




## Letter

# Quantum circuit simulation of black hole evaporation and Maxwell demon interpretation

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## ABSTRACT

We suggest a quantum circuit model which simulates the black-hole evaporation process. In particular, Almheiri-Marolf-Polchinski-Sully (AMPS) paradox and the ER=EPR correspondence are reconsidered regarding our proposed model, which assumes a Maxwell's demon operating within a black hole interior. In other words, we form a quantum circuit, mimicking the behavior of the entanglement structure of the near-horizon region and the early Hawking radiation located far from the black hole. Furthermore, we indicate how the demon, by applying nonlocal correlations, can mediate via Einstein-Rosen bridges for the purpose of simulating the transfer of quantum information across the horizon without violating the monogamy of entanglement. Finally, the thermodynamic cost of the demon's operations regarding Landauer's principle is analyzed. This indicates that the information erasure has an energy comparable to the black hole entropy.

## 1. Introduction

The complementarity is an important concept in the physics of black holes [1]. It claims that the entire spacetime created by a black hole cannot be fully described by either a stationary observer or an observer falling into the black hole separately. In other words, the full information of the spacetime can be probed when these two observers are considered simultaneously. However, it seems that the concept of complementarity is threatened by the existence of a firewall inside the event horizon. This feature of the horizon ultimately leads to a violation of the equivalence principle of General Relativity. In order to solve this problem while maintaining the principles of complementarity and equivalence, the ER=EPR correspondence is proposed [2]. In this correspondence, ER is an abbreviation for the Einstein-Rosen bridge and EPR represents the Einstein-Podolsky-Rosen pair. It is important to emphasize that the ER=EPR correspondence, besides preserving the equivalence principle and the complementarity of black holes, also resolves the AMPS (Almheiri-Marolf-Polchinski-Sully) paradox [1,3].

The AMPS find that accepting the complementarity of black holes and the following three assumptions lead to a contradiction. The three assumptions are as follows: (I) The unitary evolution of the black hole:

The black hole evaporation process preserves the quantum information, and it does not destroy information. (II) The equivalence principle: An infalling observer into the black hole does not encounter any unusual features at the event horizon. (III) The existence of a relativistic effective quantum field theory: For a stationary external observer, the relativistic effective quantum field theory remains coherent.

Our knowledge of black holes claims that the late radiation  $B$  of an old black hole [4,5], which has emitted half of its radiation, is maximally entangled with the early radiation  $R_B$ . This claim results from assumptions (I) and (III) and admits the entanglement of  $B$  with a subsystem of  $R_B$ , while assumption (II) results in entanglement between  $B$  and the interior radiation  $A$  of the black hole. Therefore, these considerations violate the monogamy of entanglement [6,7]. In this scenario, the monogamy of entanglement asserts that  $B$  cannot be entangled with both  $A$  and  $R_B$ . To avoid this paradox, AMPS suggests that the entanglement between  $B$  and  $A$  breaks down, leading to the release of a significant amount of energy at the black hole horizon. This amount of energy is a source for creating a firewall, which extends the singularity to the horizon, leading to the absence of spacetime within the horizon interior [1,3].

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The ER = EPR correspondence [8] is a possible solution to the AMPS paradox. By applying this correspondence, one not only solves the AMPS puzzle but also preserves the equivalence principle in the horizon region of the black hole. The construction of the ER bridge can be explained by EPR micro-states in entangled black holes. The studies [9,10] support this interpretation. In other words, one can explain the quantum EPR correlation system as a weakly coupled Einsteinian gravity, which can clarify the ER bridge's nature. Some fundamental works claim the existence of a quantum bridge for every single quantum entangled state.

Locality is one of the controversial assumptions of AMPS. Although there is experimental evidence for locality, one can desire the violation of it in quantum gravity in order to maintain unitarity to avoid the dramatic consequences of firewalls and without violating our experimental evidence for locality [11]. Giddings and collaborators have notably advanced the study of unitary nonlocal models in quantum gravity [12–29]. For additional black hole solutions that apply nonlocality and qubit toy models to consider the physics of black hole evaporation, one may refer to [30–55].

