Lecture 18:
Light-Field Cameras
(Plenoptic Cameras)

Kayvon Fatahalian
CMU 15-869: Graphics and Imaging Architectures (Fall 2011)

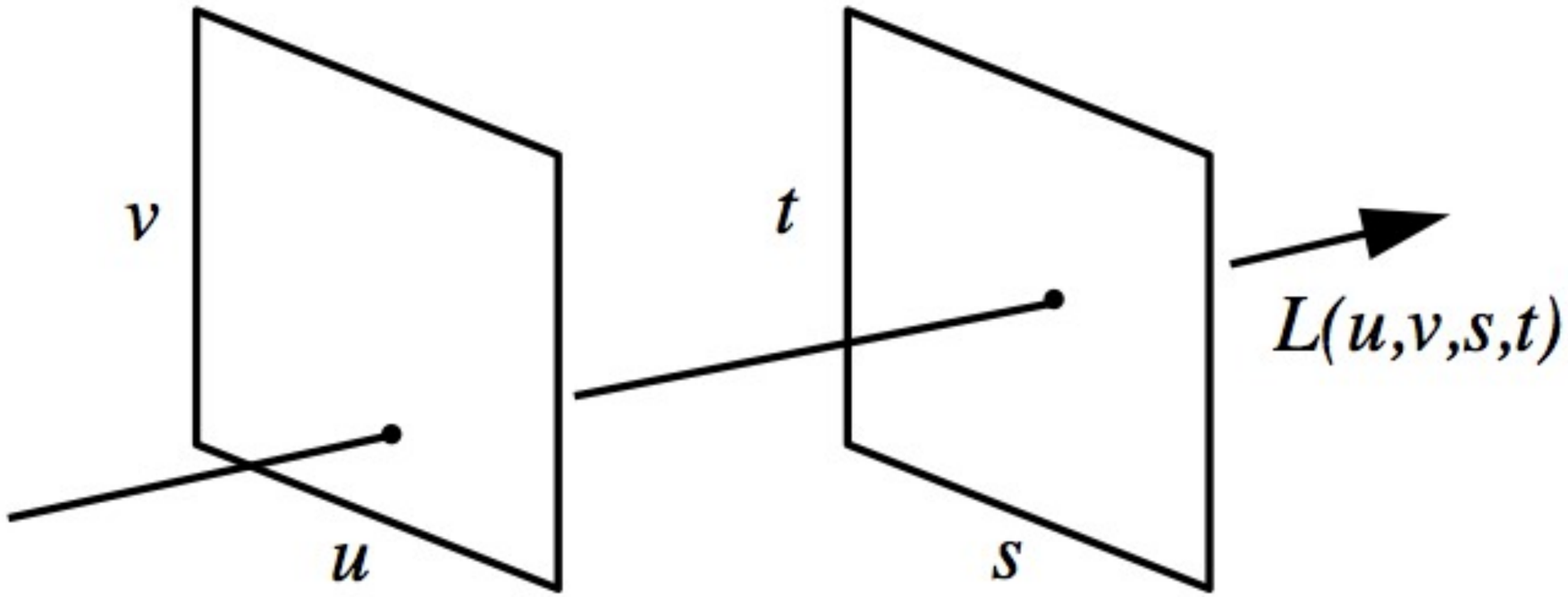
Continuing theme: computational photography

- Cameras capture light, extensive processing produces desired image

- Today:
  - Capturing light fields (not just photographs) with a handheld camera
  - Implications for photography

Recall: light-field

Light field is a 4D function (represents light in free space: no occlusion)



[Image credit: Levoy and Hanrahan 96]

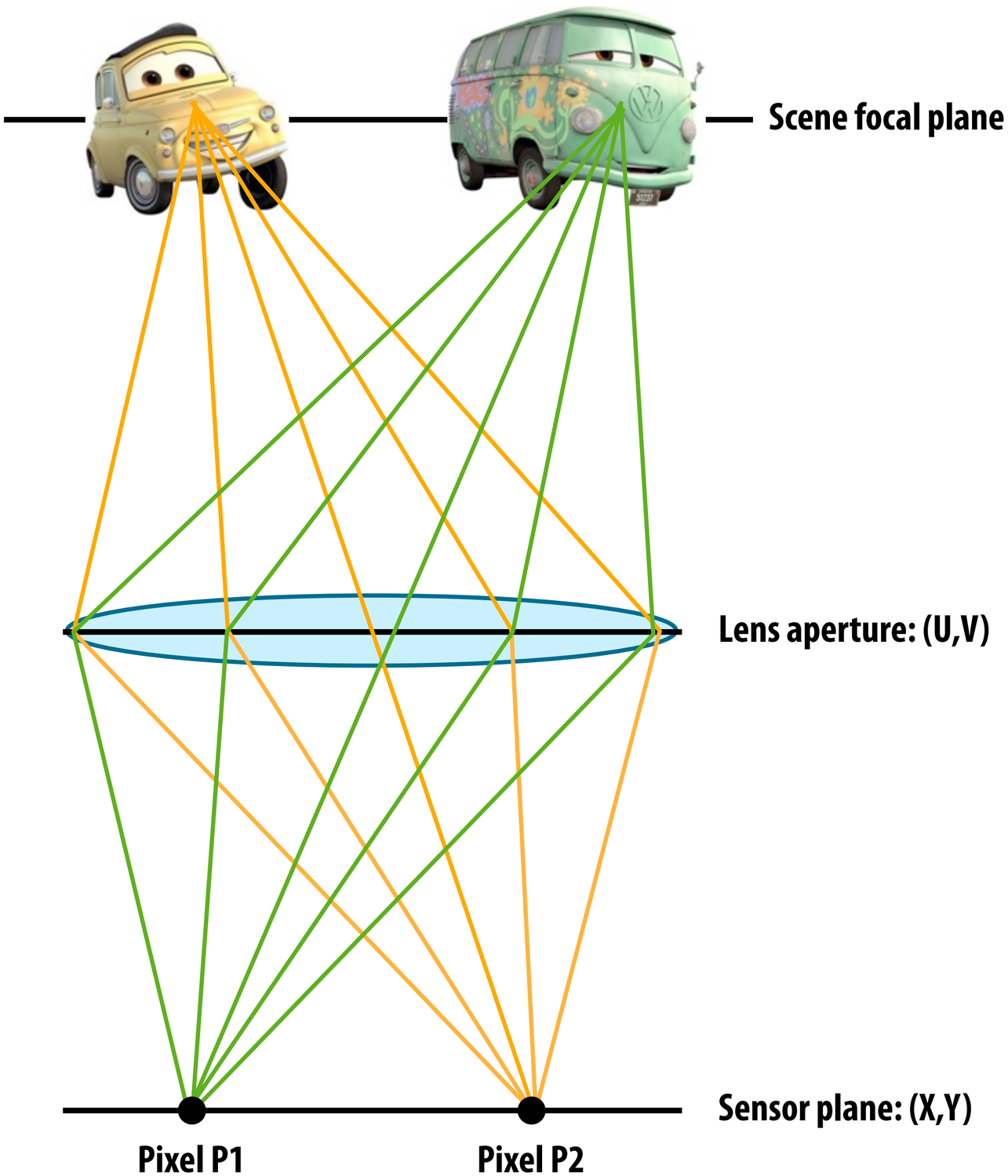
Two-plane parameterization:

Light ray described by connecting point on (u,v) plane with point on (s,t) plane

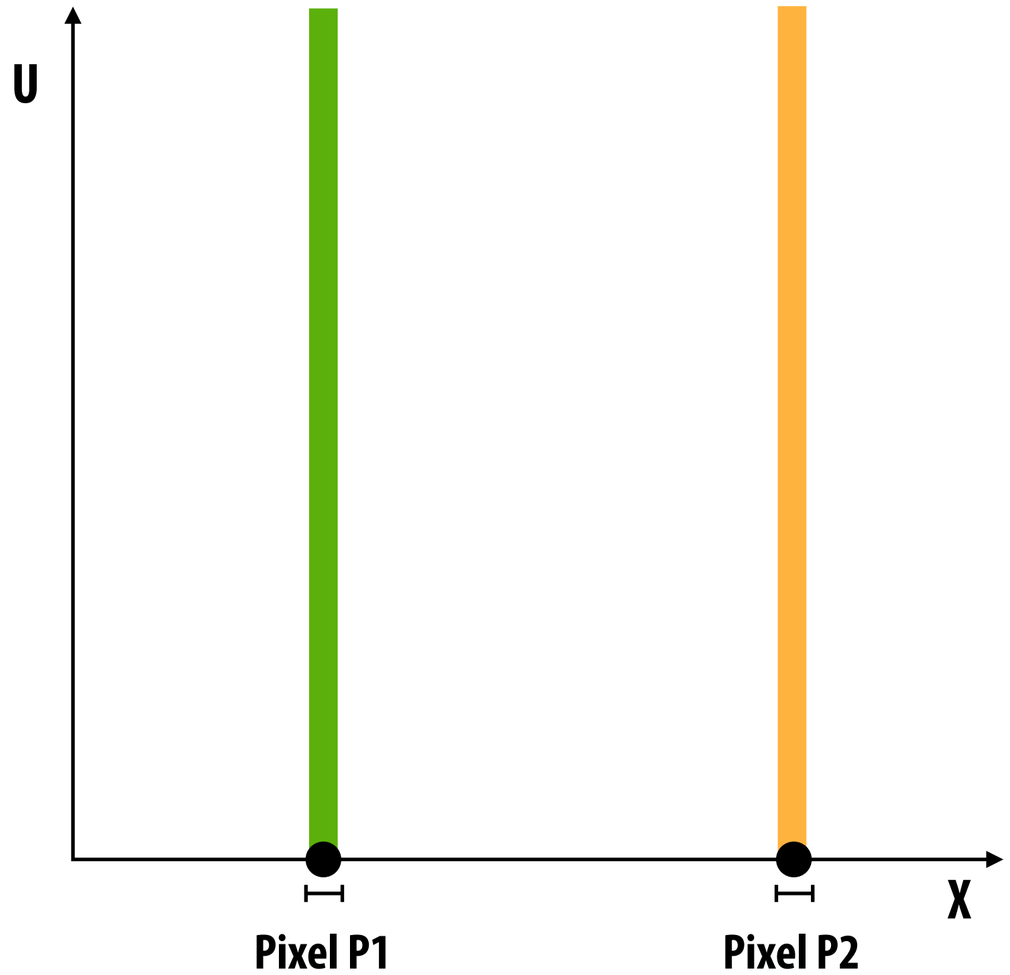
More general: plenoptic function (Adelson and Bergen 1991)

