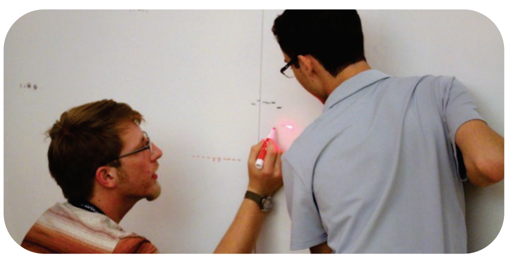
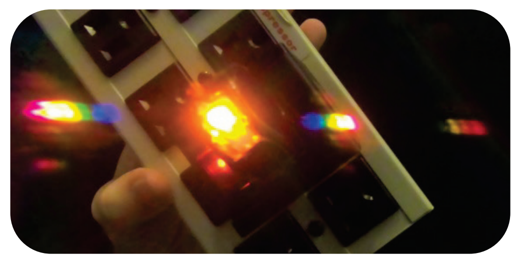
Facilitator's Guide

QUANTUM DETECTIVES





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ACTIVITY AT A GLANCE

Using cryptic clues and the tools of quantum mechanics, learners will solve a mystery. Using concepts from the science of light as an entry point, key ideas about quantum mechanics are introduced to participants early. Techniques used include polarization measurement, laser interference, and atomic spectroscopy.

For this workshop, participants will work in groups of 5-10, rotating through each activity. The activities should be set up as stations.

RECOMMENDED AGES

This activity is appropriate for participants in **late elementary and high school** (Grade 7-12). Participants in younger grades may need help with the calculations to find the width of their hair. Curriculum connections usually are stronger starting in Grade 10.

THIS DOCUMENT

This document provides tips for facilitation, including discussion points and setup, as well as scientific background and assembly guide. The discussion is oriented towards outreach workshops but can be adapted for in-class use. A set of suggested slides and necessary printouts are available as separate PDF/PPT files.

LEARNING OBJECTIVES

Participants will understand the wave-like behaviour of light and see how interference can be used to make precise measurements.

Participants will discover the rules that light obeys when interacting with atoms and how they can be used to identify elements.

Participants will see how binary information can be encoded and manipulated in light.

Participants will see how future technologies like quantum computers arise from these ideas.

Contents

WORKSHOP OVERVIEW

Using cryptic clues and the tools of quantum mechanics, learners will solve a mystery. Using concepts from the science of light as an entry point, key ideas about quantum mechanics are introduced. Techniques used include polarization measurement, laser interference, and atomic spectroscopy.

Grade Level / Appropriate Age: Grades 7-12

- Note that this topic is likely to be new to most learners in this age range, starting to be more curriculum connected in Grade 10. For Grades 7-9, approach this as an enrichment workshop.

STEM topics: Quantum mechanics, properties of light

Workshop Objectives:

- Explore the wave-like behaviour of light.
- Discover that light can be used to encode information.
- Understand that light obeys different rules at the level of atoms.
- Use problem-solving and teamwork skills to solve a mystery.

Physical Requirements:

For this workshop, learners will work in groups of 5-7 individuals, rotating through each activity. You will need space to set up three stations. For a larger number of participants, you may want two of each station to support smaller groups. It is recommended that there is a volunteer at each station, to support each group with the materials and new concepts.

- If possible to do so safely, dim the lights in the room after the introduction.
- Activities 1 and 3 require access to power outlets.
- Activity 2 requires an approximately 2 metre long clear, safe path to shine the laser.

Activity Time:

Depending on your specific event, you may choose to only do some activities or structure the groups differently. Make a plan that best fits your group.

	Approx. Time	Overall Time	Description
Intro	10 min	10 min	Introduce yourself and (briefly) quantum science. Give an overview of the mystery, the stations, and safety information.
Polarization hidden messages	12 min	22 min	Learners will spend time exploring properties of polarization and birefringence to see hidden patterns in materials before investigating a journal entry with an encrypted message.
Interference and diffraction	12 min	34 min	Learners will investigate the properties of interference and diffraction. They will form a qualitative understanding of how different objects produce different patterns when illuminated with a laser and use this understanding to determine the width of a hair.
Spectral fingerprints	12 min	46 min	Learners will investigate various light sources using a diffraction grating to separate the colours of light. They will compare atomic emission spectra to incandescent and LED light to see quantization. To solve their mystery, they will use spectroscopy to identify mystery elements in a gas.
Wrap-up	14 min	60 min	With the full group, discuss the solution to the mystery. Go through the physics explored in each station and connect to quantum science and technology. Discuss possible careers related to the topic.

MATERIALS AND SETUP

See the Assembly Guide at the end of this document for details on how to construct the materials for this workshop.

Activity #1: Polarization hidden messages	**Activity #2: Interference and diffraction**	**Activity #3: Spectral detectives**
10 polarizers 3 polarized light sources (requires power or batteries) Various transparent plastic items (e.g. forks, tape dispensers) 2 journal entry printouts 4 ASCII-to-alphabet sheets Instruction sheets Extension cord	4 red laser pointers 4 wire comparison slides with three labelled wires 4 evidence slides with one wire 10+ small binder clips 3 pairs of scissors 4 calculators 3 tape measures, >2m 4 30-cm rulers Cardstock, with pre-cut holes* Instruction sheets	3 Neon light sources (requires power) 2 white LEDs 2 orange or red LEDs 5 adjustable LEDs with a remote 10+ diffraction gratings 2 sets of transparent emission spectra masks 2 sets of reference spectra, including air and the unknown substance Instruction sheets Extension cord
Setup:	**Setup:**	**Setup:**
• Plug in the light sources to either the wall or batteries. • Set out the four light sources on edges of the station, with the items and polarizers in the centre. • Set out the journal entries and the decoder sheets.	• Set out the materials except for the lasers on one side of the table. • Hand out lasers once learners have assembled at the station. • Ensure a clear safe path to shine the laser is available.	• Plug in neon sources to the wall; do not leave on for more than 2-3 minutes at a time. • Distribute sets of spectra masks and references on each side of the table. • Spread out coloured LEDs and diffraction gratings on table.

*Consumable items

Note that these resources can be divided in half if working with a smaller group.

Based on your group, facilitator availability, and type of event, you may choose to structure this workshop differently:

- **Fewer facilitators:** Instead of rotating through all stations, switch between the Polarization Hidden Messages and Spectral Fingerprints first, then do the Interference & Diffraction experiment as a whole group. This provides a greater degree of control on the light level in the room, allows groups to space out more.

- **Larger group:** If you have more than three groups, different groups can visit the same station at a time.

- **Booth event:** Introduce quantum using 1-2 of the activities at a booth (without the mystery aspect). Ensure safety precautions are still being covered.

SUGGESTED DISCUSSION: INTRODUCTION

The suggested discussion provided in the next sections is intended for outreach-style visits to classrooms or other stand-alone workshops. It may be adapted for in-class use. Normal text is a possible speaking script, and *italicized text* is extra context and answers to expect from students.

- Introduce yourselves
- Define quantum and quantum mechanics
- Introduce the mystery
- Provide a safety overview

Today, we're going to be talking about quantum mechanics. Has anyone heard the word "quantum" before?

Answers may vary.

Where have you heard of quantum before? Or what can you tell me about it?

Answers may vary. Answers may include Ant-Man and science fiction. Oftentimes, a small number of learners will know a surprising amount about quantum, but do not expect that most are familiar with terms like "photon" and "quantization." If they struggle to come up with answers, ask them what the smallest thing they can think of is, guiding them towards molecules, atoms, and electrons if possible.

Quantum is the study of the smallest possible things like photons, electrons, and atoms.

For scientists, quantum mechanics is the rulebook of the smallest possible things. Unlike in science fiction movies like Ant-Man, where the quantum realm is weird and unknowable, quantum in the real world is used to make very accurate predictions. It just relies on probability.

