Integrating Polymer Chemistry and Optics: Creating Cheap, Portable, High-Powered Do-It-Yourself Microscopes

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Abstract:

Nowadays, the US faces a problem of confidence in its youth's scientific literacy. According to Pew Research Center, K-12 students in America rank in the middle, not the bottom of the world rank for science literacy and knowledge, but 44% of Americans view that American K-12 students rank at the bottom of the world's list (Public's knowledge of science and technology, 2013). Because of this "crisis," several researchers and educators have tried to improve the methods by which science is taught in schools. One instance by which this "scientific literacy crisis" could be alleviated is through the advancement of frugal science, termed by Professor Manu Prakash from Stanford University as the field by which high-powered scientific tools are created in a "Do-It-Yourself" fashion and are cheap and portable, accessible by all people. In this research project, an easy-to-make, cheap, efficient, high-powered, portable microscope will be created and presented to students of Mount Hebron High School taking a regular-level science class in the aim of captivating their interest in science as well as making them more scientifically literate. Hence, throughout the research project, various implications of the curing process of polymer polydimethylsiloxane (PDMS), optics, hanging droplet lens method, and microscopy were considered, and many experiments were conducted. By the end of this experiment, it was learned that in fact, there are several factors which do impact the focal length of the PDMS lens, such as the curing agent to base ratio of PDMS, the droplet size, the surface material and angle from which the PDMS is cured, and the curing time and temperature, as well as variables which do not impact the optical properties of PDMS such as stirring and degassing times.

Introduction:

Often to advance science research, scientific fields, and science education, microscopes are ubiquitous tools used around the world. Microscopes have been used extensively around the world for many years. While there are innovations which create more elaborate, more high-powered, specific-purpose microscopes, there is also a recent movement to make microscopes cheaper. As biological engineering Professor Manu Prakash of Stanford University phrases it, frugal science is the field which attempts to create high-powered, general purpose, durable and portable, easy-to-use scientific equipment for a cheap price (Cybulski, 2014). Polydimethylsiloxane (PDMS) is a cheap, commonly-used clear, flexible polymer used in microfluidics and packaging (European Centre for Ecotoxicology and Toxicology of Chemicals). However, it is also used for optical purposes, often used in disposable contact lenses. Because PDMS follows a cross-linking reaction, it is a polymer which is cured from curing agent and silicone elastomer base in a 1:10 ratio (Molla, 2012; Johnston, 2016). A series of spherical droplets can be cured upside-down from PDMS, by the hanging-droplet method (Lee, W. M., 2014). These droplets can function as ideal, small convex lens. Hence, this paper seeks to integrate the hanging droplet curing process of the polymer PDMS to create lens for use in a cheap, small, portable, high-powered microscope, and make this process educational and easily understood for all people. Commonly used light-microscopes can be innovated by the addition of a simple, descriptive guide to curing PDMS lenses targeted for the general audience.

Review of Literature:

Many people in America alone are illiterate in science. In fact, American fifteen year-olds score somewhere in the middle of a list of countries around the world on an international science standardized test (Public's knowledge of science and technology, 2013). Furthermore, according to a survey conducted by Pew Research Center and the *Smithsonian* magazine, 44% of Americans believe American students grades K to 12 score on the bottom of the world list for science literacy and education. The negative self-view by Americans on science education means science education may be an issue not only in America, but for countries scoring lower than America in science education. The solution? Frugal science is the idea of trying to make high-powered scientific tools cheaper and accessible to all. Professor Manu Prakash from Stanford University has created a cheap, portable, $1 high-powered, durable pocket-sized paper-origami microscope called the *Foldscope* (Cybulski, 2014). “Frugal science” has been termed by Dr. Manu Prakash as the idea of creating cheap, portable, high-powered, do-it-yourself scientific tools for everyone, specifically poorer, third-world countries.

