The Transactional Interpretation of Quantum Mechanics, by Ruth Kastner. Cambridge University Press, 2013, 224 pages.

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What does it mean to say that an event is physically possible? One might say, in the spirit of everyday usage, that an event is physically possible if its occurrence is consistent with the laws of physics. But which laws of physics, starting from when? Here things get tricky. In a Laplacian universe governed by the fully-deterministic laws of classical electrodynamics and mechanics, exactly one future is consistent with any complete and precise specification of initial conditions. Given an incomplete, imprecise specification — the best that human observers can achieve, even in principle — many futures may appear to be physically possible, but only one of them actually is. In this kind of universe, our intuitive notion that many different outcomes of an experiment, for example, are physically possible is just an ignorance-driven delusion.

Philosopher of physics Ruth Kastner's new book, *The Transactional Interpretation of Quantum Mechanics*, subtitled *The Reality of Possibility*, takes on this question of the meaning of physical possibility in the theoretical context defined by relativistic quantum field theory. Lest this seem daunting, be assured that this is a philosophical book; aside from Chapters 5 and 6 dealing with technical objections, it emphasizes ontological questions and employs the physics — all of which is clearly presented for the non-expert — as a way to raise them. The ontological questions that it raises, not just 'what is possibility?' but also 'what is actuality?' and 'what are space and time?' underlie not just physics but any theory of action. The *Transactional Interpretation of Quantum Mechanics* is, therefore, not just about the interpretation of quantum mechanics; it is about how 'nature makes its choice' in any circumstance, and how 'the actual arises from the potential' (205) as a result.

After briefly introducing quantum theory and its various interpretations in Chapter 1, Kastner addresses, in Chapter 2, the essential preliminary question of what is to count as an acceptable scientific explanation. The divide between realists and instrumentalists about quantum theory — or between 'ontic' and 'non-ontic' approaches to its physical interpretation — turns on this basic question. Kastner comes down explicitly on the side of Einstein, Bohm, Everett, Bell and other realists: she adopts as a 'maxim' that 'mathematical operations of a theory which are necessary to obtain correspondence of the theory with observation merit a specific (exact) ontological interpretation' (37). With this, she rejects the notion that quantum theory is just about what we can know, a position associated historically with Bohr and Heisenberg and advocated more recently by Peres, Bub, Fuchs, Spekkens and others. While Kastner might be criticized for treating Bohr as too straightforwardly Kantian — she characterizes him as 'pre-emptively denying that the formalism could be referring to anything physically real' (32) and ignores the subtleties of his views on complementarity — she takes more time with Heisenberg, presenting him as a visionary looking toward 'a new kind of metaphysical reality' (36). Indeed, Kastner characterizes her own goal as picking up where Heisenberg left off in his late-career philosophical writings.

Chapters 3, 4, 7 and 8 constitute the heart of the book; as noted earlier, Chapters 5 and 6 are technical digressions and can almost be treated as extended footnotes. Here Kastner introduces (Chapter 3), considerably extends (Chapter 4), and explores the ontological consequences of (Chapters 7 and 8) John Cramer's 'transactional' interpretation of quantum mechanics. Like Hugh Everett's 'relative state' interpretation — known following its reformulation by Bryce DeWitt as the 'many-worlds' interpretation — the transactional interpretation is based not on philosophical presuppositions but on a close and literal reading of the mathematical formalism. It begins by noting that quantum theory, like classical electrodynamics, is time-symmetric. Schrödinger's wave equation can, therefore, be written in two versions, one describing a wave — a quantum state — propagating forward in time, and the other describing a quantum state propagating backward in time. When forward- and backward-propagating quantum states overlap in phase — peak-to-peak and trough-to-trough — they reinforce each other in the same way that light, sound, or even ocean waves do. Cramer called such an overlap a 'transaction' between the forward- and backward-propagating waves, and proposed that such transactions, not quantum states themselves, are what can be measured as spots on a photographic film or clicks of a Geiger counter. In Cramer's picture, radioactive sources or hot filaments are 'emitters' of forward-propagating or 'offer' waves, while photographic films or Geiger counters are 'absorbers' that generate backward-propagating or 'confirmation' waves. A general-purpose absorber like a Geiger counter generates confirmation waves for all of the events it can detect; the offer waves that are actually encountered determine what events are actually detected.