Quantum, although it can sound super futuristic, is not new! Quantum mechanics started 100 years ago when scientists you may recognize (Schrödinger, Planck, Heisenberg and Pauli) developed a new way of understanding small particles. Since then, we have made leaps and bounds, and we now use quantum stuff in our everyday lives.

Has anyone used a tool from quantum mechanics before? You almost certainly have without knowing it!

- Lasers were developed in the 1950s by understanding how electrons behave inside atoms.
- Semiconductors used in LEDs and circuits like the one in your computer are understood thanks to quantum mechanics.
- MRIs are tools to see inside your body and manipulate the quantum properties of the atoms in your body.
- Nuclear power relies on us understanding atomic physics.
- Electron microscopes use the wave properties of quantum to see things way too small for even the most powerful optical microscopes, smaller than one billionth of a meter.
- Atomic clocks give us the timing accuracy needed for tools like GPS.

Now, quantum mechanics is being used to attempt to make new kinds of computers called quantum computers. These computers can allow us to solve some problems much more efficiently than conventional computers, and people who work on them come from fields like chemistry, computer science, mathematics, physics and engineering.

THE MYSTERY

Now it’s your turn to do some quantum investigation of your own and solve the Questionable Case of Quantum Quinn.

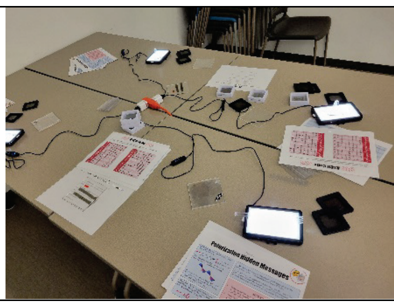
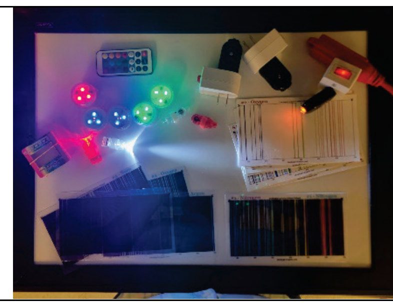
Your friend, the world-renowned research scientist Quantum Quinn, has vanished! You visited her lab this morning and found it was unlocked and emptied, with Quinn herself nowhere to be found!

Quinn was working on a very secret experiment on how to build new kinds of computers using quantum mechanics. There are only a few scientists she would have trusted enough to work with her, and some of the materials she needed can only be obtained from special sources. If you want to find Quinn, you’ll need to figure out what her breakthrough was, what materials she needs, and who she was working with.

You have a few pieces of evidence that you found in the lab, including a stray hair, a mysterious diary entry, and a sample of contaminated air. You will need to use the rules of quantum mechanics to solve this case!

Before breaking into groups, briefly explain each station.

At this station (point), you will explore the polarization of light and use it to examine Quinn’s mysterious diary entry. At this station (point), you will learn about interference and diffraction, using light’s wave-like properties to measure the width of a hair. And finally at this station (point), you will be investigating the colours of light emitted by different atoms and using them to identify mystery substances.

		
Polarization Hidden Messages station.	Interference and Diffraction station.	Spectral Fingerprints station.

ACTIVITY #1: POLARIZATION HIDDEN MESSAGES

- Exploration:
  - Introduce the polarization of light and how we can encode information in light
  - Experiment with the polarizers and plastic objects
  - Build patterns using plastic strips
- Mystery:
  - Find the binary message in the journal entry
  - Convert between binary code and the alphabet
  - Identify the culprit with the help of the journal and their gift

Before the activity, ensure that the polarized light sources are powered on and pass polarizing filters to participants (1-2 each).

Welcome to the polarization station! Have any of you heard of polarization before?

Answers may vary. Some learners will say sunglasses.

Polarization is a property of light, such as sunlight and laser light. Light is a travelling wave. Like a water wave, it goes up and down as it travels, but instead of disturbing the surface of the lake, it travels through space. If a beam of light is travelling towards you, which way could the wave go?

It could go side-to-side, or it could go up-and-down, or anywhere in between. Use your hands to demonstrate.

We call this direction the polarization.

Next, demonstrate using the polarizers.

These are special filters that only let through light if the wave is travelling in the matching direction. This means if I hold my polarizer horizontally, only horizontal light can get through, but if I rotate it 90 degrees, only vertical light can get through. Now, what do you think is going to happen if we take 2 polarizers and rotate them 90° to each other? Let's try!

Have learners pick up a polarizer and look at a partner through their polarizer while each partner rotates their filters. They should see that they can see through the polarizers when they are aligned the same way but they block all light when aligned in opposite (perpendicular) directions.

What happens if you look at other light sources while rotating the polarizer?

Have learners check with lights in the room. Most of the light around us isn't polarized, rotating our polarizer does nothing. Next, have learners test if the light source at the station is polarized by rotating their polarizers while looking through.

Are these light sources polarized? *Yes.*

What happens if we add something between the two polarizers? What do you see?

Place a piece of plastic on top of the light source and allow learners to look again. The should see rainbow colours. If the colours aren't particularly interesting, try rotating the object between the polarizers, not just the polarizers. There is often an "unlucky" angle where the object lines up with the polarizers and does not change the polarization. Rotating it by 45-degrees will have a dramatic effect.

Engineers can use this technique to see stress points within their materials.

Direct learners to try gently bending the rectangular plastic pieces and to look through the polarizer again.

We can also build our own patterns if we can adjust the angle and thickness of the material.

Direct learners to experiment layering the rectangular plastic pieces on top of each other and seeing if different colours appear.

The Mystery

Let's see if we can use polarization to help us solve our mystery. In her lab, Quantum Quinn had a journal which was found open to the page you see in front of you. But part of it is obscured; how can we read it?

The remainder of the activity is an escape-room-style puzzle that the group must solve. As much as possible, let them debate the answer among themselves to reach a verdict.

The evidence to examine for this station is a mysterious journal entry. Ask students to use some of the tools they have learned about to examine the evidence.

Use the polarizer to view the journal entry. The mosaic pattern should have some elements appear completely dark and some transparent when viewed with it. This encodes a binary message (0s and 1s).

Use the ASCII-to-alphabet decoder to translate. Learners should notice that the ASCII code for all letters start with a zero and use that to identify which of the dark or light elements correspond to 0 and 1. This may change between groups, as it depends on if the hold the polarizer aligned to the horizontal or vertical direction.

Decode each string as:

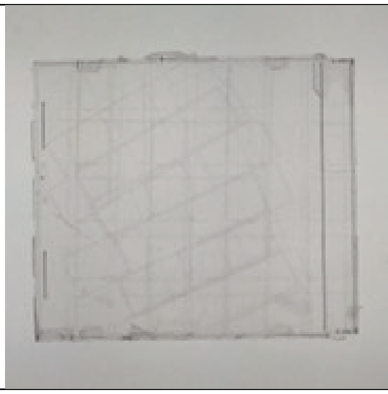
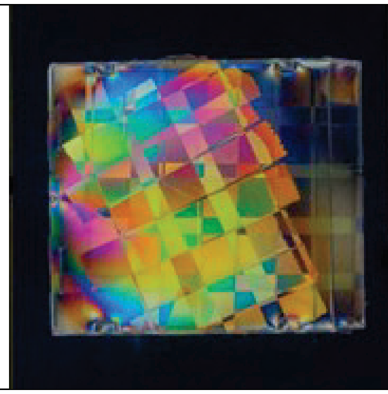
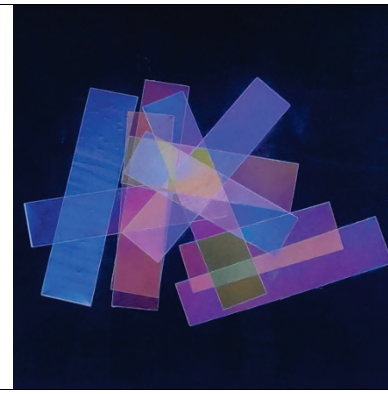
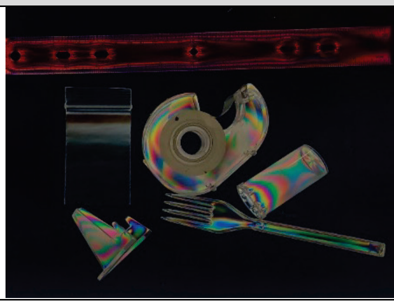
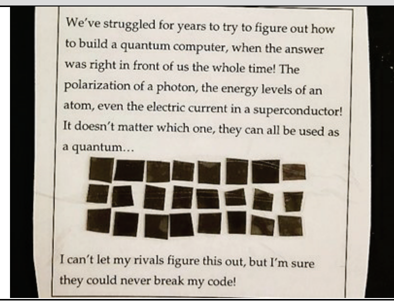
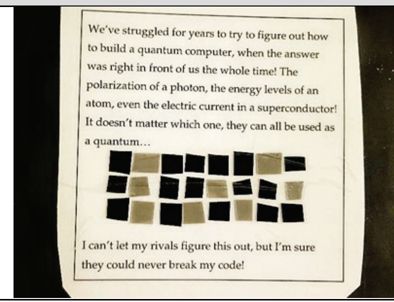
- *01000010 (B)*
- *01001001 (I)*
- *01010100 (T)*

