A fresh perspective on black hole entropy and information

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During the long history of black hole thermodynamics [1], two mysteries have persisted until the present, despite a vast number of attempted resolutions.

According to some leading experts [2], information is lost in a black hole – perhaps disappearing into the singularity or a baby universe or some other sink. According to other leading experts, the information is preserved even after the black hole has completely evaporated through Hawking radiation – e.g. in the form of gravitational memory [3].

A second issue is the origin of the entropy of a black hole, which is proportional to area rather than volume. The fact that the Hawking radiation is thermal strongly indicates that there should be a Boltzmann entropy determined by microstates associated with the gravitational field itself.

Here we address both of these issues with a theory which includes a new regularization of quantum gravity [4] and which also predicts dark matter particles with well-defined mass and couplings [5]. This description requires various kinds of topological singularities, and black holes are one variety. Even though the black hole contains a gravitational singularity, the equations of motion for all fields are completely deterministic. In the present theory, the most relevant features are that (1) a fundamental condensate density in the theory vanishes at the singularity and (2) an infinite amount of external time is required both for external matter to pass through the event horizon and for internal matter to pass into the singularity (with the proper time for the infalling matter regarded as irrelevant in this context).

In the dynamical description, therefore, no information is lost, just as in the case of an ordinary macroscopic system – for which the total Boltzmann or von Neumann entropy is constant, according to the classical or quantum Liouville theorem. In the thermodynamic description, on the other hand, information is lost when it is thrown away during the simple modeling of processes – so that the Boltzmann or von Neumann entropy (a measure of our ignorance of the microscopic state) is made to increase. Thermal emission through Hawking radiation is the thermodynamic description for a black hole, so it is not surprising that information appears to be lost.

The second issue – the origin of black hole entropy – is addressed via the Gibbons-Hawking expression for the Euclidean action of a black hole, which has the proper form to be the Bekenstein-Hawking entropy, but with no microstates originally specified. The novel feature in Ref. 4 is that its Eq. (3.29) defines the Euclidean action $\tilde{S}$ to be precisely equivalent to an entropy $S$: $\tilde{S} = S + \text{constant}$. For ordinary quantum fields, the Euclidean action is later transformed to a Lorentzian action, which then gives rise to the usual dynamics. But the gravitational action for a black hole can be left in its Euclidean version, and its precise form is fixed by the Gibbons-Hawking argument. The microstates behind this entropy are those of the fundamental system described in Ref. 4.