$$P = P(x, y, \lambda, t, V_x, V_y, V_z)$$

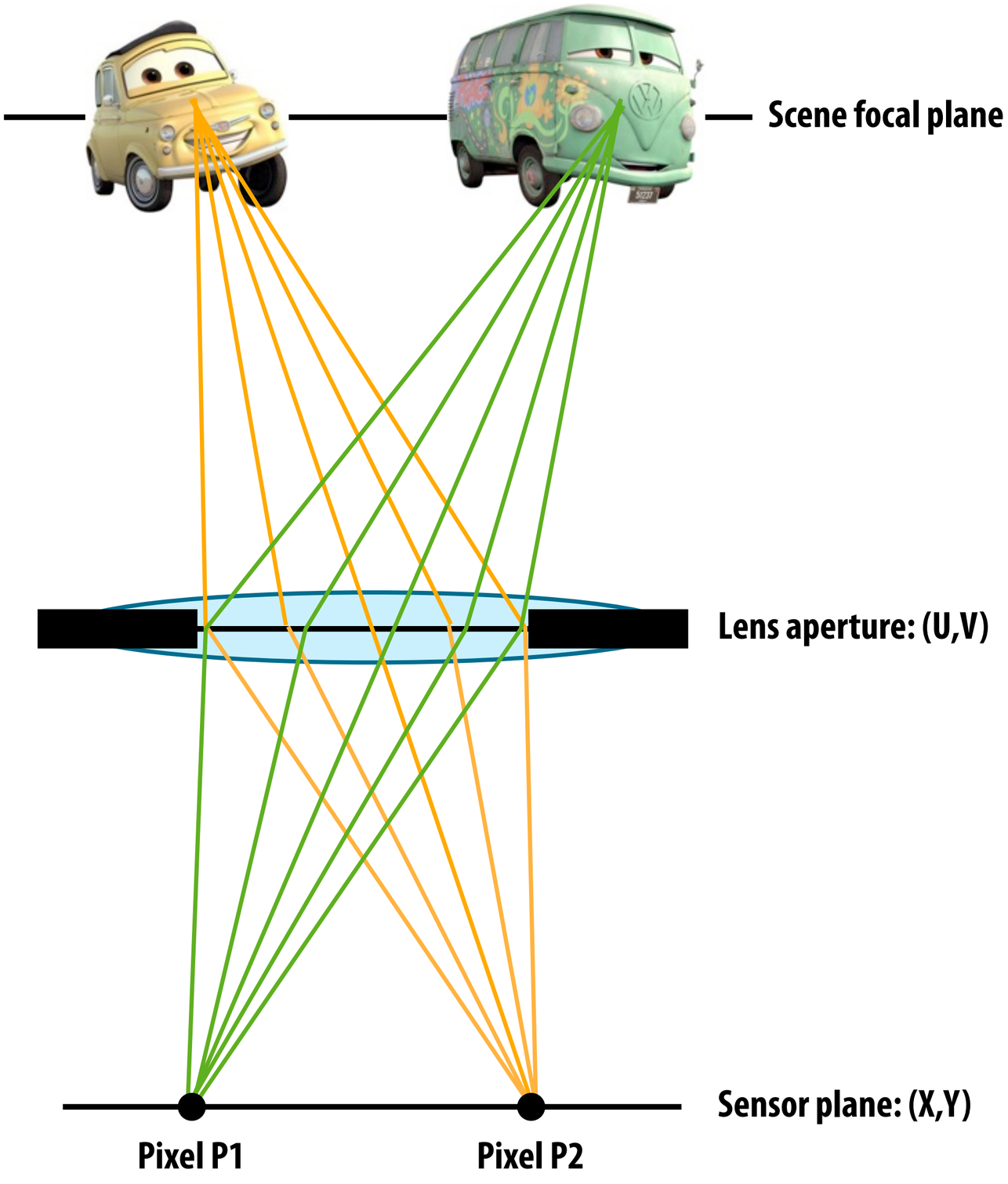
Light field inside a camera



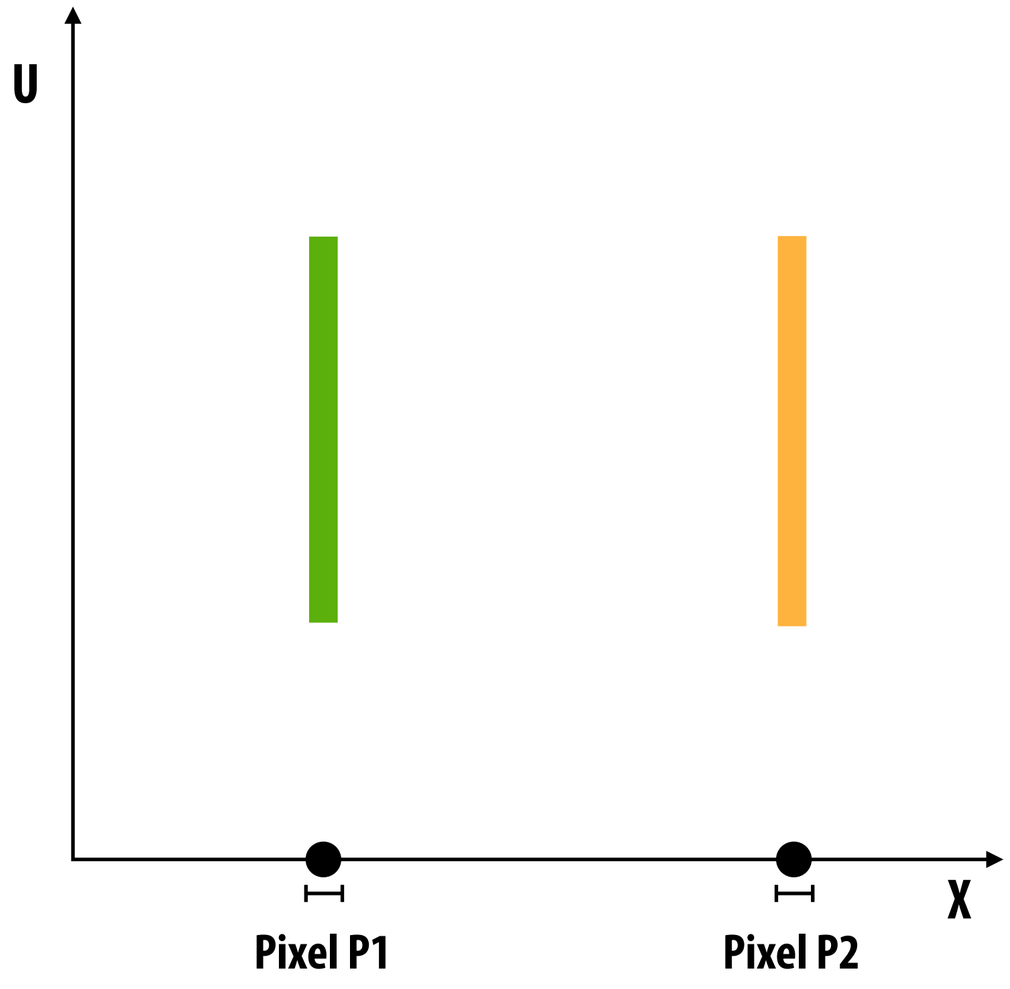
Ray space plot



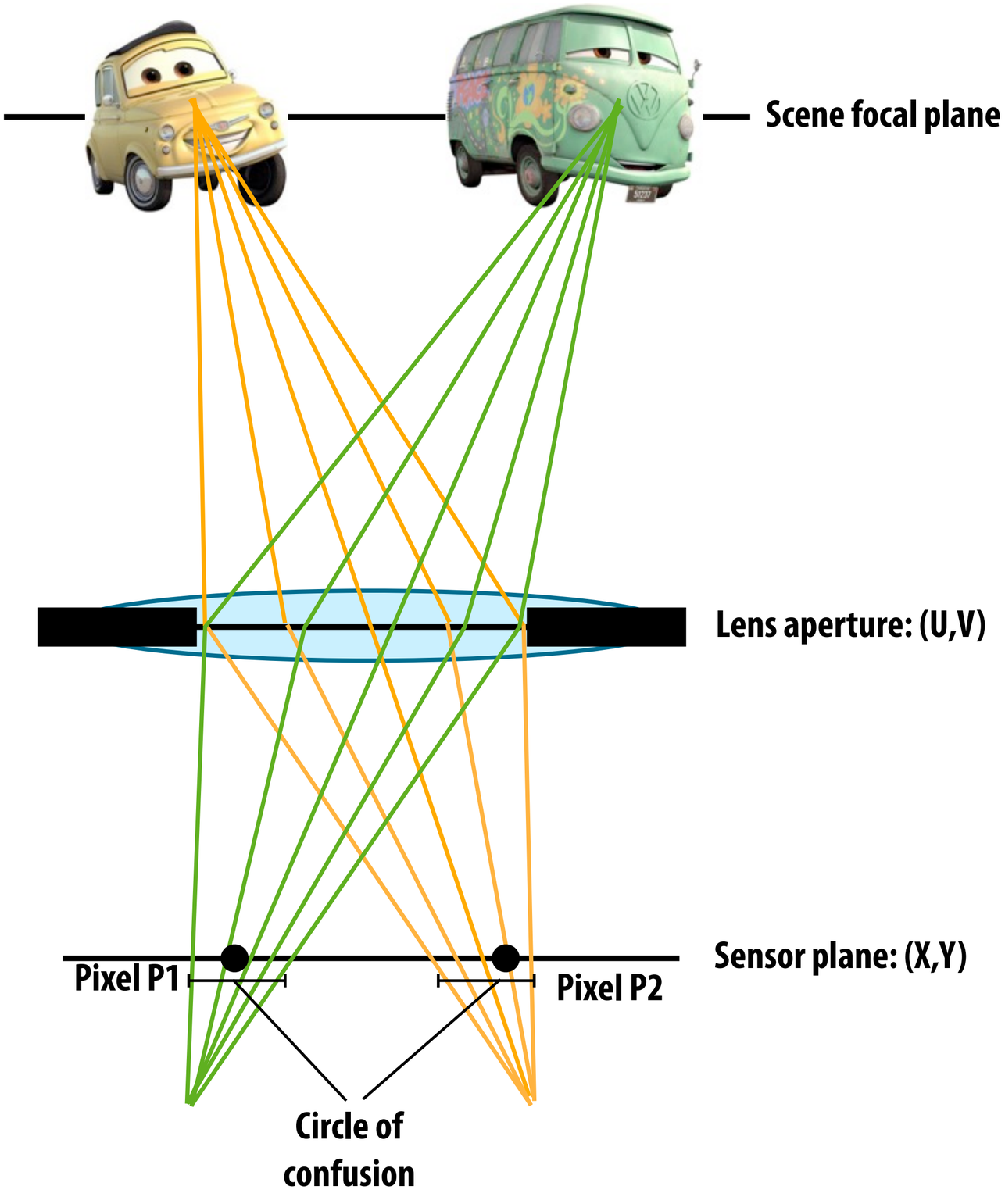
Decrease aperture size



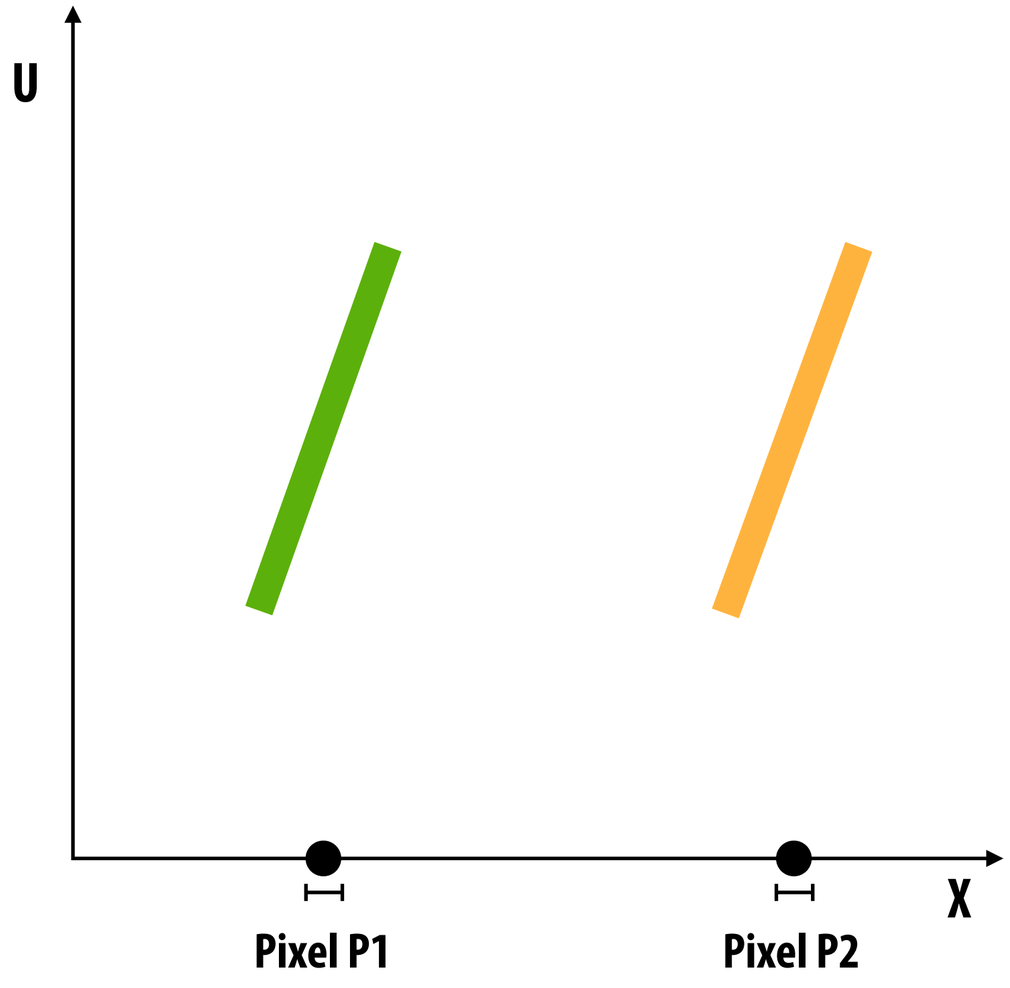
Ray space plot



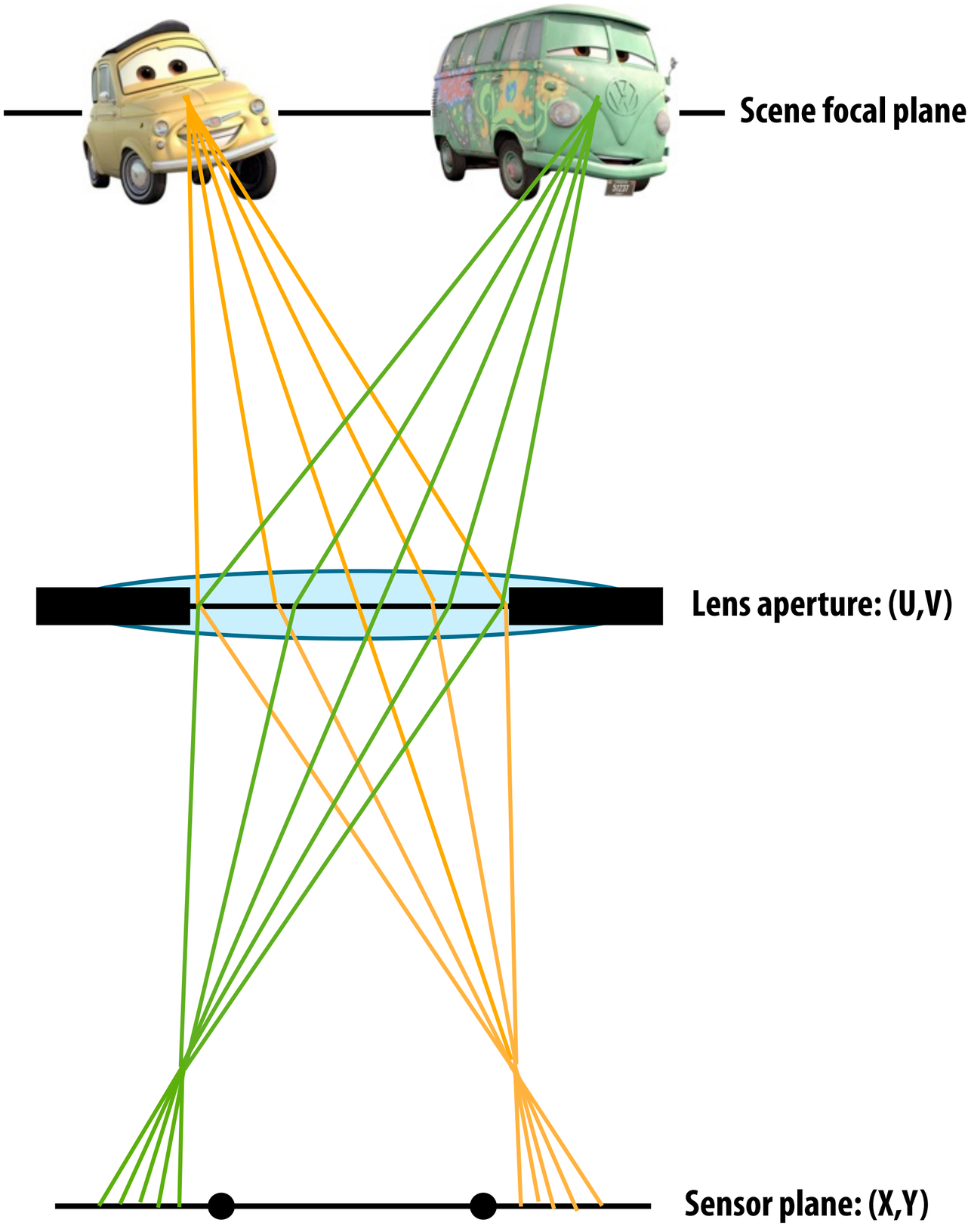
Defocus



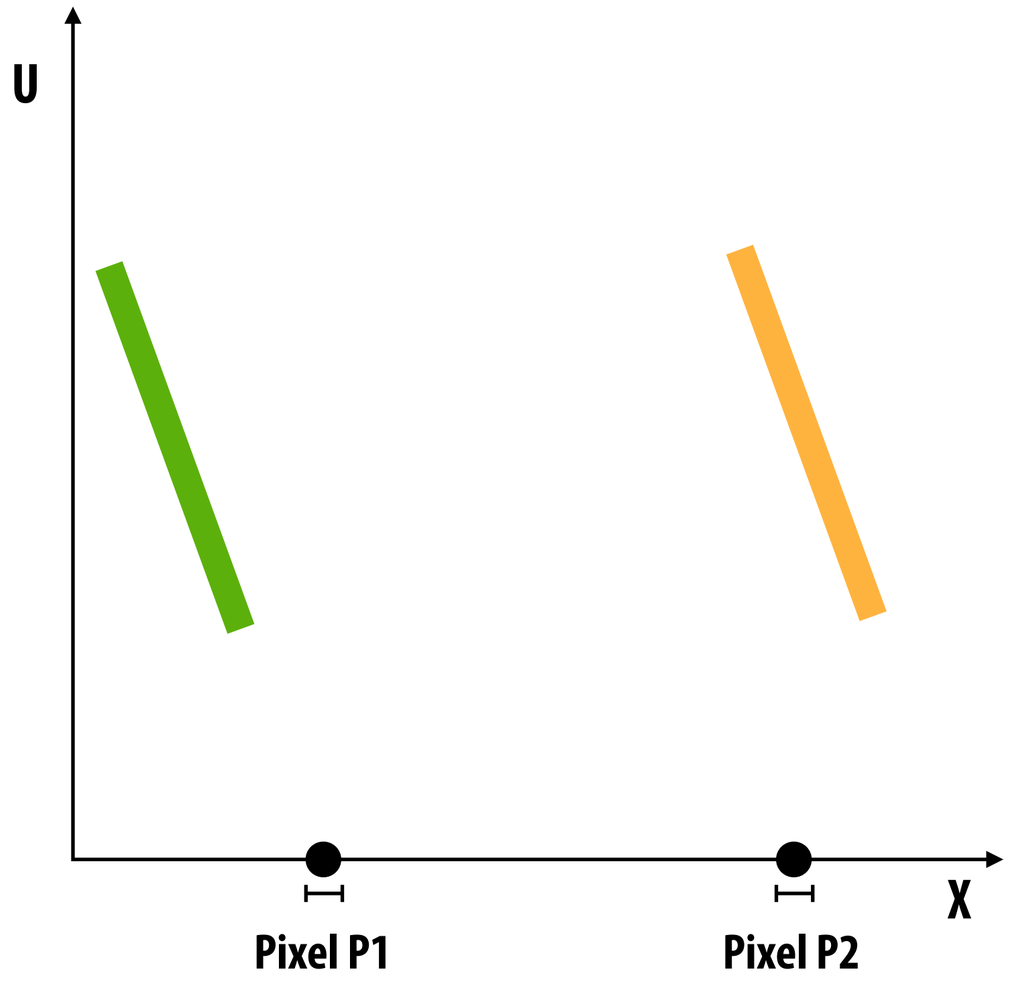