Microscopes are ubiquitous tools used in science, as they help diagnose diseases, advance scientific research, and promote scientific interests and passions. Microscopy is the study and use of microscopes in scientific research and related fields. During the time of the Ancient Romans, people knew that certain shapes of glass could magnify objects (Vandervoort, 2014). By the fourteenth century, people had used glass as corrective eyewear. In the sixteenth century the first compound light microscopes were invented. The first recorded use of a lens being created for magnification purposes was in 1267. English philosopher Roger Bacon, in *Perspectiva*, described potentially how glass lenses could be used to correct vision and magnify objects. Then, in 1595, Zacharias Jansen and his father Hans Jansen created the first microscope in Holland. Two separate lenses were moved relative to each other via a sliding tube for magnification to be increased from three times to nine times. Soon after this invention, in England, Robert Hooke added a third (eyepiece) lens to Jansen’s microscope, to create a two-lens light compound microscope. Hooke is credited as the first person to create a light microscope, as he published discoveries on what he saw using a microscope. From the invention and innovation of the microscope, scientific research advanced. He also made the discovery of a cell, with pictures from what he viewed through his microscope. In 1660, Italian physiologist Marcello Malpighi was able to prove the blood circulation theories with the use of a microscope. Microbiologist Antoni van Leeuwenhoek, using a single lens microscope, described organisms and tissues and built over 400 microscopes, each for a certain specimen. The highest resolution he achieved was about 2 micrometers. Many other innovations were made to the light microscope. Ernst Abbé was the first to apply scientific principles to the design of lens, and drastically improved the physical manipulation of lenses.

However, from the invention and innovation of the commonly used light microscope (LM), various other kinds of microscopy were discovered. For instance, in the 1920s, French physicist Louis Victor de Broglie suggested that electrons and other microscopic particles should exhibit wave properties similar to those of light (Vandervoort, 2014). However, the wavelength of electron beams are often smaller than that of visible light, and can be used as the medium in microscopy to allow for higher resolution, or the smallest distance in between two points a microscope can be magnified to and still have the two points distinguishable from one another (Vandervoort, 2014; Reece, 2011; Rack n.d.). Hence, in the 1930s, two types of electron microscopes were created: the transmission electron microscope (TEM) and scanning electron microscope (SEM) (Vandervoort, 2014). Both of these types of electron microscopy are extremely useful to medical and biological research. However, they are complex, expensive, and require extensive training and skill to be used. In the 1980s, scanning tunneling microscopy (STM) was created, and used a metal tip to have electric current induced on the tip from the electrons near the surface of the sample in question. Other advancements in microscopy have also recently been developed such as atomic force microscopy, acoustic microscopy, and near field microscopy, as well as new microscopy techniques such as multi-photon fluorescence and computerized wide-spread deconvolution microscopy. (Portable AFM images, 1999; Reece, 2011; Vandervoort, 2014).

However, there have also been recent advances in microscopy to simplify and microscopes cheaper, more portable, and more accessible to all. In a typical compound light microscope, parts of the microscope include a convex lens (or series of convex lenses), a diaphragm to adjust the amount of light which passes through the lenses, a light source, an eyepiece lens, a stage, and possibly, stage clips (Reece, 2011). Convex lens allow for magnification of an object, and the more convex lens put in a series means the total magnification is the product of the individual magnification of each lens (Halliday, 2005; Rack, n.d.). Optics is the study of sight and the behavior of light. All lenses in a microscope would hence exhibit optical properties such as refractive index, magnification, focal length, and resolution. The refractive index is a intensive property of the material from which a lens is made and determines the angle at which light is bent when passed through, or refracted, through a lens. Magnification depends on the material as well as the amount of curvature the convex lens has. Concave lens, oppositely, scatter light, and are not used in microscopy, for which light must be converged to focus on a sample, and magnify it. Magnification can also be additive when multiple lens are placed in a series with one another, yet resolution would decrease, as the focal length has decreased, and better focus is obtained. Hence, the resolution, or clarity, would be more limited, or decreased.

Curing PDMS lenses can be integrated with creating cheap, portable microscopes (Lee W.M., 2014). By integrating the use of an ubiquitous polymer, polydimethylsiloxane, with microscopy and efficient optical properties to create a cheap, lightweight, high-powered, portable, easy-to-use microscope (Lee W.M., 2014; Cybulski, 2014). Also, by the integration of these various science fields, a do-it-yourself kit can be created suited for audiences of all education levels, social and economic classes, and ages. Supplementary kits, guides, and videos can also be compiled for all people to create an affordable high-powered microscope themselves. The intended audience may also gain a better understanding of how creating a microscope can play a role in their understanding of science as well as potentially spark a renewed interest in passion in science, especially for 46% of Americans who attribute the lack of interest and education in science to the difficulty of the content and subject matter (Public's knowledge of science and technology, 2013).

