Error-correcting Nature of Emerging Spacetime(s) ?

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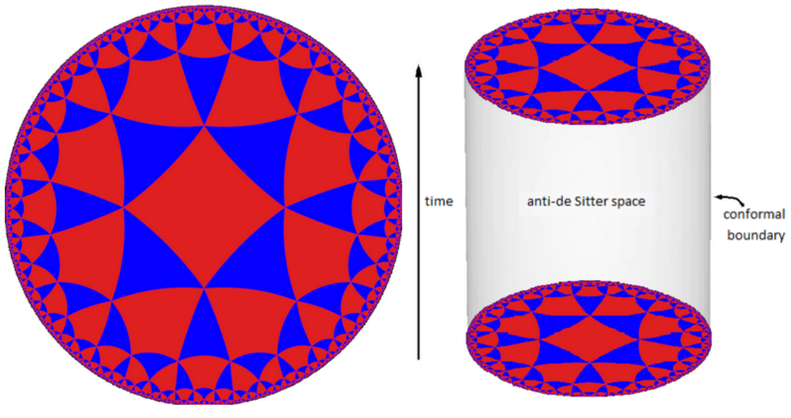
Abstract

Can we construct a hologram of an object in a d-dimensional "bulk" spacetime from a sub-region of its (d-1)-dimensional boundary without any loss of information? This is possible if we add constraints on the bulk and boundary, resulting in the anti-de Sitter spacetime/conformal field theory (AdS/CFT) duality. This duality is surprising and meaningful because it may help solve analytical difficulties in one theory by mapping them into the other seemingly different theory.

The conjecture is not complete yet because aspects of the "hologram" exhibit a non-uniqueness that calls for explanation, which is called bulk locality paradox. One possible solution is to interpret the hologram as a quantum error correction code (QECC): the non-uniqueness of the boundary representation amounts to a redundancy required by the error-correcting nature of the bulk spacetime[1]. In this project, we seeks to understand the nature of spacetime as an emergent phenomenon in holographic duality.



Works Cited

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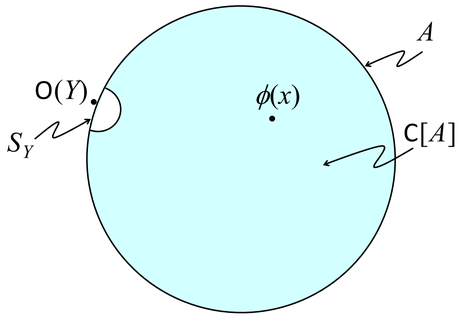
Bulk Locality Paradox

The AdS-Rindler representation of a local bulk field by a CFT operator entails the latter is trivial.

AdS-Rindler bulk reconstruction: $\phi(x)\big|_{x\in\mathcal{C}[A]} = \mathcal{O}[\phi(x)] = \int_A dX\hat{K}(x;X)\mathcal{O}(X)$

∵ *points in A and S_Y are spacelike separated,* $[\mathrm{O}[\phi(x)], \mathrm{O}(Y)] = 0$, for all $Y \in S_Y$

∵ *Y, S_Y, and A are arbitrary,* $[\mathrm{O}[\phi(x)], \mathrm{O}(Z)] = 0$, for all $Z \in \Sigma$



So: By the time-slice axiom, boundary operator $\mathrm{O}[\phi(x)]$ corresponding to local bulk operator must be a multiple of the identity[2]!

Where lies the local info of bulk operator?

Clue: All the different ways to construct AdS-Rindler representations produce the *same* $\mathrm{O}[\phi(x)]$.

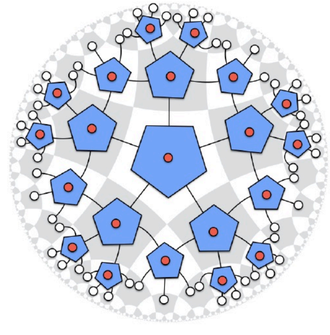
Spacetime as Error-correction Code?

Solving bulk locality paradox motivates the claim of quantum information theorist John Preskill that "Spacetime is an error-correcting code", suggesting the fundamental structure of spacetime is that of a QECC, which involves some form of code space and protection scheme against information loss via encrypting bulk information on the non-local boundary regions. A discrete realization of this structure is the HaPPY code, named after Harlow, Pastawski, Preskill and Yoshida[3].

HaPPY code lattice model

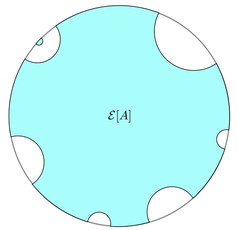
The continuum limit of the HaPPY code reproduces essential aspects of the AdS/CFT correspondence.

Suggestion: This limit is an example of an emergence relation.



Entanglement*

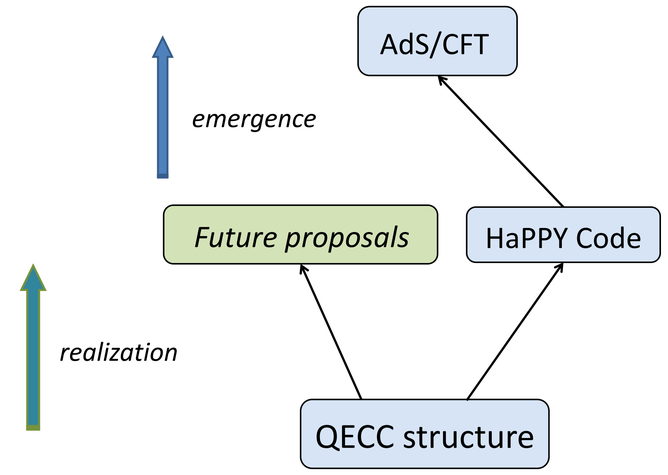
Ryu-Takayanagi Formula[4]: $S(\rho_R) = \mathrm{tr}(\rho\ \mathrm{Area}(\gamma_R)/4G) + S(\rho_{H_R})$



The role of entanglement in QECC is that of protection of bulk operators on the subspace of some entangled CFT states[2].

Give rise to other non-QECC approach towards the emergence of spacetime...

Emergence Relation



Future Insights

Though QECC structure and HaPPY code realization are promising in serving as the fundamental discrete system in the emergence relation we just specified, there are concerns about the viability over the continuum limit of the lattice model. Moreover, we live in an expanding spacetime which fundamentally differs from AdS spacetime, so other realizations of some QECC structure may produce other generalized versions of the AdS/CFT correspondence. These models may have more practical applications to making sense of our universe. There is also possibility that other proposals that better explains the emergence of spacetime[5] other than QECC being fundamental.