INTRODUCTION TO QUANTUM COMPUTING

Levels 7-8

This unit of work was created and provided to ACS by Andrew Fluck

Unit Overview

In this Unit of work, students will encounter aspects of quantum computing. This is important because quantum computing is radically different to digital computing and expected to overshadow the latter in a few decades. Significant rationales for studying quantum computing include:

1) The parallel processing of quantum computing exceeds speed limitations of conventional computers
2) Quantum communications provide instantaneous encrypted & unhackable communications

Australian Curriculum Alignment

The following sessions have been created using the Australian Curriculum: Digital Technologies Curriculum. Tasks may need to be modified to ensure state Digital Technologies Curriculum content descriptions and achievement standards are met. ACS has support and documents to help align this unit to other Digital Technology Curricular.

Further Resources

This is a teacher's guide to assist the implementation of the unit. Online learning material for students is available via the Andrew Fluck website: http://www.andrew.fluck.id.au/QCintroduction/

Key Preparation

The race to 50 qubits

In March 2018 Google unveiled the world's largest quantum computer processor to date. Dubbed Bristlecone, it is a 72-qubit gate-based superconducting system that blows the previous best, IBM's 50-qubit processor, out of the water. The race to build the world's first useful quantum computer is nearing its end[1].

On that basis there are many that propose game changing use cases such as developing new materials; because in theory it will be possible to simulate down to the atomic level. New cures or drugs to treat terminal and less serious diseases could be developed very quickly and much cheaper than they are today[2].

Quantum communications networks

A team at Delft has already started to build the first genuine quantum network, which will link four cities in the Netherlands. The project, set to be finished in 2020, could be the quantum version of ARPANET, a communications network developed by the US military in the late 1960s that paved the way for today's Internet… Wehner, who is involved in the effort, is also coordinating a larger European project, called the Quantum Internet Alliance, which aims to expand the Dutch experiment to a continental scale. As part of that process, she and others are trying to bring computer scientists, engineers and network-security experts together to help design the future quantum internet. [February 2018].

The Geneva government in Switzerland was a pioneer in the use of quantum technology in 2007, using it to secure the network linking Geneva's ballot counting centre (where the votes are counted) to the government repository (where votes are stored) in order to ensure integrity of the data and the election results. The system is still used to secure every federal and cantonal election annually in the State of Geneva[3].

We report on the performance of the Swiss Quantum quantum key distribution (QKD) network. The network was installed in the Geneva metropolitan area and run for more than one and a half years, from the end of March 2009 to the beginning of January 2011. The main goal of this experiment was to test the reliability of the quantum layer over a long period of time in a production environment.[4]

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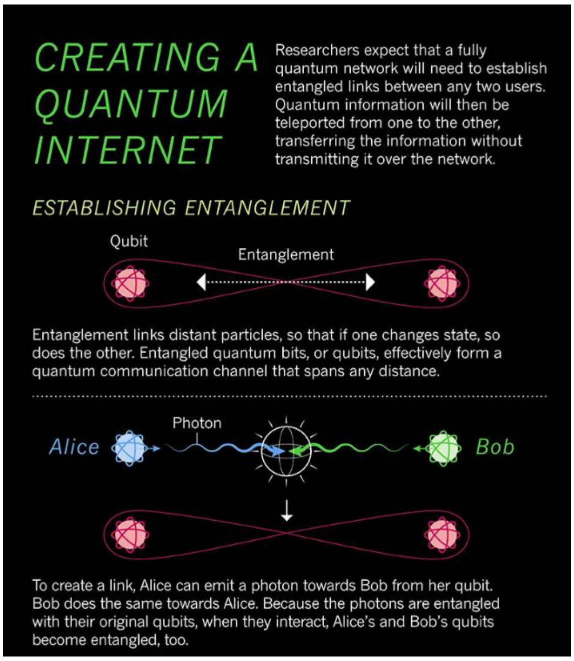
[1] https://thenextweb.com/artificial-intelligence/2018/03/06/google-reclaims-quantum-computer-crown-with-72-qubit-processor/
[2] https://irishtechnews.ie/ibm-now-have-a-50-qubit-quantum-computer-but-are-still-trying-to-figure-out-what-to-do-with-it/
[3] https://www.idquantique.com/idq-celebrates-10-year-anniversary-of-the-worlds-first-real-life-quantum-cryptography-installation
[4] https://arxiv.org/ftp/arxiv/papers/1203/1203.4940.pdf

Key Preparation



© Nature[5]

Chinese quantum communication satellite

Entangled photons were sent to Delingha and Lijiang in China with the quantum communications satellite Micius (illustrated). "In the spacecraft's first record-breaking accomplishment, reported June 16 in *Science[2017]*, the satellite used onboard lasers to beam down pairs of entangled particles, which have eerily linked properties, to two cities in China, where the particles were captured by telescopes (*SN: 8/5/17, p. 14*). The quantum link remained intact over a separation of 1,200 kilometres between the two cities — about 10 times farther than ever before. The feat revealed that the strange laws of quantum mechanics, despite their small-scale foundations, still apply over incredibly large distances…. The final piece in Micius' triumvirate of tricks is quantum key distribution — the technology that made the quantum-encrypted video chat possible. Scientists sent strings of photons from space down to Earth, using a method designed to reveal eavesdroppers, the team reported in the same issue of *Nature*."[6]

[5] https://www.nature.com/articles/d41586-018-01835-3
[6] https://www.sciencenews.org/article/global-quantum-communication-top-science-stories-2017-yir

Session Number	1	Session Topic Focus	Why quantum: How big is a bit?
Class activity			

Learning Intention
Students will predict the size of a single piece of information storage.

What is a bit?
Have a look at the Wikipedia page: https://en.wikipedia.org/wiki/Bit
A bit is a binary digit, and can be in only one of two states at a time: the two states are most commonly represented as either a 0 or 1. It stores the smallest possible piece of information in a computer.

How do you build a bit?
Well, you could construct a computer in Minecraft. See YouTube videos:
https://www.youtube.com/playlist?list=PLDN4M7O4MGcNtzYQO1oBFKYbY59jR59f9 and
https://www.youtube.com/watch?v=fYIBlJmNwTE [16 bit computer by Sw1Ftx16]
In the real world, here are some ways in which manufacturers build storage elements for computers:
This one shows how to use an existing electronic chip (integrated circuit) - http://www.instructables.com/id/Make-a-one-chip-RAM-random-access-memory/
The integrated circuits that make computer storage chips are known as RAM (random access memory). Here is a factory tour: https://www.youtube.com/watch?v=EWDirCg-Wu8
To understand how a RAM chip works, please see: https://computer.howstuffworks.com/ram.htm
You might see that bits are usually stored in groups of 8. A group of 8 bits is usually called a byte.

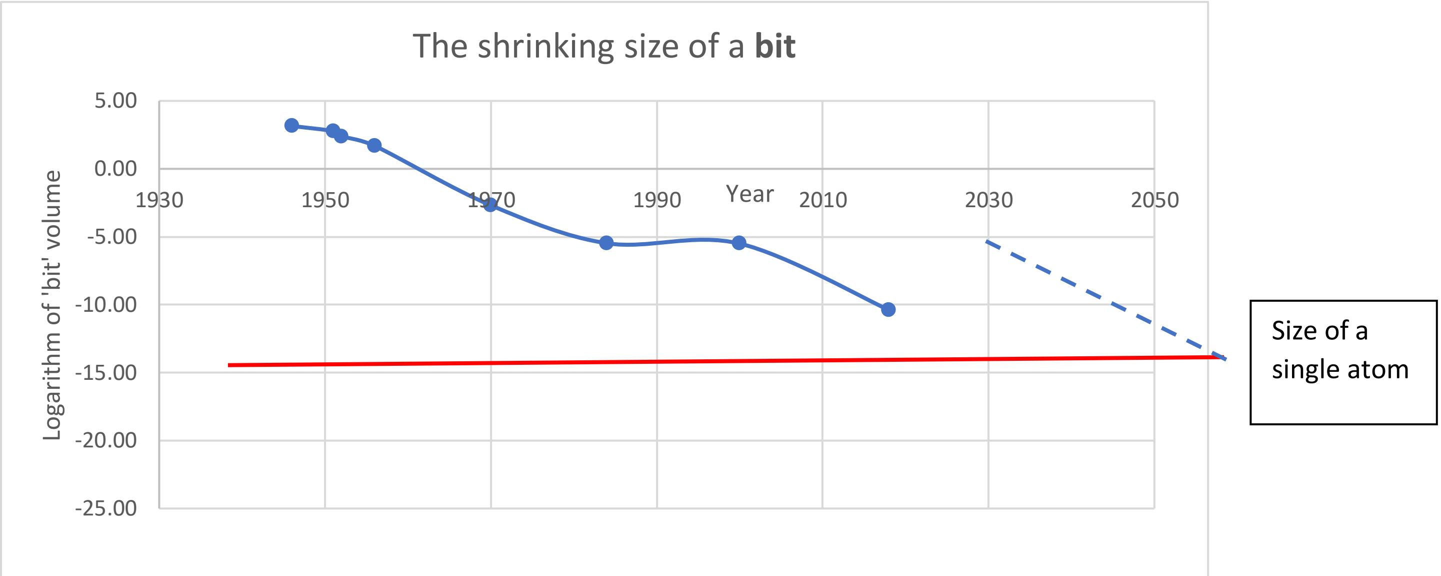
Webquest to predict bit sizes in the future
Bits come in different sizes. Let's look at how big a bit can be, by looking at computer storage devices in the past and future. Look at these websites to complete the table. HINT: to work out the size of one bit, find the volume of each storage device, and divide by the number of bits it can store.

