A Low-Cost Quantitative Absorption Spectrophotometer

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ABSTRACT

This document provides detailed information about the construction and use of the low-cost quantitative absorption spectrophotometer. Table 1 lists all of the construction materials, their cost, and provides hyperlinks to suppliers' websites (accessed June 2012).

Table 1: Construction Materials

Item	Supplier	Part Number	Hyperlink	Cost
LED	Super Bright LEDs	RL5-W18015	LED	$1
Photodiode[a]	Excelitas Tech	VTB8441BH	Photodiode	$4.10
Lens	Edmund Scientific	DCX 50 mm FL	Lens	$2.95
Grating	Edmund Optics	NT01-307	Grating	$1
Multimeter	Cen-Tech	90899	Multimeter	$4.99
Plastic cuvette	Various	Various	Plastic cuvette	$0.15
Hinge	Various	Various	Hinge	$1
Building bricks	LEGO	Various	Baseplate Blocks	~$7
Batteries	Various	AA	AA Batteries	~$1
Battery Holder	Digi-Key	BC3AAW-ND	Battery Holder	$1.27
Protractor	Printable Protractor	________	Printable Protractor	_______
Electrical Tape	Various	Various	Electrical Tape	~$0.05
Double-Sided Tape	Scotch	1/2″ Wide	Double-Sided Tape	~$0.10
50 Ω Resistor	Newark	65K2403	Resistor	$0.30
5-minute Epoxy	Hardman	04001	Epoxy	~$0.20
Insulated Wire	Newark	33C7334	Insulated Wire	~$0.50

a) The photodiode used in the prototype includes casing and electrode wires. Less expensive photodiodes (e.g. Vishay TEMD6200FX01 and Vishay TEMD5510FX01; $0.79 and $1.60 respectively) without casing or wires should behave similarly, and could be used after soldering wires to the electrodes.

1. Light Source:

Components: Super Bright LEDs RL5-W18015, 50 Ω Resistor, AA Batteries (3 ea.), Battery Holder, 4x2 blocks (2 ea.), 4x1 blocks (2 ea.)

The Light-Emitting-Diode (LED), obtained from Super Bright LEDs (Part number RL5-W18015), had design specifications of 3.5 V and 20 mA. Performance using two AA batteries in series (3.0 V) was marginal, while three AA batteries (4.5 V) alone caused irreversible damage. Optimal performance was obtained using 3 AA batteries wired in series with a current-limiting resistor (50 Ω), as shown in Figure 1. Electrical connections can be made by soldering, twisting, or clamping the wires. Typical AA batteries have a capacity >1000 mAh, allowing >50 hours of operation.

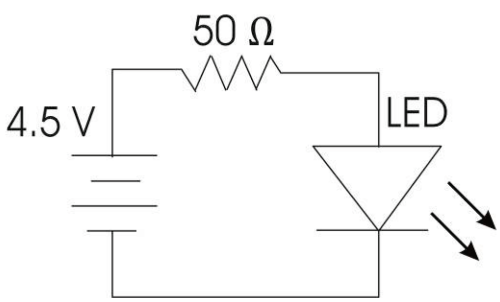

Figure 1: LED circuit diagram for 3.5 V operation at 20 mA. The LED is sensitive to battery polarity.

The LED mount was constructed by stacking two 4x2 blocks, and then placing one 4x1 block on top. The LEGO block dimensions are shown in Figure 2. The LED was secured by clamping its leads between the top 4x1 block and another 4x1 block (Figure 3).

The light source was positioned at the end of a 5″ wide x 10″ long LEGO baseplate, as shown in Figure 3c. The position and aiming of the LED was adjusted by gently bending its leads until it was centered at a height of 3.5 LEGO units above the baseplate. The light path must also be horizontal, i.e., parallel to the baseplate. The center of the LED, and the emerging light beam, defines the optic axis of the spectrophotometer. The height of the optic axis is 3.5 LEGO units above the baseplate. The horizontal location of the optic axis lies halfway between the third and fourth LEGO knobs, as measured from one of the 10″ long edges of the baseplate.

