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Bulk Locality Breakdown: Burning Black Holes & Precarious Precursors.

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Preface & Overview

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This thesis is an exposition of some of the research that I carried out during my doctoral studies. Broadly speaking, my research focused on how fundamental subjects such as general relativity, thermodynamics and quantum information appear to be connected. Various connections exist, manifested notably in black holes, holography, and the AdS/CFT correspondence in particular. All three of these related subjects will be touched upon in this work, with locality playing an interconnecting role. In what follows, I will briefly summarize and motivate the central elements in this thesis.

Introduction

To begin with, I will set the stage by providing some background information in chapter 1 on a level that should be accessible to readers holding a master in theoretical physics. The introduction contains two main parts, the first of which is focused on black holes. These fascinating objects have been studied for over 50 years, and form an excellent playground for theorists to study properties of (quantum) gravity. I will explain that black holes radiate and can be attributed various thermodynamical properties, such as a temperature and an entropy. Thereafter, I will discuss the thermodynamical stabilities of black holes, since it will be relevant for chapter 2.

The second part of the introduction is about holography and in particular the AdS/CFT correspondence. I will explain how black hole entropy leads to the holographic principle, and motivate how theoretical physicists could come up with this remarkable duality between string theory and conformal field theory living in one dimension less. Then I will proceed to discuss various aspects of AdS/CFT, especially concepts such as HKLL reconstruction and bulk locality, as they will be frequently used in chapters 3, 4 and 5.

I think it is fair to say that while AdS/CFT has been one of the most powerful tools in theoretical physics in the last 20 years, many parts of this duality are still poorly understood. In particular an understanding of core aspects of the duality related to reconstructing bulk physics from boundary data, and the miraculous property of (sub-AdS scale) locality, is still lacking. It is in these two areas that I have tried to make progress with my research, therefore, I will spend a significant part of this thesis explaining the problems and outlining my contributions.

Burning Black Holes

Almost 40 years after Hawking showed that black holes have a temperature and radiate, it is clear that they still keep many secrets until this very day. A famous consequence of Hawking's result is the information paradox: collapsing a pure state into a black hole and letting it evaporate seems to lead to a mixed state of thermal radiation, which cannot happen in a unitary theory. Various resolutions have been proposed: from the pragmatic black hole complementarity to more exotic (Planck-sized) remnants, large modifications of (semi-)classical gravity, or even soft hair. Although none of these suggestions seem completely satisfactory, I do think that holography (and more specifically, AdS/CFT) suggests that black hole evaporation is unitary, although it is far from clear how that would work from a bulk point of view.

In 2012 a new thought experiment surfaced, involving an observer falling into an evaporating black hole. Some older information paradox-like ingredients were repackaged in a sharper paradox: it was pointed that there is a trilemma between unitary black hole formation and evaporation, locality, and the equivalence principle. Some theoretical physicists gave up the latter, suggesting that an infalling observer experiences a 'firewall' instead of a smooth event horizon. Others proposed drastic violations of locality, such as ER=EPR that involves tiny wormholes connecting the interior of the black hole with the exterior. The firewall paradox is puzzling, because common sense says that doing low energy effective field theory in a weakly curved region of spacetime (such as the event horizon of a large black hole) should give perfectly accurate results. It is unclear why quantum gravity effects would suddenly be important in this particular problem.

In chapter 2, I will elaborate on this important problem in modern theoretical physics. First, I will discuss the paradox in detail, and continue by disproving the paradox at the level of s-wave Hawking quanta. I will geometrically show that the paradox generically can not be posed in the causal patch of an infalling observer, suggesting that no physical observer ever witnesses a violation of the laws of physics. While this may not be enough to settle the debate, it requires a more

careful formulation of the paradox. In particular, it seems that the holographic versions that appeared later seem quite robust to the causal patch arguments I will make. They necessitate a detailed study of bulk reconstruction (in particular near or even behind the black hole horizon) and sub-AdS scale locality, a topic which I will address extensively later in this thesis.

A complete understanding of this paradox remains elusive until this very day, with various conflicting proposals dividing the community. Further research is needed, and I am a strong proponent that a better understanding will lead to fundamental insights in the properties of bulk locality and quantum gravity.

Precarious Precursors

The rest of this thesis will focus on bulk reconstruction and locality in AdS/CFT, and consists of chapters 3, 4 and 5. One of my favorite diagnostics are precursors: non-local operators in the CFT that are dual to a local bulk field in the appropriate limit. As the title suggests, precursors often have surprising and even paradoxical properties since bulk locality is a highly non-trivial property of AdS/CFT. That is why I find it interesting to study them, since it leads to a better understanding of AdS/CFT and, eventually, quantum gravity.

In chapter 3, I will discuss some of the puzzles associated to precursors. I will explain that different precursors can be dual to the same bulk field, but bulk locality implies that these different precursors can not be equal as true operators. I will introduce a simple holographic toy model to study the redundant way in which local bulk operators are encoded in the CFT. This redundancy can be tracked to an ambiguity in the smearing function on one hand, but equivalently can be understood using the language of quantum error correction on the other hand. Interestingly, I will show using the two aforementioned approaches that this ambiguity can be used to localize the information of the bulk field in a particular region of the CFT, e.g. a Rindler wedge, provided that bulk field is contained in the corresponding bulk wedge.

Next, in chapter 4, I will dive deeper in the ambiguity that many non-local operators in the CFT seem to be dual to the same local bulk operator. I will recast this problem in the language of BRST symmetry, and make a conjecture relating two precursors corresponding to the same bulk operator. As a check, I will re-derive an earlier expression of a precursor ambiguity that appeared in the literature, which exactly translates into the smearing function ambiguity used in the toy model of chapter 3. The results suggest that precursors are related to the underlying gauge symmetry of the field theory. Once this ambiguity between precursors is understood, I will show that this ambiguity contains enough freedom to localize the bulk

information in the CFT, order by order in $1/N$. This suggests that the procedure I explicitly undertook in chapter 3 to leading order in $1/N$, could be carried out order by order in $1/N$.

Thereafter, in chapter 5, I discuss the broader issue of bulk locality in $\mathrm{AdS}_3/\mathrm{CFT}_2$ in detail, and focus on the question which CFTs have local bulk duals. In order to make some progress on this rather grand question, I will explore the breakdown of sub-AdS scale locality in the same toy model that I introduced in chapter 3. While the model is not modular invariant, it has the right low- and high energy density of states to be dual to Einstein gravity coupled to matter in AdS_3. Surprisingly, non-local effects seem to emerge at order $1/N$ due to the presence of an infinite tower of higher spins in the bulk. This leads me to formulate a conjecture about the spectrum of modular invariant CFT_2's in order to have local bulk duals, however, an explicit proof is still lacking.

Finally, I will wrap up in chapter 6 by summarizing and concluding the material presented in this thesis. Doing so, I will try at the same time to provide an outlook of which problems remain, and what would constitute some interesting next steps of research.

The thesis will end with a few mandatory parts: the bibliography, a short outline of my contributions to the publications on which this thesis is based, and a popular-scientific summary in Dutch. I will finish by acknowledging everyone that made it possible to complete this thesis.

Before continuing, a final word on writing style is in order. Throughout the thesis, I will refrain from using the pronoun 'I', but rather use the pronoun 'we' when talking about ideas and the research performed during my studies. This is not only more conventional in the field when writing papers, but also indicates better the way in which my research was performed, which was always in close collaboration with my colleagues.