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The pinhole camera: Science and Fun

This small paper is divided into two parts:

1. The (semi) scientific part (mostly for nerds). It can be skipped if you are only interested in practical stuff.
2. The practical part describes how you can easily build your own digital pinhole camera. It's great fun!

1. Investigation of the point spread function (psf) for pinhole cameras with different hole sizes

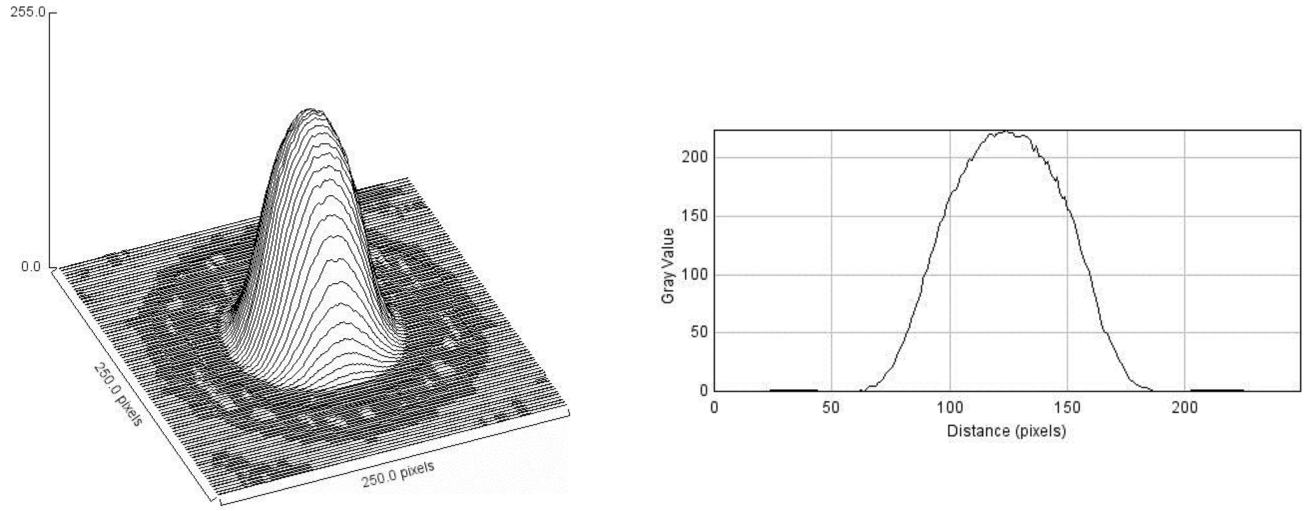
The experimental set-up consisted of:

- Point light source, consisting of a fiber light source equipped with a 0.35 mm hole in an aluminum foil mounted on the fiber opening. The point source was placed 4 meters from the pinhole camera.
- A set of apertures with diameters 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.0 and 3.2 mm (measured using a microscope with an eyepiece with built-in scale) mounted on a studio camera (bellows camera) with the film cassette removed.
- Sony A7 camera body located at the rear of the studio camera (where the film cassette had previously been).

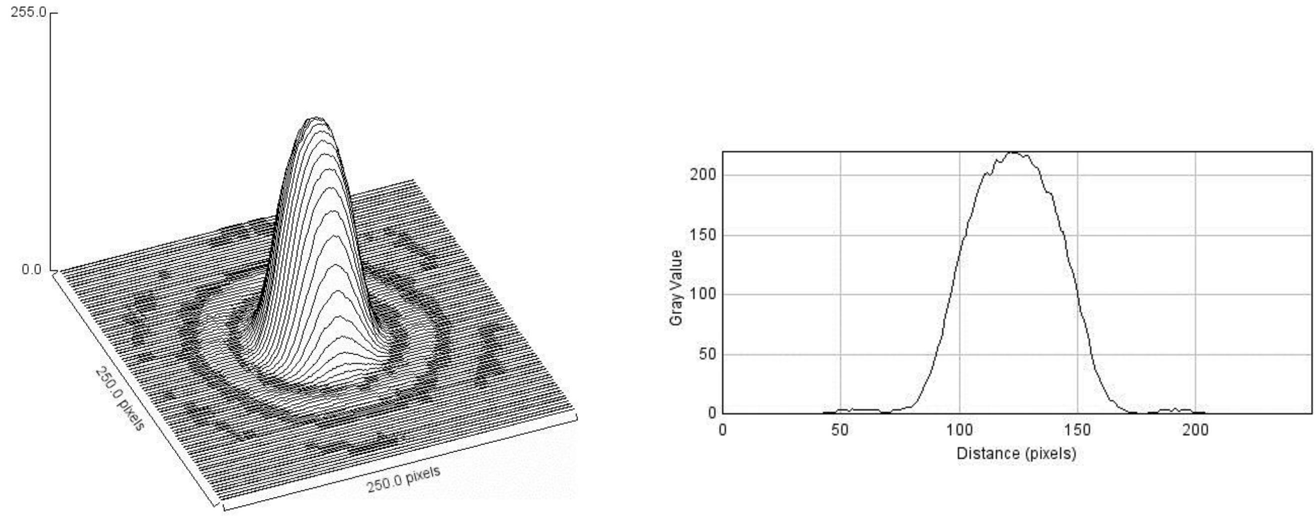
The distance between the point light source and the pinhole was 4 meters, and the distance between the pinhole and the sensor was approx. 16 cm. Images were recorded with full resolution (24 mpixels, 6.0 µm pixel size) in RAW format, and with ISO 100. The exposure time varied between 5 and 30 seconds depending on pinhole size. The images were RAW-converted using color balance and exposure adjustments, but without sharpening and noise reduction ("linear" intensity scaling was used in the RAW converter, but that means gamma correction is still done). To correct to some extent for the gamma correction (which in practice is not a pure gamma correction), an inverted correction was made in ImageJ assuming that a gamma of roughly 2.0 had been used (it is usually of that order). The images cannot be expected to be completely linear in intensity after this treatment, but that should not be so important - the geometric extent of the psf should be possible to judge quite well. Since the psf is wavelength dependent, the red image channel was selected during the analysis. Let us assume that the wavelength is then about 600 nm.

