Appendix C

Maxwell’s Demon

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Maxwell’s demon is an enduring iconic character. Born in 1867 as Maxwell’s brainchild, the midwife was Kelvin himself and followed suggestions made 5 years previously by James Thomson. These contrasted the known processes of controlling energy in bulk with at least the possibility of ‘mind or life’ becoming able to combat, even reverse, the fundamental processes of nature at molecular level. A sequel was played out in the ensuing 10 years or so. It is included in detail in the exhaustive Kelvin biography Energy & Empire, by Smith & Wise, published in 1989 [1].

Early in these years, Maxwell acknowledged that there could be several sub-species of demons. Their talents had to match the tasks set for them. Thus, the original 1867 demon was a finite being dealing with finite numbers of finite molecules, and was observant, mathematically gifted and neat-fingered. This demon made decisions from its own observations of properties of the molecules – decisions on whether or not to let any molecule continue to move unhindered. If not, the demon – using only his intelligence – could control, without any input of energy, a continually changing, artificial distribution of molecules. One in particular corresponded to an ever increasing temperature difference between two adjoining volumes constituting a complete closed sample.

By 1870, there were analogue demons presented for clarification by Maxwell, usually inspired by some convenient technology of the Victorian era – such as the actions of the railway pointsman. At his fairly easily visualised place of work (Fig. 1), he could set friction-free ‘points’ to send fast (express) trains along one line and slow (goods) trains along the other. His intelligence, got from being able to recognize any one train from all the others, was derived from experience and commitment. Another, dispensing with intelligence altogether, was a demon acting as a valve providing unhindered passage only to particles moving in one direction.

However, in 1874 there arrived Kelvin’s ‘superior’ types of demons. They had all the attributes of Homo sapiens but at molecular level, having free will and organisational abilities including exemplary teamwork. Such a demon could reverse the direction of individual molecules. Kelvin’s Victorian example was of a cricketer (Fig. 2) resulting in an ‘army’ [in suitable formation] of demons … wielding ‘molecular cricket bats’. Acting in concert, they could close ranks to all molecules except certain fast ones going in one direction and slow ones going in the other. Thus, they could readily meet Maxwell’s summary outcome to Kelvin: when [a demon] sees a swift [molecule] let him turn it to the place of the swift and when he sees a slow one let him turn it to go among the slow.
The back stories in a sequence of excerpts from recent publications (1998–2013) reveal the continuing influence of a physically unchanged Maxwell demon on developments in physics. Impasse-breaking led to the development of the science of information gathering and storing, with feedback asking for an even more talented (or, alternatively, burdened) demon. The final example – with input also now from nanoscience – refers to an actual experiment which showed that information can be converted into energy.

A satisfying starting summary, quoted and adapted here, was given by Smith in 1998 [4]. In Maxwell’s thought experiment, the two vessels of equal volume but unequal temperatures (A being hotter than B) are separated by a fixed diaphragm CD (see Fig. 3). A ‘finite being’, subsequently known as Maxwell’s demon, can open and close a hole in CD by means of a sliding door without mass. If the ‘very observant and neat fingered being’ knows the paths and velocities of all the gas molecules in A and in B, he may select molecules in A having less than the mean square velocity in B and allow such through the hole in CD. Similarly, he may select and
allow to pass from B to A those molecules with more than the mean square velocity in B. Hence, the numbers of molecules in A and B are unchanged, but A’s temperature increases and B’s temperature decreases without work being done. This reverses the natural direction of dissipation of heat. Otherwise, the second law remained inviolable.

