Holography

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Theory: The theory behind holography is rather straightforward and based on the fact that information recorded in the emulsion of photographic (or holographic) film is caused by the intensity, not the phase, of the electromagnetic wave incident on the film*. The loss of phase sensitivity consequently results in the loss of one degree of freedom in the information contained within the film and hence collapses the 3-dimensional image into a 2-dimensional image. Therefore if we could recover the lost phase information we would regain a 3-dimensional recording of the image. How holography goes about recording phase information on a medium insensitive to phase is with the use of two separate beams (one is the "usual" beam associated with the image to be recorded and the other is a completely separate beam known as the reference beam) and exploiting the interference pattern the two beams make on the film. It works like this:

Let

$$a(x,y) = |a(x,y)| \exp[-i\varphi(x,y)]$$

represent the wavefront of the image at the surface of the film which is in the x-y plane. Next let

$$A(x,y) = |A(x,y)| \exp[-i\psi(x,y)]$$

represent the wavefront of the reference beam at the surface of the film. The two wavefronts interfere and the resulting intensity at the surface of the film is

$$I(x,y) = |A(x,y)|^2 + |a(x,y)|^2 + 2|A(x,y)|\,|a(x,y)|\cos[\psi(x,y) - \varphi(x,y)]$$

Notice that the first two terms are simply the intensities for the individual waves and are independent of their phases, but the third term is dependent on their relative phases rendering intensity as a whole phase dependent. The film records this interference pattern and once the film is developed, the image (hologram at this point) can be

*The emulsion consists of microscopic silver halide (which is cationic Ag electrostatically bonded to an anionic halogen, usually Bromine) crystals. Electrons within the crystal lattice absorb photons, promoting them to the conduction bands within the crystals whereby they're free to combine with ionic silver to form metallic silver. When developed, if enough metallic silver is formed within the crystal then the developer will reduce (donate electrons) the entire crystal to metallic silver. The fixer then removes the remaining silver halide crystals from the film to yield the final product.

recovered by placing the film back in the path of the reference beam. So we notice that it is the reference beam which separates a hologram from a photograph in both the recording and viewing of their respective images. The reference beam is necessary for viewing the image since unlike a photograph, which is a direct recording of the image, a hologram is ***not*** a recording of the image; it ***is*** the recording of the interference pattern between the image and the reference beam. Therefore, reconstruction of the image occurs when the reference beam diffracts off the interference pattern.

One more thing to note, the type of holograms made here are referred to as transmission holograms because the object beam and reference beam are incident on the same side of the film, and reconstruction of the image occurs with the reference beam incident on the opposite side of the film from which it's viewed. The more common holograms that can be seen under white light are referred to as reflection holograms and are created when the object and reference beams are incident on opposite faces of the film. This creates a 3-dimensional interference pattern in the emulsion (consequently, film used for reflection type holograms are necessarily thicker than film used for transmission type) and reconstruction of the image is obtained with the reference beam incident of the same side of the film as the image is viewed from. Hence the reconstructed image is created from light "reflected" off the film rather than by light "transmitted" through the film. The reason why these holograms can be viewed under white light is because Bragg's Law entails that only light of a certain wavelength will interfere constructively when diffracted off the 3-dimensional interference pattern while other wavelengths merely scatter off in an incoherent manner. That is why most common holograms appear green because even though they are created from the red light of a HeNe laser, the emulsion shrinks a bit during the development process and the resulting wavelength corresponding to constructive Bragg diffraction is decreased as well.

Set-up: Proper initial set-up of the optical instruments is paramount in creating good holograms. The coherent light source is a helium neon laser in a cylindrical waveguide. It should be securely mounted in the far right corner of the table as it most likely already is. Because the aperture through which the laser is emitted is small compared to the face of the cylinder, the waveguide acts more like a resonance cavity, which means that there are different modes of light oscillating between the two mirrored ends. We don't want competing modes when making a hologram since their interference patterns with the object beam will not be the same and they may create an additional interference pattern between themselves.