What is PDMS? In the modern world, polydimethylsiloxane (PDMS) is a commonly used, cheap, safe polymer used to make lens for microscopes. PDMS is a polymer, a class of macromolecule materials which are synthesized from smaller monomers in polymerization reactions (*Scientific Principles,* n.d.). Amongst processes used to synthesize vastly different polymers, polymerization reactions can be categorized into two basic types: chain-reaction (addition) polymerization, and step-reaction (condensation) reactions. A chain-reaction polymerization is a three-step process which requires monomers, simple compounds used to form links in the polymer chain, and a free-radical catalyst, a chemical component containing a free electron that forms a covalent bond with the electron of another molecule, which in this case, would be a monomer molecule. In the first step, initiation occurs, and the free-radical catalyst reacts with the monomer to break the double covalent bond in the monomer, and bind the free radical and monomer together. The free electron is transferred to a free, open-ended carbon atom. Propagation then occurs, joining successive links of monomers together, and forming a long polymer chain. Termination finally occurs when the last monomer link is formed on the chain by the free-radical. The reaction is exothermic, and has an extremely quick completion rate. Polymers created by this reaction often have high molecular weight. Cross-linking, when separate polymer chains bond together, and branching, when a polymer has smaller chains attached to the main backbone chain, both can occur during this polymerization process. The other type of polymerization, step-reactions, often occur at higher temperatures and produce polymers with lower molecular weight. This reaction requires two different types of monomers which react with each other to form a chain. Another small molecule, such as water or hydrochloric acid, is also formed as a byproduct from this reaction. Short chains called oligmers form and join together during the polymerization process. This process is often slow, and does not often create branching or cross-linking but rather linear chains. Curing PDMS is a slightly different, yet similar polymerization process.

> PDMS is cured by an organometallic crosslinking reaction. The siloxane base oligomers contain vinyl groups. The cross-linking oligomers contain at least 3 silicon hydride bonds each. The curing agent contains a proprietary platinum-based catalyst that catalyzes the addition of the SiH bond across the vinyl groups, forming Si-CH_2-CH_2-Si linkages. The multiple reaction sites on both the base and crosslinking oligomers allow for three-dimensional crosslinking. One advantage of this type of addition reaction is that no waste products such as water are generated. If the ratio of curing agent to base is increased, a harder, more cross-linked elastomer results. Heating will also accelerate the crosslinking reaction (Campbell, 2006).

As seen from above, the curing process of PDMS can be similar to either type of polymerization, addition or condensation, as the process uses cross-linking of the siloxane base oligomers with the presence of the curing agent, or the free-radical catalyst. Also, no byproducts are created, and all base and curing agent molecules should be used by the reaction even if the curing agent to base ratio is slightly altered. Finally, the curing process is slow, so heating PDMS to high temperatures speeds the polymerization process greatly.

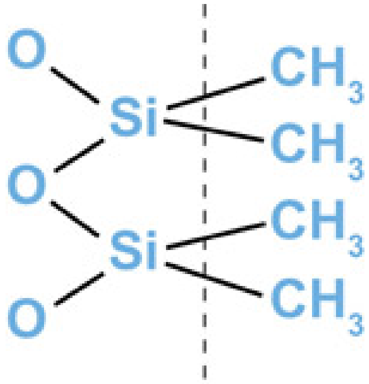

Fig. 1: A diagram which shows the structure of PDMS (polydimethylsiloxane). As seen on the left half, the siloxane backbone consists of alternating oxygen and silicone atoms. The dimethyl groups are shown on the right half, extending from the central silicone atoms (Dow Corning, n.d.).