Year	Commercially available storage device	Length (mm)	Width (mm)	Height(mm)	Volume (mm^3)	Storage capacity (bits) (multiply by 8 if stated as bytes or characters)	Volume of each bit (mm^3)	Log Volume
1946	Selectron Tube	254	76	76	1467104	1024	1433	3.16
1951	Mercury delay line	876	114	76	7589664	12800	593	2.77
1952	Magnetic Core	11	11	2	242	1	242	2.38
1956	Hard Disk	1524	736	1727	1937113728	40,000,000	48	1.69
1970	Dynamic RAM solid state integrated circuit Intel 1103	**7**	**3**	**.1**	2.1	1024	2.05E-03	-2.69
1984	Compact-Disc CD-ROM	120	120	1.2	17280	5,200,000,000	3.32E-06	-5.48
2000	Secure Digital flash memory card	32	24	2.1	1612.8	**512,000,000**	3.15E-06	-5.50
2018	micro-SD card	15	11	1	165	**4.096E+12**	4.03E-11	-10.39
(you predict)	mono-atomic memory	-	-	-	-	1	1 atom = 9.97×10^{-21}	-20.00

Session Number	1	Session Topic Focus	Why quantum: How big is a bit?

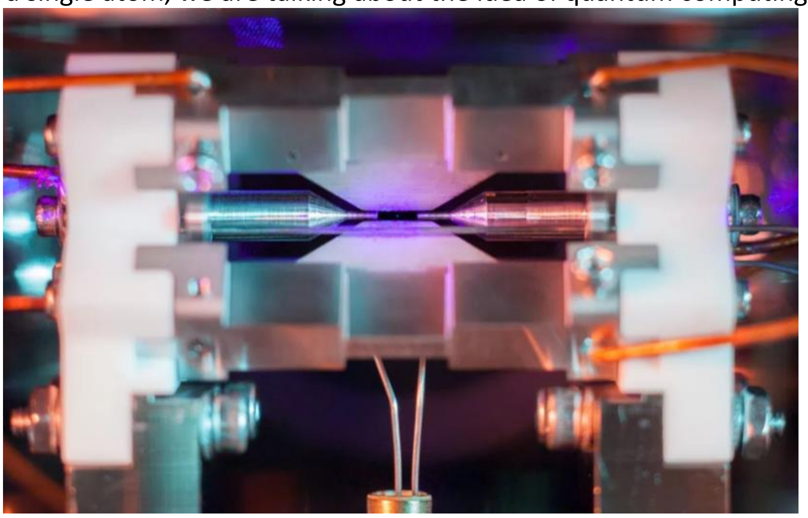
Class activity

If you put this into a spreadsheet, remember that big and small numbers are expressed in 'exponential notation'. So, 5×10^3 (5,000) is written as 5E3 in Excel. Format cells as 'scientific' to see this notation. You may find it easier to see the graph if you take the logarithm of the bit-volumes. In that case, the log of the volume of one atom would be -20, so can you predict in what year bit sizes might get there?



Conclusion

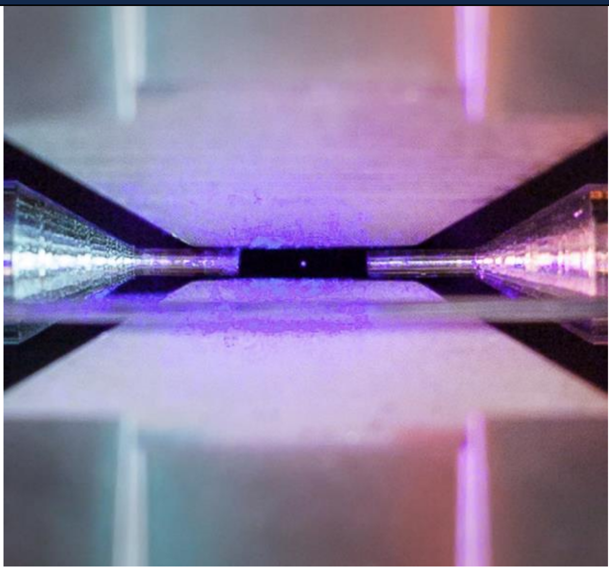
When you have plotted the size of a bit against the invention year, you should be able to predict when a bit will be as small as an atom (9.97×10^{-21} mm^3).
Others have done similar predictions. You can find many of them on the internet, perhaps at Singularity.
When a 'bit' gets as small as a single atom, we are talking about the idea of quantum computing.



Single Atom in Ion Trap (David Nadlinger/University of Oxford/EPSRC) https://qz.com/1205279

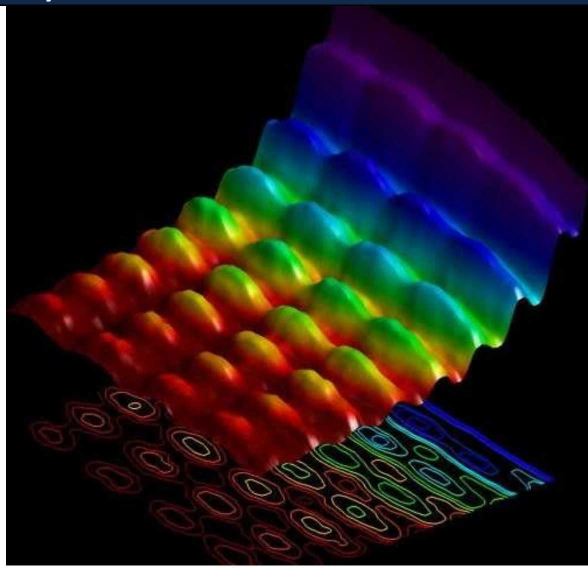
Session Number	1	Session Topic Focus	Why quantum: How big is a bit?

Class activity



A closer look. (David Nadlinger/University of Oxford/EPSRC)

When illuminated by a laser of the right blue-violet colour, the atom absorbs and re-emits light particles sufficiently quickly for an ordinary camera to capture it in a long exposure photograph.



The first ever photograph of light as both a particle and wave

https://3c1703fe8d.site.internapcdn.net/newman/gfx/news/hires/2015/1-thefirstever.jpg

Homework Task

Taking on board what you have learned about 'ket' notation, can you speculate how the state of a PAIR of qubits might be written? Try writing down some examples.

Check Quiz

How big is a bit?

1. What is a 'bit' in computing terms?
   a. A chip
   b. A binary digit
   c. * the storage space for the smallest piece of information in a computer system.
   d. An integrated circuit

2. How does a dynamic random access memory (DRAM) chip work?
   a. The chip must have electric power to work
   b. The DRAM capacitors leak
   c. You can access any memory cell directly
   d. * A transistor fills the capacitor with electric charge, or reads its level

3. From 1946 to now, the volume to store a bit has:
   a. Increased as new technologies have been invented
   b. *Decreased as new technologies have been invented
   c. Remained the same, despite new technology inventions
   d. Dropped rapidly since the year 2000

4. The volume to store a bit will be as small as an atom:
   a. By 2030
   b. It is already that small
   c. By 2100
   d. *By 2050

Session Number	2	Session Topic Focus	What is a qubit?

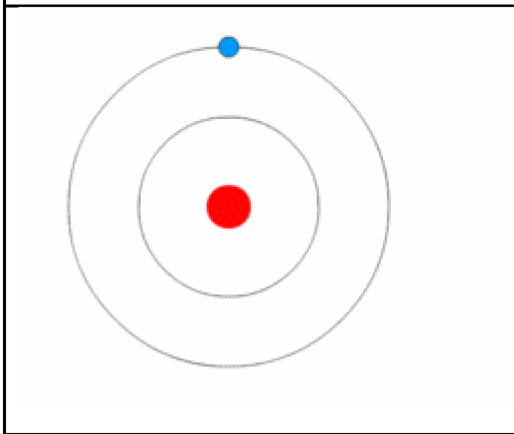
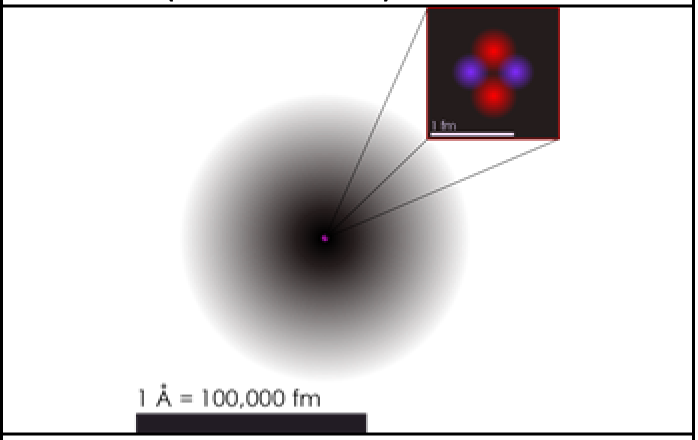
Class activity

Learning Intention

Students will compare binary digits (bits) with quantum bits (qubits)

What are atoms made of?

An atom is the smallest constituent unit of ordinary matter that has the properties of a chemical element.

Bohr model of the atom (1913)	**Helium atom, with nucleus and electron cloud distribution (1926 and current)**
	
https://en.wikipedia.org/wiki/Atom#/media/File:Bohr_atom_animation_2.gif	By User: Yzmo - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2246091

Atoms contain charged particles such as the positive nucleus in the centre, which is surrounded by electrons. These particles have other properties such as ‘spin’.

