Reconstructing the Gravitational Hologram with Quantum Information

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Abstract. Maldacena's 1997 discovery of gauge/gravity duality promised to provide a complete understanding of quantum effects in gravity, by relating gravitating quantum systems to conventional quantum field theories on fixed backgrounds. Although much has been learned, this initial promise has not been completely fulfilled, due to lingering questions associated with the basic dictionary describing the way observables are mapped between one description and the other. While the dictionary is under good control for observables near the boundary, and also at the level of perturbation theory about a classical bulk spacetime for observables further in, non-perturbative questions critical for a full resolution of the black hole information problem remain to be fully answered. Over the last few years, however, a number of developments arising from the application of quantum information theory to AdS/CFT seem to be indicating that it may now be possible to address some of these questions. This GGI workshop brought together experts and young researchers, in order to capitalize on these developments.

Keywords: gravity, holography, black holes, information paradox and firewall problem, quantum error correction.

Context and topics

A number of developments arising from the application of quantum information theory to AdS/CFT have been witnessed in the past few years. One of these developments was the discovery that AdS/CFT correspondence can be interpreted as a **quantum error correcting code** (QEC). In particular, this led to a precise

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formulation of the idea of subregion duality in AdS/CFT. This is the statement that a boundary observer who can access only the observables in some spatial subregion still has complete information about some subregion of the bulk. Using QEC techniques, it was possible to identify this bulk region as the so-called entanglement wedge, which roughly speaking is the bulk region between the boundary region and its Ryu-Takayanagi (or more generally Hubeny-Rangamani-Takayanagi) surface. One very important property of the entanglement wedge is that it usually contains points which are behind black hole horizons. Consequently, this insight is an important step towards the general problem of understanding the black hole interior in AdS/CFT. Indeed, removing boundary regions effectively adds new event horizons to the bulk, so subregion duality is intimately connected to the study of black holes.

Another important aspect of the QEC picture of AdS/CFT is that it naturally leads to simple tensor network models of the correspondence, which realize many of its features in an exactly-solvable setting. Recently, there have been several interesting results suggesting that these models can be improved by incorporating so-called superselection sectors associated with the dynamical spacetime metric. One of the main next steps for the QEC interpretation of AdS/CFT is a more systematic understanding of higher-order quantum corrections to the bulk semi-classical approximation. While such corrections are generally small, they are expected to describe important structural changes in the QEC. In particular, in the leading semi-classical approximation, the Ryu-Takayangi surface defined by a given boundary region coincides with the Ryu-Takayangi surface defined by the complementary region. But bulk quantum corrections can cause the two entangling surfaces to separate, which in turn means that, under such corrections, the QEC ceases to have a property known as complementary recovery. What, then, is the QEC structure that remains, and how does it describe bulk reconstruction? This question becomes especially crucial when black holes are studied, as the supposedly higher-order corrections can compete with the leading order ones. This is an essential feature of the recently described ``alpha-bit phenomenon", which shows that qualitatively new features that arise in approximate QECs are essential for correctly reproducing bulk physics in the presence of black holes.

A second recent development has been the realization that the consistency of quantum gravity sometimes implies novel properties of ordinary non-gravitational relativistic quantum field theory. A key example is the **Quantum Null Energy Condition** (QNEC), a lower bound on the local energy density in terms of quantum information. The QNEC can be thought of as a quantum generalization of the null energy condition, which is an essential ingredient in many of the classic results in the theory of general relativity. In those old arguments, the null energy condition was imposed by fiat as a way of excluding matter with unphysical properties. But there was no general argument that it needed to be true, and in fact in quantum field theory, it isn't. Nonetheless there must be some kind of principle which enforces causality in quantum gravity, and the QNEC can be thought of as the non-gravitational limit of a proposal for such a principle, the quantum focusing conjecture. Despite its gravitational origins however, the QNEC has since been rigorously proven within QFT. Results of this type are of great interest in their own right: they connect aspects of causality constraints on QFT, modular theory, recovery maps for quantum channels and even c-theorems for the RG flow of QFT. But they also provide powerful checks on our understanding of the AdS/CFT dictionary. Moreover, they provide strong support for the hypotheses about quantum gravity from which they were obtained. In particular, it would be very interesting to understand to what extent the quantum focusing conjecture might be proven, both within perturbative semiclassical gravity and also non-perturbatively in AdS/CFT.

A third recent development of great interest has come out of studying the dynamics of the SYK model. This is the realization that some non-perturbative physics in quantum gravity become more tractable when one considers an **average of quantum gravity theories** rather than a particular theory. In a certain sense, this idea goes back at least to the famous work of Page on the von Neumann entropy of radiation for an evaporating black hole, but it has been developed far beyond this in the context of the SYK model. The essential feature of this model is that, due to an average of coupling constants, many quantities can be precisely computed (within the large N limit), even though the model is strongly-coupled and chaotic. Recently, this observation has been simplified even further to show that the Euclidean partition of pure Jackiw-Teitelboim gravity can be computed exactly as an average of Matrix quantum mechanics systems. This has enabled a semiclassical bulk picture of surprisingly non-perturbative physics, such as the long-term behavior of the spectral form factor.

