Opinions Libres
le blog d'Olivier Ezratty

Inside Microsoft Majorana-1

Microsoft captured quantum news headlines on February 19, 2025 by publishing an **arXiv blueprint** for its future fault-tolerant quantum computers (FTQCs) using Majorana fermions, a **Nature paper** about the measurement of Majorana Zero Modes (MZMs) in a chip containing the equivalent of half a physical topological qubit, and then a **press release** summarizing the whole and introducing a Majorana-1 chip with a complete physical qubit based on four MZMs.

The company then predicted that (their) useful quantum computers were just years away, not decades, and inline with a recent prediction from **Bill Gates**. As was the case with **Google Willow** in December 2024, many folks broadcasted the gospel. Likewise, recent news abound coming from Amazon with its **Ocelot cat-qubits chip** and PsiQuantum with its **Omega photonic chip**, all based on previously disclosed arXiv papers, released respectively in **September 2024** and **April 2024**. In a scale of difficulty of understanding, cat-qubits are easy, measurement based photonic quantum computing is much harder, and topological and Majorana qubits are even harder.

In the case of Microsoft, the reaction was quite mixed, due to their poor track record with topological quantum computing research, a retracted paper and a few years ago past unfulfilled promises and the significant gap between their published scientific papers and their PR claims. This is quite a unique situation. All competing qubit technologies have their caveats, but there's never been such an opposition coming from scientific peers. The typical situation in the quantum computing world is to observe bad mouthing from scientists and entrepreneurs who are working on different qubit types. Ions folks say they have the best fidelities and qubit connectivity, superconducting qubit folks say ions can't scale and have slow gates, solid state qubits say that photon qubits have losses, etc. Here, the critics belong in the same camp, from topological condensed matter scientists, not entrepreneurs gaming with marketing. This is puzzling to say the least.

The goal of this paper is to look at what Microsoft did, and did not, what remains to be done, and what other academics and industry vendors are undertaking to create these potentially interesting topologically protected qubits. I describe some overlooked engineering challenges for Microsoft to first prove that its qubits work as planned and then, to scale them to the famous "utility" level, with thousands of logical qubits made of a million physical qubits.

TLTR Best Case Scenario: it will require many years if not decades and a lot of work!

TLTR Alternate Scenario: it does not work at all or at least, it's too complicated.

This paper may be a little technical because I try to define the terminology and put all Microsoft related information into context. You will be better off with having some preliminary knowledge of quantum computing and quantum physics, particularly since I will make some comparisons between Majorana-based quantum computing and other qubit modalities like superconducting and silicon based electron spin qubits. If you only want a high-level summary, skip until the end in the “Why” and “Conclusion” parts.

Here are the topics and questions covered in this broad paper:

- Framing quantum computing requirements
  - DiVincenzo criteria.
  - Circumventing errors.
- Topological and Majorana qubits
  - What are fermions and bosons?
  - What is an anyon?
  - What are MBSs and MZMs?
  - What is happening in MZMs?
  - How are quantum gates implemented with MZMs?
  - What are these braiding operations used in topological qubit computing?
  - How do you measure a Majorana qubit?
  - Did Microsoft invent a new state of matter?
  - How is Ettore Majorana related to these qubits?
  - What level of noise protection comes with MZMs?
  - What error correction is done?
- Majorana-1 chiplet
  - How does qubit control work?
  - What is the size of a Majorana qubit?
  - Can manufacturing scale?
- Microsoft’s roadmap towards utility scale quantum computing
  - What is the energetic cost of Majorana qubit quantum computers?
  - Why was Microsoft selected by DARPA?
  - What problems will Microsoft’s quantum computer solve?
- Other topological qubits
- Debate on Microsoft Majorana qubits
  - The Nature paper.

  - Negative reactions.
  - Neutral to positive reactions.
  - Microsoft track record.
  - Why?

- Conclusion and future outlook

The Microsoft sources are:

- **arXiv** paper containing Microsoft's blueprint and roadmap: **Roadmap to fault tolerant quantum computation using topological qubit arrays** by David Aasen, Andrew Zimmerman et al, Microsoft, arXiv, February 2025 (23 pages).
- **Nature** paper describing the measurement of the parity of a duo of MZMs: **Interferometric single-shot parity measurement in InAs–Al hybrid devices** by Justin Zilke et al, Nature, February 2025 (6 pages) with the related **Supplementary Information** (29 pages) and **peer review evaluation** (23 pages).
- **Microsoft announcement**: **Microsoft unveils Majorana 1, the world's first quantum processor powered by topological qubits** by Chetan Nayak, Microsoft Azure Quantum Blog, February 2025. Chetan Nayak is Microsoft's quantum hardware VP. In that post, Microsoft touts the creation of a "new state of matter".
- **Microsoft video** explaining the story (**video**) and a **long interview** of Chetan Nayak released after the APS Global Summit in March.

Framing quantum computing requirements

Quantum computers are usually made of qubits which are two-levels controllable physical quantum systems enabling superposition and entanglement between each other. This is the source of the so-called quantum parallelism which, along with building smart interferences between qubits, can generate some quantum speedup compared to classical algorithms.

DiVincenzo criteria

In 1996, **David DiVincenzo**, then a researcher at IBM, defined the bare minimum five criteria for the creation of a functioning quantum computer:

- **Scalable physical system** with well-characterized qubits, meaning that it is possible to clearly differentiate their state at the physical and experimental level.
- **Ability to initialize qubit state** to a simple fiducial state, commonly named the "ground state", and labelled |0> in Dirac's notation.
- **Qubit coherence times** that are compatible with the duration of the algorithm. This is currently problematic with all qubit modalities. Qubits are not stable long enough to accommodate the usual length of useful quantum algorithms.

- **Universal set of quantum gates** enabling the creation or arbitrary transformations of the qubits state vector in its Hilbert space (aka “unitaries”, which are square complex number matrices). In programming parlance, it means having a combination of Clifford gates (X, H, CNOT) and non-Clifford (a T or Toffoli gate). The later gates happen to be mandatory for the creation of arbitrary unitaries and for potentially enabling some exponential computing time theoretical speedups.

- **Qubit measurement capability**, preferably nondestructive, of the qubit state, meaning that after readout, the qubit is still there, in its collapsed state that is either |0> or |1>. There is an exception with photonic qubits which belong to the “flying qubit” category and are usually destroyed after being detected.

At this point, Microsoft Majorana qubits have been experimented with 2 (initialization) and partially with 5 (measurement). The rest is in Microsoft’s roadmap but not in their announced Majorana-1 chip presented on February 19th, 2025. All competing commercial quantum computing platforms support 1, 2, 4 and 5 and most of them struggle with 3 as we’ll see.

The chart below shows this in a simplistic manner as of **today**, the orange areas being “work in progress” in most cases.

While, if they worked, Majorana qubits could bring many benefits, their current status or TRL (technology readiness level) is very low with regards to the basic DiVincenzo criteria when compared with all other qubit modalities. They are below the level where superconducting and trapped ion qubits were around 2002. So, even if there was no scientific debate (that we’ll cover later) on the reality of their Majorana qubit, they have a long way to go to deliver a functional quantum computer, let alone a scalable one. And since they can’t implement their qubit in a NISQ fashion, without error correction, it’s an “all or nothing” proposition.

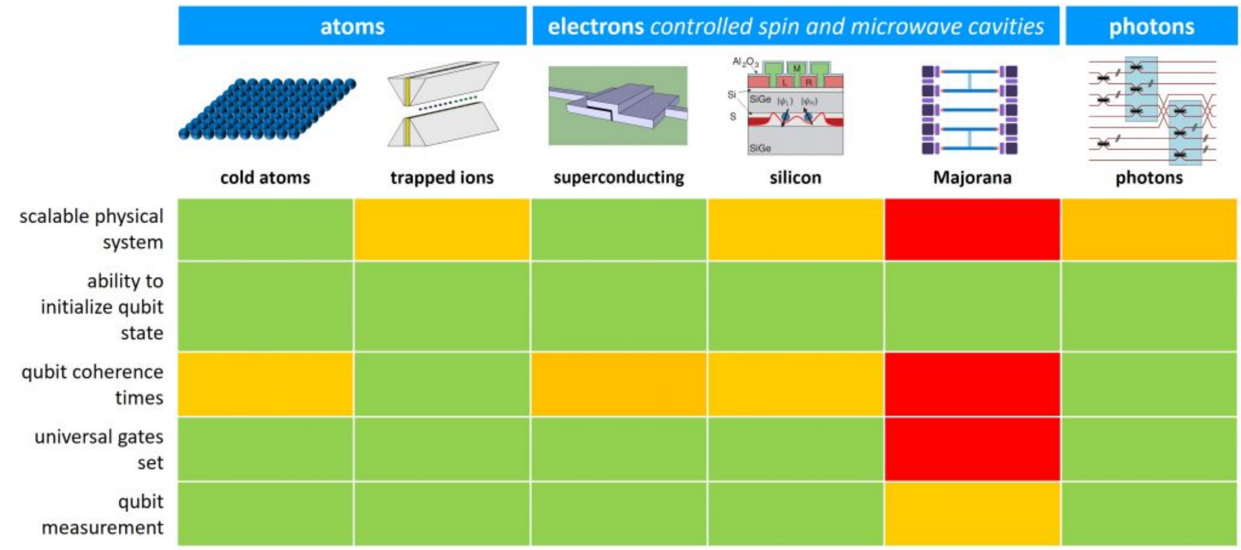


Chart above: Comparison as of today of the maturity of qubit platforms with regards to matching DiVincenzo criteria. It doesn’t provide indications on the trend of progress, like with scalability. If you look at current scales in number of physical qubits for commercial and sometime advanced experimental systems: we have about 280 atoms (experimental QuEra-Harvard system in gate-based mode), 56 with trapped ions (Quantinuum), 156 with superconducting qubits (IBM, with records reaching 504 in China with low fidelities and 1,121 with IBM Condor, that was dismantled and not operational), 12 in silicon (Intel, low TRL), 1 for Majorana, and various numbers from 12 to about 216 for photons depending on the paradigm (KLM, Boson Sampling, Gaussian Boson Sampling, qumodes).

Circumventing errors

The current noisy qubit quantum computers are subject to errors which occur during all steps of a quantum circuit execution: initialization, gate operations, idle state, and measurement.

These errors have multiple sources and effects:

- The most famous one is decoherence, when qubits lose their own superposition, and their entanglement with other qubits, due to their interactions with their environment and *despite* their specific conditions of operations (cryogenic temperature, magnetic shielding, vacuum, depending on the qubit type).
- Several qubit types are also subject to spontaneous emission, when they transition from their excited state to their ground state by emitting a photon into the surrounding electromagnetic field. This happens for example with cold atoms, ions and superconducting qubits.
- Qubit can also be occasionally lost, as is the case with atoms and ions, which can escape their control zone due to some control defect or some form of randomness, or with photon qubits where losses happen along their computing path, when they travel in wave guides and fiber and with efficiency issues at the photon source and detector levels.
- Other sources or errors are the tiny defects of qubit control devices. Electronic signal jitter or laser phase noise can generate gate operations errors which can't be assimilated to decoherence. For example, a tiny error in the duration of a microwave pulse sent to a superconducting qubit can generate a phase error in a phase change gate (Z, S or T gate) without generating any decoherence.
- Errors can be local (happening to a single qubit), nonlocal (like when one qubit interacts with another, in a crosstalk effect) or correlated (affecting simultaneously several qubits, like when generated by cosmic rays bursts).