As seen in Figure 1, PDMS is a polymer consisting of a siloxane backbone and dimethyl side groups (Dow Corning, n.d.). In terms of polarity, the siloxane backbone is polar, whereas the dimethyl groups are nonpolar. This dual polarity of the PDMS polymer allows for great flexibility and strength. PDMS also has long bonds between the silicone and oxygen molecules, as well as a large O-Si-O bond angle. Hence, PDMS has less competition among functional groups, larger free volume, and greater compatibility with many different materials. PDMS is an extremely stable molecule, as dimethyl side groups are chemically inert. PDMS can easily spread on surfaces, is highly breathable material, and can perform well at a wide range of temperatures. PDMS can also have its side chains easily substituted for other molecules, or in other terms, can be doped with molecules or atoms of other elements (Dow Corning, n.d.). Overall, PDMS also has high UV radiation resistance, thermal stability, great surface interactions and great gas permeability (Kuo, 1999). PDMS is also hydrophobic for overall polarity of the molecule, as well as great shear stability, or resistance to breaking of the material, and great dielectric effect, or adding material in between two plates of a capacitor to maximize charge for the same amount of electric field generated by the plates (Kuo, 1999; Kamali, 2016; Halliday, 2005). PDMS is also very flexible, meaning it can easily be molded into various desired shapes

(Liebestraut, 2013). Finally, PDMS is relatively nontoxic, making it safe both biologically and ecologically (European Centre for Ecotoxicology and Toxicology of Chemicals, 2011; Kuo, 1999).

PDMS is often used for variety of purposes other than for creating lens, as primarily discussed in this paper. PDMS is probably most commonly used in the field of microfluidics, to fabrication and prototyping of microfluidic chips, as PDMS has a extremely versatile in shape and structure (Eddings, 2008; Lee, J.N., 2003). PDMS can be found as a common polymer used in the synthesis of flexible, disposable contact lenses (European Centre for Ecotoxicology and Toxicology of Chemicals, 2011). PDMS is not always used for technological or scientific purposes. For instance, PDMS has common industrial applications. It is even used in the toy industry, in products such as silly putty, and for cosmetic purposes, as in plastic surgeries, especially in silicone breast implants (Clegg, 2015). PDMS is even found in drugs, surfactants, oils, and sometimes in fast food and soda. PDMS is also used in skin moisturizers to prevent the loss of water, and sometimes used in conditioners as lice repellent. PDMS has applications in various other industries, such as the automotive, aerospace, textile, fiber, film, packaging, and pipe industries (PDMS market applications, n.d.). Recently, MIT researchers have found some optical properties of PDMS useful, and have cured PDMS to be rubbery and flexible, so that with different stretches of PDMS, different amounts of light would be absorbed through the PDMS sample (Massachusetts Institute of Technology (MIT), 2016). They have proposed the PDMS stretching technique could be used to create more ecologically friendly “smart windows” that can change in the amount of light which passes through.

PDMS also has many desirable chemical and physical properties, some of which have already been discussed. For instance, PDMS has a mass density of .97 kg/m^3, and is lightweight in structure, allowing for better portability of lenses (Massachusetts Institute of Technology, n.d.). PDMS has a Young's Modulus of 360-870 kPa, or in other terms, that it is flexible in the ratio of stress it can withhold to the strain and deformation of the material. Also, PDMS has a good tensile strength of 2.24 MPa. PDMS has a decently high specific heat capacity of 1.46 kJ/kgK and a relatively low thermal conductivity of .15 W/mK. PDMS is also a good dielectric material as its dielectric constant is 2.3 to 2.8, or greater than the dielectric constant of air, which is 1. PDMS is not a good conductor of electricity as it has a high resistivity value of $4x10^{13}\Omega m$. According to Dow Corning, the company which supplies the PDMS used in the experiments conducted, the average shelf life is 720 days, and the PDMS can cure at room temperature when left for 48 hours (Dow Corning, n.d.). The PDMS is also advised to be cured at a 10:1 base to curing agent ratio. PDMS also has useful optical properties such as a refractive index of 1.4 and a transparent color (Massachusetts Institute of Technology, n.d.; Dow Corning, n.d.).

