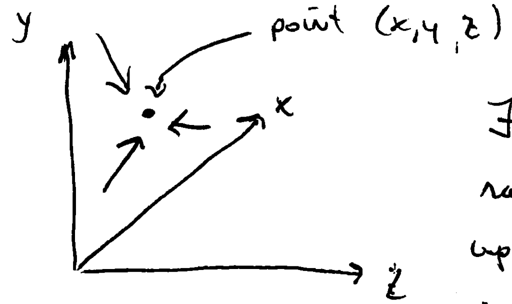
LIGHT FIELD



For a given point in space, the radiance at that point will be dependent upon all of the rays incident upon that point. Each of these rays will have a trajectory associated with it. If we integrate the contribution of all of the different trajectories that pass through the point, we'll get the total irradiance at that point. The light field $L(x, y, z, \theta, \phi)$ describes the contribution at a given point (x, y, z) for a ray incident on that point in angles (θ, ϕ). Integrating over all possible θ, ϕ gives the irradiance $I(x, y, z)$. In general time, polarization, and wavelength can be incorporated in here too.

The geometry can often be simplified and the dimensionality reduced for cases that we will deal with. Consider the case of the image space of a conventional camera.

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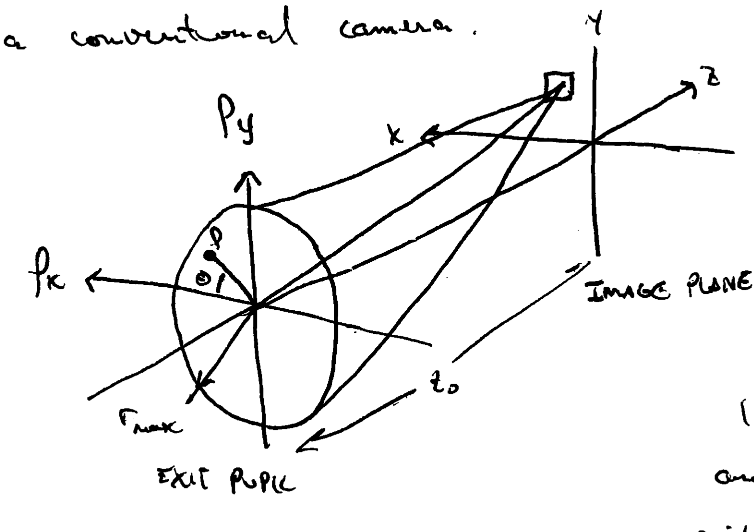

The light field in this case can be described by

$$L(x, y; \rho, \theta)$$

Since z is a constant, where (x, y) are the image plane coordinates and $p_x = \rho\cos\theta$ and $p_y = \rho\sin\theta$ are the exit pupil coordinates.

The angle of incidence for a given ray incident on (x, y) is related to $\frac{r_{max} p_x - x}{z_0}$ and $\frac{r_{max} p_y - y}{z_0}$.

If we integrate this light field over the exit pupil coordinates, we get the irradiance at the point (x,y)

$$I(x,y) = \int_0^{2\pi}\int_0^{1} L(x,y;\rho,\theta)\,\rho\,d\rho\,d\theta$$

Here, we have ignored wavelength ~~and the size of a pixel recording the image irradiance~~

$$I(x,y;\lambda) = \int_0^{2\pi}\int_0^{1} L(x,y;\rho,\theta;\lambda)\,\rho\,d\rho\,d\theta$$

Suppose we have the i^{th}, j^{th} pixel in a camera sensor and it has a transmission filter $T(\lambda)$ placed over it and a size $\Delta x, \Delta y$. This pixel will record

$$I_{ij} = \iint_{\substack{x=x_0-\frac{\Delta x}{2}\\ y=y_0-\frac{\Delta y}{2}}}^{\substack{x=x_0+\frac{\Delta x}{2}\\ y=y_0+\frac{\Delta y}{2}}} \left[\int_{\lambda=0}^{\lambda=\infty} T(\lambda)\, I(x,y;\lambda)\, d\lambda\right] dx\,dy$$

where x_0, y_0 is the center of the i^{th}, j^{th} pixel in the array

For simplicity and clarity, we'll just use

$$I(x,y) = \int_0^{2\pi}\int_0^{1} L(x,y;\rho,\theta)\,\rho\,d\rho\,d\theta$$

with the understanding that we can do this for each color channel in the camera and incorporate the finite size of the pixel if needed.

A conventional camera loses information regarding the incident ray trajectories bc it integrates over the entire entrance pupil.

~~Plenoptic cameras seek to retain this trajectory information. Unfortunately, they give up spatial resolution in the process~~

We can increase the depth of field of a conventional camera by stopping down the aperture. Similarly, we can swap lenses to give different fields of view. However, once the picture is captured these effects are fixed in the image

Increased depth of field

$$I(x,y) = \int_0^{2\pi}\int_0^{\varepsilon} L(x,y;\rho,\theta)\,\rho\,d\rho\,d\theta \qquad 0 \le \varepsilon \le 1$$

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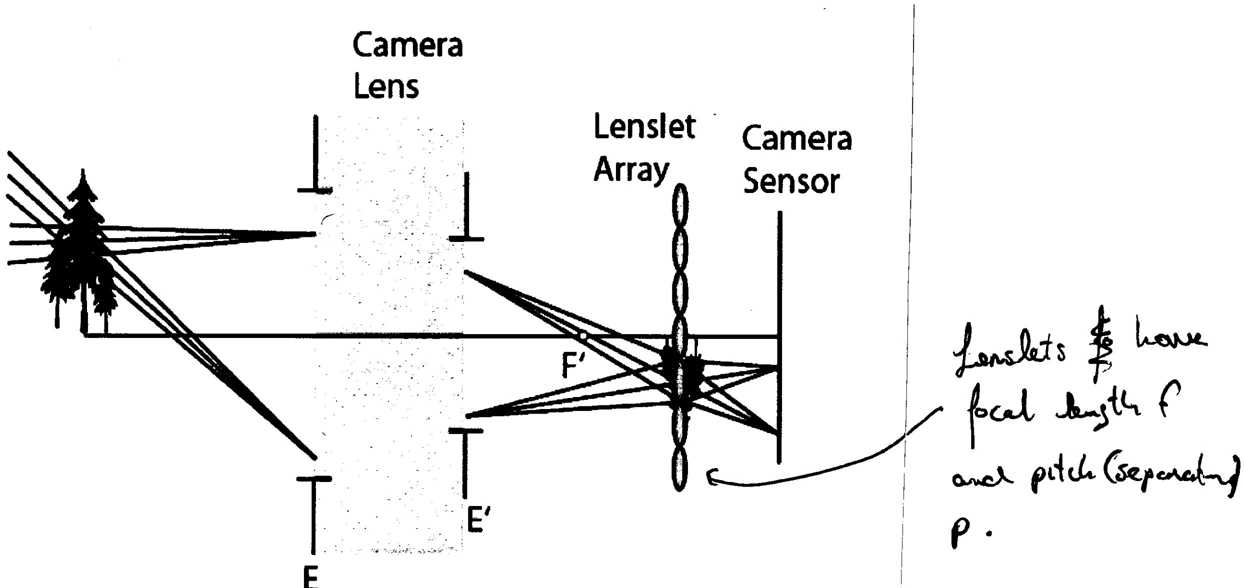
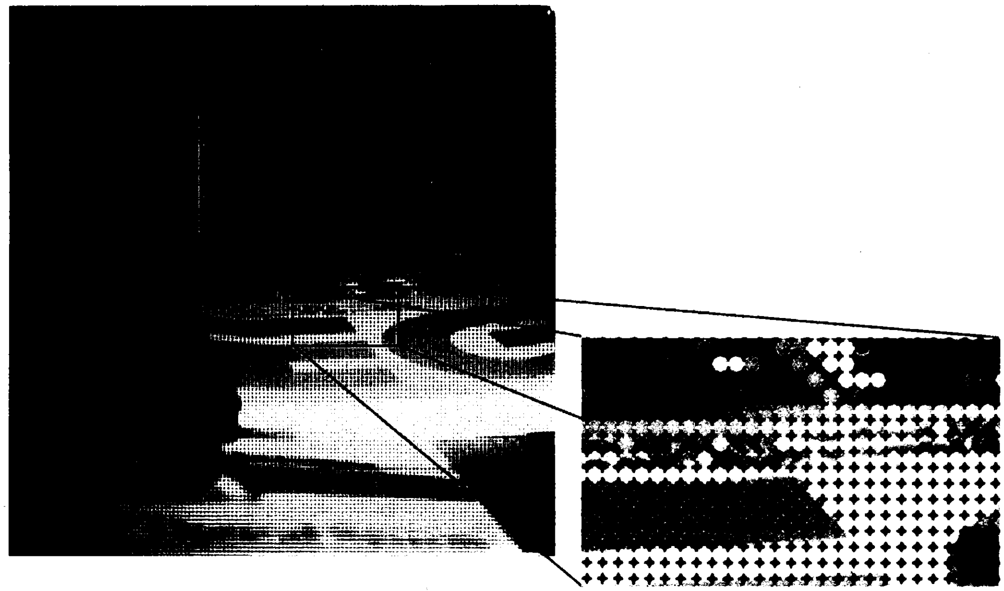
From the preceding ~~slide~~ equation, if we somehow knew $L(x,y;\rho,\theta)$ instead of just $I(x,y)$, we could vary ε after the image is captured and create a range of images with all different fields of view. Plenoptic cameras seek to capture $L(x,y;\rho,\theta)$ instead of $I(x,y)$ to enable this post processing. We'll also see that other effects such as changing viewpoint and focal length are possible too once $L(x,y;\rho,\theta)$ are known.

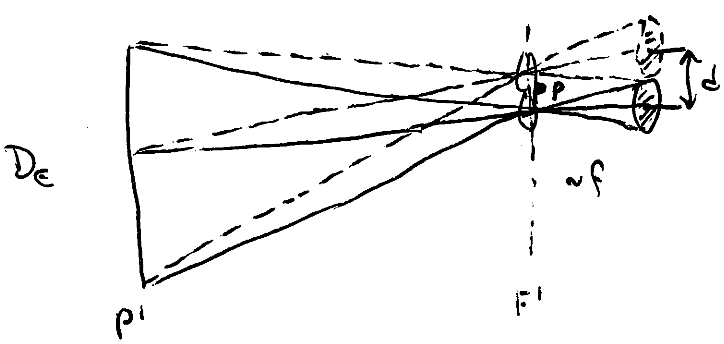
<u>Plenoptic Camera</u> - The convention plenoptic camera (sometimes call plenoptic 1.0) is shown below. A lenslet array is placed at the image plane of a conventional camera lens. The camera sensor is placed so that it is conjugate to the exit pupil of the camera lens.