The next piece of equipment is designed to transform these temporal modes into spatial modes whereby all but the lowest order mode can be selectively blocked from the beam. The piece consists of a fixed converging lens and an adjustable pinhole. It is mounted directly in front of the laser and odds are it's probably already mounted in the correct location. If it's not, then it should be placed so that the laser is about 1½ inches from the entrance to the apparatus. The lens focuses the beam to a point and the pinhole should be adjusted until it corresponds to that point as well. The pinhole is responsible for transforming the temporal modes onto spatial modes and the lens is used to conserve as much energy as possible by focusing the beam into the pinhole. The resulting diffraction pattern created by passing coherent light through a circular aperture is a bright disk with concentric light and dark fringes. The bright central disk is the lowest order mode and each of the succeeding concentric bright fringes are the higher order modes. This central disk is the so-called Airy disk and contains 84% of the total energy of the diffracted beam, leaving the remaining 16% to be contained within the higher order fringes. This makes circular apertures the most efficient of any possible shape in terms of directing the most light into the lowest order mode.

Now, let's discuss a bit about pinhole selection. There are a variety of pinholes to choose from ranging from 1 micron to 25 microns. The choice of pinhole diameter is the result of a tradeoff between filtering and beam output. Obviously the smaller the pinhole, the smaller the amount of incident beam actually passes through. However, the equation governing the diffraction pattern, and ultimately the filtering capabilities, states that the size of the Airy disk is:

$$\theta_A = 1.22\lambda / D$$

where θ_A is the angular half-width, λ is the wavelength, and D is the diameter of the circular aperture. Therefore the smaller the diameter of the pinhole, the greater the spatial separation of the modes. I used the 20 micron pinhole for all my holograms but I would have liked to have tried the 15 micron pinhole as I found myself using filters in order to decrease the beam intensity. Whatever pinhole you decide on, it's a *very* good idea to clean it first in the ultrasonic bath located in the lab; it made a huge difference for me.

The pinhole magnetically attaches to the apparatus via the ends of the two adjustment devices used to move the pinhole around in the plane normal to the beam. The two adjustment devices look a lot like micrometers and function similarly. A third adjustment device oriented parallel to the beam moves the pinhole back and forth along the beam axis. This gives the pinhole 3 degrees of freedom for proper placement at the focal point of the beam. The process of properly positioning the pinhole is iterative, so adjust each knob individually. Once optimal output is reached from the adjustment of one knob, it can generally be left alone and adjustments on the remaining knobs can be performed accordingly. Now, take a look at the pinhole (always hold the pinhole by its extended leg, otherwise you may find yourself having to clean it again; for it doesn't take much dirt or oil to clog a 20 micron hole) and notice how one side is flat and the other is conical. The beam should be incident on the flat side, i.e. the beam enters the flat side and exits the conical side. This is important because if the laser is incident on the wrong side you'll find that you won't be able to bring the pinhole into the focal point, the mechanism of the apparatus simply won't adjust back far enough to do so. I initially had the pinhole flipped the wrong way and was unable to get any decent output until I changed it. One last thing, this is the touchiest part of the entire set-up, so spend some time positioning the pinhole so that the diffraction rings are clear and distinct and the Airy disk is bright and well defined. There is a large white disk that can be mounted to the table that should be used initially for most of the adjustments. You can see very clearly on the surface of the disk what the diffraction pattern looks like, and if the pattern is not circular then the pinhole probably needs to be cleaned. Once you think you've positioned the pinhole properly, mount the power meter in front of the beam and make any final adjustments to maximize the output. Once the pinhole position has been optimized, check that the beam height remains constant and isn't being deflected up or down. I used the clear right triangle and marked the beam height on it directly in front of the pinhole. Then I moved the triangle all the way to the far left edge of the table to make sure the beam hadn't drifted anywhere. It shouldn't be a problem assuming the pinhole is properly positioned, but if the beam is drifting up or down you're going to have a difficult time positioning the mirrors. If the beam is drifting and you suspect the pinhole is not at fault then the problem may be in the mounting of the laser. Use a level to determine if the laser is at fault and make any needed adjustments accordingly.

