



3-D Printing

Description:

The students design and produce a three-dimensional object using a PowerPoint slideshow, a data projector, and a photoreactive polymer.

Prerequisites:

None

Instruction Time:

Two to five class periods The first period is for the PowerPoint presentation, and the rest are for designing and “printing” the three-dimensional objects.

Audience:

High School Science or Technology

Lesson Objective:

Students will develop an understanding about the relationships between science and engineering.

National Science Education Standards:

Content Standard A: Abilities Necessary To Do Scientific Inquiry.

Content Standard E: Understandings about Science and Technology.

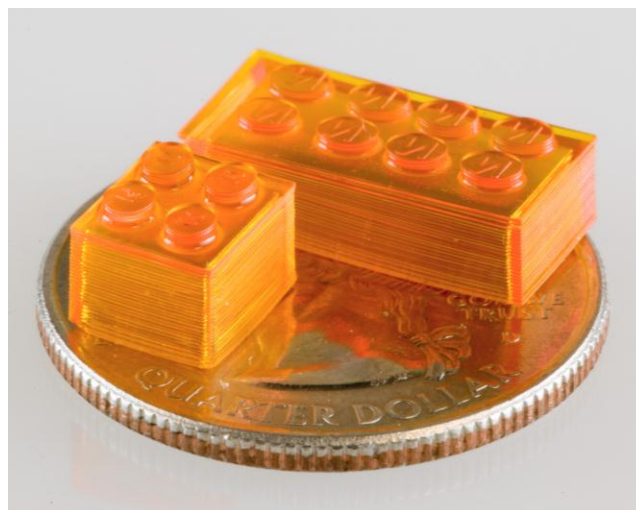
Illinois State Learning Standards:

11.B.5a Identify a design problem that has practical applications and propose possible solutions, considering such constraints as available tools, materials, time and costs.

12.C.5b Analyze the properties of materials in relation to their physical and/or chemical structures.

13.B.5b Analyze and describe the processes and effects of scientific and technological breakthroughs.

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Instructional Method:

The instructor gives a presentation on microstereo lithography. Students design computer images to create a three-dimensional object. Students then use photoreactive polymer and their computer images to create an actual three-dimensional object.

Background Information:

This lab uses a process based on a research project headed by Professor Nicholas Fang and developed at the Nano-CEMMS center at the University of Illinois. Dr. Fang's research group uses a UV sensitive monomer to do a form of three-dimensional printing called microstereo lithography. Using a video projector with a UV output, they are able to create incredibly thin polymer layers (on the order of 400 nm) and build objects layer by layer. This activity demonstrates the basic challenges of nanoscale engineering and manufacturing by using the same principle at a much larger scale.

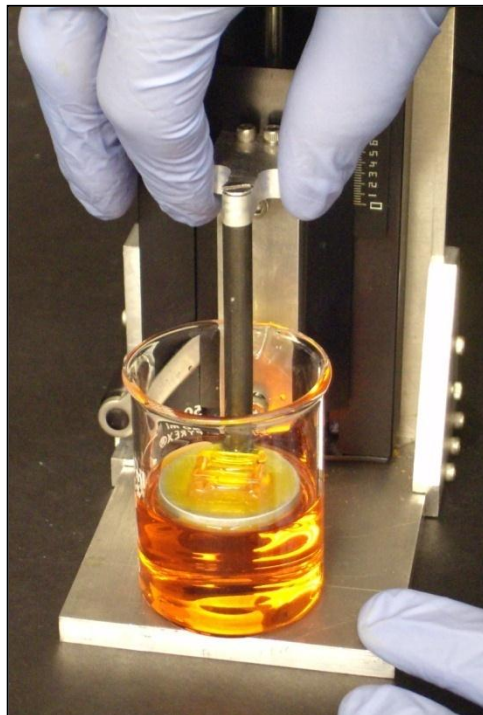
The reaction will occur with white light from a regular video projector. The light initiates a photochemical reaction by cleaving a molecule to form free radicals. The free radicals polymerize a monomer through an addition polymerization reaction. The reaction polymerizes the solution, becoming solid only where the white light is projected. Elsewhere it remains an unreacted liquid.

The photosensitive monomer Polyethylene Glycol Diacrylate (PEG) works under the process of addition polymerization. The photoinitiator, Phenylbis (2,4,6-trimethylbenzoyl)phosphine oxide, (Irgacure 819) absorbs UV-wavelength photons and produces free radicals. These free radicals react with the monomers (HDDA or PEG) to cause chain propagation, polymerizing the monomer.

Successive layers are made by lowering the polymerized shape into a beaker of the solution. A thin layer of fresh solution flows over the top, and light is again projected to solidify portions of the fresh layer. This is repeated, creating a three-dimensional object layer by layer.

Overview:

In this lab, students make a three-dimensional object of their own design. A photoreactive mixture of chemicals polymerizes when exposed to ultraviolet light, leaving nearby polymer unreacted. Using PowerPoint and a data projector, one can create different shapes by shining the light of the data projector into a beaker of the photoreactive polymer. PowerPoint allows black and white cross sections to be designed in a user friendly interface that is available on most computer systems. Adding an ultraviolet absorber prevents the light from penetrating into the polymer more than a fraction of a millimeter. By continually lowering the previous layer of hardened polymer into the beaker, a three-dimensional object is made one cross-sectional layer at a time.





Materials:

- Polyethylene glycol diacrylate (CAS: 26570-48-9)
- Phenylbis(2,4,6-trimethylbenzoyl)-phosphine oxide (CAS: 162881-26-7)
- Sudan I (CAS: 842-07-9)
- 100 mL amber bottle
- Balance
- Weighing paper
- Spatula
- Stir plate and stir bar
- 50 mL beaker
- Data Projector
- Computer (with PowerPoint)
- Magnifying glass
- First surface mirror
- Ring stands, clamps, and clamp holders
- Staging device*



Safety:

Goggles and aprons should be worn as in all chemistry laboratory activities. Staring at a white data projector image can cause damage to eyes.

