S4: Building a Wooden or PVC Version of the OPN Spec

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In this supplement, we explain how to make an alternative version of the OPN Spec, using parts available at most hardware stores (e.g., wood or PVC board, PVC tubing, electrical tape, etc.) or online (e.g., a light dependent resistor or LDR and digital multimeter). As with other OPN instruments that we have developed,[1, 2] we list the basic materials needed to build this spectrophotometer (and their estimated costs at October 2016 prices) in Table S4-1. Of course, many of these items (especially the wood or PVC board and the PVC pipe) will make more than one OPN Spec. We also provide the dimensions for these wooden and PVC pieces in lumber units (i.e., inches) since those are the standard units of measurement for these types of materials and their related tools.

Table S4-1. Description and Approximate Cost of the Parts for a Wooden or PVC Version of the OPN Spec

Part	Approx. Cost
¾-inch thick wood or PVC board	$2 to $20
½-inch thick plywood board (2-feet x 2-feet panel)	$2 to $8
¾-inch PVC pipe (Schedule 40; 5 feet long)	$2
⅜-inch diameter wooden dowel (4 feet long)	$1 to $2
CD or DVD (from a pack of 5 of more)	$2 to $10
LED flashlight	$10 to $20
Light Dependent Resistor (LDR)	$1 to $3
Digital multimeter	$5 to $25
Jumper wires with "alligator" clips	$5
Index card(s) or similar item	$1
Electrical tape	$1 to $2
AA or AAA batteries (one four-pack)	$2
Total	**$34 to $100**

Also, even though readers can make this version of the OPN Spec using hand tools, as with other OPN devices that we have built,[1, 2] the process will go more quickly and smoothly using power tools (e.g., a chop or table saw, a portable drill or drill press, a disk or belt sander, etc.), which should be available at most high schools, colleges, or universities. In addition, any readers who are unfamiliar with these types of tools should review the Hazards section below given the significant dangers associated with this type of equipment.

The Components of the OPN Spec

Like its 3D-printed counterpart, the wooden or PVC version of the OPN Spec consist of three major components: (i) a holder for a standard cuvette; (ii) a holder for the light source (an LED flashlight; and a holder for part of a CD or DVD that serves as a diffraction grating (Fig. S4-1). To make these components, we used ¾-inch thick board that we purchased from the "spare wood" bin at a regional hardware chain, a piece of ½-inch thick plywood, a 4-inch length of ¾-inch PVC pipe, and a ⅜-inch diameter wooden dowel. These items cost around $2 each (for a grand total of roughly $8), and they will make several sets of OPN Spec parts.

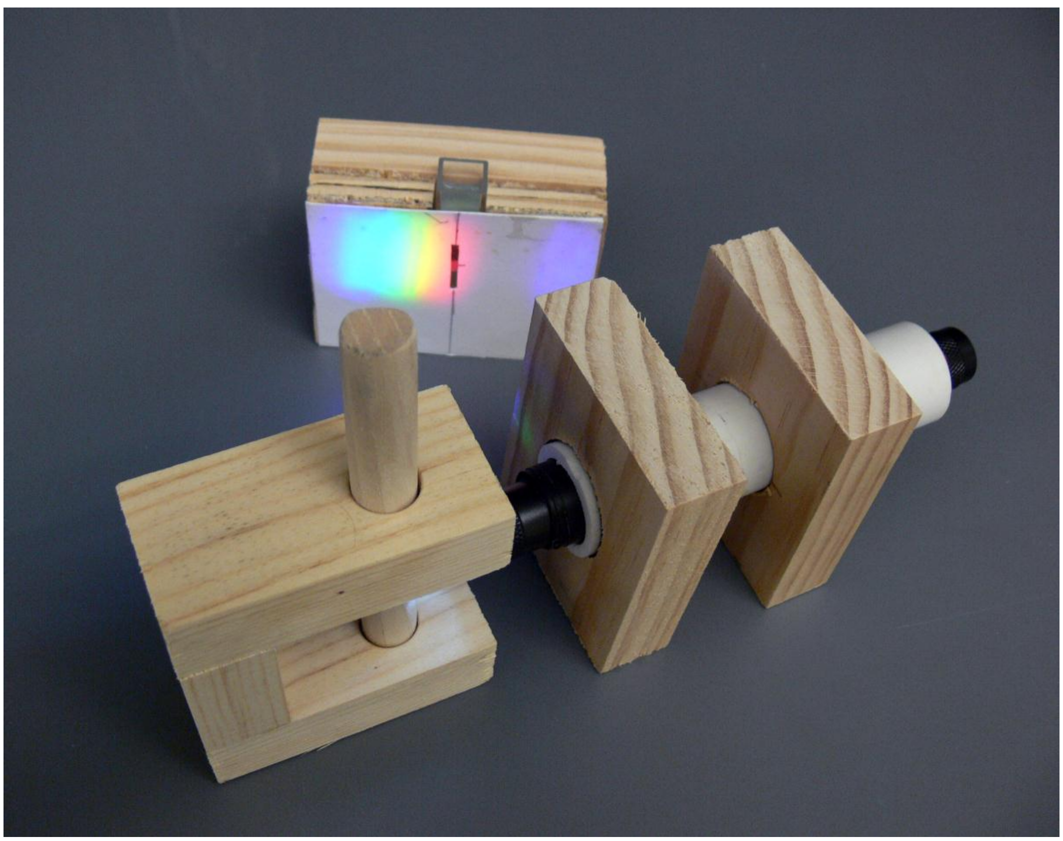

Figure S4-1. The components of the OPN Spec. The cuvette holder (top). The flashlight holder (left). The CD or DVD holder (right).

The Cuvette Holder

To make the cuvette holder, we use a piece of ¾-inch thick wood as the back, a piece of ½-inch thick plywood to hold the cuvette, and an index card or piece of card stock with a slit cut in it as the face plate – each piece measuring 2¼-inches x 3-inches (Figure S4-2A).

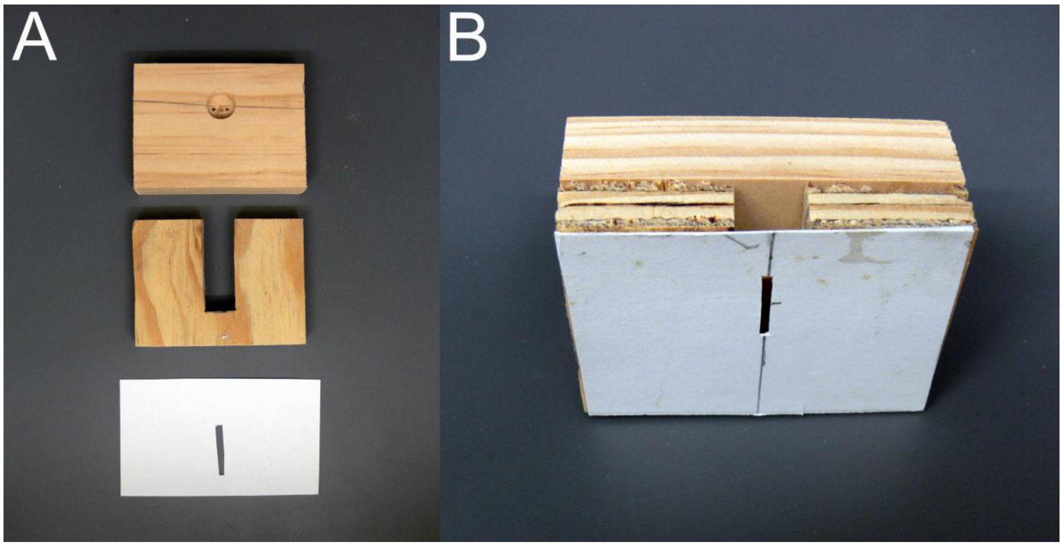

Figure S4-2 The cuvette holder for the OPN Spec. (A) The back piece, cuvette holder, and face plate (from top to bottom). (B) The assembled cuvette holder held together with superglue. Note that we placed the hole for the LDR slightly above the center of the back piece. Readers, however, can center this hole if they prefer.

