



# Plenoptic Camera 2.0

*“Lightfield photographers,  
focus your cameras!”*

Todor Georgiev  
Adobe Systems

Andrew Lumsdaine  
Indiana University

# Summary

Plenoptic cameras produce final rendered image with very low resolution, **one pixel per microlens**. Is it possible to improve this resolution and finally make lightfield photography practical?

The main idea behind this work is that the reason for the low resolution is that Plenoptic cameras are **not properly focused** on the object we are imaging. With appropriately focused plenoptic camera and a new rendering algorithm we can produce a final image utilizing **multiple pixels per microlens**, thus significantly increasing resolution.

Plenoptic cameras have 2 lens systems: the main lens and the microlens array. While the main lens is focused as in a conventional camera, the microlenses are focused at infinity rather than on the object we are imaging. The consequent assumption is that each microlens image is completely defocused and **only** a single pixel in the final image can be rendered from it.

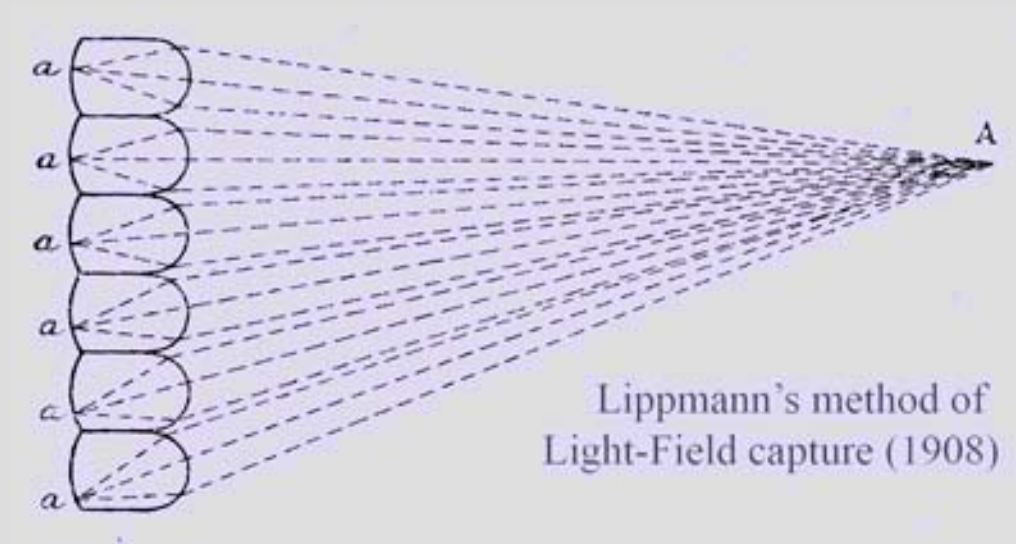
In this work we show that if we instead focus the microlenses on the image plane of the main lens, we can achieve an **extraordinary increase in resolution** of the final rendered image. This can be done with two different approaches, one using the Galilean telescope, the other one using the Keplerian telescope imaging model. The plenoptic camera itself becomes an array of telescopes with a common objective lens.

# Two types of telescopes



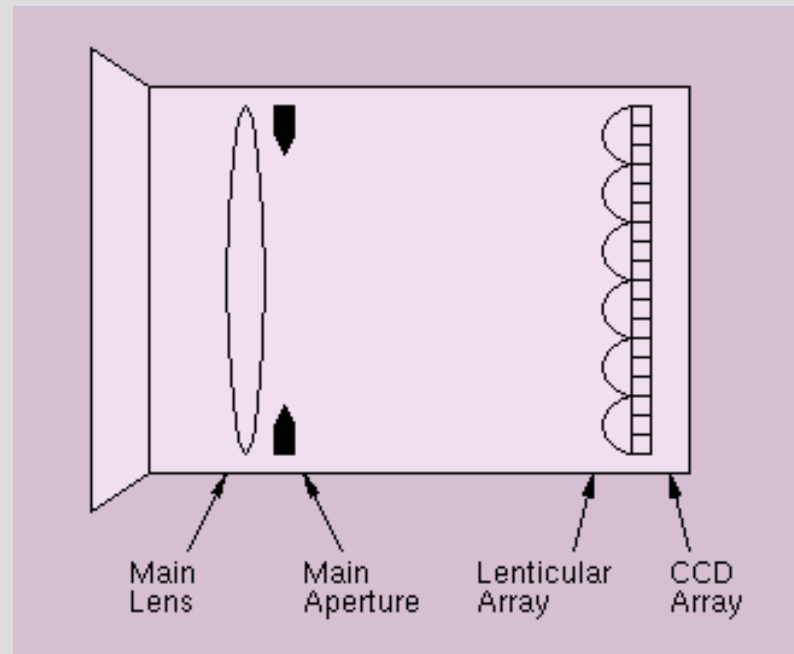
- Galileo's first telescope, 1609
- Kepler's new design, 1611