An enhanced version, here summarised, was given by Hunt [5] in 2010 (Fig. 4). In 1860, James Clerk Maxwell had derived a formula for the distribution of velocities of the molecules of a gas in equilibrium, providing a definitive statistical interpretation of their mean square velocity. Drawing on this, he introduced in 1867 an imaginary “demon” whose actions would illustrate the statistical nature of the second law of thermodynamics. The diagrams are a guide to the association of temperature with average velocity and velocity range, in line with Maxwell’s own description. ‘Imagine a box of air divided into two parts with … a small door between them … Over time the demon is thus able to gather all of the faster “hot” molecules on the left hand side of the box and all of the slower “cold” ones on the right … Such a separation of hot from cold without any net expenditure of work [with the hot becoming hotter at the expense of the cold, which becomes colder] would violate the second law. Moreover … we could connect the two sides through a heat engine and proceed to extract useful work. We would … in thermodynamic terms, have been able to get something for nothing.’
The ordered selection of key points in an article by Al-Khalili [6] in 2013 introduces the beginning of the pivotal development of theory by Szilard in 1929 [7]. This neatly links changes in ‘order’, and thereby in entropy, to transfers of information. The second law is now expressed as a constraint on entropy: it must always increase – or, in the limit, be constant. Drawing on [6] ‘imagine a closed box partitioned into two halves by a thick insulating wall. In the middle of this partition is a trap door that opens and closes very quickly … in 1867, James Clerk Maxwell described his famous thought experiment (Fig. 5) in which a demon sits on the box and can see all the individual molecules of air inside it and knows how fast they are moving … we let the demon control when it opens … It only allows faster moving molecules through from the left chamber to the right and only slow moving molecules from right to left … Using the demon’s knowledge alone we seem to have created a temperature difference between the two halves [of the now more ordered system – with corresponding decrease in entropy], in violation of the second law of thermodynamics … In 1929, Leo Szilard proposed a version of Maxwell’s demon that has since become known as Szilard’s engine … it was the demon’s intelligence and knowledge about the state of the molecules that made all the difference … [acquisition of such knowledge of random motion of molecules would be accompanied by an increase in entropy within the demon] … Szilard’s resolution was a brilliant affirmation of the universality of the second law and the notion of increasing entropy … To an entropy tally of zero, any resulting from heat dissipation in the process could only make the tally positive … Thus, the total entropy of the box plus demon always goes up. The Second Law is saved.’

In 2000, in his book ‘Investigations’ [8], Kauffman addressed, among others, the question ‘What is life?’ In the Introduction, in seeking criteria to move forward, he chose to look back to the faculties of Maxwell’s demon. He speculated on how the demon, on its own, might cope with a non-equilibrium system ‘in one of the major places in physics where matter, energy, work, and information come together.’ [By way of illustration here, a non-equilibrium system is exemplified by the hot and cold halves, produced by Maxell’s demon, of a gas sample originally in equilibrium at a uniform temperature throughout.] William Thomson (Lord Kelvin) and his brother James and several others had also speculated on the science beyond that of inanimate matter in the few years before the arrival of Maxwell’s demon.

More than a century later, Kauffman had the benefit of the much higher level of sophistication across the sciences, particularly now including information. Quoting from the main text directly, ‘Maxwell’s demon [is] flummoxed (Fig. 6). The demon is considering the gas system in which he finds himself and is trying to decide what feature of the system to measure in order to detect if the system is displaced from equilibrium in some way such that work can be [subsequently] extracted. Unfortunately, he decides to measure the positions of all gas particles at a single instant, a strenuous measurement from which he cannot detect a displacement from equilibrium from which work can, in principle, be extracted [in preference to other processes which preclude it]. How does the demon know what to measure?

Beginning with some of Maxwell’s contemporaries, many have speculated on the possibility of a very close control of molecules in inanimate systems. Central to an article by Ball [9], also in 2013, is a discussion of how such speculation led to interest in a range of (in hindsight) peripheral concerns such as invisible and spiritual domains. Moving on from there, however, is his undistracted telling of the stepwise approach to the close control of matter at the microscopic
level. Again the concept of Maxwell’s demon is fundamental – but at risk of being usurped. Ball’s illustration, as retold here, was chosen from recent studies establishing that Maxwell’s thought experiment is now accessible to direct experimental probing, and that such efforts are at the forefront of information science and technology. A microscopic (typically silica) bead, in a suitable environment, has a thermal motion during which it experiences tiny random changes in energy. A structured electromagnetic field can match the energy fluctuations with optical traps into which the bead can be coaxed. Quoting selectively from Ball’s particular example [10] ‘… a group of physicists led by Shoichi Toyabe of Chuo University in Tokyo … put a nanoscale polystyrene bead in a system of traps [with energies represented symbolically by] a spiral staircase of sorts, on which the bead could hop up or down one step at a time between traps, using thermal energy. Left to its own devices, the ball would, on average, move down the staircase (left side of Fig. 7) … if a demon knew the position of the ball, it could place [an electromagnetic] barrier to prevent any downhill motion, so that (right side of Fig. 7) the ball only moves uphill [to a trap of ever higher potential energy]. In the experiment, the physicists [controlled
the barrier placing and so] took on the role of the demon … This demonstrated experimentally that – using no energy as such – information [in the form of the position of the bead] can be [sourced and hence] converted into energy.’

References