As seen from many different sources, PDMS can be used as an optical lens. In order to synthesize these lens, a cross-linking polymerization process is used to "cure" the PDMS in the desired shape, which in this case, would be the shape of a concave lens, with a rounded edge. There are many different techniques used to mold such desired concave shape in PDMS. For instance, a needle-moving technique subjected to high temperatures can be used to form a strong adhesive attraction between a PDMS drop and the needle, in order to counteract the forces of gravity (Amarit, 2016). An advantage of this method is that a PDMS base is formed for anti-contamination purposes. However, temperature manipulation and needle-moving curing techniques within an oven may be a difficult to conduct. In another method, PDMS cured in 1:40 curing agent to base ratio was injected between two lens which act as a mold for the newly molded lens (Beadie, 2008; Liebestraut, 2013). PDMS was then cured at room temperature for three days. The advantage of this technique is that the lens can be tuned to create different optical properties, yet the required materials and precision is far too great for a fairly simple process. However, to cure PDMS lens in this experiment, the hanging droplet method was conducted and arguably a common and relatively simple method in curing lens, because what creates a concave shape of a lens is gravity acting upon a droplet, as well as the cohesive nature of viscous PDMS (Lee, W.M.). A PDMS mixture was mixed in a 1:10 curing agent to elastomer mass ratio. This mixture was then stirred vigorously well for one minute and placed in a dessicator to remove all remaining bubbles. PDMS was then dropped on a clean glass slide with a micropipette in a desired amount. This PDMS droplet was then hung upside down on a metal rack and then cured for ten minutes at 200°C. The PDMS was cured in a 1:10 curing agent to elastomer base ratio, as arguably used in many experiments, including the experiment conducted in this paper (Amarit, 2016; Beadie, 2008; Johnston, 2016; Lee W.M., 2014; Liebestraut, 2013; Molla, 2012). As many early experiments have been conducted, it has been observed that deviating from the 1:10 curing agent to base ratio would make the PDMS removal from glass difficult, and often leave PDMS residue behind. Extreme deviations, such as curing PDMS in an extremely large curing agent to base ratio would cause the PDMS mixture to have the formation of a few bubbles when the mixture was stirred, and the cured PDMS to have an “oily” texture. Oppositely, PDMS with an extremely low curing agent to base ratio often had a long degassing process due to the formation of lots of bubbles, and a sticky, sometimes not fully cured, PDMS product. However, an ideal 1:10 curing agent to base ratio PDMS hanging droplet should be ideal for use in optical devices, such as a small, lightweight light microscope.

An efficient method to cure PDMS lens could be added to microscopes to make these tools high-powered, cheap, portable, and accessible to all. The goal of reading this paper is to understand the mechanics and scientific principles behind the cross-linking reactions of curing a convex lens from PDMS, to understand how an image can be magnified and clarified by the lens in a small microscope, and the basic essentials of a microscope itself and its uses in the modern world. By creating an open-ended, yet descriptive procedure or kit, anyone can afford to build their own microscopes, and hopefully gain exposure to to their interest in science. Scientific awareness and knowledge can be promoted by the creation of an easy-to-assemble do-it-yourself microscope.

Research Methods and Data Collection:

For this research, the most efficient, simple, yet innovative method to make a cheap, portable, high-powered microscope was investigated, including locating the optimal parameters of the set of optical lens to be used. Through this research, although creating an effective, easy-to-understand procedure to create cheap, portable, high-powered lens would hypothetically be difficult, it was believed that the process would be possible, for instance, just as Dr. Manu Prakash has made so many cheap, high-powered, pocket-sized scientific tools for the sake of frugal science (Cybulski, 2014). A data collection notebook belonging to the Kyoung Lab Group of the UMBC Department of Chemistry and Biochemistry was used to note the descriptions of all performed multiple experiments as well as collect data. A standard protocol was followed for most of the experiments that were conducted (see Appendix C).

Results and Data Analysis:

Data collected from several similar and different experiments conducted throughout the year show that while tedious, and perhaps incomplete, the data support the idea that a cheap, high-powered, easy-to-understand microscope could be created—but perhaps better or in more detail had time not been a factor limiting the scope of the research conducted. For most data collection experiments, a variable or levels of a variable potentially impacting the PDMS-lens curing process as well as the optical properties of the cured PDMS lens were investigated. For instance, in experiments 11 and 12, the different droplet sizes (µL) of PDMS cured were compared to their respective focal lengths (See Appendices A and B).