# Integral Photography 1908



# Adelson 1992, Plenoptic Camera

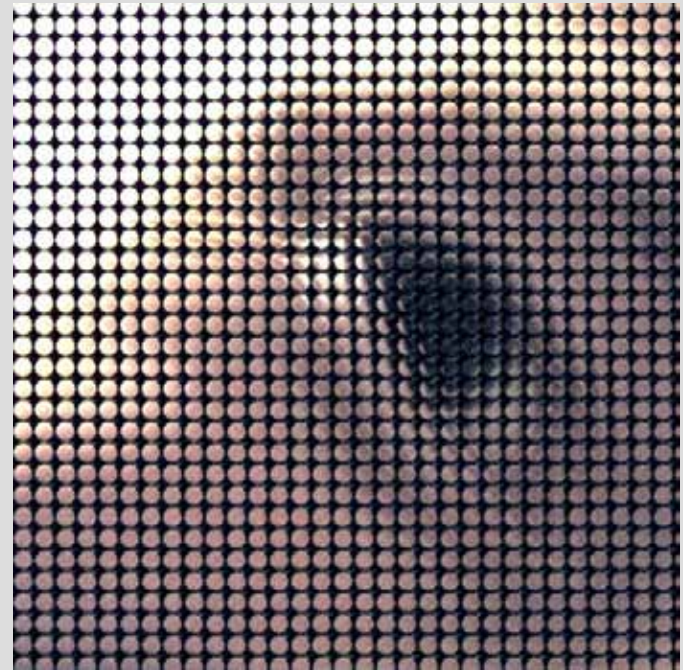
Designed with the idea to solve **Computer Vision** problems  
Previous versions from H. Ives and others



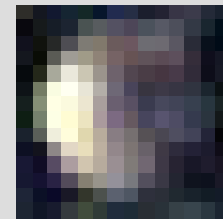
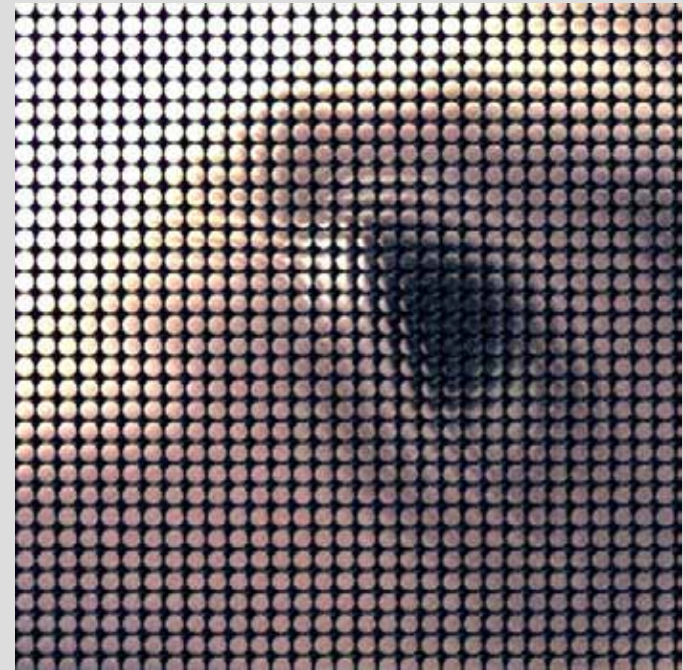
# Ren Ng: Photography with plenoptic camera (Tech Report 2005)



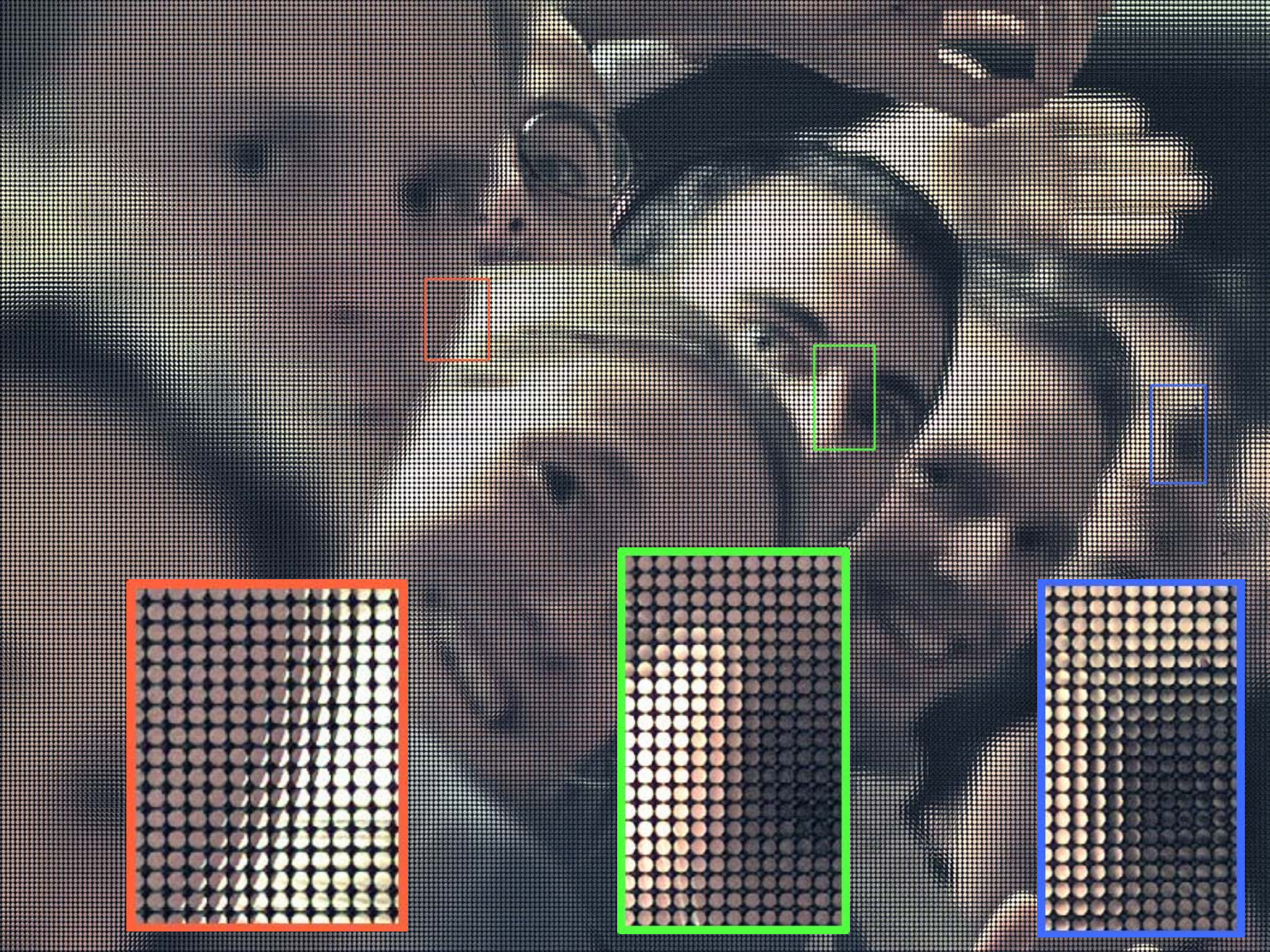
# Ren Ng: Photography with plenoptic camera (Tech Report 2005)



