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Quantum Control: Teaching Schrödinger’s Cat to Compute the Impossible

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Abstract

Quantum mechanics has revolutionised the way we understand the world around us, and has already produced technologies that have had an enormous impact on our daily lives. From medical imaging such as MRI to the mobile device in your pocket, quantum physics has played a key role in their design and manufacture. As our understanding of quantum physics has matured, a second generation of quantum technologies are now becoming a reality. This second generation of quantum technology pushes even further the boundary of what is possible, from new sensors that measure beyond classical limits, to quantum computers that can solve problems no classical computer can. However, a major roadblock to developing these new technologies is fast and stable quantum control. Of the many quantum control techniques available, analytic techniques have several advantages. Our research has extended a class of analytic control methods called shortcuts to adiabaticty (STA) to control problems where STA could not be used before. Our new technique is called enhanced shortcuts to adiabaticity (eSTA), and offers new analytic control protocols that have applications across a wide range of practical quantum technologies, from quantum computers to quantum sensors and thermal devices.

Keywords: Quantum Mechanics, Quantum Control, Quantum Computing.

> *The task is ... not so much to see what no one has yet seen; but to think what nobody has yet thought, about that which everybody sees.*
>
> — *Erwin Schrödinger*

Introduction

Add the word quantum to anything and it immediately becomes exotic, unusual and somehow intriguing; from “quantum fashion” to “quantum lemon dishwasher tablets”, “quantum” has become our modern day magic. In reality, quantum physics has already revolutionised many technologies that we take for granted; from medical imaging like MRI to the mobile device in your pocket, quantum physics has played a key role in their design and manufacture.

Today we are on the cusp of a second quantum revolution. There is a new wave of quantum technology emerging that uses the most unintuitive ideas of quantum physics to engineer solutions to problems that cannot be solved with classical physics. One of the most exciting quantum technologies to emerge is quantum computing, where the weirdness of quantum physics is used to design computers than can outperform any current computer technology. At the core of quantum computing is quantum control – methods that allow us to engineer and control quantum systems. My research is concerned with a certain type of quantum control that I will discuss later. First, I will give a short introduction to quantum physics and quantum computing, and then I will describe our work on quantum control.

Quantum Mechanics

In the beginning of the 20th century, technology progressed to the point where we could conduct experiments on objects as small as an atom. It is hard to imagine just how small an atom is – a human hair is about 1 million atoms wide. When we isolate these tiny atoms and shine them with light, all kinds of behaviour happens that we do not experience in our everyday lives. Why is the world so different at small scales? No one knows! What we do know is that we can conduct repeatable experiments that demonstrate this strange behaviour, and from these experiments we can construct a consistent theory that predicts correctly the outcomes of these experiments. The theory that describes small objects and small scales is called ‘quantum mechanics’.

We use the word ‘quantum’, because it turns out that the universe has discrete ‘quantum’ jumps built into it, and this discreteness is related to the weird things that happen at very small scales. We add the word ‘mechanics’ from classical mechanics, meaning that our theory describes how things behave at these small scales. The quantum nature of our universe manifests itself when we perform measurements on our experiments – some quantities we measure can only take exact values separated by fixed amounts, and do not take any value in between. This would be extremely bizarre to experience in our everyday lives – imagine a passing car that could immediately jump in speed forwards and backwards in front of you, or imagine being able to walk directly through solid walls.

The mathematical underpinnings of quantum mechanics are built from one simple fact; quantum mechanics only tells us the probability of a certain outcome, once we make a measurement. This means that quantum objects can only be described with probabilities. They can flow and overlap, but when they are measured they will be in a definite state with a defined probability. Again, no one why this is the case, all we know is that this theory matches extremely well with the results of physical experiments.

Schrödinger’s cat

Erwin Schrödinger was an Austrian physicist and one of the founders of quantum mechanics. As Schrödinger and others developed quantum mechanics, the probabilistic nature of quantum mechanics began to reveal apparent contradictions in the theory. Schrödinger framed one of these conundrums in a thought experiment known as ‘Schrödinger’s cat’, and is illustrated in Figure 1.