According to theory, an optimal hole size (diameter) is somewhere in the interval $1.6\sqrt{\lambda b}$ to $2.0\sqrt{\lambda b}$ (depending on whether resolution or MTF is considered, Carlsson 2004), where b is the distance between hole and sensor (corresponding to the focal length of a lens). In the current set-up, the optimum hole size would then be between 0.50 and 0.62 mm, ie hole sizes 0.50 and 0.60 mm should give good results. On the next pages the measured psf for all hole sizes are shown, both as line profiles through the center and as surface plots. In all cases, except for the largest hole size, image sections of 250 x 250 pixels corresponding to 1.5 mm x 1.5 mm in the sensor plane are shown. For the largest hole, an image section of 720 x 720 pixels, corresponding to 4.3 mm x 4.3 mm, is shown.

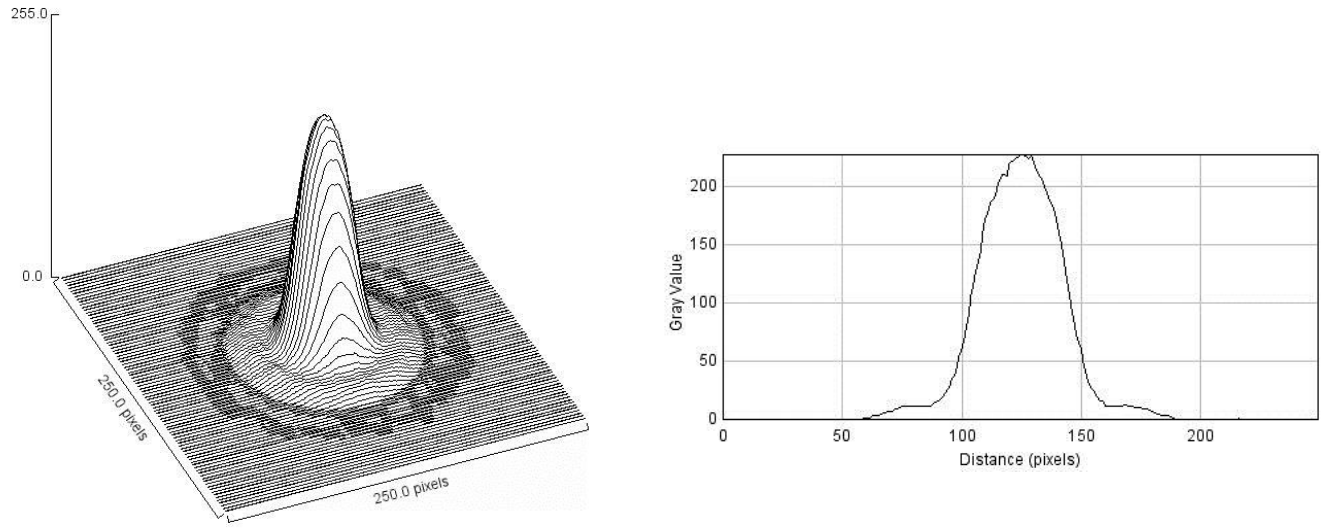
For small hole sizes, the psf corresponds rather well to the Fraunhofer diffraction case $\left(\frac{2J_1(r)}{r}\right)^2$, while larger openings exhibit clear Fresnel diffraction with growing multiple side lobes. The narrowest psf occurs in the borderland between Fraunhofer and Fresnel diffraction.