Chemical Safety:

- Polyethylene glycol diacrylate (CAS: 26570-48-9) – Irritating to eyes and skin.
- Irgacure 819 *phenylbis(2,4,6-trimethylbenzoyl)-phosphine oxide* (CAS 162881-26-7) – Skin sensitizer, avoid contact with skin, eyes, and clothing. Do not inhale.
- Sudan I (CAS 842-07-9) – May cause skin irritation by contact, limited evidence of a carcinogenic effect.

Preparation:

Before printing an object, three things need to be done:

1. the solution needs to be made,
2. the device needs to be set up,
3. the PowerPoint image slides need to be prepared.

At least 24 hours before the experiment begins, mix up the solution. To make the PEG solution, combine 98mL of Polyethylene Glycol Diacrylate with 2.00 grams of Irgacure 819. Add 0.02 grams of Sudan I, used here as a UV absorber. The concentration of Sudan I can be adjusted to make thinner or thicker layers. Adding more Sudan I will make thinner layers because more UV light will be absorbed.

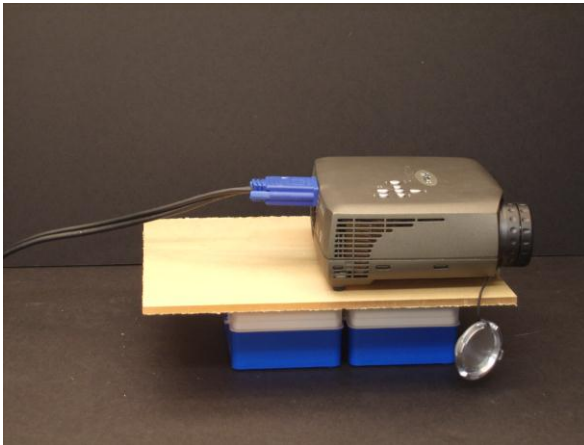
Preparing the optical set-up takes just a few moments. Along with the projector, use a converging lens and a mirror to align the focal plane parallel with the table. Use the clamps and stands to fix the objects in position. This may require some adjusting and trial and error.





Generally speaking, the converging lens should be physically as close as possible to the data projector. It is usually helpful to put the mirror close to the data projector. This allows the use of a smaller mirror and more flexibility in elevator placement. The focal plane of your image should be along the surface (parallel to the table) of a beaker containing the PEG solution. To focus, remove the beaker and use a piece of paper placed at the height of the top surface of the PEG solution.

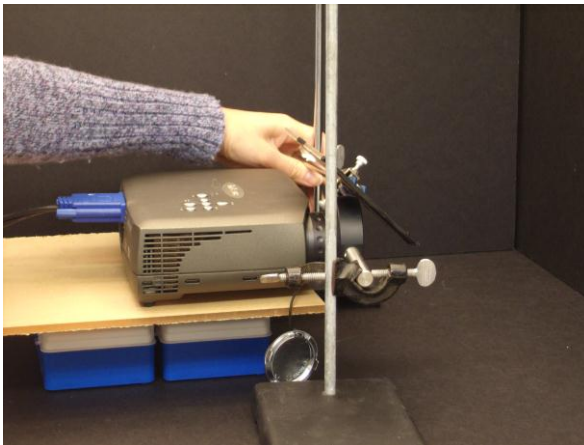
Set up the Printer



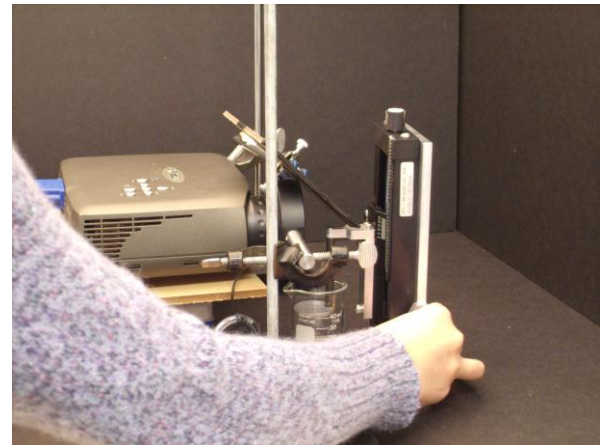
1. Place a data projector.



2. Put a magnifying glass (on a ring stand) in front of the projector, allowing light to pass through the lens.



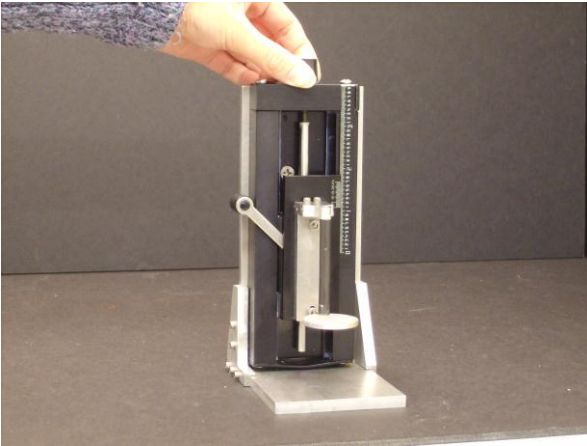
3. Put a mirror in front of the lens to direct the light downwards. The mirror should be at a 45° angle.



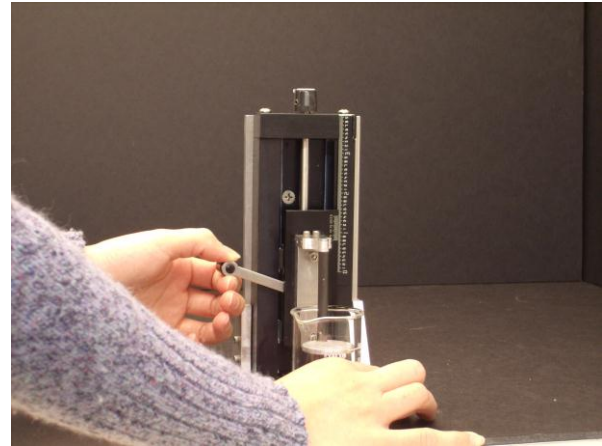
4. Light from the projector will bounce off the mirror and project onto the staging device.



