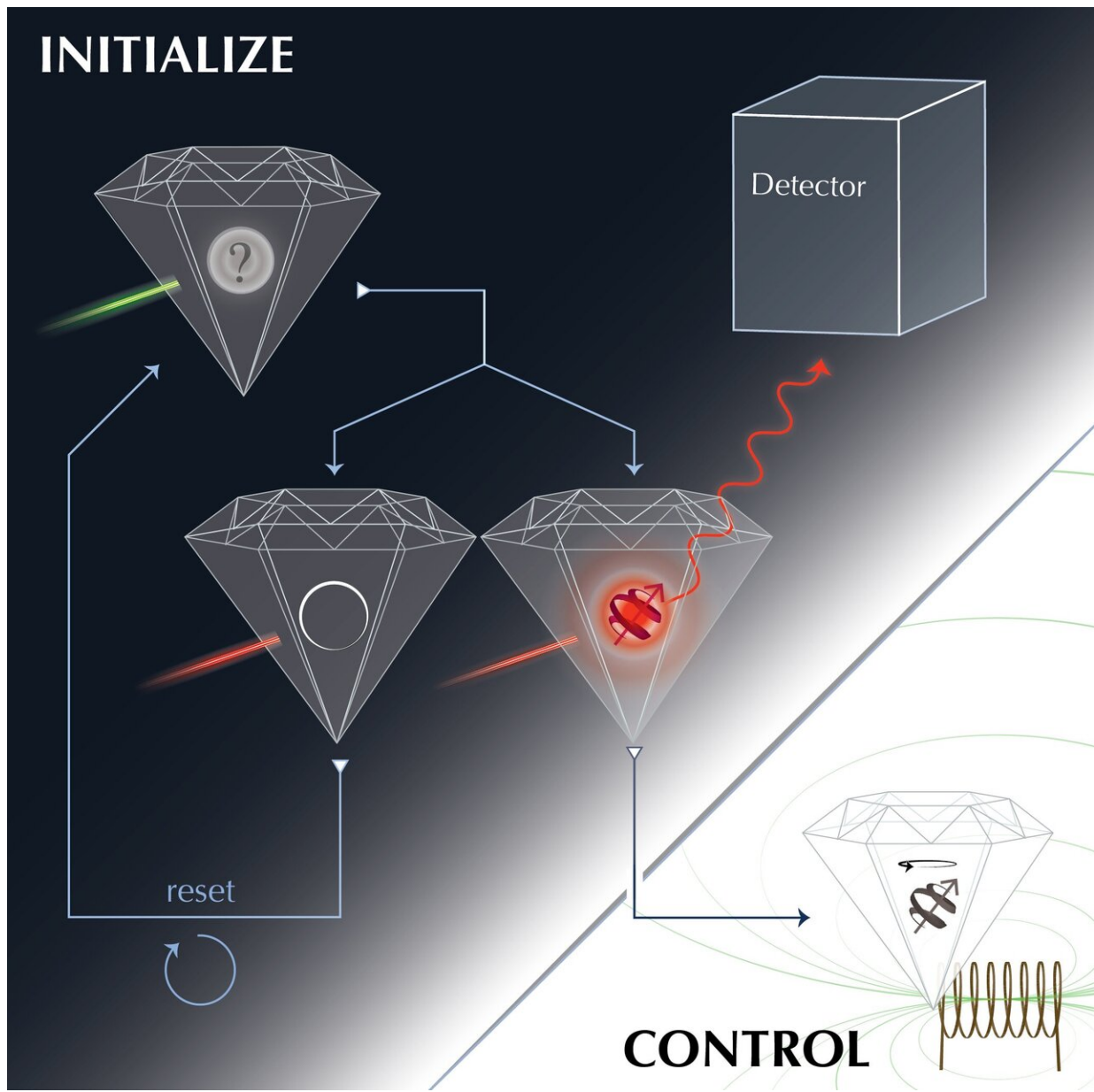


# Engineers ensure quantum experiments get off to the right start

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Quantum experiments that utilize a defect within diamond to store information have to contend with uncertainty, specifically, the number of electrons trapped at that defect when the experiment begins. Penn Engineers have now developed an initialization procedure that addresses this problem. Credit: Ann Sizemore Blevins

The quantum mechanical properties of electrons are beginning to open the door to a new class of sensors and computers with abilities far beyond what their counterparts based in classical physics can accomplish. Quantum states are notoriously difficult to read or write, however, and to make things worse, uncertainty about those states' starting conditions can make experiments more laborious or even impossible.

Now, Penn Engineers have devised a system to reset those starting conditions, test them to see whether they are correct, and automatically start the experiment if they are, all in a matter of microseconds.

