Time Travel Simulation Resolves “Grandfather Paradox”

模擬時間旅行 破解「祖父悖論」

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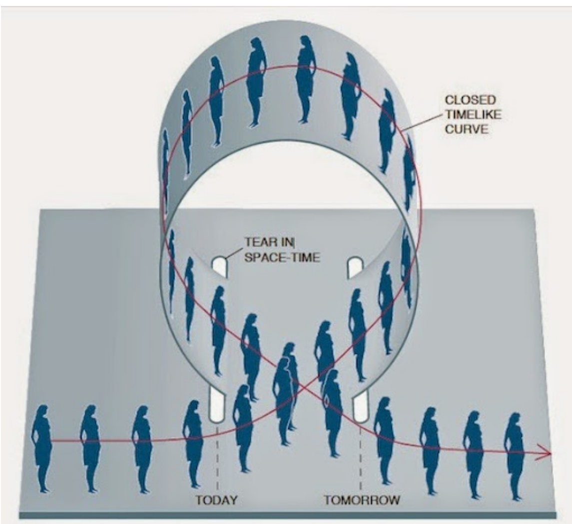
What would happen to you if you went back in time and killed your grandfather? A model using photons reveals that quantum mechanics can solve the quandary—and even foil quantum cryptography

如果你可以回到過去殺死你的祖父，事情將會怎樣？光子模型揭示量子力學(quantum mechanics)可以破解「祖父悖論」這一窘境，甚至破解量子密碼學（quantum cryptography）

當你進入封閉類時曲線後，明天就意味著今天的結束。



圖片來源：德米特裡・謝德洛夫斯基（Dmitry Schidlovsky）

On June 28, 2009, the world-famous physicist Stephen Hawking threw a party at the University of Cambridge, complete with balloons, hors d'oeuvres and iced champagne. Everyone was invited but no one showed up. Hawking had expected as much, because he only sent out invitations after his party had concluded. It was, he said, "a welcome reception for future time travelers," a tongue-in-cheek experiment to reinforce his 1992 conjecture that travel into the past is effectively impossible.

2009年6月28日，世界著名物理學家史蒂芬·霍金（Stephen Hawking）在劍橋大學舉辦了一場宴會，宴會上有氣球、飯前點心和冰鎮香檳。每個人都收到了邀請，但卻無一人出席。情況和霍金預料的差不多，因為他是在宴會結束後才發出的邀請。他說，這是「為未來的時間旅行者舉辦的一次歡迎會，」是為了證明他2009年的一個推測——人類實際上不可能回到過去——而進行的一次玩笑實驗。

But Hawking may be on the wrong side of history. Recent experiments offer tentative support for time travel's feasibility—at least from a mathematical perspective. The study cuts to the core of our understanding of the universe, and the resolution of the possibility of time travel, far from being a topic worthy only of science fiction, would have profound implications for fundamental physics as well as for practical applications such as quantum cryptography and computing.

但霍金可能錯了。近期研究至少從數學角度為時間旅行的可行性提供了初步證據。該研究觸及到了我們對宇宙認識的核心。時間旅行絕不僅僅是科幻小說的一個主題，解決這個問題將對基礎物理學（fundamental physics）和一系列如量子密碼學、計算機技術等實際應用產生深刻影響。

封閉類時曲線（Closed Timelike Curves）

The source of time travel speculation lies in the fact that our best physical theories seem to contain no prohibitions on traveling backward through time. The feat should be possible based on Einstein's theory of general relativity, which describes gravity as the warping of spacetime by energy and matter. An extremely powerful gravitational field, such as that produced by a spinning black hole, could in principle profoundly warp the fabric of existence so that spacetime bends back on itself. This would create a "closed timelike curve," or CTC, a loop that could be traversed to travel back in time.

