The Preservation of Intrinsic Information in Quantum Physics

Yaakov Ostrover

Abstract

This article proposes that the information intrinsic to a complete subatomic state is preserved by physical processes. Information here means the physical distinctions embodied in a state, including distinctions that reside in relationships between its parts. Quantum entanglement supplies the starting point. Two joint states can differ in a measurable way even when every measurement on either constituent alone gives the same statistics. Closed-system unitarity gives the proposed principle a precise form by preserving the distinguishability of complete states. Energy conservation constrains a different feature of a process and does not by itself imply this result. The question is whether there is any fundamental process for which two distinct complete physical states have exactly the same complete physical consequence.

Information as a feature of physical existence

A physical system has a state whether or not anyone describes it. By intrinsic information I mean the distinctions embodied in that state, including its correlations with other systems. An observer can acquire evidence of those distinctions, and a mathematical description can represent them. The premise concerns the distinctions themselves. It requires neither an observer nor a separate medium in which information is stored.

This premise is independent of any choice of time coordinate. One can ask whether two physical states differ without specifying when either is realized. Preservation makes a further claim about the relation between complete states admitted by a physical process. It can be formulated as a condition on that relation without assigning a duration or a date. The premise that existence entails information supplies the subject of the conservation claim. The conservation claim supplies the additional requirement that complete physical distinctions survive the process.

Entanglement and the reality of relational information

Consider two qubits prepared in either of the Bell states $\Phi_+ = (|00\rangle + |11\rangle)/\sqrt{2}$ and $\Phi_- = (|00\rangle - |11\rangle)/\sqrt{2}$. The reduced state of each qubit is the maximally mixed state in both preparations. Even a complete set of measurements on either qubit alone gives the same statistics for the two preparations. The pair has a different property. If both qubits are measured in the X basis, the outcomes agree for Φ_+ and disagree for Φ_-. Equivalently, the joint observable $X \otimes X$ has eigenvalue $+1$ in Φ_+ and -1 in Φ_-. The measurable distinction is the relative phase of the two amplitudes [1].

The relative phase is indispensable to this difference in the correlations. If the pair is instead described by an equal incoherent mixture of $|00\rangle$ and $|11\rangle$, the two X measurements agree only half the time. The mixture retains the local statistics and the correlations in the computational basis, while losing the distinction revealed by the X measurements. This example gives precise content to the idea that information exists in a physical relationship. It also identifies what the observation establishes. The joint measurement gives evidence that the phase distinction exists in the state

being measured. To use the measurement as evidence of preservation through a particular process, one must also establish which distinction was present in the preparation and how the outcomes depend on it.

Why consider preservation universal

Entanglement makes the generalization worth taking seriously. A distinction can be absent from every local description while remaining physically consequential in the joint description. A loss inferred from the parts can therefore arise from the scope of the description. The question is whether there is a physical reason to expect a different conclusion when the description includes all the degrees of freedom involved.

Standard quantum mechanics gives a general reason for expecting preservation in its domain. Let ρ and σ denote two density operators of a closed system, and let U be the unitary operator representing a process. The trace distance, defined as half the trace norm of $\rho - \sigma$, is a measure of distinguishability. Conjugation by U preserves that distance [1]:

$$D(U\rho U\dagger, U\sigma U\dagger) = D(\rho, \sigma).$$

The result follows because unitary conjugation preserves the singular values of $\rho - \sigma$. Thus each distinction is preserved to the same degree, even for states that were only partly distinguishable to begin with. This statement is stronger than the minimal requirement that distinct complete states remain distinct. It applies to all pairs at once because the same operation acts on the complete state space. Its physical scope rests on the applicability of the closed-system unitary description.

The difference between local and complete descriptions is especially important for an open system. A quantum channel can map distinct input states to identical output states on the system being observed. The same channel can be represented by coupling the system to additional degrees of freedom and then restricting attention to the system. Within that representation, the complete description can retain the distinction. The no-hiding theorem gives a sharper result for a particular case. When a unitary implementation removes all dependence on an arbitrary input from one subsystem, the input information is recoverable from the complementary subsystem. Braunstein and Pati derived the theorem, and Samal and colleagues tested a realization using nuclear magnetic resonance [2, 3]. The experiment tested an implemented quantum process under controlled conditions. Its bearing on a universal law comes from the structure it exemplifies.

The relation to energy conservation

The proposal that information conservation belongs alongside matter and energy conservation is physically meaningful. It can be made precise by asking whether a conservation law constrains only a quantity or also constrains the full range of distinctions among physical states. These are mathematically different requirements.

Take a two-dimensional sector in which both $|0\rangle$ and $|1\rangle$ have the same energy E. The Hamiltonian restricted to this sector is E times the identity. A formal reset channel that sends every state in the sector to $|0\rangle$ preserves the energy, including its measurement distribution. It identifies $|0\rangle$ and $|1\rangle$ at the output. If the reset is implemented by swapping the system state with an ancillary system prepared in $|0\rangle$, the observed system is reset and the ancillary system carries the original distinction. In that implementation, energy conservation and information preservation both hold in

the complete description. The energy constraint alone leaves open whether the distinction is retained. The reversible implementation accounts for its retention.

The proposal, then, is that complete subatomic processes obey an information conservation principle in addition to any applicable energy conservation law. Its stronger interpretation, that both are consequences of one physical principle, remains a separate theoretical claim. A derivation would need to explain why the underlying physics preserves both energy and distinctions among complete states.

What would count against the principle

A counterexample would require two distinct, physically admissible complete states and a fundamental process that maps them to one and the same complete physical result. In an experiment on a finite apparatus, identical readings establish indistinguishability within the measurements performed. The stronger inference requires an account of the apparatus and its surroundings, including any degrees of freedom that could carry the distinction. Claims of fundamental erasure must therefore specify what counts as the complete system and why the proposed description is complete.

This also clarifies the role of an information field. The entanglement argument locates a distinction in the joint quantum state. A separate field would be a further hypothesis, with empirical content if it specified a physical coupling and a measurable effect distinct from the predictions of the joint-state description.

Conclusion

Entanglement shows why preservation deserves to be considered a general principle. A distinction can be essential to a physical phenomenon even when it cannot be found in the constituents examined separately. The full quantum state gives that distinction a physical place in the description. Unitary quantum mechanics goes further and preserves every distinction between complete states to the same degree. I propose that this feature expresses a general constraint on subatomic physics. The substantive question is whether nature admits a fundamental exception once the complete physical state is taken into account.

References

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