In this work we investigate the nonlocality of gravitational effects in black holes. It is done by exploring EPR pairs in a spacetime created by a black hole by using a quantum circuit model. Our model and studies like this may shed light on the mechanism underlying the ER = EPR correspondence. Regarding this, we assume a Maxwell demon working in conjunction within a black hole by applying an ER bridge to study the ER = EPR correspondence. For this purpose the demon engages in a quantum circuit.

The concept of the Maxwell's demon, which was initially introduced by James Clark Maxwell in 1867, as a thought experiment, indicates that the second law of thermodynamics is statistical. This point of view is different from the laws of Newton, which are based on dynamical laws. The Maxwell demon posed a paradox, which was solved by Landauer in 1961 by applying the concept of logical irreversibility in the process of memory erasure [56]. The principle asserts that information erasure is a logically irreversible process involving energy dissipation, which increases the entropy in the environment. Besides the significant role of Maxwell's demon in unfolding the connections between thermodynamics [57] and information theory, it has also been extensively studied in quantum thermodynamics and quantum information theories [58,59].

The applications of Maxwell's demon in quantifying the amount of entanglement and the quantumness of correlations can be found in [60–62]. In addition, the amount of work that can be extracted from a correlated pair [63–65], using Maxwell's demon, has become of interest among researchers over the past two decades. In parallel, some investigations focus on quantum Maxwell demons and heat engines respecting Maxwell demon [66–70].

In this paper, the entanglement between early and late Hawking radiation of an old black hole is investigated by simulating it through a quantum circuit using a Maxwell's demon situated inside the black hole and using the Einstein-Rosen (ER) bridge for this purpose. We construct a quantum circuit in collaboration with a Maxwell's demon to model this entanglement. In this approach, an observer outside the old black hole and another observer detecting early Hawking radiation far from the black hole can identify these entangled pairs. The paper is structured as follows: In Section 2, we present a model for the Hawking radiation using a Maxwell's demon. Section 3 focuses on the design of a quantum circuit that aids a Maxwell's demon in the evaporation of a black hole. Finally, we conclude with the summary section

## 2. Modeling Hawking radiation via Maxwell demon

The AMPS paradox plays an important role in understanding the black hole evaporation process and Hawking radiation. As we have mentioned in the Introduction, ER = EPR can be a resolution for this paradox. In this section we suggest a quantum circuit which can play the role of ER bridge in the ER = EPR correspondence. Additionally, we apply it for an old black hole and discuss the consequences.

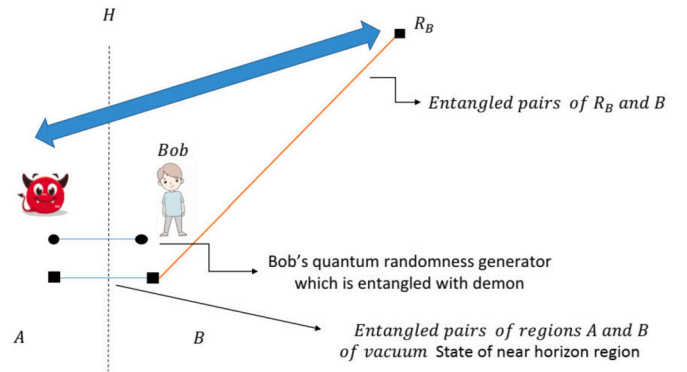


Fig. 1. Measuring of the near-horizon vacuum state and early Hawking radiation using two observers and one demon inside the black hole.  $A$  and  $B$  indicate the near-horizon region of inside and outside the black hole, respectively. Additionally,  $R_B$  denotes the early Hawking radiation, and the entangled pairs between Hawking radiation with late radiation  $B$  are also shown. The outside and inside of the near-horizon region are entangled, and the demon can entangle with Bob's quantum randomness generator. The two-sided arrow indicates a map between  $A$  and  $R_B$ . Charlie is not depicted in the figure (see text).

We posit the presence of a Maxwell demon within the event horizon of a black hole, performing quantum computations to simulate the entangled pair between the near-horizon region  $B$  and the early Hawking radiation  $R_B$ . In Fig. 1 we present an illustration of the near-horizon region and Hawking radiation. Before discussing the details of this model, it is constructive to review the specific characteristics of the near-horizon region and early Hawking radiation in an old black hole.