Whatever their origins, qubit errors are detrimental to the successful execution of a quantum circuit (or "code"), particularly given these errors accumulate quickly. To make things overly simple, if for example you have an average 1% error rate for each operation, after about a hundred operations, you'll lose any chance to obtain a good result, even considering most quantum algorithms are based on a sampling technique. It means that you run your circuit (or algorithm) many times, usually in the 1000s, and post-process the result to retrieve useful data, like with averaging the results. The best in class qubits are nearly reaching 99.9% fidelities for two-qubit gates, which enables them to run circuits with a couple thousand operations, even including quantum error mitigation. Useful algorithms require millions to billions of operations.

As a result, quantum scientists and engineers are looking for ways to fight or circumvent these errors. Their arsenal contains a mix of hardware and software techniques:

- **Qubits physical quality improvements** to minimize error rates. This can for example come from the manufacturing quality of their supporting chips and raw materials chemical or isotopic purity, depending on the qubit type. You not only need to improve the qubit quality, but also reduce the qubit quality variability within a qubit chip.
- **Autonomous error correction** at the qubit physical level. This is done for example with bosonic qubits in the superconducting qubit field, with the cat-qubits from Alice&Bob (France) and AWS (USA) as well as with GKP qubits from Nord Quantique (Canada). These qubits have an internal mechanism that reduces physical error rates. Topological qubits are also implementing sort-of autonomous error correction. You reduce physical errors but don't cancel them entirely. These qubits still need some software-based error

correction, but, supposedly, with a lower qubit number overhead.

- **Control signals quality improvements** to reduce extraneous sources of errors. Like reducing laser phase noise when controlling cold atom and trapped ions based qubits, or reducing electronic signals jitter when sending microwave pulses to control superconducting and silicon qubits.
- **Quantum error suppression and mitigation** in the noisy regime (QES, QEM). This is a software post-processing technique, often using classical machine learning, which reduces the effects of noise in a circuit. It has a cost. You need more circuit execution, some initial training and calibration, and then some additional classical computing cost. It can’t scale easily beyond 200 physical qubits with the current physical qubit quality we have.
- **Quantum error correction** (QEC). This corrects errors *during* computing, not after. It is usually implemented after each qubit operation. Error correction relies on so-called logical qubits which are assembling several physical qubits and use error correction codes. Their overhead is significant. QEC’s effect is to increase the coherence time of (logical) qubits and it reduces their error rate to acceptable levels, compatible with the complexity of your quantum circuit. The overhead of QEC then depends on the size of your algorithm and should be adjusted accordingly to avoid spending too many classical and quantum computing resources.
- **Fault-tolerance** is about making sure that all your circuit will run as expected. It is based on using quantum error correction on all operations, with single and two qubit logical gate corrections, including non-Clifford gates like a T or Toffoli gate, avoiding error propagation and amplification during error correction, and also implementing fault-tolerant results readout. There is no perfect fault-tolerance. Its specification is algorithm dependent, mainly based on the circuit size in number of gates.

Despite Microsoft Majorana qubits seemingly implementing 2 (some autonomous error correction), they still need 3 (signals quality, at lesser level), 5 (error correction) and 6 (fault tolerance). Topological qubits are sometimes wrongly described as “fault-tolerant”. They are not. They just have some autonomous error correction, but do not natively implement fault-tolerance.

Recasting these two sets of definitions is important to avoid misunderstanding what Microsoft is doing. We will reuse them in this paper.

Topological and Majorana qubits

Ettore Majorana predicted in 1937 the existence of a new class of fermionic elementary particles that are their own anti-particles. At this point in time, no particle of the standard model behaves as a Majorana fermion. The sterile neutrino which is a specific breed of chargeless particle, the neutrino, is a potential candidate but its existence is not demonstrated yet.

Initially labelled Majorana fermions, Majorana modes (*aka* MZMs as we will see) are not elementary particles like electrons or atoms. These refer to special breeds of “non-Abelian anyon quasiparticles”. We will define all these terms!

<u>What are fermions and bosons?</u>

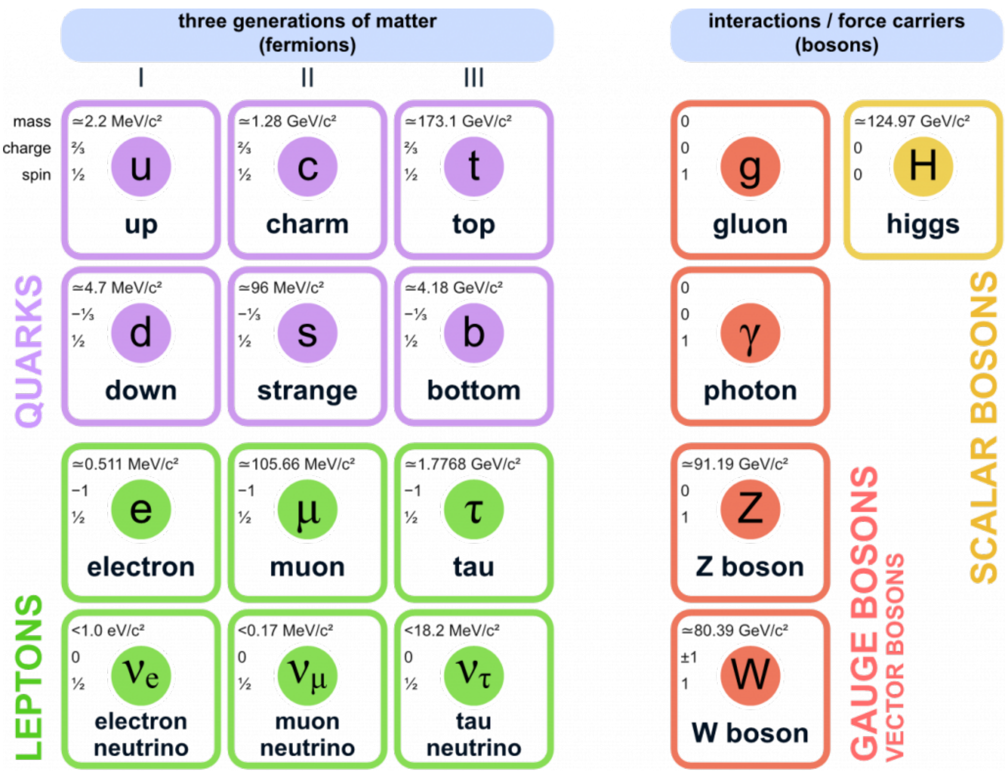
Fermions and bosons are the two classes of particles distinguished by their intrinsic angular momentum, or spin, and the quantum statistics they obey.

- **Fermions** are characterized by half-integer spins such as 1/2, 3/2, etc. and they respect the Pauli exclusion principle, which means that no two fermions can occupy the same quantum state simultaneously, like two electrons with the same 4 quantum numbers in an atomic shell. This explains how electrons fill shells and orbitals in atoms. Their statistical behavior is described by Fermi–Dirac statistics.

- **Bosons** have integer spins – 0, 1, 2, and so on and do not follow the Pauli exclusion principle, allowing them to gather in the same quantum state. This property is found in superconductivity with Cooper pairs of electrons with opposite spins and in superfluidity. The collective behavior of bosons is governed by Bose-Einstein statistics. They can form exotic states of matter like Bose-Einstein condensates.

You can distinguish four categories of particles which can be either fermions or bosons:

- **Elementary particles** which are the indivisible building blocks in the Standard Model of particle physics. They include fermions (with quarks and leptons, including the electron), their respective antiparticles (like the positron for the electrons, and antiquarks for quarks), and bosons that include the force-carrying particles of nature, such as photons, gluons, and the W and Z bosons, which mediate the fundamental interactions. Their behavior is described by quantum field theories, where particle is an excitation of an underlying field. I wrote a **little primer** on this after my January 2025 visit at CERN.



- **Composite particles** are systems bound together by fundamental interactions. A prime example in nature are protons and neutrons which are made up of three quarks held together by the strong nuclear force. These hadrons are baryons, the subclass of hadrons which are fermions due to their odd number of quarks. Mesons are bosons and made up of an even number of quarks and antiquarks are very unstable. Atoms are made of nucleons (protons and neutrons) and electrons. Neutral atoms are fermions when their number of neutrons is odd and bosons when it is even. For example, rubidium 87 is a boson since it contains 50 neutrons.

- **Quasiparticles** are emergent phenomena that occur in many-body systems, particularly in condensed matter physics. They are collective excitations like phonons which represent quantized vibrational energy in an atomic crystal lattice. Quasiparticles are mathematical constructs that simplify the analysis of complex interactions within materials. The collective behavior of interacting electrons, atoms, or particle spins can be mathematically described as if they behave as a single coherent particle with some quantized observable, and exhibiting superposition and, potentially, entanglement with other similar quasiparticles. Quasiparticles can exhibit fermions or bosons statistics. Quasiparticle examples include electrons in a conductor treated as Landau quasiparticles in Fermi liquid theory, Bogoliubov quasiparticles in superconductors, where strong electron-electron pairing correlations create mixed electron-hole excitations, or pairs of electrons of opposite spins in superconductors, *aka* Cooper pairs, which are bosons. Microsoft Majorana fermions and, generally MZMs (Majorana Zero Modes), sit there, as a specific breed of quasiparticles. They do not correspond to Ettore Majorana's definition of its fermionic elementary particles that are their own antiparticle.

- **Artificial atoms**. Although also belonging to the field of condensed matter, superconducting qubits are not classified as quasiparticles, but as artificial atoms as they are engineered to have discrete, controllable quantum states that mimic the properties of real atoms. Superconducting qubits are built on one macroscopic degrees of freedom, such as the charge or phase of the current in the superconducting circuit that is traversing a Josephson junction. The JJ tunnel effect creates an anharmonic oscillator in the current loop that helps create two distinguishable quantum states in the loop current. A superconducting qubit behaves as a bosonic excitation.

Condensed matter physics is the branch of physics that is dedicated to understanding the properties of matter in its condensed phases, primarily solids and liquids. In quantum physics, the branch of condensed matter of interest is the study of solids at very low temperatures, where physicists usually leverage various superconducting effects.