*The answer is "**BIT**"*

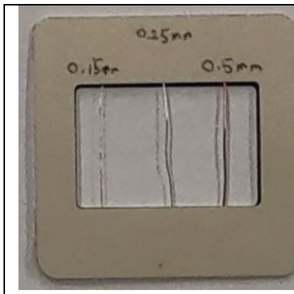
If the group needs guidance, the following hints may help:

- What tools do you have available to examine the sheet? **Polarizers**
- It seems like the squares are only light or dark. What encoding would only need two options like that? **Binary**
- Do you notice any pattern with the squares? Consider the ASCII sheet
  - If they don't know which polarization is "0" and which is "1", note that all ASCII characters for letters start with the same bit (0)

If you have extra time with your group, have learners find other birefringent objects in the room or on the table. Most clear plastics will exhibit the effect.

		
Example of a taped object placed on the light source. There is nothing special to note about it yet.	The same object viewed between two perpendicular polarizers, revealing hidden colours.	Re-usable tape strips viewed between two perpendicular polarizers, which can be re-arranged by participants.
		
Household objects viewed through the crossed polarizers, revealing hidden colours.	Diary entry viewed without a polarizer.	Diary entry viewed with the polarizer, revealing the encoded binary message.

ACTIVITY #2: INTERFERENCE AND DIFFRACTION



Wire comparison slide with wires of varying widths.

- Exploration:
  - Introduce the wave behaviour of light (constructive and destructive interference)
  - Use interference to make precise measurements
  - Compare the diffraction patterns from a variety of wires and their hair
- Mystery:
  - Compare the pattern from the evidence with their hair
  - Identify if the suspect had thin, thick, or average hair

Before the activity,

- ➢ Ensure long (2m or longer) clear path is available
- ➢ Darken the room, if possible
- ➢ Divide learners into groups of 2-3
- ➢ Review safety about laser pointers

Welcome to the diffraction station. A strand of hair was found in the lab, and it couldn't have been Quinn's, since her purple hair would stand out. The lab is incredibly secure, and Quinn would never let anybody in unless they were essential to her research. Knowing more about it could tell us who else was in the lab and help us find Quinn!

How can we measure the width of our hair? Can we do it with a ruler or measuring tape?

Answers may vary. It could be measured with a microscope, but is too small to use a ruler or measuring tape.

Your job today is to determine whether the suspect had thin hair or thick hair, and we can use light to do that! To figure out how, we have a slide containing three wires with the thicknesses written on top. We see they go from quite thick to very thin. If we shine light on each, what do we expect to see on the wall? Would the thicker or thinner wire make a bigger shadow?

A thicker wire casts a larger shadow.

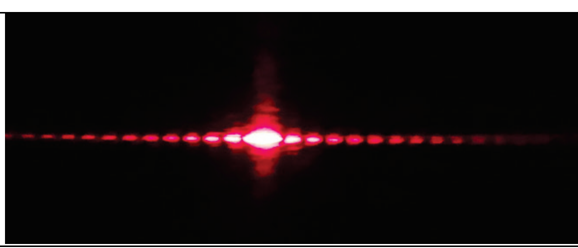
But what if we use a laser instead? Take one laser per group, but **safety first**! Lasers are dangerous to our eyes. Do not shine the lasers at anyone's eyes, including your own, and always be aware of the laser when it is on.

Guide learners to try shining the laser on each of the wires and looking at the pattern on a wall at least 2 m away. If you'd like, trace the pattern you see from each on a piece of paper or post-it note. Let learners experiment with the comparison slide and laser.

What did you notice?

The thinner wires produced larger patterns.

This is a wave behaviour called **diffraction**, where waves like light spread out when they encounter an object. The bright and dark spots are a phenomenon called **interference**, where the waves sometimes add up to an even bigger wave constructively and sometimes cancel each other out destructively. By measuring the interference patterns, we can learn about the width of the object.

	
Sample diffraction pattern of alternating bright and dark spots (fringes) seen by illuminating a thin object with a laser and looking at the pattern on the wall.	The pattern seen by illuminating a thinner object, causing the fringes to be more widely spaced out.

The Mystery

Only two people could have been working with Quinn. Superposition Sam is a chemist, always wearing a lab coat and a hat to cover his thin hair. Wavefunction Wendy is a theoretical computer scientist whose thick glasses complement her thick hair. Compare with the evidence left behind at the scene of the crime. Can we compare the evidence with your hair to see if it is thick or thin?

- *Ask for a few volunteers to measure a strand of their own hair.*
- *Mount the strand of hair using a hole cut into cardboard and binder clips as stands is recommended (see schematic).*
- *They will need to hold the laser very still. Using an object such as a book to rest the laser on can help dramatically.*
- *Have them trace the pattern created.*

Not all learners will want to test with their own hair, so only do this if there are interested volunteers. If no one wants to, you could instead do your own hair or skip this part and compare with the wires used in the exploration. Most hairs are between 0.001 and 0.01 cm wide, smaller than any of the wires used in the activity.

Learners should see that the pattern from their hair is much wider than that from the evidence, implying that the person who left the hair behind had thick hair. Sam has thin hair and Wendy has thick hair, pointing to Wendy as the mystery collaborator.

Most hairs are 10-100 micrometres (0.001-0.01 centimetres) wide. If the learners calculate a number that doesn't make sense, ensure they check their units. If your group is uncomfortable with unit conversations, keep everything in centimetres. Also double-check that they are measuring the distance from the hair to the wall, not from the laser to the wall.

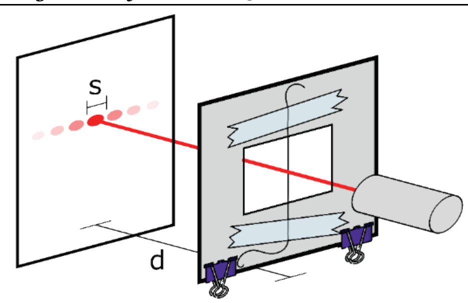
If participants have trouble seeing the pattern, ensure the hair is being illuminated. If you look closely at the hair, you should see a bit of laser light being scattered off of it. If the pattern is still hard to see, try darkening the room if possible. Ensure that they are letting the beam spread out enough for the pattern to appear, but not so much that the laser light is spread over a very wide area and too dim to see. Anywhere from 1 to 3 metres is ideal.

Extension

If time allows, learners can calculate the width of their hair.

We've figured out who the hair points to. But just how wide is our hair anyways? We can use a simple math equation on your worksheet to calculate it with the width you already measured!

$$\text{Hair Width} = 2 \times \frac{\text{Laser Wavelength } \times \text{Distance to wall}}{\text{Dark spot Separation}} = \frac{2d\lambda}{S}$$



Schematic of the setup for measuring the width of your hair. The distance between the hair and the wall is labelled "d" and the separation of the dark spots is labelled "s".