Representing a qubit on a Bloch sphere

When we work at the atomic or quantum scale, the properties of matter obey different laws. You will be aware of the ‘laws of physics’ regarding momentum and energy. Heavy trucks can cause more damage when they crash than bicycles. The more energy you put into a ball, the higher it will go when you throw it.

At the quantum scale, energy comes in ‘packets’ of a fixed size (which are called ‘quanta’). Electrons are somewhere near the nucleus of their atom, distributed in space according to a probability equation. Our common language of trucks and bicycles is replaced by new terms about chance and likelihood.

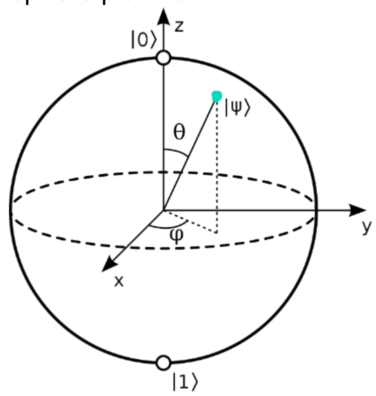
Therefore we need some new ways to think about atoms and quantum particles. One way to think about a quantum bit is to visualise a sphere with a dot on it.

https://www.seyberts.com/pool-balls-single/aramith-blue-dot-cue-ball/

Session Number	2	Session Topic Focus	What is a qubit?

Class activity

As you begin to use a quantum computer, you can imagine working with a number of these spheres acting as your qubits. Your programming can cause the dot to move into different positions. To describe these positions, we need a frame of reference. This is given by the Bloch sphere picture:



Bloch sphere representation of a qubit (from Smite-Meister CC BY-SA 3.0)

Using this picture of a qubit, the light blue dot can be located using the three angles (φ from the x-axis and θ from the z-axis, giving a qubit value of |ψ>. That's right – qubit values are written in a funny way. You can see that if the little blue dot goes to the bottom of the sphere, the qubit value would be |1> (or just ONE if it were a binary digit). And if it went up to the top, the qubit value would be |0> (or zero if it were a binary digit). So you can see, a qubit can act like a binary digit, but there are lots of other values it can hold as well.

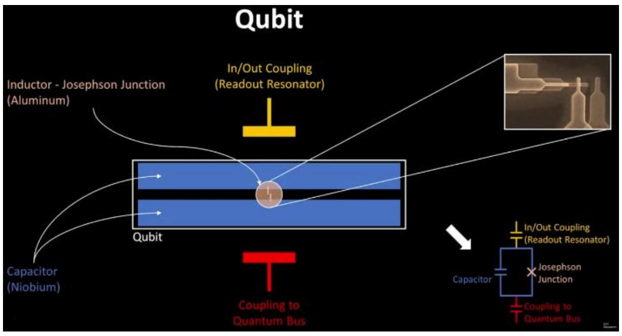
Exercise

This link provides a page of Bloch sphere qubits. Can you mark on each one where you think the blue dot should be to represent the given values?

If you are interested, qubit values are written using vector notation, so |0> = $\begin{bmatrix}1\\0\end{bmatrix}$. This short form is called Dirac or 'bra-ket' notation. So, you pronounce |0> as 'ket 0' and |1> as 'ket 1'. We will use this notation to show qubit values to distinguish them from the values of a conventional binary digit.

Making a real qubit

Qubits can be made in several ways. IBM creates them from super-conducting junctions of Niobium, silicon and aluminium. The junctions have to be kept very cold. In fact, they are kept close to absolute zero, at a temperature of less than one degree Kelvin (-273° Celsius). Here is a diagram of such a qubit, and a video of how it was made.



Homework Task	Taking on board what you have learned about 'ket' notation, can you speculate how the state of a PAIR of qubits might be written? Try writing down some examples.

Session Number	2	Session Topic Focus	What is a qubit?
Class activity			

Check Quiz

What is a qubit?

1. What is an atom?
    a. * The smallest constituent unit of ordinary matter that has the properties of a chemical element
    b. The smallest piece of a substance that is still that substance
    c. The smallest piece of anything
    d. A small molecule

2. What does the Bloch sphere picture show?
    a. How a ball is like an atom
    b. The direction an atom is pointing
    c. *The state of a qubit
    d. How to play billiards

3. What elements are the qubits in IBM's quantum computer made of?
    a. Nickel, Silver and Arsenic
    b. *Niobium, Silicon and Aluminium
    c. Neon, Strontium and Astatine
    d. Niobium, Scandium and Actinium

4. At what temperature is the IBM quantum computer kept?
    a. 100° Celsius
    b. 0° Celsius
    c. 273° Celsius
    d. * -273° Celsius

Session Number	3	Session Topic Focus	Writing my first quantum score
Class activity			

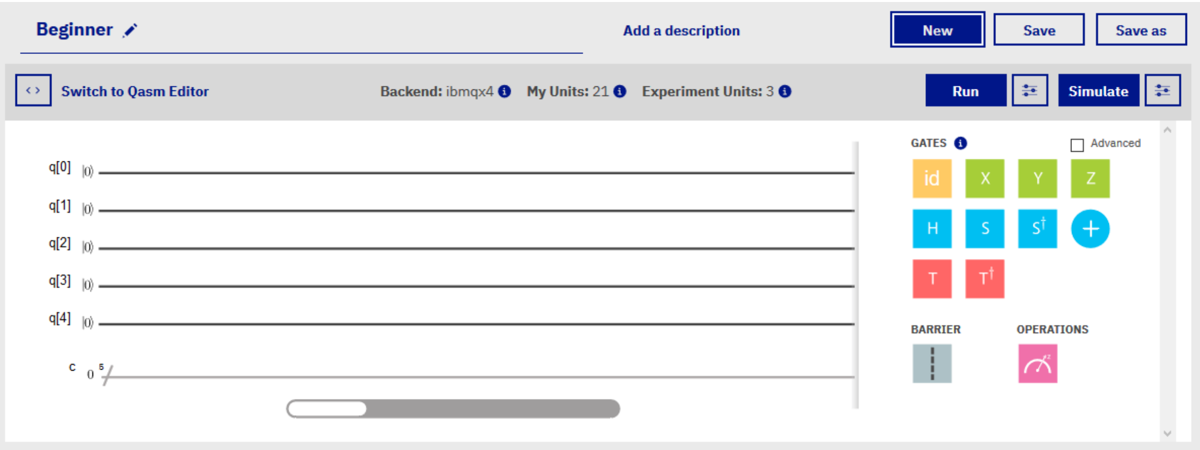
Learning Intention
will create an account on the IBM Q Experience site and use Composer to copy recipe programs/scores and validate output using the measurement tool.

Create an account
IBM is a computer company that has made a quantum computer available to the public. To run any programs on this quantum computer, you need to create an account. Use the link on the right to point your browser to the IBM Q Experience web page and click Sign in > Sign Up > .

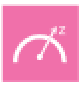
Q Experience

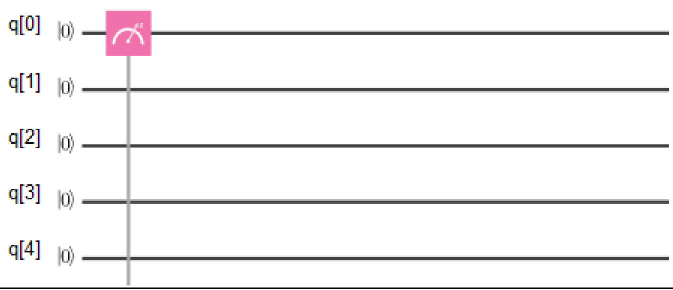
Once you have an account, you can begin to use the quantum computer simulator. Make sure you write down your username (e-mail address) and password, or put these into your password manager application. [Keepass is a suitable app for your mobile phone to manage all your passwords, or others are reviewed here].

Composer
If you now go to this web-page, you will see the composer. https://quantumexperience.ng.bluemix.net/qx/editor
This is where you can create your quantum programs. Let's start with a simple one. Click on 'New' and provide a name for this experiment – let's call it 'Beginner'. Choose the ibmqz4 (5 qubit transmon bowtie chip 3) to run it on. You'll see a display rather like this:



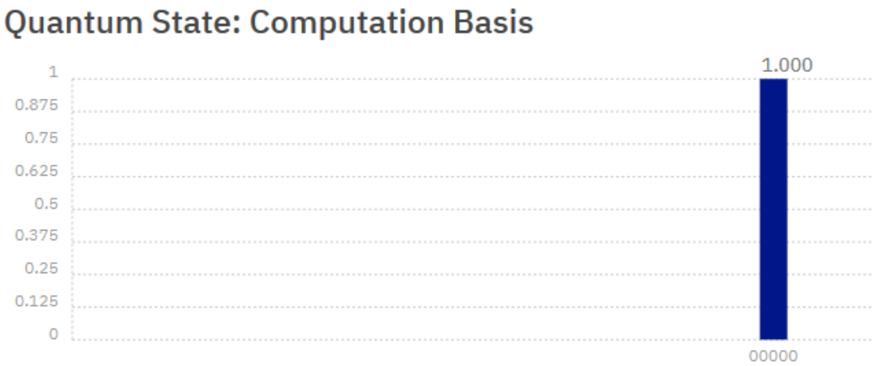
On the left you can see the five lines for each of the five qubits (q(0) to q(4)). On the right you can see some of the gates which correspond to the instructions for the quantum computer.
So, what state are the qubits in right now?
Let's find out.

