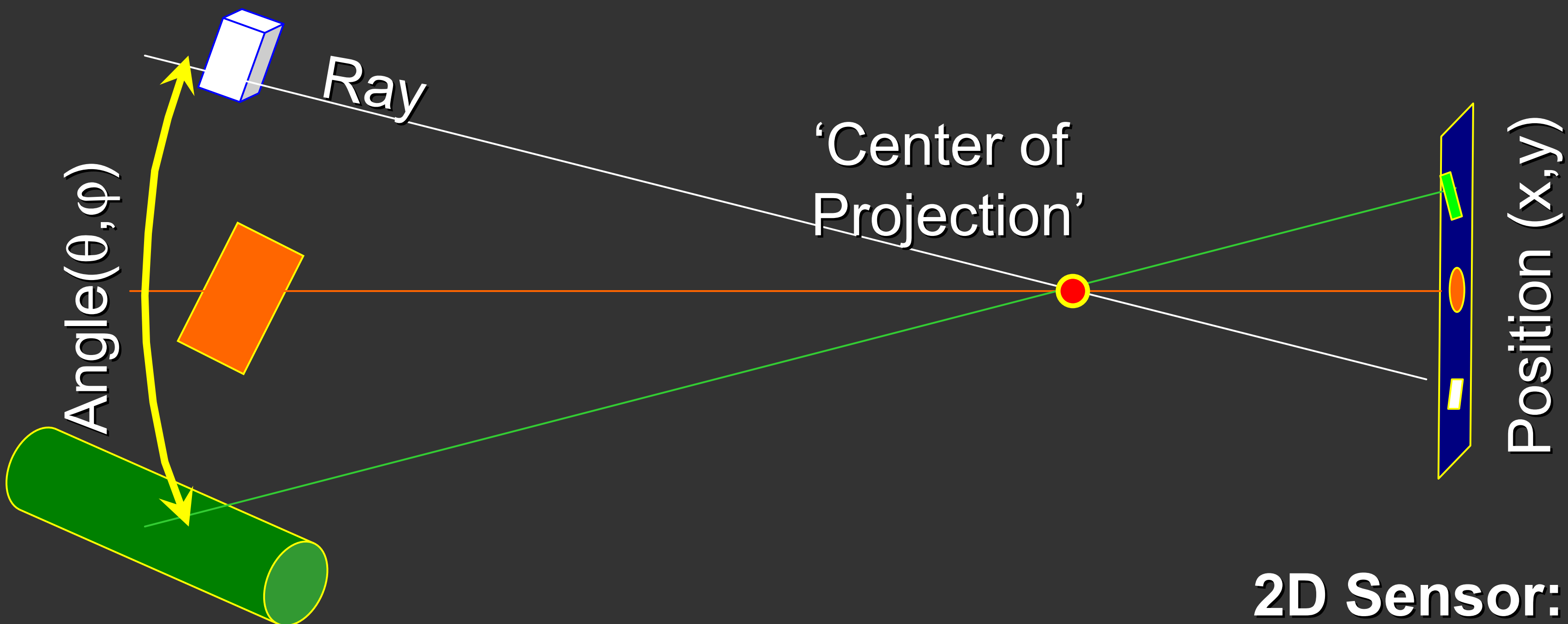
Improving Film-Like Photography

aka,

Epsilon Photography

Ankit Mohan

Film-like Optics: Imaging Intuition



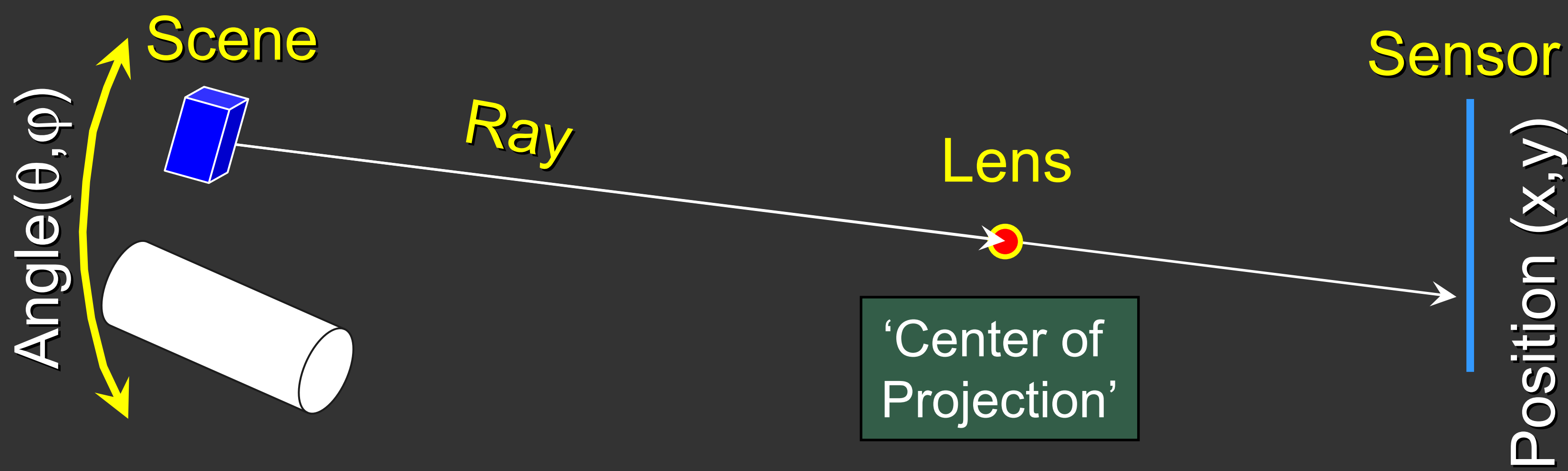
Well-Lit 3D Scene:

2D Sensor:

Pixel Grid
or Film,…

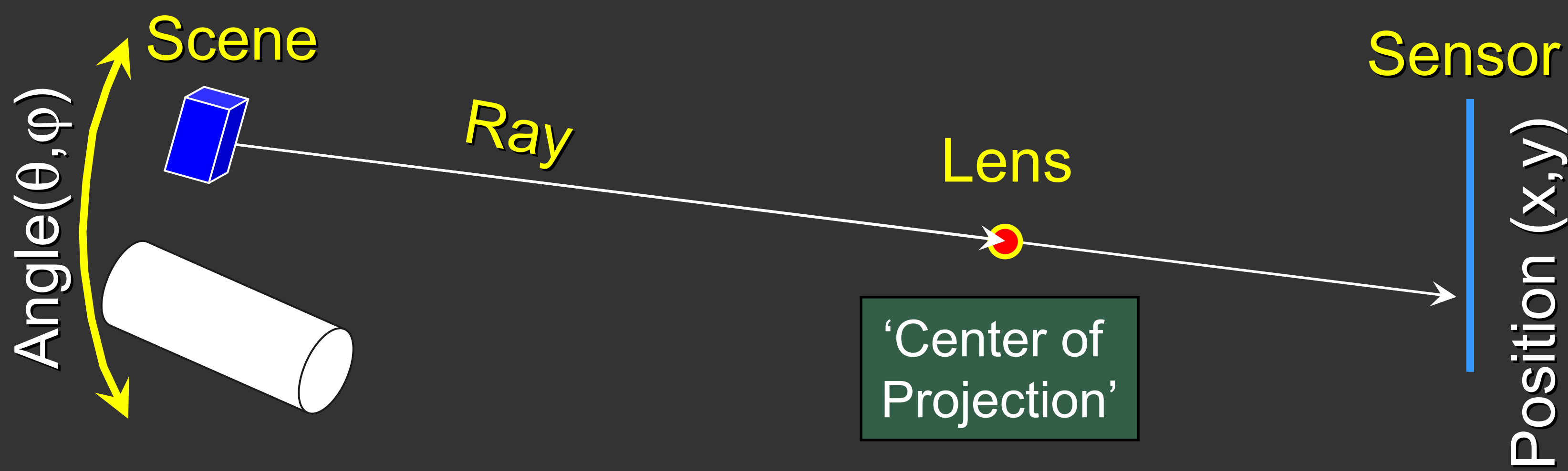
'Pinhole' Model: Rays copy scene onto 'film'

Film-like Optics: Imaging Intuition

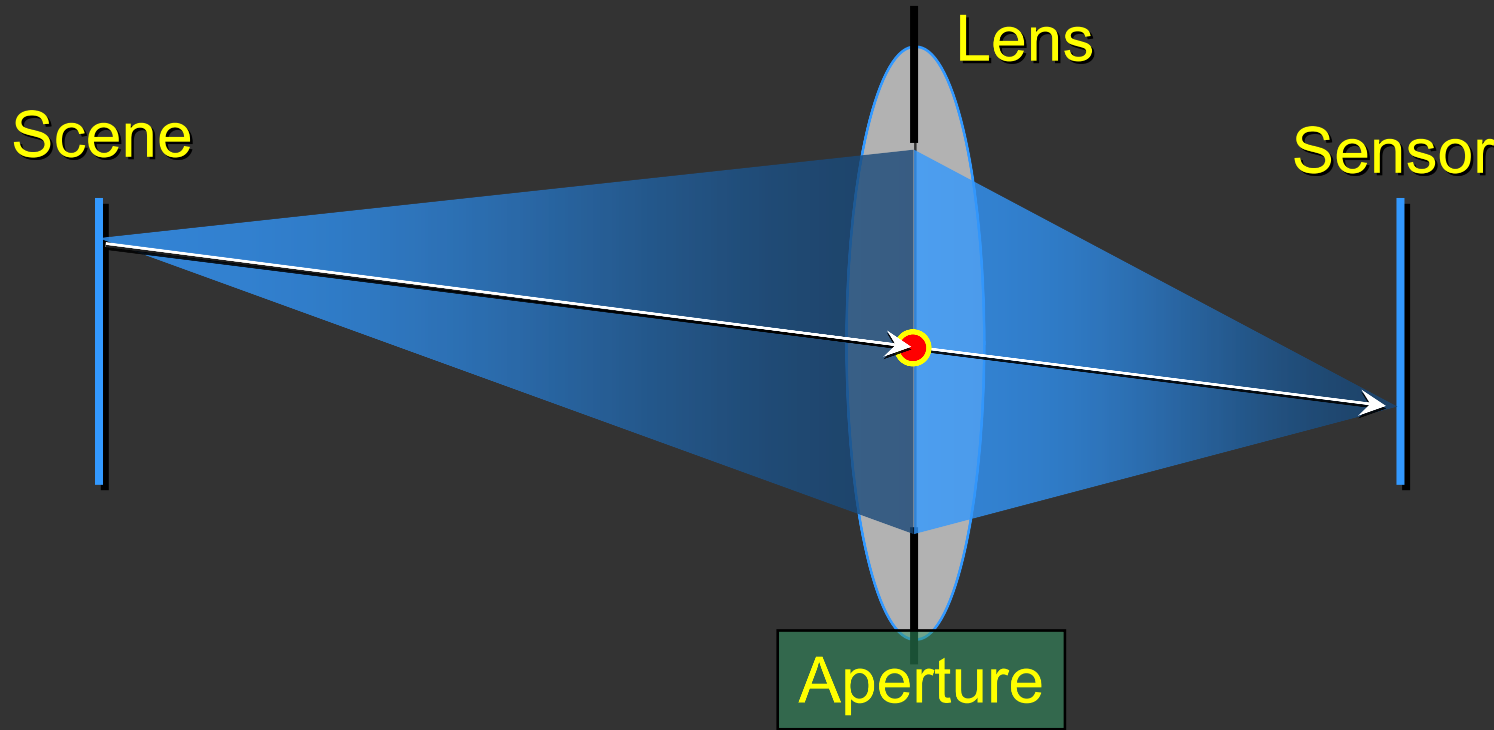


'Pinhole' Model: Rays copy scene onto 'film'

Not *One* Ray, but a *Bundle* of Rays



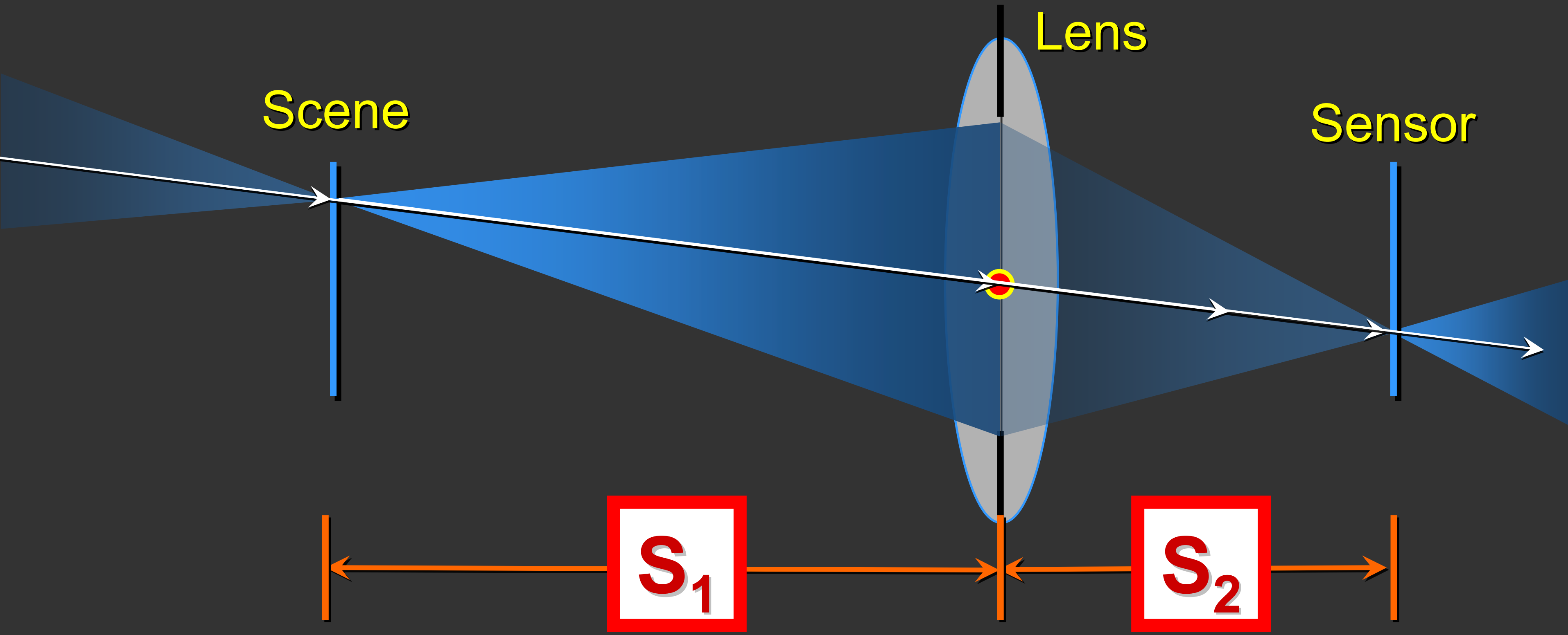
Not *One* Ray, but a *Bundle* of Rays



- (BUT Ray model *isn't perfect*: ignores diffraction)
- Lens, aperture, and diffraction
  sets the point-spread-function (PSF)

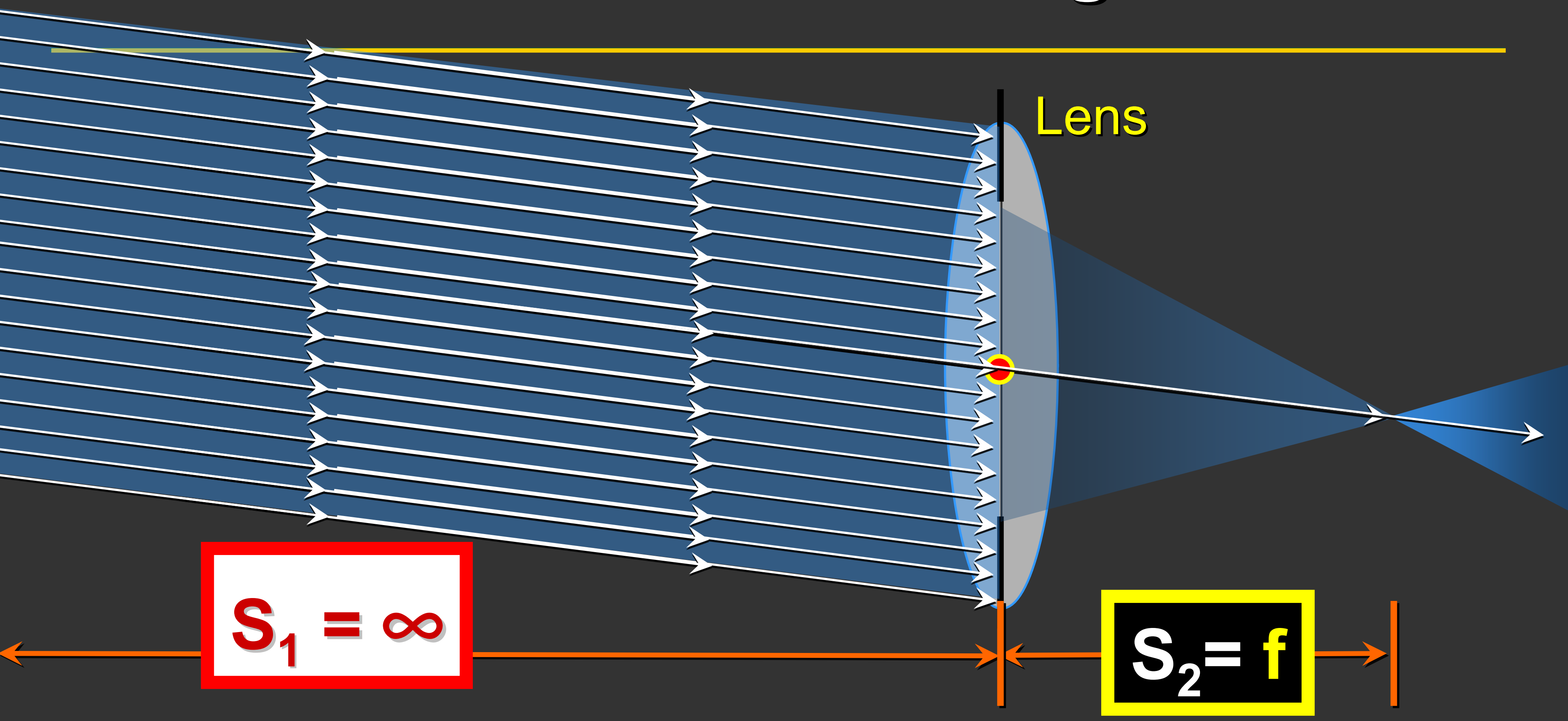
(How? See: Goodman,J.W. 'An Introduction to Fourier Optics' 1968)

