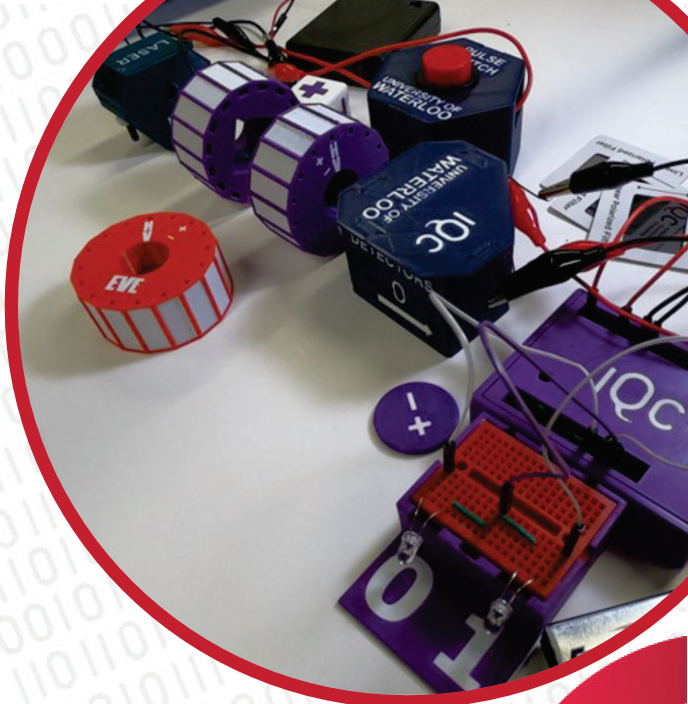

Assembly Instructions

BUILD YOUR OWN QUANTUM KEY DISTRIBUTION

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Assembly Instructions

BUILD YOUR OWN QKD

1. INTRODUCTION

Quantum key distribution (QKD) is one of the key technologies of the quantum information era, using the phenomenon of superposition and measurement disturbance to share secrets securely. To build a QKD system in real life, scientists and engineers need access to source of quantum light, sensitive photon detectors, precision optical components, and significant data processing capabilities.

Using affordable lasers and photosensors, this interactive kit demonstrates the key capabilities of QKD. While this analogy kit is vulnerable to eavesdropping through a pulse-copying or partial reflection attack (which the no-cloning principle prevents when using single-photon signals), it allows students to work through the protocol in full, including experimental alignment, information exchange, and data processing. Using these hands-on tools should give students a greater understanding and intuition for superposition and quantum measurement, as well as experience with basic electronic and optical components.

As a pre-requisite, we assume familiarity with the BB84 QKD protocol, as outlined the Quantum Cryptography lesson plan by the IQC (link).

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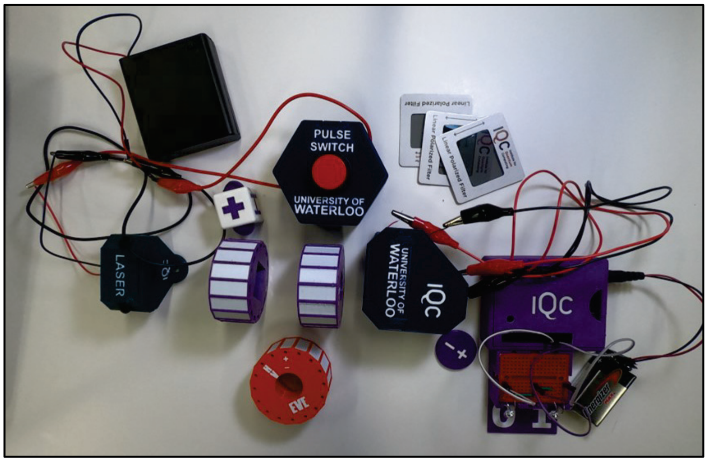
POSSIBLE SETUP ORIENTATIONS

The QKD kit can be set in two main orientations, depending on the needs of your class. The materials will differ slightly depending on which version you plan on setting up.

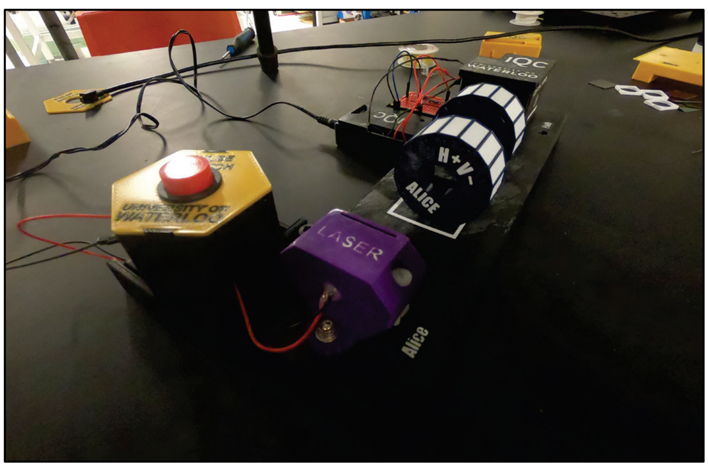


Option 1 – Magnetically mounted

In this version, each piece has a rare earth magnet inserted into it, allowing the pieces to be re-arranged on a magnetic surface such as a whiteboard.

Advantages: Students can assemble it themselves and have to do some laser alignment, allowing for more teamwork to be integrated into the activity.

Disadvantages: Many wires needed to connect the various pieces, which can be a burden for day-to-day setup and easy for students to accidentally disconnect.



Option 2 – Base mounted

In this version, the kit components are secured to a 3D printed base, keeping the device aligned at all times. Wave plates are kept separate to allow polarization rotation.

Advantages: Electronics are secure and can be soldered in place if desired. No alignment necessary, less likely to need debugging. Generally preferred for science fairs and public demonstrations.

Disadvantages: Less of a build-it-yourself setup for student engagement.

2. LIST OF COMPONENTS

3D-Printed Components

The below components need to be printed with a 3D printer. Anything with a "Dual" marking has test markings that can be merged with the main model if you have a dual-extrusion printer available. These are optional (you may paint the recesses instead to make them stand out) except where noted.

