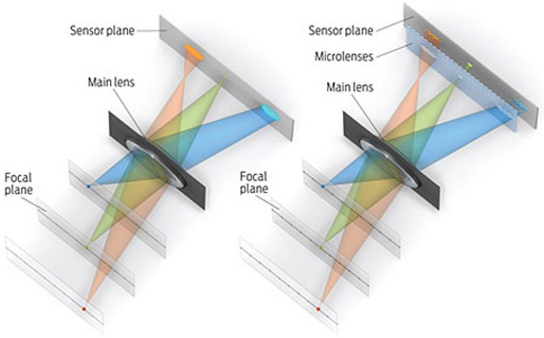
Image-Based Graphics



Computer Graphics

Computational Photography

Camera models and light fileds

Light Fields

Light field imaging enable the capture of richer high-dimensional scene information

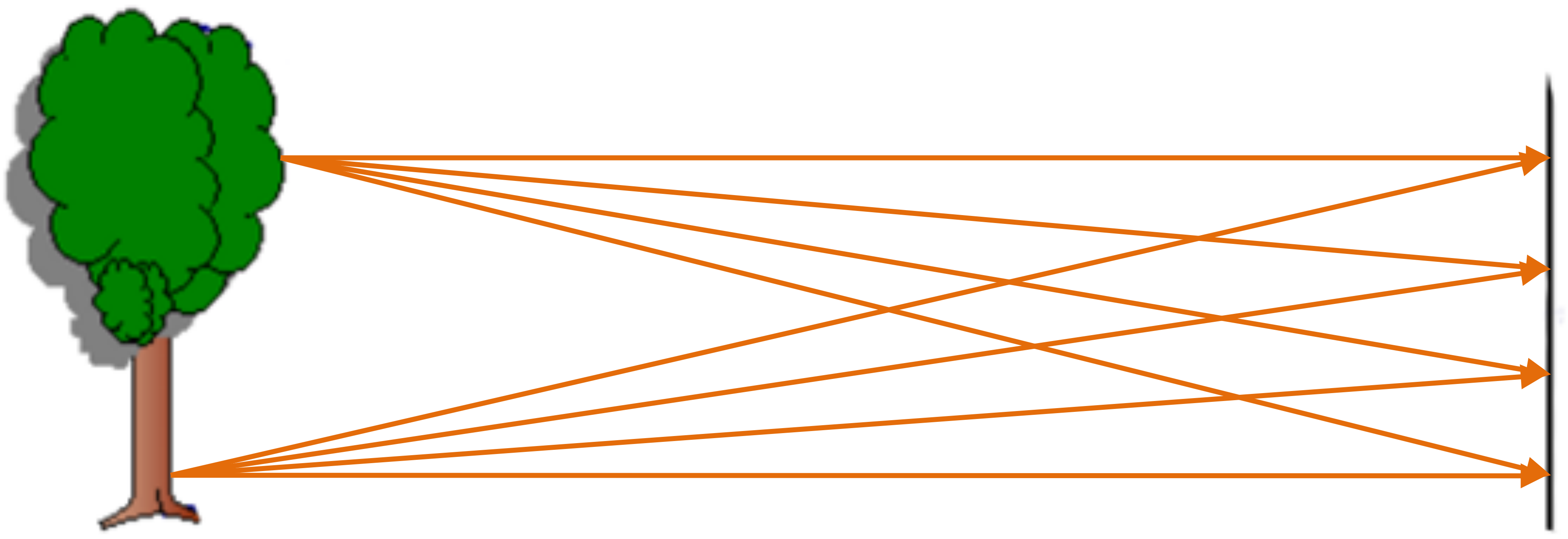
Light Fields

In this part:

- What is the light field
- Architecture of a light field camera
- How to get synthetic images using light fields

How do we capture the world

Just put a piece of film in front of an object



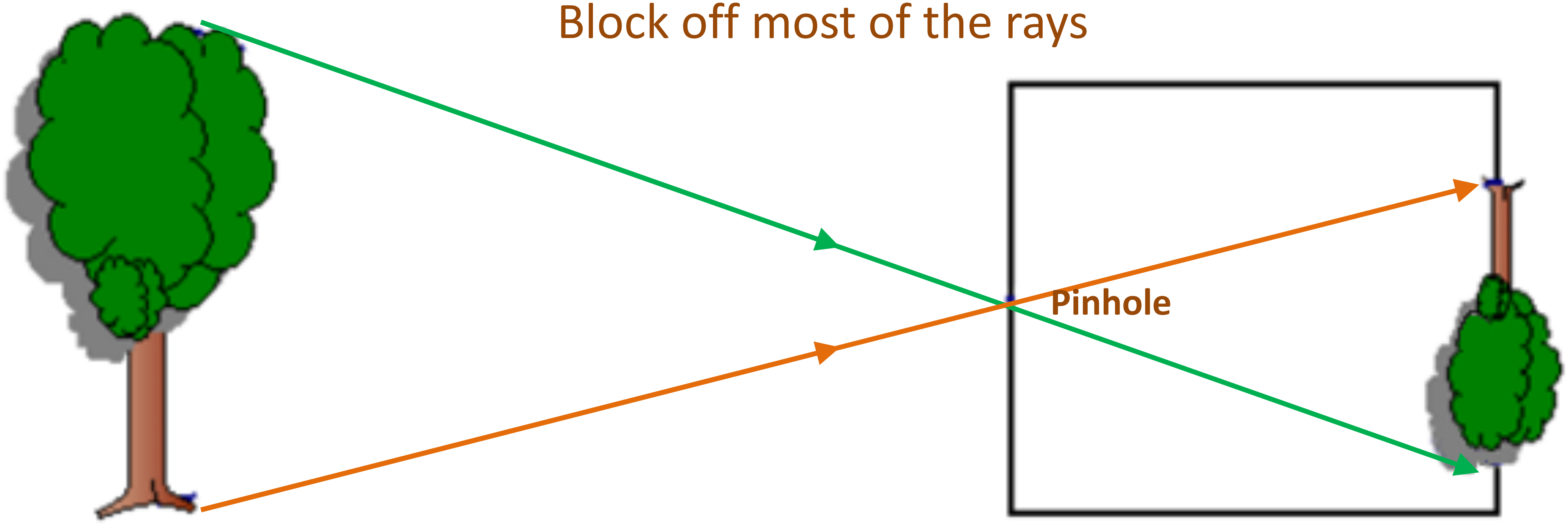
Object in real world

Film

Do we get a reasonable image?

Pinhole Model

Pinhole camera model:
Block off most of the rays

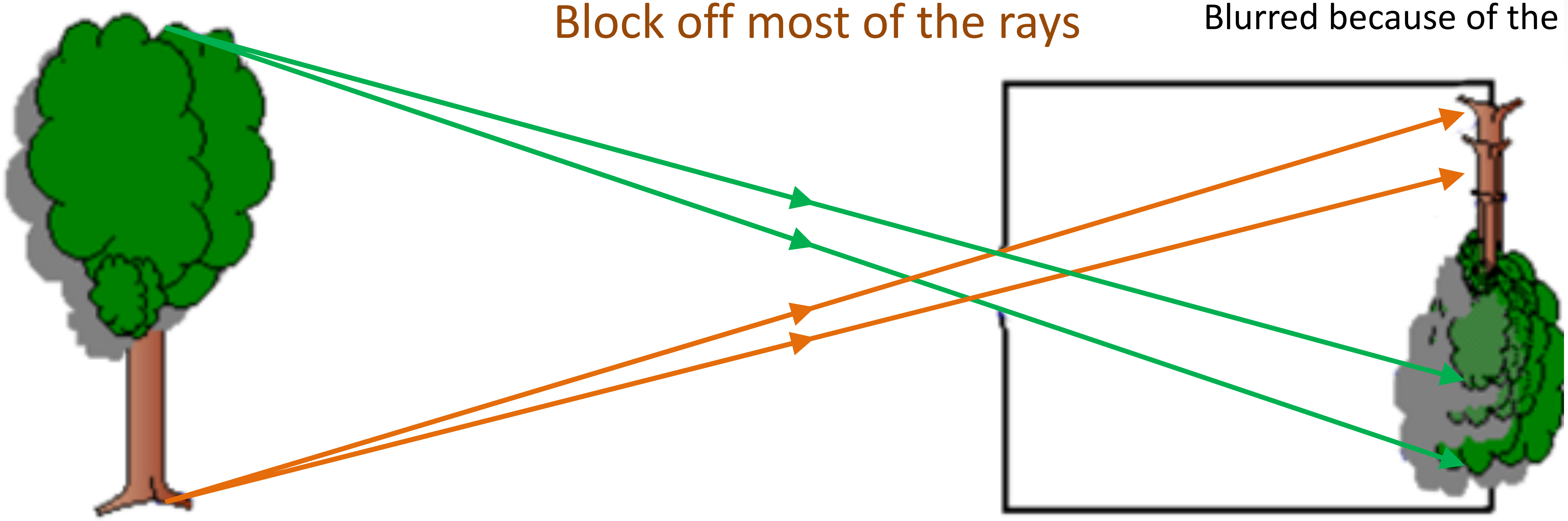


What is the problem of this model?

Pinhole Model

Pinhole camera model:
Block off most of the rays

Blurred because of the confusion



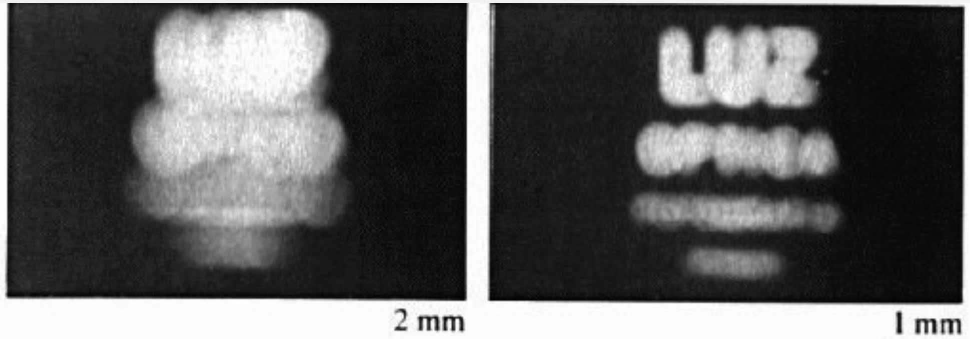
Object in real world

Film

Pinhole Model

Homemade pinhole camera and the generated photo

Shrinking the aperture



Why not make the aperture as small as possible?

The smaller the aperture is, less light gets through

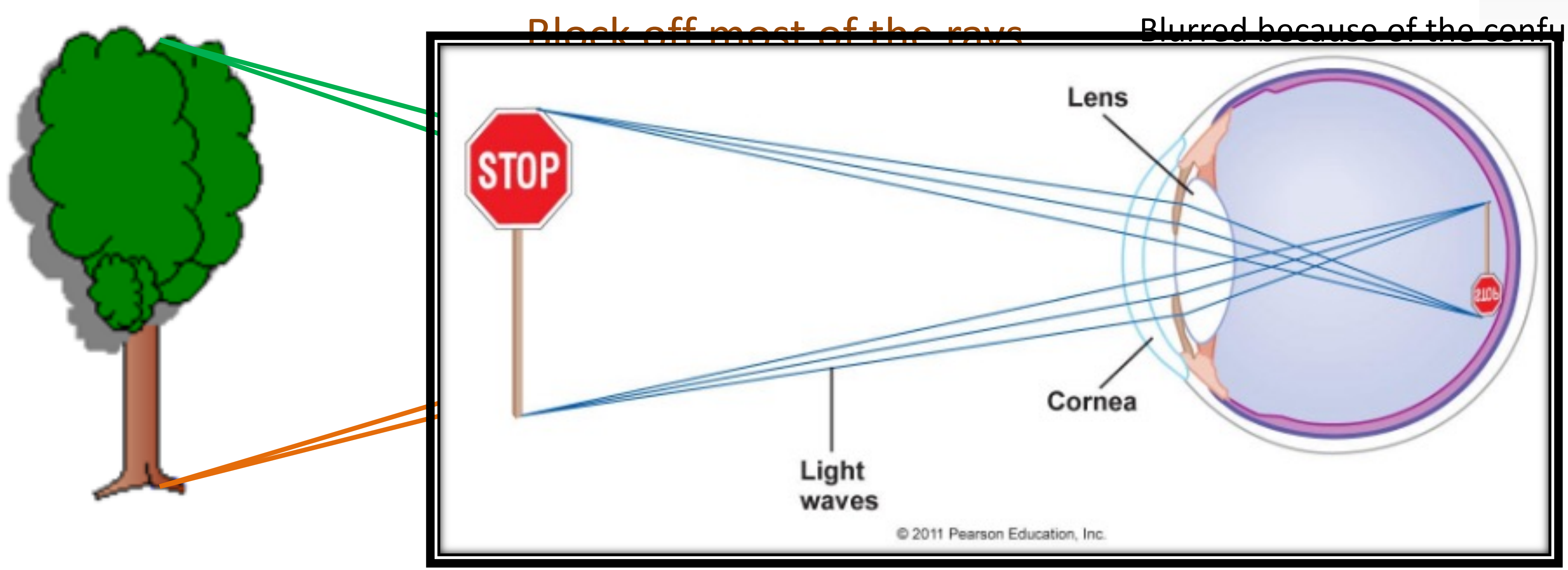
When it is too small, diffraction effects will be obvious

How our eyes work?

Pinhole camera model:

Block off most of the rays

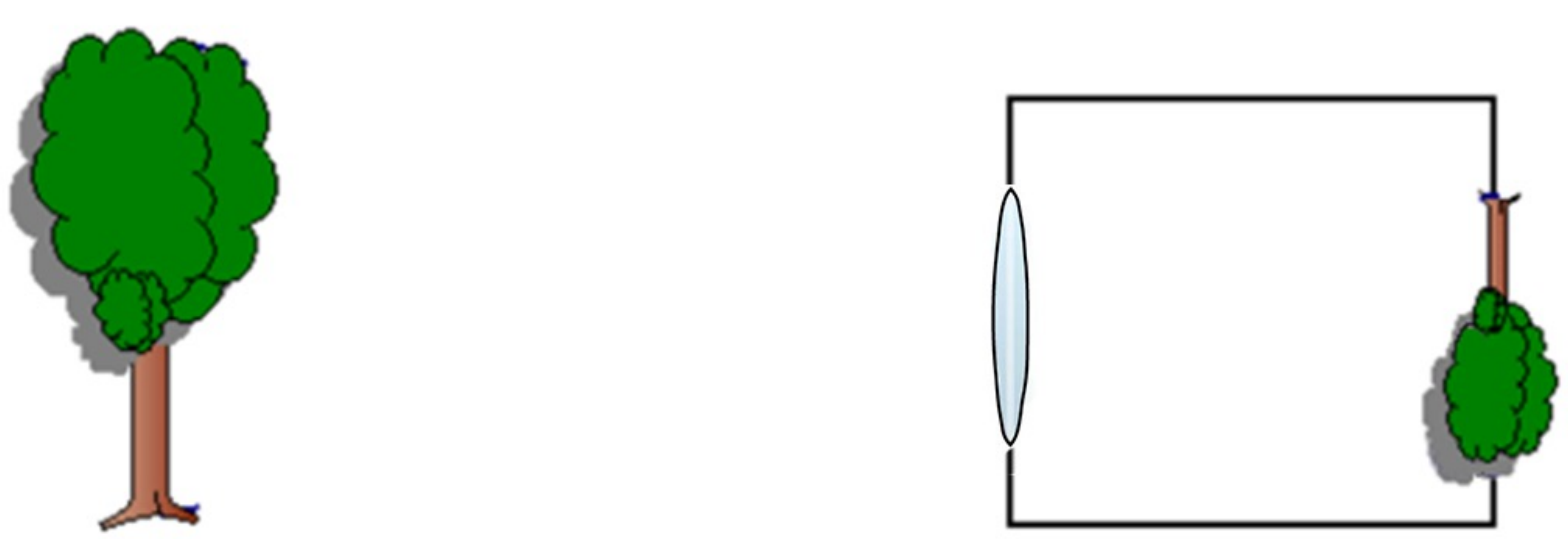
Blurred because of the confusion



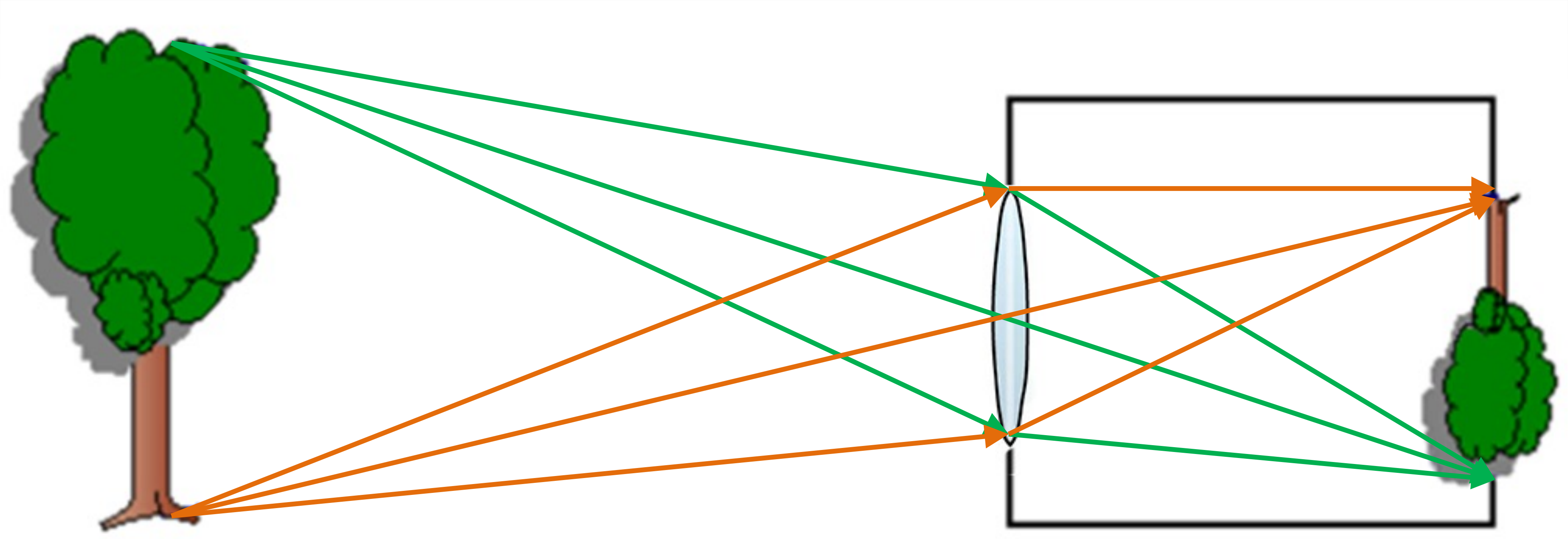
Object in real world

Film

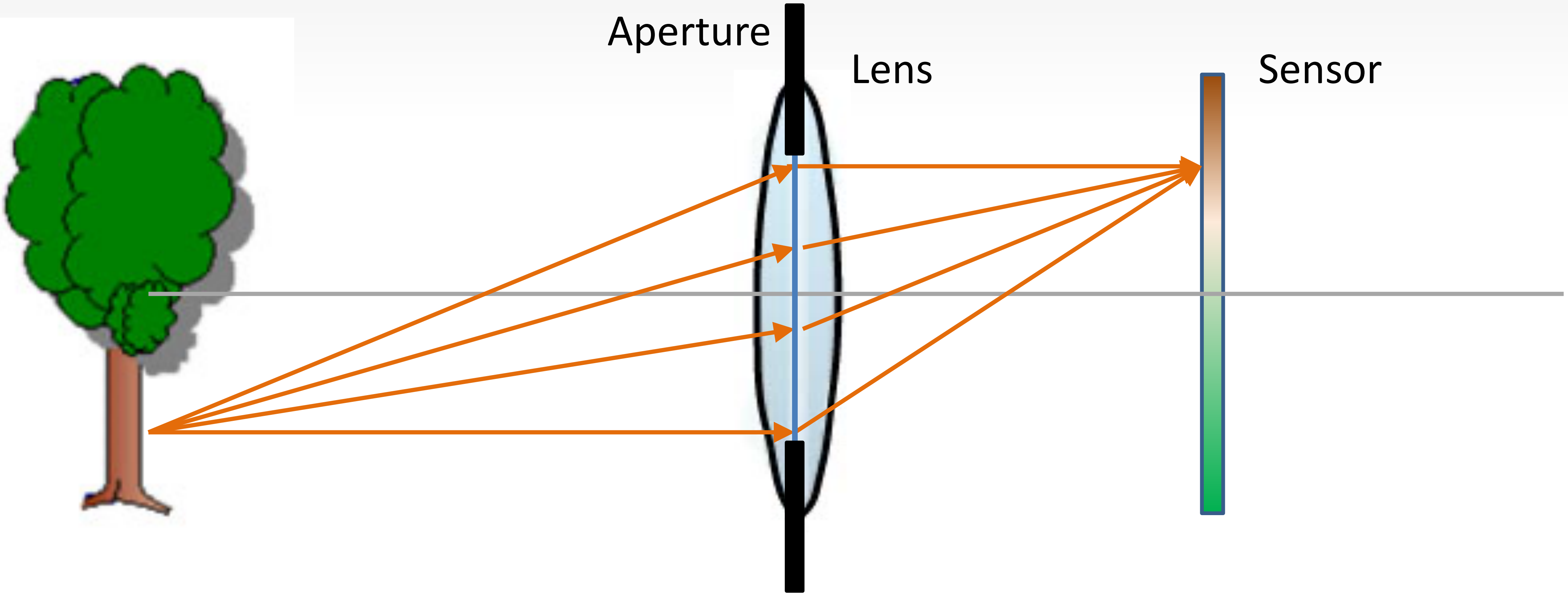
How our eyes work?



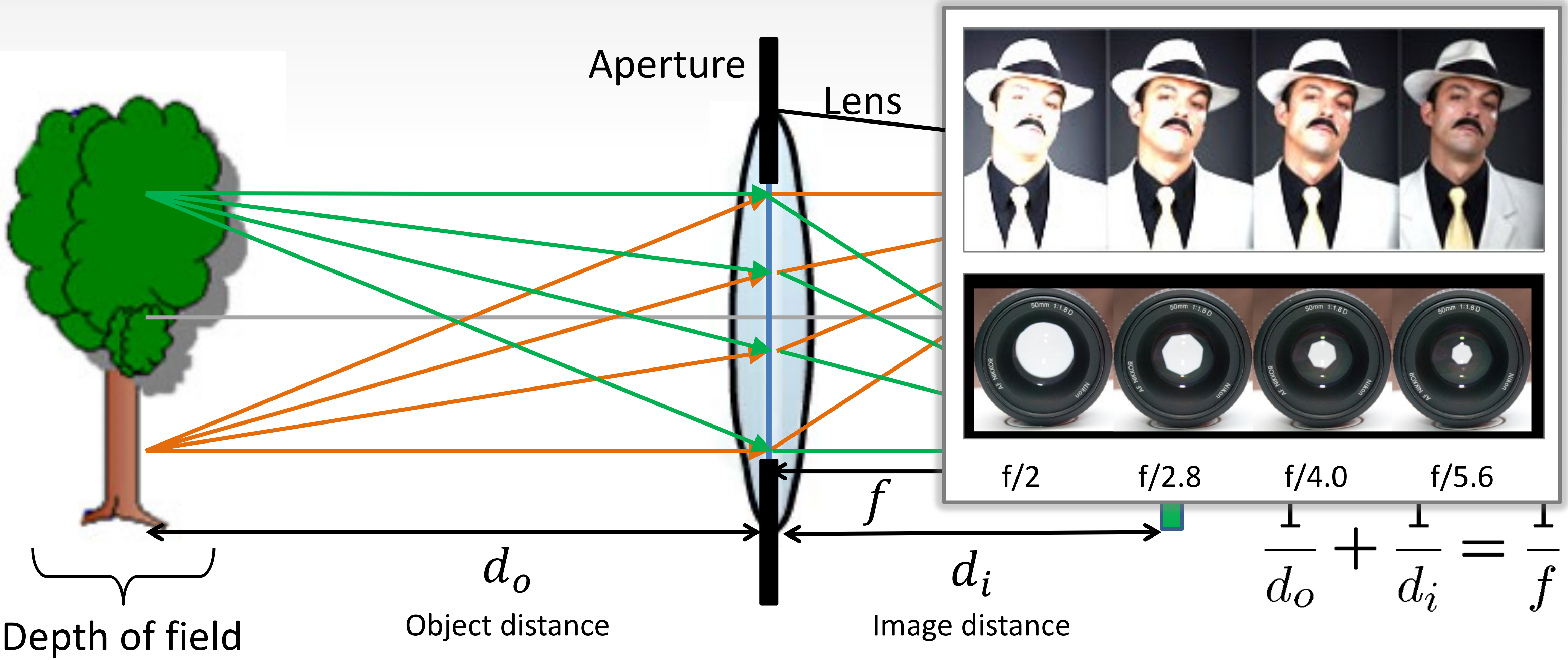
Using lenses



Traditional Camera Model



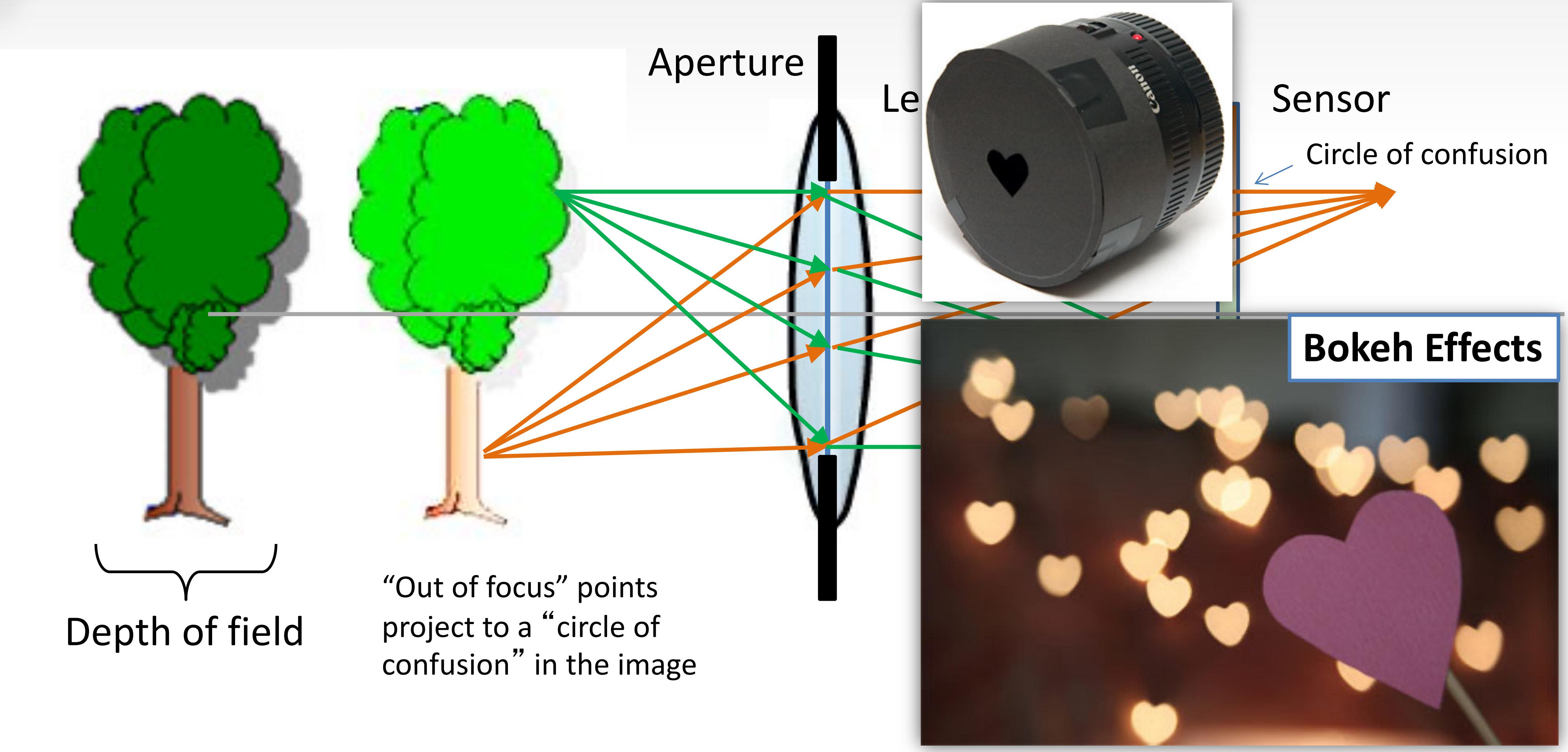
Imaging



$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

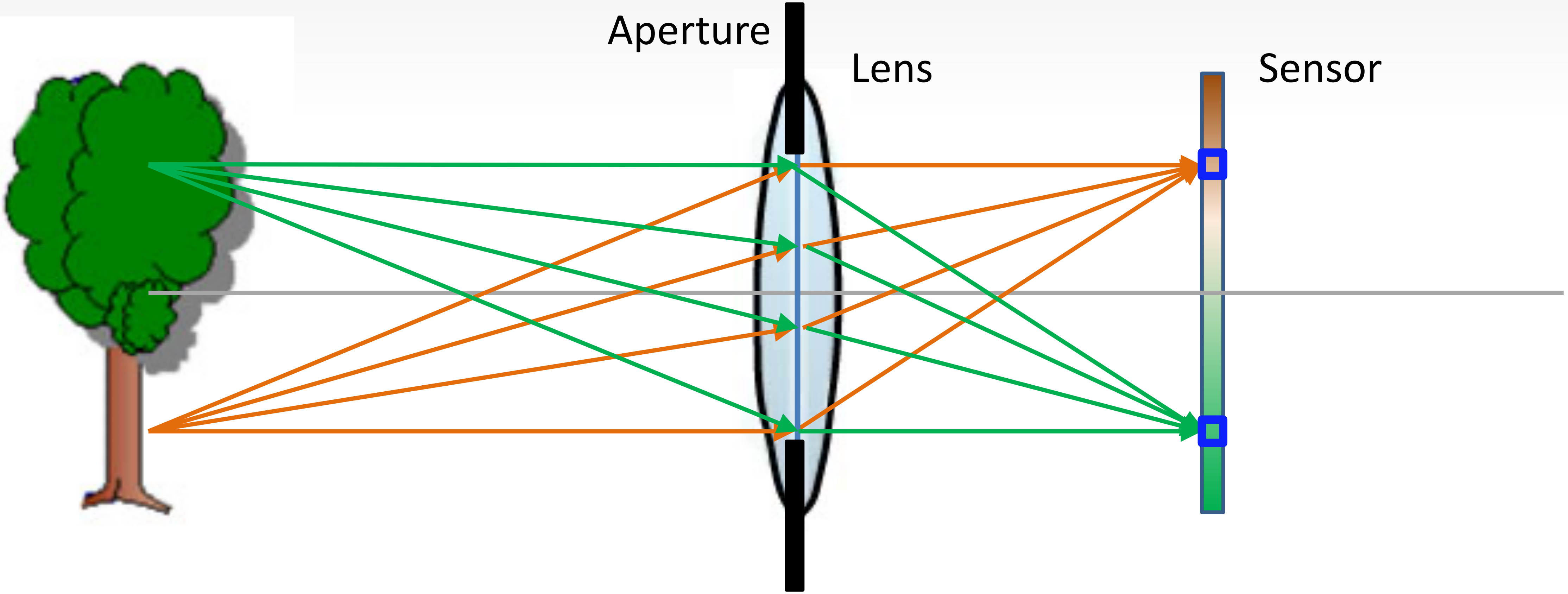
There is a specific distance at which objects are "**in focus**"

