Pinhole Photography

A Guidebook for Teachers

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Preface

Photography is everywhere in our society. We are constantly involved with still pictures in newspapers, magazines and billboards. Virtually everyone has personal experience in creating pictures. However, due to the advanced state of photographic technology, practically the entire process is hidden from the operator. With modern cameras, photography is reduced to a single button and a drop off at the local department store.

Yet photography is particularly rich in examples of the principles and basic processes of physics and chemistry. Study of photography is a way students can not only experience the hidden technology of photography but also many general principles of physical science. Since photography is so commonplace in our personal experience, this study can be extended to it's role as a scientific tool, in journalism, art, and society in general.

Pinhole photography is an inexpensive way students can gain this experience. It also provides for some of the most direct hands-on experience of the underlying principles.

Making pictures with as simple a device as a pinhole camera is a somewhat magical experience. The fact that the cameras can be made by the students themselves increases their involvement in the lesson.

The concept that images can be created by a pinhole aperture goes back to antiquity. Natural examples of the effect are not unusual. Looking at the circles of light dancing around beneath a tree on a sunny day, it's not obvious that they are actually projected images of the sun. During a partial solar eclipse, however, those circles take on the shape of the crescent of the sun.

Once when I was in college, while sitting in a darkened room waiting

Crescent shaped images of the sun during a partial eclipse projected on the sidewalk by the small gaps between the leaves of a tree. (courtesy of Merlin Passow) for a slide lecture to begin, on the wall opposite the shaded windows, the class suddenly noticed the image of cars driving by on the street outside, projected by a small gap in the curtains. This must have happened with some regularity since prehistory. (The word camera comes from the Italian *camera obscura*, for darkened room.)

We know the principles involved have been generally understood from the writing of the ancient Greeks. Leonardo da Vinci devotes a section in his notebooks to the phenomena. Images projected by small apertures (and later, lenses) were used by artists to create more realistic paintings.

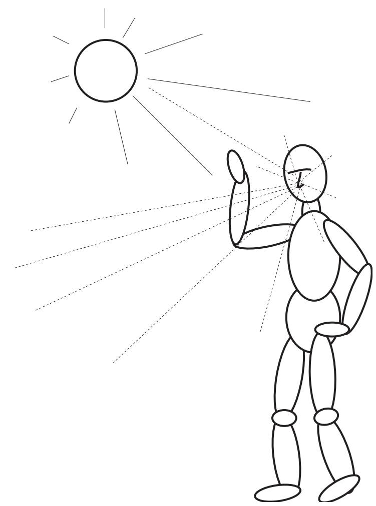
I have worked with pinhole photography with children as young as third grade. If working with an older partner, I think even kindergartners could benefit. The experience could be compressed into a rather intensive single day, or with additional experiments and demonstrations of the general physical science principles involved, could provide the outline for an entire semester.

Creation of an Image.

When we are looking at a scene, we are not sensing the objects in the scene directly, but only the light reflected from them. A scene also might include the light sources themselves, and equally important, areas which are not illuminated at all. A scene is made of an infinite number of points of different brightness levels.

Each point in the scene is most likely illuminated by several light sources, each contributing to the brightness of that point. In an outdoor scene, the main source is, of course, the sun, but the rest of the sky, and light reflected off of the rest of the scene also contribute to the illumination.

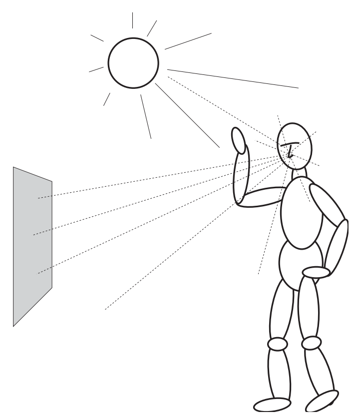
The illuminating light is reflected from the point in all directions. This is easy to demonstrate. I can look at an object from one position, and then move to a new position and still see the object, because the light is reflected off the object and to my eye in both directions.



Light reflected off an object scatters in all directions.

When we create an image, (either with our camera or with our eyes) we are seeing only that light which has traveled in a straight line from the object to us. It’s easy to demonstrate that light travels in straight lines. If I put an opaque object between me and the object I was looking at, I can no longer see the original object, because the light can’t curve around it. Light sometimes behaves as though it were a stream of particles, and sometimes as though it were a wave. This characteristic of traveling in straight lines makes it seem like a stream of particles.

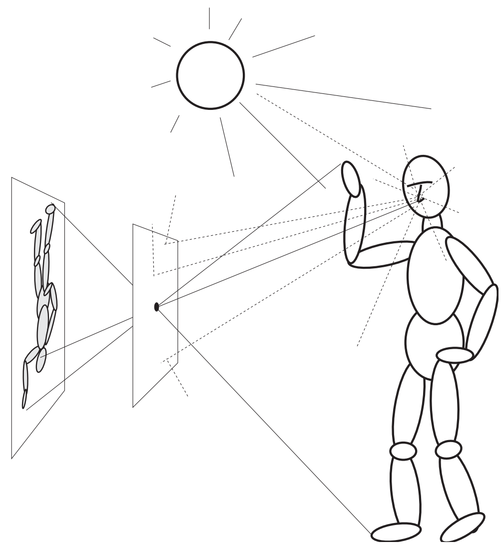
In order to create an image, for each point in the original scene, we have to create on a two dimensional surface a point of corresponding brightness. The composite of all these points then creates the image. If you just hold up a white card, no image will form, because each point in the original scene will illuminate (or not depending on the point in question) all points on the card, creating a uniform grey.



Light reflected from a point will not form an image, but will just evenly illuminate a surface on which it falls.

In order for an image to form, we need to restrict the light from our point source to illuminating only a corresponding point on the image plane. Most typically, in a camera, we use a lens to bend the light which has spread out after reflecting on the point on our object, to form back into a point in our image. A curved mirror can also accomplish this same task, as in a telescope.

A third way to create an image is to restrict the opening through which the light can pass so that only a very narrow beam of the light reflected off the object can fall on the image plane. Since light travels in straight lines, it will continue in this narrow beam, illuminating a tiny point. The composite of all the points in the original object, illuminate corresponding points on the image plane, forming an image.



Because the pinhole aperture allows only a narrow beam of light to pass, each point in the scene creates a corresponding point on the film .

The larger this hole which restricts the beam of light is, the larger the points projected on the back of the camera will be, and the more they will overlap, and the less sharp the image will be, so the hole we use needs to be pretty small, typically described as a pinhole.

There are practical differences in using a pinhole to create an image from using a lens or a curved mirror.

Principally, the lens gathers light from a large area and concentrates it creating a much brighter image. Since this is quite an advantage, all manufactured cameras use lenses to create an image.

However the pinhole has several advantages which we can exploit in order to explore the science of photography.

Lenses are fairly difficult to manufacture, and must be mounted in the camera rather precisely, in both distance from the film and in alignment. The tolerances for a pinhole which will form an acceptable image are easily within the capabilities of elementary school students, as well as being inexpensive enough to provide each child with their own apparatus. Most of the practical and scientific considerations in photography are also at their simplest using a pinhole camera.

The pinhole aperture.

The pinhole is made in brass shim stock, .002 inch thick, available in some auto parts stores, and in hardware stores. This material is thin and soft enough to easily drill a hole through, yet rigid enough to maintain a sharp edge. If this material is unavailable ordinary aluminum pop cans can be cut up. The aluminum is a little thick, but an acceptable pinhole can be drilled in it. Heavy duty tin foil is a little soft, but can be used as a last resort.

The important characteristics of the pinhole are its size, circular shape, and smooth edge.

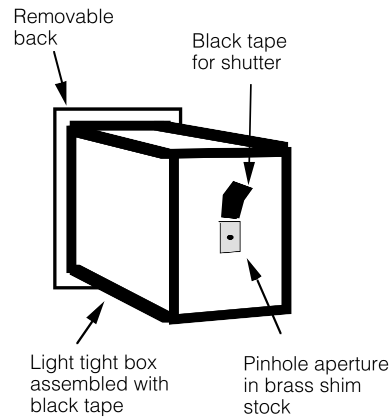
Since the image is formed by restricting a beam of light to form a point on the image, the sharpness of the image is directly related to the size of the pinhole, therefore we want as small an aperture as possible for maximum sharpness.

There other considerations. The amount of light we're letting in, therefore the brightness of the image, is also directly proportional the size of the pinhole. If the pinhole is too small, it will take too long to let in enough light to make an exposure.

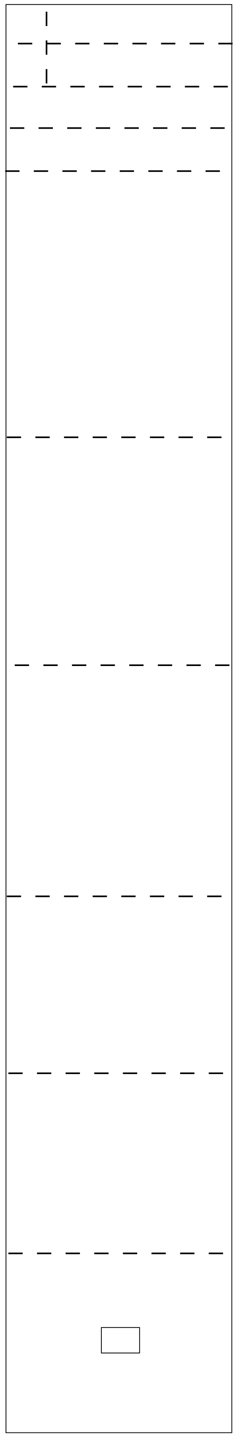
There is another limiting factor on the minimum size of the pinhole related to the wavelength of light. (Here light is acting as though it were a wave). If the aperture is too small, the light will be bent, or diffracted, as it passes through the pinhole and will spread out reducing the sharpness of the spot projected on the image. There are several factors involved, but its interesting to note that it's possible to actually construct something that is restricted by the wave-length of light, a quantity generally considered to be too small for human perception.

Because of these diffraction effects, it's also important that the pinhole be as round as possible, with as smooth an edge as possible. The effect of diffraction can be perceived by viewing a bright light source through a window screen at night. The diffraction pattern caused by the window screen will create four spikes extending from the light source.

The optimum size hole for our purposes can be made with a number 10 sewing needle, (.49 mm or .018 inch in diameter). Images can be made with up to a number 7 needle (.7mm or .026 inch in diameter) but they will be less sharp. In situations where shorter exposures are more important than trying to get the best image, larger apertures are useful. This will be covered more completely when we



A pinhole camera



All the parts in one 5 inch wide strip

discuss exposure. The size of the image and the focal length, also to be discussed later, also affect what the optimum size of the pinhole could be.

It’s much easier to handle if the dull (eye) end of the needle is pushed into a pencil eraser with a pair of pliers. Try to get it centered and parallel with the pencil, since it will be used as a drill. Since a #10 needle is fairly delicate, leave only about a half inch exposed. (Keep close track of these pencils, since the needle is hard to see when placed like this.)

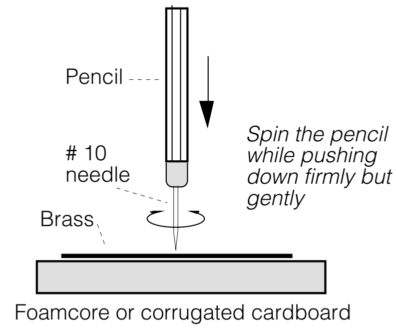
Place a one inch square piece of the brass shim stock on a couple layers of corrugated cardboad or on some styrofoam. With the needle/pencil, using slight pressure and rotating it back and forth, **drill** a hole in the brass. Just pushing it through will tear through the metal creating a non-circular hole, with more of a spur and more rough edges than you want, and might bend the needle. With a piece of fine emery paper, polish off the slight spur that was created on the other side to create a nice, smooth, circular pinhole.

