Contemporary Physics, 1998, volume 39, number 5, pages 393 – 395

Essay review

Time's quantum arrow revisited

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A review of *The End of Certainty: Time, Chaos and the New Laws of Nature*. Edited by ILYA PRIGOGINE. (Simon and Schuster, 1997). Pp. ix+ 207, £20.00, (hbk). ISBN 0 684 83705 6. Scope: Monograph. Level: undergraduate and general reader.

The underlying laws of physics possess two apparently intuitive yet puzzling properties. One is that they are *deterministic*. By this we mean that, given sufficient information about an object and the objects around it, we can predict what properties it will have at some future time (or, indeed, what properties it must have had in the past in order to have reached its current state). The other property is one of *time symmetry*. Any process described by the laws of physics is just as reasonable if played backwards in time.

Why are these properties puzzling? Determinism appears to deny the possibility of free will, the freedom to choose between courses of action. Humans seem to possess free will, somehow putting them at odds with determinism. The puzzle of time symmetry is the apparent existence of a number of so-called *arrows of time*. We all experience a flow of time from past to future (a subjective arrow of time), but we can be more empirical than that. Everyone is familiar with the famous problem of mixing milk into coffee. Despite the fact that the process is just a large number of time symmetric collisions the overall effect is not time symmetric — the milk does not spontaneously unmix itself and leap back into the bottle. This is an example of the thermodynamic arrow of time, expressed in the Second Law of Thermodynamics. There are other arrows such as the cosmological arrow and they may or may not be linked to some underlying process which makes them all point the same way.

In *The End of Certainty*, the Nobel Prize-winning chemist Ilya Prigogine addresses these two problems, ties them together and claims to have solved not only the problems of determinism and time symmetry but also the quantum measurement paradox while he is at it. From the outset I have to say that the book fails to convince me. The physics within may well be correct to some extent but it is the major flaw of this book that it does not communicate that physics in some way which is persuasive or, indeed, interesting. It suffers partly from brevity. Not only does the author short-change himself, not taking the time to explain his meaning fully, but he also chooses to ignore all other work in the field. Writers are often at their most entertaining, arguing most incisively, when denouncing rival theories and it is regrettable that Prigogine does not play this game.

Prigogine is justly famous for his visionary work in non-equilibrium thermodynamics. Mostly physicists and chemists have stuck to considering systems in equilibrium or near to it. However there exist many fascinating and perplexing phenomena when one pushes a system far away from its equilibrium. Indeed there are islands of stability and order which arise from the chaos one would naively expect. A beautiful example is the Belousov – Zhabotinski chemical reaction in which the whole reaction volume oscillates between red and blue in a precisely ordered manner. Such behaviour is described in detail by Prigogine in *From Being to Becoming* and it leads him to describe equilibrium matter as 'blind', where far from equilibrium matter is 'far seeing'. A whole industry has been built up around such studies, with applications across the sciences and into economics and social sciences.

The story of *The End of Certainty* is this (with the necessary caveats when one reduces a 200 page book to a few lines): modern physics does not describe the world we see, as outlined in the first paragraphs. If we abandon classical, deterministic dynamics we can move to a different approach, one which is inherently statistical in nature, and describes the world in terms of probability distributions. These reduce to classical trajectories in most cases. However, when one deals with *persistent* events the reduction is not possible for mathematical reasons. Prigogine claims that irreversibility arises naturally in this description and gives some examples. In *persistent* rather than *transient* processes there is a build up towards an arrow of time. In fact there are two solutions and the author takes Nature to be the sub-group of processes proceeding

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0010-7514/98 $12.00

'forwards'. If this same approach is applied to quantum mechanics the same result is obtained and it is not necessary to invoke a collapse of the wavefunction or any other irreversible add-on to link the observed world to the quantum description.

If all that sounds like a heavy load for 200 pages, I am afraid you are right. I will work through the book chapter by chapter to lighten the load a little, and to put my criticisms in context.