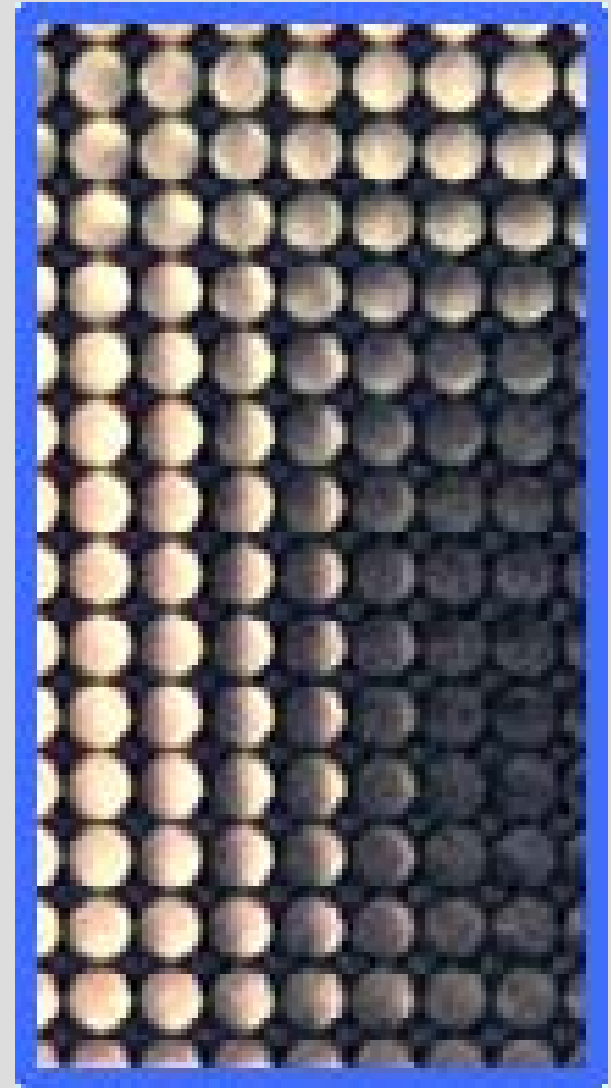
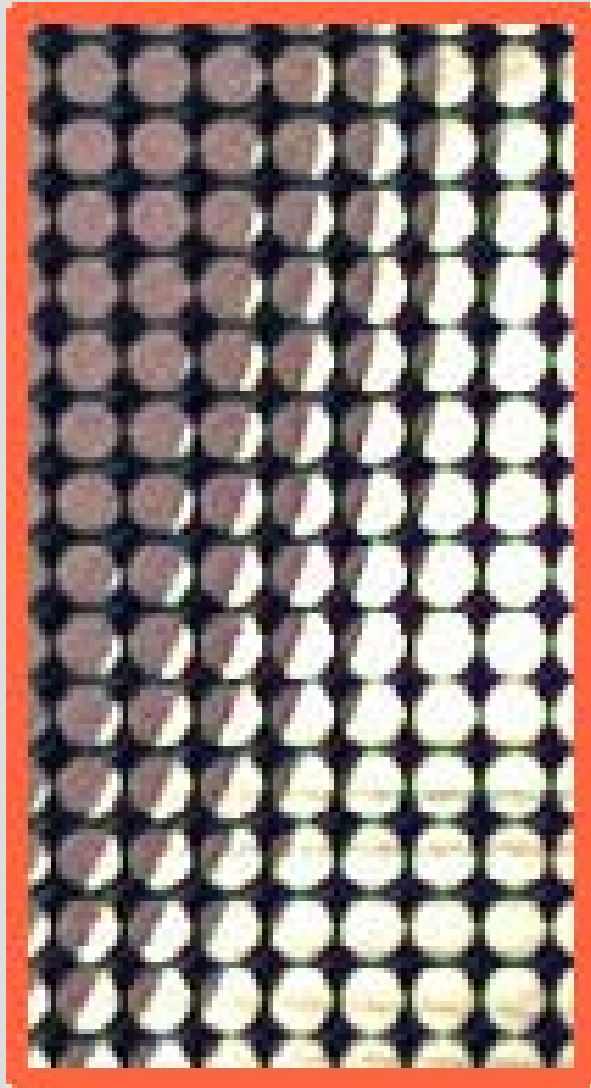
# Ren Ng: Photography with plenoptic camera (Tech Report 2005)



