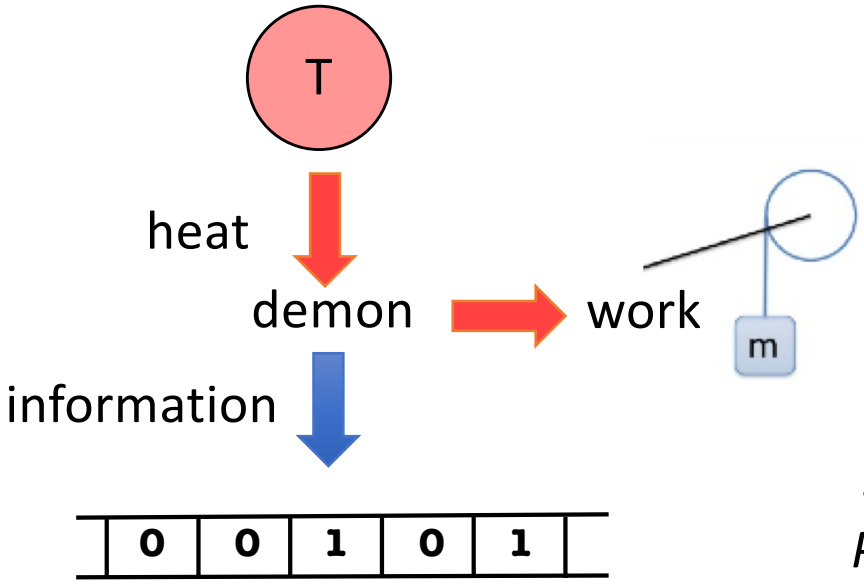

S. Deffner & C.J.,
*Phys Rev X* (2013)

- A blank memory is a thermodynamic resource.

| | |
|---|---|
| my laptop | 16 gigabytes of memory = 128,000,000,000 bits |
|  a flea | 0.5 mg (or 1.0 mg after feeding) |

At room temperature, 16 GB of memory could be used to lift a (hungry) flea by about 1/10 mm.

# *Information is Physical*[*]



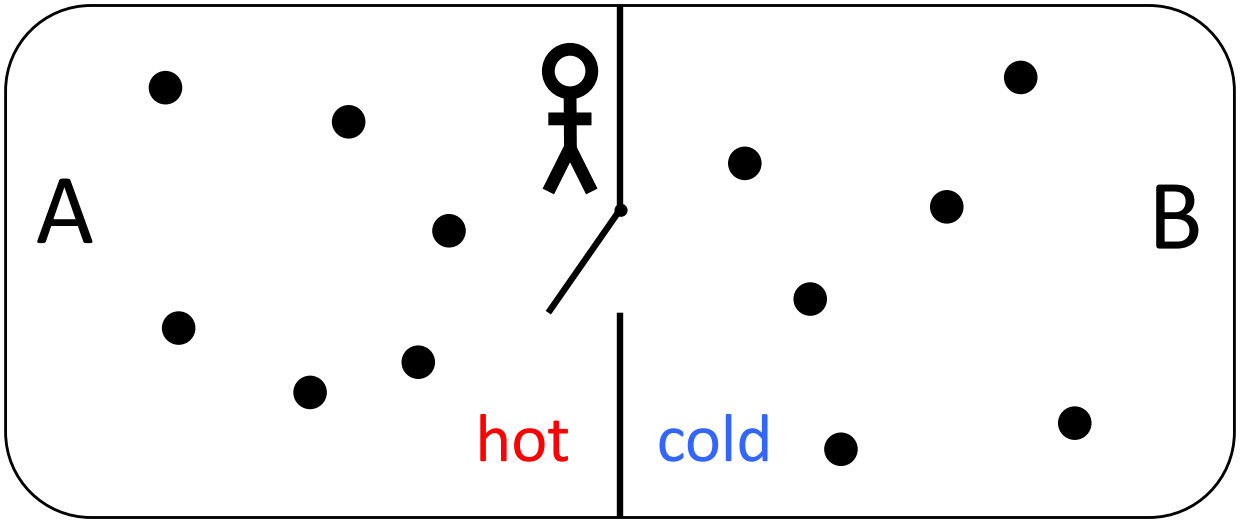

S. Deffner & C.J.,
*Phys Rev X* (2013)

- Landauer's principle: erasure costs $k_B T \ln(2)$ per bit

How much energy is needed to erase 16 GB of memory
at room temperature?

~ 1/3 nano Joule (0.0000000003 J)

# Maxwell's demon




This is only one of the instances in which conclusions which we have drawn from our experience of bodies consisting of an immense number of molecules may be found not to be applicable to the more delicate observations and experiments which we may suppose made by one who can perceive and handle the individual molecules which we deal with only in large masses.

J.C. Maxwell, *Theory of Heat* (1871)
Limitations of the Second Law of Thermodynamics

# ON GOVERNORS

*From the* Proceedings of the Royal Society*, No.100, 1868.*

A GOVERNOR is a part of a machine by means of which the velocity of the machine is kept nearly uniform, notwithstanding variations in the driving-power or the resistance.

Most governors depend on the centrifugal force of a piece connected with a shaft of the machine. When the velocity increases, this force increases, and either increases the pressure of the piece against a surface or moves the piece, and so acts on a break or a valve.

...

I propose at present, without entering into any details of mechanism to direct the attention of engineers and mathematicians to the dynamical theory of such governors.

...