SCIENCE

What is going on under the bonnet?

Werner Heisenberg, and new answers to old quantum riddles

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HELGOLAND
CARLO ROVELLI
Translated by Erica Segre and Simon Carnell
208pp. Allen Lane. £20.

Len Cariou, left, as Niels Bohr, Mariette Hartley as Margrethe Bohr and Hank Stratton as Werner Heisenberg in Michael Frayn's "Copenhagen", Los Angeles, 2001

In the early 1910s, the Danish physicist Niels Bohr realized that classical mechanics – the physics that had been accepted since Newton – couldn't explain the stability of the atom. According to classical mechanics, an electron in orbit around an atomic nucleus should emit electromagnetic radiation continuously. The resulting loss of energy would cause the electron to spiral into the nucleus. Bohr proposed in its place a model according to which electrons are restricted to certain fixed orbits. Electrons could jump between the orbits, absorbing or emitting light as they did so in packets of a fixed quantity, but otherwise they were stuck in their orbits.

Bohr's model made some correct predictions, but the behaviour it imputed to electrons was a radical departure from the smooth continuity of classical motion. Nobody understood why electrons could only occupy their fixed orbits or what force induced the jumps. Bohr gathered around him the best young people he could find and charged them with the task of unlocking the mysteries hidden inside the atom. One of these investigators was Werner Heisenberg, who in 1925 travelled to Helgoland – a barren island in the North Sea – to think through this difficult problem while escaping his allergies. The equations he wrote down there would serve as the basis for quantum theory as we have it today.

The equations didn't look the way people expected physical equations to look. They employed different mathematics and, instead of describing the actual movements of electrons, they allowed one to calculate only the measurable light emitted when an electron leapt from one orbit to another. But they worked. They passed from hand to hand in letters among the small circle of people working on the mysteries of the atom in Copenhagen – Bohr, Wolfgang Pauli, Max Born – and from there on to Albert Einstein, Paul Dirac and others.

The names have become mythologized, and the events ossified by history, but Carlo Rovelli, in his new book, strips all that away, revealing what he calls "the beating heart of scientific thinking": uncertainty, audacity, the courage to undo the acquired convictions of past centuries on the strength of tiny hints from nature. He puts fragile humanity at the centre of the story: Erwin Schrödinger's retreat with one of his mistresses to a mountain cabin, where he developed the ideas that led to his wave mechanics; his bickering with Heisenberg; Bohr's playing the father figure to the squabbling brood of young Turks. The whole thing is so freshly told, with such strange human titbits surrounding these figures, that it seems almost new. Schrödinger for example, emerges as especially surprising: Rovelli tells us that the lifestyle of the bespectacled German, who lived openly with his wife and pregnant lover, proved too eccentric for the conservative halls of Oxford and Princeton. Eventually, after having been dismissed from his post at the University of Graz for "political unreliability", he moved to Dublin in search of a more liberal environment, which he proceeded to scandalize by fathering children with two of his students.

The decades since Heisenberg wrote down his equations on Helgoland have done nothing to blunt the mysteries they introduce. Attention from physicists and philosophers over the ensuing decades has brought them into increasingly sharp focus. Although experts will find a great deal of interest here, Rovelli speaks most directly to the uninitiated, and the book can be easily understood without any technical background. The language, as translated by Erica Segre and Simon Carnell, is rich and unabashedly suggestive. The central principles of quantum mechanics, the rival frameworks of Heisenberg and Schrödinger, and even the rather subtle notion of non-commutativity are introduced with only the tiniest whisper of mathematics.

In quantum mechanics, as interpreted by Heisenberg and Bohr, it is when we probe the world that it manifests itself with a certain level of probability in a certain way – depending on the manner of the investigation. These probes are laboratory interactions where one puts a quantum mechanical system – an electron, a stream of photons – in interaction with a measuring device that produces some observable result. There is no account of what the properties of the world are that is independent of our probes, and no account of what happens in the limbo between measurements. There has been an immense struggle particularly over the past half century to provide an explicit account of what is "actually" going on under the bonnet to produce the observed behaviour. A number of alternatives have been developed but none has achieved consensus and the field is in acknowledged disarray.

