

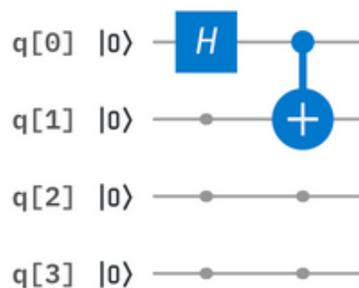
## Getting started with quantum circuit composing

Here are some instructions in case you would like to play around designing your own quantum circuits. I'll try to explain enough so that even if you don't know anything about quantum computing you'll have an idea of what you are doing. First, though, set up an account with IBM so that you can use their Qiskit tools. For that, do the following.

- Go to <https://quantum-computing.ibm.com/login>.
- Click on "Create IBM account". You will be asked a few simple questions and then, presto, you'll have an account.
- If you're not taken directly to the IBM Experience page, then click on "Try it Now". You should then be on this page <https://quantum-computing.ibm.com/>.
- Here you have two options. You can click on "Create a notebook" that will allow you to compose a quantum circuit using Python code, or you can click on "Create a circuit". If you're just starting out, I recommend you do the latter even if you know Python.
- Now you're on the Circuit Composer page. At the top, you'll see a bunch of colored squares. These are the various gates that you can use to build a circuit. The only gates that you will need are: the H (Hadamard) gate, the X gate, the Z gate, the T gate and the CNOT gate (the sixth one from the right in the upper row). The first four are single-qubit gates with one input and one output. The CNOT gate is a two-qubit gate with two inputs and two outputs. These five gates form a universal gate set. If you know digital electronics, then you might know that the NAND gate is a universal gate for digital circuits. That is, any digital circuit can be composed by using only NAND gates. Here we have something similar. Any quantum circuit can be composed using only the universal set of five gates: H, Z, X, T and CNOT. Any digital circuit can be turned into a corresponding quantum circuit using only the set of five universal gates. You see how simple this is. You might not know what the five gates in the universal set do but they are very simple. I'll describe them in a later posting. So all you need are these five simple gates and you can design any quantum circuit. Come up with your own original circuit and you'll be very famous!
- Also on the page, you'll see six horizontal lines. The top five of these represent five qubits. The bottom one is a five-bit (not qubit) line. You can compose a quantum circuit by clicking and dragging the gates onto the qubit lines. There are five qubits because the IBM quantum computer that you can submit your circuit to is a five-qubit machine. There is also a sixteen-qubit machine called Melbourne that you can also submit to. If you want to do that, you will need to create a circuit with Python using the Notebook. I don't think that Circuit Composer will allow you to use more than five qubits, but five should be enough to get started.
- On the third row just below the gates, you'll see a black square with what looks like a needle and a meter. That's what you'll use for measuring the qubits after the calculation is completed. When you drop that onto the qubit line that you want to measure, it will

connect a line to the bit line at the bottom and your measurement will appear as one of the bits on that line. Note that although qubits are in superposition states and are entangled with each other, when you measure a qubit you get only a bit's worth of information. That is, you will measure a bit of information, either 0 or 1.

- OK, now we're ready to create a circuit. For your first one, I suggest doing the example that you can see by clicking on "Composer guide" in the left-hand column. [If you do this, note that the Composer Guide is for an earlier version of Circuit Composer. The layout and style of the gate symbols is a little different.] Here I give complete instructions on making the circuit example described in the Composer Guide. The circuit you will make is the following. You put a Hadamard gate on the first qubit and connect the first and second qubits with a CNOT gate. That's it



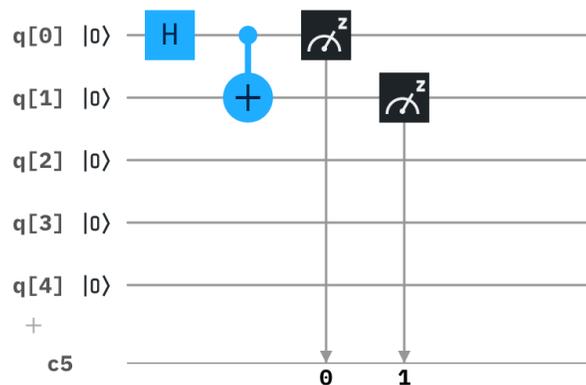
- What you've made is a Bell pair producer. If the initial state of each of the two qubits is set to  $|0\rangle$ , then the input state of the two qubits is the product state  $|00\rangle$ . The output state will then be:

$$\frac{1}{\sqrt{2}} (|00\rangle + |11\rangle)$$

The factor of  $1/\sqrt{2}$  is needed to normalize the state to unit length, but for now don't worry about it. This state is a maximally entangled state of two qubits. It is one of the most remarkable consequences of quantum mechanics. Neither of the two qubits is in a definite state. If either one is measured there is a 50% chance of measuring  $|0\rangle$  and a 50% chance of measuring  $|1\rangle$ . However, the two qubits are completely correlated. If one of them is measured to be  $|0\rangle$ , then the other is certain to also be measured as  $|0\rangle$ . Similarly, if one of the qubits is measured to be  $|1\rangle$  then the other is certain to also be measured as  $|1\rangle$ . If Alice had one of these qubits and Bob had the other, then even if they were on opposite ends of the galaxy, the instant that Alice measured her qubit to be  $|0\rangle$ , Bob's would instantaneously also be in the state  $|0\rangle$  while if Alice measured her qubit to be  $|1\rangle$ , Bob's qubit would instantaneously also be in the state  $|1\rangle$ . This means that Alice's and Bob's qubits have no local reality before they are measured. Einstein wouldn't accept this. He thought that there must be something deeper than quantum mechanics, a theory with so-called hidden variables, that, if known would specify the