Aperture



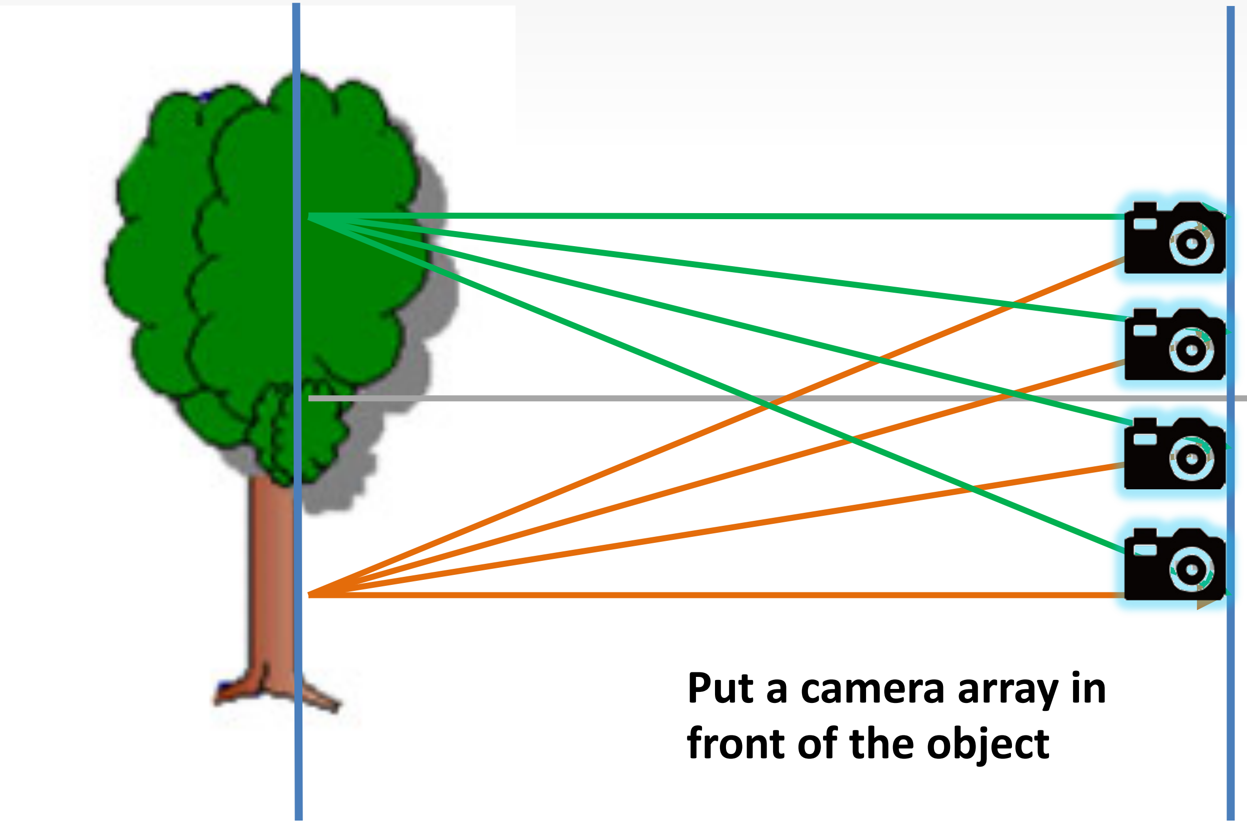
Aperture
Sensor
Circle of confusion
Bokeh Effects
Depth of field
“Out of focus” points project to a “circle of confusion” in the image

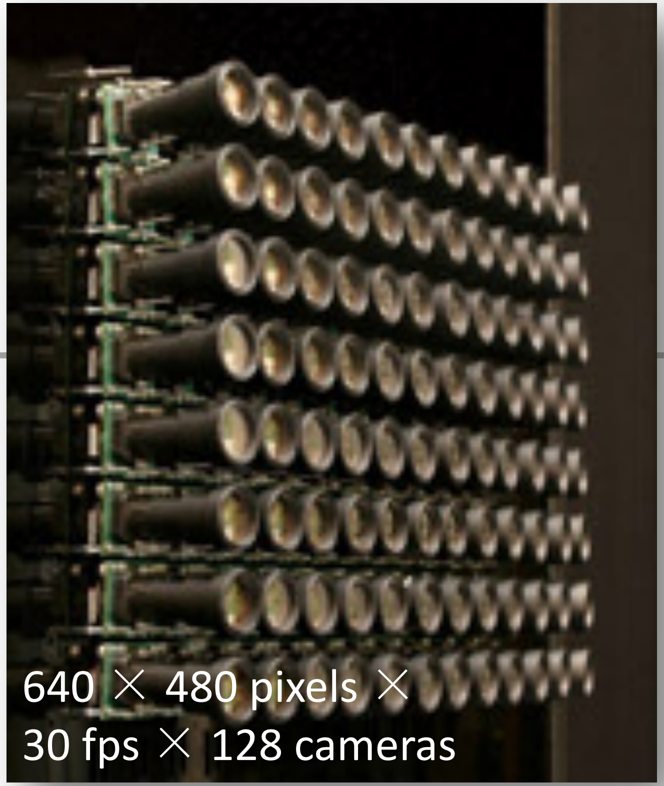
Can we have more?



How to capture all light rays

Scene focal plane (st) Camera plane (uv)

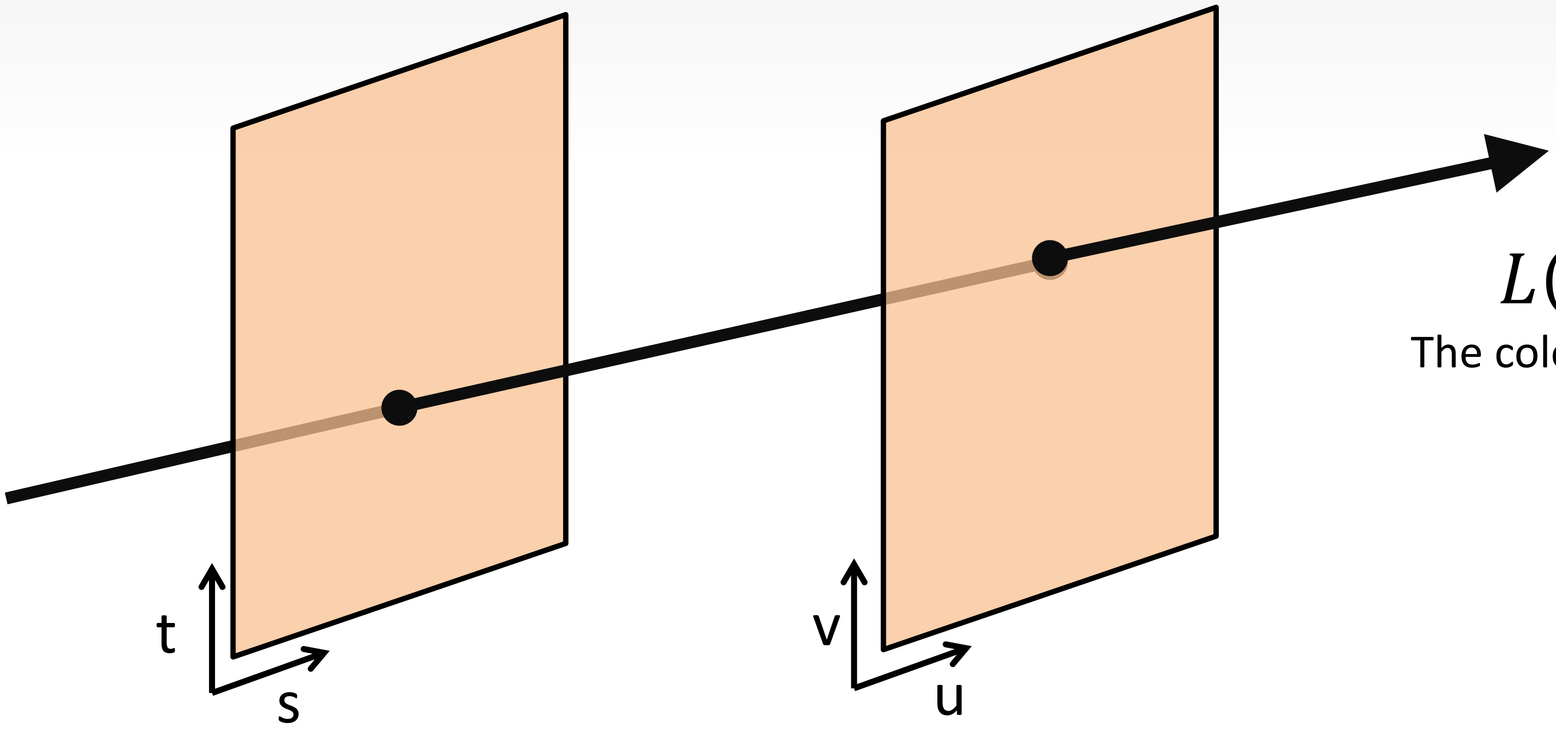




[Levoy and Hanrahan 1996]

Light filed is the collection of all the light rays in the scene

Light-field Parameterization



$L(u, v, s, t)$

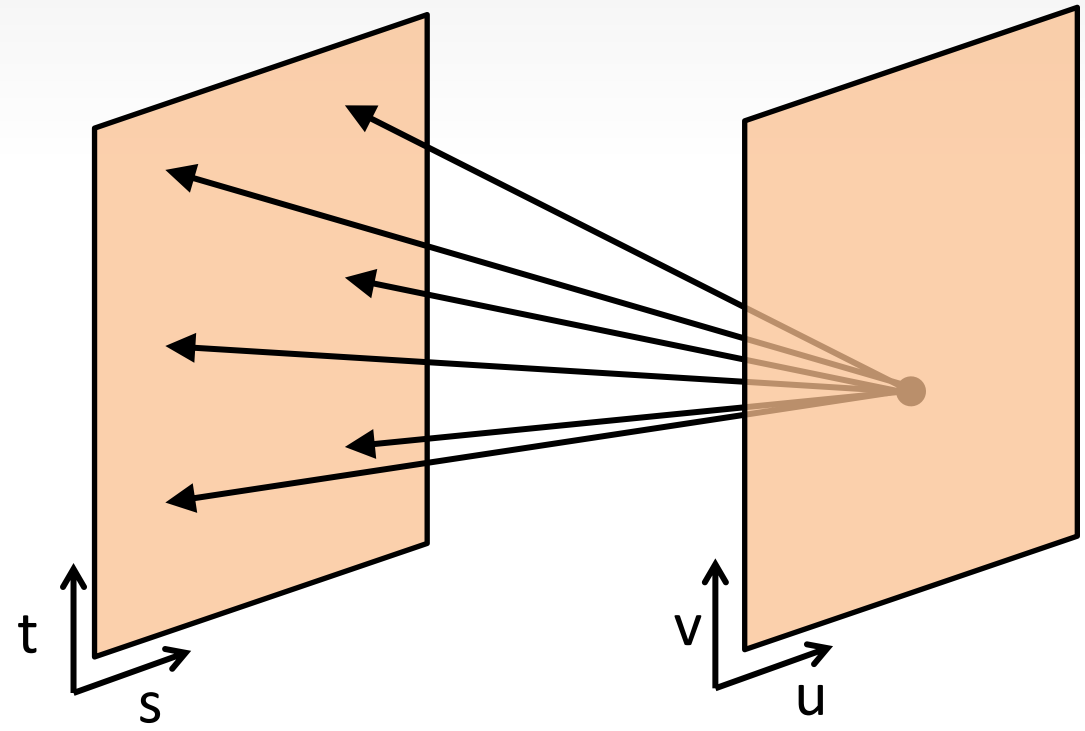
The color value on this ray

Light field is a 4D function (represents light in free space: no occlusion [Levoy and Hanrahan 96])

It has the advantage of relating closely to the analytic geometry of perspective imaging

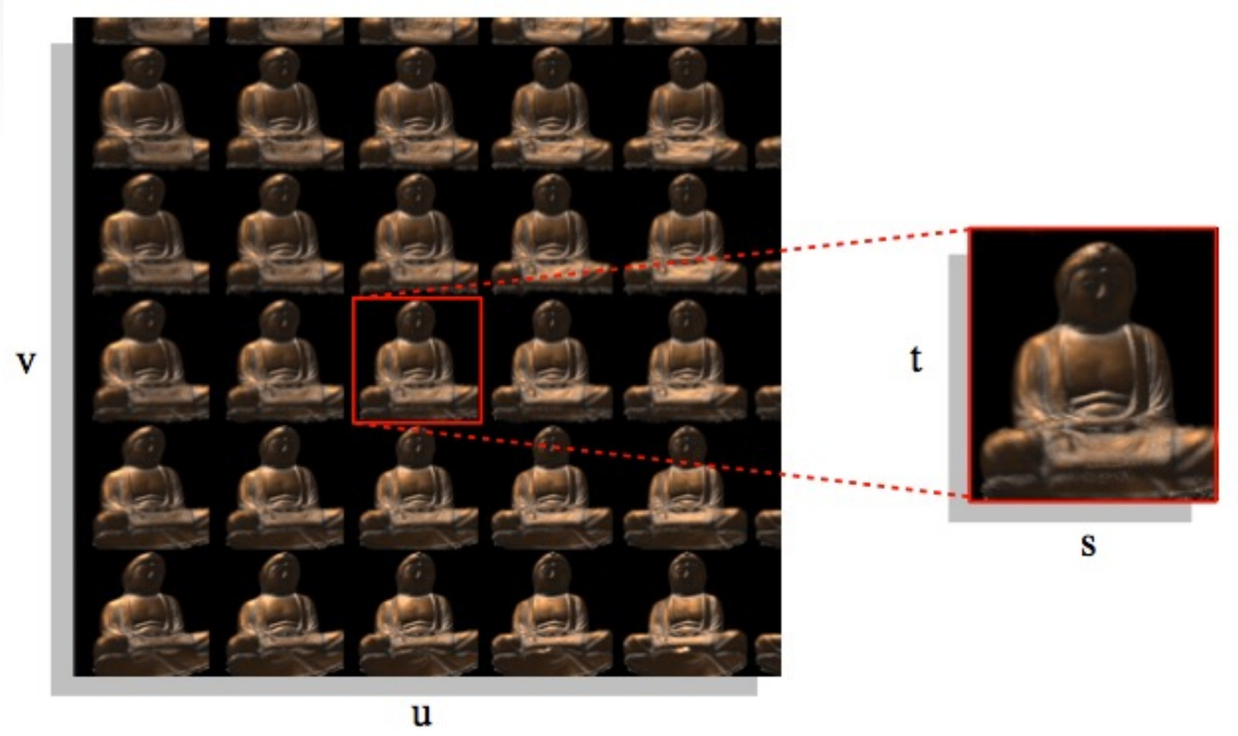
Levoy/Hanrahan refer to this representation as “light slab”

Light-field Parameterization



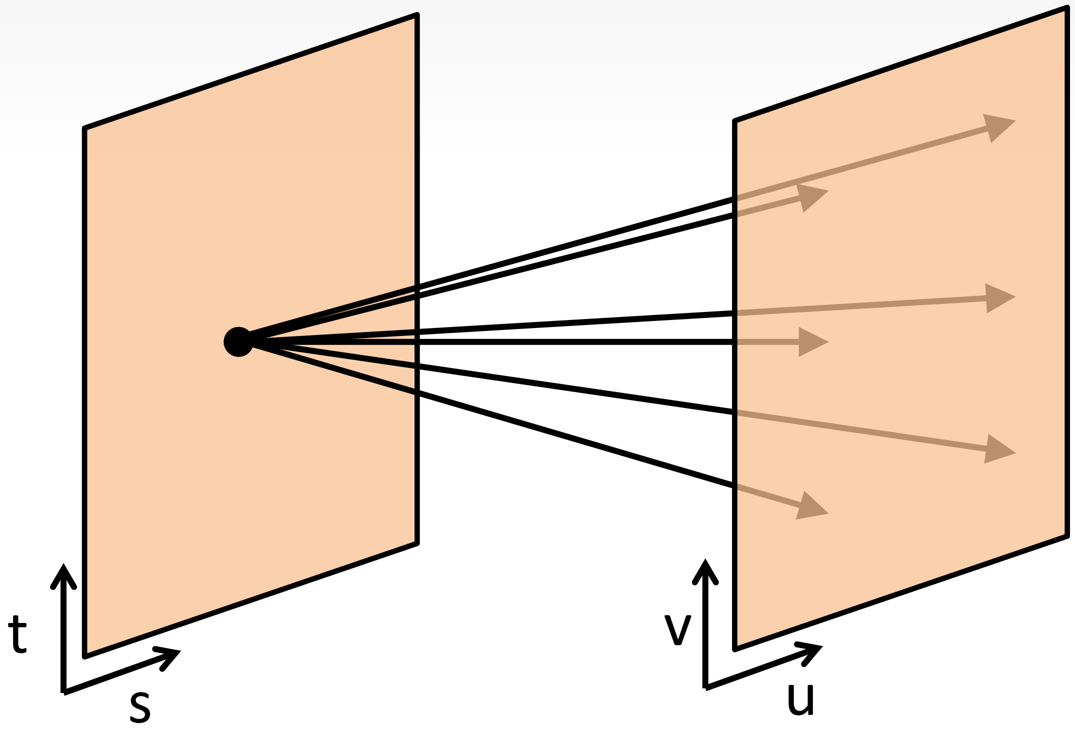
Every position in UV, we can collect all the pixel value at different (s, t), it is an image of the object from this perspective.

Then we can get a UV Array of ST images



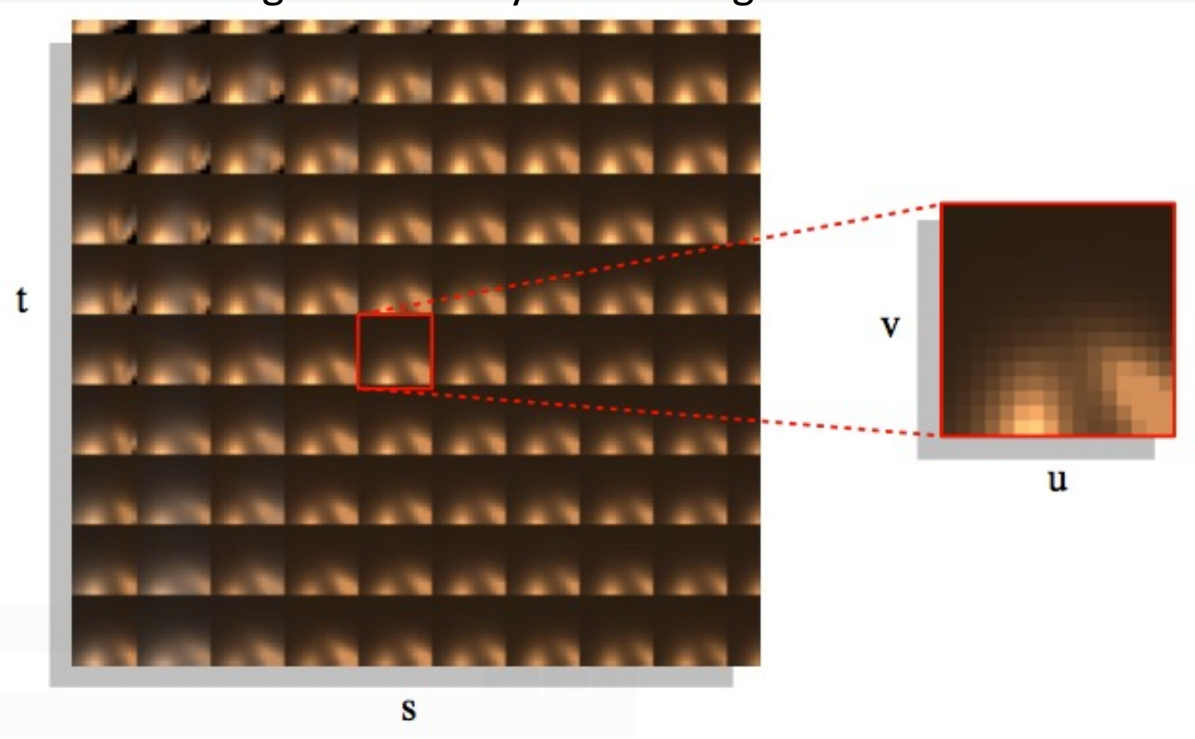
Plenoptic Light Field
Field Radiance Map

Light-field Parameterization



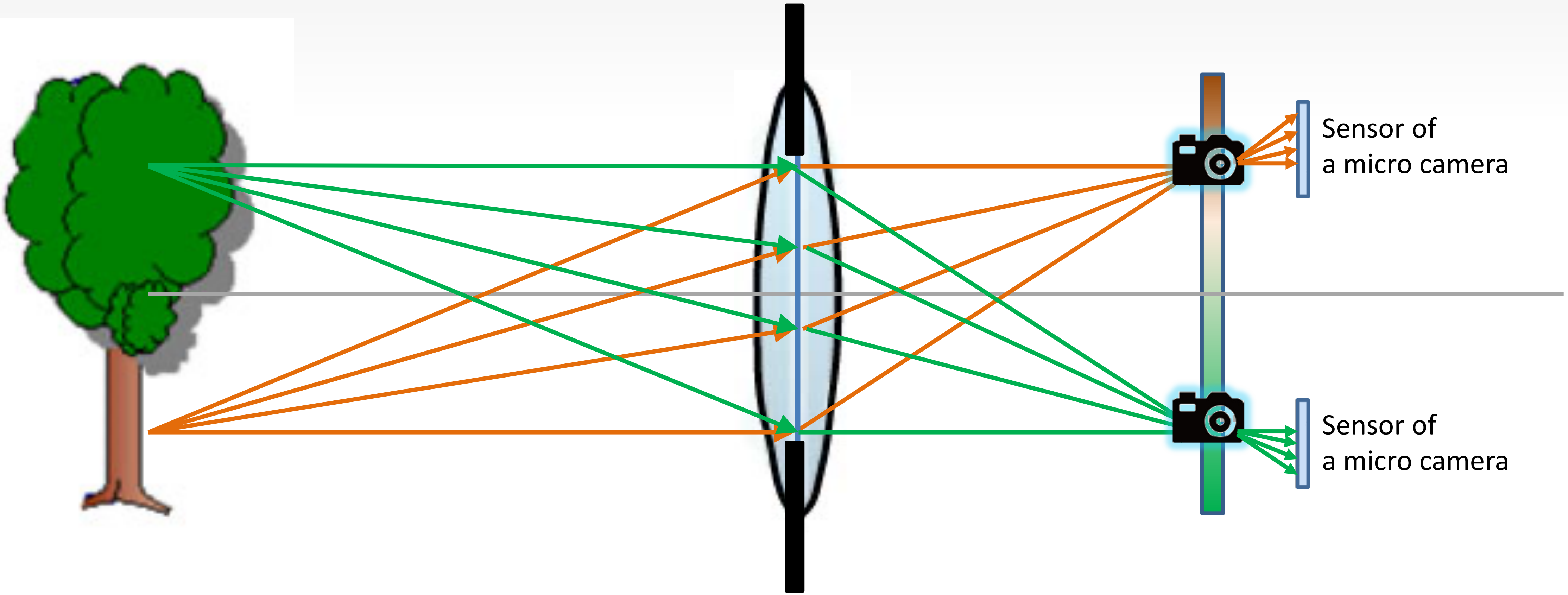
Every position in ST, we can collect all the pixel value at different (u, v), it is actually the appearance of one surface point when watching from different direction.

Then we can get a ST Array of UV images



Surface Light Field
Surface Radiance Map

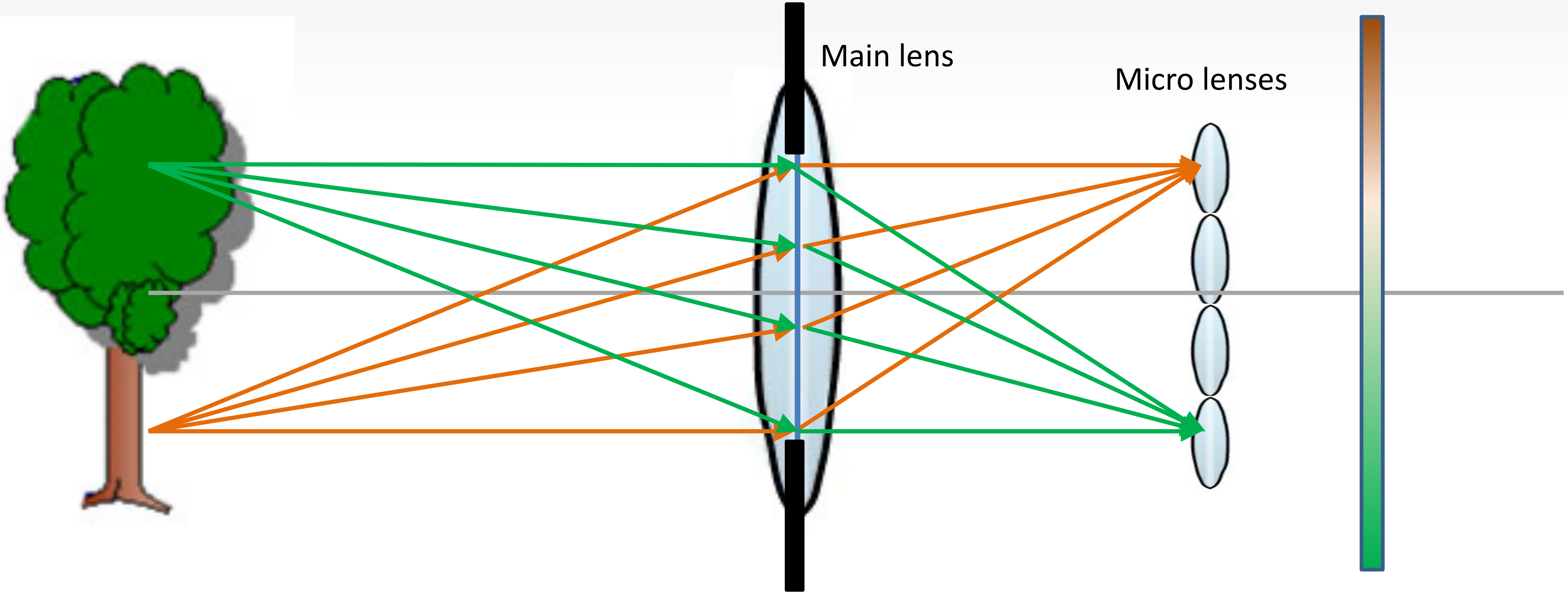
Can we make a micro camera array?