If learners traced their hair pattern earlier, they could reuse it. Otherwise, they may need to measure again. They may measure directly on the wall or by tracing it out. All numbers must be in the same units (centimetres recommended). The important numbers to get are:

- *The wavelength of the laser (you may approximate it as 650 nm = 0.000065 cm).*
- *The dark spot separation "s", which is the distance between the first dark spots in the pattern. Alternatively, you can think of as the width of the central "blur" in the diffraction pattern.*
- *The distance to the wall "d"; note this is the distance from the hair to the wall, not the laser.*

ACTIVITY #3: SPECTRAL FINGERPRINTS

- Exploration:
  - Explore the spectra from a variety of light sources, including an atomic one
  - Use a spectrum to determine which elements are in air
  - Understand light as a discrete unit
- Mystery:
  - Compare a sample from the crime scene to air to see what may have been used to knock out Quantum Quinn
  - Understand the purpose of spectroscopy, and why atomic emission spectra exist

Before the activity,

- Have the neon and LED lights ready
  - Do not leave on when not in use
  - The neon lights are HIGH VOLTAGE. Do not touch the light bulbs. Do not leave the neon lights on for extended periods of time; they get hot!
- Set aside enough diffraction gratings to have one per learner
- Prepare the sets of spectra reference cards and transparent masks

Welcome to the spectroscopy station! Spectroscopy is the study of how different materials absorb and emit light of different colours, like the yellow glow of a sodium streetlight or the elements in far-away stars. This process allows us to identify materials in a variety of different conditions.

Pass out diffraction gratings and direct learners to hold them up to their eyes and look towards overhead lights in the room. DO NOT LOOK AT THE SUN. Although it may be tempting to use the sun as a light source, the sun is dangerous to human eyes.

What do you see?

Most likely answer will be rainbows. However, you may hear some answers like "red, green, and blue" depending on what kind of light sources you have.

These are called diffraction gratings. They work by making the different colours of light travel in different directions, which lets us see them side-by-side. The range of colours that you see is called the spectrum of light, and it can change a lot between different light sources. What happens when we look at other light sources?

Answers may vary. Some light sources have continuous rainbows that contain red, blue and all colours in between, or discrete spectra that only contain a few specific colours.

Some light sources are continuous, containing the complete range of colours from start to end with no gaps or dark spots. Other light sources look discrete, with sharp features and many gaps between the colours.

As learners explore various light sources, ask them what they see, and then help them to identify them as continuous or discrete. It may help to darken the room to ensure that students can separate the background light from the light sources they're trying to look at.

Now, we have two LED sources, one white and one red/orange. Let's look at the white one. What do we see? Is it continuous or discrete?

It looks white without the grating. With the grating, we see that it has a continuous spectrum made of all colours of the rainbow.

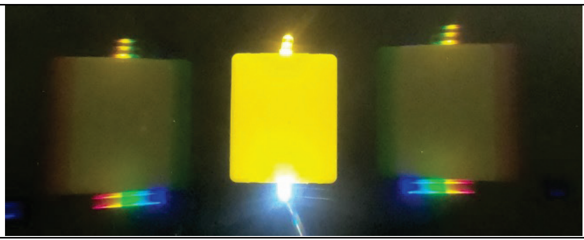
Now, let's look at the red/orange LED. What does it look like? How does it look different through the grating? Is it continuous or discrete?

It looks orange/amber without the gating. Through the grating, we see that it is continuous, but a smaller spectrum, mostly orange/yellow with a bit of green/red. The white LED is designed to emit light over a wide spectrum, but the amber LED is designed to only emit amber/orange light. The range of colours is different, but they both have a smooth and continuous spectrum.

Let's look at another source of light – neon lights. Neon lights have a small amount of Neon gas inside that is heated up with electricity until it gets so hot that it glows!

This light source looks similar to the amber LED light when we look using only our eyes. What do you notice when you look at it through your diffraction grating? How does this compare to the LED?

It looks like it has many colours, but with gaps between them. It has a discrete spectrum, while the LED was continuous.

	
A neon lamp viewed through a diffraction grating. The light looks very orange to the naked eye, but when the colours are separated, we see it contains many different colours. The spectrum is discrete, with isolated colours rather than a smooth distribution.	An orange (top) and white (bottom) LED viewed through a diffraction grating. The colours of the white LED are seen to spread the entire rainbow, while the orange LED has a narrow spectrum. However, both are smooth and continuous. Note that your LEDs may look different.

Depending on how the light is created – the source of the light – we see different spectra.

Every atom is made up of charged particles we call electrons. Quantum science shows us that they can only have very exact energies and that they release light with very specific colours when they change energy. If we see a specific set of colours, we can use it to figure out what elements something is made of. Each element in the periodic table has a unique discrete pattern.

On your worksheet, you should see three spectra, each from a different atom. Can you identify which one is neon?

"B" is neon, identifiable from the many oranges and reds. A is argon and C is xenon.

The Mystery

There was a faint chill and an odd smell in the lab when you arrived. You took a sample of the air to test it. Maybe heating it up and looking at the colours that come out could help figure out what materials Quinn has been using?

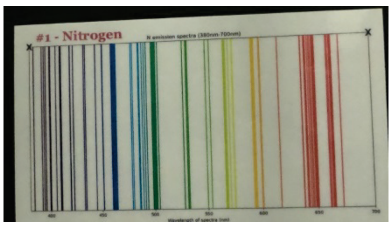
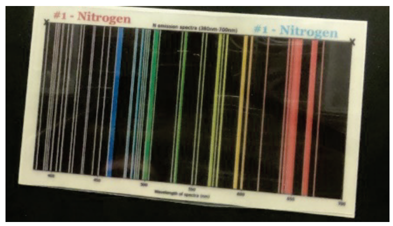
Try the spectra identification sheets provided. By overlaying the transparent sheets and lining up the “X”s, you can identify if a gas was present or not.

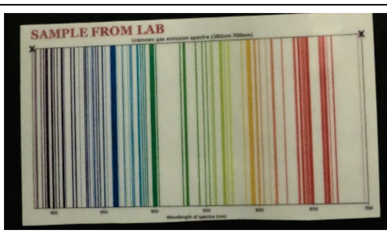
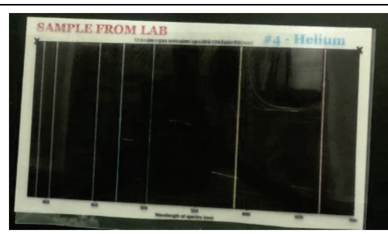
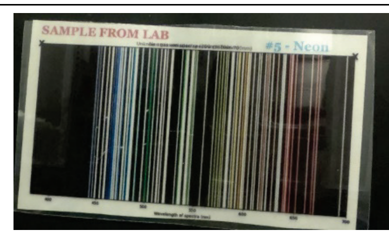
Direct learners to try identifying if oxygen is present in plain air. They should see it contains oxygen and nitrogen, but not neon or helium.

Now it’s up to you to determine which gas is present in the air in the lab that isn’t normally there.

Learners should see that the lab sample contains nitrogen, oxygen, and helium in significant quantities, indicating that helium was added to the room.

If there is extra time, encourage the group to find more lights in the room that could have different patterns when viewed through the diffraction grating. Having interesting sources ready, like remote-controlled LEDs, is best. A mixed colour, like teal, may be clearly made of red, green, and blue components when viewed through a diffraction grating.

		
Nitrogen reference card.	Nitrogen reference card with the transparent nitrogen mask on top. The lines match up to the openings, indicating a match.	Nitrogen reference card with the transparent Neon mask on top. The lines to do not and many white regions are visible, indicating no match.

		
Lab sample reference card to be used in the mystery.	Lab sample reference card with Helium mask, showing a match. The lab sample will also match all elements present in air.	Lab sample reference card with a Neon mask, showing no match.