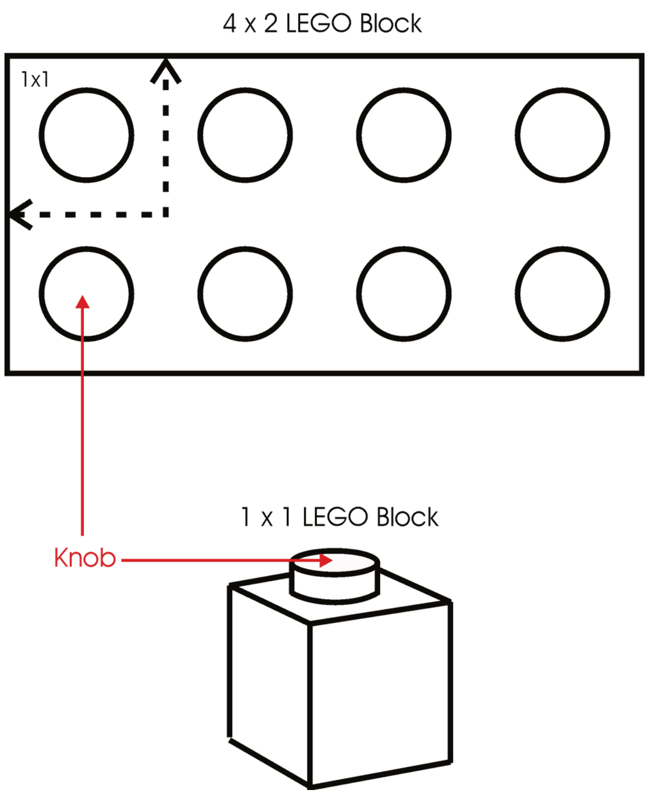

Figure 2: Top view of a 4x2 block and side view of a 1x1 block.

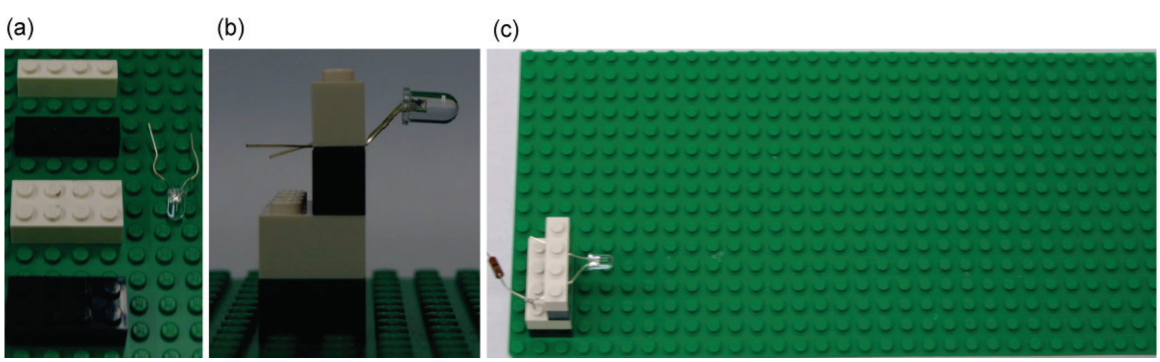

Figure 3: Light source construction (a) components for light source (b) assembled light source (c) placement of light source on baseplate.

2. Lens Assembly:

Components: 50 mm focal length lens, 2x1 blocks (4 ea.), 6x1 blocks (3 ea.), Electrical Tape

The lens support was constructed by stacking three 6x1 blocks and then stacking two 2x1 blocks on each end (Figure 4). The lens was centered exactly on the optic axis at a distance of 2″ from the LED to collimate light from the LED. It was secured with electrical tape, as shown in Figure 4.

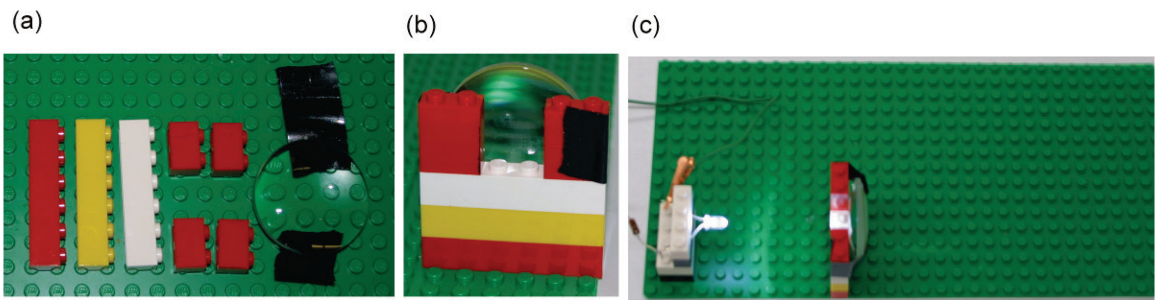

Figure 4: Lens assembly construction: (a) components for lens assembly (b) constructed lens assembly (c) placement of lens assembly on baseplate.