<u>What is an anyon?</u>

An anyon is a specific type of quasiparticle that emerges in single and two-dimensional quantum systems, often carrying properties and statistics fundamentally different from the familiar categories of bosons and fermions. In three-dimensional space, interchanging two particles just swaps their positions. In one or two dimensions, the paths that particles take around each other cannot be entangled in the same way, allowing for richer forms of quantum statistics in which the wavefunction acquires not just a simple plus or minus sign under exchange, but possibly a complex phase or even a matrix operation. The fractional quantum Hall effect (QHE) is an enabler of the creation of these anyons. fQHE was discovered by Robert Laughlin, Horst Störmer, and Daniel Tsui which led them to be awarded with the Nobel Prize in Physics in 1998. It is a phenomenon happening in two-dimensional electron systems at low temperatures and under strong magnetic fields where the transverse current per unit applied electric field (aka Hall conductance) is quantized.

There are Abelian and non-Abelian anyons, the later exhibiting topological properties that may protect quantum information against noise and decoherence. Non-Abelian anyons obey non-commutative exchange statistics, meaning that when two identical non-Abelian anyons are exchanged, their wave function undergoes evolutions which depend on the order of these exchanges. The final quantum state depends on the sequence of exchanges. This is what gives them some topological protection against quantum noise.

Particle representation models describing the collective state of electrons in the superconducting regime and in 2D was first proposed by Jon Magne Leinaas and Jan Myrheim from the University of Oslo in 1976 and then elaborated by Frank Wilczek in 1982. Chetan Nayak, the Microsoft quantum hardware lead and main author of their papers, did his PhD with Franck Wilczek in 2006!

What are MBSs and MZMs?

Alexei Kitaev then had the idea in 1997 to use anyons for quantum calculations when he was a researcher at Microsoft. He published two foundational papers in 2000 describing the category of **fermionic quantum computers** and a model of **spinless fermions** in a 1D superconducting nanowire, *aka* a Kitaev chain. The first category is quite generic and could potentially be implemented with neutral atoms, but it is more complicated to experiment compared to bosonic cold atoms like the ones used by Pasqal and QuEra. In 2001, Alexei Kitaev and **Michael Freedman** set the stage for **topological quantum computation** when they worked at Microsoft Research.

In 2008, Liang Fu and C.L. Kane from the University of Pennsylvania predicted that **Majorana bound states** (MBS) can appear at the interface between topological insulators and superconductors.

In 2010, two independent theoretical proposals established the foundation for realizing Majorana modes in semiconductor nanowires coupled to conventional superconductors. One came from Roman Lutchyn, Jay Sau, and S. Das Sarma, from the University of Maryland. It **detailed** how a semiconductor nanowire placed in proximity to an s-wave superconductor and subjected to an external magnetic field, could host Majorana zero modes at its ends. The other, from Yuval Oreg, Gil Refael, and Felix von Oppen from Israel, Germany and the USA, was a **similar framework**, showing that the interplay between induced superconductivity, spin-orbit interactions, and Zeeman splitting could drive the system into a topological superconducting phase supportive of Majorana bound states.

Then, in 2012, Leo Kouwenhoven from TU Delft announced the detection of the signature of **Majorana zero modes** (MZM) quasiparticles in a paper published in Nature, coauthored by Vincent Mourik and Sergei Frolov. In 2018, while a Microsoft researcher in Delft, he published another Nature paper reporting the observation of conductance plateaus at zero bias, another key signature of MZMs.

In May/June 2019, a group of German and Austrian researchers said they **succeeded** in creating two-dimensional topological phenomena like Majorana zero modes. Princeton researchers also **published** in June 2019 the results of their work that led them to control the state of a quasiparticle.

2021 marked the beginning of a crisis winter for Majorana qubits. It started with an expression of concern and a withdrawal of Leo Kouwenhoven's 2018 Nature paper. The withdrawal came after **Sergey Frolov** and his former fellow Pittsburgh researcher **Vincent Mourik** unsuccessfully tried to reproduce Kouwenhoven's experiment. Leo Kouwenhoven left Microsoft in March 2022. TU Delft's Research Integrity Committee conducted two **investigations** into possible violations of scientific integrity related to this research. Investigations concluded that while there was no malicious intent, there was negligence in data processing.

Sergei Frolov et al from the University of Pittsburgh made in 2019 a **proposal** for the creation of Majorana bound states using the 4? Majorana-Josephson effect using a fluxonium superconducting qubit, the ensemble being branded a braidonium. A TU Delft team with Leo Kouwenhoven along with researchers from Purdue University (which collaborates with Microsoft) **found** in 2023 a way to create a two-sites quantum dots based Kitaev chain to engineer Majorana bound states.

Other researchers in Germany **integrated** a topological insulator into a superconducting qubit in 2022, following on a 2013 **proposal** from researchers from Caltech and Harvard. Another 2020 **proposal** is to couple a Majorana qubit playing the role of a well-protected quantum memory and a superconducting qubit for computation and to implement a SWAP gate between these.

In August 2019, NIST physicists led by Nick Butch announced the accidental discovery of interesting properties of uranium ditelluride (UTe_2). It would be superconducting at 1.7K with the ability to do so via Cooper pairs with identical spins in addition to opposite spins, allowing three types of pairs. This would give it a rare ability to get magnetic flux resistant superconductivity. This material would thus have topological properties in this framework allowing the creation of topological qubits that are more stable and less subject to decoherence. Related work was published by researchers from John Hopkins University in 2018 with superconducting topological qubits made of a bismuth-palladium alloy. And the story goes on and on around Majorana fermions that are discovered, believed to be discovered or rediscovered depending on the case. Most of the time, the discoveries deal with very weak experimental signals that can be confused with ambient noise.

Majorana fermions are also developed in various materials and heterostructures:

- On the surface of superconducting nanowires, particularly in Denmark and with Microsoft.
- In heterostructures with different magnetic materials in the USA and China.
- On gold, mostly in the USA.
- In 2D graphene, in Spain and France.
- With ?-$RuCl_3$ (alpha ruthenium trichloride) in Japan, which is a potential Kitaev quantum spin liquid.
- In ??BiPd (alpha-Bismuth Palladium) crystals, in the USA.

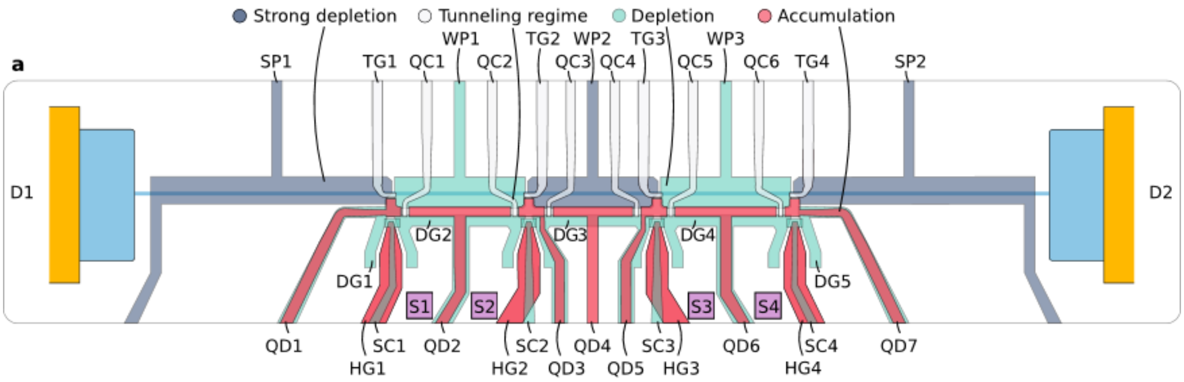
At this point of this paper, you should be lost, like me! But hold on!

What is happening in MZMs?

In the Majorana superconducting wire, all free electrons are assembled in Cooper's pairs with opposite spins, like in any superconducting material. When there is an unpaired electron in the nanowire, it exhibits a curious wave function splitting it in the two opposite edges of the nanowire. Each edge contains a supposedly "half-electron", but it is a probabilistic view of it. In general in superconductors, only electrons close to the chemical potential form Cooper pairs. The additional state present in a topological superconductor is exactly at the chemical potential.

Microsoft Majorana qubits are made with four Majorana zero mode (MZM) and are named "tetrons". They are made of two superconducting nanowires with an MZM at each end, the nanowires being connected in the middle by a regular superconducting nanowire, probably made of aluminum. The topological nanowires are made in a material stack featuring a two-dimensional electron gas (2DEG) formed in an InAs quantum well next to an aluminum based "s-wave" superconductor.

The qubit two possible states are complex to describe. They represent a nonlocally encoded fermionic state defined by the collective parity of the system. The four MZMs labelled ??, ??, ??, and ?? are paired in two different ways to define two Dirac fermions. One common pairing is to define two complex fermion operators, for instance, c? = (?? + i??)/2 and c? = (?? + i??)/2. However, because the overall fermion parity (the total number of electrons modulo 2) is conserved in an isolated superconducting system, the four-MZM system has a fixed global parity. This parity constraint reduces the four-dimensional Hilbert space of the two Dirac fermions down to an effective two-dimensional qubit subspace. In simple terms, to create a two-level quantum system.



Pictured above: two Majorana modes and their controls: QDi (7 quantum dots along the superconducting nanowire), QCi (quantum dot cutter gates control inter-dot tunnel couplings), TGi (tunnel gates control coupling between the small dots and the nanowire), SCi (source cutter gates control coupling between the small dots and the two dimensional electron gas), SPi (side plungers), WPi (wire plungers), HPi (helper gates which run from the dot region all the way to metallic Ohmic source contacts), and DGi (depletion gates).

The operators c? and c? represent the emergent fermionic modes formed by pairing Majorana zero modes that live in the superconducting nanowire. c? and c? do not correspond to a localized electron that can be directly seen in one location or the other. They describe nonlocal collective excitations that are spread over two spatially separated regions where the Majorana modes reside (the left and right end of the nanowire, a double thin green line in the above figure).

The “0” or “1” occupation numbers indicate whether the corresponding composite fermionic mode is unoccupied or occupied by a quasiparticle excitation. This excitation is not a traditional electron but a coherent superposition of electron and hole components that arises due to the superconducting pairing. The occupation numbers reflect the overall parity of the system rather than the presence of a single, localized electron, embodying the nonlocal encoding that protects the qubit from local disturbances. This weird encoding protects the qubit from local perturbations, since any local disturbance would generally affect only one of the MZMs and not change the collective parity without acting on both pairs simultaneously.

This topological encoding is the basis of the proposed Majorana-based quantum computation. It ensures that the qubit manifold represents a delocalized, nonlocal degree of freedom that is robust against local errors rather than a simple charge localization picture.

How are quantum gates implemented with MZMs?

Microsoft’s topological qubits are not handled like with most other solid state qubits where a quantum algorithm is decomposed into a sequence of quantum gates operating in either single or two qubits. Two qubit gates are important since these are the one generating entanglement between qubits and creating qubit interdependencies. Single qubit gates are usually handled by sending some microwave on the qubit through some waveguide, or optical photons beams onto atoms and ions. Two qubit gates require more complicated operations, like the use of tunable couplers connecting two superconducting qubits or lowering a potential barrier between two potential wells hosting electrons in silicon qubits.