Ray space plot



Defocus



Ray space plot



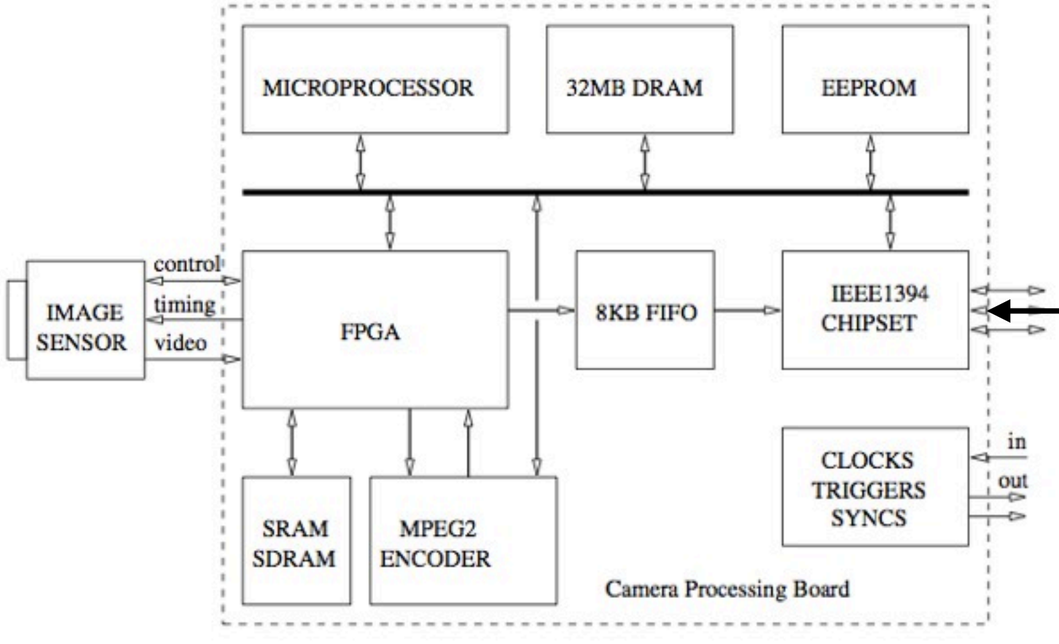
Stanford Camera Array

Wilburn et al. 2005

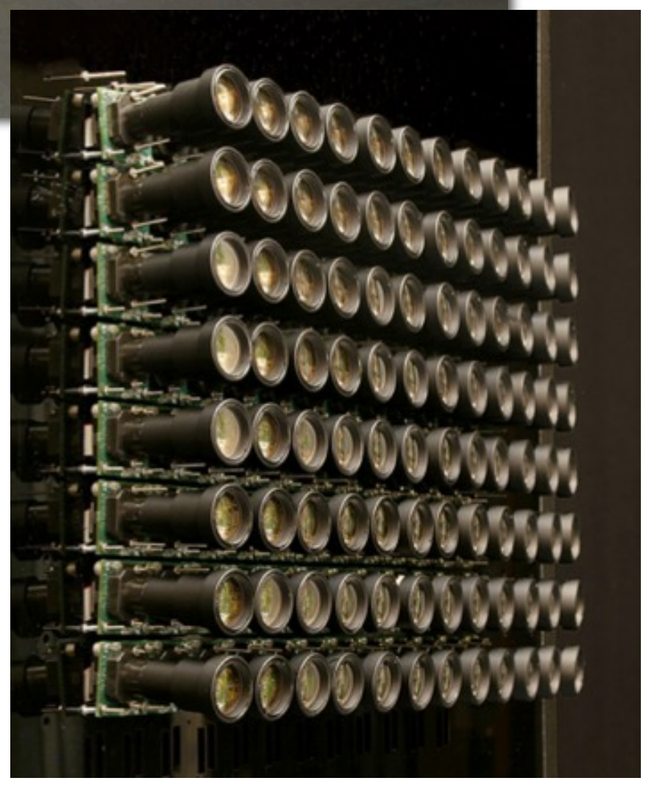
640 x 480 tightly synchronized, repositionable cameras

Custom processing board per camera

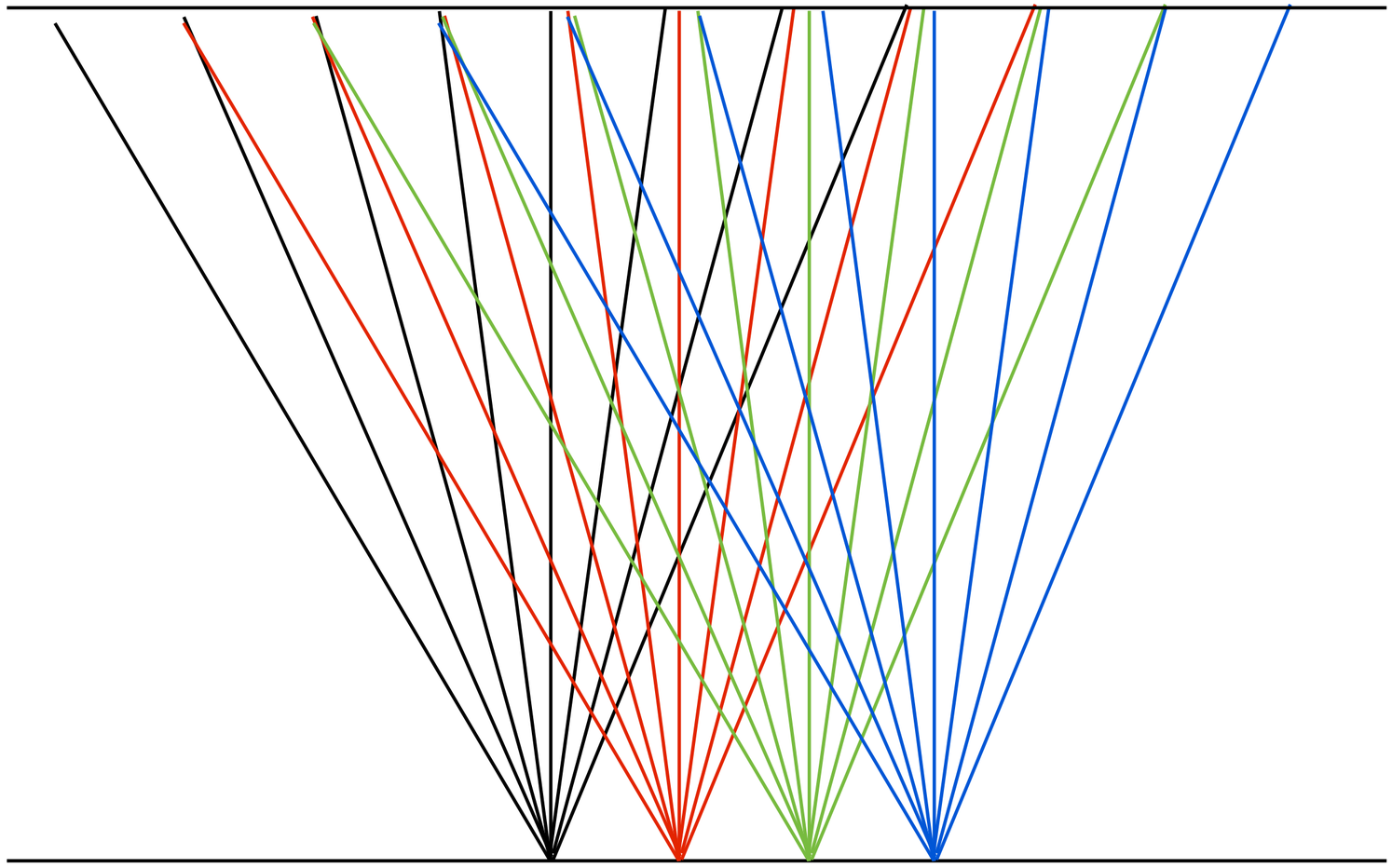
Tethered to PCs for additional processing/storage