Staging Device

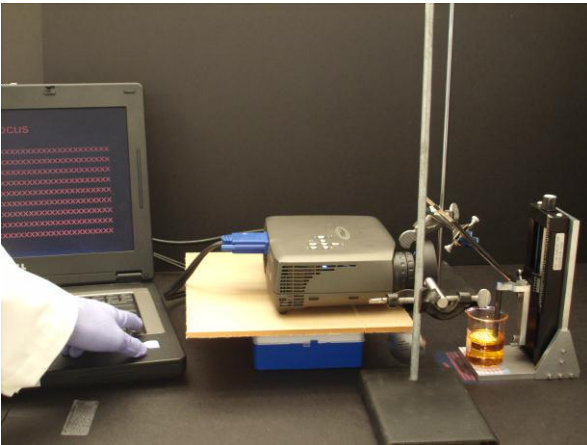


5. The staging device moves on a threaded rod, so that the stage can go up and down by turning a knob. Movement should be very fine.

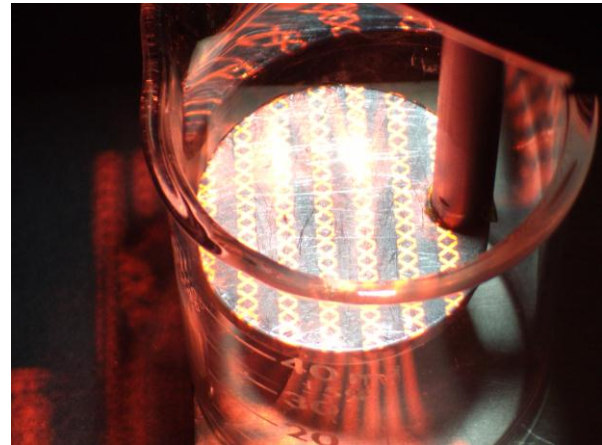


6. The stage has a locking mechanism. Unlock the stage to pull it up or down. Have it locked for small changes using the knob.

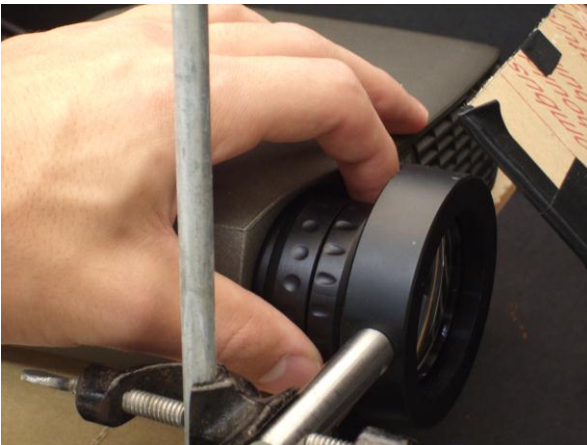
Focus



7. Make a PowerPoint slide that has red text on it. This allows 3-D printing operators to focus the image from the projector onto the stage.



8. The image can be adjusted by moving the stage up or down to focus.



9. The projector's focus may also be adjusted to focus the image on the stage.



(3) PowerPoint slides need to be prepared for each of the different cross sections needed to make the object. Each cross section should be white where the polymer should solidify on a black background. The polymer will not solidify where there is the black background. Testing should be done to determine how large the cross section should be on the screen to correspond to the correct size projected into the beaker. On all the projectors the authors have tested, the cross-sectional area that projects correctly is roughly 1/4th to 1/8th of the screen. Duplicate one of the cross-sectional images but replace the white area with red. This will make an initial slide containing a red and black image. The red will allow you to position and check focus without polymerizing the solution.

Notes:

The use of optical physics may help ($1/f=1/p+1/q$, where f is the focal length, p is the object and q is the image)

The photoactive initiator is UV sensitive. The red light will not initiate the reaction.

Printing:

Load PowerPoint Onto the Computer

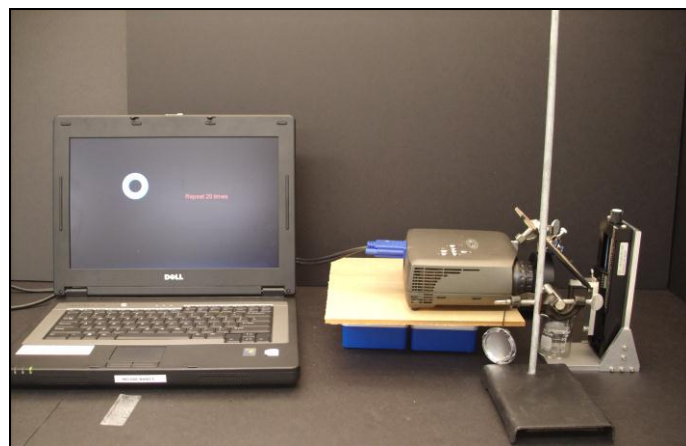


1. Load the PowerPoint with the 3-D object onto computer.

Add 3-D Polymer



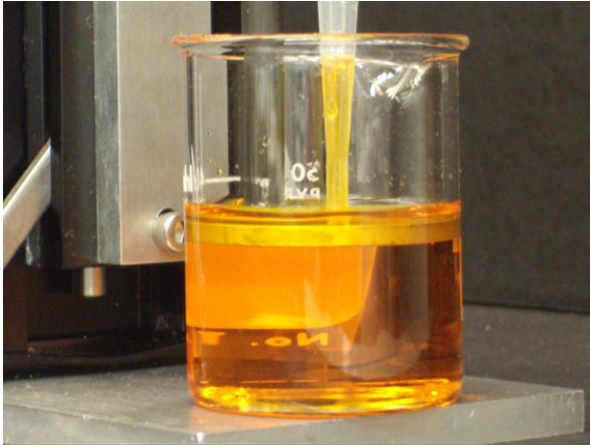
2. Pull the staging device out from the set-up; don't change the height of stage if possible. Place a 50-mL beaker around the stage.