Component	Dual?	QTY	3D Print Filename (.STL)
Arduino Box – Base		1	ArduinoBox-Case
Arduino Box – Lid	Opt	1	ArduinoBox-Lid *OR* ArduinoBox-Lid-Alt
Arduino Box – Breadboard holder	Opt	1	Breadboard-Basket
Switch Box – Base		1	SwitchBox *OR* SwitchBox-ForBase
Switch Box – Lid	Opt	1	SwitchBox-Lid
Laser Mount – Base	Opt	1	Laser-Bottom
Laser Mount – Top	Opt	1	Laser-Top
Detectors – Box	Opt	1	Detector-Body
Detectors - Lid	Opt	1	Detector-Lid
Alice Wave Plate	Opt	1	WP-Alice
Bob Wave Plate	Opt	1	WP-Bob
Eve Wave Plate	Opt	1	WP-Eve
General Wave Plate – Square Film Holder		3	WP-FilmHolder
Base – Main body	Opt	1	Base-Body
Base – Battery holder		1	Base-BatteryCase
Randomizers	Req	2	D4-Cube, Coin-01, and Coin-Basis
Stencils (for cutting polarizers and films)		1	21mmSquare
Materials organizer	Opt	1	QKD-Materials-Holder

Purchased and Gathered Components

Note that many of these components usually come in large sheets or rolls, and only a small amount is needed. If possible, coordinate with the supplier or other builders to use for multiple kits.

Component	Detail	QTY	Sample Source (CDN, as of November 2024)
Laser Source	520nm Green Laser Diode (Class II Laser)	1	DigiKey VLM-520-03LPT-ND
Laser Power	6V Battery (4 AA batteries in holder)	1	DigiKey 1528-830-ND
Switch Button	Push-Button with Off-Mom functionality	1	DigiKey PR144C1900
Gator-Clip Leads		3-7	DigiKey 2407 (10-pack)
Solar Panel	Amorphous solar cell, 0-5V, 20.7 uW	2	DigiKey AM-1819CA
Beam Splitter	50/50 beam splitter, non-polarizing	1	ThorLabs EBS1
Half-Wave Plate	λ/2 film for 520nm light, 21-mm square	2	Edmund Optics 88256 (sheet)
Quarter-Wave Plate	λ/4 film for 520nm light, 21-mm square	1	Edmund Optics 88253 (sheet)
Polarizer	Thick material preferred, 21-mm square	3	PolarizationDotCom PF030 (sheet)
Green Filter	Chrome Green Colour Filter, 21-mm square	2	Production Supplies R389 (sheet)
Reference Polarizer	Polarizing slide, any labelled one will do	1-3	Rainbow Symphony 04601
Breadboard	Small breadboard	1	DigiKey BB-32650-R
Arduino Uno	Rev3 tested, see firmware installation tips	1	DigiKey A000066
USB Cable	USB-B to USB-A, male-to-male	1	DigiKey SC-2ABE003F
9V AC adapter *or* battery plug	2.1mm ID, 5.5mm OD barrel plug for 9V, used to power the Arduino		DigiKey L6R06H-090 (AC) DigiKey 1927-1053-ND (battery)
Jumper Wires	Male-to-male jumper wire for Arduino, or a spool of AWG22 wire	~10	DigiKey 1957 (20-pack) and/or DigiKey CAB-13191 (4-pack)
Screws & Nuts	8-32 thread Nylon to avoid surface scratches 2 1", 2 ½", 4 nuts	2 2 10	McMaster Carr 94735A741 (pack) McMaster Carr 94735A737 (pack) McMaster Carr 94812A400 (pack)
Magnets	12.5-mm square rare earth magnets 12.5mm X 5mm rare earth magnets	5 8	Indigo Instruments 44234-2.5 Indigo Instruments 44231-2.5
Magnetic Surface	Ideally 12”x8” or larger whiteboard laid flat	1	Office supply store
Generic tools	Phillips screwdriver, need-nose pliers, Scotch tape, crazy glue, hot glue, scissors, pen, notepads. White card or paper for beam tracking. Voltmeter and soldering kit optional.		
Randomizer	A source of random binary numbers	2-3	Coins or dice

For magnetically mounted version only

Magnets	12.5-mm square rare earth magnets	5	Indigo Instruments 44234-2.5
	12.5mm X 5mm rare earth magnets	8	Indigo Instruments 44231-2.5
Magnetic Surface	Ideally 12”x8” or larger whiteboard laid flat	1	Office supply store

For base-mounted version only

Magnets	12.5mm X 5mm rare earth magnets	8	Indigo Instruments 44231-2.5
Magnetic strip	4-inch X 0.75-inch plate, Zinc works well	1	Everbilt 859-750