3. Cuvette Holder:

Components: 4x2 blocks (3 ea.), 2x2 blocks (4 ea.), 2x1 blocks (12 ea.), 1.3″ x 0.45″x .05″ thick cardboard shims (2 ea.), 0.65″ x 0.45″ x 0.05″ thick cardboard shims (2 ea.), double-sided tape

Two of the sidewalls of the cuvette holder were each constructed by stacking four 2x1 blocks and taping (with double-sided tape) one 1.3″ x 0.45″ cardboard shim to the stack (Figure 5). The two smaller sidewalls of the cuvette holder were each constructed by stacking two 2x1 blocks and taping one 0.65″ x 0.45″ cardboard shim to the stack (Figure 5).

The cuvette holder was assembled by placing a taller sidewall on each end of a 4x2 block and positioning the smaller sidewalls on separate 4x2 blocks with the cardboard shims facing each other (Figure 5).

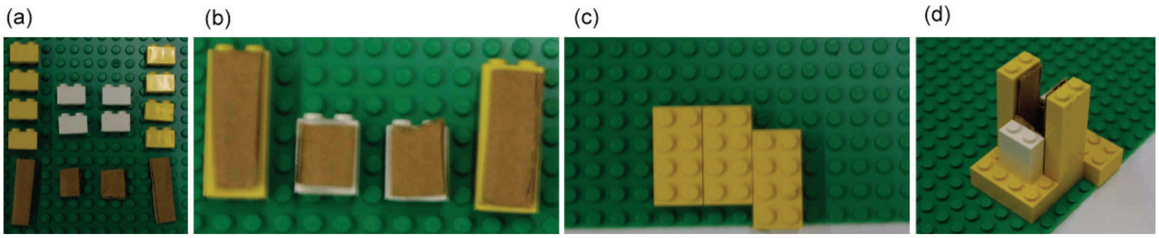

Figure 5: Cuvette Holder Assembly (a) sidewall components (b) assembled sidewalls (c) base for sidewalls (d) assembled cuvette holder.

The cuvette holder was completed by stacking four 2x2 blocks and placing them on the base of the cuvette holder (Figure 6). The stack of four 2x2 blocks is later used to mount the exit aperture. The cuvette holder was positioned on the baseplate with the front edge of the cuvette holder touching the back edge of the lens assembly. The light opening for the cuvette was centered between the third and fourth knobs from the edge of the baseplate (Figure 6c).

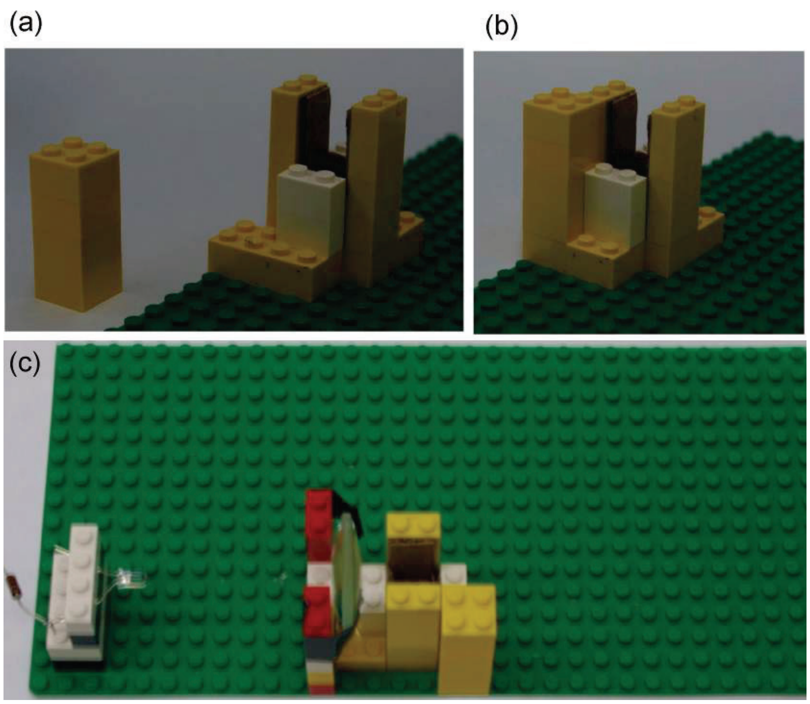

Figure 6: Cuvette holder assembly and positioning: (a) stack of four 2x2 blocks and cuvette holder (b) stack of four 2x2 blocks was added to cuvette holder (c) placement of cuvette holder on baseplate.

4. Rotatable Detector Arm:

Components: Photodiode (Excelitas Tech VTB8441BH), 4x2 blocks (10 ea.), 2x2 blocks (4 ea.), 2x1 block (2 ea.), hinge (1 ea.), 5 minute epoxy.