We assume that the old black hole has evaporated half of its entropy, and the Hawking radiation is now far removed from the near-horizon region of the black hole. According to black hole physics, the region  $A$  inside the black hole is entangled with the outside region  $B$ . Additionally, the states in region  $B$  are entangled with the early Hawking radiation  $R_B$ . Hence, the monogamy of entanglement prevents region  $B$  from being simultaneously entangled with both  $A$  and  $R_B$ .

To resolve this paradox within the ER = EPR paradigm, as illustrated in Fig. 1, the states of the Hawking radiation  $R_B$  are mapped to the states of region  $A$  inside the black hole as

$$|n\rangle_{R_B} \rightarrow |n\rangle_A, \quad (1)$$

through the ER bridge. Consequently, the states of  $B$  are entangled with  $R_B$ , and  $A$  is merely a map of  $R_B$ , thereby avoiding any contradiction with the monogamy of entanglement. In other words, Charlie, in essence, can utilize a quantum computer near the Hawking radiation  $R_B$  of an old black hole to compress the radiation and form a new black hole. This new black hole is linked to the old black hole through a wormhole [71]. Inside the old black hole, Alice can encounter Charlie as he descends into his own black hole. Therefore, an observer can deduce that  $R_B$  is entangled with  $B$ , and by entering the old black hole can observe that  $B$  is also entangled with  $A$ . However,  $R_B$  serves as a representation of  $A$ , and there is no inconsistency.

Now we describe and simulate the phenomenon of Hawking evaporation via a quantum circuit. The circuit considers an entangled pair consisting of  $B$  and  $R_B$ , equipped with a Maxwell demon placed inside the black hole. Bob is positioned outside near the horizon of the black hole as an external observer; however, we simplify our analysis by assuming the existence of a Maxwell demon inside the black hole, as depicted in Fig. 1. Our knowledge of black holes asserts that the regions outside and inside the horizon are entangled, however, the assumed demon can establish entanglement with Bob's quantum randomness generator. The combined state of the demon and Bob's quantum randomness generator is expressed as

$$|0\rangle_D \otimes \frac{1}{\sqrt{m}} \sum_{n=1}^m |n\rangle_B \quad (2)$$

where  $|0\rangle_D$  denotes the standard state of the demon, and  $m$  represents the total number of measurement configurations. As usual, the orthogonal states  $|n\rangle$  are associated with various measurement settings.

Upon Bob's confirmation of his state  $|n\rangle_B$  and subsequent choice through measurement, the demon's state collapses to the corresponding state  $|n\rangle_D$ . Consequently, the composite state (2) transforms into

$$\frac{1}{\sqrt{m}} \sum_{n=1}^m |n\rangle_D |n\rangle_B \quad (3)$$

In addition to the entanglement between the demon and Bob's devices, the demon can control a qubit that becomes entangled with Bob's qubit. Consequently, at the beginning of the process, there are two entangled pairs between Bob and the demon. Following this, after Bob selects the measurement setting  $X$  or  $Z$ , the demon can determine Bob's chosen measurement setting through the entanglement it shares with Bob's devices. Thus, after Bob's measurement which causes the collapse of the entangled state, the demon performs a measurement on its own state, and thereby identifying Bob's measurement setting  $X$  or  $Z$ .

At the next step, before Bob measures his qubit, the demon performs a measurement corresponding to Bob's chosen setting  $X$  ( $Z$ ). The demon then transmits its measurement results, for instance  $+1$ , in the  $X$  ( $Z$ ) direction, to Charlie, who is positioned near the early Hawking radiation  $R_B$  far from the black hole, as illustrated in Fig. 1. Note that Charlie is not depicted in the figure. The transmission of measurement results (Bob's measurement setting  $X$  ( $Z$ ) and the result of the collapse of the entangled pair, for example  $+1$ ) can be achieved via two classical control-control-U gates and control-R gates (see Fig. 2).

However, it is important to recall that the demon is inside the black hole and thus it cannot send information to the outside. Nevertheless, if we restrict the model to the ER=EPR correspondence, this information can be transmitted through the Einstein-Rosen bridge. The ER bridge in this scenario can be explained in two different ways. Firstly, as previously mentioned, Charlie can use his quantum computer to collapse the Hawking radiation  $R_B$  and create a new black hole that becomes entangled with the original black hole. These two black holes are linked by an ER bridge, known as wormhole, too. Secondly, every state of radiation  $R_B$  is connected to the old black hole through ER bridges.