The image captured on the sensor now looks like an array of images of the exit pupil. Each sub-image shows the exit pupil from a slightly different direction



It is important to match the working f/# of the camera lens to that of the lenslet array so that the exit pupil sub-images don't overlap which gives ambiguity to ray trajectories or are too spread out which ~~wastes~~ under-utilizes the camera sensor



For a rough approximation, assume the object is at ∞ and lenslets located at rear focal plane of camera lens. The f/# of the camera lens is $f/\# = \frac{\overline{P'F'}}{D_E}$ where D_E is entrance pupil diameter

From the drawing $\frac{d}{\overline{P'F'}+f} = \frac{p}{\overline{P'F'}}$ where we have assumed $f \ll \overline{P'F'}$. Also

$\frac{d}{f} = \frac{D_E}{\overline{P'F'}} = f/\#$ This leads to

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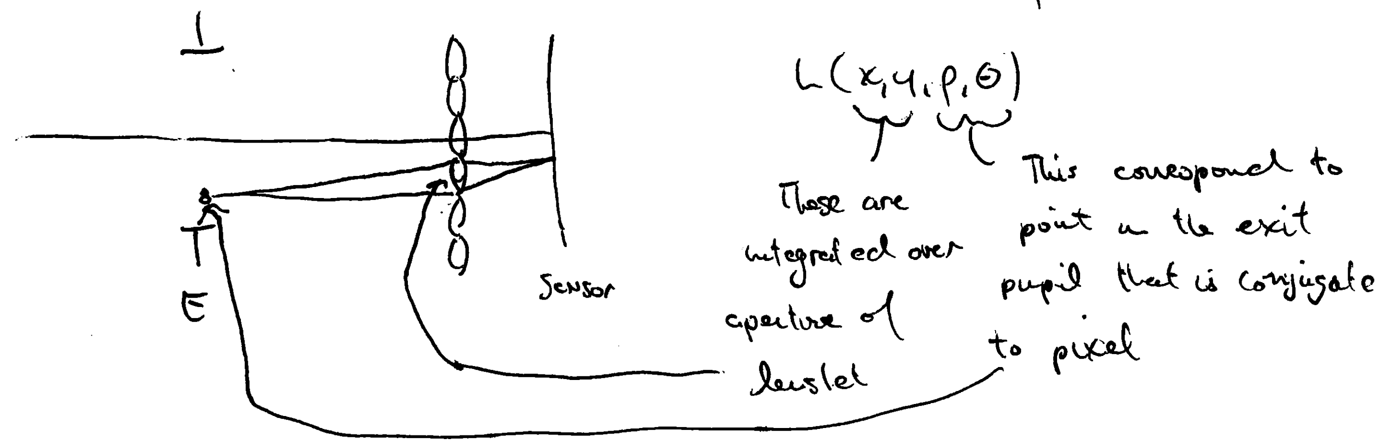
~~$\frac{p}{\overline{P'F'}} = \frac{D_E f}{\overline{P'F'}} \frac{1}{\overline{P'F'}+f}$~~

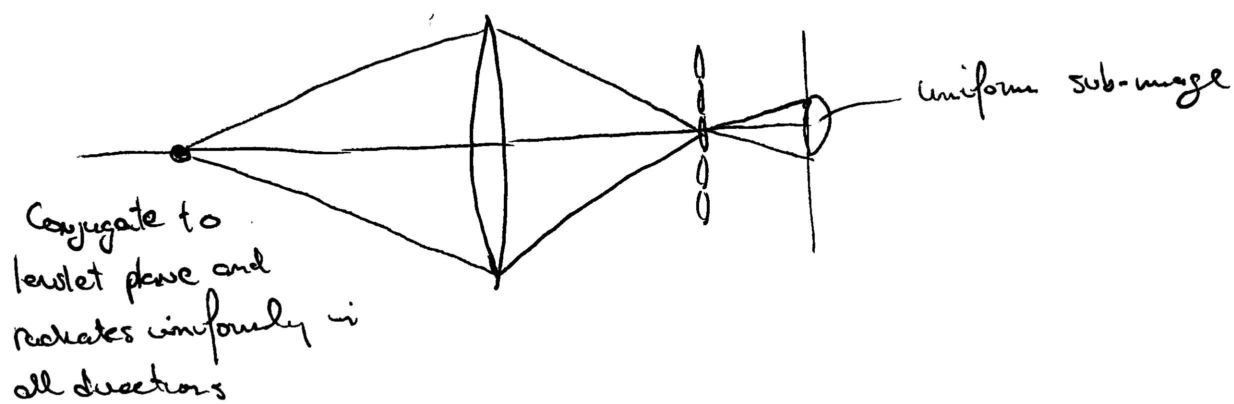
$$\frac{p}{\overline{P'F'}} = \frac{D_E f}{\overline{P'F'}} \frac{1}{\overline{P'F'}+f}$$

$$\frac{p}{f} = \frac{D_E}{\overline{P'F'}+f} \simeq \frac{D_E}{\overline{P'F'}} = f/\#$$

Each pixel in the camera sensor records a specific point in the exit pupil for roughly a given point in the image. This irradiance value is an estimate of



Content of subimages



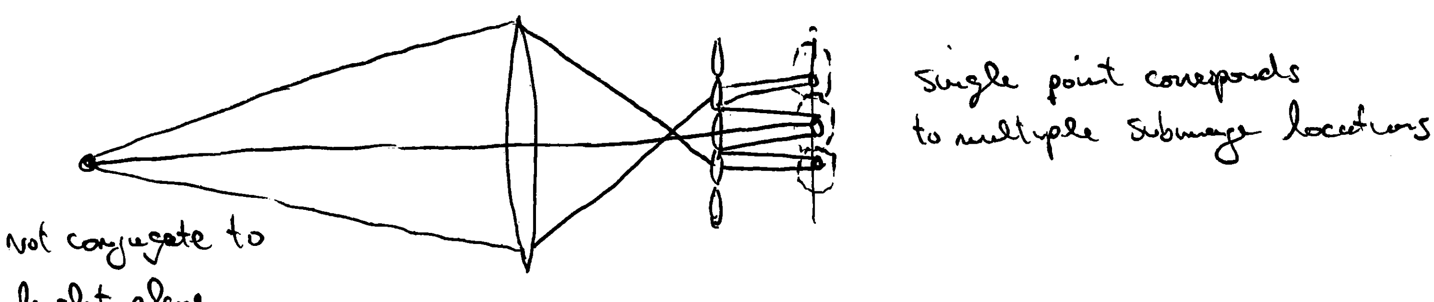
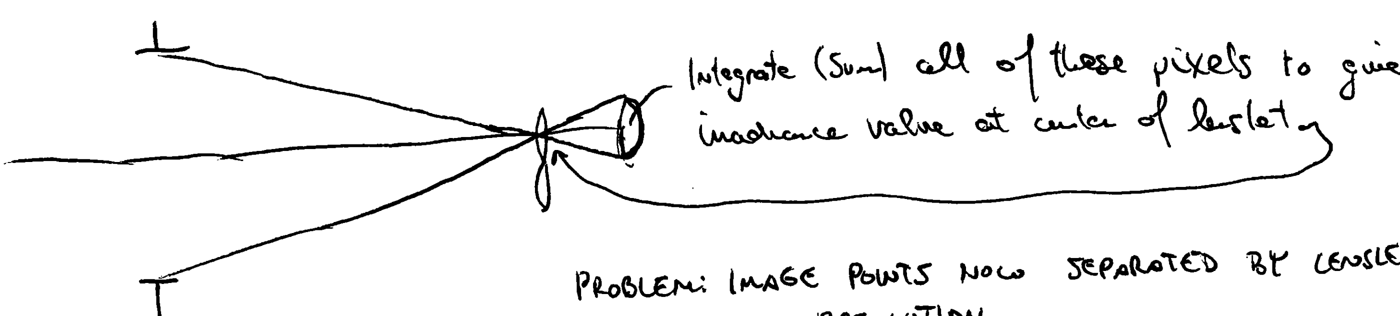


Image Reconstruction



PROBLEM: IMAGE POINTS NOW SEPARATED BY LENSLET SPACING - LOW RESOLUTION

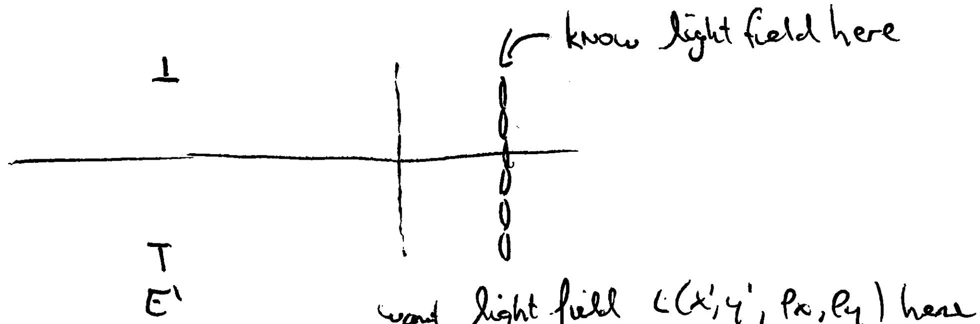
Changing Depth of Focus

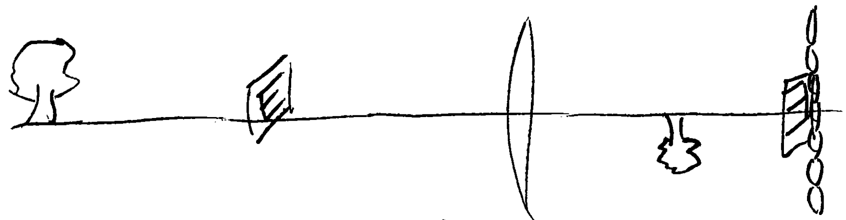
See Slide

Perspective Change

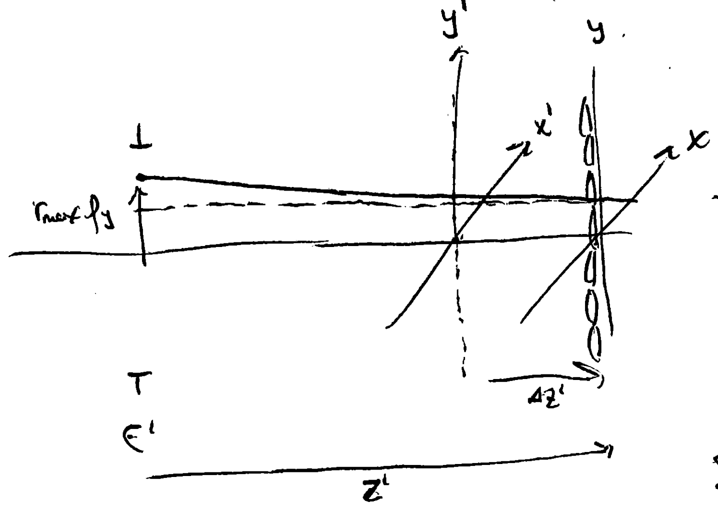
See Slide

PLENOPTIC REFOCUSING - More convenient to write light field in Cartesian coordinates for this case $L(x, y, \rho_x, \rho_y)$. For refocusing we want to determine the light field at a different plane given the light field $L(x, y, \rho_x, \rho_y)$