Instead of advocating for the kind of realism that tries to fill in the spaces between measurements, Rovelli goes rather radically in the other direction. What quantum theory describes, he argues, is the way in which one part of nature manifests itself to any other. In his view, objects have no intrinsic properties. They have probabilistic dispositions to manifest themselves in various ways to other objects. The way that an object manifests itself to me may be different from the way it manifests itself to you. Objects have properties only in the context of interactions and only in relation to the objects they are interacting with.

> **"Perversity is inherent in quantum mechanics**

In practical terms, this means that the conclusions that you can normally draw from making an observation (that there is an apple in front of you, that the cat you can see is asleep) are no longer valid. You can infer what you would see if you looked again and what you can expect to hear if you asked someone else what they are seeing, but these are all expectations about what you will see and hear yourself, not facts about what things are really like in themselves, or from another system's perspective. There is no possibility of leaping outside one's own perspective for an independent account of what there *is*.

In classical physics and in good common sense, the bottom layer of reality is constituted by material objects with their own intrinsic repertoire of properties, arranged in space. These things together determine the network of relations among objects, and each object has a point of view determined by its place in the network. It is, however, the objects and their properties that unite all the various points of view and make them views of a single world. In Rovelli's quantum mechanics, there are relations, but no absolute account of independent entities with intrinsic properties behind these relations.

One way of understanding this is to see Rovelli as taking an idea from Ernst Mach – one of the great empiricists of the nineteenth century – and radicalizing it. Mach held that science was really about finding a framework for the most economical way of organizing phenomena. For Mach, the concrete objects of the classical world were themselves only nodes in a network of relations, nodes that – according to Rovelli, in a quantum setting – no longer have intrinsic properties of their own, but which play the organizing role of co-ordinating different perspectives with one another. This upends the ordinary way of thinking and involves a deep and thorough rejection of the common-sense categories for understanding the world. Rovelli is clear in his view that those categories have no authority except as convenient encodings of regularities.

You may wonder whether this counts as realism. It isn't the kind of reticent empiricism that refuses to give an explicit account of what the world is like. Rovelli argues that the quantum conception breaks down the deepest of philosophical dichotomies: mind and matter. Reviving some ideas of the Russian polymath Alexander Bogdanov (1873–1929), Rovelli tells us that sensations are not private mental events, but the elementary phenomena whose relations to one another are systematized in a physical theory. Scientific knowledge is nothing other than collectively organized experience. When the classical organization is made quantum-mechanical, the result is the dizzying vision of mirrors mirroring mirrors: mirrors all the way down. Rovelli reaches into the eastern tradition where he sees this view most fully articulated by the Buddhist philosopher Nagarjuna.

It would be easy to worry here that Rovelli's view is not just subtle, but perverse. However, the perversity is not Rovelli's. The perversity is inherent in quantum mechanics. Attempting to maintain a view that doesn't embrace it (which many have tried to do) is like seeing shapes drawn in the stars. Instead of looking at the intrinsic organization of the stars themselves, one fills in a lot of stuff that nobody can really see to make it look like a more familiar object.

Time will tell whether Rovelli's view is the right way of understanding the world according to quantum mechanics. As physics, it will stand or fall depending on how well it explains the full range of quantum phenomena. Our philosophical scruples – our presuppositions about what is intelligible or not – will ultimately have to accommodate what the physics says. One of the things that is so philosophically fruitful about letting physics guide our understanding of the world is that it pushes the imagination beyond the parochial boundaries discovered in the armchair. Rovelli's is a new vision, one with a remarkable power in delivering new answers to old quantum riddles, and it is conveyed lucidly in this original and graceful book. ■

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