The detector arm was constructed using seven 4x2 blocks and two 2x2 blocks. The completed arm was 16 units long, two units wide and two blocks high (Figure 7a). The hinge mount was assembled by stacking three 4x2 blocks and then gluing one side of the hinge to the stack with 5-minute epoxy. Care must be taken in the gluing process to ensure that the arm will be aligned with respect to the optic axis and that no epoxy clogs the area near the hingepin. The pivot of the hinge must be aligned with the edge of the stack (Figure 7b). We found it convenient to glue the hinge in two steps, i.e., in the first step, the hinge was glued to the hinge mount and the epoxy was allowed to cure. In the second step, the arm was glued to the hinge. To help ensure good alignment in the second step, the hinge assembly was placed on the base plate and the arm was positioned (elevated one unit from the base plate by temporarily attaching a few 2x1 blocks underneath the arm) at a 90º angle with respect to the hinge assembly (Figure 7). The free side of the hinge was then glued to the arm. After the epoxy cured, the hinge assembly was removed from the baseplate.

We understand that LEGO manufactures hinges which might be used in place of the steel hinge described here. This would require purchasing a more extensive (and expensive) LEGO set.

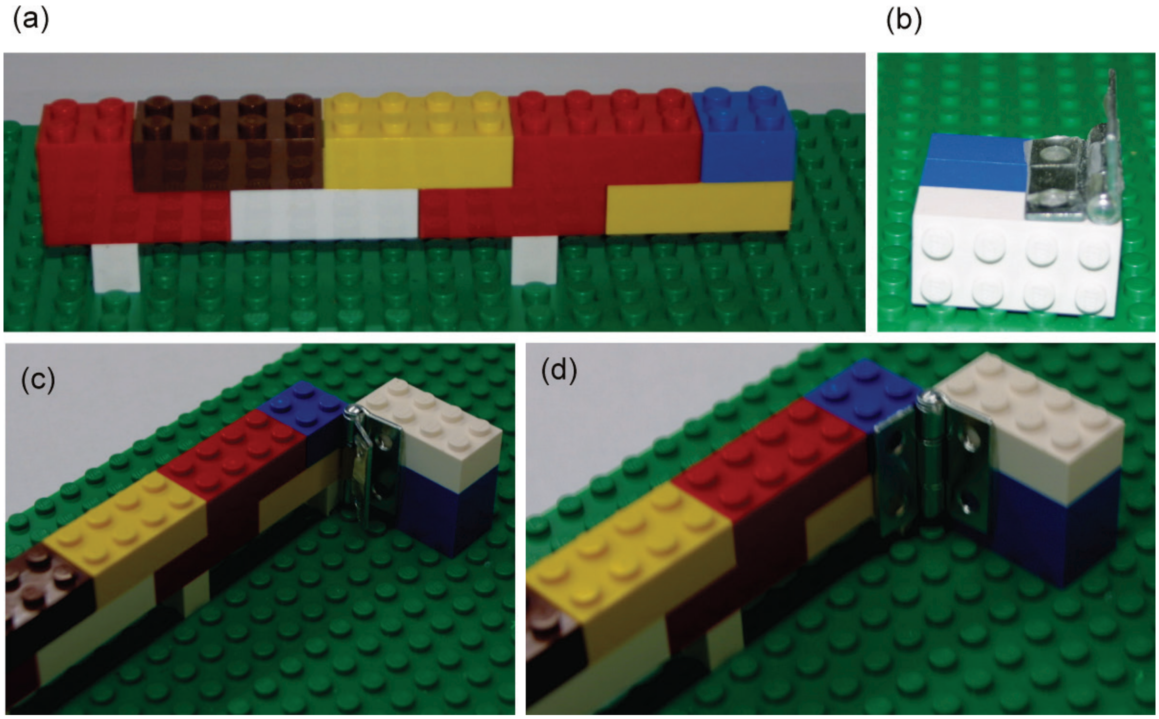

Figure 7: Assembly of the rotatable detector arm (a) detector arm (b) hinge mount assembly (c) positioning the arm and hinge mount for attaching the hinge to the arm (d) gluing the hinge to the arm.

The photodiode was attached to a 1x1 block with epoxy (Figure 8). Insulated wires (24″ long) were soldered to the photodiode leads to allow the arm to rotate while the multimeter remains fixed. The photodiode active area was centered at the end of the arm. With the detector arm at zero degrees, the active area must lie on the optic axis. One 2x1 block was mounted to the bottom of the rotatable arm to keep the detector at a constant height, i.e., 3.5 blocks above the base plate, as it is rotated (Figure 8). A stack of two 2x2 blocks was placed on top of the hinge mount to provide a surface for later taping the exit aperture and grating. The rotatable arm assembly was then added to the base plate (Figure 8).

