Quantum Procrastination

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tions, encompassing hundreds of species that occupy various ecological niches across replicate adaptive radiations.

To keep up with these advances on the molecular and genomic aspects of cichlid diversification, it will be important to increase the efforts at the organismal and life-history level by surveying ecology, morphology, and behavior. This integration would make cichlids a role model not only for adaptive radiation and explosive speciation but also for the survey of interactions at all levels of biological organization.

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PHYSICS

Quantum Procrastination

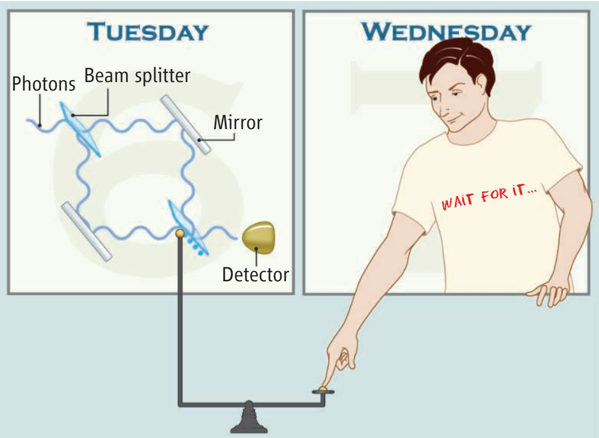
Entangling two photons allows the wave and particle nature of light to be interchanged even after the light has already been detected.

Seth Lloyd

Do you have a decision you have to make but you just can't bring yourself to do it? As the irrevocable moment approaches, you squirm more and more, but something inside you says, "Not now, not yet." Then when it's already almost too late, in a burst of energy and shame, you come through—or not. Afterward, you are irrationally resentful, as if someone other than yourself is responsible for disturbing your peace of mind. You vow that the next time a decision arises, you will make it expeditiously. If you are a severe procrastinator like me (at least when it came to starting this article), have hope—quantum mechanics is coming to your rescue. On pages 637 and 634 of this issue, experiments by Kaiser *et al*. (*1*) and Peruzzo *et al*. (*2*) show that in the presence of quantum entanglement (in which outcomes of measurements are tied together), it is possible to hold off making a decision, even if events seem to have already made one. Quantum procrastination ("proquastination") allows you to put off for tomorrow what you should have done today.

The experiments are based on Wheeler's famous delayed-choice experiment (*3*). Although photons are particles of light, they also possess a wavelike nature and can exhibit interference effects. Suppose that the path lengths of a Mach-Zehnder interferometer (*4*, *5*) have been tuned to make the photon come out of one port of the final beam splitter with probability 1 (see the figure). After the photon has passed the first beam splitter, so that it is fully inside the interferometer, and before it has reached the second beam splitter, you decide to whisk away that second beam splitter, preventing any interference between the photon's two paths from taking place. Without interference, the photon behaves like a particle and emerges with equal probability out of either of the two ports of the apparatus where the second beam splitter used to be.

If instead you choose to leave the beam splitter in, the wavelike nature of the photon asserts itself to exhibit interference between the two paths that the single particle takes in quantum superposition, and the photon would emerge from only one port with probability 1. That is, even though you have delayed the choice of removing the beam splitter until after the photon—if it really were a classical particle—should be traveling along one path or the other, by restoring the beam splitter, you can reinstate the photon's wavelike nature and have it report that it was traveling along both paths simultaneously.



Welcomed delays. Two studies use quantum entanglement in delayed choice experiments; the outcome for the first photon detected (whether it is a particle or a wave or has intermediate character) is determined by later measurements. Kaiser *et al*. entangle the first photon's polarization with that of the second photon, so that its outcome depends on the second photon's polarization. Peruzzo *et al*. entangle the photon with the presence or absence of a beam splitter in the setup and again delay the outcome of the first photon's state. If the photon states could be stored in quantum memories, it might be possible to delay the outcome of the first photon detection (on a Tuesday) until the observer makes a choice on Wednesday.

Since Wheeler proposed his delayed-choice gedanken experiment in 1984, a horde of theories and experiments exhibiting weird quantum effects has spread across the scientific landscape, including experimental demonstrations of Wheeler's proposal (*6*). Quantum information theory has supplied a general language for discussing such quantum weirdness, and small but effective quantum information processors have provided the wherewithal to demonstrate virtually any effect of quantum superposition and entanglement on a small number of quantum bits (*7*). As effects such as Wheeler's delayed-choice experiment and its relatives, such as the quantum eraser (*8*), have become commonplace, they have lost some of their power to amaze.