We further drill a ½-inch diameter hole half way into the ¾-inch thick back piece to hold a light dependent resistor (LDR). Although we tend to place this hole slightly above the center of the wooden piece (Fig. S4-2A, top), readers can drill it into the center of the piece instead. As long as the cuvette holder is placed far enough away from the CD or DVD that serves as the diffraction grating, the resulting spectrum should be tall enough to strike the LDR. In addition, readers can drill the hole for the LDR all the way through the ¾-inch thick back piece, and then use a #4 cork stopper to hold the LDR in place (as explained in the Supporting Information for our OPN Colorimeter paper).[2, 3]

From the center piece of plywood, we cut out a ½-inch x 2½-inch section to hold a standard plastic cuvette (Fig. S4-2A). In much the same way that we make this piece for the OPN Colorimeter,[2] we place a standard cuvette in the center of the piece of plywood, roughly ½ to ¾ inches above the bottom edge (we take this approach so that the top of the cuvette sticks out roughly ¼ to ½ inches above the top of the plywood piece; Fig. S4-1). Next, we use a pencil to trace out the shape of the cuvette on the piece of plywood, and we then use a band saw to cut out the section.

For the front face plate, we cut a small index card to size (roughly 3 inches x 2¼ inches) and then cut a thin slit into using an X-Acto knife or single-edged razor blade, so that the beam of light can strike the LDR (S1).

We hold these three pieces together using super glue (Fig. S4-2B), although readers can use hot glue, wood glue, or other adhesives instead. Also, we let the pieces dry by simply placing each one on top of the other. As explained in the Supporting Information for our OPN Colorimeter paper,[2] we do not place the pieces in a vice or otherwise press them firmly together as they dry because this approach can compress the wood so tightly that a standard cuvette will no longer fit into the holder.

The Flashlight Holder

To make the holder for the flashlight, we use two 2¼-inch x 3-inch (l x h) pieces of wood that are both ¾-inches thick and a 4-inch long piece of ¾-inch Schedule 40 PVC pipe, which has an outer diameter of roughly 1.05 inches (Fig. S4-3A). We further drill two 1⅛-inch diameter holes into the center of each piece of wood, which can be easily marked by drawing an "X" between the diagonal corners on each piece.[2] Also, as with the OPN Scope and OPN Colorimeter,[1, 2] we use a compression fitting to secure the PVC tube in place, wrapping it with a few layers of electrical tape, so that it would fit tightly into the holes in each wooden piece (Fig. S4-3B).

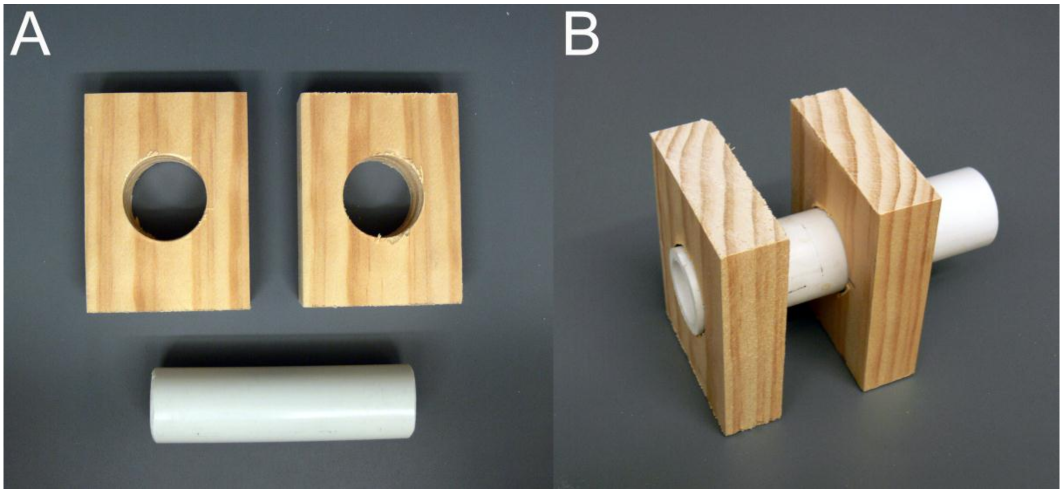

Figure S4-3. The flashlight holder for the OPN Spec. (A) The individual parts for the flashlight holder. (B) The assembled flashlight holder.

In addition, given the smaller diameter of the Coast G20 flashlight, we wrap it with several layers of electrical tape in two different places, so that it fits more snugly into the PVC pipe (Fig. S4-6), which is the same approach that we use with the OPN Scope and OPN Colorimeter.[1, 2] We further include some ideas for alternate holders below if using other LED flashlights that have different dimensions (Figs. S4-6 – S4-8).

The Holder for the Diffraction Grating (Made from a CD or DVD)

To construct the holder for our diffraction grating, which is made from a CD or DVD,[4-14] we use three pieces of ¾-inch thick wood (two measuring 2¾-inches x 1¼-inches, and one measuring 1¼-inches x 1½-inches), and a 5½-inch long piece of a wooden dowel that is ⅜ inches in diameter (Fig. S4-4A). We further drill a ½-inch diameter hole all the way through one of the large pieces of wood and half way through the other large piece, so that the wooden dowel will fit through the top piece while staying anchored in the bottom piece (Fig. S4-4). In addition, we sand one side of the dowel flat (Fig. S4-4B), so that we can more easily attach part of a CD or DVD to it using double-sided tape (S1).

