

WHAT IS QUANTUM COMPUTING?

Andrew E. Fluck for TC3 and the IFIP TC3 Task Force on the Curriculum

Hello there! This is a brief introduction to quantum computing. Since I am not a quantum computing expert, I have used simple terms and only given single examples from a range of possible alternatives.

Let's look at the main points I will cover in this short presentation.

Main points

- a) As data storage technology advances, we are approaching atomic limits.
- b) Matter at such a small scale is best described using wave theory and probabilities.
- c) Single atoms can be trapped and manipulated by microwaves – making a qubit.
- d) When programming a computer using qubits, solutions can be found more rapidly than with digital binary computers (e.g. Shor's algorithm).
- e) Quantum Information science goes further than just quantum computing.

2/13

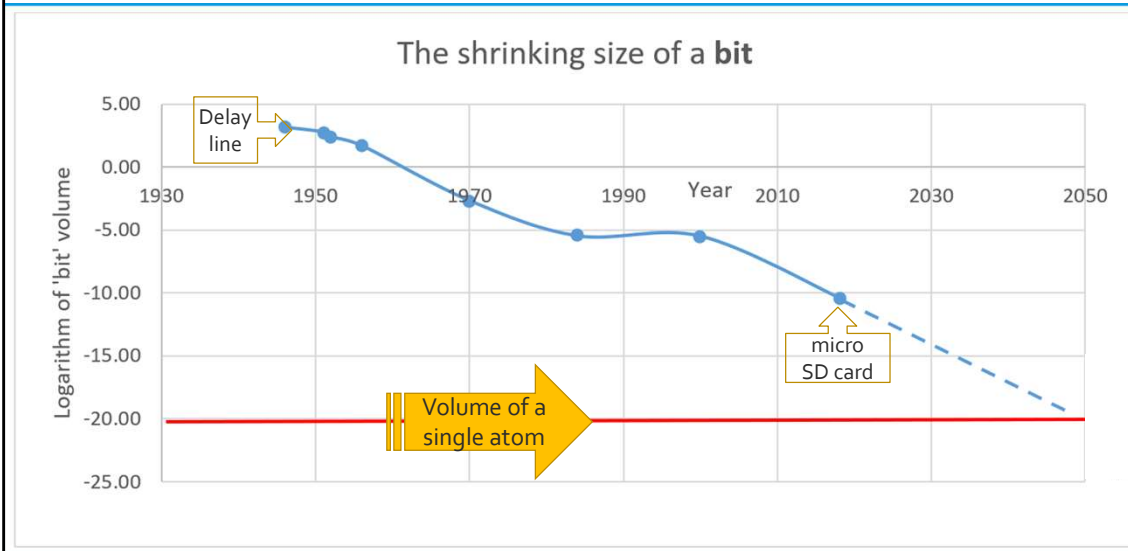
Firstly, I will show how data storage technology is shrinking the physical volume required for information

But our understanding of the universe is divided into big things and small things. Objects on the small atomic scale seem to follow very different rules. Two home experiments illustrate this.

Then we will see how an atom can be trapped and manipulated. This can be a component in a quantum computer. But quantum computers require a different approach to classical binary computers. In some cases, they can find solutions faster.

We'll begin by looking at data storage technology over the past seventy years.

Approaching the quantum limits



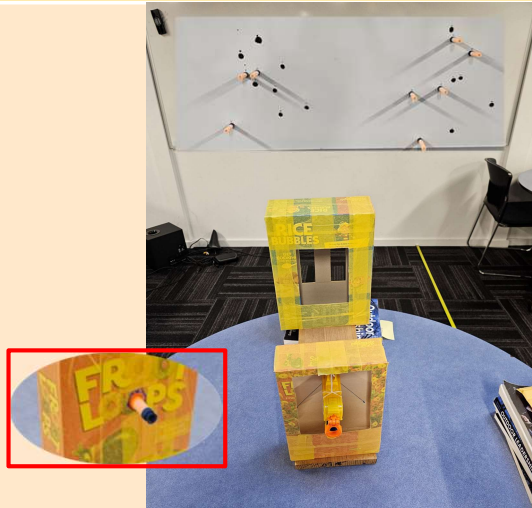
This graph uses a logarithmic scale to show the downward trend of physical storage space per bit in digital computers. It shows how we are approaching the quantum limits.

It begins in 1950 with a mercury delay line holding 1.6 kilobytes. Nowadays, micro SD cards store one terabyte. By extrapolation, we can see the physical storage volume for a single binary digit will reach atomic proportions in the next generation. Matter behaves very differently at these very small scales.