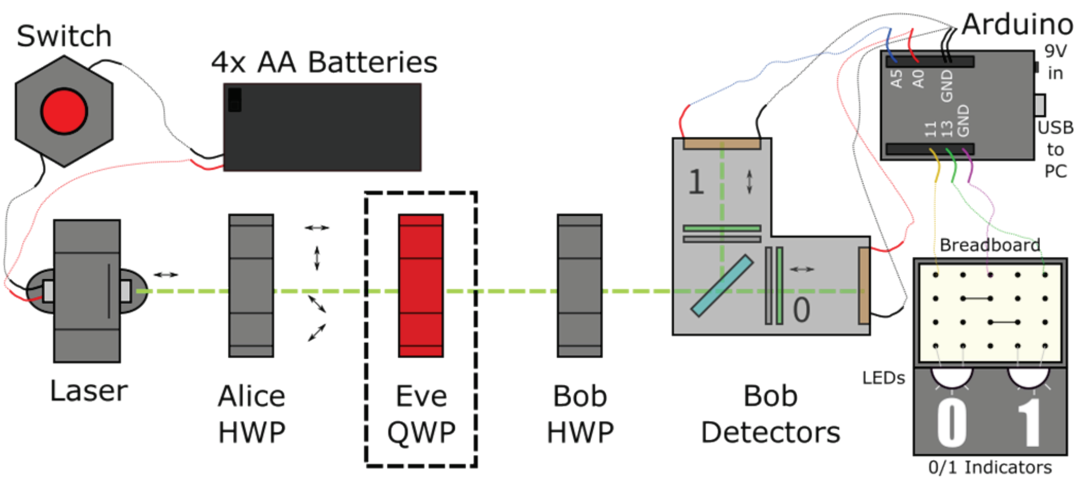
3. EXPERIMENT AND COMPONENT OVERVIEW

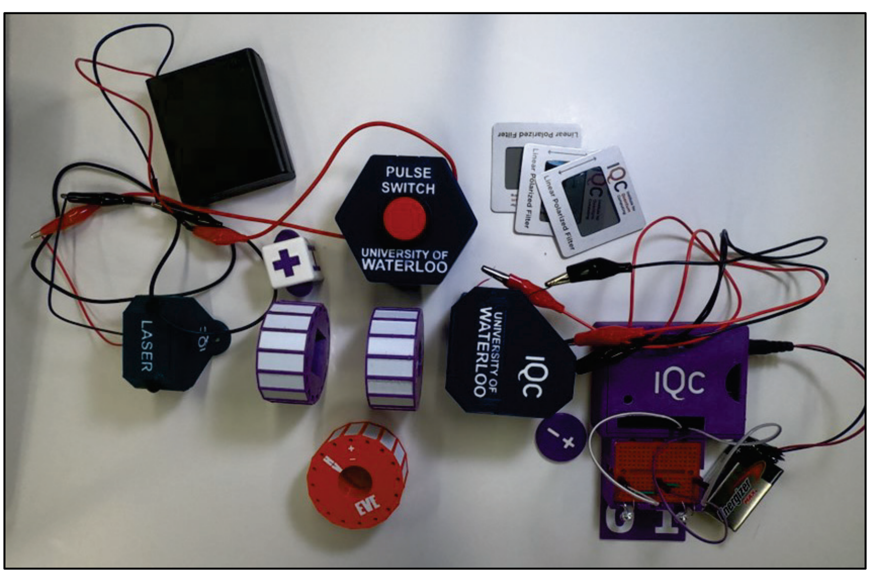
In the QKD experiment, students will take on the role of Alice or Bob (in teams if needed). Alice will prepare one of four polarization states of light, and Bob will measure polarization in one of two bases. An optional eavesdropper (Eve) can be introduced, whose action of measuring in one of two bases is mimicked with a polarization rotator.

Each player will need the following components, in addition to a notebook for tracking results:

Alice	Eve	Bob
Laser Polarized to ↔	Quarter-Wave Plate (Polarization Rotator)	Detector Set with Built-In Polarizing Beam Splitter
Half-Wave Plate (Polarization Rotator)		Half-Wave Plate (Polarization Rotator)
Pulse Switch		Voltage Measurement (Arduino)
Power Source (AA batteries)		LED Measurement Display (or PC)

The fully-constructed setup should look something like the below diagram. Most components have magnetic bases, so the setup can be securely assembled on a surface such as a whiteboard.





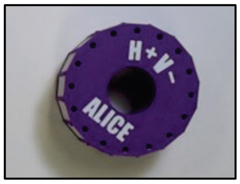
ALICE'S COMPONENTS

Alice's role is to prepare random polarization states, which will then be sent to Bob. Alice's source of light is a **green laser diode**, which is originally set to the **horizontal polarization state**, which can be written as any of $\rightarrow = |H\rangle = |0\rangle = \binom{1}{0}$, depending on your preferred notation. A **switch button** only allows power to the laser diode when pressed, so that Alice can send pulses of laser light one-at-a-time.

To prepare arbitrary polarization states, Alice uses a polarization rotator called a **half-wave plate** (HWP). The HWP is a birefringent material, meaning that different polarizations of light have different indices of refraction. They are balanced such that, when lined up to the horizontal/vertical basis, the HWP introduces a phase of 180° (π) between horizontally and vertically polarized light. If the HWP is at a different angle, it will introduce a phase between two other perpendicular polarization directions, changing the polarization state of the light.

In particular, a HWP at the following angles will rotate a polarization state that was initially $\rightarrow$ to:

Input State	HWP Angle	Output State	HWP Matrix
$\rightarrow = \|\boldsymbol{H}\rangle = \|\boldsymbol{0}\rangle = \binom{\boldsymbol{1}}{\boldsymbol{0}}$	**0°**	$\rightarrow = \|\boldsymbol{H}\rangle = \|\boldsymbol{0}\rangle = \binom{\boldsymbol{1}}{\boldsymbol{0}}$	$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
	22.5°	$\nearrow = \|\boldsymbol{D}\rangle = \|+\rangle = \frac{\boldsymbol{1}}{\sqrt{\boldsymbol{2}}}\binom{\boldsymbol{1}}{\boldsymbol{1}}$	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$
	45°	$\uparrow = \|\boldsymbol{V}\rangle = \|\boldsymbol{1}\rangle = \binom{\boldsymbol{0}}{\boldsymbol{1}}$	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
	67.5°	$\searrow = \|\boldsymbol{A}\rangle = \|-\rangle = \frac{\boldsymbol{1}}{\sqrt{\boldsymbol{2}}}\binom{\boldsymbol{1}}{\boldsymbol{-1}}$	$\frac{1}{\sqrt{2}}\begin{pmatrix} -1 & 1 \\ 1 & 1 \end{pmatrix}$

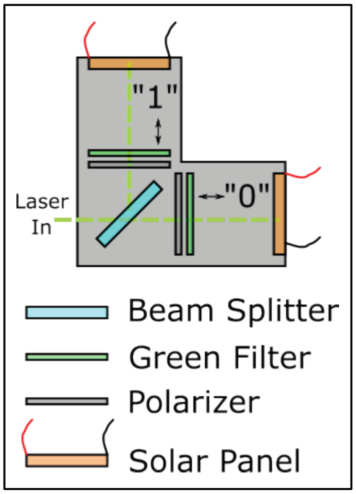


By rotating to one of these four angles, Alice can prepare any of the polarization basis states in the HV or ±45° bases, as required for BB84 QKD.

These angles are labelled on the HWP mount. If the input is set to horizontal polarization, the output will be rotated to whichever polarization corresponds to the upright letter. By rotating the waveplate, any of the four BB84 states can be prepared.

BOB'S COMPONENTS

Bob's role is to measure the light that Alice sends. To do so, Bob needs a way to detect light depending on its polarization, and to measure in different polarization bases.



Bob's **detectors** are made of two **solar panels**, which produce a voltage when they see light. They are arranged as seen on the left and contained in a box to shield them from room light. **Green filters** are introduced to further reduce background.

To measure the polarization state of light, we need the detectors to be polarization-sensitive. By themselves, solar panels do not discriminate between different polarizations of light, so extra components are required.

First, we insert a **50/50 beam splitter** into the laser beam path, splitting the light into two pulses with the same polarization, one reflected and one transmitted. A **horizontal polarizer** is placed in the transmitted path "0", and a **vertical polarizer** is placed in the reflected path "1", and the intensity in each path is measured with a solar panel. If the light was horizontally polarized, it will only be measured in the transmitted path, and if it was vertically polarized, it will only be measured in the reflected path. If the light was in a ±45° state or any other non-HV state, both solar panels will see some light, with an intensity proportional to the H or V component.