SUGGESTED DISCUSSION: WRAP-UP

- Break down pieces of evidence and solve the mystery
- Explain what we learned at each station
- Share how participants can learn more about quantum science and technology

Welcome back everyone! What was your favourite activity today? Now that we are all back, lets break down the mystery.

Try to build excitement for solving the mystery. You could make a chart like the one below and fill in what was discovered at each station.

Station	*Polarization*	*Interference*	*Spectroscopy*
Mystery	*Breakthrough*	*Collaborator*	*Materials*
Answer	*Quantum Bit*	*Wendy the Computer Scientist*	*Helium gas*

First, at the Polarization station, we worked with polarizers. Light travels as a wave, and the direction the wave waves in is called its polarization. It can be up-and-down, side-to-side, or anything in between.

How did we use this to decode the journal entry in our mystery?

Different polarizations encoded 0s and 1s.

What did the hidden message in the journal entry say?

The hidden message was "BIT"

Yes, Quinn has built a quantum bit, which we sometimes call a "qubit" (pronounced "cue-bit"). In quantum technologies, we use properties like polarization to encode information. We saw that we could read binary 0s and 1s from whether the polarizer blocked or let through the light. We can do the same process one photon at a time to encode messages or build quantum computers, similar to how our computers use binary code.

Next, at our interference and diffraction station, we saw light form a pattern on the wall.

When we shone our laser at thick and thin wires, which made the larger patterns?

The thin wire.

We see this effect not just with light waves, but also water waves, and with particles like photons and electrons. This is used to build things like electron microscopes that can see even smaller things.

In our mystery, we had a hair found at the scene of the crime. Using your laser pointer, you should have seen it made a much smaller pattern than your hair. Does that imply that it is a very thick or very thin hair?

Thick

We had two suspects: Wavefunction Wendy, the computer scientist with thick hair, and Superposition Sam, the chemist with thin hair. Who is the likely collaborator?

Wendy!

Our final station was Spectroscopy. When atoms absorb light, their electrons gain energy. As electrons lose energy, they emit light at specific wavelengths, creating a spectrum unique to each element. This spectrum appears as discrete lines when we look through a diffraction grating viewer, which is what we saw when we looked at the neon light, and what we were looking at in the gas samples.

In quantum science, we can use this for identifying and controlling atoms. If we shine laser with just the right energy on the atoms, we can control what energy their electrons have. In quantum computing, we use this to encode our binary 0s and 1s into the energy of the electrons in the atom.

In the sample of the atmosphere at the crime scene, something was present that isn't in normal air. What element was present?

Helium!

Do you know what helium is used for?

Expect answers like "balloons". Helium's use for cooling is likely to be new to the learners.

It turns out we can use helium to make things incredibly cold, too! Liquid helium is used in many research labs to bring temperatures down to below one-hundredth of a Kelvin. That's about -273 degrees Celsius, or 300 times colder than the depths of outer space!

Now we know that Quinn was working with Wendy, a computer scientist, on something involving encoding information using quantum bits that need to be kept at ultra-cold temperatures.

We confronted Wendy with this information, and she spilled the beans! Quinn was building a quantum computer using special materials called superconductors as quantum bits. These need to be kept incredibly cold to work, requiring liquid helium. Wendy let us know that Quinn is safe and moved their lab to a government facility. Researchers there are using quantum mechanics to build new technologies out of photons, atoms, superconductors, and more!

If time allows, some photos and descriptions about these technologies are included in the printouts file to facilitate a discussion. These include interference patterns built up photon-by-photon, an image taken of individual trapped atoms, and a photo of a superconducting circuit, all used in real experiments.

What is something new you learned about quantum today?

If you are interested in quantum, there are a lot of different ways to get into the field. People are working hard around the world to understand the theory of quantum and how to build neat experiments to control quantum systems. People get into the field through physics, chemistry, math, computer science, engineering, and more.

GLOSSARY

ASCII (American Standard Code for Information Interchange): A character encoding standard for electronic communication, representing text in computers and other devices using binary code.

Binary Code: A coding system using binary digits 0 and 1 to represent information.

Birefringence: A property of a material that causes polarized light to be rotated based on its colour, resulting in the appearance of different colours when viewed through a polarizer.

Diffraction: The expansion of waves (such as light) after they encounter a hard edge or narrow opening. After the wave spread out, it is common to see a series of light and dark fringes, called a diffraction or interference pattern.

Diffraction Grating: An optical component with a regular pattern that splits and diffracts light into several beams. Different colours split at different angles, allowing us to measure the light's colour spectrum.

Electromagnetic wave: A wave consisting of oscillating perpendicular electric and magnetic fields. Examples include visible light, microwaves, radio waves, and x-rays.

Emission Spectra: The distribution of colours of light emitted by atoms when electrons transition from higher to lower energy levels, consisting of discrete colours (wavelengths) corresponding to the specific structure of the element or molecule.

LCD: Liquid-crystal display technology, which works by quickly rotating the polarization of the light emitted from each pixel in a screen.

LED (Light Emitting Diode): A semiconductor device that emits light when an electric current passes through it, available in various colors and used in many applications.

Photon: The smallest possible unit of light energy.

Polarization: The direction of the electric field of a light wave.

Polarizer: A filter that allows light waves of a specific polarization to pass through and blocks others.

Quantum physics or **quantum mechanics**: The field of study pertaining to how the world behaves at the scale of atoms, photons, electrons, and other sub-microscopic particles.

Qubit: A quantum bit is the smallest unit of quantum information. It can be built by controlling a system that obeys quantum mechanics and can exist in one of two states, labelled "0" and "1" traditionally. The polarization of a single photon is a useful example of a qubit, though others like electrons, atoms, and superconductors are possible.

Quantum information science and technology (QIST): The field of research related to encoding and processing information in systems that obey the rules of quantum physics instead of traditional physics.

Stress Points: Areas within a material that experience high levels of mechanical stress, which can be visualized using techniques like birefringence.

Wavelength (λ): The distance between successive peaks of a wave, typically measured in nanometers (nm) for visible lights.

Wave-particle duality: A statement describing a somewhat counter-intuitive feature of quantum mechanics. The behaviour of light, electrons, and other objects at the quantum scale is reminiscent of wave physics in some ways (such as interference) and particle mechanics in other ways (such as discretization).

BACKGROUND INFORMATION

Polarization of Light

What is Polarization? Polarization refers to the orientation of the oscillations of light waves. Normally, light waves vibrate in multiple planes, but when light is polarized, its waves oscillate in just one plane. This can occur through reflection, refraction, or by passing light through a polarizing filter.

Applications of Polarization

- **Sunglasses:** Polarized sunglasses reduce glare by blocking horizontally polarized light reflected from surfaces like water or roads.
- **Photography:** Polarizing filters enhance contrast and color saturation in photos.
- **3D Movies:** Use polarized light to create a perception of depth.
- **Quantum communication**: Polarization lets us encode binary information into light, which can be sent over long distances for communication. If we do this one photon at a time, we can create schemes to communicate securely through quantum key distribution,
- **Birefringence and Stress Analysis** Birefringence is a phenomenon where a material rotates coloured light's polarization, creating colorful patterns when viewed through polarizers. This property is used in stress analysis to identify stress points in transparent materials.

Diffraction and Interference of Light

What is Diffraction? Diffraction occurs when light waves encounter an obstacle or a slit and bend around it, causing the light to spread out. This bending results in a diffraction pattern of light and dark bands.

Diffraction Patterns and Obstacle Size The size and spacing of the diffraction pattern depend on the wavelength of the light and the size of the obstacle. A smaller obstacle causes a wider diffraction pattern. This relationship helps in various scientific and engineering applications, such as measuring small dimensions and analyzing wave properties.

