Irreversibility versus Demon

Imagining an intelligence intervening into the Laws of Nature has historically been a useful way of delving into fundamental principles, as we had previously seen with the determinism of Laplace's Demon. In 1867, Maxwell wrote in a letter to P.G. Tait concerning two compartments *A* and *B* connected by a diaphragm: "Now conceive of a finite being who knows the paths and velocities of all the molecules by simple inspection, but who can do no work except open and close [the] hole in the diaphragm by means of a slide without mass" [379, pp. 213-215]. His task would be to allow molecules to pass from *A* to *B* if they have greater than average speed in *A*, and from *B* to *A* if they have less than the average speed in *B*. The result of these tactics is that molecules in *B* become more energetic than they were originally and those in *A* less energetic, resulting in heat flowing the wrong way. The being has arranged for entropy to decrease and thus violate the Second Law of Thermodynamics. In his important

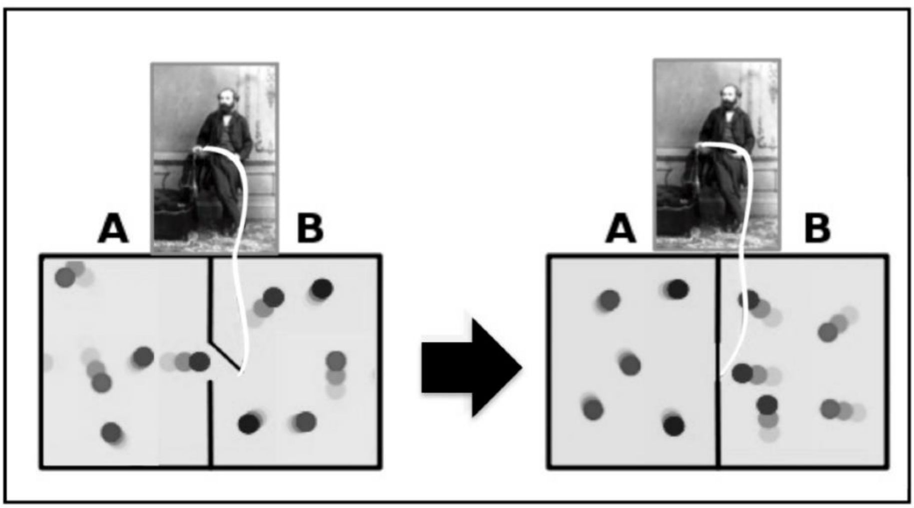

Figure 5.12: Maxwell's Demon. Maxwell re-enacting his thought experiment of "a being whose faculties are so sharpened that he can follow every molecule in its course," allowing the temperature of B to be elevated above A without the expenditure of work, violating the second law of thermodynamics.

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1874 Nature paper on energy dissipation, William Thomson (Lord Kelvin 1824-1907) dubbed this selective influence a *demon*, "an intelligent being endowed with free will, and fine enough tactile and perceptive organization to give him the faculty of observing and influencing individual molecules of matter" [380]. This was in the original Greek sense of *daemon* as an intelligent deity and not the malevolent scarlet imp often pictured. The demon as intelligent guide is no doubt an alter-ego for Maxwell himself, Figure 5.12.

The three laws of thermodynamics have been debated since they were formulated in the late 19th and early 20th centuries. The First Law states that energy cannot be created or destroyed; the Second Law that the amount of disorder or entropy in an isolated system can never decrease; and the Third Law that it is impossible to cool an object to absolute zero in a finite number of steps. In 1847, James Joule (1818-1889) stated the principle of conservation of energy (and thereby the First Law), concluding that "Experiment has shown that whenever living force [kinetic energy] is apparently destroyed or absorbed, heat is produced," [381] and further he gave the amount of heat equivalent to the converted kinetic energy. Rudolph Clausius (1822-1888) formulated the Second Law in 1850 based on empirical evidence that there is a favored direction for spontaneous processes. He quantified the notion of irreversibility of macroscopic processes by defining the thermodynamic entropy S, which can only increase for isolated systems. Decrease of entropy required energy exchange with the environment. Lord Kelvin framed the Second Law equivalently in terms of the work produced by a cyclic engine. Walther Nernst (1864-1941), during the years 1906-12, formulated the Third Law. The Second Law implies that heat flows from hot to cold, devices of perpetual motion of the second kind cannot exist and that the production of disorder is irreversible although this appears to conflict with the reversible laws of mechanics at the microscopic level. Understanding the issues involved with the classical mechanical demon took another 115 years, and much progress has been made on Maxwell's demon in the context of quantum mechanics [382]. Maxwell's demon by construction did not change the energy but its "selective influence" did involve observation or measurement. A final understanding of the quantum demon must wait for a complete theory of measurement so that it is known with confidence which assumptions made in various formulations of the demon are valid.