So far we have described three seemingly unrelated developments but the main cause of excitement is that all three actually do seem to be related, in a way that we are only just beginning to grasp. Between the topic of QEC and quantum energy conditions, there is a common theme of modular flow. One of the unsolved problems in the QEC picture is to give an explicit bulk description of entanglement wedge reconstruction, and it seems that modular flow may be the key to achieving this. Between the topic of QEC and the topic of averages of chaotic systems, there is an emerging connection based on using entanglement wedge reconstruction to compute the Page curve and explain the Hayden-Preskill mirror phenomenon for evaporating black holes in AdS/CFT. Several recent papers have proposed models for how this should work, each of which seems to capture some important features of the problem but also has unrealistic features. The bulk calculations seem to be most tractable in Jackiw-Teitelboim gravity, where, as explained above, they should be interpreted as describing averages of quantum systems. In particular, in these average systems, new phenomena, which, as in the case of the spectral form factor, seem as though they may give semiclassical descriptions of otherwise intractable phenomena, arise. There are also hints of some kind of state-dependent operator phenomena, which may tie into earlier proposals on how to describe the black hole interior.

Moreover, the relationships are providing a new and perhaps decisive perspective on the **black hole information problem**, which is one of the great challenges of theoretical physics. Originally formulated by Hawking and more recently refined as the firewall paradox, it distills a sharp conflict that arises when attempting to reconcile unitary black hole evaporation with the principles of general relativity. Understanding how to resolve this paradox may teach us important lessons about the nature of space-time at quantum level. For example, it may imply that the predictions of general relativity are drastically modified by quantum effects near the horizon; it may allow us to identify and clarify possible limitations of locality in quantum gravity; and it might potentially reveal novel aspects of quantum mechanics in the black hole interior. On a more technical side, this paradox is closely related to a concrete and precise question regarding a missing part of the AdS/CFT dictionary: can the boundary CFT describe the black hole interior, and if so, how?

Scientific activities

This six-week program took place at GGI in from June 6 to July 15, 2022. It included a training week and a focus week in hybrid format. Throughout the program, seminars, lectures and talks were recorded and these are available through the GGI repository.
https://www.ggi.infn.it/showevent.pl?id=367

The scientific activities of the program was articulated along several lines, details of which are provided below.

Daily seminars (weeks 1, 3, 4, 5)

In-person attendance during regular weeks was capped at a maximum of 45 participants to guarantee office space for everyone. During these weeks, the schedule included at least one 1h talk (plus discussion) a day. The rest of the day was devoted to smaller group discussions and collaborations.

Training week (week 2)

During week 2 of the program, we had three 1h 30min lectures a day. The goals were to train younger participants and to set a common background on the topics of the workshop. We hosted ~ 80 in-person participants for the week, with a high percentage of PhD students and young postdocs. All lectures were also streamed and 90 online participants could join remotely.

The lecturers invited and topics covered were:

- Chris Akers: *Entanglement wedge reconstruction: state-independent and state-specific*
- Stefan Hollands: *Entropy and Operator Algebras*
- Kristan Jensen: *Wormholes in holography*
- Geoff Penington: *Black holes and holographic entanglement entropy*
- Andrea Puhm: *A celestial holography primer*
- Brian Swingle: *Complexity and Black Holes*

Focus week (week 6)

The focus week was the final event of the workshop and was attended in person by ~ 60 participants. There were morning and afternoon sessions every day from Monday through Thursday, and one morning session on Friday. The event featured 21 one-hour presentations. All talks were also streamed and approximately 90 online participants could join remotely.

Posters

Throughout the workshop, approximately ten younger participants were given the opportunity to present a poster.

Attendance and funding

The program was attended in person by approximately 150 scientists, running at maximal office space capacity during the regular weeks, and reaching peaks of ~ 80 and ~ 60 participants during the training and focus weeks, respectively. The lectures and talks of these two events were streamed and about 90 online participants were given the opportunity to join remotely.

Four distinguished scientists attended the workshop supported by the Simons Foundation: Vijay Balasubramanian, Kristan Jensen, Juan Maldacena, Andrea Puhm.

The participation of junior researchers was remarkably high, approximately 50%, also thanks to GGI financial support devoted to young participants. The training week was an excellent opportunity for them to get educated and updated in this very active research area.

The majority of participants who stayed for at least two weeks received financial support towards accommodation from GGI, while everybody was responsible for their own travel expenses. Lunches, morning coffee breaks during the training and focus weeks, and a reception, were offered on site to all participants. This significantly simplified the daily organization and eased scientific interaction. There was no other official source of financial support besides GGI and the

Simons Foundation, but the expenses of all MIT participants were covered by the personal grants of MIT organizers D. Harlow and N. Engelhardt. From the point of view of logistics, the organization ran smoothly thanks to the support of the GGI staff and local organizers.