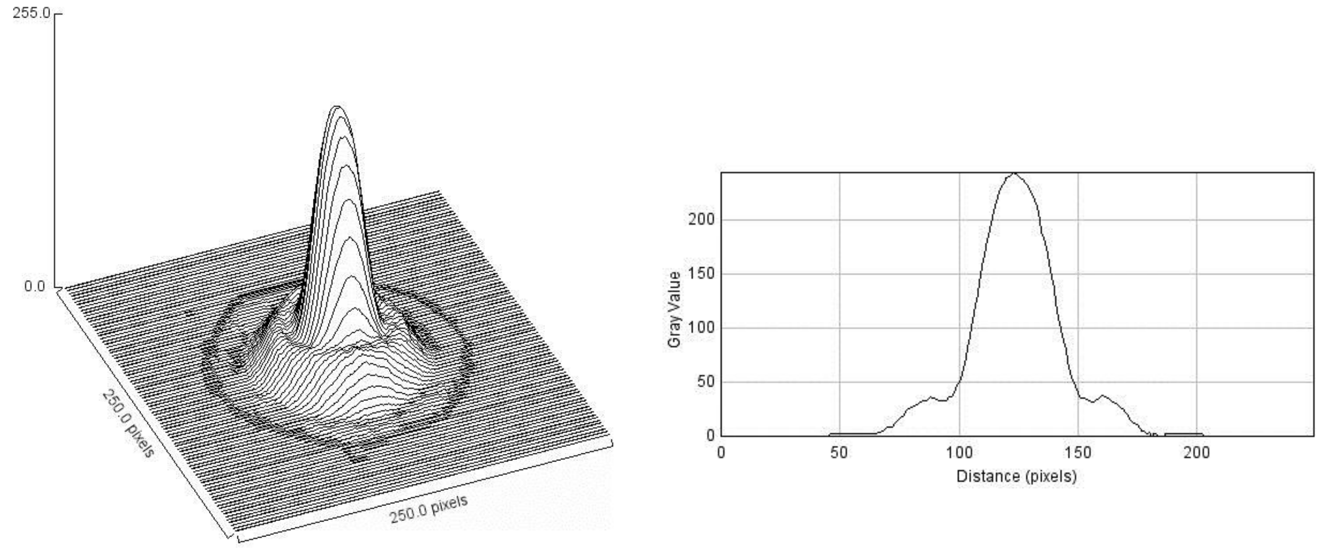
Hole size 0.30 mm



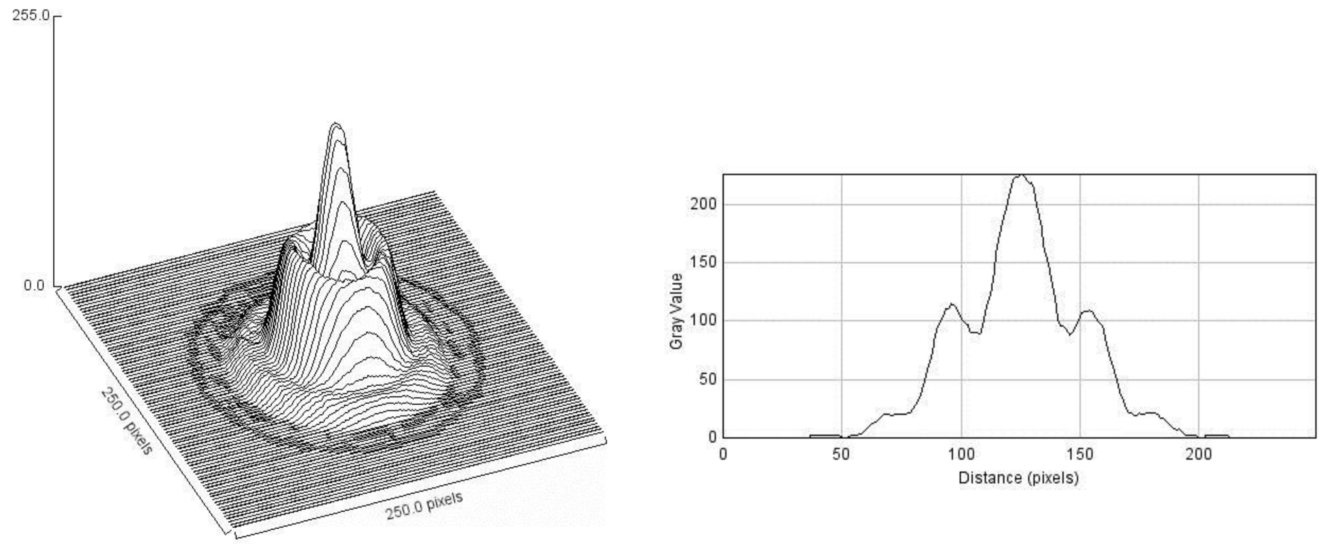
Hole size 0.40 mm



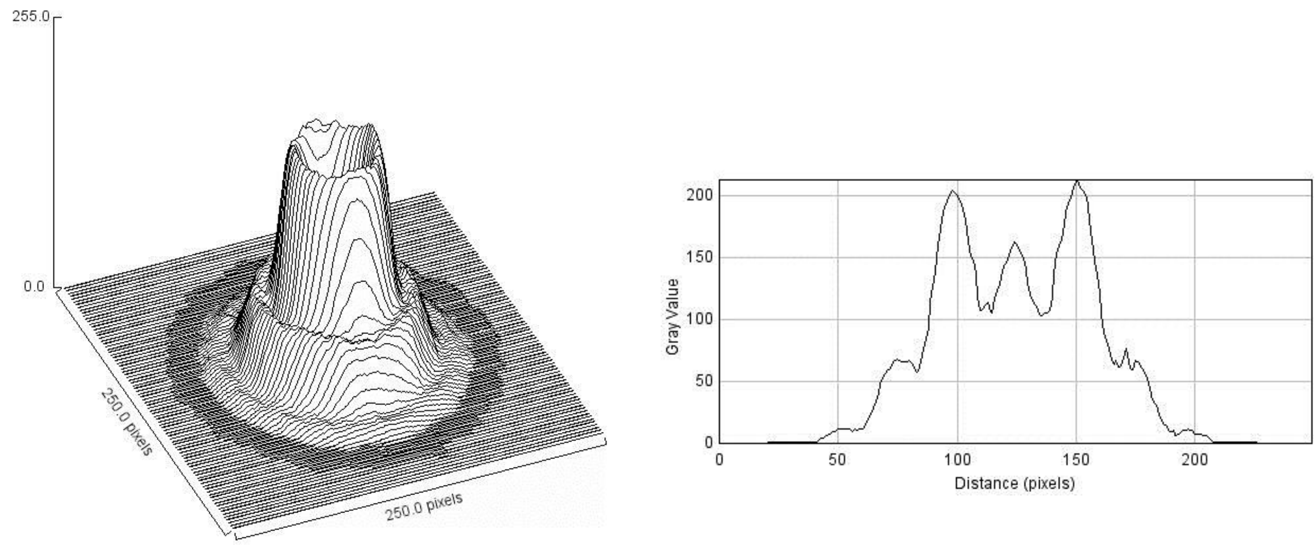
Hole size 0.50 mm



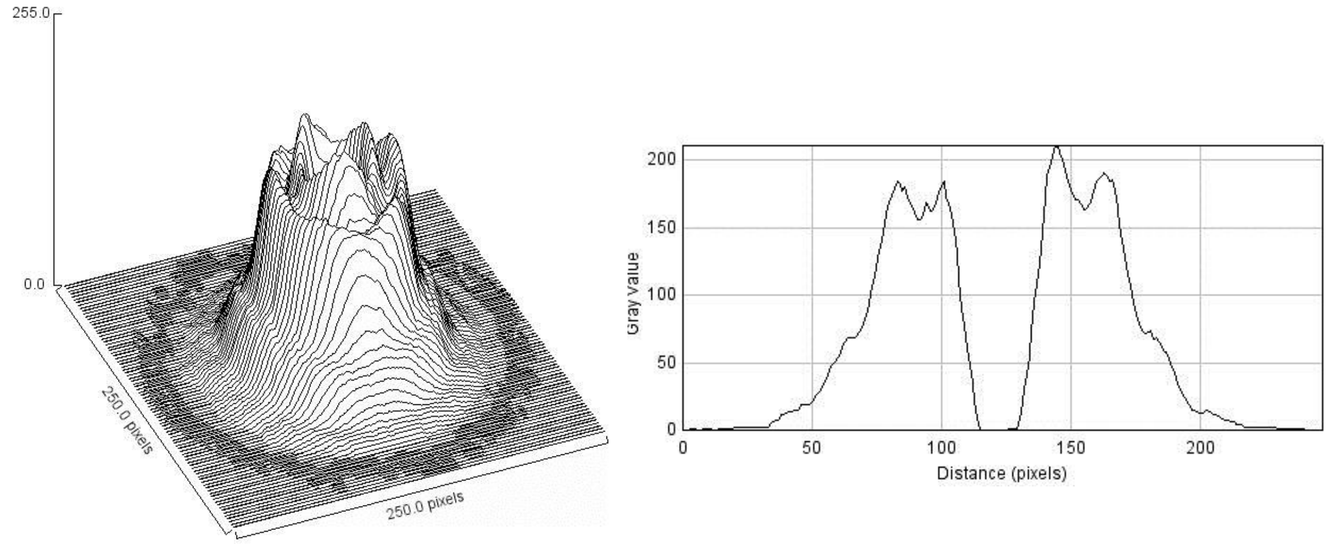
Hole size 0.60 mm