Suppose we have focused camera on near object. A far object will form an image closer to the rear focal point of the camera lens



From the geometry

$$\frac{y' - y}{\Delta z'} = \frac{r_{max}\rho_y - y}{z'}$$

Solve for y'

$$y' = y + \frac{\Delta z'}{z'}\left(r_{max}\rho_y - y\right)$$

Similar for x'

New light field

$$L(x', y'; \rho, \theta)$$

Can form new images

$$I(x', y') = \iint L(x', y'; \rho, \theta)\, \rho\, d\rho\, d\theta$$

Light Field Imaging and Plenoptic Cameras

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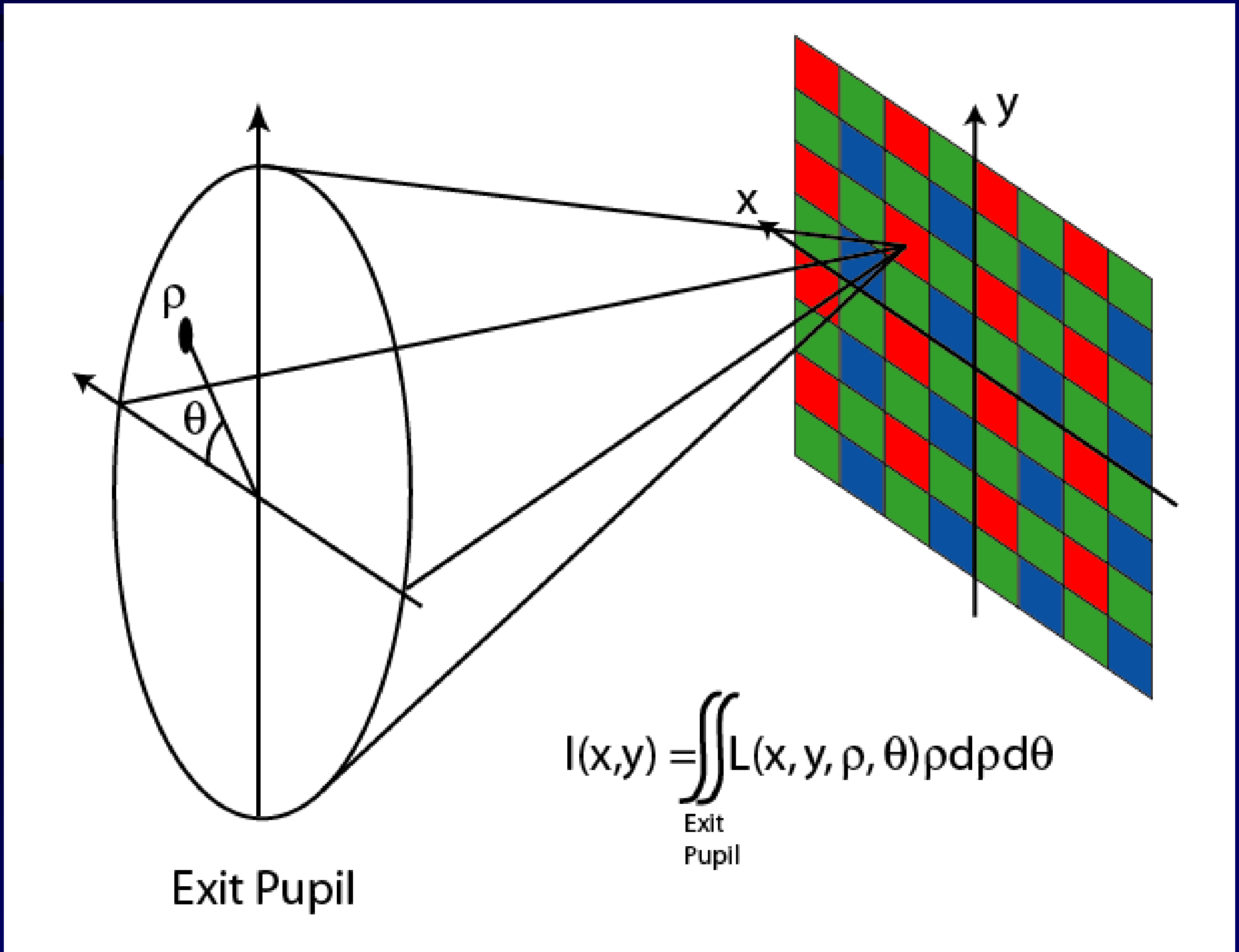
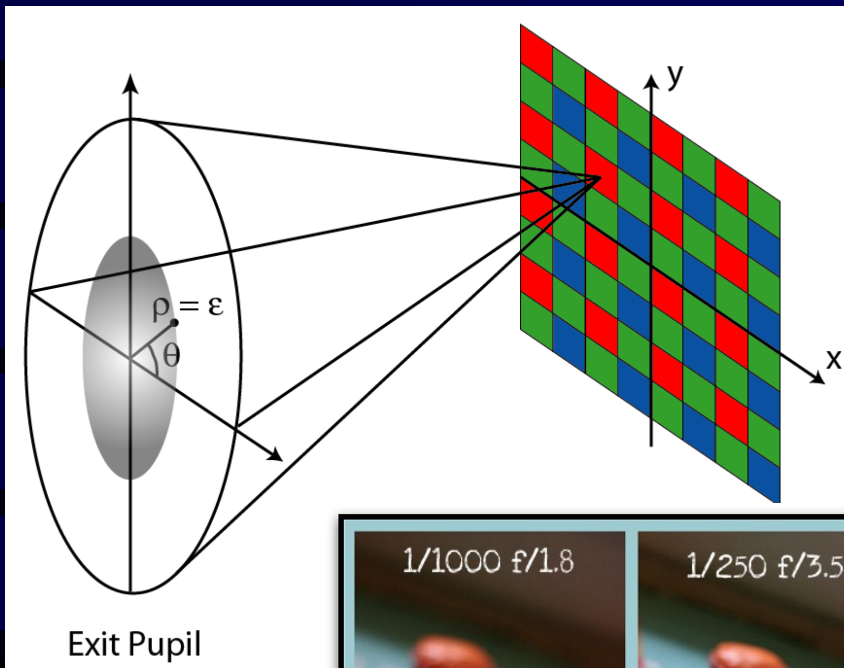
Introduction

- Light field describes the trajectory of rays incident on a given point in space.
- Plenoptic cameras are a novel portable technology that have recently emerged commercially (e.g. Lytro, Raytrix)
- Post-processing the light field data allows multiple unique images to be created from a single snapshot.
- Variation in focus, depth of focus, and perspective can be achieved by post-processing the single data set.

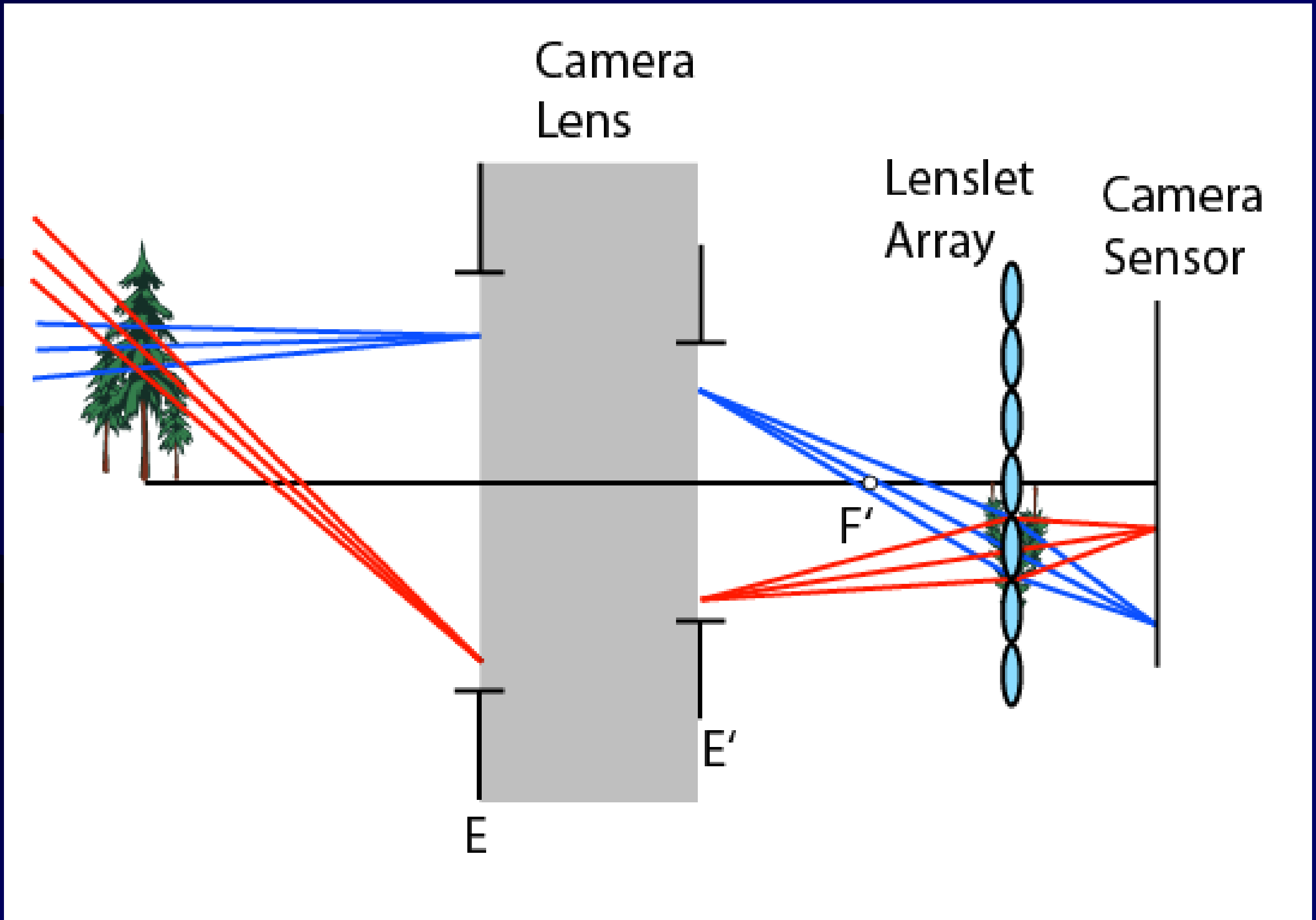
Light Field


y
x
ρ
θ
$I(x,y) = \iint_{\text{Exit Pupil}} L(x, y, \rho, \theta)\rho d\rho d\theta$
Exit Pupil

