Educator's Guide

QUANTUM CATS

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Quantum Cats is a video game developed by The Games Institute and the Institute for Quantum Computing at the University of Waterloo. Teachers can use this game to introduce students to how quantum physics work!

ACTIVITY AT A GLANCE

Students will learn various ideas about quantum physics through an interactive and fun game, *Quantum Cats*. Students will be exposed to key concepts such as:

CONCEPT: **Superposition**
Superpositions are states that quantum particles can exist in, where they have a component of two separate states at the same time. They can behave as if they are both "here" and "there" simultaneously, but when measured collapse to one or the other.

CONCEPT: **Quantum Tunnelling**
A quantum particle might not have enough energy to go over or break through a barrier, but still be able to travel through it.

CONCEPT: Uncertainty
The uncertainty principle is an important rule that limits the properties we can observe for a particle. For example, we cannot precisely know the speed and position of a particle simultaneously.

Teachers will be able to give students a fundamental and intuitive understanding of quantum physics with the help of different cats that represent the concepts above.

LEARNING OBJECTIVES

Understand some differences between classical and quantum mechanics.

Explore various properties of quantum systems and particles.

Learn important vocabulary used in quantum physics.

THE BIGGER PICTURE

Quantum physics is widely applicable today. For example, hospitals use Magnetic Resonance Imaging (MRI) technology to produce detailed images within the body and lasers for a variety of treatments. Active research in the field includes quantum computing, which uses quantum systems to solve problems in novel and powerful ways.

MATERIALS

Quantum Cats is playable in-browser on the Quantum Arcade at the below link:
https://quantumarcade.org/quantum-cats/

Desktop or laptop devices are recommended.

Quantum Cats is not currently available in the Google Play or Apple stores.

RECOMMENDED AGES

This game is appropriate for introducing quantum concepts to students of all ages. The discussion of quantum principles outlined in this guide is recommended for middle-school and up, as students should have a basic (non-mathematical) understanding of physics principles like projectile motion.

If you are incorporating this game into a quantum unit at a senior high-school or university level, try including the "Quantum Leap" questions with your students to compare the behaviour of the cats to real quantum objects.

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BACKGROUND KNOWLEDGE

Quantum mechanics describes the rules obeyed by objects on the sub-microscopic level, like atoms, electrons, and photons. Our understanding of these rules has come from over 100 years of experiments, which allow us to understand and predict the behavior of these objects. The behaviour of quantum objects can be very different than the rules of the world around us. By understanding the differences, we can use quantum mechanics to build technologies like lasers, medical imaging systems, and even new kinds of computers.

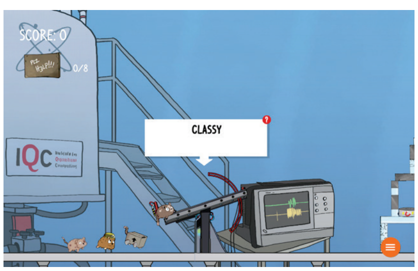
HOW TO PLAY

In ***Quantum Cats***, you'll use some of the key features of quantum mechanics to solve a series of puzzles. In the world of the game, an evil scientist has kidnapped all the kittens. Their only hope is the quantum cats, a group of cats with powers taken directly from quantum mechanics. Over the course of ten levels, you'll use these rules to solve problems that otherwise seem impossible.

In each level, you will have the opportunity to launch a different combination of quantum cats to free the kittens, who are trapped in the brown boxes labelled "PLZ HELP". If your cat hits the box or the box is broken by a fall, the kittens will escape. Break all the boxes with the cats you have available to solve the puzzle!

Step 1:

Pull back the cat on the launcher, aiming at the structures with the brown boxes.

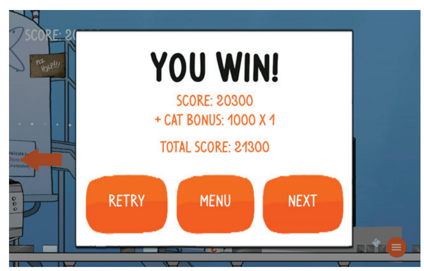


Step 2:

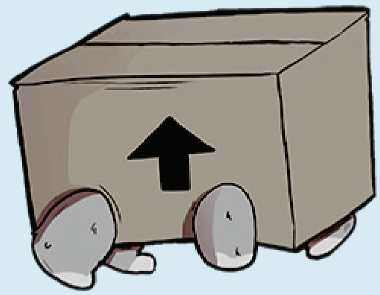
Observe the path the cat takes and adjust to hit the brown boxes or take down the structures.