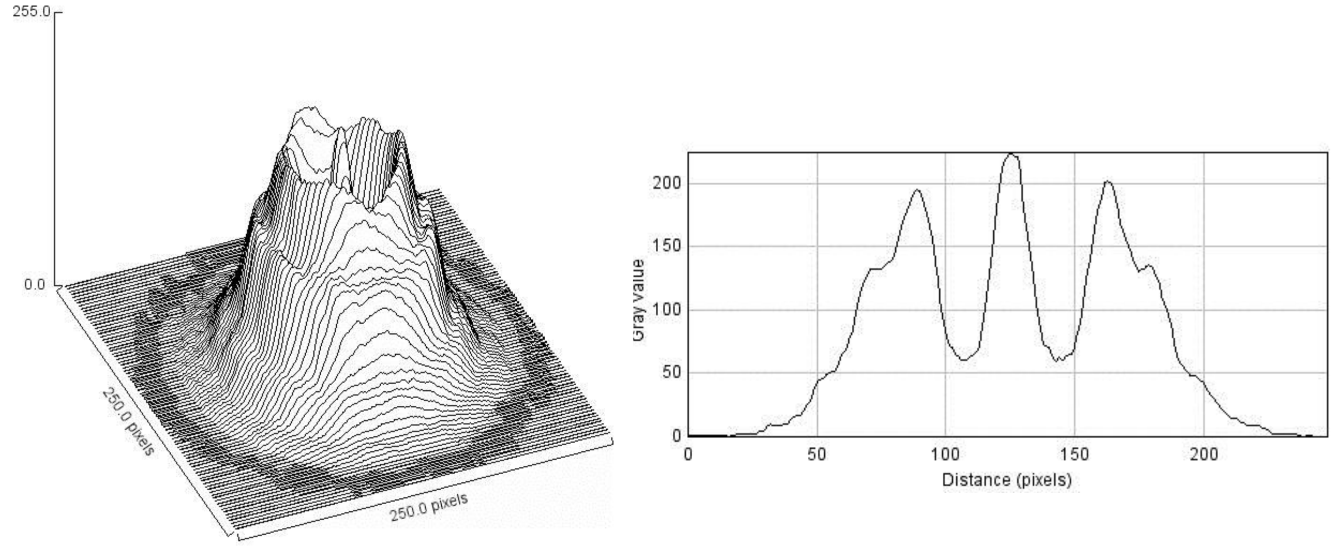
Hole size 0.70 mm



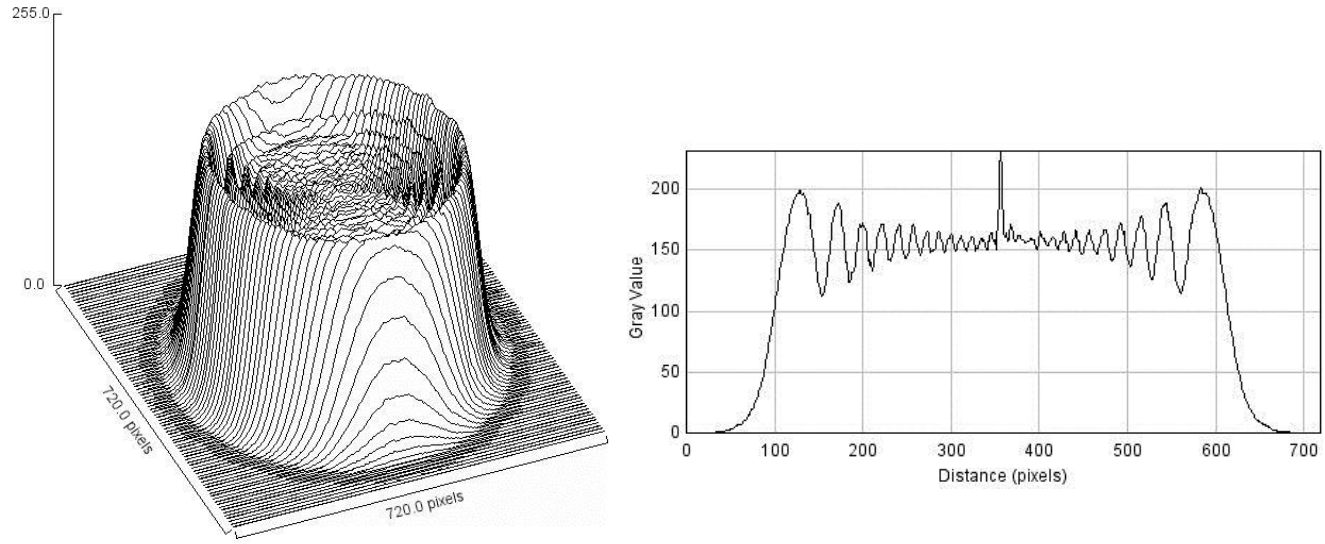
Hole size 0.80 mm



Hole size 0.90 mm

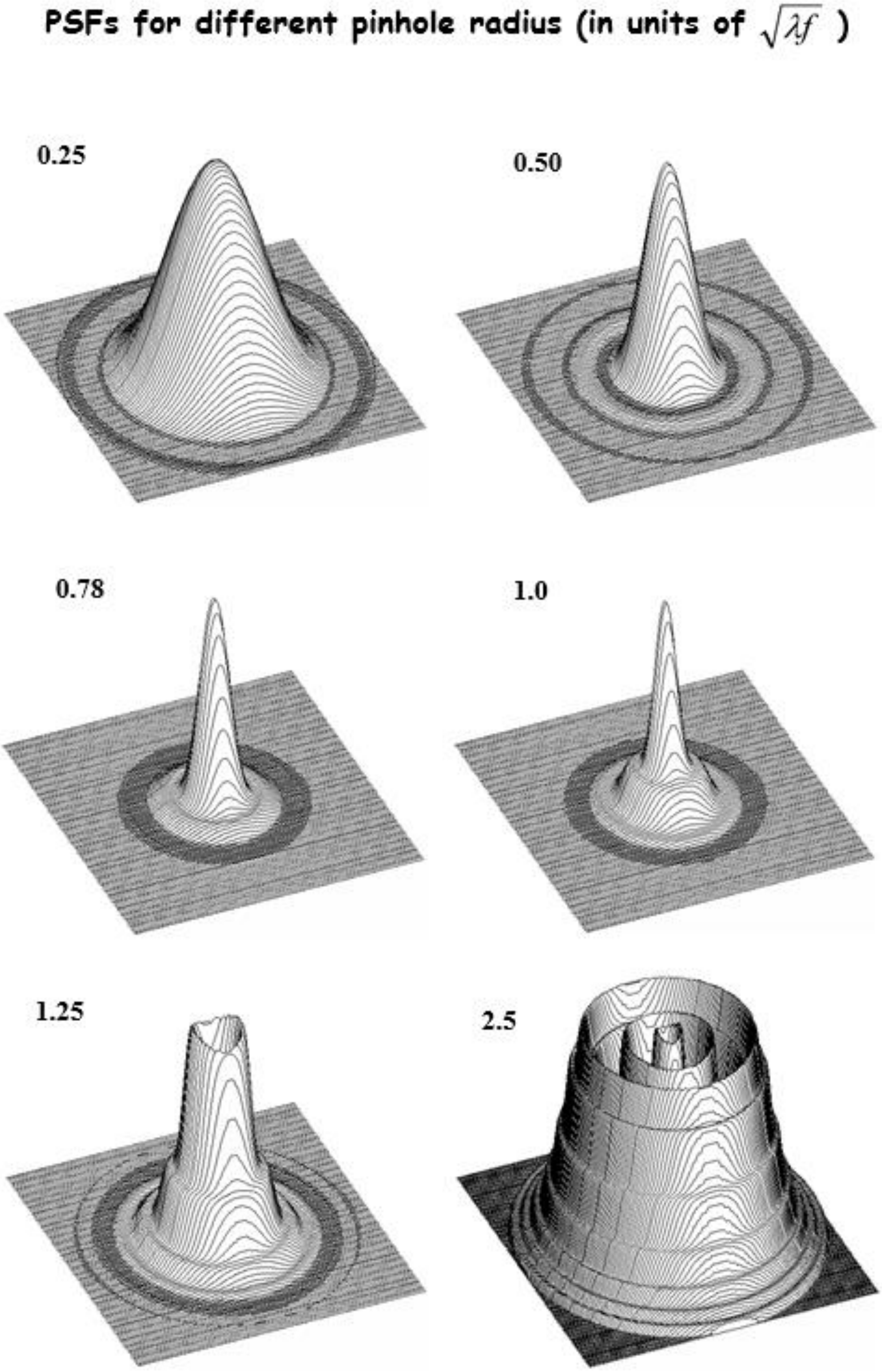


Hole size 1.0 mm

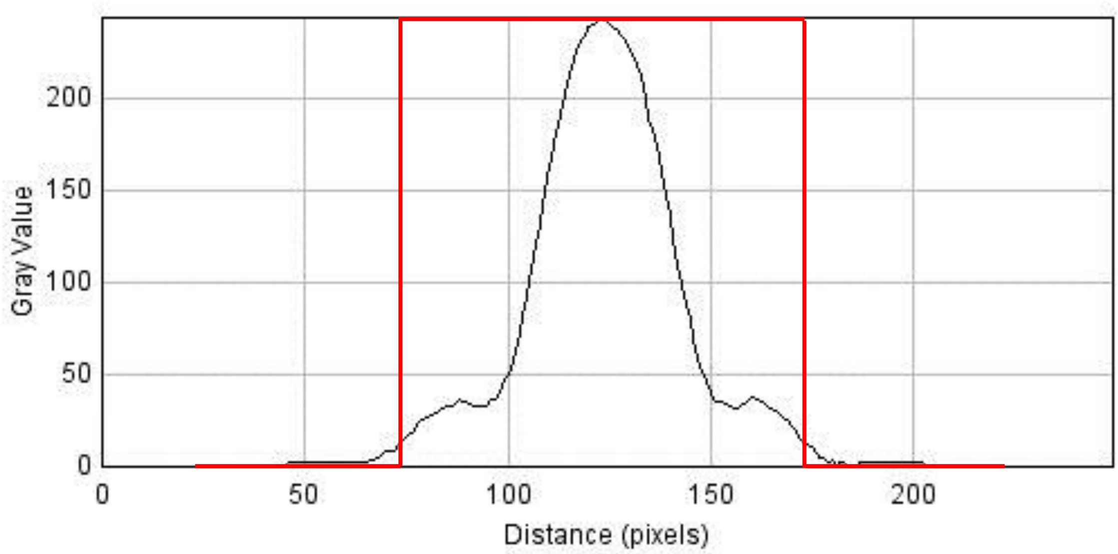


Hole size 3.2 mm (NOTE: The distance scale is different from the other images)

The measured psf:s correspond well with theoretically calculated psf:s (Carlsson, 2004), which are reproduced below, where radius 1.0 corresponds to a hole diameter of 0.62 mm in the current experiments.