The Second Law characterizes the difference between reversible processes which do not change the entropy and irreversible ones in which work done is dissipated as heat, resulting in increased entropy of the system. In thermodynamics, entropy is a state variable whose change is defined for a reversible process at temperature T as $dS = \delta Q/T$ where δQ is the heat absorbed, so the task of a potential demon is to somehow decrease the entropy for each cycle of the process. For example, in 1912 Smoluchowski (1872-1917) [383] considered an inanimate object without intention as a possible demon in the form of a spring attached to a door that only opens to one side, so that slow moving particles could be prevented from returning from A to B by the door's snapping shut. However, Smoluchowski showed that thermal fluctuations prevent the spring door from acting as a demon as they cause the door to execute a Brownian motion so that it occasionally gets kicked in the wrong direction just enough to foil the demon.

However, it was Leo Szilard (1898-1964) in 1929, in the heightened period after the discovery of quantum mechanics, who analyzed an intentional demon in terms of *information*. He analyzed a single-particle in a two-chamber heat engine in which a Maxwell demon could extract work from the closed cycle and once again violate the Second Law [384]. This was the same Szilard who conceived of the nuclear chain reaction in 1933 and in 1939 wrote the confidential letter that the reluctant Einstein signed to convince President Roosevelt to begin building the atomic bomb. Szilard's two-state engine was limited by the Second Law to producing a maximum amount of work equal to $k_B T \ln 2$. The two-state engine essentially constituted a computational bit, thus $k_B T \ln 2$ is also the maximum energy that can be obtained by one bit of information. Here was a first indication that information and energy were related and Szilard's article may have been the first information theory paper. Claude Shannon (1916-2001) later defined an informational entropy that increased with information content establishing the field of information theory in 1948. Szilard concluded that there was an entropic price paid caused by the demon's measurement that balanced the extracted work.

Rolf Landauer (1927-1999) showed in 1961 that the entropy change in Szilard's model actually came in the step that erases the information previously acquired during the measurements [385]. The dissipation of heat into the environment due to the process of erasing compensates the entropy decrease caused by Maxwell's demon. That the erasure of one bit of information is necessarily accompanied by the release of at least $k_B T \ln 2$ of heat is called *Landauer's erasure principle*. For this to be valid, the erasure process should not depend on the initial state of the system. Arguments by Brillouin and Gabor had previously claimed that the Second Law was not violated because the demon's measurement resulted in an energetic penalty [386] [387]. However, Charles Bennett demonstrated that general-purpose computation can be performed in a logically and thermodynamically reversible manner, and in 1982 he proposed that Maxwell's demon was prevented from breaking the Second Law due to the thermodynamic cost of erasing the information by Landauer's principle and not due to acquiring it during information processing [388]. This erasure is necessary after a full cycle of information processing and energy production because the demon's memory must be reset to allow the next iteration. Landauer's principle guarantees that the erasure dissipates more energy than the demon produces during each cycle, in agreement with the Second Law. Landauer erasure has been experimentally verified in classical systems such as trapped colloidal particles and RC-circuits [389] [390] [391]. Experiments have also demonstrated that a vanishing amount of heat is dissipated for reversible systems [392]. Therefore, any attempts by classical mechanical demons to intervene in irreversible processes are vanquished by Landauer's principle.