Drag the measuring tool  from the gates area onto the line for q(0). Your score should look like this:



Session Number	3	Session Topic Focus	Writing my first quantum score
Class activity			

Now click on the 'Simulate' button in the top right corner. After a short time, you should see the output of your program, something like this:



This is a probability diagram. It shows you the probability that your measurement has found the value at the bottom. We can see that the value is '00000' or zero. And the probability of q(0) being in this zero state is given by the height of the blue bar. This is level with '1', which means it is CERTAIN.

Explanation

You might be wondering why there is a probability associated with the output of your first program. Well, this is a quantum computer, and it obeys quantum rules. When a ball drops down, it contains many millions of atoms. Collectively, their behaviour is very predictable. The ball does not stop falling unless you catch it. It does not rise up again unless you throw it.

But individually, atoms obey probabilistic quantum rules. Electrons tend to stay near to the nucleus of their atom, but their position cannot be determined precisely. Looking at an electron would require us to hit it with a photon of light, and see the reflection. But in hitting the electron with the photon, we would have disturbed it!

Complicated mathematics called 'wave-mechanics' can plot the expected positions of an electron. We can say where it can probably be found using these equations. You won't need to work them out, but need to understand this quantum behaviour is reflected in the quantum computer you are programming.

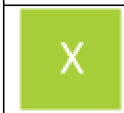
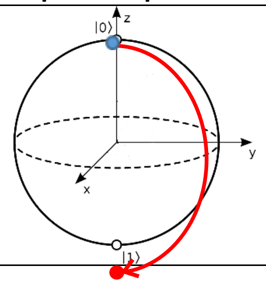
Homework	Find out about the Schrödinger Equation by watching this video: https://www.youtube.com/watch?v=O6g-7rUgrdg

Session Number	3	Session Topic Focus	Writing my first quantum score
Class activity			
Quiz	**Writing my first quantum score** 1. Have you created an account on the IBM Q-Experience site? a. * Yes b. No 2. Did your first quantum computing score show the qubits start in the 'zero' (|0>) state? a. *Yes b. No 3. Does a quantum computer give definite answers? a. * Quantum behaviour is expressed in probabilities - so answers are too b. Yes c. No d. Probably not 4. Which chip configuration were you asked to use in programming the quantum computer? a. 3 qubit transmon bowtie chip 5 b. * 5 qubit transmon bowtie chip 3 c. 5 qubit model d. 3 qubit model		

Session Number	4.	Session Topic Focus	Quantum Gates
Class activity			

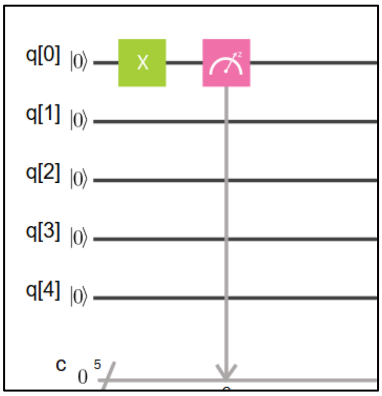
Learning Intention
Students will use a single qubit with Pauli X, Y and Z gates

Quantum Gates – the Pauli X gate
You have used some of the programming instructions, or gates, in the quantum computer composer. Last time you only used the measurement tool, and found a single qubit started in the |0> state had a 100% chance of registering zero when no other operations were performed.
This time we are going to try the effect of a few other gates. Let's start off with the Pauli X gate.

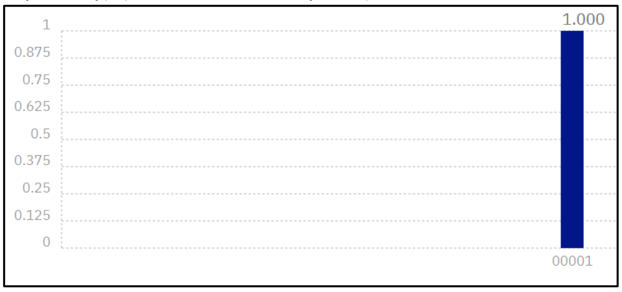
Gate icon	Gate name	What it does	Bloch sphere representation
	Pauli X gate or bit-flip	180° turn around the X-axis	

Create a new program in the Quantum Experience using ibmqx4. Drag the X-gate to qubit q(0) on the score, and then apply the measurement tool. If you make a mistake, double-click on the gate to delete it, or drag it to the top left (a delete bin will appear). This is how your program should look:

Q Experience



Run the program by clicking on the 'Simulate' button, and it will be run 100 times. Look at the output.
This time, there is 100% chance that qubit q(0) has the value |1>. (Last time, without the X-gate, it had the value |0>).

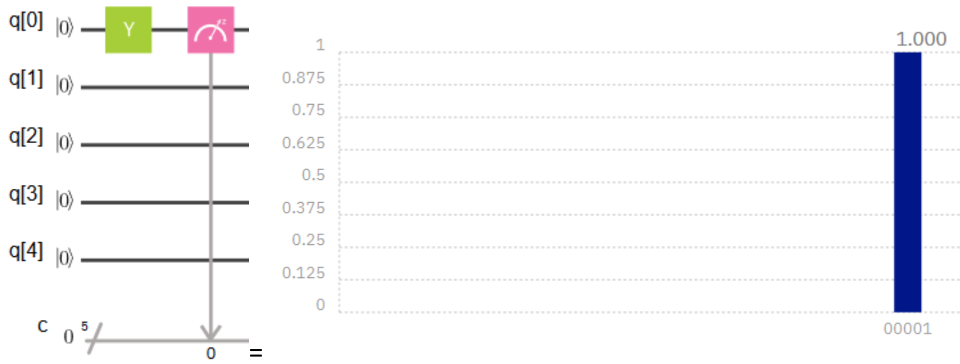


So, the X-gate can flip the value of our qubit, from |0> to |1>.

Session Number	4	Session Topic Focus	Quantum Gates

Class activity

Other Pauli gates
Now it is your turn. Find the effect of using the Pauli Y and Z gates.
This is what you should see.



= 1

=0

Now you can experiment. Please use any combination of X, Y and Z gates to see if you can make the qubit have any value other than |0> or |1>. When you have tried several combinations, add just one more gate to some of your trials.

Homework Task

Glance at the IBM quantum experience user guide at:
https://www.qiskit.org/ibmqx-user-guides/full-user-guide/introduction.html

Quiz

Quantum Gates

1. What is another name for the Pauli X gate?
    a. Switcher
    b. Bit-flop
    c. Reverser
    d. *Bit-flip

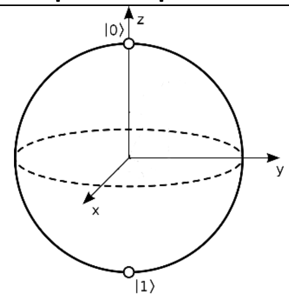
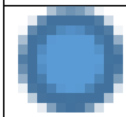
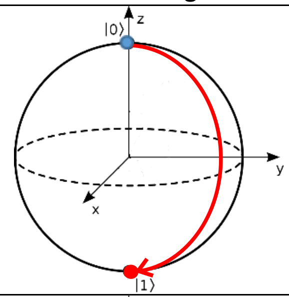
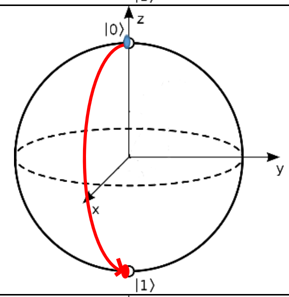
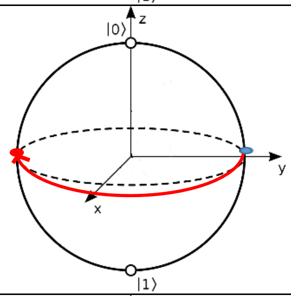
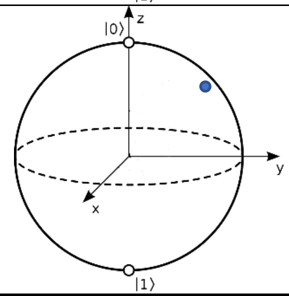
2. What are the other two Pauli gates called?
    a. * Pauli Y and Pauli Z
    b. Pauli 1 and Pauli 2
    c. Nobel X and Schrodinger 2
    d. George and Fred

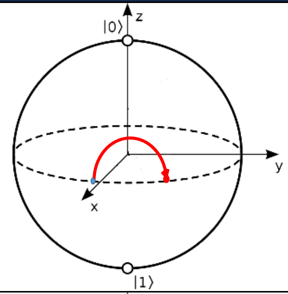
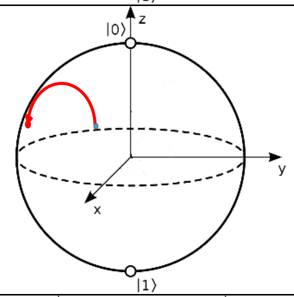
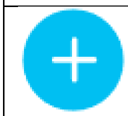
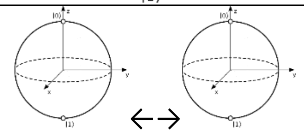
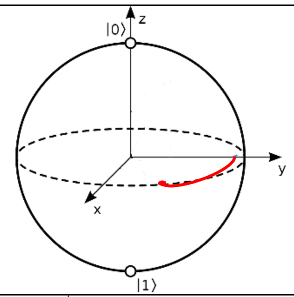
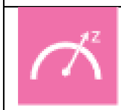
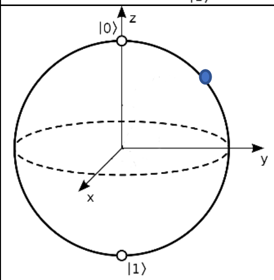
3. Did you use a number of gate combinations in your quantum computer scores?
    a. * Yes
    b. No

Session Number	4	Session Topic Focus	Quantum Gates

Class activity

Here is a short description of the most popular quantum gates with a Bloch sphere illustrating their action. Most illustrations are done on a qubit in the |0> state, but the twists and turns would apply on a qubit in any other state.