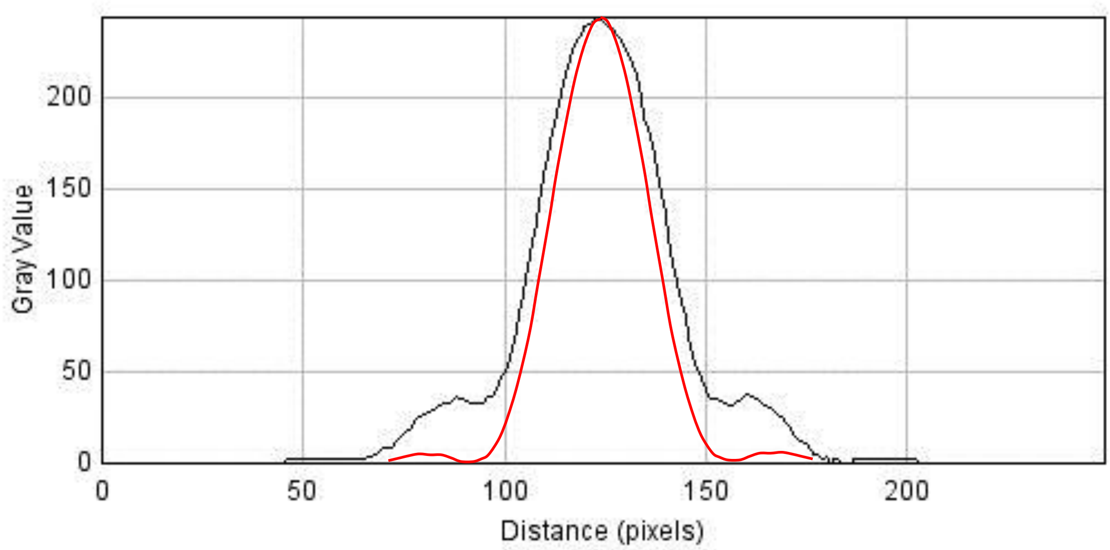
It is interesting to note that for optimal hole size, the psf is considerably narrower than what is given by geometrical optics (ie if you neglect diffraction). This is illustrated for hole size 0.60 mm in the figure below.



Measured psf for 0.60 mm hole size (black curve) compared to psf according to geometrical optics, ie without diffraction, (red curve). One pixel equals 6.0 µm.

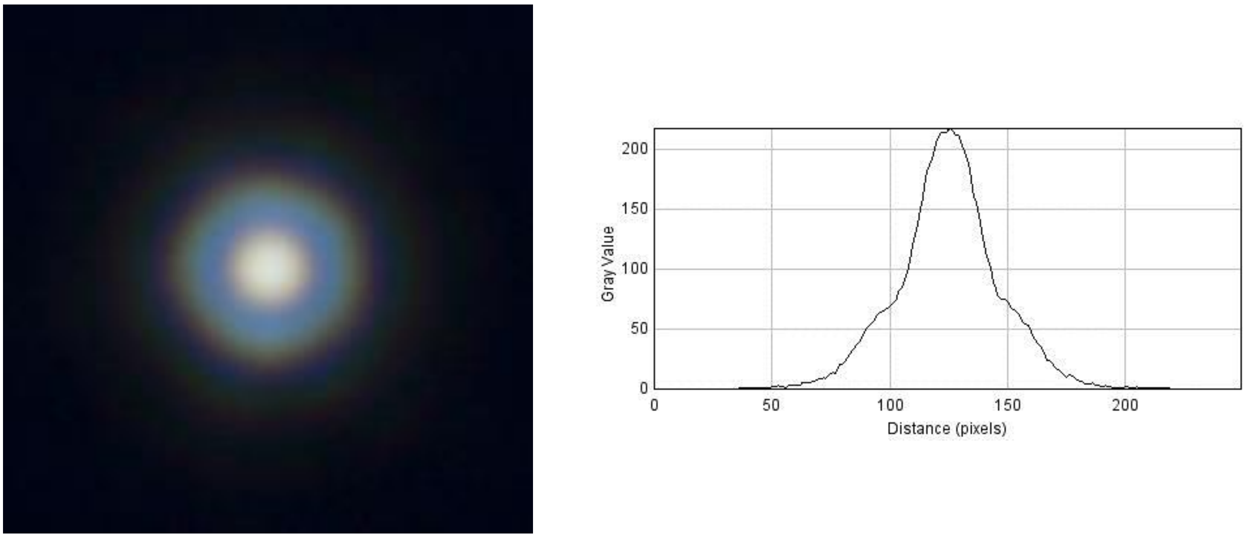
For very small hole sizes, however, the psf will be wider than that given by geometrical optics, while for large hole sizes (like 3.2 mm on page 4), the psf becomes more and more similar to that given by geometrical optics (but with some oscillations).

How would the psf look if we inserted a diffraction limited lens with a focal length of 160 mm after the 0.60 mm hole? The result is shown as a red overlay in the figure below. No major difference. When using very high F-numbers (in this case approximately 270) it obviously matters very little if we remove all the glass in the lens so that only the aperture remains!