Review: Lens Measurements



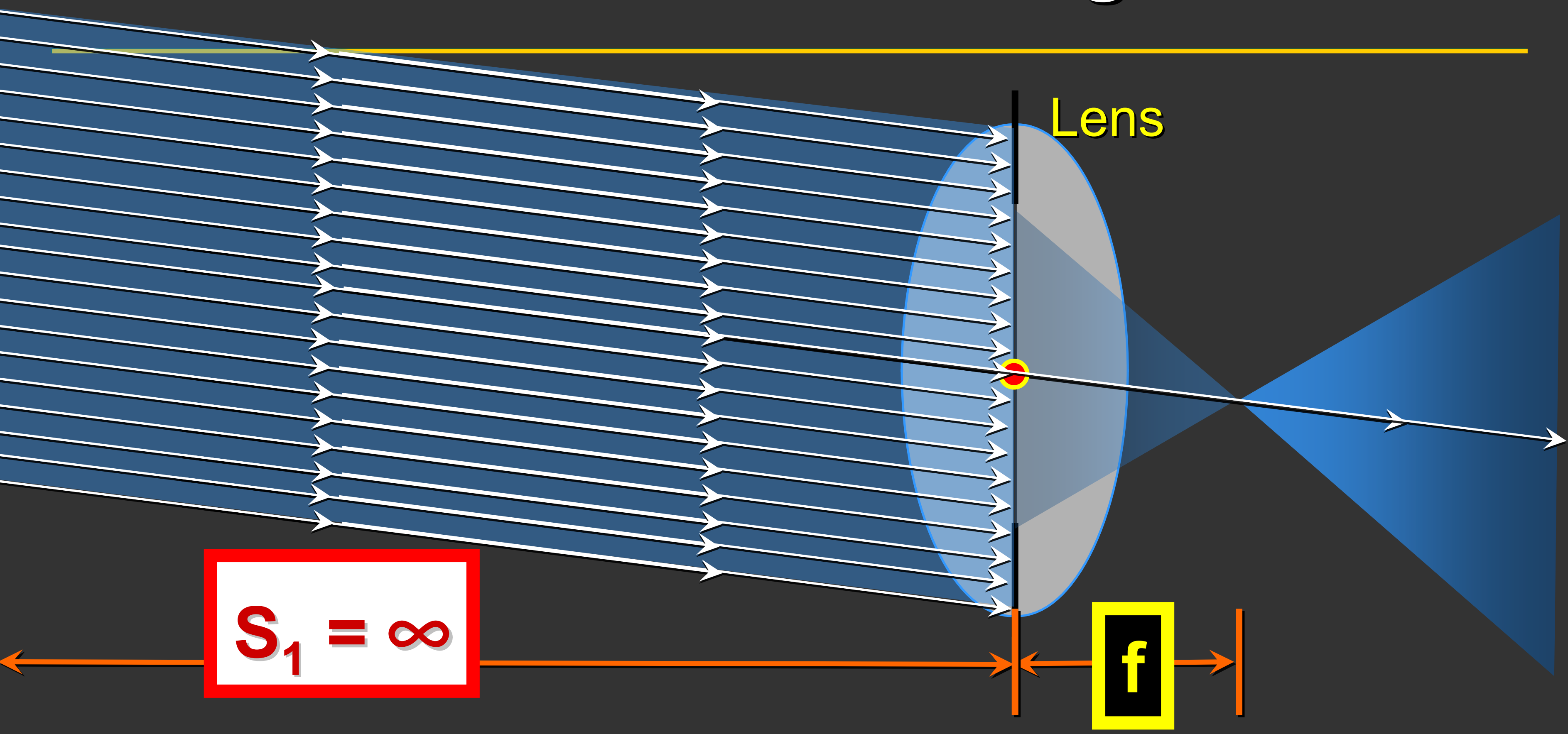
- How do we compute S_1 and S_2 for a lens?
- What is the 'Ray-Bending Strength' for a lens?

Review: Focal Length f



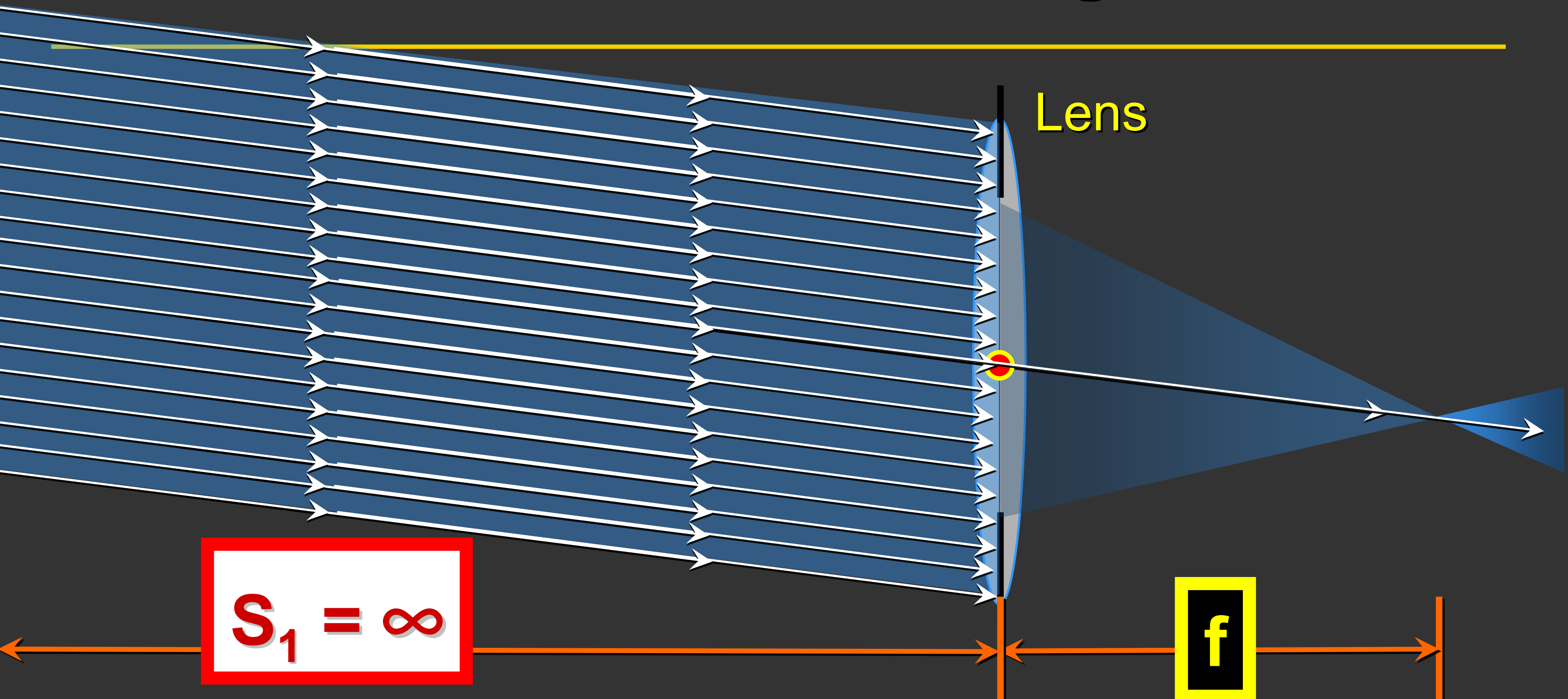
- Lens focal length f : <u>where parallel rays converge</u>

Review: Focal Length f



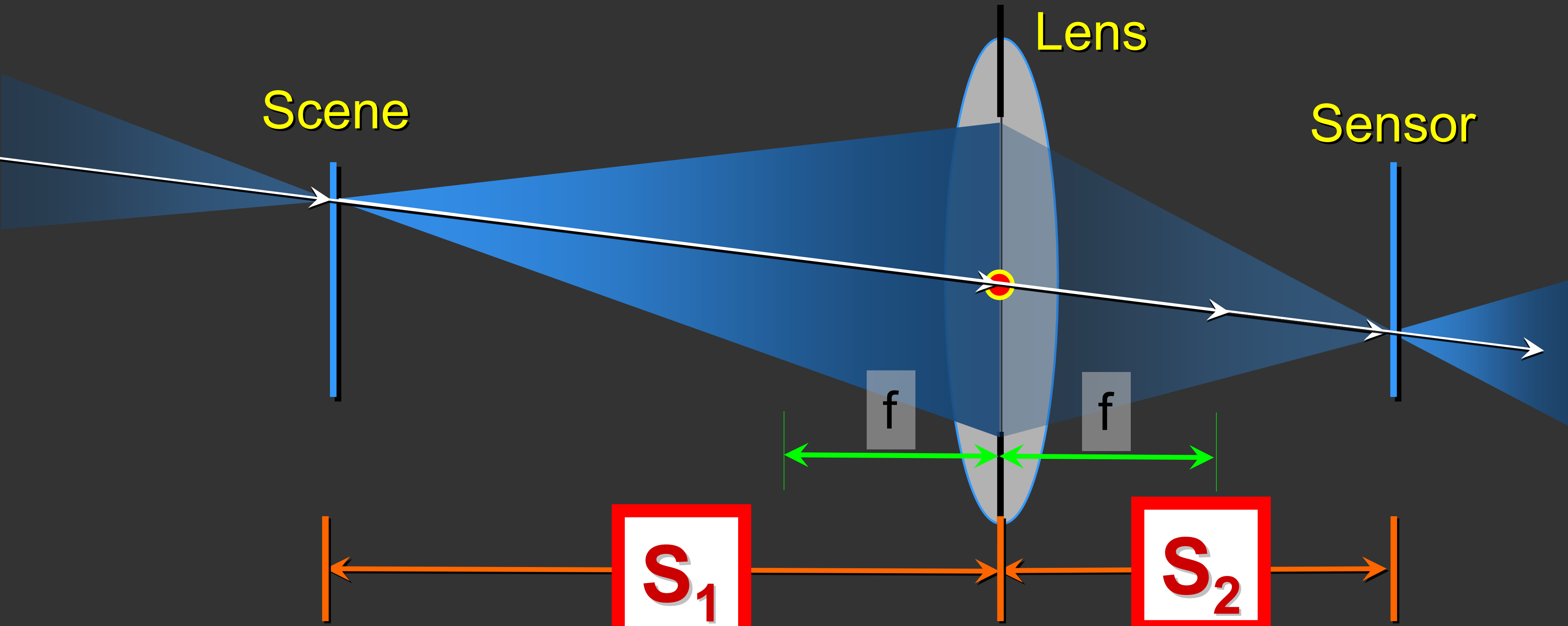
- Lens focal length f : <u>where parallel rays converge</u>
- <u>*smaller*</u> focal length: <u>***more***</u> ray-bending ability…

Review: Focal Length f



- Lens focal length f : <u>where parallel rays converge</u>
- <u>*greater*</u> focal length: <u>***less***</u> ray-bending ability…
- For flat glass; for air : $f = \infty$

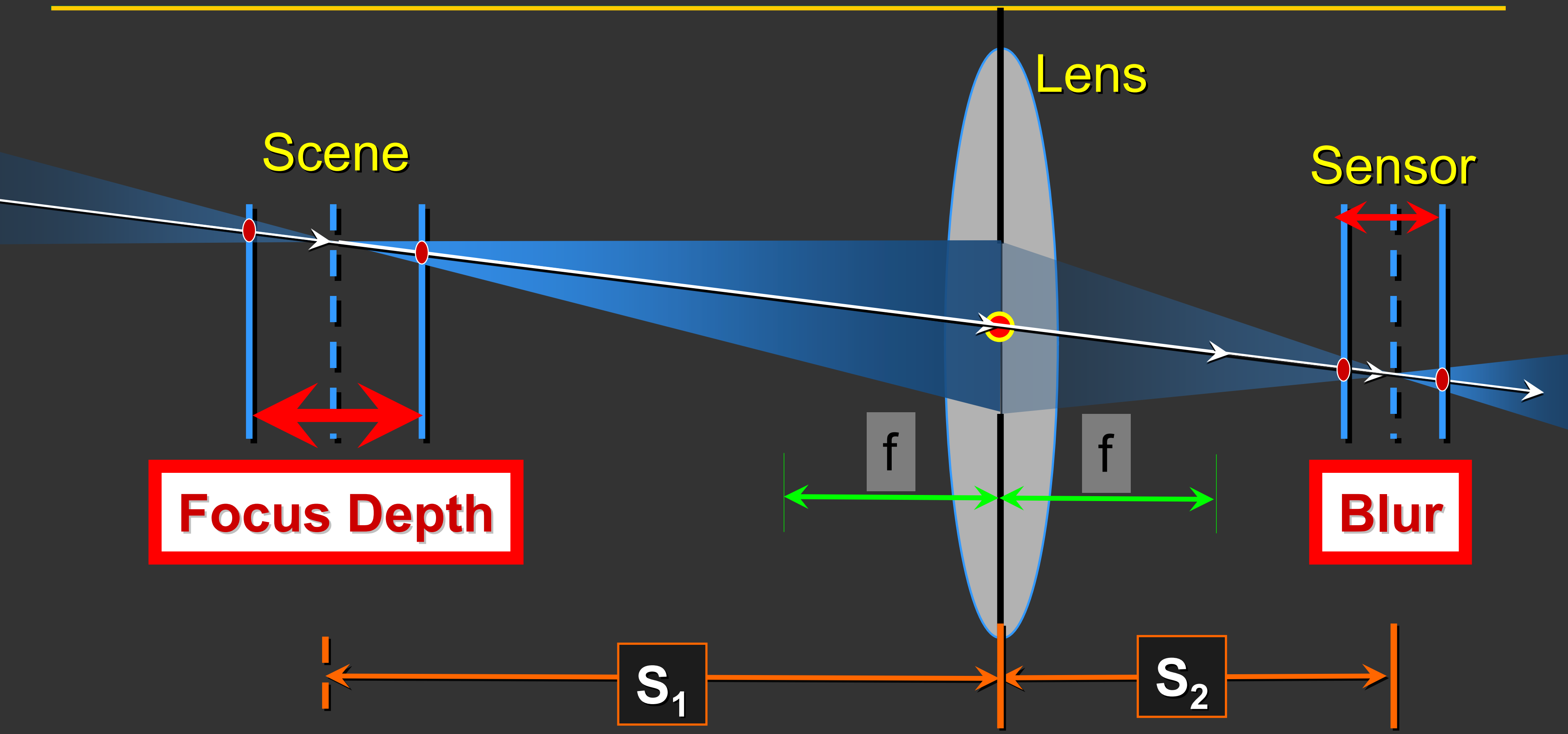
Review: Thin Lens Law



- **Thin Lens Law:** in focus when: $\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}$
- Note that $S_1 \geq f$ and $S_2 \geq f$

