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What Makes an Observable? Invariance Under Quantum vs. Classical Reference Frames

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In the presence of symmetries, observables are defined as quantities that remain invariant under transformations of reference frames or coordinates. Recently, the concept of quantum reference frame (QRF) transformations has emerged, where reference frames themselves are treated as quantum systems subject to superposition and entanglement. This generalization extends the classical notion of symmetry and motivates a reconsideration of what constitutes a physically meaningful observable. While any observable invariant under classical transformations is also invariant under QRF transformations, I will show that the converse does not necessarily hold: there exist observables that are invariant under changes of QRFs but not under classical ones. What is the physical meaning of observables that are invariant only under QRF transformations? Do they reveal a deeper, genuinely relational structure of quantum theory that goes beyond the classical frame-dependent perspective?

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