Microsoft topological qubits implement quantum gates with single qubit measurements and two-qubit parity measurements and with leveraging “braiding” mechanisms. It is reminiscent of the measurement based model that is being developed by photonic qubits companies like Quandela and PsiQuantum, but it is a bit different.

The Microsoft arXiv blueprint explains how gates are implemented with measurements, covering the Clifford group and then the T gates, and the associated error correction.

In the current Majorana-1 single qubit chip, Microsoft is implementing single qubit gates which are based on a series of measurement on X, Y and Z bases on single qubits and parity measurements on multiple qubits. For example, a Hadamard gate is the result of consecutive X, Y, ZY and X measurements. An S gate (half a Z gate) is a series of X, Y, ZZ and X measurements.

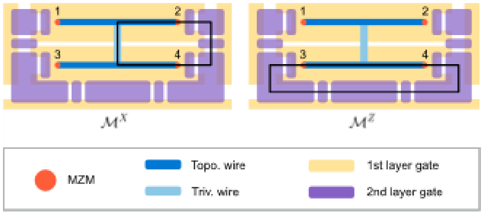


FIG. 2. *Gate schematic of the single-qubit device with measurement loops indicated.* The tetron is formed by two parallel topological wires connected by a trivial superconducting backbone. MZMs form at each end of the topological wires and are labeled $1-4$ as shown. The chemical potential in the wires is controlled by first layer gates that deplete the 2DEG away from the superconductor. Quantum dot plungers and cutter gates between quantum dots and the MZMs are second layer gates. Depletion gates surround the device. The top and bottom panels show X and Z measurements formed by tuning the gates along the black lines and measuring on one of the quantum dot plunger gates involved in the loop.

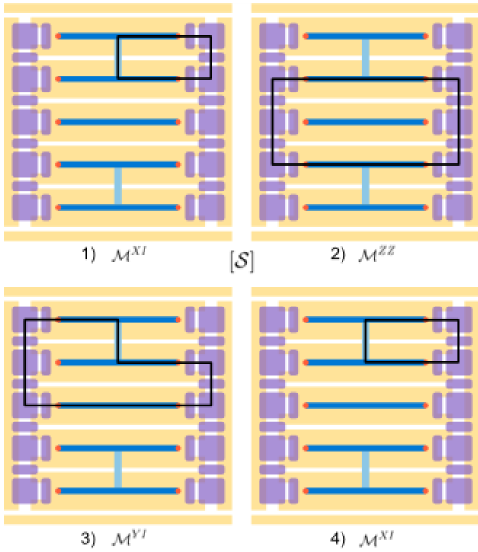


FIG. 3. Measurement sequence for implementing $[\mathcal{S}]$ in Eq. (13) on the two-qubit device (same legend as in Fig. 2). The sequence is equivalent to applying a braid to MZMs 1 and 2 on the computational (bottom) qubit, see Appendix C for the explicit connection.

Above picture: Microsoft chart from their arXiv blueprint explaining how measurements are implemented. You see how basic X and Z measurements are done on a single tetron on the left. And on the right, how and S gate is implemented with XI, ZZ, YI and XI measurements using two tetrons with an ancilla 2-MZM sitting in-between the two tetrons and I standing for identity for the other qubit.

The described gates are not natively deterministic. Indeed, all these measurements being probabilistic, they naturally generate errors. These errors are then handled by a classical correction of the final measurement outcome or a modification of subsequent non-Clifford operations. This explains why Majorana topological qubits are tightly associated with error correction and FTQC. It can't work in a "NISQ" fashion with physical qubits being used without error correction.

These quantum gates implemented via measurements do not rely on the preparation of entangled states as in the MBQC/FBQC paradigm proposed for FTQC photonic quantum computers (PsiQuantum, Quandela). MBQC stands for measurement based quantum computing using large cluster states of entangled photons and measurement only computing, and FBQC for fusion based quantum computing which is a variant of MBQC using small cluster states that are connected by probabilistic entangling gates.

The topological programming model seems therefore closer to the traditional gate-based approach in the way it is sequencing computing operations.

In an older Microsoft paper, XX and ZZ joint two-qubit measurements on top of individual X and Z qubit measurements are used to create a CNOT gate as shown in the example below. It is not far from a teleportation protocol used to entangle distant qubits.

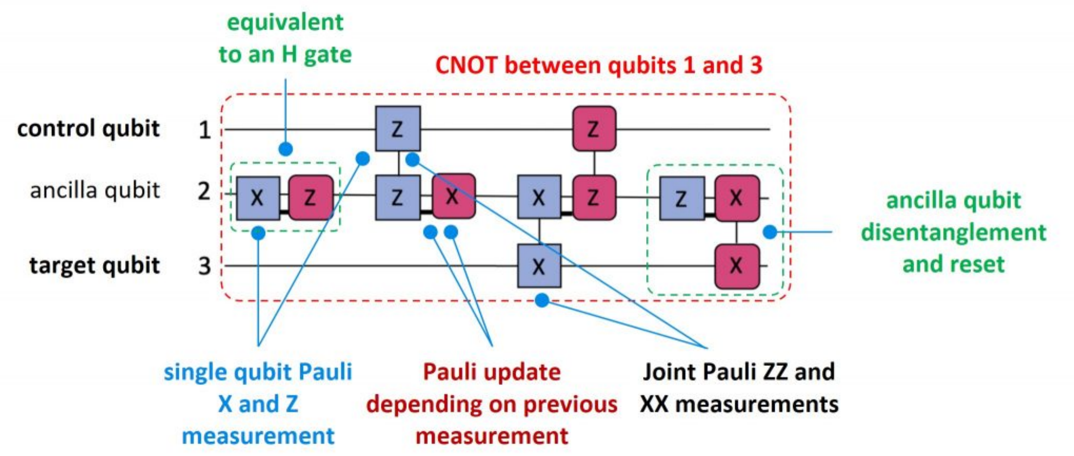


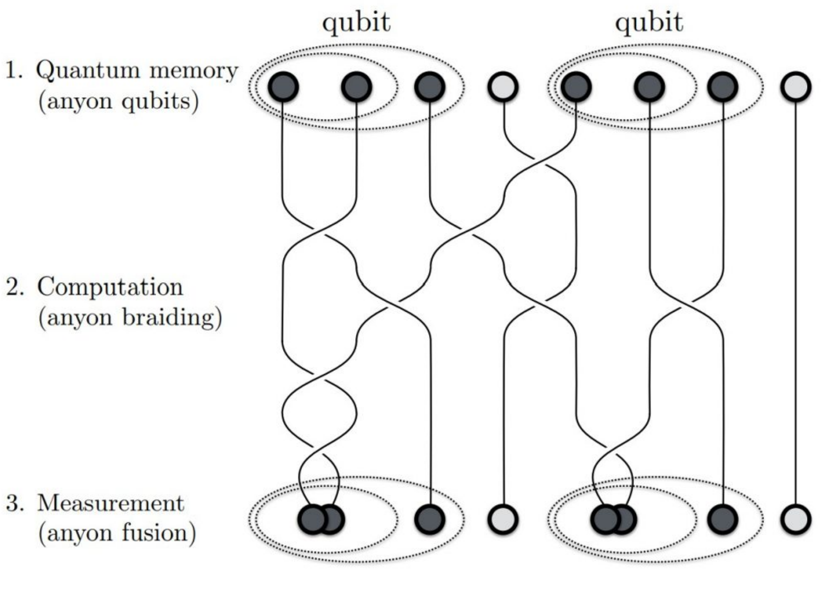
Chart inspired from ***Optimization of the surface code design for Majorana-based qubits*** *by Rui Chao, Michael E. Beverland, Nicolas Delfosse and Jeongwan Haah, Microsoft and USC, October 2020 (19 pages). I am not sure this is the way a CNOT two-qubit gate is implemented in Microsoft tetrons.*

The arXiv explains that single and two qubit gates won't be implemented using the above mentioned techniques, but directly through quantum error correction codes and measurements.

The operations are relatively slow, on the order of several ?s. However, in various estimates of resources generated with Microsoft's resource estimator for FTQC algorithms, execution on Microsoft's topological qubit architecture still has a favorable place, in terms of execution time as well as in the number of physical qubits needed.

What are these braiding operations used in topological qubit computing?

Braiding with Majorana qubits refers to the process of moving MZMs around one another in a controlled way such that their positions exchange. This movement generates a specific change on the qubit register quantum state. It is usually visualized like in the chart below with MZMs, each Majorana zero mode being like a knot tied into a fabric of quantum information. These knots are exchanged or "braided".



The computing outcome depends only on the history of how these particles were exchanged rather than on the precise details of their motion. As a result, the information encoded in the braiding is inherently resistant to errors from local disturbances. This process is explained in **Introduction to topological quantum computation with non-Abelian anyons** by Bernard Field, and Tapio Simula, arXiv, February-April 2018 (51 pages).

This being said, based on the literature, I have not yet understood how this works in practice! When looking at the way it is implemented in the latest Microsoft design, the braiding process corresponds to the way a gate is decomposed in a series of measurements, like the S gate described earlier. This is described in Figure 9 of Microsoft's blueprint arXiv (*below*). In the chart, solid lines correspond to MZMs labelled 1, 2, 4, 3 from left to right, dashed lines correspond to MZMs fusing to the trivial state I and squiggly lines correspond to MZMs fusing to the fermionic state ? of the computing qubit. So, on the left, the MZM pairs are stacked vertically while they are organized horizontally in the braiding diagram, with the arrow of time flowing from top to bottom.