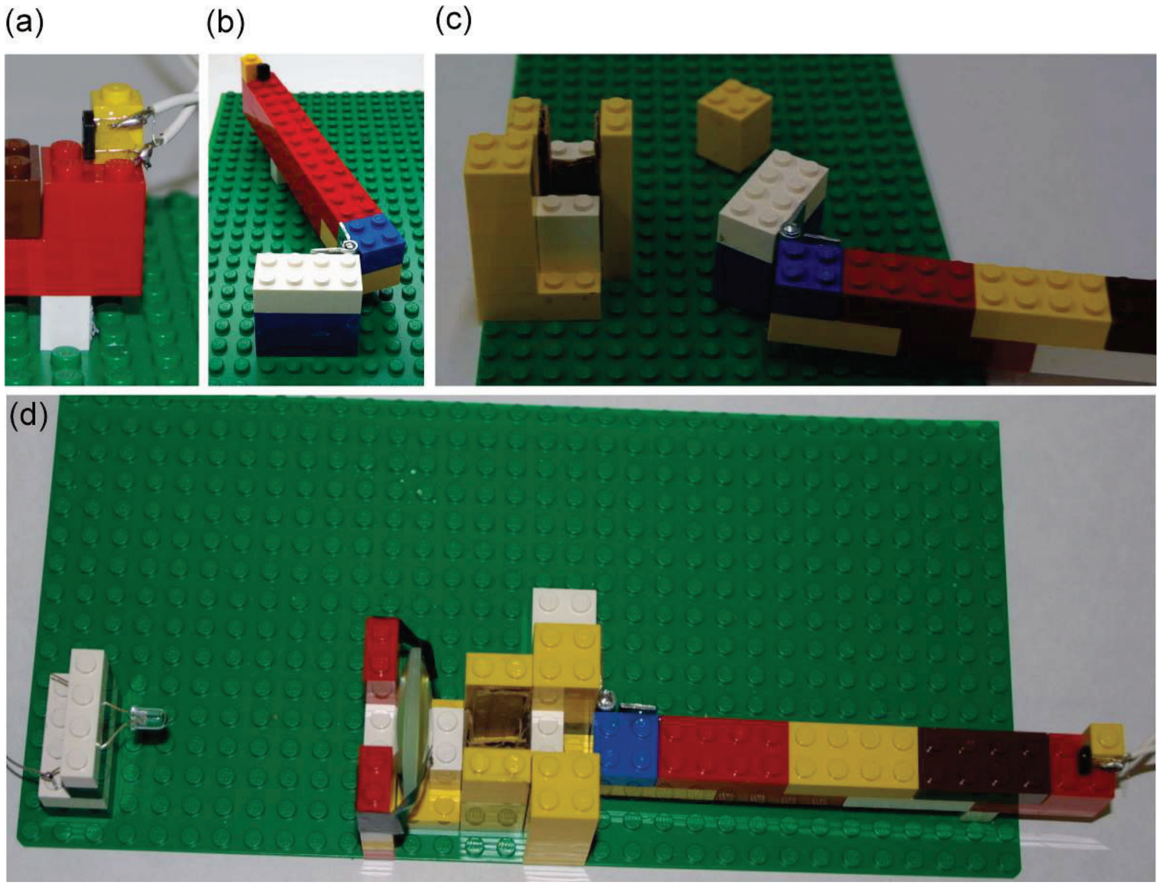

Figure 8: Rotatable detector arm assembly and positioning: (a) photodiode attached to a 1x1 block (b) assembled rotating arm (c) positioning rotating arm, stack of two 2x2 blocks was placed on hinge mount (d) installation of rotating arm on baseplate

5. Apertures and Grating:

Components: 1x1 block (2 ea.), Diffraction grating, 2 cardboard apertures (template provided), electrical tape

Defining apertures were employed to further collimate the light beam, thereby increasing the spectral resolution. The defining apertures (available as a template at the end of this document) were constructed from cardstock. Both slits were 0.15″ wide. The wider aperture was taped to the entrance of the cuvette holder and the narrower one was taped to the exit of the cuvette holder. The slits in both apertures were carefully centered on the optic axis and secured with electrical tape. A 1x1 block was placed on top of both sides of the cuvette holder to secure the exit aperture (Figure 9).

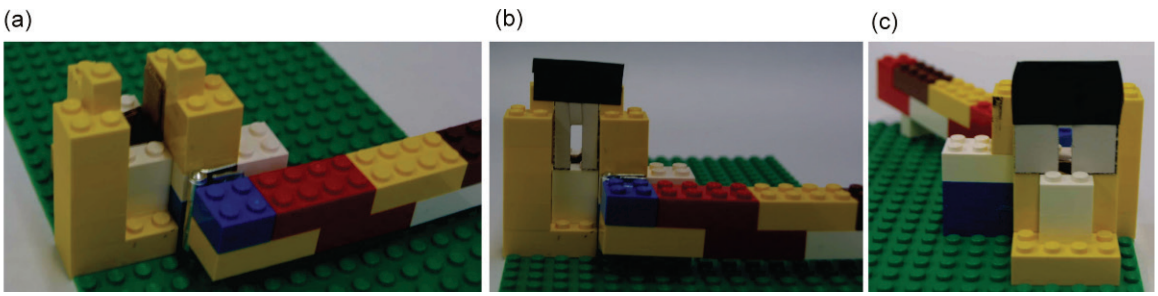

Figure 9: Installation of apertures (a) two 1x1 blocks were used to secure the exit aperture (b) installing the exit aperture (c) installing the entrance aperture.