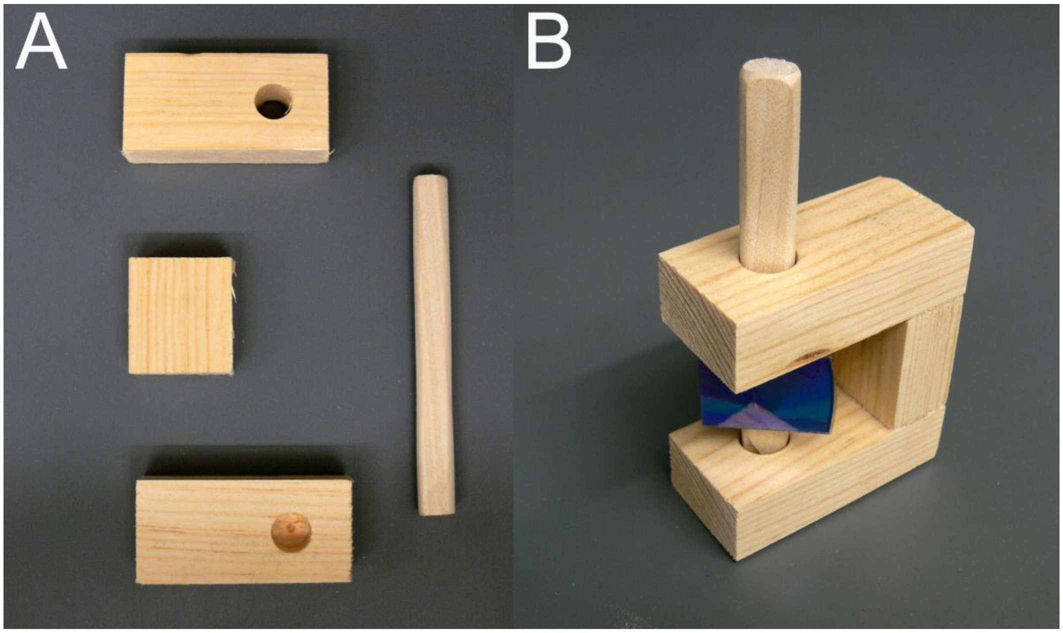

Figure S4-4. The CD or DVD holder for OPN Spec. (A) The individual parts of the holder for the diffraction grating. (B) The assembled holder for (along with a piece from a standard DVD).

As with the cuvette holder, we use super glue to hold the three wooden pieces together, although other adhesives will again suffice. Once assembled, the piece of the CD or DVD that we use as a diffraction grating can be rotated to "dial in" different colors (and, thus, wavelengths) for the OPN Spec (S1; Figs. S4-1, S4-11). If the wooden dowel tends to stick as it rotates, readers can simply sand it down slightly using a small sheet of sandpaper (or, alternatively, widen the holes in the two wooden pieces slightly by using a wood file or a piece of sandpaper).

In addition, we have found that placing the flashlight up close to the CD or DVD tends to generate the most useful spectrum (S1). Similarly, placing the cuvette holder roughly 5 cm away from the CD or DVD typically generates a rather tall and intense spectrum, and moving the cuvette holder further back (e.g., 10 to 15 cm) tends to widen out the bands in the spectrum, which may make it easier for students to "dial in" a narrower band of wavelengths (S1).

The Light Source

As with other OPN instruments that we have developed,[1, 2] we frequently use a Coast G20 LED inspection light as our light source, and we have purchased these flashlights for around

$11 at a regional hardware chain (Fig. S4-5). Also, as explained in our OPN Scope and OPN Colorimeter papers,[1,2] we typically wrap the Coast G20 flashlight with several layers of electrical tape, so that it will fit snugly into ¾-inch PVC tube that we use as our light holder (Figs. S4-5; see also Figs. S4-1, S4-11, S4-13).

Figure S4-5. Wrapping a Coast G20 LED inspection light with electrical tape, so that it will fit snugly into a ¾-inch PVC tube.

Of course, readers can use other flashlights instead, and we have had success with several different tactical LED flashlights, such as: the Outlite A100; the Outlite WT03; the UltraFire; the SkyWolfEye; and the GeakLight (Fig. S4-5). Importantly, each one of these models has a powerful LED inside of it along with a convex lens that helps to focus the beam – both of which help to generate an intense white light that makes a bright and useful spectrum.

Figure S4-6. The tactical LED flashlights that we use with our OPN Specs. From left to right, the Coast G20 LED inspection light, Outlite A100, Outlite WT03, UltraFire, SkyWolfEye, and GeakLight.

However, given their individual dimensions, readers will need to make separate holders for these tactical LED flashlights, and we recommend the following approach. First, measure the diameter of the head and handle of the flashlight. Then, drill holes in the center of two 3-inch x 3-inch (or similar) pieces of wood that are ¾ inches thick to fit the handle and head of the flashlight (Fig. S4-7A). Again, the easiest way to center these holes is by drawing an “X” between the opposite diagonal corners of each wooden piece.[2] Next, use a band saw to cut each piece in half length-wise, which will create two separate sets of “cradles” for the flashlight (Fig. S4-7B). Then, use removable poster tack or mounting putty to hold the pieces in place on the table top when using them with the OPN Spec.

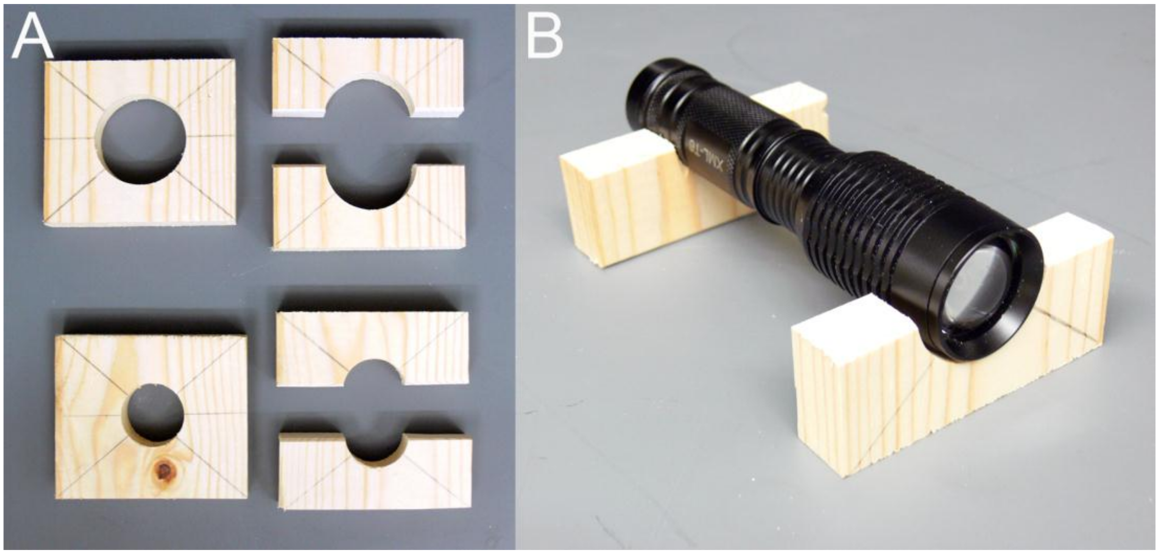

Figure S4-7. Making a holder for a tactical LED flashlight out of two ¾-inch thick pieces of wood.

In addition, to provide a stable base between the two cradles, readers can cut a piece of ½- or ¾-inch thick wood to size, so that it fits the length of the flashlight (Fig. S4-8). Readers can then hold these three pieces together using super glue, wood glue, hot glue, or screws (Fig. S4-8B), and the light can be placed in front of the CD or DVD to generate a spectrum.