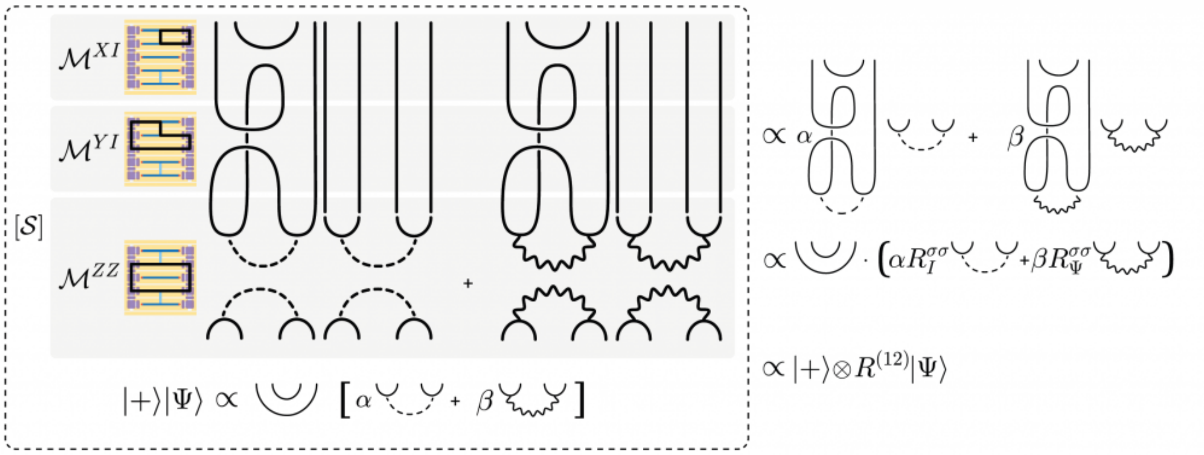


FIG. 9. Mapping the measurement sequence for $[\mathcal{S}]$ to the braid of MZMs 1 and 2 on the computational qubit. The solid lines correspond to MZMs labeled 1, 2, 4, 3 from left to right, dashed lines correspond to MZMs fusing to the trivial state I, squiggly lines correspond to MZMs fusing to the fermionic state ψ. *Left panel.* The state $|+\rangle|\Psi\rangle$ is the two-qubit state prepared after applying $\mathcal{M}^{XI}$ to a generic state. The expression within the dashed-line box maps each measurement to its corresponding diagrammatic expression, with shaded sections separating different measurements. The sequence is read from bottom to top. *Right panel.* Applying the operator to the state on the left and collapsing the diagram results in the diagrammatic expressions shown, which can be rewritten as the braid on MZMs 1 and 2 applied to the state $|+\rangle|\Psi\rangle$. The diagrammatic calculus is explained in greater detail in Refs. 177 and 178 Appendix E.

This graphical notation is different from **ZX Calculus**, a graphical language used to describe quantum operations including error correction. It was created by Bob Coecke and Ross Duncan in 2008. Bob currently works with Quantinuum as chief scientist. But the current braiding graphical representation is not yet using ZX Calculus. It is at the proposal level, as shown in **The ZX-calculus as a Language for Topological Quantum Computation** by Fatimah Rita Ahmadi, and Aleks Kissinger, arXiv, November 2022-August 2023 (14 pages).

How do you measure a Majorana qubit?

Qubit measurement is performed by forming interferometric loops between qubit islands and nearby quantum dots. This causes a state-dependent shift in the quantum capacitance of the dots, which is detected using microwave reflectometry, using a resonator positioned in a secondary chip.

By enabling single-electron tunneling between the MZMs and an adjacent chain of quantum dots, a qubit state-dependent shift of the energy spectrum of the quantum dots is induced. This shift is measured as a change in the quantum capacitance.

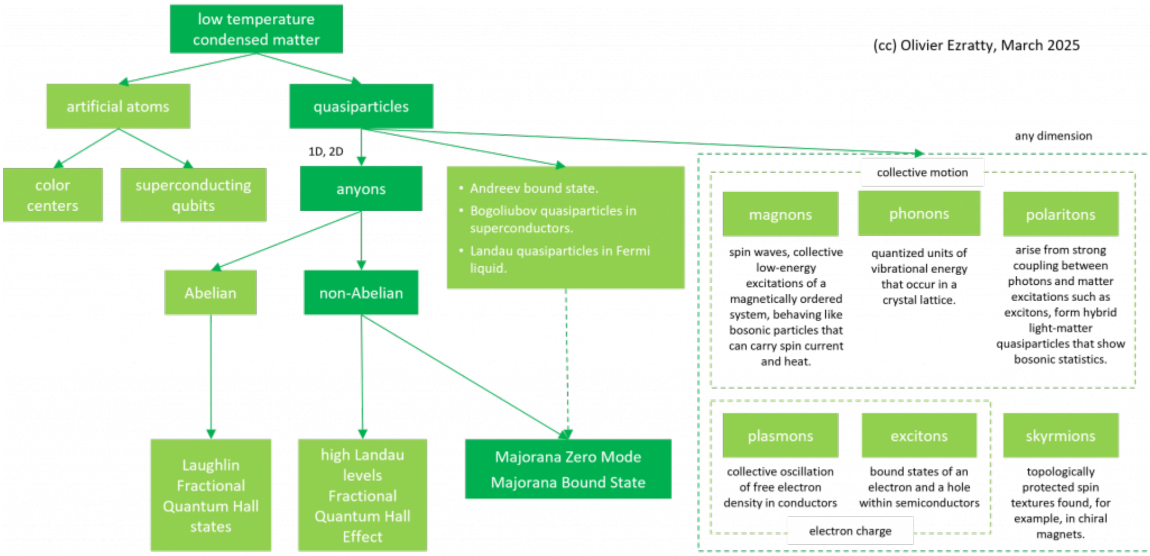
The Nature paper that underpins their arXiv blueprint is about their demonstration of the ability to "read" the state of a pairs of MZMs. This consists of determining whether the number of electrons flowing in a nanowire is even or odd… on a billion electrons, via a simple quantum dot. The measurement must therefore be extremely accurate and scale, which has not yet been tested. It is affected by unwanted quasiparticles and various charge noise sources.

These measurements use a microwave resonator that is reminiscent of what is done with superconducting and silicon qubits. Like in **Fast Gate-Based Readout of Silicon Quantum Dots Using Josephson Parametric Amplification** by S. Schaal et al, PRL, February 2020 (7 pages) that is mentioned in the Nature Supplemental Materials.

Did Microsoft invent a new state of matter?

Not really. It depends on how you define matter and state. A topological qubit is not a phase of matter, like in plasma, gas, liquid, solid, superfluid, supersolid, or a Bose-Einstein condensate. It is a quasiparticle based on the collective state of electrons in superconducting nanowires. The material is this nanowire.

And there are many such quasiparticles around, as shown in the chart below that I created for this paper. There are also various states of electrons in semiconductors and light-electrons interactions generating polaritons. You also have various spin systems like spin liquids, skyrmions, magnons and so on, which are related to the way electron spins are handled in semiconducting materials. A superconducting current in a loop traversing a Josephson junction is made of Cooper pairs of electrons with opposite spins. It is behaving as an artificial atom.



How is Ettore Majorana related to these qubits?

Not much!

In 1937, he had the idea of a fermion being its own antiparticle which was supposed to be an elementary particle and not a quasiparticle. He had no idea this would lead to creating quantum computers, a concept created in the early 1980s, and its name created in 1995. The basic principles of quantum computing were created between 1979 and 1982 by Yuri Manin, Paul Benioff and Richard Feynman, and later in 1985 by David Deutsch. The word qubit was created later, in 1995, by Benjamin Schumacher, from the Los Alamos National Laboratory, in his Physical Review A paper **Quantum coding**.

The idea of fermionic computing based on Majorana-inspired quasiparticles in condensed matter came from Alexi Kitaev in 1997 as previously explained.

What level of noise protection comes with MZMs?

Topological qubits are supposed to be protected against certain types of errors thanks to the way their two possible states are physically handled and can resist various sources of noise. The mitigated errors are local and are the so-called Pauli errors affecting individual qubits: the X amplitude errors (or “flip errors”) and the Z phase errors.

However, these qubits are not entirely error proof. The physical error rates they display is between 10^{-4} and 10^{-6} given it is not entirely clear how they are benchmarked and whether it corresponds to "assembled" Clifford gates or to simple X/Y/Z or XX/ZZ measurements. It will maybe fare better than the 10^{-3} to 10^{-4} error rates that you have with superconducting and trapped ion qubits but this remains to be demonstrated experimentally. Residual errors require correction, thus the need for redundancy and error correction codes like with any qubit type.

One caveat is that topological qubits only mitigate local errors at the individual qubit level. It doesn't correct errors linked to the interactions of multiple qubits. Also, it doesn't protect the qubits against the so-called correlated errors that can affect multiple qubits simultaneously like the one that are generated by cosmic rays induced quasiparticles. Like with superconducting qubits, these cosmic ray radiations create quasi-particles in the circuit and alter the qubit state. Their frequency is low, but incompatible with most FTQC algorithms computing times that can easily exceed one hour.

What error correction is done?

In Microsoft roadmap, quantum error detection will start with their first 8-qubit chip, arranged in a 4 × 2 array.

They plan to use a "ladder code" using XX measurements between qubits in columns and YY and ZZ measurements between rows of qubits. It is a subclass of the Hastings-Haah Floquet code, which is related to the surface code, but rely entirely on one- and two-qubit measurements for the extraction of error syndromes.

They also plan to use pair-wise measurement-based surface code. With this code, at distance 7, each logical qubit patch will use a 13×13 array of tetrons, with a single row of tetrons between the patches to support lattice surgery, enabling error correction for T gates, and totaling 182 tetrons. The Hastings-Haah Floquet ladder variant will use 14×14 arrays, and 196 tetrons.

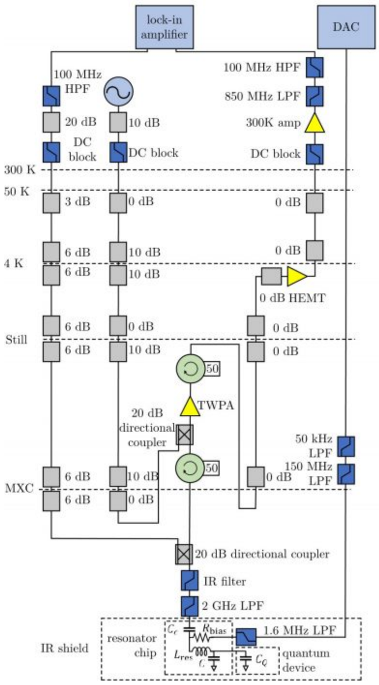
As the correction code distance increases, error syndrome detection will grow in classical computing cost. There is no indication of how that cost will scale in the arXiv blueprint. However, the cost of syndrome error detection may be cheaper than with other qubit modalities due to smaller distance codes needed to obtain a similar logical error rate. But that is not clearly documented.