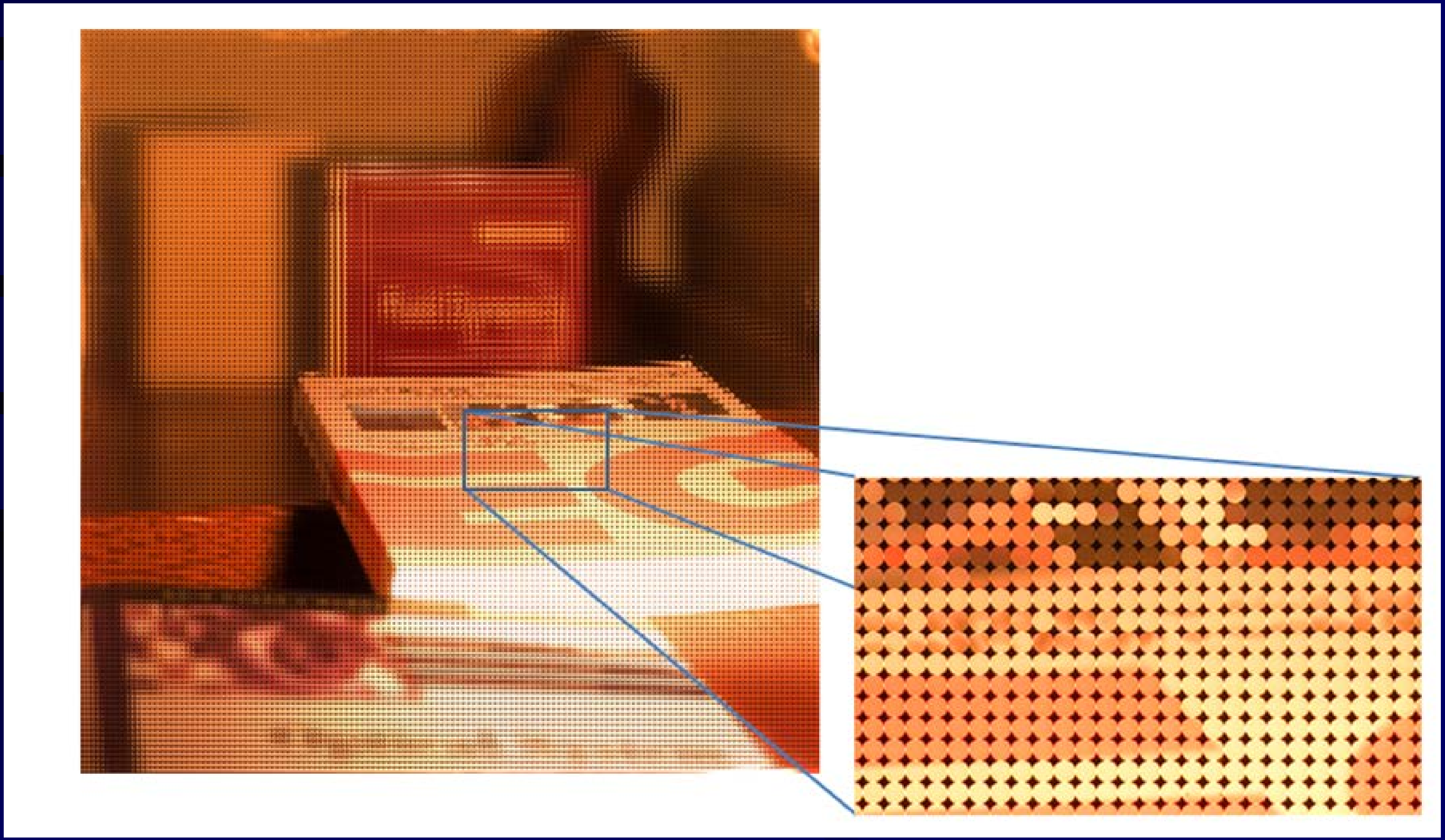
Increased Depth of Field



Conventional Plenopic Camera



Raw Plenoptic Image



Source: www.tgeorgiev.net/Input.jpg

Plenoptic Image

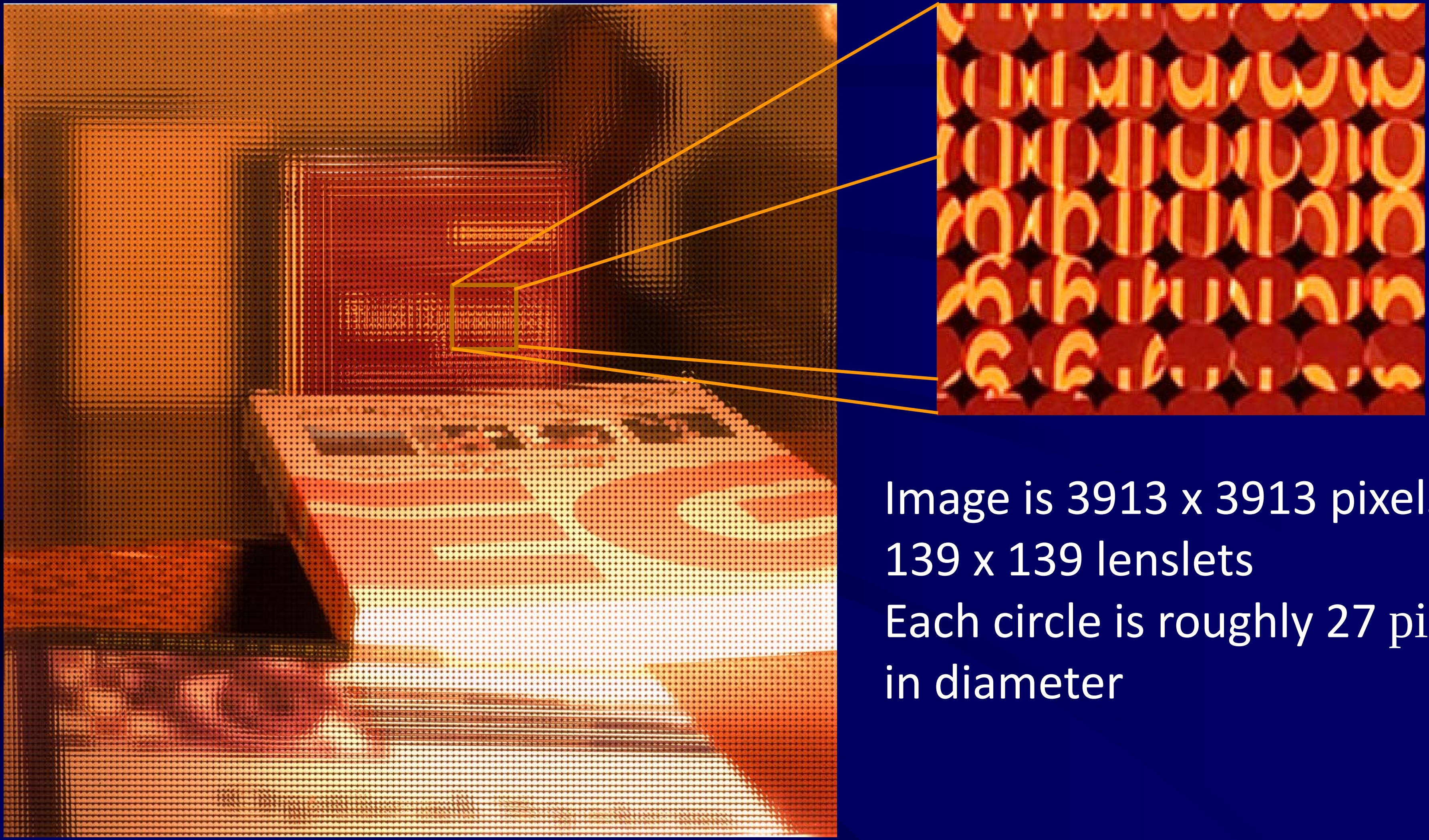


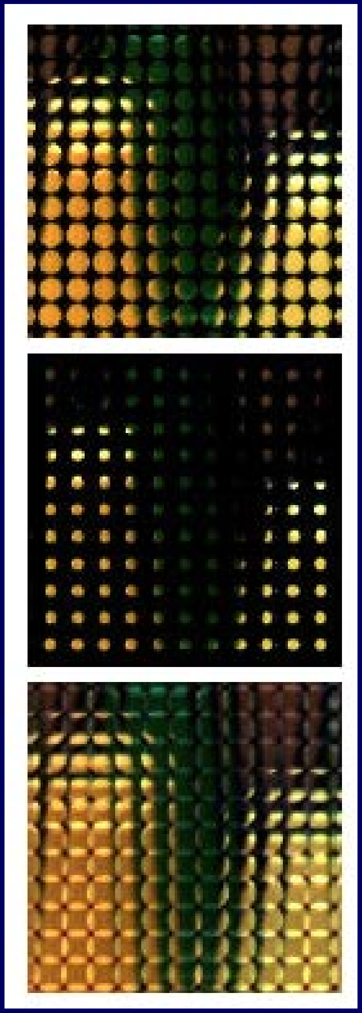
Image is 3913 x 3913 pixels
139 x 139 lenslets
Each circle is roughly 27 pix in diameter

