What can Maxwell's Demon do for you?

http://tph.tuwien.ac.at/∼svozil/publ/2011-demon-pres.pdf
http://arxiv.org/abs/1105.4768

Karl Svozil

Institut für Theoretische Physik, University of Technology Vienna,
Wiedner Hauptstraße 8-10/136, A-1040 Vienna, Austria
svozil@tuwien.ac.at

StatPhysI, May 25th, 2011

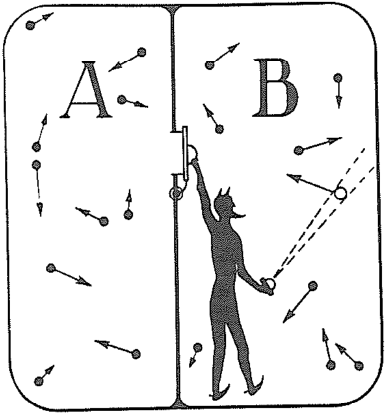
Part I:

Introduction of the Demon

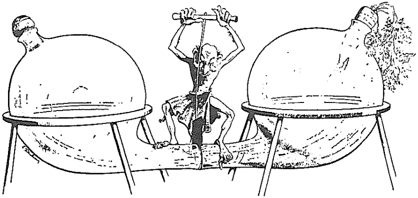
Maxwell's Theory of Heat

```
@BOOK{Maxwell-1871,
  title = {Theory of Heat},
  year = {1871},
  author = {James Clerk Maxwell},
  url={http://www.archive.org/details/theoryheat02maxwgoog}
}
```

Maxwell's Demon



Maxwell's Demon



Maxwell's demon at work

What could go wrong?

?

Part II:

Early explanations & exploitations

Early explanations & exploitations

```
@article{Szilard-1929,
   author = {Le\'o Szil\'ard},
   affiliation = {Berlin},
   title = {{\"{U}}ber die {E}ntropieverminderung
              in einem thermodynamischen {S}ystem bei
              {E}ingriffen intelligenter {W}esen},
   journal = {Zeitschrift f{\"u}r Physik},
   publisher = {Springer Berlin / Heidelberg},
   issn = {0939-7922},
   keyword = {Physics and Astronomy},
   pages = {840-856},
   volume = {53},
   issue = {11},
   url = {http://dx.doi.org/10.1007/BF01341281},
   doi = {10.1007/BF01341281},
   year = {1929},
   note={English translation in \cite[pp.~110-119]{maxwell-demon
}
```

Part III:

Present understanding

Information theoretic "solution" to Maxwell's Demon

R. Landauer, Irreversibility and Heat Generation in the Computing Process, IBM Journal of Research and Development **3**, 183-191 (1961)

- logical irreversibility in connection with information-discarding processes — "cleared" memory can be from a variety of previous states — due to a two-to-one change of state volume in "phase space" associated with $\Delta S = k_B \log 2$

Information theoretic “solution” to Maxwell’s Demon

R. Landauer, Irreversibility and Heat Generation in the Computing Process, IBM Journal of Research and Development **3**, 183-191 (1961)

- logical irreversibility in connection with information-discarding processes — “cleared” memory can be from a variety of previous states — due to a two-to-one change of state volume in “phase space” associated with $\Delta S = k_B \log 2$
- Each logical step must somehow correspond to a physical state

Information theoretic “solution” to Maxwell’s Demon

R. Landauer, Irreversibility and Heat Generation in the Computing Process, IBM Journal of Research and Development **3**, 183-191 (1961)

- logical irreversibility in connection with information-discarding processes — “cleared” memory can be from a variety of previous states — due to a two-to-one change of state volume in “phase space” associated with $\Delta S = k_B \log 2$
- Each logical step must somehow correspond to a physical state
- (“the bad news”) logical irreversibility is associated with physical “heat dissipation” and “entropy increase” ;-(

Information theoretic “solution” to Maxwell’s Demon

R. Landauer, Irreversibility and Heat Generation in the Computing Process, IBM Journal of Research and Development **3**, 183-191 (1961)

- logical irreversibility in connection with information-discarding processes — “cleared” memory can be from a variety of previous states — due to a two-to-one change of state volume in “phase space” associated with $\Delta S = k_B \log 2$
- Each logical step must somehow correspond to a physical state
- (“the bad news”) logical irreversibility is associated with physical “heat dissipation” and “entropy increase” ;-(
- (“the good news”) logically reversibile operations need not be associated with physical “heat dissipation” and “entropy increase” ;-) $\Rightarrow$ (reversible) dissipationless universal computation possible!