The next apparatus to be mounted is the shutter. The shutter is responsible for blocking out the higher order modes and only allowing the Airy disk to pass. It is also used to expose the film as a black compression ball is attached to manually open and close the shutter. There are two rings surrounding the shutter used for adjustments. The larger ring closer to the plate holding the shutter can be turned to adjust the shutter diameter. First mount the shutter about 2½ inches from the edge of the apparatus housing the lens and the pinhole. Next adjust the shutter so that the center of the shutter opening corresponds to the center of the Airy disk. Finally, with the ring adjustment, open the shutter just enough to let the Airy disk through while blocking the rest of the modes. You're far better off blocking some of the outer edge of the Airy disk than not for two reasons. First is that you definitely do not want any of the 1st order mode transmitting through and because the shutter opening is not exactly circular, if you try to open the shutter so that it resides in the 1st dark fringe you'll probably let some of the 1st mode pass. Second is that the intensity of the Airy disk looks somewhat like a gaussian with the intensity at a maximum in the center and then falling off to zero as it approaches the 1st dark fringe. By blocking the outer edge of the Airy disk, the transmitted beam has a more uniform intensity. Having a uniform intensity beam is *very* good because the intensity of the beam governs the exposure time of the film. If the beam consists of a gradient of intensities then the result will be that portions of the film will expose too much while other portions won't expose enough. So shutter diameter is a tradeoff as well between beam uniformity and beam area. If the beam area isn't large enough then the reference beam won't cover much of the film and the object beam may not cover the entire object. For my holograms, I closed the shutter just enough so that all corners of the shutter opening were contained within the Airy disk, basically letting almost the whole disk through. You may want to try closing it slightly more and see what kind of holograms can be produced. Once the shutter diameter has been adjusted, the next adjustment to be made is the shutter speed. The outer ring on the shutter adjusts the speed the shutter opens and closes. The numbers marked on the perimeter indicate what fraction of a second the shutter remains open, e.g. 1 corresponds to 1/1 or 1 second, 2 corresponds to ½ of a second, the 50 corresponds to 1/50 of a second and so on. Following the numbers are two letters, B and T. B corresponds to the shutter closing instantly after being opened and most likely won't ever be used. The T corresponds to the shutter never closing, which means that the compression ball has to be squeezed a second time in order to close the shutter. Essentially the T corresponds to manual opening and closing of the shutter requiring the compression ball to be squeezed twice, while the other settings correspond to manual opening and automatic closing, requiring the compression ball to be squeezed only once. I used the T setting exclusively and timed my own opening and closing interval for all my holograms. However, in hindsight I wished I had used the automated settings since towards the end most of my exposure times were between .5 and 1 second anyway. For now, leave the dial on T because you'll need the shutter open for the rest of the set-up.

The next instrument to be mounted inline with the beam is the beam-splitter. The beam-splitter can be mounted anywhere after the shutter, but I found that mounting it about 8½ inches past the shutter provided a good location for keeping the object and reference beams' path lengths the same. Mount the rod holding the beam-splitter out of the beam path on the far side of the table. For obvious reasons you don't want to mount the rod inline with the beam and you don't want to mount the rod closer to you because when the beam-splitter intersects the beam it will send the reflected beam off to the far wall. In my set-up, I had the apparatus that holds the rod mounted in at the 2nd and 4th screw-holes from the far edge of the table. Make sure the beam-splitter is mounted high enough so that the beam is incident on the bottom of the splitter and that the black mounting apparatus connecting the splitter to the rod is above the beam. The reason for this is to give you the most freedom of how far you can turn the splitter. If the laser is incident on the side of the splitter then you can't swing the splitter around very much before it is either no longer in the beam's path or intersects the beam with the large black knob protruding from its center. Once the splitter is properly mounted, the beam transmitted through the splitter is the reference beam and the beam reflected off the splitter is the object beam.