Applications of Diffraction and Interference

- **Gratings in Spectrometers:** Diffraction gratings separate light into its component wavelengths for spectral analysis.
- **Optical Instruments:** Telescopes and microscopes must account for diffraction to improve image resolution.
- **Quantum Computing**: Quantum computers process information encoded in systems that behave like waves. Interference between possible states of the computer is an important part of how they are different from today's computers.
- **Quantum Sensing**: Interference effects are very sensitive, allowing us to detect small changes. Interference was used in the LIGO experiment to measure the tiny effect of gravitational waves.

Spectroscopy

What is Spectroscopy? Spectroscopy is the study of the interaction between light and matter. It involves analyzing the spectrum of light emitted, absorbed, or scattered by materials to identify their composition and properties.

Atomic Emission Spectra When atoms absorb energy, their electrons move to higher energy levels. As electrons return to lower levels, they emit light at specific wavelengths, creating an emission spectrum unique to each element. This spectrum appears as discrete lines, indicating the presence of particular elements.

Continuous vs. Discrete Light Sources

- **Continuous Spectrum:** Produced by incandescent bulbs and the sun, where light is emitted at all wavelengths without gaps.
- **Discrete Spectrum:** Emitted by gases like neon when excited, showing specific wavelengths as sharp bright lines with gaps in between.

Applications of Spectroscopy

- **Astronomy:** The spectrum of light from distant stars and planets can help us identify what elements they are made of. Small deviations due to special relativity called blue-shifts and red-shifts can help us figure out how fast they are moving.
- **Chemistry:** Spectroscopy can be used to identify the elemental composition of substances and find out interesting things about the structure of molecules. Spectroscopy is often done in not just the visible regime, but with other wavelengths of light like x-rays and radio waves.
- **Environmental Science:** The quality of the environment, such as air and water, can be monitored using spectroscopy.
- **Quantum Computing**: The discrete energy levels of atoms can be used to encode binary information in an atom. For example, the "0" could be encoded as a low-energy state and the "1" as a high-energy state. The light that comes from atoms helps us learn the energy needed to jump from one energy level to another. Using laser light to control these "jumps" is how we change the atom from "0" to "1". Today, we can trap chains of individual atoms and use them as prototype quantum computers.

SUGGESTED RESOURCES AND REFERENCES

Websites

- IQC's Quantum 101: https://uwaterloo.ca/institute-for-quantum-computing/resources/quantum-101
- Perimeter Institute's Quantum 101 videos: https://perimeterinstitute.ca/outreach/general-public/quantum-101
- The Quantum Atlas: https://quantumatlas.umd.edu/

Books

- "Q is for Quantum" by Terry Rudolph: https://www.qisforquantum.org/
- "How to Teach Quantum Physics to Your Dog" by Chad Orzel

PRINTOUTS

A set out printouts is available in a separate file. They are arranged to be printed double-sided (except the Spectral Fingerprints transparency sheets). Items marked with a star (*) should be laminated.

- Polarization Hidden Messages
    - Station setup card with photo
    - Participant instructions and mystery task card
    - Evidence, journal entry *
    - ASCII-to-alphabet sheets
- Interference and Diffraction
    - Station setup card with photo
    - Participant instructions and mystery task card
    - Tracing and calculation sheet (six per printout)
- Spectral fingerprints
    - Station setup card with photo
    - Participant instructions and mystery task card
    - Reference spectra (N, O, Ar, He, Ne, the visible spectrum, air, and Sample from Lab) *
    - Filter spectra (N, O, Ar, He, Ne) *
        - Must be printed single-sided on transparent paper
        - Must be laminated to prevent scratching off the printer ink
- Quantum research and applications (images to use for optional discussion at end)
    - Photons
    - Trapped atoms
    - Superconductors

Be careful to print the Spectral Fingerprints reference spectra and filters using the same printer settings, aside from the type of paper used. If they are printed at different sizes/scales, the activity will not work.

MATERIALS AND ASSEMBLY GUIDE

To build the activities, you will need the materials below. The listed amounts support one small station for each activity. The suggested sources are not necessarily endorsed by the workshop authors nor are they necessarily unique.

Polarization Hidden Messages

#	Item	Description	Sample source
3	Polarized light source	A polarized light source is needed to illuminate the object. An LCD monitor set to a white screen works well. Alternatively, you may use an LED panel light or fill light with a polarizer inserted inside to build into a polarized light source.	Fill Light - Temu USB plugs may be helpful
10	Polarizers	To see the effect, participants will need polarizers to look through. Polarizing slides work well as viewers. Larger rolls of polarizers are recommended for bulk purchases and may be used in constructing light sources as well.	Rainbow Symphony Polarization.com
2	Tape, transparent	Transparent tape is birefringent. Be careful to get tape that is transparent to the eye; some tape is sold as "invisible" but is opaque before being applied, this will not work. Packing tape is an excellent option.	Dollarama
15	Clear surface or pre-taped strips	Any clear surface will work, but be careful that the surface does not scramble polarization. Laminate and overhead transparencies sometimes have this effect. Old CD cases, acrylic, and cut page protectors work well. One option for demonstrating birefringence is to let participants build their own art on a transparent surface. For a zero-waste solution, we recommend pre-taping plastic sheets with one piece of tape each and cutting them into strips so they can be overlaid. Participants will then make a mosaic by layering rather than taping, meaning it can be reused.	Large cuttable acrylic - Amazon
1	Set of birefringent objects	Other birefringent materials that participants can explore include clear plastic cutlery, safety goggles, tape dispensers, and more. Minerals like Mica may be acquired to show a natural (non-plastic) birefringent material. Mica can be messy, so we recommend sandwiching it in plastic sheets.	Mica – Ed. Innovations
2	Journal entries with hidden code	The journal entries may be assembled by cutting small adhesive polarizer squares and orienting them on a piece of laminated paper to represent the code.	Adhesive polarizers
3	Reference sheets	Reference sheets to convert ASCII to the standard alphabet are needed to solve the mystery.	

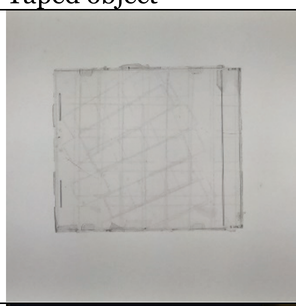
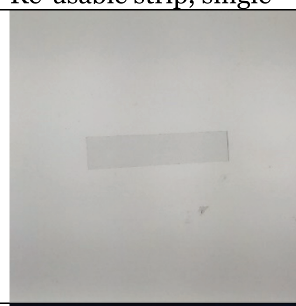
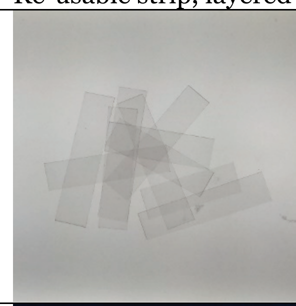
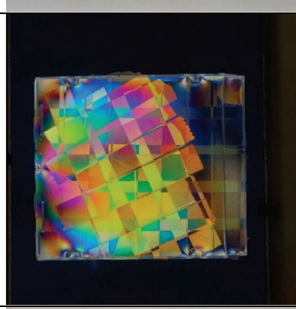
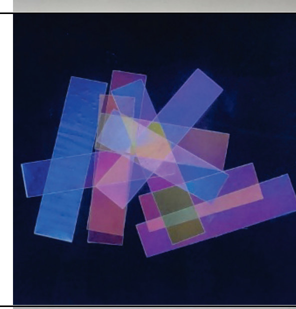
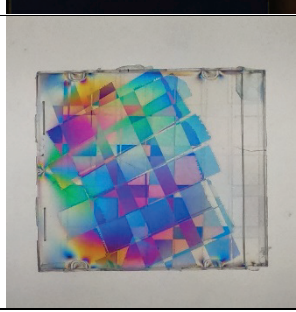
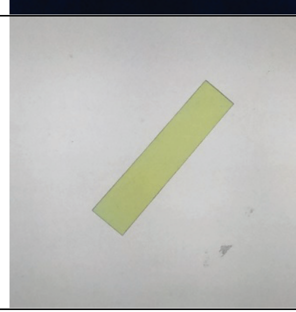
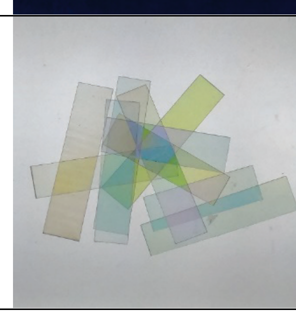
Choosing and using tape