Modern-day “solution” of Maxwell’s question

```
@ARTICLE{bennett-82,
  author = {Charles H. Bennett},
  title = {The Thermodynamics of Computation---A Review},
  journal = {International Journal of Theoretical Physics},
  year = {1982},
  volume = {21},
  pages = {905-940},
  note = {Reprinted in Ref.~\cite[pp. 283-318]{maxwell-demon2}},
  doi = {10.1007/BF02084158},
  url = {http://dx.doi.org/10.1007/BF02084158}
}
```

Modern-day "solution" of Maxwell's question

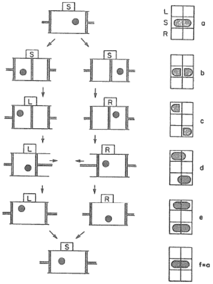


Fig. 12. A one-molecule Maxwell's demon apparatus.

Figure 12 shows the cycle of operation of a one-molecule Maxwell's demon apparatus. The left side of the figure shows the apparatus, and the right side shows the sequence changes in its phase space, depicted schematically as a product of a horizontal coordinate representing the location of the molecule and a vertical coordinate representing the physical state of the demon's "mind." The demon's mind has three states: its standard state S before a measurement, and two states L and R denoting the result of a measurement in which the molecule has been found on the left or right, respectively. At first (a) the molecule wanders freely throughout the apparatus and the demon is in the standard state S, indicating that it does not know where the molecule is. In (b) the demon has inserted a thin partition trapping the molecule on one side or the other. Next the demon performs a reversible measurement to learn (c) whether the molecule is on the left or the right. The demon then uses this information to extract $kT \ln 2$ of isothermal work from the molecule, by inserting a piston on the side not containing the molecule and allowing the molecule to expand (d) against the

piston to fill the whole apparatus again (e). Notice that a different manipulation is required to extract work from the molecule depending on which side it is on; this is why the demon must make a measurement, and why at (d) the demon will be in one of two distinct parts of its own phase space depending on the result of that measurement. At (e) the molecule again fills the whole apparatus and the piston is in its original position. The only record of which side the molecule came from is the demon's record of the measurement, which must be erased to put the demon back into a standard state. This erasure (e–f) entails a twofold compression of the occupied volume of the demon's phase space, and therefore cannot be made to occur spontaneously except in conjunction with a corresponding entropy increase elsewhere. In other words, all the work obtained by letting the molecule expand in stage (d) must be converted into heat again in order to compress the demon's mind back into its standard state.

International Journal of Theoretical Physics
21 (12) 905 - 940 (1982) DOI: 10.1007/BF02084158

The Thermodynamics of Computation—a Review

Charles H. Bennett

IBM Watson Research Center, Yorktown Heights, New York 10598

Received May 8, 1981

Computers may be thought of as engines for transforming free energy into waste heat and mathematical work. Existing electronic computers dissipate energy vastly in excess of the mean thermal energy kT, for purposes such as maintaining volatile storage devices in a bistable condition, synchronizing and standardizing signals, and maximizing switching speed. On the other hand, recent models due to Fredkin and Toffoli show that in principle a computer could compute at finite speed with zero energy dissipation and zero error. In these models, a simple assemblage of simple but idealized mechanical parts (e.g., hard spheres and flat plates) determines a ballistic trajectory isomorphic with the desired computation, a trajectory therefore not foreseen in detail by the builder of the computer. In a classical or semiclassical setting, ballistic models are unrealistic because they require the parts to be assembled with perfect precision and isolated from thermal noise, which would eventually randomize the trajectory and lead to errors. Possibly quantum effects could be exploited to prevent this undesired equipartition of the kinetic energy. Another family of models may be called Brownian computers, because they allow thermal noise to influence the trajectory so strongly that it becomes a random walk through the entire accessible (low-potential-energy) portion of the computer's configuration space. In these computers, a simple assemblage of simple parts determines a low-energy labyrinth

Part IV:

Brownian ratchet
(Molekulare Ratsche nach Smoluchowski-Feynman)

Modern-day “solution” of Maxwell’s question

```
@ARTICLE{Smoluchovski-1912,
  author = {Marian Smoluchowski},
  title = {{E}xperimentell nachweisbare,
            der {\"u}blichen {T}hermodynamik
            widersprechende {M}olekularph{\"a}nomene},
  journal = {Physikalische Zeitschrift},
  year = {1912},
  volume = {13},
  pages = {1069-1080},
  url1 = {http://www.physik.uni-augsburg.de/theo1/hanggi/History
  url = {http://matwbn.icm.edu.pl/ksiazki/pms/pms2/pms2122.pdf}
}
```

Brownian ratchet (Molekulare Ratsche)

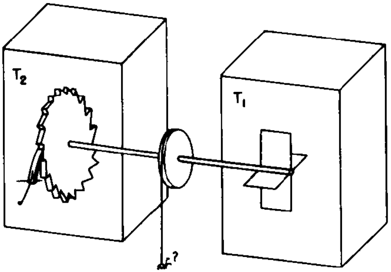


Fig. 46–1. The ratchet and pawl machine.

What could go wrong?

?

Impossibility of . . .

. . . perpetual motion machines of (the first, and of) the second kind.

. . . the construction of a device which *permanently* – that is, in continuation – solely extracts work from a heat reservoir. In "small" time scales, such an extraction seems possible.