Cellular Automata and the Measurement Problem

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Abstract

I argue that a macroscopic apparatus such as a measuring device has never been satisfactorily modelled in terms of microphysics. It may be unrealistic to expect to do so in terms of quantum physics, so I argue that it would be worth building such a model in a system with simplified form of physics, and that Cellular Automata provide the best place to start.

1 The Classical Measurement Problem

The measurement problem is generally thought to be a problem which arose in quantum theory. We are told that there is no problem in classical physics, measurements can in principle be done exactly and will have a definite result. But was there ever a theory of classical physics in which a measuring device could be represented? If the quantity being measured is small then there will need to be amplification to move some sort of pointer which will be visible. However, once the pointer starts moving what it going to stop it? There needs to be damping, which means the energy has to go somewhere - a heat bath. This leads to the realm of thermodynamics.

At the end of the nineteenth century, the status of thermodynamics was uncertain. Statistical thermodynamics explained bulk thermodynamics - in particular the 2nd law - in terms of the motion of atoms. Not everyone was convinced though. Some people thought of the 2nd law as a fundamental law rather than just highly probable. Some didn't even believe in atoms, although it's hard to see how the conversion of the energy of a moving object into an increase in temperature could be explained in a world of continuous physics. But even if we accept that matter is made of atoms and that thermodynamics is based on statistics, there is still a problem with modelling a measurement device. A measurement device needs solid parts, so you need to explain how atoms join together to form a solid. You might hope that forces between particles would be such that they would stick together in the right way, but there are problems with this. Earnshaw's theorem says that charged particles can't possibly join together in a stable object, and it seems unlikely that any other classical force law would do any better.

In summary, at the end of the 19th Century, classical physics was far from being a complete theory. Those who claimed that there was little left to do seem to me to be in a state of denial rather than accurately describing the way things were. Something like quantum theory was going to be necessary to sort out the inconsistencies in classical physics, not simply to explain new results.

2 Quantum Theory

We are sometimes told that in quantum theory that it is possible to do the calculations, it is the interpretation that is a problem. If this were true then its hard to see why it should be any different from earlier physical theories, for instance Newtonian gravity. When Newton introduced this there was plenty of resistance to a mathematical theory which didn't have any underlying mechanical model to explain it. There seems to be a wish to explain the equations in terms of 'intuitive' behaviour, i.e. explaining microphysics in a way familiar from the macroscopic world. I don't share this wish. The

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trouble is that we then want to explain the macroscopic world based on microphysics, which seems to me to be more of case of circular reasoning than a satisfactory way of understanding the world. The success of Newtonian physics in modelling what goes on in the world gradually made the search for an underlying mechanism seem less important. Should we expect the same for quantum theory?

No. The trouble is that 'shut up and calculate' isn't as practical as it is claimed to be. We can calculate the properties of single particles with great accuracy [1] But when it comes to macroscopic objects it's a different story. Quantum theory avoid the instabilities of classical physics, but proving this - that macroscopic collections of atoms have a ground state and don't just collapse together - has taken years of effort by some of the best theorists [2]. Going further and modelling a measurement device sufficiently well to understand what is going on just isn't practicable with current methods. While quantum theory can talk in general terms about the behaviour of macroscopic objects, there is always the worry that important features of the transition from microscopic to macroscopic are being missed.

2.1 Lasers

The operation of a laser seems reasonably straightforward. A molecule in an excited state emits a photon, which then stimulates the emission of a photon from another molecule in an excited state, and so on. Thus a large number of coherent photons are produced. That's all very well, but having all of those atoms in an excited state is rather strange thermodynamically - there needs to be an external system maintaining this situation. But the thermodynamic worries are minor compared with the quantum worries. When the principle of stimulated emission was first suggested, it was thought that it was forbidden by the laws of quantum mechanics. Lasers were invented anyway, to the great surprise of some. John von Neumann said 'That can't be right' and Niels Bohr 'But that is not possible' [3]. But lasers worked, so it seemed that amplification via stimulated emission was fine after all. However, in [4]Nick Herbert described how lasers could be used to build a device which exhibited superluminal communication. Something was clearly not right, and it was found that the device didn't obey the laws of quantum mechanics, in a result which became known as the no-cloning theorem[5]

The point of all this is that the straightforward description of the operation of a laser - one photon stimulating the emission of an identical photon - is indeed forbidden by quantum theory. In the proper description it cannot be said that a particular photon has been duplicated - it requires a collection of molecules and photons.

2.2 Interpretations

As I see it the plethora of interpretations of quantum theory are an attempt to compensate for the inability to do calculations. Bohr's Copenhagen Interpretation said that measuring devices obeyed classical physics, which was not reducible to quantum physics, but as I've indicated above appealing to classical physics doesn't solve anything. The 'textbook' Copenhagen Interpretation, introduced the collapse of the wavefunction, a mysterious process which was supposedly separate from the rest of physics [6]. The Many Worlds interpretation claims to get away from problematical ideas such as observer induced collapse, but requires that your mind splits into several minds when it observes the outcome of a quantum event. I think that its time to stop worrying about what it all means, and to try to see what the calculations say. Those calculations may need to be simplified, but I think that by looking at the problem in the right way it might be possible to see aspects of the transition from microscopic to macroscopic which are currently being missed.

