PhysicsQuest [2025]: Putting the rhythm in quantum algorithms

Date - Revised: 2024-09-20

| **Title:** Putting the rhythm in quantum algorithms  **Subtitle:** Learn quantum programming basics with the 2-Qubit dance  Developed by - Dominique Wolfshagen - Institut quantique, Université de Sherbrooke | | |
| --- | --- | --- |
| **Total Time:** 45-60 minutes  **Audience:** Middle School Science and High School Teachers  **Education Level:** Grades 6 - 10 | | |
| **Content Area:** Quantum information science : quantum programming  **Educational topic:** Quantum mechanics, quantum programming, algorithms, quantum logic gates, classical computing, qubits  **Objectives:**   * Having students differentiate the hardware of classical computers VS quantum computers * Making students experiment with the concept of a binary code and how it applies in computing with bits of information * Introducing key quantum principles (superposition of states and entanglement) and how they are used in quantum computing * Introducing the representation of a qubit with the Bloch sphere * Using the 2-Qubit Dance to introduce quantum logic gates and how they translate into the manipulation of the qubits to execute an algorithm   **Key Question:** If we could see inside a quantum computer, how would it work to execute a quantum algorithm? | | |
| **Next Generation Science Standards:**  **MS-PS4-3.** Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.  [**QIS Key Concepts**](https://q12education.org/wp-content/uploads/2023/12/MS-QIS-Key-Concepts-FINAL-12-7-2023.pdf)**:**  MS Science 4.1 Qubits - Unlike a classical bit, each qubit can represent information in a superposition, or vector sum that  incorporates two mutually exclusive quantum states.   * Quantum bits (qubits) are encoded in quantum systems.   + Qubits can be 0, 1, or a superposition of 0 and 1. | | |
| **Materials** | The kit will contain:   * [PowerPoint presentation](https://docs.google.com/presentation/d/1wGOBVEZo5YlCdYjv0YG99EpGuMZPa94R/edit?usp=sharing&ouid=109602940898607476571&rtpof=true&sd=true) (which covers the notions and structures the proceeding of the workshop), * Link to the YouTube videos of the final activity (the 2-Qubit Dance tutorial and game) * Tutorial: <https://www.youtube.com/watch?v=x45eb2joUkY> * Game: <https://www.youtube.com/watch?v=LulkWbW5hso> * The teacher’s and students’ guides   To go through the workshop in your class, you will also need:   * An internet connection * A way to display the PowerPoint presentation and the YouTube videos (with sound) * Cardboard and markers * Tape or Tac 'N Stik Reusable Adhesive | |
| **Overview:** Through a series of interactive activities, students will progressively learn about some basic notions of classical computing and build from there to understand how quantum computers are different, how they work and how they are programmed. The first 2 activities let the students experiment with binary code, and the last activity teaches them how to dance a quantum algorithm. | | |
| **Teacher Background:**  Quantum mechanics is the branch of physics that studies energy and the behavior of matter at an infinitesimally small scale. Since its beginning 100 years ago, quantum physics’ advances have highlighted counterintuitive but rigorously proven properties of matter, which led to modern applications such as the MRI used daily in hospitals, or the atomic clock on which the GPS is based.  In addition to the present-day applications across a wide range of fields, a particular future application is monopolizing the attention towards quantum technology: quantum computers. While none is performant enough to be applied to real-life problems at the moment, there’s nonetheless a hype because of the many breakthroughs in the recent years and because its potential applications are very promising.  This new type of computer will come with an entirely new way of programming. This is due to the fact that quantum computers are not “simply faster classical computers”: they are not made the same way and don’t work the same way. In a classical computer, the hardware is made of transistors, each of which can be a bit of value 0 or 1. In a quantum computer, the hardware is made of qubits (quantum bits), which can take the values 0 or 1, like classical computers, but also a superposition of 0 and 1 at the same time, in any proportion. In other words, every qubit can compute many different information at the same time, so the calculating power grows exponentially with each qubit. Furthermore, the qubits can be entangled, another quantum phenomenon where they become linked and are affected spontaneously. When the qubits are measured, they collapse (lose their quantum state), and we obtain the results. Since the quantum properties are not exploited in classical computers, the way to program quantum computer has nothing to do with classical programming.  Currently, the quantum computers aren’t efficient enough to be applied to real-life problems, because the quantum states of qubits only last for fractions of a second and because they are very “noisy”, meaning imperfectly prepared and measured, so there are many errors. That being said, we already know how the computer will function if those hardware challenges are resolved, and it is also possible to run simulations of quantum algorithms on classical computers for simpler problems. Thus, it is already possible to develop and test quantum software programs and algorithms, and this new way of programming is a growing part of quantum research.  