Matching F/#s

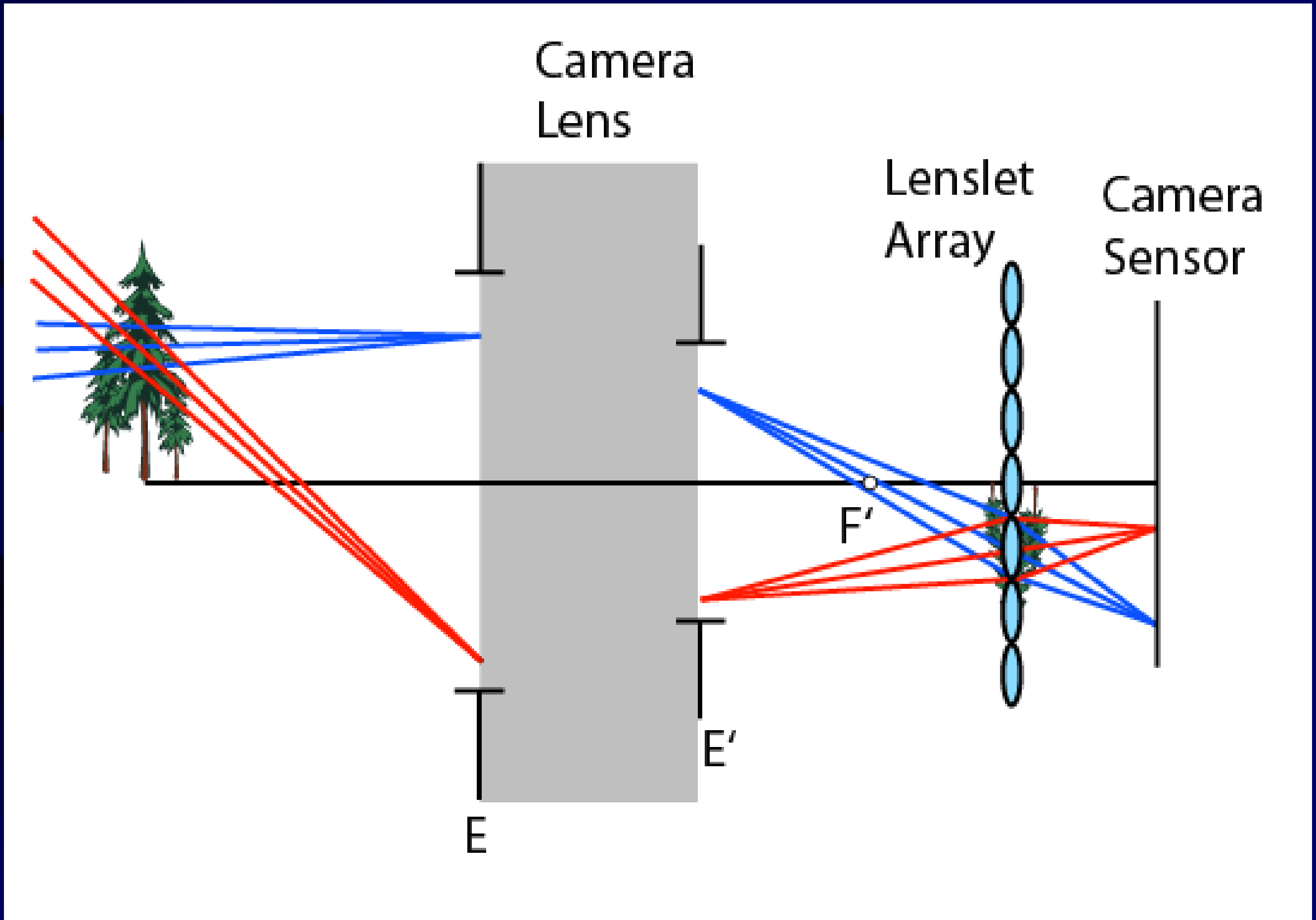
F/#s of camera lens
and lenslets match

F/# of camera lens
greater than lenslet F/#

F/# of camera lens
less than lenslet F/#



Conventional Plenopic Camera



Plenoptic Sampling

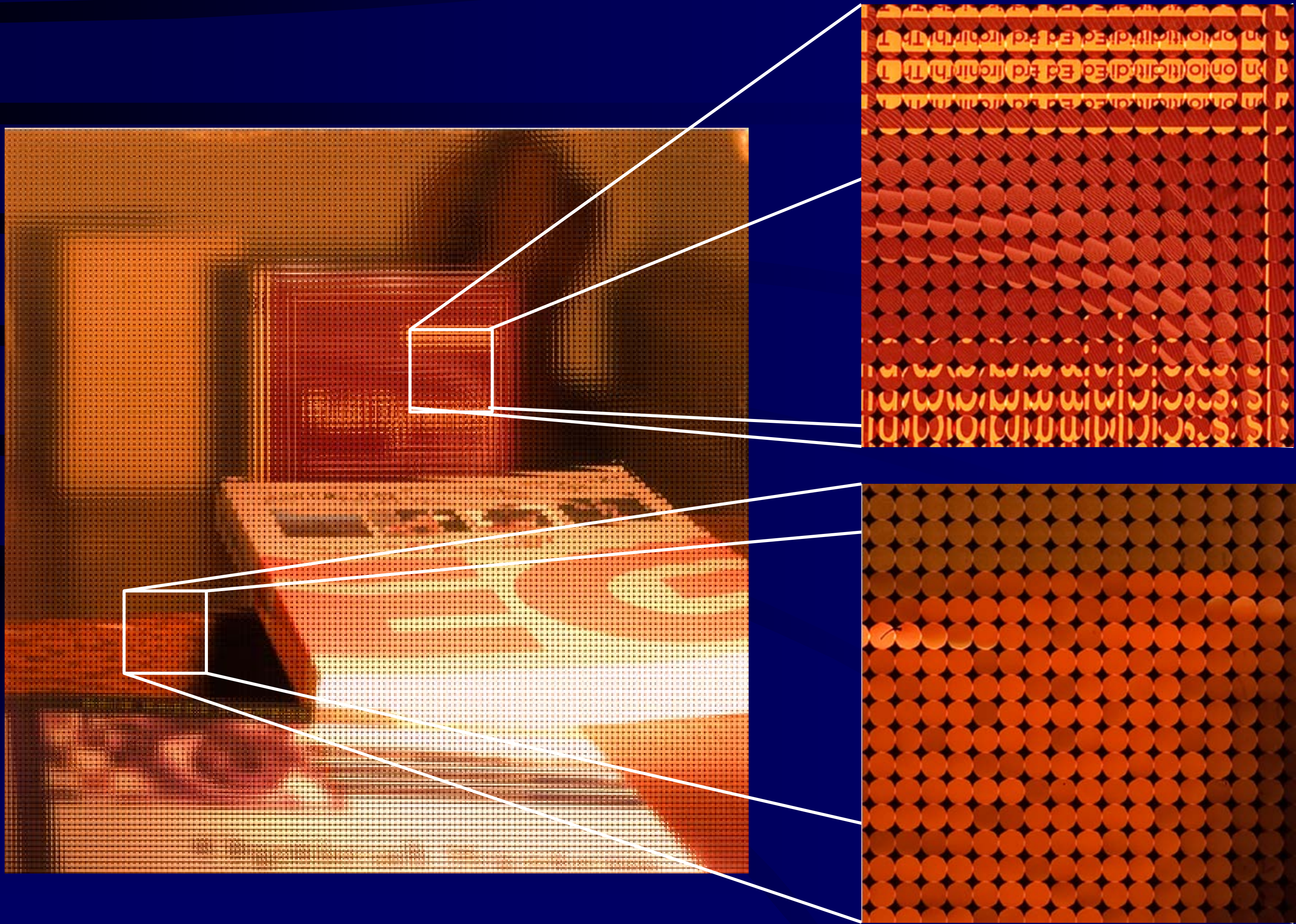
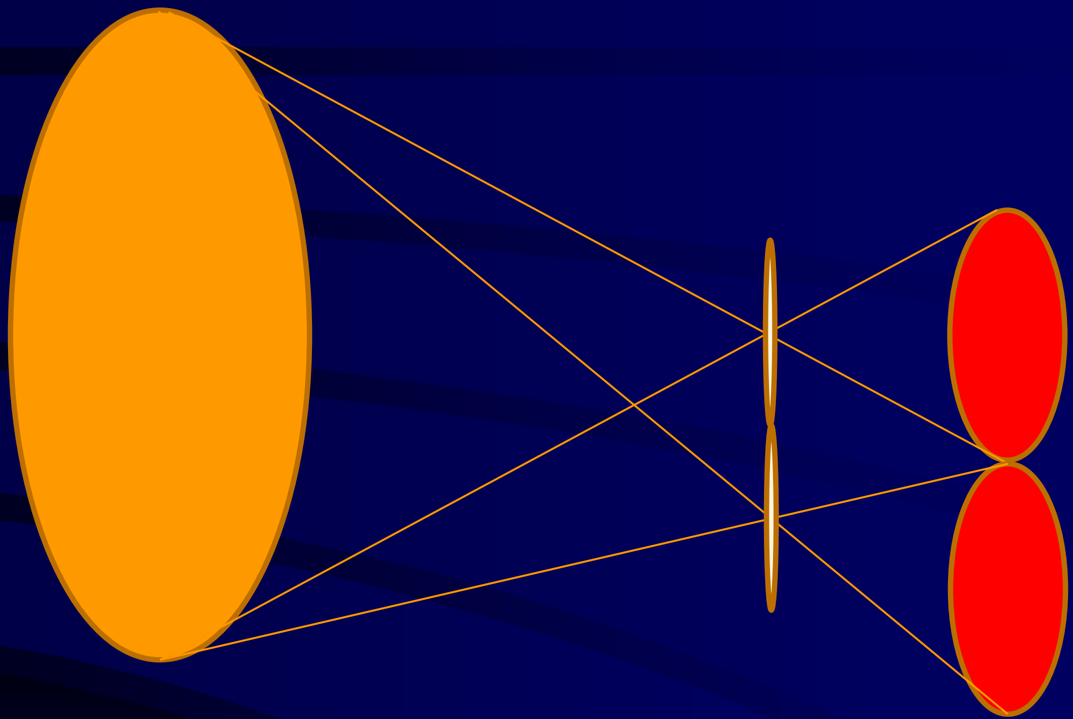


Image Reconstruction

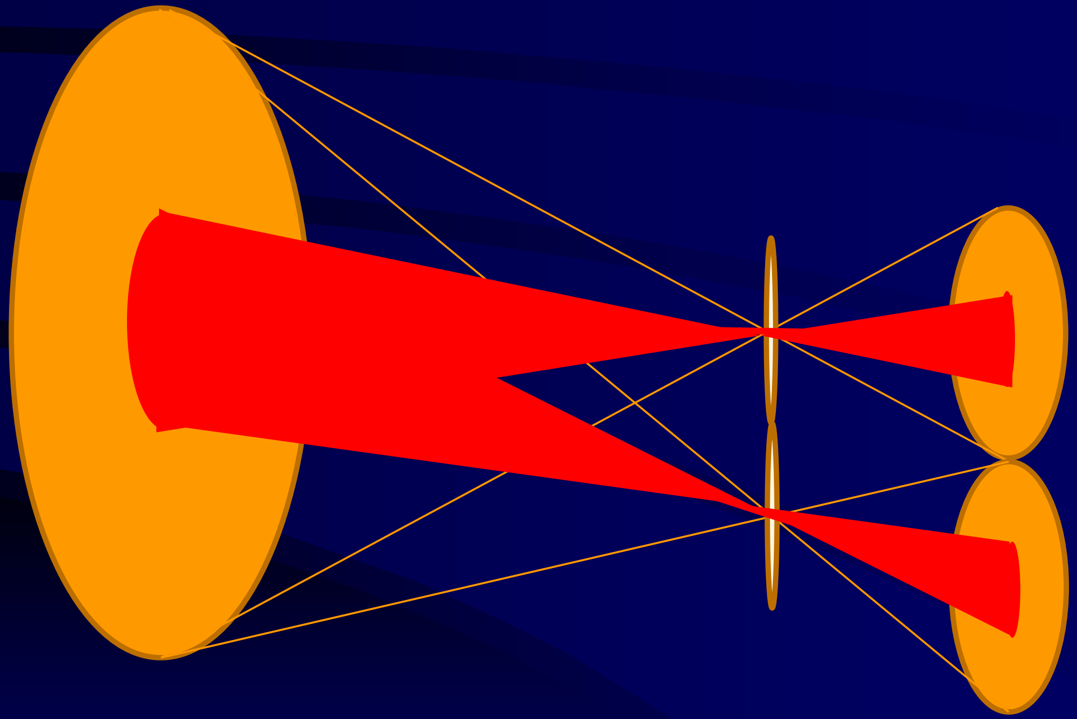


Sum all pixels in circle and assign value to pixel in final image. Acts like the camera aperture is wide open.