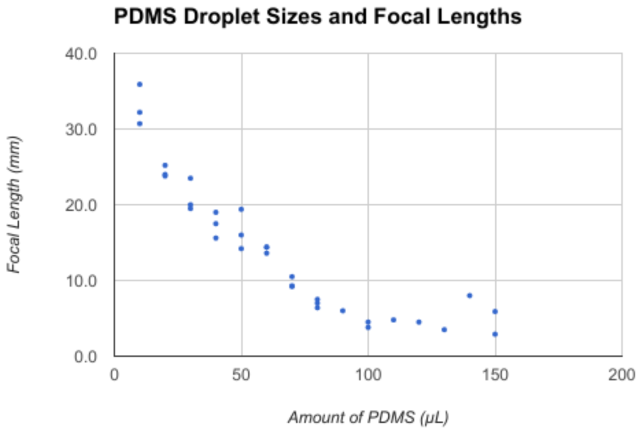

Fig. 2: A graph depicting the likely exponential relationship between PDMS droplet sizes (µL) and the respective focal length (mm) for droplet sizes 10 µL to 150 µL; experiment number 11

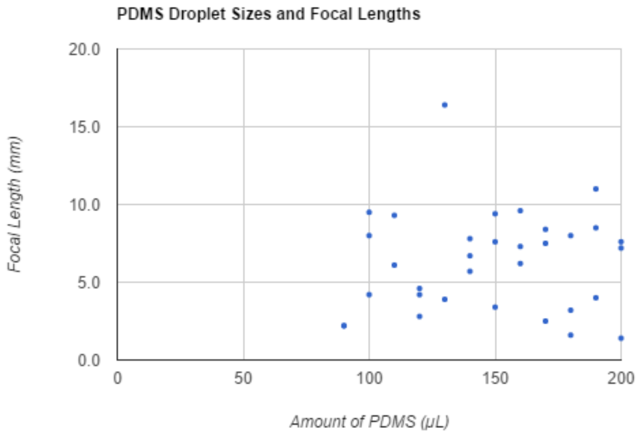

Fig. 3: A graph depicting the relationship between PDMS droplet sizes (µL) and the respective focal length (mm) for droplet sizes 90 µL to 200 µL; experiment number 12

As seen from Figures 2 and 3, there are a mixed range of analysis that can be done on the experiments. From Figure 2, it seems that droplet size does indeed have an impact on the focal lengths of the PDMS lens, and that relationship seems to be seen by a negative exponential curve. Hence, it appears that there is a strong association between PDMS droplet sizes and the corresponding focal lengths of the lens, yet that association is stronger for smaller droplet sizes, as seen from Figure 2, and a lot less apparent for larger droplet sizes, as seen from Figure 3. For raw data, refer to Appendix D.

There have been many other experiments which have been performed throughout the course of my internship. However, most of the first ten experiments conducted did not yield any significant results, or had some issues with precision of the measuring equipment or the procedure that the experiment had to be reconducted with better procedures and measuring devices.

Discussion/Conclusion:

In conclusion, all the data collected through the research conducted show that a method to create a cheap, portable, high-powered microscope is definitely possible, as well as realistic. Some parameters of the microscope, including the arrangement of the lens, as well as the characteristics the PDMS droplet lens have, are, in fact, impacted by other variables, such as the curing agent to base ratio of the PDMS mixture, the droplet size, curing time and temperature, and orientation of the droplet lens, for instance, that the droplets are hanging upside-down on a completely flat rack.

From finding out that a cheap, portable, high-powered microscope may be feasible to make, possible utilizations of this knowledge would be to distribute the method by which the microscope is made to others, in the form of a video, paper guide, kits, or by oral presentations to others. This may be a fun activity that could inspire young children, or potentially people who are not as scientifically inclined or affluent to get involved in learning about science, and becoming more scientifically literate.