In a hand-held camera, there are also a bundle of light rays received by a sensor element.
Can we make a micro camera at each element to receive all the rays?

Light Field Camera Based on Micro Lenses

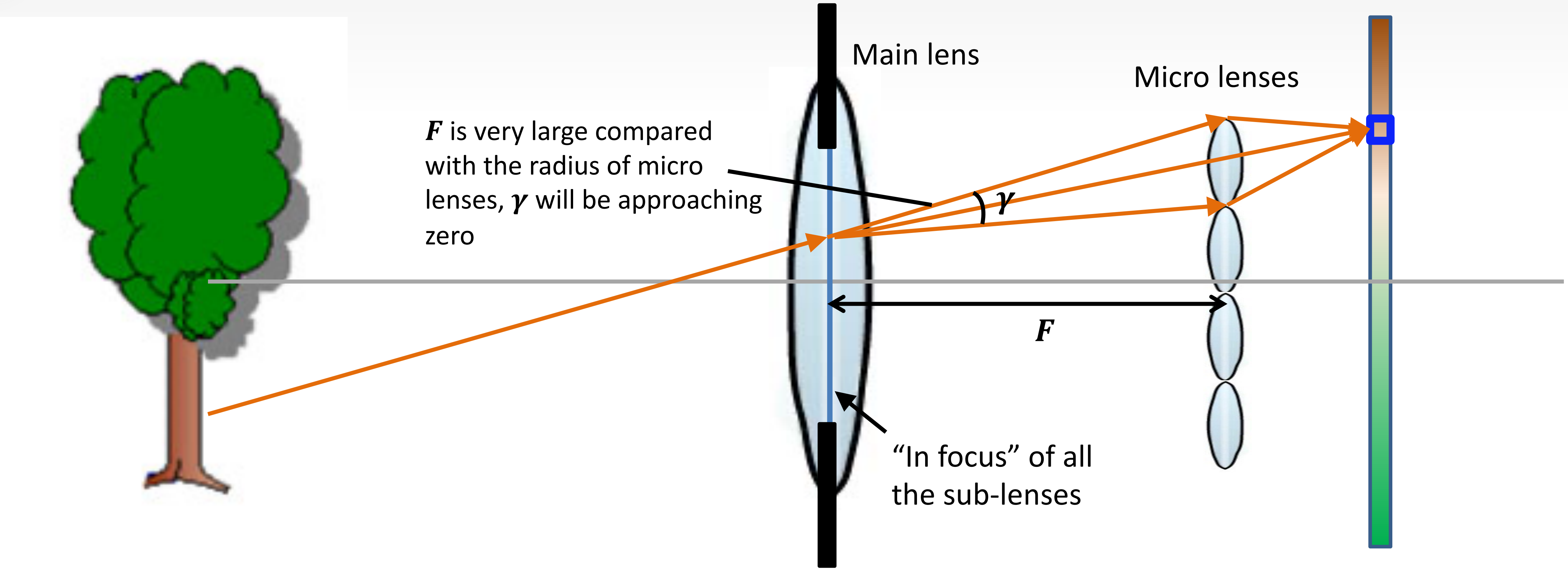
[Ng et al. 2005]



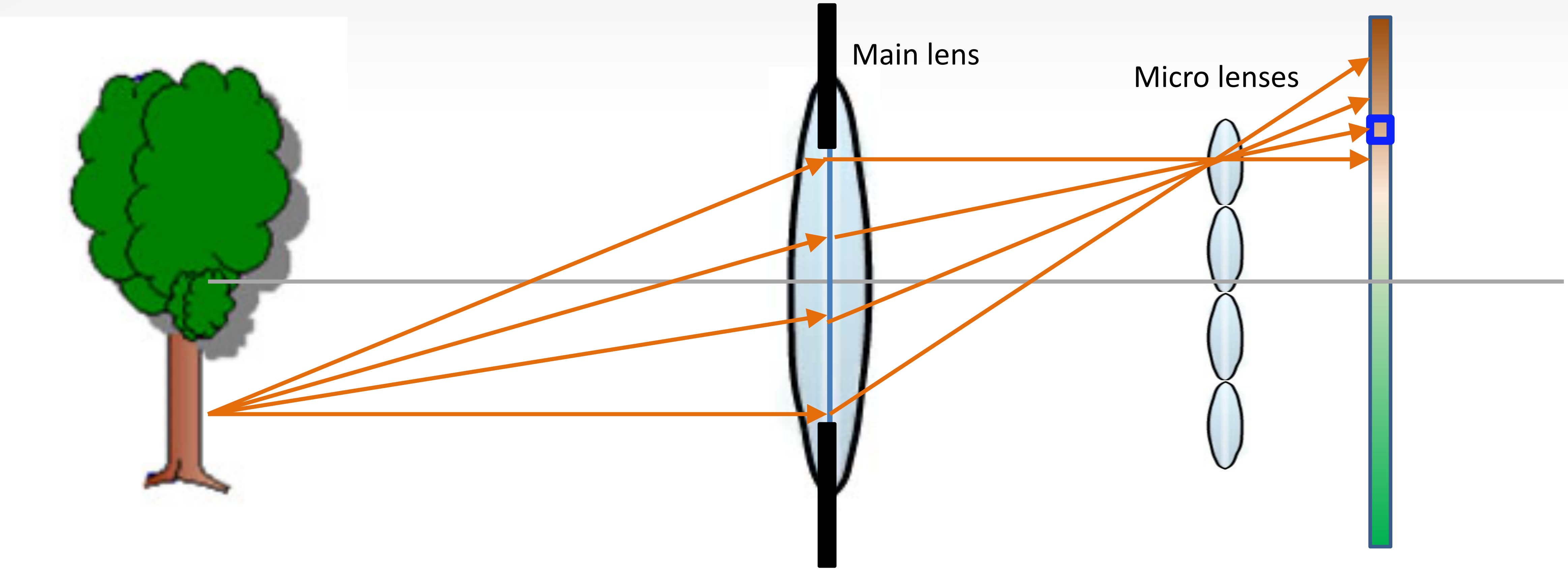
Equivalent to put a micro lens array at the original sensor plane

Sensor will be move back to receive the lights passing through sub-lenses

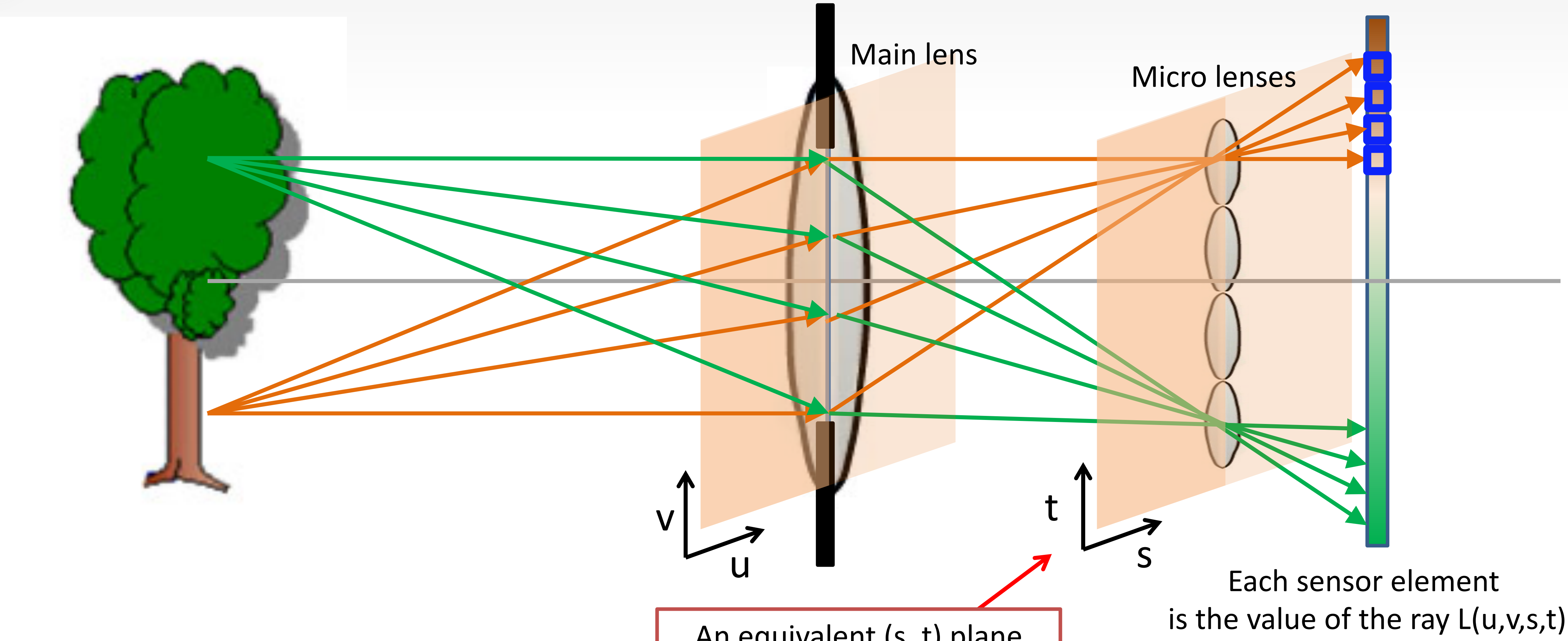
Light Field Camera Based on Micro Lenses



Light Field Camera Based on Micro Lenses

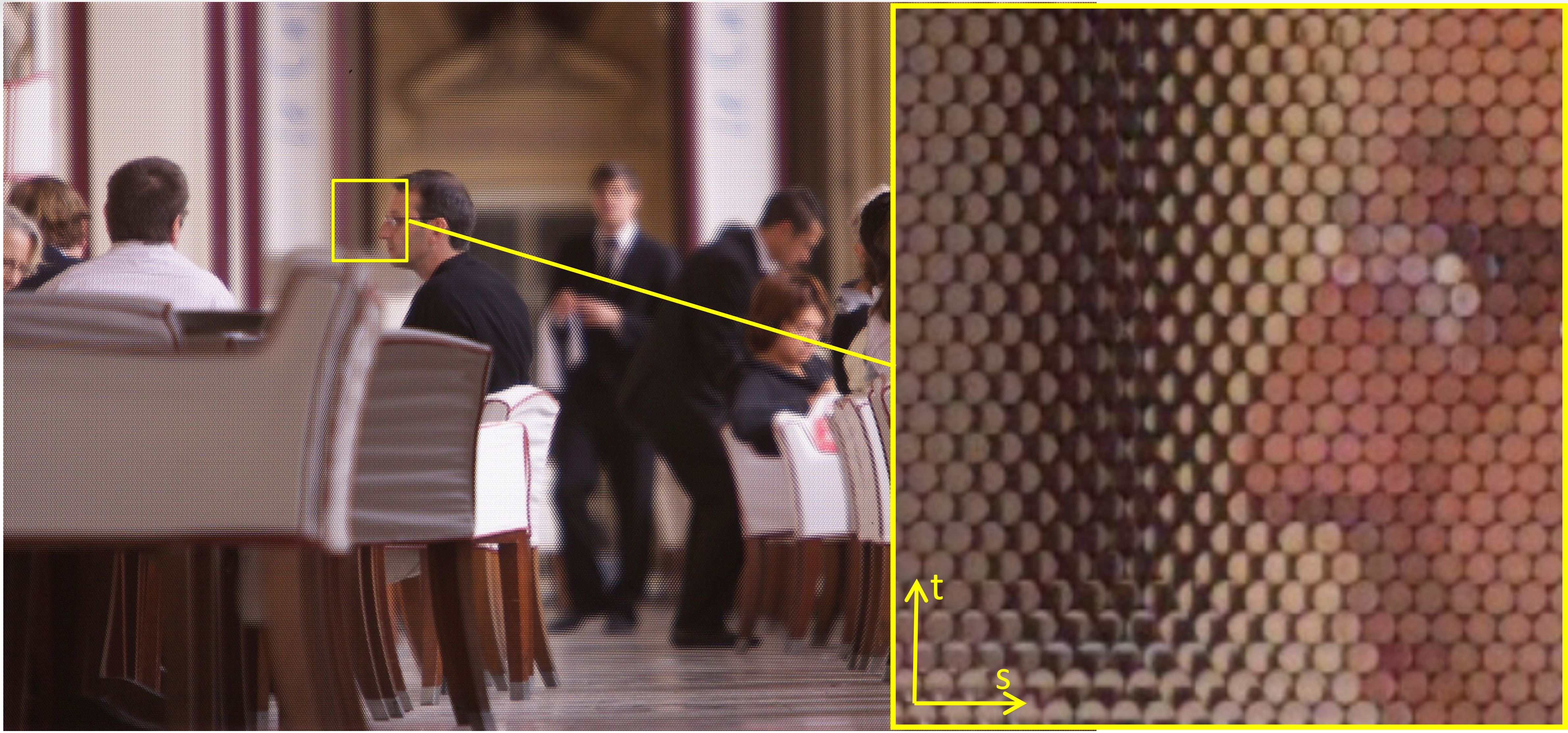


Light Field Camera Based on Micro Lenses



An equivalent (s, t) plane
with the plane in the scene.

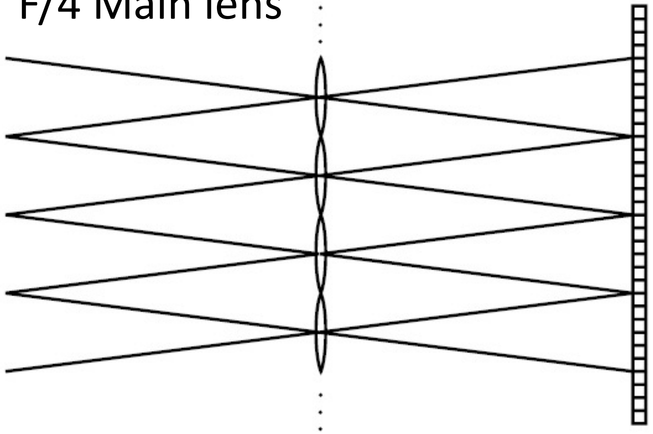
Raw Data From Light Field Camera Sensor

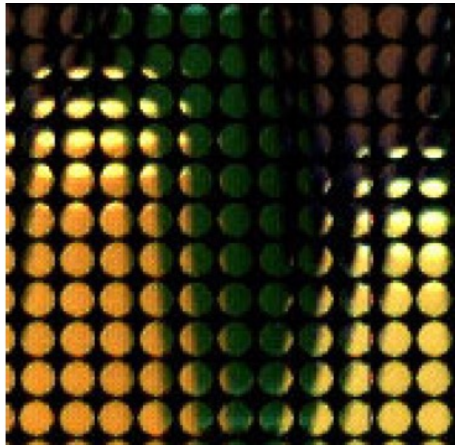


Check your understanding

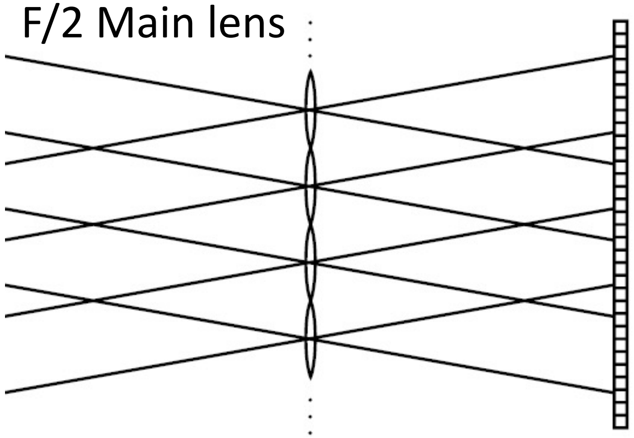
- What will the raw data look like with different aperture sizes?