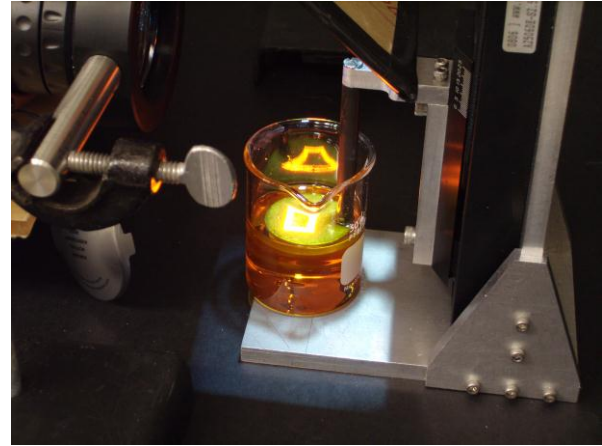
Start PowerPoint



3. Pour 3-D polymer into the beaker so it covers the stage.

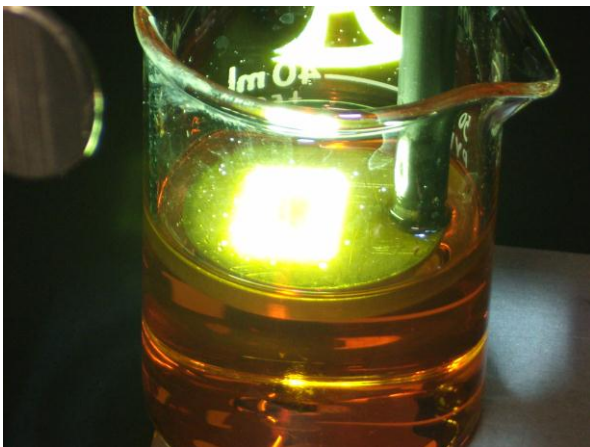


4. Use a disposable pipette to decant extra polymer from the beaker.



5. Put the staging device back into the set-up. Make sure the light is focused and the object is centered on stage.

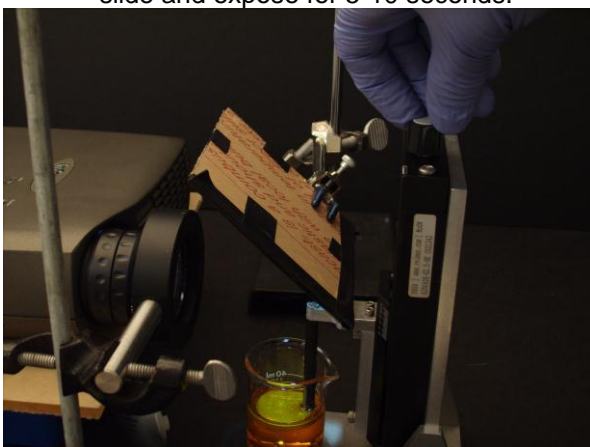
Print the 3-D Object



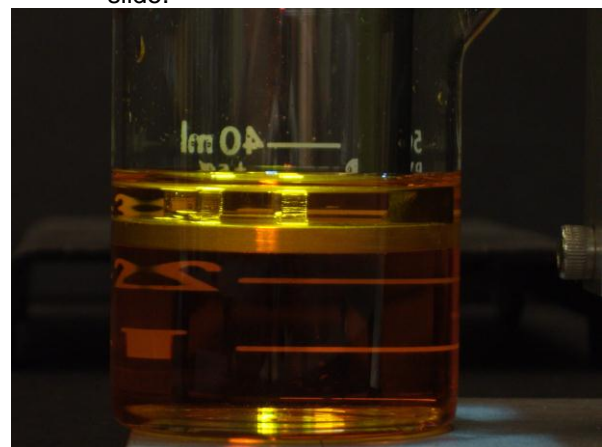
6. Advance the PowerPoint to the first white slide and expose for 5-10 seconds.



7. Advance the PowerPoint to an all black slide.



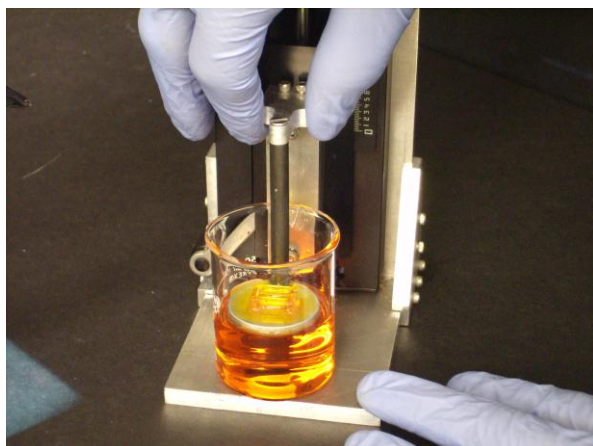
8. Lower the stage into polymer, using the knob.



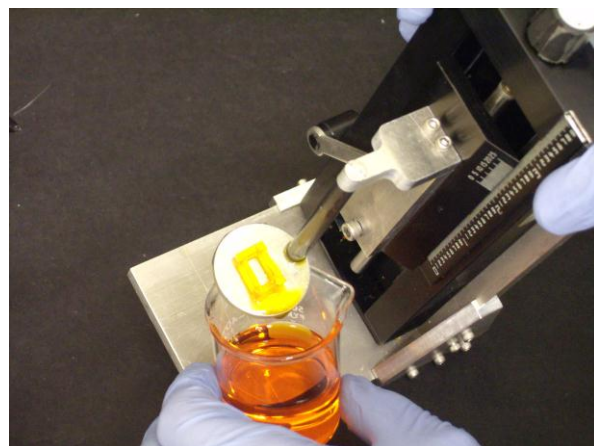
9. Allow for new 3-D polymer to flow over the existing structure. Expose the next white slide. Continue process until the object is complete.



