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Maxwell's Demon*

Though the demon of physics may seem a strange choice for a paper to the Victoria Institute, no apology is necessary. The present year (1967) marks the centenary of the birth of this strange brain child of James Clerk Maxwell, a man who, as our President recently reminded us, was 'often gifted with prophetic vision'.[1]

Maxwell's writings have indeed an astonishingly modern ring about them. We have been reminded of how, in accepting both mathematical and physical models of reality, he foreshadowed complementarity. On the same occasion he also insisted that analogical understanding should be accorded equal status both with understanding dependent upon physical models and also with that derived from mathematical equations. He believed that God as Creator could be conceived in terms of an analogy between the source of our own creative acts and that of the far vaster creativity exhibited in nature. To the objection that such thinking is woolly and unproductive, he would have reflected that this was precisely the status of Faraday's lines of force at a time when they were an object of ridicule amongst the élite of the astronomer mathematicians – yet the stone which the builders rejected became the headstone of the corner.

Today Clerk Maxwell is chiefly remembered as the first to formulate the mathematical theory of electromagnetic propagation of waves, and the first to have laid the foundations of statistical mechanics. But his investigations led to important advances in many other fields also and he is commonly regarded as the greatest physical scientist to have lived between the time

* It is hoped that the substance of this lecture, expanded and fully documented, will appear later in book form.

[1] R. L. F. Boyd, *Faith and Thought*, 1965, **94**, 191.

of Newton and our own century. His prevision of the future of physics was such that were he to return to be with us today, he would certainly feel more at home in our scientific world than any of his contemporaries.

Clerk Maxwell was a sincere, unostentatious and deeply Christian man – a saint in the truest sense. From his earliest years to his death his concern was with the welfare of others – from the day when as a boy his mother died of cancer and young James was so glad to know that she would suffer no more pain, to the day when at the early age of 48 he too was called home, suffering in the same way, his only worldly concern being the welfare of his invalided wife. His correspondence with his wife– which consists of deeply devotional comments on the passages in the New Testament which they had both been reading, testify to the thoughts which largely occupied his mind.

Maxwell looked for and found a good many connections between his Christianity and his science. At the devotional level, he made it a matter of earnest prayer that God would aid his understanding of nature – conversely he insisted that the glories of the natural world must be given free scope to enlarge our sense of the wonder of God the Creator.

Maxwell believed that the Second Law of Thermodynamics pointed to a beginning of time – to a Creation in fact. He saw it as one of the lessons of science that, however well and truly we understand a phenomenon, there are always depths below, which we are not even aware of – so that no advance of science can ever drive God out of our thinking.

Again, two or more different concepts could give rise to the same physical results (e.g. the action at a distance of the astronomers – Farady's lines of force) so that theology might easily lie behind reality unnoticed.

Maxwell was deeply interested in 'molecules' (he used the word to cover atoms as well as molecules) which he regarded as relics of the original Creation (today we might read protons, or electrons, for 'molecules'). They were, he said, the only things which have remained unchanged since they came straight from the hand of God. Their spectra indicated that they were highly complex and, with Hershel, he thought of them as 'manufactured articles'. He believed that they could teach us a good deal about God. In addition, by the constancy of their properties – for they do not improve by natural selection during the course of ages – they teach us that Creation is the bedrock on which we must build our thinking – evolution is by comparison unimportant and trivial.

Perhaps Thomson's vortex theory of atoms explained their non-creatability and indestructability which would necessarily follow in a frictionless fluid. (Yet 'Was it quite frictionless?' he asked. If not, there should be an 'ether drift' which he looked for, but like Michelson and Morley in our own century, failed to find.) But the ether was conjectural, he knew, and he did not wish to tie Christian interpretations to a mere conjecture which might later become outdated.

It is obvious, Maxwell thought, that in creating 'molecules' all alike, God has provided us with divinely-given absolute standards of mass, length and time: he advocated that these should be adopted. Today, after a century, we have so far got only as far as defining length in terms of a wave-length. Maxwell is still too modern for us!

Maxwell reckoned that in a gas the particles move with very varying speeds, so that the gas laws must arise as a result of averaging. He saw at once that the laws of nature were therefore to be divided into two kinds – those that are absolutely true and those that are true only in a statistical sense, like the laws governing births and deaths in a community. Frequently, therefore, no final deterministic pattern emerges when we deal with small quantities of matter. The problem of nature governed by inexorable laws, with no room for God, simply did not arise.

Maxwell's friend, Balfour Stewart, spent many years studying the connection between solar changes, particularly the sunspot cycles, and the positions of the planets in the solar system. This led him to see the importance of relatively small events in nature, the effects of which might be magnified enormously. The vast orb of the sun was greatly affected by the gnat-like planets situated at a great distance away. In nature, said Balfour Stewart, we encounter both stable systems which cannot be greatly altered by acting on them from without, and also systems in which very minute phenomena can be and are enormously magnified by natural amplifying devices. In discovering nature's laws mankind has confined himself to the first class only, so that his conclusion is not representative of nature as a whole.