It’s actually pretty easy to do this well. It's a nice reinforcement to have the students inspect their pinhole with a 10x magnifer or low power microscope to see if it's smooth and perfectly circular. Putting the needle back in and spinning it might be necessary to remove any tiny rough edges left.

Construction of the camera.

Many designs for a pinhole camera are possible. Probably the most common in the literature involves the use of an oatmeal box. (When was the last time you bought oatmeal in a round box?) The primary characteristics of the camera are a round pinhole, and a light tight box which can be easily loaded and unloaded with film. Although a little more difficult to construct than the oatmeal box camera, the design proposed here is intended to be uniform, constructed from readily available materials, uses a common size of photographic material, and illustrates the principles of optics without complication.

The box is constructed from card stock which is black on at least one side. The black side becomes the interior of the camera and prevents light being scattered on the inside of the camera. (Look at the inside of your commercial camera. It's also matte black.) If you used a pre-made box, it's necessary to paint the inside matte black. The box is made from three 4" x 5" rectangles, two 5" x 5" rectangles, one 5" x 6" rectangle, two 1" x 5" strips and two 1" x 4" strips. All the parts of the box can be cut with a paper cutter from 5" wide strips of the stock.

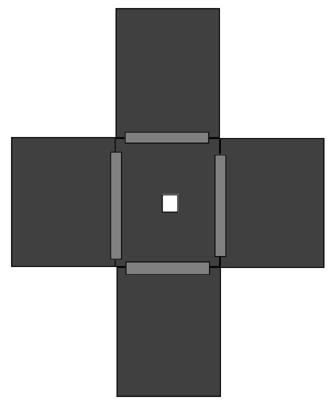


Drilling the pinhole

It's assembled with black masking tape in order to make the seams light proof. It can be easily torn with bare hands, but it's only available from larger art supply houses and is more expensive. Also since black masking tape isn't perfectly opaque it's necessary to use a couple of layers on both sides of the seams. The most effective tape is black photographic masking tape. Electrical tape is okay, but doesn't allways stick really well.

Step 1 *The front of the camera*

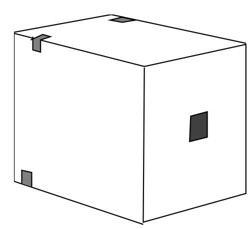
On one of the 4" x 5" rectangles, a hole has to be cut in the center in which the pinhole should be mounted, about a half inch square. It's important that this hole be exactly in the center, easily identified by drawing diagonals from corner to corner. There's no way getting around the necessity of using a craft knife of some kind to cut this hole, so close supervision of this step is necessary. This piece becomes the front of the camera.



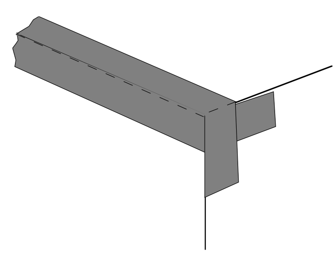
Starting the box

Step 2 *The box of the camera*

Lay the front of the camera, black side up, with the two 5" x 5" rectangles against the 5" sides and the two remaining 4" x 5" rectangles against the four inch sides to form a cross (black sides up). Tape the seams together. Then fold the sides up and tape them together to form the box. Then tape over *all* the seams. Pay particular attention to the corners. The corners are made by using a strip of tape slightly longer than the seam. Place it on the seam, and then split the part which extends beyond the box with scissors. Then fold one part in one direction and the other in the other to form a tight corner. Perfect neatness isn't important, the main thing is to make the seams absolutely light tight.



The box



Corner taping

This is a good point to pause and get some idea of the angle of view of the camera. By looking into the box through the hole in the front of the camera, the back of the box will frame the view your pictures will contain. With the 5" focal length and 4"x5" picture, the view is somewhat wide angle, not unlike the lenses on point and shoot 35mm cameras. Notice how close you have to get to fill the frame with a smaller object like a person's face. Go around and practice composing pictures and note how far away you were to get the view you wanted. Since the finished camera has no direct way to view the scene to be photographed this experience will help getting the picture you want.

Now attach the pinhole in the center of the hole in the front of the camera and firmly tape it down.

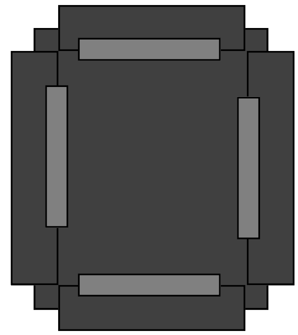
It really doesn't matter whether the piece of brass is attached to the inside or outside of the box. Attaching it to the inside of the box is preferable since it helps insure that it won't accidentally get pulled off when removing the shutter or just in handling it generally. However it's a little difficult to manipulate the small piece of brass inside the confines of the box and get it attached and taped down without any gaps. If you decide to put it on the outside, just make sure it's firmly attached so it won't get pulled off. Be sure not to cover the pinhole itself.

It's a little tricky to get it right, but on a sunny day you can actually see the image formed by the pinhole. Tape a piece of wax paper across the back of the camera to form a projection screen, and wrap your head and the camera in a coat or jacket with the front of the camera sticking out. Viewing a white building or other bright object makes it easier. Remember that your eyes can only focus down to about eight inches so you have to hold the back of the camera at least that far away to see an image.

A good demonstration technique might be to create a larger camera, perhaps out of a case of copier paper, using larger pinhole (a sixteenth of an inch or so) with a wax paper or tracing paper screen in the back. The front of the camera could be attached to the classroom window and the shades drawn around it so the students could see the image projected by the pinhole. If you’re lucky to have a classroom that can be sufficiently darkened, using a larger aperture, maybe a quarter inch, you can project an image on the wall opposite the window.

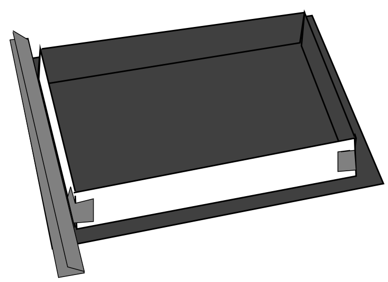
Step 3 *The removable camera back*

The removable back of the camera is constructed from the 5" x 6" rectangle and the 1" strips. Centered on the back of the camera, draw a 4" x 5" rectangle. (Use the front of the camera - prior to assembly, of course.) Lay the edges of the 1" strip against these lines and tape them on with small pieces of tape, and fold up and tape the corners as with the box (black to the inside). It is very important that the back fits very snugly into the box of the camera, so at this point check the fit. If the strips are a little long, the box or back will bend if forced together creating gaps, and if too short, a gap will be left all around. If necessary, disassemble the back, trim the 1" strips as necessary or spread them apart and keep adjusting until the best fit is attained. Then tape the seams several times to make them light tight. This time you'll be working with an inside seam instead of outside. In order to get the tape tight into the corner, fold it length wise, adhesive side out, and then press it into the corner. The technique of taping the corners is similar to the outside corners of the front assembly. It might take a little wiggling to get the back inside the front of the camera the first time. The tape is stretchy enough to accomodate a less than exact fit. The important thing is that the fit is fairly tight with no gaps to let light through. Since the back of the box will take a bit of a beating getting the back in and out, once your have gotten the back fit inside the back, place a single strip of tape around the back of the box to keep the seams from coming apart.



Starting the back

A couple of strong rubber bands are a useful accessory to keep the back on tightly when loaded, not to mention keeping it from falling off.



Taping the seams on the back

The photosensitive material that's best to use in one of these cameras is photographic paper. Under safelight in the dark room, the paper to be exposed in the camera is placed inside the back. The light sensitive side should face out. The sensitive side of photographic paper is the shiny side. Paper also usually has a slight curl with the sensitive side on the outside. Although a 4" x 5" piece of photographic paper will fit fairly tightly inside the back of the camera, it's probably a good idea to put a piece of tape, doubled back on itself inside the back of the camera to keep the paper in place while transporting the camera to and from the darkroom.

Step 4 *The shutter*

The shutter is made from a piece of the black tape placed over the pinhole with a little handle created on one side so that it can be easily grasped. Exposures are made by simply removing the tape for the length of the exposure and then replacing it.

Step 5 *Testing for light tightness*

The most common cause for failure in making photographs with a pinhole camera are light leaks in the camera. It's very disheartening to come back in the darkroom, put your film in the developer and have it immediately turn black. Probably the most likely location for light leaks are those inside corners around the back, but just about any seam and corner is susceptible. Visual inspection should be encouraged. However, it's surprising how much better that visual inspection is at detecting gaps in the tape after it's been demonstrated that the camera is not light tight. Testing does require the darkroom to be set-up, but, especially with younger children, less than perfect camera construction is fairly common, so it's worth the trouble to test for it. It also demonstrates the common practice of testing scientific apparatus before use.

To check if the camera is light tight, place a small piece of photographic paper in the back of the camera. It's not necessary to use a whole piece. A quarter of a 4 x 5 sheet is sufficient. Then expose the camera to the conditions in which you expect to take pictures, five minutes or so in full sun. Remember to keep the pinhole covered and the back firmly on. Then develop the paper. If there is any kind of light leak at all, the paper will probably turn completely black. Compare the paper to an undeveloped, fixed piece of paper. Any fogging at all is grounds for improvement.

If it is determined that like leaks exist, the answer is more tape. Most often, the source of the light leak can be found by closely inspecting all the seams. Continue testing until you're certain the camera is absolutely light tight.

Light leaks sometime develop after use as the seams loosen and the tape pulls away from the cardboard. The most common problem occurs with the tape that holds the one inch strips to the back. As the removeable back is slid in and out of the box, the tape in this area gets pushed back and the strip may come loose and gaps appear. Try to get the tape in this area as smoothly pressed down as possible and keep an eye on it as the camera is used.

Decoration is an unnecessary, but appealling, final step.

Effects of focal length

One of the primary characteristics of a lens is its focal length. This is the distance from the lens at which the light from a point at infinity is bent back to form a point on the image plane. Note the specification of the point at infinity. For a closer point, the lens has to be farther away from the image plane in order to form a focused image. In a fairly sophisticated camera, the lens is mounted so that it can be moved back and forth, depending on the location of the object. In focus free cameras, the lens is fixed, but a minimum distance is specified, usually about 6 feet, at which an object will be in acceptable focus.