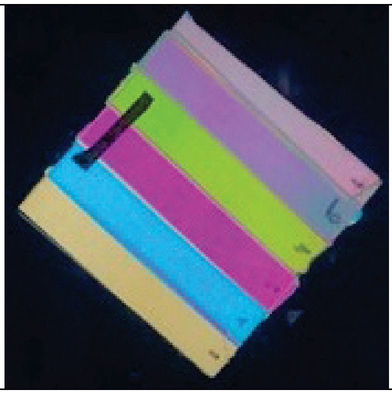
Transparent pressure-sensitive tape, like Scotch tape or packing tape, is an easy and affordable material for building polarization art. Different brands will have different behaviours, with some producing vivid colours with only a layer or two while others are quite dull unless a great deal of tape is used. In Canada, the Studio-brand transparent tape available at common dollar stores is an excellent option.

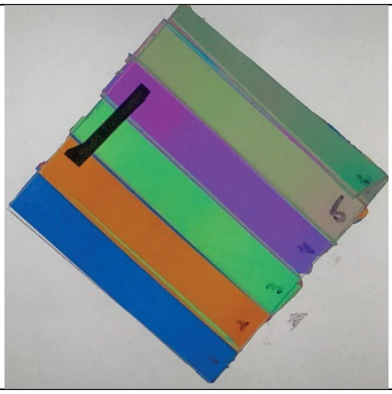
Note that it is important to get transparent tape. Some tape is marketed as “invisible”, which is opaque to the eye but blends into the paper when applied. This tape scrambles polarization and cannot be used in this activity. Any tape that is effective will be near-completely transparent before it is applied to the surface.

You will need a surface for the participants to place the tape onto, which must also be transparent and not scramble polarization. Transparency papers used for overhead projectors work well, though if you layer them you will find that they eventually scramble polarization. Old CD cases are an option as well. In a pinch, a plastic baggie will work too.

This activity can create a great deal of waste if participants each create their own artwork, which will certainly end up in the trash immediately. In this activity, we pre-tape a hard piece of transparent plastic [like PET] which can be cut into strips. By stacking the strips, participants can make their own art piece without creating waste. The colours may be slightly muted in comparison. To apply tape to the PET, we recommend using a small shipping tape roll and cover one full length of the PET at a time. Use a credit card (or similar) as the tape is applied to ensure no bubbles form. Then, cut the PET into strips roughly 2 cm by 8 cm.

	Taped object	Re-usable strip, single	Re-usable strip, layered
No polarizer			
Crossed polarizers			
Parallel polarizers			





Transparent tape viewed through crossed (left) and parallel (right) polarizers, with the number of layers increasing from 1 (bottom-right) to 6 (top-left). A test piece like this can help identify the number of layers required for each colour, and will vary between different brands of tape.

Building a light source

A standard LCD monitor can be used as a light source, but separate LED lights are more economical. Fill lights (often used for photography) or panel lights for home lighting are both options, but are not polarized by default. To turn them into a polarized light source, cut a polarizer or polarizing film to be slightly larger than the screen and cover the LED with the polarizer. It is best if you can take the light apart to hide the edges.

Polarizer cut to cover an LED fill light to act as a light source.

Assembling journal entries

Print the diary entry ("evidence"). Lamination is strongly recommended. You will need to place 24 small (approximately 1-cm-by-1-cm) squares of polarizer onto the blank space in the middle of the entry so that, when read using a polarizer, the squares corresponding to "0" appear dark and the squares corresponding to "1" are unaffected, as in the table below:

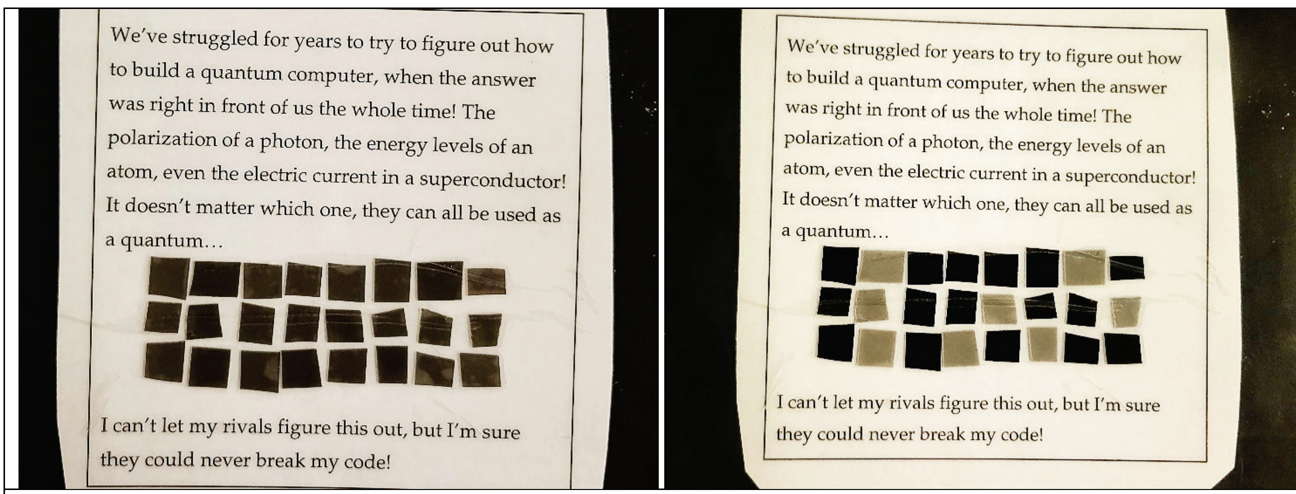
B	=	0	1	0	0	0	0	1	0
I	=	0	1	0	0	1	0	0	1
T	=	0	1	0	1	0	1	0	0

When building the setup, it is helpful to wear glasses that act as polarizers. Polarizing sunglasses, if available, are the easiest solution.

Cut a long 1-cm-wide strip of polarizing film with an adhesive backing. When you are ready to orient the polarizers, put on the polarizing sunglasses. Peel off the protective layer on the polarizer (likely on both sides) while it is still a strip, then cut and place the squares accordingly. It is much easier to peel the protective film off while it is a long strip rather than small squares.

To protect the polarizers, cover with a single layer of transparent shipping tape. Remember that multiple layers or crumpled tape will rotate polarization, so try to keep it flat and single-layer.

Note that it does not matter which polarization is "0" and which is "1", so long as it is consistent. Participants can determine the encoding by noting that all letters in the ASCII code start with the bit "0".



Diary with the overlay viewed without (left) and with (right) a polarizer. Note that the bilingual version will have the same polarizer sequence shared between the English and French versions (positioned so that it is in between the two to avoid needing to duplicate).