Maxwell adopted these views with enthusiasm and, like Balfour Stewart, regarded the brain as an amplifying device with the mind acting as the steersman of the body. By acting on moving micro-particles in a direction at right angles to their motion a controlling action can be exerted, but no physical work is done and no laws of nature are contravened.

As with Faraday and Kelvin, Maxwell's view of nature was highly coloured by theological considerations. It brought no honour to God, he thought, to suppose that the universe consists largely of sheer empty spaces – sheer nothingness. Faraday's picture of a vast web of lines of force, all interconnected together in the great Plan of nature, which brought structure into the universe and dignity to the work of God, was greatly to be preferred. Maxwell's work on electro-magnetic radiation, including his recognition of the nature of light, and his prediction of radio waves, was thus the direct result of his theological preference for a theistic rather than an atheistic picture of nature.

One of Maxwell's most remarkable ideas concerns his 'demon'; to this we now turn. The historical setting is as follows.

Kelvin, then William Thomson, first defined the Second Law of Thermodynamics in 1851, but in doing so was careful to leave a loophole – the law applied to *inanimate* nature only. In effect, the law stated that a perpetual motion machine is not possible in the absence of life – whether it is possible if life is present he left an open question for the time being.

Why did Kelvin mention living matter? The answer is plain. All Kelvin's earlier thought was dominated by the idea that at the beginning of time God had arranged the heat distribution in the earth or sun (and later the universe) in such a way that it could not have been the result of any previous physical state of affairs – an argument the reverse of that which Philop Gosse was to use in his famous work *Omphalos* (1857) in which he urged that all created things must necessarily be created with a false *appearance* of a previous existence.

Kelvin was thus committed to the idea that God, the great Mind, had the power to rearrange the energy share-out among fantastically vast numbers of atoms. But if God, as supreme Mind, could do this, then might not the power to do the same in a limited way be a property of minds in general? In short does the Second Law of Thermodynamics operate in the presence of minds? From his point of view this was a natural enough question to ask and it fully accounts for the fact that in his first formulation of the Law he mentioned the possibility.

Not very long after this, in 1853, we find young Maxwell giving a paper to his fellow undergraduates on the intriguing subject: *Ought the Discovery of a Plurality of Intelligent Creators weaken our Belief in the ultimate First Cause?* His notes for this lecture contain the following words: 'The search for such invisible potencies or wisdoms may appear novel and unsanctioned . . . for my part I do not think that any speculations about the personality or intelligence of subordinate agents in creation could ever be perverted into witchcraft or demonology. Why should not the Original Creator have shared the pleasure of His work with His creatures and made the morning stars sing together?'[2]

From this it is certain that Clerk Maxwell had long harboured the idea that at the Creation God might first have created a vast number of subordinate beings, each allotted his small assignment of work in the Great Plan!

As the years passed, Kelvin's idea that life might in some way be able to circumvent the Second Law occasioned a good deal of discussion. Kelvin himself came to the conclusion that this was most improbable, but not all were convinced. Only after Maxwell's death was the matter finally solved at the crude level, in that animals and men placed in calorimeters were shown to generate heat which corresponded precisely to the food metabolised: they were *not* perpetual motion machines! Nevertheless, the notion that God might act directly on the microscopic physical world, and if God why not lesser minds made in His image, remained in the air.

[2] Campbell and Garnett's *Life*, 1884 ed., p. 339.

At the end of 1867 Maxwell thought of his 'demon' – he described it first on a post card which he sent to his friend P. G. Tait at Edinburgh. Unfortunately this card cannot be found; Tate's reply is all we have – and it is evident that he was not pleased: 'I object to your infinitely sharp individual that he *lets his gases mix*, and so spoils the theorem. But let him wait long enough to catch a quick one from the colder medium and a slow one from the hotter which are moving in the same line so as to impinge centrically when he moves the slide. How many Darwinian ages will that require? And, when he has caught these two, won't he have to wait longer for a repetition? Good'.[3]

From this it would appear that Maxwell had imagined two boxes filled with air, and separated by a partition in which there was a small hole. The hole was supplied with a little trapdoor and an imaginary spirit or intelligence sat at the hole. When he saw an extra fast molecule moving towards him in one of the compartments, he allowed it to pass through the hole into the opposite compartment. By repeating the performance he was able to collect the hot molecules in one box so making the air which it contained hotter, this being at the expense of the other box which became colder. Tait seems to be complaining that the pressure will rise in one box and fall in the other, so that when the trapdoor is opened the high pressure gas will tend to surge through. He suggests that it would be better if the intelligence was given more work to do – let him allow the molecules to pass in *both* directions – the slow in one direction and the fast in the other, in such a way that the pressures are kept equal. This is the form that Maxwell finally adopted, which first made its début in print in 1871 in the first edition of Maxwell's *Theory of Heat* (p. 308): 'But if we can conceive of a being whose faculties are so sharpened that he can follow every molecule in its course, such a being whose attributes are still as essentially finite as our own would be able to do what is at present impossible to us.'