# **Our classification of lightfield data**



# Three types of behavior of radiance images:

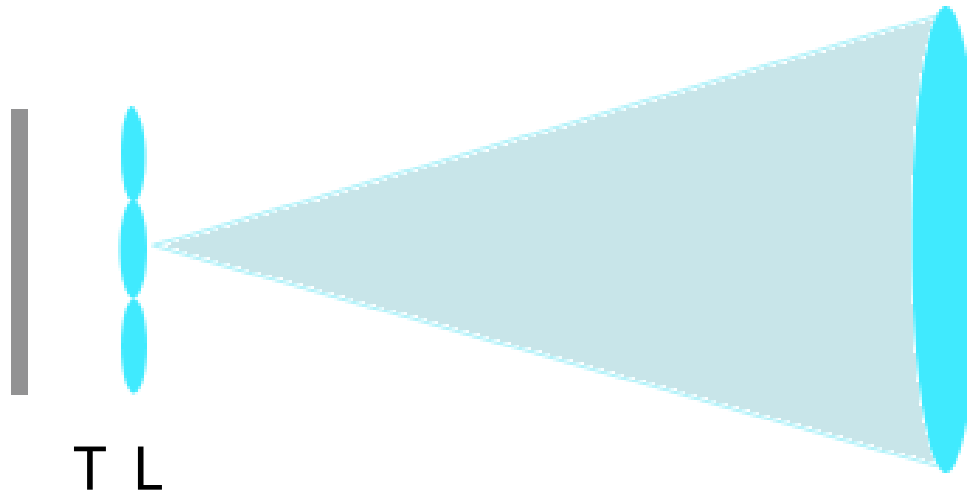


# Ng's photography with plenoptic camera: ***Resolution is low!***



# Integral View Photography (Georgiev&Intwala, 2006)

Ren's design: Main lens focused ***on the micro lenses***

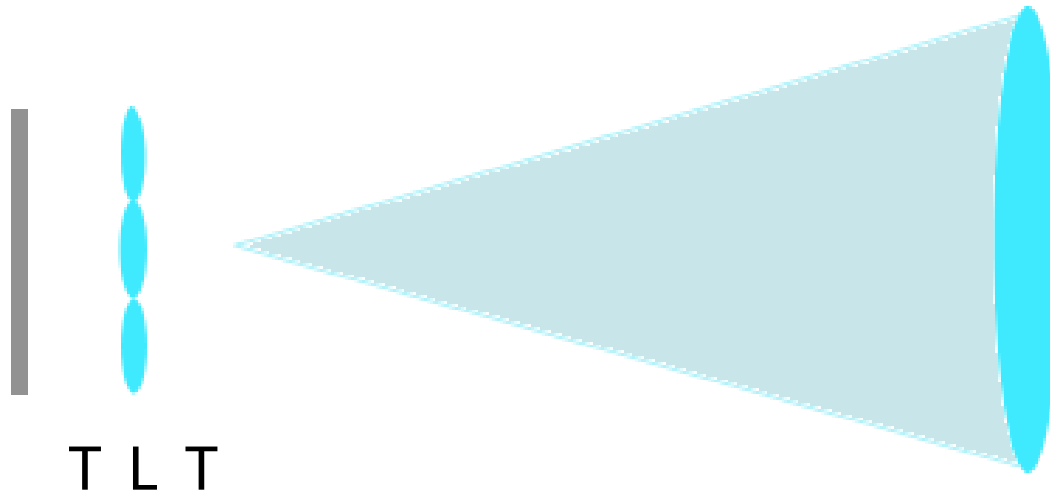


T L

= Translation ° Lens

# Integral View Photography (Georgiev&Intwala, 2006)

Ren's design: Main lens focused ***on the micro lenses***  
***Is that the only way to do it?***



= Translation ◦ Lens ◦ Translation

Our suggestion: ***Shift image by one focal length*** (See next)

# Integral View Photography (Georgiev&Intwala, 2006)

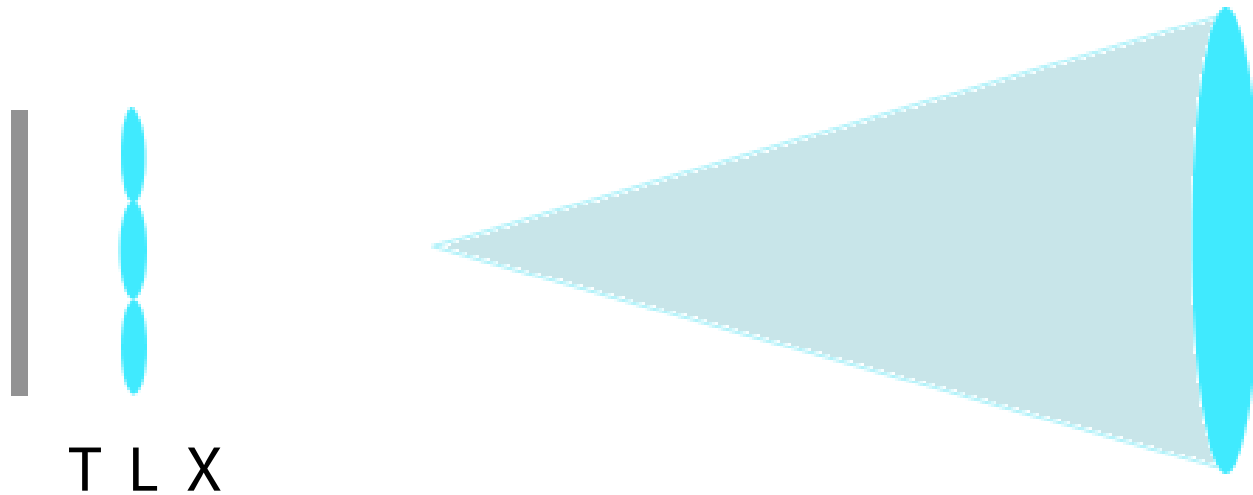
Main lens -- focused **in front of** the microlenses, not **on** the microlenses:

The plenoptic camera is based on multiple use of an optical device that consists of a microlens of focal length  $f$  and a distance  $f$  behind it. This device is described by the transfer matrix  $M$ . We redefine it as **translation-microlens-translation**.

$$M = TL = \begin{bmatrix} 1 & f \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} = \begin{bmatrix} 0 & f \\ -\frac{1}{f} & 1 \end{bmatrix}$$

$$M = TLT = \begin{bmatrix} 1 & f \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & f \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & f \\ -\frac{1}{f} & 0 \end{bmatrix}$$

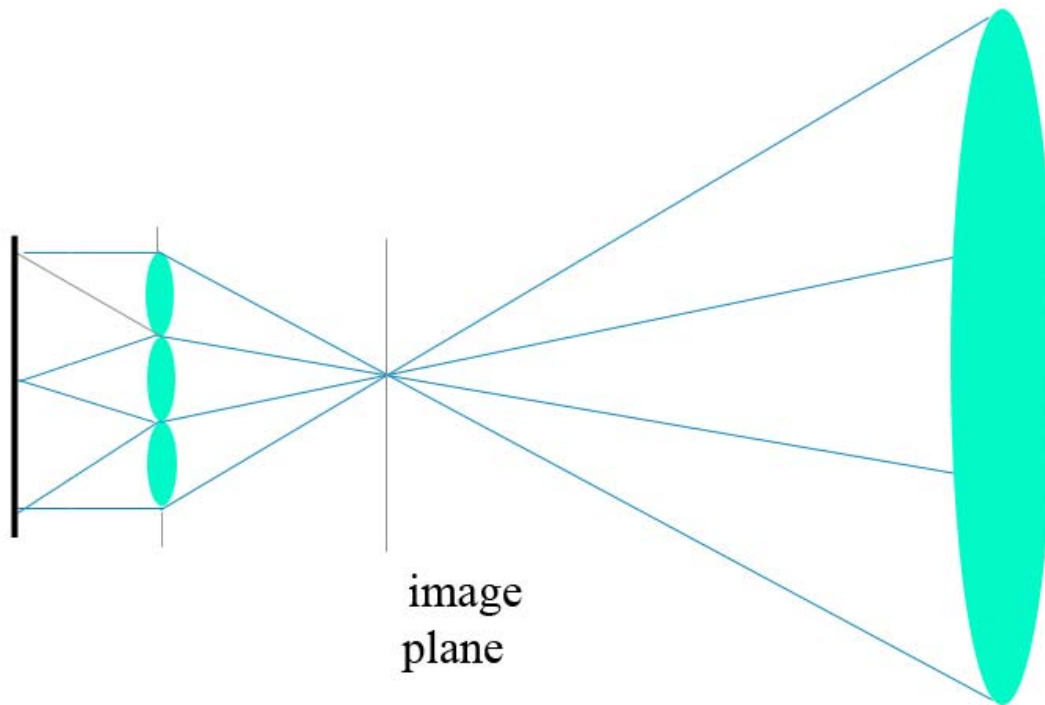
This formula shows the image plane does not have to be **on** the microlenses. It can be shifted **any distance  $X$**  from the microlenses, and they will still capture the angular component of the radiance because the top left matrix element is 0.



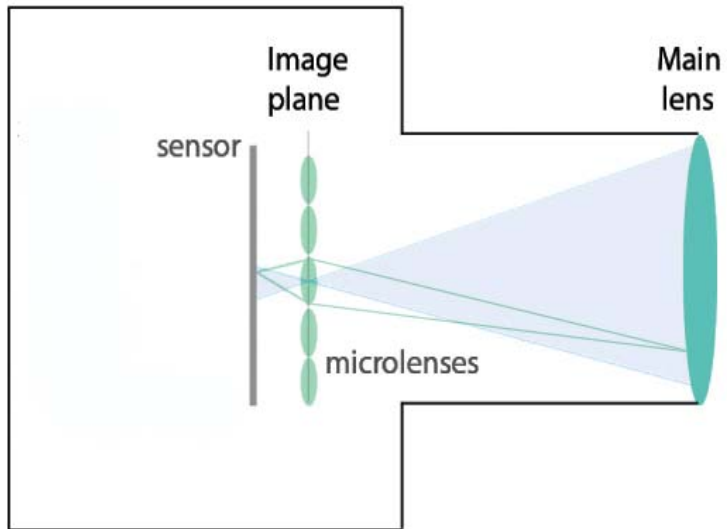
# Lumsdaine&Georgiev, 2008

What is the condition for **exact focusing** with a shifted image?  
Answer: *Simple relay imaging!*