Note that a **polarizing beam splitter** (PBS) would be a more efficient way to implement this, but these devices are generally much more expensive.

The combination of the beam splitter, polarizers, and solar panels allows us to measure in the HV basis. If we see a voltage in Solar Panel "0", we know the light was horizontally polarized. If the light was vertically polarized, we'll see a voltage in Solar Panel "1" instead. If the light was a superposition state, we'll see a lower voltage in each.

To measure in the ±45° basis, we also provide Bob with a **half-wave plate** (HWP) to rotate the polarization. While Alice used the HWP to rotate horizontal polarization to another polarization state, Bob will use the HWP to rotate the entire ±45° basis to the HV basis. The below table shows what the HWP does to each polarization state used in QKD at 0° and 22.5° (you can check with the matrices in Alice's table if you like):

Input State	Output State for HWP at 0°	Output State for HWP at 22.5°
$\rightarrow = \|\boldsymbol{H}\rangle = \|\mathbf{0}\rangle = \begin{pmatrix}\mathbf{1}\\\mathbf{0}\end{pmatrix}$	$\rightarrow = \|H\rangle = \|0\rangle = \begin{pmatrix}1\\0\end{pmatrix}$	$\nearrow = \|D\rangle = \|+\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$
$\nearrow = \|\boldsymbol{D}\rangle = \|+\rangle = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}\begin{pmatrix}\mathbf{1}\\\mathbf{1}\end{pmatrix}$	$\searrow = \|A\rangle = \|-\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix}$	$\rightarrow = \|H\rangle = \|0\rangle = \begin{pmatrix}1\\0\end{pmatrix}$
$\uparrow = \|\boldsymbol{V}\rangle = \|\mathbf{1}\rangle = \begin{pmatrix}\mathbf{0}\\\mathbf{1}\end{pmatrix}$	$\uparrow = \|V\rangle = \|1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$	$\searrow = \|A\rangle = \|-\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix}$
$\searrow = \|\boldsymbol{A}\rangle = \|-\rangle = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}\begin{pmatrix}\mathbf{1}\\\mathbf{-1}\end{pmatrix}$	$\nearrow = \|D\rangle = \|+\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$	$\uparrow = \|V\rangle = \|1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$

The HWP at 0° keeps the ±45° basis states in the ±45° basis. However, the HWP at 22.5° rotates the +45° to horizontal, and the -45° state to vertical. If Bob measures horizontally polarized light after the HWP, he can infer that the photon had a +45° component before the HWP. In this way, Bob's combined system of a HWP and the HV polarization measurement works as a measurement in the ±45° basis. Note that Bob's HWP has only two settings (0° and 22.5°), corresponding to measurements in the two BB84 bases.

ALL ABOUT EVE

In BB84, if an eavesdropper measures the photon that Alice sends to Bob, they will have a significant chance of disturbing the quantum state. The method in which they measure the quantum state doesn't matter; whether they try to clone the photon, or measure the photon and re-send a new photon, or even use fancy processes like non-demolition measurements, they will disturb the polarization state in most bases.

To mimic the effect of Eve, students could combine two systems in one, and have Eve work as a "fake-Bob" who measures Alice's photons, and a "fake-Alice" who re-sends photons back to Bob depending on their measurement. The amount of alignment and coordination needed for this may test your student's patience.

To more simply mimic Eve, you can use a **quarter-wave plate** (QWP) instead. This plate is also a polarization rotator, but instead of changing the HV basis to the ±45° basis, it changes either basis to the circular polarization basis. The circular polarization state are both completely random when measured in the HV or ±45° basis, so Eve's presence will scramble the polarization state in one of the two bases.

Input State	Output State for QWP at 0° $\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$	Output State for QWP at 45° $\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}$
$\rightarrow = \ket{H} = \ket{0} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$	$\rightarrow = \ket{H} = \ket{0} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$	$\circlearrowleft = \ket{R} = \ket{+_i} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ i \end{pmatrix}$
$\nearrow = \ket{D} = \ket{+} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\circlearrowleft = \ket{R} = \ket{+_i} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ i \end{pmatrix}$	$\nearrow = \ket{D} = \ket{+} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$
$\uparrow = \ket{V} = \ket{1} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$	$\uparrow = \ket{V} = \ket{1} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$	$\circlearrowright = \ket{L} = \ket{-_i} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -i \end{pmatrix}$
$\searrow = \ket{A} = \ket{-} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$	$\circlearrowright = \ket{L} = \ket{-_i} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -i \end{pmatrix}$	$\searrow = \ket{A} = \ket{-} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$

Note that this implementation of Eve doesn't actually make a measurement, but the results that students will observe are the same as if they had.

The Eve wave plate included in the kit has two labels, corresponding to 0° and 45° settings. This corresponds to Eve making a "measurement" in the HV basis (and scrambling the ±45° basis) or in the ±45° basis (scrambling the HV basis).

Due to a loophole in the implementation presented here, we can actually eavesdrop effectively with another beam splitter. By picking off a small amount of the laser energy, Eve can measure a laser pulse that shares the same polarization as what Bob measures. This attack is called the photon-number-splitting attack, and works here because we don't have a true source of single photons, using a laser diode instead. With two kits, you can mimic this attack by having Eve act as a Fake-Alice and Fake-Bob.

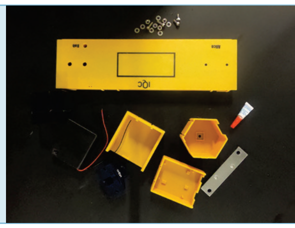
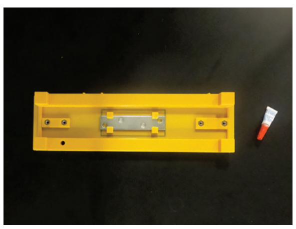
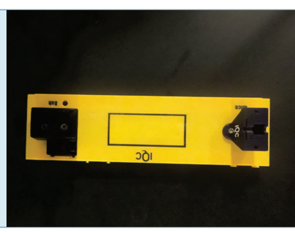
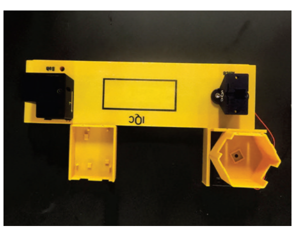
Now that we understand what components we need, in the next section we'll assemble them piece-by-piece. The following section is only applicable if you've 3D-printed the components yourself; if they are pre-assembled, you may skip to Page 12 for Software Installation, or Page 16 for experiment assembly and testing.