Try it Live! Physlets… http://webphysics.davidson.edu/Applets/Optics/intro.html

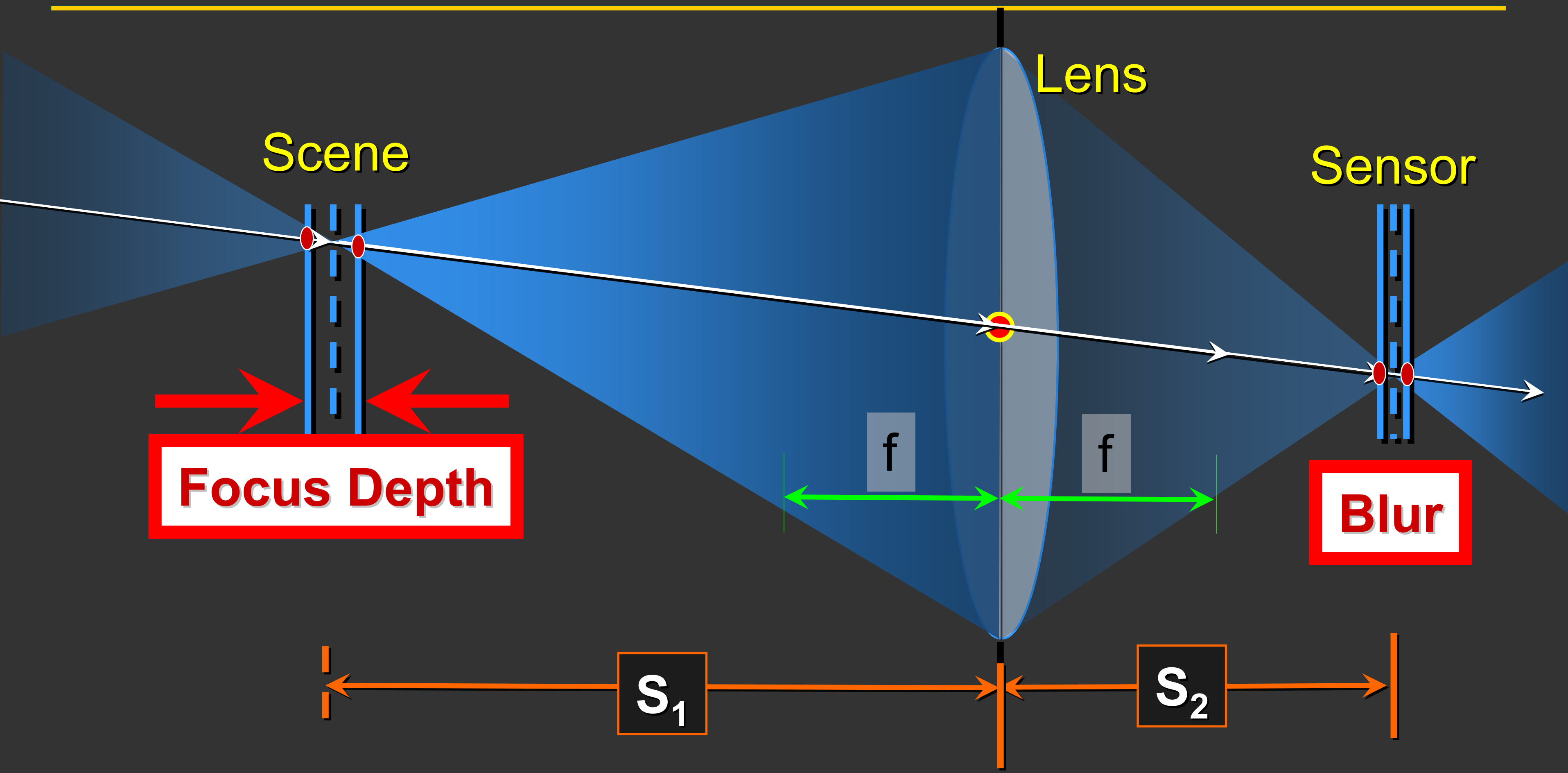
Aperture and Depth-Of-Focus:



For *same* focal length:

- **Smaller Aperture → Larger focus depth, but less light**

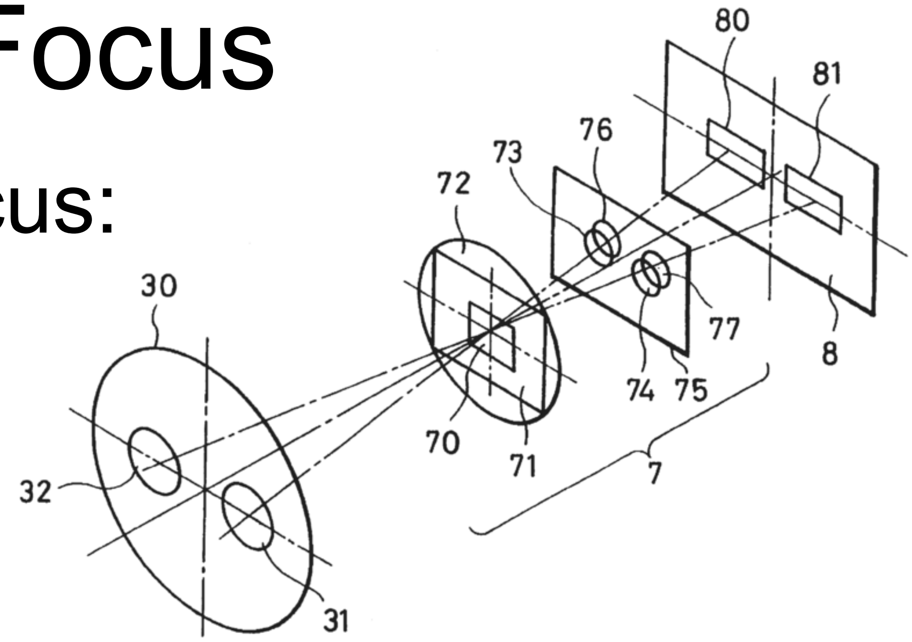
Aperture and Depth-Of-Focus:



For *same* focal length:

- Larger Aperture → smaller focus depth, but more light

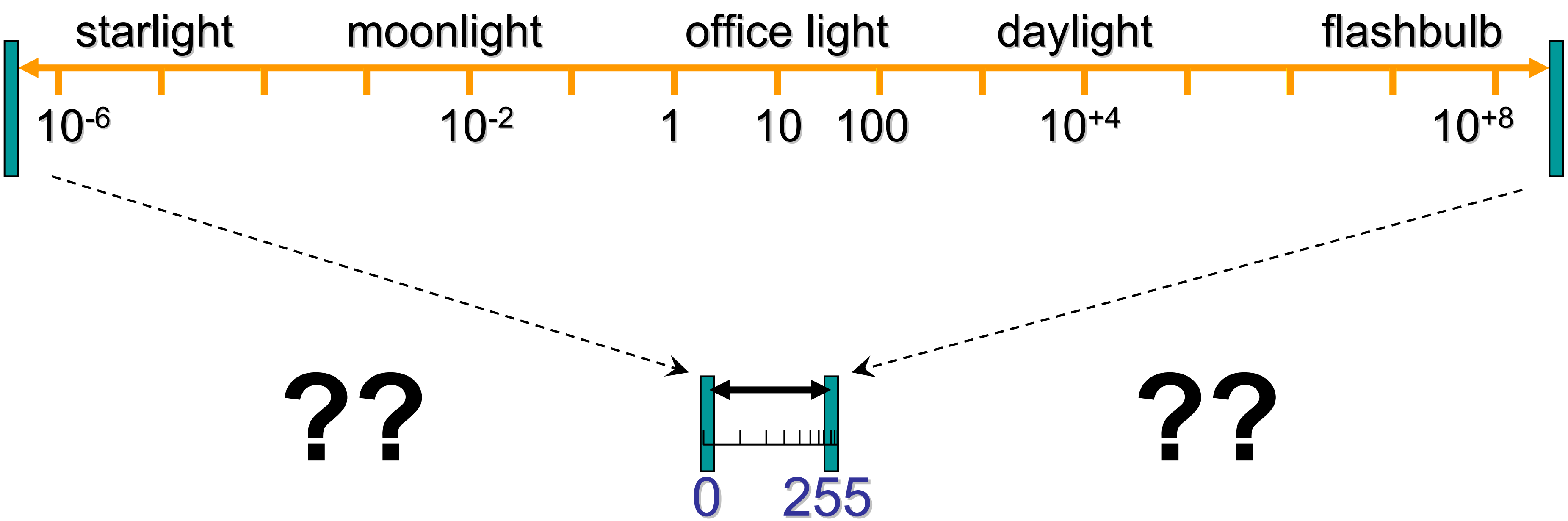
Auto-Focus



- Phase based autofocus: Used in most SLR cameras.
- Contrast based autofocus: Maximize image contrast in AF region; used in most digital compact cameras.
- Active autofocus: Ultrasonic and IR based; used in compact film cameras.

Problem: Map Scene to Display

Domain of Human Vision:
from ~10^{-6} to ~10^{+8} cd/m^2

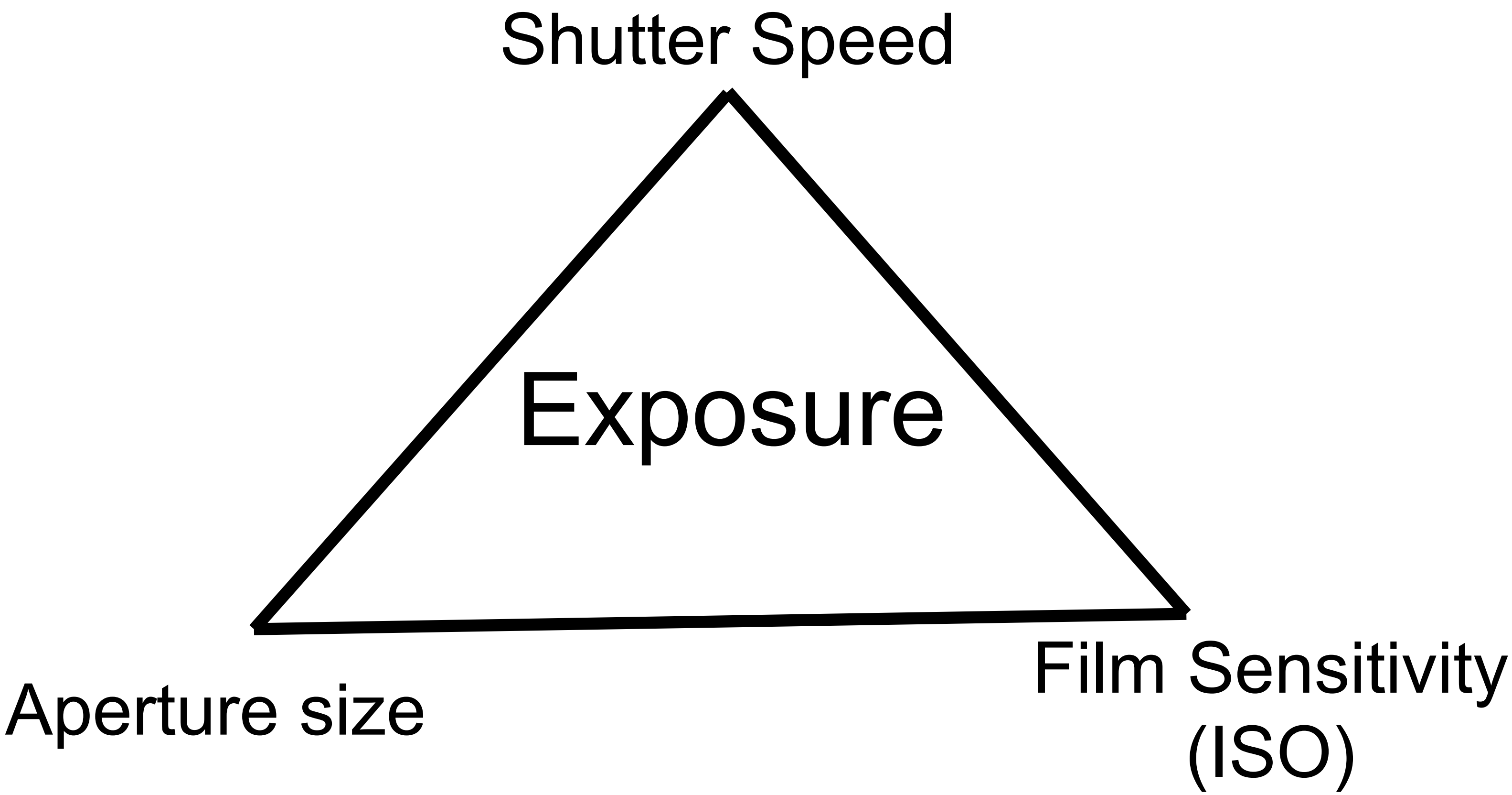


Range of Typical Displays:
from ~1 to ~100 cd/m^2

Dynamic Range Limits

Under-Exposure
- Highlight details: Captured
- Shadow details: Lost

Over-Exposure
- Highlight details: Lost
- Shadow details: Captured

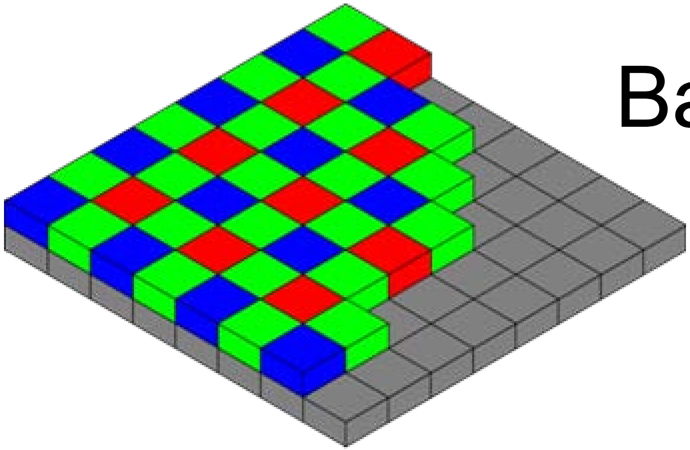


Linear Relationship

Auto-Exposure

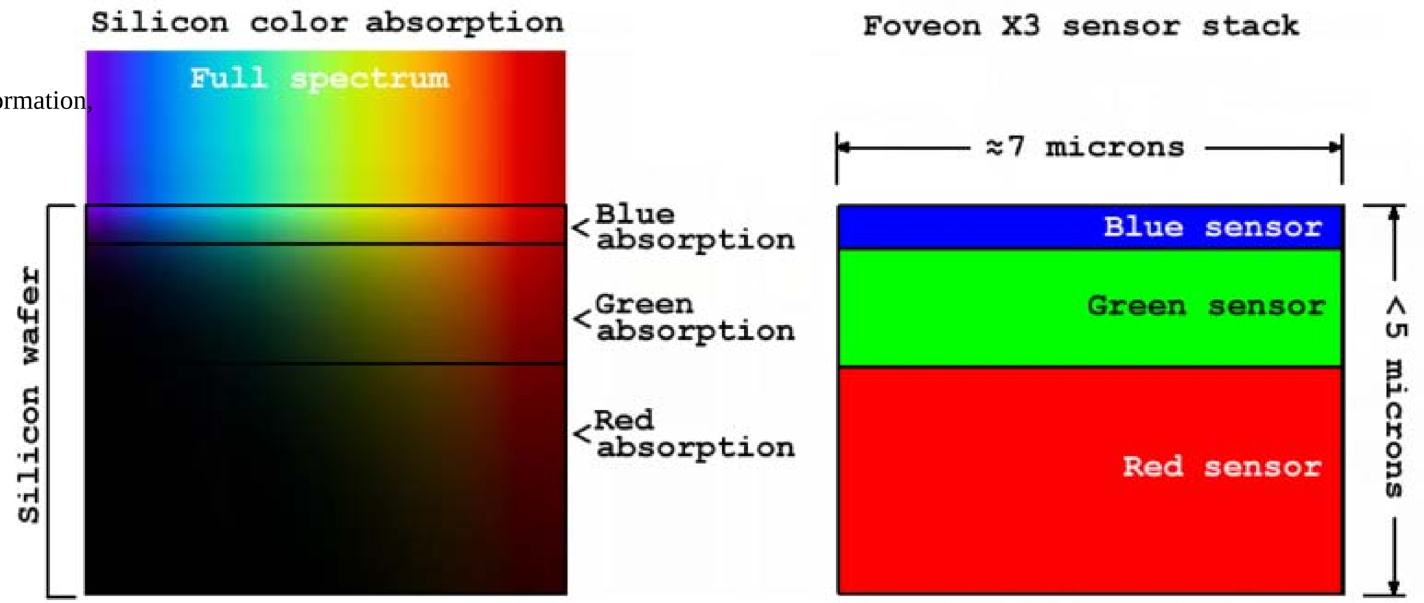
[Nikon Matrix Metering]