To approach quantum programming in a more intuitive way, it is possible to visualize qubits as Bloch spheres, a 3D geometrical representation where a qubit is a vector starting at the center of a sphere and stretching to the outer perimeter of the sphere. You can then use a convention to determine the value of the qubit based on the position of the vector. For instance, if “up” means “0” and “down” means 1, a 50%-50% superposition of state is represented by a vector pointing at the equator of the sphere, right between 0 and 1.  Quantum programming is based on logic gates that affect qubits. The logic gates can put them in a superposition of state or to entangle them. The effect of the gates applied on qubits can be visualized with vectors in the Bloch sphere. For example, if you apply the Y gate, the vector will go through a rotation of 180˚ around the Y-axis. This is like when you spun the coins in the kit’s previous activity and got “heads or tails”. The Y gate can rotate the qubit to the opposite state.  The fun begins when you consider that each of your arms can be seen as a pointing vector on a Bloch sphere, a convenient way to represent the qubit state graphically, because then, you can dance a quantum algorithm with your arms! **Teacher Tips:**  1. Suggested [STEP UP Everyday Actions](https://engage.aps.org/stepup/curriculum/everyday) to incorporate into activity    1. When pairing students, try to have male/female partners and invite female students to share their ideas first    2. As you put students into groups, consider having female or minority students take the leadership role.    3. Take note of female participation. If they seem to be taking direction and following along, elevate their voice by asking them a question about their experiment. 2. Consider using white boards so students have time to work through their ideas and brainstorms before saying them out loud. 3. As students experiment, roam around the room to listen in on discussion and notice experiment techniques. If needed, stop the class and call over to a certain group that has hit on an important concept. 4. Consider [culturally responsive tools and strategies](https://www.nciea.org/blog/a-culturally-responsive-classroom-assessment-framework/) and/or [open ended reflection questions](https://www.cde.state.co.us/standardsandinstruction/es-student-reflections-mc) to help push student thinking, have students track their thinking during the activity, connect to their lives, and create opportunities to develop STEM identity. 5. Allow the work of physicists to come alive by signing up for a virtual visit from a working physicist using [APS’s Physicist To-Go](https://www.aps.org/initiatives/physics-education/k-12/physicists-to-go) program. You can request a plasma scientist to talk about the concepts students learned in this activity! | | |
| **Key Terms (used or presented after the activities - see Foreward for details)**  **Quantum mechanics:** The branch of physics that studies energy and the behavior of matter at an infinitely small scale.  **Algorithms:** A set of rules that allow the execution of a particular computer process.  **Hardware:** The physical equipment and electronic parts of a computer.  **Software:** Instructions that makes a computer do a particular task.  **Transistor:** An electronic device used to control electrical currents; commonly found in radios, calculators, televisions and computers.  **Bit:** Most basic unit of information used by computer and electronic devices (the name is the contraction of “binary digit”).  **Qubits:** Unit of information measurement in quantum computing.  **Bloch sphere:** A geometrical representation of the pure state space of a qubit or any other two-level quantum mechanical system.  **Entaglement:** A phenomenon of a group of particles where the quantum state of each particle of the group cannot be described independently of the state of the others, including when the particles are separated by a large distance.  **Quantum logic gates:** A fundamental component in quantum computation that performs operations on qubits based on quantum principles. | | |
| **Teacher’s Guide** | | |
| **Objectives:**  – \*Understanding quantum computers, including how they differ from classical computers and how they are programmed.  \*It is important to understand that student goals may be different and unique from the lesson goals. We recommend leaving room for students to set their own goals for each activity. | | |
| **Before the Experiment:** | | 1. We invite you to watch a [brief video demonstration](https://www.youtube.com/watch?v=G8RDtnKbdS4&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=10) of the developer conducting the experiment you’ll be facilitating with your students. 2. Consider exploring XXX’s narrative using the lessons ideas detailed on the Introduction found in your materials kits. 3. Verify that you are able to project the videos with sound in the classroom. 4. Go through the [PowerPoint](https://docs.google.com/presentation/d/1wGOBVEZo5YlCdYjv0YG99EpGuMZPa94R/edit?usp=sharing&ouid=109602940898607476571&rtpof=true&sd=true) presentation, read the presenter’s notes and make variations if desired. With the PowerPoint presentation, you will understand what is taught by each of the 3 interactive activities, which are:    1. Activity 1: Experimenting with binary code via answering with pairs of answers written on cardboard.    2. Activity 2: Using binary code to encode words in ASCII code.    3. Activity 3: Dancing quantum algorithms. 