4. COMPONENT ASSEMBLY

BASE MOUNTING (optional)

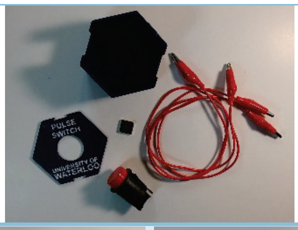
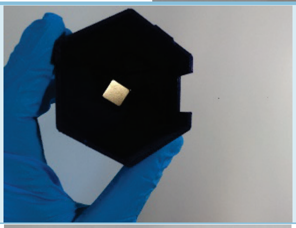
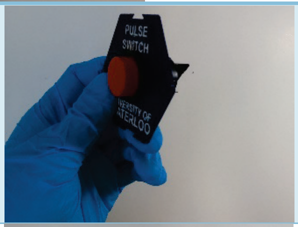
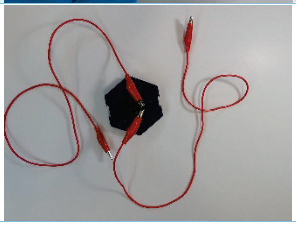
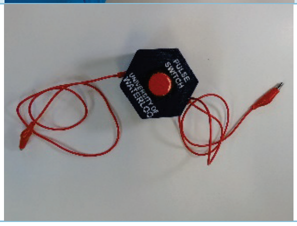
Using an incorporated base rather than the magnetic base may be attractive for student groups who may struggle with the alignment, for science fairs where misalignment is common, or for travel to avoid disassembling the electronics. The components can be mounted on a plastic base in these circumstances, such that the entire unit moves as one piece. Note that you may choose to solder the electrical connections to increase the robustness of the unit. If you go this route, you only need magnets on the waveplate mounts.

If you are mounting the device onto the 3D-printed base, you will want to screw in as many components as possible before assembling. The assembly process of the individual pieces follows afterward.

	You will need base board and battery case, along with the magnetic metal bar. You will also need the bases for the laser, Arduino, switch box, and detector box. You will also need four #8 nuts and washers and 4 corresponding 8-32 screws about ½” long. Glue is useful for this assembly.
	Turn the base upside-down. Put the nuts into the slots seen underneath. Push them into the recess and secure them so they don’t fall out when you turn it back over. If using glue, be sure to glue the edges of the nuts, not the threading inside the nut. Slide the metal bar into the slots underneath the base. This may require some force, which a large flat screwdriver may help with. This will magnetically secure the wave plates. Ensure in advance that the bar attracts magnets.
	Fasten the laser base by the “ALICE” label and detector base by “BOB” (with the hole facing the laser). Continue with setup for these pieces as in other sections. If, after setup, you find the laser is tilted and not aligned to the detector, consider adding washers to the front or back to tilt the laser.
	Slot the Arduino base near “BOB” and the battery case base by “ALICE” using the slots and forked extrusions. This may be a tight fit depending on your 3D printer settings. Some force or light sanding may be required. To ensure they are flat to the ground, we recommend inserting them from the bottom, which makes it easier to align with the base. Afterwards, slot the Switch Box base above the battery base.

SWITCH BOX / PULSE BUTTON

The button included allows use to pulse the laser, sending a quick burst of laser energy when pressed. Wiring the button into one terminal of the battery pack will ensure that the circuit only completes and the laser only fires when pressed.

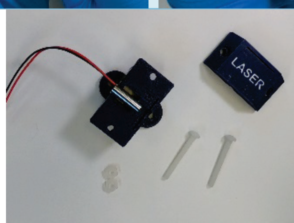
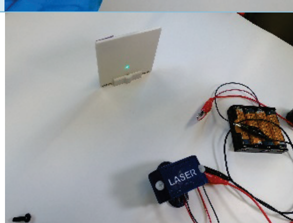
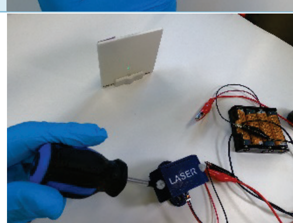
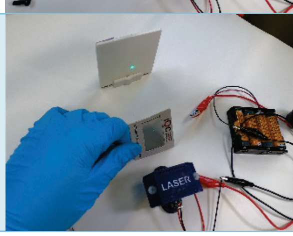
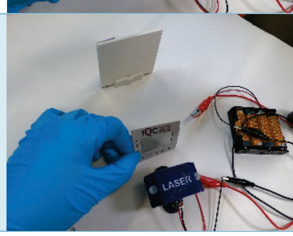
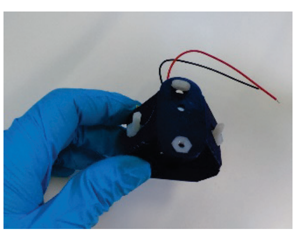
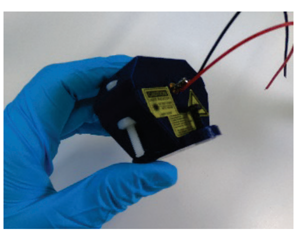
	You will need the switch box and lid, along with the button, two gator-clip leads, and a magnet.
 	Push the button through the lid. The flexible wings should secure it in place. If magnetically mounting, push the magnet into the recess in the switch box base with a pen.
 	Attach one end of each gator-clip lead to the terminals on the button. Rotate the button until it is easy to pass both leads through the slots in the base. Once secure, either tape or glue the lid to the base.

For added reliability, consider snipping the wire and soldering the bare end directly to the button leads.

If you are base-mounting, you may solder the lead from the battery pack directly to one lead from the button and the lead from the laser to the other. Ensure that you use the same lead in both cases (both red or both black). Guide these wires through the long holes in the switch box to keep things tidy. This may be easiest to do once all pieces are screwed into the base.

LASER MOUNT

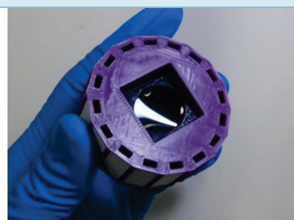
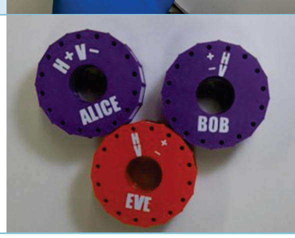
Note: the laser recommended with this kit is a Class 2 laser. Be careful to keep away from eye level.