Color sensing in Digital Cameras

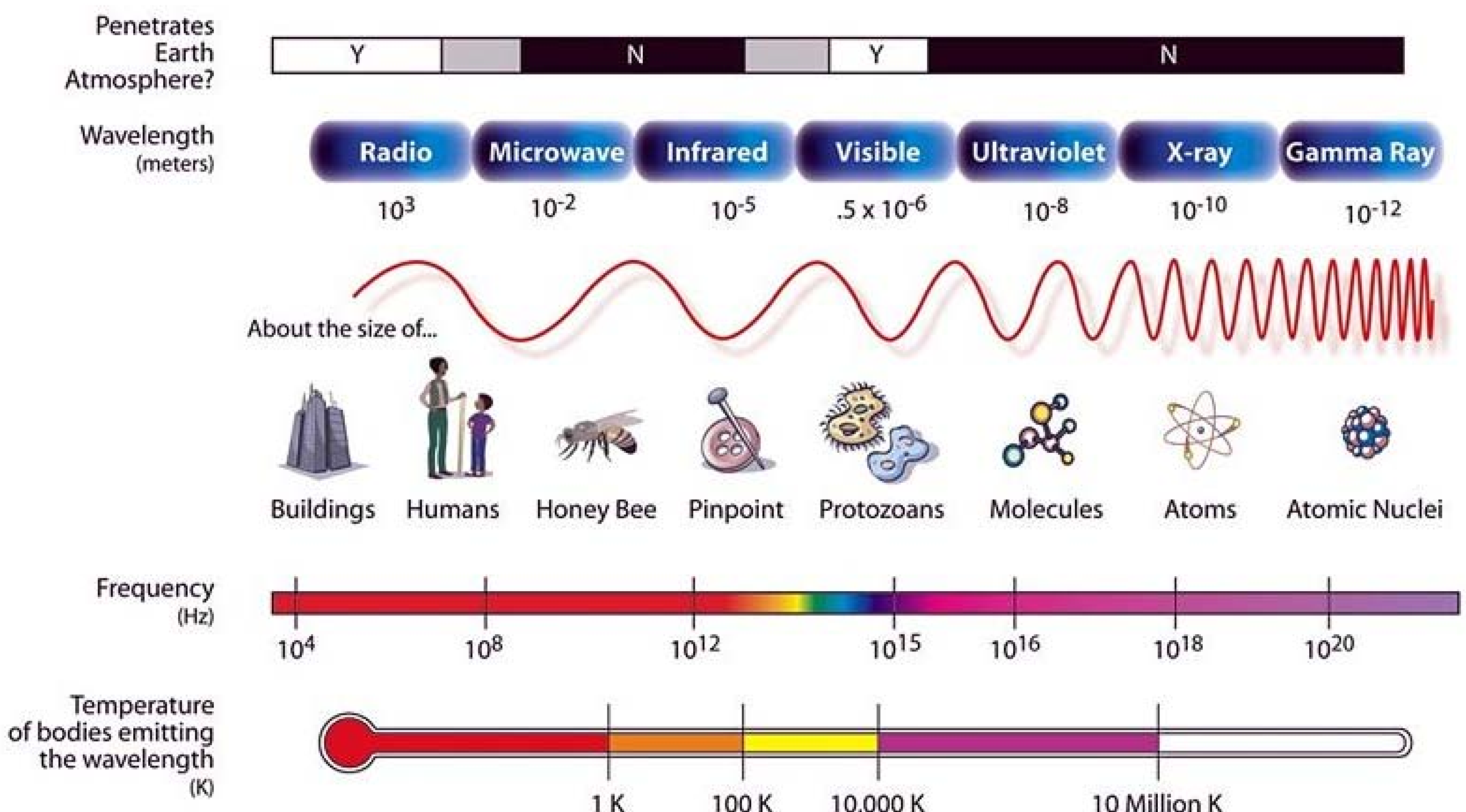


Bayer filter pattern

Foveon X3 sensor



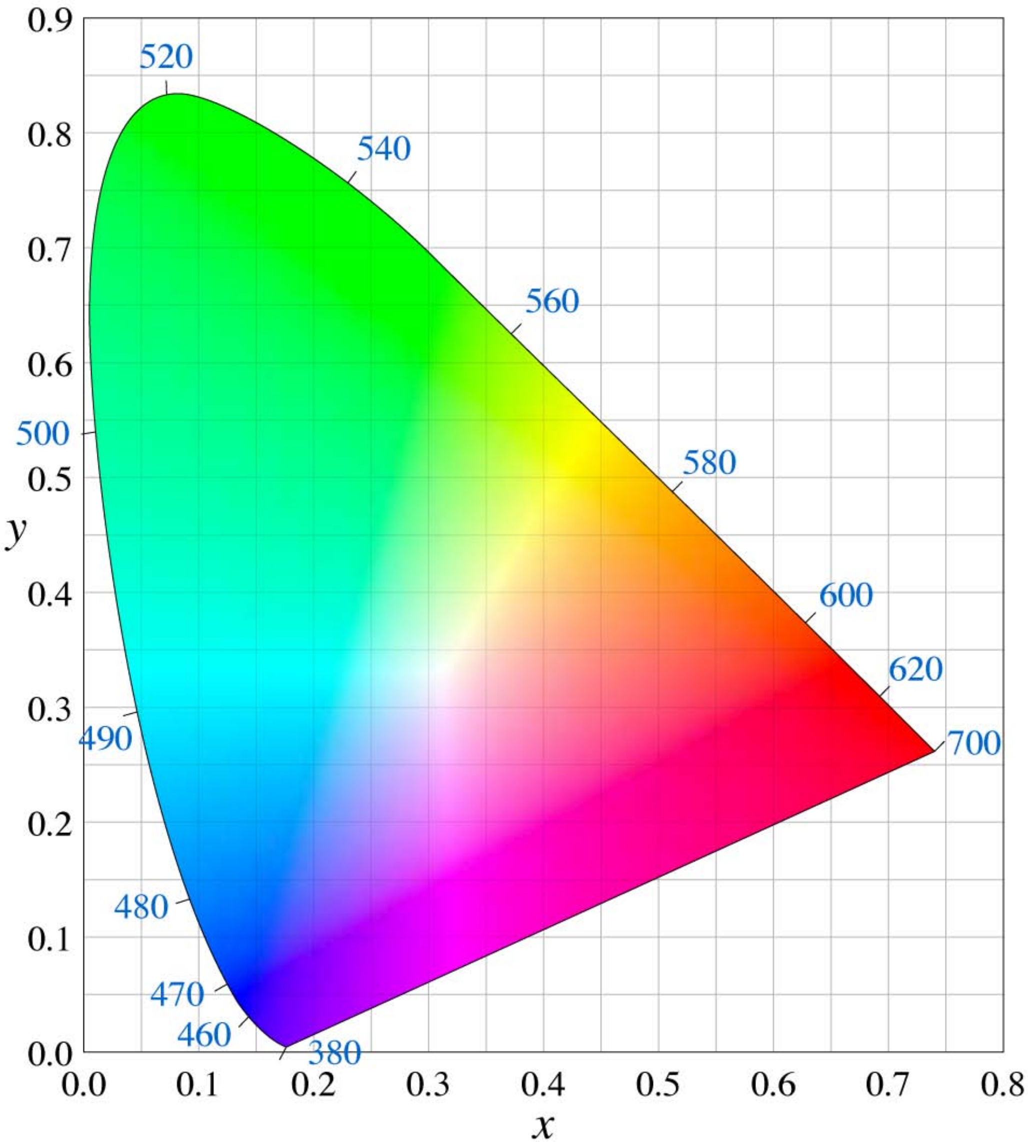
Electromagnetic spectrum



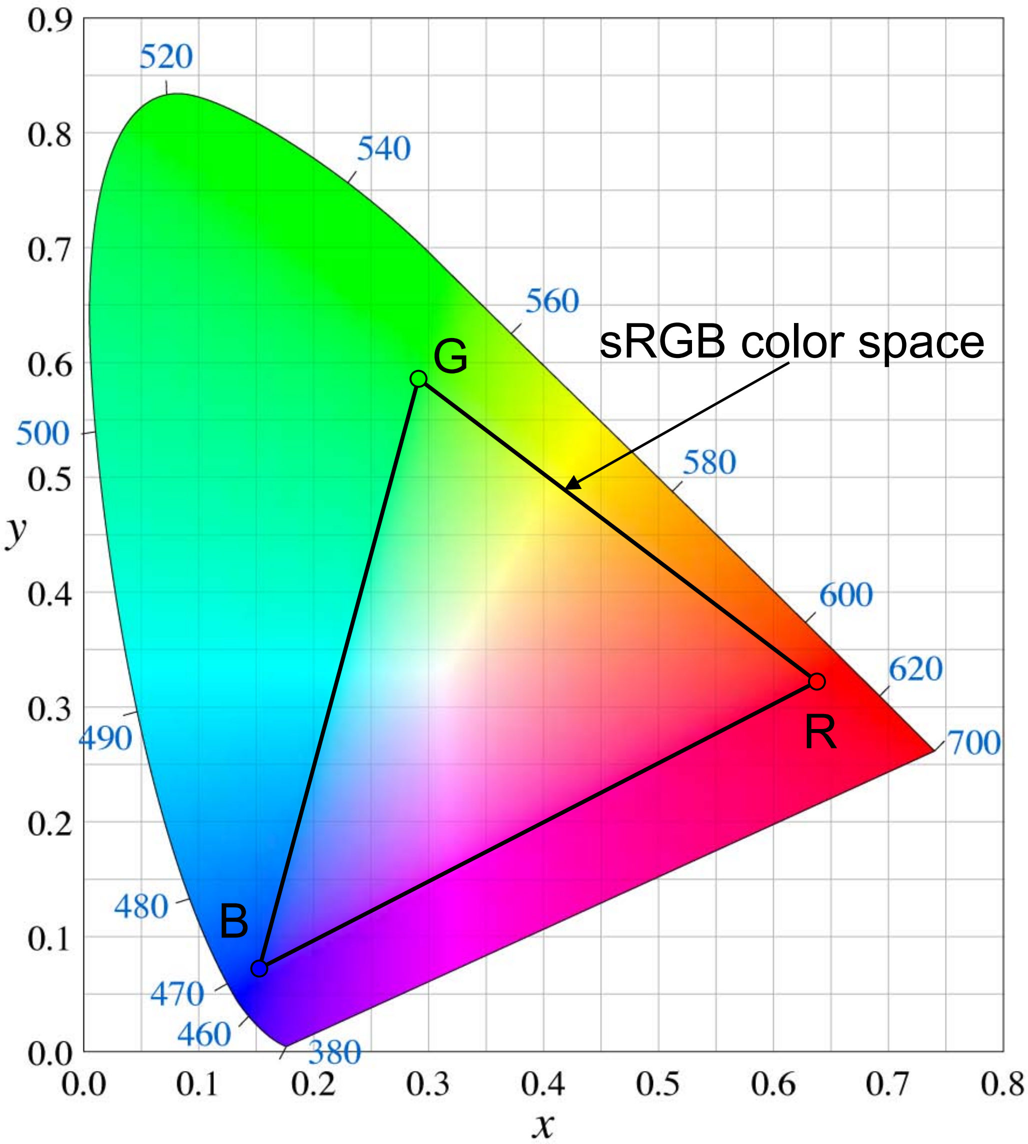
Source: NASA

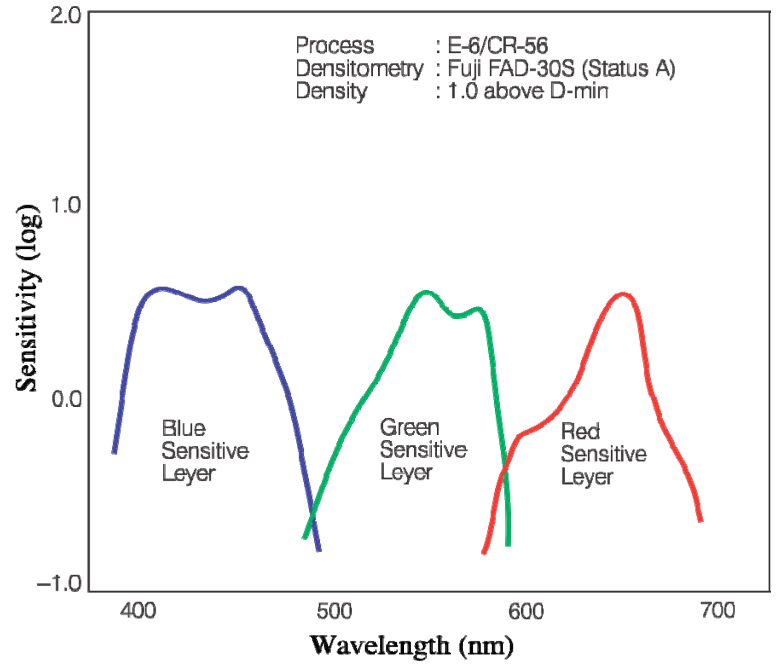
Visible Light: ~400-700 nm wavelength

CIE 1931 Chromaticity Diagram



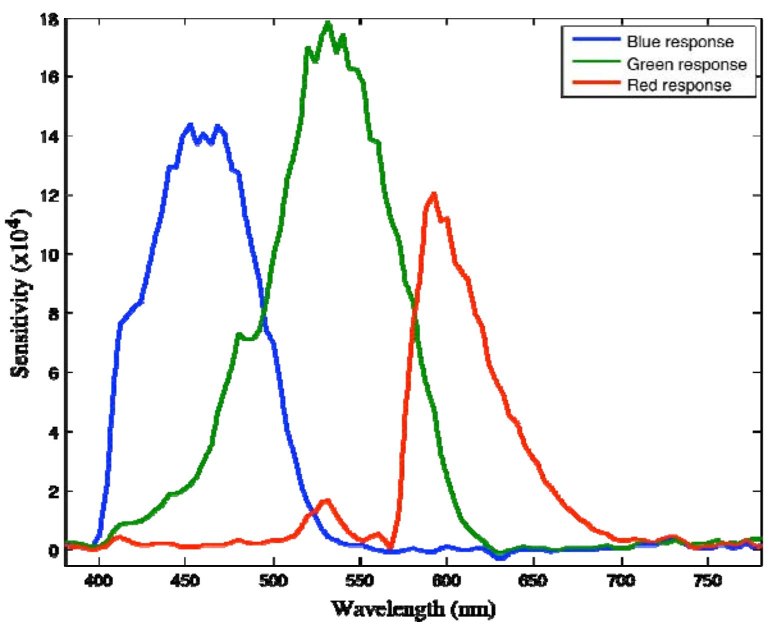
Three color primaries





Fuji Velvia 50 film

Nikon D70 camera



Epsilon Photography

Capture multiple photos, each with slightly different camera parameters.

- Exposure settings
- Spectrum/color settings
- Focus settings
- Camera position
- Scene illumination

Epsilon Photography

- epsilon over time (bracketing)
- epsilon over sensors (3CCD, SAMP, camera arrays)
- epsilon over pixels (bayer)
- epsilon over multiple axes

Epsilon over **time** (*Bracketing*)

Capture a sequence of images (over time) with epsilon change in parameters

High Dynamic Range (HDR) capture

- negative film = 250:1 (8 stops)
- paper prints = 50:1
- [Debevec97] = 250,000:1 (18 stops)
- Old idea; [Mann & Picard 1990]
  hot topic at recent SIGGRAPHs

Memorial Church photo sequence from Paul Debevec,
"Recovering High Dynamic Range Radiance Maps from Photographs."
(SIGGRAPH 1997)

Epsilon over **time** (*Bracketing*)

Prokudin-Gorskii, Sergei Mikhailovich, 1863-1944, photographer. ``The Bukhara Emir'', Prints and Photographs Division, Library of Congress.

Epsilon over **time** (*Bracketing)*

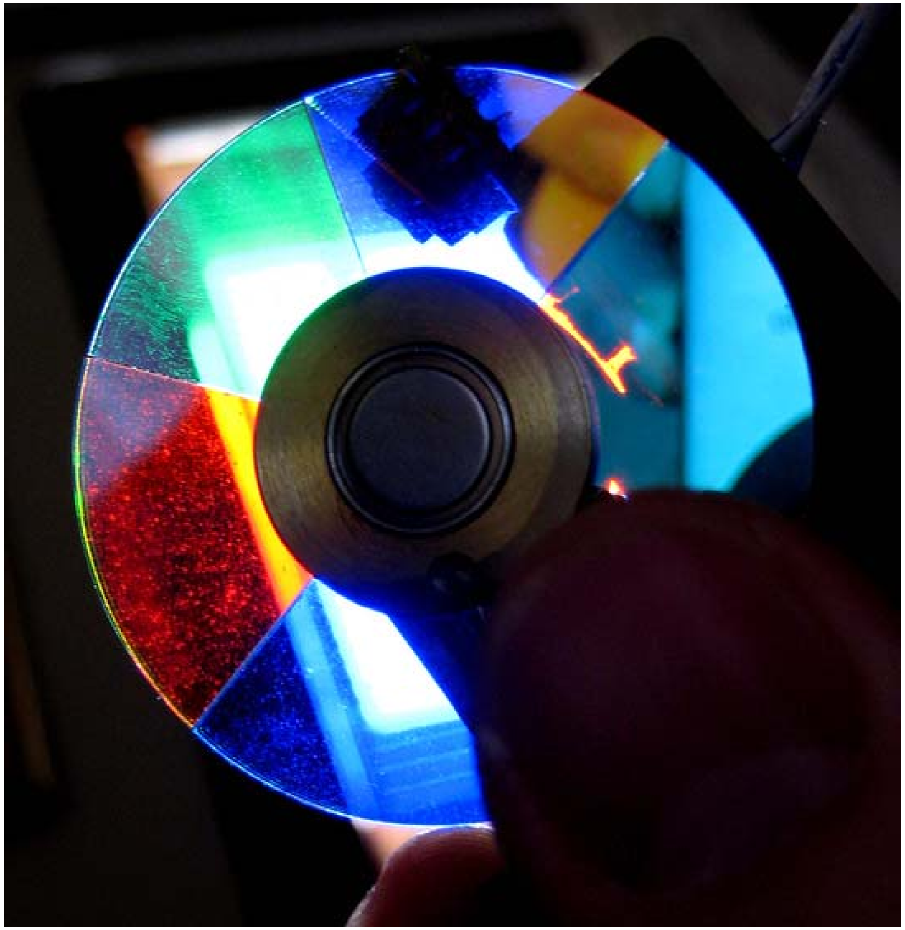


Image courtesy of shannonpatrick17 on Flickr.