As Kastner emphasizes, the transactional interpretation replaces the observer-induced 'collapse of the wavefunction' posited by the Copenhagen interpretation with a purely physical process. It therefore offers the philosophically-attractive possibility of a fully observer-independent and therefore objective quantum theory, in which determinate 'classical' outcomes are not the result of someone looking, but simply the result of Nature going about her business. It does so, moreover, in a way that explains the mathematical structure of the Born rule, the rule for calculating the probabilities of different outcomes for a defined measurement of a defined quantum state. As the Born rule must be assumed as an axiom in Copenhagen quantum theory, this is a substantial conceptual advance. Just as importantly for Kastner, treating absorption as a '*real physical process*' (55, emphasis in original) allows events — i.e. transactions — in which a quantum state is absorbed to be treated as unambiguously actual. It thus allows the transactional interpretation to be fully realist about the classical world of ordinary experience. Being fully realist about both quantum and classical worlds is the Holy Grail sought by Einstein, Bohm and Bell. Standard interpretations of quantum theory fall well short of this goal, and hence face — whether they admit it or not — a stark choice of viewing either the classical or the quantum world as essentially illusory.[1]

The obvious question raised by the transactional interpretation is whether it is too good to be true. Demonstrating that it is not requires explaining what 'emission' and 'absorption' of quantum states amount to, and hence what the transition from 'possibility' to 'actuality' really is. To do this, Kastner moves from the language of ordi-

[1] Landsman, N. P. 2007. Between classical and quantum. In *Handbook of the Philosophy of Science: Philosophy of Physics*, ed. by J. Butterfield and J. Earman, 417-553. Elsevier.

nary, nonrelativistic quantum theory to that of relativistic quantum field theory. Here 'emission' and 'absorption' become the actions of creation and destruction operators on a quantum field, the field corresponding to the quantum states of interest. This is a bold move: quantum field theory is generally thought of as a theory of elementary entities such as electrons or quarks, not as a general approach to quantum states. By glossing emission and absorption as field-theoretic creation and destruction, Kastner is implicitly proposing that every quantum state can be viewed as a field excitation, and hence that every collection of degrees of freedom amenable to quantum-theoretic description can be considered as a quantum field. Just how bold this identification is becomes clear in the discussion surrounding Figure 4.1, which shows a man observing a table. Kastner's caption reads: 'Macroscopic objects are perceived via transactions between offer waves emitted by components of the object and confirmations generated by absorbers in our sense organs' (71). What 'components'? The surrounding discussion suggests that the 'components' are atoms. Is Kastner referring to creation and destruction operators for generic quantum states of electrons, or is she suggesting that there are specific quantum fields for carbon, oxygen, iron and so forth? Or are the relevant 'components' themselves macroscopic? Is Kastner suggesting that there are quantum fields for tabletops?

The answer to these questions does not come until almost 100 pages later, and is developed in Kantian terms. The observer's experience of the table as a macroscopic object, and hence the intersubjectively-confirmable existence of an 'empirical world' is taken for granted. As a realist, Kastner must postulate something external to the observer — an 'object in itself' — that generates the experience. This entity is defined by contrast to the 'empirical' object: 'the 'object in itself' is precisely *that aspect of the real object which is not perceived*' (162, emphasis in original). Kastner continues: 'the 'object in itself' can be considered to be the offer wave(s) giving rise to possible transactions establishing the appearances of the object'; such objects 'do not live in spacetime and can be considered a kind of abstract but physically potent information' (162). The answer, then, is that the quantum field in question is a quantum field of information, information that observers experience as a table. This idea that quantum theory is at bottom a theory of information has become commonplace in the past decade, but is advocated primarily by instrumentalists, not realists. Kastner generally avoids the 'quantum information' vocabulary in *The Transactional Interpretation of Quantum Mechanics*, possibly to avoid its typically instrumentalist connotations. She therefore misses what would seem to be an obvious inference: if offer waves are a kind of physically potent information, confirmation waves must be a kind of physically potent information, too. Confirmation waves, however, originate in the observer; if they are physically potent information, they are physically potent information that the observer brings to the table. Kastner treats observers in the standard Einsteinian way, simply as points of view on a physical situation. The potential consequences of an observer contributing physically potent information to an observation are never explored.