	Collect the laser mount base and top, along with a polarizer square, the laser diode, the battery pack, and two gator-clip wires. You'll need two 1" 8-32 screws and #8 nuts. For magnetic mounting, you'll also need 1-2 0.5" screws, one more nut, and a magnet. You'll also need pliers, a screwdriver, a pen, and a reference polarizer. Hot glue is useful.
 	Remove the hole plugs from the laser top and base pieces with pliers and discard. Insert the magnet and push to the bottom of the base with a pen if base mounting.
	Mount the laser diode over the magnet. Secure the top using the 1" screws and nuts, but do not fasten tightly.
 	Use the reference polarizer to find the vertically polarized axis of the square polarizer, as in the picture. This is the direction such that all horizontally polarized light is blocked. Insert the polarizer into the slot in front of the laser, aligned to vertical polarization.
 	Use the battery pack and gator wires to power on the laser. Place such that a nearby surface is illuminated. Grip the laser and rotate until the spot is as dim as possible. This will set the laser to horizontal polarization. Tighten the screws on the laser mount when set.
 	Remove the polarizer from the laser mount. Use the reference polarizer to align it to horizontal polarization by blocking vertically polarized light. Re-insert the test polarizer aligned horizontally. Check that it is correct using the test polarizer, which should block the laser if held vertically but not if horizontal.
 	If magnetically mounting, insert a nut into the recess at the bottom of the mount behind the laser. Insert the 0.5" screw into the hole until secure. This will act as a tilt adjustment for your experiment, in case your whiteboard is unlevel. If base mounting, these holes will be used to secure the laser to the base

Tip! The wires on the back of the laser may break off if mishandled. For extra security, add a bit of hot glue to the back of the laser after assembly to make sure the wires can't be "wiggled" off the laser circuit.

WAVE PLATES / POLARIZATION ROTATORS

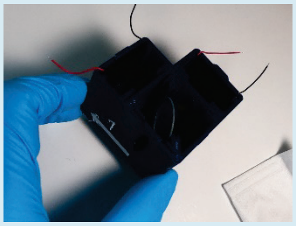
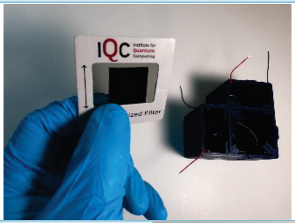
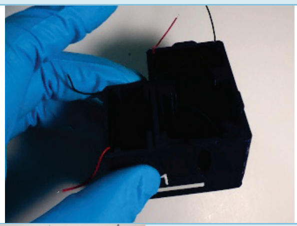
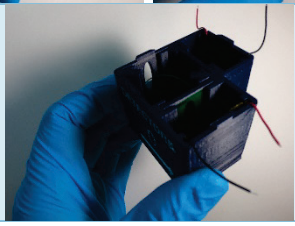
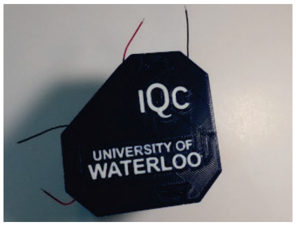
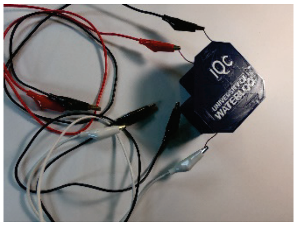
There are three polarization rotators in the kit: one each for Alice, Bob, and Eve. The assembly process is identical for each, but the settings each can use differs.

	You will need the “Alice” / “Bob” / “Eve” wave plate holders, 8 12.5mm X 5mm magnets, three square film holders, and three pieces of wave-plate film: two half-wave plate (HWP) and one quarter-wave plate (QWP). You will also need tape and crazy glue. Tweezers and scissors may be helpful.
	Remove the protective film on both sides of the HWP using Scotch tape. Cover one side and slowly remove the tape until the protective cover starts to peel. The bare HWP film should be completely transparent. Try to avoid getting the bare HWP film dirty and minimize fingerprints, especially at the centre of the film. Note that Eve uses a QWP film instead of HWP film.
 	Place the HWP film in the back plate’s recess, trimming if needed. Secure with the square film holder, squeezing it so the tab applies enough pressure to keep it in place. If needed, apply a small amount of crazy glue to the corner of the holder to keep it in place. Take care to avoid getting glue on the wave plate film itself.
	Push the 12.5 x 5mm magnets into the recesses on the back face such that they are opposite to the letters on the front face. Alice should have four magnets, while Bob and Eve will each need two.
	Repeat for all three wave plate holders to build the complete set. You may wish to keep a second copy of Eve with no film inserted at all, so that students are unsure whether an eavesdropper is present or not.

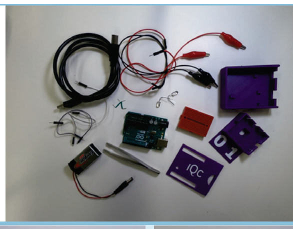
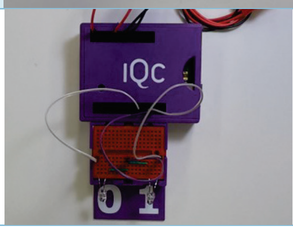
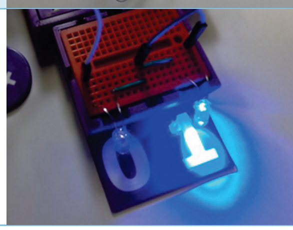
Tip! The magnets can be removed and moved around by overly curious users. Consider gluing them in place (hot glue works well) and adding a “magnet guard” piece to prevent students from casually moving them around.

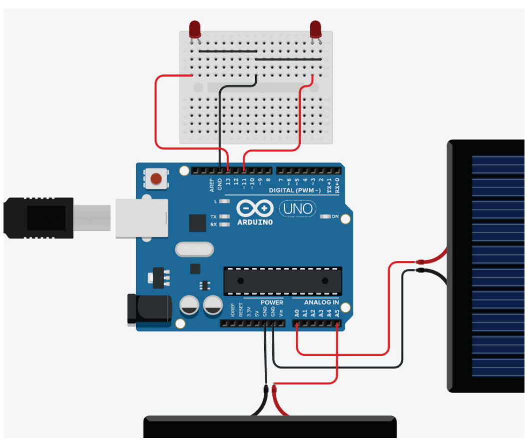
DETECTOR BOX

The detectors will be used to measure Bob's bit by measuring the polarization of Alice's photon. This is made using two solar panels as photodetectors. Without any rotators in place, only vertically polarized light will hit one detector, and only horizontally polarized light will hit the other.

