Quantum Literacy Project

Alice in Quantum Land

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Introduction

Quantum computing promises to be one of the groundbreaking technologies of the 21st century. Over the past decades, a solid theoretical framework has been built, showcasing the vast computational potential of a quantum computer and its advantages over an ordinary, "*classical*" computer. Technology is evolving at a steady pace, and little by little, theory is being put into practice. Unfortunately, at present these techniques are only understood by a small group of specialists, as most of the existing material on the matter presumes a heavy mathematical background. In line with the Lindau goals 9 and 10, communicating the basic ideas of such a transformative technology to a wider audience is a central challenge. At the same time, educating a new generation of young scientists, in a way that is accessible for students from many countries and backgrounds, is crucial.

This project's goal is to produce an open learning environment that explains the fundamentals of quantum computing at the high school level. As a first step, we have created an interactive online notebook introducing its users to the quantum world through a hands-on quantum game with an amusing storyline. This way, we can stay as close as possible to the experience of our target audience.

Format and intended audience

Our notebook is meant to be self-explanatory, allowing students at the high school level to get familiar with the basics of quantum mechanics. Instead of formulating the learning material as a complicated mathematical theory, we build it up as a children's tale, which is thereafter translated into a more rigorous scientific language. Even then, we avoid heavy use of intricate terminology or mathematical notation. The format of an online notebook allows us to not only tell a lively story but to also complement it by vivid colorful images, as well as interactive blocks of Python code that invite the students to experiment.

These coding sections of the notebook utilize IBM's quantum computing toolkit Qiskit. In a hands-on approach, the students can execute the quantum computing experiments described in the storyline, and observe how practice matches theory. Students can go through the notebook and run the pre-programmed commands with a simple mouse click, thereby making it as accessible as possible. They can modify existing code or write their own. Interactive widgets allow for additional experimentation. This way they do not only develop an intuition for the theory behind quantum computing but also acquire practical skills in a state-of-the-art quantum computing software toolkit.

In the following, we will briefly outline the storyline, and illustrate how our interactive coding examples aid in learning about the topic of quantum computing.

Storyline

An object in the quantum world is described by a ket, a vector containing its internal data. This ket evolves by passing through so-called quantum gates, which change the object's internal state. However, this evolution comes with some restrictions or rules, such as superposition of states and quantum entanglement. If those words don't mean anything to you, don't worry! They will become clear after you have stepped through the story in the notebook.

The main characters of our tale are Miss Schroedinger, who works as a scientist, and her cat named Alice. At first, Alice seems like an ordinary cat, but when she drinks quantum milk, she turns into a quantum cat, or as physicists would say, a ket. As such, Alice can take on different states: she can be asleep or be awake. Nothing a "*classical*" cat can't do, you would think, but Alice can do more. As a quantum cat, she can also be both awake and asleep at the same time, a so-called superposition of states.

Like all pet owners, Miss Schroedinger would like to share her cat's peculiar behavior with her friends, so she takes hundreds of pictures of Alice and uploads them on social media. But much to her surprise, about half of the photos show a cat which is asleep, while the other half shows Alice awake. None of the hundreds of photos shows Alice while both awake and asleep. This is due to a phenomenon called "*state collapse upon measurement*": whenever somebody watches Alice, her internal state will change to either awake or asleep, both with the same probability. One afternoon, Miss Pauli comes to visit Miss Schroedinger, and she brings her own cat named Bob. Alice and Bob drink quantum milk and begin to play with a ball of yarn, very quickly becoming tangled up in an adorable bundle. This also causes their internal states to interact or "*entangle*" with each other: they are both awake and both asleep as before, but now they are linked together. Miss Pauli then goes home with Bob and takes a picture of him. She sends Miss Schroedinger the photo, which shows Bob quietly asleep. Up to that point, her own cat Alice had been both awake and asleep, but when she glimpsed at Alice just after having seen Bob's picture, Alice was asleep as well. These visits are repeated regularly and every time the same thing happens: when looking at Bob's picture and at Alice in her basket, Miss Schroedinger sees them either both awake or both asleep, but never will Bob be asleep when Alice is awake or vice versa. Over time the two scenarios prove to be equally likely. This is again a manifestation of collapse upon measurement, only this time the likelihoods to see Alice either awake or asleep are dependent upon Bob's likelihoods, a dependence caused by quantum entanglement.