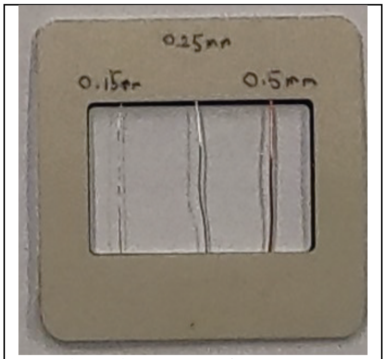
Interference and diffraction

#	Item	Purpose	Sample source
4	Laser pointers, red	Light to illuminate the hair. Laser light is essential; the same effect will not be seen with a flashlight. Red light is safest, and most pointers will be closer to 650 nm in wavelength.	DH Gate Amazon
3	Measuring tape	Measure the distance from the hair to the wall. At least 3 metres is recommended.	
3	Ruler	Measure the spot on the wall; ensure that it uses the same units as the measuring tape (both in centimeters or both in inches)	
3	Sets of craft supplies	Scissors, tape, cue cards, and binder clips are recommended to help participants mount their hair. Clips or surfaces to help participants rest the laser for stability are also helpful.	
4	Wire strand, 0.1mm (38 AWG)	Reliable-width fake hair to be presented as evidence found at the scene of the crime. To mimic your hair reliably, use a strand of wire. 0.1mm is the smallest wire that can be easily found commercially, which is equivalent to a rather thick hair. For added effect, mount in a microscope slide or equivalent size of plastic or cardstock to present as 'evidence'.	Amazon
4	Set of wire strands	To allow participants to prove to themselves that thicker objects produce thinner interference patterns, provide them with a set of labelled wires mounted in cardstock. Jewelry wire is easy to find in a variety of thicknesses between 0.15 and 0.50 mm.	0.5 mm / 24 AWG 0.25 mm / 30 AWG 0.15 mm / 34 AWG

We recommend pre-cutting the wire strands and taping to a labeled card with a hole cut out for the participants to examine using the laser. It's tempting to cover the wires in a plastic case for protection, but small imperfections and scratches in the plastic will scramble the diffraction pattern. Expect that these will need to be fixed periodically as participants will often touch them and bend the wires.

Participants may struggle to keep the laser stable when making measurements. Including some tools to help them stabilize their system, like clamps or even stacks of books to lean against, is helpful.

To save time, cut holes in squares of cardstock in advance so participants can quickly mount their hairs.



Card with wires of varying widths, cut and labelled.

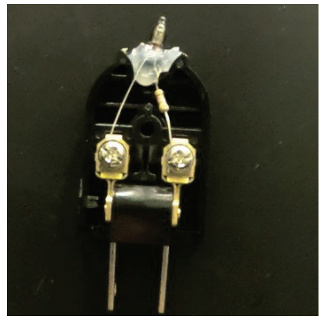
Spectral fingerprints

#	Item	Purpose	Sample source
3	Neon bulb	Neon bulbs are available in bulk, often used for AC indicator lights.	Amazon
3	Neon bulb power source	Neon bulbs require voltages above 70V to operate, and are best used with AC current. Wire the bulb in series with a resistor between 4-6 kΩ, which produces a bright signal while not risking burning out the bulb quickly. Do not leave plugged in when not in use to avoid over-heating the bulb. A single-outlet plug with an on/off switch is helpful.	AC plug case - Amazon Plug switch
2	Orange/red and white LED	Use LEDs as comparisons for the Neon bulb, showing that they have a continuous spectrum rather than discrete. An orange or red LED is important, since it's colour isn't far from the Neon light but the spectra is distinct. A white LED shows a full rainbow. LEDs made to go on your finger-tips are convenient. You can use individual LED bulbs as well if desired. Connect to two AA or AAA batteries or a coin battery (3V) in series with a 100-1000 Ω resistor. A 3D-printed mount can be useful, but alligator clips or a breadboard work as well.	Finger LEDs
10	Diffraction gratings	A diffraction grating is used to separate the wavelengths of light, revealing the spectra of various light sources. Participants should hold it directly to their eye to see the effect. The amount that the colours separate is determined by the lines-per-millimetre of the grating. 500 lines-per-millimetre is sufficient for this activity. A spectroscope which labels the wavelengths when participants view through a device is an option, but more than is needed for this activity. Similarly, if available, a digital spectrometer is a useful add-on, but is not essential and rather expensive. Note that these elements are the most common ones that participants may try to take as souvenirs.	Rainbow Symphony
2	Sets of spectral mask/filter and reference cards	Print the black-and-white spectral mask cards on transparent (overhead) paper. Laminate for durability. Make sure to print the colour spectra reference cards using the same settings to ensure the sizes are compatible.	Transparent paper
1	Set of lights for comparison	Additional light sources to explore are a welcome add-on to this activity in case time remains at the end. Try to find items that have distinct spectra, such as white-light sources made of RGB components versus fully continuous sources. Remote-controlled LEDs are particularly useful, as they are portable and can be used to show many colours. If you can control the colour, you can demonstrate that red,	Controllable LED lights (can be broken into two sets)

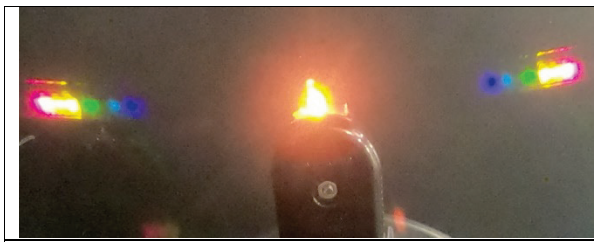
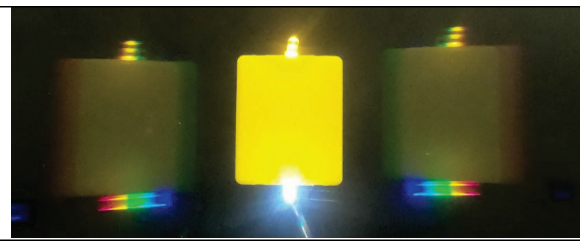
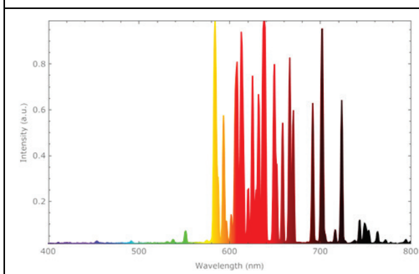
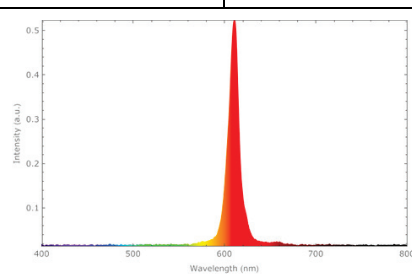
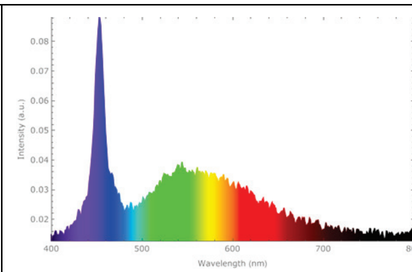
		green, and blue are the default colours and other options (like teal) are made up of combinations of those, since the diffraction grating will split those elements.	

<u>Assembling the Neon bulb</u>

The neon bulbs must be connected to wall power to receive the appropriate voltage (60V or greater). If wires are exposed, there is an electrocution risk for participants. We recommend using a closed power source like the AC plug case recommended. On the inside, solder the neon bulb in series with a 4-8 kΩ resistor. Unlike an LED, the direction of current through the neon bulb does not matter. Connect the ends of the joined bulb/resistor to the leads of the casing, screw tightly, and seal shut. If some wire is exposed at the base of the bulb, use a small amount of hot glue.



Sample wiring set-up for the Neon bulb and resistor, which are first soldered together and then connected with screws to a plug adapter. The case would then be closed to avoid shock risk. Hot glue is applied at the bulb to completely seal it.

		
A neon lamp viewed through a diffraction grating. The light looks very orange to the naked eye, but when the colours are separated, we see it contains many different colours. The spectrum is choppy, with isolated colours rather than a smooth distribution.	An orange (top) and white (bottom) LED viewed through a diffraction grating. The colours of the white LED are seen to spread the entire rainbow, while the orange LED has a narrow spectrum. However, both are smooth and continuous.	
		
Neon bulb	Orange LED	White LED
Spectrum (wavelength vs. relative intensity) of the three sources used as measured with a digital spectrometer, showing more detail but the same essential features as seen with the diffraction grating.		

Activity developed by the **IQC Scientific Outreach team**
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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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