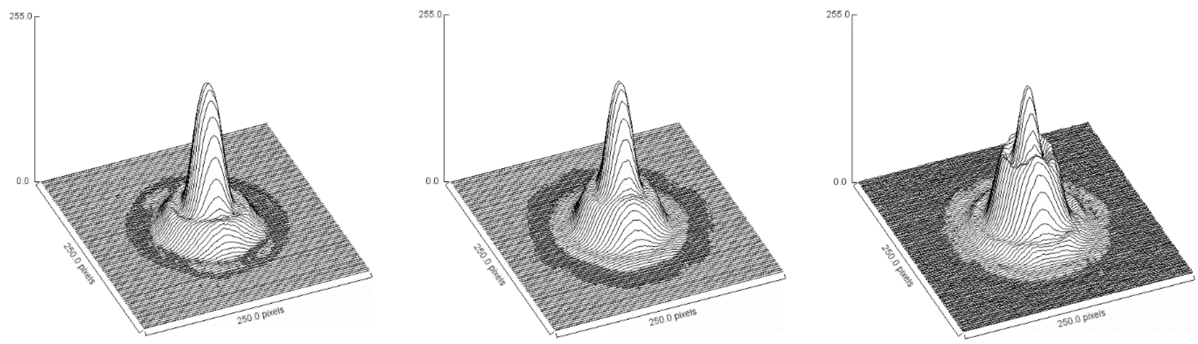


Theoretical psf for a diffraction limited lens (red), and measured psf for a pinhole (black) for an aperture number of 270 (f = 160 mm, aperture diameter = 0.60 mm)

Before moving on to the description of how to build a simple digital pinhole camera, I just want to mention how the psf is affected if we look at all three color channels in the pictures (not just the red channel as so far). Let's look again at the psf for the 0.60 mm hole. In color, it looks like the figure below.



Measured psf for the 0.60 mm hole shown in "full color". The diffraction pattern is different for different wavelengths. The right figure shows a profile through the center where "Gray value" means the total brightness impression from all color channels (unknown weighting of RGB in ImageJ). Compared to the profile of only the red channel (page 3, and the left figure below), the psf with all colors becomes a little wider and exhibits less oscillations. The psf for the three subchannels is illustrated below.



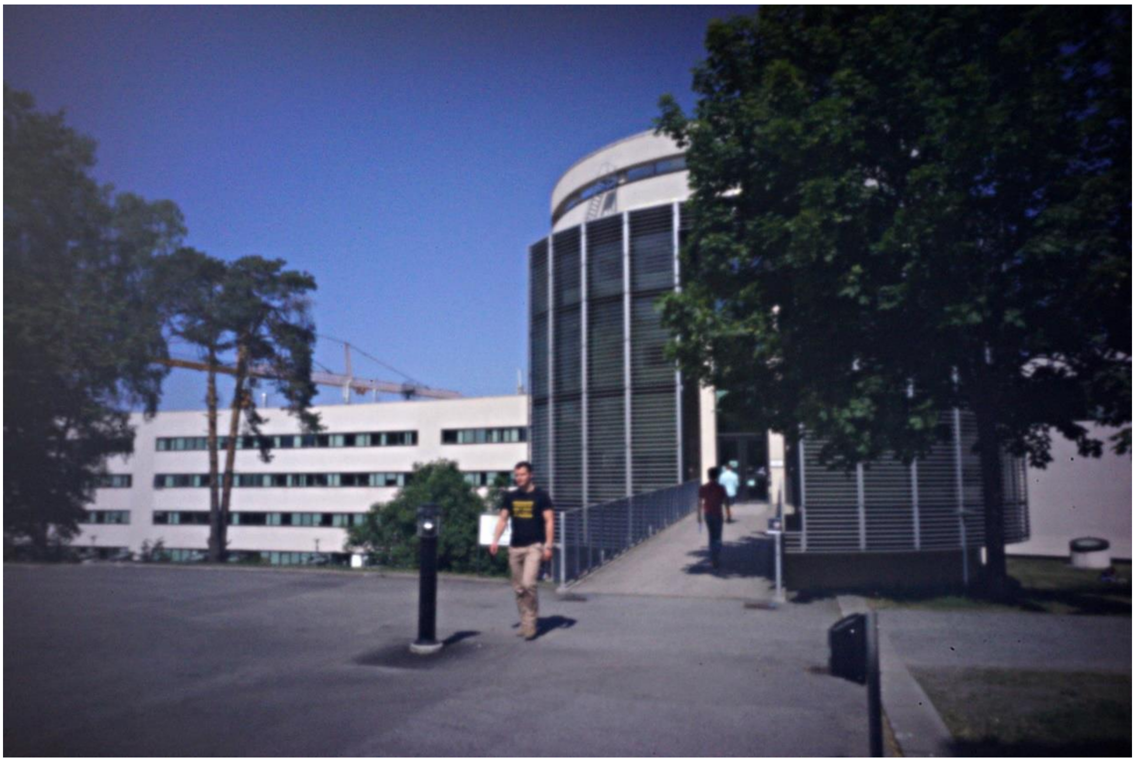
The above psf divided into R, G and B channels (from left to right). The hole size is near optimal for red light, but is too large for green and (even more so) for blue light (the first side lobe becomes higher and therefore the psf becomes wider).

2. How to build a pinhole camera that can record as much image detail as possible

Now let's look at how we can easily make a pinhole camera that takes decent pictures. At optimum hole size, the cut-off frequency for the MTF of a pinhole camera is approximately $\frac{1.6}{\sqrt{\lambda b}}$, where b is the distance between hole and sensor (Carlsson, 2004). The units are then periods per unit length (m^{-1}). As can be seen from Carlsson, 2019, it is preferable to use periods (or line widths) per sensor height as units if one is to get an idea of the sharpness impression produced by an image. If we introduce the sensor height h then the MTF cutoff frequency will be approximately $\frac{1.6h}{\sqrt{\lambda b}}$ periods per sensor height. The recipe for a high cut-off frequency, and hence good image sharpness, is thus a large sensor height h and a short distance, b, between the hole and the sensor. To test this concept, a digital camera body with the largest sensor available to me (Sony A7, ie full format with h = 24 mm) was used with a 0.2 mm hole mounted 24 mm from the sensor. The size of the hole was selected to be approximately in the middle of the optimum range indicated on page 1, and the size was checked using a microscope having an eyepiece with a measuring scale. The hole was made by gently pressing a needle onto a piece of aluminum foil (kitchen type) lying on a semi-hard surface.Trial and error was used to get the correct size. The aluminum foil was then mounted on a piece of cardboard that was attached to the cover lid of the camera body (a hole had been made in the lid). The arrangement is illustrated in the figure below. Sealing is important so that no stray light can enter the camera body, because the image on the sensor is very faint. With ISO set to 1000 (this gives perfectly OK quality with a full-format sensor) you can shoot freehand outdoors in sunlight (the exposure time is typically 1/30 second). A couple of pictures taken with this camera are shown on the next page. The sharpness is of course a bit "soft", but the pictures often have an artistically appealing look. Notice the lack of distortion (otherwise common for extreme wide-angle lenses) and the extreme depth of field.

