Journal of Holography Applications in Physics
Volume 7, Issue 1, Winter 2027, 162–167
©Available online at http://jhap.du.ac.ir
DOI: 10.22128/jhap.2026.3172.1171
Online ISSN: 2783–3518

Letter

AdS/CFT Correspondence: The Fountain of Quantum Youth

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Received: November 30, 2025; **Revised:** May 21, 2026; **Accepted:** May 21, 2026

Abstract. We argue, in the context of AdS/CFT correspondence, that the structure of the geometry dual to two entangled CFTs is a time non-orientable spacetime. Further, we elevate this argument to any entangled quantum system. Accordingly, we should expect entangled quantum systems (particles in a subsidiary) not to experience the flow of time. As a result, the lifetimes of the entangled particles should be considerably longer than those of their unentangled counterparts.

Keywords: AdS/CFT Correspondence; Time Non-Orientability; Black Holes.

Quantum entanglement is one of the most counterintuitive properties of quantum systems. Einstein, Podolsky, and Rosen used entanglement to argue that quantum mechanics predicts a breakdown in locality [1]. In recent years, the concept of entanglement has been applied in understanding high energy and gravity physics. This leads to some surprising discoveries about the connection between entanglement and geometry. It has been proposed that spacetime connectedness in AdS is related to quantum entanglement in dual field theory [2,3]. Moreover, it was conjectured in [4–6] that this occurrence should be elevated to a general principle: whenever two quantum systems are entangled, there should be some version of a physical spacetime connection between them.

In this essay, we will argue that if this scenario is correct, then the spacetime connecting the two quantum systems should be time non-orientable. This statement is based on another interesting insight into the phenomenology of quantum entanglement that comes from the emergence of the thermodynamic arrow of time [7–9], in the presence of initial high correlations between the quantum systems. On this line of work, we previously argued [10], in the context of AdS/CFT correspondence, that the global spacetime dual to quantum entanglement in the field theory must be time non-orientable.

The argument of time non-orientability of the global spacetime dual to any entangled quantum systems has one notable consequence: the entangled pair is not experiencing the flow of time. As a result, the lifetimes of quantum entangled particles should be considerably longer than their unentangled counterparts.

To motivate this result, let us start considering two non-interacting copies of CFT on sphere S^d noted left (L) and right (R), such that we can decompose Hilbert space H_{LR} of the composite system as $H_{LR} = H_L \otimes H_R$. We assume that the two subsystems are initially uncorrelated to begin with, such that the joint state of the system is the product state, $\rho_{LR} = \rho_L \otimes \rho_R$, with ρ_L, ρ_R and ρ_{LR} the density matrix of the left, right and the composite system, respectively, corresponding to the thermal states of the field theory. From this initial product state, the correlations between the two quantum systems can only increase.

We employ here as a natural measure of the correlations between the two subsystems the mutual information:

$$I(\rho_{LR}) = S(\rho_L) + S(\rho_R) - S(\rho_{LR}), \tag{0.1}$$

where $S(\rho_L)$, $S(\rho_R)$ and $S(\rho_{LR})$ are the entropies of the left, right, and composite system, respectively, defined as the von Neumann entropy, $S(\rho) = -Tr(\rho log \rho)$.

Since we are in a low-entropy environment, $I(\rho_{LR}) = 0$, which reduces Eq. (0.1) to:

$$S(\rho_{LR}) = S(\rho_L) + S(\rho_R). \tag{0.2}$$

As a result, the mutual information and consequently the entropy of the composite system can only increase. To see this, let us now consider entangling some of the degrees of freedom of the individual components, evolving in this way the entropy of the joint state from the initial $S_i(\rho_{LR}) = S_i(\rho_L) + S_i(\rho_R)$, to the final entropy $S_f(\rho_{LR}) \leq S_f(\rho_L) + S_f(\rho_R)$. The initial and final states of the composite system are related unitarily, thus $S_f(\rho_{LR}) = S_i(\rho_{LR})$, such that we have

$$\Delta S(\rho_L) + \Delta S(\rho_R) \geq 0. \tag{0.3}$$

This result is consistent with the second law of thermodynamics, which states that the entropy of an isolated system can only increase. In this case, in accordance with the formulation of the second law, the flow of time is directed toward the standard thermodynamic arrow. On the gravity side of the AdS/CFT correspondence, the interpretation of this initially uncorrelated state is straightforward [3]. The two separate physical systems determined by the density matrix ρ_L and ρ_R, correspond in the dual geometric description, to a global time-oriented spacetime having two separate asymptotically AdS spacetimes.

We consider now that the two copies of the field theory are highly correlated, to begin with. In this scenario, the joint state of the two subsystems can be represented as $\rho_{LR} = |\Psi_\beta\rangle \langle\Psi_\beta|$, with $|\Psi_\beta\rangle$ defined as the thermofield double state,

$$|\Psi_\beta\rangle = \frac{1}{\sqrt{Z_\beta}} \sum_n e^{\frac{-\beta E_n}{2}} |E_n\rangle_L |E_n\rangle_R, \tag{0.4}$$

where $|E_n\rangle_L$ ($|E_n\rangle_R$) is the n-th energy eigenvector for the subsystem $L(R)$, β is the inverse temperature, and $Z_\beta^{-1/2}$ is a normalization constant. We may remark here that the two subsystems are initially entangled in a pure state. However, note that the individual states of the two subsystems are the thermal states.