時間旅行這一推測來源於一個事實，即即便是最無懈可擊的物理理論也沒有說我們不可能回到過去。根據愛因斯坦的廣義相對論（general relativity），回到過去的可能性是存在的。在廣義相對論中，引力被描述為由能量和物質導致的時空彎曲。非常強大的引力場（gravitational field），如旋轉黑洞產生的引力場，理論上可以徹底改變世間萬物的構造，使時空自動反彈回去。如此便產生了「封閉類時曲線」，簡稱CTC，即人們可以穿越回過去的一個封閉圈。

Hawking and many other physicists find CTCs abhorrent, because any macroscopic object traveling through one would inevitably create paradoxes where cause and effect break down. In a model proposed by the theorist David Deutsch in 1991, however, the paradoxes created by CTCs could be avoided at the quantum scale because of the behavior of fundamental particles, which follow only the fuzzy rules of probability rather than strict determinism. "It's intriguing that you've got general relativity predicting these paradoxes, but then you consider them in quantum mechanical terms and the paradoxes go away," says University of Queensland physicist Tim Ralph. "It makes you wonder whether this is important in terms of formulating a theory that unifies general relativity with quantum mechanics."

霍金和其他物理學家並不認可封閉類時曲線，原因在於，如果任何肉眼可見的物體可以穿越CTC，勢必會造成因果關係破裂的悖論。然而，物理學家戴維· 多伊奇（David Deutsch）於1991年提出的一個模型認為，在量子尺度上我們可以因為基本粒子的行為避免CTCs造成的悖論，這些悖論遵循的只是模糊概率規則，並不是嚴謹的決定論。昆士蘭大學（University of Queensland）的物理學家提姆・拉爾夫（Tim Ralph）說，「有趣的是，人們用廣義相對論預測CTC導致的悖論，但一旦從量子力學的角度考慮時，這些悖論就消失不見了」。他還說，「這會讓人疑惑，構建一種可以統一廣義相對論和量子力學的理論究竟重要與否」。

曲線試驗 Experimenting with a curve

Recently Ralph and his PhD student Martin Ringbauer led a team that experimentally simulated Deutsch's model of CTCs for the very first time, testing and confirming many aspects of the two-decades-old theory. Their findings are publishedin Nature Communications. Much of their simulation revolved around investigating how Deutsch's model deals with the “grandfather paradox,” a hypothetical scenario in which someone uses a CTC to travel back through time to murder her own grandfather, thus preventing her own later birth. (Scientific American is part of Nature Publishing Group.)

Deutsch's quantum solution to the grandfather paradox works something like this:

最近，拉爾夫和他的博士生馬丁・瑞巴爾（Martin Rinbauer）帶領的團隊第一次模擬了多伊奇的CTCs模型，測試並驗證這個歷經20年的舊理論的諸多方面。其發現結果發佈在《自然通訊》（Nature Communications）雜誌上（《科學美國人》是自然出版集團的一部分）。他們的多數實驗是以研究多伊奇模型如何解決「祖父悖論」為中心。所謂「祖父悖論」，即某人通過CTC回到過去殺死自己的祖父，從而阻止自己的出生。多伊奇破解「祖父悖論」的量子解決方案如下：

Instead of a human being traversing a CTC to kill her ancestor, imagine that a fundamental particle goes back in time to flip a switch on the particle-generating machine that created it. If the particle flips the switch, the machine emits a particle—the particle—back into the CTC; if the switch isn't flipped, the machine emits nothing. In this scenario there is no a priori deterministic certainty to the particle's emission, only a distribution of probabilities. Deutsch's insight was to postulate self-consistency in the quantum realm, to insist that any particle entering one end of a CTC must emerge at the other end with identical properties. Therefore, a particle emitted by the machine with a probability of one half would enter the CTC and come out the other end to flip the switch with a probability of one half, imbuing itself at birth with a probability of one half of going back to flip the switch. If the particle were a person, she would be born with a one-half probability of killing her grandfather, giving her grandfather a one-half probability of escaping death at her hands—good enough in probabilistic terms to close the causative loop and escape the paradox. Strange though it may be, this solution is in keeping with the known laws of quantum mechanics.