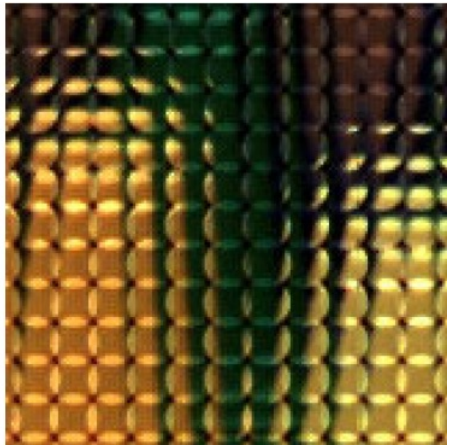
F/4 Main lens



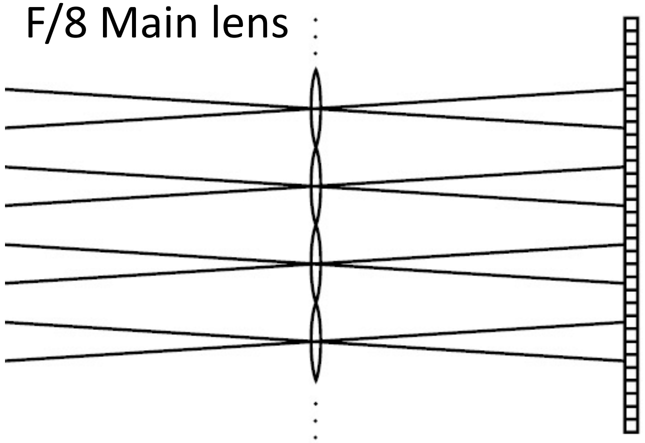


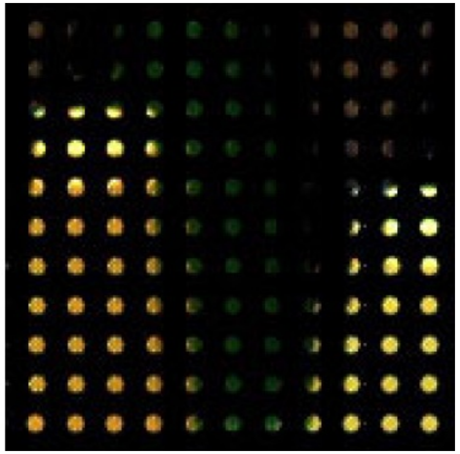
F/2 Main lens



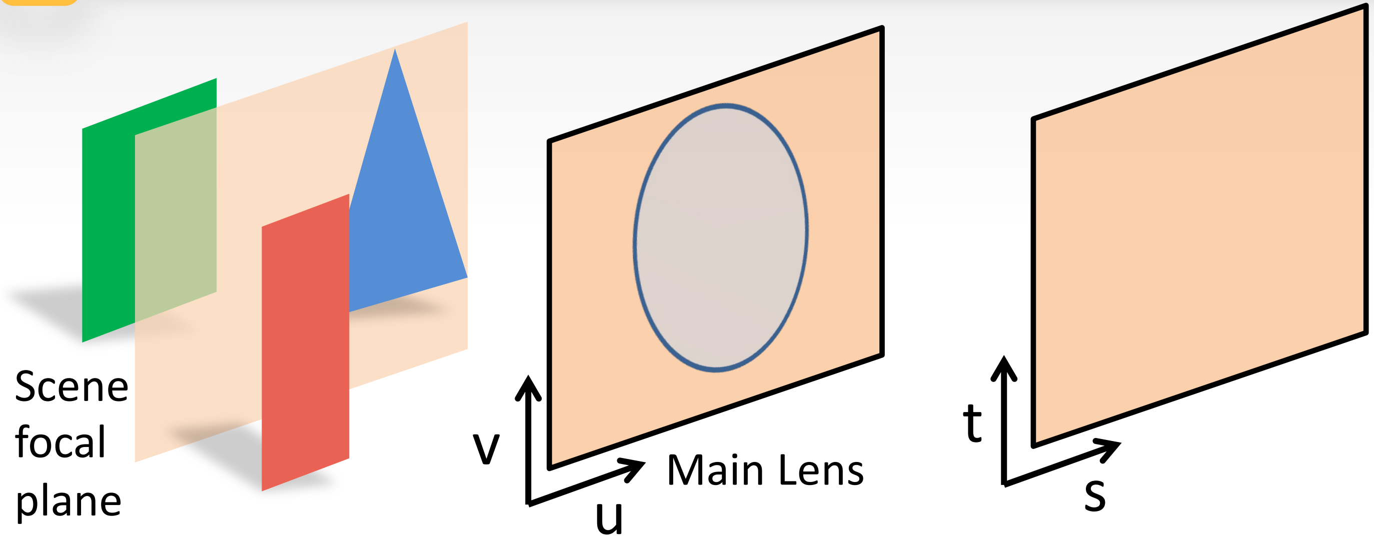


F/8 Main lens

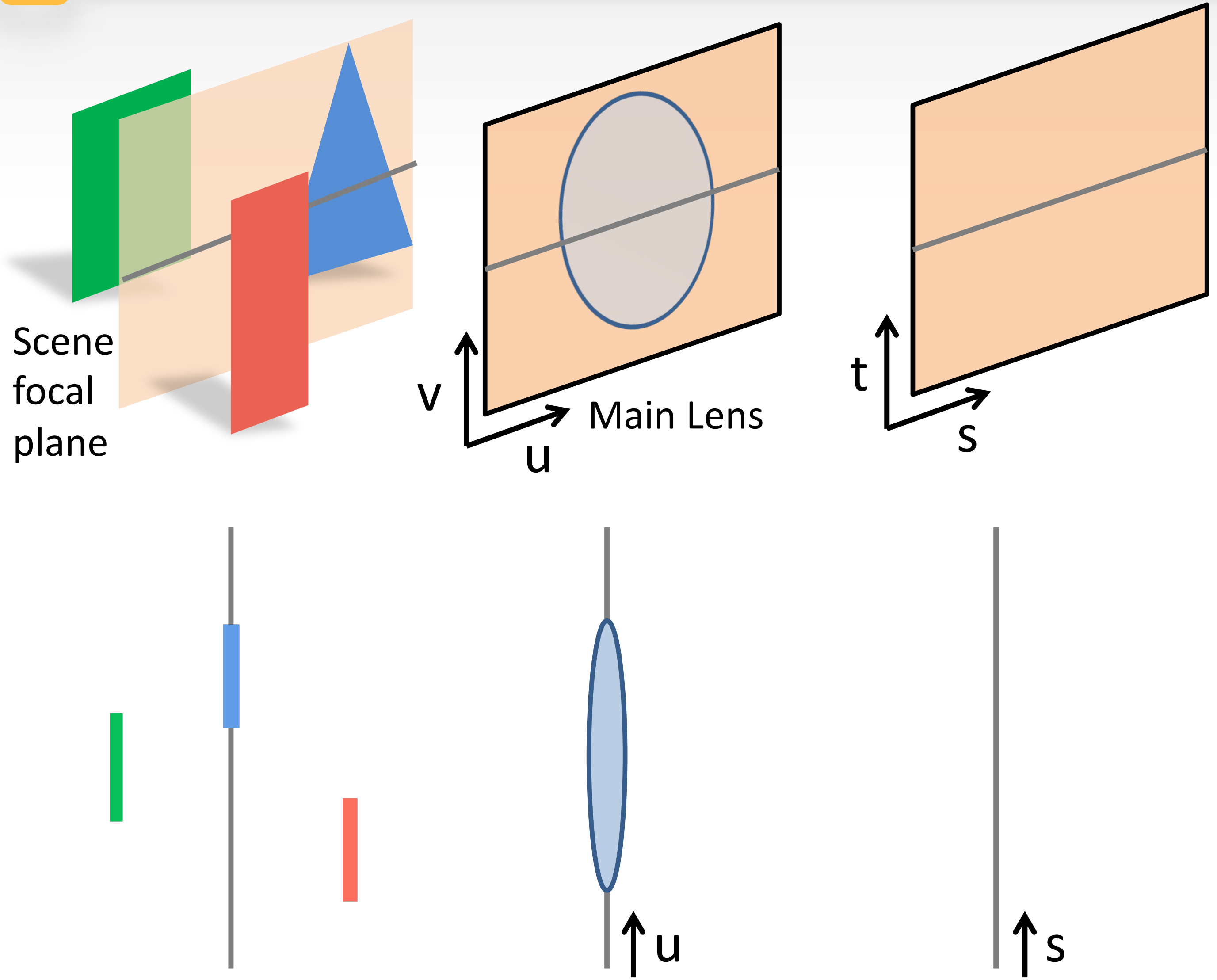


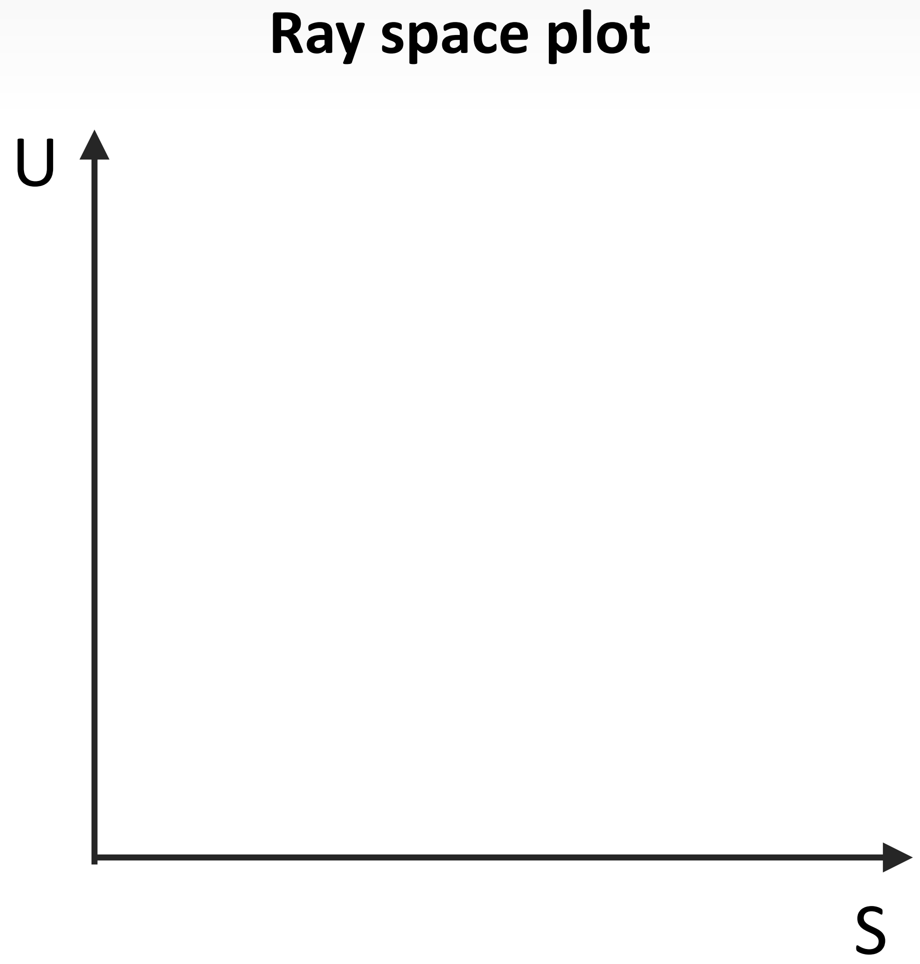


Analysis in Ray Space

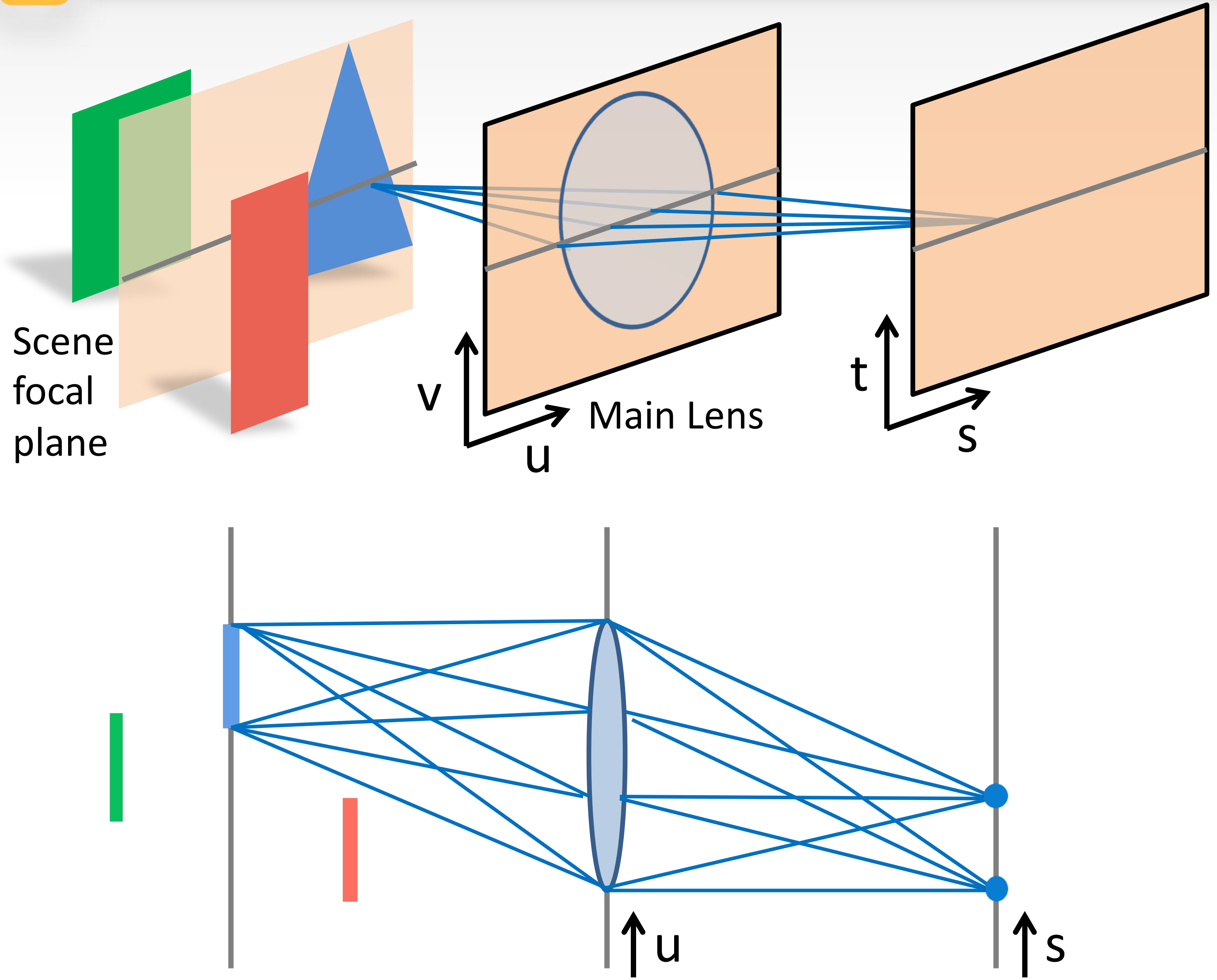


Analysis in Ray Space

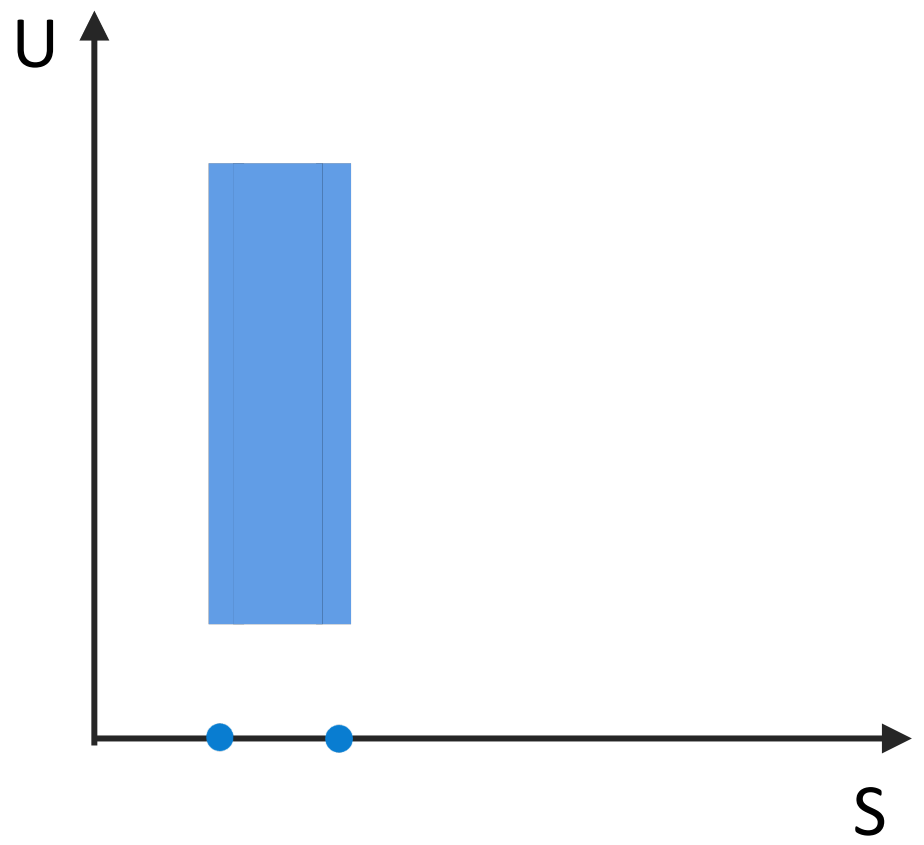




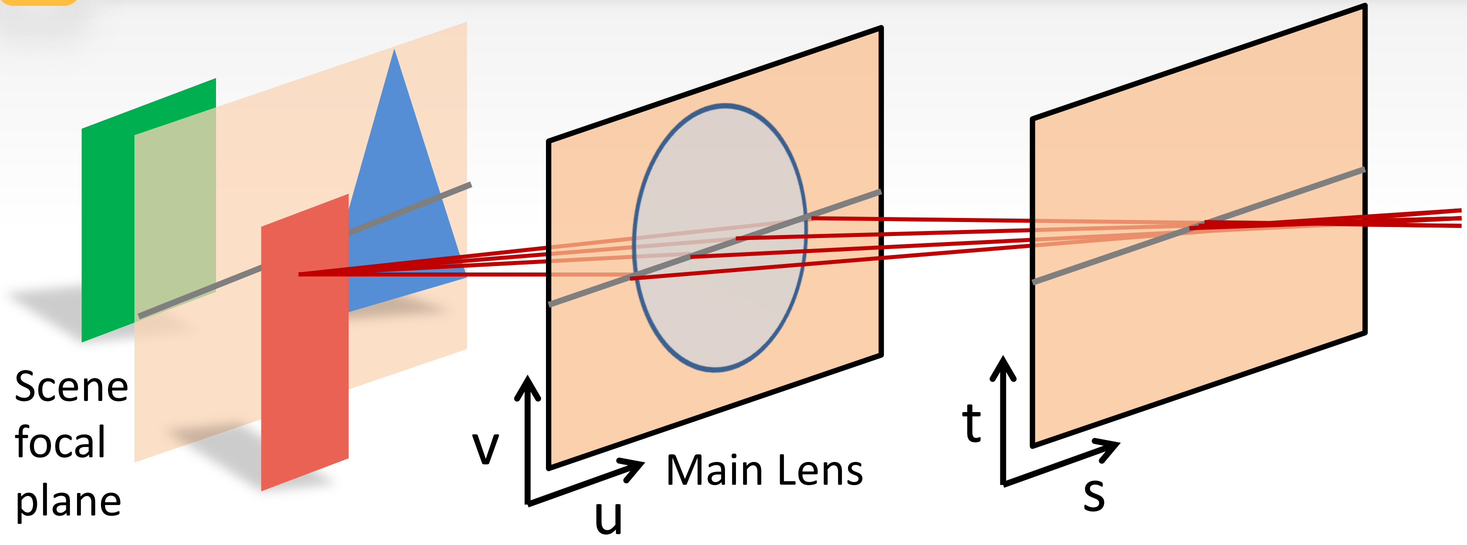
Analysis in Ray Space

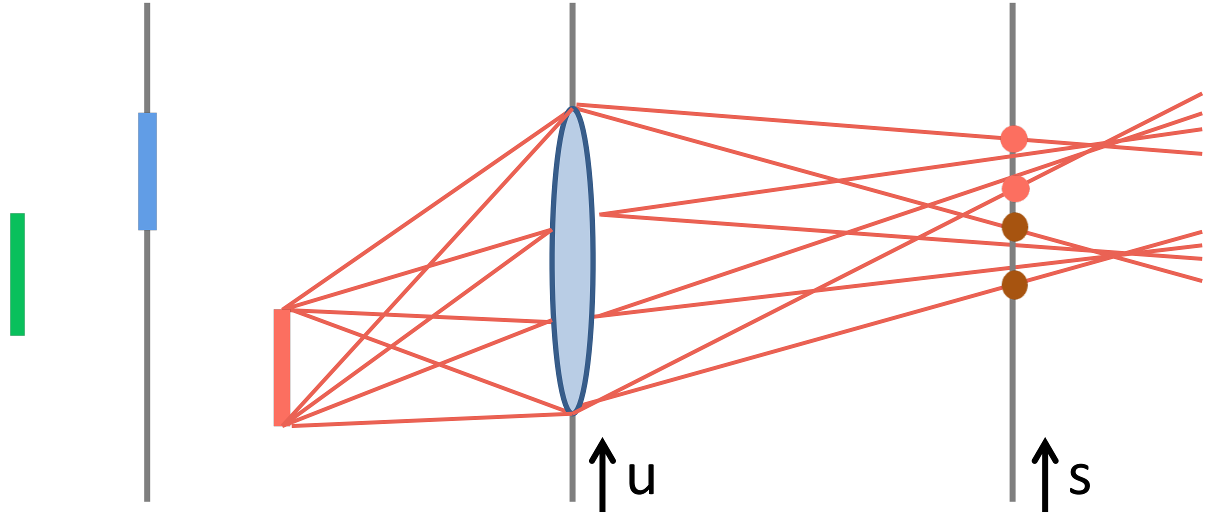


Ray space plot

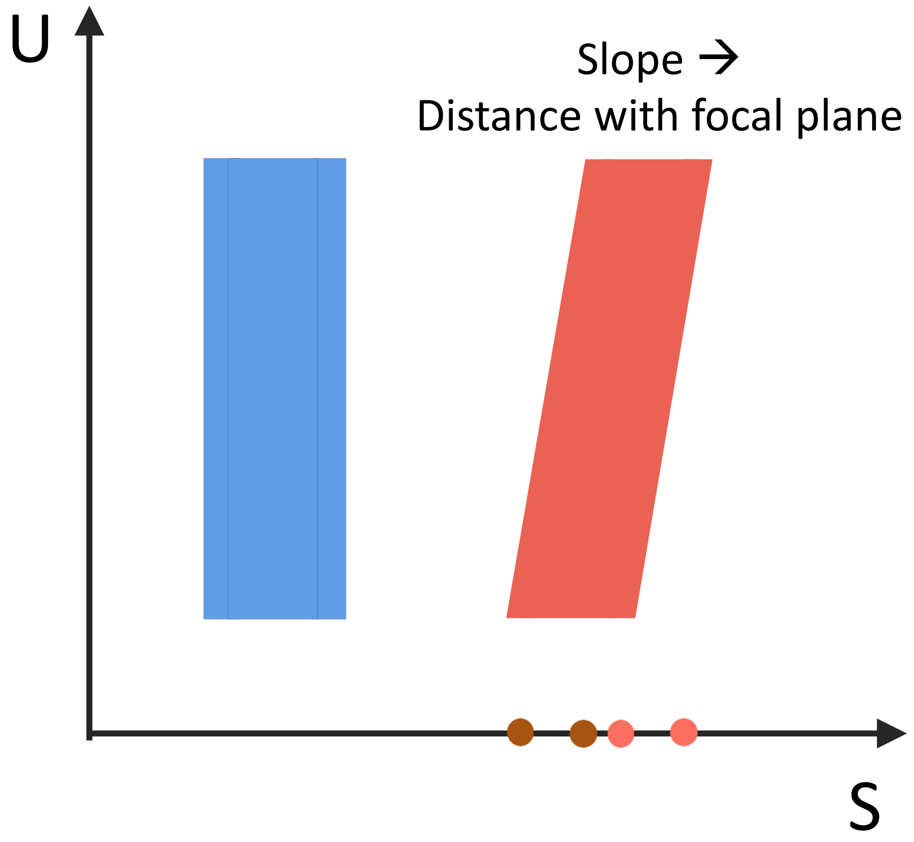


Analysis in Ray Space

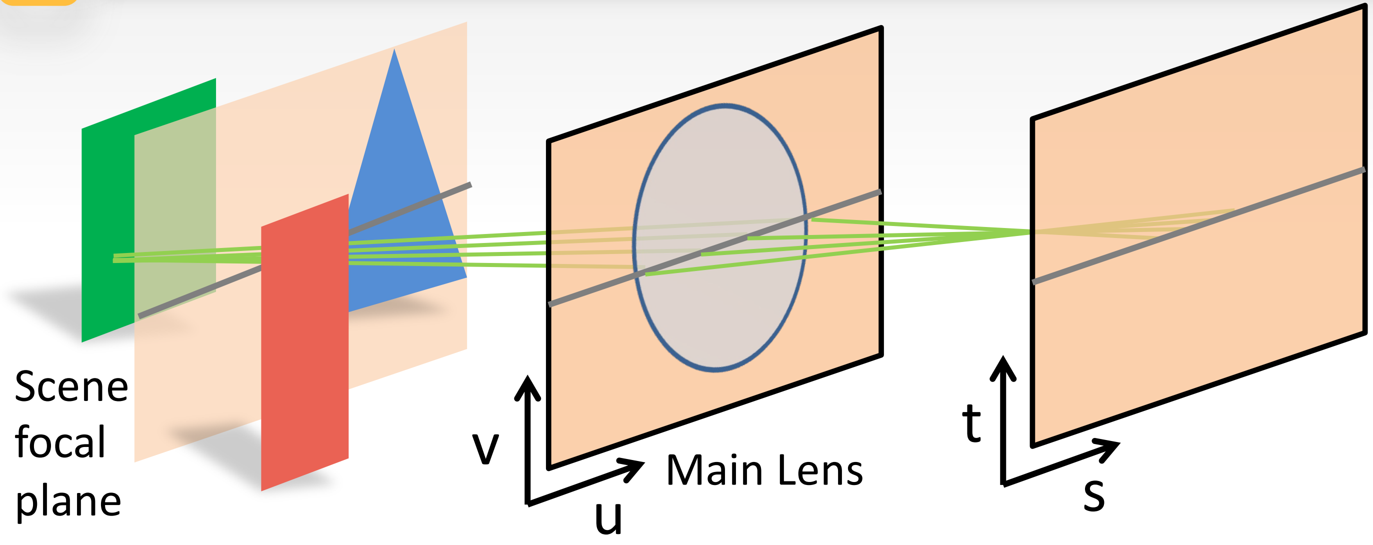


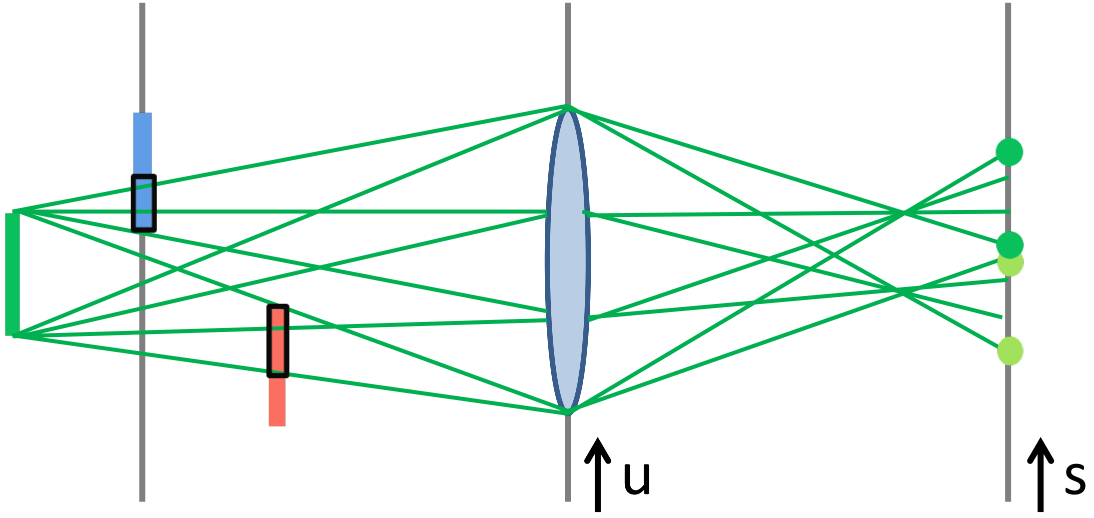


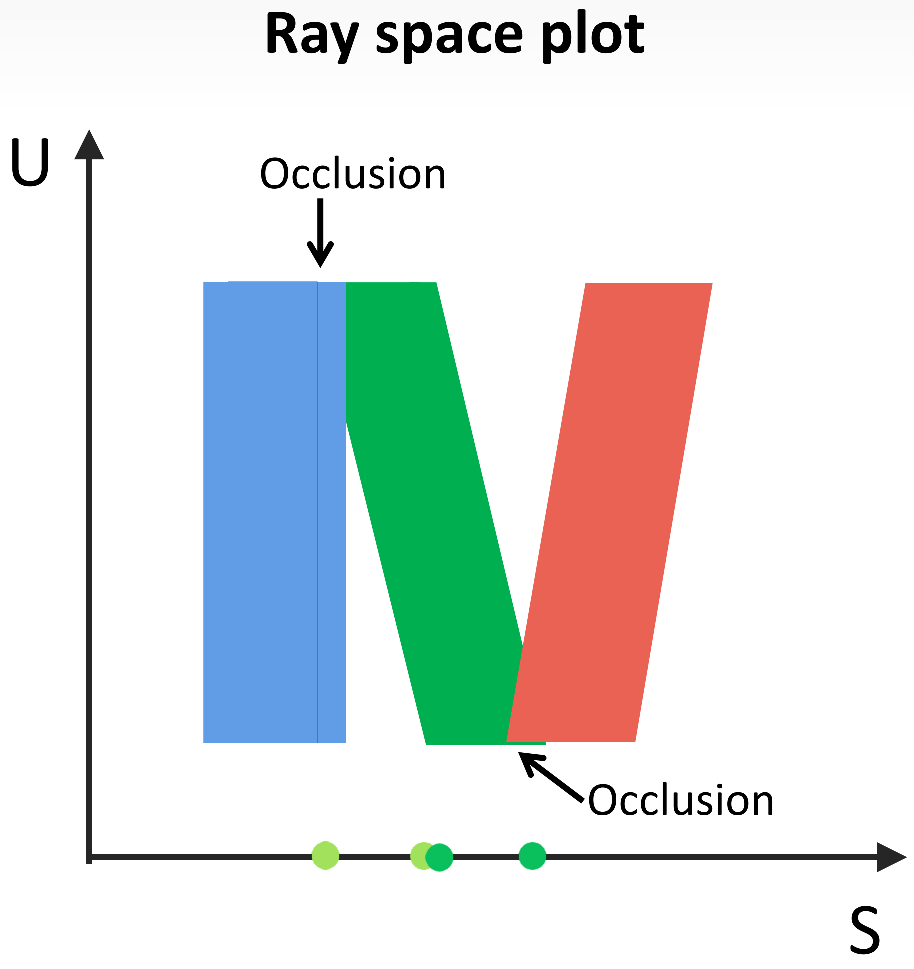
Ray space plot



Analysis in Ray Space







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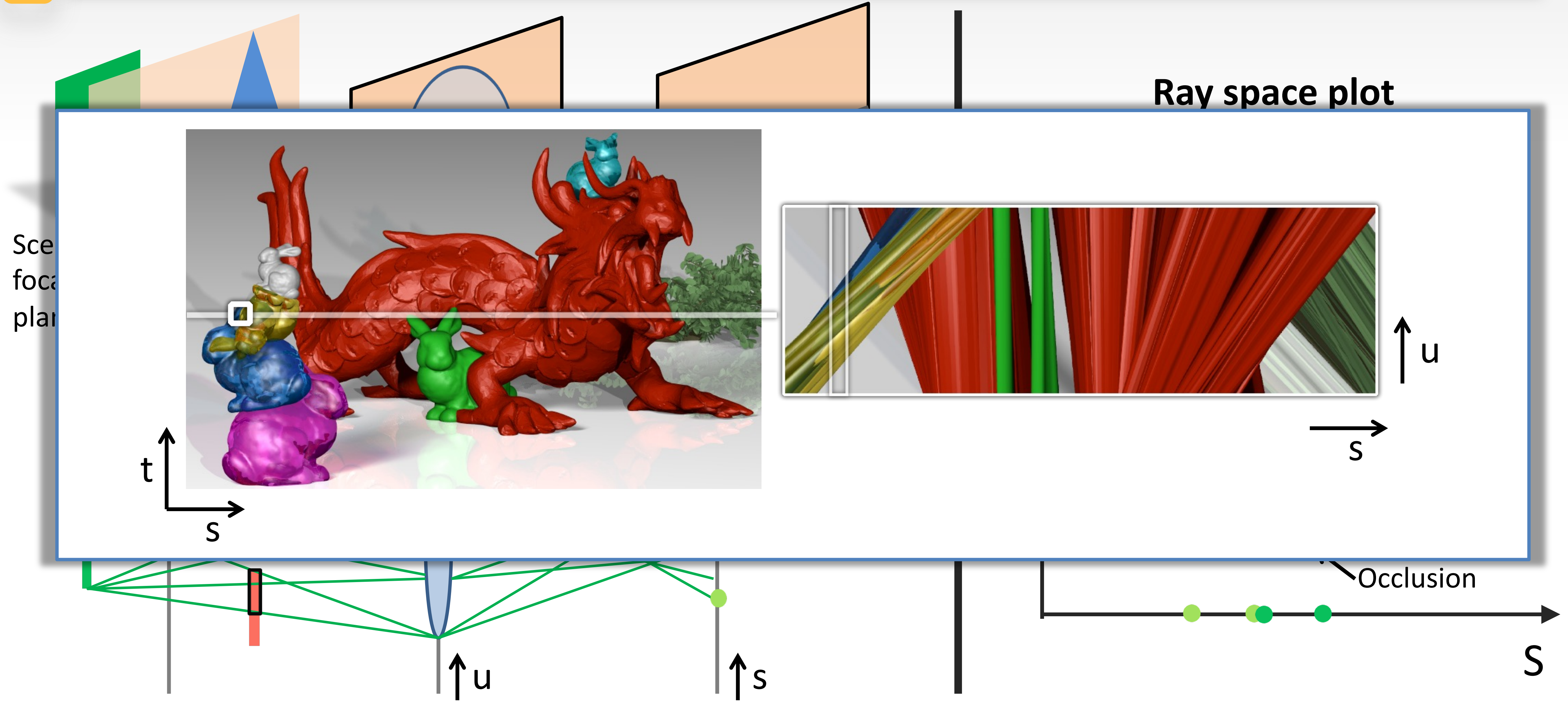
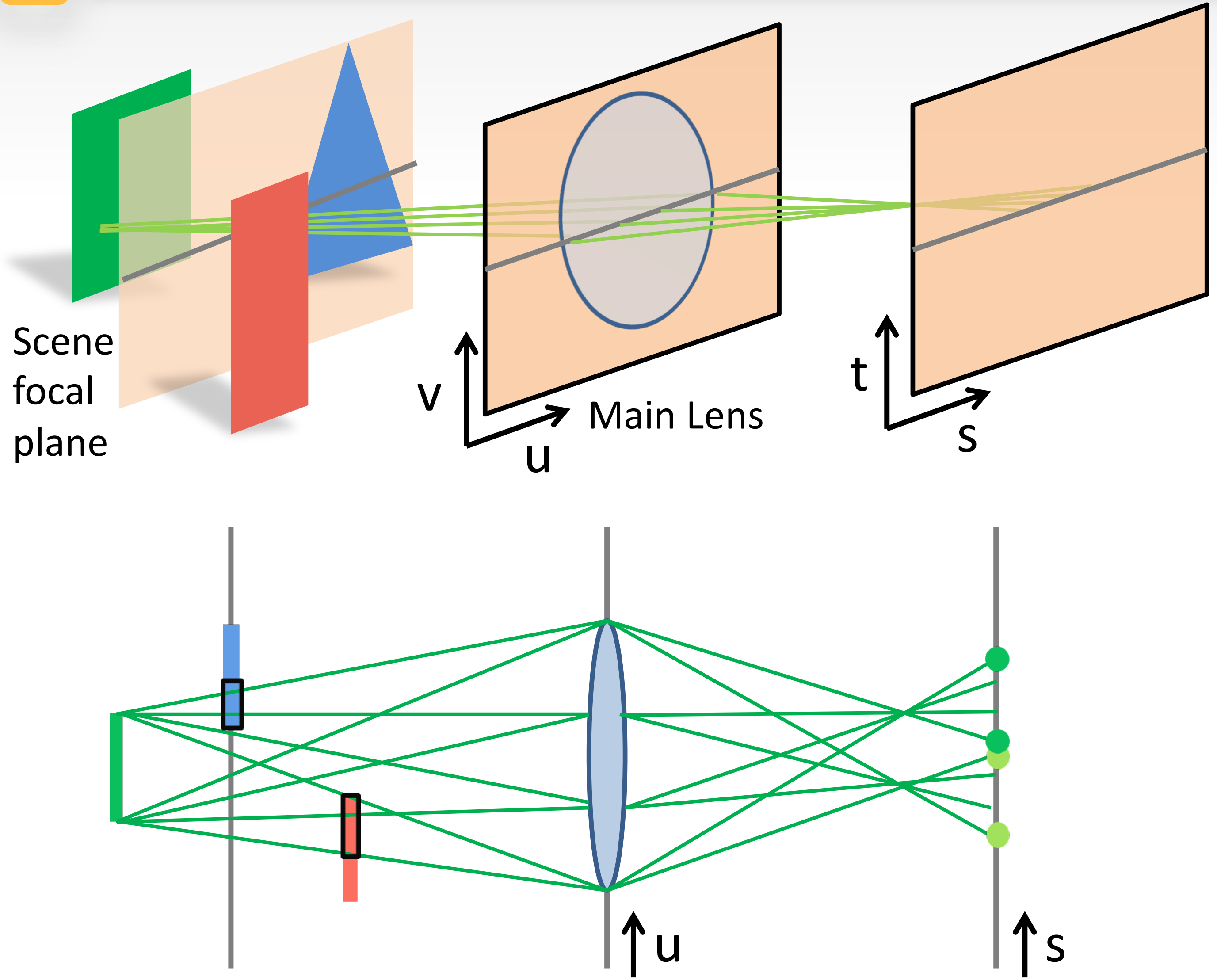
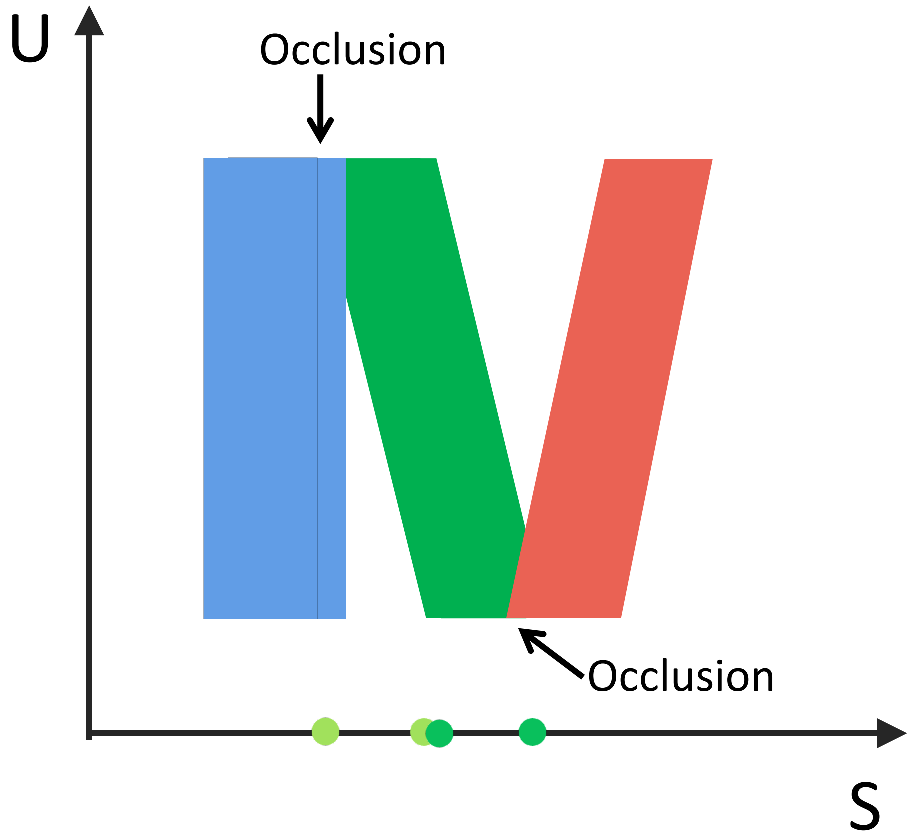