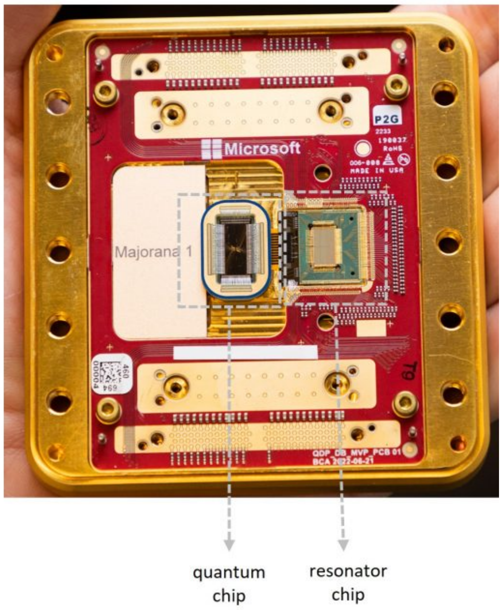
The Majorana-1 chiplet

The chiplet presented in February 2025 is made with several components:

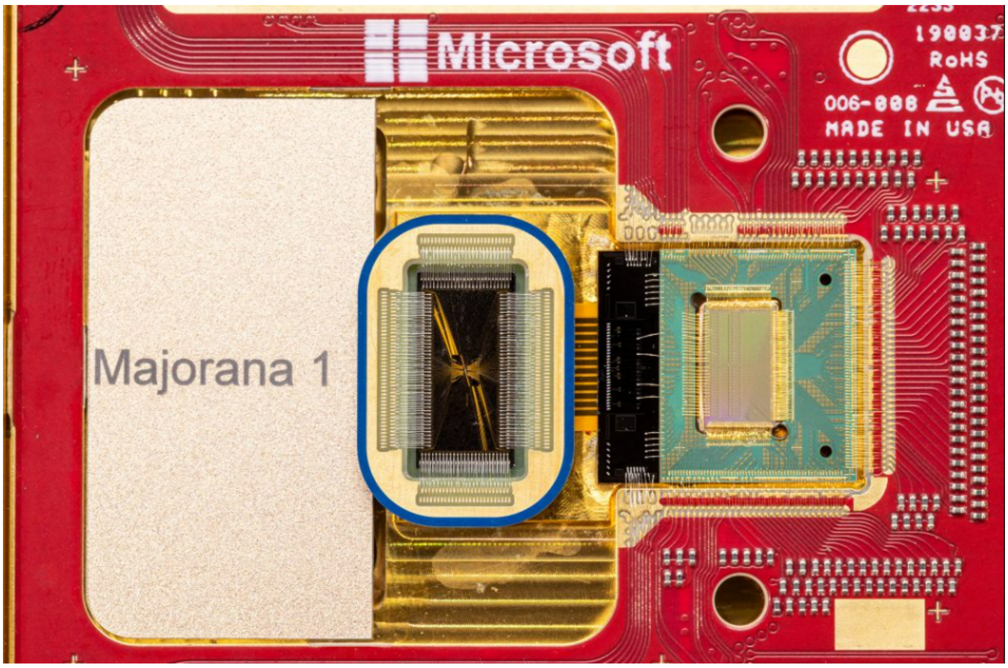
- A chip containing a **single qubit**, *below*, in the box indicating "Majorana 1". The chip is manufactured using a fairly classic techniques in III/V. Chetan Nayak mentioned that the chip actually hosts 8 qubits and that the shown chip is not the actual chip due to some IP restrictions.

- A chip containing the **resonator** allowing the qubit readout, *below* in the green area. But **GQI** states that "*99%+ of the electronic circuitry is digital and controlled by a cryoCMOS chip which sits right next to the qubit chip*" which they probably got from Microsoft. It is not consistent with Microsoft's Nature paper supplemental materials, meaning that the electronic design presented below on the left in this paper may not correspond to the one used in their Majorana-1 system.





- Some **interconnect wiring** between the two chips and connecting the resonator chip to outside electronic components. The complexity of this wiring is not documented at scale. For a single qubit, it seems already quite complicated as you can see below when zooming on the two chips wires.



This chiplet which operates at 50 mK is not "the whole computer". It has a similar size than most quantum chips like the one you have in superconducting qubit quantum computers. You then still need a cryostat with a dilution, control electronics and cabling, including room temperature electronics, which occupies several cubic meters in a dedicated room. Viewed from the outside, a Microsoft quantum computer looks like and IQM, Rigetti or IBM System One computer.

How does qubit control work?

However, the way qubits are controlled is a bit simpler than with superconducting qubits as shown in the above left diagram. You don't need AWGs (arbitrary wave generators). As the blueprint arXiv states: "*While* *conventional qubits typically rely on precise shaping of control pulses, measurement-based topological qubits are more digital in nature: the pulses need to tune from an idle configuration to approximately the optimal measurement point, but the precise timing and shape of the pulse have negligible effect on the overall measurement performance. This digital nature of the control pulses significantly simplifies tuning and control of the device*“. The measurement pulse duration seems to have a lower bound of 1 ns, with a planned length of 10 ns, which is inline with the best single qubit gate time with superconducting qubits.

The measurement uses an amplifier operating at the quantum limit (a TWPA like the one that are used with superconducting qubits), then a HEMT secondary amplifier operated at 4K (same) and, at last, a room temperature amplifier completes the picture.

In the long term, Microsoft should integrate most of the qubit controls into a cryo-CMOS components. Until 2024, this work was carried out by a Microsoft Research team based in Australia. This laboratory was closed in 2024 and the corresponding activity was repatriated to the USA, probably in their “Station Q” laboratory in Santa Barbara, California. They developed various cryo-CMOS chips to support part of solid state qubits at cryogenic temperature but it doesn’t seem to be used in their current experiments.

What is the size of a Majorana qubit?

A complete Microsoft topological qubit has a size of 5 ?m×3 ?m. These qubits are called “tetrons” because they are made with four Majorana fermions, which are the red dots in the chart below, which are the two ends of two superconducting nanowires, assembled with indium, arsenide and aluminum heterostructures, on InP (indium phosphide) III-V wafers. It also uses hafnium, titanium, aluminum and gold for the creation of various gates.

The resonator size that sits in the other chip is not documented in Microsoft’s papers. It seems to operate at 776 MHz. Its size is probably of at least of 100 ?m×100 ?m if not a square millimeter like with some superconducting qubits. You need then to add at least two capacitances and one resistance. It is thus much larger than the qubits, probably with about a real estate (surface area) 1,000 times larger than the qubit. It may become another scalability concern.

Microsoft says that its chip design could accommodate a million qubits, but it doesn’t say if this includes the resonator chip. We can also suspect that the resonator chip is built using a more traditional technology, either on silicon or sapphire (aluminum oxide), like with most superconducting qubits and electronic chips.

Can III-V manufacturing scale?

The prototype Majorana test chips are currently manufactured in Microsoft’s own cleanroom in Santa Barbara, California. But some part of the fabrication is also done in Delft as well as in Lyngby near Copenhagen.

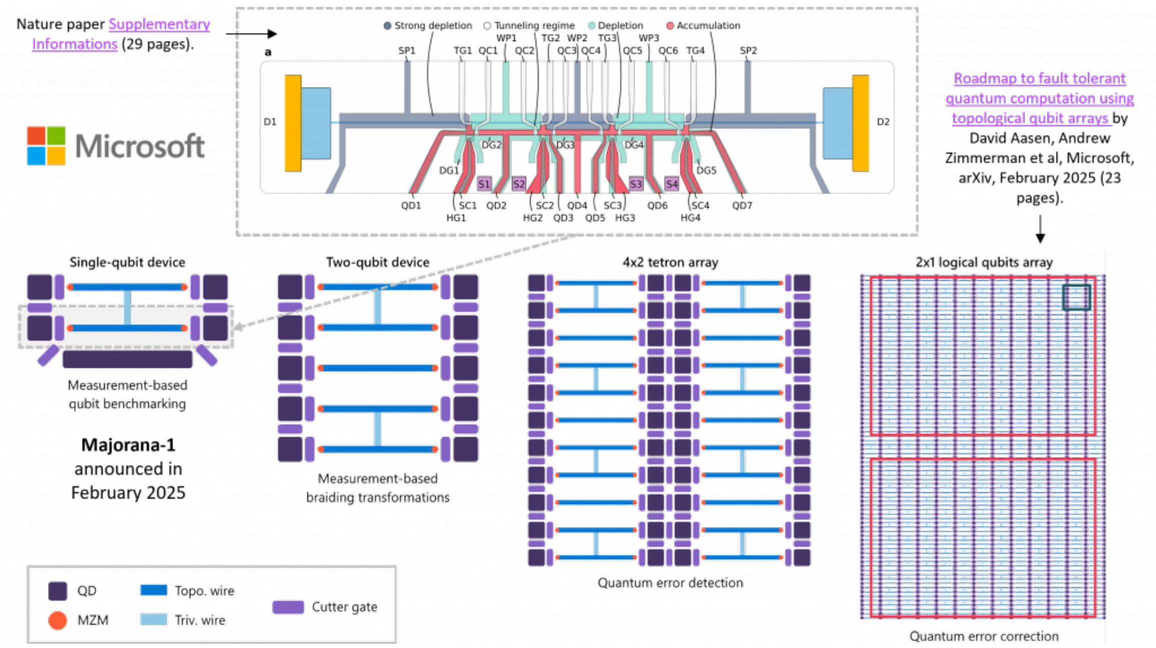
Most of the traditional III-V commercial products in photonics and RF signals handling have only a few electronic elements, and their tiny chips are glued on silicon chips in so-called heterostructures. Nobody has ever manufactured any III-V chip with thousand elements, let alone several millions of elements like what Microsoft is planning for the realization of a million-qubit monolithic chiplet. And there is no industry-grade large scale manufacturing plants for this.

Also, Microsoft’s chip design is highly complex, merging difficulties usually found with manufacturing superconducting qubits (for their MZM nanowires), with silicon qubits (for the quantum dots used in measurement), with cryoelectronics (with their resonators), with cabling at the chip level (which is already incredibly complicated for a single physical qubit). So, there’s a huge uncertainty here with scaling this beast and maintaining high manufacturing quality, high yield and low variability across large chips.

Microsoft roadmap and scaling plans

The next stages of their roadmap are to create:

- A chip with **2 physical qubits** for testing joint measurements on these two qubits that enable the creation of a two-qubit gate (second column).
- A chip with **8 physical qubits** for detecting (residual) errors (third column).
- A chip with **371 physical qubits** containing two logical qubits of 13×13 qubits assembled with a distance 7 surface code (fourth column) and separated by a row of 13 physical qubits. This surface code size is the same as the one that was tested on Google Willow's 105-qubit chip.
- Then, much later, a chip with a **million physical qubits** which could support about 1,000 logical qubits, but with undocumented logical gate fidelities.



<u>What is the energetic cost of Majorana qubit quantum computers</u>?

At this point in time and given the many uncertainties around the qubits themselves, there are still some available technical elements to consider to assess the energetic footprint of quantum computers based on Microsoft topological qubits.

The energetic footprint of these future quantum computers could potentially be favorable for a couple reasons. The first one is that the error correction overhead might be lower than with typical qubits, unless they also implement autonomous error correction like cat-qubits. The second is that qubit drive seems simpler than with superconducting qubits and, potentially, spin qubits. There seems to be no need for AWG and control pulses are simpler to generate. They may be potentially easier to generate at cryo-temperature, thus saving cabling. The qubits run at an intermediate temperature, 50 mK, between superconducting qubits (15 mK) and silicon qubits (about 500 mK).

There is still some dissipation happening in the cryostat, driving energetic needs for ongoing cooling. The main one comes from driving and readout cabling dissipation. It might be reduced if cryo-CMOS (or SFQ) electronics is used for qubit control, at a 4K level.

Qubit operations are based on dispersive gate-sensing measurements of the quantum capacitance. It is dissipative. Other sources of dissipation may happen at interfaces where MZMs interact with external degrees of freedom: at the superconductor-normal metal interface, where charge fluctuations lead to decoherence, in the bulk of the superconducting host material, and in the electrostatic gating environment, where charge noise may perturb the MZM states. This must be investigated but I would suspect that the bulk of the energetic cost lies more in the control electronics than this.