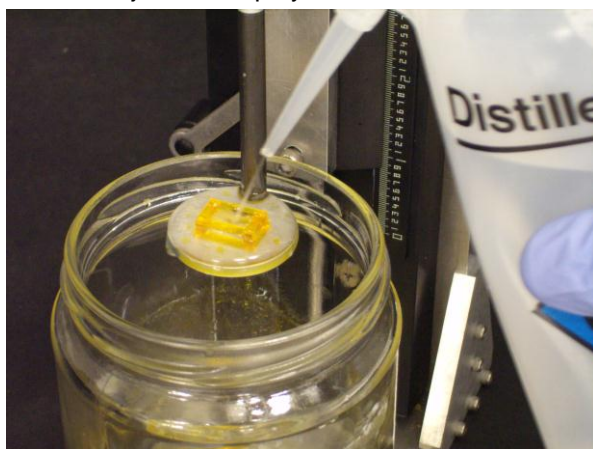
Remove the Excess Polymer



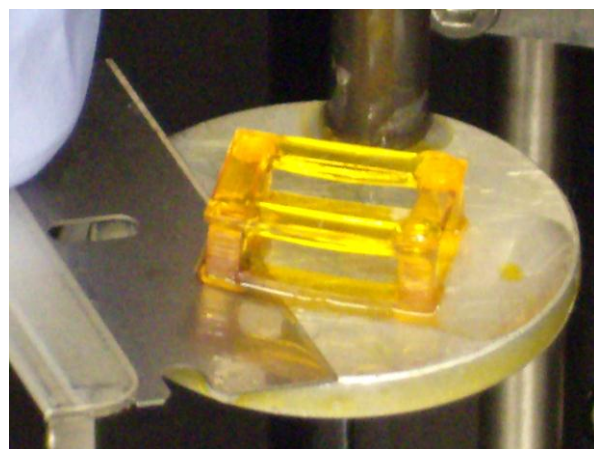
10. Once the 3-D object is complete, pull the stage out of the set-up and raise the 3-D object out of polymer.



11. Decant the excess polymer into the beaker and return any left over polymer to the amber bottle.



12. Place a waste jar under the 3-D object on the stage and rinse off the extra polymer using distilled water.



13. Using a razorblade, gently lift the 3-D object off the stage. Expose the 3-D object to ultraviolet light. Unreacted polymer will then polymerize.



Presentation Details:

Slide 1 (3-D Printing): Our focus today and tomorrow will be on 3-D Printing

Slide 2 (Objective): Students will learn about creating nanosized 3-D objects, why this might be useful. They will learn about polymerization and how it can be initiated by light. They will learn how to use the same technology to create three dimensional objects in their class.

Slide 3 (Micro-Manufacturing): Until recently, methods to create micro or nano-sized objects were limited to making very flat objects. Only thin layers could be made, and making each layer was an expensive, complex process often taking hours to fabricate. Then, to make the next layer, perfect alignment had to be achieved so that the new layer was correctly positioned over the previous layer. This effectively limited all objects to only a few layers, making only very flat objects such as the micro-gears shown in the picture.

Very flat objects, although they do have some thickness in the third dimension, do not have much structure in that third dimension. They can be thought of as 2- or 2.5-dimensional objects. A piece of paper is a good example. It does have some thickness, but not much functional structure in that third dimension.

Microstereo lithography overcomes these limitations and allows the creation of truly 3-D micro-sized and nano-sized objects.

Slide 4 (Examples of Microstructures): Here are some SEM images of small, truly 3-D objects. These are examples of some early work from researchers around the world. The feature size of these objects are not quite in the nanometer range, but are nice examples of the types of structures that are possible. The first image is a photonic crystal that might one day be needed in quantum computers. The second object is a bull. Although there are many very functional applications of this technology, the applications of this sort of technology in art are often overlooked.

Slide 5 (Application: Artificial Microvessels): A useful biomedical application of this technology might be in organ replacement. Currently, we can grow cells on tissue culture media – flat agar plates where we have a flat lawn of cells. Although this is significant, we are not going to replace a patient’s liver – for example - with a lawn of cells grown on an agar plate. If, instead, we could grow those cells on a three-dimensional scaffold of artificial capillaries, we could grow replacement organs. This is the inspiration for what researchers call “the world’s smallest shower head.” The picture on the right shows water flowing through this branching network created to the same dimensions found in human capillaries. Oxygen and other small molecules diffuse through the thin wall of the polymer, providing nutrition for the growing cells.

Slide 6 (3-Dimensional Printing): Dr. Nicholas Fang, at the University of Illinois at Urbana-Champaign (UIUC) has created a device that uses a photoactive polymer to generate very small truly three-dimensional objects. With this device, the feature size of an object can be about 400 nm, but research is ongoing to create objects with even smaller features.

Slide 7 (3-Dimensional Printing): The machine that Dr. Fang has put together is the result of about \$500,000 in research money. Clearly we can’t bring this machine into the classroom. But,





the idea behind this invention can be taken into the classroom and modified so that students can create their own 3-D objects.

Slide 8 (3-Dimensional Printing): Dr. Fang's expensive device can be reduced to just a few rather inexpensive parts. A computer running PowerPoint (or some similar presentation software) controls the projected images. A data projector shines light into a beaker filled with a photoactive polymer. The projector puts out UV light. A magnifying glass refocuses the image so it is small. A mirror reflects the light so it shines down into the beaker, not onto a large wall. An elevator or staging device lowers a stage into the beaker. This holds the bottom of the fabricated object. More about this elevator later.

Slide 9 (Light Activated Polymer): The polymer reaction begins with UV light splitting an initiator (in our case, Irgacure 819 from Ciba Corp). This forms two free radicals - molecules with unbound electrons looking for something to bond to.

Slide 10 (Light Activated Polymer): If the two free radicals found each other, they would reform and the reaction would stop. However, it is likely that each free radical will instead find a monomer to bond to. This forms a bond between and moves the unbound electron to the end of the monomer. Now this end is looking for something to bond to.

Slide 11 (Light Activated Polymer): This continues until termination, when the unbound electrons from two elongating polymers find each other and bond.

Slide 12-20 (Animation): This animation shows the basic parts of the device. It serves as a refresher of the components as the following slides demonstrate the process. After labeling the components, the presentation waits for the presenter to advance the presentation.

Slide 21 (Elevator Design): A homemade staging device or "elevator" is shown here. A commercial drawer slide is used to move the stage smoothly up and down. A threaded rod attached to a T-nut is what controls the location of the stage. As the threaded rod is turned, it causes the T-nut to move up or down on the rod. The T-nut is attached to a wood block. The wood block holds the stage and is attached to the drawer slide.

This design is conceptually the same as Dr. Fang's device. His has a motor attached to the threaded rod to automatically turn the rod.