In the first scenario, Charlie can enter his black hole after transmitting the measurement results through the wormhole, conduct a measurement, and discover that the state of the Hawking radiation reflects the state inside the black hole. This process can replicate the mapping between the internal states of the black hole and the Hawking radiation using a quantum circuit. Once the demon obtains Bob's measurement results using its own method, it can access Charlie's state through the wormhole. The demon can then rotate Charlie's state towards the  $X$  ( $Z$ ) direction based on the previous measurement result, such as  $+1$ . By sharing the measurement device result  $X$  ( $Z$ ) with Charlie, who is inside his black hole, the demon can help simulate the entangled pair of  $B$  and  $R_B$ . The procedure of assisting the demon inside the black hole to simulate the entangled pair, can be described by a quantum circuit. The arguments presented for the first case can similarly be applied to the second case. However, our focus will remain on the first case, which involves two entangled black holes.

We close this section by examining the physical constraints of the quantum demon. Each time the demon performs two measurements, one for the apparatus and the other to detect the collapsed state of the entangled pair. It transmits this information through the ER bridge, rotating Charlie's state in the same direction as the state inside the black hole, preparing for either a  $X$  or  $Z$  measurement. Consequently, Charlie can conduct a measurement and the state collapses to the expected state. During this process, the demon introduces two bits of information, and if it is to prepare for the next run, it must erase these two bits as heat into the environment. In order to consider the other entangled pair

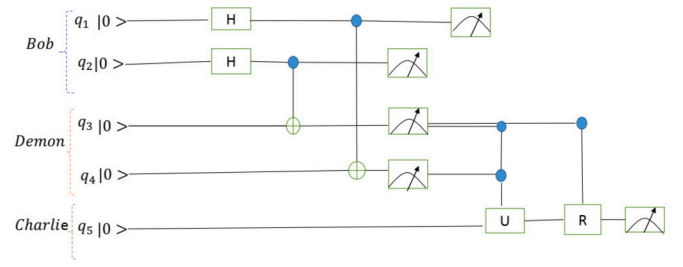


Fig. 2. The quantum circuit: A demon inside an old black hole can collaborate as part of a quantum circuit in order to simulate the entangled pair of Hawking radiation  $B$  and  $R_B$  of the black hole.

in the near horizon region, the demon must erase the bit of information to prepare for the next run, erasing one bit of information into heat equivalent to  $kT \ln(2)$ , where  $T$  is the temperature of the environment. Since the demon performs two measurements in every run, it introduces  $2kT \ln(2)$  of energy into the environment inside the black hole. In other words, in every run it distills one entanglement pair and introduces an amount of energy comparable to the entropy of one of the entangled pairs. By repeating this process for all entanglement pairs, the demon distills all entanglement pairs and introduces an amount of energy to the system comparable to the entropy of the black hole. In the following section we will consider this process as a quantum circuit, simulating the evaporation of the black hole in more detail.

### 3. Quantum circuit of black hole evaporation process

In this section we construct the quantum circuit for Hawking radiation and its measurement process, as it was illustrated in Fig. 1. The detailed quantum circuit is depicted in Fig. 2.

#### 3.1. Quantum circuit

A quantum circuit implementing Maxwell demon using EPR pairs is created as follows. The demon is composed of two qubits, where  $q_3$  entangles with Bob's random generator  $q_2$  using a Control-Not gate to access measurement basis information. Additionally,  $q_4$  acts as the random choice generator for the demon. Moreover, the demon is located inside a black hole and can communicate through a wormhole. Bob, who is outside the black hole near the horizon, also has two qubits.  $q_1$  represents the qubit of the near-horizon region, entangled with the qubit inside the region, while  $q_2$  serves as the random choice generator for his measurement basis. In this scenario, the state of  $q_2$ , being  $|0\rangle$  or  $|1\rangle$ , corresponds to Pauli measurement basis  $Z$  or  $X$ , respectively. As shown in the quantum circuit diagram in Fig. 2, at the start of the process,  $q_3$  of the demon becomes entangled with  $q_2$  through a Control-NOT gate, and therefore their state becomes

$$|\psi\rangle_{23} = \frac{1}{\sqrt{2}}(|0\rangle_2|0\rangle_3 + |1\rangle_2|1\rangle_3). \quad (4)$$