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For quantum weirdness with more kick to it, we need look no further than the two delayed-choice experiments of Kaiser *et al*. and Peruzzo *et al*. Both experiments use quantum entanglement to delay the choice of what quantum effects are demonstrated not merely until after the photon has entered the interferometer, but until after the photon has emerged from the interferometer and the measurement that detects it has already taken place. In the first proquastination experiment, polarizing beam splitters ensure that vertically polarized photons entering the Mach-Zehnder interferometer undergo quantum interference, while horizontally polarized photons do not. Photons whose polarization is in between vertical and horizontal—diagonally polarized photons—exhibit partial interference.

There is nothing here that the two Ludwigs, Mach and Zehnder, couldn't already have observed in the early 1890s, but now the tricky part comes in. Kaiser *et al*. do not send a photon with a definite polarization into the interferometer. Rather, they send a photon whose polarization is entangled with the polarization of a second photon. After the first photon has already emerged from the interferometer and the port by which it has emerged has been detected, Kaiser *et al*. measured the polarization of the second photon. If they measure the polarization of the second photon along the vertical/horizontal axis and obtain the result "horizontal," then the first photon has behaved like a particle: No interference has taken place. If they obtain the result "vertical," then the first particle has behaved like a wave, and interference has taken place.

So far, the results of the experiment could be explained simply by saying the two photons are either both horizontally polarized or both vertically polarized. If one chooses to measure the second photon along the diagonal/antidiagonal axis however, so that first photon exhibits partial interference, then Bell's inequalities (*9*) can be used to show that this convenient classical explanation won't wash. It is the measurement on the second photon—apparently retroactively—that made interference take place or not.

The second demonstration of quantum procrastination, by Peruzzo *et al*., is if anything even more audacious. In this experiment, a photon is sent through a Mach-Zehnder interferometer as before, but the presence or absence of the second beam splitter in the Mach-Zehnder interferometer is entangled with the state of a second photon. As a result, even after the first photon has been detected, the question of whether it has exhibited wave nature, particle nature, or something in between, is determined by measurements made on the second photon. Strong violations of Bell's inequalities again rule out easy classical explanation.

Although the two quantum procrastination experiments reported here delay the choice of whether to exhibit wave- or particle-like nature of entangled particles for just a few nanoseconds, if one has access to quantum memory in which to store the entanglement, the decision could be put off until tomorrow (or for as long as the memory works reliably). So why decide now? Just let those quanta slide! Sadly, the applications of quantum procrastination are for the moment limited to making only a few highly quantum types of decision ex post facto. I wish I had decided to start writing this article a week before it was due, but no amount of entanglement can hide that I decided to the day before.

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PLANT SCIENCE

Chloroplast Delivery by UPS

Identification of a membrane-anchored E3 ligase in plants reveals a role for the ubiquitin proteasome system in chloroplast development.

Felix Kessler

Chloroplasts are the organelles of photosynthesis in plants and are responsible for much of the food and biomass production on our planet. But chloroplasts are only the best-known members of an extended family of organelles termed plastids. Their name suggests plasticity and, indeed, plastids exist in various incarnations depending on developmental cues (e.g., nonphotosynthetic etioplasts in dark-grown leaves, colored chromoplasts in petals and fruit, and starch-storing amyloplasts in roots). Yet, the mechanisms underlying the transformation from one plastid type to another are largely unknown. On page 655 in this issue, Ling *et al*. (*1*) show that the ubiquitin-26*S* proteasome system (UPS) directly targets plastids and promotes chloroplast biogenesis, controlling yet another important facet of cell biology.

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Plastids originate from an endosymbiotic process that started ~1.5 billion years ago when a eukaryotic host cell engulfed a photosynthetic prokaryote. Over time, the two organisms became almost completely integrated. A permanent and ongoing flow of genetic material from the prokaryotic endosymbiont resulted in the transfer of most plastid protein-encoding genes to the host nucleus (*2*). The *Arabidopsis* chloroplast today has ~2000 proteins (*3*, *4*), only 87 of which are encoded in the organelle. Concurrently with their transfer to the nucleus, the former endosymbiont genes acquired genetic information encoding amino-terminal targeting sequences resulting in synthesis of preproteins in the cytosol. The amino-terminal sequences enable the recognition and the translocation of preproteins across the dual-membrane chloroplast envelope and are later removed.

Preprotein recognition and envelope translocation are facilitated by the chloroplast protein import machinery (*5*), which consists of translocon complexes at the outer (TOC) and inner envelope membranes of the chloroplast. The main components (identified by their molecular mass in kilodaltons) of the Toc complex (Toc159, Toc34, and Toc75) were first identified in isolated pea chloroplasts (*6*–*8*) and play essential roles in chloroplast biogenesis in *Arabidopsis thaliana* (*9*, *10*). Toc159 and Toc34 are outer membrane preprotein receptors shar-

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