Analysis in Ray Space



Ray space plot



Use Light Field to Get a Synthetic Image

Irradiance image value on the virtual film plane s'-t'

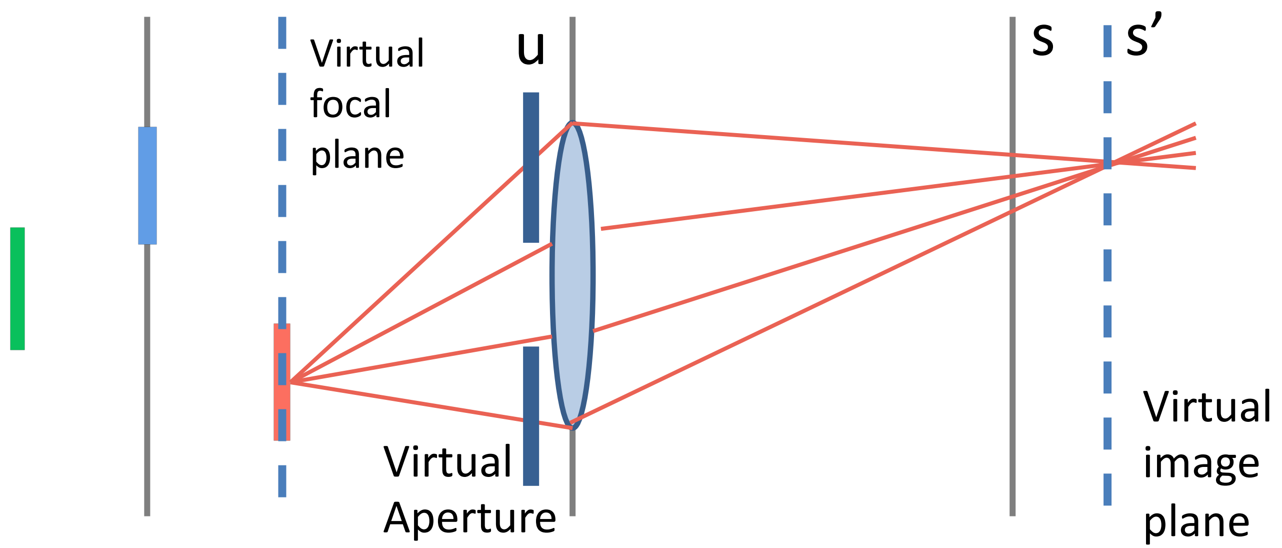
(Stroebel et al. [1986])

Synthetic Aperture

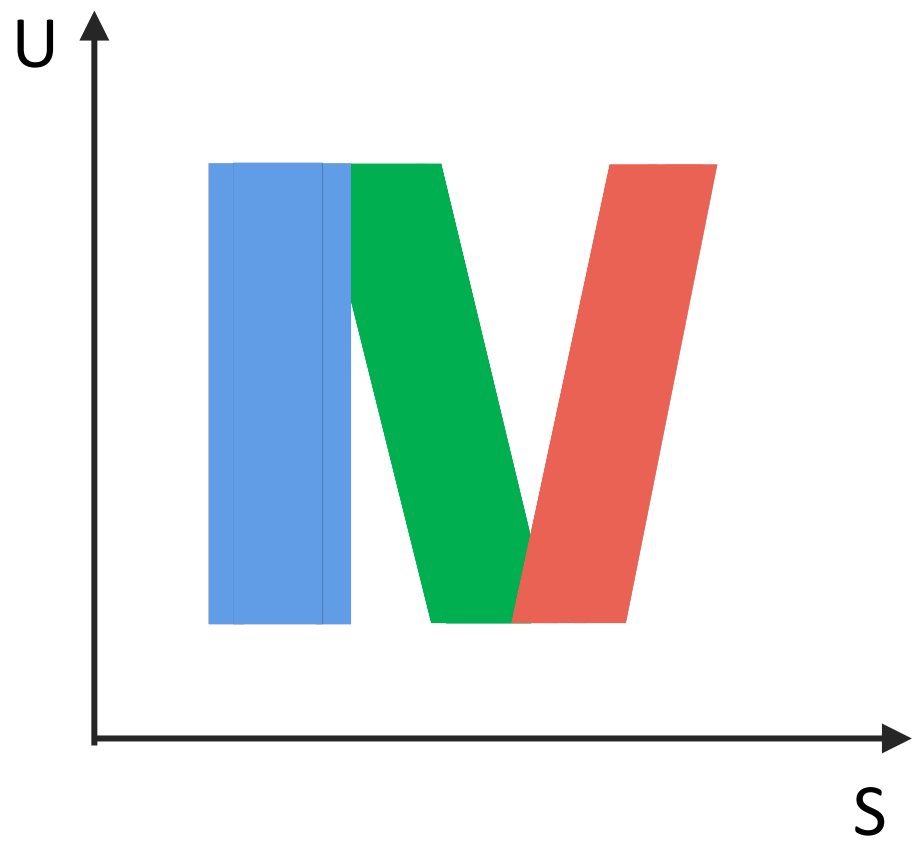
$$E(s', t') = \iint L'(u, v, s', t')\, A(u, v) \cos^4 \theta \, du \, dv$$

Color value of a ray in the virtual light field

Angle between the incident ray and the normal of the sensor plane



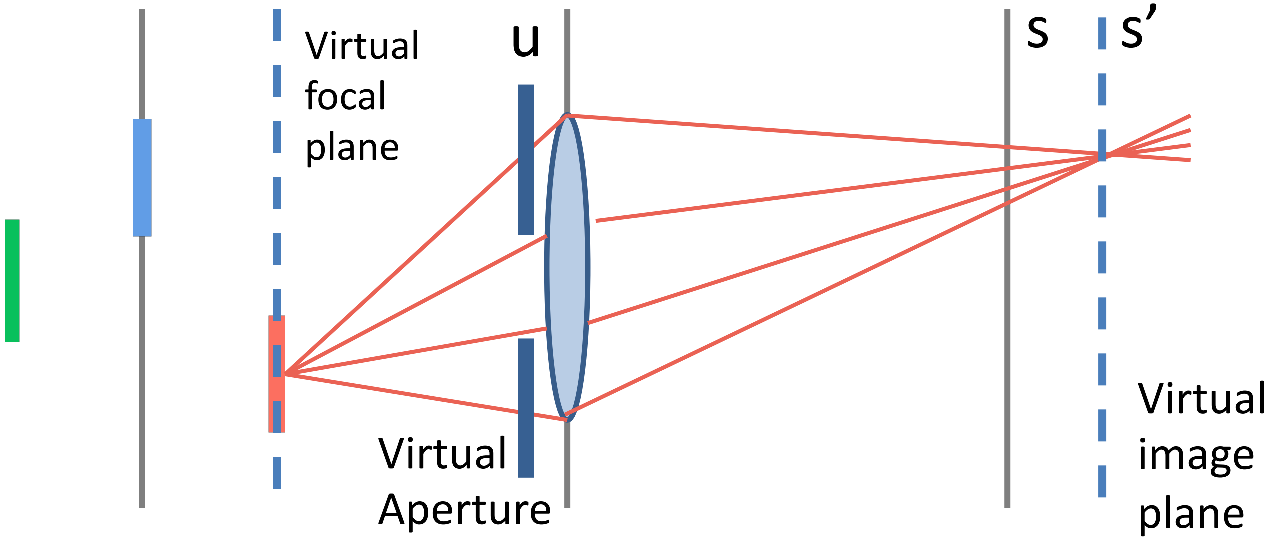
Ray space plot



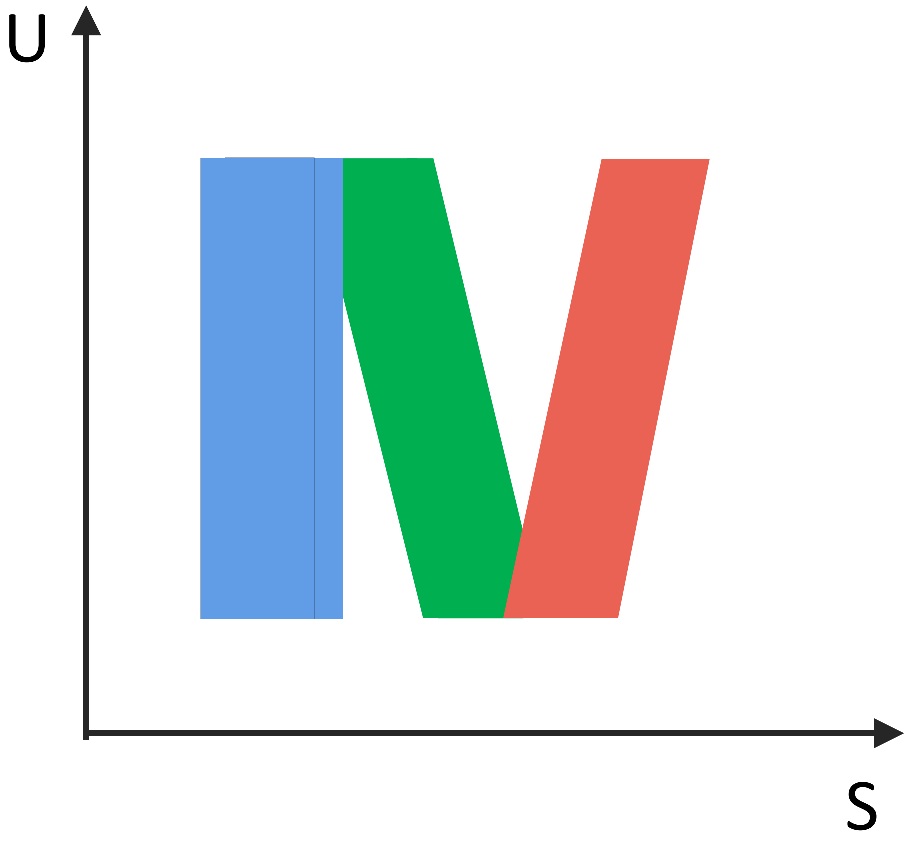
Use Light Field to Get a Synthetic Image

Make a paraxial approximation to eliminate $\cos^4\theta$

$$E(s',t') = \iint L'(u,v,s',t')\,A(u,v)\,du\,dv$$



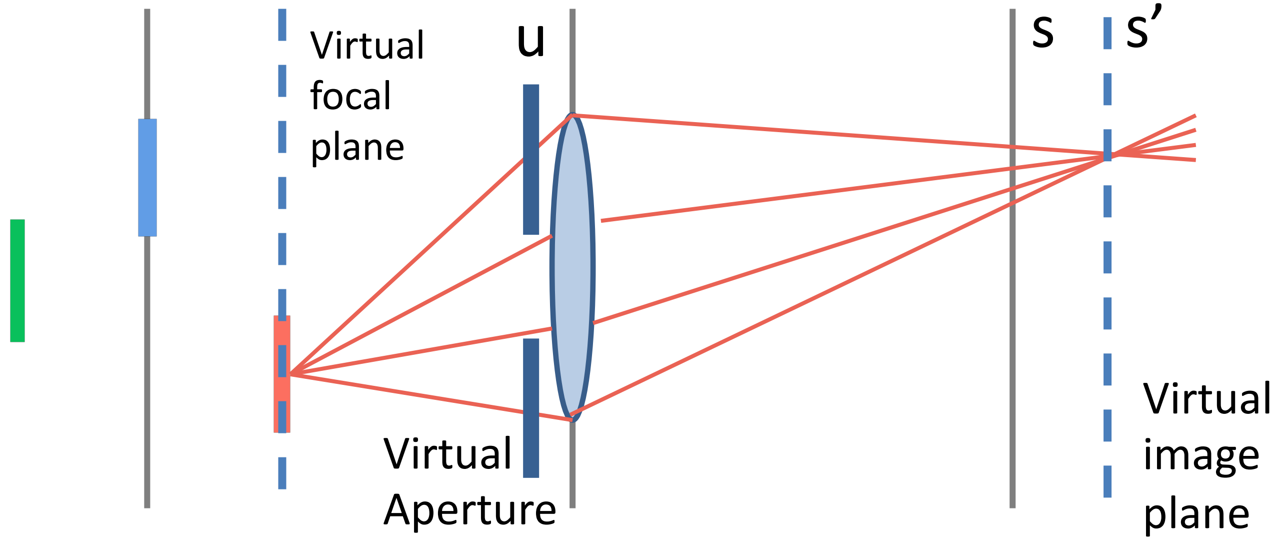
Ray space plot



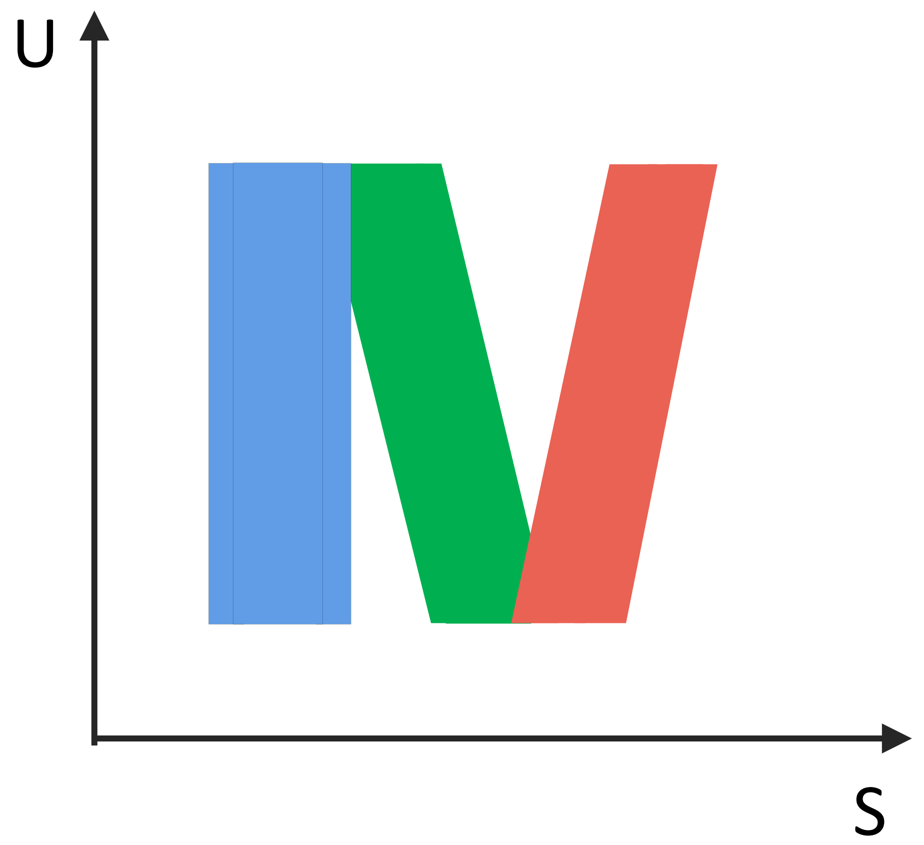
Use Light Field to Get a Synthetic Image

Just consider a full aperture at first.
It means that $A(u,v)$ = 1 for every (u,v)

$$E(s',t') = \iint L'(u,v,s',t')\, A(u,v)\,du\,dv$$



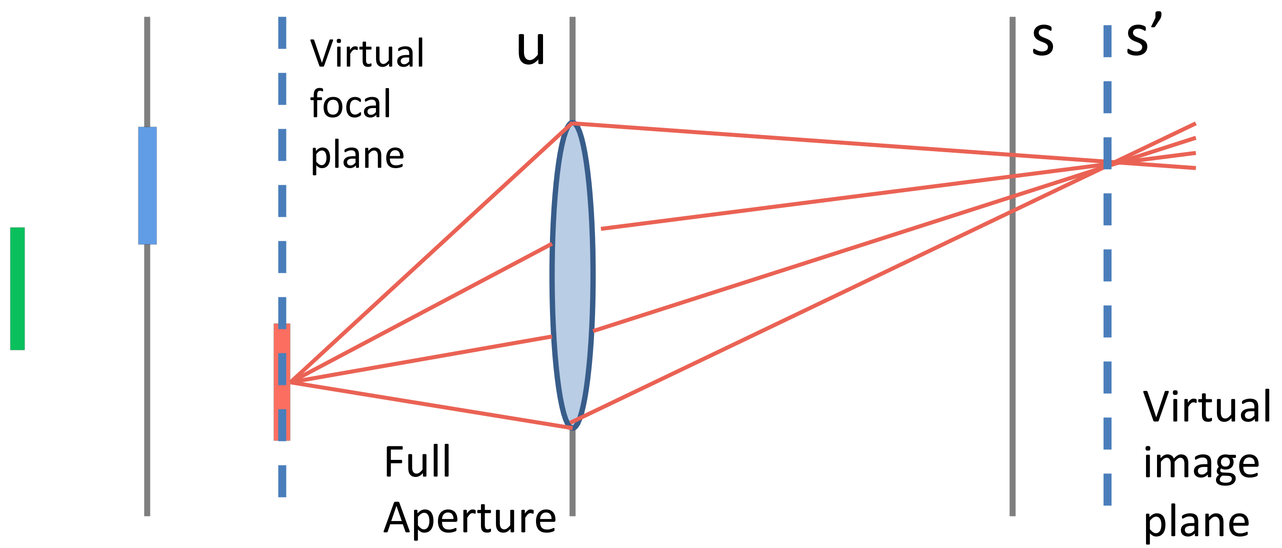
Ray space plot



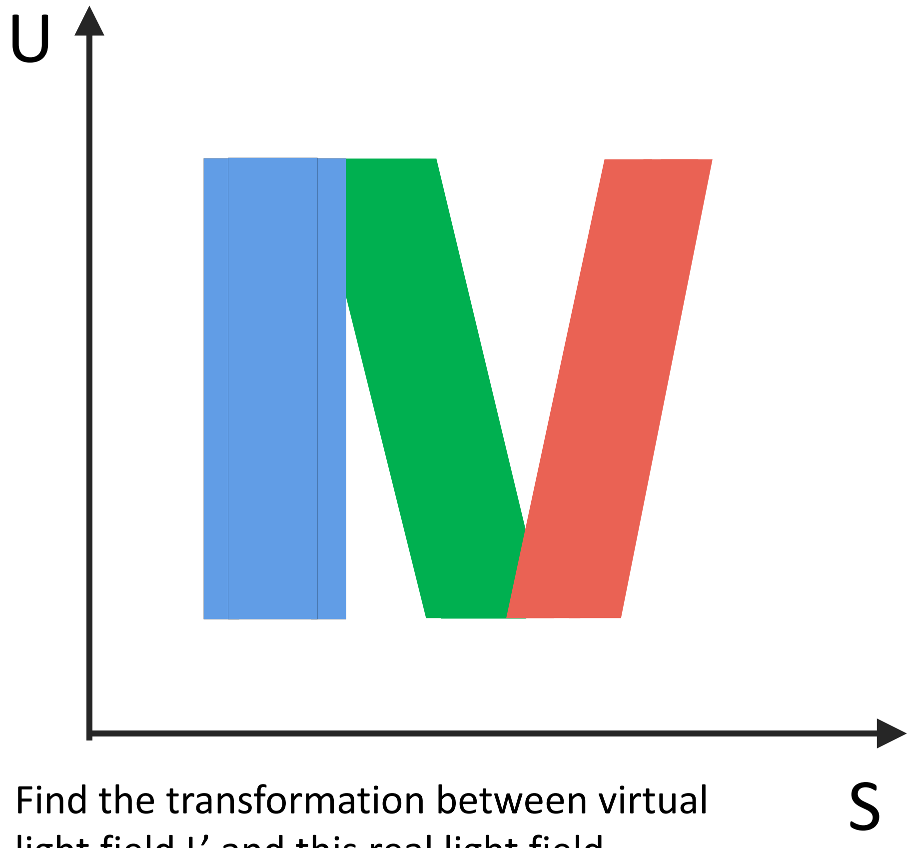
Use Light Field to Get a Synthetic Image

Now just use the simplified formula:

$$E(s', t') = \iint L'(u, v, s', t')\, du\, dv$$



Ray space plot



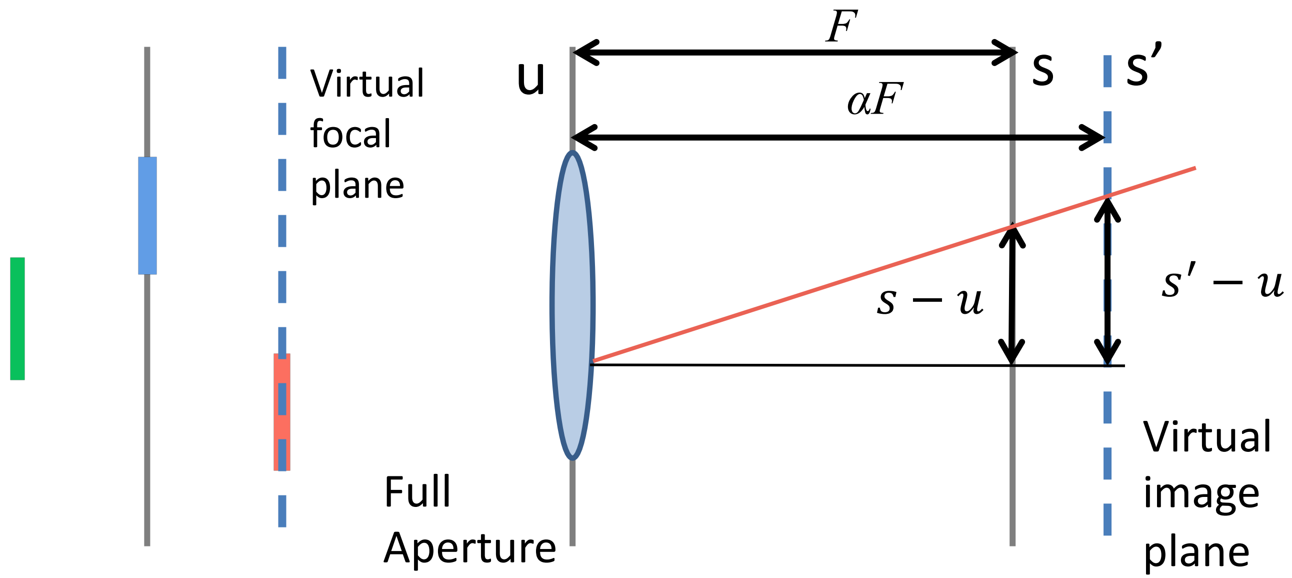
Find the transformation between virtual light field L' and this real light field

Use Light Field to Get a Synthetic Image

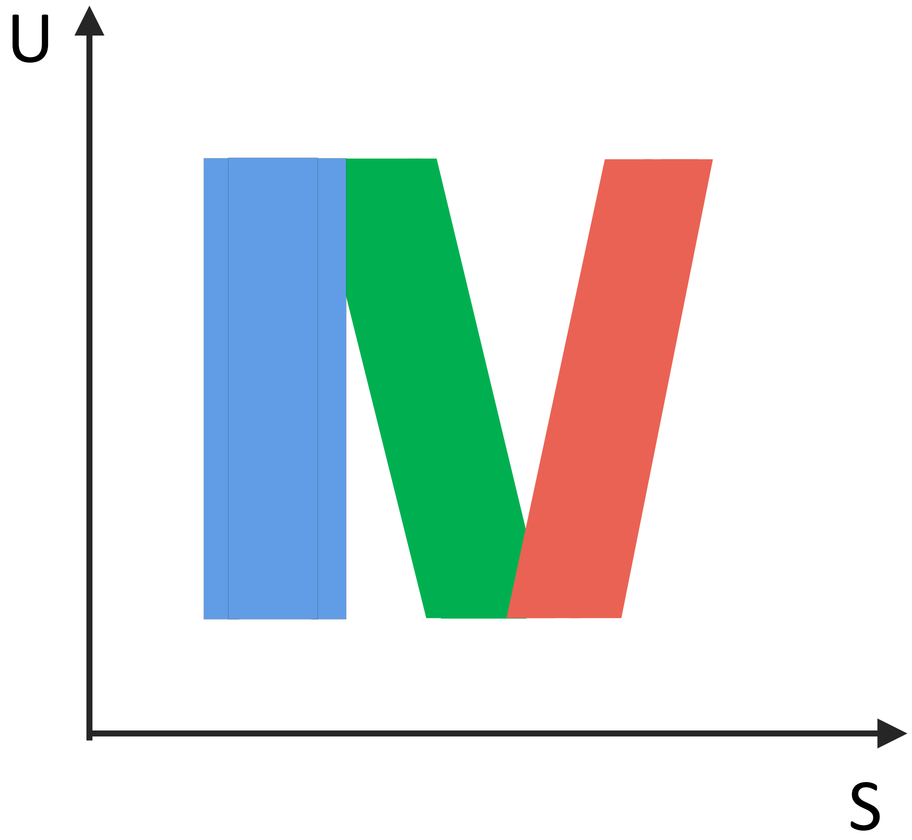
Now just use the simplified formula:

$$E(s', t') = \iint L'(u, v, s', t')\, du\, dv$$

What is the relationship between a ray in *L'* and *L*?