What Kastner does explore, in Chapters 7 and 8, is the idea that offer waves — and hence confirmation waves also — do not 'live' in spacetime. It is this idea that principally distinguishes her 'possibilist' extension of the transactional interpretation from Cramer's original. From a purely formal perspective, this is obvious: quantum states have always 'lived' in Hilbert space, not in spacetime. From a physical perspective, however, explicitly banishing quantum states from spacetime is refreshing; the confusion of entanglement with faster-than-light communication, for example, is only a confusion if an entangled quantum state is imagined to be localized in spacetime. As Kastner points out, banishing quantum states — in the form of offer and confirmation waves — from spacetime immediately banishes 'particles' as well. If an electron, for example, is a 'quantum' particle, it cannot be localized; this is the fundamental lesson of quantum field theory. Banishing quantum states from spacetime also banishes causality; Kastner agrees with Hume and Russell that 'causality is *not* an ontological feature of the world' (166, emphasis in original). It is just an inference from the high probabilities of certain transactions.

Where then does spacetime come from? The standard position in quantum theory is a kind of embarrassed silence; position and hence spatial location is a quantum-theoretic observable, whereas time is not. Kastner's position on this question, outlined in Chapter 8, is both interesting and problematic. She starts with the idea of an observer — again, an Einsteinian point of view — for whom 'the past' is the backward-facing light cone. This past is populated by empirical observations: actualized transactions. The future, however, is not actualized; it is filled, to revert briefly to Cramer's original conception, with offer waves that have not yet arrived. Kastner calls this 'space' of unactualized possibilities 'prespacetime'; as a container for quantum states, it has the properties of Hilbert space. What connects prespacetime to spacetime is what happens at the instant that defines the present: absorption, and hence the actualization of some transaction. Kastner presents this idea with an analogy: the spacetime past is like a knitted fabric that '*continually falls away from us*' (176, emphasis in original), i.e. from our intersubjective and hence approximate present.

The idea that empirical, spacetime-bound reality is created out of a prespacetime of physically-real possibilities by a physical process of absorption allows Kastner to tackle philosophical riddles from the origin of time to the possibility of free will. In doing so, however, Kastner sidesteps the issue that has been lurking in the background since Figure 4.1: why a table? How does the physical process of absorption assign collective properties — or classical, collective degrees of freedom like center-of-mass position — to zillions of elementary emitters? Or are the zillions of elementary emitters somehow pre-organized into macroscopic collectives like tables? Where, in other words, does classical information, the kind that can be written down in laboratory notebooks, come from? In particular, where does classical information about gross, macroscopic properties — the mass of the Earth, for example, or the 3-dimensional structure of your laptop computer — come from? Saying that this information is generated by the same process that generates space and time is helpful and possibly correct, but it is not enough. What is most perplexing about the story of Schrödinger's cat, after all, is not how the cat's quantum state collapsed, but how Schrödinger could ever have found his cat, let alone confined it to a box, before its state collapsed.

The only answer to this question seems to be spontaneous symmetry breaking, the inscrutable stochastic process that determines, in Kastner's often-repeated example, why the 24-pointed splash of a droplet of milk is oriented this way or that way with respect to a coordinate system in the plane of the splash. Spontaneous symmetry breaking is commonly evoked in association with the big bang — or these days, in association with inflation — but there is a long explanatory road to travel between the big bang and the existence of macroscopic entities like cats or tables. The usual story told along this road is evolutionary, but getting this story going requires classical information, in particular, classical information about entities that maintain their identities through time. Quantum theory does not provide us with this information, and the extension to relativistic quantum field theory does not help in this regard.

Kastner closes *The Transactional Interpretation of Quantum Mechanics* with a diagnosis: 'it is the omission of the back-reaction (i.e. absorption) which gives rise to the notorious intractability of the measurement problem' (204, parenthetical added). This is surely true: there are no detection events until whatever is being detected interacts with whatever is doing the detecting, and as Newton told us, interactions go both ways. Characterizing the back-reaction of the absorber, however, requires characterizing the absorber itself. It is this question — what is the absorber, or more poetically, what is the observer — that lies at the heart of the measurement problem. Despite over 80 years of effort, interpretations of quantum theory have yet to answer it.

The main virtue of a philosophical book, however, is to raise questions, not to answer them. *The Transactional Interpretation of Quantum Mechanics* raises many questions, and raises them forcefully and well. Anyone interested in the thorny questions of possibility and actuality will find it intriguing, and with some study, perhaps inspiring.

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