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PERSPECTIVE

Gibbsing spacetime: a group field theory approach to equilibrium in quantum gravity

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Abstract

The symmetries, subtle nature of observables, and lack of a preferred notion of time evolution all make defining a quantum statistical mechanics of general relativity difficult. The paper of Kotecha and Oriti takes up the challenge of building equilibrium Gibbs states in the group field theory approach to quantum gravity. Their broad perspective and the many open challenges emphasize the potential hidden in a generally covariant quantum statistical mechanics.

No matter how subtle the exact nature of the discreteness, quantum spacetime should be built on a set of enumerable quantum states. Ultimately, it is in counting these states that we expect to find an explanation for the Bekenstein–Hawking entropy and to illuminate the remarkable thermodynamic properties of black holes. But, building a statistical mechanics or thermal physics of these gravitational degrees of freedom is remarkably subtle. Challenges arise even before considering the quantum theory: what does equilibrium mean without a preferred notion of evolution leaving the equilibrium state invariant? That is, without a preferred notion of time, which is missing in general relativity. Even the character of observables, such as energy, becomes delicate in this nonlinear and generally covariant theory.

Kotecha and Oriti have taken up the challenge of understanding equilibrium in the group field theory (GFT) approach to quantum gravity in their paper [1].

Their focus is on constructing Gibbs states of this theory. They begin by providing a broad categorization of the existing methods in the literature for constructing Gibbs states. The idea of their categorization is to see the final Gibbs state as having different facets. Focusing on one of these facets can provide a construction procedure. The end result of each procedure will be a full equilibrium state containing all of the facets, but pulling them apart allows you to handle different starting points.

Their principal distinction is whether the operator $\mathcal{O}$ in the Gibbs state

$$\rho = e^{-\beta\mathcal{O}}$$

determines the state dynamically or thermodynamically. If the flow of the operator $\mathcal{O}$ is initially known and the state ρ is constructed by requiring that it satisfy the Kubo–Martin–Schwinger (KMS) condition, then they call the construction dynamical. On the other hand, if the mean value of $\mathcal{O}$ (or more generally of a set of such operators) is known, and the state is required to maximize entropy subject to these constraints, *à la* Jaynes [2], then they say that the state has been constructed thermodynamically. While the first construction procedure has been somewhat extensively explored in general covariant statistical mechanics [3–7], the latter less so and one aim of the Kotecha and Oriti paper is to bring this tool to bear on the problem.

A secondary distinction that they draw is between 'physical' and 'structural' flows determined by $\mathcal{O}$. Here the idea is to characterize whether the operator $\mathcal{O}$ is only specified when the particular physical system of interest is fixed, this is the sense of physical that they have in mind, or whether it is specified in a more general, perhaps kinematic sense, which they call 'structural'. Examples of the latter would be rotations of a base manifold or geometric observables like area and volume. The authors emphasize that any of the four possible combinations of their first and second distinction can arise in applications.

The central result of Kotecha and Oriti is the construction of three examples of Gibbs states in group field theory (GFT). A GFT is a quantum field theory where the arguments of the fields are Lie group elements. This is a rich setting with connections to loop quantum gravity and to tensor models. Their first example uses Jaynes' maximum entropy principle to build a Gibbs state based on the total volume of a spacetime. In GFT, as in loop quantum gravity, there is a spectral discreteness of space that arises from the direct quantization of geometrical operators, like the volume of a region. By imposing a fixed average value for this volume, they describe a maximum entropy state at this volume in the theory.

Their second example is more standard in the sense that it uses dynamical flows and the KMS condition. However, it nicely leverages the character of GFT; the flow that they build is 'structural' in their terminology and utilizes the fact that the base space of the field theory is a Lie group. By considering the flows generated by one-parameter subgroups of the GFT base space they can define flows of the field and consider the equilibria that are invariant under these flows. They further generalize this to spacetime geometries also coupled to scalar matter fields. In their third and final example they consider a deparametrized spacetime evolution where a matter field has been taken to be a clock Hamiltonian.

The broad contextualization that Kotecha and Oriti bring to the problem of quantum general covariant statistical mechanics, together with the innovations in applying Jaynes' maximum entropy procedure and leveraging the structural features of GFT are intriguing. Their approach is top down and there is much left to explore. Even when they work out examples of Gibbs states they remain at a fairly abstract level and it will be quite interesting to see these examples treated in detail for cosmological and black hole spacetimes. Do these new characterizations of equilibrium lead to physical insights? Do they illuminate the thermodynamical laws of black hole mechanics? There is also much to be done in comparing and contrasting the different senses of equilibrium that they identify. The network of relations between the three examples of Gibbs states is yet to be uncovered and doing so will help to identify when each of these construction procedures is most relevant and useful.

General covariant statistical mechanics is in its infancy and its quantum manifestation even more so, but the proposal that providing foundations for a statistical theory of general covariant systems will shed light on quantum gravity continues to gain steam. Indeed, it was in the fruitful overlap between thermal physics, statistical mechanics and electromagnetic radiation that quantum theory first emerged. The dialog between relativity, thermality, and the quantum is full of rich questions. Questions that should be answered on the road to a full theory of quantum gravity.

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