Why was Microsoft selected by DARPA?

DARPA selected Microsoft and PsiQuantum in February 2025 as part of their **Underexplored Systems for Utility-Scale Quantum Computing** (US2QC) program launched in 2023. About 9 other companies which are not considered working in “underexplored systems” are in the selection process for the Quantum Benchmark Initiative call, which complemented the US2QC program in Summer 2024.

You may wonder why Microsoft and PsiQuantum were selected. They are probably the most contested players in the FTQC realm. A third player initially selected in 2023, Atom Computing, was the unlucky one. They rely on neutral atoms qubits where the considered state is the atoms nuclei spin.

As to the why, well… I don’t really know! Three options: DARPA evaluators are gullible, they are high risk-takers, and/or they have access to undisclosed information.

What problems will Microsoft’s quantum computer solve?

Microsoft’s topological qubits are supposed to enable fault-tolerant quantum computing, operating in “gate-based” mode. It will be generic as to which kind of algorithm it will be able to run. It can cover the usual suspects like material and chemical simulations, solving optimization problems, solving various differential equations for various engineering use cases like in aerospace and fluid mechanics and machine learning. There are uncertainties here on which of the related algorithms will deliver practical speedups vs best-in-class classical algorithms and hardware, but they are not directly related to the qubit type.

There are other questions like the cost of quantum code compilation and optimization for large quantum circuits. How error correction will operate? What will be its classical cost? We can presume here that the topological protection of the qubits, if it works well, and other technical details we examine in this paper, will enable the creation of simpler circuits to solve these problems. It may thus reduce the classical middleware and software engineering workload. But there’s a clear lack of information there.

Other topological qubits

Different quantum physics laboratories are working on topological qubits, notably in China, Germany, the UK, the Netherlands, Denmark, Australia, Japan, Finland, Finland, Switzerland and Russia.

In the USA, **Maryland**, **Caltech**, **Wisconsin Madison University** and **Purdue University** have teams working on topological quantum computing and/or Majorana fermions, the two later working with Microsoft Research. It is also the case of the Quantum Science Center (QSC) from the DoE **ORNL** as well as the **Sandia Labs**. The KouBit Lab from the **University of Illinois** and led by Angela Kou also investigates topologically protected superconducting qubits as well as a team led by Javad Shabani at the **New York University**. Researchers from **Cambridge University** are proposing to create NISQ QPUs with topological qubits. Majorana zero modes (MZMs) were also found by researchers in **China** in 2022 with iron-based superconductors showcasing topological vortices.

In **France**, Julia Meyer at CEA-IRIG in Grenoble, Pierre Mallet at CNRS Institut Néel in Grenoble, and Pascal

Simon at the LPS in Orsay do work on various topological matter physics. Some of these researchers are conducting joint projects with TU Delft and Sergei Frolov at Pittsburgh.

Topological qubits are tested with other qubit types like superconducting qubits. It is about creating sort of topological error correction codes with "classical" qubits. In 2022, an **IBM Research** team published a paper showing how they could simulate Majorana Zero Modes (MZM), Majorana Pi Modes (MPM) and Majorana braiding on 27-qubits quantum computers. A **Google AI** team did a similar experiment with 47 qubits from its Sycamore processor and simulating Majorana Edge Modes. A team led by the **Flatiron Institute** emulated MZM on ten ytterbium trapped ions. Likewise, a team from **Quantinuum**, **Harvard University** and **Caltech** **implemented** a topological error correction code with trapped ions.

Microsoft is not the only industry vendor in the topological qubit realm. A **Nokia** team led by Robert Willett is working on topological qubits in their Murray Hill labs in New Jersey. They conduct fundamental research, have no commercial approach, and therefore do not publish any fancy roadmaps. At some point, they even **collaborated** with Microsoft Research but parted ways since then.

There is also a startup, **Quoherent** (2021, USA, 6.2M), that wants to create a portable quantum computer using topological insulators, and operating at room temperature. Their CTO is David Carroll, a quantum materials physicist and the Director of the Center for Nanotechnology and Molecular Materials at Wake Forest University in North Carolina. The startup which is based in Alabama has not released any public roadmap.

You can find references about all these mentioned teams in the Topological qubits section of **my book**. All the above mentioned work relates to fundamental research with no pretense to build a topological qubit quantum computer in years.

The debate on Microsoft Majorana qubits

The new Nature paper

The Microsoft paper published in Nature in February 2025 sparked a new controversy. It began with its troublesome evaluation. In the **peer-review paper**, Nature's editorial team begins by stating that: "*the results in this manuscript do not represent evidence for the presence of Majorana zero modes in the reported devices*". Of the four referees, two were opposed to the publication of the paper even after Microsoft authors responded to their first comments. In the remaining two, it appears that one of them, Hao Zhang, is "conflicted," having been the lead author of Microsoft's 2018 retracted paper from Nature.

Here are some of the dissenting referee's feedback:

*Referee #1: "The text is plagued with such **misleading and ambiguous wording** where theoretical prediction, device design and actual proof in experiment/data is mixed in a rather careless manner.". "**These measurements do not, by themselves, determine whether the low-energy states detected by interferometry are topological**… How can we then know that the interpretation is correct?". "I have no great criticisms of the experiment and the data … but rather in the rather **misleading way in which these data are presented** and the extreme simplifications of the modeling which, essentially, assumes a topological state and includes Majoranas by hand, yet again forcing an a priori interpretation of the data.".*

*Round 2: "I stand by my previous report and, in fact, I must now be harsher since after one round of evaluation the authors have had the opportunity to rewrite the article carefully and avoiding the continuous mixing of objective facts with interpretation (sometimes bordering on a strong bias towards a priori conclusions on the part of the authors) but have largely ignored my suggestion (and also that of other referees).". "**Given my***

***overall impression and comments above, I cannot recommend the paper for publication in Nature*.”.**

Referee #4: “The conclusions drawn in this work rest on questionable hypothesis and methodologies. As a result, ***I cannot recommend publication in Nature****.”. “****I am firmly convinced this work should not be published in Nature or any other high visibility journal****.”.*

*Referee #3 (on novelty): “…****the manuscript did not report any material advancements that would lead to new or stronger MZM signatures****… The novelty of this manuscript does not lie in providing stronger evidence for MZMs…”.*

And the part of the paper that explains why it is not yet certain that they have detected a true Majorana fermion: “*We have presented dispersive gate-sensing measurements of the quantum capacitance in InAs–Al hybrid devices using a system architecture that can be adapted to other materials platforms. After tuning the nanowire density and in-plane magnetic field into the parameter regime identified by the TGP14 and balancing the interferometer formed by the nanowire and the quantum dots, we observed a flux-dependent bimodal RTS in the quantum capacitance, which we interpret as switches of the parity of a fermionic state in the wire. We have fit these data to a model in which the fermion parity is associated with two MZMs localized at the opposite ends of a 1DTS and find good agreement.* ***These measurements do not, by themselves, determine whether the low-energy states detected by interferometry are topological****. However, our data tightly constrain the allowable energy splittings in models of trivial Andreev states*“.

The argument is put forward that what Microsoft measured is not necessarily an MZM topological state but potentially an Andreev state, which does not have the characteristics of an MZM state and is not sufficient to protect the qubits against noise.

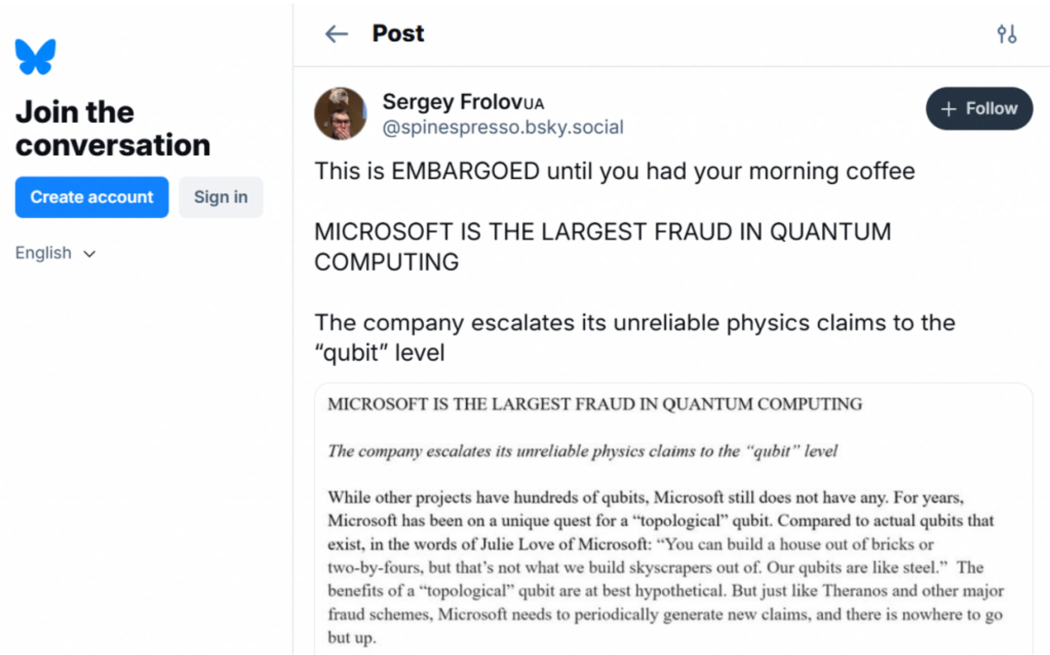
However, it seems that the chip presented to the media by Microsoft does not correspond to the one tested in the Nature paper, which is nearly a year old, and that a new paper should be published on this new version of their physical one-qubit chip for which the measurement of the MZM would seem more conclusive. More news is to come during the APS March meeting in Anaheim mid-March 2025 where Microsoft researchers will do several presentations on their work. I’ll update this paper accordingly when more information is available.

Negative reactions

Very negative reactions came from condensed matter and topological matter specialists, not random uneducated zombie commenters:

- **Victor Galistki** from Maryland University, on **LinkedIn**. This researcher is known for his hard stance on the quantum hype, with his essay **Quantum Computing Hype is Bad for Science** published on LinkedIn in 2021.

- **Sergei Frolov** from Pittsburgh University, on **BlueSky**, who is behind the several paper retractions mentioned above. He worked with Leo Kouwenhoven at Delft in the early 2010s and couldn’t replicate their experiments on MZMs. He also **recalled** how Microsoft has been toying with experimental data and scientific integrity. Another way to understand the critics is that they give the impression that Microsoft researchers are subject to some confirmation bias when exploiting their experiments results.