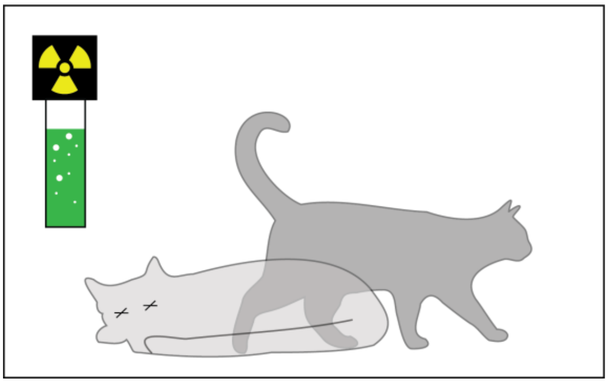

Figure 1: A diagram of Schrödinger’s cat in a state of being both alive and dead, with the radiation detector and vial of poison shown on the left.

Suppose we place a vial of poison in a cat-sized box that is connected to a special device. This special device measures whether a radioactive atom emits radiation or not, and if radiation is emitted it releases the poison and kills the cat immediately. Radioactive atoms emit radiation randomly, so there is no way to predict exactly when the radiation will be emitted. Into this box we now put Schrödinger’s pet cat, and we seal the box, and we assume we have no way of knowing how the cat is until we open the box.

The difficulty here is when we ask the question: what state is the cat in just before we open the box? According to quantum mechanics the cat is a mixture of being both dead and alive, and we can only know the probability or whether the cat is dead or alive. When we open the box, our observation of the cat decides the fate of the cat.

If this is hard to imagine, you can find some solace in knowing that Einstein himself found this aspect of quantum mechanics difficult to accept. Ultimately, Schrödinger’s cat is a reminder that quantum mechanics is describing reality in a regime that is far beyond our intuition. However, it must be stressed that quantum mechanics is one of the most experimentally verified theories that exists in physics. Furthermore, our understanding has progressed to the point where we can use quantum mechanics to engineer technologies that go far beyond our current technological ability.

Quantum Computing

To understand the incredible power of quantum computing, we first have to review how today’s standard classical computers work. Classical computers are designed using Boolean logic, a system of deduction that uses 0s and 1s that was formulated in the 19th century by UCC's own George Boole. At the core of Boolean logic is the unit of memory called a bit, and a bit can only be in two possible states: in state 0 or in state 1. The power of Boolean logic is that everything you see on your computer or mobile phone screen can be written as strings of 0s and 1s. These strings can be stored in a physical memory and manipulated using Boolean logic gates, the building blocks of computer programming. This is the basis of all modern digital technologies, from the computers that control our car engines to the computers that keep the international space station in orbit.

Quantum computers are fundamentally different; the qubit (quantum-bit) is their unit of memory, and a qubit can be in a state that is a combination or 'superposition' of both 0 and 1 (like Schrödinger's cat, both dead and alive). It is this superposition property that underpins the enormous power of quantum computers. The difference between a bit and a qubit is depicted in Figure 2.

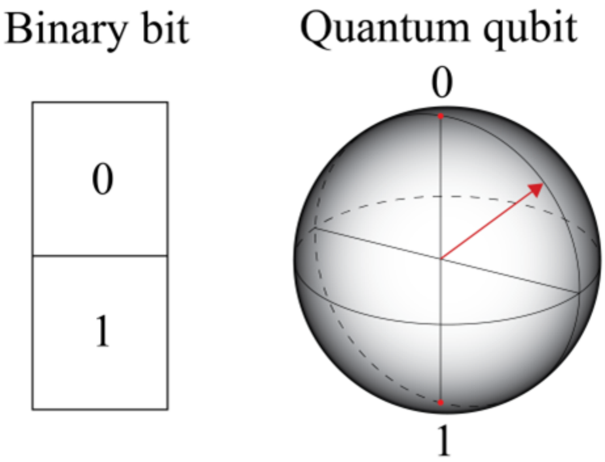

Figure 2: The classical binary bit on the left can only be in state 0 or state 1, while the qubit on the right can be in a superposition of 0 and 1. This superposition can be represented by a sphere of possible values, as shown on the right. The red arrow represents the qubit in a given state, but it can be any arrow that points from the centre to the surface of the sphere. This sphere is called the 'Bloch sphere'.