Now that the splitter is mounted, the next apparatus to be mounted is the filter holder. The holder holds neutral density filters in the path of the reference beam to attenuate the beam intensity. The filters come in a range of densities and I primarily used the 0.90 density filter for my holograms. Mount the holder with the leg horizontal, parallel to the table, and pointing towards the far wall. Attach the leg to a rod, which is fastened to one of the mounting instruments that you can screw into the table, with one of the various devices used to secure rods at 90° to one another. Mounted in this fashion, the clips that hold the filter should be pointing toward you allowing you easy access to inserting and removing the filters. Make sure the holder does not obstruct the beam in any way and is oriented so that the filter is normal to the beam. In my set-up, I had an additional holder mounted in front of the beam-splitter to attenuate both the object and reference beams when I was making holograms of the drumhead, in an attempt to mitigate the speckle affect off the metal diaphragm. In the end though, it didn't produce exceptional results and I don't think it's really necessary.

Next mount a mirror in the path of the reference beam. This mirror should be mounted as far to the left side of the table as possible. By doing so, the reference beam is given more distance to diverge so that when it does arrive at the film it will be more spread out. In addition, the extra path length will allow more freedom in the placement of the object mirror, film, and the object itself while still maintaining equal path lengths. Check that the mirror intersects the whole beam. This is done by using the square white cutout (it's made of really stiff paper and should be lying around somewhere in the room) with cross-hairs drawn in pencil on it. Place it close (but ***not touching***) in front of the mirror to gauge its location. Then use it to look at the beam reflected off the mirror and compare if the beam shape is the same or if some has been lost. The easiest way I found was to touch the square to the **side**, again not touching the front, of the mirror and sliding it all the way around the circumference; if I saw any light on the square then I knew the mirror was missing some and if I didn't see any light on the square then I knew the mirror got it all.

Since we're discussing the mirrors, a few comments about them are in order. First, notice the image of these is much sharper than that of normal mirrors and that there is never any glare on them. This is because these mirrors are silvered on the outside, most are silvered on the inside. There are some key benefits associated with this. One is that glare* on common mirrors is the result of light reflecting off the glass surface before propagating to the silver; since there is no glass interface between the light and the silver, there can never be any glare off these mirrors. Another is that since there is only one medium reflecting the light, there is never any interference between the light reflected off the glass and the light reflected off the silver, since there is simply no glass to be reflected from. In our case with coherent light, this means that the integrity of the beam is maintained since there are no phase differences in the beam caused by path length differences resulting from the light reflecting off two spatially separated mediums. So while these benefits result in images that are so sharp and clear you don't even know you're looking at a mirror, there is one main drawback. And that is that these mirrors scratch very easily. That means in addition to handling them carefully, you should never touch anything, including your fingers, to their surface. It also means that they should always be screwed into the table because if they accidentally fall over they will probably get scratched. Cleaning them is performed with two organic solvents. First wash down the mirror with acetone, preferably over a wad of Kimwipes, to clean dust and dirt off the surface. Then wash the acetone off with methanol. The methanol is fairly volatile, so it should evaporate quickly. Use a compressed gas container to blow the methanol off the mirror. You can clean the beam-splitter the same way.

Placement of the remaining two components, the object mirror and the film-mount, is somewhat arbitrary, but should follow some general rules. Start out by screwing in the black film holder into the center of the film-mount and take out the plastic cover slip if it's in the film holder. I cut out two pieces of vellum paper to the exact size of the film, if they're not still around then use an old hologram as a template and cut out two more pieces of vellum paper and slide them both into the same side, on atop the other, of the film holder. This gives a nice reflective surface for determining where the reference beam is on the film holder. The height of the film holder should correspond very well

*All this about the mirrors pertains to the beam-splitter as well, which is why the silvered side of the splitter should always face the laser. If the beam is not incident on the silver first then you are effectively splitting the beam twice, once off the glass and then a second time off the silver.