Image Reconstruction

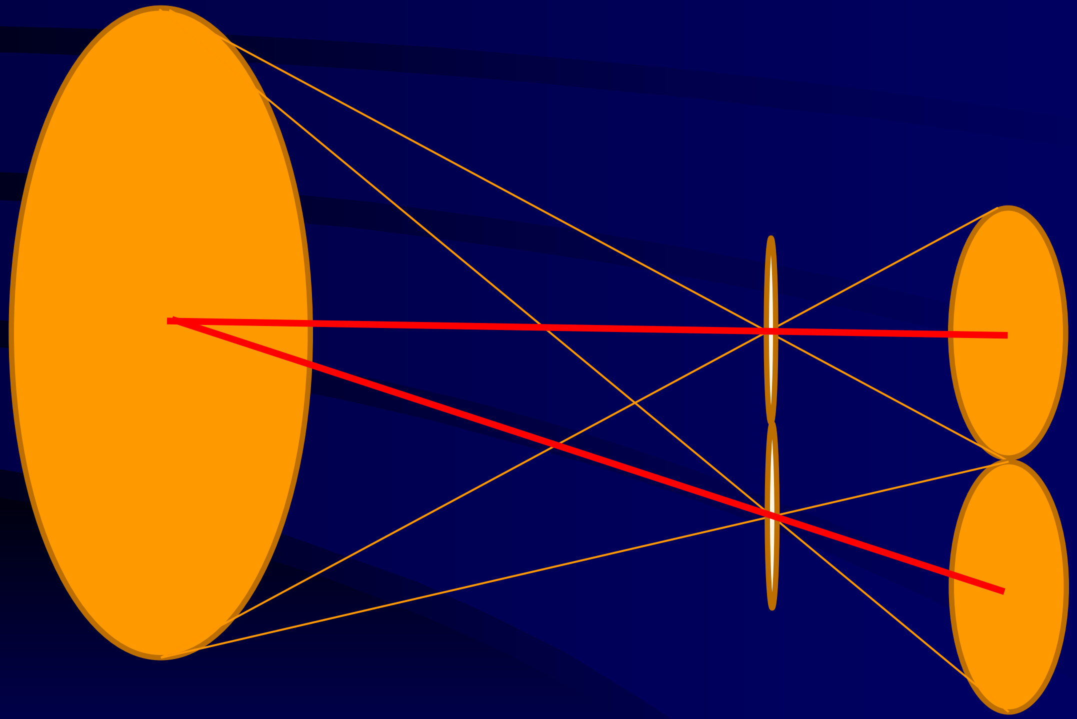
4x Bicubic Spline

Change DOF



Sum the pixels over a reduced circular region to give pixel in final image. Acts like stopping down the camera aperture.

Large DOF Image



Use center pixel from each subimage as pixel in final image. Acts like stopping down the camera aperture to a pinhole.

Large Depth of Field

4x Bicubic Spline

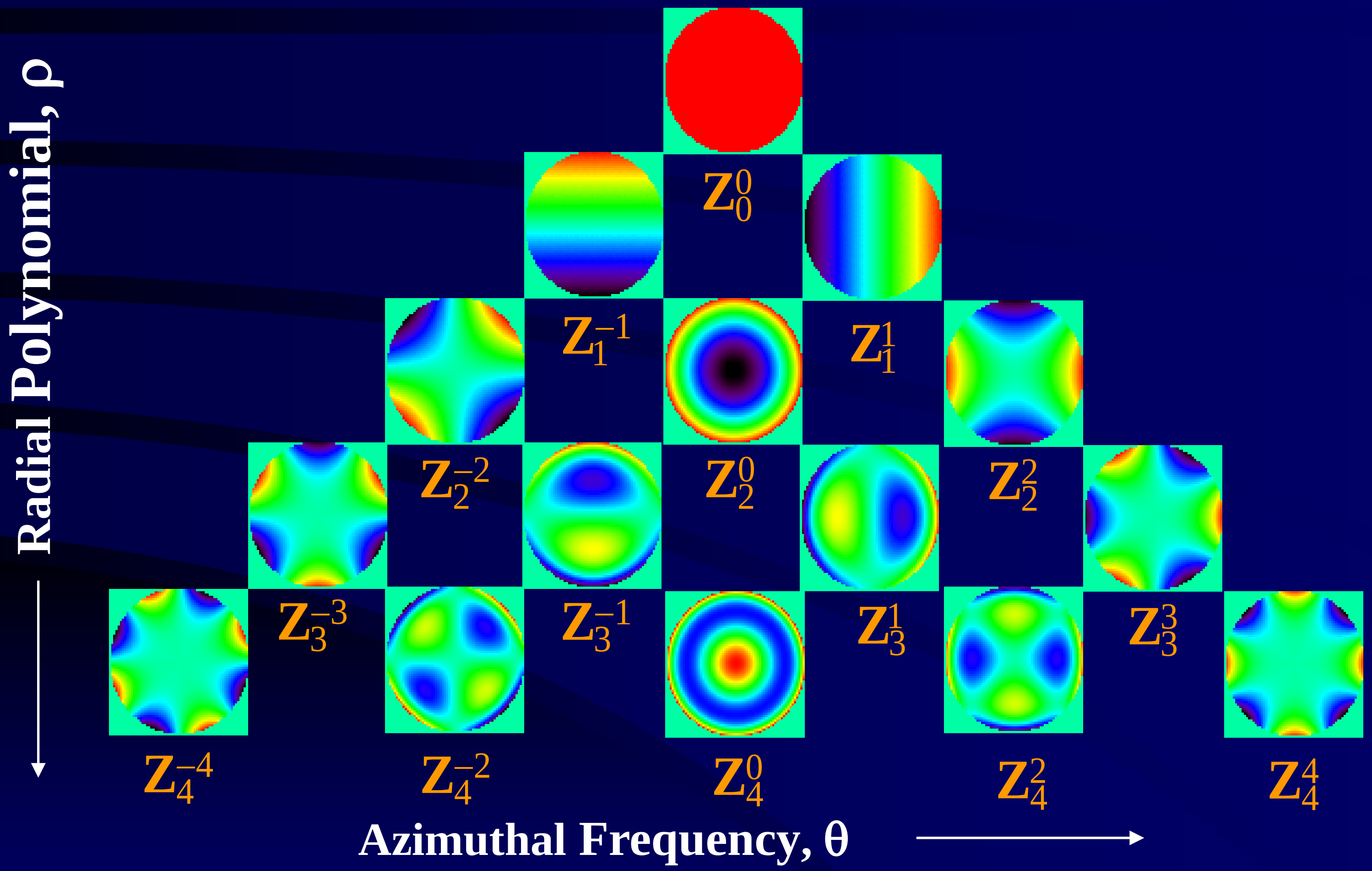
Depth of Field Comparison

Zernike Expansion

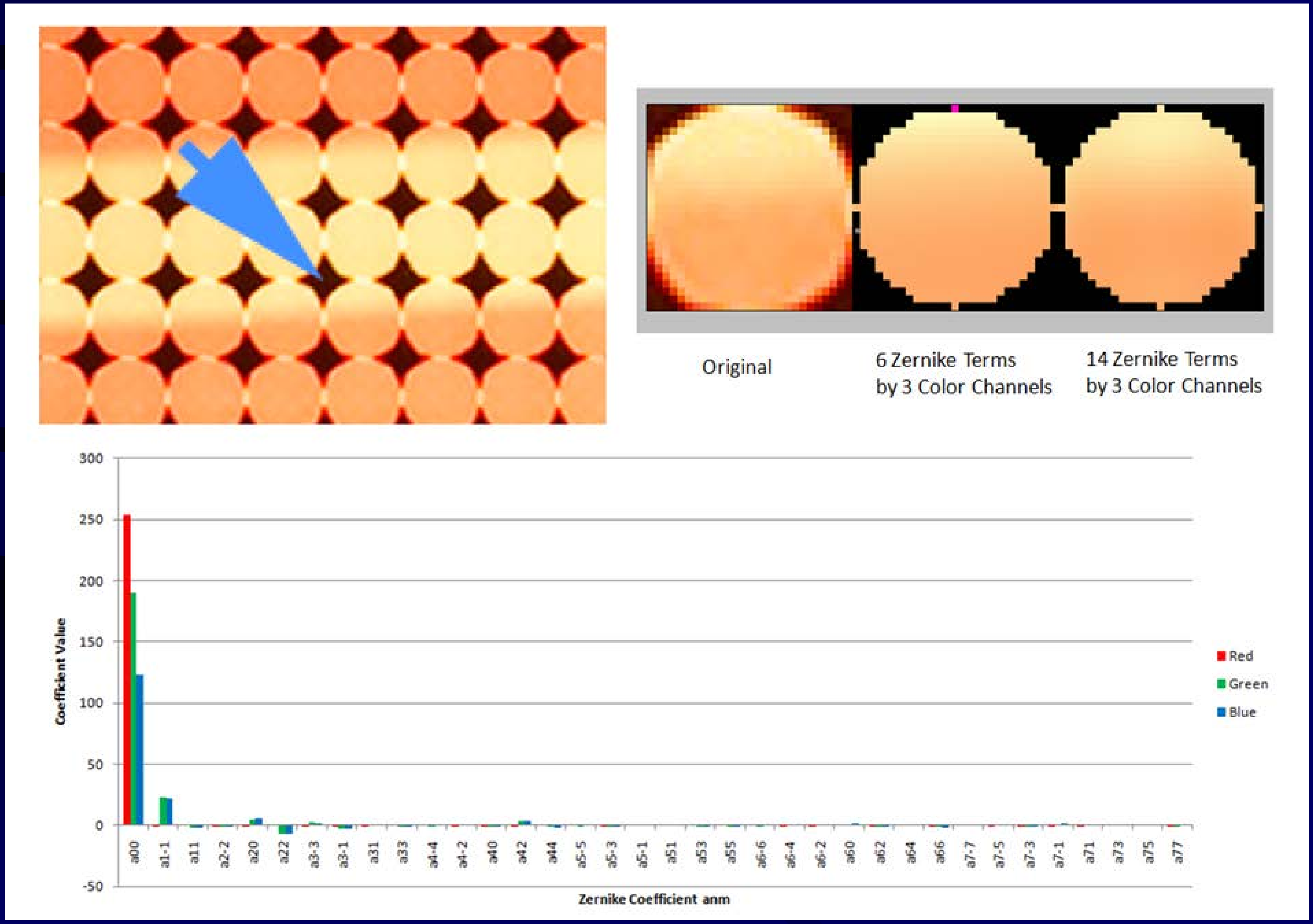
$$W(\rho,\theta) = \sum_{n,m} a_{n,m} Z_n^m(\rho,\theta)$$