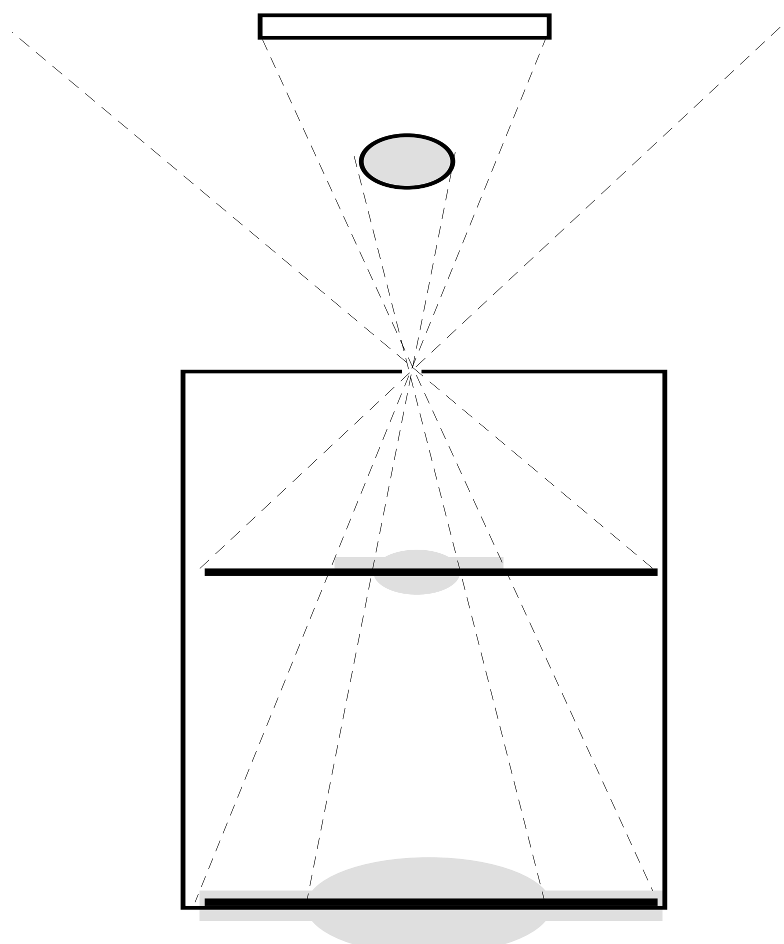
A big advantage of a pinhole camera is, since it does not form an image by *bending* light rays, objects at all distances are always in focus. This allows us to take close ups or landscapes without adustment. With a pinhole camera, the focal length is simply the distance from the pinhole to the film.

Focal length also has other effects besides focus. The angle of view of a lens, the magnification of the image, and the rendering of perspective are determined by the geometry of the distance of the objects in the scene to the lens, the distance from the lens to the the film (the image plane), and the size of the film used to record the image.

Close up pinhole photograph

If we look at two points in the scene and trace their paths to the film, they cross at the pinhole and diverge again to form two points on the image. If we move the film back farther (making the focal length longer), they will diverge farther, and their corresponding points on the picture will be farther apart, that is, the image of the object will be magnified.

Angle of view is essentially the same effect but also involves the size of the picture made in the camera. If we trace lines from the edges of the film through the pinhole, we will define an angle. If a piece of film of a certain size is placed closer to the pinhole, the angle will be larger, and if farther away, narrower. If we use a larger piece film it will have to be farther away to form the same angle as a smaller piece of film. The five inch focal length of our camera yields about a 50 degree angle of view on the



The angle of view of a pinhole camera is determined by the angles created by lines drawn from the edge of the film through the pinhole. The closer the film is the the pinhole, the larger this angle will be.

Focal length also determines magnification. If the light from two points are allowed to travel further from the pinhole, they will be farther apart when they eventually reach the film, so the image they represent will be larger.

5" width of our piece of film. The size of the negative from the ordinary 35mm camera is 24mm x 36mm or about 1.3 inches wide (When talking about a 35mm camera, the 35mm refers to the width of the film from edge to edge including the sprocket holes). The 35mm (1.3 inch) focal length lens built into the average point and shoot camera which uses 35 mm film gives an angle of view about 50 degrees on the wide dimension of the picture. Even though the focal length of these cameras is much shorter than our pinhole camera, the angle of view is the same because the size of the picture is also much smaller. The 50mm (1.9 inch) lens normally supplied with a single lens reflex 35mm camera gives about 40 degrees.

In general short focal length lenses are known as wide-angle. Long focal length lenses are referred to as telephoto and are used for magnifying distant objects.

Another effect of focal length involves the perception of perspective or the way we perceive depth. One of the main cues we have to the relative distance of objects is their relative sizes. If we see two objects which we know to be about the same size, we will consider the one which appears larger to be nearer. The greater the difference in their size, the greater we perceive the distance between them.

Long focal length lenses are thought of as compressing our perspective of depth, to make things seem closer together than they are. This is often used in films to make it seem as though a person walking toward the camera is not getting anywhere, and in portraiture to reduce the effect of a long nose.

Wide angle lenses seem to expand our impression of depth. Filmmakers often use this in chase scenes to make a car really seem to zoom around a corner, since it seems like a car coming toward the camera is moving a greater distance in a given time than it really is. With really wide angle lenses there can be quite a difference in the distance (therefore magnification) from the lens in the center of the picture and the edges of the picture which creates sort of a funhouse effect.

Again this is a simple effect of the angles created by the path of light of different points on the images. The difference in angle between two objects of differing distances is going to be minimized with a longer focal length lens and maximized by a shorter focal length.

The most noticable effect of a change in focal length is the difference in angle of view and magnification. All three of these photographs were taken from the same location with pinhole cameras of three different focal lengths. When magnifying the image, the same amount of light must spread over a larger area, yeilding a dimmer image. In order to make the quantity of light striking the image equivalent in all three pictures, the opening had to be kept open longer.

Taken with a 4 x 5 inch camera of 3 inch focal length. Angle of view is about 90°. Exposure time was 30 seconds

Taken with a 4 x 5 inch camera of 5 inch focal length. Angle of view is about 45°. Exposure time was 1 minute.

Taken with a 4 x 5 inch camera of 10 inch focal length. Angle of view is about 20°. Exposure time was 4 minutes.

Another effect of focal length has to do with the brightness of the image created on the film. When constructing the pinhole we referred to the fact that a larger pinhole would let in more light, creating a brighter image, but with less sharpness. The distance from the pinhole to the film also affects the brightness. To form an image, we are spreading the light transmitted by the pinhole over a two dimensional area. If we increase the distance from the pinhole to the film, as shown earlier, we will magnify the image. However, the amount of light which creates the image won't change, but it will be spread over a larger area, and therefore any point on it will be less bright. Since area varies with the square of the dimensions involved, the brightness will vary with the inverse of that difference. That is if we move the pinhole twice as far away from the film, the image will be twice as large but will cover four times the area, so any unit will have only one fourth the brightness. This would then require four times longer exposure to get the same image darkness on the negative.

Using essentially the same camera construction techniques, but varying the length of the sides of the camera, it would be easy to verify these effects. It might be a good idea to have different teams of students construct cameras with different variables of focal length and film size and observe how angle of view, magnification and exposure time change.

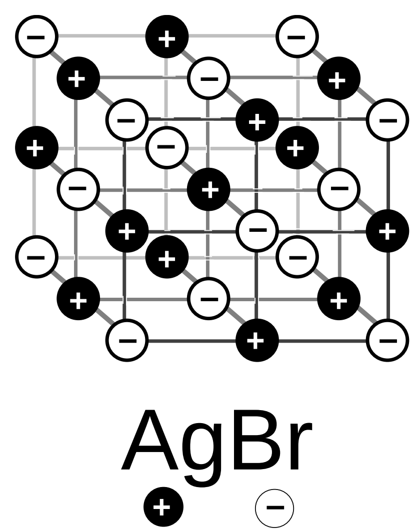
Exposure

Now that we have an image formed in the camera, how do we keep it there? In order to record the image, we have to have a substance that changes when exposed to light, a property known as Photosensitivity. In most photographic materials this substance is one of the compounds known as Silver Halides, compounds of silver and one of the highly reactive class of elements, the halogens, Flourine, Bromine, Iodine, and Chlorine. Modern films and papers are primarily Silver Bromide. The most convenient photographic material to use for pinhole photography is resin coated black and white photographic paper (normally intended only for prints), to be used both as the negative in the camera, and to print the positive.

Photosensitivity in general is a fairly common phenomenon. Photosynthesis in plants, tanning and sunburn, and fading of dyes are all the result of interaction with light. In addition to the Silver Halides, various salts of iron, platinum and palladium have photosensitive properties. Photosensitive materials and processes are used in many applications from printing T-shirts to hardening temporary fillings in your teeth.

Silver Bromide forms cubic crystals, similar in structure and appearance to Sodium Chloride, common table salt, although in photographic applications the grain size is much smaller than found in table salt. The crystal lattice is made up of alternating ions of Silver and Bromine. The change which occurs when this crystalline structure is exposed to light is the formation of metallic silver. A silver ion, normally exchanging electrons with the bromine ions as part of the crystal structure, when excited by the light, will pick up instead a free electron and will become an atom of free metallic silver. Metallic silver, the same metal in expensive flatware and jewelry, is the what makes up the black parts of a photograph. It appears black because it consists of clumps of grains which scatter light, rather than a smooth metallic surface we associate with silver.

This reaction normally occurs on a more than microscopic level. In any grain of the Silver Bromide, only a few out of millions of available silver ions will form metallic silver. If examined after a normal exposure, a piece of film would look no different than before. The image you recorded is invisibly encoded in the tiny amounts of silver created in reaction to the light. This is referred to as a



The structure of a Silver Bromide crystal latent image. It's there, you just can't see it. Further action, this time with a chemical, is required to create a visible image from the latent image.

With sufficient exposure, a visible image could be made by the action of light alone. It's easy to see the process occur by placing a piece of photographic paper in bright light with an opaque object sitting on it. In sunlight the difference between the exposed and unexposed areas is obvious in minutes. To create a visible image by the action of light alone in a pinhole camera would take several months.

Any scene we would want to photograph is made up of a variety of brightness levels. In order to form a reasonably accurate recording of the image in the camera, photographic materials must not only change when exposed to light, but must change in an amount proportional to the amount of light in each point in the scene.

The brightness variations in a scene result not only from the different shades of the objects in the scene themselves, but also from the amount of light illuminating each object. A black object in full sunlight can reflect more light than a white one in a deep shadow . The range of brightness in different scenes can vary quite a bit also. The brightest tone in an indoor scene can be dimmer than the darkest one on a sunlit day. Our eyes, and our brains compensate somewhat for these differences. In the camera we can compensate somewhat also. We can't change

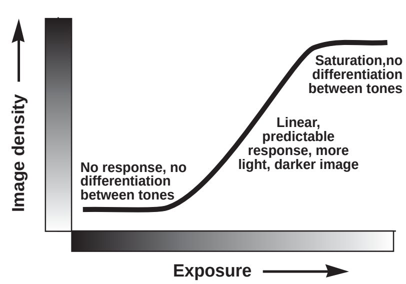
A scene with a variation in tone of the objects in the scene, and a variation in light and shadow.

sensitivity of the paper we're using, and with our pinhole camera we can't increase the amount of light by enlarging the hole the light's coming through (besides, that would reduce the sharpness of the image). We can increase the amount of light falling on the paper by letting it come in longer.

The differences in brightness are recorded in a continuous range of grey levels because the more light which strikes the Silver Bromide, the more atoms of silver are created. Note that this is a negative process. The more light that hits a point, the darker the point gets. We will eventually make a positive image by essentially rephotographing this negative, not with the camera, but by placing it in contact with a fresh piece of paper and shining a light throught it. The image that we get is an exact opposite of the range of tones in the negative.

In the 1830's Louis Daguerre, one of the inventors of photography, knew about this inverse relationship of silver halides but didn't pursue it because he thought a negative image was useless. He developed a direct positive process on sheets of silver. At about the same time, William Henry Fox Talbot realized the negative image could be reversed and developed the process we use today. (He also used pinhole cameras.)

Photographic materials respond to light in a very predictable way, which allows us to predict how long to let the light expose our film. This response can be described by a graph with a characteristic curve. This curve can vary with difference kinds of photographic film and paper but always maintains the same characteristic shape. The vertical axis of the graph represents the darkness of the image in the finished negative, how dense a layer of silver has been created. The horizontal axis is the amount of light the material has been exposed to. This amount is a combination of how bright the source of illumination is, the shade of the object reflecting the light, the amount of time we allow the light to fall on the film and the sensitivity of the film we're using. In our pinhole camera, when we're taking a picture, the only one of these we can vary is the time of the exposure.



