around. Quantum models of cognition offer formal exercises that might produce impressive fits to data but, by their founding assumptions, cannot offer some of the most basic insights into the causes, effects, and relevant factors that underlie the workings of human cognition.

Jaynes (1993, p. 269) puts the physicists' epistemological dissent bluntly, saying "I am convinced, as were Einstein and Schrödinger, that the major obstacle that has prevented any real progress in our understanding of Nature since 1927, is the Copenhagen Interpretation of Quantum Theory. This theory is now 65 years old, it has long since ceased to be productive, and it is time for its retirement." It would be unfortunate if a theory ready for retirement in its professional field of physics were to enjoy a second hobbyist career in psychology.

Grounding quantum probability in psychological mechanism

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Abstract: Pothos & Busemeyer (P&B) provide a compelling case that quantum probability (QP) theory is a better match to human judgment than is classical probability (CP) theory. However, any theory (QP, CP, or other) phrased solely at the computational level runs the risk of being underconstrained. One suggestion is to ground QP accounts in mechanism, to leverage a wide range of process-level data.

Pothos & Busemeyer (P&B) make clear that quantum probability (QP) theory offers a rich array of theoretical constructs, such as superposition, entanglement, incompatibility, and interference, which can help explain human judgment. The authors illustrate how these concepts, which are strongly contrasted with the basic tenets of classical probability (CP) theory, can be used to accommodate aspects of human choice that deviate from normative CP accounts. For example, the conjunction fallacy is explained in terms of incompatible questions requiring sequential evaluation, which induces an interference effect.

Although new frameworks can provide novel insights, one worry is that QP will recapitulate some of the shortcomings of rational CP approaches by sticking to a computational-level analysis. To the authors' credit, they acknowledge how notions of optimality in CP approaches can be impoverished and not match the goals of the decision maker. However, these criticisms largely serve to question CP's status as the preferred normative account rather than question the wisdom of eschewing process-level considerations in favor of a computational-level analysis.

In a recent article with Jones (Jones & Love 2011), we, too, critiqued rational (Bayesian) CP approaches to explaining human cognition, but our critique was broader in scope. Although many of our points are particular to the rational Bayesian program (which we refer to as "Bayesian Fundamentalism"), some of the central critiques apply equally well to any approach largely formulated at the computational level. The basic issue is that such accounts wall off a tremendous amount of related data and theory in the cognitive sciences, including work in attention, executive control, embodiment, and cognitive neuroscience, as well as any study using response time measures. It seems unlikely that a complete theory of cognition or decision making can be formulated when neglecting these insights and important constraints.

The suggestion offered in Jones and Love (2011), which we referred to as "Bayesian Enlightenment," is to integrate probability and mechanistic approaches. In the context of QP, one could imagine construing operations, such as projections to subspaces, as psychological operations that unfold in time, may have brain correlates, be limited in capacity, and change over development. Such an approach would retain the distinctive characteristics of QP while linking to existing theory and data.

Grounding QP in mechanism may offer a number of other advantages, such as better motivating the assumptions (that are psychological in nature) that make QP successful. Many of the effects considered in the target article require assumptions on the order in which statements are considered and the role context plays. These topics may be addressed in a principled manner when situated within a mechanism that aims to explain shifts in focus or attention. Such mechanistic models would also make clear what role QP plays in accounting for the results, as opposed to the ancillary assumptions.

The authors note that one key challenge is to anticipate new findings rather than simply accommodate existing data. Grounding QP ideas in mechanism may facilitate making a priori predictions. Once the move to mechanism is made, second generation questions can be asked, such as which QP model best accounts for human judgment. My guess is that moving away from evaluating general frameworks to testing specific proposals will hasten progress. As the authors note, it is very difficult to invalidate an entire framework, as ancillary assumptions can always be made (e.g., CP models can be modified to account for the main findings in the target article). In contrast, particular models can be evaluated using model selection procedures.

My prediction is that moving toward evaluating particular models grounded in mechanism will lead to a rapprochement between QP and CP approaches. For a view that allows for superposition, many aspects of the QP are very rigid. For example, according to the approach advocated by the authors, statements are either compatible or incompatible. One possibility is that successful models will be more fluid and include a mixture of states, which is a notion from CP. Given the complexities of human cognition and decision making, it would be surprising if one unadulterated formalism carried the day. Although physics undergraduates may complain about how confusing QP is, human cognition will likely prove more vexing.

Cognition in Hilbert space

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Abstract: Use of quantum probability as a top-down model of cognition will be enhanced by consideration of the underlying complex-valued wave function, which allows a better account of interference effects and of the structure of learned and ad hoc question operators. Furthermore, the treatment of incompatible questions can be made more quantitative by analyzing them as non-commutative operators.

Pothos & Busemeyer (P&B) argue for the application of quantum probability (QP) theory to cognitive modeling in a function-first or top-down approach that begins with the postulation of vectors in a low-dimensional space (sect. 2.1), but consideration of the high-dimensional complex-valued wave function underlying the state vector will expand the value of QP in cognitive science. To this end, we should import two premises from quantum mechanics. The first is that the fundamental reality is the wave function. In cognitive science, this corresponds to postulating spatially distributed patterns of neural activity as the elements of the cognitive state space. Therefore, the basis vectors used in QP are basis functions for an infinite (or very high) dimensional Hilbert space. The