However, there are some limitations to this research, as time and precision of equipment has been a large barrier to the expansion and precise data collection and analysis of the experiments. Also, with a goal for such simplistic procedure and a cheap cost for the microscope itself, there are some obvious limits to the efficiency and power of the microscope. Yet if more time and access to high-precision materials were available, then the microscope could plausibly be better-made, and more scientific experiments performed on the variables which impact the dimensions and properties of the microscope, including its optical power and both resolution and magnification abilities. The project could also potentially be improved by the exploration of other variables which may impact the optical properties of the PDMS lens, such as the curvature of the lens created, the amount of time the PDMS droplet is allowed to sit invertedly off the metal rack, and perhaps other factors. Perhaps, even a different scientific invention could be created in hopes of advancing frugal science, and to hopefully cut down the lack of confidence Americans have in the scientific literacy of their youth.

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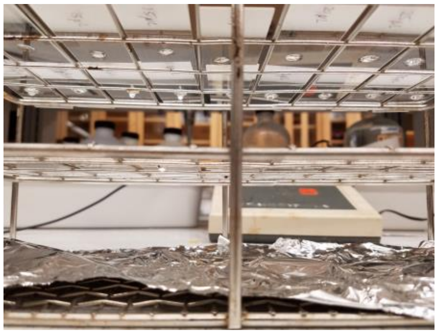
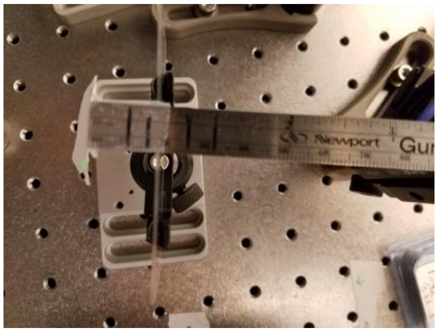
Appendices:

Appendix A



A picture of the hanging-droplet lens method which was used to create the plano-concave shape of the PDMS lens; droplets hang invertedly from glass microscope slides on shelves of a metal rack

Appendix B



A picture of the set-up to measure the focal length of each PDMS droplet of all the trials conducted using a high-voltage laser for precision

Appendix C

Materials:

- Dow Corning Sylgard 184 Curing Agent & Silicone Elastomer Base
- 20-200 µL micropipette
- 20-200 µL micropipette tips
- Digital Mass Scale
- Vacuum Desiccator
- Plastic Cup
- Microscope Slides
- Razor

Safety Equipment:

- Oven Mitts
- Disposable Gloves
- Fume Hood

Protocol for Typical Curing of PDMS Lens (Modified Version of Experiment No. 1)

- Set Oven to Desired Temperature (>100 Degrees Celsius)
- Weigh Out 1:10 Mass Ratio (CA:B)
- Stir for 1 Minute with Pipette Tip
- Place in Desiccator and Degas Until All Air Bubble Released
- Cut Off Small Parts of Pipette Tips with Razor
- Pipette Desired Amount On Glass Microscope Slide
- Hang Slides Upside Down Off Metal Rack
- Place Rack in Oven Until Hanging-Droplet Lenses are Fully Cured
- Remove & Cool Samples on Rack

Appendix D

Project No. 11

Amount of PDMS (μL)	**Trial #**	**Inner Diameter (±.5 mm)**	**Outer Diameter (±.5 mm) (if any)**	**Focal Length (mm)**	**General Observations**
10	1	6.8	none	32.2	
	2	6.8	none	30.7	
	3	6.1	none	35.9	
20	1	8.6	none	23.8	
	2	7.8	none	24.0	
	3	7.2	none	25.2	
30	1	7.9	none	20.0	
	2	7.2	10.0	19.5	a bit elongated & shifted
	3	7.1	9.1	23.5	a bit shifted
40	1	7.3	11.2	15.6	shifted w/outer radius
	2	7.5	9.2	17.5	shifted w/outer radius
	3	9.0	10.0	19.0	crescent-shaped
50	1	9.6	10.5	14.2	shifted w/outer radius
	2	10.3	none	19.4	
	3	10.0	12.0	16.0	very shifted
60	1	10.0	11.2	14.4	shifted w/outer radius
	2	9.7	11.0	14.4	shifted moderately
	3	9.8	10.9	13.6	shifted moderately
70	1	10.0	11.8	10.5	shifted moderately