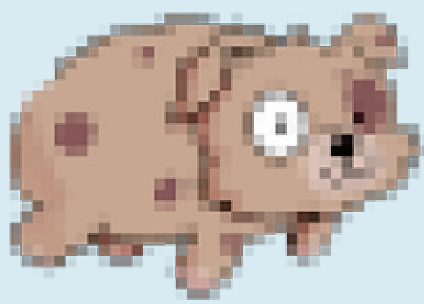
Step 3:

Break all the brown boxes to complete each level.



MEET THE QUANTUM CATS

CLASSY	SCHRÖ
	
The first cat you'll meet is ***Classy***. She acts like you would expect – you know where she's going and where she's been. She follows the laws of physics that we experience every day.	Next, you'll meet ***Schrö***. Is this cat *actually* in the box or not? She can be in multiple states at once, meaning she can be interpreted as two different things at the same time, but eventually collapse to one.
Connection: Classical Physics Classy represents Newtonian Physics – the classical physics that describes most behaviours in our world.	**Connection: Superposition** Schrö symbolizes the idea that particles can exist in two different states at the same time, like "up" and "down".

DIGGER	FUZZY
	
The third cat you'll meet is ***Digger***. Digger is special – she can travel through walls! Even though she doesn't always have enough energy to go over or break down the wall, she can travel straight through it.	Last but not least, you'll meet ***Fuzzy***. She is the most unpredictable of all the cats. When she is launched, you don't always know where she'll land.
Connection: Quantum Tunnelling Digger demonstrates the wave-like behaviour of quantum particles that allows them to travel through walls.	**Connection: Uncertainty** Fuzzy embodies the uncertainty in quantum particles. She represents the idea that there is limited information we can know about a particle.

ENGAGING AND PLAYING WITH STUDENTS

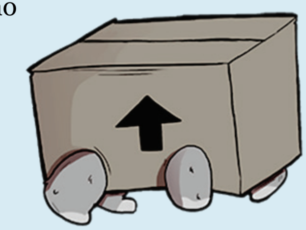
Key questions student should be able to answer after playing *Quantum Cats*:

1. What makes quantum mechanics different from the world around us?
2. What does superposition mean?
3. What is quantum tunnelling?
4. What does it mean for something to be uncertain?

GUIDING STUDENTS THROUGH THE GAME

Introduction: What is quantum mechanics?
Before beginning the game, ask students if they know what "quantum" means. Possible discussion points include: • Quantum mechanics is the theory that describes objects like atoms, electrons and photons. • Quantum objects behave in ways that are very different than how we experience the world. • Quantum science is applied in technology like lasers, MRI machines, and precise clocks. • Emerging quantum technologies include quantum computing and quantum sensors. In this game, we'll explore some of the ways that quantum objects behave in ways that differ from large, or "classical", objects. Instead of working with atoms, we'll observe this behaviour in the quantum cats!
Level One: Meet Classy
Play the first level of *Quantum Cats*. In this level, you'll only be able to use Classy. What rules of physics does Classy follow? What types of rules describe how Classy interacts with other objects? What other objects would behave the same way Classy behaves? • Classy obeys the rules of projectile motion. • All of Classy's behaviour can be described using classical (Newtonian) physics. • When Classy interacts with an object, they collide at a single point and what happens afterwards can be predicted using conservation of momentum. • Objects like balls or wooden blocks would behave similarly to Classy. • Objects like glass will shatter, while solid objects will remain intact.

Level Two: Superposition



Proceed to the second level of *Quantum Cats*. Here, you can use another cat, Schrö, who can use the concept of quantum superposition to more effectively free the kittens.

When you launch Schrö, you'll see three cats launch. When they collide with an object, you can choose which of the three will hit and the other two will vanish. In quantum, we say that Schrö *collapsed* into one of the three possible states.