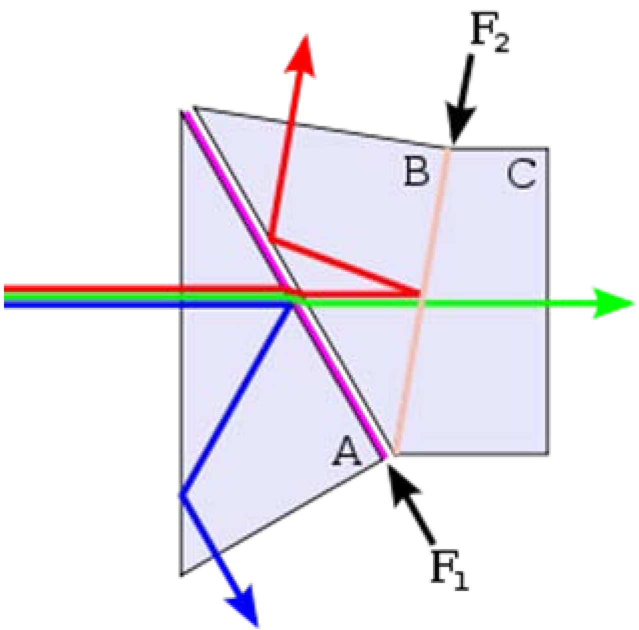
Color wheel used in DLP projectors

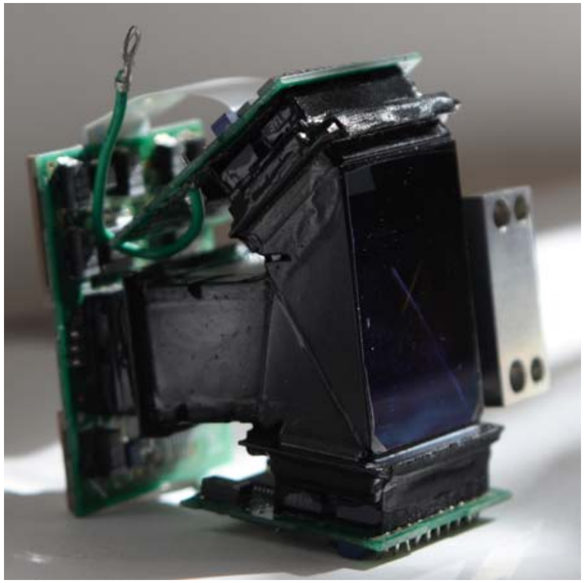
Epsilon over **sensors**

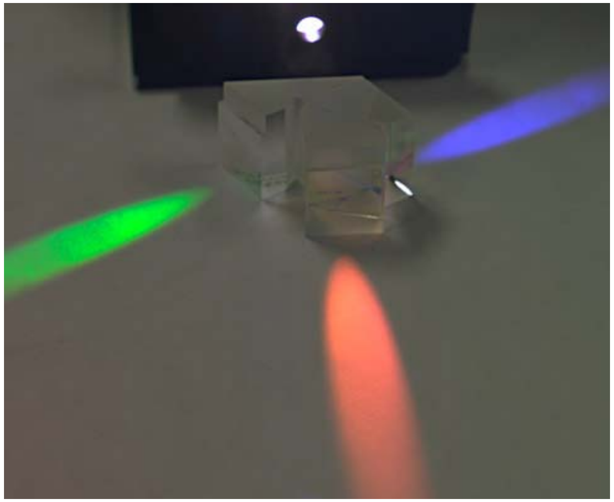
Capture a set of images (over different sensors or cameras) with epsilon change in parameters

Epsilon over **sensors**

3CCD imaging system for color capture







Epsilon over **sensors**

Single-Axis Multi-Parameter (SAMP) Camera
[McGuire et al, 2005]

Multiple cameras at the same virtual position

Images removed due to copyright restrictions.

Epsilon over **sensors**

Camera Arrays

Epsilon over camera position

Image removed due to copyright restrictions.

64 tightly packed commodity CMOS webcams, 30 Hz, scalable, real-time

[Yang, J. C. et al. "A Real-Time Distributed Light Field Camera." *Eurographics Workshop on Rendering* (2002), pp. 1–10]

Epsilon over **sensors**

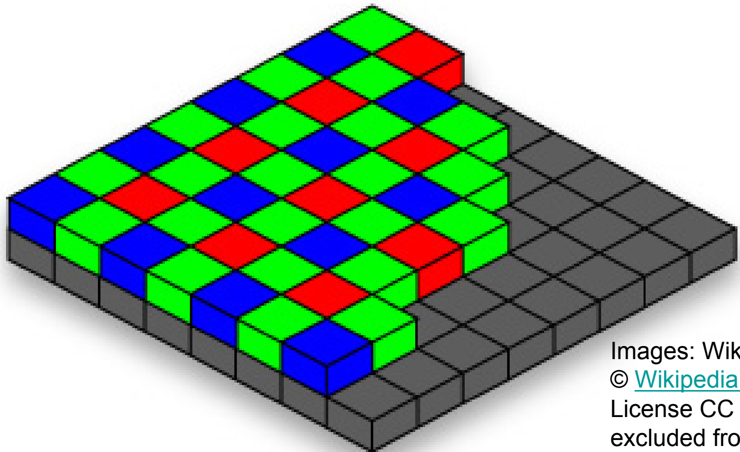
Stanford Camera Array [Wilburn et al, SIGGRAPH 2005]

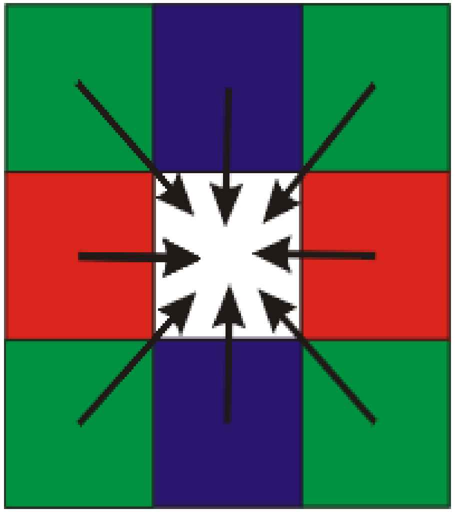
Epsilon over **pixels**

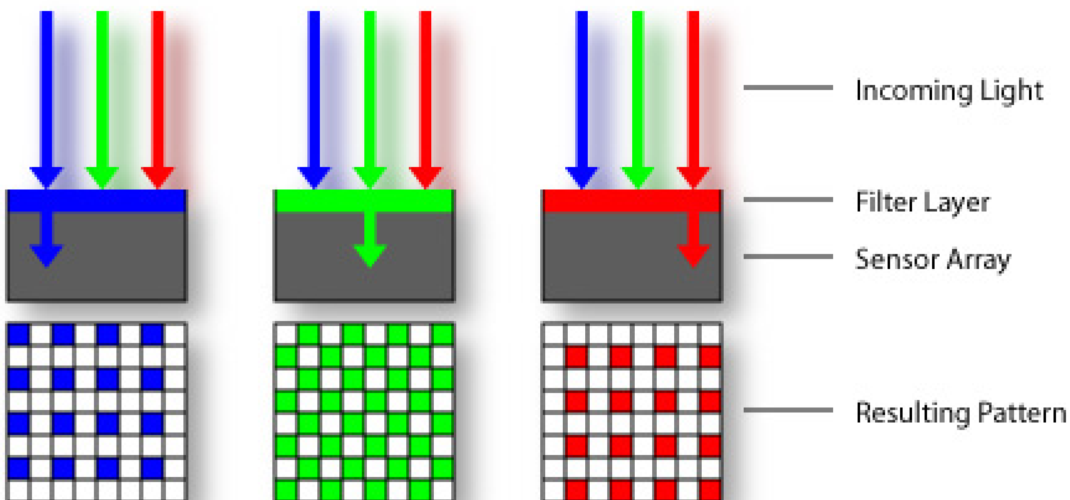
Capture images (over different pixels on the same sensor) with epsilon change in parameters

Epsilon over **pixels**

Bayer Mosaicing for color capture







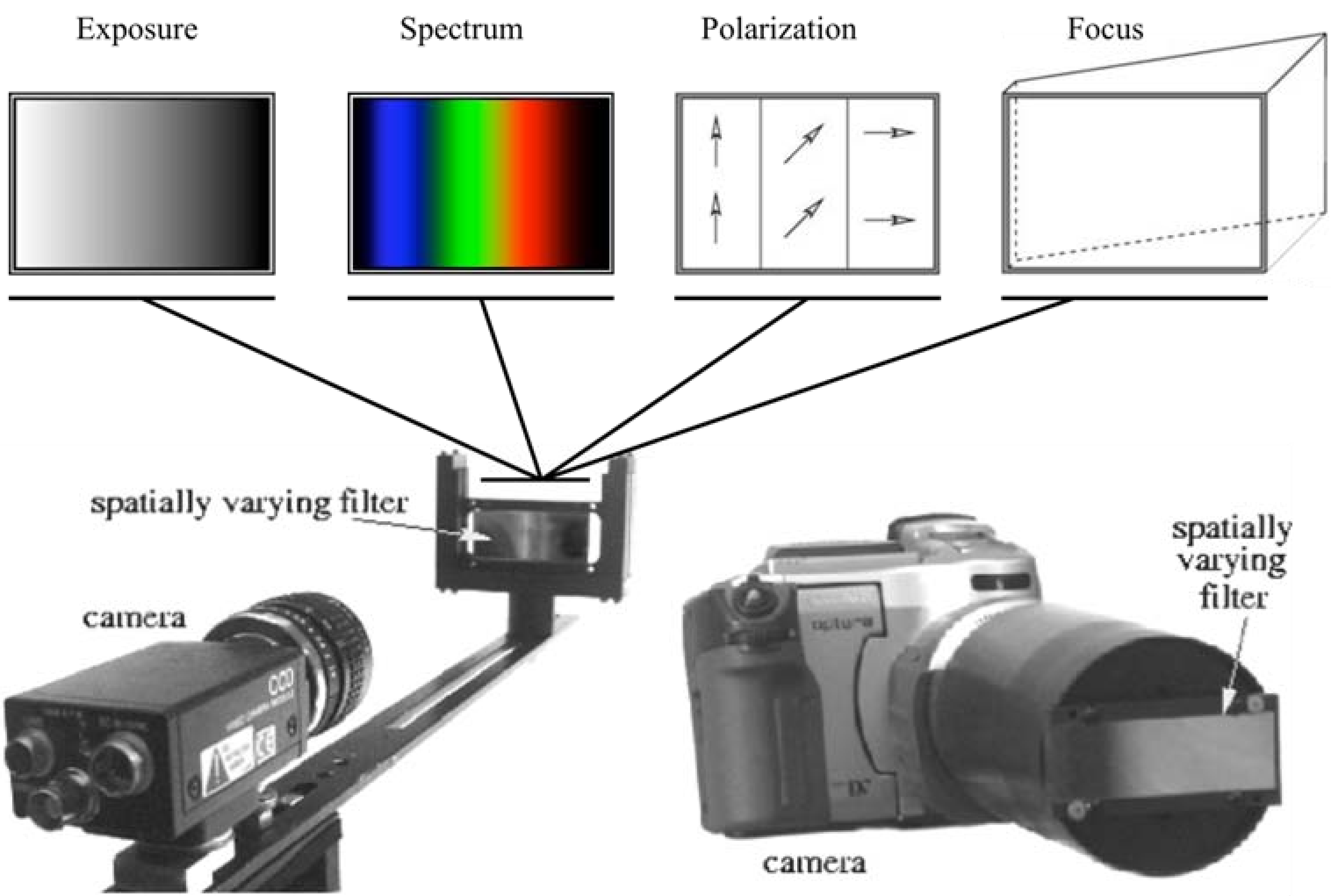
Estimate RGB
at ‘G’ cells from
neighboring values

Epsilon over **multiple axes**

Image removed due to copyright restrictions.

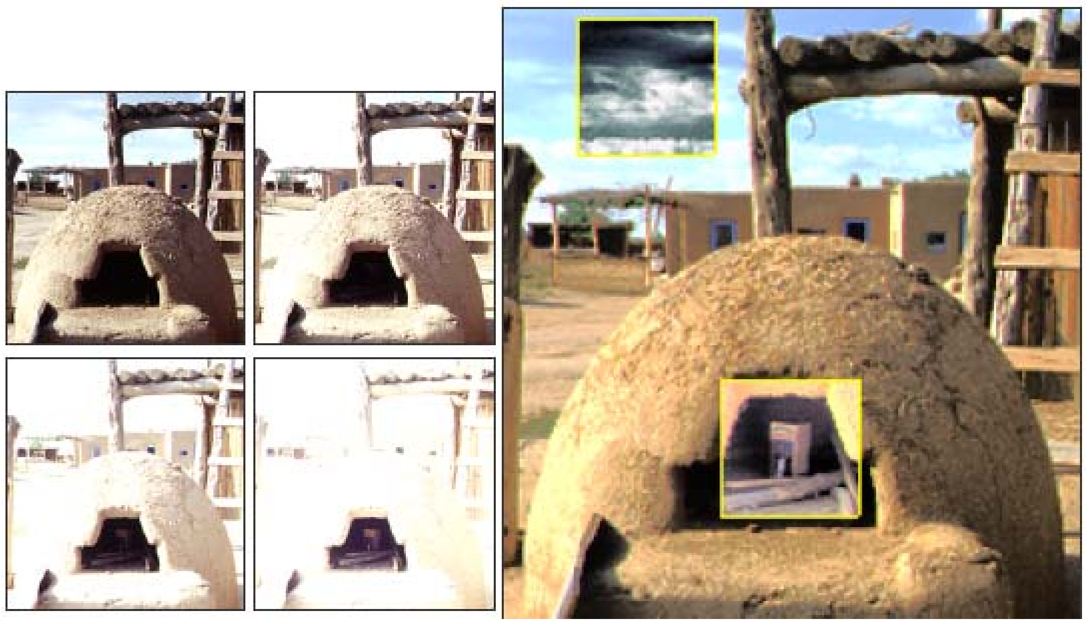
Generalized Mosaicing

[Schechner and Nayar, ICCV 2001]



HDR From Multiple Measurements

Captured Images Computed Image

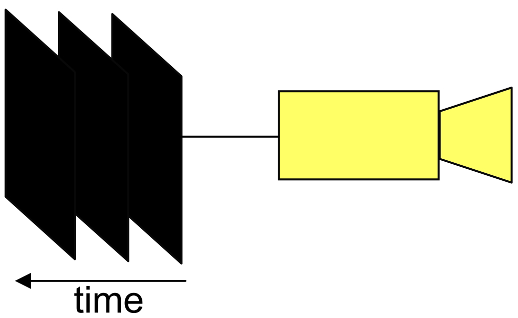


Mitsunaga, T. and S. Nayar. "Radiometric Self Calibration." CVPR 1999.

Ginosar et al 92, Burt & Kolczynski 93,
Madden 93, Tsai 94, Saito 95, Mann & Picard 95,
Debevec & Malik 97, Mitsunaga & Nayar 99,
Robertson et al. 99, Kang et al. 03

Sequential Exposure Change:

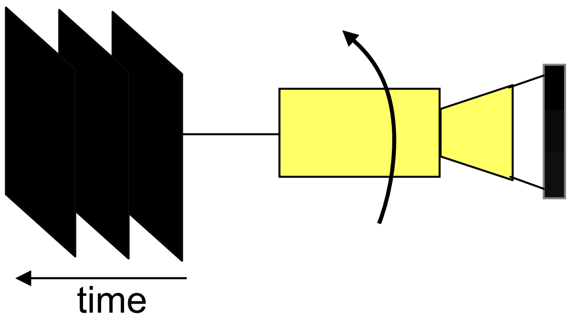
Ginosar et al 92, Burt & Kolczynski 93,
Madden 93, Tsai 94, Saito 95, Mann 95,
Debevec & Malik 97, Mitsunaga & Nayar 99,
Robertson et al. 99, Kang et al. 03



Mosaicing with Spatially Varying Filter:

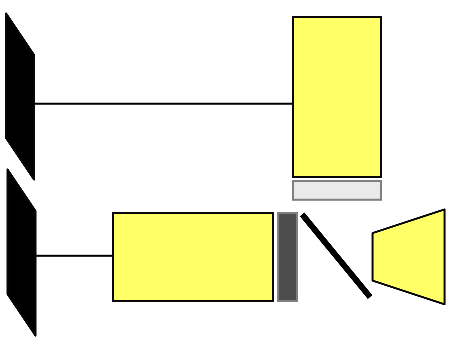
(Pan or move the camera)

Schechner and Nayar 01,
Aggarwal and Ahuja 01

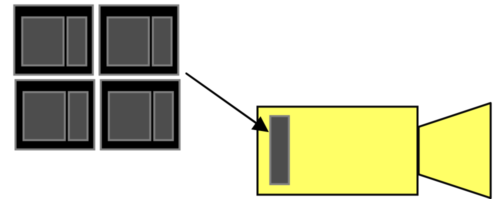


Multiple Image Detectors:

Doi et al. 86, Saito 95, Saito 96,
Kimura 98, Ikeda 98,
Aggarwal & Ahuja 01, …



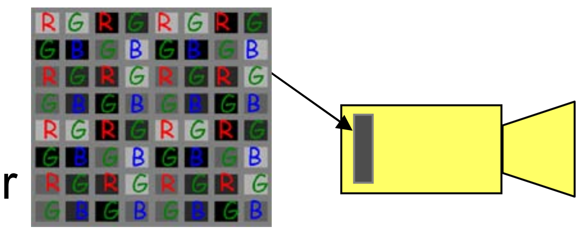
Multiple Sensor Elements in a Pixel:



Handy 86, Wen 89, Murakoshi 94,
Konishi et al. 95, Hamazaki 96, Street 98

Assorted Pixels:

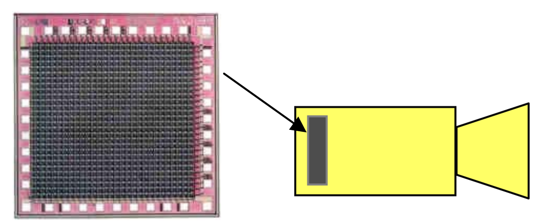
Generalized Bayer Grid:
Trade resolution for multiple exposure,color



Nayar and Mitsunaga 00,
Nayar and Narasimhan 02

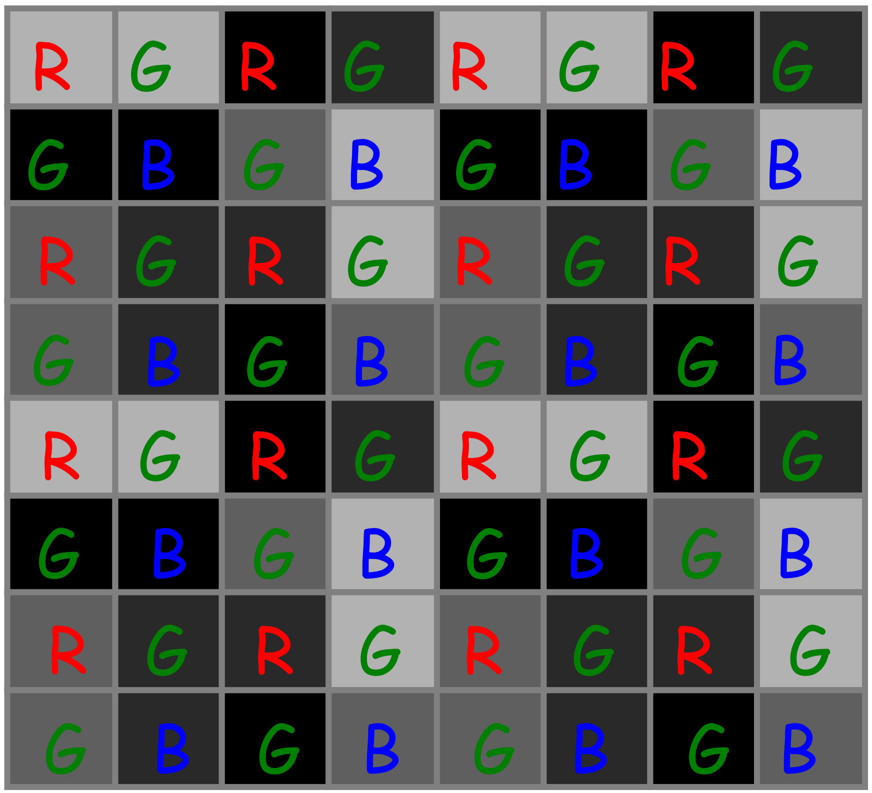
Computational Pixels:

(pixel sensivity set by its illumination)



Brajovic & Kanade 96,
Ginosar & Gnusin 97
Serafini & Sodini 00

Assorted Pixels [Nayar and Narsihman 03]



Bayer Grid
Interleaved color filters.