- For each color channel, represent the irradiance in the exit pupil as a linear combination of Zernike terms.
- Only a finite number of terms are needed to adequately represent the pattern.
- Note: a_{00} represents the average irradiance level over pupil.

Zernike Polynomials



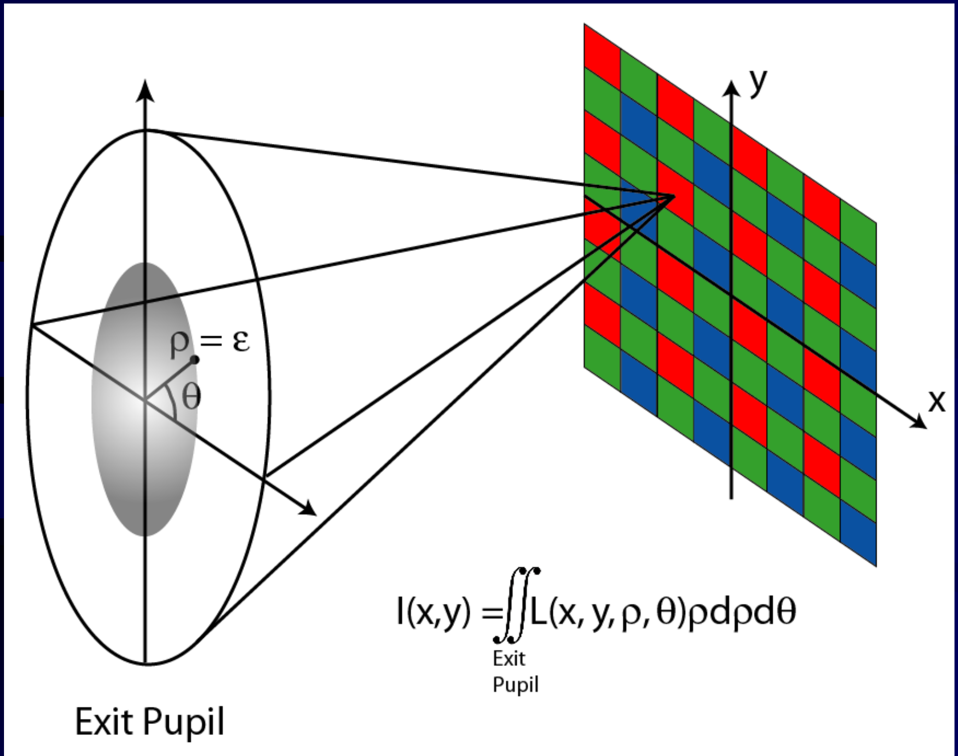
Zernike Fit (Low Frequency)



Zernike Fit (High Frequency)

65 Expansion terms in these cases

Increased Depth of Focus



$$b_{00} = \sum_{n'} a_{n'0} N_{n'}^{0} \left[R_{n'}^{0}(\varepsilon) - R_{n'}^{2}(\varepsilon) \right]$$

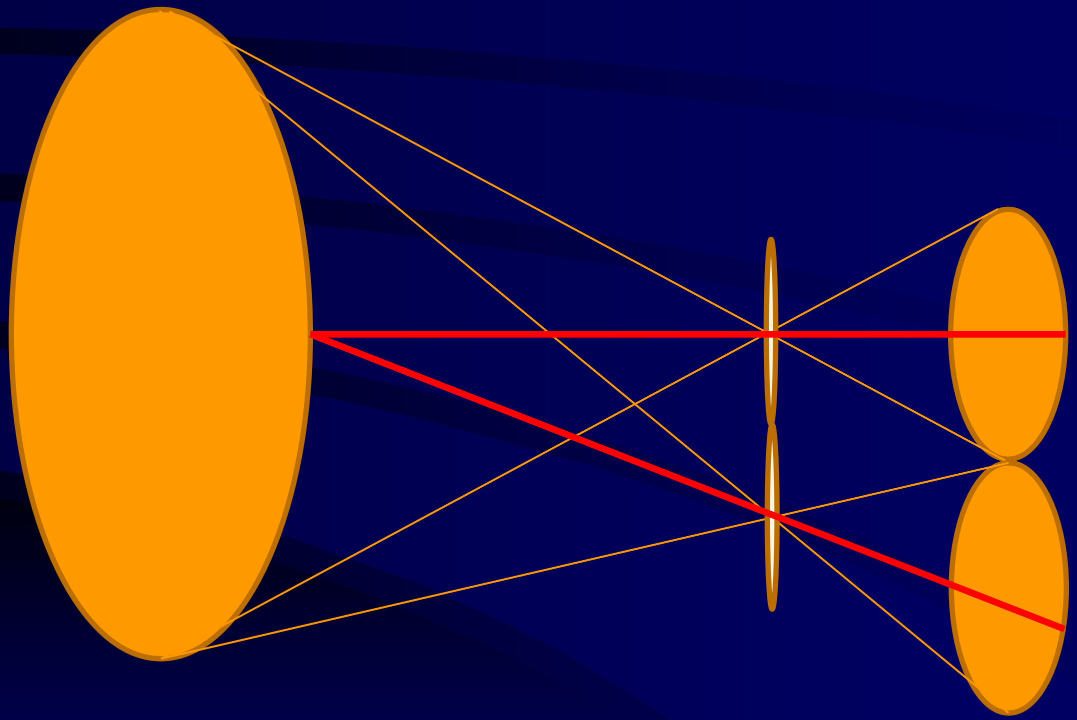
Average irradiance $b_{0,0}$ over smaller pupil is given by a linear combination of the $a_{0,0}$, $a_{2,0}$, $a_{4,0}$,… coefficients from the original pupil.

Depth of Focus Modification

Full Aperture (ρ = 1.0)

Reduced Aperture (ρ = 0.2)

Perspective Change



Use an oblique pixel from each circle as pixel in final image.
Acts like pinhole shifted to different location in the camera aperture

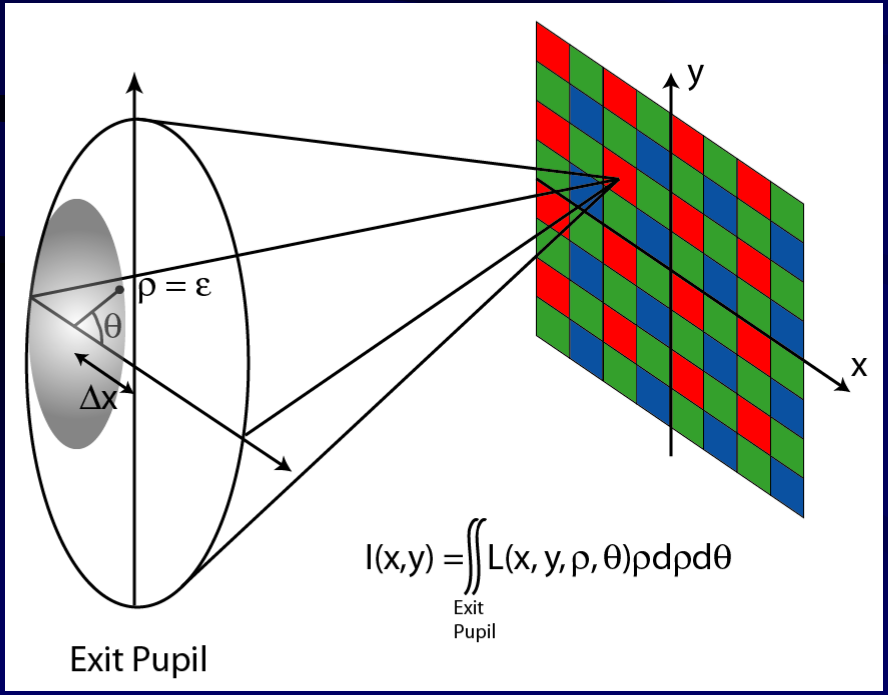
Change of Perspective

Translate Zernike expansion by Δx.

$$c_{00} = a_{00}$$

$$c_{20} = 2\sqrt{3}\Delta x^2 a_{00} - 2\sqrt{3}\Delta x a_{11} + a_{20}$$

$$c_{40} = 6\sqrt{5}\Delta x^2\left(1+\Delta x^2\right)a_{00} - 2\sqrt{5}\Delta x\left(1+6\Delta x^2\right)a_{11} + 2\sqrt{15}\left(2a_{20}+\sqrt{2}a_{22}\right)\Delta x^2 - 2\sqrt{10}\Delta x a_{31} + a_{40}$$