with the height of the reference beam. Minor adjustments to the height of the beam can be made with the bottom knob behind the mirror. Keep in mind that you want to keep the object beam and reference beam path lengths as equal as possible, so you don't want to mount the film holder on the far right side of the table. I found that mounting it on the front of the table directly opposite to the beam-splitter about 2 or 3 screw-holes in was a good location. The object mirror should be placed directly, or very close to, one side of the film holder. The angle the object beam makes with the normal of the mirror should not be very much, although obviously it can't be exactly normal for the beam would just be sent back to the splitter. The reason is that the cross-section of the beam is only circular when normal to a surface and becomes an ellipse for all angles deviating from the normal, the eccentricity of which becomes more extreme as the angle increases. So if the beam doesn't hit the mirror fairly head-on, then the mirror won't encompass the entire beam. As for why the mirror should be placed either touching or next to the film holder is two-fold. First is to maximize the amount of light scattered off the object onto the film. Because laser light is so directional, the illumination of the object is highly dependent on the angle it's viewed from relative to the incident beam. The brightest side of the object will be the side directly facing the mirror, so having the film close to the mirror will expose the film to a brighter image of the object. The second reason is much more practical. Remember that when you actually load the film holder into the film-mount to take a hologram you'll be in complete darkness, but you've adjusted the angle of the reference mirror to place the reference beam exactly on the film *only if the film-holder is exactly replaced in its original position when you adjusted the mirror* (as well as the position of the object and adjustment of the object mirror). It's difficult enough to exactly replace the film holder in the light let alone the dark unless you have something you can butt-up the film holder against as a reference. If you initially make all you're adjustments with the film holder pressed against the mirror (the black casing that houses the mirror that is, you don't want the film holder touching the mirror itself) then when it comes time to reload the film holder in the dark, you can simply place it in the film-mount and slide it over until it touches the mirror. In any case, you should mount something against the side of the film holder, whether it's the mirror or not, so as to guarantee proper replacement in the dark. I built a little contraption out of small rods and mounted it next to the film holder so that I could have more freedom as to the placement of the object mirror. One last note, make sure that whatever is mounted against the film holder is ***not*** mounted on the side that the cover slip slides out from; otherwise, in the dark you'll find that the cover slip is blocked and merely flipping the film holder around doesn't relocate it in the same position.

At this point, a good place to mount the film-mount is, as stated earlier, in the front of the table opposite the beam-splitter, and a good place to mount the object mirror (or other contraption you've chosen as a film holder reference) is butted-up against the **right** side of the film holder. If you've opted for something other than the object mirror as a film holder reference, then mount the object mirror to the right side of that but still as close as possible to the film holder. The reason for placement on the right side is because it's generally a good idea to keep the angle subtended by the original beam incident to the beam-splitter and the object beam less than 90°, otherwise it's difficult to place the object in front of the film without obstructing the object beam. It's also a good idea at this point to turn the lights off and crack the door open a bit to better see (with the safety goggles on of course) exactly where the beam is. Turn the beam-splitter so that the object beam is entirely reflected off the object mirror and adjust the film holder so that it's roughly facing the space between the splitter and the shutter. Now adjust the reference mirror so that the reference beam is centered on the vellum paper encased in the film holder. Notice the reference beam is incident on the film holder at a fairly severe angle to the normal. This is good, and here's why. The angle subtended by the reference beam and the light scattered off the object must be greater than a particular minimum angle governed by the equation which states:

$$\theta_{min} \geq \tfrac{1}{2} \arcsin(B\lambda)$$

where θ_{min} is the minimum angle, B is the *spatial* frequency of the object in cycles/mm, and λ is the wavelength. There's no need to actually try and calculate this, just know it exists. A good rule of thumb is that the minimum angle subtended by the reference beam and scattered light off the object should be greater than the solid angle the object subtends at the surface of the film. By having the reference beam incident at a large angle you virtually guarantee avoiding any problems. If you were to position the plate so that the reference beam and the image were incident at nearly the same angle, so that the angle was less than θ_{min}, you would run into what is known as the twin-image problem. The twin-image problem occurs when the real and virtual images created by the hologram overlap, and it's caused by cross talk between the interference patterns for the two images. Another more practical reason for having the reference beam incident at a large angle to the film is that it spreads the beam more uniformly across the film. The more severe the angle of approach of the reference beam to the film, the less of a gradient of intensities there is across the film as well as more film area is exposed. This helps eliminate a common problem you can see on a lot of the holograms where the center is so exposed that you can't see through it while the edges aren't exposed at all; you can only catch glimpses of the image outside the opaque center. It's certainly possible to have the reference beam approach at such a severe angle that the film, and film holder, can't intercept all of it, but the risk you run with that is having some of the reference beam incident on the object mirror. Basically you want the angle large enough to spread the beam over all the film without being so large that the beam is surpassing the edges of the film holder. On a final note, place a 0.90 neutral density filter in the filter holder, twist the beam-splitter so that the beam is incident on the most silvered portion of the glass (i.e. so that most of the beam is reflected into the object beam as possible), shut off all the lights and close the door, and look at the reference beam intensity on the vellum paper in the film holder. I've found that for most standard holograms, excluding the drumhead, the best reference beam intensity produced a soft dull glow on the vellum paper, almost like nothing was shining on it at all but that the paper itself was glowing. If you can't see anything at all then switch to a lower density filter. If the paper appears fairly bright then you may want to switch to a higher density filter. In any case, clean the filter with acetone and methanol to eliminate diffraction ***but be careful, acetone will eat through the black outer casing of the filter!***