As the story proceeds, several other basic ideas of quantum mechanics are introduced, all through the eyes of Miss Schroedinger and her cat. Alongside we go deeper into the scientific significance of the tale. A quantum cat, which can be either awake or asleep (or a bit of both) corresponds to a qubit. A qubit captures the idea of an object which can be in two states, typically denoted by 0 and 1. This is in analogy with a classical bit, which can be either 0 or 1. In this metaphor, two or more quantum cats (or qubits), will become entangled by letting them play with a ball of wool (or applying a two-qubit gate, such as a so-called controlled-NOT gate). This way we can create an entangled state of two cats. A strange feature of this state, as observed by Miss Pauli, is that we will see the same image despite independently taking pictures of each cat. In the quantum computing language, the measurement outcomes of two entangled qubits are correlated, and what we did see, is that whenever we measure the first qubit to be in the 0 state, the second qubit is also 0; similarly, if the first qubit is 1, then the second one has to be 1 as well. This very peculiar feature caused a lot of headache even for such scientists as Einstein!

By intertwining the gentle metaphor with some semi-mathematical notation and lively pictures, the reader is familiarized with some essential concepts on the matter. The interactive coding examples follow the story (Figures 1-4) and allow the reader to acquire some intuition on typical quantum behavior. For example, a particular measurement can be executed multiple times. A student can then observe how the results will fluctuate due to the probabilistic nature of quantum mechanics. This will help him/her understand the nature of the world at its smallest scales of length, and to have a uniquely exciting first experience with quantum mechanics.

In the final section, we also explain the translation to more scientific concepts. To give an example, we discuss the similarities and differences between quantum and classical bits in more detail. This allows us to also introduce more advanced notions, such as the concept of quantum teleportation. In doing so we go beyond explaining basic ideas, and introduce interested students to the building blocks of state-of-the-art research on algorithms for quantum computing. An interactive quantum simulator also allows students to explore more advanced setups.

Summary and future work

Within the first 48 hours we have

- developed an engaging story, teaching high-school students about the core concepts of quantum mechanics and quantum computing; and
- set up an interactive online notebook that not only tells our story but also illustrates it with small coding examples and fun visualizations. The notebook format allows students to experiment with quantum computing codes on their own using state-of-the-art technology.

These materials provide an easy-to-use and hands-on introduction to the complex topic of quantum computing, that comes with a low barrier-to-entry. Extending this project further, future deliverables will include:

- building a full website with additional educational material and more Jupyter notebook quantum computing examples (Python code);
- transform the storyline into a comic book, following the example of "*Quantum Physics for Babies*" by Chris Ferrie; and
- the team is also intending to present this work to students and broader audiences at Open Days organised by their respective institutions, reaching potentially hundreds of students in face-to-face settings.

The authors hope that this work will find a broad interest among high school students and beyond and that it will improve the general understanding of the emerging field of quantum computing by building capacity and quantum literacy among young audiences. In doing so we hope to contribute to educating the next generation of scientists and communicate the basic concepts of this transformative technology to a wider audience.