	Collect the detector box and lid, along with the 50/50 beam splitter, two solar panels, two 1" square polarizers, two 1" square green filters, two magnets, and four gator-clip wires. You will also need the reference polarizer. You may want to consider slightly stripping the solar panel leads to make them easier to connect alligator clips to.
	If magnetically mounting, insert a magnet into each of the square recesses. If base mounting, use these holes to mount onto the base before continuing. Place the solar panels wires-up in the back slots of the detector box. Insert the beam splitter into the centre slot, holding it by the edge to avoid smudging it's centre.
 	Use the reference polarizer to align one 1" polarizer to horizontal polarization by block vertical; put this polarizer in the back slot (transmitted light) of the detector box. Use the reference polarizer to align the other 1"polarizer to the vertical polarization by blocking horizontal light, and put it in the left slot (reflected light) of the detector box.
	Place the 1" green filter squares in the slots behind each polarizer. These will help reduce noise due to room light by only allowing green light to reach the detectors. Placing the filter behind the polarizer is preferable to avoid any unwanted polarization rotations in the filter.
 	Place the solar panel wires into the slots at the back of the box. Secure the lid on top of the detector box. The lid fits very tightly to block out light and can snip the wires if they are not in the slots. Connect the gator clips to the solar panel wires. These will connect directly to the Arduino Uno. You may also solder a length of wire to it if you are base-mounting.

ARDUINO BOX & BREADBOARD WIRING

	Collect the Arudino Uno, the box base/lid, the mini breadboard, the breadboard basket, nine jumper cables, two LEDs, a 9V battery with barrel connector, and a USB cable (B-type to A-type, commonly used for printers).
 	Snap the Arduino into the base and slide the lid on. Plug jumper cables in analog pins A0, A5, and the two ground (GND) terminals, shown in red and black. Plug jumper cables into digital pins 5, 13, and GND, shown in white and purple.
 	Push the breadboard into the basket and connect the basket to the Arduino box. Connect the LEDs and digital pin outputs to the breadboard as in the circuit diagram below. Bend the LEDs downward so that they illuminate the “0” and “1” indicators.



The digital pins 5 and 13 should connect to the positive (long) pins of the LEDs. The ground GND should connect to both of the negative (short) pins of the LEDs.

The analog pins A0 and A5 will connect to the positive (red) wires of the solar panels, and the analog GND pins should connect to the negative (black) wires of the solar panels. For default settings, A0 should connect to the horizontal (transmitted) path of the detector box and A5 should connect to the vertical (reflected) path.

The Arduino may be powered by a 9V battery **or** by plugging into a computer via USB. Once the Arduino has been set with the proper firmware (as explained on the next page), it can be run independently by plugging into a 9V power source.

Note that there are two lid options for the Arduino. The standard fits securely into the base, but cannot be removed without taking out the wires. The second (Alt) is less secure, but slides off without disturbing the wires.

5. RUNNING THE ARDUINO

Simple Setup

Before using the Arduino Uno, you will need to update its firmware. This will teach the Arduino how to process the data from the solar panels and communicate to the LEDs. You can also use the Arduino software as a monitor for debugging.

Install the Arduino Software (IDE) from www.arduino.cc/en/main/software. Connect the Arduino Uno to your computer via USB. Open the software and select your Arduino device under **Tools → Port**.

Open the file "**QKD_Arduino_Demo_v3.ino**" with the Arduino IDE. To initialize your Arduino, simply hit the green checkmark button to verify and then the green arrow button to upload to the Arduino. Just like that, your device should be working!

Once the firmware has been updated, you can disconnect the Arduino from your computer and power it with a 9V battery source. Alternatively, you can continue using the USB port as a power source.

Adjusting, Monitoring, and Debugging

Some of the parameters can be tuned by adjusting the initialization of the code, as seen to the left.

- **VOL0** and **VOL1** control which pins connect to the solar panels.
- **pinZERO** and **pinONE** control which pins connect to the LEDs.
- **threshold** determines the voltage needed for the solar panels to register a bit. Adjust this if you find the device is too sensitive or not sensitive enough.
- **serialmode** controls what is displayed on the IDE serial monitor.
- **bkgdsub** controls whether background light is subtracted from the signal (0 for no, 1 for yes). If on, the first reading the Arduino measures when powered on will be taken as the background level. This is not usually necessary, but could be helpful in some situations.
- **Mode** defines the operational mode of the device. Leave mode=1 for QKD analysis, others require different LED setups.
- **enableOpenCircuitDetection** monitors the voltages on the Arduino to catch if one of the wires has come unplugged. If it detects an open circuit, both LEDs will flash. It does not catch all open circuit faults, but may be useful if you find this issue to be common.

While plugged into the PC, you can view the signals directly. Under **Tools**, open the **Serial Monitor** and **Serial Plotter**. If **serialmode=0**, the Serial Monitor/Plotter will display the voltages measured by the solar panels. If **serialmode=1**, the Serial Monitor will display the bits recorded in the QKD protocol (which can be used as a backup display for Bob if an LED breaks).

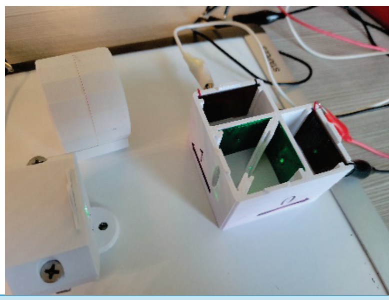
6. EXPERIMENT ASSEMBLY AND TESTING

The QKD experiment works best in a darkened room. We recommend closing all blinds and turning off unnecessary overhead lights to reduce background. Natural light sources tend to be more problematic than artificial ones.

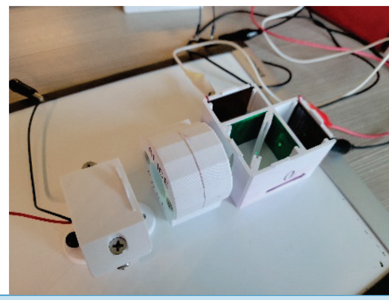
To begin testing, we'll first check that the laser and detector polarizers are properly set.

- Place the **Laser**, **Detectors**, and **Alice HWP** on the magnetic surface
- Connect the laser to the battery (bypassing the switch for simplicity)
- Align the laser such that it passes through the oval opening in the detector box, adjusting the tilt with the back screw if necessary
- Open the lid to the detector box. Check that the laser beam is only visible on one solar panel ("0").
- Insert the Alice HWP. Check that the laser spot remains at "0" if set to "H", and switches to "1" if set to "V".
- Check that the laser beam appears in both paths if the HWP is set to "D" or "A".