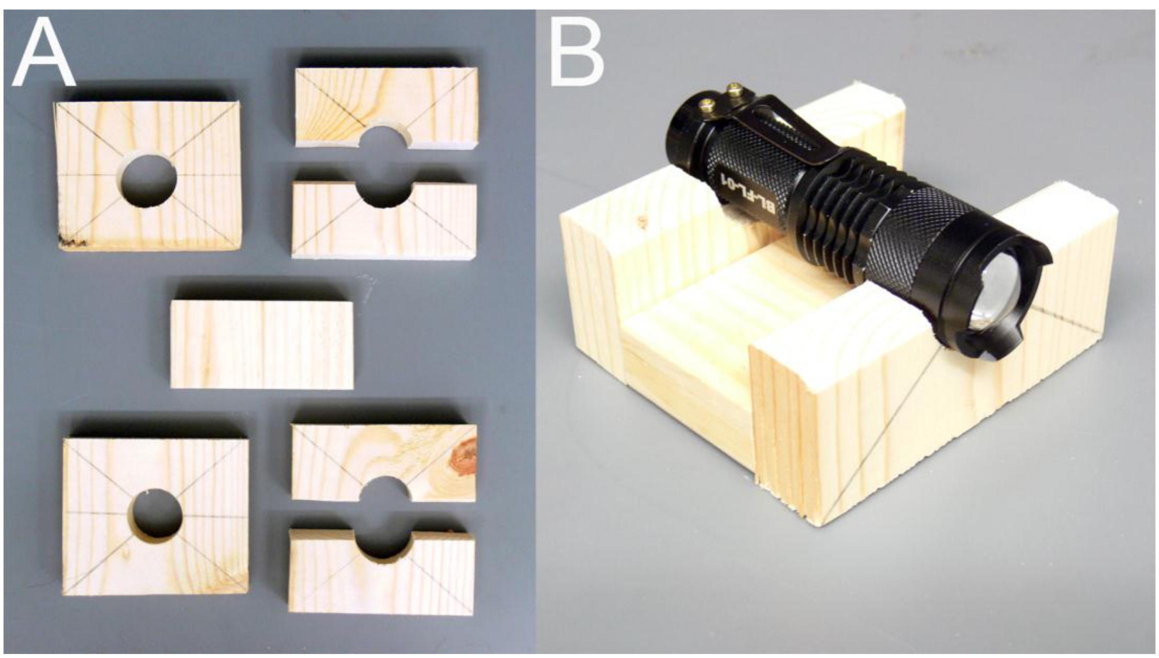

Figure S4-8. Making an alternative holder for a tactical LED flashlight out of ¾-inch thick wood.

The Light Dependent Resistor (LDR) and Digital Multimeter

As with the 3D-printed version of the OPN Spec (S1), we typically use an 85-cent light dependent resistor (LDR) for our detector – specifically, a PDV-P8103 photocell by Advanced Photonix, Inc., which has a 500-kOhm "dark" resistance and can be purchased at www.digikey.com or on other websites that sell electronic components (Fig. S4-9A). We have also had success using a variety of different digital multimeters with the OPN Spec, and these instruments can be purchased online or at various hardware stores for between $5 and $25 each, depending on the make and model (Fig. S4-9B). Readers, however, can use other LDRs or multimeters instead, but please make sure to conduct a series of pilot tests with them to ensure that the OPN Spec is working properly and generating expected results before using the set-up with students.

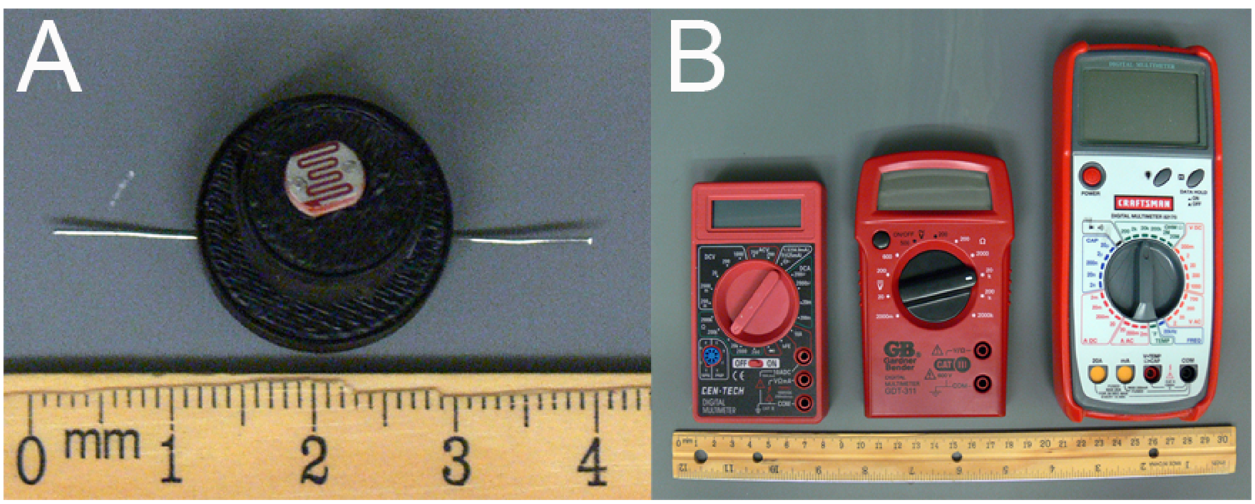

Figure S4-9. The Light Dependent Resistor (LDR) and multimeters that we use with our OPN Spec. (A) PDV-P8103 LDR by Advanced Photonix, Inc. mounted in the back plug for the 3D-printed version of the OPN Spec. (B) Cen-Tech (left), Gardner Bender (center), and Craftsman (right) digital multimeters.

The CD or DVD that We Use as a Diffraction Grating

As with the 3D-printed version of the OPN Spec (S1), we use a small piece (roughly 1¼-inch x 1-inch) from a CD or DVD as our diffraction grating.[4-14] Specifically, we cut a small wedge from a standard CD or DVD and then trim its top and bottom to create the rectangular piece (Fig. S4-10). We then use double-sided tape to hold the CD or DVD in place against the flat side of the wooden dowel (Figs. S4-1, S4-4, S4-11). If using a ⅜-inch diameter dowel with a ½-inch diameter hole drilled into the two larger pieces of the CD or DVD holder, the post should then turn rather easily, and students should be able to “dial in” different colors (and, thus, different wavelengths) in their experiments.