The characteristic curve of the response of photograhic materials to light

At the left hand side of the graph, where the horizontal axis represents very little light, the line is straight and horizontal, representing no density of silver. It takes a minimum amount of light to create the response. Although the amount of light varies in this part of the graph, there is no difference in tones recorded.

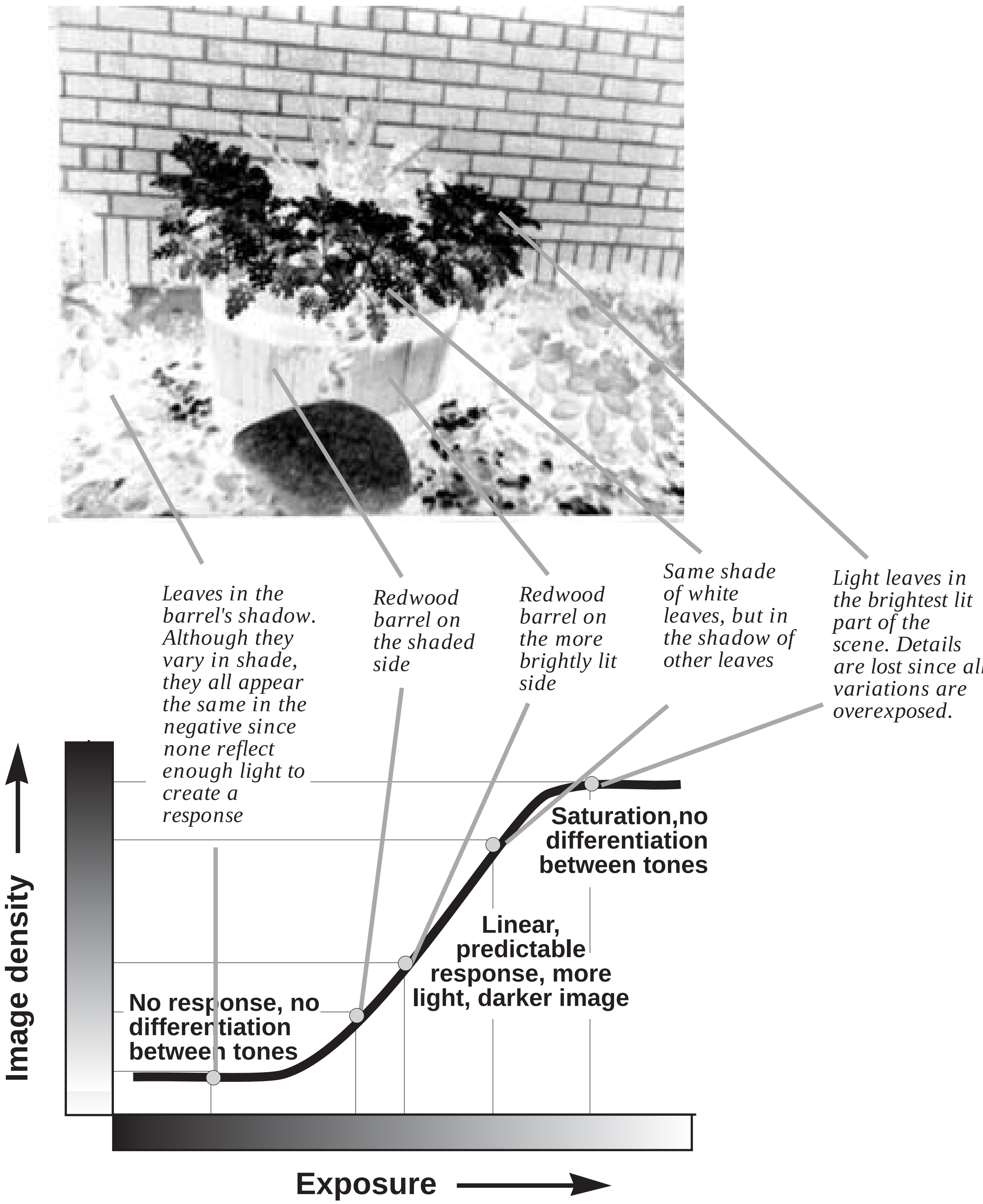
At a certain point the line begins to curve up and quickly defines a straight line. As more light falls on the material, more silver is produced and the image gets darker. The straightness of the line indicates that this is a very regular and predictable reaction. If twice the amount of light falls on the material, it will get twice as dark. At the right side of the graph, the line again curves back to horizontal. At this point, so much silver has built up that the image is as dark as it can get. Adding additional light won't make a darker image, so there is no differentiation in tones beyond this point.

Remember that this graph represents the response of photographic materials to a continuous range of brightness. The scene we wish to photograph may contain only a limited range (a person in a grey suit against a concrete wall on a cloudy day), or only a few tones on the extreme ends (a lump of coal in the snow). Most scenes do contain a fairly continuous range of tones.

It's also important to note that we can always match the range of tones in our scene with the range represented by the graph. In a bright scene we can hold back the amount of light with a short exposure, in a dark scene we can let in light longer. The end result is the amount of light which strikes the film is the same in both cases.

The difference from the brightest to the darkest tones in a scene can vary quite a bit. Photographic materials can only record a limited amount of that range, represented by the angled straight line portion of the graph. If parts of our scene fall on the left side where the line is horizontal, even if we can see a variation in the tones in the scene (like the difference between blue jeans and black sneakers), no difference will be recorded and they will all appear black in the final print. Similarly if the brightest parts of the scene fall to the far right (like the difference between the blue sky and white clouds), they will all end up as solid white. This effect is really noticable in brightly sunlit scenes, where the difference between the sunlit and shadowed parts of an object can be quite extreme.

Photographers usually measure the difference in the brightness of a scene in units referred to as f-stops or more frequently, just stops. One stop is twice the amount of light. Two stops would be four times, and three stops


Leaves in the barrel's shadow. Although they vary in shade, they all appear the same in the negative since none reflect enough light to create a response
Redwood barrel on the shaded side
Redwood barrel on the more brightly lit side
Same shade of white leaves, but in the shadow of other leaves
Light leaves in the brightest lit part of the scene. Details are lost since all variations are overexposed.
Saturation,no differentiation between tones
Linear, predictable response, more light, darker image
No response, no differentiation between tones
Image density
Exposure

would be eight times the amount. This idea of doubling the amount of light seems like a drastic step, but our eyes and photographic material respond as though this doubling were a series of equal steps. So it's usual to plot the characteristic curve as a range of equal f-stops rather than in absolute units. The range of tones in an average scene is about seven or eight stops. Not surprisingly this is matched by the range most films intended for use in the camera can record. Using photographic paper in a pinhole camera will render somewhat less of a range of tones, leading to loss of detail in the brightess and darkest parts of a scene.

The idea of doubling the amount of light does become important when we try to calculate how long to expose a picture. In order to make a negative a little darker, you have to expose it twice as long. With normal photographic materials, exposure is calculated by taking into account the average brightness of a scene (measured with a light meter), the speed of the film, the size of the lens aperture, and the time of exposure. Of course with the modern point and shoot camera, this is all completely hidden from the operator.

With the pinhole aperture, the size of the opening is much smaller than with a lens. In order to easily calculate the differences in lens aperture between lenses of different focal length, aperture is usually expressed as a ratio of the focal length of the lens over the diameter of the opening, usually just called f.

$$f = \frac{\text{Focal length}}{\text{Aperture Size}}$$

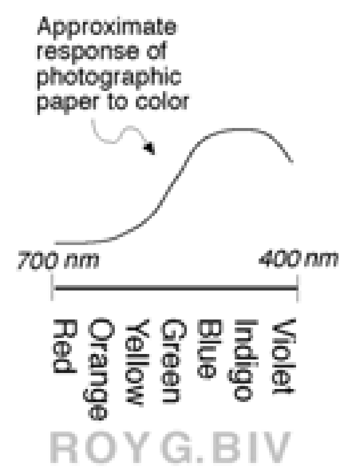
The formula for ***f****, a ratio used to compare the amount of light transmitted by lenses (and pinholes) of difference focal lengths and sizes.*

As seen earlier a lens of longer focal length spreads the light from the scene over a larger area, and therefore creates a dimmer image. Expressing the size of the opening as a ratio evens this difference out. If the 35mm focal length lens of a point and shoot camera is f3.5 that means the opening must be 10mm. (35mm/10mm = 3.5) This will let in the same amount of light as a 600mm super telephoto with a f3.5 aperture, although the longer lens will require an opening of 170 mm. (and about a $1000 more on the price tag). To control the amount of light, most commercial lenses have a device like the iris in our eyes that vary the size of the opening, and can be closed down to at least f16 to control for different levels of illumination indifferent scenes. Note that since f stops are ratios, the larger the number, the smaller the hole, and therefore the less light it will let in.

The diameter of our pinhole aperture is .46 mm and the focal length is 5 inches or 127mm, so our f ratio works out as a whopping f276. To compare that with the f3.5 lens on a point and shoot camera, since f ratios are a measure of area, we have to compare the square root of the f ratios, which works out to a little over nine stops *less* light.

One characteristic of photosensitivity which we haven't covered is its relationship to the color or frequency of the light involved. Visible light covers a fairly limited range of the electromagnetic spectrum which ranges from radio waves on the very long end to gamma rays on the very short end, with visible light just about in the middle. We earlier have seen how light sometimes is best described as a wave (diffraction) and sometimes best described as a stream of particles (traveling in a straight line). Since all electromagnetic energy travels at the same speed (the speed of light, of course) wavelength (the distance between wave crests) and frequency (the time it takes for succeeding wave crests to pass a fixed point) are really equivalent, just expressed with different units. The wavelength of visible light varies from 400 to 700 billionths of a meter.

The only thing that distinguishes visible light from the rest of the electromagnetic spectrum is that these are the frequencies to which our eyes are sensitive. Red represents the long end of the visible range and violet the higher end. A good analogy is to sound. Red can be related to the low notes and violet to the high notes. On this scale infrared, microwave and radio energy are really low notes, and ultraviolet, x-ray and gamma rays are like silent dog whistles. (Be careful not to imply that dogs can see in the ultraviolet!) Silver Bromide, the primary photosensitive component of photographic papers is only sensitive to the blue end of the visible spectrum. This means it can't distinguish between red light and no light at all. This is one of the primary reasons for choosing to use paper as a medium in our pinhole cameras. It can be loaded and unloaded, and then developed, under reddish safelights rather than in absolute darkness.



The visible spectrum and the response of photographic paper

Pictures made in this way will render red things darker than we perceive them with our eyes and blue things lighter, but this effect will probably be unnoticable in your pictures. It might be interesting to try some experiments to detect this effect. Occasionally, you'll get someone with fair pink skin and a dark blue sweater showing up in a photograph with a tan and a light shirt.

Using photographic paper in the camera also simplifies things since the same material and developers are used in the camera and in printing.

This characteristic of limited sensitivity to a narrow band of the electromagnetic spectrum is common to most phenomena related to photosensitivity. For example, tanning and sunburn are caused by the ultraviolet portion of the spectrum, a slightly higher frequency than visible light. Full noonday sun in the summer will cause sunburn in just a few minutes. By standing behind a glass window, which allows all the visible light to pass, but blocks the ultraviolet, you could stand there all day without a burn. Similarly, the people who change the lights in radio towers can stand right next to an antenna sending out 50,000 watts of radio energy without a problem, but your 700 watt microwave can cook beef.

Normal camera films are doctored with the addition of other silver halides and dyes so that their color sensitivity matches the full range of color sensitivity of the human eye.

Another reason to use photographic paper in the camera rather than film has to do with the time of exposure. Exposures in a normal camera are in the range of 1/30th to 1/1000th of a second, far too short to be controlled by the human hand. We want to get exposures down to a length where the average elementary student can control the time of exposure with a second hand of a watch (or even by counting “ one thousand and ...”) and have a reasonable margin for error. With exposure times even of 1 or two seconds, a half second error is fairly large. With 15 second exposures, a one second error is negligible, and five seconds is in the ball park.