Ray space plot



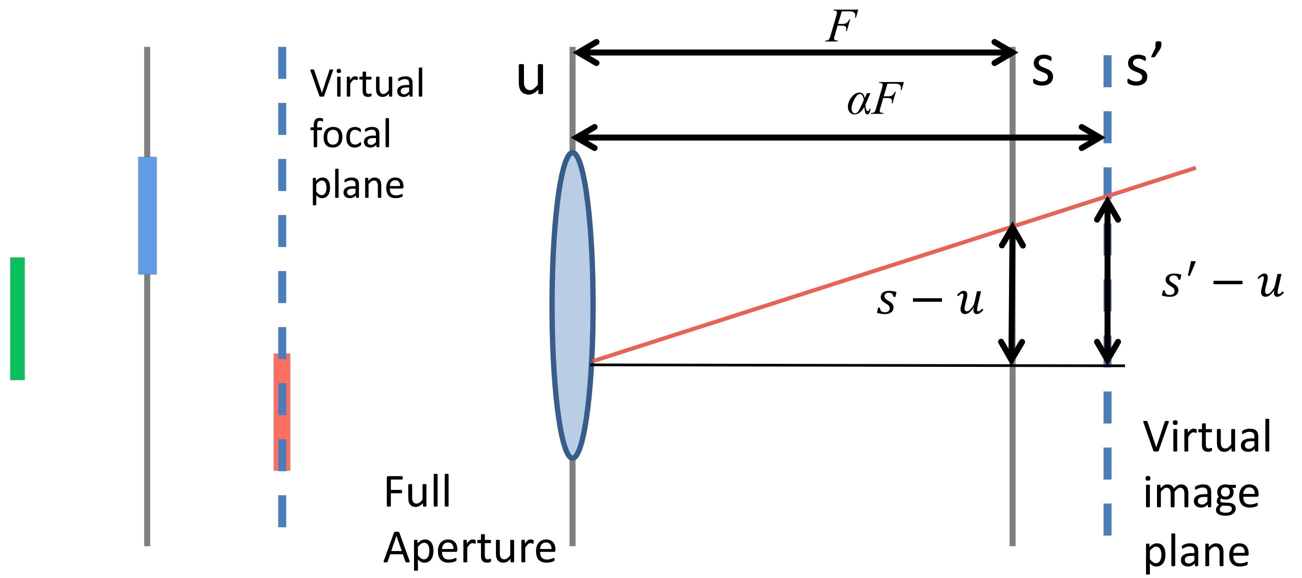
Use Light Field to Get a Synthetic Image

Get the light ray value from the original light field

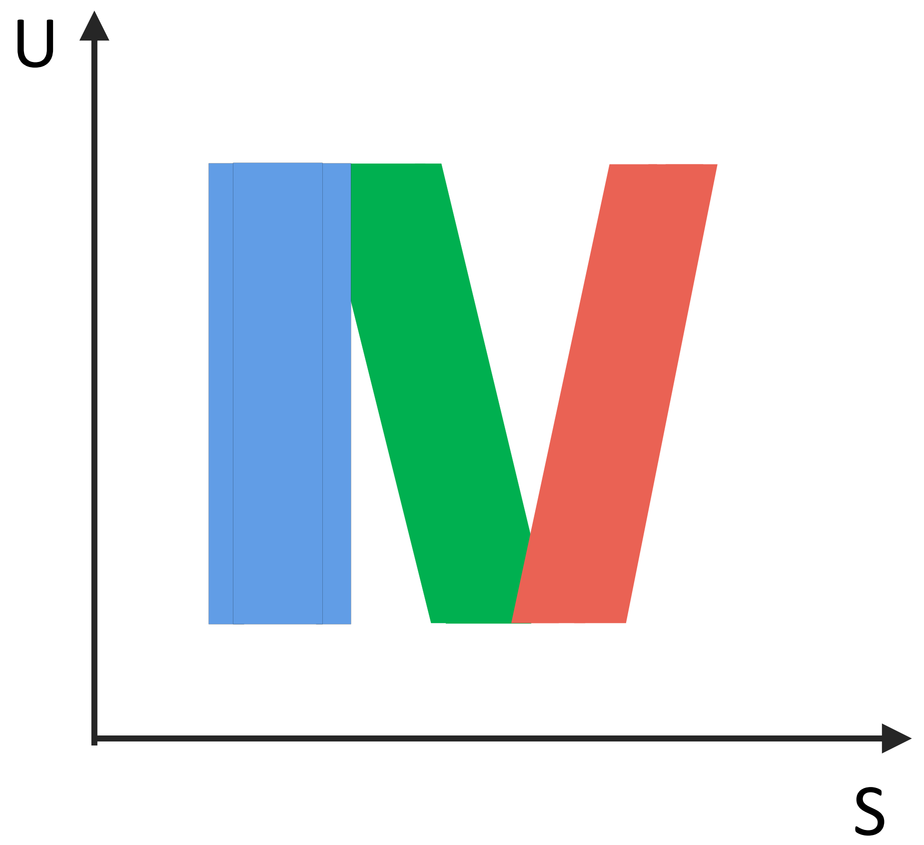
$$\frac{s-u}{s'-u} = \frac{F}{\alpha F}$$

$$\begin{cases} s = u + \dfrac{s'-u}{\alpha} \\ t = v + \dfrac{t'-v}{\alpha} \end{cases}$$

$$L'(u,v,s',t') = L\left(u, v, u + \frac{s'-u}{\alpha}, v + \frac{t'-v}{\alpha}\right)$$



Ray space plot

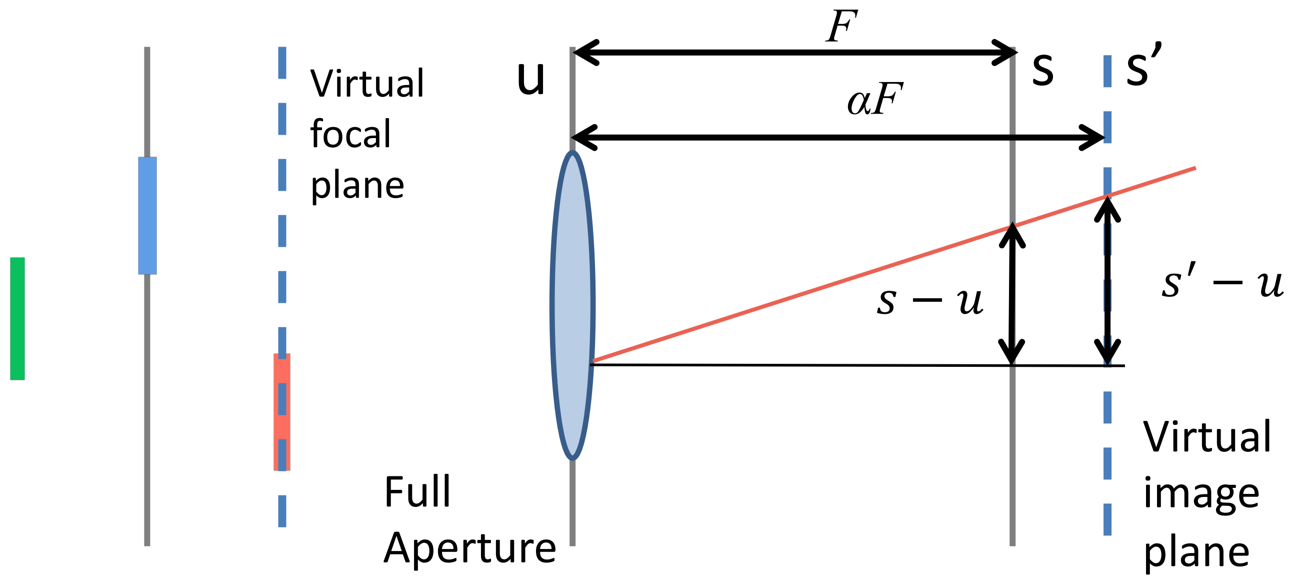


Use Light Field to Get a Synthetic Image

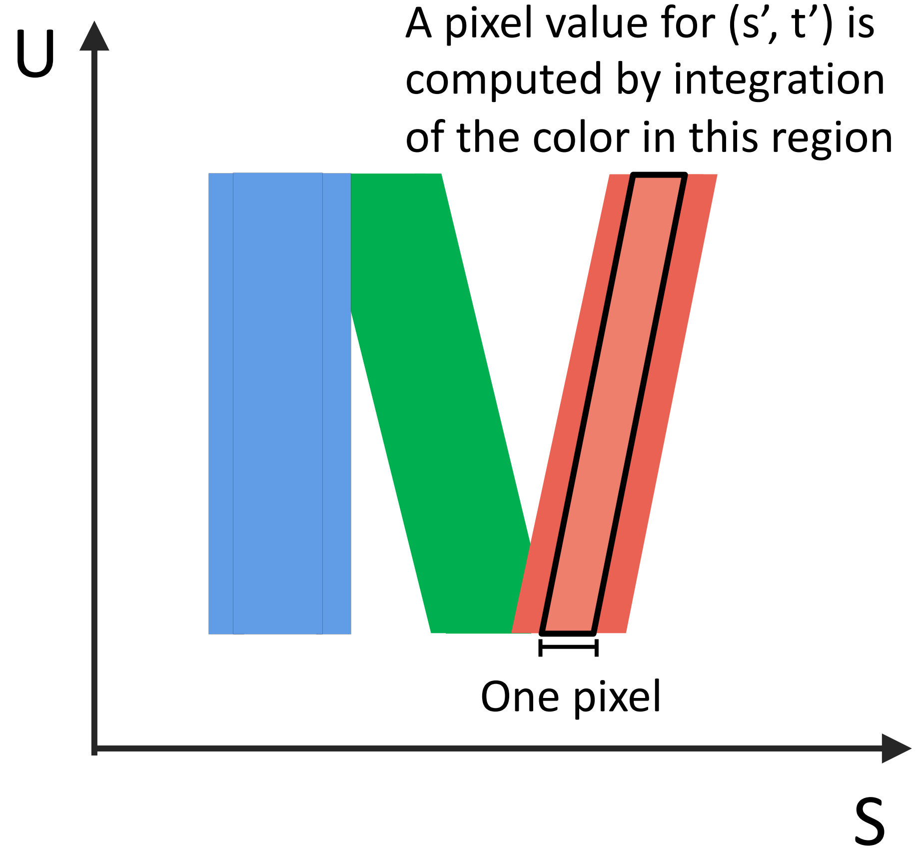
$$E(s',t') = \iint L'(u,v,s',t')\,du\,dv$$

$$= \iint L\left(u, v, u + \frac{s'-u}{\alpha}, v + \frac{t'-v}{\alpha}\right) du\,dv$$

s’ and t’ are constant when integrating



Ray space plot

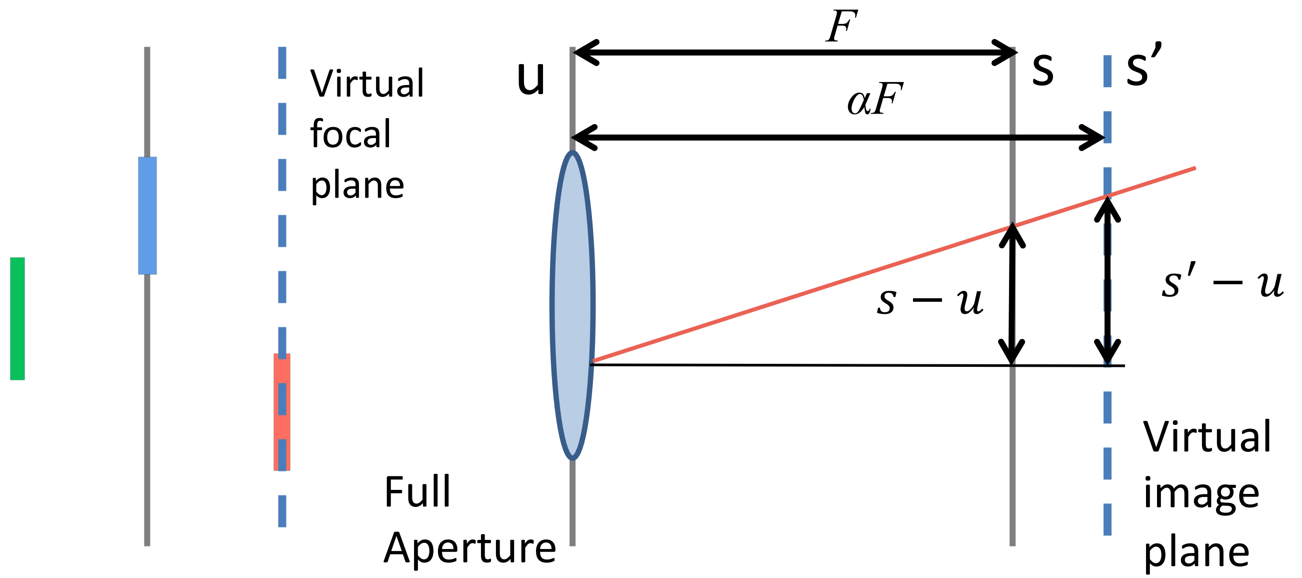


Use Light Field to Get a Synthetic Image

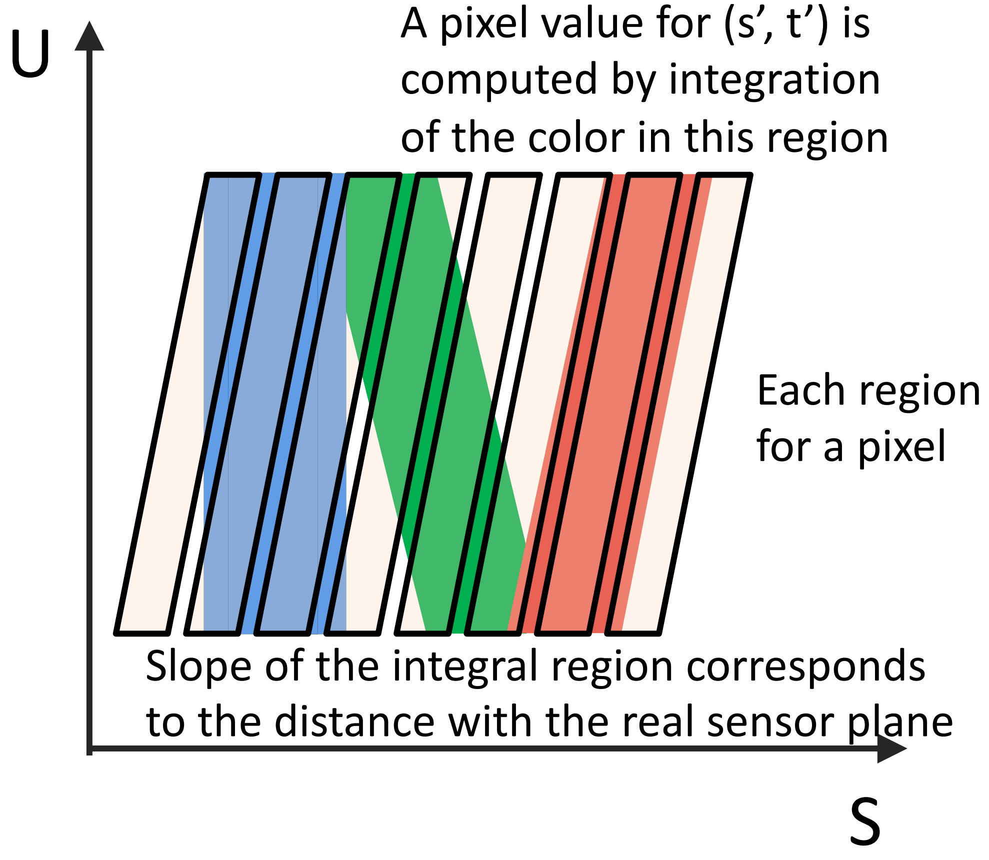
$$E(s',t') = \iint L'(u,v,s',t')\, du\, dv$$

$$= \iint L\left(u, v, u + \frac{s'-u}{\alpha}, v + \frac{t'-v}{\alpha}\right) du\, dv$$

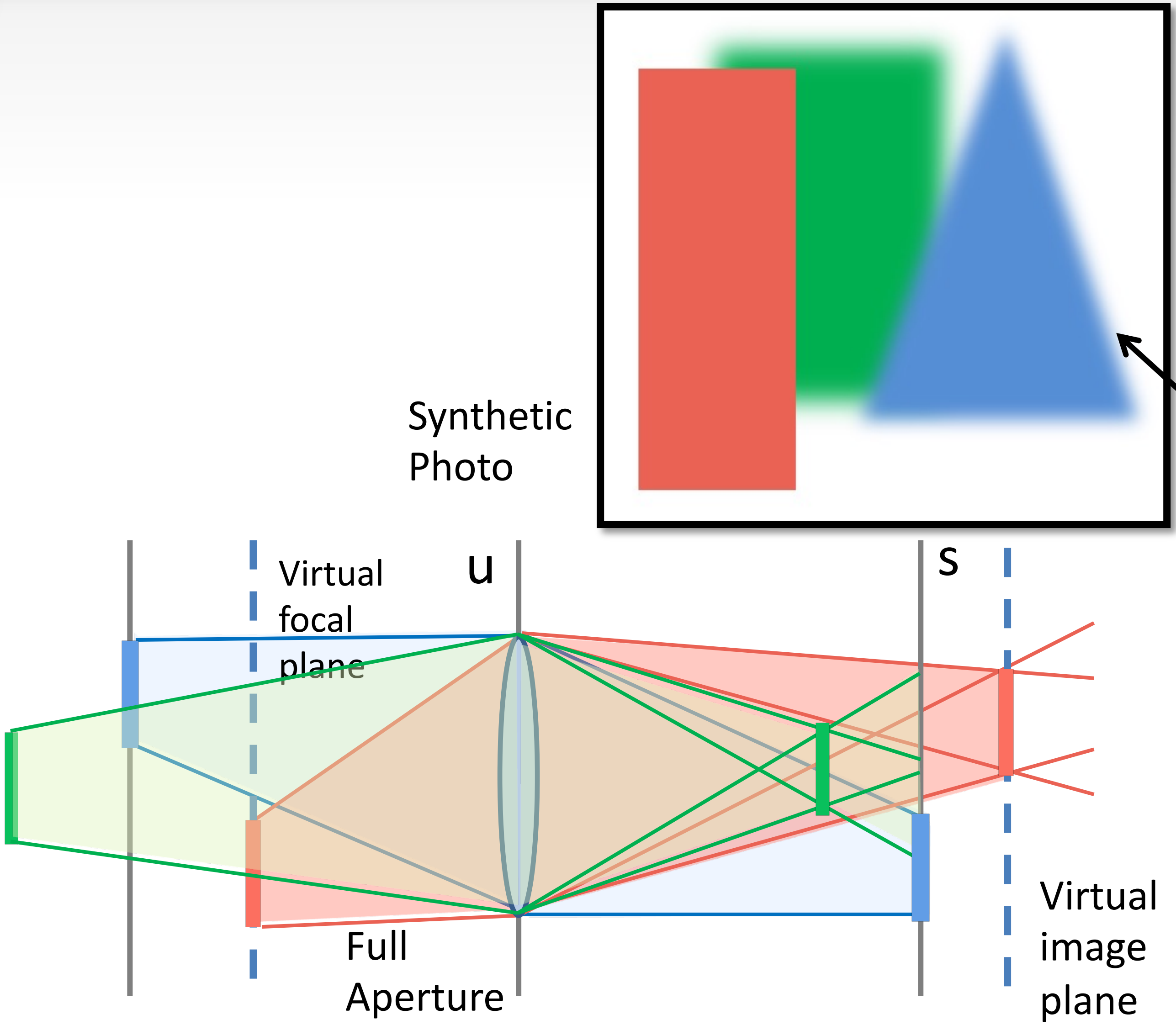
s' and t' are constant when integrating



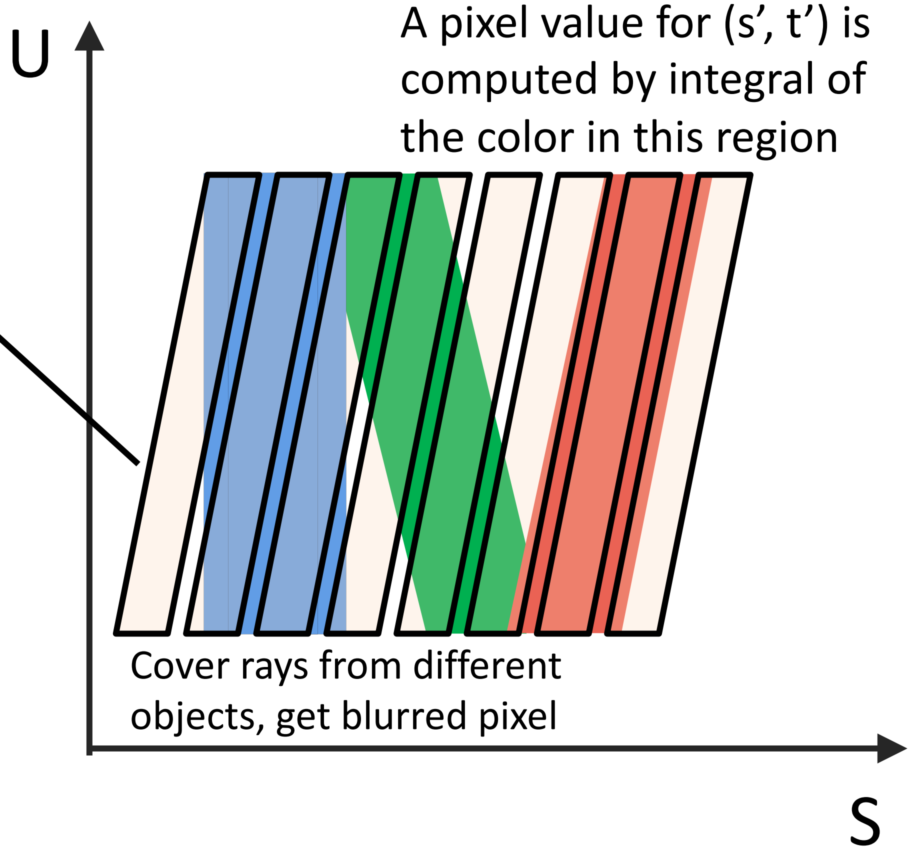
Ray space plot



Use Light Field to Get a Synthetic Image



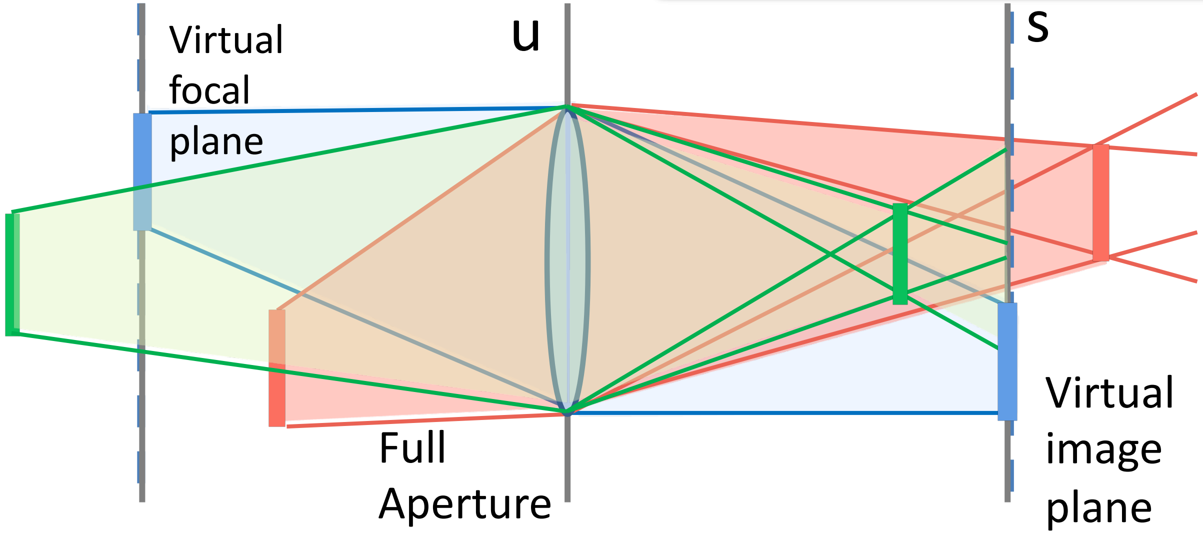
Ray space plot



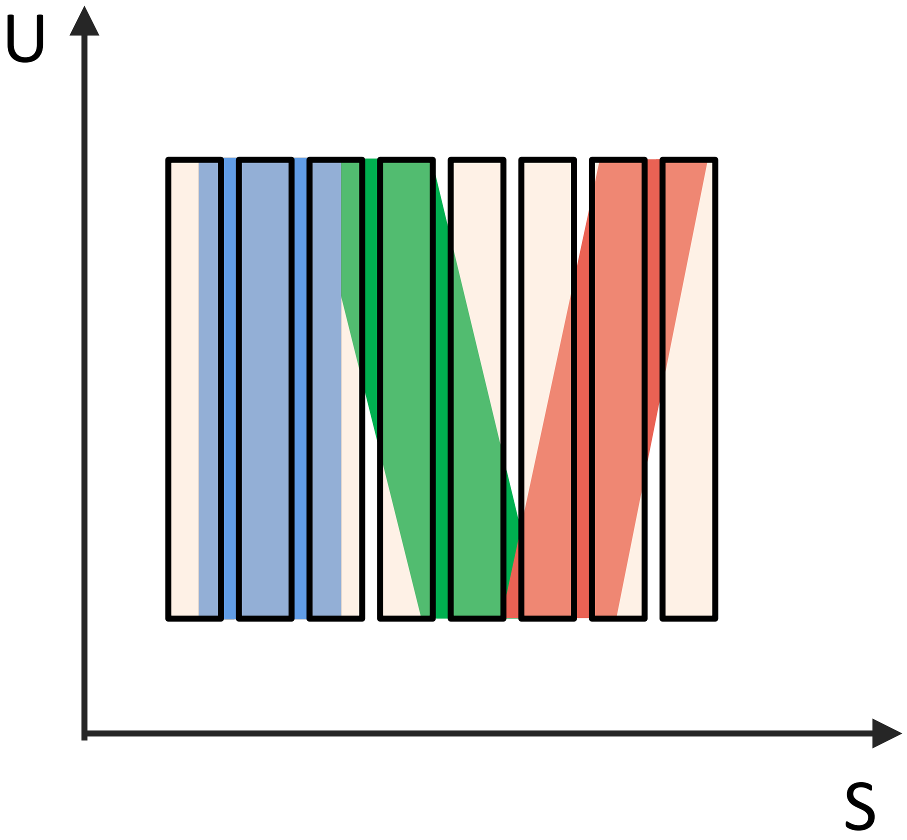
Changing Focal Length

Generated images with different virtual focal length

Synthetic Photo

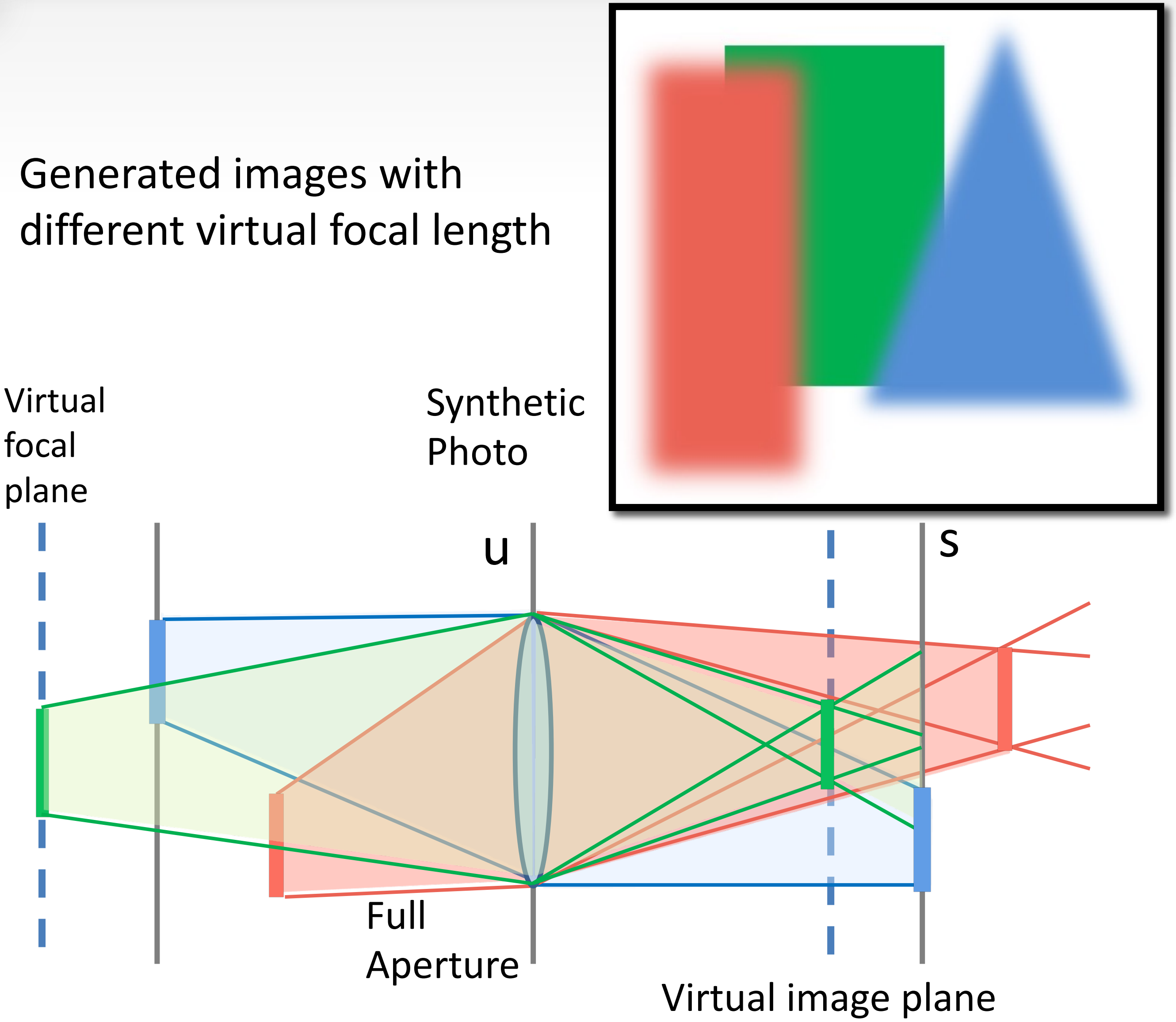


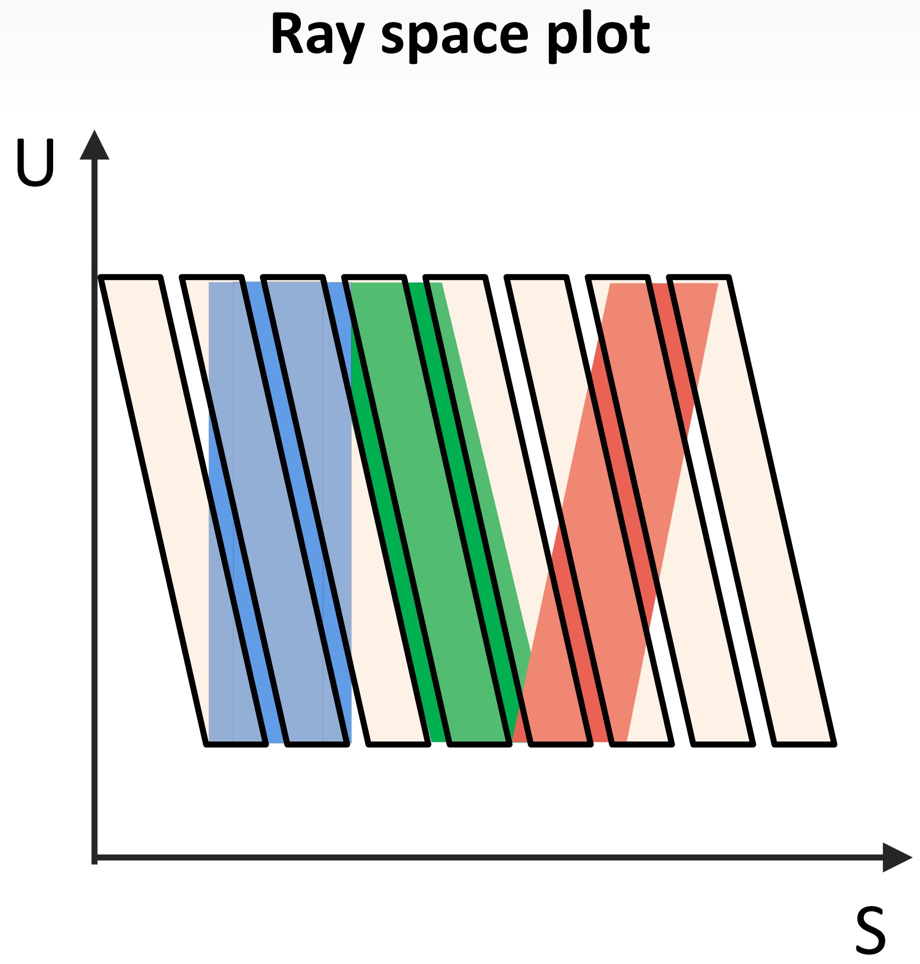
Ray space plot



Changing Focal Length

Generated images with different virtual focal length





An example on real sensor data

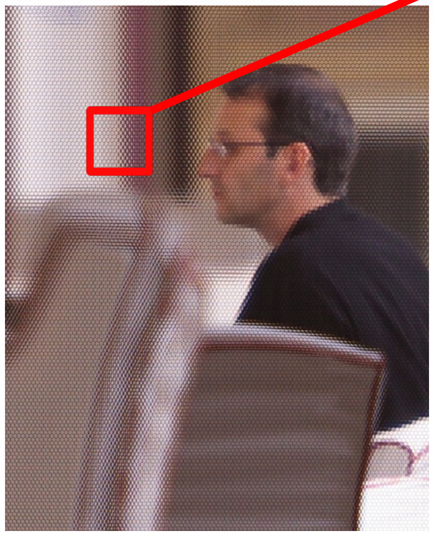
$$E(s',t') = \iint L\left(u, v, u + \frac{\alpha s' - u}{\alpha}, v + \frac{\alpha t' - v}{\alpha}\right) du\, dv$$