Slide 22 (Slicing 3-D object): To create an object, layers need to be built one at a time. To generate the images for each of these layers, the final desired object needs to be thought of as cross sections. Each cross section should be made using white for the area to be polymerized, on a black background. The bottom layer is made first, so that image needs to be displayed first. Between each image is a black slide. This slide is used to stop the reaction and lower the stage of the elevator. A few seconds are needed to allow the fresh polymer to flow over the top of the object.

Slide 23 (Overhanging Structures?): The thickness of each layer is controlled by the addition of a UV light absorber. Sudan I is one such compound that works well. The more Sudan I added, the thinner the layer. If no UV absorber is added, the layers will be quite thick and overhanging structures will not be possible.





Slide 24 (What to do): Students will need to design an object and create the images needed to make the object.

Slide 25 (Slicing 3-D object): Recall that an image needs to be created for each cross section. Here are what the cross sections would need to look like to create a solid cone.

Slide 26 (Sample): In the next section, the images to make a rectangular cube will be detailed. Notice that this box has only three cross sections.

The cross section of the object's bottom is a rectangle. The image to make that cross section is displayed in the top slide. Notice that the rectangle does not take up the entire screen, but only a small section of it. This is because most of the screen space is actually outside the beaker.

Next is a blank black slide to allow time to lower the stage.

The next cross section is the four posts. These are made by the four boxes in the middle slide.

The top of the rectangular cube, like to bottom, is a rectangle, shown in the last slide.

Slide 27 (Sample): This four-post slide might be repeated numerous times to give the cube some height. Each of those repeats could be duplicated as a new slide, or the user could just display the four post slide, advance to the blank slide, lower the stage and then move back to the four post slide. Each time this is done, the height of the rectangular cube will increase.

Slide 28 (Alignment is Important): It is very important that all the cross sections are placed properly on the screen. In our example, notice that the four posts to make the sides line up perfectly with the corners of the rectangle. You can use the properties box for the object to check and adjust this alignment.

Copying slides and then making modifications can help ensure that the cross sections are aligned.

Slide 29 (Preparation Slides): Recall that UV light was used to initiate the reaction. The intense white light from the data projector will provide enough UV light. Room light will initiate the reaction at a very slow rate, and the solution can sit in room light for several hours before any noticeable polymerization occurs. Red light is at the other end of the light spectrum and will not cause the polymer to react. However, we can see red light just fine. This provides a useful tool for us in handling the polymer. Red light can be used if you need to see where the light will go but do not want this to cause any polymerization.

Slide 30 (Focus Slide): A slide with fine red lines is very useful to focus the stage. The red light can be seen, but will not cause the polymer to react. A red and black "focus" slide like the one shown here is typically the first slide used.

Slide 31 (Alignment Slide): The image with the largest cross sectional area should be duplicated and changed to a red and black image. This slide typically appears after the focus slide to make sure that the stage is aligned properly under the light.





Slide 32 (Instructions): Instructions, such as shown in this slide, can be written in red so the user can see them, but it does not cause unwanted polymerization.

Slide 33 (Final): The final file includes all of the slides. Notice that we start with the focus slide and display the largest cross section, both using red. We include blank black slides between each cross section to allow the elevator stage to be lowered and fresh liquid to flow over the top of the object. The last slide needs to be black to allow the elevator to be pulled out from under the light and the completed object to be removed from the beaker.

Slide 34 (Examples of Objects): Here is a sample of some objects that can be made. These are 5 chess pieces next to a dime to show their relative size.

Slide 35 (Examples of Objects): Very small objects can be made. Here is a complete chess set and board sitting on the glass slide that was used to support it during construction.

Slide 36 (Examples of Objects): This piano shows some interesting detail. The foot petals can be seen sticking out at the bottom. The angled music stand is behind the piano keys.

Slide 37 (Examples of Objects): This is a model of the Lincoln Memorial. Although it is hard to see in this picture, Lincoln's chair is in the center of the building. The structure is on top of a Lincoln penny to give a sense of size.

Elevator Design:

This section describes how to make a functioning elevator for the 3D classroom printing procedure. It uses a threaded rod and t-nut for positioning control and a drawer slide for tracking.

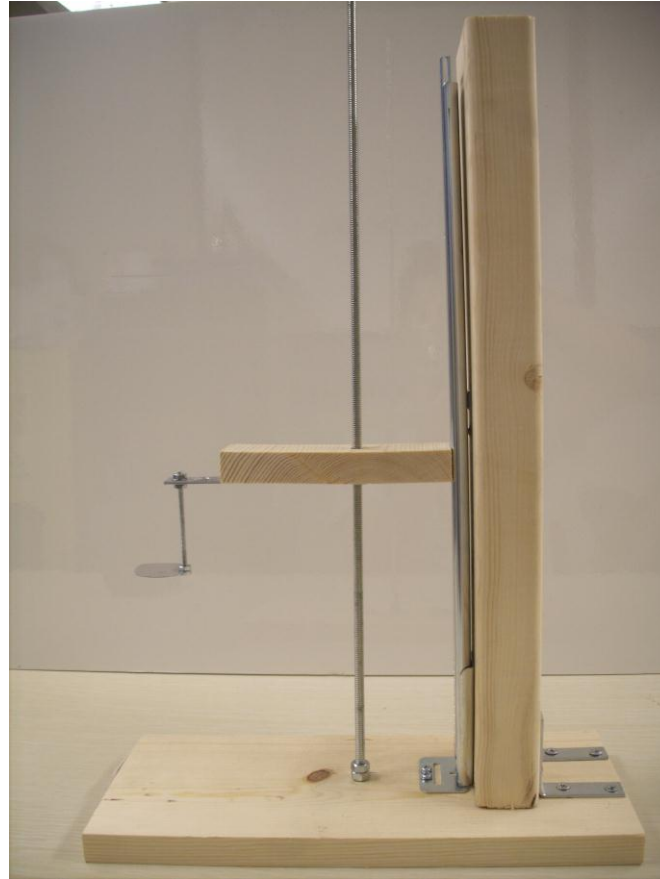
Materials:

- Drawer slide
- $\frac{1}{4}$ x 20 threaded rod
- $\frac{1}{4}$ x 20 t-nut
- 2" L-bracket (2)
- 3" straight bracket
- Carpenters Square
- 1" x 6" wood
- 2" x 4" wood
- Tape measure
- Screwdriver
- Wood screws
- Saw
- Hammer
- Tin snips
- Aluminum sheet metal
- Sharpie
- 8 x 32 threaded rod
- 8 x 32 nuts
- Drill (with 9/16 bit)
- Dremel tool
- WD-40 (Lubricant)

Safety:

Goggles should be worn to protect eyes.