Gate icon	Gate name	What it does	Bloch sphere representation
id	Identity gate	Performs an idle operation on the qubit for one unit of time	 No change
	Pauli X gate or bit-flip	180° turn around the X-axis	
Y	Pauli Y gate	180° turn around the Y-axis	
Z	Pauli Z gate or phase-flip	180° turn around the Z-axis	
H	Hadamard gate	Makes superpositions	

Session Number	4	Session Topic Focus	Quantum Gates
Class activity			
S	Phase gate	Makes complex superpositions: maps X→Y	
$S^{\dagger}$	Opposite Phase gate	maps X→−Y	
	Controlled-NOT gate	Generates entanglement between two qubits	
T	Phase gate	45° rotation around the Z-axis	
	Measurement gate	Gives the value of the qubit in the Z-axis (i.e. |0> or |1>)	 $= \|0>$

Session Number	5	Session Topic Focus	Superposition

Class activity

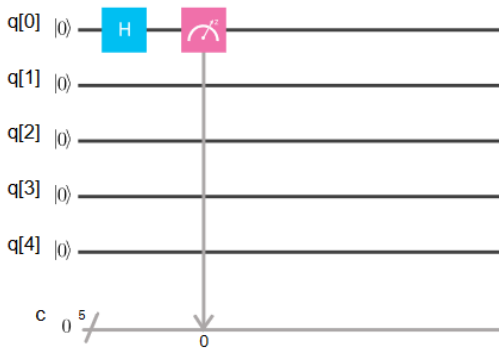
Learning Intention
Students will learn about Hadamard gate and its applications.

Superposition
Previously, we used the Bloch sphere to represent a qubit. However, the output from your first program could only show the probability of the qubits being in the 0 or 1 state. To get values in between, we use superposition. That is, we organise for the qubit to be set to a mixture of 0 and 1 states, such that the probability of being in between can be shown.

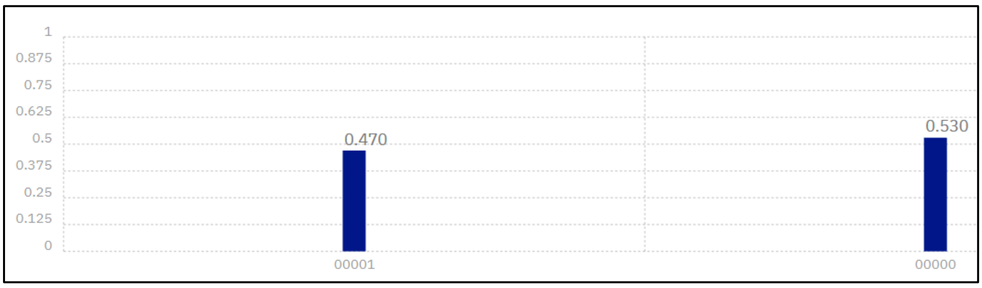
For example, if I wanted to have half a chance of drawing a black ball from a hat containing 100 balls, I would put in 50 white and 50 black balls. So when we use superposition, we are arranging the qubit to be a bit like the hat – we set it up so that over one hundred observations, the ratio of times when it is seen as a '1' or as a '0' are exactly in the proportion we want. Since this ratio (expressed as a probability) will lie between 0 (never) and 1 (always) we can effectively use a qubit to represent a decimal number in the range 0 to 1. Perhaps the easiest way to see this is to program a qubit to represent the value 0.5 (a half). The power of this demonstration is that a binary digit in a conventional computer can NEVER hold such a value!
Log into https://quantumexperience.ng.bluemix.net to try this out.
A qubit has some properties of a continuous variable, and some properties of a discrete one.

The Hadamard gate
Set up this program in the composer. It only works on one qubit (q(0)) but comes up with a rather interesting result:

Q Experience



Interpreting the output of the Hadamard gate
The first time I ran this program, I got:



So, there was a probability of 0.47 the result came to |1>, and a chance of 0.53 the output was |0>.
Try running your program several more times in the simulator, and write down the values from the output.

Session Number	5	Session Topic Focus	Superposition

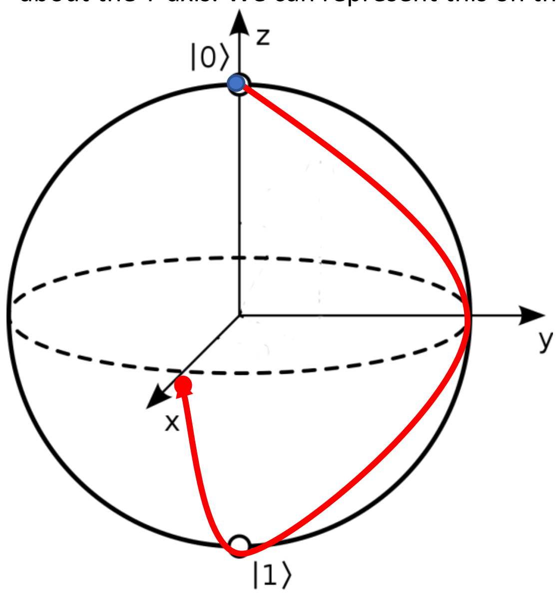
Class activity

I ran it a few more times and got the following probability results – compare them with yours:

Output Run	00001 = |1>	00000 = |0>
1	0.51	0.49
2	0.5	0.5
3	0.5	0.5
4	0.42	0.58
5	0.5	0.5

Isn't that strange! You don't get the same result every time! And I thought computers were accurate. But this is a Quantum Computer, and therefore we have to average our results over time, and beware of instabilities. Would you agree the result is getting close to 0.5 for |1> and 0.5 for |0>? In which case, we can average these results and agree the qubit is in the half-way state between 0 and 1 – so it is telling us the result is |0.5>.

The Hadamard gate can put a qubit into an in-between state, not quite 1, and not quite 0. It combines two rotations: 180° about the X-axis followed by 90° about the Y-axis. We can represent this on the Bloch Sphere as a turn:



Intermediate states

Previously, you saw the output from a qubit can only be |0> or |1>, but if we run our programs 100 times, these values can occur with different probabilities. This tells us the qubit is in an intermediate state. We have learned the Hadamard gate can put a qubit into a state which corresponds to the value |0.5>.
Here are the output runs from three different quantum composer programs. Can you find what the qubit state represents for each one?

Program 1

Output Run	00001 = |1>	00000 = |0>
1	0.31	0.69
2	0.29	0.71
3	0.3	0.7
4	0.28	0.72
5	0.32	0.68

Session Number	5	Session Topic Focus	Superposition

Class activity

Program 2

Output / Run	00001 = |1>	00000 = |0>
1	0.45	0.55
2	0.44	0.56
3	0.46	0.54
4	0.42	0.58
5	0.45	0.55

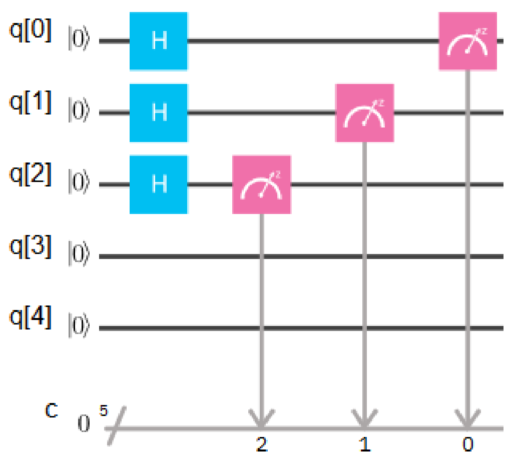
Program 3

Output / Run	00001 = |1>	00000 = |0>
1	0.75	0.25
2	0.73	0.27
3	0.74	0.26
4	0.76	0.24
5	0.77	0.23

You may find taking the average of the first or |1> column the easiest way to calculate the number our qubit is representing!

Superposition for multiple qubits

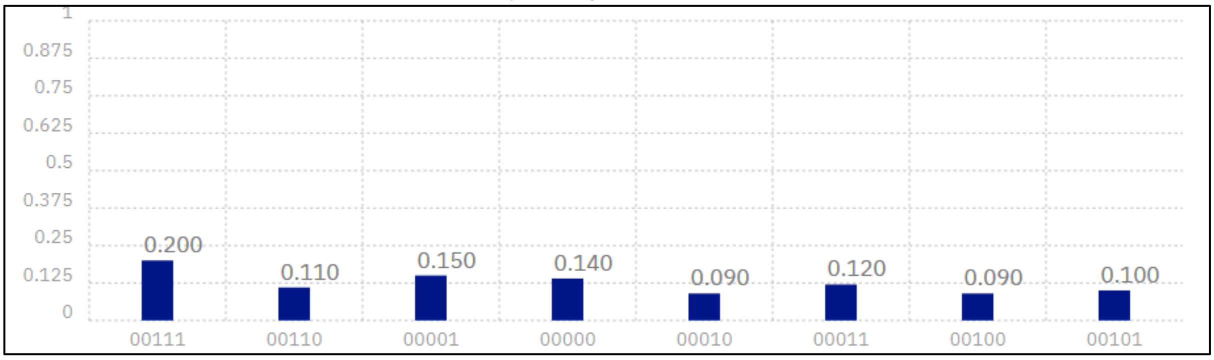
By now, you should be able to write a quantum program that measures the state of three qubits started in the |0> state. I will guess there is a 100% chance (probability = 1) they will all be in the |000> state. Now prove it!
However, here is a tricky question. What happens if you apply a Hadamard gate to each of these three qubits before measuring their values? Try it and see!
Your program should look like this:



Session Number	5	Session Topic Focus	Superposition

Class activity

And the output might look a bit like this:



This shows us that multiple Hadamard gates can create multiple qubit values which have low probabilities.