One of the functions of determining exposure time is the sensitivity of the light sensitive material. Some materials require less light to create a response than others. This is usually measured in ISO ratings (ISO simply stands for International Standards Organization) The films we use in our snapshot cameras range from ISO 100 to 400. Recently films have been developed with ratings as high as ISO 3200. Although photographic papers are generally rated with a separate scale, on the ISO scale they would rate about 5, pretty slow. (Photographic papers vary in speed also. The general purpose RC papers we're using are about as fast as they get.)

The combination of the extremely high f ratio of the pinhole aperture and the relatively low sensitivity of the photographic paper will give us exposure times in the range of 30 seconds in full sunlight. (With the number 10 needle; with a number 7 needle, it would be about half that, since the area of that hole is about twice that of a number 10 needle.)

To adjust for various other lighting situations we'll use a relatively inaccurate but tried and true method for determining exposure. Included with almost every roll of film until recently was a chart that recommended exposures for different lighting situations. Using this system, our exposures range from 15 seconds for a light scene in full sunlight to about 4 minutes on a heavily overcast day.

Extremely bright scenes in full sun, such as those containing much sand or snow.	**15 seconds**
Bright or Hazy Sun (Distinct Shadows)	**30 seconds**
Cloudy Bright (No Shadows)	**60 seconds**
Overcast	**Two minutes**
Heavy Overcast or in open shade on a sunny day	**Four minutes**

Adjustments should be made depending on the light or darkness of the scene. For example, a person with a very light complexion in a white shirt will require less exposure, or an arrangement of bushes with green leaves would require longer exposure for any given level of illumination.

Exposure table for pinhole camera with 5 inch focal length, a number 10 needle pinhole, using rapid RC photographic paper

Interior photographs are possible, but exposures get into several hours. The margin for error with this system is great enough that acceptable negatives are fairly easy to make.

A consequence of the long exposures is that only stationary objects can be photographed, and the camera must be placed on a stable platform and remain absolutely motionless during the exposure. (Hand held exposures are limited to 1/30th of a second or less). The light reflected from a moving object won't stay in the same place on the negative for long enough to create an image. A 5 minute exposure of a playground full of children will usually yield a picture of an empty playground, since nobody stayed in position long

Group portrait with a pinhole camera with an exposure of over a minute. Note some of the faces are blurred where they turned during the exposure. In the upper left corner, the photographer's image is barely visible. He entered the scene after the exposure began, and left before it ended. When he wasn't there, the bright sky exposed the negative. However, his shirt was light enough to expose over the darker landscape.

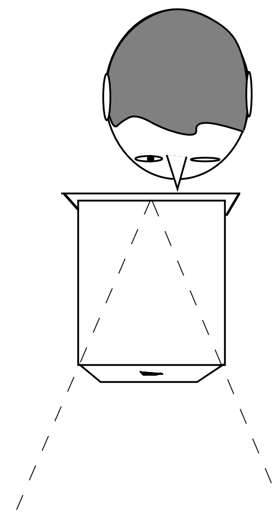
enough to be recorded, but the playground didn't move at all. *(The first photograph of a human being was in a street scene outside Daguerre's studio. One person who stopped to have his shoes shined is recorded in an otherwise deserted street.)*

As a result of the long exposures, some special effects which appeal to children can be easily created. Having a subject move out of the scene half way through an exposure will yield a ghostly transparent figure. In a lighting situation where the foreground is brightly lit, but the background is in deep shadow, (and therefore unexposed), you can make an image with a subject on one side of the picture, and then have them move to the other side. If you're carefull not to overlap the images, twins are the result.

A stable platform for the camera can be found on fence posts, chairs, benches, walls, window sills, slides, any where the camera can be set down. Another recommended accessory would be to rubber band a sandwich bag of lentils to the bottom of the camera. *(In a photographic situation, lentils are recommended, since the word lens is derived from the word lentil, because of its similar shape, but I suppose sand, popcorn or any bean would do.)* This adds sufficient mass to keep the rather light camera from being moved by the wind, and is malleable enough to adjust the direction the camera is pointed. Playdough or other clay could provide the same function. A tripod, of course, makes the ultimate support. In brighter situations, it's possible to hold the camera against a wall or tree with sufficient stability.

It should be emphasized to students that it's impossible to get a picture with this length of exposure by hand holding the camera.

Lack of a viewfinder is a minor problem in use of a pinhole camera. Determining what part of a scene is included in your picture can be done by sighting along a line from the center of the back of the camera to the corners of the front of the camera on both the top and sides to recreate the angle of view of the pinhole. It might not be a bad idea to actually draw these lines on the top and sides of the camera.



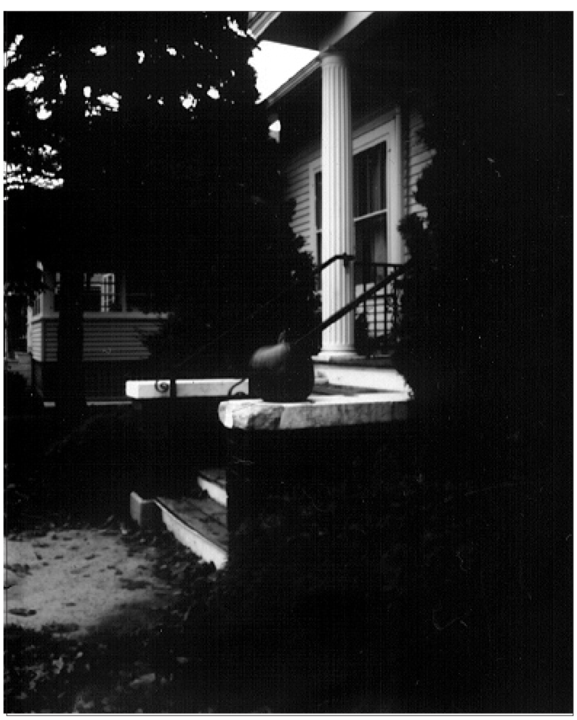
Sighting along the front of the camera to determine field of view

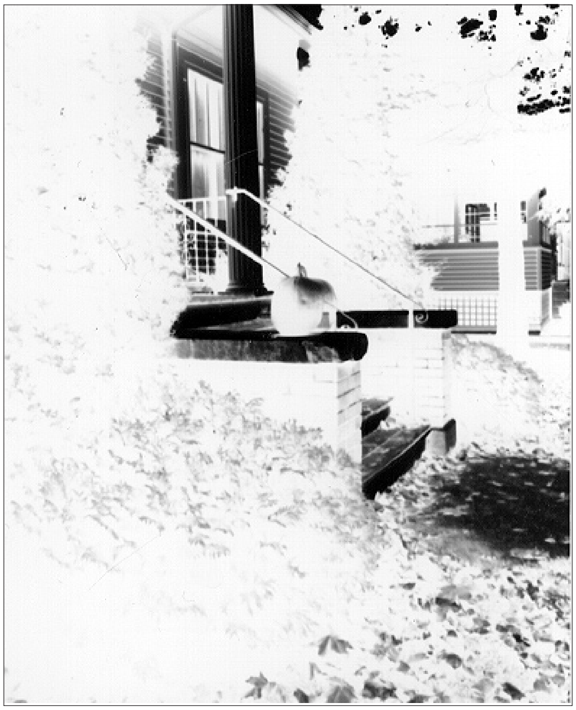
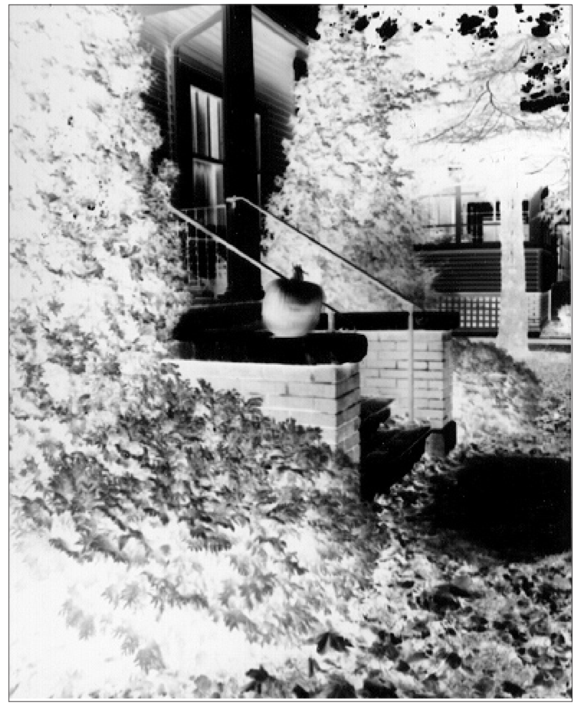
In brighter lighting situations portraits are possible. It's difficult to get a human to hold perfectly still enough for the 30 seconds to two minutes necessary for a pinhole exposure. Having the subject sit or lean against a wall or tree can provide additional steadiness.

Movement is also exaggerated the closer up the subject is, because the angle a movement defines will be greater than the same movement on more distant object. Pretty good closeup portraits can be done if the subject leans on her hands or leans her head against a tree or wall and really freezes. The earliest portrait studios regularly used head clamps to hold subjects still. Closeup portraits are a situation where using a larger pinhole to reduce the length of exposure might be beneficial. The reduced sharpness delivered by the larger pinhole might be offset by the reduced blurring caused by movement of a close up subject during a longer exposure.

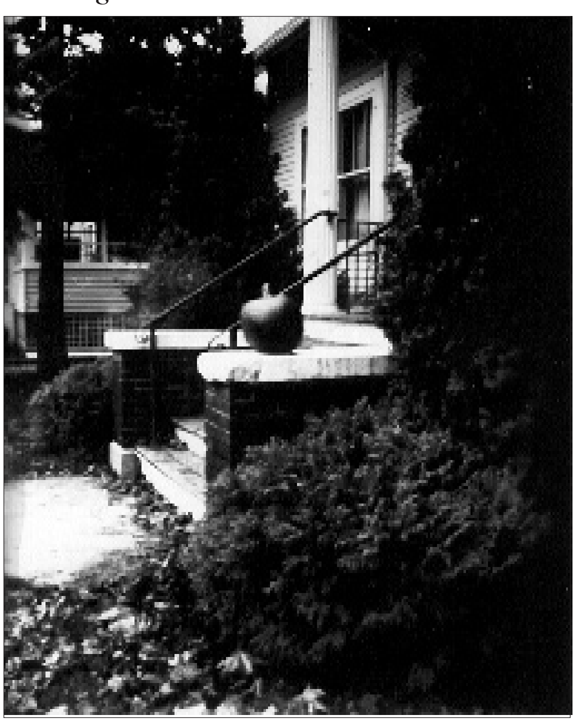
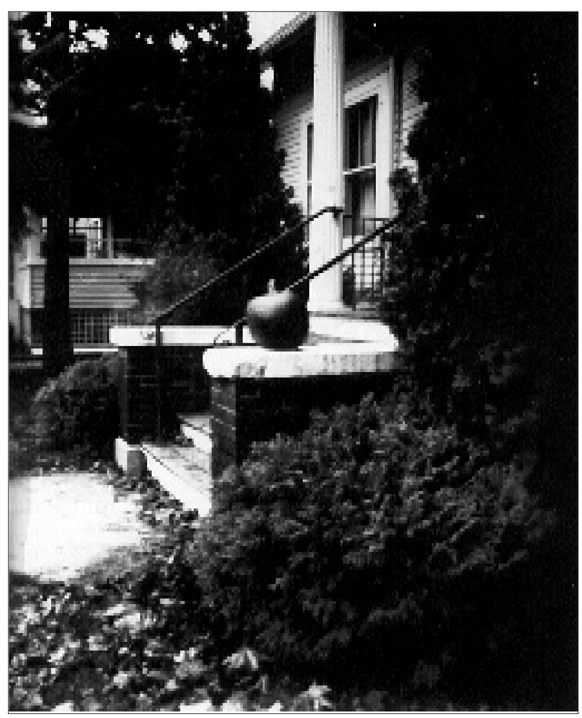
An extremely close up portrait