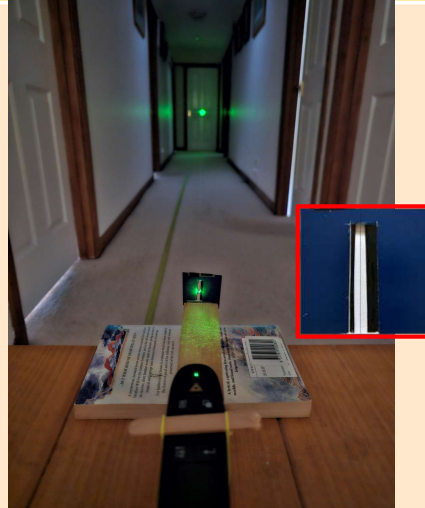
I am now going to show you two home experiments which illustrate how these small quantum elements behave very differently from the objects we see in the world around us.

The double slit experiment – for big and small things

Big things – Nerf pellets shot through slots in a carton



Small things – a laser shone over a human hair



On the left you can see a toy Nerf gun shooting soft, suction-capped pellets. It is mounted in one carton, and was fired through another carton which had two slots. The pellets hit the whiteboard, and their positions were marked.

<CLICK> On the right you can see a green presentation laser shining on a small card with a slot. A single human hair divided the slot into two. It's the same experiment, but on a much smaller scale. It's using laser photons instead of nerf gun pellets.

In the next slide we will see the results of both versions of the experiment.

Results

Big things



Nerf pellets produce two distinct groups of pellet marks

Small things



Photons from a laser produce light and dark interference fringes

Here are the results. As you can see, the Nerf pellets produced two groups of marks on the whiteboard.

<CLICK> On the other hand, the laser made a series of light and dark fringes. These correspond to constructive and destructive interference of the laser photons passing through the double slit. This is a very different result to the pattern of nerf gun pellets.

Small molecules and atoms also behave like photons in the double slit experiment, providing they are not recorded.

The boundary between big things and small things seems to be clusters of about 2000 atoms (Kiatka et al., 2022).

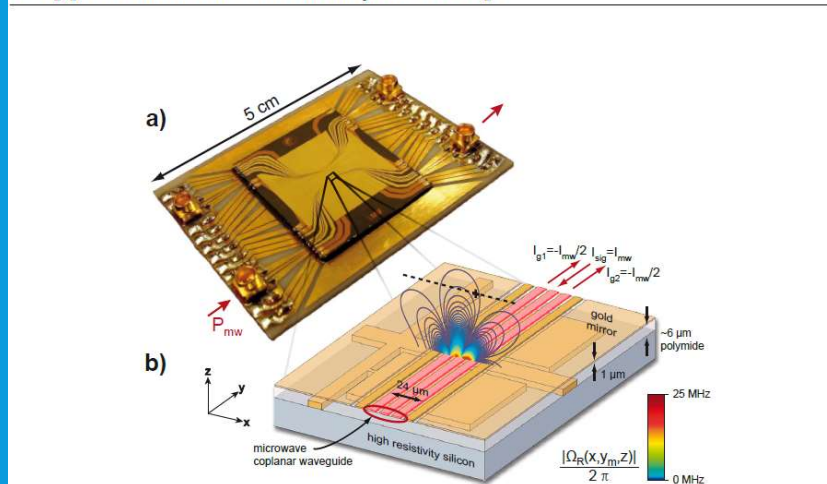
Now we have seen the differences of working at the atomic or quantum scale, let's see how a quantum computer can be built. The next slide shows how a single qubit can be constructed.

Kiałka, F., Fein, Y. Y., Pedalino, S., Gerlich, S., & Arndt, M. (2022). A roadmap for universal high-mass matter-wave interferometry. *AVS Quantum Science*, 4, 020502. <https://doi.org/10.1116/5.0080940>

Making a qubit

Single atoms (quanta) can be trapped in place and manipulated using microwaves.

Trapped-atom interferometry on a chip



6/13


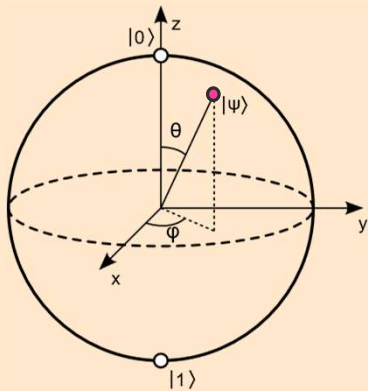
A qubit is the fundamental component of a quantum computer. It usually consists of a single atom.