5. To do the binary code activities (activity 1 and 2), you need to prepare pairs of answers on cardboard. Prepare them by precutting pairs of cardboard rectangles, and then use the markers to write the following (keep in mind they need to be seen from the whole class):    1. For the first pair, write “1” on one and “0” on the other.    2. For the second pair, write “Yes” on one and “No” on the other.    3. Optional: Do as many other pairs as you would like where you have 2 different answers. For example, “hot / cold” “Calm / excited”, “light / dark”, “fruit / vegetable”…      1. For each pair of cardboard, prepare a list of questions that can be answered with those pairs of answers (except for the “0 / 1” pair).    1. Examples of questions for the “Yes/No” pair: Was your birthday last month? Are you having a good day today? Did you sleep well last night? Do you like cilantro? 2. Watch the YouTube [tutorial video](https://www.youtube.com/watch?v=x45eb2joUkY&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=1) to familiarize yourself with them, and to decide if you will warn the students before or during the game (second video) about the addition of the second player that happens mid-game. Either way, you will have to instruct the student how to deal with it (for example: the left side of the class to follow the left player and the right side to follow the right player; or have the student execute it in pairs). 3. Print enough student guides for the whole class. |
| **Setting Up** | | Note : it is best to have all your material ready from the start at your desk, but to display or distribute the material for the next activity only when you reach that point in the workshop (each moment to do the activity will be indicated in the PowerPoint presentation), as to not distract the students.  When opening the PowerPoint, make sure that you accept the access to multimedia content (the dance videos are external), or alternatively, open the 2 YouTube videos as well as the Powerpoint presentation.  You can distribute the student’s sheets before the students’ arrival or when starting the first activity.  Activity 1 : Experimenting with binary code   1. Assemble the pairs of answer cards on your desk.   Activity 2 : Discovering how code can carry information   1. Display the ASCII code for the upper-case alphabet (in the PowerPoint presentation) 2. Use tape (or Tac 'N Stik Reusable Adhesive) to stick the “0” card in the top position (at arm’s reach) on a wall and the “1” card on the bottom position, below the “0” (in a way that all students can see both cards).     Activity 3 : Dancing quantum logic gates   1. Open the first video, titled “[Tutorial](https://www.youtube.com/watch?v=x45eb2joUkY&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=1)”. 2. Open the second video, titled “[Game](https://www.youtube.com/watch?v=LulkWbW5hso&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=2)”. |
| **During the Activities** | | There are some questions to be answered by the class at some points in the PowerPoint presentation. When you come across one, ask the student to answer them verbally or on their sheet before continuing the PowerPoint (every question is answered in the next slide).  Activity 1 : Experimenting with binary code   1. Take the “Yes / No” pair, with the “Yes” in one hand and the “no” in the other, with arms spread apart to separate the cardboard left and right. Have the students note the convention on their student’s sheet with the appropriate arrows. Then ask 1-2 questions to your class that can be answered by yes or no, and have them respond by pointing left/right (at the answer). 2. Change the position of the cards to put them up and down instead of left and right. Make the students note the new convention, then ask 1-2 new questions where they answer by pointing up/down. 3. Optional: repeat with another pair of cardboard with different answers. 4. Use the PowerPoint presentation to underline the notions experienced with the activity.   Activity 2 : Discovering how code can carry information   1. Present to the class the ASCII code for the upper-case alphabet (in the PowerPoint presentation), where 8 bits (0 or 1) in a certain order means a certain letter (ex : A = 01000001) 2. Tell the student a letter of your choice (letter used for this example in the PowerPoint : I) and ask them to write on their sheet the sequence of 0s and 1s coding for it in ASCII code. Then, referring to the 0 and 1 sticked to the wall, ask the class to execute it, all at the same time. You can do it along with them or let them do it together without you, depending on their level of ease. 3. Then, test if they can understand what letter you are trying to communicate by using only the sequence of up and down (letter used for this example in the PowerPoint : W) 4. When they feel at ease with the ASCII code, go to the next slide and test if they can understand the word encoded with the series of up and down arrows. You can also do the sequence by pointing up and down correspondingly. Have the students translate it to find the word (answer : CAT). Leave a few seconds for them to translate it and then ask the class how many letters were in your word and what was the word. 5. Use the PowerPoint presentation to underline the notions experienced with the activity.   Activity 3 : Dancing quantum logic gates   1. Use the PowerPoint presentation to present the basic notions, including the Bloch sphere and the quantum logic gates.    1. You may want to have students produce posters or signs to remember what each logic gate does to a qubit and post them on desks or around the room during the game. 2. Tell the class to stand up and to spread themselves in the classroom so that their extended arms can’t touch anyone else. 3. Display the YouTube video for the tutorial and have them follow the movements (they are supposed to follow as if the image was a mirror of themselves). 