In the introduction the concept of the thermodynamic arrow of time is introduced. The author immediately assumes that it is due to asymmetry in the underlying physics, a view not universally supported (see, for example, Huw Price's *Time's Arrow and Archimedes' Point*). He points out that the Universe is clearly coherent and suggests that this is due to the self-organization properties of far from equilibrium systems. We are introduced to quantum mechanics as a deterministic system. That may seem odd but it is a very important point that the wavefunction description of physics *is* perfectly deterministic — the Schrödinger equation acts just like classical equations in determining the time evolution of the wavefunction. Non-determinism is essentially added on to quantum mechanics when people talk about collapse of the wavefunction for example. This is only really a problem if you follow the Copenhagen Interpretation or something akin to it. Many-worlds descriptions, for example, can remain deterministic but this alternative is ignored presumably for reasons of space.

Prigogine's approach, to attack the added assumption of collapse, is laudable. In *About Time* Paul Davies quotes David Bohm as saying 'In my opinion progress in science is usually made by *dropping* assumptions' and physicists have longed for a way to drop any assumption about quantum measurements.

In chapter one we get an introduction to the problems of irreversibility starting from the ancient Greeks and taking us through Descartes and Spinoza to Einstein. We get a brief tour of Boltzmann's probabilistic description of gases and the way physicists in the 20th century have tried to ignore or deal with the problem. But, as the author asserts, 'Irreversible processes...are as real as reversible processes described by the fundamental laws of physics; they do not correspond to approximations added to the basic laws'. This part is classic Prigogine and will appeal strongly to fans of *Order Out of Chaos* and his other more philosophical works. Deep intellectual problems are explained clearly and put neatly into a historical perspective, leaving the reader feeling quite the expert. However, even here the reader is railroaded into the author's view and no concession is made to the wider field of philosophy surrounding quantum mechanics and time reversal.

Unfortunately this clarity and precision do not seem to carry over into his descriptions of physical phenomena. For example, the author presents a case of order arising from irreversibility in terms of thermal gradients. The system is poorly explained and I was unable at first to follow the argument. Such problems break the narrative flow and weaken one's sense of having grasped a difficult issue.

The second half of this chapter suffers largely from a failure to identify the level of the intended audience. The publisher's blurb claims it is for the general reader. Frankly the general reader will be lost before the end of this chapter. What level of readership will not bat an eyelid at the mention of complex conjugates, yet needs resonance explaining to them? Incidentally the description of resonance is flawed. The author claims that if a mass on a spring is driven at its fundamental frequency *or at multiples or sub-multiples of that frequency* it will respond strongly. A mass on a spring has a single resonance and will only respond strongly at that frequency. There are ways to drive it at fractions of its natural frequency (by giving it a brief impulse at the end of a cycle, like pushing a child on a swing) but this is not the same set-up as the author describes. Presumably Prigogine was thinking of systems which do possess multiple resonant frequencies, such as the strings of a violin. Alas his poorly chosen and explained example adds confusion rather than clarity. This is meant to introduce us to the idea of Poincaré resonances which are a keystone in the book. Poincaré resonances mean that even elementary classical systems can defy calculation and simple trajectories diverge. In a sense certainty ended a hundred years ago when Poincaré showed that even the three-body problem was non-integrable.

In chapter two we find a description of entropy and one of the most satisfying aspects of the book, a discussion of systems far from equilibrium. This is brief, but the point that systems can evolve spontaneously to greater complexity is surprising yet very important. Indeed, vitally important according to Prigogine as it appears to underlie our very existence! As systems are driven away from equilibrium they reach forks, where two or more paths are possible. The path they follow is essentially random, governed by fluctuations and thus is born chaos. Unfortunately the author uses the term random to describe this where earlier he has told us that chaos is deterministic. Random is a loaded word, and when discussing Second Law puzzles one really has to be clear what one means by it. Prigogine never does make his usage clear alas. The physics of this chapter is not closely related to that of the rest of the book, but is included to give us a feel for how the author developed his ideas about science.

Chapters three and four are really the meat of the book, wherein lies the claim that a probabilistic description of dynamics is fundamentally different from a trajectory-based description. Again the methods and the maths are weakly explained. Terms such as the Perron–Frobenius Operator, apparently crucial to his argument, appear from the magician's sleeve and the reader is left either to accept it or to go away and read numerous technical references. We then get into the mathematical description at the core of this work. Prigogine demonstrates that a process known as the Bernoulli map leads to a simple description in statistical terms, but not for any single trajectory which behaves chaotically. He discusses operators and the space in which they act, and shows that we need to move beyond Hilbert space, the standard range of simple well-behaved functions which physicists usually use, in order to understand this statistical simplicity.