Now comes the time to actually measure the path lengths, this will tell how far from the object mirror and film holder the object needs to be placed. Before doing so, it needs to be said why the path lengths need to be equalized. Every laser has what is called a coherence length for the beam it emits. It's a quantum mechanical ramification of the Heisenberg uncertainty relation corresponding to trying to produce a delta function in frequency space; it simply cannot be done. The output of any laser can never be exactly monochromatic, it will always be some gaussian of frequencies no matter how good the laser. The coherence length for a laser is a function of the type of laser it is (gas, solid state, semiconductor, optically pumped ruby, etc.) and the actual construction of that particular laser. Therefore it's a measured quantity unique to each laser. It's the distance the beam can travel before it loses phase coherence with itself. In other words, it's the shortest length along any beam in which the two points defining that length are no longer coherent in phase. It's measured by using the laser in an interferometer and increasing the path length difference until light and dark fringes are no longer obtainable, and it is at that length that fringes are no longer obtainable that is defined to be the coherence length for that laser. The coherence length for the HeNe laser used in the lab has not been measured, and I've found conflicting information from sources I researched as to the average length for a HeNe laser ranging from .5mm to 8 inches. The only thing that all the sources I've read have emphatically agreed on is to make the path lengths the same. The point of all this is simple, ***Equalize The Path Lengths!*** The easiest way I've found to do so is by changing the position of the object, which is certainly a lot easier than re-mounting any of the instruments. Do this by using a string and the ruler. Pull the string under the beam-splitter at the point the beam is incident and pull the other end to the reference mirror centered where the beam hits and at a constant height above the table. Use this string against the ruler to measure the distance. In my set-up, the beam-splitter to reference mirror distance was 11¼ inches. Do the same to measure the distance from the reference mirror to the center of the film holder. This distance for me was 15 inches. Next measure the beam-splitter to object mirror distance. The difference between the sum of the splitter/reference mirror and reference mirror/film holder distances with the splitter/object mirror distance gives the remaining path length to be traversed from the sum of the object mirror/object and object/film holder distances. For instance, in my case the reference beam distance was 11¼ + 15 = 26¼ inches. My splitter/object mirror distance was 15 inches. Therefore 26¼ - 15 = 11¼ inches to traverse the remaining difference (the fact that the two pairs of numbers turned out to be the same was mere coincidence). I positioned the center of my object (the typewriter ball) 7 inches from the object mirror and 4¼ inches from the center of the film holder for a total of
15 + 7 + 4¼ = 26¼ inches, equal to the reference beam distance. You get the idea.

One final piece remains to be placed. You'll notice that even when the shutter is closed, a lot of stray beam is scattered off the lens and pinhole apparatus. This stray light needs to be eliminated so as not to expose the film when making a hologram. I spent some time making an exact cutout out of black felt that wraps around the apparatus with holes for the adjustment knobs and switching mechanism on the shutter to protrude through. It starts at the shutter and extends all the way across to the laser, and can be completely wrapped around all of it and secured with tape. When properly fastened, it completely blocks any stray light from escaping and I highly recommend using it if it's still around.

If it has somehow managed to find itself elsewhere, then you will need to construct something of your own that eliminates this stray light. In either case, be sure not to accidentally move any of the adjustment knobs for the pinhole; for you probably don't want to go through that whole process again.