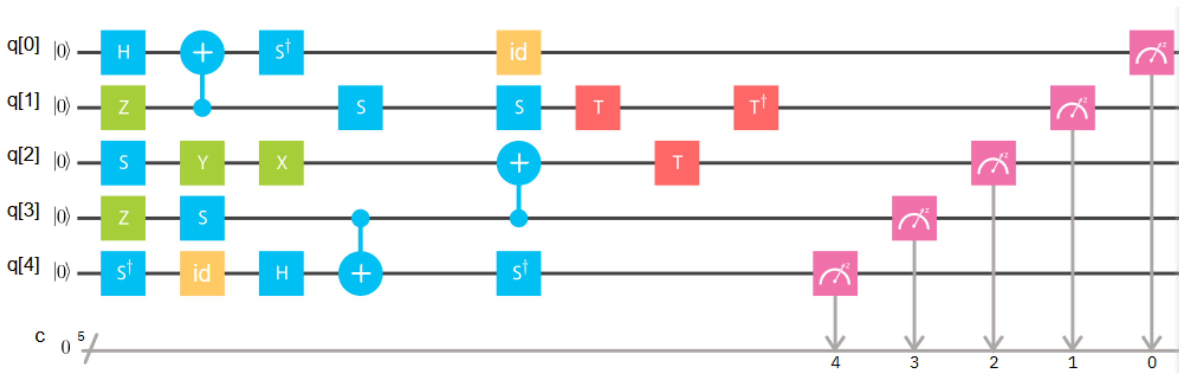
Running a more complicated quantum program.

Here is a quantum program which is a bit more complicated. The text below gives an idea of the way in which is works (from Robert Lisiecki here).

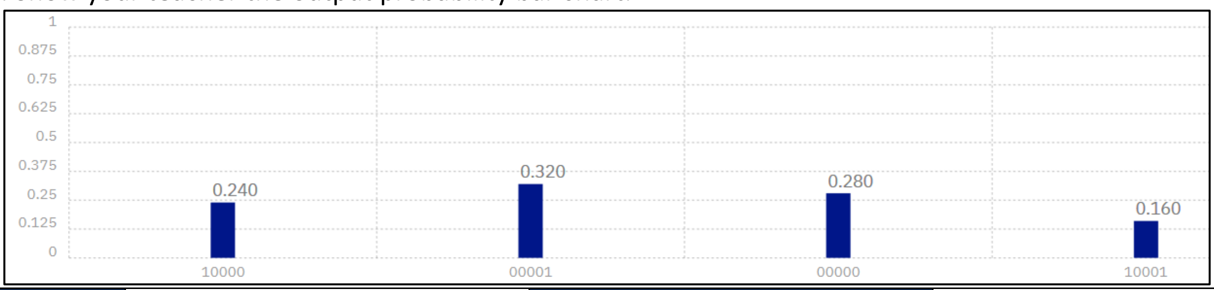
```
N 2           # create a new quantum bit and identify it as '2'
E 1 2         # entangle qubits '1' and '2', qubit 1 already exists and is considered input
M 1 0         # measure qubit '1' with an angle of zero (angle can be anything in [0,2pi]
              # qubit '1' is destroyed and the result is either True or False
              # operations beyond this point can be dependent on the signal of '1'
X 2 1         # if the signal of qubit '1' is True, execute the Pauli-X operation on qubit '2'
```

Create a new program in the Quantum Experience using ibmqx4. As before, drag the gates to the indicated point on the score. If you make a mistake, double-click on the gate to delete it, or drag it to the top left (a delete bin will appear). With the + gates, place them on the score line, then click on the adjacent control line. This is how your program should look:

Q Experience



Run the program using the 'Simulate' button (you may not have enough credits to run it on the real quantum computer just yet!). Show your teacher the output probability bar chart.



Class activity	
Quiz	**Superposition** 1. Which quantum gate causes a qubit to enter a superposition state? a. *Hadamard gate b. Pauli X gate c. Pauli Y gate d. Pauli Z gate 2. Does the Hadamard gate give the same result every time? a. Yes b. * No - you have to average the results over time c. Maybe d. Not sure - it depends upon the weather 3. Does running a Hadamard gate on multiple qubits produce low or high probabilities? a. *Low probabilities b. High probabilities 4. Were you able to create a complex quantum score and run it? a. No b. * Yes

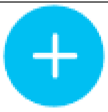
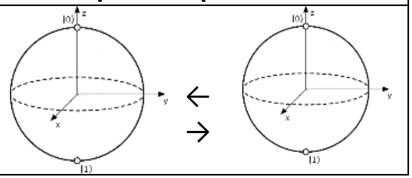
Session Number	6	Session Topic Focus	Entanglement

Class activity

Learning Intention

Students will learn how to use a controlled NOT gate (or C-NOT).

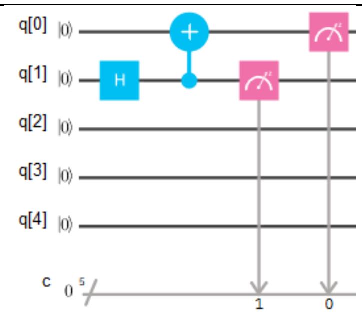
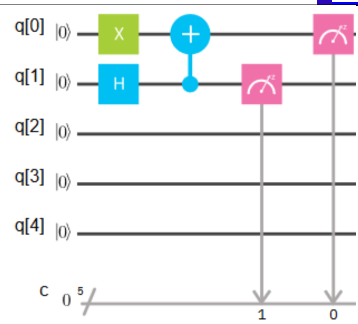
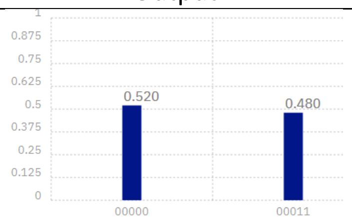
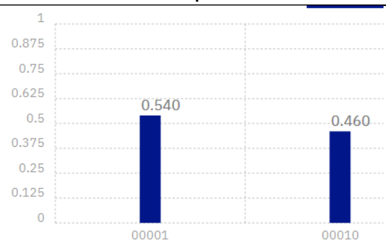
The CNOT gate

Gate icon	Gate name	What it does	Bloch sphere representation
	Controlled-NOT gate	Generates entanglement between two qubits	

The CNOT gate flips the second qubit (the target qubit) if, and only if, the first qubit (the control qubit) is |1⟩. Einstein referred to entanglement as "spooky action at a distance" because it works even when the qubits are quite far apart. A common application of the C_{NOT} gate is to maximally entangle two qubits into the Bell state; this forms part of the setup of the superdense coding, quantum teleportation, and entangled quantum cryptography algorithms.

Check it works

First of all, check that it works. Implement these two programs in the Composer: Q Experience

	
Output	Output
	
|00> or |11>	|01> or |10>
The control qubit q(0) is |0>, so the other q(1) qubit can be |0> or |1>.	If q(0) is |1> (forced by the X-gate), then q(1) becomes |1> as well.

Did you get the same kind of results?

Session Number	6	Session Topic Focus	Entanglement

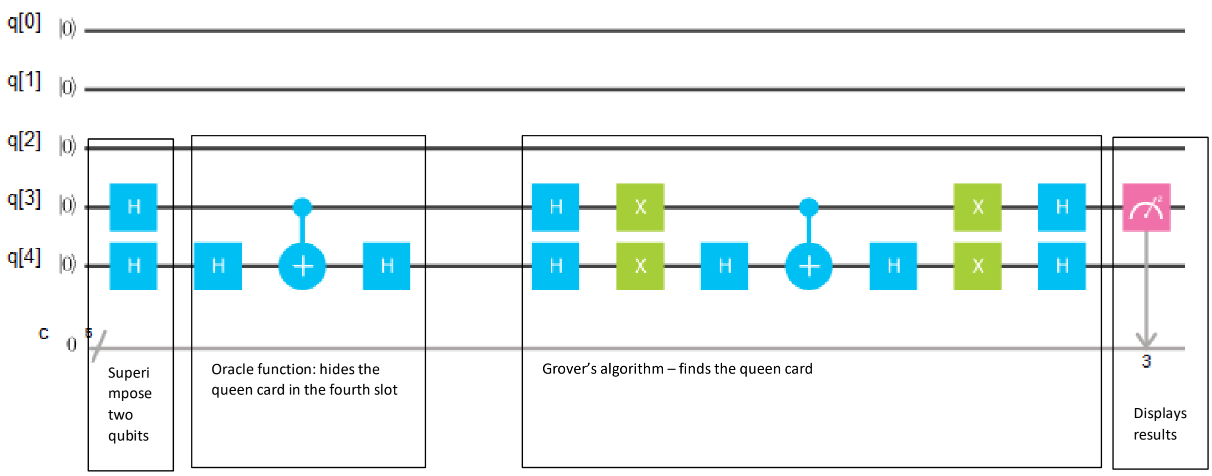
Class activity

Grover's algorithm – or 'Find the Queen'

Grover's algorithm is a way to select items from a database extremely quickly. It uses superposition (Hadamard gates) and entanglement (CNOT gates). When you copy this program into the Composer, you will be showing how much faster a quantum computer can be compared to a conventional digital computer.