Host PC with disk array



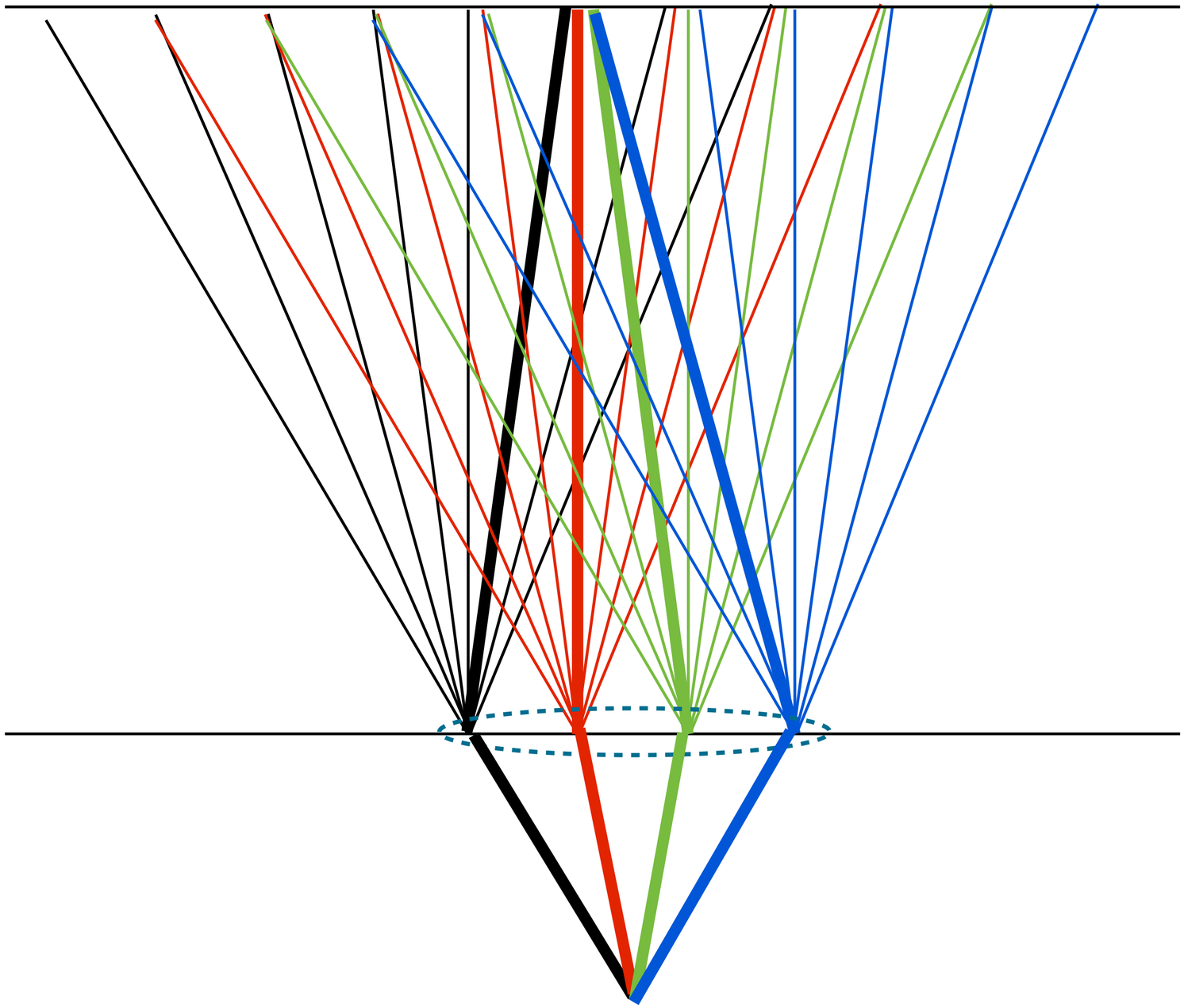
Captured light field



Synthetic aperture

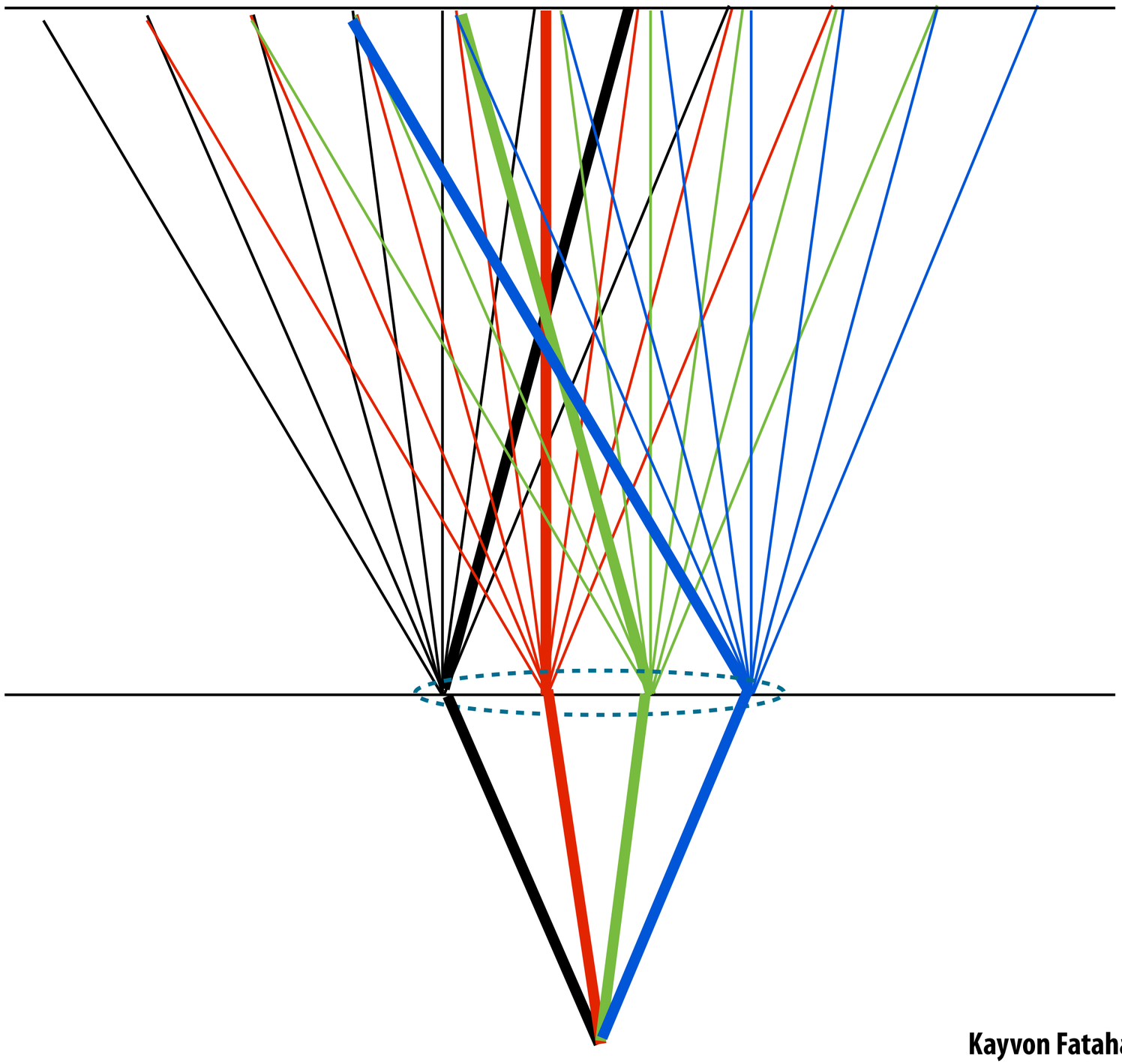
Simulate image formation by virtual camera with large aperture