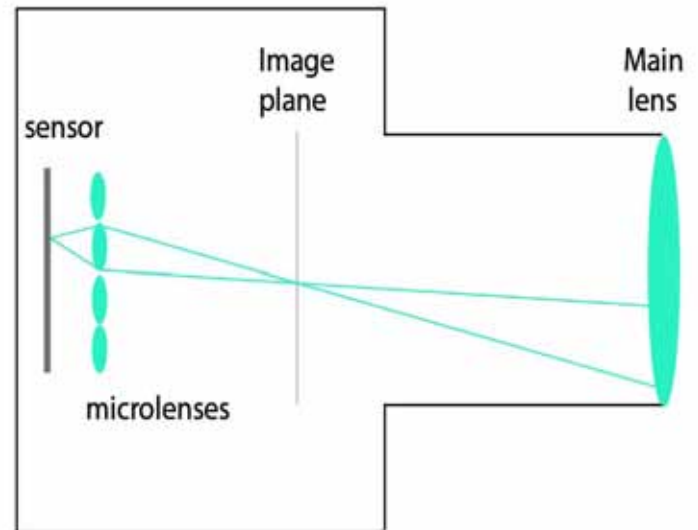
This is like a telescope with multiple eyepieces.



## Plenoptic Camera

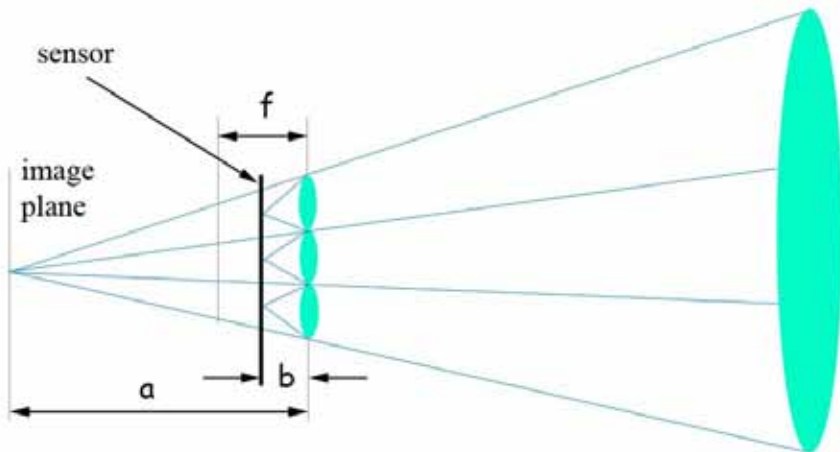


## Focused Plenoptic Camera

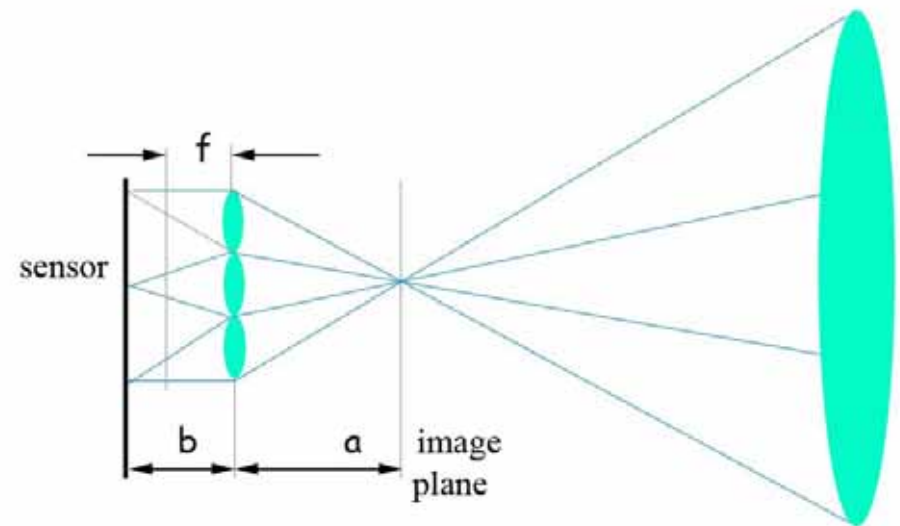


# **Two ways of focusing: Galilean and Keplerian**

## Galilean telescopic array



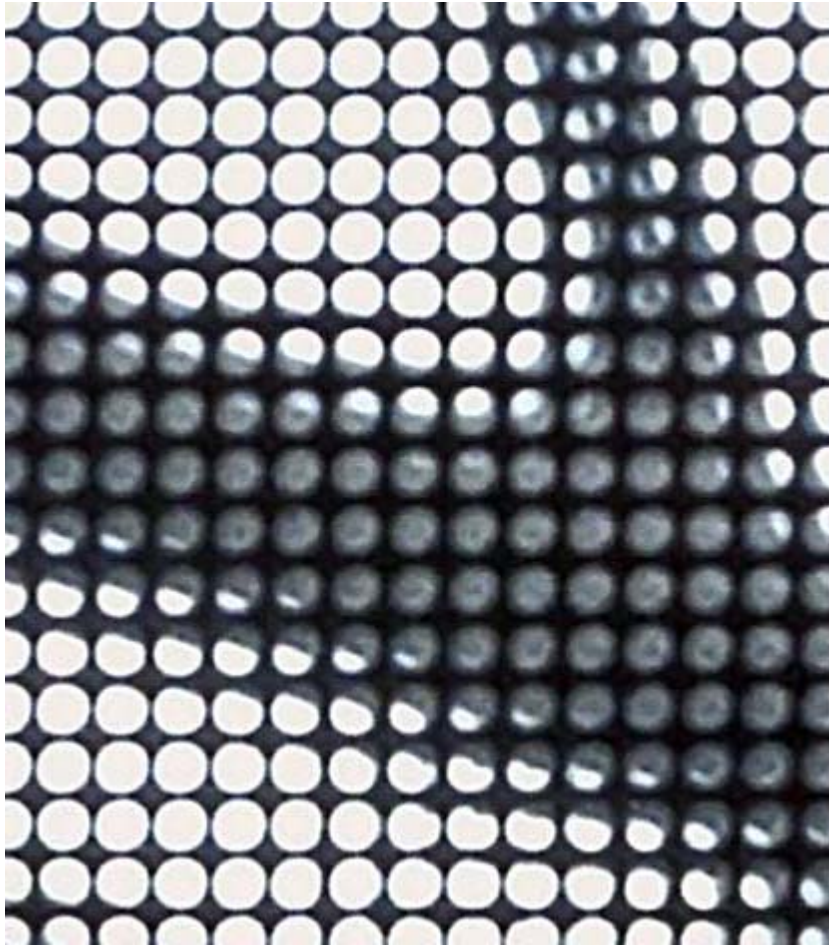
## Keplerian telescopic array



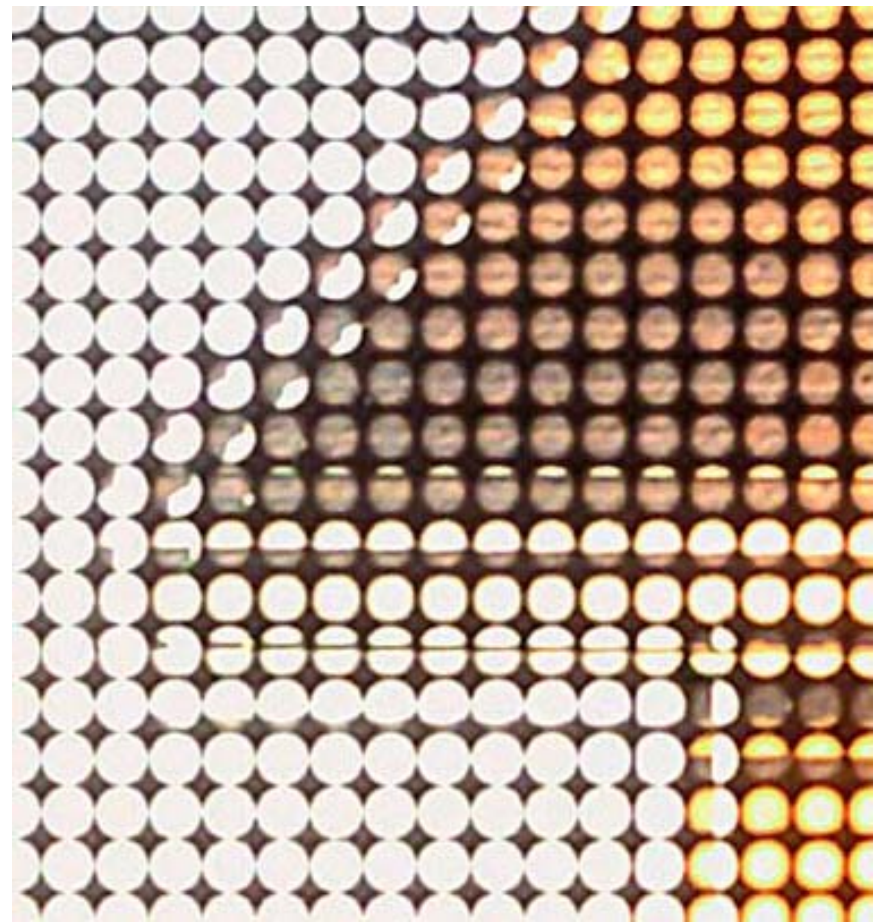