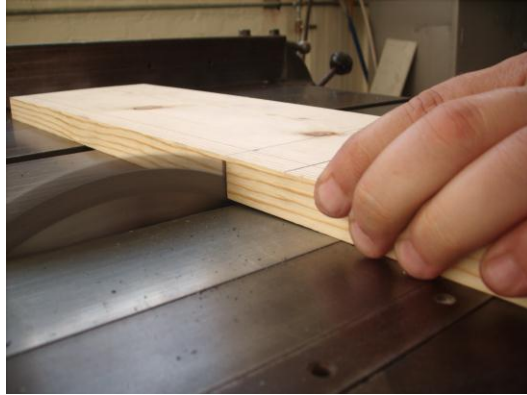




1. Mark a 1" x 6" board at 13 inches and 14½ inches from one end.



2. Mark a 2" x 4" board 18 inches from the end.



3. Cut the 1" x 6" at the marks so that you have a 13" length that will be the base and a 1½" length that will be the arm.



4. Cut the 2" x 4" board at the mark so you have a piece 18 inches long. This will be the vertical support



5. Using two 2" L-brackets, attach the 2" x 4" vertical support perpendicular to the 13" long 1" x 6" base.



6. Check that the 2" x 4" vertical support is square with the base. Make any adjustments needed to ensure it is square.



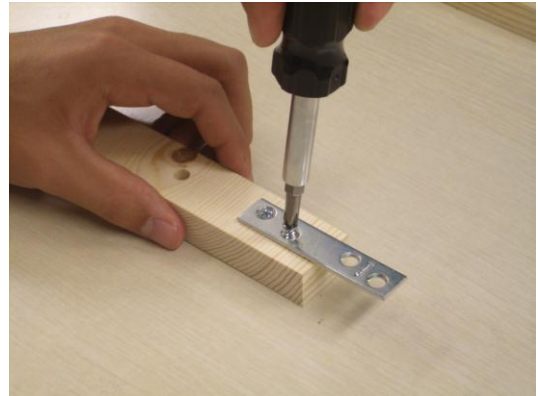
7. Attach the drawer slide to the 2" x 4" vertical support.



8. Check the drawer slide to ensure it is square to the base. Make any adjustments needed.



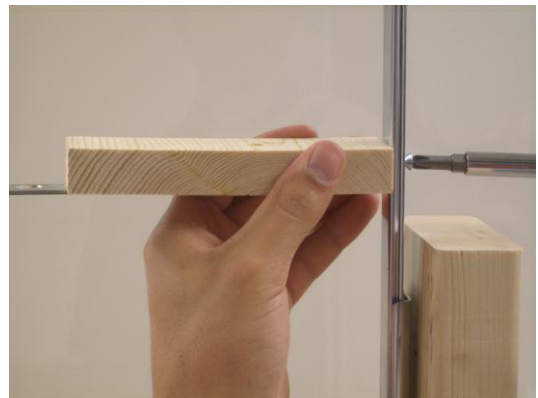
9. Using a $19/64$ " drill bit, drill a hole $2 \frac{1}{4}$ inches from one end. This hole is to place the t-nut. Also drill 2 pilot holes for the straight bracket in the appropriate location.



10. Attach the straight bracket to the $1 \frac{1}{2}$ " long arm. Half of the straight bracket should extend past the end of the arm.



11. Insert the t-nut into the arm at the $19/64$ " hole. Be sure this is firmly attached using a hammer to pound it in.



12. Attach the arm to the drawer slide so the straight bracket extends out the end and the t-nut is attached to the bottom of the arm.



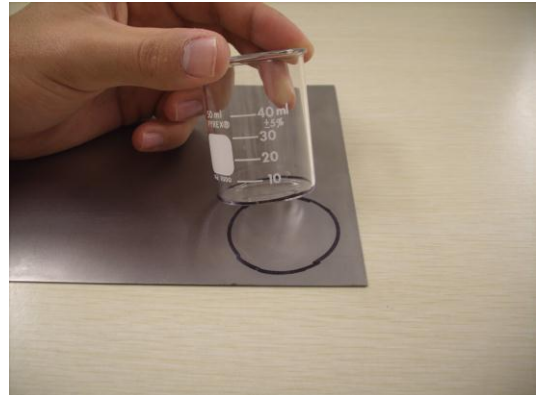
13. Check that the arm is square with the drawer slide. Make any adjustments needed.



14. Screw the 2 foot long $\frac{1}{4}$ x 20 threaded rod into the t-nut.



15. Attach two nuts to the bottom of the $\frac{1}{4}$ x 20 threaded rod. The bottom nut should be even with the bottom of the threaded rod. Tighten the two nuts against each other to lock them in place.



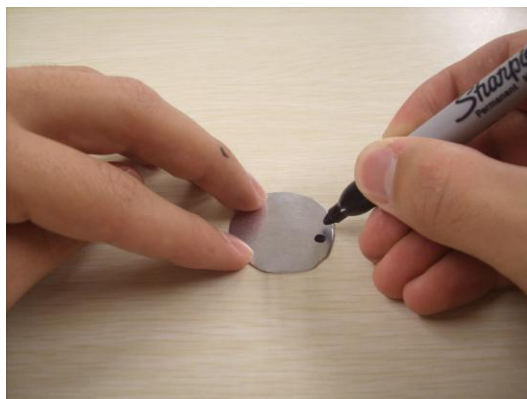
16. Mark a circle slightly smaller than the beaker you will use on a piece of aluminum.