Once you've eliminated all the stray light, you're just about ready to make a hologram, but before you do, the issue of relative beam intensities needs to be addressed. The information given from various sources couldn't possibly be more conflicting than when it comes to this topic. Some sources say that reference/object intensity ratios of 3:1 or higher are required to have a sufficiently high signal to noise ratio to produce a good hologram. Other sources state that for transmission type holograms, 96% of the beam intensity should be directed into the object beam with only 4% directed into the reference beam; this is a 24:1 object/reference intensity ratio. I can say from experience that if you use a 3:1 reference/object intensity ratio, the only holograms you'll be making are of some really charred film. The source of confusion seems to stem from what is being considered as the "object beam" and mistaking it for "light scattered off the object." Using the typewriter ball atop the metal block for the object, position it at the point you've previously determined in the set-up. If the beam-splitter is not already in the correct position, twist it so that the beam is incident on the most silvered side of the glass directing the most light into the object beam. Now, with all the lights off and the object mirror directing the beam at the typewriter ball, look at the shadow made by the object beam on the far wall. Notice how the object really doesn't intersect all that much of the beam, as deemed by the size of its shadow relative to the rest of the beam. And of the light it does intersect, most of that light is not scattered onto the film; consider the very fact that you can see the ball at all, and from all sorts of locations, none of that light ever finds its way to the film. So once the beam is split, the fact that the relative intensity of the object beam may be much higher than the post-filtered reference beam, does not entail at all that the intensity of the beam scattered off the object onto the film will be higher than the reference beam. In this light, both sources could be correct, for starting with a 24:1 object/reference intensity ratio may very well end up as a 1:3 light scattered off object/reference intensity ratio. You'll find that for most of the holograms you're going to make, objects like the typewriter ball and the light bulb, that you'll want the beam-splitter directing as much light into the object beam as possible as well as further attenuation of the reference beam with a filter. The only exception to this is the drumhead. The drumhead is different because it is large enough to intersect the entire beam, and not only that, the flat metal diaphragm is shiny and very proficient in reflecting incident light. In a sense, the drumhead doesn't scatter light but rather re-directs it. See for yourself by shining the object beam on it. The metal diaphragm looks very dark until you get close to looking at it at the same angle of incidence to the normal as the beam, and you'll know when you're at the same angle of incidence as the beam because it will be too bright to even look at. In this case, you need to increase the reference intensity and decrease the object intensity because most of the object beam is actually reaching the film. In general, if the holograms being made are too dark then either the exposure time or the reference intensity needs to be decreased. If the holograms are light but no image is formed then either the exposure time or the object beam needs to be increased.

Procedure: Now that the set-up is complete, the hardest part is over. Assuming that the object is in place and all the mirrors are properly oriented, make sure the shutter is closed and the door is completely shut with all the lights off. The procedure for making a hologram will be as follows.

1) In the dark room with the door closed, remove a single film and locate the cutout notch in the film. Orient the film so that the notch is on the bottom right corner of the film. Basically, hold the notch between your thumb and index finger of your right hand and slide the left side of the film into the film holder. The film is directional and this guarantees the proper orientation for exposure. Finally, slide the cover slip into the film holder over the film.
2) Proceed into the hologram room and locate the film-mount carefully with your hands. Place the film holder into the film-mount and slide it over until it touches your film mount reference. Now secure it in place with the film-mount screws
3) Slide the cover slip out just enough to reveal the entire film, you can feel with your hands when the cover slip is no longer covering any of the film, but don't remove it completely.
4) Locate the compression ball and while sitting on the chair, roll away from the table a few feet and sit still for 45 sec to 1 min.
5) Squeeze the compression ball to open the shutter, wait for 1 sec, and squeeze it again to close the shutter.
6) Slide the cover slip back into the film holder and remove the film holder from the film-mount.
7) Proceed to the dark room and shut the door to guarantee no stray light reaches the film. Remove the cover slip, open the film holder, and remove the film.
8) Locate one of the metal film holders used to bath the film in the developer. Twist the metal opening, slide the film in place, and close the metal film holder. Now place the film in the developer, the film holder will suspend it in the solution.
9) Immediately after placement in the developer, set the large fluorescent timer to 6 minutes and wait until the time expires.
10) When the time is up, remove the metal holder from the developer ***and remove the film from the holder***. Place the film in the acetic acid bath for 30 seconds, agitating the water if you feel inclined to do so.
11) Now place the film in the fixer. After about 30 seconds in the fixer, you can safely turn the lights back on. Leave the film in the fixer for another minute, agitating the solution with the film tongs. Don't actually grab the film with the tongs though, they leave nasty marks that don't come off; you can see tong stains on many of the previously made holograms.
12) Finally, place the hologram in the water bath and let it sit for about 10 minutes. Agitate periodically to remove the pink residue from the fixer. Remove and place on the wood rack on the floor to dry.