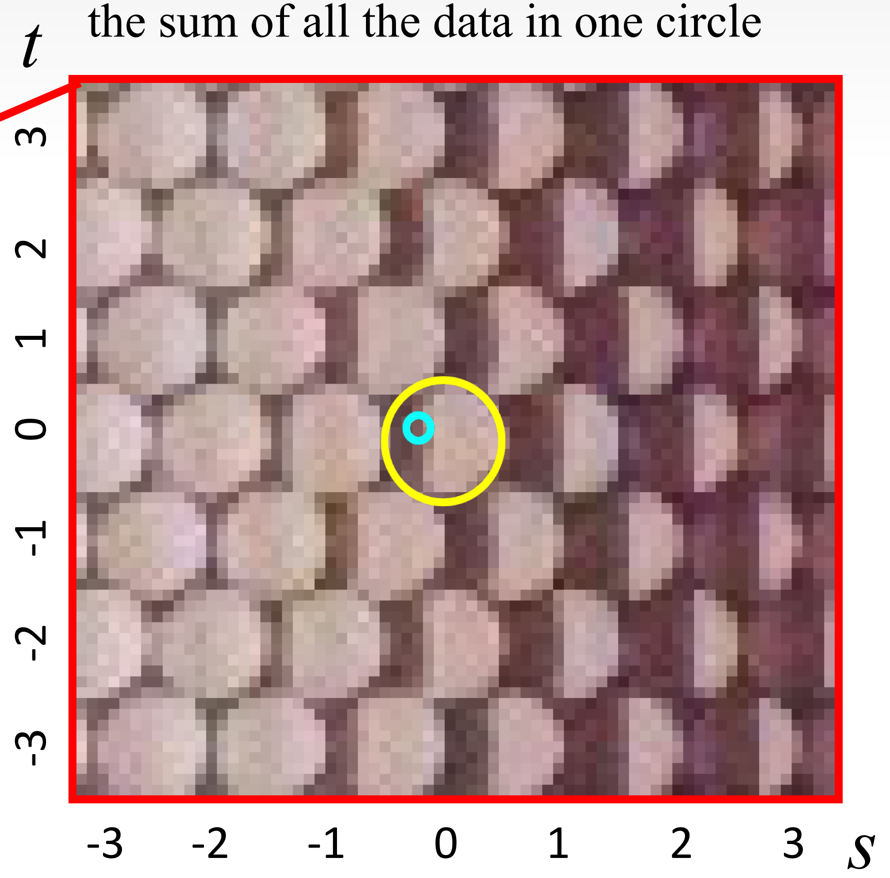
When α=*1*, the focal plane doesn't change, then

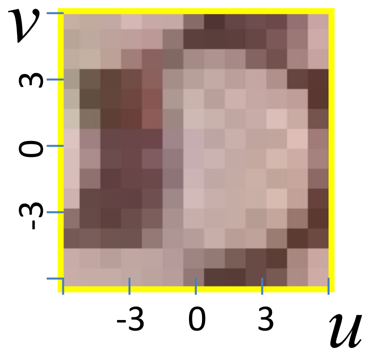
$$E(s',t') = \iint L(u, v, s', t') du\, dv$$

E.g.:
To get the value for s' = 0 and t' = 0,
for all different u, v, use the value in the (0,0) element in s-t plane

When α =*1*, the pixel value equal to the sum of all the data in one circle







In real sensor, we have **discrete** (s, t) elements.
Their coordinates are the **centers of the circles**.

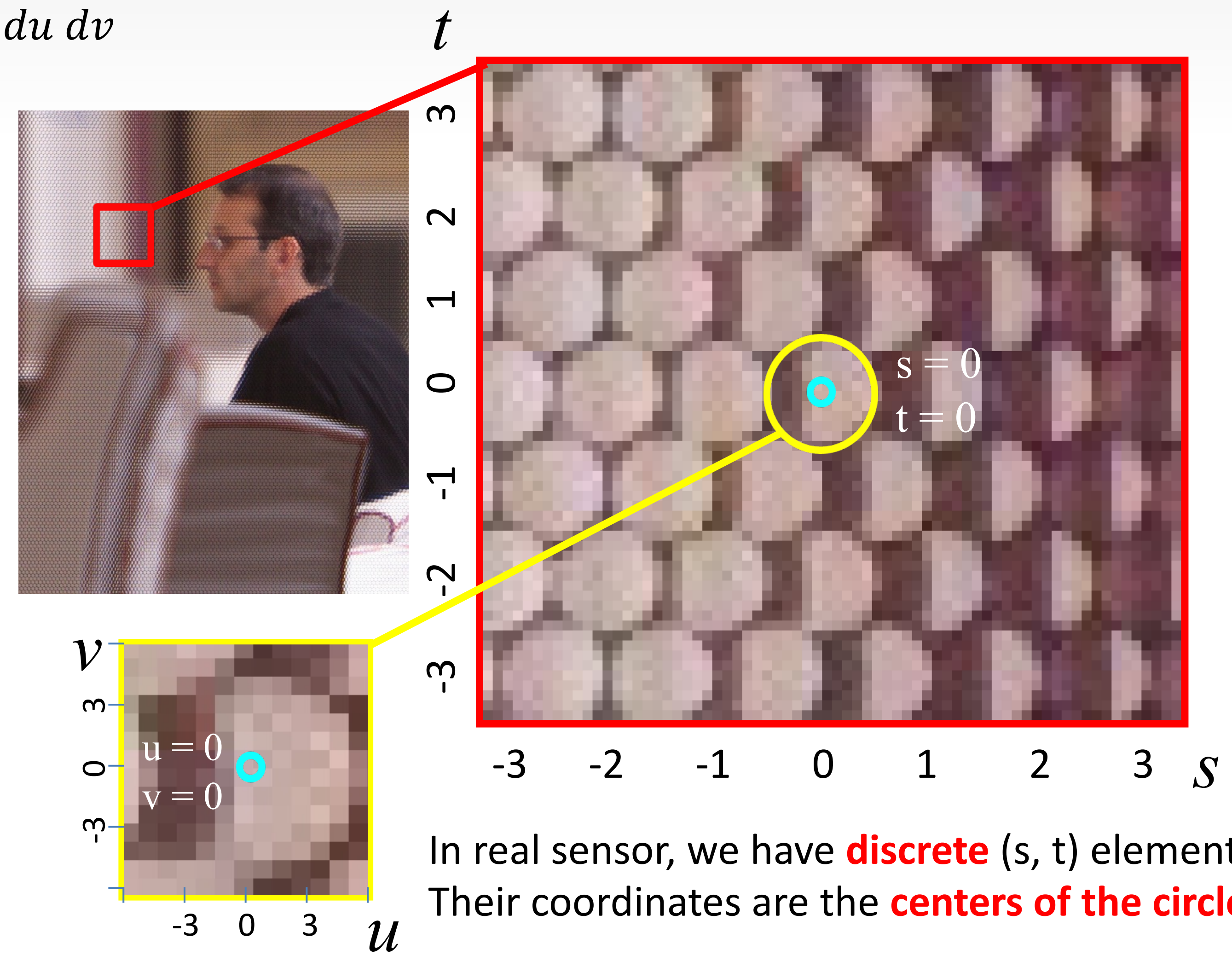
An example on real sensor data

$$E(s',t') = \iint L\left(u, v, u + \frac{\alpha s' - u}{\alpha}, v + \frac{\alpha t' - v}{\alpha}\right) du\, dv$$

If $\alpha = 2$, when performing integration on $s'=0$, $t'=0$

$$E(0,0) = \iint L\left(u, v, \frac{1}{2}u, \frac{1}{2}v\right) du\, dv$$

When $u = 0$, $v = 0$, use the value of $L(0,0,0,0)$



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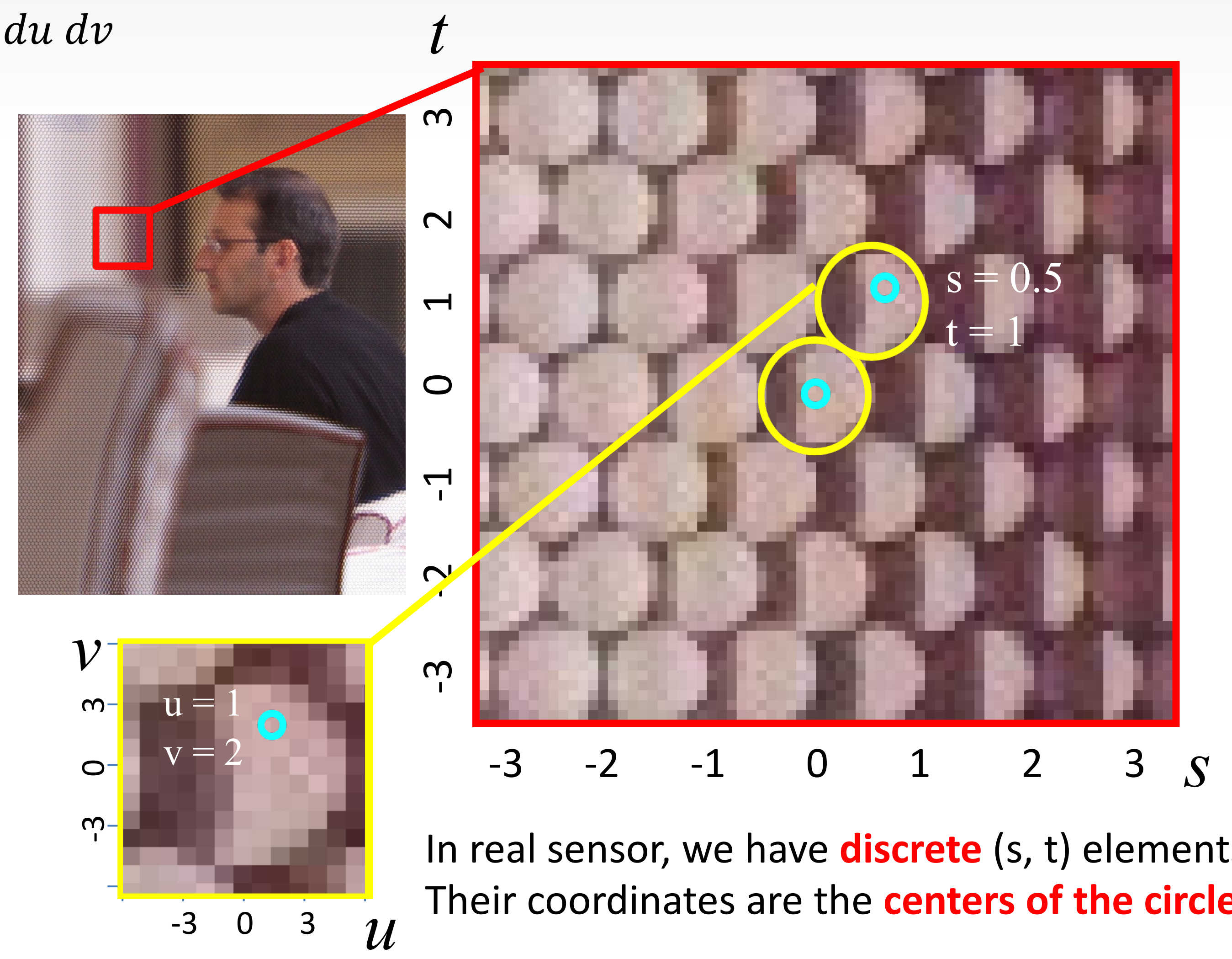
When $u = 0$, $v = 0$, use the value of $L(0, 0, 0, 0)$

When $u = 1$, $v = 2$, use the value of $L(1, 2, 0.5, 1)$



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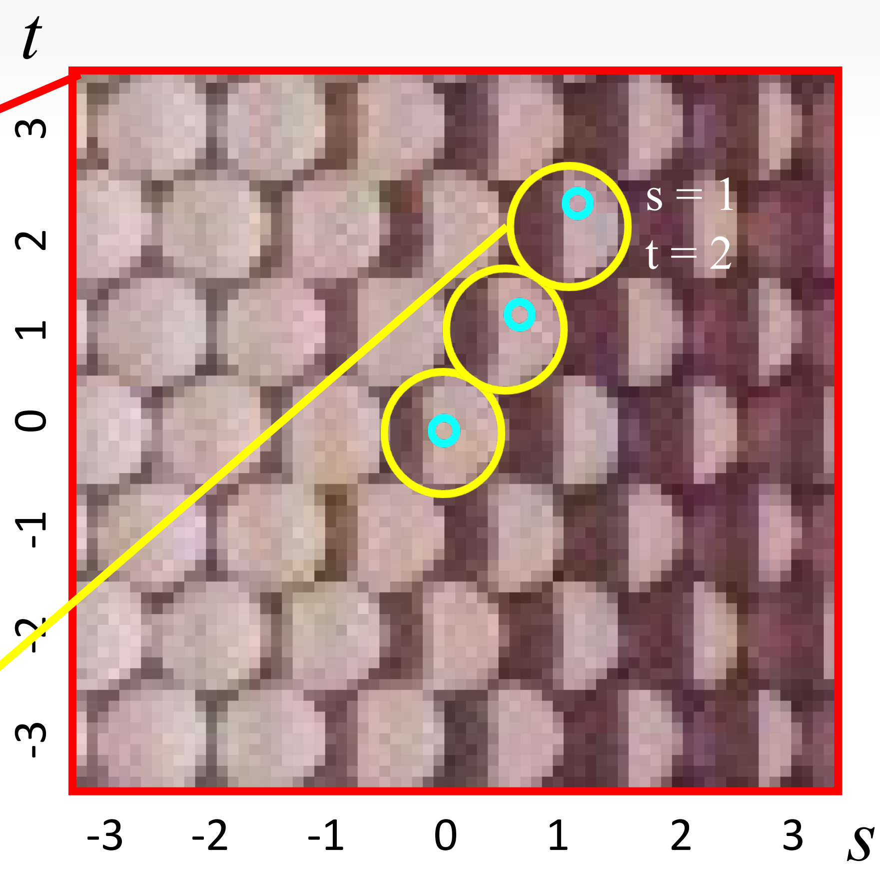
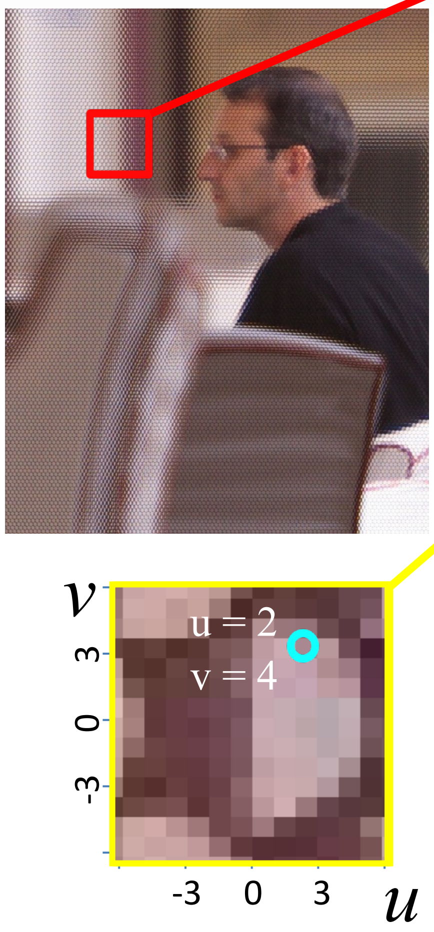
When $u = 1,\ v = 2,$ use the value of $L(1, 2, 0.5, 1)$

When $u = 2,\ v = 4,$ use the value of $L(2, 4, 1, 2)$





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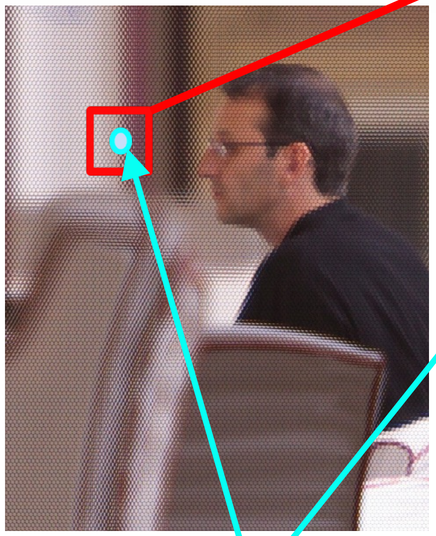
When $u = 0$, $v = 0$, use the value of $L(0,0,0,0)$

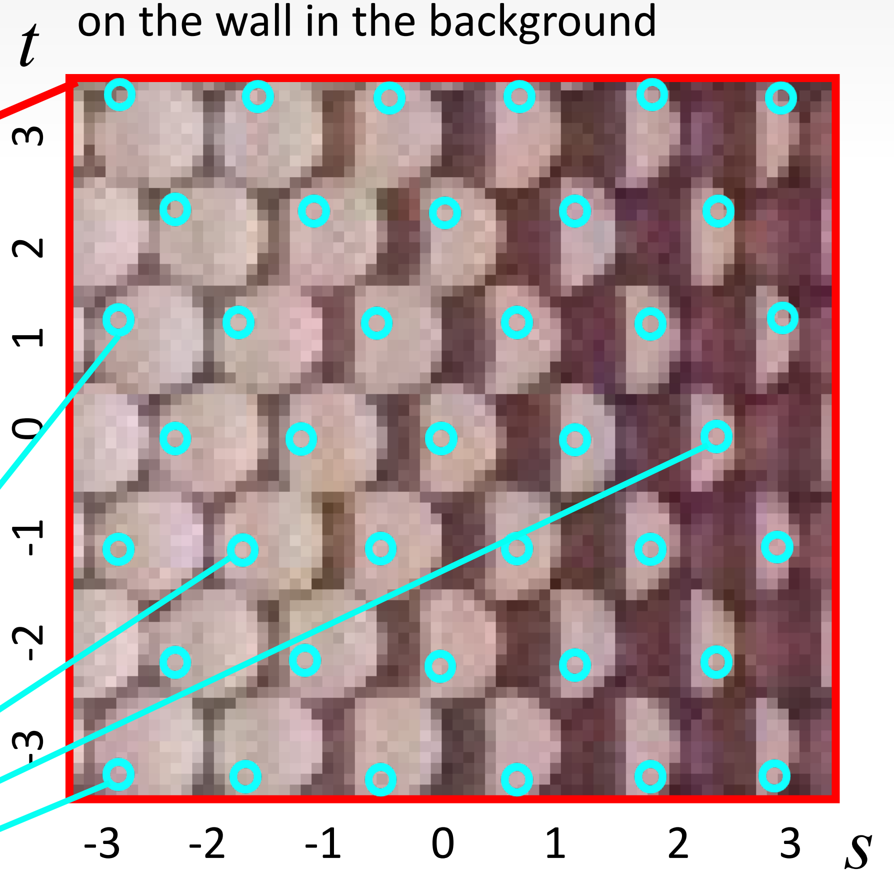
When $u = 1$, $v = 2$, use the value of $L(1,2,0.5,1)$

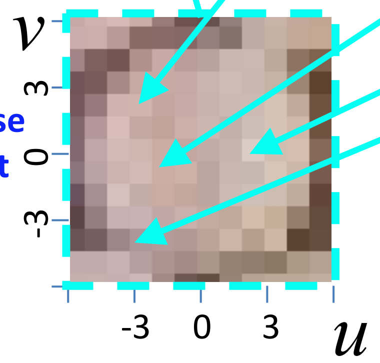
When $u = 2$, $v = 4$, use the value of $L(2,4,1,2)$

For all the u and v, find the corresponding element in s-t plane, and get its value for the position $(u,\ v)$.

This is a sharp pixel for this point on the wall in the background

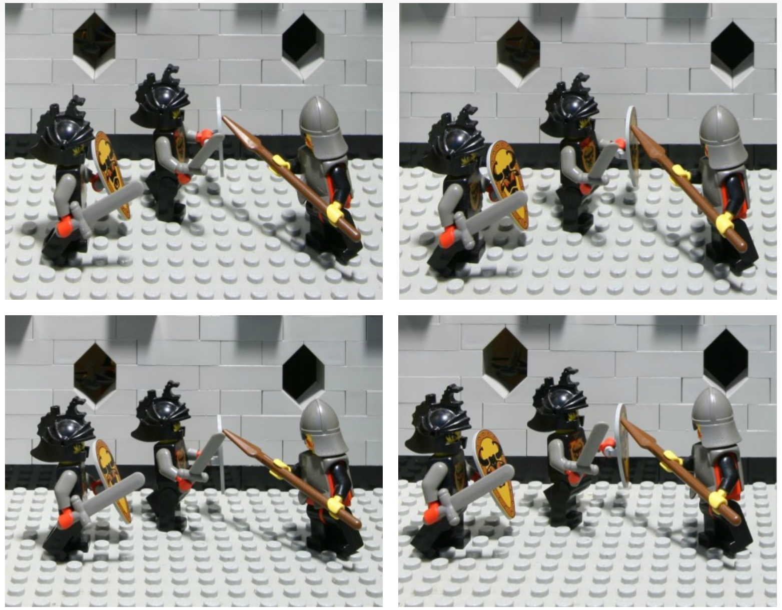


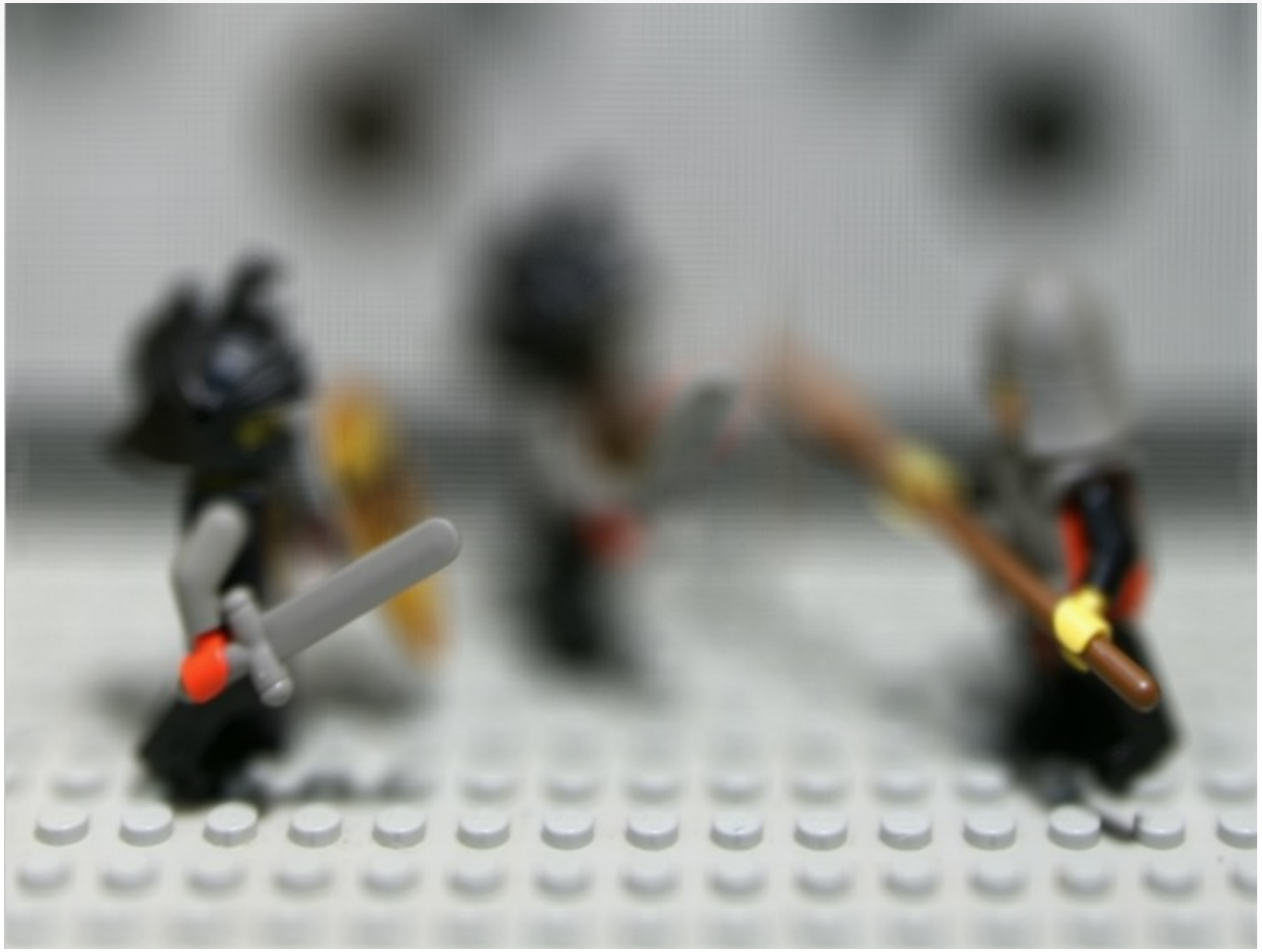




In real sensor, we have **discrete** (s, t) elements. Their coordinates are the **centers of the circles**.