One side of the cardboard grating mount was trimmed by ~0.2″ to allow the grating to be aligned with respect to the optic axis. The grating was secured to the outer edge of the cuvette holder, located two LEGO units away from the cuvette and positioned to diffract light in the horizontal plane (i.e., in the plane of rotation of the arm). Since only a small portion of the grating was needed, the remainder was covered with electrical tape to help reduce scattered light (Figure 10).

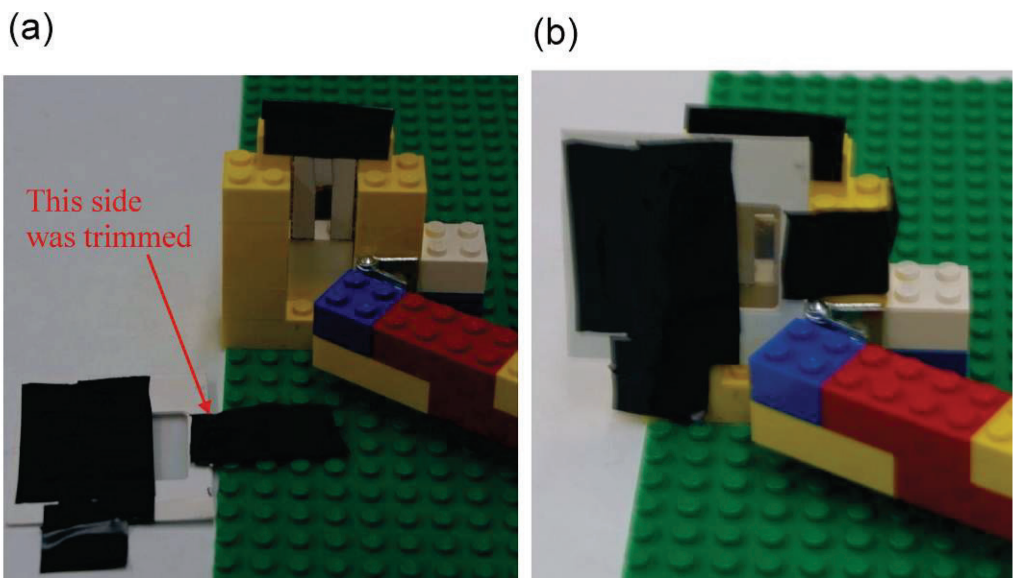

Figure 10: Diffraction grating installation: (a) preparing grating for installation (b) installed grating.

6. Operation:

The detector angle was measured with a protractor. A printable protractor, available via the link in Table 1, may be used to minimize cost. Two 2x2 blocks were positioned to ensure the protractor was parallel to the sample cell and grating (Figure 11). The vertex of the protractor was placed directly below the leading edge of the rotatable arm. The angle between the photodiode and optic axis is the angle of diffraction, θ. This angle corresponds to a specific wavelength according to the Fraunhofer diffraction formula (equation 1):

$$n\lambda = d \sin\theta \qquad (1)$$

In equation 1, n is the grating order (here n = 1), the desired wavelength is λ and the grating spacing is d. For a 1000 line/mm grating ($d = 1.0 \times 10^{-6}$ m), orange light (λ = 589 nm) was diffracted at $\theta = 36^{o}$.

To ensure that all of the components are properly aligned the angle of the narrow orange band (λ=587-591 nm) from a white LED was observed at $\theta = 36^{o}$ as illustrated in Figure 11b. As long as the orange light arrives within one degree of the expected angle, the alignment should be sufficient for obtaining accurate absorbance measurements

(a) (b)