Lets interleave OTHER assorted measures too

'De-mosaicking' helps preserve resolution…

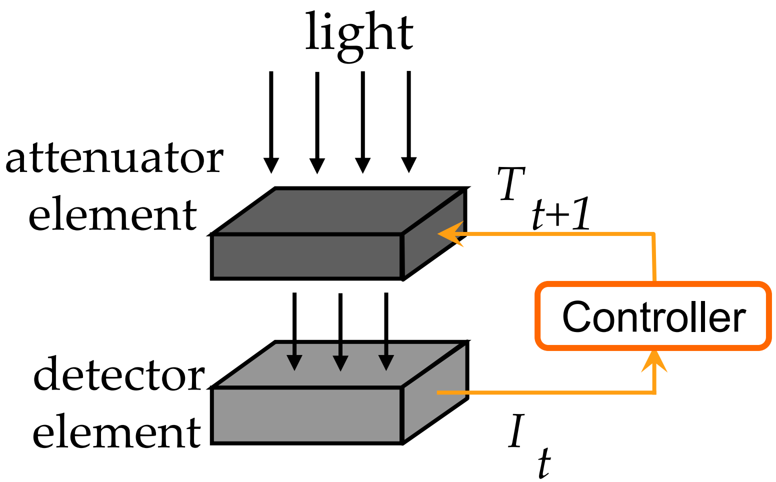
Assorted Pixels [Nayar and Narsihman 03]

Digital Still Camera

Camera with Assorted Pixels

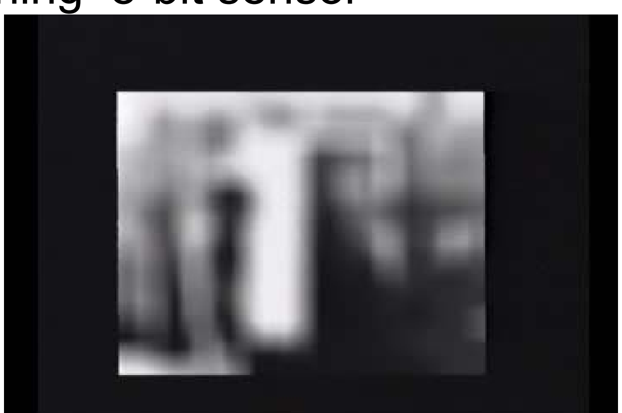
LCD Adaptive Light Attenuator

[Nayar and Branzoi, ICCV 2003]



Unprotected 8-bit Sensor Output:

LCD Light Attenuator limits image intensity reaching 8-bit sensor



Attenuator-Protected 8-bit Sensor Output

High Dynamic Range (HDR) display

[Seetzen, Heidrich, et al, SIGGRAPH 2004]

Schematic of HDR display with projector, LCD and optics; and photo of the working display.
See Figure 4 in Seetzen, H., et al. “High Dynamic Range Display Systems.”
ACM Transactions on Graphics (Proceedings of SIGGRAPH 2004) 23, no. 3 (August 2004): 760-768.

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.128.1621&rep=rep1&type=pdf

Focus: extending the depth of field

- Focal stacks - used in microscopy
- Light field cameras

FUSION: Best-Focus Distance

Source images

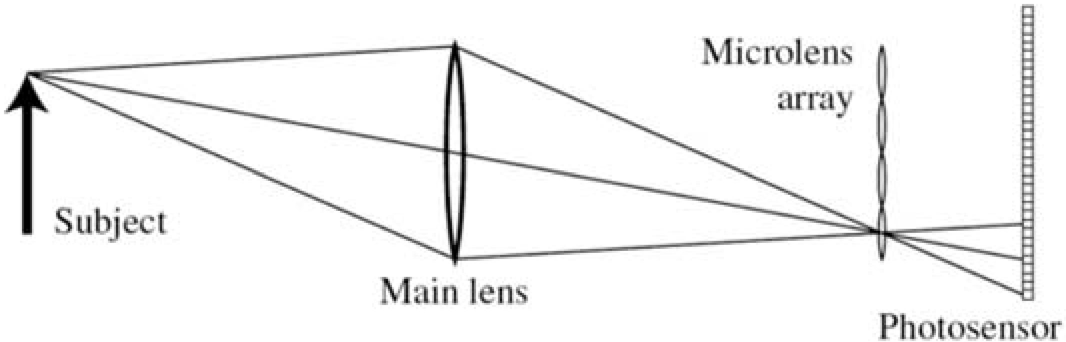
'Graph Cuts' Solution

FUSION

Several slides removed due to copyright restrictions.
Sequence of photos of insect head, with progression of different focal points.
See "Extended depth-of-field" example at:
Agarwala, A., et al. "Interactive Digital Photomontage."

Agrawala et al.,
Digital Photomontage
SIGGRAPH 2004

Focus: Light field camera



Light field

↓

focal stack

↓

extended DOF

Focus: shallow depth of field

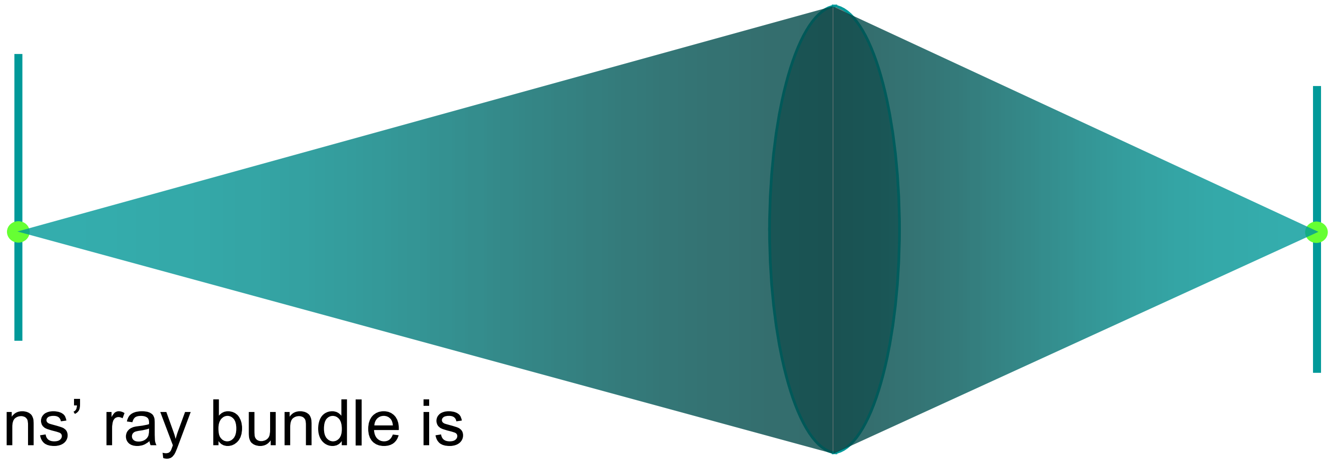
Lots of glass; Heavy; Bulky; Expensive

Defocus Magnification

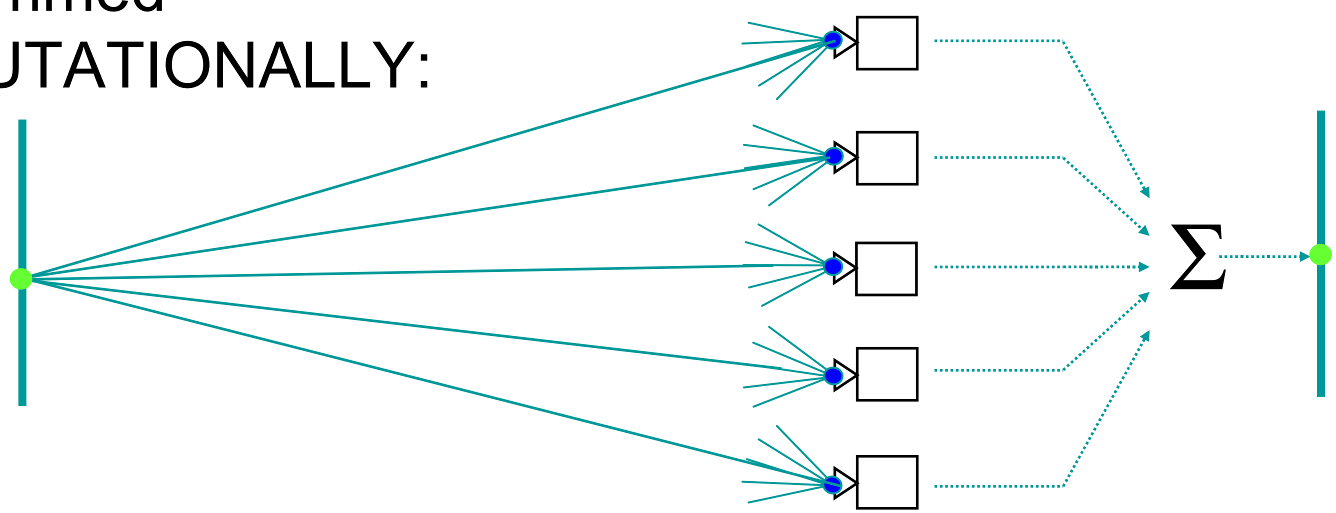
[Bae and Durand 2007]

See Figure 1 in Bae, S., and F. Durand. "Defocus Magnification." *Comput Graph Forum* 26, no. 3 (2007): 571-579.

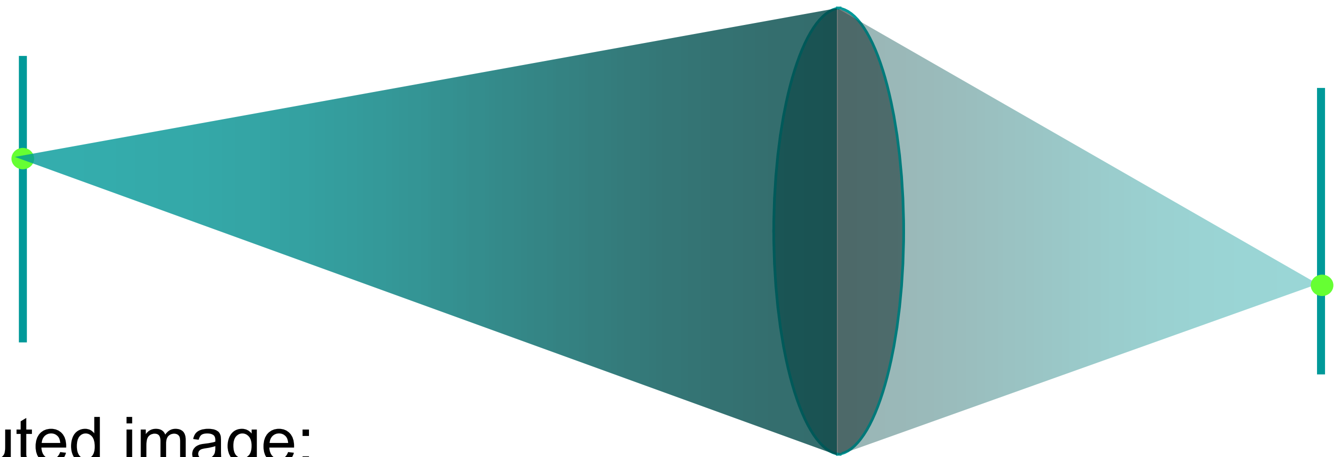
Synthetic aperture photography



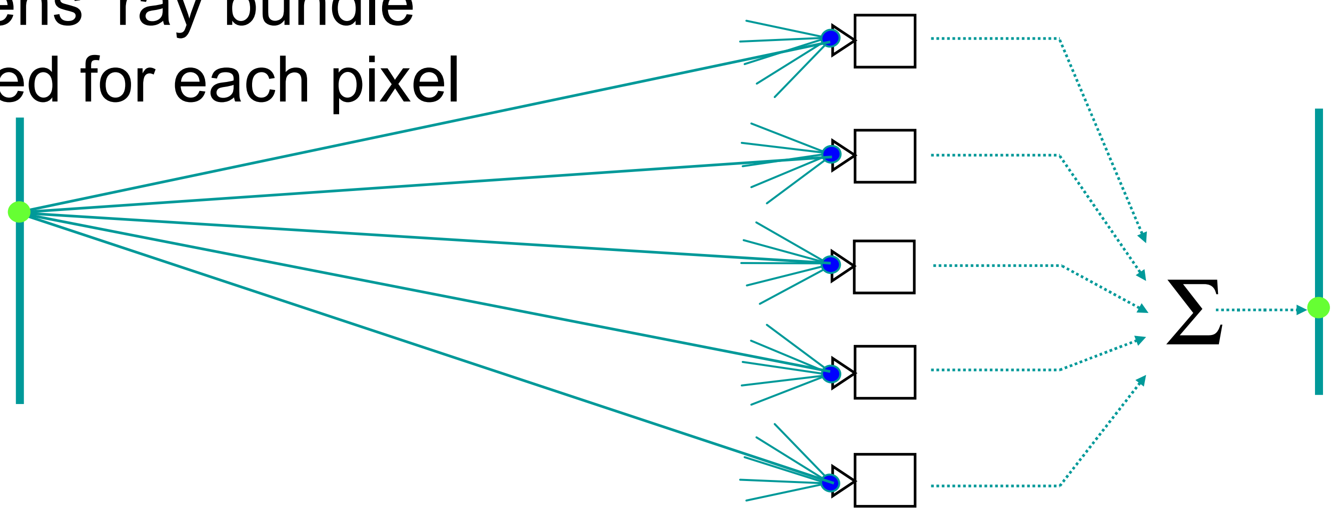
Huge lens' ray bundle is now summed COMPUTATIONALLY:



Synthetic aperture photography

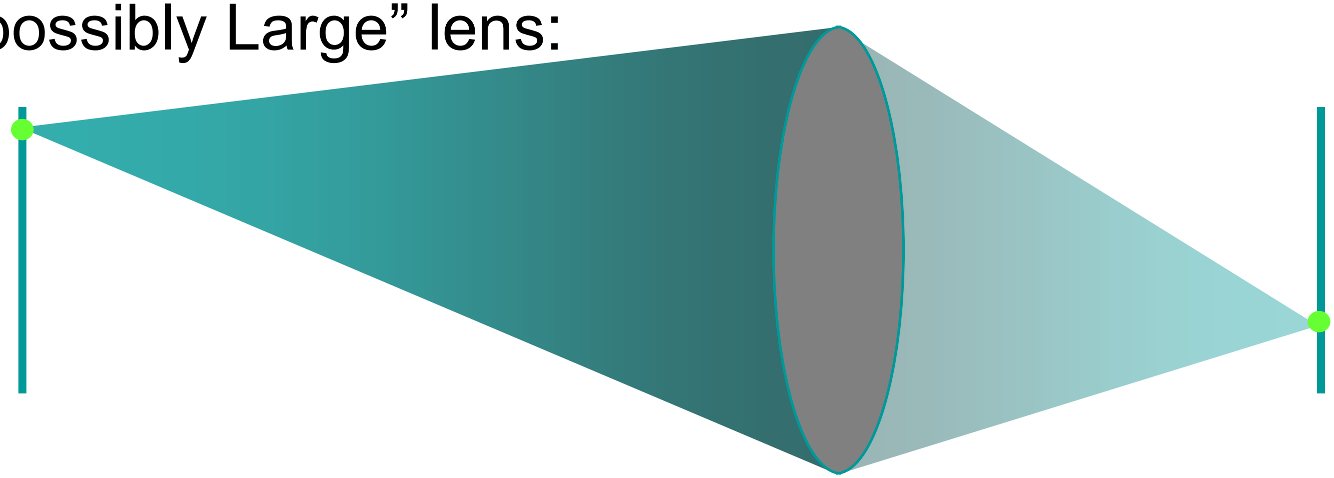


Computed image:
large lens' ray bundle
Summed for each pixel

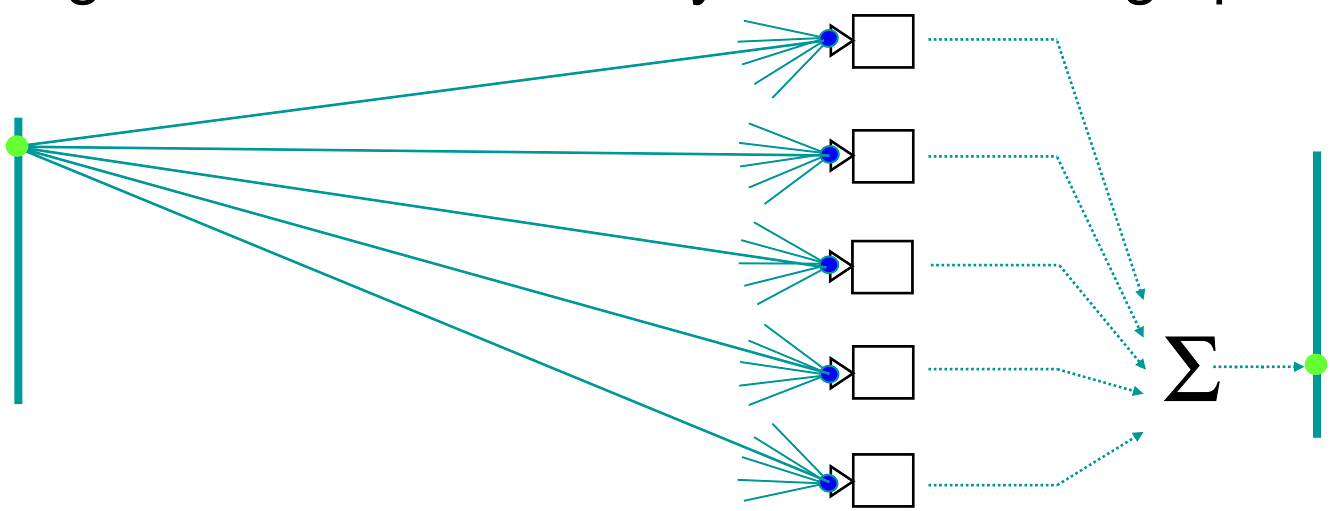


Synthetic aperture photography

"Impossibly Large" lens:

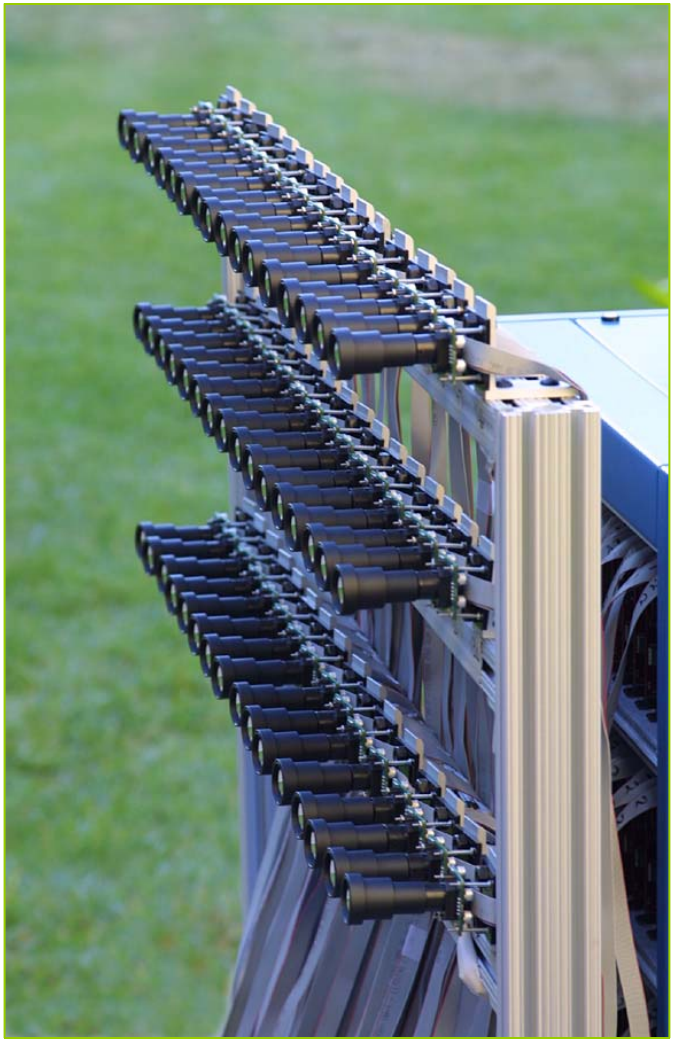


Lens gathers a bundle of rays for each image point…



Camera array gathers and sums the same sets of rays

Synthetic aperture photography



Camera array is far away from
these bushes, yet it sees…

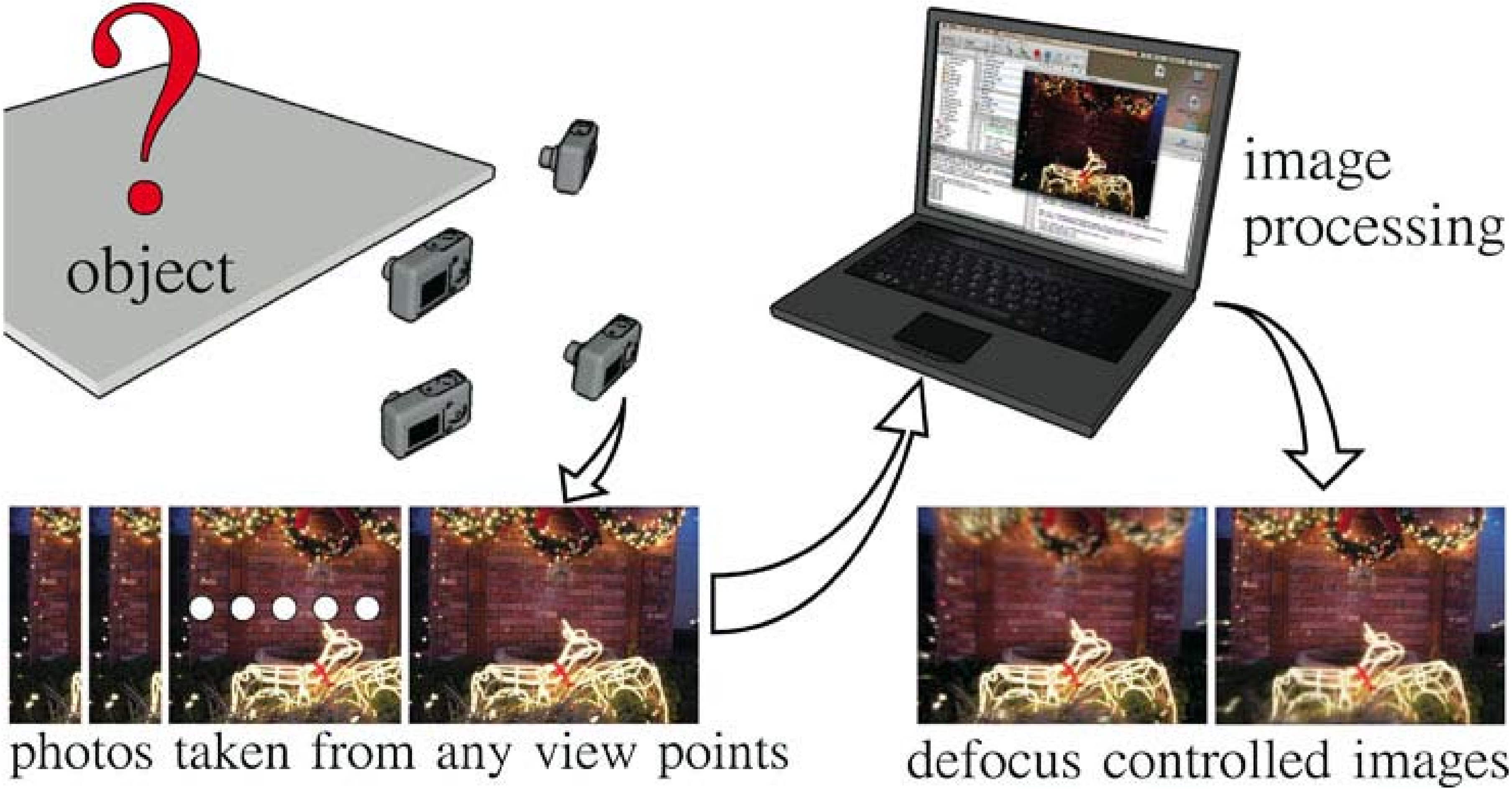
Vaish, V., et al. "Using Plane + Parallax for Calibrating Dense Camera Arrays." *Proceedings of CVPR 2004*. Courtesy of IEEE. Used with permission. © 2004 IEEE.

Focus Adjustment: Sum of Bundles
[Vaish et al. 2004]

Vaish, V., et al. "Using Plane + Parallax for Calibrating Dense Camera Arrays."
Proceedings of CVPR 2004. Courtesy of IEEE. Used with permission.

Uncalibrated Synthetic Aperture

[Kusumoto, Hiura, Sato, CVPR 2009]



Uncalibrated Synthetic Aperture

[Kusumoto, Hiura, Sato, CVPR 2009]

Focus in front

Focus in back

Image Destabilization

[Mohan, Lanman et al. 2009]

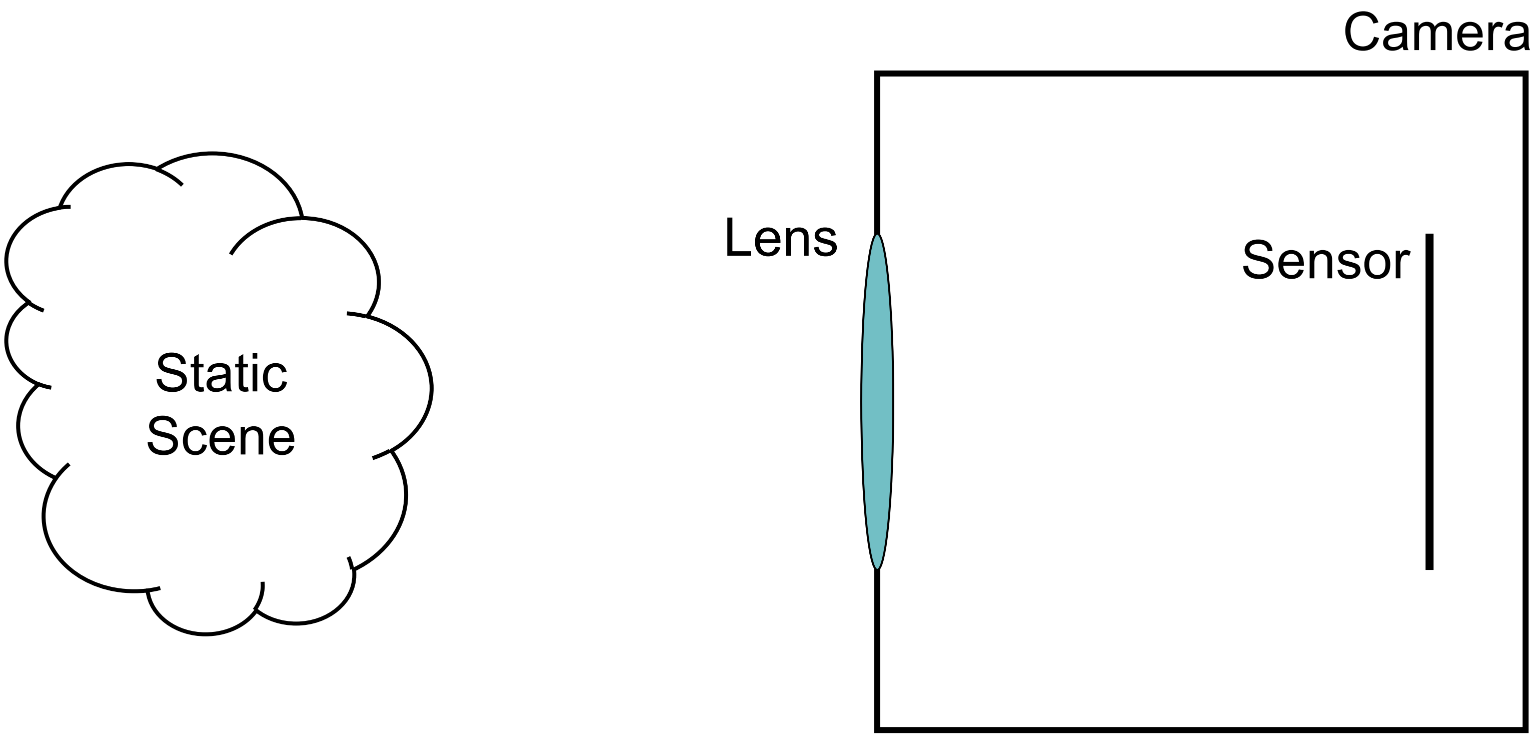
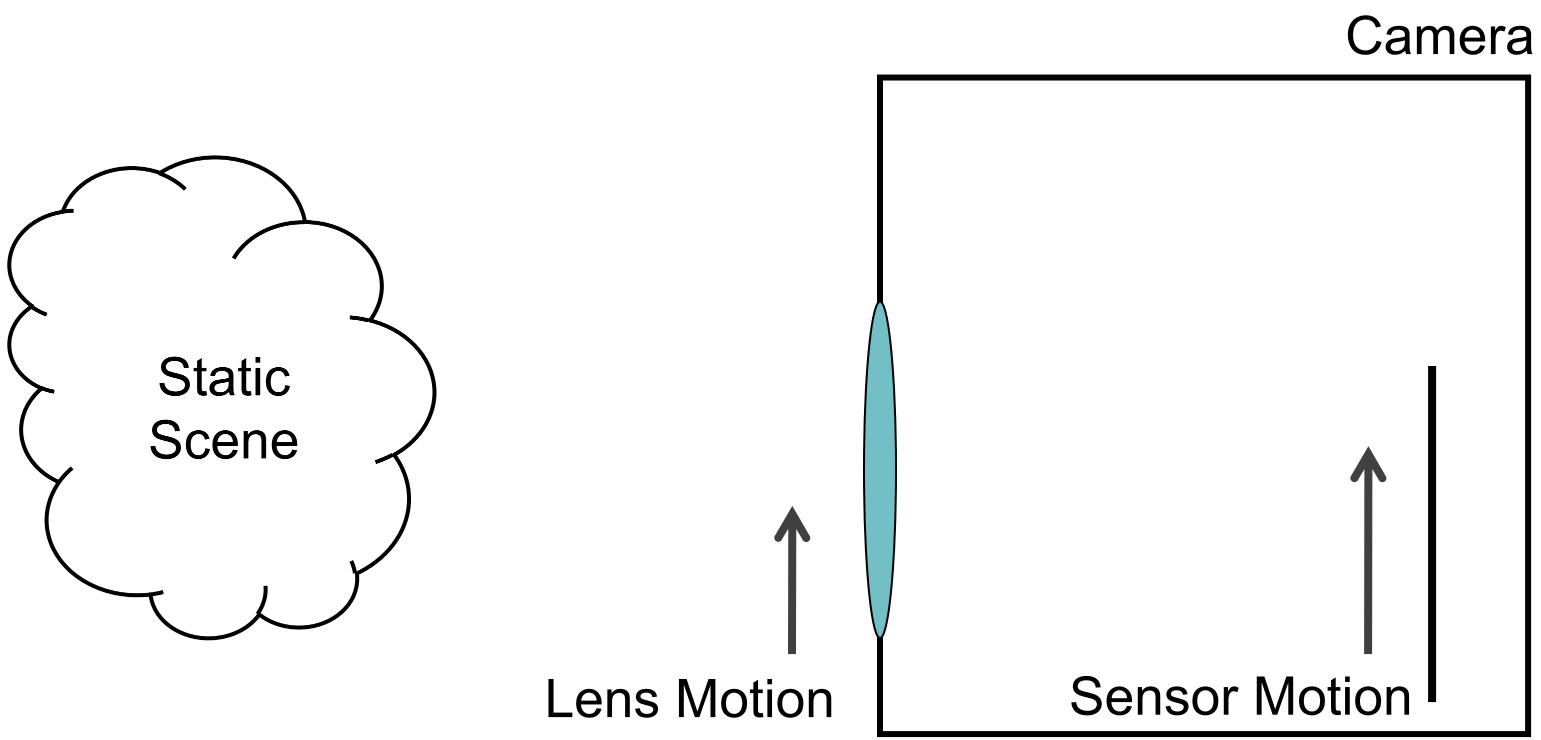
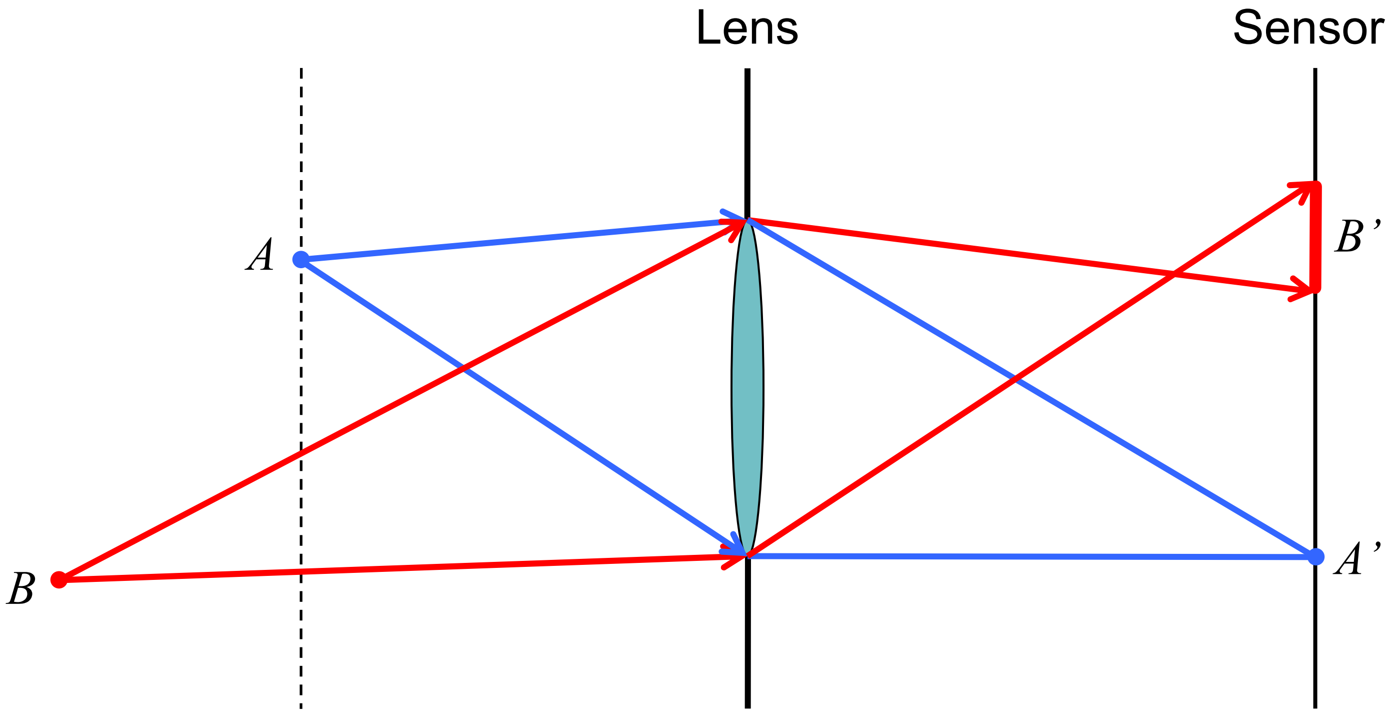