	2	10.0	12.9	9.3	shifted w/outer radius
	3	8.0	12.3	9.2	very shifted
80	1	8.2	9.5	6.4	random line of PDMS on slide
	2	8.0	none	7.0	
	3	8.6	12.0	7.5	shifted moderately
90	1	7.0	12.0	14.3 *cannot measure accurately*	splattered & demented
	2	7.2	13.2	6.0	splattered & demented; overlapping
	3	none	13.1	**unmeasurable**	line of PDMS through
100	1	7.1	12.6	3.8	splattered & demented; line of PDMS
	2	~7.0???	14.0	20.8 *cannot measure accurately*	splattered & demented
	3	~6.9???	13.2	4.5	splattered & demented
110	1	none	~14.0???	**unmeasurable**	line of PDMS through; demented
	2	none	~14.4???	**unmeasurable**	line of PDMS through; demented
	3	9.0	13.3	4.8	shifted moderately
120	1	none	13.4???	**unmeasurable**	line of PDMS through; demented
	2	10.0	14.0	4.5	line of PDMS; moderately shifted
	3	none	14.0???	**unmeasurable**	line of PDMS on edge
130	1	9.3???	14.5???	21.9 *cannot measure accurately*	line of PDMS on side; moderately shifted

	2	7.2	14.4	3.5	slight PDMS line; very shifted
	3	~9.1??? *Not sure if this is even inner circle*	14.7	**unmeasurable**	very shifted; demented
140	1	9.6???	15.0???	17.7 *cannot measure accurately*	very shifted & splattered
	2	9.3	14.8	8.0	very shifted & slightly demented
	3	none	15.0???	**unmeasurable**	very demented w/PDMS lines
150	1	~9.0???	~15.0???	11.9 *cannot measure accurately*	shifted & demented
	2	7.7	15.0	5.9	lines of PDMS on side; moderately shifted
	3	8.2	15.1	2.9	very shifted

Project No. 12

Amount of PDMS (µL)	**Trial #**	**Inner Diameter (mm)**	**Outer Diameter (mm) (if any)**	**Focal Length (mm)**	**General Observations**
90	1	???	10.9	**unmeasurable**	line of PDMS; very demented
	2	8.5	11.0	2.2	very shifted; demented; splattered
	3	8.0	10.8	2.2	very shifted; demented
100	1	9.1	11.0	8.0	shifted moderately
	2	9.0	10.8	9.5	very shifted
	3	4.0	11.0	4.2	shifted, pointy

110	1	~7.3?	12.2	9.3	line of PDMS; demented; splattered
	2	9.0	12.2	6.1	line of PDMS; splattered; very shifted; a bit elliptical
	3	???	12.2	**unmeasurable**	line of PDMS; very shifted; demented
120	1	8.0	12.0	4.6	line of PDMS; demented; very shifted; a bit elliptical
	2	8.0	12.3	4.2	very shifted
	3	8.2	11.8	2.8	very shifted; slightly demented
130	1	???	12.0	**unmeasurable**	lines of PDMS; very demented
	2	7.0	12.5	3.9	very shifted
	3	~9.0?	11.3	16.4	line of PDMS; slightly demented; shifted
140	1	9.5	12.2	6.7	
	2	8.9	12.0	7.8	moderately shifted
	3	7.6	12.2	5.7	
150	1	8.0	12.3	3.4	slightly shifted
	2	8.0	11.4	7.6	
	3	8.8	11.3	9.4	*has droplet on back interfering; slightly shifted
160	1	9.0	13.5	6.2	*has droplet on back that doesn't interfere
	2	10.0	12.6	9.6	
	3	9.7	12.0	7.3	slightly shifted
170	1	8.5	12.2	8.4	

	2	9.0	11.6	7.5	
	3	8.4	13.0	2.5	
180	1	8.6	14.0	3.2	
	2	9.0	10.9	8.0	line of PDMS
	3	7.2	9.3	1.6	*has droplet on back interfering; slightly demented
190	1	8.3	12.8	11.0	shifted slightly
	2	7.2	11.0	4.0	shifted slightly; splattered
	3	9.0	11.0	8.5	moderately shifted
200	1	5.4	13.2	1.4	very pointy
	2	8.0	13.0	7.2	
	3	~8.8	~10.9	7.6	a bit shifted; elliptical
*Note: if any droplet was on back and interfering with focal length measurements, it was removed carefully with a razor blade					