This new "initialization procedure" will save quantum researchers the time and effort of re-running experiments to statistically account for uncertain starting states, and enable new kinds of measurements that require exact starting conditions to be run at all.

Lee Bassett, assistant professor in the Department of Electrical and Systems Engineering and director of the Quantum Engineering Laboratory, along with lab members David Hopper and Joseph Lauigan, led a recent study demonstrating this new initialization procedure. Lab member Tzu-Yung Huang also contributed to the study.

It was published in the journal *Physical Review Applied*.

"Initialization is one of the key, fundamental requirements for doing almost any kind of quantum-information processing," Bassett says. "You need to be able to deterministically set your [quantum state](#) before you can do anything useful with it, but the dirty little secret is that, in almost all quantum architectures, that initialization is not perfect."

"Some of the time," Hopper says, "we can accept that uncertainty, and by running an experimental protocol many thousands of times, come up with a measurement we're ultimately confident in. But there are other experiments we'd like to do where this type of averaging over multiple runs won't work."

The particular type of uncertainty the researchers investigated has to do with a commonly used quantum system known as a nitrogen-vacancy (NV) center in diamond. These NV centers are defects that naturally occur within diamond, where the regular lattice of carbon atoms is occasionally disrupted with a nitrogen atom and a vacant spot next to it. The electron clouds of neighboring atoms overlap at this empty space, creating a "trapped molecule" in the diamond that can be probed with a laser, allowing researchers to measure, or alter, the electrons' quantum property known as "spin."

The electrons trapped at an NV center form a "qubit"—the basic unit of quantum information—that can be used to sense local fields, store quantum superposition states, and even perform quantum computations.

"Electrons are excellent magnetic sensors," Bassett says, "and they can even detect the tiny magnetic fields associated with carbon nuclei surrounding the defect. Those nuclei can serve as qubits themselves and be controlled using the central electron to build up the entangled quantum states that form the basis of quantum computers. They also couple to photons, which are used to transmit quantum information over long distances. So NV centers really merge the three main areas of

quantum science: sensing, communication and computation."

As promising as NV centers are, researchers still must contend with an uncertain variable: the number of electrons that are trapped at the NV center when an experiment starts, as electrons can hop in and out of the defect when it is illuminated with a laser. An initialization procedure that guarantees a predictable number of electrons every time would reduce the amount of time it takes to successfully run an experiment, or enable experiments where uncertain starting conditions can't be statistically corrected for after the fact.

"The NV center is like a box with a coin inside," Lauigan says. "If we want to do our experiment only when the coin is on heads, we have to shake the box, check the coin, and repeat until we find that it landed the right way up. That's the initialization procedure."

To execute this initialization, the researchers used a pair of lasers, photon detectors and specialized hardware that could handle the precise timing necessary.

"We shine a green laser at the NV center, which basically 'flips the coin' and mixes up the number of electrons that are trapped in the defect," Hopper says. "Then we come in with a red laser, and depending on the number of electrons that are there, the defect will either emit a photon or remain dark."

"Once we detect the photon that tells us the right number of electrons are in the defect, specialized circuitry automatically starts the experiment," Huang says. "This all happens in about 500 nanoseconds; there isn't time to have the signal analyzed by a normal computer, so it all has to happen on these specialized chips called field programmable gate arrays."

The researchers leveraged the power of advanced classical electronics to

better control a particular quantum sensing system. They showed that, thanks to ideal starting conditions, their device can detect a tiny oscillating magnetic field of only 1.3 nanoteslas in one second of measurements, which is a sensitivity record for room-temperature quantum sensors based on single NV centers.

The researchers' initialization procedure may also help hasten progress on new quantum architectures for computation and communication. Diamond is typically composed of two stable isotopes of carbon, carbon-12 and carbon-13. The former is the most common, but every few tenths of a nanometer, there is an atom of the latter. And because carbon-13 has an extra neutron, it exhibits nuclear spin and can be used as a qubit.

An NV center can be a "handle" for controlling those nuclear-spin qubits in a quantum computer, but in this situation the ability to precisely initialize its state becomes crucial. The errors associated with poor initialization multiply, and it quickly becomes impossible to perform a complex calculation. The type of real-time measurement and control used by the team in this work is a major step towards implementing more sophisticated error-correcting protocols in these quantum devices.

In the near term, the improved sensing ability will be useful in determining the locations of carbon-13 atoms in the diamond lattice.

"Finding all of those special carbon atoms is a laborious process, since there are so many atoms and each measurement takes a very long time," Hopper says. "When we started this project, our goal was to see what was making those measurements take so long and whether there was any way to shorten it."

**More information:** David A. Hopper et al. Real-Time Charge Initialization of Diamond Nitrogen-Vacancy Centers for Enhanced Spin

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