local states of Bob's and Alice's qubits. In the 1960's, John Bell developed a set of inequalities that would be obeyed if quantum mechanics were the correct theory but would be violated by theories with hidden variables that preserved local reality. Since then, many sophisticated experiments have been carried out to test this. In all of them, quantum mechanics has come through with flying colors. The hidden variable theories are wrong. This is an important lesson. Even though a theory doesn't make "sense", it doesn't mean it is an incorrect theory. Quantum mechanics doesn't make sense to anyone but given that it is mathematically and logically consistent and that it agrees with every experiment that has ever been done, it is almost certainly correct. Of course, tomorrow someone might do an experiment that is in violation of quantum mechanics and the theory would then need to be rejected, but this is extremely unlikely. It would mean that all of our current physics is wrong (well, except for maybe general relativity). Do not use your common sense when judging a theory. There is no reason why nature should satisfy your common sense, not even Einstein's. By the way, you can see here one of the main differences with classical physics. In classical physics, if you completely know the state of a system, then you know everything about the individual parts of the system. For the system of entangled qubits, on the other hand, we can know everything about the system but we know nothing about the individual parts, the individual qubits.

- Now, back to your circuit. Your circuit produces an entangled pair of qubits but now to see what is going on you need to measure them. To do that, put a black square measuring block on each of the two outputs. The circuit will then look like this.

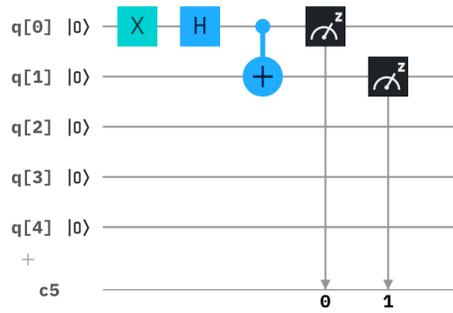


The measurement of the top qubit will appear on bit 0 of the 5-bit line and the measurement of the second qubit will appear on bit 1 of the 5-bit line. Now you're ready to run your circuit.

- First you will have to save it. Click on "Save" in the upper left of the page. That will save it as "Untitled experiment". Hover the mouse over the name and click the edit symbol that appears to give it the name of your choice.
- Then click "Run" on the upper right of the page. This will open up a window in which you can select the backend that you want to run on and the number of shots you want. I

suggest that you first run your circuit on the simulator. That is a classical (digital) computer that simulates a quantum computer. In order to do that select `ibm_qasm_simulator`. A number of shots equal to 1024 is probably a good choice.

- You might be wondering why a quantum computer, if it is so powerful, can be simulated by a classical computer. A quantum computer with a large number of qubits would be vastly more powerful than any digital computer, but here we are working with just a 5-qubit computer and the circuit that you built uses only two qubits. During computation, an  $n$ -qubit computer operates on and keeps track of  $2^n$  real numbers (well, really they are complex number but we needn't be concerned with that now). So, a 5-qubit computer is operating on  $2^5 = 32$  numbers. A digital computer can easily handle that. If we had say a 300-qubit computer, then it would be operating on  $2^{300} \approx 10^{100}$  numbers. That is more than the number of protons in the visible universe. You can see why a quantum computer is able to do amazing things if it has enough qubits. It will be quite awhile though before we have a 300-qubit computer. Note that, we are talking about 300 logical qubits, that is, qubits that are doing the calculating. Because all of the qubits must act coherently, a quantum computer is very susceptible to noise. It's possible to correct for errors but that is much harder in a quantum computer than in a digital computer for reasons that I'll explain in later post. With a qubit fidelity (error rate) of about 1% that is expected to be available within the next decade or so, about 1000 qubits will be needed for error correction for each logical qubit. So, a 300 logical qubit computer would need 300,000 physical qubits. We're still a long way from that.
- In your circuit, you use two qubits. That means your circuit is operating on four numbers. Can you think what they are?
- After you've selected `ibm_qasm_simulator`, you're ready to run the simulation. To do that, click the large blue "Run" tab. The status of your job will appear at the bottom of the page. It should take only a few seconds for the simulator to run. After it is finished, you'll see "Status: COMPLETED". Click on the job and you'll see the results.
- Scroll down until you see the histogram. This is a histogram of the 5-bit line that your measurements went into. The labels of the histogram bins show the values of the five bits from right to left. So, for example, a histogram bin labelled 00010 would show the number of shots for which the first bit is 0 and the second bit is 1. See if you can understand what the results mean.
- Now run on one of the actual quantum computers. Depending on how full the queue is, this might take a few minutes. Look at the results and see if you can explain why they are somewhat different from the results with the classical simulator.
- You might also want to try running your circuit with inputs other than the  $|00\rangle$ . To do that, just stick an X gate on one or both input lines. For example, the following circuit will give an input of  $|01\rangle$ .



- You can make each of the four maximally entangled qubit pairs, called Bell pairs, by using the appropriate input. The output of the circuit for each of the four inputs is:

$$|00\rangle \rightarrow \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle)$$

$$|10\rangle \rightarrow \frac{1}{\sqrt{2}} (|00\rangle - |11\rangle)$$

$$|01\rangle \rightarrow \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle)$$

$$|11\rangle \rightarrow \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle)$$

- Have fun exploring. If you have any questions or would like further suggestions, please email me at [steve.schnetzler.physics@gmail.com](mailto:steve.schnetzler.physics@gmail.com).