Compare & Contrast: How is Schrö different than Classy? In which ways is Schrö the same?

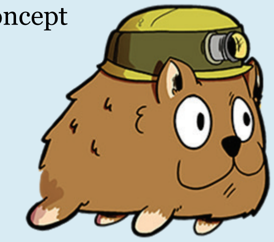
- DIFFERENCE: Schrö can spread to multiple places on her way to the destination.
- SAME: When Schrö reaches the destination, she collapses to one an only one location, and only one cat hits the structure.
- SAME: Schrö obeys rules like conservation of momentum and, while the three components of the superposition are strange, they each individually obey the rules of projectile motion.

Quantum Leap: How does Schrö differ from how quantum superposition actually works?

- In the game, you get to pick which location Schrö collapses to. In real quantum mechanics, which of the three parts of the superposition it collapses to is completely random.

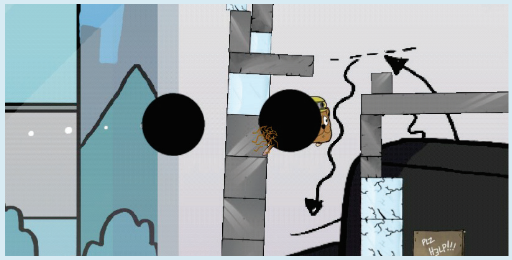
Technology Connection: Quantum computers encode bits of information in quantum systems that can be in a superposition of "0" and "1". Controlling these superposition states and how we measure them is important in using them to perform better computations.

Level Three: Tunnelling



Proceed to the third level of *Quantum Cats*. Here, you will be Digger, who can use the concept of quantum tunnelling.

When Digger hits an object, she will pass through the first object and emerge on the other side, as if it wasn't there at all.



Compare & Contrast: How is Digger different than Classy? In which ways are they the same?

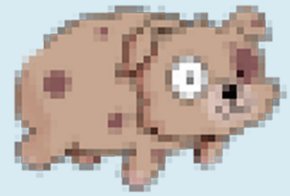
- DIFFERENCE: Digger can tunnel through barriers that Classy would not be able to pass through.
- SAME: When Digger does collide with another object, it is a kinetic collision.
- SAME: Digger's arc follows the rules of projectile motion.

Quantum Leap: How does Digger differ from how quantum tunnelling actually works?

- In the game, Digger always tunnels through the first object. For real quantum systems, tunnelling is defined by probabilities. Most of the time, the particle would not be able to tunnel through the barrier, but given enough attempts some will pass through.

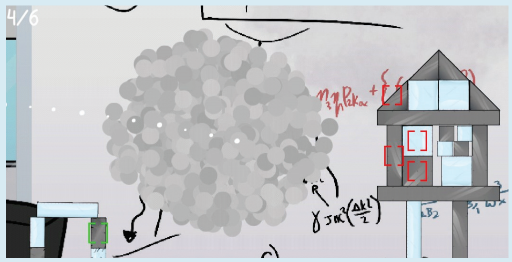
Technology connection: Scanning tunnelling microscopes allow us to measure objects at the level of atomic structure, as the rate of tunnelling depends on the atomic thickness of the material.

Level Four: Uncertainty



Proceed to the fourth level of *Quantum Cats*, where you will meet the final member of the crew. Fuzzy uses the concept of quantum uncertainty to help free the kittens.

When Fuzzy is launched, she expands into a cloud of uncertainty. At any point on her flight, you can press on the cloud (also known as her wavefunction) to measure it. Fuzzy will then randomly collide with one of the objects near her cloud.



Compare & Contrast: How is Fuzzy different than Classy? In which ways are they the same?

- DIFFERENCE: If Classy is launched the same way twice, she will end up in the same location. If Fuzzy is launched in the same way twice, she may end up in two different places due to randomness.
- DIFFERENCE: We can follow Classy's path at every point on her way to the final destination. If we measure Fuzzy early, we interrupt her progress.
- SAME: While Fuzzy's cloud has a larger range, her general arc follows the rules of projectile motion.
- SAME: While Fuzzy's location is uncertain, once measured she is in one place and one place only.