You can view the explanatory video at https://www.youtube.com/watch?v=pYD6bvKLI_c

Then implement the Grover's algorithm as shown in Composer below:



When we run this program on the simulator, we get this result:

This shows it is certain (probability = 1) that the queen is in the fourth slot (counting from the right). What is significant about this program? Well, if you had four cards laid out in front of you, how quickly could you pick the one with the queen? You have a 0.25 (one in four) probability of picking it first time, 0.33 (one in three) chance of picking it at the second attempt, and so on. In general, it will take you 2.5 selections to find the queen.

However, Grover's algorithm picks it at the FIRST attempt! So it is a much faster algorithm than any conventional computer can use!

Homework	Explore a 360 Video of the IBM Research Quantum Lab – click on picture to view 		
Session Number	6	**Session Topic Focus**	Entanglement
Class activity			
Quiz	**Entanglement** 1. What is another name for the CNOT gate? a. Entanglement gate b. Flipper gate c. Flopper gate d. *Controlled NOT gate 2. What is another name for Grover's Algorithm? a. Find them b. Find the King c. Find me d. * Find the Queen 3. What did Einstein call entanglement? a. Just plain weird b. Ghostly action at a distance c. Seeing without believing d. * Spooky action at a distance		

Session Number	7	Session Topic Focus	Project

Class activity

Learning Intention
Students will create their own quantum score.

By now you have used many of the quantum gates available. You can encountered the concepts of superposition and entanglement. Each of these are very powerful tools in the quantum computer.

[Q Experience]

In this lesson, you are encouraged to write your own quantum program. One way to conceive of your program is to see you have five qubits at the start which you can set to zero (|0>) or, by using the X-gate, can be set to one (|1>). After your program has run, the qubits will have five different values (from 00000 to 11111). It may be that the values will have probabilities associated with them.

Here are some programming ideas to get you started:

> "My quantum program adds the first two qubits to the last two qubits".
> "My quantum program turns the first two qubits into their opposites".
> "My quantum program distributes all the possible combinations of results evenly through all five qubits".

By the end of the lesson you should have created a document in your word processor that contains a screenshot of your Composer program, and a picture of the output with a verbal description like those above. When you view your output, mouse-over the Quantum circuit to see a download button which can give you a PNG (picture file).
Another way to document your quantum project program is to use the 'Download all data' button at the bottom right of the output window. You'll need to unpack the compressed folder, but the graphics you'll need are in there.

Homework

In the Quantum Results output, you will see a 'Download CSV' button. Can you use this to create a really sharp chart of your program output?
Also, it might be possible to turn that CSV spreadsheet file into a really nice Bloch sphere diagram. Can you find a way to do this?

Quiz

Project

1. Were you able to plan a quantum computing project?
   a. * Yes
   b. No
2. Did you create a quantum score of your own?
   a. * Yes
   b. No

Session Number	8	Session Topic Focus	Conclusion and Assessment

Class activity

Learning Intention

Students will view and demonstrate your knowledge of quantum computing.

Review

Here is a list of the topics presented in this introduction to Quantum Computing.

Lesson	Topic	Main ideas
1	Why quantum: How big is a bit?	Digital computers use binary digits The volume of a binary digit has been shrinking The time when a binary digit will be as small as an atom may be in the next 10-20 years.
2	What is a qubit?	What atoms are made of Representing quantum particles like atoms with the Bloch sphere. How a qubit is constructed
3	Writing my first quantum score	Creating an account on the IBM Q Experience Using Composer Measuring qubit quantum states and their probabilities
4	Quantum gates	The Pauli X, Y and Z gates Combinations of gates on a single qubit
5	Superposition	The Hadamard gate Probability of output states Superposition for multiple qubits The simple Lisiecki program
6	Entanglement	The CNOT gate Grover's selection algorithm
7	Project	Implementing your own quantum program Documenting the quantum score, output and programming intention

Session Number	8	Session Topic Focus	Conclusion and Assessment

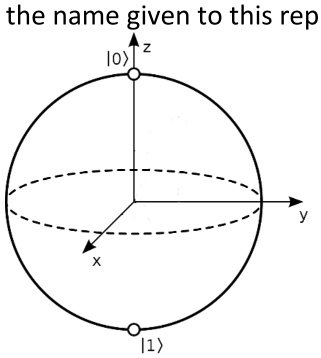
End of module Test

Here is a short test to help you confirm what you know about quantum computing.

1. What is a 'bit' in computing terms?
   a. A chip
   b. A binary digit
   c. The storage space for the smallest piece of information in a computer system.
   d. An integrated circuit

2. The volume to store a bit will be as small as an atom:
   a. By 2030
   b. It is already that small
   c. By 2050
   d. By 2100

3. What is the name given to this representation of the state of a qubit?



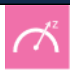
   a. IBM ball
   b. Black sphere
   c. Binomial circle
   d. Bloch sphere

4. What is the temperature of the core of a quantum computer?
   a. <1° Kelvin
   b. -273° Celsius
   c. 0° Celsius
   d. As cold as possible

5. What is this quantum scoring system called and used for?
   a. Compiler – for writing programs for a quantum computer
   b. Composer – for writing programs for a quantum computer
   c. Confuser – for composing scores for a quantum violin
   d. Confounder – for creating music on new instruments

6. What is another name for the Pauli X-gate, and what does it do?
   a. 'flip-bit' – it turns the qubit left or right
   b. "bit-flip' – it turns |1> into |0>
   c. 'bit-flip' – it turns |0> into |1> and vice versa
   d. 'X' – it turns the qubit inside out

Session Number	8	Session Topic Focus	Conclusion and Assessment
End of module Test			

7. What does this tool do in Composer? 
    a. Measures the Z value of a qubit (|0> or |1>)
    b. Measures the Z value of a qubit (|0> or |1>) and its probability
    c. Measures the value of a qubit
    d. Measures the values of all the qubits

8. Which gate is used to put a qubit into superposition?
    a. T phase gate
    b. Pauli X-gate
    c. Pauli Y-gate
    d. Hadamard gate

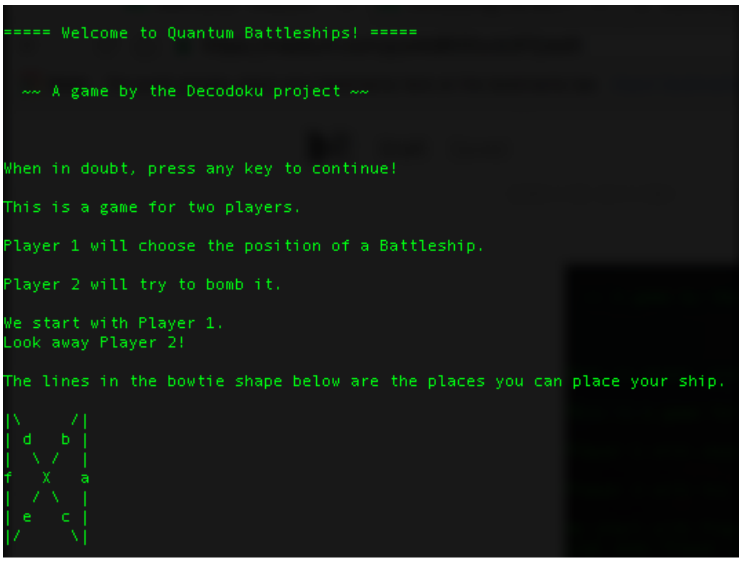
9. The CNOT gate entangles the control and target qubits. What is strange about entanglement?
    a. It can be used for cryptography
    b. It's spooky
    c. It works at a distance
    d. No one knows how it works

10. What is special about Grover's algorithm?
    a. It's a quantum program
    b. It finds things in one go
    c. It uses entanglement
    d. It is much faster than conventional sorting algorithms

11. How can you get a really nice picture of your quantum score?
    a. When viewing the output, take a screen shot of the score
    b. When viewing the output, mouse-over the Quantum circuit and use the download button
    c. Take a screenshot of the score before you run the program
    d. Copy the score onto a piece of paper

Fun

Relax with a game of quantum battleships



Session Number	8	Session Topic Focus	Conclusion and Assessment

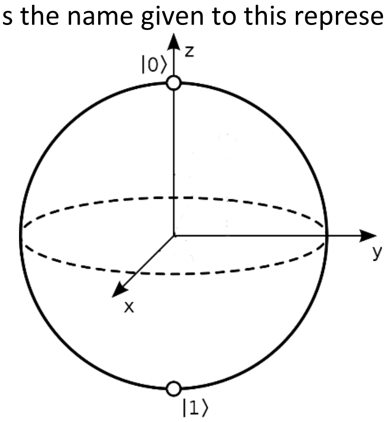
End of module Test - Answers

Here is a short test to help you confirm what you know about quantum computing.

1. What is a 'bit' in computing terms?
   c. * the storage space for the smallest piece of information in a computer system.