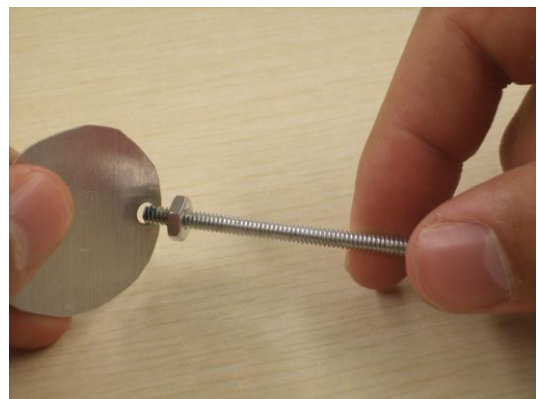
17. Using tin snips, cut out the aluminum disk.



18. Check that the aluminum disk will fit in the beaker



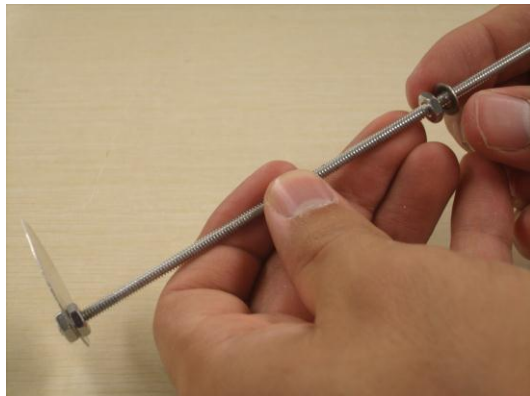
19. Mark the aluminum disk about $\frac{1}{4}$ inch from the edge. This is the location you will drill to attach the 8 x 32 inch stage support rod.



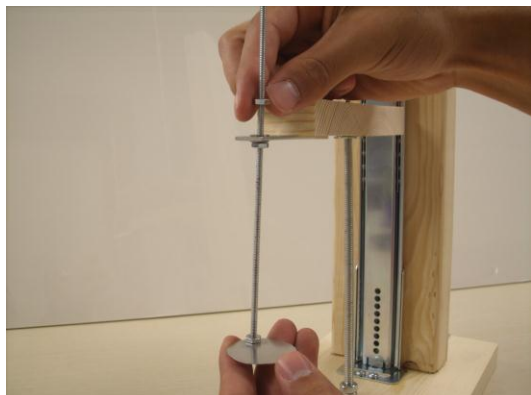
20. Attach an 8 x 32 nut to the bottom of the 8 x 32 rod. Slide the aluminum disk on the rod.



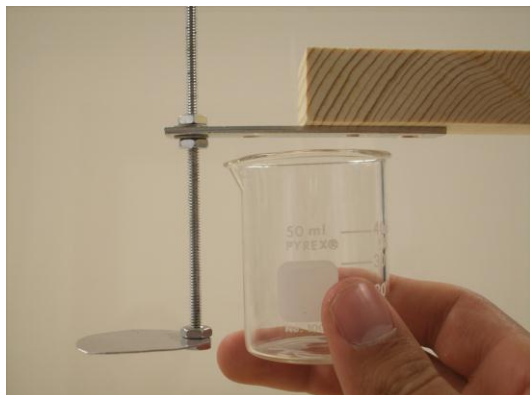
21. Attach a second 8 x 32 nut to the bottom of the rod to hold the aluminum disk in place.



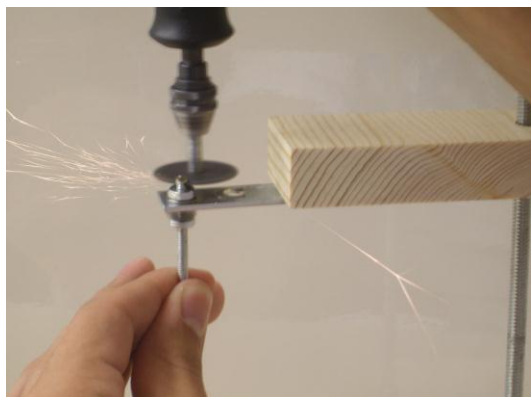
22. Attach a third 8 x 32 nut to the rod about 3 inches from the aluminum disk. Slide a small washer down on top of this third nut.



23. Slide the top of the rod through the straight bracket. Slide a second washer onto the rod. Finally add a fourth 8 x 32 nut to the top.



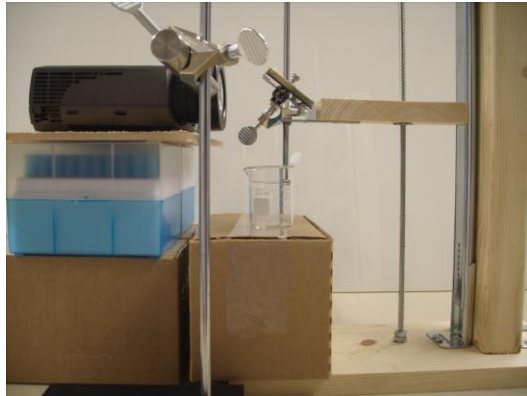
24. Adjust the position of the top two nuts so that the aluminum disk would be at the bottom of the beaker and the straight bracket at the top of the beaker.



25. Cut the excess rod off with a Dremel or with bolt cutters.



26. Spray the $\frac{1}{4}$ x 20 rod with a lubricant and turn the rod several times in all directions to spread the lubricant around. This will ensure smooth operation.



27. Set up the rest of the equipment to print. See the document “3D printing – set-up” for more information.

Established in 2003, the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS) is funded by the National Science Foundation. Partnering Institutions include the University of Illinois, the California Institute of Technology, Stanford University, and North Carolina Agriculture and Technical State University. Researchers are developing a nanomanufacturing system that will build ultrahigh-density, complex nanostructures. The Center’s research will ultimately result in a new way of working and has the potential to create millions of jobs for American workers. Our nation’s school children must be prepared to assume the new roles that will be the inevitable outcome of these emerging technologies.

This learning module is one of a series that is designed to interest middle and high school students in pursuing this new field. The Center also offers ongoing professional development for teachers through a continuous series of workshops and institutes. To sign up for a workshop or to order more learning modules, visit our website at <http://www.nano-cemms.illinois.edu>.

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