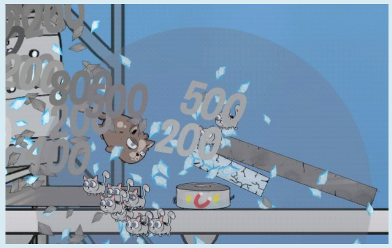
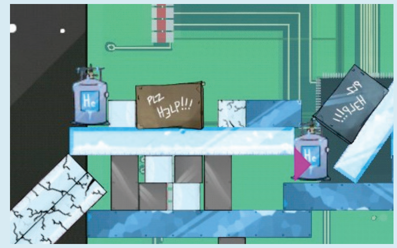
Quantum Leap: How does Fuzzy differ from how quantum uncertainty actually works?

- In the game, Fuzzy is capable of passing through objects and only interacts when we make a measurement of the cloud. In reality, if a particle's wavefunction has overlap with an object it could interact with, there's a probability they will interact regardless of measurement.

Technology connection: Uncertainty places limits on how much information we can get out of a quantum measurement. Controlling uncertainty so that we can optimize the information we get for the feature we care about is one of the key ideas in quantum sensing. For example, in the Laser Interferometer Gravitational-wave Observatory (LIGO), quantum uncertainty limits how well they can detect the effects of black holes. Special quantum states of light are used to minimize this uncertainty.

Now that you've met all the quantum cats, save all the kittens! Think carefully about how each cat is useful in different contexts.

As you progress through later levels, you will also encounter various helpful devices from the quantum laboratories:

Laser Level 4	**Magnet** Level 6	**Liquid Helium** Level 7
		
Lasers are one of the most common quantum technologies that we use today and are used in many quantum labs. But we have to be careful not to hurt ourselves with the beam. Turn on the lasers in Level 4 and above to zap objects.	Strong magnets are essential in many quantum experiments, but be careful about what you bring near them! In Level 6 and above, turn on the magnets to bring structures tumbling down.	Cooling objects to incredibly cold temperatures can change their properties. In Level 7 and above, use liquid helium to freeze the environment and make it easier to smash through objects.
Quantum Connection	**Quantum Connection**	**Quantum Connection**
Lasers can carry a lot of energy, but if used right, they can be used to cool things down! Laser cooling uses carefully arranged laser beams to trap small numbers of atoms in a very tight space for atomic clocks and quantum computing.	In Magnetic Resonance Imaging (MRI), we use the magnetism of the atoms we're made of to measure high-resolution images of the inside of our body. By laying a patient in a large magnet, the magnetic properties of our body's atoms line up in one direction, allowing us to measure their magnetic fields.	With a boiling point of 4 K, liquid helium is very cold. For some devices, we need to get even colder! Devices that use a mixture of different varieties of liquid helium called *dilution refridgerators* are used to cool quantum devices to colder than 10 mK, just one one-hundredth of a degree above absolute zero.

SUMMARIZING OUR LEARNING

Explain each of the below concepts in your own words, using examples where possible.

1. Quantum physics:

   Examples:

2. Superposition:

   Examples:

3. Quantum Tunnelling:

   Examples:

4. Uncertainty:

   Examples:

Connections to QIS Key Concepts

	Concept	Fundamental	*Quantum Cats* Connection
3b	Quantum Measurement	A quantum state determines the probability of a single quantum measurement, but one outcome rarely reveals complete information about the system.	Measurements of Fuzzy result in random outcomes.
4a	Quantum Bits	Unlike a classical bit, each qubit can represent information in a superposition, or vector sum that incorporates two mutually exclusive quantum states.	Schrö can be in a superposition of mutually exclusive states (different locations).

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Concept and design by James Wallace, Victor Cheung, and Neil Randall.
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About IQC
The Institute for Quantum Computing (IQC) is a world-leading research centre in quantum information science and technology at the University of Waterloo. IQC's mission is to develop and advance quantum information science and technology through interdisciplinary collaboration at the highest international level. Enabled by IQC's unique infrastructure, the world's top experimentalists and theorists are making powerful new advances in fields spanning quantum computing, communications, sensors and materials. IQC's award-winning outreach opportunities foster scientific curiosity and discovery among students, teachers and the community.

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