Refocusing Results

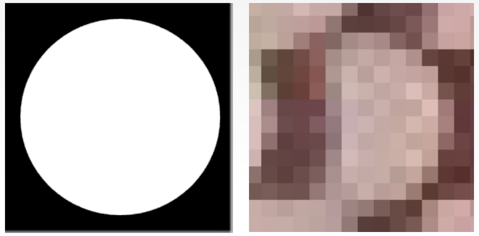




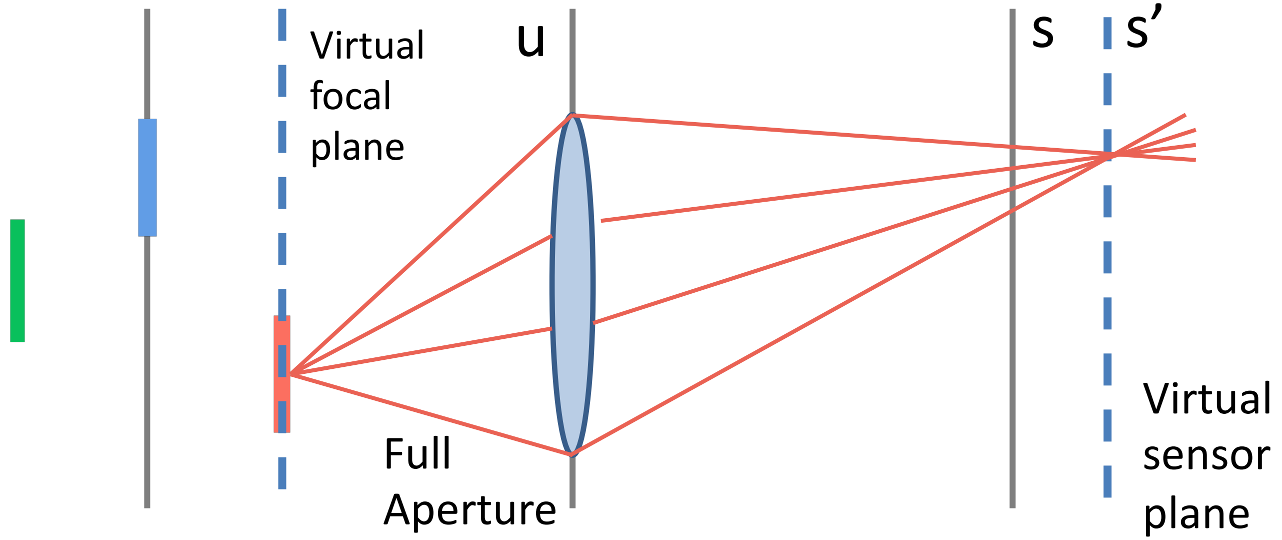
Lego Knights from Stanford Light Field Archieve
289 views on a 17x17 grid
image resolution 1024x1024

Virtual Aperture

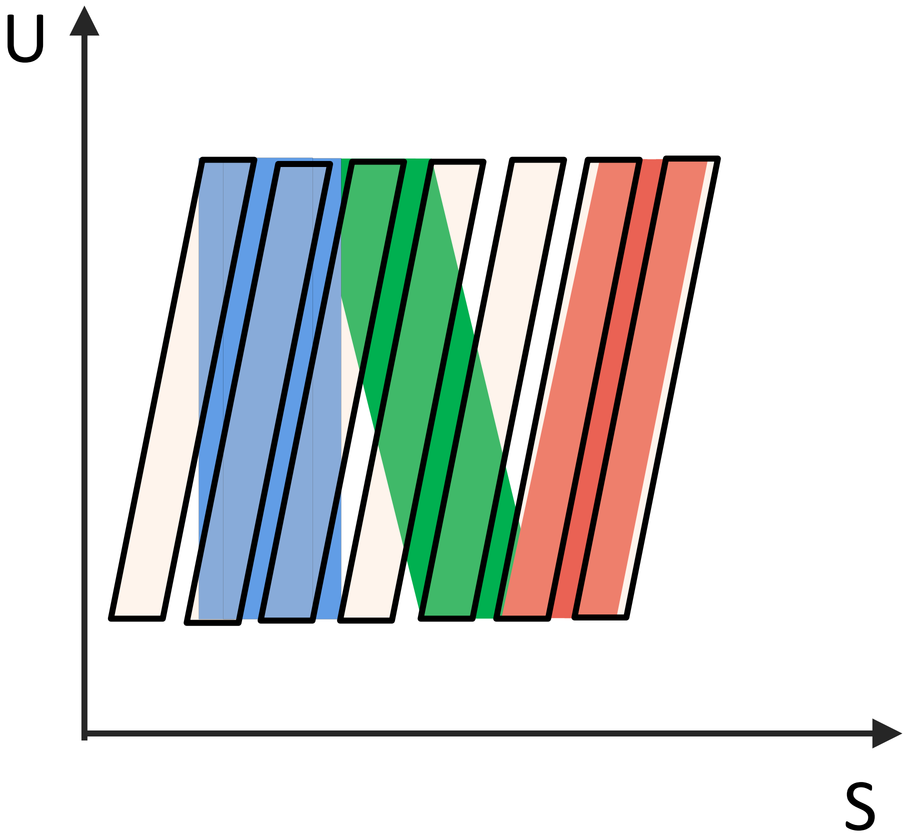
Virtual aperture is a mask when picking (u,v) values in each sub-lens picture



$$E(s',t') = \iint L\left(u, v, u + \frac{\alpha s' - u}{\alpha}, v + \frac{\alpha t' - v}{\alpha}\right) A'(u,v)\,du\,dv$$



Ray space plot



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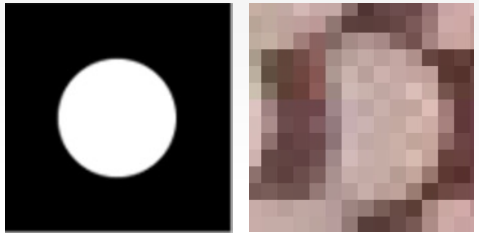
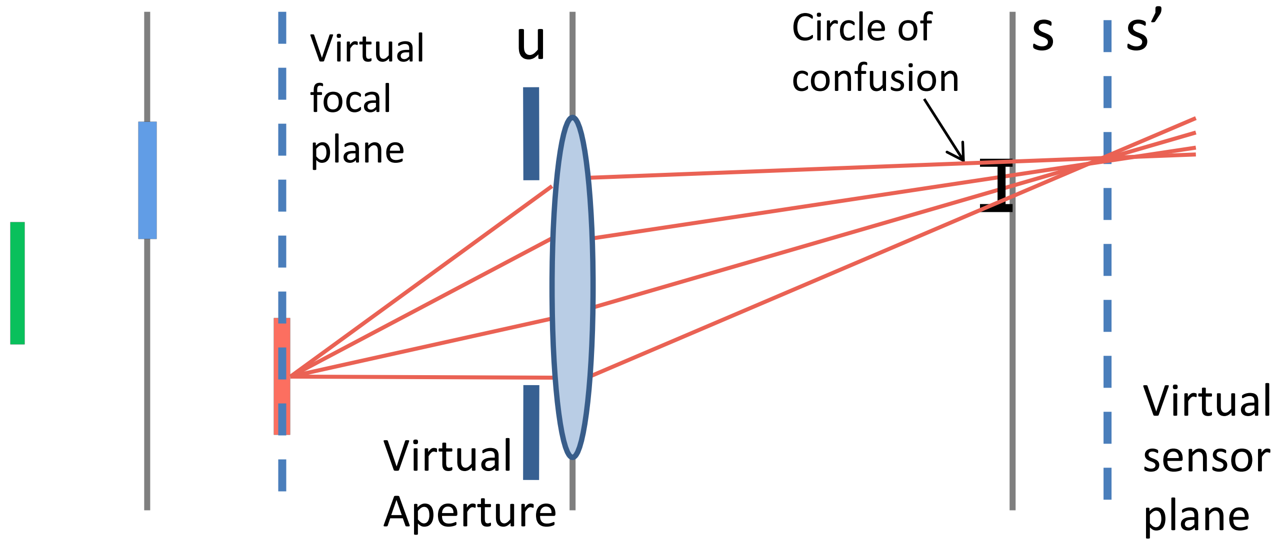
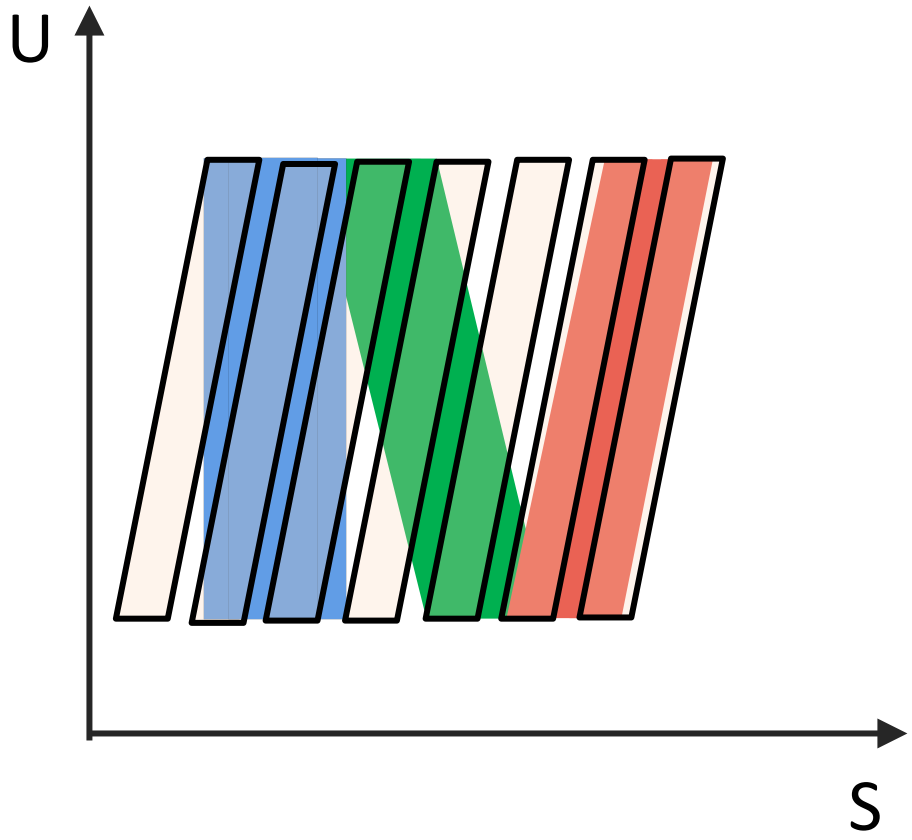


$$E(s',t') = \iint L\left(u, v, u + \frac{\alpha s' - u}{\alpha}, v + \frac{\alpha t' - v}{\alpha}\right) A'(u,v)du\, dv$$



Ray space plot



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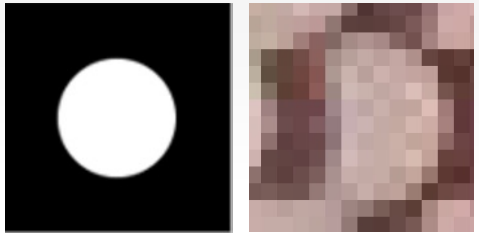

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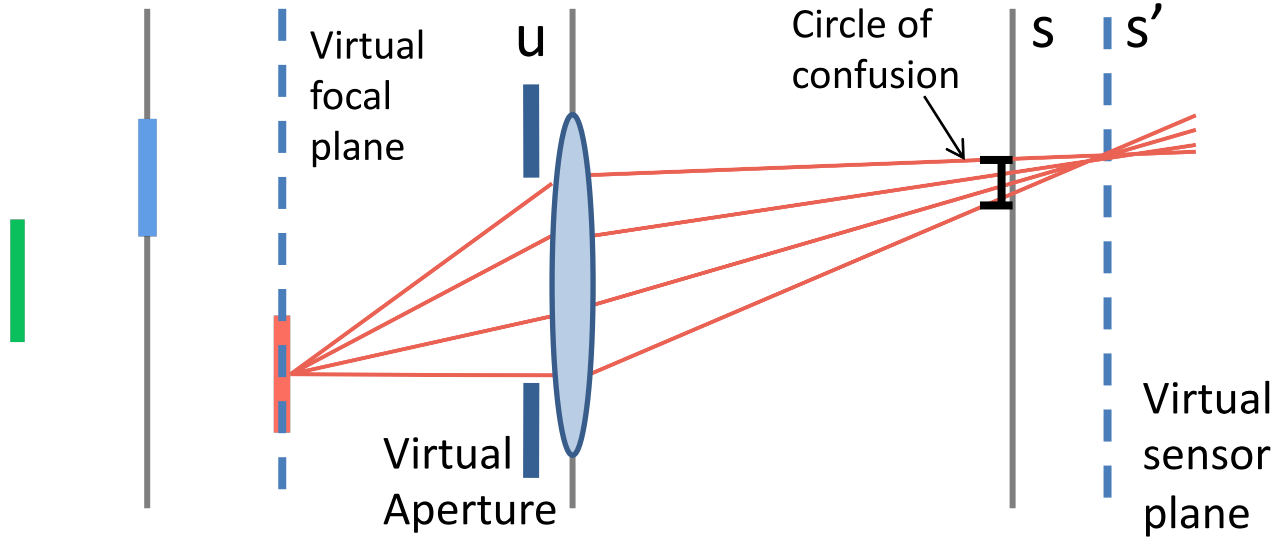
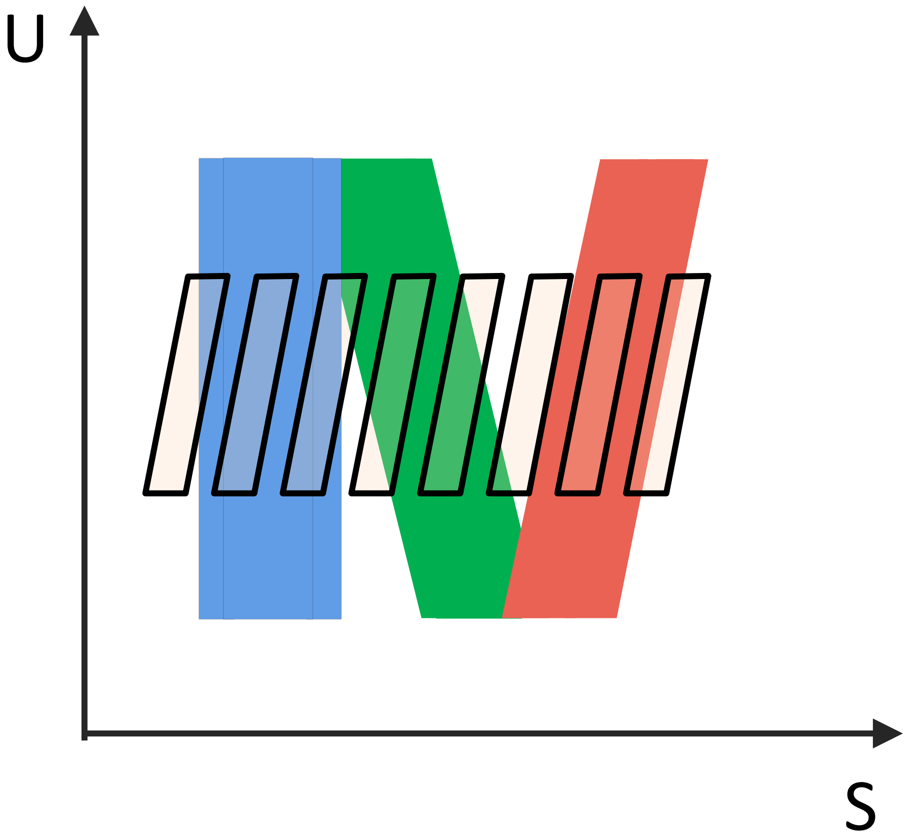


Ray space plot



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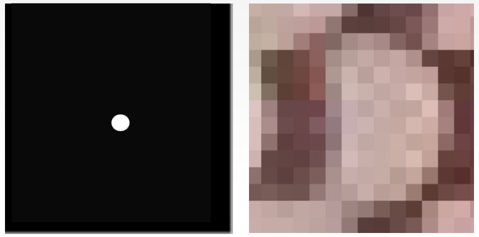

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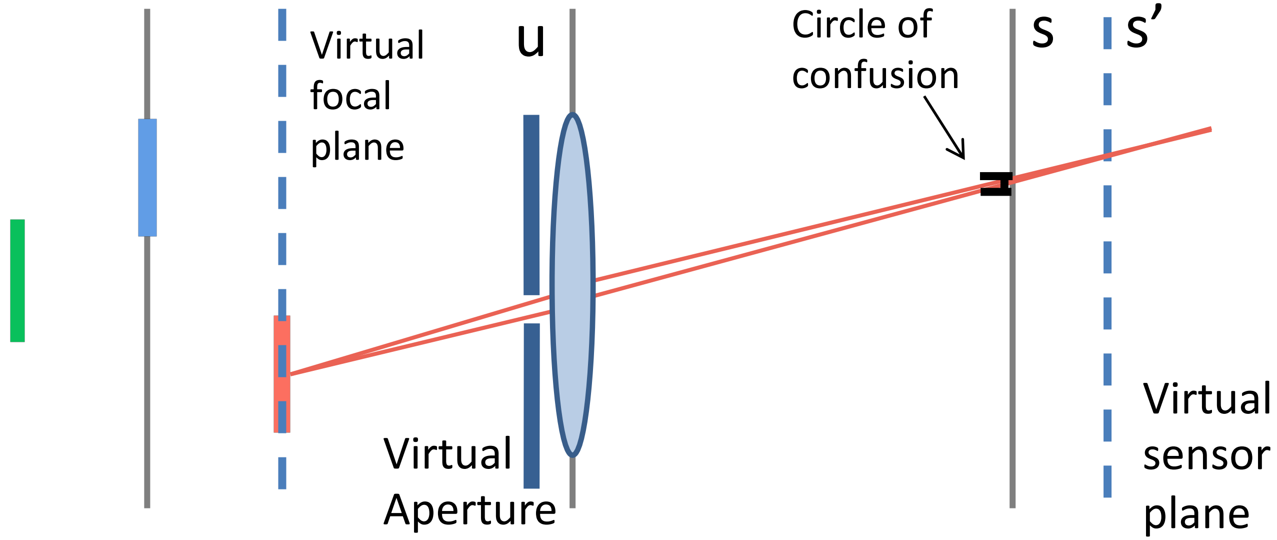
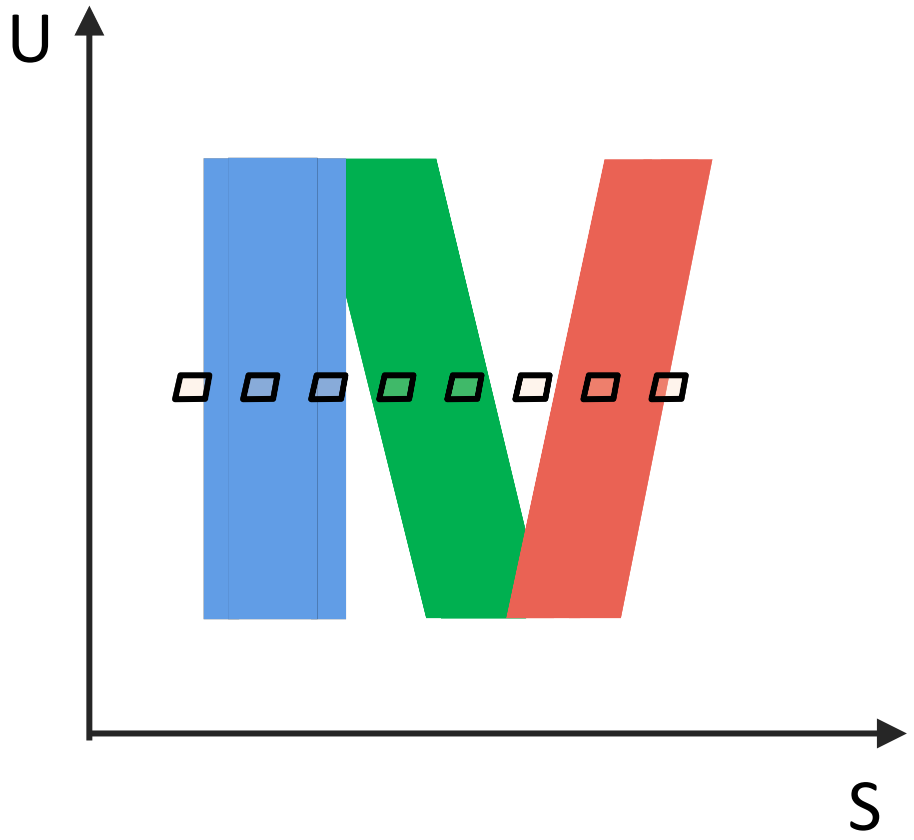
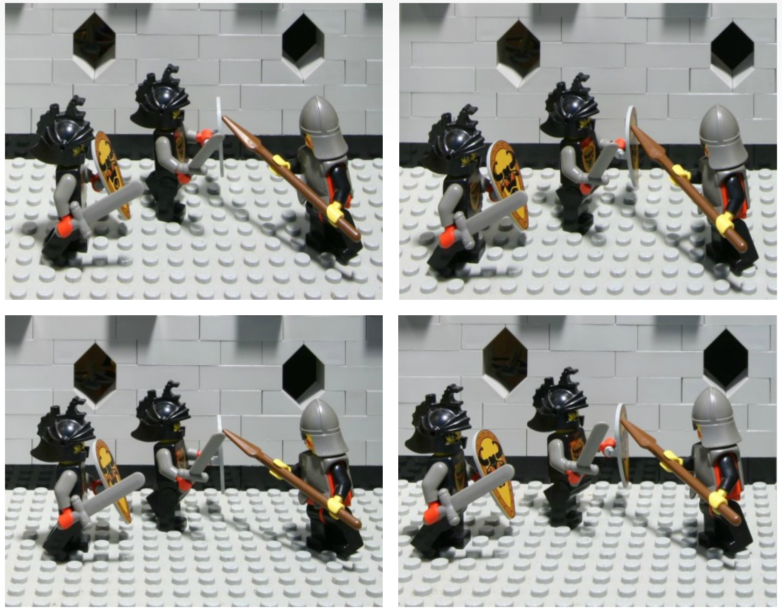


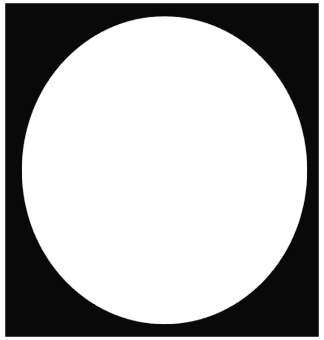
Ray space plot



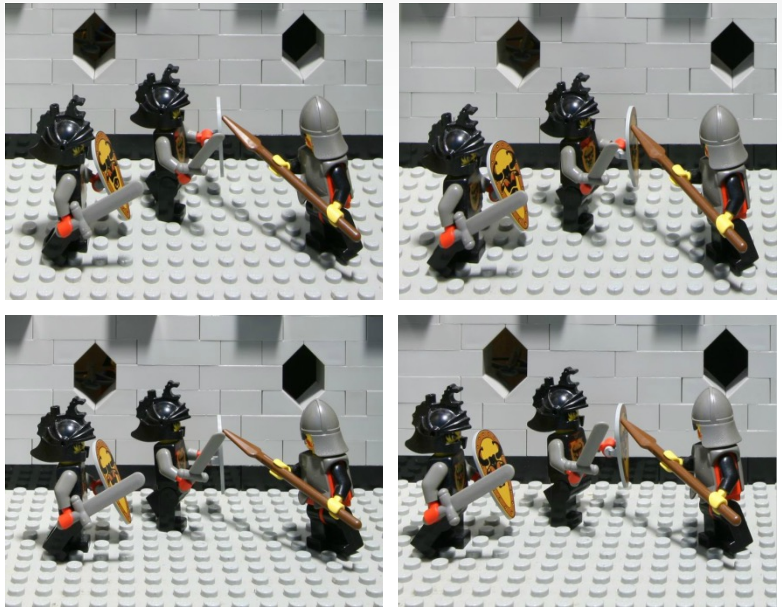
Synthetic Aperture



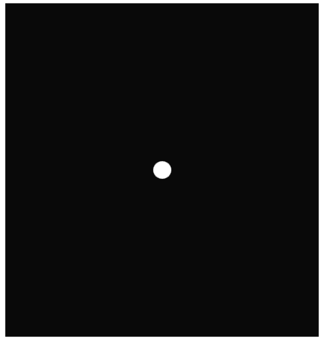
Virtual Aperture



Synthetic Aperture



Virtual Aperture



Advantages of the Light Field Camera

Single shot to generate many different photographs

- Digital (post shot) refocusing
- Parallax (computational change of viewpoint)
- Extended depth of field (put entire image in focus)
- Stereo images

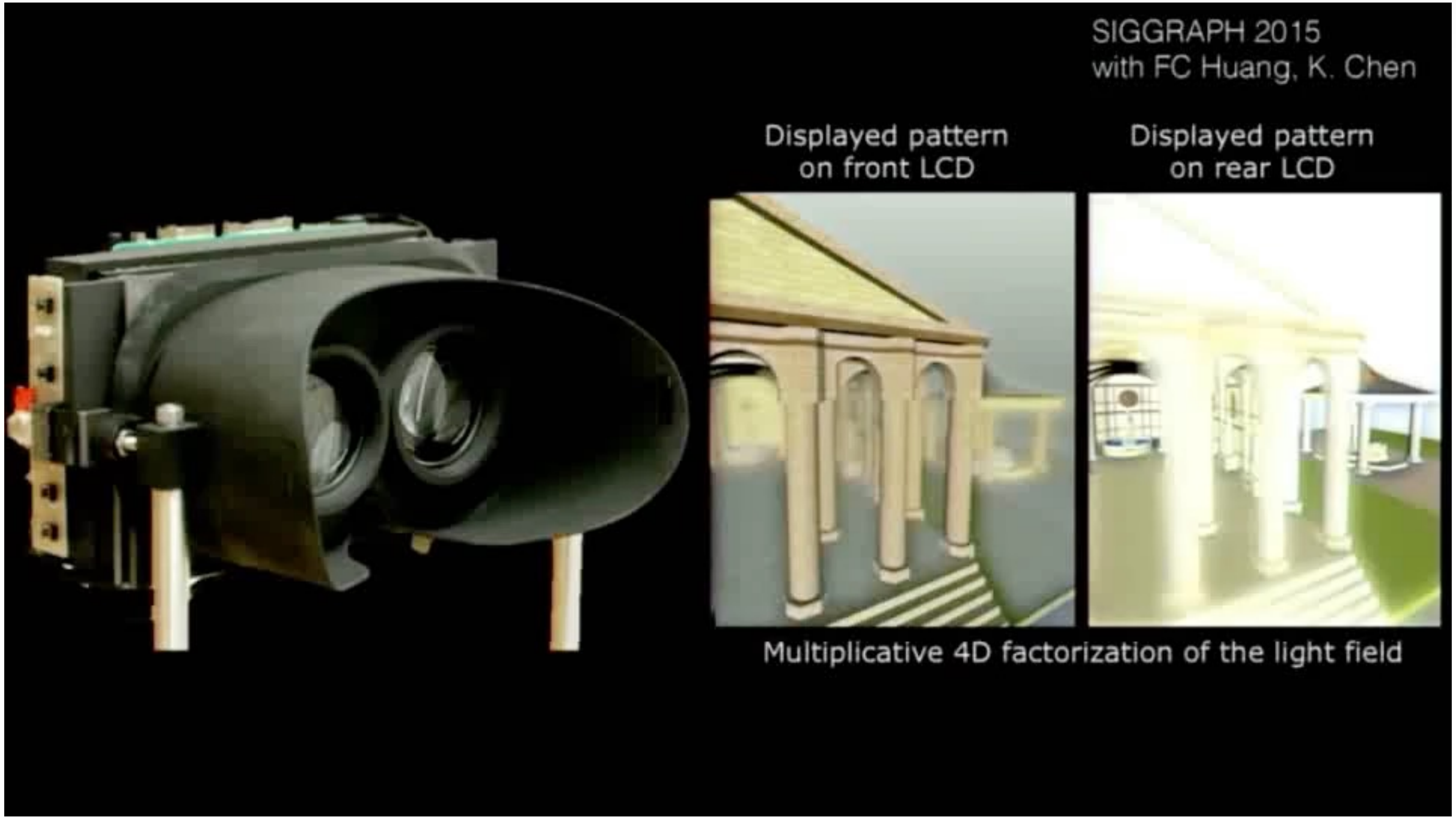
Better camera performance:

- Reduced shutter lag: in the limit, no need for autofocus
- Potential for better low-light performance
- misfocus due to shallow depth-of-field can be corrected after the shot
- Correction of lens aberrations

Applications of Light Fields

- **Example 1: Better Near-Eye Display:**

The Light Field Stereoscope, SIGGRAPH 2015



Applications of Light Fields

- Example 2: Image-based Rendering

Unstructured Light Fields, EG2012