A sequence of exposures that illustrates the effect of doubling the exposure, and gives some idea what a correctly exposed negative looks like. These exposures, made on an overcast day,were (from left to right) 2, 4, 8, and 16 minutes.The 2 minute exposure is somewhat underexposed. Only the lighter parts of the scene, bits of the sky, the column, the cement parts of the stairway and a few clapboards on the house, are visible at all.There is no detail at all in the shrubbery and no distinction between the dark green bushes, the shadow under the eaves, and the red brick sides of the stairs. The 4 minute exposure is a distinct improvement. The lightest parts of the scene have gotten quite dark, and enough detail has appeared in the bushes to distinguish them as separate from the brick wall. There is however still no detail in the bricks and in the darker parts of the shrubs. The 8 minute exposure is slightly overexposed.There is detail



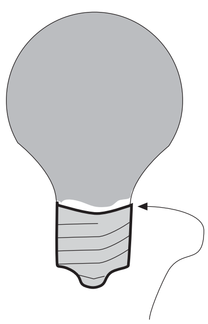
in all but the darkest shadows. The highlights in the column and the sidewalk appear to have gotten solid black with no detail. However, if you could hold this negative up backlit a strong light, you could see that the fluting in the column is still there. The 16 minute exposure is getting rather overexposed. The shadow detail is getting quite dark and the difference between the white column and the shaded white window frame behind it is getting lost and the column has become completely featureless. Despite the variation in these four negatives, recognizable prints could be gotten from all four of them, and quite good prints out of the darker three. Of course the exposure times for the prints from the darker negatives would have to be much longer to achieve the same tonal range in the prints. *See pages 44 & 45 for a discussion of printing these negatives.*

The Darkroom

Adapting school facilities to use as a group darkroom is probably the most difficult part of using pinhole photography in a classroom settings. Several requirements must be met. The room must be absolutely light tight. Some safelight must be provided. There must be some arrangements to get in and out without exposing light sensitive materials. Slightly noxious chemicals will be used, and somehow hands must be cleaned and dried after being in the chemicals before handling fresh (or worse yet, exposed) paper.

A room which can be made light tight is available in most schools. Most classrooms with windows cannot be made light tight. Any leakage around the doors or windows will fog photographic paper. However, there is usually some room in the basement which doesn't have windows. A window on the door can be blocked off with black card stock or black plastic from a garbage bag. If much of a gap exists at the bottom of the door, a black plastic flap can be attached to block most of the light coming into it.



Watch out for gaps in the coloring near the base of the bulb.

Safelights are available that screw into standard light sockets for about $10.00. Safelight is a relative term. Modern papers are formulated to be very insensitive to a specific wavelength of amber light. Professional safelights with a very narrow band can be quite bright without fogging paper. However, orange christmas tree lights and some red lights can make acceptable safelights for under $2.00. Be careful that the coloring on the bulb has no gaps where it attaches to the base. Since the low wattages of these bulbs keeps them from getting very hot, gaps can be covered with electrical tape.

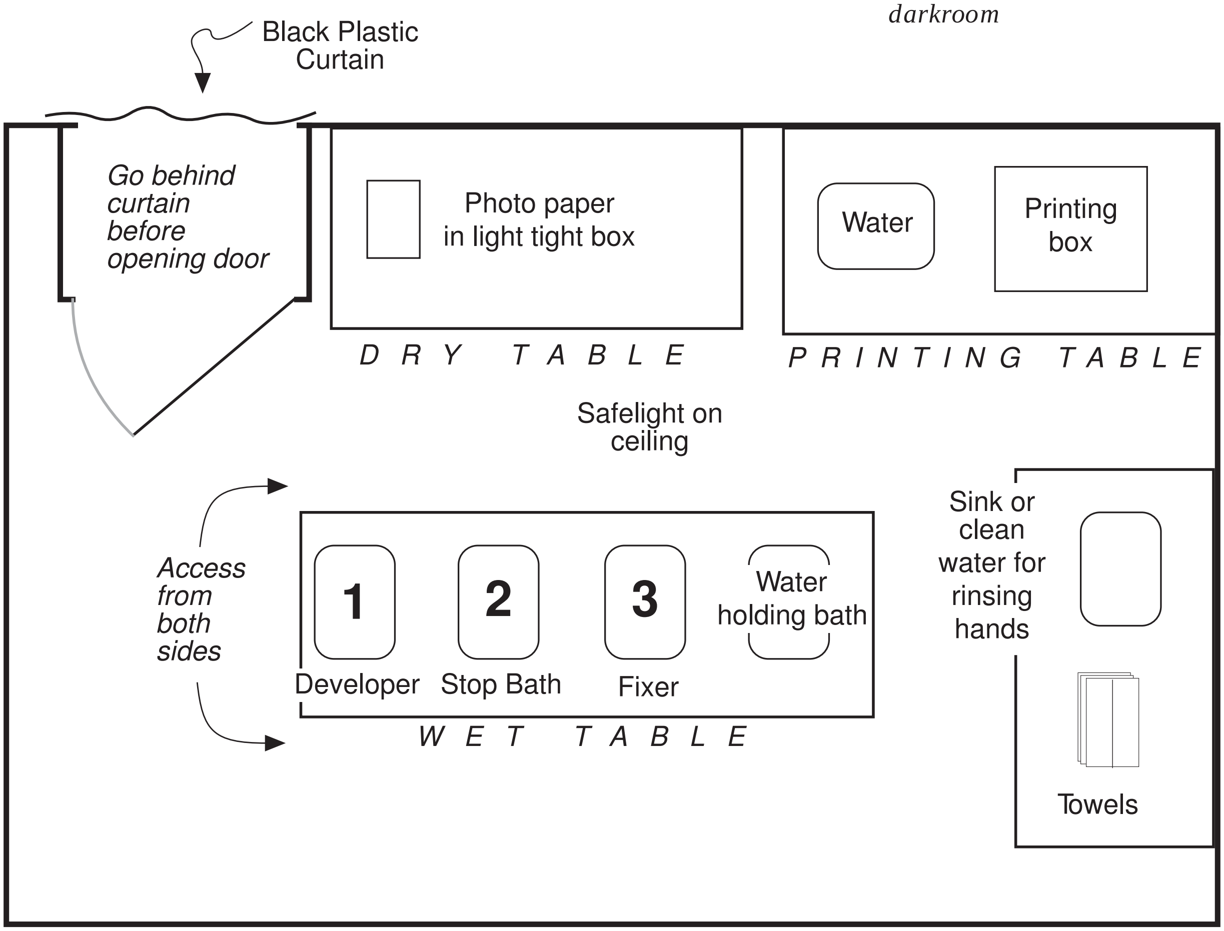
Keep the illumination far from the area involved. Since it should be emphasized that processing should be controlled by time, safelight needs only be bright enough to allow easy handling of the materials, not bright enough to see with a lot of detail. A room that seems absolutely dark upon entering from sunlight, will be acceptably lit after the eye adapts to the dark in about a minute.

Test the effectiveness of the safelight by leaving a sheet of paper exposed to it for about a minute (as long as it will be necessary to keep materials exposed), then processing it and comparing it to a fixed but undeveloped sheet.

Exposing the materials only as long as necessary is another safeguard. Keeping materials in light tight boxes and getting them out of the box and into the camera, and out of the camera into the developer expeditiously will minimize the problems of less than perfect safelights.

The activities that must occur in the darkroom are loading and unloading the pinhole camera, printing negatives and developing the papers. Getting in and out of the darkroom requires some care. The door can only be opened when no light sensitive materials are exposed. This can be handled by emphasizing to the children that they must wait till all light sensitive materials are safely put away, before opening the door and putting a big sign stating that on the door. Having groups come and go can minimize the number of ins and outs. If you're lucky enough to have the right room configuration, a light trap that can allow unrestricted access to the darkroom without breaks in safelight conditions can be constructed. Often classroom doors are recessed from the hallway by a few feet. A curtain made of the kind of black

The ultimate temporary darkroom



plastic sheeting used in construction and gardening can be hung over the opening. Students can go behind that and then open the darkroom door preserving safelight conditions inside. If the hallway outside the room can be kept fairly dark, that can serve as a light trap.

At all times light sensitive materials should be kept in light tight containers except when actually being loaded or processed, just in case. Cookie tins are usually light tight, and empty photo paper boxes can usually be obtained from local photographers, printers, or newspapers. Taping over the normal light switches in the room is an added precaution to avoid accidental exposure.

Ventilation is a concern with permanent darkroom facilities, but normal room ventilation is sufficient for a temporary facility.

Generally speaking, a darkroom should have a dry table, where cameras are loaded and paper handled, and a wet table where the processing will be done. It would be handy to have a third table for printing, since this process will involve getting things wet too.

Three chemicals are involved in processing, developer, stop bath and fixer, in that order. Labeling the order of the chemicals is helpful since starting at the wrong end will yield a blank piece of paper (especially distressing when processing a once in a lifetime negative) and also will contaminate the chemicals. It's also necessary to have a plain water bath to keep processed photos if they are going to be washed in batches.

Although processing can be done in a pretty small space, the bigger the better. It's probably best if the processing could be done on a table with access from both sides so that several children could get at the chemicals at once.

When processing paper, it is necessary to immerse at least a few fingers. Before handling a fresh piece of paper, it is necessary to have clean and dry hands. Handling a piece of photographic paper with hands wet with fixer will leave white marks. With the paper to be exposed in the camera, even plain water drops may leave visible images.

Obviously running water is a plus. However, a large bucket of fresh water, changed fairly often, can do a sufficient job of rinsing off chemicals. Plenty of towels, paper or otherwise, should be available. Tongs can be utilized to immerse paper in the chemicals, but inevitably someone is going to handle a wet, unwashed print.

Some care is necessary when handling photographic chemicals. Obviously any sort of ingestion or finger licking is to be avoided. (They really taste terrible!) Excessive exposure can cause drying of the skin, but is unlikely with the processing of eight or so sheets involved in this kind of classroom exercise. Staining of clothes is a more likely problem. Developer and fixer usually dry without leaving a mark, but some synthetic materials will develop an indelible stain after washing and drying. Dripping in general is to be avoided, but a moderate amount is easily cleaned up.

Developer and fixer come in powders that must be mixed up. (Some developers are available in liquid form.) Plastic milk bottles would make good containers.

The most common developer, Kodak Dektol, is mixed up to a concentrated solution and then normally diluted 2:1 for use. A quart of working strength developer (11 oz. developer to 22 oz. water) has a capacity to develop about 100 sheets of 4 x 5 paper. Since developer is susceptible to oxidation, it's best to mix only as much working strength developer as will be used in that session, and discard it when finished. (Some developers will have other dilutions recommended)

Stop bath is a dilute solution of acetic acid, a common reagent in school chemistry laboratories. If you start with glacial acetic acid, the dilution is about $1\frac{1}{2}$ %.

Fixer is used full strength and saved until exhausted. A quart of fixer is good for about 300 sheets of 4 x 5 paper. After each session, return it to its container and reuse.