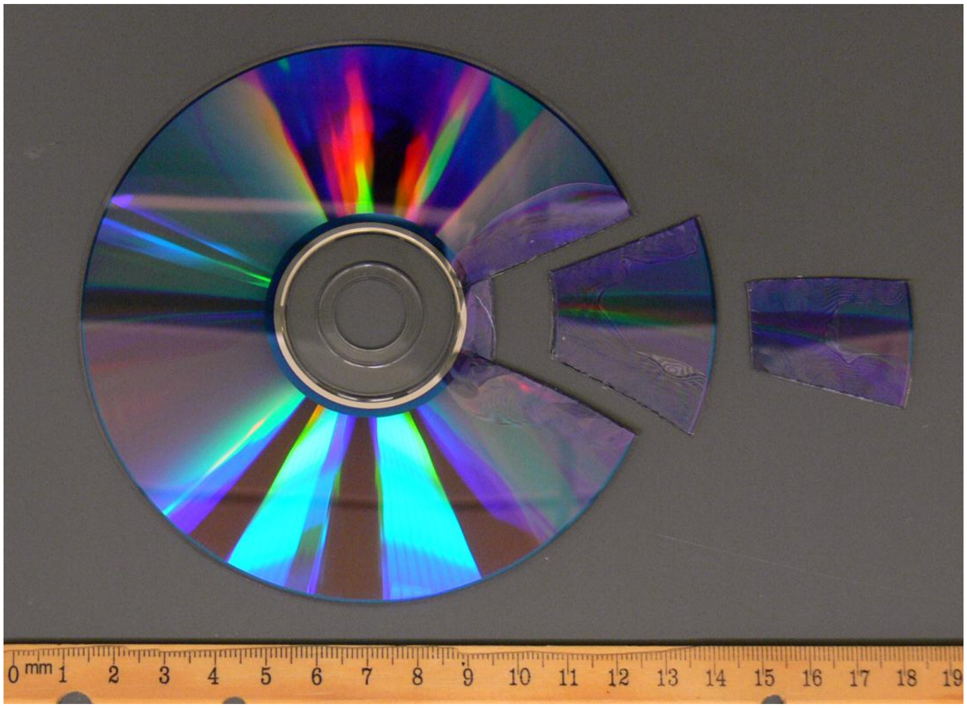

Figure S4-10. Making a diffraction grating from a standard DVD to use in the OPN Spec.

Also, as explained in the Supporting Information for the 3D-printed version of the OPN Spec (S1), given the data that we have collected, this set-up appears to be an improvement upon the OPN Colorimeter. However, the OPN Spec still does not seem to be able to select for a specific wavelength (e.g., 450 nm exactly). Instead, it appears that a wider band of wavelengths strikes the cuvette – probably due to the width of the slit in the index card that serves as the face of the cuvette holder. Nevertheless, like the OPN Colorimeter,[2] teachers and students can still use the OPN Spec for a variety of instructional and educational purposes, such as generating standard curves for a protein concentration or enzyme assay or creating a transmission spectra for certain chemicals in solution.

Assembling the OPN Spec

Once the individual components of the OPN Spec have been made, putting the three pieces together is rather simple (Fig. S4-11). Specifically, readers only need to arrange the pieces, so that a bright, tall, and wide spectrum falls on the front face of the cuvette holder (Figs. S4-1, S4-11, S4-13). Towards this end, we have found that placing the LED flashlight close to the CD or DVD and the cuvette holder roughly 5 to 15 cm (2 to 6 inches) away from the CD or DVD tends to generate useful results. Of course, the shorter the distance between the cuvette holder and the CD or DVD, the more intense the spectrum (but also the greater number of wavelengths striking the sample). On the other hand, the greater the distance between the cuvette holder and the CD or DVD, the less intense the spectrum (but the lower number of wavelengths striking the sample given the wider spectrum displayed on the front face of the cuvette holder).

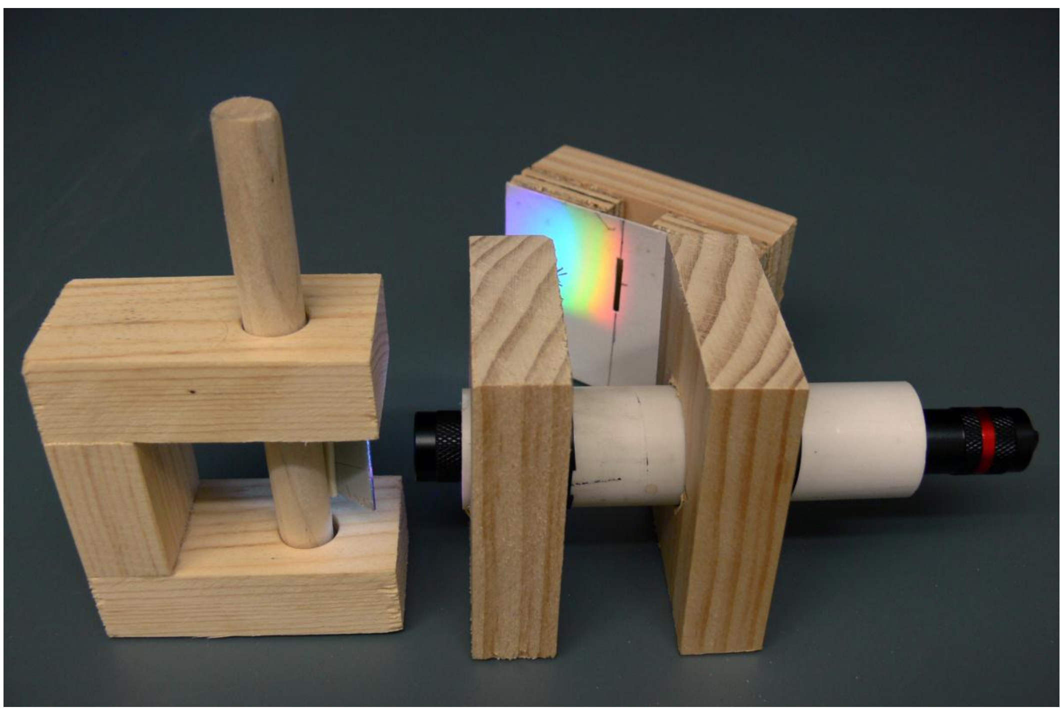

Figure S4-11. An assembled OPN Spec.

Also, intead of using wood, readers could make the components of the OPN Spec out of ¾-inch thick PVC board. For the cuvette holder, readers could cut ½-inch thick strips of PVC board in place of plywood or use a belt or disc sander to remove ¼ inch from a ¾-inch thick

PVC piece (although this approach may be rather time consuming). While readers could still use super glue, hot glue, or epoxy to hold these various pieces together, they could also use PVC cement for this purpose as well. In addition, because PVC board is often white and glossy, readers may need to coat the inside of the cuvette holder with a few layers of flat black spray paint before gluing the index card in place (in order to prevent light from reflecting off of the white PVC). While we did not find this approach necessary for the wooden models of the OPN Spec that we built, the brighter surface of the PVC may prove different.

Hazards

As explained in the Supporting Information for the OPN Scope and OPN Colorimeter,[1, 2] using hand and power tools can be very dangerous, and the associated risks of injury are as significant as they are obvious. As a result, readers should exercise a great deal of care when using any tools to build or assemble this instrument, including wearing the proper eye and ear protection. In addition, readers who are unfamiliar with these types of tools should work with an experienced craftsperson or technician for safety reasons. As an alternative, in some schools, a shop class could build a set of OPN Specs for a science class as part of a group project.

Helpful Hints

Given the similarities between the two, many of the "helpful hints" for the 3D-printed version of the OPN Spec apply to the wooden version as well. As a result, we summarize those suggestions here.

First, instructors may want to have their students use removable poster tack or mounting putty to keep each component of the OPN Spec in place during an experiment. This approach should also allow the students to move their pieces around before starting a test, enabling them to adjust the placement or intensity of the light beam striking the cuvette holder in advance. In addition, as soon as the students begin their experiment, they should not move any of the components of the OPN Spec around (or change the position of the flashlight) since even slight alternations could change the intensity or color of the light striking the cuvette and LDR, which would likely render subsequent readings incomparable to earlier ones. For this reason, instructors may want to have their students tape their flashlights into place as well before starting their assay.