Figures and code snippets

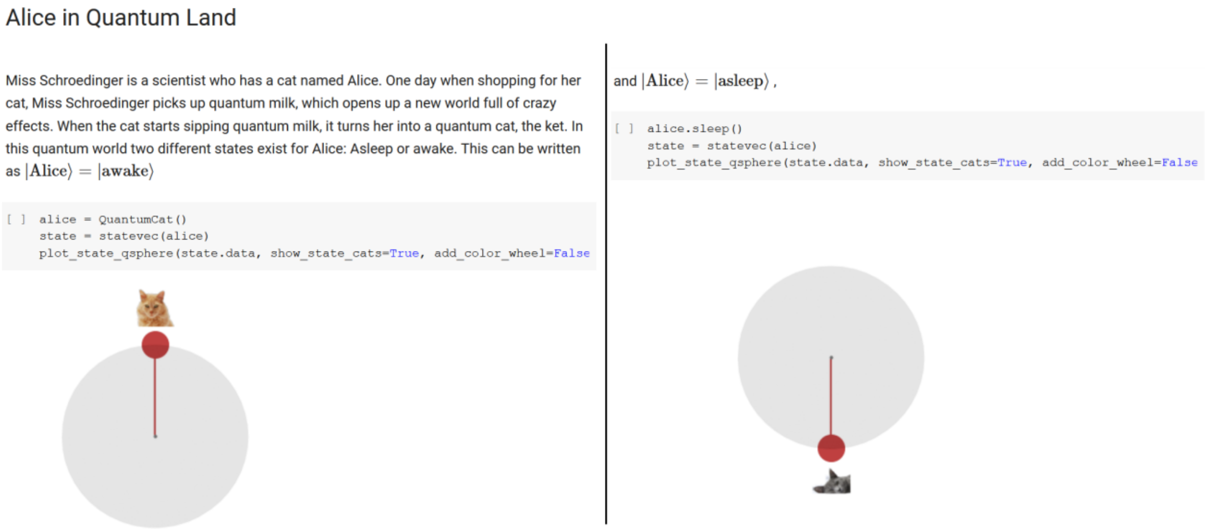

Figure 1. In Alice’s quantum world two states exist: awake and asleep, in correspondence to 0 and 1 in real qubits.

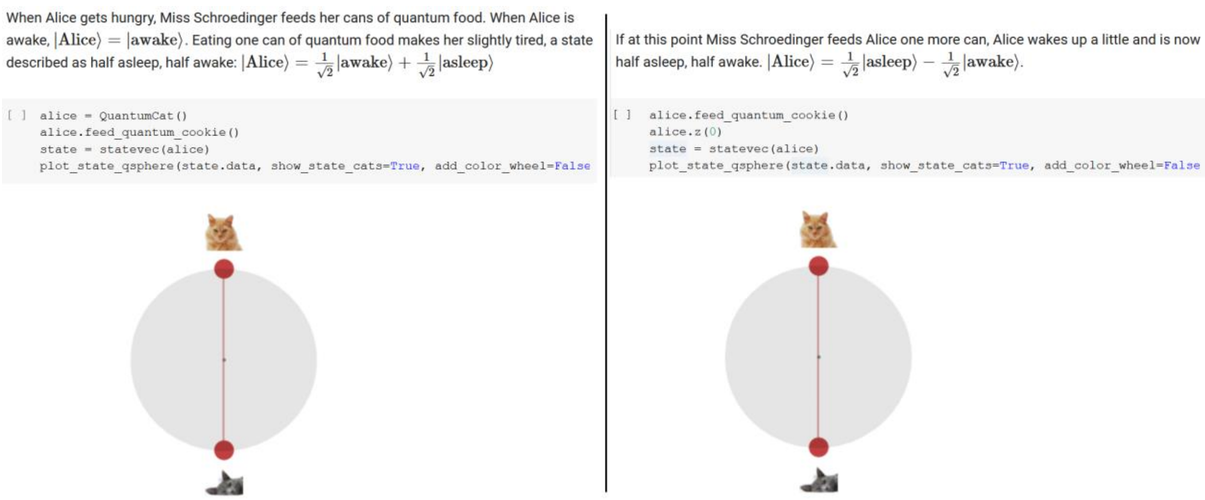

Figure 2. The concept of superposition is explained by feeding Alice quantum cookies, which results in different superpositions of the states “asleep” and “awake”.