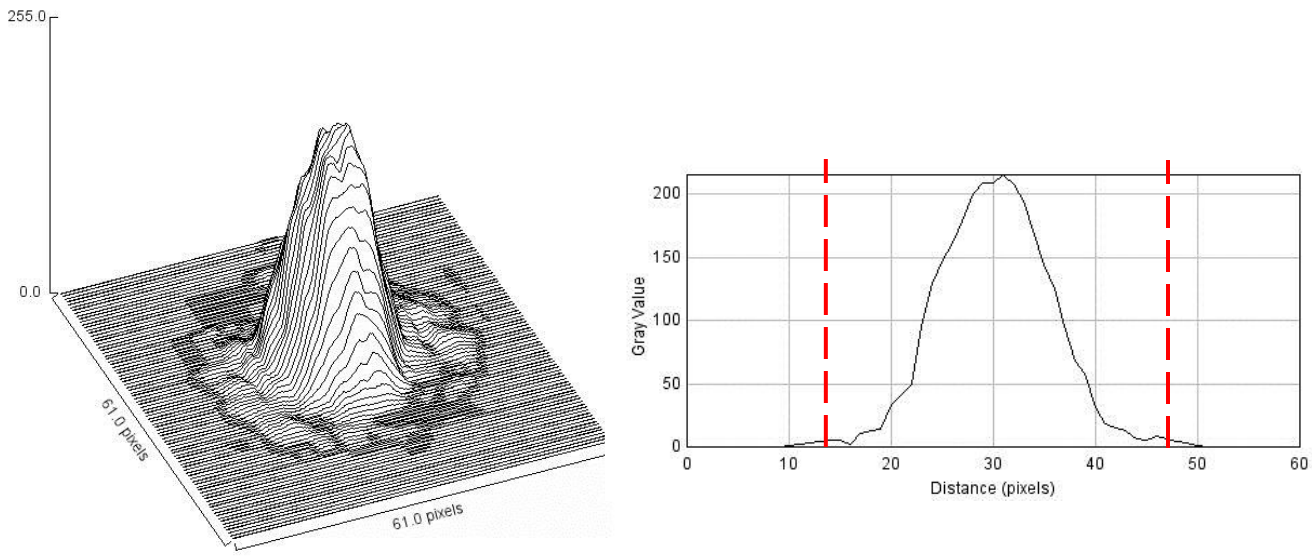
Sony A7 converted to pinhole camera. ”Sticky tack” was used to attach to the camera body a piece of cardboard with an Al foil having a 0.2 mm hole in the center. Not so neat, but it works and stray light is blocked!

Picture taken with the camera on the previous page. Note the immense depth of field. The flowers in the foreground (Bunias orientalis or "Hill mustard") are approx. 8 mm in diameter and located approx. 9 cm in front of the camera. Equivalent F-number is approx. 120. Total freedom from distortion (and other aberrations) despite an extremely wide angle (corresponding to 24 mm focal length on a full-format camera).



Another picture taken with the camera on the previous page.

A primitive pinhole camera of the kind described here will not have a hole that is perfectly ideal. When the Al foil is penetrated by a needle, it will generally not result in a hole that is circular. Also, the edges tend to be jagged. This will of course affect the psf so that it does not become circularly symmetrical. The figure below shows what it looked like for the camera in question. As can be seen, the psf is a bit irregular, but it is narrow enough to give a decent image sharpness, which is essential.



Measured psf for the A7 pinhole camera. Note again that the psf is clearly narrower than the hole itself (indicated with red lines).

When photographing line patterns in a photo studio, it was found that a spatial frequency of approx. 340 periods/sensor height could just barely be resolved. This value corresponds very well with the theoretical frequency limit of the MTF stated on page 8, ie approx. $\frac{1.6}{\sqrt{\lambda b}}$, which for 550 nm wavelength and b = 24 mm gives 334 periods/sensor height. This suggests that the hole used is near optimal.

One could argue that reducing the image distance b to below 24 mm would produce even sharper images (and even more wide-angle effect). But a problem that becomes increasingly serious for smaller b-values is the the fall-off in light intensity towards the edges of the image (furthermore the psf is probably wider towards the edges). The fall-off in light intensity has been partially compensated for by software in the pictures on page 9, but this only works to a certain limit. Another (and better) way to improve the image sharpness is to increase the sensor size h. For constant image angle, the frequency limit of the MTF increases as $\sqrt{h}$. The problem is that digital cameras with sensor sizes larger than full format are very expensive. However, large photo papers are quite inexpensive, and this has been utilized by sanitation workers in Hamburg to build a "garbage can pinhole camera" using a huge photo paper as sensor (see reference). The image sharpness is superb, but the exposure times become very long and the camera is very cumbersome. So at present, it seems most convenient to use a digital camera of the type described above (possibly one could reduce the image distance b a little and use a smaller hole, let me see where did I put that needle ??).

End of story (so far)!

References

Carlsson, 2004, https://www.kth.se/social/files/542d2d2df276546ca71dffaa/Pinhole.pdf

Carlsson, 2019 (in Swedish),
https://www.kth.se/social/files/5c7faed456be5bc5b2cd7ac5/FOTOKOMPENDIUM.SK1140.VT19.pdf

Garbage can camera: https://www.designboom.com/art/garbage-bin-pinhole-camera-image-series-by-the-trashcam-project/

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