3 Maxwell's demon

Suppose we have a container with two compartments, each filled with gas at the same temperature. Maxwell suggested that an intelligent being could control a shutter, and let through faster than average molecules going one way and slower than average molecules going the other. Hence the temperature of one side would become greater than the other, disobeying the 2nd law of thermodynamics. Clearly if we wanted to build a device which did the work of this demon, we would need to supply energy, so the device would be a heat pump which obeys the 2nd law. But precisely where would the energy have to be supplied? At first it was thought that the observation of the molecule would necessarily take a certain amount of energy, but later results seemed to indicate that this could in fact be done with an arbitrarily small amount . The device would need to store the data - how much energy would this require? Currently it is thought that it isn't the storage of data which needs energy, it is the erasure of it afterwards. However, there is considerable disagreement about this. [7] I can't help thinking how informative it would be to model a measuring device and a data store based upon the microphysics of a system, to be able to find out where exactly energy is used by a Maxwell's demon type of device.

4 Cellular automata

The above suggests it would useful to be able to model a measuring device in some way, even if the physics is highly simplified. Cellular automata come to mind for this. These have been used to model computing devices and self reproducing devices. One thing to note, though, is that to be satisfactory for our purposes the model must have microscopic reversibility, since this plays an important part in discussions of thermodynamics. This excludes some of the best known cellular automata, such as John Conway's *Game of Life*, but there has been a significant amount of work done on cellular automata which are reversible, such as Norman Margolus's *Critters* simulation. This can show a central mass diffusing outwards, but eventually coming into equilibrium with a gas of 'Critters'. A more direct modelling of physics might be via Lattice Gas simulations. Both of these types of cellular automata have been used to model fluid flow.

To model a measuring device requires that we go beyond fluids and model the behaviour of solids, which can then be made into structures. It might be thought that it would be better to model the physics of solid bodies directly. However, this would seem to necessitate moving away from exact computations, to the approximations of real numbers. This might not seem too much of a problem, but I think that as reversibility is an important part of the model, one needs to make sure that if you model the evolution of a low entropy state to a high entropy state, then running this in reverse gets back to the low entropy state. Introducing approximations could well mean that it does not.

Note that one aim of work which has been done involving cellular automata is to show how computation can be done using the simplest of systems as a base. We do not necessarily have to follow this path, we might, for example, make the rules involve more complex calculations than is usually the case. However, one also needs to make sure that there is a limit to the possible complexity for each cell or atom. For instance we might have positions represented by rational numbers (with rules which made sure that they continued to be rational). What might happen is that the denominators became ever larger. This would cause problems in the running speed of the model, and might also call into question the results of the model - the entropy which we are trying to track might become hidden in the numbers.

4.1 The way forward

Cellular Automata thus seem to be a useful way to investigate the transition from microphysics to macrophysics, so one is led to see what work has already been done in this area. In[8]the authors investigate how digital logic can be implemented within a model of crystal growth, and suggest that their model could be extended to allow clouds of particles to represent a logical bit, and so bridge the microscopic/macroscopic divide. I think that the best way forward, however, is suggested by [9], where self-organization is modelled in a biological context, and the authors see the next step as simulating 'protocells'. In both of these cases the next step is the one which macroscopic devices arise out of microphysics. So far there does not seem to have been much progress in taking this step, so it is likely to be difficult, but I think that it is worth considerable effort, as it would provide insight into many areas of science apart from the system being modelled. It would provide insights into thermodynamics - above I mentioned Maxwell's demon and Landauer's principle, but it would also enable investigation into non-equilibrium thermodynamics including speculated principles of energy dissipation and entropy production. [10]

The insights into thermodynamics would be very valuable, but I think it would also help with our understanding of quantum theory. Although the system being modelled is not a quantum system, it might be thought of as having some of the properties of quantum systems, in that it has discrete states and energies. It will thus be interesting to see what aspects of a quantum system show up in such a model.

I therefore believe that it would be very worthwhile to model a macroscopic device, such as a measuring device, in terms of microscopic entities in a cellular automaton.

References

[1] Wikipedia, "Precision tests of qed — wikipedia, the free encyclopedia," 2012. `http://en.wikipedia.org/w/index.php?title=Precision_tests_of_QED&oldid=490162726`. [Online; accessed 23-May-2012].

[2] E. H. Lieb and R. Seiringer, *The Stability of Matter in Quantum Mechanics.* Cambridge University Press, 2009.

[3] C. H. Townes, *How the Laser Happened: Adventures of a Scientist.* Oxford University Press, USA, 2002.

[4] N. Herbert, "FLASH - A superluminal communicator based upon a new kind of quantum measurement," *Foundations of Physics* **12** (Dec., 1982) 1171–1179.

[5] W. K. Wootters and W. H. Zurek, "A single quantum cannot be cloned," *Nature* **299** (1982) 802 – 803.

[6] J. Faye, "Copenhagen interpretation of quantum mechanics," in *The Stanford Encyclopedia of Philosophy*, E. N. Zalta, ed. fall 2008 ed., 2008. `http://plato.stanford.edu/entries/qm-copenhagen/`.

[7] J. D. Norton, "Waiting for landauer," January, 2011. `http://philsci-archive.pitt.edu/8635/`.

[8] R. D'Souza, G. E. Homsy, and N. H. Margolus, "Simulating digital logic with the reversible aggregation model of crystal growth," in *New Constructions in Cellular Automata (Santa Fe Institute Studies in the Sciences of Complexity Proceedings).* Oxford University Press.

[9] T. Nozawa and T. Kondo, "Construction of Reversible Lattice Molecular Automata," *International Journal of Modern Physics C* **20** (2009) 901–929, `arXiv:0802.4365 [nlin.CG]`. `http://arxiv.org/abs/0802.4365`.

[10] Wikipedia, "Non-equilibrium thermodynamics — wikipedia, the free encyclopedia," 2012. `http://en.wikipedia.org/w/index.php?title=Non-equilibrium_thermodynamics&oldid=512264635`. [Online; accessed 22-September-2012].