After Bob measures his state  $q_2$ , causing the collapse of the state  $|\psi\rangle_{23}$ , the demon can identify  $q_3$  as the same state as  $q_2$ . This implies that the demon gains immediate knowledge of Bob's basis information. Subsequently, the demon measures qubit  $q_4$  before Bob measures his qubit  $q_1$ . Consequently, the demon knows Bob's measurement outcome before Bob himself. Through the wormhole, the demon can enter region  $R_B$  and share the measurement outcome of  $q_3$  with Charlie. The demon then acts on qubit  $q_5$  before Charlie measures it with his chosen basis. The demon's objective is to rotate the state of  $q_5$  into one of the eigenstates of the measurement basis. This rotation is achieved using a three-qubit classically Control-Control-U gate, illustrated in Fig. 2. The specific form of rotation  $U$  is defined by

$$U|q\rangle_3|q\rangle_4|0\rangle_5 = |q\rangle_3|q\rangle_4 e^{-\frac{i\pi}{4}(q_3+2q_4)\sigma_{RY}} |0\rangle_5, \quad (5)$$

where  $q_3 \in \{0\}$ ,  $q_4 \in \{0, 1\}$  and  $\sigma_{R_Y}$  represents the Pauli operator. In this case  $|q\rangle_4$  is  $|0\rangle_4$  for  $q_4 = 0$ , and it is  $|1\rangle_4$  for  $q_4 = 1$ . Furthermore for  $q_3 \in \{1\}$ ,  $q_4 \in \{0, 1\}$  the rotation is given by

$$U|q\rangle_3|q\rangle_4|0\rangle_5 = |q\rangle_3|q\rangle_4 e^{-\frac{i\pi}{4}(q_3+2q_4)\sigma_{R_Y}}|0\rangle_5. \quad (6)$$

Note that,  $|q\rangle_4$  is  $(|0\rangle_4 + |1\rangle_4)/\sqrt{2}$  for  $q_4 = 0$ , and it is  $(|0\rangle_4 - |1\rangle_4)/\sqrt{2}$  for  $q_4 = 1$ .

It is important to mention that we are exclusively focusing on the scenario involving two measurement settings, specifically the orthogonal Pauli measurement basis  $Z$  and  $X$ . In order to incorporate additional measurement settings, a greater number of qubits will be necessary for the random generator. Furthermore, we have employed a single entangled state encompassing the  $A$  and  $B$  regions of the black hole. In order to fully explore the entire horizon area for Bob and the whole radiation state  $R_B$ , a larger number of additional qubits will be required. The inclusion of more additional qubits will result in an increased need for executing multi-qubit gates within the quantum circuit.

### 3.2. Energy dissipated by the demon

In this subsection we examine the energy dissipated to the system by the demon. With the quantum circuit model of the Maxwell demon black hole we can now explore the correlation between the demon's work. Our model consists of a minimum demon with two qubits,  $q_3$  and  $q_4$ , as depicted in Fig. 2. Since  $q_3$  is entangled with  $q_2$  and  $q_4$  is entangled with  $q_1$ , there are two entangled pairs that need to be reset to the ground state  $|0\rangle$  after each run. The possible states for qubits  $q_3$  and  $q_4$  at the end of the circuit are  $|0\rangle_3|0\rangle_4$ ,  $|1\rangle_3|0\rangle_4$ ,  $|0\rangle_3|1\rangle_4$ , and  $|1\rangle_3|1\rangle_4$ . Resetting the state to the ground state  $|0\rangle$  for a qubit with the state  $|1\rangle$  is equivalent to erasing 1 bit of information. On average, the reset of  $q_3$  and  $q_4$  for 2 entangled states results in the erasure of 2 bits of information for each run. According to Landauer's erasure principle, at least  $2KT \ln(2)$  energy is dissipated into the local environment due to the work done by the demon to erase 2 bits of information in each run.