Shift and add images



Wilburn et al. 2005

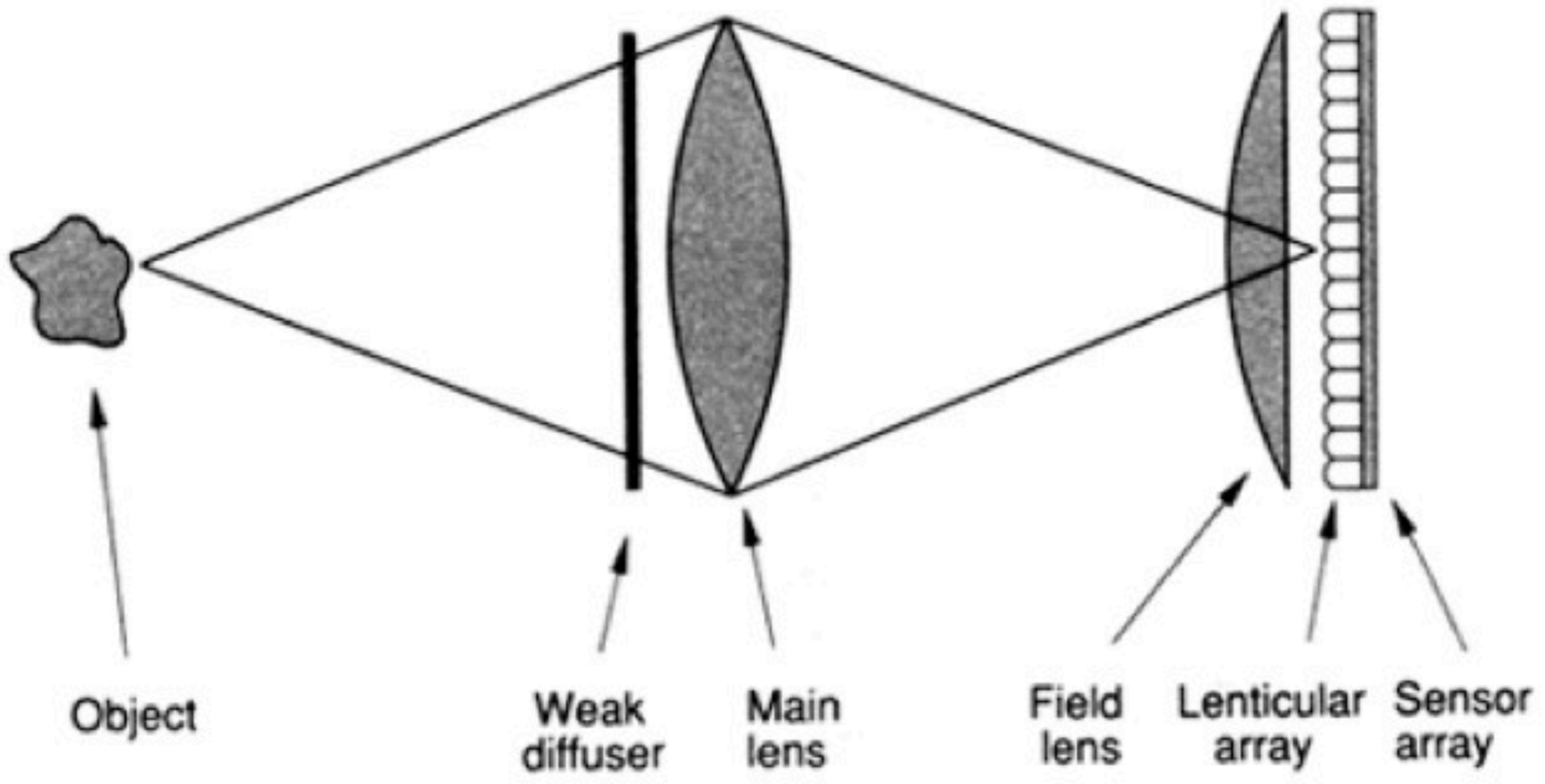
Refocused synthetic aperture image



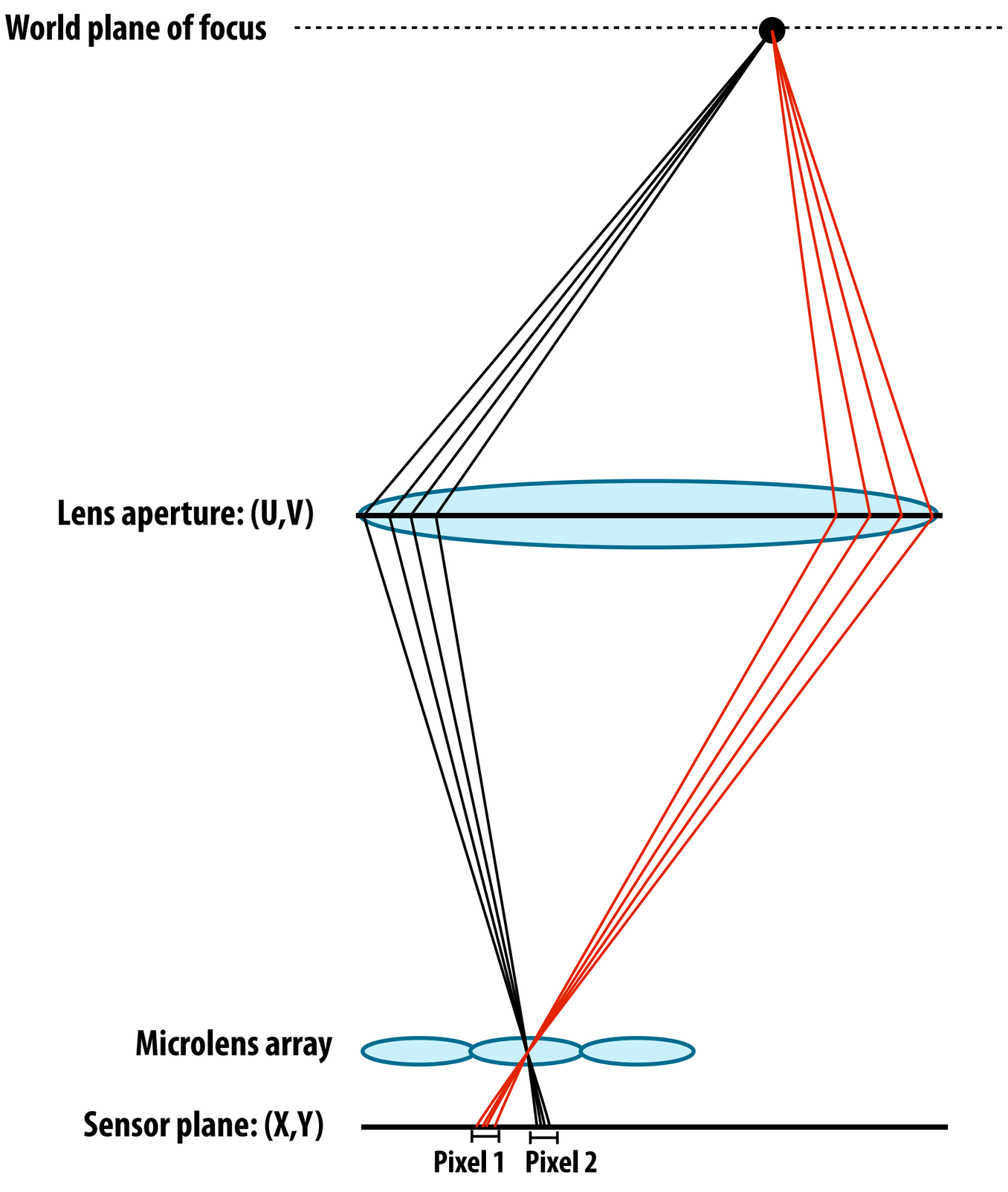
Plenoptic camera

Adelson and Wang, 1992

Measure plenoptic function for single lens stereo application

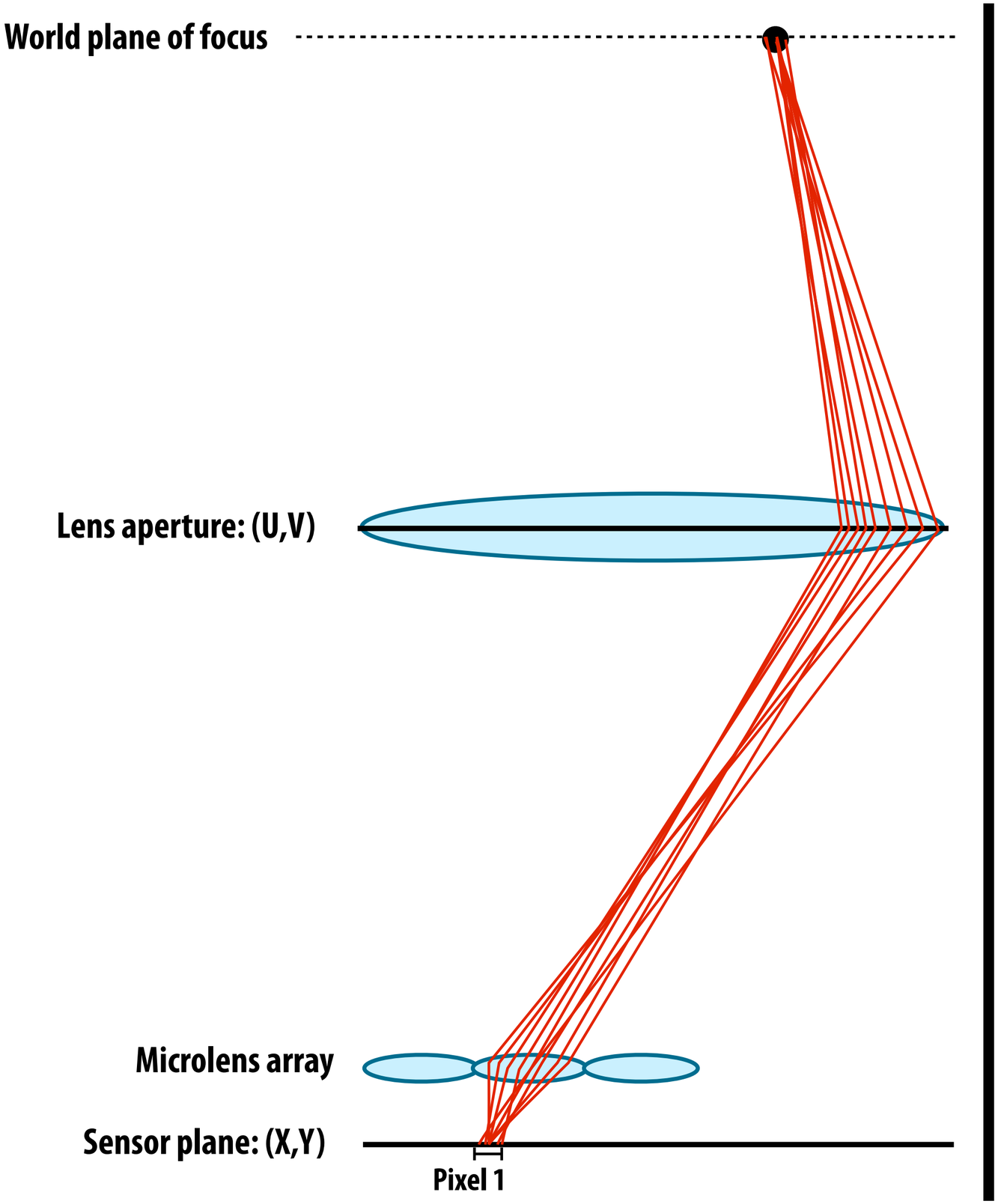


