**Q&A “Universal Logic with Encoded Spin Qubits in Silicon” Nature publication.**

**What is a quantum computer?**

A useful quantum computer will end up as something like a supercomputer – it will largely be employed for solving “big problems” such as the simulation of materials and molecules and be housed in some kind of centralized datacenter. The difference between a quantum computer and a traditional supercomputer is that quantum processors use quantum entanglement, a fragile feature of quantum mechanics easily destroyed by noise that is prevalent at room temperature. This requires quantum processors to operate at very, very cold temperatures inside specialized refrigerators and shield their entangled components from many sources of noise. Maintaining entanglement massively increases the virtual “memory space” in which computations can happen without a corresponding increase in number of components. Another quantum mechanical behavior known as “interference” between quantum states enables specialized quantum algorithms to make effective use those resources to solve certain computational problems much faster than otherwise possible.

**Why is a quantum computer useful?**

The large “working space” offered by quantum entanglement enables the more efficient solution of certain computational problems – not all problems, and typically not those that utilize “big data.” An example flavor of problem suited to a quantum computer is the simulation of the behavior of a large molecule: it only takes a little bit of data to describe the atoms in a molecule, but it requires a very large working space to calculate all of the quantum mechanical things electrons in that molecule might do. This was the first application of quantum computers identified, back in the 1980s by Richard Feynman, and more modern theory work has provided numerous implementations for a future quantum computer in this direction. There are other applications already known and it is probably true that, like with traditional computers, many of the best uses of quantum computers will be discovered along the way. Some believe quantum computing will be a “revolution” in computing – for example unlocking critical abilities for artificial intelligence -- time will tell.

**What exactly has been done in this paper?**

Scientists and engineers at HRL experimentally demonstrated a kind of quantum bit (qubit) that was theoretically predicted around 2000 and successfully showed all the functionality needed to execute any kind of quantum computational algorithm. This is known as a demonstration of “universal control”. While this has been done for many kinds of qubits, a unique aspect here is that this an “encoded” or “virtual” qubit, which is encoded in the states of “physical” or “fundamental” qubits – single electron spins in very small silicon devices. This encoded qubit uses three spins and a control scheme where applying voltages to metal gates partially swaps the directions of those electron-spins, but without ever requiring them to be aligned in any particular direction.

Silicon-based devices were fabricated to reliably trap six controllable single electrons, each next to the other in a row. Procedures were developed to set voltages that trap, initialize, measure, and then precisely and partially swap individual electrons 100 million times a second. Those procedures were used to implement mathematically derived control sequences, and those sequences were formed into metrics which tell us just how well they performed quantum operations – the fundamental things qubits do in quantum computers. The result is that the gates performed on encoded qubits performed very well, exactly implementing the correct encoded two-qubit, six-spin logic 97% of the time. It is not perfect, largely because of imperfections in the isotopic content of the underlying silicon material, but it shows the possibility of this approach for logic and tells us how performance could be improved.

**Explain to the non-expert how this qubit works. How is it different from other qubits?**

Three basic quantum concepts, unique to quantum mechanics, are required to understand operation.

1. First is the “quantum spin”, in this case the spin of electrons, which remarkably only has two quantum states: up and down. This is hard to imagine as spinning things usually can spin with any speed about any axis; not so for electrons!
2. Second is the “Pauli-exclusion principle”, which states that it is impossible for an electron to occupy the same state as another. One result of this principle is that if you try to push two electrons together, they want to swap their states, causing an interaction known as “exchange.”
3. Third is “superposition”: the ability to do a “partial” interaction and leave a system in a superposition of one state and another. Famously Erwin Schroedinger attempted to render this aspect of the theory absurd by imagining a device which “partially” kills a cat: it doesn’t make the cat sick, it puts it into a superposition of killed and not killed.

These are well known and well accepted quantum phenomena, although they are all somewhat counterintuitive.