# Lumsdaine&Georgiev, 2008



**Galilean imaging**



**Keplerian imaging**



**For comparison with traditional lightfield rendering see videos:**

**<http://www.tgeorgiev.net/FullResolution.wmv>**

**<http://www.tgeorgiev.net/FullResolution.gif>**

**For demonstration of refocusing with full resolution rendering, see:**

**<http://www.tgeorgiev.net/FullResolutionRefocusing.gif>**

# Sampling pattern in Plenoptic Camera 2.0

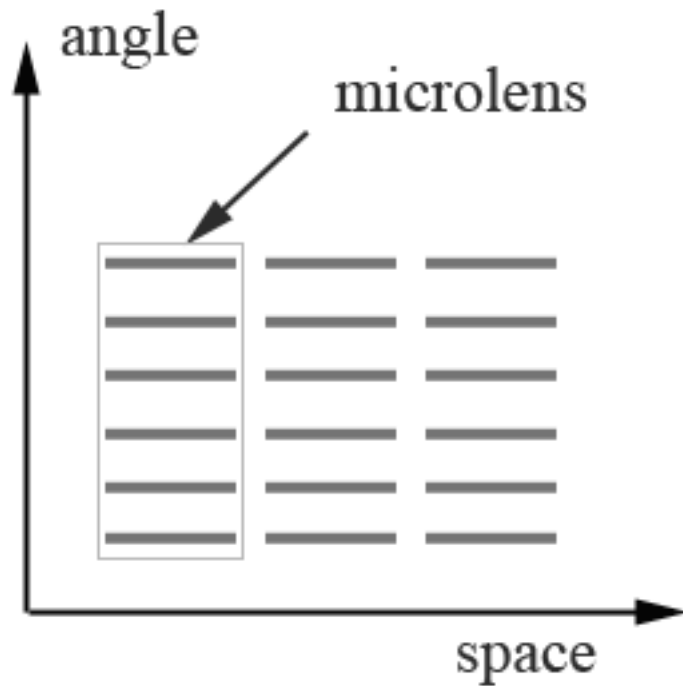
***“It's my intuition that it takes advantage of scene statistics in the natural world”***