Some sort of containers will be necessary to contain the the three chemicals involved in processing. In most situations working with a quart of chemistry at a time is sufficient, but with larger groups or a particularly long session, a half gallon might be necessary. Something with fairly high sides like a dishpan is a good idea to prevent sloshing over. Some sort of Tupperware with a tight lid would be handy so the chemicals could be left in their basins overnight. If more than a day would come between processing sessions it would be a good idea to return the chemicals to their original containers. A fourth container is necessary to hold prints in water if they will be washed in batches.

The biggest problem in doing this with large groups seems to be that everyone seems to have to have access to the chemistry at once. Having a container with as large surface area as possible (kitty litter pans?) helps since more than one person can actually be processing in the same tray at once. Having multiple processing stations is another possiblity but then some control has to be made to make sure the activity is evenly spread so one station doesn't become exhausted.

Another scheme to reduce congestion is to work as teams. First one student is the photographer and another the assistant and then reversing the roles. This reduces the numbers needing access to the chemistry in half at any one time. Another advantage is that one team member can pay attention to timing and the other actually do the task. This is also helpful when taking pictures in bright conditions. Getting the shutter off and on and paying attention to a watch can be difficult for children to coordinate by themselves, especially when the exposure time is only 15 seconds. (Also, kids seem to like to work in teams.)

Summary of capacities of photographic chemicals

Developer *- used diluted 2:1*

100 sheets of 4" x 5" sheets per quart of working solution (therefore 300 sheets per quart of straight developer)

Stop bath *- 1½ percent solution of glacial acetic acid*

100 sheets of 4"x 5" sheets per quart. This will vary tremendously depending on whether the paper is allowed to drain over the developer for a few seconds or if lots of developer is sloshed into the stop bath. It's easy to tell when stop bath is exhausted. You can feel the difference from the "squeaky clean" feeling of acids and the slippery feeling of bases. An acid/base indicator could also be included, but it would have to be something that would be noticeable under safelight.

Fixer *- used straight*

300 4" x 5" sheets per quart

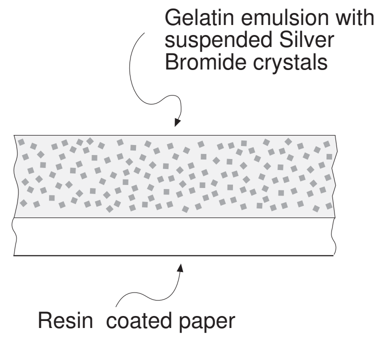
Processing

At this point, we have recorded an image in our camera, but it's a latent, invisible image. In order to make the image visible, we have to act on it with a chemical.

In order to accomplish this we have to get to the Silver Bromide and act on it with a liquid chemical, but we can't move it since the formation of the image is dependent on the location of the exposed grains of Silver Bromide. Here we take advantage of a type of materials called emulsions, which can hold particles suspended in place, like fruit cocktail in a Jello salad. The Silver Bromide particles are suspended in a thin coat of a gelatin emulsion, quite a bit like Jello, but harder. The emulsion also has the special property of absorbing liquids without disturbing the structure of the suspension.

We'll also take advantage of a physical property of Silver Bromide; it's insolubility in water. If it could be dissolved in water, it would just wash away, destroying the picture.

The combination of the liquid absorption of the emulsion and the insolubility of the Silver Bromide allows us to get at the exposed grains in order for them to be involved in chemical reactions, without disturbing the picture recorded by them.



Cross-section of photographic paper

The material I've been recommending for pinhole photography is resin coated (RC) photographic paper. In this material, the paper base is impregnated with a resin which makes it essentially waterproof. In processing, only the light sensitive gelatin coating absorbs the chemistry. This minimizes the time involved in all steps and allows the paper to air dry flat without need for special dryers. With a hair dryer you can dry RC paper in about a minute. Since we're using the same material in both the camera and printing phases of the process, the chemicals and steps involved are the same.

Development

The basic chemical reaction involved in development is the action of a reducing agent on the Silver Bromide salt to yield Metallic Silver. A reduction reaction is roughly defined as one where electrons are gained. (Oxidation is the opposite, where electrons are lost.) Recall that the image was recorded when the silver ions, stimulated by light, captured a free electron to become metallic silver. Development is doing essentially the same thing that happened during exposure, except it's doing it chemically, and on a much larger scale, so we can see the silver image.

Why does the developer act only on the Silver Bromide grains that were exposed in the camera? The key is the minute amounts of silver that already exist, where they were created during exposure. The silver in the latent image acts as a catalyst to speed the reaction tremendously.

In general, a catalyst is a substance which accelerates a chemical reaction without being changed itself. The most familiar example of this is the catalytic converter on your car. As the exhaust gases pass over a catalyst, they break down into simpler, safer substances. The catalyst remains unchanged. We often hear that leaded gasoline ruins a catalytic converter. This is because the lead compounds react with the catalyst, making it unavailable to continue in assisting in the breakdown of the exhaust.

The catalyzed character of development is often confusing to students of photography since the catalyst, the silver in the latent image, and the product of the reaction, the silver which makes the visible image, are the same substance. The principle is the same, the reaction is catalyzed, or sped up, by the presence of the silver in the latent image which remains unchanged. The reduction reaction of the developer would occur without the presence of the silver in the latent image, but would take much longer, and of course wouldn't yield a picture.

As with virtually all chemical reactions, the speed of the reaction is also governed by temperature. The recommended temperature for processing photographic paper is 68 degrees Fahrenheit, but the useful range is from about 60 degrees to 90 degrees. In order for the reaction to be predictable, the temperature should be stable from one session to another however. In order to be sure the chemical temperature is stable, it’s easiest just to let them sit for a half hour or so to attain room temperature.

With modern resin coated photographic papers, development is complete in one minute. Some additional density can be gained by additional time, but not much. Students should always be encouraged to develop by time, and not by appearance, for several reasons. Development time should be seen as a controlled variable, especially in the printing phase of the process, using exposure time as the changing variable. (Temperature and the strength of the developer are also controlled variables.) A wide range of negative densities can yield acceptable prints with the correct exposure time. Secondly, it's really impossible to judge images under safelight. Stopping development based on the appearance of the image under safelight is probably going to result in light, low contrast prints. Negatives especially that might appear too dark during development can result in excellent prints. Always develop for the recommended time, inspect the results under normal lighting, and then adjust the exposure time in the camera or in printing in order to get better results.

It's an instructive exercise to make a number of identical exposures and develop them for 10, 20, 30, 40, 50, and 60 seconds to see what difference it makes and how the reaction proceeds. What should become apparent is that the entire picture appears fairly quickly, but with a very limited range of tones. Then as development proceeds the darker parts of the print get darker expanding to the full range of tones available.

Stop Bath

Developers are alkaline in nature. This can be confirmed by the slippery feeling characteristic of bases. The simplest equations which describe this reaction show that additional hydroxide ions are necessary to combine with the Hydrogen in the reducing agent to form water.

We can exploit the necessity of an alkaline environment when it comes time to stop the reaction. When we reach full development we want to stop the action of the developer and neutralize it so it won't continue. To do this we use a dilute solution of acetic acid. Because the reaction can't continue in an acidic environment, it stops quickly. Then the alkaline developer reacts with the acidic stop bath to neutralize the developer and prevent it from long term action.

Fixation

We now have a visible, permanent image in metallic silver. But it's still embedded in the unexposed and undeveloped Silver Bromide which is still light sensitive. If we expose it to light, it will darken, ruining the picture.

Silver Bromides are insoluble in water. This has been an advantage up to this point. It allowed us to act on the crystals with developer without them washing away, destroying the image. Now we have an image in silver and we want to get rid of the remaining silver bromide. We'll use another chemical reaction to change the insoluble silver bromide into soluble silver compounds which dissolve in the fixer, leaving the still insoluble silver of the image. This step is called fixation. The fixer is primarily Sodium Thiosulfate, but also includes chemicals which harden the gelatin emulsion. With the modern resin coated photographic papers, fixation only takes 2 minutes. Pictures can be examined in room light after about 30 seconds.

The presence of the soluble silver compounds could be confirmed in used fixer by using it to electroplate a penny. Reclaiming the silver from used fixer by electrolysis is an important part of the photographic industry.

Washing

Fixer and all the residue of the other reactions involved will eventually oxidize and otherwise change to form stains, so we still have to wash the paper for about 5 minutes. After fixation, the paper can be held for a while in just a bath of water. It's usually a most efficient to wash in batches. Care must be taken that the sheets of paper are kept separate. It's fairly common for RC papers to stick together in a bath of water. The important point is to ensure a continual change of water. The easiest way to do this is to place a wash basin in a sink, hold a hose at the bottom of the basin and let the water run and flow over the top. A fairly light flow is sufficient. (In a large group situation this might not be sufficient wash for really long term permanence. It might be suggested to students that they give their pictures an additional wash at home.)

In a classroom setting a handy alternative is to have the students take the paper out of the darkroom and wash them by holding it under running water for 30 seconds or so. (Use paper plates for carrying to prevent dripping.) This isn't the best for archival permanence, but it has the advantage of reducing congestion in the darkroom, completes the process without waiting, and forces the student to get the picture out into the light for a good look before proceeding.

Drying

RC paper can be dried just lying on a flat surface or hanging on a line. It can't withstand temperatures higher than about 190 degrees so print dryers should be avoided even if available. (Hair dryers work pretty well if you're in a hurry.) Care must be taken to be sure that papers do not overlap. If RC papers dry stuck together, it's practically impossible to get them apart without damaging the image. If this does happen, try soaking them for about 5 minutes and then gently peeling them apart.

Summary of steps in processing photographic paper

Development	1 part Developer mixed with two parts water	1 minute
Stop Bath	1% solution of glacial acetic acid	15 seconds
Fixer	Used straight	2 minutes (Can be examined in room light after 1 minute)
Washing	Running water	1 to 2 minutes
Drying	–	15 min - 1 hr. Varies with temperature & humidity

Letting the paper drain for a few seconds over the tray before going into the next solution will increase the life of the chemicals, not to mention making less of a mess.

It's not necessary to let a negative dry if proceeding directly to printing.

Printing

When to make a print of the negative is a procedural question that has to be considered. As soon as a negative is washed, it's possible to continue on to printing, but there are several other considerations. By separating shooting negatives and printing into two separate sessions, both the similarities and the differences in the two processes are emphasized. This also encourages experimentation in both phases. If a print is to be made immediately after processing the negative, students are less likely to want to go back out and try different exposures or experiment in other ways.

Before printing it's important to take a close look at the negative in good light. Separating shooting and printing negatives encourages such an inspection. Try to determine how good the exposure was. Is there detail in the highlights and shadows? Is the negative thin or dense overall? Look at the negative backlit by a bright light. Is there detail in the darkest areas that you couldn't see without the backlighting. Getting to know what information is there in the negative allows you to make decisions as to whether you have made as good a print as possible or whether to continue trying different exposures.

In order to make a positive print of the negative, we have to place the negative in contact with a fresh piece of paper and shine light through the negative. The new piece of paper will be exposed in proportion to the density of the image on the negative, recreating the original tones in the scene.

It's important that the negative and positive are in good contact to get a sharp image. There are two methods of accomplishing this, dry and wet.

Holding a dry negative and positive in contact is traditionally done by holding the negative-positive sandwich in a frame with a spring back and a piece of glass. Because the RC paper we're using dries pretty flat, just laying a piece of glass on top of them is sufficient. Plexiglass might work, but it is much less dense than glass, therefore a sheet of it might not be heavy enough to hold the two completely in contact. It also scratches easily. Scratches refract the light and result in an uneven exposure. The dangers of glass in a darkroom with children are obvious.