There are many physical implementations of qubits. Most require cooling to near absolute zero, so that the qubit state is not thermally disrupted. This image shows a single atom, with a microwave guide to manipulate it.

The way we represent a qubit is rather different to the classical binary digit. Let's look at it.

Pascal Alexander Böhi (2010). Coherent manipulation of ultracold atoms with microwave near-fields. Max-Planck-Institut für Quantenoptik.
<https://www.mpg.de/5720882/MPQ333.pdf>

Qubits can store information

Big things Classical Digital Computer – binary digit (bit)	Small things Quantum computer (qubit)
	

Here are representations of a classical binary digit – on the left. And of a qubit, on the right.

Classical binary digits have two clearly defined states – zero and one. There is often an indeterminate zone between them in physical implementations, to make these states quite distinct.

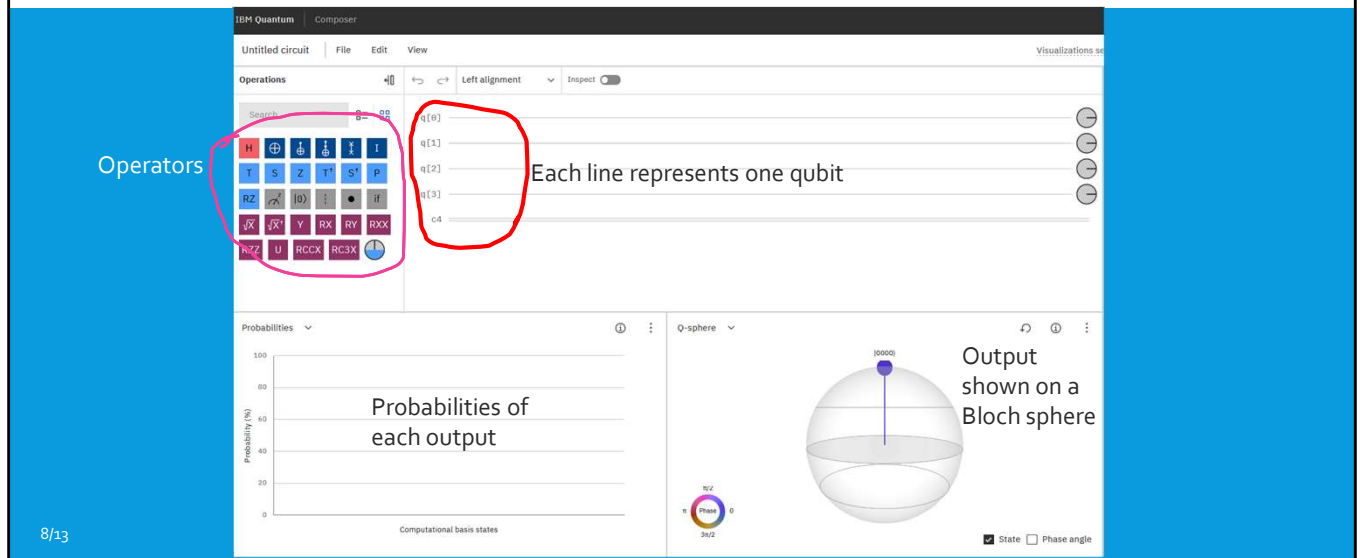
<CLICK> The state of a qubit is sometimes represented by a spot, area or volume on a Bloch Sphere. When the spot is at the 'north pole', this can be interpreted as a zero in a classical digital computer.

So, when we program a quantum computer, the result is often expressed in a Bloch sphere diagram.

Next, we'll look at programming a quantum computer.

Study.com (2016). [Binary Numbers & System | What is the Binary System?](https://study.com/academy/lesson/binary-number-system-application-advantages.html)
<https://study.com/academy/lesson/binary-number-system-application-advantages.html>

How to code for quantum



Here is one visual coding platform for developing simple quantum programs. To code, you drag the required operators onto the line for each qubit.

In the next slide we will see an animation of some simple quantum coding using this graphical interface.