Miss Schroedinger is very proud and excited about her cat which can be in intermediate states of half asleep, half awake at the same time. Miss Schroedinger wants to share this impressive phenomenon on her social media account and takes a picture of Alice. To her surprise, whenever she takes a picture of Alice, the cat loses its quantum superpower and turns back into a normal (classical) cat, which is either awake or asleep. On average after taking several pictures Alice is awake in half of the pictures taken.

```
[ ]  # this defines a recipe of what we want to do
     alice = QuantumCat()
     alice.feed_quantum_cookie()
     alice.take_picture()
     # this runs our recipe 1000 times
     result = qiskit.execute(alice, backend_sim, shots = 1000).result()
     counts = result.get_counts() # we get the counts
     print(counts)
     plot_histogram(counts)
```

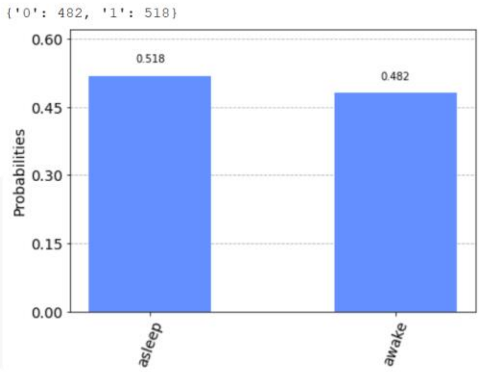

Figure 3. The measurement of a qubit in a superposition results in a collapse to one state. For our quantum cat in a superposition of “awake” and “asleep”, this will result in a nearly equal distribution of the two measurement outcomes after 1000 measurements.

Alice and Bob

One afternoon Miss Pauli, a very good friend of Miss Schroedinger, visits for afternoon tea. Miss Pauli also happens to have a cat called Bob. Whenever they meet up, she brings Bob with her, so that the two cats can play together with a ball of wool. Miss Schrödinger is very excited about what she has discovered earlier and tells Miss Pauli about it. They decide to give quantum milk to both cats and see what happens during their playtime. Due to quantum effects, the cats become a cute mess of two kittens tangled up in wool. Their quantum state is described by $|\text{Alice\&Bob}\rangle = \frac{1}{\sqrt{2}}|\text{awake}\rangle \otimes |\text{awake}\rangle + \frac{1}{\sqrt{2}}|\text{asleep}\rangle \otimes |\text{asleep}\rangle$

```
[ ]  catpair = TwoQuantumCats()

     # Alice eats a cookie
     catpair.feed_quantum_cookie(ALICE)
     # The two cats play
     catpair.tangle(ALICE, BOB)

     state = statevec(catpair)
     plot_state_qsphere(state.data, show_state_cats=True, add_color_wheel=False
```

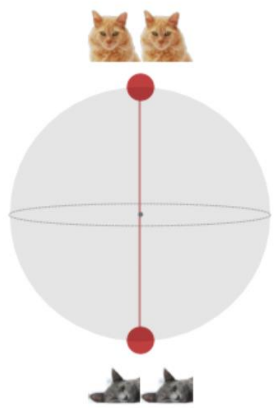

Figure 4. Entanglement is taught by introducing Miss Pauli and her cat Bob. When Bob and Alice play in the quantum world, they will be in an entangled state.

References

1. Lindau Nobel Laureate Meetings (2020) *Lindau Guidelines*. http://lindauguidelines.org/goals.html Accessed on 21/06/2020.
2. Ciaran Hughes, Joshua Isaacson, Anastasia Perry, Ranbel Sun, and Jessica Turner (2020) *Teaching Quantum Computing to High School Students*. **arXiv:2004.07206**
3. Lewis Westfall, and Avery Leider (2019) *Teaching Quantum Computing*. In: Arai K., Bhatia R., Kapoor S. (eds) **Proceedings of the Future Technologies Conference (FTC) 2018**. Advances in Intelligent Systems and Computing, vol 881. Springer, Cham.
4. H. K. E. Stadermann, E. van den Berg, and M. J. Goedhart (2019) *Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic*. **Phys. Rev. Phys. Educ. Res.** 15, 010130.
5. Ryan LaRose (2019) *Teaching quantum computing through programming*. **Medium**. https://medium.com/@rlarose_26759/teaching-quantum-computing-through-programming-799283c9769a Accessed on 20/06/2020.
6. Héctor Abraham, et al. (2019) *Qiskit: An Open-source Framework for Quantum Computing*. Available at: https://qiskit.org/.