試想，如果不讓人類穿越時空回到過去殺死自己的祖先，而是讓一個基本粒子回到過去打開粒子發射機器的開關。如果該粒子成功按下開關，機器會發射出一個粒子，而這個粒子就會回到CTCs；反之，機器便什麼也不發射。在這一設想方案中，沒有人能夠事先知道該機器是否一定能發射出粒子，只知道其發射概率。多伊奇的理解在於假設量子範疇內的自治性，並

堅持認為任何進入CTC一端的粒子必然會出現在CTC的另一端，而且性質不變。因此粒子發射機器能夠發射粒子的機率是50%，而該粒子進入CTC，再從CTC另一端出來，打開粒子發射器開關的機率也是50%。如果換做是人，那麼她能否殺死自己祖父的機率各佔一半，假設他祖父有可能從她手裡逃脫——那麼時間曲線就極有可能閉合，這樣，我們就可以從概率角度上逃脫悖論。雖然這一解決方案聽起來很奇怪，但它符合目前我們已知的量子力學。

In their new simulation Ralph, Ringbauer and their colleagues studied Deutsch's model using interactions between pairs of polarized photons within a quantum system that they argue is mathematically equivalent to a single photon traversing a CTC. "We encode their polarization so that the second one acts as kind of a past incarnation of the first,” Ringbauer says. So instead of sending a person through a time loop, they created a stunt double of the person and ran him through a time-loop simulator to see if the doppelganger emerging from a CTC exactly resembled the original person as he was in that moment in the past.

在拉爾夫、瑞巴爾和同事進行的新型模擬實驗中，他們利用量子體系中偏振光子對(pairs ofpolarized photon)的相互作用研究多伊奇的模型。他們認為這一體系可以精確地等同於穿越CTC的單光子（single photon）。瑞巴爾說，「我們對光子的偏振作用進行了編碼，如此一來，從某種程度上我們就可以把第二個光子看做是第一個光子過去的化身。」所以我們不用把人類送入時間封閉圈，只需要將某個人的替身送入模擬的時間曲線中，再檢測出現在CTC中的替身是否和過去的真人完全一樣。

By measuring the polarization states of the second photon after its interaction with the first, across multiple trials the team successfully demonstrated Deutsch's self-consistency in action. "The state we got at our output, the second photon at the simulated exit of the CTC, was the same as that of our input, the first encoded photon at the CTC entrance," Ralph says. "Of course, we're not really sending anything back in time but [the simulation] allows us to study weird evolutions normally not allowed in quantum mechanics."

在第一個光子與第二個光子進行電子相互作用後，通過多重實驗測量第二個光子的偏振狀態，拉爾夫團隊成功演示了多伊奇自我一致性的可行性。「位於CTC模擬出口的光子狀態和我們放入CTC入口的光子狀態是一樣的。」拉爾夫說。「當然，我們並沒有把什麼東西真正送回到過去，但模擬時間旅行可以讓我們研究在量子力學中不可行的怪異進化論。」

Those "weird evolutions" enabled by a CTC, Ringbauer notes, would have remarkable practical applications, such as breaking quantum-based cryptography through the cloning of the quantum states of fundamental particles. "If you can clone quantum states,” he says, “you can violate the Heisenberg uncertainty principle,” which comes in handy in quantum cryptography because the principle forbids simultaneously accurate measurements of certain kinds of paired variables, such as position and momentum. "But if you clone that system, you can measure one quantity in the first and the other quantity in the second, allowing you to decrypt an encoded message."

瑞巴爾說，CTC可以讓「怪異的進化論」成為可能，而且這些進化論具有巨大的實際用途，比如通過複製基本粒子的量子態，破解量子密碼。他還說，「如果可以複製量子態，就可以打破海森堡測不準原理（Heisenberg uncertainty principle），」這在量子密碼學中遲早會派上用場，因為這一原理不允許同時對成對變量進行精確測量，比如位置和動量（momentum）「但是，如果你可以複製量子體系，你就可以分別測量第一個體系中的一個量和第二個體系中的另一個量，從而破解加密訊息。」

"In the presence of CTCs, quantum mechanics allows one to perform very powerful information-processing tasks, much more than we believe classical or even normal quantum computers could do," says Todd Brun, a physicist at the University of Southern California who was not involved with the team's experiment. "If the Deutsch model is correct, then this experiment faithfully simulates what could be done with an actual CTC. But this experiment cannot test the Deutsch model itself; that could only be done with access to an actual CTC."