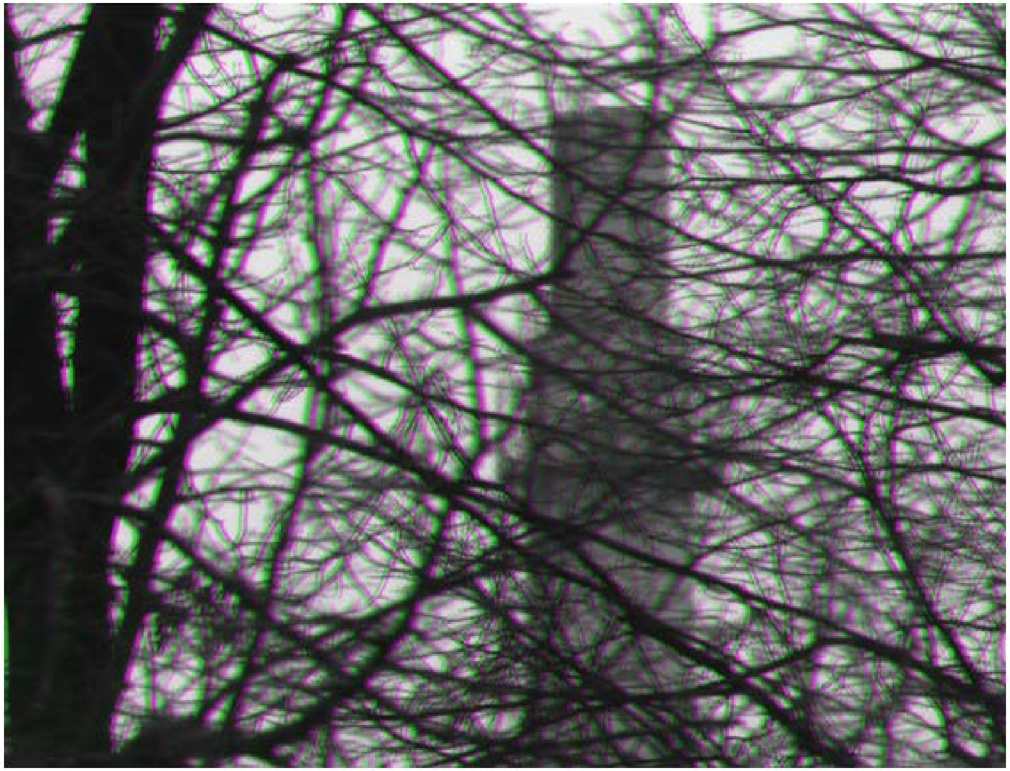
Reduce pupil size as in DOF calculation.

$$b_{00} = \sum_{n'} c_{n'0} N_{n'}^{0}\left[R_{n'}^{0}(\varepsilon) - R_{n'}^{2}(\varepsilon)\right]$$

Change of Perspective

Stereo Images

Anaglyphic Stereo Image



You need green/magenta glasses to see this image in 3D.

The next generation of photography
Dr. Christian Perwaß, Lennart Wietzke, Raytrix GmbH, January 2010

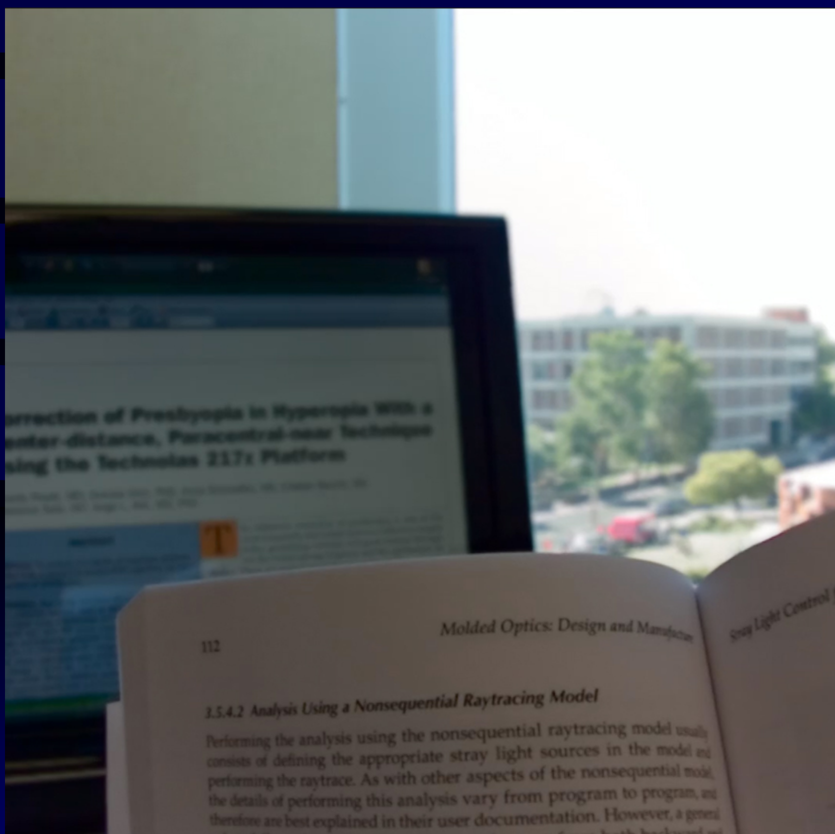
raytrix

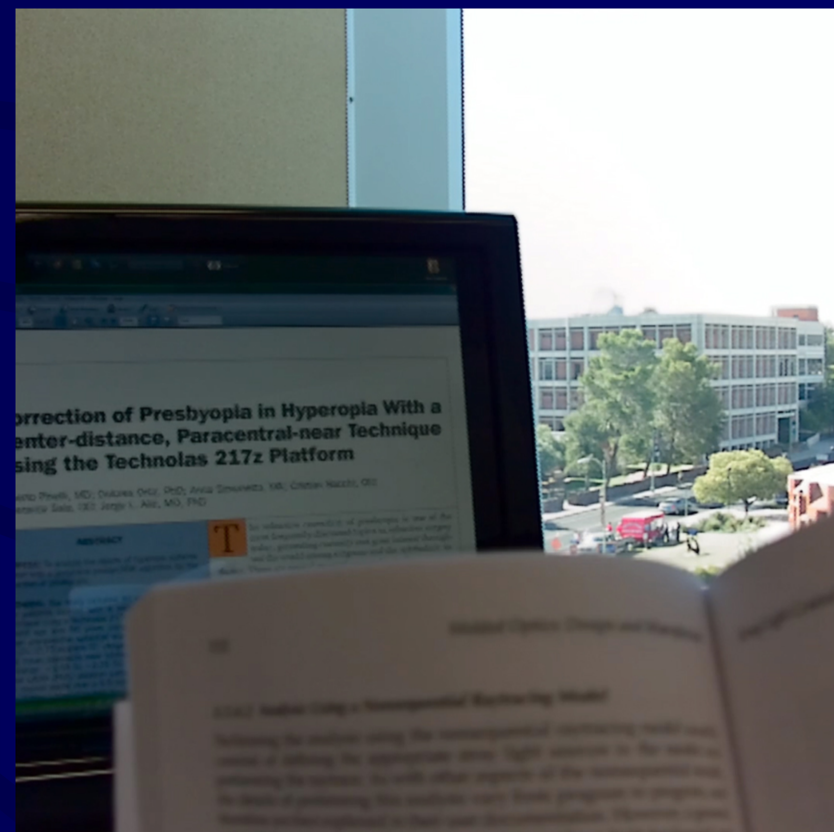
Refocusing

alpha=0.9

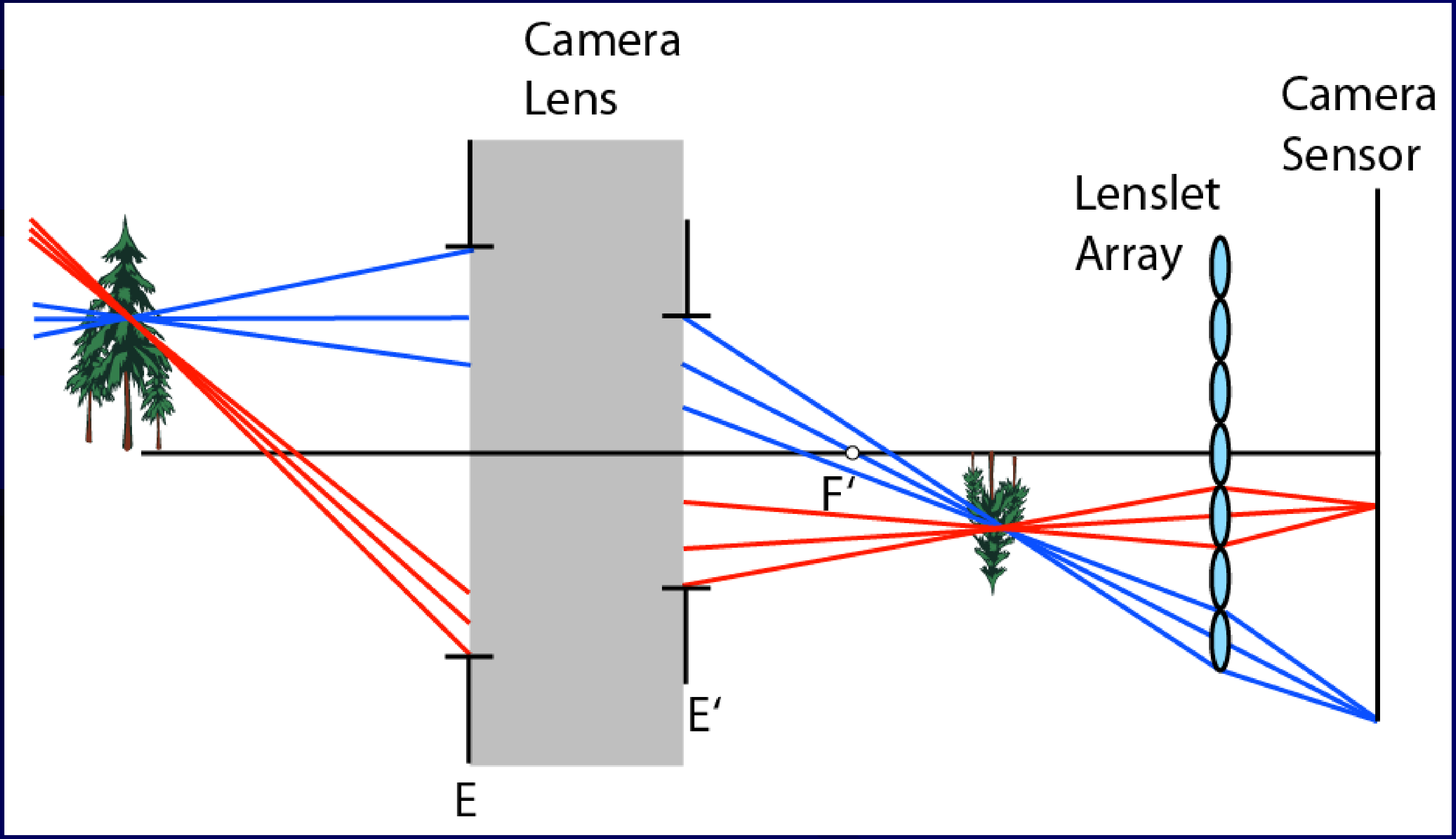
alpha=1.1

Change in Focus





Plenoptic 2.0



Stanford Camera Array