- **Vincent Mourik**, who collaborates with Sergei Frolov, on **LinkedIn** and a **reaction** to a post from John Preskill about Jason Alicea's paper.
- **Sergei Frolov** and **Vincent Mourik** together in a **one hour video**.
- **Henry F. Legg**, a physicist from the University of Saint Andrews (UK) and Basel who works on topological matter who **describes on X** the way Microsoft toyed with experimental data in its papers, and who published a detailed arXiv: **Comment on "InAs-Al hybrid devices passing the topological gap protocol", Microsoft Quantum, Phys. Rev. B 107, 245423 (2023)** by Henry F. Legg, arXiv, February 2025 (9 pages) which related to an older and also controversial paper: **InAs-Al hybrid devices passing the topological gap protocol** by Randall D. Kamien, Jessica Thomas, Stephen E. Nagler, Anthony M. Begley, and Sarma Kancharla, Physical Review B, June 2023 (54 pages). It concludes that: "*Our findings also suggest that subsequent studies, e.g. Nature 638, 651–655 (2025), that are based on tuning up devices via the TGP are built on a flawed protocol and should also be revisited*". TGP, topological gap protocol, is the protocol used by Microsoft to detect the topological effects in its physical experiments.
- The **Wall Street Journal** which, in **Physicists Question Microsoft's Quantum Claim** by Nidhi Subbaraman, compiles the many doubts from physicists on Microsoft's work.
- **Thomas Claburn** from The Register in **Microsoft quantum breakthrough claims labeled 'unreliable' and 'essentially fraudulent'**, March 2025, which casts the disagreements from Sergei Frolov, Henry F. Legg and others and Microsoft's response.
- **Sabine Hossenfelder** with a succinct **video**.

Neutral to positive reactions

There were other, neutral to positive reactions, who unfortunately were not very deep analysis, particularly given they were frequently prepared in less than a day:

- **Scott Aaronson** with its **short FAQ** published a day after the announcement. The comments are interesting, including those coming from Chetan Nayak and his boss Zulfi Alam.

- **Jason Alicea** in **What does it mean to create a topological qubit?**, Quantum Frontiers.
- **A detailed analysis** from **GQI** which seems to reformat Microsoft's announcement.
- **Dimitrios Angelakis**, a Greek researcher based in Singapore, who **describes** Microsoft's work and the difference between the Nature paper and Microsoft's subsequent marketing communication.
- **Ramon Aguado**, a Spanish researcher who **highlights** how difficult it is to control a MZM. He explains very well why MZMs topological effects can be identified due to "false positive" measurement results.
- **Christian Dickel**, a German physicist on **LinkedIn**.
- **Michaela Eichinger** who works with Quantum Machines and is very active on **LinkedIn**.
- **Todd Bishop** with a good paper on the announcement: **Microsoft quantum breakthrough promises to usher in the next era of computing in 'years, not decades'** in GeekWire, February 2025.
- **Cogni Down Under** (who's that person?) in **The Quantum Long Game: Microsoft's Majorana 1 Chip Is Unlike Anything We've Seen** Medium which recast some confusing information such as Microsoft's current chip having 8 qubits white it has only 1 qubit, made of 4 MZMs. The 8-qubit chip is second in-line in Microsoft's roadmap after the current Majorana-1 version. But Chetan Nayak was supposedly heard saying they already had such an 8 qubit chip.
- **Maria Violaris**, a physicist who now works at OQC, in a video, **Quantum Physicist Reacts to Microsoft Majorana 1 Quantum Chip!**, February 2025 (17mn 25s).

And so many others I can't recount!

Microsoft track record

Microsoft's reputation with Majorana fermions got a bad turn when one of their papers was retracted in 2021 as mentioned at the beginning of this post. First, **Quantized Majorana conductance** by Leo Kouwenhoven et al, 2017 in arXiv and 2018 in **Nature** (26 pages) which was followed by an "**expression of concern**" from the authors warning readers about the veracity of the published results, which were not reproducible due to a problem with the calibration of measuring instruments. The coverage on the paper withdrawal in 2021 was dense, starting with **Data manipulation and omission in 'Quantized Majorana conductance', Zhang et al**, Nature 2018 by Sergei Frolov and Vincent Mourik, March 2021 (31 slides) which spurred **Microsoft's Big Win in Quantum Computing Was an 'Error' After All**, by Tom Simonite, Wired, February 2021. Another of their paper was later retracted. See **Retraction Note: Epitaxy of advanced nanowire quantum devices** by Sasa Gazibegovic, Leo Kouwenhoven et al, Nature, April 2022.

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Letter | Published: 28 March 2018

RETRACTED ARTICLE: Quantized Majorana conductance

Hao Zhang, Chun-Xiao Liu, Sasa Gazibegovic, Di Xu, John A. Logan, Guanzhong Wang, Nick van Loo, Jouri D. S. Bommer, Michiel W. A. de Moor, Diana Car, Roy L. M. Op het Veld, Petrus J. van Veldhoven, Sebastian Koelling, Marcel A. Verheijen, Mihir Pendharkar, Daniel J. Pennachio, Borzoyeh Shojaei, Joon Sue Lee, Chris J. Palmstrøm, Erik P. A. M. Bakkers, S. Das Sarma & Leo P. Kouwenhoven

Nature **556**, 74–79 (2018) | Cite this article

55k Accesses | **458** Citations | **449** Altmetric | Metrics

A Retraction to this article was published on 08 March 2021

An Addendum to this article was published on 29 April 2020

This article has been updated

Another Majorana paper was retracted in 2021, but not from Microsoft. It came from UCLA. **Chiral Majorana fermion modes in a quantum anomalous Hall insulator–superconductor structure**, Science, 2017 (7 pages) was the subject of an **expression of concern** in December 2021 and was retracted in November 2022 by Science with the following comment: "*Readers who failed to reproduce the findings requested raw data files from the authors, which they provided. Subsequently, the provenance of the raw data came into question; additionally, an analysis of the raw and published data revealed serious irregularities and discrepancies*".

Microsoft's track record is also full of past promises on the advent of Majorana fermion based qubits which were around the corner 8 to 2 years ago:

- In 2017, Microsoft was **empathetic** on Majorana fermion « breakthroughs ».
- Microsoft announced at the Build conference in May 2018 that they would release their first fermion-based quantum computer from Majorana in 2023.
- Chetan Nayak touted the creation of a Majorana qubit in 2023: **Microsoft achieves first milestone towards a quantum supercomputer** by Chetan Nayak, Microsoft Azure Quantum Blog, June 2023.

Why?

One question I'm frequently being asked is why is Microsoft risking so much in damaging its image and scientific integrity?

I can bring several explanations, but I am not sure which one is right, if any is missing or if I'm totally wrong:

- **High-risk bet**: Microsoft decided a long time ago to make a high-risk bet with potential high rewards, when selecting to work on topological qubits.

- **Leadership**: Majorana fermion quantum computing is currently the quest of **Chetan Nayak**, a theoretician physicist whose **impressive biography** starts with a thesis done about 30 years ago with Franck Wilczek, who later became a Nobel physic laureate. He is the VP of Microsoft quantum hardware and the main author of the recent Microsoft papers. None of his papers have been retracted so far. He may then be trusted in the company.
- **SPOF**: Chetan Nayak's boss seems to be **Zulfi Alam**, the Corporate VP leading all quantum efforts. Before 2020, he was managing the HoloLens business and is therefore, not a specialist in quantum technologies. He still has a background in semiconductors. He may carry the belief that creating a quantum computer is just a matter of engineering. Chetan Nayak's main peer seem to be **Krysta Svore**, VP Advanced Quantum Development, who leads quantum software efforts. So, Chetan Nayak's surrounding management team is not made of physicists like him. He is then a kind of potential "single point of failure" in the leadership chain. Worth mentioning, Microsoft's CEO Satya Nadella is not a hardware guy, which doesn't help as well.
- **Beliefs**: maybe, some corporate hubris and the belief that any scientific problem can be fixed. When you have the cash, it's just a matter of effort and time. Brute force will pay off. Another naive belief is that once you have a single qubit – which we're not sure they really have -, it becomes easy to scale to a million. As well explained in a recent **Qolab blueprint**, each scalability stage brings its own challenges (from 10 to 100 qubits, 100 to 1,000, 1K to 10K, 10K et 100K and so on). So, definitively, anybody in this field can say confidently that a scalable utility-scale quantum computer, whatever the technology and particularly this one, is not a matter of a couple years.
- **Comforted**: they were, thanks to their selection by DARPA as part of their US2QC program. The selection was announced on February 9th, thirteen days before Microsoft's public announcement of its roadmap and its Majorana-1 chiplet.
- **Affordability**. They can invest in any such risky scientific endeavor. Failing won't affect their mainstream cash cow high-margin cloud business. On top of that, they also hedged their bets with investing in PsiQuantum and Photonic Inc, and with partnering at the software and error correction levels with Quantinuum and Atom Computing. So, they have many potential Plan Bs if their topological qubits endeavor totally fails.
- **Survival**: large corporations' quantum computing teams are fighting for their survival. Cost cutters may loom around. They need to constantly demonstrate advances and drive PR awareness even when they are built on overpromises. And Microsoft is not the only company making overpromises. A few are also champions there, like PsiQuantum, IonQ, and others.

Conclusion and future outlook

One key point is that, even if it works as expected by Microsoft, the practical benefits of their Majorana fermion based qubits seems to be a little oversold, particularly when compared with high-fidelity non topological qubits like trapped ions. When the idea of using topological qubits was created, competing qubit modalities didn't have good fidelities. Things have changed since then, many of these modalities having widely improved their figures of merit. Topological qubits are not the only one with autonomous correction, particularly now that we have the bosonic qubits from Alice&Bob, AWS and Nord Quantique, which are just starting to be demonstrated. The first cat-qubit of Alice&Bob is even already testable on Google's cloud. Also, even though they are slow, trapped ions showcase very high fidelities and qubit connectivity that could compete very well with topological qubits, if they could scale.

Still, if it worked, Microsoft's topological qubits could be interesting with their scaling potential, and relatively low energy footprint. But there are a lot of missing operational prospective data on the physical qubit overhead to obtain a given logical qubit fidelity, which is important to assess the cost of computing large FTQC circuits. You can dig into the work from **Microsoft** and others like **GQI** to find resource estimates for key FTQC algorithms running on topological qubits.

Despite all the negative scientific buzz around Microsoft's work, I would still credit them with some benefit of the doubt. Building FTQC systems is a very hard task, whatever the qubit modality. It takes time. Their work could also potentially benefit other qubit modalities, like silicon qubits and photonic qubits, given they share some technology and challenges on high-precision quantum dot measurements, cryo-electronics and III-V large scale manufacturing. Let's give them this time and forget their overpromise that FTQC is around the corner in a couple years. We need that diversity of approaches in the quantum computing realm.

Disclaimer 1*: this paper is quite technical and may contain factual errors. I correct it on the fly as I detect them or when someone (gently) warns me about it.*

Disclaimer 2*: I worked in marketing (including CMO and director of developer relations) at Microsoft in France between 1990 and 2005 but believe this is not clouding my judgement there.*

Cet article a été publié le 5 mars 2025 et édité en PDF le 25 mars 2025.