南加利福尼亞大學（University of Southern California）的物理學家托德・布朗（Todd Brun）說道，「正是由於CTC的存在，量子力學可以使人們從事非常複雜的訊息處理工作，這些工作比我們認為的傳統甚至是普通的量子計算機所能做的工作還要複雜得多。」不過，他沒有參與拉爾夫團隊的實驗。他還說，「如果多伊奇的模型是正確的，那麼這一實驗就如實模擬了在真正的CTC條件下發生的事情。但實驗本身並不能證明多伊奇模型，唯一的檢測標準就是進入真正的封閉類時曲線」。

其它理論 Alternative reasoning

Deutsch's model isn’t the only one around, however. In 2009 Seth Lloyd, a theorist at Massachusetts Institute of Technology, proposed an alternative, less radical model of CTCs that resolves the grandfather paradox using quantum teleportation and a technique called post-selection, rather than Deutsch's quantum self-consistency. With Canadian collaborators, Lloyd went on to perform successful laboratory simulations of his model in 2011. "Deutsch's theory has a weird effect of destroying correlations," Lloyd says. "That is, a time traveler who emerges from a Deutschian CTC enters a universe that has nothing to do with the one she exited in the future. By contrast, post-selected CTCs preserve correlations, so that the time traveler returns to the same universe that she remembers in the past."

不過，多伊奇模型並不是破解「祖父悖論」的唯一辦法。麻省理工學院的理論家賽斯・勞埃德（Seth Lloyd）於2009年提出了另外一種模型。該模型不及CTC全面，運用的是量子傳輸（quantum teleportation）和一種稱之為事後選擇（post-selection）的技術，而不是多伊奇量子範疇內的自我一致性。2011年，勞埃德和其加拿大合作者模擬實驗成功。「多伊奇的理論有一種破壞關聯性的奇怪影響，」勞埃德說道。「換言之，即一個出現在多伊奇式CTC的時間旅行者進入一個宇宙，而這個宇宙和她之前所在的那個宇宙卻毫不相關。相比之下，後選擇式CTC沒有破壞關聯性，因此時間旅行者可以回到與她過去記憶中完全相同的那個宇宙」。

This property of Lloyd's model would make CTCs much less powerful for information processing, although still far superior to what computers could achieve in typical regions of spacetime. "The classes of problems our CTCs could help solve are roughly equivalent to finding needles in haystacks," Lloyd says. "But a computer in a Deutschian CTC could solve why haystacks exist in the first place.”

雖然CTC在特有的時空領域中遠比計算機的訊息處理功能強大，但勞埃德這一模型的屬性減弱了CTC對訊息處理的影響力。勞埃德說，「CTCs幫助我們解決問題的可能性如同大海撈針，但在多伊奇式CTC中，一台計算機能夠首先解決大海為什麼會存在的問題」。

Lloyd, though, readily admits the speculative nature of CTCs. “I have no idea which model is really right. Probably both of them are wrong,” he says. Of course, he adds, the other possibility is that Hawking is correct, “that CTCs simply don't and cannot exist."

Time-travel party planners should save the champagne for themselves—their hoped-for future guests seem unlikely to arrive.

儘管如此，勞埃德卻欣然承認CTC還僅僅是一種推測。他說，「我不知道哪個模型真正有效。或許以上兩個模型都是錯的。」他還補充到，另一種可能性自然就是霍金的說法是正確的，「CTC根本就不存在。」為時間旅行者舉行歡迎會的籌劃者應該把香檳留給他們自己——他們滿懷期待迎接的來自未來的客人似乎不可能來了。

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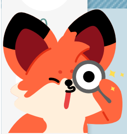

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