***“I believe that these are the same properties of the world that make the coded aperture camera possible”***

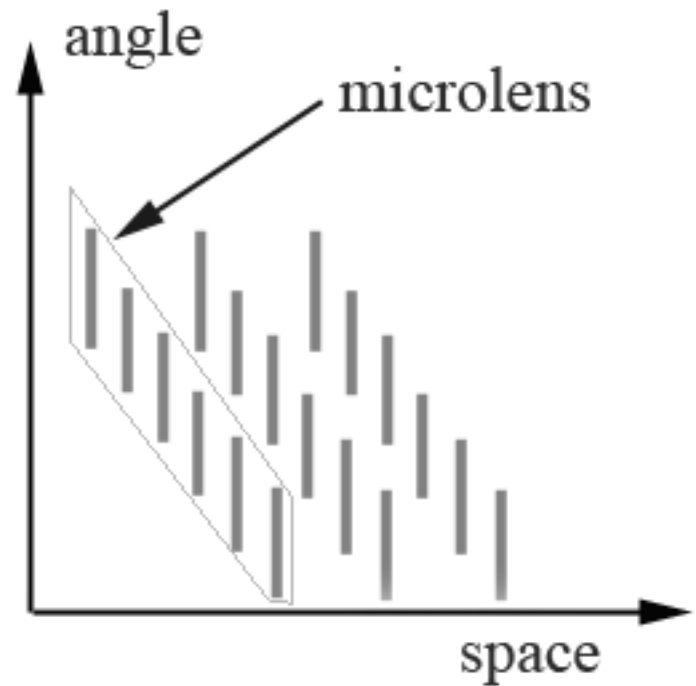
***-- Ted Adelson***

# Sampling pattern in Plenoptic Camera 2.0

## Plenoptic



## Plenoptic 2.0

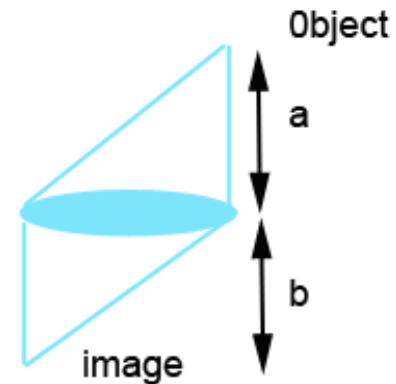


Please, see the formulas that motivate this (next)

# Sampling pattern in Plenoptic Camera 2.0

$$A = \begin{bmatrix} 1 - \frac{b}{f} & ab \left( \frac{1}{a} + \frac{1}{b} - \frac{1}{f} \right) \\ -\frac{1}{f} & 1 - \frac{a}{f} \end{bmatrix} \quad \leftarrow \text{Camera matrix (as in the tutorial)}$$

$$= \begin{bmatrix} -\frac{b}{a} & 0 \\ -\frac{1}{f} & -\frac{a}{b} \end{bmatrix} \quad \leftarrow \text{Condition for focusing}$$



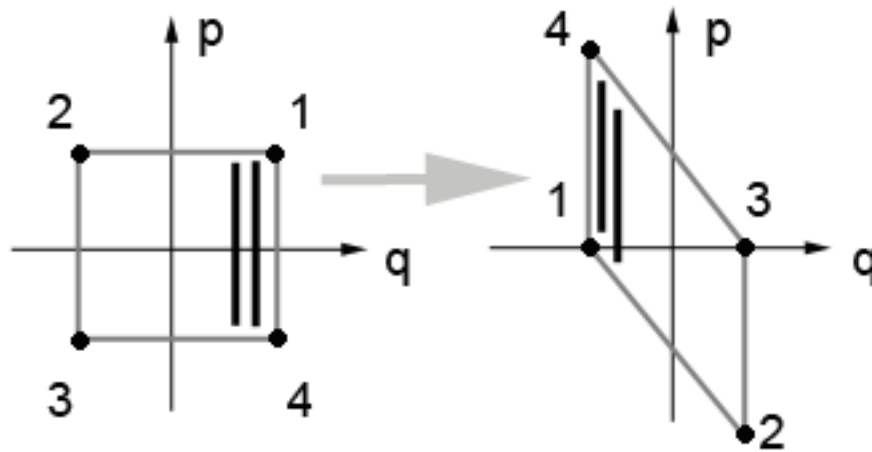
$$A^{-1} = \begin{bmatrix} -\frac{a}{b} & 0 \\ \frac{1}{f} & -\frac{b}{a} \end{bmatrix} \quad \leftarrow \text{Sensor surface is mapped to the image plane by this matrix}$$

# Sampling pattern in Plenoptic Camera 2.0

Example:  $a=1, b=1, f=\frac{1}{2}$

The image is mapped to the object by:

$$A^{-1} = \begin{bmatrix} -1 & 0 \\ 2 & -1 \end{bmatrix}$$



When  $a$  is big and  $b$  is small, the parallelogram gets stretched, and slope gets small

# Sampling pattern in Plenoptic Camera 2.0

**Plenoptic 2.0 sampling is more flexible:  
By spacing the microlenses we can choose the spatial-angular tradeoff point.**

**We can actually reach very low angular resolution not possible with traditional plenoptic camera (because edge effects would introduce noise).**

**Very high spatial resolution can be achieved!**