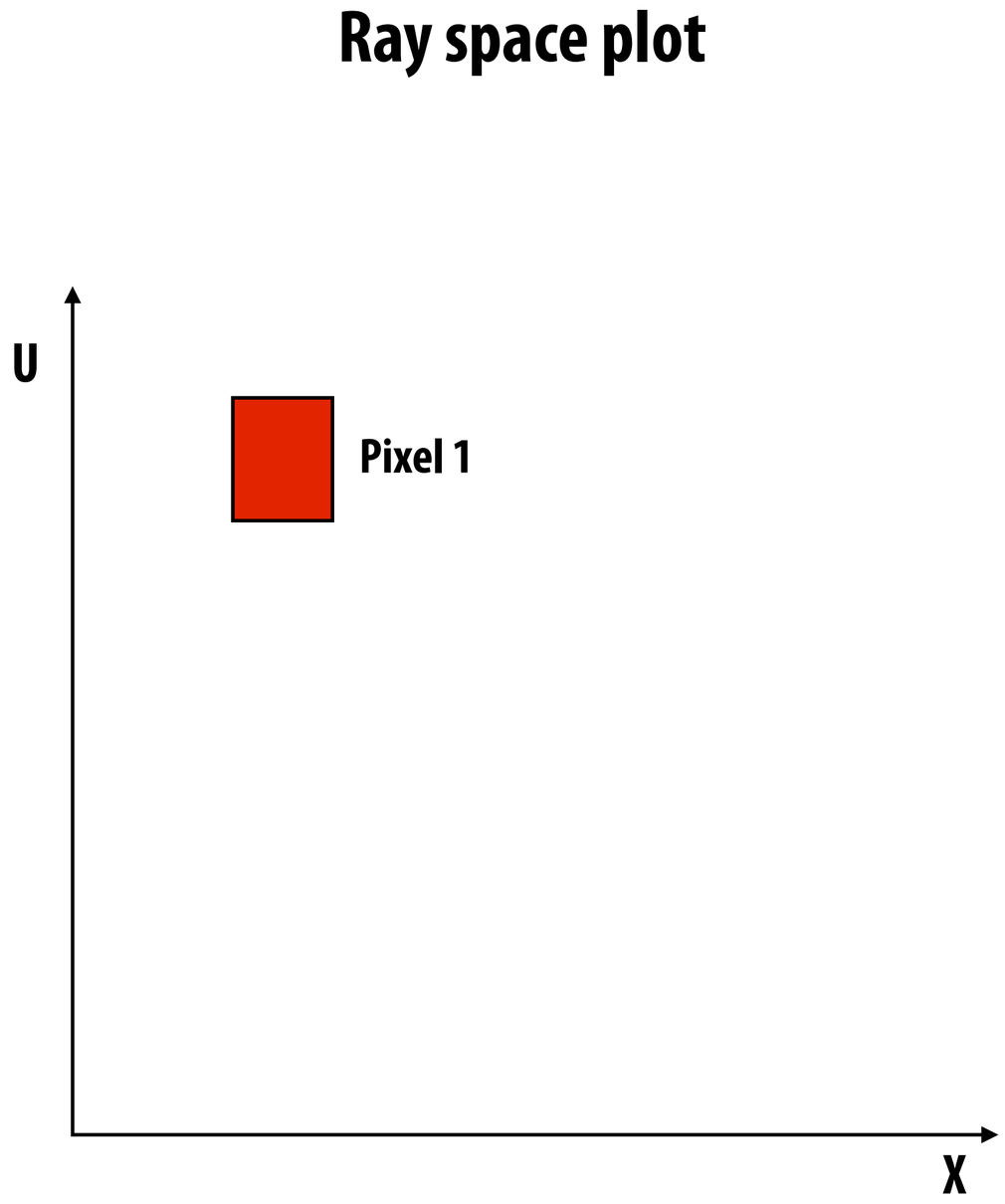
Handheld light field camera



Ng et al. 2005

Each sensor pixel records a beam of light





Captured light field

16 MP sensor
296 x 296 micolens array
12 x 12 pixels per microlens

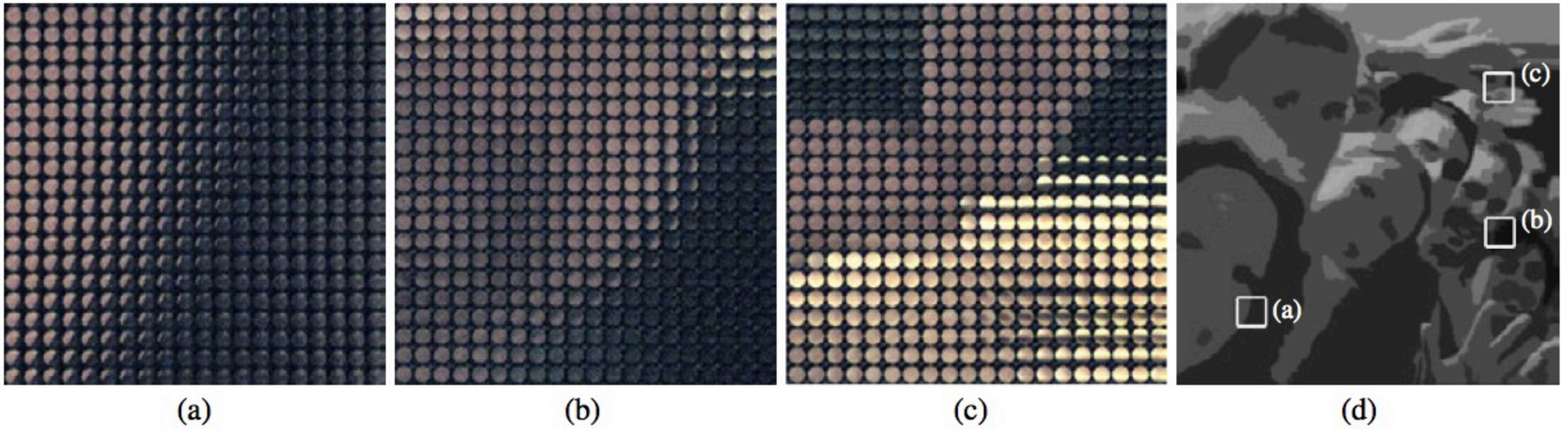
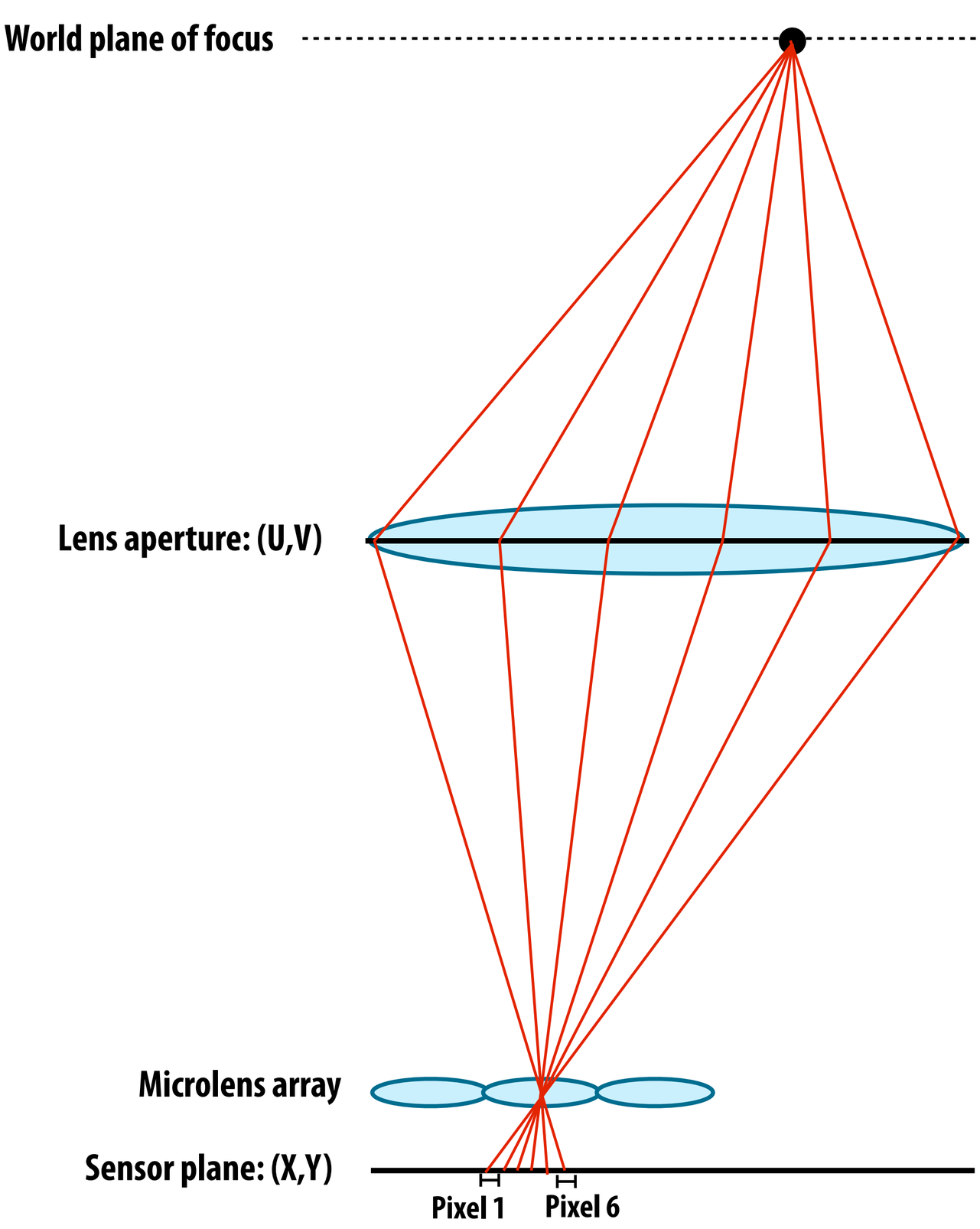
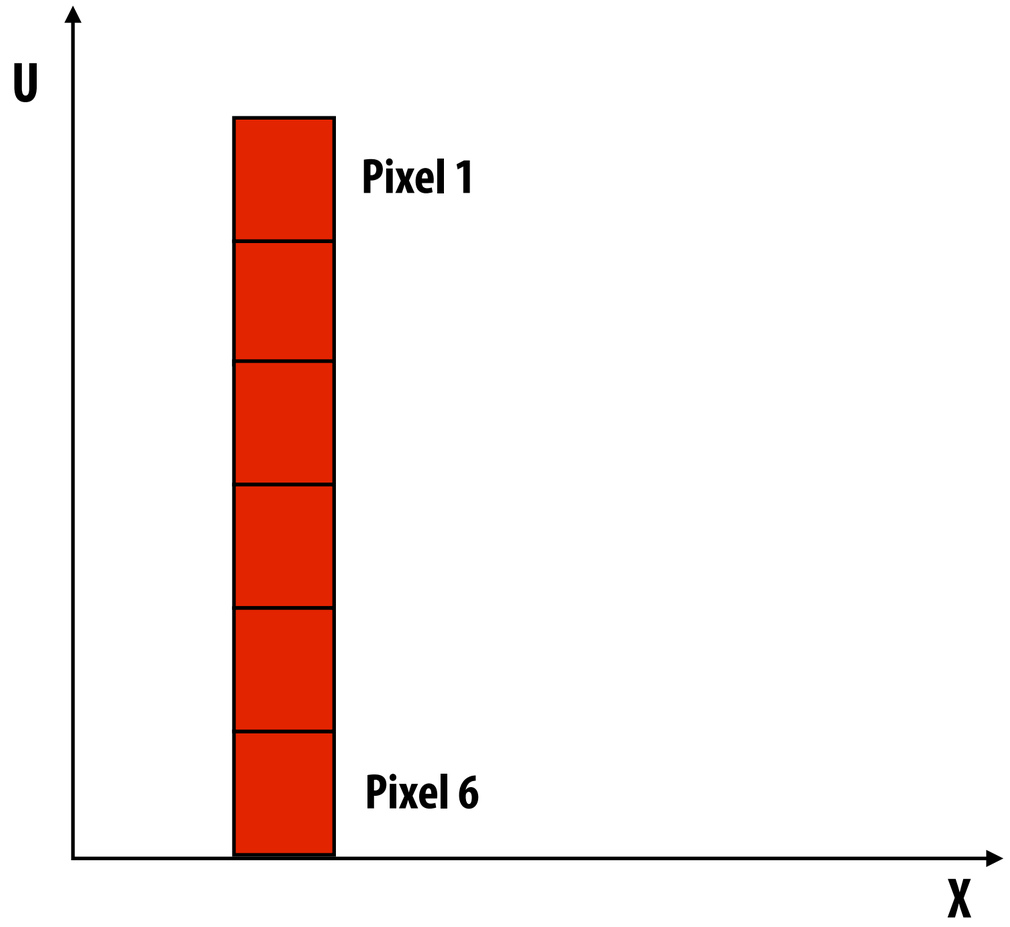