The main point of concern in the development process is *not to mix the developer and the fixer.* I accidentally did this by using the metal film holder to place the film in the two solutions without removing it and it ruined every hologram. You certainly can't hurt the hologram by leaving it in the water for too long, I left many in overnight and I'm convinced they turned out a little better. You'll get a feel for how long the holograms need to be exposed for, but 1 second is certainly a good place to start. You'll also find it's easier in the dark to sit in a chair the whole time and roll yourself around.

One rather interesting last note to consider. I noticed that the best holograms I made were late at night, and while the ones I made during the normal daylight hours were good, they just didn't quite compare. I was here all night once when I noticed that the ventilation systems for the building turned on early in the morning and ran all through the day, but turned off in the evening and remained shut down through the night. Now the business of making holograms is extremely sensitive to motion, and any movement on the order of half a wavelength (which for red light is somewhere around 350nm) will ruin the hologram; that's why in the procedure you're asked to sit still for awhile before opening the shutter. It's certainly possible that convection currents change the optical density of the air through regions of the beam enough during the exposure to produce such wavelength shifts. So having the vents blowing huge volumes of air around while you're trying to make a hologram may have some ill consequences. I say this because the motion of air around the room may have caused the root of my observation, and you may want to alleviate this if you notice the vents are on. You'll find a large wood and plastic contraption in the room, it's used to encase the entire table and settle any air motion inside. It is placed atop the four large rods on each corner of the table with sheets that are draped along the sides. The extra plastic on the sides can be taped to the table and taped to each other. You may want to consider using it, for someone didn't go to all the trouble to make if they didn't think it was that important, and I didn't go to all the trouble to fix it if I didn't either.

Final Thoughts: If there was one thing I would say was the single most important rule for making a good hologram it would be by far that the path lengths need to be equal. Nothing else you do will make any difference if they're not. Also, the guidelines laid out in the set-up are not carved in stone, but should certainly provide a really good place to start. If I had more time there are a few things I would have liked to have tried. One is that I would have liked to use the 15 micrometer pinhole; the smaller hole would have produced a larger diameter Airy disk that would have spread out more uniformly on the film and I wouldn't have had to loose so much reference beam energy to the filter. Another is that I would have loved to get by hands on a beam expander. The problem with the filter is that it attenuates the entire beam so that the center of the beam is still more intense than anywhere else. What really needs to be done is simply spreading that intensity out evenly over the entire film. An expander placed in the path of the reference beam after it's been deflected off the mirror would solve the whole problem and eliminate the filter and severe angle requirements altogether. I really wish I would have used the automated exposure time on the shutter, I got so used to doing it manually that I forgot all about it and I think it would have eliminated one more source of error. I would also have liked to make some different holograms. It wasn't until the very end that I discovered that you could take multiple holograms on the same film by changing the reference beam angle for each new exposure. I was only able to make one where the image is the light bulb with the reference beam approaching from the far left and the typewriter ball with the reference beam approaching from the far right. The possibilities with this are nearly endless, and I'd encourage you to explore them. This is a very cool lab station to be working at and once you become proficient at making the standard holograms, try making some that have never been tried here. Who knows what will happen, at least you have the opportunity use your own imagination instead of simply following the same mundane procedures everyone else has in the past.