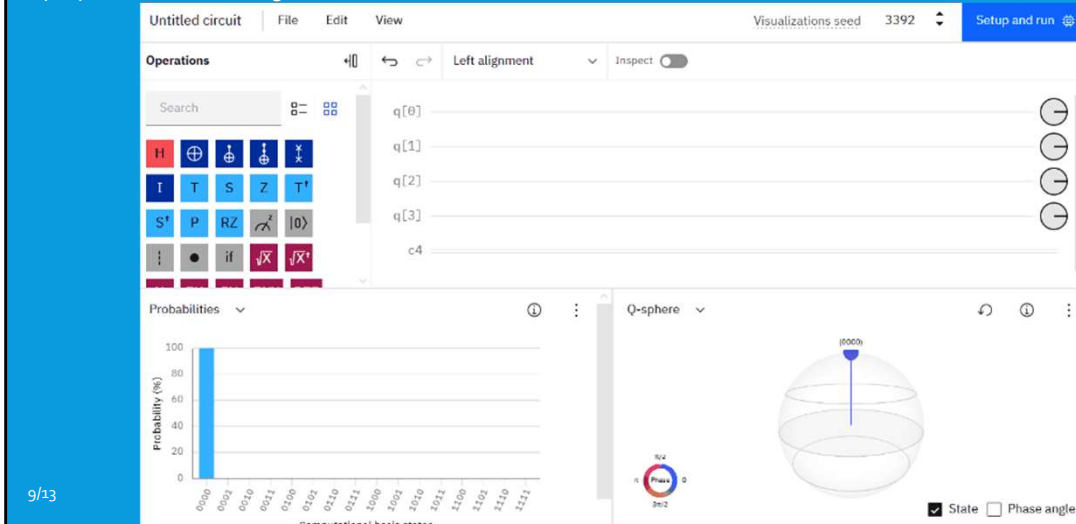
The first operation to be put in place will be a red square with the letter 'H' in it. This is a Hadamard gate.

Please watch the Bloch sphere as the icon is placed – you should notice a SECOND spot appear. This is an example of superposition, where the qubit holds two states at the same time.

An analogy for this is to think of the Earth spinning around its axis (giving day and night); and then the axis tumbling – north pole over south pole. This would give the Earth two rotations at the same time.

An example of quantum coding

Superposition and entanglement



The Hadamard gate is similar to the classic exclusive-or (XOR) gate. It adds a new value to the Bloch sphere, on the equator. This brings the qubit into superposition, so it now has two binary values which are equally likely.

The Controlled NOT (C-not) gate looks like a plus sign. It performs the NOT operation on the second qubit only when the first qubit is $|1\rangle$, and otherwise leaves it unchanged. This links the two qubits together. The C-not gate can be used to [entangle](#) two qubits.

The dial icon represents measurement of the qubit value. Generally, each program is run 100 times to find the most probable output state.

Visual coding is a good start, but more complex programs can be expressed in textual code.

<https://quantum-computing.ibm.com/composer/docs/idx/>

The circuit can be coded in text form using the *Qiskit* language:

```
from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
from numpy import pi

qreg_q = QuantumRegister(4, 'q')
creg_c = ClassicalRegister(4, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

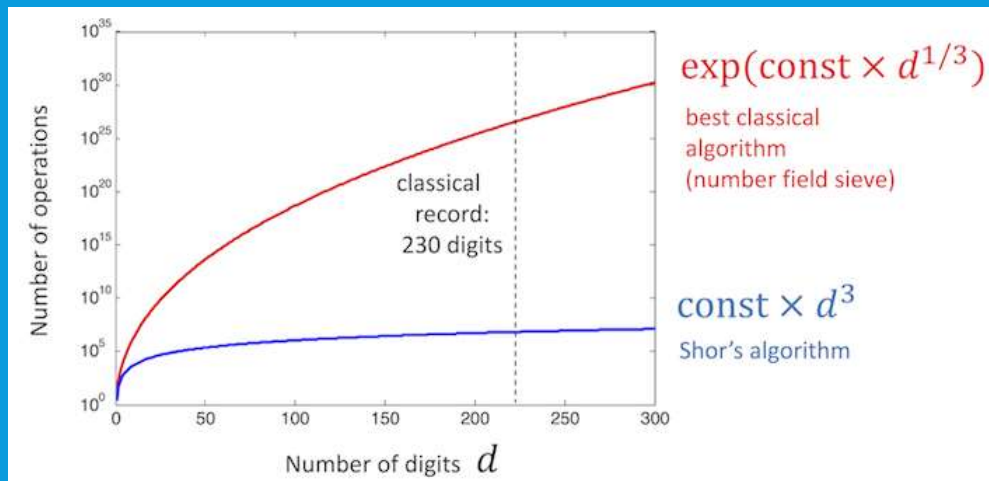
circuit.h(qreg_q[0])
circuit.cx(qreg_q[0], qreg_q[1])
circuit.measure(qreg_q[0], creg_c[0])
circuit.measure(qreg_q[1], creg_c[1])
```

10/13

This is the same program written in a textual language.