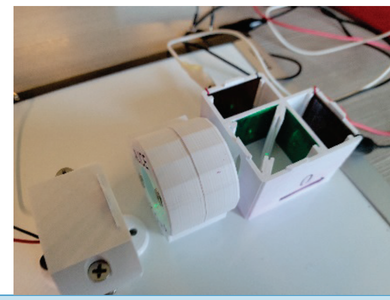
Note that the detector in the transmitted path is labelled "0", and the detector in the reflected path is labelled "1".



With no HWP, you should see the laser spot on the "0" detector.



With the HWP set to "H", the laser spot remains in the "0" path.



With the HWP set to "V", the laser spot switches to the "1" path.

This process shows how we will be sending 0's and 1's of information, encoded as horizontal or vertical polarization.

If the beam does not show up where it was expected, it is likely that one of the polarizers in either the laser or the detector box is rotated by 90° from the intended angle. Use the reference polarizers to double-check.

Next, connect the detectors to the Arduino Uno to test the data processing:

- Cover the detector box with the lid, ensuring it sits flat to cover the solar panels from outside light and that the solar panel wires fit in the grooves between the box and lid.
- Connect the ground (black) wires of each solar panel to the jumper cable in the GND Arduino slot
    - Both grounds can be connected to the same GND terminal, but the system is more stable if each solar panel is connected to a separate GND terminal.
- Connect the red wire of the "0" solar panel to the "A0" jumper wire with a gator cable.
- Connect the red wire of the "1" solar panel to the "A5" jumper wire with a gator cable.
- Connect the Arduino Uno to a computer with a USB cable **or** to a 9V battery power source.

If you have not already done so, connect the pulse switch in between Alice's laser and the battery pack. Ensure the breadboard is connected and wired.

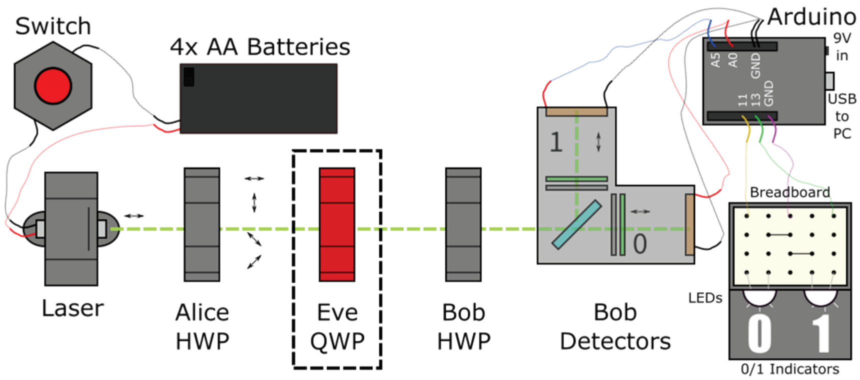
Introduce the Alice and Bob wave plates and reproduce the table to the right. Ensure that the text on Alice's wave plate faces the laser and Bob's faces the detector, and try to insert the wave plates such that they are as close to perpendicular to the laser beam as possible. Hold down the button to see if the result is constant or random.

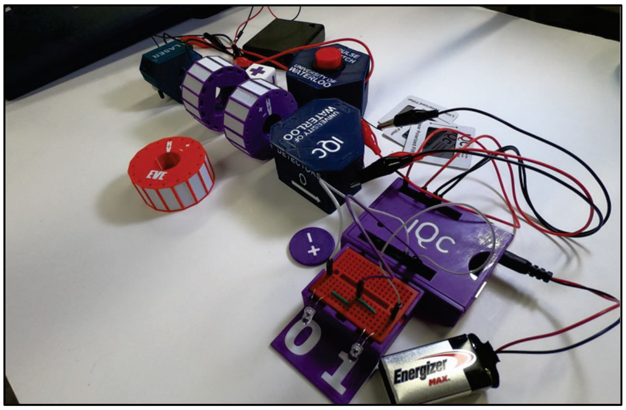
Alice Setting	Bob Setting	
	H/V	+/−
H	0	RANDOM
+	RANDOM	0
V	1	RANDOM
−	RANDOM	1

NOTE
The lights will flicker randomly when the Arduino is plugged in if the circuit is not complete. This is not an error, but a result of the circuit not being grounded.

7. DEBUGGING AND TROUBLESHOOTING

- ***Problem****:* The Arduino IDE won't let me upload to the Arduino Uno.
    - Ensure the correct USB port is selected under **Tools > Port**.
- ***Problem***: The lights are going off even when there is no laser present.
    - Ensure that the solar panels are well-connected to the Arduino on both ends.
    - Ensure that the lid for the detector box is secured snugly on top of the box.
    - In the Arduino code, turn on background subtraction (bkgdsub) to subtract room light. If already on, reset the background level unplugging the Arduino briefly and plugging it back in with the lid closed and the laser off.
- ***Problem***: I'm not able to read any bits / measure any light.
    - Ensure that the Arduino is receiving power (a green LED on the board itself should be on).
    - Ensure that all jumper wires are connected to the Arduino in the right spots.
    - Check in the Arduino Serial Monitor with serialmode=0 that voltages are being read by the Arduino.
    - Reduce the threshold value to trigger bits if needed.
- ***Problem***: The LEDs are random when they shouldn't be random.
    - Ensure that the solar panels and the Arduino are well-connected. If one of the connections is broken, the circuit will be open/ungrounded and the pins will register a random floating voltage, which will cause the lights to flicker randomly.
    - Enable background subtraction. If already on, reset the background level unplugging the Arduino briefly and plugging it back in with the lid closed and the laser off.
    - Increase the threshold slightly (this may be solar-panel dependent).
- ***Problem***: The LEDs are constant when they should be random.
    - Ensure that you have measured enough bits to be confident that the output is constant (five 0's in a row could be consistent with random statistics).
    - Decrease the threshold slightly (this may be solar-panel dependent).
- ***Problem***: The LEDs are constant or random correctly, but the states aren't what I expect.
    - If the states don't match but are constant/random when expected, this is OK as long as Alice and Bob agree. Ensure students start by calibrating their system to determine which state corresponds to 0/1.
    - Ensure that the wave plates are oriented in the right direction (text facing each user).
    - Ensure that the breadboard is wired correctly (the pins aren't accidentally swapped).
    - Check that the laser beam goes where you expect, using a white business card to track its path. If it goes in unexpected directions, check that the polarizers in the laser and detector box are properly aligned.





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