And so on as before.

[3] Letter to Tate, Dec. 12th. University Library, Cambridge, MS Add 7655/Ia, 5.

When Kelvin heard of the idea he was vastly amused. His first reaction was to call the 'being whose faculties are so sharpened . . . ' a *demon.* He was a little apologetic about this and explained to at least one audience that he had derived the word from the *Greek* and that no connection with the powers of darkness was intended! The name stuck ever after. 'Who gave them this name?' asks Maxwell on a piece of paper in the Cavendish archives (probably notes for a lecture) and answers, 'Thomson'.

The demon proved exactly what Thomson wanted to add fun and interest to his lectures. For ten years he continued to amuse audiences with the antics of the little creatures – and sometimes newspapers printed *columns* of the stuff!

Kelvin imagined, wrongly as we now think, that the direction of time is connected with the directions of the movements of molecules. If all the molecules in the universe were to move in the reverse direction, then events would move backwards, time would be reversed!

His favourite concept was that of the demon armed with an object like a cricket bat. If he holds this up in front of an oncoming molecule, the direction of motion of the latter will be reversed. There was little which armies of weaponed demons could not accomplish. Populate your universe with them and, at the word – Go! – time will begin to go backwards – the earth and sun will get hotter, old men will get younger, become children, shrink and return to their mothers' wombs.

With smaller demon armies, distributed as thought fit, the strangest things might happen. The water at the bottom of the waterfall gets colder and with the heat it has lost it pushes itself up the cliff face to the top of the hill once more; rocks collect themselves from river beds and rise up to the mountains whence they had fallen; warm water divides itself up into the hot and cold water from which it has been prepared by mixing. But Kelvin was a little apprehensive lest the Cliffords, Huxleys and Tyndalls of the day would think that he was introducing theology unawares! So he is most insistent that the demon is intended to illustrate the statistical nature of the laws of heat and that it has no other function whatsoever.

Maxwell seems to have been greatly amused by these lectures of Kelvin. What a dreadful lot of arithmetic the little fellows would have to do, he reflected, in order to keep formation after they had once used their bats! After reversing the direction of motion of a molecule, a demon-plus-bat would have gained twice the momentum of the reversed molecule and would be swept right out of line. To keep in formation he must arrange for exact momentum compensation from the opposite direction!

Unlike Thomson, Maxwell does not say that the *only* purpose of the demon is to illustrate the statistical nature of the gas laws. He says, instead, that this is its *chief* purpose – which suggests that he is entertaining other ideas as indeed we have suggested.

It may, of course, seem highly absurd to suppose that Maxwell would ever have invented so crude and silly a model of creation, as if it could throw any light on how God made the universe! It is, however, typical of his genius that this is the kind of way he *did* think. He experienced great difficulty in fixing his mind on a topic on which he sought illumination, and could only do so by inventing some kind of model, however crude. No model could be more crude or far-fetched than that of space filled with rotating cylinders squeezing against one another (to correspond to lines of force of magnetic field), but prevented from rubbing by the presence of little spheres like those used in ball-races (to represent electricity) – yet it was this astonishing 'model' which led him to his greatest achievement – the prediction of wireless waves, the very velocity of which he was able to calculate correctly. He used models freely, however far-fetched, but he did not make the mistake of confusing his models with reality. When he had worked a problem out, he would let his model fall away like the scaffolding of a building.

We may think then of Maxwell's demon as in some way the model of a unit mind, making unit choices – to open or not to open his trapdoor. Given an idea, an intention, mind could accomplish its desire in the physical world – for the movement of a trapdoor requires, in principle, the expenditure of no energy. And a vast number of such minds, operating in unison, could intervene in the statistical laws of nature. In this way, perhaps, though very dimly, one could see how God might intervene in nature. But the picture was crude and Maxwell rightly left it in its whimsical, half serious form. From the nature of the case there was no concrete evidence to which appeal might be made.

But the great ideas of science, the foundations on which we build today, were often formulated by theological considerations. What then, is the importance of the demon?

Owing to his early death, preceded by the building of the Cavendish Laboratory and the editing of the MSS of Henry Cavendish at the request of the Earl of Devonshire, Chancellor of the University of Cambridge, who had financed the laboratory, there were many ideas which Maxwell had no opportunity to develop. Had he been spared, he would probably have noticed, sooner or later, what Szilard[4] pointed out in 1929. The demon, in effect, takes information and converts it into negentropy (the opposite of entropy), in such a way that there is a point-to-point correspondence between information and entropy loss. This fascinating idea, which makes it possible to apply thermodynamic principles to information, was developed later by Shannon and is the cornerstone of modern communication theory. It is evident that Maxwell laid the foundation of this important branch of knowledge which, like so much else in science, owes its origin more or less directly to theological considerations. Though the idea seemed so foolish it too, like Faraday's lines of force, has become the headstone of a corner.

[4] L. Szilard, *Zeit. f. Physik.*, 1929, **53**, 840.