The Bernoulli map leads to solutions which show a time asymmetry (they are damped, like an oscillating spring). However, the original function which generated all this discussion is itself time asymmetric which seems to make the whole argument invalid. Prigogine himself picks up this point and takes us through another example using the baker map which is time symmetric. I am drawn to ask the question of why we did not start with the baker map. Still, the same results are obtained and we find a system which apparently can distinguish its future from its past despite being based on a purely symmetrical mathematical law. Prigogine describes it as being composed of two semi-groups, one which converges towards the future, the other divergent as it heads towards the past. From these he selects the future oriented dynamical group as being the one we experience.

I have difficulties with his argument. Firstly the situation he describes does not lead to any kind of time paradox. The baker transformation splits a group into two sub-groups which define an arrow of time *when one arbitrarily disposes of one sub-group*. This is hardly surprising. Secondly the claim is that the underlying process has no inbuilt time direction. The author describes the process as transforming a square by 'First we flatten a square...then we cut it in half and build a new square'. That seems to have a very definite time sequence built into it, as the words 'first' and 'then' indicate.

Finally, the role of chaos in these processes is introduced. Once again I find the book deeply unsatisfactory at this stage. It seems as though the direction of time arises through our access to limited information, an inability to define a state perfectly. This is very similar to an argument the author dismisses earlier in the book but the difference is not addressed at all and the reader can only be left to wonder.

By chapter 5 the explanations are getting fewer and the metaphors broader. The argument is now extended to integrable Large Poincaré Systems and it is shown that we need to consider special cases for persistent interactions. Poincaré resonances make their return and it is asserted that they couple correlations in some unspecified way to break time symmetry in a manner which is not even hinted at. This is the pattern for the rest of the book alas, making it impossible to judge the validity. Naturally some of the arguments are bound to be too complex to include in a general text but it would have been nice to have had some kind of explanation of what the author was claiming.

There is, however, within this chapter a very neat discussion about complex eigenvalues and the reduction of statistical descriptions to single trajectory descriptions. Essentially in trying to make that reduction we are forced outside Hilbert space under certain conditions (because we end up having to deal with ill-behaved functions such as the Dirac-delta function). The argument is brief and well-presented but more mathematical than the general reader would enjoy.

The unification of quantum mechanics and thermodynamics is the topic for chapter 6. Here Prigogine claims that it is necessary to move to a description in terms of real probabilities rather than probability amplitudes (the wavefunction of traditional quantum mechanics). Again, without demonstration, we are told that this leads to a solution of the problem of how time-independent states can change (such as when an atom emits a photon). Finally we have a glimpse of something we can grasp. Prigogine tells us that this approach makes predictions about the shape of spectral lines but, like Tantalus' fruit, this is whisked away before we can satisfy ourselves with it. The first question which leaps to mind is how Prigogine's system allows for quantum interference and other probability amplitude effects. Such technical matters are, presumably, assumed to be beyond the grasp of the readership and so are ignored entirely.

The last three chapters are more discursive and philosophical. Often it is difficult to tell metaphor from physics. Does the author really mean that time is experienced differently for a chemical reaction which is speeded up by a catalyst? Only in a metaphorical sense, surely? The Twins Paradox is mentioned (and incorrectly, it is asserted that the travelling twin is the older) but left hanging. Similarly Hawking's imaginary time is mentioned but not put in context. Here at last, Prigogine introduces the cosmological arrow of time, but assumes that it automatically follows the thermodynamic arrow. Again this is not universally accepted. And there is a further error — typographical no doubt — in the definition of the Planck length, but such errors as I *can* spot always leave me wondering what I missed in the parts I am less familiar with.

The author closes with the claim that he has trod the narrow path between a deterministic world, void of free will and that of an incomprehensible, dice-playing God. Also we are meant to have been shown the role of human creativity in science. I am left cold by it however. For an overview of time's arrow the reader is much better off with Paul Davies' *About Time*. For a deeper more philosophical book I would choose Huw Price's *Time's Arrow and Archimedes' Point*. *The End of Certainty* failed to interest me in the problem and failed to justify the rather grand claims made by the publisher.