To illustrate of the power of quantum computing, suppose we program a modern supercomputer to search an unsorted list that has as many entries as there are atoms in an Olympic swimming pool – about 1032 atoms. It would take more than the age of the universe to perform this search, while on a quantum computer we could complete this task in a matter of minutes.

Despite their potential, there are major barriers to constructing practical quantum computers. Quantum states are fragile and sensitive to noise from the environment, and there are practical limits to the extent we can isolate them. The longer quantum states are exposed to environmental noise, the worse the performance of the quantum computer. Thus, fast and stable control of quantum states is critical in any practical quantum device. This has led to the field of quantum control, where fast and efficient control strategies are designed to meet this need.

Quantum Control via enhanced Shortcuts to Adiabaticity

Quantum control describes a collection of techniques that allow fast and stable manipulation of quantum systems. The goal of quantum control is to find out how to manipulate a quantum system so that it evolves from a given starting state to a chosen target state - a process called state transfer. The manipulations required to achieve this goal are encoded in a ‘control protocol’. For example, in Fig. 2 a control protocol could specify how to transfer the arrow from one point on the Bloch sphere to another point. There are two main classes of control protocols; numerical and analytic. Numerical techniques can be applied to many quantum systems, but they may reveal little insight into the control problem and be difficult to scale. Analytic control techniques are techniques that we can ‘write down’ with a formula. They are more general and offer insight into the control problem, but they only exist for a few known quantum systems.

In quantum mechanics there is an analytic result called ‘the adiabatic theorem’. In essence it states that a given state transfer can be implemented perfectly, as long as the quantum system is manipulated very slowly and is isolated extremely well. In reality, quantum computers will need much faster control protocols that are also stable with respect to noise. Inspired by the adiabatic theorem, shortcuts to adiabaticity (STA) are a collection of analytic techniques that allow very fast and stable quantum control. They have been applied to many practical quantum control tasks, and have been experimentally implemented in a number of settings. However, STA like most analytic techniques are only known for a select number of quantum systems.

Figure 3: From eSTA to STA. The turtle on the left represents quantum control using the adiabatic theorem, which is very slow. STA produces an improved control faster protocol, while eSTA extends the control even further.

Our research has extended STA beyond their current limits: we have developed a new technique called enhanced shortcuts to adiabaticity (eSTA, Phys. Rev. Research 2 (2020) 023360). The idea behind eSTA is to use STA as a starting point, and then analytically extend the STA control protocol to problems beyond the current scope of STA. This is illustrated in Fig. 3, where the turtle with no wings represents a slow adiabatic process that is sped-up with STA wings, and finally made even faster using the eSTA rocket.

Some nice proprieties of STA are inherited by eSTA; eSTA is analytic, and the resulting control protocols are fast and very stable against the effects of noise. We have simulated applying eSTA to several systems that are used in many quantum computing settings; for example, atom transport and expansion with different trap geometries, and population inversion (going from north to south on the Bloch sphere in Fig. 2) that goes beyond the rotating wave approximation. Both of these processes are critical to quantum computers constructed using trapped ions. We have found that eSTA performed very well and in some cases the performance improvement was even close to the quantum speed limit (Phys. Rev. A 105 (2022) 013311). There are many directions to pursue in the future; from using eSTA to improve quantum thermodynamic cycles, to using eSTA to engineer many body quantum states, with applications in quantum computing.

Conclusions

Quantum mechanics has revolutionised the way we understand the world around us, and has already produced technologies that have had an enormous impact on our daily lives. As our understanding has matured, a second generation of quantum technologies are now becoming a reality. A major obstacle to developing these new technologies is fast and stable quantum control. Our research has extended a class of analytic control methods called shortcuts to adiabaticity (STA) to control problems where STA could not be used before. Our new technique is called enhanced shortcuts to adiabaticity (eSTA), and offers new analytic control protocols that have applications across a wide range of practical quantum computers and devices.

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Declaration of Interests

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