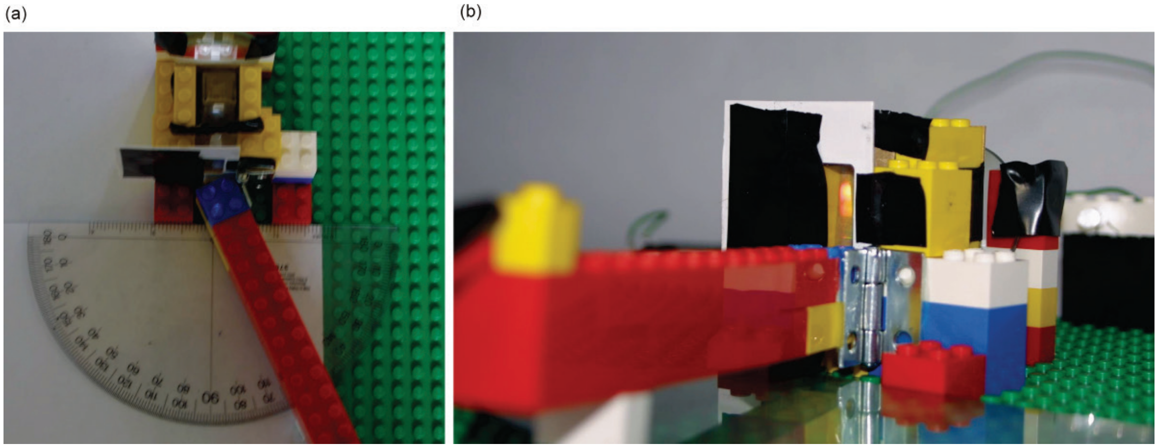

Figure 11: (a) A protractor was used to measure the detector angle. (b) Orange light (λ ~ 589 nm) is visible on the grating over a small range of angles and was used to check alignment.

When measurements were taken for a given wavelength, the arm was secured in place by positioning two sets of two 2x1 blocks on either side of the rotatable arm (Figure 12).

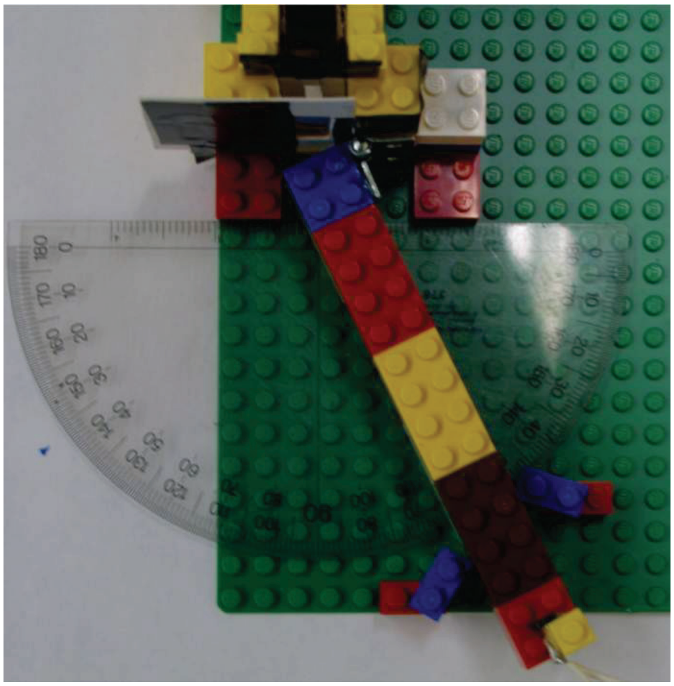

Figure 12: The detector arm was secured during measurements using the blue and red 2x1 blocks at the bottom of the image.

After the detector was secured at a given angle, three measurements (reference, sample and dark) were taken to determine the absorbance at that wavelength. The reference signal was measured by filling the cuvette with the solvent used to dissolve the dye or indicator of interest, placing it in the cuvette holder, and recording the voltage on the multimeter. The cuvette was then rinsed, filled with the sample of interest, placed back in the cuvette holder and another voltage reading was recorded. To improve the precision of measurements, it is important that the cuvette be placed in the holder with the same orientation and position for each measurement. A marker can be used to denote the front of the cuvette in order to help ensure reproducible orientation of the cuvette. The dark signal was measured by taking a voltage reading with the cuvette filled with milk or some other non-transmitting liquid. The absorbance of the sample is given by Equation 2,

$$A = \log_{10}\left(\frac{V_0 - V_d}{V - V_d}\right) \qquad (2)$$

where V_0 is the reference, V is the sample, and V_d is the dark signal. At any given angle, the dark signal and reference signal only needed to be measured once, assuming the output of the LED was constant over the course of the experiment. Whenever the angle of the detector was changed, the dark and reference samples were recorded.

Stray light was found to cause substantial background signals. To block stray light from reaching the LED, a piece of cardboard or a wall built from blocks was positioned between the LED and the detector on the side of rotation (Figure 13). To eliminate background from room light, some of the room lights were turned off or the spectrophotometer was covered with a shoebox (15″ x 8″ x 4″). When the box was used to eliminate room light, a piece of cardstock was placed over the LED, lens mount, and cuvette holder to prevent light from scattering off the inside top of the box and reaching the detector (Figure 13b). By following these procedures, it was possible to obtain quantitative data with the low-cost spectrophotometer shown in Figure 14.