It has been argued in [2–4] that the thermofield double state $|\Psi_\beta\rangle$ corresponds, on the gravity side, to the eternal AdS black hole spacetime, whose extended Penrose diagram is depicted in Fig. 1. Note from Fig. 1 that the time coordinate t runs in opposite directions in the two asymptotic regions associated with the quadrants I and III, in contrast with the familiar [2] AdS/CFT correspondence where the time flow in the same direction on both boundaries.

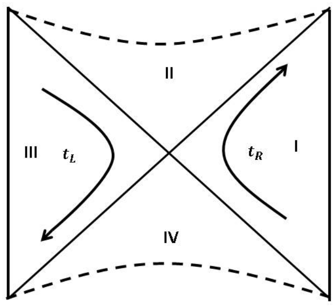

Figure 1: Extended Penrose diagram of AdS eternal black hole. Note that the time coordinate t runs in opposite directions in the two asymptotic regions associated with the quadrants I and III.

In stark contrast to the initially uncorrelated case, we can emphasize here that the initial pure state of the two copies of the field theory ensures that ρ_L and ρ_R are isospectral, so that $S(\rho_L) = S(\rho_R)$. Let us now start from the thermofield double state and gradually disentangle the degrees of freedom. The initial entanglement of the composite system forces the individual entropies $S(\rho_L)$ and $S(\rho_R)$ to move in the same direction, such that, $\Delta S(\rho_L) = \Delta S(\rho_R)$, at all times. In addition, we can say that the initial pure state implies that the individual entropies can only decrease, such that $\Delta S(\rho_L) = \Delta S(\rho_R) \leq 0$.

In this case, Eq. (0.3) is reversed as:

$$\Delta S(\rho_L) + \Delta S(\rho_R) \leq 0, \tag{0.5}$$

a result which suggests that from the perspective of the second law of thermodynamics, both orientations of the thermodynamic arrow are allowed, such that there is no opportunity for the dominance of one direction of time over the other [7–9].

The initial high correlations of the two CFT's ensure that in the dual spacetime the arrow of time may be oriented normal, from the past to the future or reversed, from the future to the past. In this context, since there is no preferred orientation of time on the spacetime, we may conjecture that the gravity dual is a time non-orientable spacetime, [10].

To strengthen this point, recent studies on non-orientable BTZ black holes detailed [11,12] that the eternal BTZ geometry emerges from swapping spatial and temporal roles inside the horizon, resulting in an interior metric that corresponds to a thermofield double state. Merging interior and exterior thermofield doubles yields a complete spacetime exhibiting Klein bottle-like non-orientability, where trajectories traversing the horizon connect asymptotically AdS regions of opposing orientations.

Let us now consider a scenario in which we start with the two copies of the field theory entangled in the thermofield double state and gradually disentangle the degrees of freedom to zero. It has been pointed out in [3], that as the entanglement between L and R CFTs decreases to zero, the mutual information also goes to zero, $I(\rho_L R) = 0$. As a result, we remain in the end with two completely separate physical systems which do not interact, such that the joint state of the system is the product state $\rho_{LR} = \rho_L \otimes \rho_R$, as in the case of initially uncorrelated CFTs.

From the gravity dual perspective, the above scenario is translated into the following statement: starting with a global time non-orientable surface and decreasing to zero the entanglement of the dual copies of CFT, the resulting spacetime is time orientable. Roughly speaking, disentangling the degrees of freedom between two copies of field theory implies, on the geometry side, a transition from a time non-orientable spacetime to a spacetime having a definite orientation of time, thus a time-orientable spacetime.

Let us now assume in the spirit of [4–6] that the structure of global spacetime plays a role in non-gravitational systems. Thus, even the singlet state of particle pair spins should be related by some version of a physical spacetime connection between them. As we have argued in the discussion above, the global spacetime in which the entangled pair lives must be a non-orientable time spacetime. This statement, as abstract as it might seem, has remarkable consequences.

As a result of the absence of a preferred orientation of time on time non-orientable spacetime manifolds, the entangled pair ensemble does not evolve in time. In other words, the entangled pair does not experience the flow of time. We can think of some properties devolving from here, like a possible resolution of the non-locality of entangled quantum states. Here we like to draw the reader attention to another particularity implied by the time non-orientability of the spacetime dual to entangle d quantum systems. The absence of flow of time is reflected in the lifetime of the entangled pair. As a result, when particles are considered, the lifetimes of quantum entangled particles should be considerably longer than the lifetimes of their unentangled counterparts.

To see this more clearly, let us disentangle (by some measurements) the entanglement between the pair of particles. From the point of view of the geometry, there is a transition to a time orientable spacetime, in such a way that the unentangled particles live now on a time-orientable spacetime. The, now, unentangled pair will experience the flow of time and consequently all phenomena associated to motion.

We conclude the article by pointing out that measuring the lifetime of an entangled particle compared to the lifetime of the same unentangled particles could shed light on some theoretical aspects of AdS/CFT duality.

Data Availability

The manuscript has no associated data or the data will not be deposited.

Conflicts of Interest

The author declares that there is no conflict of interest.

Ethical Considerations

The author has diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

Funding

This research did not receive any grant from funding agencies in the public, commercial, or non-profit sectors.

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