With these understood, the qubit used in this work works by “partial swaps” of electron spins. If we had two electrons, A and B, with A spin-up, and B spin-down, then a swap between them would leave us with A spin-down, and B spin-up, the opposite where it started. The spins are “exchanged.” A partial swap is a quantum operation which leaves us in a superposition of swapped, and not swapped. Now, with a healthy dose of mathematics, one may show that this operation of (precisely controlled) partial swapping of spins is sufficient to perform any quantum operation on a desired, limited set of states of many spins. We call this “exchange-only operation.” Moreover, this operation can be done by merely pushing electrons together, and is accomplished with simple (operationally-convenient) voltage pulses on gates. To make these operations look like the traditional ones for quantum computing (single-qubit rotations and two-qubit controlled-not gates), an encoding is used, chosen here to employ three spins per encoded qubit. Demonstrating universality is accomplished by performing rotations on a single-qubit and entangling two such encoded qubits with controlled-not gates, requiring complex sequences of partial swaps across the six spins.

This operational paradigm is fundamentally different from how most other qubits work. In analogy to classical computing, conventional qubits are like switches which can be flipped on or off with a pulse of energy, whereas our qubits are more similar to “conservative logic” where bits can be swapped for one another, but never flipped. Other silicon-spin-based approaches do not bother with an encoding, and treat each spin as a qubit. Superconducting qubits do not use single spins, but employ fundamental two-state systems with control very similar to single spins. In order to flip a single spin or a superconducting qubit, one needs to apply energy, usually in the form of microwaves somehow delivered to the spin or the superconducting circuit. While this certainly works in smaller systems, it may be hard to isolate microwave signals from one another, keep the various microwave sources in sync with one another, or prevent those microwaves from unsustainably heating the system in a large future machine. The key difference in the exchange-only approach is that such microwaves are never utilized since single spins are never flipped. Instead, we use partial swap operations that are superpositions of either “doing nothing” or swapping the positions of two otherwise identical electrons; these are fundamentally energy-conserving operations, eliminating the need to inject energy into cryogenic environments via microwave signals to flip spins or excite circuits.

**What are next steps? How does this turn into a useful quantum computer?**

As with all current quantum technologies, many, many steps are needed before a useful quantum computer can be built with these exchange-only quantum dot qubits. Key among these is that the operational fidelity – that is, the probability of error-free operation – needs to be improved. While qubit operations fortunately do not need to be absolutely perfect because of the concept of quantum fault tolerance and error correction, they must be much better than possible now. The theory of fault-tolerance has indicated that if you have enough qubits with low enough error, a quantum computer can correct itself by encoding information redundantly and continuously looking out for errors with special measurements. While the error we have shown is as yet insufficient for fault-tolerance, it may cross that threshold after fixing known problems in the device materials, in the control signals, and various other factors identified in this study.

Of course even that is not enough---one also needs to worry about building more and more qubits, wiring those qubits, keeping the system cold enough while operating those qubits, making sure the errors that do occur do not become too correlated with one another, and a host of other scaling challenges. One promising feature of silicon-based spin qubits is that they are small and based on silicon lithography, a set of processes for which, in the case of classical transistors, constitute mankind’s greatest engineering success story. Another is that, for the exchange-only encoded qubit we demonstrated, each fundamental qubit is small and desires to be exactly the same, simplifying scaled physical designs. A third and more subtle advantage is that we completely avoid the problems of distributing synchronized microwave signals across a large chip and preventing those signals from producing unwanted crosstalk or correlated errors. The silicon-based exchange-only approach we have demonstrated at small scale may very well be the most promising pathway to scaling to fault-tolerant operation, and beyond that to a scale at which there is advantage over traditional supercomputers for useful problems. But for this system as for any, such scaling is far from easy. The bright side is that we can look forward to many fun science and engineering problems in figuring out how to do it!

**Why is this kind of qubit not studied more broadly?**

The exchange-only quantum dot qubit is not widely studied largely because of the challenge of fabricating these devices. Other types of qubits, such as superconducting circuits and ion-traps, require only much larger feature sizes and as such are far easier to make. Silicon spin qubits have intrinsic length scales set by the physical properties of silicon which require precision material growth and printing of metal at the level of a billionth of a meter. Although such processes are increasingly routine in semiconductor fabrication for established commercial transistors, is almost unheard of to achieve this level of fabrication precision at an academic research institution.

Beyond fabrication, there are a variety of other complexities associated with exchange-only control that raise the barrier to entry even higher. One of the major enabling capabilities we relied on in this work is sophisticated control and calibration software, which can effectively manage the complexity of exchange-only operation. As an example, while entangling two single-spin qubits requires only one calibrated exchange operation, our encoded qubit requires more than 40.