Image: Ng et al. 2006

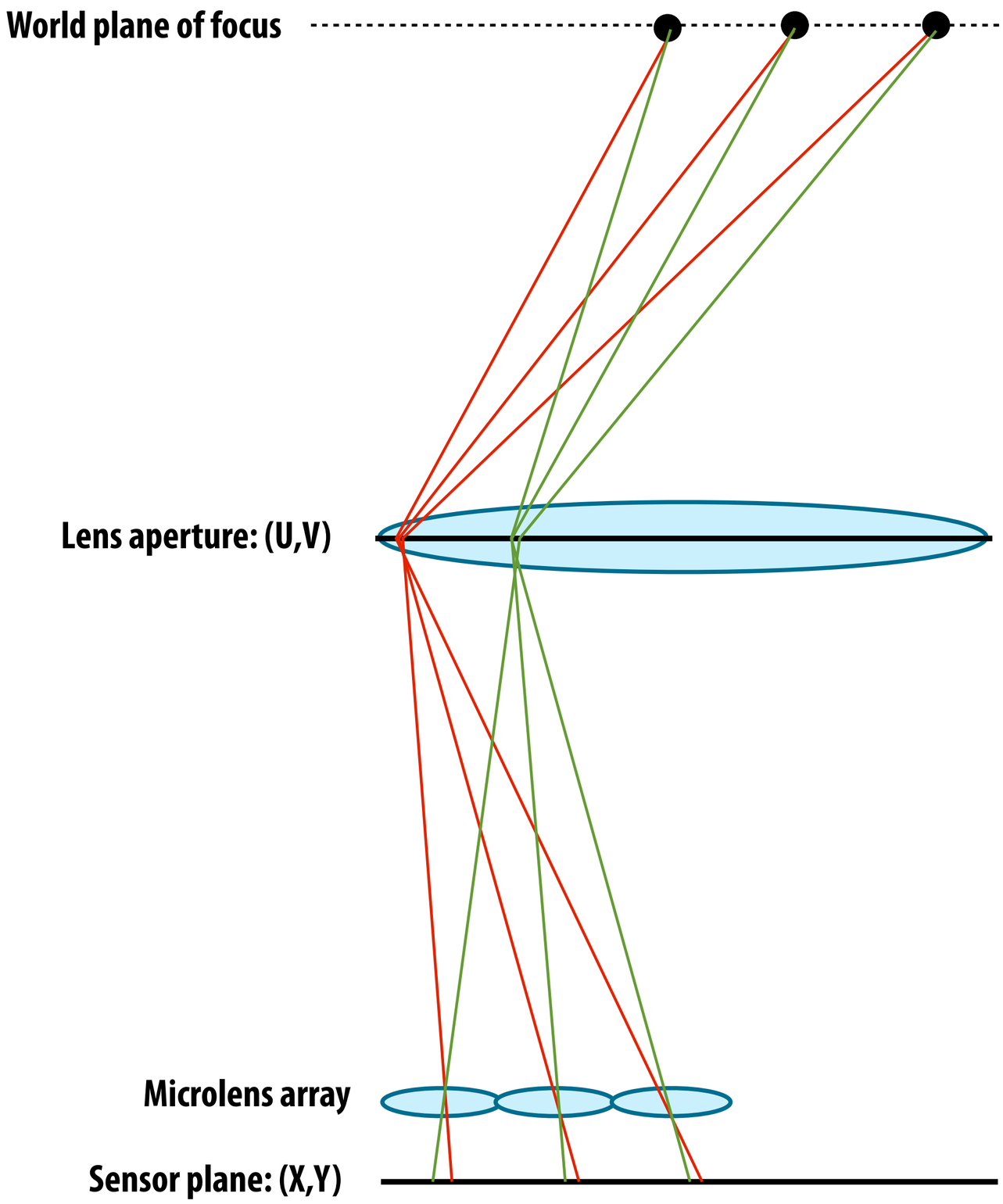
Computing a photograph



Ray space plot

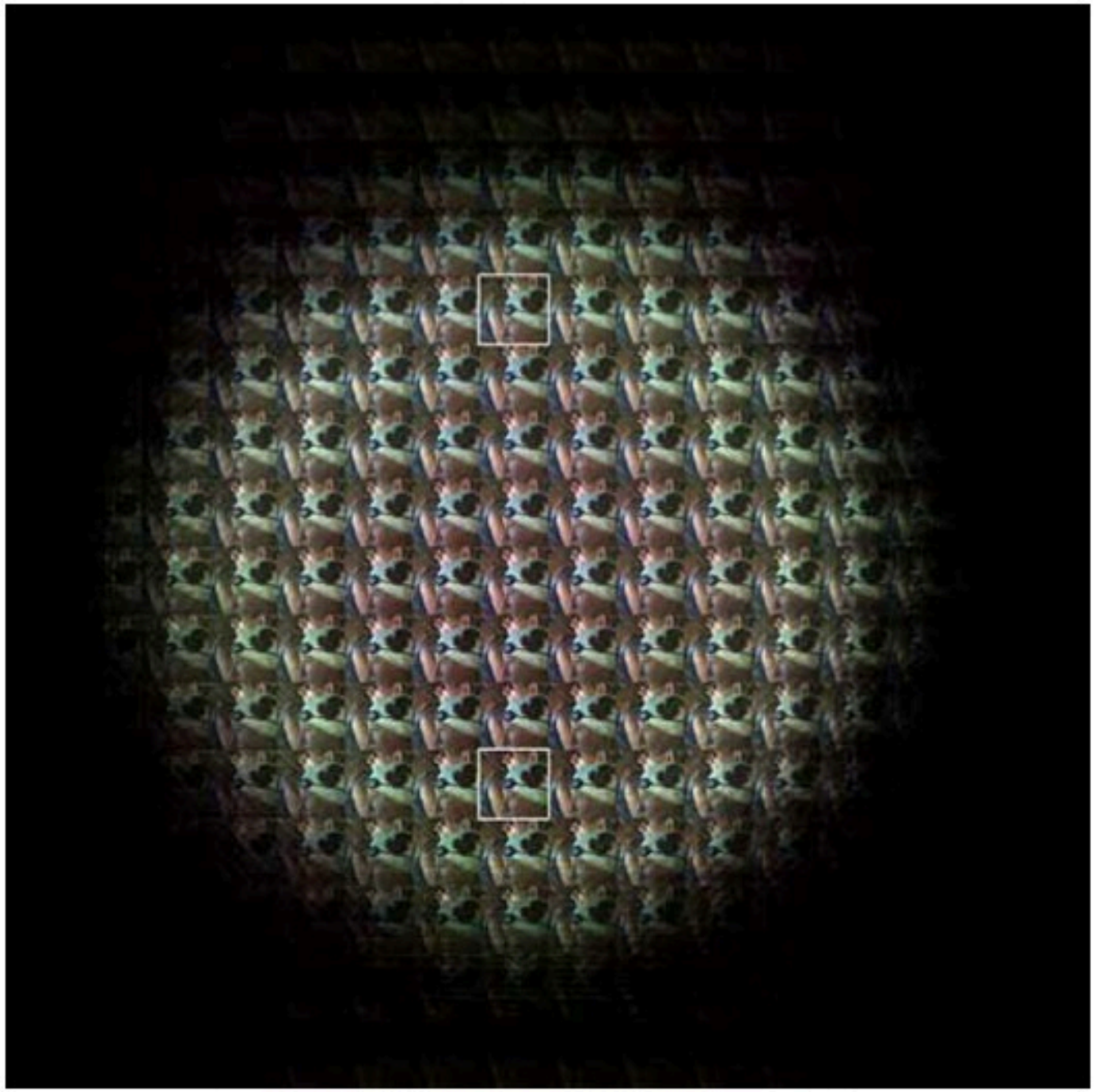


Sub-aperture image

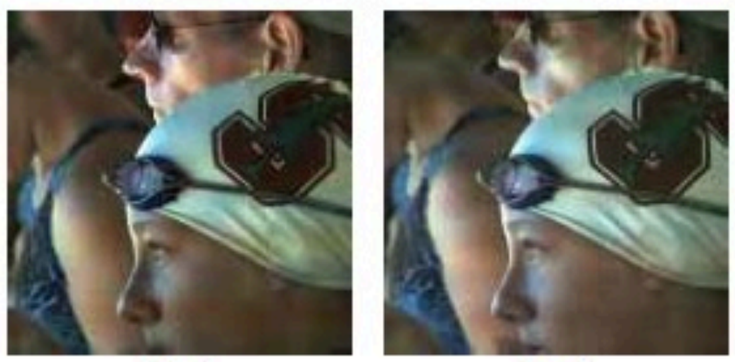


Sub-aperture images

Each image displays light incident on sensor from a small region of aperture



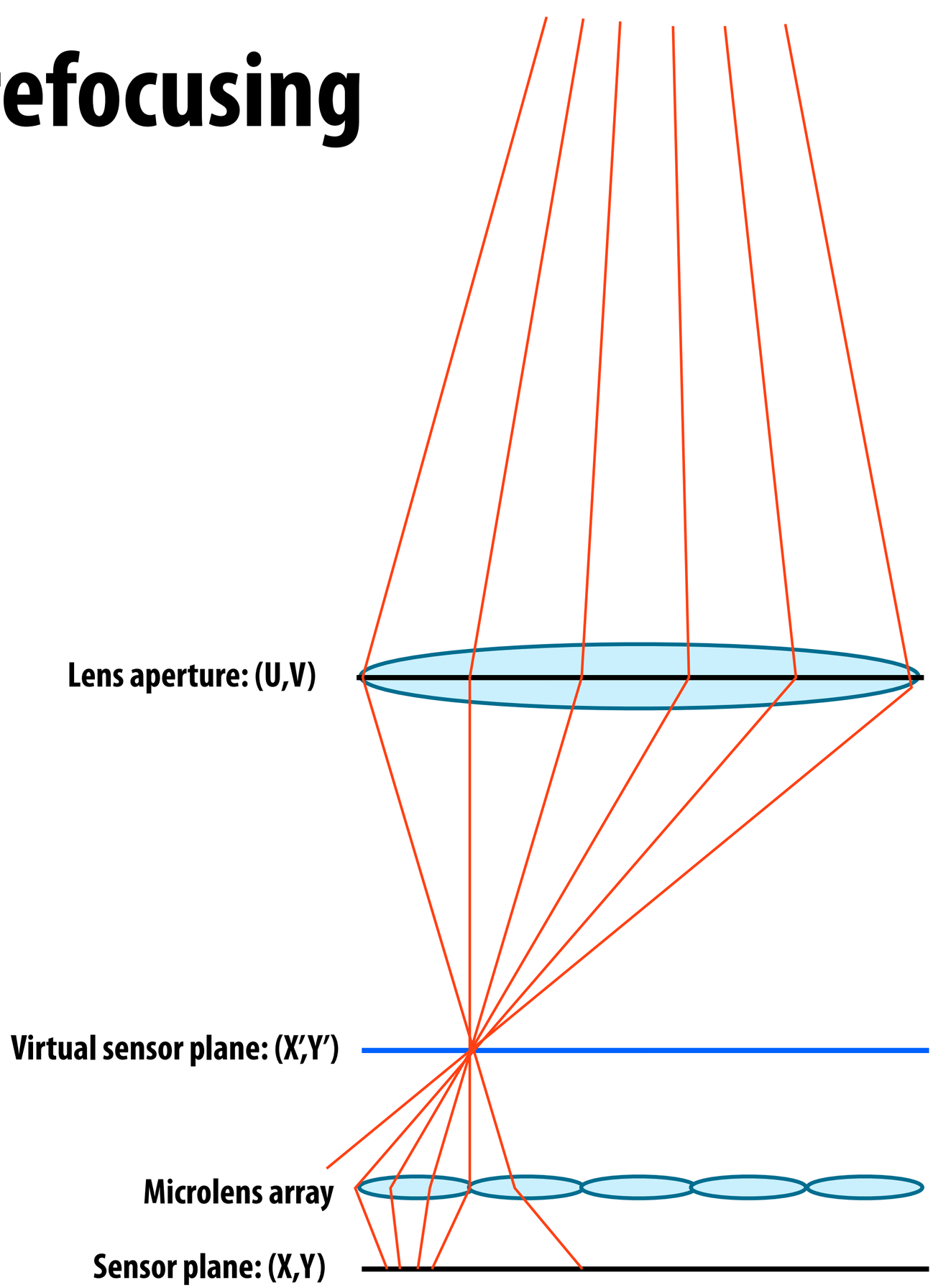
Note slight shift in perspective



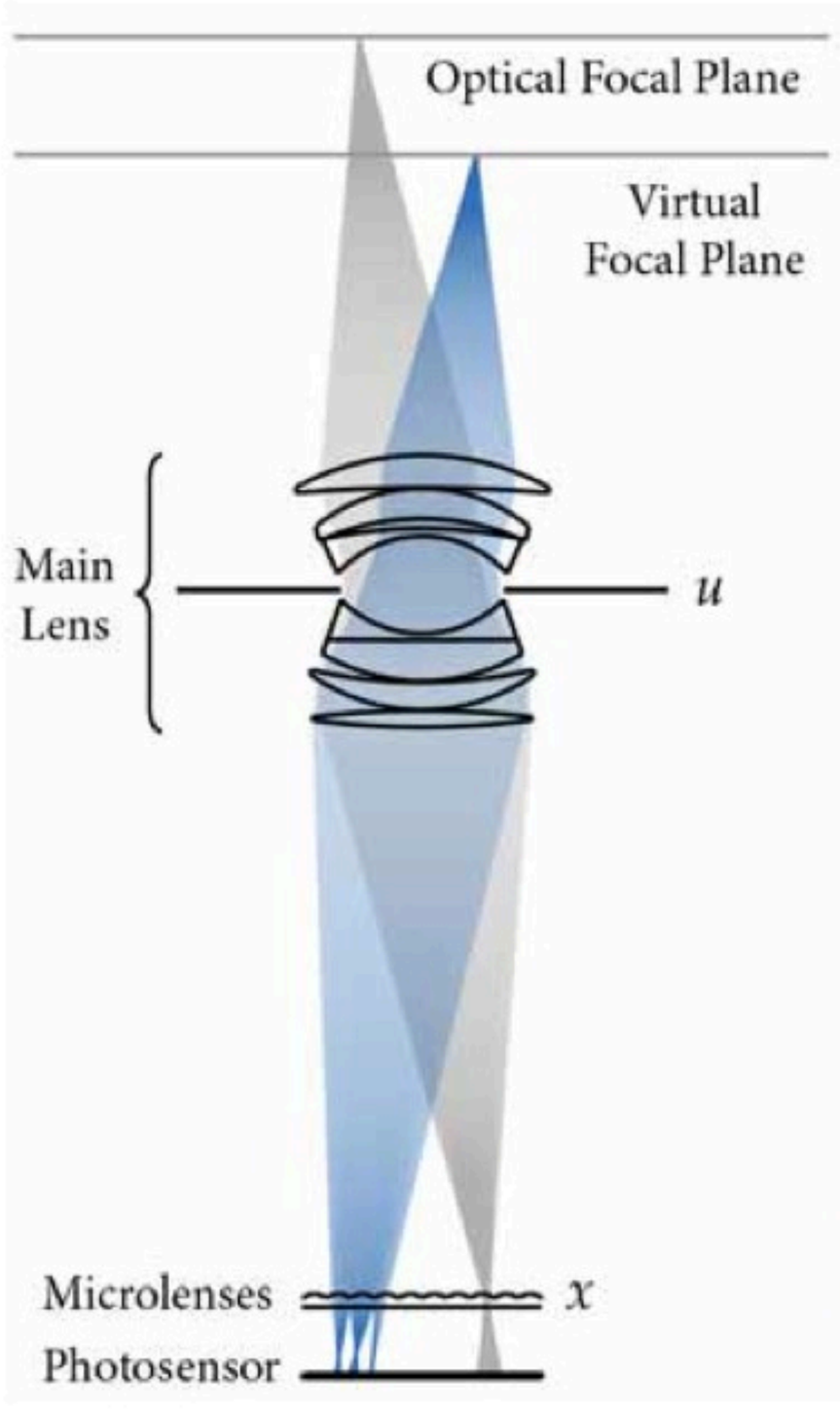
(z1) (z2)

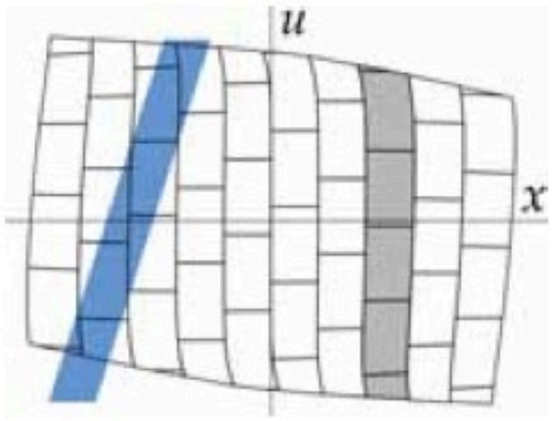
Image: Ng et al. 2006

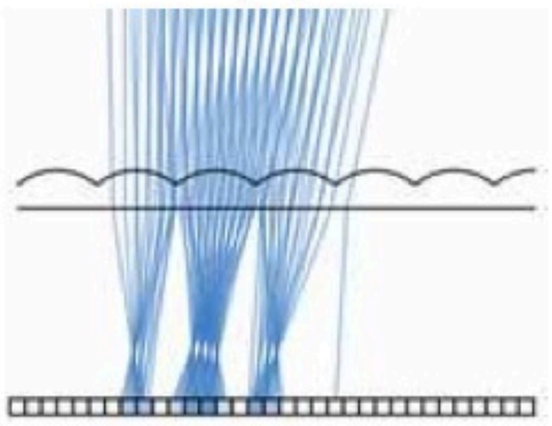
Digital refocusing



Digital refocusing







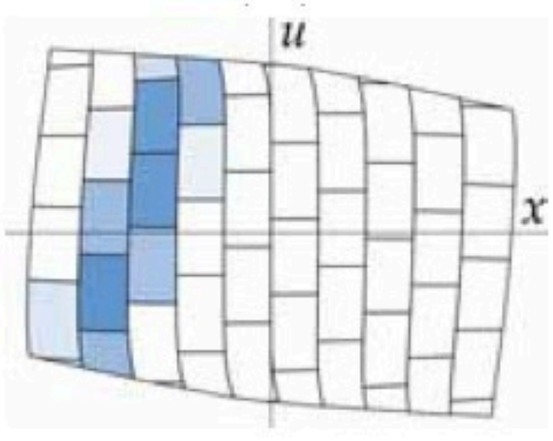
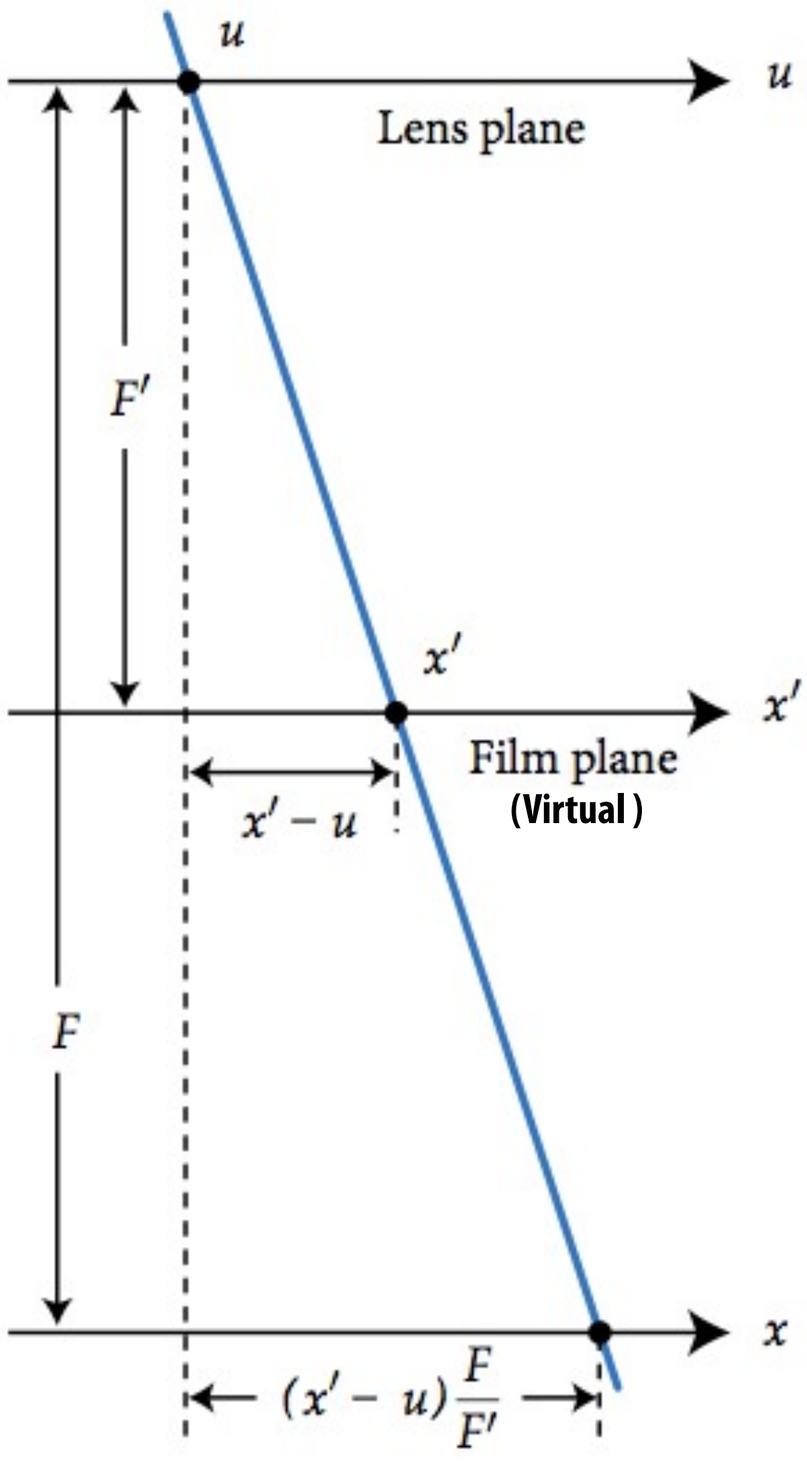


Image: Ng et al. 2006

Reparameterization



L_F = light field parameterized by lens and F plane
$L_{F'}$ = light field parameterized by lens and F′ planes