Second, instead of using poster tack or mounting putty to fix the various parts of the OPN Spec in place, readers can instead use Velcro strips or Scotch Extreme ® fasteners, especially if attaching the pieces to a thin plastic sheet or wooden board. This approach may also minimize the amount of set-up time required since the components of the OPN Spec would already be placed in their desired locations. Of course, instructions should still test out the placement of these parts ahead of time to make sure that their arrangement will lead to useful test results for the students.

Third, to project a fairly tall and wide spectrum on the front face of the cuvette holder, readers should place their flashlights up close to the CD or DVD (Fig. S4-12). Readers should also place the cuvette holder at least 5 cm away from the center of CD or DVD since this distance tends to allow for a bright light to strike the cuvette (Figs. S4-1, S4-11). Alternatively, readers can place the cuvette holder further back (e.g., 10 or 15 cm away from the CD or DVD), which should broaden the spectrum that strikes the face of the cuvette holder (and, thus, make it easier for students to "dial in" a narrower band of wavelengths). In addition, before beginning an experiment, readers should position the cuvette holder so that the light beam directly strikes the LDR. While readers can typically see the final location of the beam by looking into an empty cuvette chamber, they can also slide a small rectangular piece of white paper into the chamber to see where the light falls.

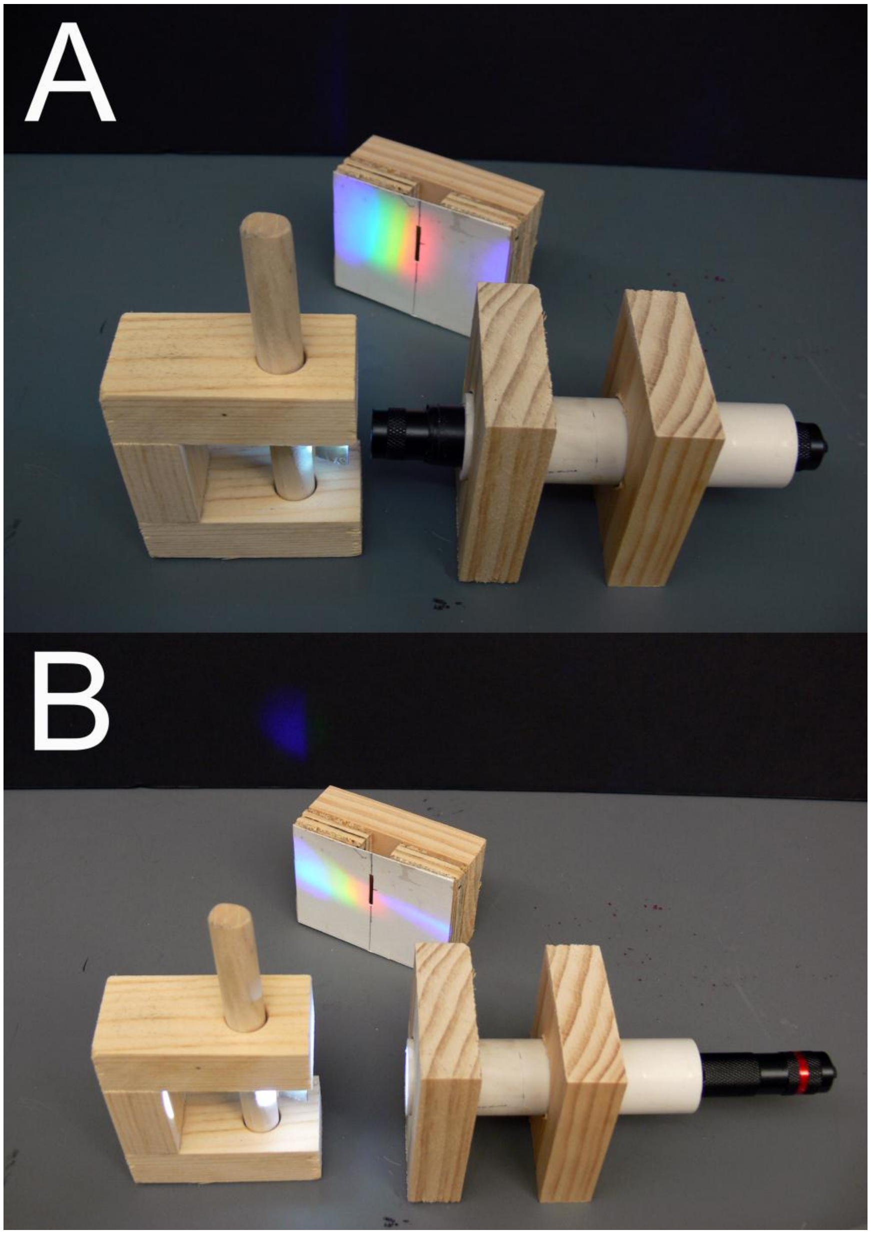

Figure S4-12. Placing the flashlight up close to the CD or DVD generates a tall and wide spectrum (A) while moving the flashlight further away from the CD or DVD generates a shorter spectrum (B).

Fourth, although the design for the cuvette holder described above generates useful results for in-class demonstrations or educational activities in a teaching lab, we have found that using only an index card as the front face of the cuvette holder may allow some ambient light to pass through the sample, which can lead to elevated Absorbance readings at times. For example, if generating a simple Absorption spectrum for Methylene Blue, using an index card as the front face of the cuvette holder appears to increase the Absorbance readings for the "lower" wavelengths (i.e., blue, indigo, and violet) possibly due to the presence of "higher" wavelengths (yellow, orange, and red) contained in the ambient light passing through the paper face and striking the sample (Fig. S4-13). As a result, readers may want to turn off the overhead lights in the classroom or lab when using the OPN Spec and light the room with a faint white light (e.g., a clear 25-W bulb) instead as long as this approach did not create any safety issues with the demonstration or exercise. Alternatively, readers could make a front piece for their cuvette holder out of ¾-inch thick wood with a ½-inch diameter hole placed in the same location as the hole in the back piece, which should cut down on the amount of ambient light passing through the index card (Fig. S4-13).