So, we have seen how to code for a quantum computer. But why would you want to use a quantum computer instead of a classical binary computer?

Relative computation times



11/13

Shor's algorithm on a quantum computer finds the prime factors of an integer faster than a classical digital computer

Despite the probabilistic nature of a quantum computer, it can overcome some of the inherent speed restrictions imposed by conventional algorithms.

For example, Shor's quantum algorithm finds the prime factors of an integer in polynomial time. However, the best known classical algorithm requires exponentially greater time as the integer gets larger.

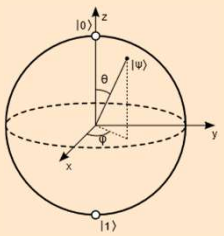
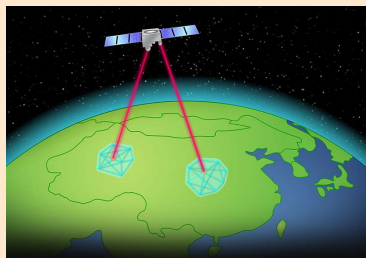
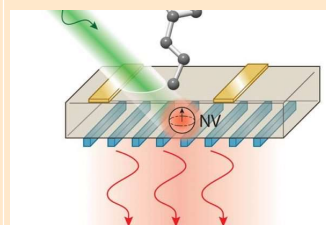
So, this speed advantage is a major reason why quantum computing is attracting plenty of attention.

It is important to note that the story does not end there. Other aspects of the quantum world are also being investigated.

Wikipedia contributors. (2023, February 22). Quantum supremacy. In *Wikipedia, The Free Encyclopedia*. Retrieved 06:08, April 9, 2023, from [https://en.wikipedia.org/w/index.php?title=Quantum supremacy&oldid=1140855416](https://en.wikipedia.org/w/index.php?title=Quantum_supremacy&oldid=1140855416)

Graph: <https://quantum-computing.ibm.com/composer/docs/iqx/guide/shors-algorithm>

Quantum information science

Quantum Computing	Quantum Communication	Quantum Sensing
 <p>Faster solutions</p>	 <p>Entanglement for unhackable messages</p>	 <p>Ultra-precise detection of fields</p>

12/13

Quantum Information Science is a way of referring to these other aspects of the quantum world.

On the left is quantum computing, which we have just described. It requires error correction and other concepts analogous to classical digital computing. Therefore, it would fit into the Computer Science or Informatics subject areas. For TC3, I believe the initial emphasis of our Quantum Inquiry should be on quantum computing alone. This is an important counterpoint to traditional digital computing. Any further extension of scope would be difficult to fit into the often overcrowded school curriculum. Access to quantum computers and simulators is freely available, so students can easily engage with the technology.

In the centre we see quantum communications. Using entangled qubits, quantum communications cannot be intercepted without disrupting the entanglement. This makes messages impossible to spoof or change. Quantum communications could be included in the more senior years of computer science or informatics education. However, I am not aware of accessible practical activities to enhance student learning. [However, see Quantum Key Distribution Network Simulator at <https://www.open-qkd.eu>].

On the right, we have quantum sensing. The position of a Nitrogen atom next to a vacancy in a diamond crystal lattice is measured by a laser. This maps magnetic fields and acceleration with extreme precision. For instance, a quantum compass can provide your exact location without access to satellites. Magnetocardiography devices can provide better pictures of a patient's heart.

Research into these kinds of applications is predominantly undertaken in university Physics, Medical, and Chemistry departments. Therefore, these subject areas of the school curriculum would provide better pathways to advance study in quantum sensing.

I hope this introduction has been helpful.

[Joseph C. Chapman](#) and [Nicholas A. Peters](#) (2022). Paving the Way for Satellite Quantum Communications. *APS Physics* 15, 172.

<https://doi.org/10.1103/Physics.15.172>

[Wisconsin Quantum Institute](#) (2022). WQI Research Projects in Quantum Sensing.

<https://wqi.wisc.edu/quantum-sensing/>

Questions?

Please contact me after the webinar at:

Andrew.Fluck@utas.edu.au

13/13

Back to Mary Webb now for any questions.