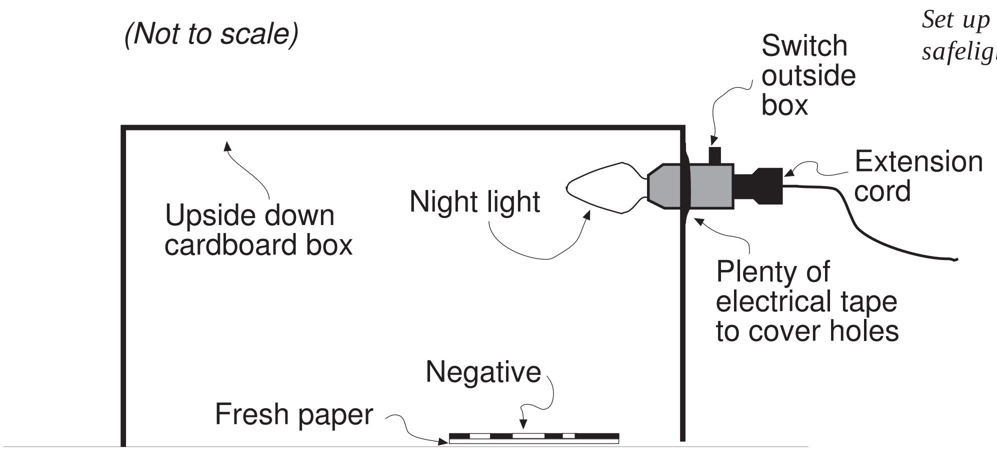
The second, wet, method has the advantage of safety and no additional apparatus. The surface tension of water and the smoothness of the surface of the RC paper holds the negative sufficiently in contact with the fresh paper to make a good print.

In the darkroom, soak the negative and fresh piece of paper in clean water for 10 seconds and sqeegee them together against a waterproof surface like plexiglass, or linoleum, emulsion side to emulsion side (the shiny sides). This can be done with the fingers or a damp sponge, but a rubber spatula is a little more effective. The important point is that the two emulsions are in contact. RC paper sticks together pretty well in this sort of situation, and can even be slid around a bit for alignment without separation.

When the paper is wet it's difficult to tell which side is shiny, and when they're stuck together, its hard to tell which is the negative and which is the new sheet of paper. It's a good idea to mark the back of the fresh piece of paper with a pencil (pens and felt tip markers tend to run) so you can tell what's what. (If you marked the back of the negative, the mark would show up on the finished print because it would block part of the light.)

In a group situation one difficulty is how to expose the print without breaking safelight conditions. The overhead light can be used, but that obviously breaks safelight conditions. The problem with that is that only one individual can make an exposure at a time, lasting from removing the fresh paper from it's storage box, to a good rinse in the fix, at least two minutes. This problem is commonly overcome with a photographic enlarger, which projects a well defined beam of light. This is a little high tech and expensive for our purposes.

An exposure unit can be easily constructed so that printing can be done without affecting safelight conditions. Place a night light in a hole in a cardboard box with the switch outside the box, using the black electrical tape



Set up for printing under safelight conditions to cover the gaps. The box has to be fairly big to get the light far enough away, and therefore dim enough to make the exposure of a controllable length. (Copier paper boxes work fine.) The box is then inverted over the negative-positive sandwich and the light switched on for the duration of the exposure. Any sort of light fixture with a built in switch that could extend outside the box would work, but the little light bulbs used in night lights are about the right intensity. Most bulbs for a regular light socket would probably be too bright to use this close up.

The amount of time will vary depending on the the intensity of the light source, the distance from it and the density of the negative. As with exposure in the camera, you want a time that is long enough that a fair margin of error exists, but not so long that attention wanders. Working about 7 feet beneath a bare 60 watt light bulb requires exposure times averaging 15 seconds. Light intensities in schools vary quite a bit, so this will have to determined experimentally. The night lights come with diffused white bulbs or with clear bulbs. The clear bulbs are twice as bright as the white bulbs. Exposure with the white night light in the box will average about 30 seconds.

The darkness of a negative is a great source of variation. It wouldn't be unusual for print times to vary from 8 seconds for an underexposed negative to 4 minutes for an overexposed one.

Since the materials used for the print are exactly the same as for exposure in the camera, the processing is exactly the same.

After development, in order to assess the quality of the print, it's necessary to turn on the room lights, if possible, or take the print out of the darkroom. It's really impossible to judge under safelight. If the print turns out too dark, try again with more time, if too light, less time. A lighter negative will require less time, and a darker negative more time. Recall that doubling the time of exposure only results in a small step in darkness. This is also true with printing. If a print is too light, try again with double the amount of time, if too dark, halve it.

It’s an almost universal truth that the first print can always use a little improvement, so emphasize that experimenting with exposure times is an expected part of the process. Using the knowlege of the negative that you gained by examining it before printing, decide how good a print you have. Are the clear areas with no detail on the negative completely black on the print or only moderately grey? (Not enough exposure.) Have details in the shadow areas held or have they dissappeared in blackness? (Too much exposure) Are the details in the darkest areas of the negative apparent, or is it all white. (Not enough exposure.) Are the brightest areas of the print white or are they grey? (Too much exposure) As with exposing negatives in the camera, often some trade off is necessary between highlight and shadow detail. Which can be sacrificed to provide a better print with your negative? The point is to look at the print and the negative and decide what would make it better. With a lot of negatives it's going to be a judgement call. Sometimes prints of different darknesses can give different impressions, either of which could be called correct.

One characteristic of photography that could be examined here is that it is an analog process. The negative is an analog, or approximation, of the original scene, and the print is an approximation of the negative. Every generation will result in a slight degrading of the image. Students could try making a new negative by contact printing a print, and then reprinting that to make a positive. Is the new positive as good as the first one? How did it change? How does this differ from digital image recording techniques that are now replacing traditional photographic methods, particularly in scientific applications?

Sound is an analog process students might be more familiar with. The difference in quality of a cassette copied from another cassette is noticeable after one or two generations. The difference between a digital compact disc, and an analog copy on cassette is easy to detect.

Incidentally, most of the pictures in this book were never printed traditionally. Except for the following examples of printing, the negatives were scanned with a digital device and then electronically manipulated to make positives, to adjust darkness, and to resize them.

It's a little difficult for a group to view the small prints that result from this method for discussion. Most home video cameras will focus close enough to fill the screen with a 4 x 5 inch picture, which is then pretty easy to see on the average classroom TV. It also makes a pretty impressive, although fleeting, enlargement. Some cameras even have a switch that inverts the image into a negative, allowing you to view positive images from negatives.

Extremely enlarged section of one of the pictures in this book showing the individual pixels which have a digitally specified shade of grey.

A sequence of prints from a rather underexposed negative using the set up illustrated on page 41 using a frosted bulb in the night light. This is the the lightest negative (the 2 minute exposure) shown on pages 28 & 29. The prints were made with exposures of 4, 8, and 16 seconds. In the 4 second print the shadow areas are only moderately gray and the highlights in the column are still washed out. Notice that no additional detail was gained in the shadow areas by making a light print, they're just flat. In the 8 second print the shadow areas have gotten black and more details in the highlight areas have appeared. In the 16 second exposure, the bright areas have started to get grey and the details are getting lost is the darker areas such as the steps and the house in the background.

This sequence is from the third negative in the sequence on pages 28 & 29 (the 8 minute exposure) . Since its a much darker negative, the print times were much longer, 30 seconds and 1 and 2 minutes. Notice that unlike the prints from the lighter negative, the full range of tones from black to white exists in all three prints, since a much greater range was recorded in the negative. Also detail in the column, which isn't readily apparent in the negative has appeared. In the lighter print, the highlights in the column and the sidewalk are washed out, but the shadow detail is much clearer. In the darkest the details in the shadows which separate the tall bush from the pine tree are lost, but the details in the columns and the light caps on the brick sides of the stairs are clearer. The middle print is a good compromise, and probably the best of the three.

Extensions

Photography is one of the most pervasive technologies in our society. It has impact on almost all fields of endeavor. In the first photographically illustrated book, *The Pencil of Nature,* William Henry Fox Talbot, one of the inventors of photography predicts applications in many fields. The study of pinhole photography can be extended into many disciplines.

Art

Photography and painting have influenced each other many times. The academic painting of the first half of the 19th century emphasized realism, and it was partially to better his painting that Louis Daguerre pursued the invention of photography.

The ease with which realistic rendering could be done with photography somewhat led to the emphasis on color and form of the Impressionists. The haphazard composition of amateur photographers influenced the composition of some painters, notably Degas and Toulouse-Lautrec.

In return, the pictorialist photographers of the early twentieth century, in order to identify photography with fine art, emulated the style of the Impressionist painters. Later in the twenties and the thirties, photography returned to extremely sharp detail, sometimes in rather abstract compositions, in order to allay the criticism that pictorialist photographs were poor imitations of paintings.

Photography, and art in general, has occasionally brought the values of society into question, such as with the recent controversy surrounding Robert Mapplethorpe.

Journalism

Photography has made us much more familiar with the world. George Washington could probably have walked down the street in any city without being recognized. Even before TV, however, FDR would have been recognized universally. Despite the fact that modern war *is* more horrible, does our familiarity with photographic images of it make the general public feel differently about it?

Prior to photography, news events were occasionally illustrated with drawings. How does a photograph differ from a drawing in relating information. Is the information gained from viewing a photograph more trustworthy than that gained from viewing a drawing?

Even modest sized libraries have microfilm collections of newspapers and magazines that extend into the prephotographic era. The technology for reproducing photographs in print didn't arrive until the 1890's so that's not as far back as you might think. When did your local newspaper start using photographs?

Family Life

Everyone today is familiar with what their grandparents and even great-grandparents look like. Prior to photography, only the rich could afford portraits. By the Civil War, photographic portraits were within reach of the average American.

It would be interesting to have students bring in the oldest photographs in their family. How far back would color start? It wouldn't be surprising to have a tintype or two show up.

How did the older photographs differ from what we do today? Probably the older photographs would tend to be more formal. If candid shots did show up they were probably taken at auspicious events like weddings and family reunions. Today we tend to photograph everday family life as well.

Incidentally, older technologies such as tintypes and ambrotypes are commonly available in antique stores and local historical societies. Daguerrotypes, faint images on shiny silver plates, are not all that rare.

Science.

Photography made many phenomena observable that could not have been studied with the naked eye because they were to dim, either too short or too long in duration, too dangerous or simply out of the spectral range of human vision.

There was virtually no distinction in the variety of nebulae and galaxies prior to photographic observation. Anything that wasn't a star was a nebula. Long duration exposures allowed astronomers to see the wealth of detail that has differentiated spiral and elliptical galaxies, open and globular star clusters and planetary and galactic nebulae. More detail could also be gleaned from stellar spectra which led to the modern science of Astrophysics.

Events such as the dynamics of a drop of milk falling on a plate or the vibration of an aircraft wing are much too short in duration for a human to see in any detail. About a thirtieth of a second is the shortest duration human beings can distinguish an event. An electronic flash is only on for a thousandth of a second. How long would you have guessed from observing it? The work of Dr. Harold Edgerton particularly explored the world of short duration phenomena. The tracks of subatomic particles with lifetimes in the thousandths of seconds were also discovered using photographic materials.

Some events would be too dangerous to observe. Cameras have been placed and retreived from the ocean floor and inside volcanoes where an observer could never have survived.

X-rays were discovered accidentally when Roentgen left a piece of uranium ore sitting on a photographic plate.

Photography also made it possible to make permanent records that were not dependent on the drawing talent or subjective description of the observer.

Today photography is being replaced in almost all applications by electronic, digital devices, which are either more sensitive to light, or yeild more reliable numerical data which can be recorded and analyzed.

What scientific observations could be done with a pinhole camera?