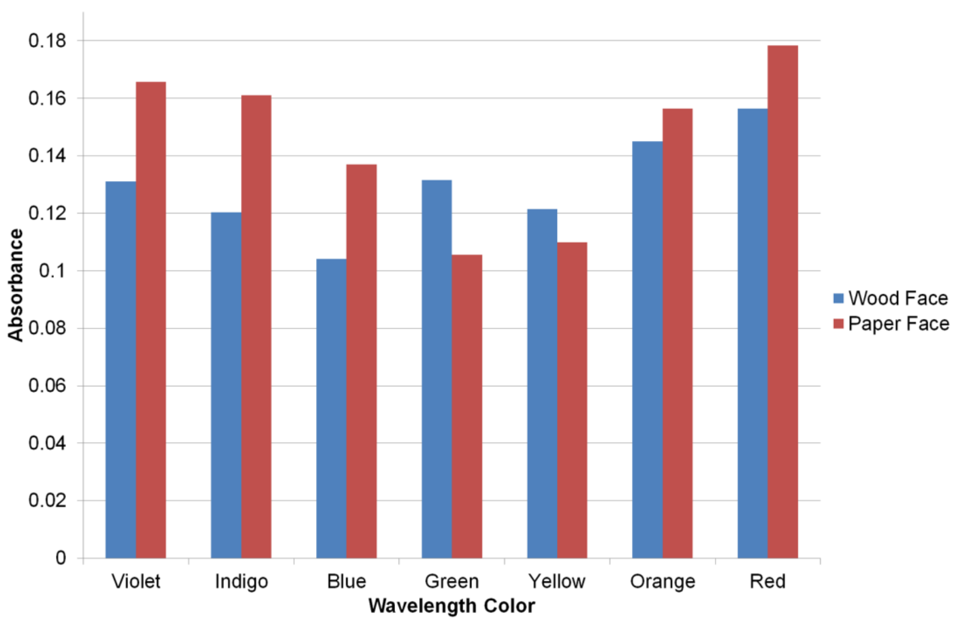

Figure S4-13. The effect of adding a ¾-inch thick wooden face to the cuvette holder of the wooden OPN Spec. The graph shows an Absorption spectrum for 40 µL of Methylene Blue (100 mg/L) in 3 mL of deionized water (DI H_2O) determined using different two cuvette holders in the wooden version of the OPN Spec. The first cuvette holder (blue columns) included a 3/4-inch thick wooden face with an index card containing a slit attached to it. The second cuvette holder (red columns) contained only a paper face made from an index card with a slit cut into it. Note how the "lower" wavelengths (violet, indigo, and blue) have a higher Absorbance reading when the cuvette holder with the paper face is used – likely due to the presence of "higher" wavelengths (yellow, orange, and red) in the ambient light passing through the paper and into the sample contained in the cuvette. .

Fifth, for related reasons, readers can make a lid to cover the cuvette in the wooden version of the OPN Spec, which may help to further reduce the amount of ambient light striking the cuvette (and, thus, lead to Absorbance readings that are more in line with the trends or results that one would expect in these types of experiments, especially if generating an Absorption spectrum as part of a classroom demonstration or during a lab exercise; Fig. S4-14). We therefore describe two relatively simple ways to make a wooden lid for the cuvette holder.

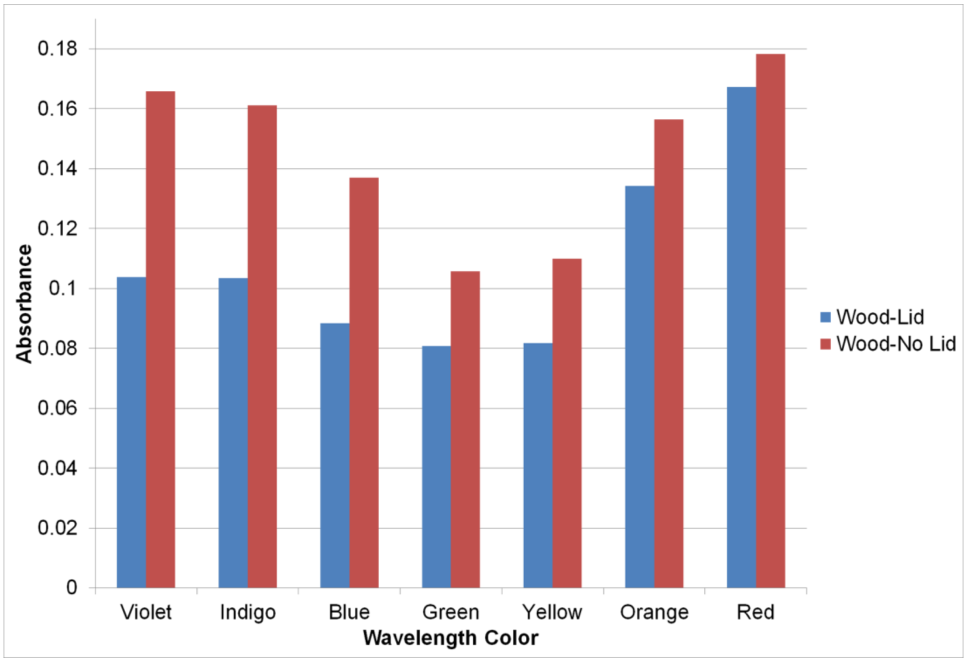

Figure S4-14. The effect of using a lid to cover the cuvette in the wooden OPN Spec. The graph shows an Absorption spectrum for 40 μL of Methylene Blue (100 mg/L) in 3 mL of deionized water (DI H_2O) determined using a lid (blue columns) or no lid (red columns) in the wooden version of the OPN Spec. Note how the "lower" wavelengths (violet, indigo, and blue) have a higher Absorbance reading when no lid is used – possibly due to the presence of "higher" wavelengths (yellow, orange, and red) in the ambient light striking the solution.

One approach would be to use the method described in our OPN Colorimeter paper and cut roughly ¼ to ½ of an inch from the "top" of the plywood piece that holds the cuvette before gluing all of the pieces together.[2] Readers could then make a corresponding lid for the cuvette out of ½-inch thick plywood (Fig. S4-15A), which should slide nicely into place.

Alternatively, readers can leave the small piece of plywood entact, cut a lid for the cuvette, and then cover the front and back sides of the lid with electrical tape to keep out any light (Fig. S4-15). In addition, readers can use smaller rectangular pieces of electrical tape (with the smooth side facing towards the cuvette) to prevent the larger pieces of electrical tape from sticking to the cuvette (Fig. S4-15B).