2. The volume to store a bit will be as small as an atom:
   a. *By 2030

3. What is the name given to this representation of the state of a qubit?



   d. *Bloch sphere

4. What is the temperature of the core of a quantum computer?
   b. *-273° Celsius

5. What is this quantum scoring system called and used for?
   b. *Composer – for writing programs for a quantum computer

6. What is another name for the Pauli X-gate, and what does it do?
   c. *'bit-flip' – it turns |0> into |1> and vice versa

7. What does this tool do in Composer? 
   b. *Measures the Z value of a qubit (|0> or |1>) and its probabilit

8. Which gate is used to put a qubit into superposition?
   d. *Hadamard gate

9. The CNOT gate entangles the control and target qubits. What is strange about entanglement?
   c. *It works at a distance

10. What is special about Grover's algorithm?
    b. *It finds things in one go

11. How can you get a really nice picture of your quantum score?
    b. When viewing the output, mouse-over the Quantum circuit and use the download button

Assessment – Australian Digital Technologies Curriculum			
Content Description	**Session**	**Assessment Piece**	**Achievement Statement**
Investigate how data is transmitted and secured in wired, wireless and mobile networks, and how the specifications affect performance (ACTDIK023)	N/A		
Investigate how digital systems represent text, image and audio data in binary (ACTDIK024)	2	Comparing binary bits and cubits	Students investigated and compared binary bits and qubits in relation to quantum computing.
Acquire data from a range of sources and evaluate authenticity, accuracy and timeliness (ACTDIP025)	N/A		
Analyse and visualise data using a range of software to create information, and use structured data to model objects or events (ACTDIP026)	N/A		
Define and decompose real-world problems taking into account functional requirements and economic, environmental, social, technical and usability constraints (ACTDIP027)	N/A		
Design the user experience of a digital system, generating, evaluating and communicating alternative designs (ACTDIP028)	N/A		
Design algorithms represented diagrammatically and in English, and trace algorithms to predict output for a given input and to identify errors (ACTDIP029)	N/A		
Implement and modify programs with user interfaces involving branching, iteration and functions in a general-purpose programming language (ACTDIP030)	7	Student project	Students developed and created code to write a quantum score.
Evaluate how student solutions and existing information systems meet needs, are innovative, and take account of future risks and sustainability (ACTDIP031)	1	Investigating and Analysing quantum computing	Students investigated the importance and development of quantum computing.
Plan and manage projects that create and communicate ideas and information collaboratively online, taking safety and social contexts into account (ACTDIP032)	N/A		

Assessment – Victorian Digital Technologies Curriculum			
Content Description	**Session**	**Assessment Piece**	**Achievement Statement**
Investigate how data is transmitted and secured in wired, wireless and mobile networks (VCDTDS035)	N/A		
Investigate how digital systems represent text, image and sound data in binary (VCDTDI036)	2	Comparing binary bits and cubits	Students investigated and compared binary bits and qubits in relation to quantum computing.
Acquire data from a range of sources and evaluate their authenticity, accuracy and timeliness (VCDTDI037)	N/A		
Analyse and visualise data using a range of software to create information, and use structured data to model objects or events (VCDTDI038)	N/A		
Manage, create and communicate interactive ideas, information and projects collaboratively online, taking safety and social contexts into account (VCDTDI039)	N/A		
Define and decompose real-world problems taking into account functional requirements and sustainability (economic, environmental, social), technical and usability constraints (VCDTCD040)	N/A		
Design the user experience of a digital system, generating, evaluating and communicating alternative designs (VCDTCD041)	N/A		
Design algorithms represented diagrammatically and in English, and trace algorithms to predict output for a given input and to identify errors (VCDTCD042)	N/A		
Develop and modify programs with user interfaces involving branching, iteration and functions using a general-purpose programming language (VCDTCD043)	7	Student project	Students developed and created code to write a quantum score.
Evaluate how well student-developed solutions and existing information systems meet needs, are innovative and take account of future risks and sustainability (VCDTCD044)	1	Investigating and Analysing quantum computing	Students investigated the importance and development of quantum computing.

Assessment – New South Wales Technology Syllabus			
Outcomes and Content	**Session**	**Assessment Piece**	**Achievement Statement**
designs, communicates and evaluates innovative ideas and creative solutions to authentic problems or opportunities TE4-1DP	N/A		
plans and manages the production of designed solutions TE4-2DP	N/A		
designs algorithms for digital solutions and implements them in a general-purpose programming language TE4-4DP	N/A		
explains how data is represented in digital systems and transmitted in networks TE4-7DI	N/A		
explains how people in technology related professions contribute to society now and into the future TE4-10TS	N/A		
evaluate how existing information systems meet needs, are innovative, and take account of future risks and sustainability (ACTDEK029, ACTDIP031)	N/A		
evaluate the suitability of hardware with particular performance characteristics against the needs of different users	N/A		
develop criteria to evaluate design ideas, processes and solutions, the functionality, aesthetics and a range of constraints, eg accessibility, cultural, economic, resources, safety, social, sustainability, technical (ACTDEP038, ACTDIP027, ACTDIP031)	1	Investigating and Analysing quantum computing	Students investigated the importance and development of quantum computing.
investigate how digital systems represent text, image and audio with whole numbers, for example: (ACTDIK024)	2	Comparing binary bits and cubits	Students investigated and compared binary bits and qubits in relation to quantum computing.
explore how data is transmitted and secured in wired, wireless and mobile networks ACTDIK023)	N/A		
design the user experience of a digital solution, generating, evaluating and communicating alternative ideas (ACTDEP036, ACTDIP028, ACTDIP032)	N/A		
collect and access data from a range of sources, for example: (ACTDIP025)	N/A		
evaluate the authenticity, accuracy and timeliness of data (ACTDIP025)	N/A		
interpret and visualise data using a range of software to create information, for example: (ACTDIP026)	N/A		
model objects or events using structured data, for example: (ACTDIP026)	N/A		
plan and manage projects individually and collaboratively (ACTDEP039)	N/A		
implement and modify programs involving branching, iteration and functions in a general-purpose programming language, for example: (ACTDIP030)	7	Student project	Students developed and created code to write a quantum score.
implement a functioning user interface, for example: (ACTDIP030)	N/A		
evaluate how student solutions address defined functional requirements and constraints (ACTDIP031)	1	Investigating and Analysing quantum computing	Students investigated the importance and development of quantum computing.
trace algorithms to predict output for a given input and to identify errors (ACTDIP029)	N/A		
identify social, ethical and cyber security considerations of digital solutions	N/A		

Assessment – Western Australian Digital Technologies Syllabus			
Year 7			
Content Description	**Session**	**Assessment Piece**	**Achievement Statement**
Different types of networks, including wired, wireless and mobile networks (ACTDIK023)	N/A		
Hardware components of a network (ACTDIK023)	N/A		
Digital systems represent text, image and audio data (ACTDIK024)	2	Comparing binary bits and cubits	Students investigated and compared binary bits and qubits in relation to quantum computing.
Explore how to acquire data from a range of digital sources (ACTDIP025)	N/A		
Create information using relevant software, and create data to model objects and/or events (ACTDIP026)	N/A		
Design the user experience of a digital system (ACTDIP028)	N/A		
Create digital solutions that include a user interface where choices can be made (ACTDIP030)	7	Student project	Students developed and created code to write a quantum score.
Create and communicate information collaboratively online, taking into account social contexts (ACTDIP032)	N/A		
Define and break down a given task, identifying the purpose (WATPPS39)	N/A		
Consider components/resources to develop solutions, identifying constraints (WATPPS40)	N/A		
Design, develop, review and communicate design ideas, plans and processes within a given context, using a range of techniques, appropriate technical terms and technology (WATPPS41)	N/A		
Follow a plan designed to solve a problem, using a sequence of steps (WATPPS42)	7	Student project	Students developed and created code to write a quantum score.
Safely make solutions using a range of components, equipment and techniques (WATPPS43)	N/A		
Independently apply given contextual criteria to evaluate design processes and solutions (WATPPS44)	1	Investigating and Analysing quantum computing	Students investigated the importance and development of quantum computing.
Work independently, and collaboratively when required, to plan, develop and communicate ideas and information when using management processes (WATPPS45)	N/A		

INTRODUCTION TO QUANTUM COMPUTING

Levels 7-8

Assessment – Western Australian Digital Technologies Curriculum			
Year 8 Syllabus			
Content Description	**Session**	**Assessment Piece**	**Achievement Statement**
Methods of data transmission and security in wired, wireless and mobile networks (ACTDIK023)	N/A		
Specifications of hardware components and their impact on network activities (ACTDIK023)	N/A		
Binary is used to represent data in digital systems (ACTDIK024)	2	Comparing binary bits and cubits	Students investigated and compared binary bits and qubits in relation to quantum computing.
Evaluate the authenticity, accuracy and timeliness of acquired data (ACTDIP025)	N/A		
Evaluate and visualise data, using a range of software, to create information, and use structured data to model objects or events (ACTDIP026)	N/A		
Design the user experience of a digital system (ACTDIP028)	N/A		
Design plans, using a sequence of steps, and represent them diagrammatically and in English, to solve a problem and to predict output for a given input to identify errors (ACTDIP029)	N/A		
Implement and modify solutions, that include user interfaces within a programming environment, including the need for choice of options and/or repeating options (ACTDIP030)	7	Student project	Students developed and created code to write a quantum score.
Create and communicate interactive ideas collaboratively online, taking into account social contexts (ACTDIP032)	N/A		
Investigate a given need or opportunity for a specific purpose (WATPPS46)	N/A		
Evaluate and apply a given brief (WATPPS47)	N/A		
Consider components/resources to develop solutions, identifying constraints (WATPPS48)	N/A		
Design, develop, evaluate and communicate alternative solutions, using appropriate technical terms and technology (WATPPS49)	N/A		
Produce a simple plan designed to solve a problem, using a sequence of steps (WATPPS50)	N/A		
Safely apply appropriate techniques to make solutions using a range of components and equipment (WATPPS51)	N/A		
Develop contextual criteria independently to assess design processes and solutions (WATPPS52)	1	Analysis of quantum computing	Students investigated the importance and development of quantum computing.
Work independently, and collaboratively when required, to plan, develop and communicate ideas and information when managing processes (WATPPS53)	N/A		