Pinhole Theory Explained

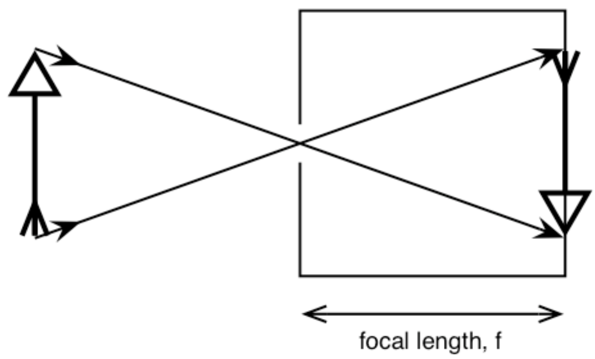
There are lots of good 'how to make one' articles on pinhole photography in books and on the web, so you won't find much on that in here. But many of the technical articles are complex and scientific, and hence off-putting.
This document aims to be 'pinhole theory for the non-scientifically inclined', though it does contain a formula or two.

Pinhole theory actually explains a great deal about cameras and lenses in general, like why aperture numbers are what they are, how the aperture is worked out, and what causes depth of field. Read on and be enlightened.

(When talking about cameras with lenses I will refer to film, but this also covers CCDs and any other digital capture device.)

Focal Length and F-stop

Light rays from the subject pass through the pinhole to form an inverted image in the camera.
The focal length, called 'f', of the pinhole is simply the length of the camera, so a 'wide angle' camera is short and a 'telephoto' camera is long.



On a camera with a lens, the lens focuses light from a distant object (at infinity) at its own focal length. Moving the lens nearer to or further away from the film changes the distance at which an object needs to be in order to be brought to focus on the film.

The f-stop of the pinhole is the focal length (f) divided by the diameter (d) of the pinhole, or as a formula this is:
f-stop = f/d

So a pinhole camera which is 300mm long and with a 1.5mm pinhole has an f-stop of 300/1.5 = 200.

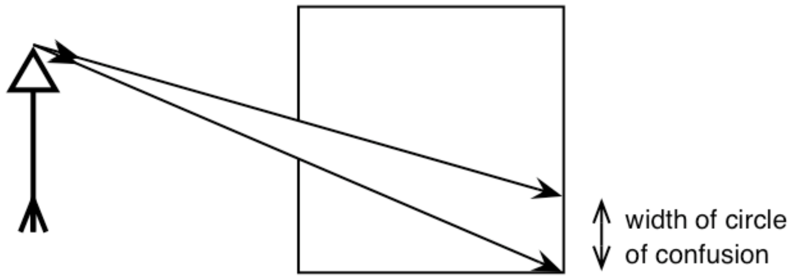
This is also true for lenses.
The biggest f-stop of a 50mm lens with a maximum aperture diameter of 25mm is 50/25 = 2. This is fairly typical of a standard lens, and is often written f/2 to denote that the physical width of the aperture is the focal length divided by 2.
As the aperture is closed down its diameter reduces.
If the 50mm lens aperture is reduced to only 4.5mm its f-stop is 50/4.5 = 11.

The amount of light that actually enters through a pinhole or lens is dependent on the **area** of the pinhole or aperture hole, not the diameter. The area is related to the square of the diameter (remember πr^2 ?).
This is why f-stops do not double in number each time the exposure doubles, they go up by the square root of the exposure increase (√2, or approx 1.4 for each doubling in exposure).
This gives rise to the aperture sequence you should know:
1 1.4 2 2.8 4 5.6 8 11 16 22 32 45 64
Each one goes up by a factor of 1.4, and each alternative one by a factor of 2. Each change in f-stop corresponds to a doubling or halving of exposure.

Sharpness and Depth of Field

Because the pinhole has a width, and is not infinitely small, the light rays from one part of an object can pass through the pinhole centrally, or near the edges of the hole, or anywhere in between. The diagram shows light rays passing through the extreme top and bottom of the pinhole. (The size of the pinhole is greatly exaggerated to make the point!)

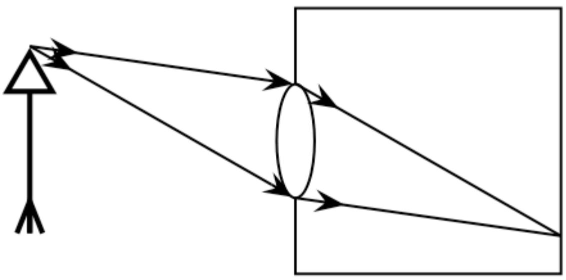
Instead of forming a single point on the back of the camera, the light rays from one point on the subject fall in a circle. This is known as a 'circle of confusion'. The object then appears blurred.



The size of the circle, and hence the amount of blur, gets larger as the pinhole gets larger.

If the pinhole is small enough, the circles of confusion are so small that the object appears fairly sharp to the eye.
If the image is enlarged, through printing, scanning or magnification, the circles of confusion are enlarged too and the image appears unsharp again. The apparent sharpness of the image therefore depends on the size of the pinhole, the degree of enlargement and also the distance the image is viewed from.

In a pinhole camera, the hole is normally so small that the circles of confusion remain much the same size however far away the object is, and so the sharpness does not vary greatly with distance.
The range of subject distances over which an image is acceptably sharp is called depth of field, so it is fair to say that pinhole cameras have a very large depth of field.



One of the advantages of using a lens over a pinhole is that a lens can bring all the light from one subject plane to a sharp focus on the film plane.