Fortunately, semiconductor device fabrication and spin control is a specialty of HRL Laboratories; we have been developing this technology for well over a decade. Outside of HRL, universities and start-ups have largely focused on devices with easier control and fabrication processes, and only a couple other institutions with significant research fabrication facilities have been able to yield silicon quantum dot devices of similar size to the one shown here. Now that there are a few institutions yielding devices of this scale, though, perhaps exchange-only qubits will enjoy more attention outside of HRL.

**How does this compare to similar results, such as from Google, IBM, Intel, or Delft?**

HRL Laboratories is by no means the only place developing qubits. Big tech companies such as Google and IBM have been developing superconducting qubits, which are very different from exchange-only silicon qubits in their use of microwaves and larger feature sizes. Others go after ion traps and neutral atoms, which require lasers and operate at a much slower speed but enjoy even simpler fabrication and intrinsically identical qubits. As fabrication of these other kinds of qubits is easier, companies pursuing these approaches can more directly leverage academic contributions and have managed to build devices with far more working qubits. The performance of individual qubits are however still comparable to our results, and not yet good enough for fault-tolerance or actual utility. T.U. Delft, UNSW, U. Tokyo, U. Wisconsin, UCLA, and a few other academic institutions have pursued a somewhat similar silicon qubit route, and are steadily increasing their count of qubits, but these use the single-spin design, again with comparable operating fidelity. Intel and other research foundries such as IMEC and LETI are interesting as they have obvious experience commercializing silicon devices, obviating one of the biggest barriers to progress. Focus from these companies, along with a variety of start-up companies such as Quantum Motion and Diraq who employ commercial semiconductor foundries, appears to be largely on the single-spin qubit, which requires different features for control than the exchange-only, triple-spin approach we have demonstrated. These institutions also show very similar operational fidelities and qubit counts recent publications; none stand out as obviously better on that front. We believe our approach has significant advantages for fidelity improvement and scaling, but there are many complex trade-offs, so ultimately it is healthy for the field to go after multiple, competing but complementary directions at once.

**What kind of place is HRL? How and why did HRL reach this result?**

HRL is a research and development laboratory with a charter to study the plausibility of technology development in a host of areas. Its primary customers are its LLC members (Boeing and GM) and the US government. Located in Malibu, CA, it was formerly Hughes Research Lab, whose largest claim to fame is the demonstration of the first laser in 1960. It has contributed heavily to many technologies in the ensuing decades, especially in advanced semiconductor devices. Developing a qubit of this complexity required an unusual level of risk tolerance and patience without undue forces for market commercialization, as utility remains years off. At the same time, this work could not have been easily done in a university because of the complexity of fabrication and engineering required. The industrial resources of HRL were necessary to establish sufficient device yield, modeling and control software, and test and measurement infrastructure, while the unusual corporate structure of HRL was needed to invest for so long in developing this technology. Hence HRL is uniquely positioned to research a new semiconductor device for many years without excess pressure to prove profitable short-term products.

**What are notable challenges that were overcome to reach this point?**

Device yield has always been a major challenge for semiconductor qubits, and prior generations of this device used gate stacks and designs for which making 6 or more working quantum dots at once depended on far too much luck. This result follows the publication of the Single-Layer-Etched-Dot-Gate-Electrode (SLEDGE) architecture HRL developed, which has proven to greatly reduce this challenge. However, many other challenges also had to be overcome: good software in conjunction with experimental techniques developed over many years were required to load, tune, and operate the quantum dots. Fortunately, much is available to be learned from the larger spin-qubit community, allowing many ingredients to culminate in the present result.

**Is this a “breakthrough?”**

Yes and no. It is in the sense that no one has ever demonstrated this kind of encoded universality, and certainly not in a sextuple Si/SiGe quantum dot device. However, the encoding and control concepts employed here trace back to ideas developed around the turn of the millennium, far before anyone understood how to actually build devices to make use of them. And many of the key improvements that this work depends on have been made by and incorporated into earlier work. Additionally, just as there has been >20 years of work leading to this result, there are probably >20 years more work yet needed to take it to a society-changing technology. So it is hard to say which of the many key results in that timeline should count as “breakthroughs.” Nevertheless, this is indisputably a consequential achievement that would be included in any summary-level history of the technology.