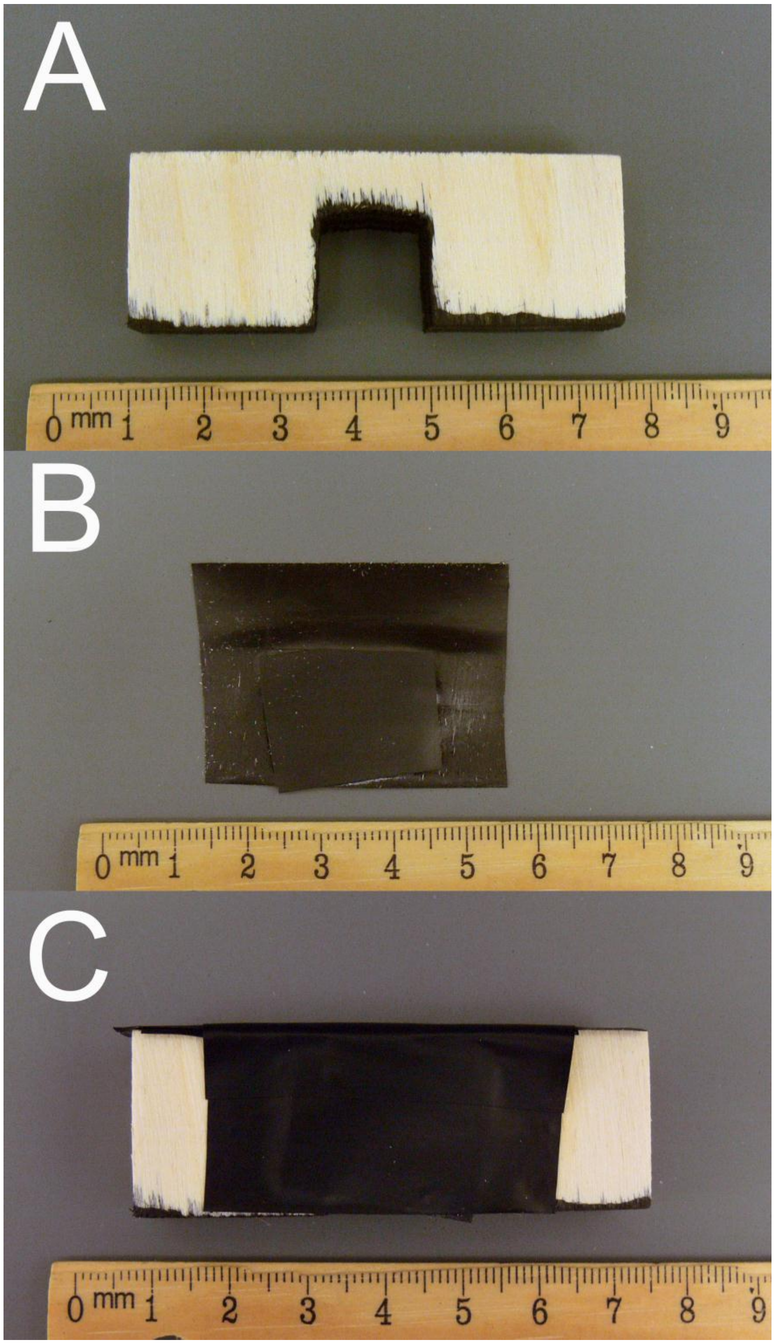

Figure S4-15. Making a lid to cover the cuvette in the OPN Spec.

Otherwise, many of the other "Helpful Hints" for using the wooden version of the OPN Spec are similar to those for the OPN Colorimeter.[2] For convenience, we summarize those suggestions below.

Importantly, readers should turn on their flashlights and multimeters at least 10 minutes before beginning an experiment to let these devices warm up and stabilize. During this time period, readers should further record and graph the output of their resistance values to determine how much warm-up time is actually necessary. Depending upon these results, readers may want to have their students do the same before beginning their lab exercises.

In addition, like the OPN Colorimeter,[2] readers may need to use “jumper wires” with “alligator clips” on them to connect the leads of their LDRs to the probes on their multimeters (Fig. S4-16).

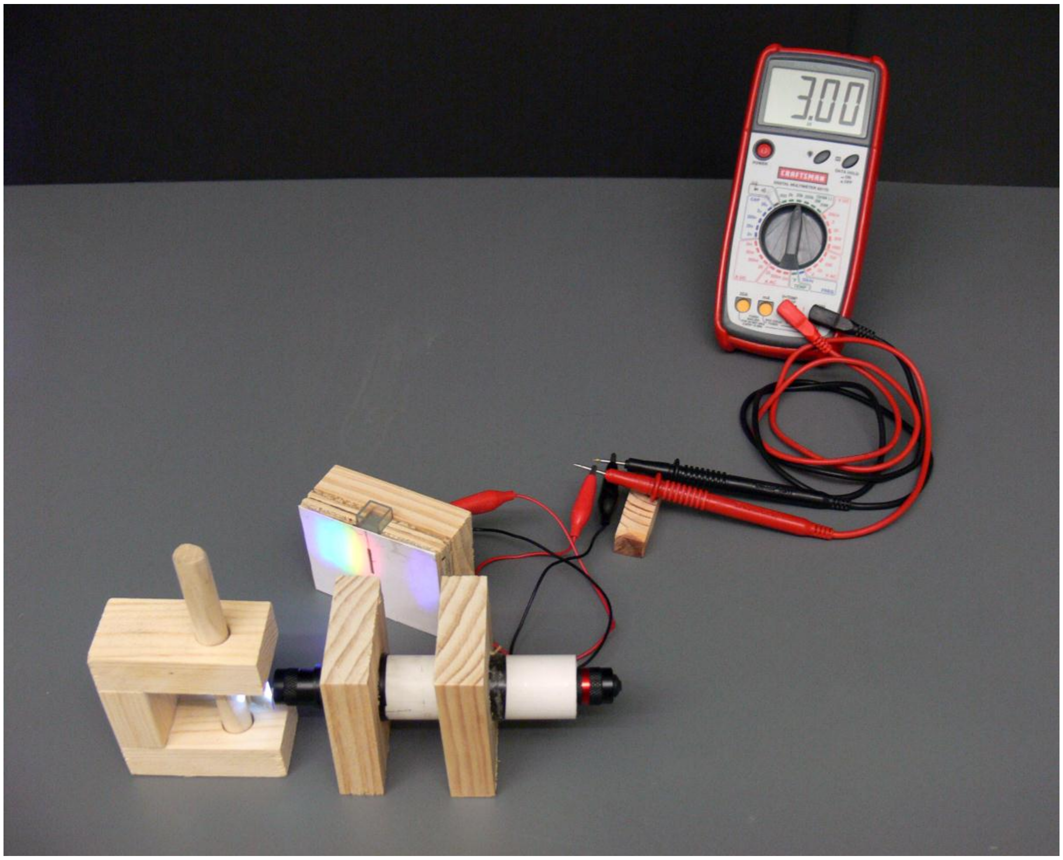

Figure S4-16. Connecting the probes of a digital multimeter to the leads of a light dependent resistor (LDR) using jumper wires with alligator clips.

Instructors should also make sure that the placement of the various components of the OPN Spec results in an initial reading on the multimeter that will lead to useful results as their experiment progresses. For example, in the various Methylene Blue assays that we conducted (S5 and S6), we found that an initial reading between 2 and 300 kOhms for an empty chamber (depending on the test) generated useful as data as the experiment progressed. Of course, if using different LDRs or LED flashlights than the ones listed above (or a different chemical assay than the one outlined in Supporting Information S5 and S6), then readers might obtain different initial values. For this reason, we recommend that instructors run a series of pilot tests with their experimental set-up in advance to understand the types of resistance values that students should obtain during the exercise.

Readers should additionally note that the resistance of the PDV-P8103 photocell is inversely proportional to the intensity of the light striking it. As a result, the correct formula for measuring Absorbance (A) with this set-up is $A = \log_{10}(T/I)$ without a negative sign in the equation.[2] In this equation, T denotes the intensity of the transmitted light passing through the cuvette and I denotes the intensity of the incident light striking the cuvette (as measured by the resistance value for an empty chamber).

Finally, as with the wooden version of the OPN Colorimeter,[2] when drilling holes through any of the wooden pieces, readers should consider putting a piece of scrap wood underneath the one that they are drilling to avoid chipping or cracking the back of the top piece. In addition, although readers can use standard "twist" bits to drill at least some of these holes, "paddle" bits or "Forstner" bits may work better since they are specifically designed for drilling holes into wood.[2]

References

(1) Stewart, C.; Giannini, J., Inexpensive, open source epifluorescence microscopes. *Journal of Chemical Education* **2016,** 93, (7), 1310-1315.

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