Finally, note that in a more practical situation, the demon may execute operations with a probability  $p$  for each iteration. The simulation of the entangled  $B$  and  $R_B$  states, which are detected by Bob and Charlie in the black hole, respectively, through a Maxwell demon participating in a quantum circuit and operating with a probability  $p$  for each iteration, is represented by

$$\rho = p|\psi\rangle_{15}\langle\psi| + (1-p)|0\rangle_1\langle 0| \otimes |0\rangle_5\langle 0|, \quad (7)$$

where  $|\psi\rangle_{15}$  is an entangled state of two qubits  $R_B$  and  $B$ .

### 3.3. Maxwell-demon-assisting quantum circuit model

It appears that the demonstration of quantum non-locality through EPR steering can be replicated using local operations and classical communication. In our scenario, which involves the state of near horizon  $B$  and early Hawking radiation  $R_B$  steering, the local operations carried out by Bob and Charlie, as well as the local operations of the demon and its non-local communication through a specific geometry, namely a wormhole, can simulate the entangled pair of  $B$  and  $R_B$ . It is crucial to emphasize that the non-locality feature is made possible by the particular structure of spacetime, known as the ER bridge, which allows for the transmission of information through a shortcut in spacetime. It is worth noting that the collaboration of the demon in constructing a quantum circuit takes place inside the black hole, and the non-locality of the EPR occurs within the horizon. Additionally, the local operation over EPR occurs outside the horizon and can be detected by exterior observers. Therefore, the physics inside the black hole is responsible for the non-locality of the EPR, while our actions in quantum mechanics involve only local operations. In summary, to uncover the non-local trace of EPR and quantum mechanics, one must examine the other side of the horizon.

## 4. Conclusions

In this work we have constructed a quantum circuit model to simulate black hole evaporation, inspired by the ER=EPR correspondence and involving a Maxwell demon operating within the black hole interior. By combining concepts from quantum information theory, gravitational non-locality, and thermodynamic considerations, our framework reproduces the entanglement structure between the near-horizon modes and the early Hawking radiation.

We first revisited the Almheiri-Marolf-Polchinski-Sully (AMPS) paradox and the ER=EPR correspondence within the context of this quantum circuit. The demon, through entanglement with an external observer's quantum randomness generator, can access measurement information and steer external qubits via an ER bridge, effectively simulating the necessary correlations to maintain unitarity without violating the principles of monogamy.

In our scenario, which involves the state of near-horizon  $B$  and early Hawking radiation  $R_B$  steering, the local operations performed by Bob and Charlie, along with the local operations of the demon and its non-local communication through a specific geometry, namely a wormhole, can simulate the entangled pair of  $B$  and  $R_B$ . As we discussed, the non-locality feature is enabled by the particular structure of spacetime, known as the ER bridge, which makes possible the transmission of information through a shortcut in spacetime.

A key feature of our model is the explicit inclusion of the thermodynamic cost associated with the demon's operations. Each iteration, corresponding to the creation of an entangled pair between interior and exterior modes, necessarily involves an entropy increase consistent with Landauer's principle. The cumulative effect of this energy dissipation is of the order of the black hole's entropy, connecting the quantum circuit description to the macroscopic evaporation process. This connection offers a microscopic realization of how information flow through a wormhole could encode the Hawking radiation's correlations while satisfying the second law of thermodynamics.

Furthermore, our model reveals the subtleties involved in reconciling locality and unitarity in black hole physics. The simulated quantum steering between the late and early Hawking radiation - assisted by the demon and mediated via the wormhole geometry - reflects an effective nonlocality embedded in spacetime structure. Hence, from the perspective of external observers, only local operations and classical communication are visible, preserving operational locality while allowing for nonlocal correlations at the quantum gravitational level. This supports the view that spacetime entanglement, as captured in the ER=EPR conjecture, can be applied as the underlying mechanism ensuring consistency between quantum mechanics and gravitational physics.

In summary, the quantum circuit model we propose offers a framework to study aspects of black hole evaporation, quantum information flow, and spacetime geometry in a unified setting. Future work could extend this approach to more general black hole backgrounds, include more complex measurement bases, or incorporate noise and decoherence effects. Additionally, it would be valuable to further explore the relation between the demon's energy dissipation and the dynamics in holographic systems. These investigations are left for future projects.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

No data was used for the research described in the article.

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