# **List of achievements/papers to date**

A detailed list of relevant published work from HRL is available at [*quantum.hrl.com*](http://www.quantum.hrl.com/). Key papers to point out begin with the first coherent manipulation of exchange in Si/SiGe dots, published in Nature in 2012 (Maune et al.). This demonstrated to the community that some of the device directions taken by HRL (in particular the use of undoped heterostructures) could lead to exchange-based qubits, and many results around the world followed. The demonstration of a triple dot and the introduction of isotopic purification was published in Science Advances in 2015 (Eng et al.) which validated the exchange-only approach. The ability to reduce charge noise by reducing sensitivity to it was published in Phys. Rev. Lett. in 2016 (Reed et al.), and randomized benchmarking of a single triple-dot qubit using these aggregated methods was shown in a Nature Nanotechnology publication in 2021 (Andrews et al.). In 2022, the SLEDGE device architecture was published (Ha et al.), as well as high fidelity state preparation and measurement (Blumoff et al.). Now, in 2023, we have published the demonstration of universal encoded control in a pair of triple-quantum dot exchange only qubits, in Nature.

 **BIOGRAPHIES**

**ARI WEINSTEIN**

Dr. Aaron (Ari) Weinstein completed his PhD in 2015 from Caltech, measuring and manipulating quantum noise in coupled electromechanical resonators. After spending years in sub-basement cryogenic labs, he joined HRL Laboratories to work on silicon spin qubits, focusing on calibration and control of exchange-only qubits. Today he leads a computational modeling effort that sits at the interface of circuit and quantum simulation, with the goal of validating full system performance and predicting improved qubit control schemes.

What do you see as the major features of this new result?

“I think it’s amazing that we have six individual electrons all bouncing off their neighbors in a precisely controlled dance of swaps and partial swaps, and it all works.”

What technical challenges had to be overcome?

“Beyond the immediate challenges of design and fabrication, a lot of robust software had to be written, for example to tune up and calibrate our control scheme. Significant effort was placed in developing efficient, automated routines for determining what applied voltage led to what degree of partial swap. Since thousands of such operations had to be demonstrated to achieve our low error levels, each one had to be precise. We worked hard to get all that control working with high precision.”

What do you see as the biggest advantage of this technology over others?

“It’s hard enough to get this level of control when your only knob is delivery of voltage pulses to gated devices. We operate under this constraint for a reason, to simplify the infrastructure we need to control lots of spins together. It’s one thing to master a single control knob, it’s so much harder if you also have to wrestle with oscillators, lasers, acoustics, or other elements. I used to work on such things and it is hard to imagine how they scale in comparison to this kind of electrical control. But to be clear, our control scheme is not dull, it is rich with problems in modeling, design and optimization. We have a lot more work to do to realize the full potential of this control paradigm”.

## **MITCH JONES**

Dr. Aaron Mitchell Jones has had an affinity for cryogenic test of solid-state systems since starting his undergraduate research in 2008. After receiving his PhD from the University of Washington in 2015 for his studies on 2D layered semiconductors, he joined HRL to work with spin qubits, lured by the prospect of being able to explore rich device physics & precisely control quantum states. He now leads a team of scientists in cryogenic test, with a charter to advance this technology by probing & validating physical models, and pushing the limits of qubit performance.

Tell me about the team that made this result happen.

“This was very much a team effort. The enabling work of talented control software, device growth & fabrication, and theory teams were crucial. Additionally, many measurements of devices were needed to understand enough of the internal physics and develop routines to reliably control these quantum mechanical interactions. This work & demonstration is the culmination of those measurements, made all the better by the time spent working alongside some of the brightest scientists I’ve met.”

What were critical challenges?

“Really, the fabrication of the devices is one of the most challenging aspects with this technology. This in no way minimizes of the work by my team and many others to develop precise control capabilities in both hardware & software, nor the various device physics discoveries along the way. But the R&D fab capabilities at HRL are big factor in making this possible.”

Name something you think is cool about this demonstration.