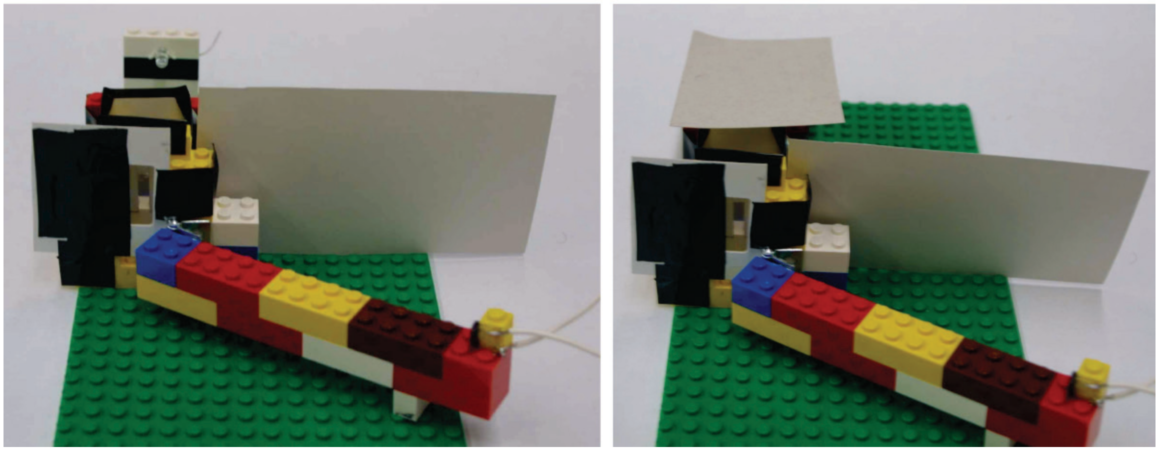

Figure 13: Pieces of cardstock were used to prevent stray light from reaching the detector: (a) wall to block stray light (b) wall to prevent light from scattering off of the top of the cardboard box.

(a)

(b)

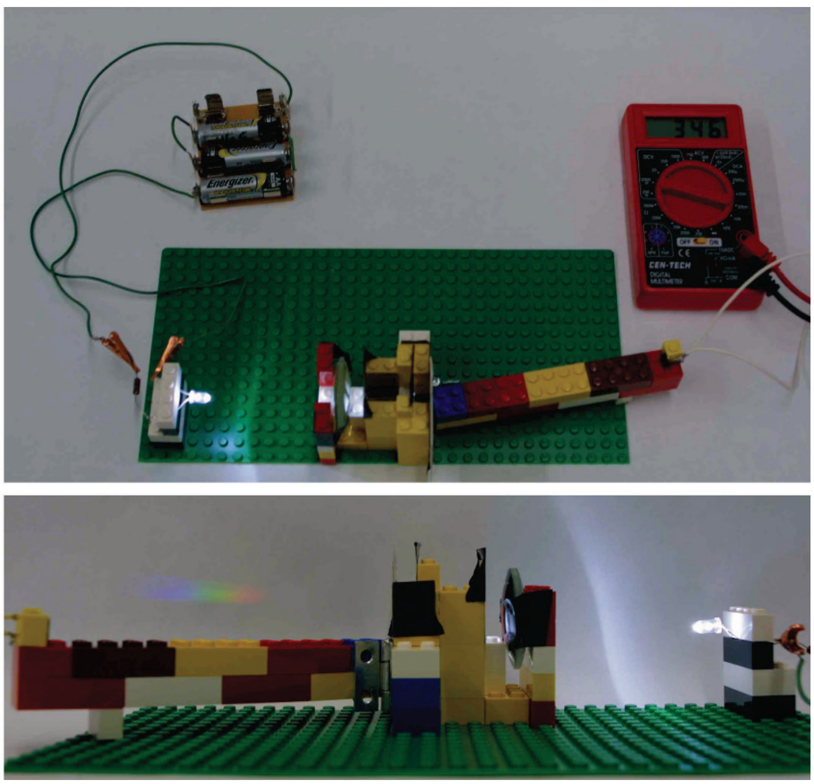

Figure 14: Completed spectrophotometer: (a) Top View (b) Side View, notice that all components are centered 3.5 units above the baseplate.

7. Acknowledgments:

The authors would like to thank members of the Cornell University lab services for supplying the materials used in testing the apparatus. This material is based upon work supported by the National Science Foundation under Grant No. CHE-0809622.

8. Aperture Template:

Cut out and then cut along the dotted lines and tear off or fold up the resulting flap.