This means that when the lens is focused on an object there are no circles of confusion and the image is pin sharp.
However, anything nearer or further away than the plane of focus is not brought to one point on the film, creating circles of confusion and appearing blurred.

The smaller the aperture of the lens, the smaller the circles of confusion will be (as with the pinhole), and the sharper the image will appear.
This is why small apertures create more depth of field.

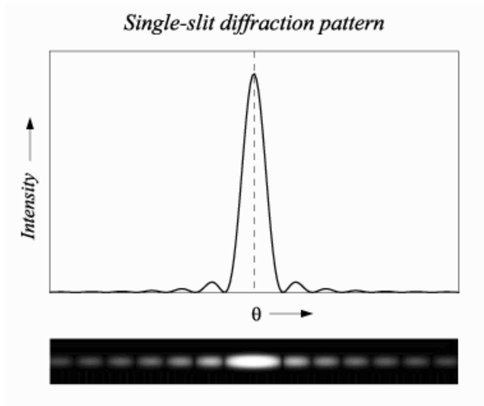
Another advantage of a lens is because it focuses light it can be much larger than a pinhole and still produce sharper images. A lens gathers a lot more light than a pinhole, leading to shorter exposures.
However, the aperture of a lens will never be as small as a pinhole, so a lens has less depth of field than a pinhole even when stopped right down.

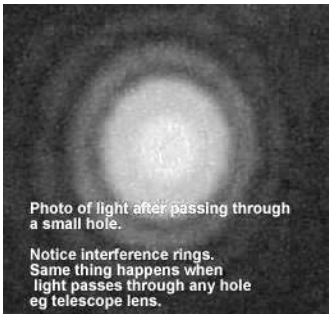
Diffraction

This is defined as 'the bending of waves when they meet an obstruction'.

Light travels in waves, and the edge of a pinhole forms an obstruction, so despite the nice straight lines in the first diagram, they do actually bend a little.
The nearer they go to the edge of the pinhole, the more they bend, and this gives rise to a degree of unsharpness in the resulting image.

For the scientifically minded, this diagram shows the interference pattern formed by diffraction through a pinhole. The big central peak shows that most of the light gets through just fine, but the little peaks to either side are light that has been scattered. This scattered light will make the image blurred.
The little photograph underneath shows how the image is scattered when it records on film. (It only shows it in a horizontal direction, it actuality it scatters the same all around the circle of the pinhole.)





For the non-scientifically minded, this photograph of light passing through a pinhole shows the central area of light which is not scattered by diffraction, and also the concentric circles of scattered light which will cause the image to blur.

The smaller the hole, the more diffraction there is.

So whilst it is good to make a really small pinhole to reduce the circles of confusion, you also need to make a large pinhole to reduce diffraction.

The optimum size for a pinhole is when these two opposite effects are equal.
Fortunately there is a way of working out the optimum pinhole size for maximum sharpness:

optimum pinhole size = square root of the focal length, divided by 25.
(Do the square root bit first, then divide by 25.)

Or as a formula: $d = \sqrt{f}/25$

Most calculators will do this one.
Some sources give slight variations on this, or more mathematically precise formulae, but this is near enough. You still need some trial and error to get the best size spot on, though.

Exposure Calculation

Don't be put off by the word 'calculate', all you have to do is count along an aperture scale.

You can measure the aperture of your pinhole.

If it's big enough you might do it roughly with an accurate ruler and a lupe or linen tester. Otherwise you can scan it on a good flatbed transparency scanner, at 100% enlargement (ie actual size), and then use photoshop's ruler to measure it. Most accurate is to mount the pinhole material in a 35mm slide mount and project it. You will also a 1cm scale on acetate, mounted in a slide. Project the 1cm scale and measure how wide it is on the wall. Work out how much it has been enlarged. Project the pinhole, and it will have been enlarged by the same factor. Get help if this makes no sense! Then use the method on page 1 to work out the aperture (f/d).

You can find out the ISO of your sensitive material.

If it's film, it's printed on the box! If it's paper, although paper has ISO speed ratings they are not equivalent to film ones. Usually paper is around 6 - 12 on the film scale, but you will need to do some trials to work this out for certain. Lith film is also around ISO 6 - 12 on the film scale.

You can measure the light.

Any light meter will do this, including your camera.

There are two big BUTs:

Firstly, the pinhole aperture will be a lot smaller than the smallest one your light meter can handle. A pinhole is probably in the hundreds and your camera lens only goes to about f/22 or f/32. Even an upmarket hand held meter usually only goes to f/90 or so.

You will need to count how many f-stops your pinhole is beyond the range of the meter, and compensate accordingly when making the exposure.
The extended range of apertures into pinhole territory (which you should now be able to figure out, by the way) is:
16 22 32 45 64 90 128 180 256 512
For example, if your pinhole aperture is 5 stops beyond what the meter reads, you will need to give five stops extra exposure over the meter's suggested shutter speed. That means 5 doublings of the time. It soon runs into minutes on a dull day.

The other issue is that of reciprocity failure when using film or paper. When film exposures get beyond one second or so, the film usually gets slower and you have to add exposure to compensate for this. Manufacturers usually provide information on how much on their technical data sheets.
Similarly for paper, though you might not find the info on data sheets and have to work it out through trial and error.

Common Problems with Pinhole Cameras

Although this isn't a 'how to make one' guide, here are some of the most common problems, in no particular order:

- Light leak in camera
- Reflections inside camera - not matt-black enough
- Pinhole too big or too small
- Pinhole not round enough - if it's jagged the image gets very blurry
- Camera not held steady enough - they are often quite light and easily blown or jogged