“We showed the ability to perform all operations required for quantum computation using a control paradigm rather similar to what’s going on in the classical computer chip in the camera filming me – namely, just turning on/off a bunch of voltage levels. I like to visualize controlling our qubit as someone playing the piano. Sure, there are a lot of keys, but you just briefly hit each one in a well-tuned instrument, and as the various notes coalesce into a song, briefly turning on voltages culminates in the entanglement of qubits.”

Can you explain intuitively what exactly this demonstration is?

“By judiciously applying voltages to our device, we pulled 6 electrons from a large electron reservoir, held them in a nice line, all next to each other, prepared a starting quantum state in each qubit on either end of the device, applied about 30 voltage pulses to entangle the qubits, and then maintained that quantum entanglement as we manipulated the joint quantum state through the application of hundreds more control pulses. And we did all of that quantum state preparation & manipulation in one ten-thousandth of a second.”

## **THADDEUS LADD**

 Dr. Thaddeus Ladd began his career researching silicon-based goals for quantum computing at Stanford University, where he received his Ph.D. in 2005. He explored many schemes for semiconductor-based qubits, including RF, optical, and electrical control, prior to focusing on the exchange-only scheme in Si/SiGe at HRL Laboratories, which he joined in 2009. Today he leads a group computationally maturing control schemes and physical models for these qubits and other quantum technologies.

Is this the best qubit technology?

“Well that’s our burden to show. Unfortunately it’s difficult to even know what “best” means. There are many aspects of qubits that could ultimately render them useless, and they’re not always the obvious things such as how error-prone they are or how easy they are to make. Their speed matters, their size matters, their regularity matters, as well as their likelihood of encountering new errors at different scales. The worst thing quantum engineers and futurists can do is look at only one metric. I think the silicon exchange-only qubit is at least the best-balanced: the challenges in improving error, scale, speed, uniformity, crosstalk, and other aspects are nontrivial but none requires a miracle. For many other kinds of qubits, there’s at least one aspect that still looks really, really hard.”

Where do you see this technology going? And when?

“I have been working on silicon-based quantum computing for a couple decades now and if there’s anything I am convinced of, it’s that I cannot predict. The state of commercial quantum computing today is so very, very different from where it was five years ago, in ways I could not predict, and I do not pretend to know where it will be five years from now. This much I know: this particular technology, silicon quantum dots, has been steadily improving and does not face an obvious roadblock. I think we’ll see some technology paths clearly fizzle, but this one will keep moving forward, possibly toward a moving target. It may be decades before commercialization or it may be much sooner than I think. Fortunately, my own path is understanding the physics and possibilities of these devices, and I can guarantee a steady stream of fun problems to solve.”

Name something you think is cool about this demonstration.

“It is interesting to think about, for any kind of computer, where the real guts of the computation are actually happening. What interaction deep inside a machine, buried far underneath the keyboards and mice and monitors and cables and chip packing and copper wiring, what physical interaction is allowing logic to happen. For quantum, there has to be some sort of quantum phases and interference effects happening, and in this demonstration, those phases result from fermions being antisymmetric. There is no classical analogy here, we are using a property of quantum mechanicals coming from a deep symmetry of quantum field theory, and manipulating it to a potentially useful computer. It’s really a very beautiful demonstration of the fact that we understand the workings of the quantum universe as well as we do to actually make a new kind of computational technology out of it.”

Can you explain intuitively what exactly this demonstration is?

“Well my intuition is a bit different from most people’s so not quite sure I can. But it starts by building a very tiny microchip that traps single subatomic particles, electrons, that have an intrinsic spin. At this point I think of the demonstration as a kind of line dance. There is a choreography set by our electronics and mathematical programming, and the electrons basically hold hands and twirl around each other following the music. But – and here’s where intuition is not helpful – with every twirl there is a quantum phase, a mysterious, hidden way in which the relationship between the dancers change. As a result, by the end of the dance, they haven’t just gone around each other, they have gone through and become each other, in a mathematically very precise way, which could be used to make a quantum computer. In order to observe how well it worked, though, the choreographer arranges the dance to assure all the dancers end up where they started, and the measure of success is how many dancers tripped or somehow lost their subtle quantum phase along the way. Well that very mixed metaphor may be the best I can do without quantum angular momentum algebra!”