Part III

Quantum channels for fundamental physics

Chapter 12

ENTANGLEMENT AND SPACETIME

Entanglement is a fundamental feature of quantum mechanics, signifying a sharp departure from classical notions of locality and realism [1]. Its experimental verification through violations of Bell inequalities [2, 3, 4, 5] has made it central to both quantum technologies and the foundations of physics. As described in Part II of this thesis, entanglement is essential to quantum communication protocols such as teleportation (Chapter 8), entanglement swapping (Chapter 10), measurement-device-independent quantum key distribution [6] and quantum repeaters [7] that can enable secure communication, quantum-enhanced sensing, and distributed quantum processing in a quantum network. In fundamental physics, entanglement continues to play a central role in debates over the nature of reality, ever since the early days of quantum theory.

12.1 Foundations of quantum mechanics

In 1935, Einstein, Podolsky, and Rosen (EPR) raised objections to the completeness of quantum mechanics by proposing a thought experiment in which measurements are performed on a pair of entangled particles [8]. They reasoned that if a physical theory allows one to predict the outcome of a measurement on one particle by performing a measurement on its entangled partner, with out disturbing its state, then the outcome must correspond to a pre-existing "element of reality." Furthermore, because the two particles could be far apart, they assumed that no influence could travel between them faster than light. Taken together, these two assumptions—realism (that measurement outcomes reflect pre-existing properties) and locality (that no instantaneous influences exist between distant systems)—formed the basis for their argument that quantum mechanics must be supplemented by hidden variables. In the 1960s, Bell's theorem formalized this reason, stating that any theory satisfying both locality and realism must obey certain mathematical constraints, known as Bell inequalities [1]. According to quantum mechanics, maximally-entangled bipartite states, such as Bell states, violate these inequalities. In the past decade, landmark experiments demonstrated loop-hole-free violation of Bell inequalities with entangled photon pairs [9, 10], verifying the consequences of quantum mechanics and dismissing the classical assumption of "local realism."

However, Bell's theorem does not address a special case of EPR's original argument in which a measurement on one particle allows one to predict the state of the other particle with 100% certainty. Confronting this case requires moving beyond Bell's theorem and bipartite entanglement. To this end, Greenberger, Horne, and Zeilinger (GHZ) introduced a class of multipartite entangled states, known as GHZ states,

$$|\mathrm{GHZ}\rangle = \frac{|0\rangle^{\otimes N} + e^{i\phi}\,|1\rangle^{\otimes N}}{\sqrt{2}}, \tag{12.1}$$

with the minimal case of $N = 3$ qubits described by $|\mathrm{GHZ}\rangle = (|000\rangle + e^{i\phi}\,|111\rangle)/\sqrt{2}$. GHZ showed that such states allow for a contradiction with local realism at the level of deterministic predictions, providing a stronger refutation of EPR's assumptions. Experimental realizations of GHZ states can be used to prove that it is impossible to construct not only a classical, local-realistic theory of quantum mechanics in general, but also one that makes deterministic predictions of a system in the sense of EPR. In Chapter 13, I report our progress on the first experimental generation of tripartite GHZ states with time-bin qubits, which is particularly suited for implementation in a quantum network. This work not only opens a path to fundamental tests of physics, but also advanced networking protocols based on multipartite entanglement distribution, such as quantum secret sharing [11] and distributed quantum sensing [12].

12.2 Quantum nature of spacetime

Beyond the foundations of quantum mechanics, entanglement has also emerged as a key concept in understanding the quantum nature of spacetime. The interplay between quantum entanglement and the geometry of spacetime has emerged as a central theme in the quest to reconcile quantum mechanics with general relativity, particularly through the lens of the anti-de Sitter/conformal field theory (AdS/CFT) correspondence. In AdS/CFT, spacetime geometry in a $(d+1)$-dimensional gravitational theory is encoded in the entanglement structure of a d-dimensional boundary quantum field theory. This perspective leads to the idea that spacetime is not fundamental, but an emergent property arising from patterns of quantum correlations. A particularly striking manifestation of this idea is the ER=EPR conjecture, proposed by Maldacena and Susskind, which posits that entangled pairs (EPR) are dual to Einstein-Rosen bridges (ER), i.e., wormholes [13]. In this view, quantum entanglement generates geometric connectivity, with multipartite entanglement structures potentially corresponding to multiboundary wormholes or topologically complex bulk geometries [14]. These insights suggest a unifying framework where quantum information is not only a tool for studying gravity but may be the microscopic substrate from which spacetime itself emerges.

A significant breakthrough in this line of thought came with the discovery that certain wormhole geometries can be rendered traversable. In the context of the AdS/CFT correspondence, wormholes can be interpreted as geometries connecting entangled black holes, such as the eternal black hole dual to the thermofield double state. However, in general relativity, such wormholes are non-traversable, meaning that no causal signal or observer can pass from one mouth to the other without encountering a singularity or violating energy conditions. This limitation arises due to the averaged null energy condition (ANEC) [15, 16], which prohibits the negative energy required to keep a wormhole throat open. In 2017, Gao, Jafferis, and Wall showed that a double-trace deformation, corresponding to a weak coupling between the two boundaries of an entangled thermofield double state, can lead to a violation of the ANEC in the bulk, thereby allowing signals to propagate through the wormhole without violating causality [17]. Remarkably, the resulting process is formally equivalent to quantum teleportation between entangled systems, with the traversable geometry offering a dual gravitational description of the underlying protocol. These results suggest that certain quantum communication protocols may admit gravitational duals, and that spacetime connectivity itself may be understood as a manifestation of quantum entanglement and information flow through an underlying quantum channel.

In 2019, Gao and Jafferis constructed a traversable wormhole teleportation protocol within the coupled Sachdev–Ye–Kitaev (SYK) model [18], where a probe inserted into one side of a thermofield double state reappears on the other after a double-trace deformation [19]. The SYK model is a many-body system of randomly interacting Majorana fermions with an emergent conformal symmetry that is holographically dual to Jackiw–Teitelboim (JT) gravity in nearly-AdS_2 spacetime [18]. In the bulk dual, the protocol corresponds to a signal traversing a dynamically opened wormhole [20]. In Chapter 14, we demonstrate an experimental realization of this protocol using a sparsified SYK model on Google's Sycamore quantum processor. This work is the first experimental simulation of traversable wormhole dynamics on a quantum processor, a step in the program of investigating quantum gravity in the lab.

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