4. Have them come back to their desks. 5. Use the PowerPoint presentation to highlight some elements of the tutorial (the sequence that creates a superposition of states; how the measurement of a superposed state makes it collapse sometimes up, sometimes down; etc.) 6. Have the students stand up and spread again in the classroom. 7. Display the YouTube video for the game and have them follow the movements. Note : in the middle of the game video, a second player is added, so warn them about this when you think best (before starting the game, or when this situation arises in the game). 8. Use the PowerPoint presentation to highlight final remarks and to conclude the workshop. 9. Following up this activity with Activity 8 - Bits vs. Qubits Module 1: Bits vs Qubits Lesson 3: What are qubits? can give students another representation of the superposition of bits and what happens to a qubit as it goes through logic gates and is then measured. |
| **Conclusion** | | 1. Quantum computers are entirely different from classical computer in the materials they are made of, in the way they work and in the way we program them. 2. Quantum algorithms are made by using logic gates are used to prepare quantum states on qubits. 3. If we could look inside a quantum computer while it runs an algorithm, it would look like it is dancing just like we did! |
| **Student’s Guide** | | |
| **Intro:**  Quantum sciences is a branch of physics that is 100 years old. Its breakthroughs are behind many of our everyday technologies and applies to many fields of applications. But there’s also an exciting future application: quantum computers. Today, you’re going to learn how those are different from classical computers and how to program them. Embark on this journey through the fascinating quantum world! | | |
| **Objective:**  Understanding quantum computers, including how they differ from classical computers and how they are programmed.  After reading the introduction, what is your essential question or objective for this activity? | | |
| **Before the Experiment** | | 1. Ask yourself what you already know about quantum physics and about quantum computers. Have you heard of them before? Do you know any possible keywords or notions related to the subject? |
| **Setting Up** | | 1. This workshop includes 3 activities. Pay attention to the instructions given by your teacher for each of the activities. 2. Make sure you have your pencil or pen ready to take notes during the activities. |
| **During the Experiment** | | Activity 1 : Experimenting with binary code   1. Answer this question to the best of your knowledge : How do classical computers work?    1. Your answer: 2. Note the first convention presented by your teacher (ex : ← = yes, → = no).    1. Answer teacher questions by pointing with your hand according to the directions of the convention presented. 3. Note the subsequent convention(s). (ex : ↑ = yes, ↓ = no).    1. Answer teacher questions by pointing with your hand according to the directions of the convention presented.   Activity 2 : Discovering how code can carry information   1. Answer this question to the best of your knowledge : How can 0s and 1s encode complex information like words?    1. Your answer: 2. On your sheet, note the letter told by the teacher and its corresponding series of 0 and 1. 3. Do the same with the 2 letters told by the teacher (ex : AB = 0100000101000010). 4. Note the series of 0 and 1 showed by the teacher to transmit you a coded word. 5. Answer those 2 questions:    1. How many letters are in the word?    2. What is the word?   Activity 3 : Dancing quantum logic gates   1. Answer this question to the best of your knowledge: What is quantum physics?    1. Your answer: 2. Answer this question to the best of your knowledge by circling A or B: Compared to classical computers, do you think quantum computers…:    1. work the same, but faster?    2. Work differently?   *That’s it, just have fun with the dance!* |
| **Conclusion** | | 1. Quantum computers are entirely different from classical computer in the materials they are made of, in the way they work and in the way we program them. 2. Quantum algorithms are made by using logic gates are used to prepare quantum states on qubits. 3. If we could look inside a quantum computer while it runs an algorithm, it would look like it is dancing just like we did!   Was your personal essential question answered? If so, what is the answer? If not, what additional information would you need to answer it? |
| **Additional Resources:**   * N/A | | |
| **Assessment/Extension activities\*\* (optional to extend thinking after the lesson):**   * To go further into your quantum programming journey, visit the link below to solve puzzles with quantum algorithms: <https://students.yourlearning.ibm.com/activity/MDLPT-341> * To understand how quantum properties can be used to do cryptography, you can play the BB84 game on this app : https://www.cryptoquantique.app/ * Design your own choreography! If you wish, film yourself dancing your quantum algorithm and send it to us at: curieuxquantiques@usherbrooke.ca * Real world connections -   + Sign up for [Physicists To-Go](https://www.aps.org/programs/outreach/physiciststogo.cfm) to have a scientist talk to your students.   \*\*Real world situations/connections can be used as is, or changed to better fit a student’s own community and cultural context. | | |