Define $L_{F'}$ using L_F

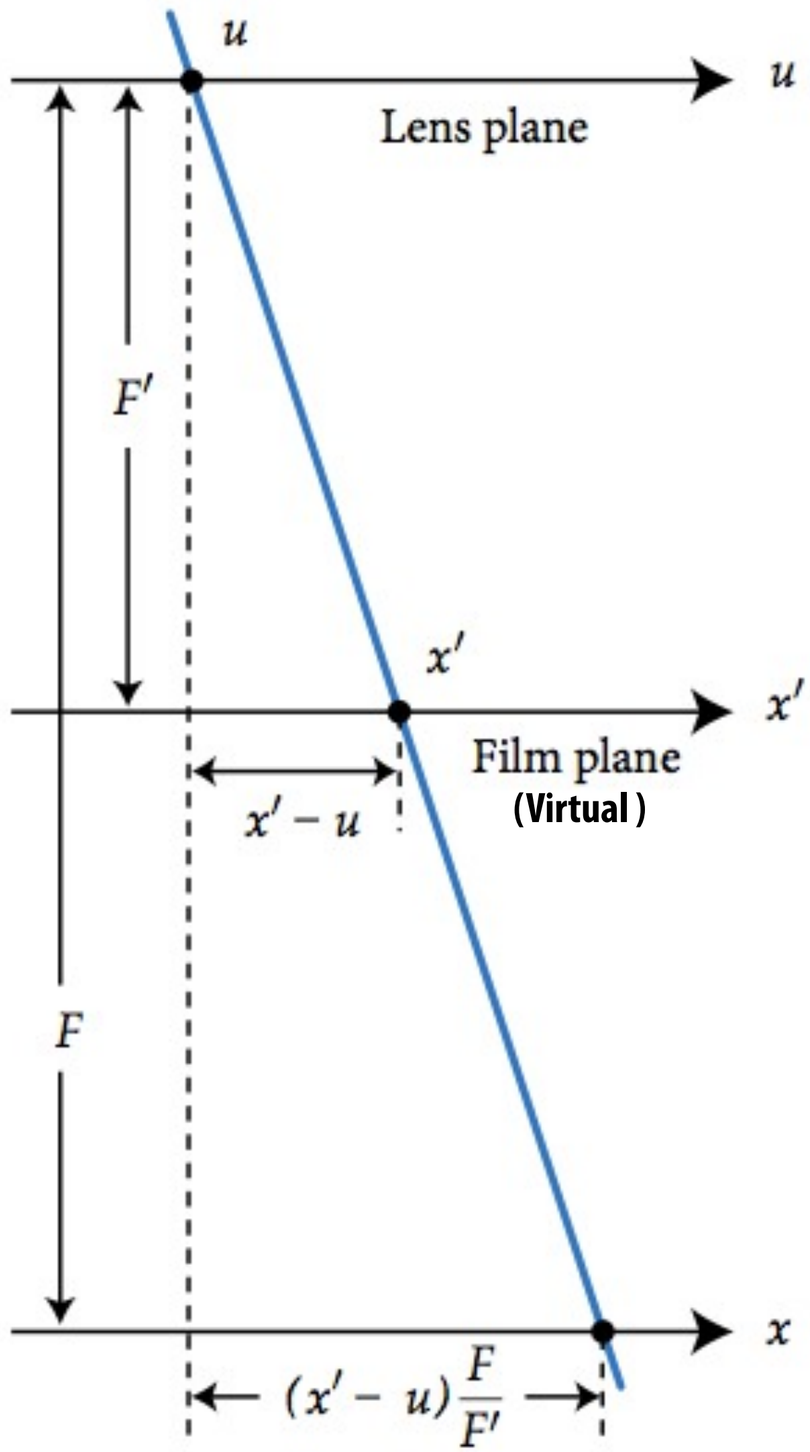
$$\alpha = F'/F$$

$$L_{F'}(x',y',u,v) = L_F\left(u + \frac{x'-u}{\alpha},\ v + \frac{y'-v}{\alpha},\ u,\ v\right)$$

$$= L_F\left(u\left(1-\frac{1}{\alpha}\right) + \frac{x'}{\alpha},\ v\left(1-\frac{1}{\alpha}\right) + \frac{y'}{\alpha},\ u,\ v\right)$$

Image: Ng et al. 2006

Refocused photograph



Integrate all light arriving at point (x′,y′) on F′ plane

$$E_{(\alpha \cdot F)}(x', y') = \frac{1}{\alpha^2 F^2} \iint L_F \left(u(1-1/\alpha) + x'/\alpha,\ v(1-1/\alpha) + y'/\alpha,\ u,\ v\right)\, du\, dv$$

Define $L_F^{(u,v)}$ to be sub-aperture image from lens region (u,v)

$$E_{(\alpha \cdot F)}(x', y') = \frac{1}{\alpha^2 F^2} \iint L_F^{(u,v)} \left(u(1-1/\alpha) + x'/\alpha,\ v(1-1/\alpha) + y'/\alpha\right)\, du\, dv$$

Sum of shifted, scaled sub-aperture images

Scale image by α (can ignore, invariant of lens position)
Shift image by ($u(1\text{-}1/\alpha)$, $v(1\text{-}1/\alpha)$)

Image: Ng et al. 2006

Video

Potential advantages of light-field cameras

(For traditional photography)

- Remove (or significantly simplify) auto-focus
  - Diminished shutter lag
- Better low light shooting
  - Shoot with aperture wide open (traditional camera has shallow depth of field = high possibility of misfocus)
    - Can digitally refocus after the shot
    - Can digitally extend depth of field
- New lens form factors, capabilities
  - Correct for aberrations digitally

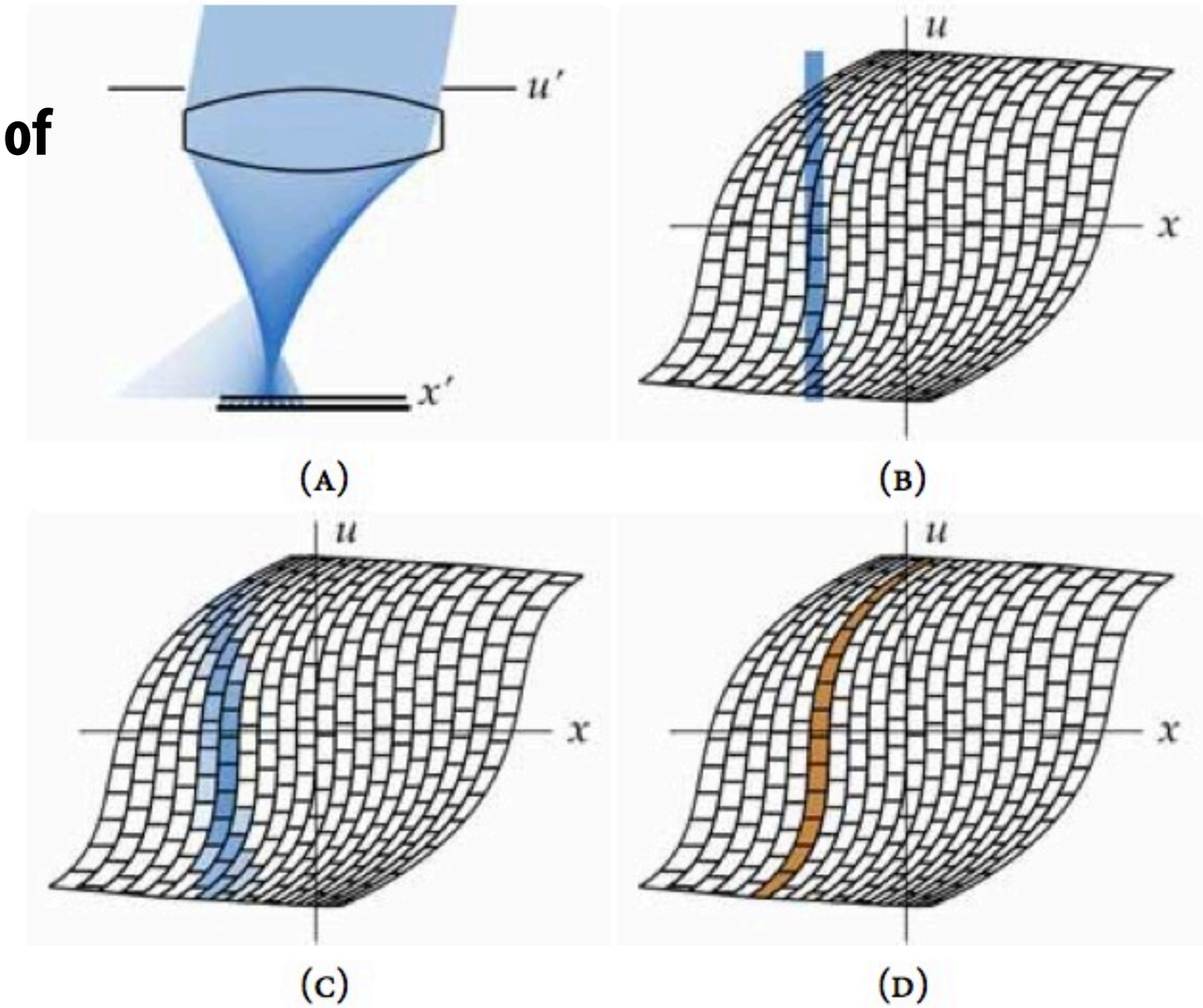


Image: Ng et al. 2006

Cool new applications

- Interactive pictures
  - Post shot refocusing
  - Parallax
- Stereo (3D!)
- Extended depth of field

Lytro consumer light field camera

11 Megapixel (“Megaray”) camera

F/2 8x zoom lens

Other computational cameras

Pelican Imaging

Raytrix Plenoptic Camera

Trends

- No free lunch: sense directional information at cost of spatial resolution
  - Ng's original prototype: 16 MP sensor, 300x300 images

- Light field cameras will make use of increasing sensor pixel densities
  - More directional resolution = increased refocusing capability
  - More spatial resolution at fixed directional resolution
  - Few reasons to make larger resolution sensors for traditional cameras today

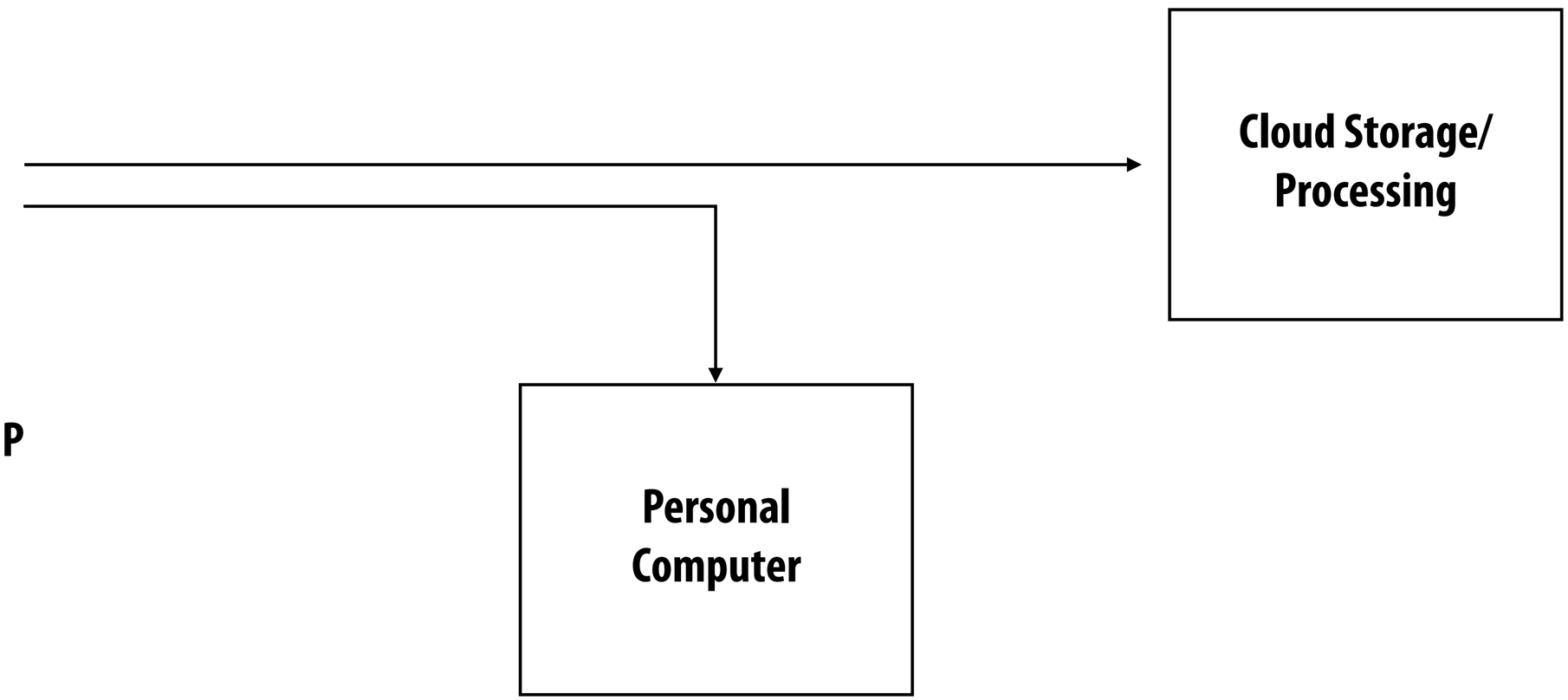
- High resolution cameras pose challenges!
  - Computation challenges
  - Storage challenges
  - Transfer challenges

Sense - process - communicate

Where to perform computation?

What representation to transmit? Full light field? Single image?

Future consumer light field camera ~ 50-100 MP



Summary

- Light field photography
  - From camera user's perspective, very much like traditional photography
  - Capture light field in a single exposure
  - Perform (large amounts of) computation to compute final image

- Happy Thanksgiving! Take some great pictures!