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Olimpia Lombardi, Sebastian Fortin, Federico Holik and Cristian López, eds. 2017. *What is Quantum Information?* Cambridge/New York: Cambridge University Press.

One does not face too much trouble in defining *quantum information* as a field: It is the study of how quantum physics pertains to, and indeed transforms, issues of communication and computation. It came into its own in 1993, with the proposal of the "quantum teleportation" protocol, though it had predecessors in the work of pioneers like John Archibald Wheeler and Alexander Holevo. The title of this compilation raises the question "What is quantum information?" in a different sense, asking instead what kind of entity the basic subject of that field might be. Is "quantum information" a sort of fluid, a newer and more subtle phlogiston, in danger of flowing into a black hole like spoiled soup down the garbage disposal? Or, is it a more personal possession, tied to a specific agent the way that a Bayesian probability belongs to the individual gambler who asserts it? Many answers to this question have been declaimed, and the variations are hard enough to tally, let alone choose among. Like with so many debates in the region where quantum mechanics shades into philosophy, this one exemplifies the old problem: You put two rabbis into a room, you get out three opinions. The essays in this volume stake out a variety of answers, seldom if ever with enough force to compel assent, but often with sufficient clarity to confirm that the points being raised are indeed worth time, attention and professional respect.

I have more than one physicist friend whose response to the inquiry "What do you think about the philosophy of physics?" is, essentially, "I think it would be a good idea." They do think that physics can now and then bear on Big Questions, and that the sort of work philosophers do should by rights inform how we physicists conduct ourselves. Philosophy, they feel, should suggest new problems, reveal connections between problems already known, help us minimize confusion when we teach physics to the next generation—and yet the interesting conversations, on these fronts and more, seem to happen with frustrating rarity. (Part of the trouble may be that we tend to hear about philosophers the most when they have behaved badly.) And yet, sooner or later we need those conversations: "Shut up and calculate!" is not a stable position. Even the most ascetic claim—the assertion to shut up and calculate with one mathematical formalism rather than another—is in some way a claim about the character of the world. Perhaps bound up with historical happenstance and social convention, but a claim about Nature nonetheless: Were the world a different way, would we not, after we shut up, calculate in a different fashion?

A good example of cutting through the general confusion is the chapter by Adán Cabello. His taxonomy of the "interpretations of quantum mechanics" could doubtless be refined—for example, both "Copenhagen" and "Many Worlds" are more like genera than species—but it is already quite helpful in putting one's finger on the main divisions of thought and temperament. Other selections in the book which particularly stood out for me include the following:

The chapter by David Wallace is also commendable, attaining that pleasant level where, even when the reader disagrees with a remark, the system of thought from which that remark arises is transparent. Likewise, while the chapter by Sebastian Fortin and Olimpia Lombardi may be more closely wedded to Shannon's original context for information theory than most physicists care to be—I can easily see one grumbling, "We don't call it *telegram theory,* for crying out loud"—it does a solid job pointing out places where we could stand to be less sloppy. For example, I do not think their critique of the "epistemic interpretation" of information theory would dissuade an epistemicist who has devoted several sleepless nights to thinking that interpretation through ("Ah, what you call E, I call $H(D/S)$, and it is the expected number of . . ."). However, the challenges they raise are the healthy sort, which at the very least ought to help put the important matters first when teaching information theory.

I was most disappointed with the chapter by Amit Hagar. His account of subjectivist, or personalist, interpretations of probability, such as that espoused by Bruno de Finetti, is seriously garbled. In turn, this confusion cascades into his discussion of *Quantum Bayesianism,* the view that mathematical entities employed in quantum theory—particularly "quantum states"—have the same status as Bayesian probabilities. I confess myself partial to this view, and in particular to what is perhaps the most radical form of it, the *QBism* advocated by Fuchs, Mermin and Schack; so, I felt rather let down to see it challenged in such a muddled way. Hagar considers the statement "There is [a] 50% chance of rain in the DC area tomorrow." He writes, "On the subjective account of probability, this statement *can only mean* that if one would have done a random sampling of the residents of the DC area, and asked them what is their belief about the weather tomorrow, around half of the subjects would answer they believed it would rain" (emphasis added). I do not know of any school of probability whose thought this describes accurately. The de Finettian account presumes only one necessary gambler: the agent who asserts the probability value in the first place. Following the tradition of information theory, let us call this agent Alice. When Alice states, "My probability for rain in the DC area tomorrow is 50%," she is saying that she is willing to buy or to sell for fifty cents a lottery ticket worth one dollar should it rain in DC tomorrow. The formal rules of probability theory then follow from the normative requirement that Alice should not make a set of gambling commitments which open her up to a sure loss. In the jargon, one says that Alice should avoid the possibility of being "Dutch-booked" (for details, see, e.g., Jeffrey's textbook *Subjective Probability: The Real Thing*). Nothing in this account insists that Alice take a poll of commuters grumpily waiting for the Metro!

This confusion over who possesses the probabilities in the de Finettian interpretation is compounded when Hagar turns to the "Wigner's Friend" thought-experiment and attempts to use it to expose an inconsistency in Quantum-Bayesian views. I do not think that Hagar's discussion adds anything to the pages which QBists and proponents of similar interpretations have already devoted to Wigner's Friend. (For examples thereof, see respectively Fuchs' essay "Notwithstanding Bohr" and Brukner's "On the quantum measurement problem.")

An unfortunate omission is the lack of substantial discussion on the "epistriction" research program spearheaded by Spekkens. By devising theories that act as foils to quantum mechanics, resembling it in many qualitative and quantitative ways while admitting interpretation in terms of local hidden variables, this work demonstrates that not all the peculiarities of quantum theory are made equal. Some of its features, even celebrated ones like entanglement, the no-cloning theorem and "teleportation," are only *weakly nonclassical*—not nearly so enigmatic as they had first appeared. Wallace briefly mentions the original paper by Spekkens, but discusses neither the follow-ups nor the key idea of identifying which aspects of quantum theory cut to the essence of how it departs from classicality. (Since the "epistricted" theories are explicitly constructed to be examples of what Wallace terms "inferential" theories, they are much more pertinent to his argument than their glancing mention might suggest.) This work has tangible relevance to our understanding of what resources a quantum computer requires in order to outperform its classical counterparts.

On the topic of computation, the talk of "quantum parallelism" by Federico Holik and Gustavo Martín Bosyk feels rather dated. The image of a quantum computer working by "trying all the solutions in parallel" is not a very good one, as work since the turn of the century has made increasingly clear. In fact, it obscures crucial points, particularly the fact that quantum computers offer greater advantages for some computational tasks than others. (Steane's "A quantum computer needs only one universe" is a fairly approachable essay on this topic.)

Overall, *What Is Quantum Information?* is a convenient reference point for discussions in that region where physics and philosophy intermingle. However, it should not be taken as the last word in any of those conversations. The philosophers may be more accustomed to this feeling of inconclusiveness than the physicists.

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