Image Destabilization

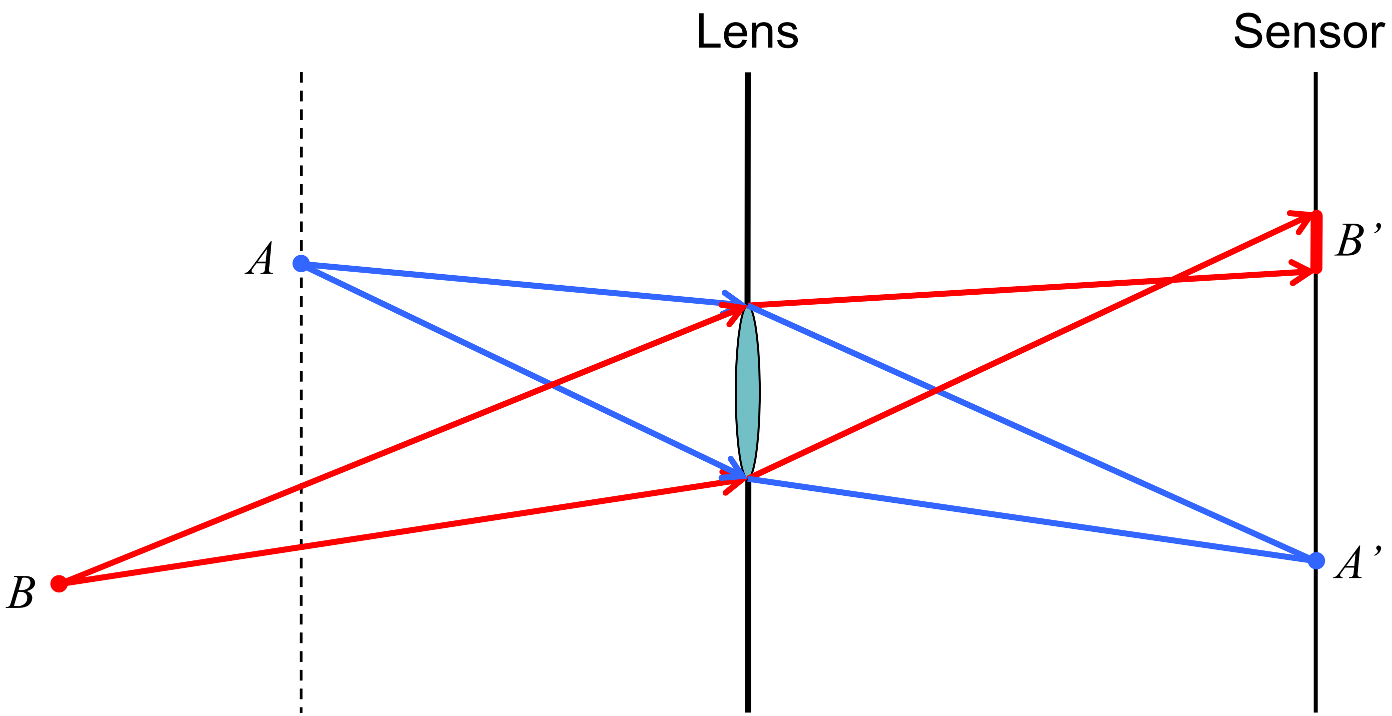
[Mohan, Lanman et al. 2009]



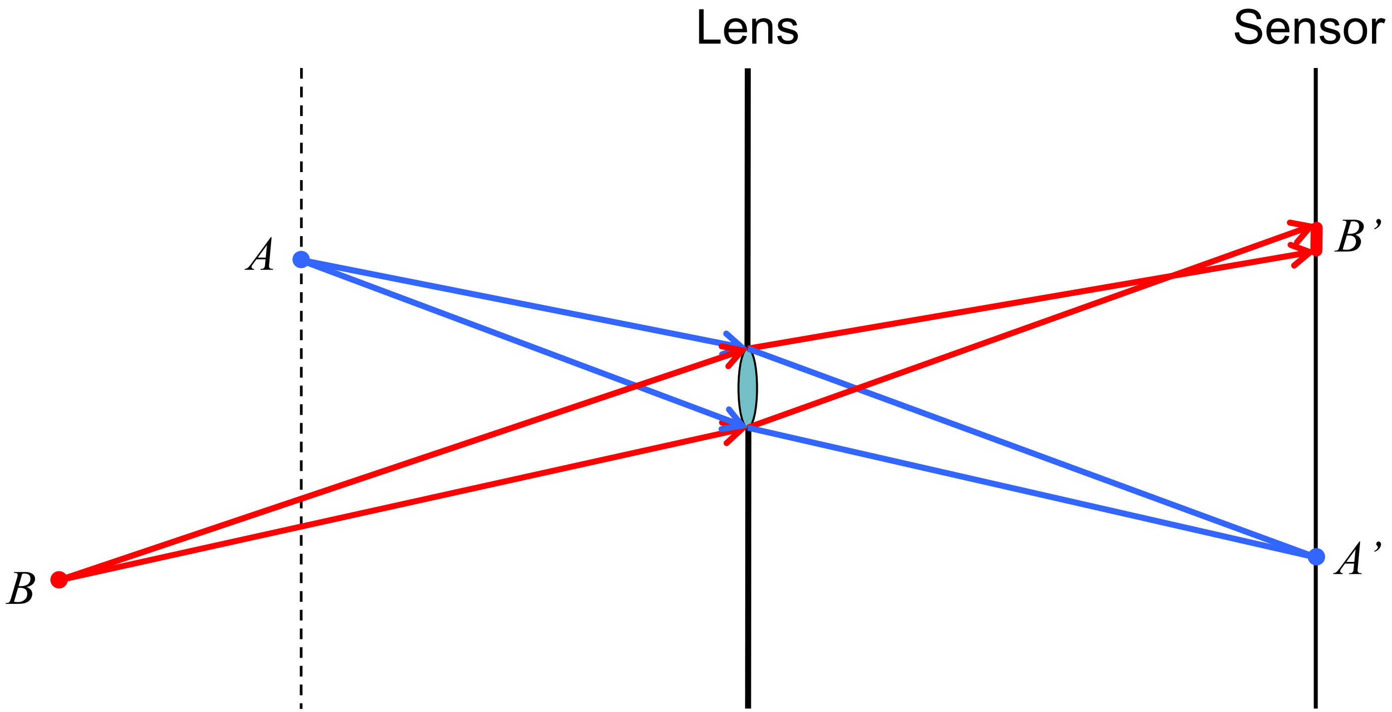
Lens based Focusing



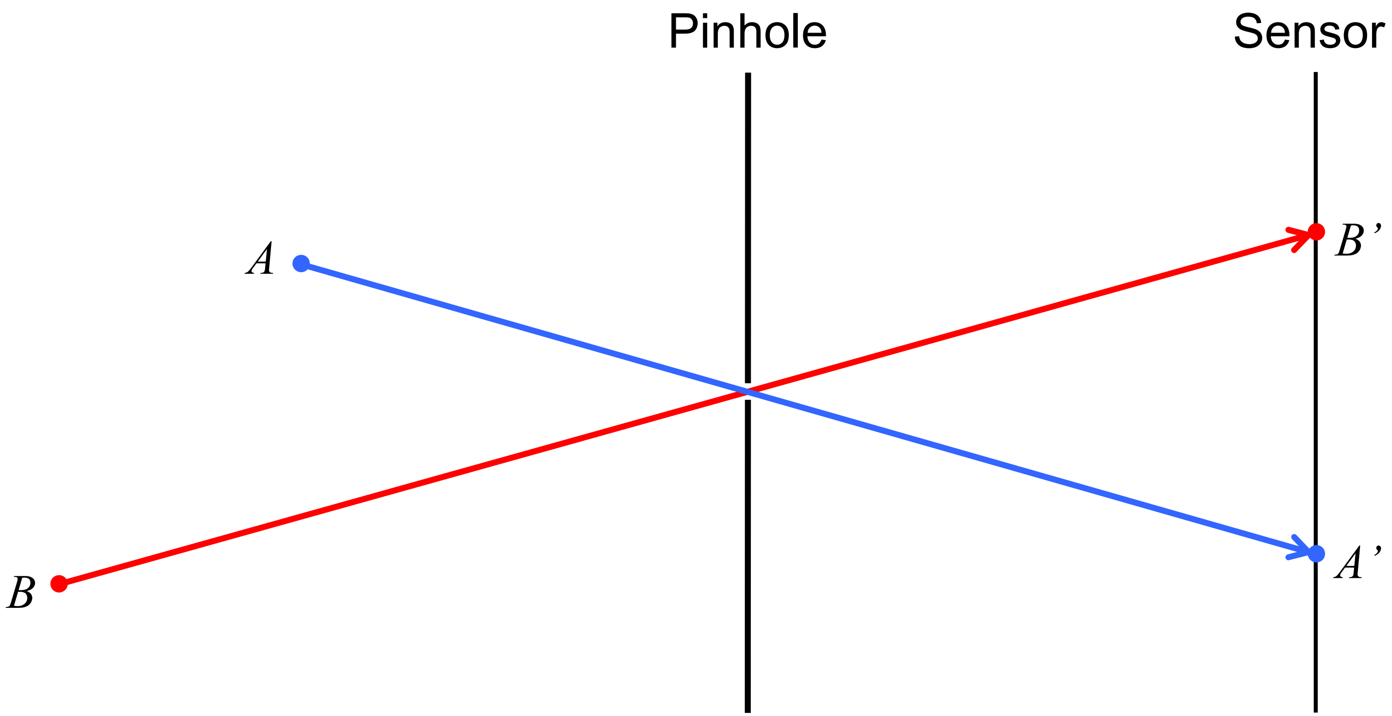
Lens based Focusing



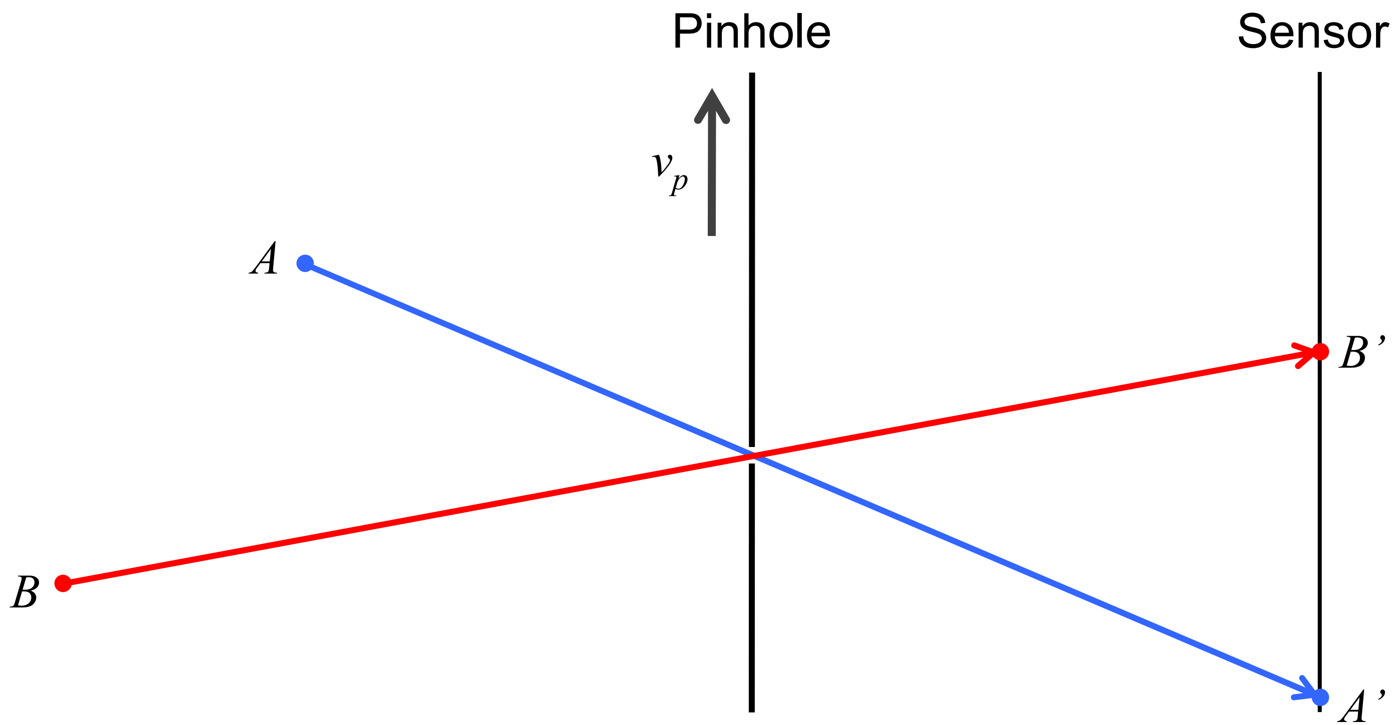
Smaller aperture → Smaller defocus blur



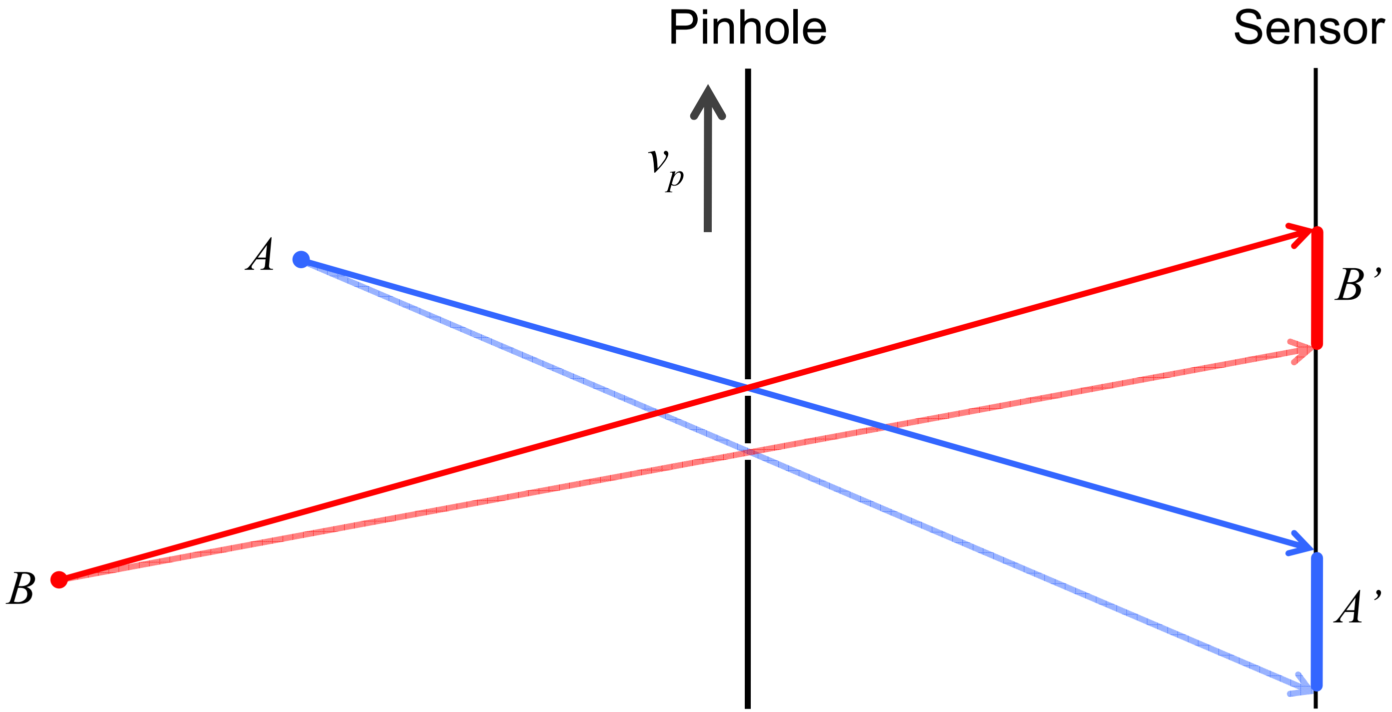
Pinhole: All In-Focus



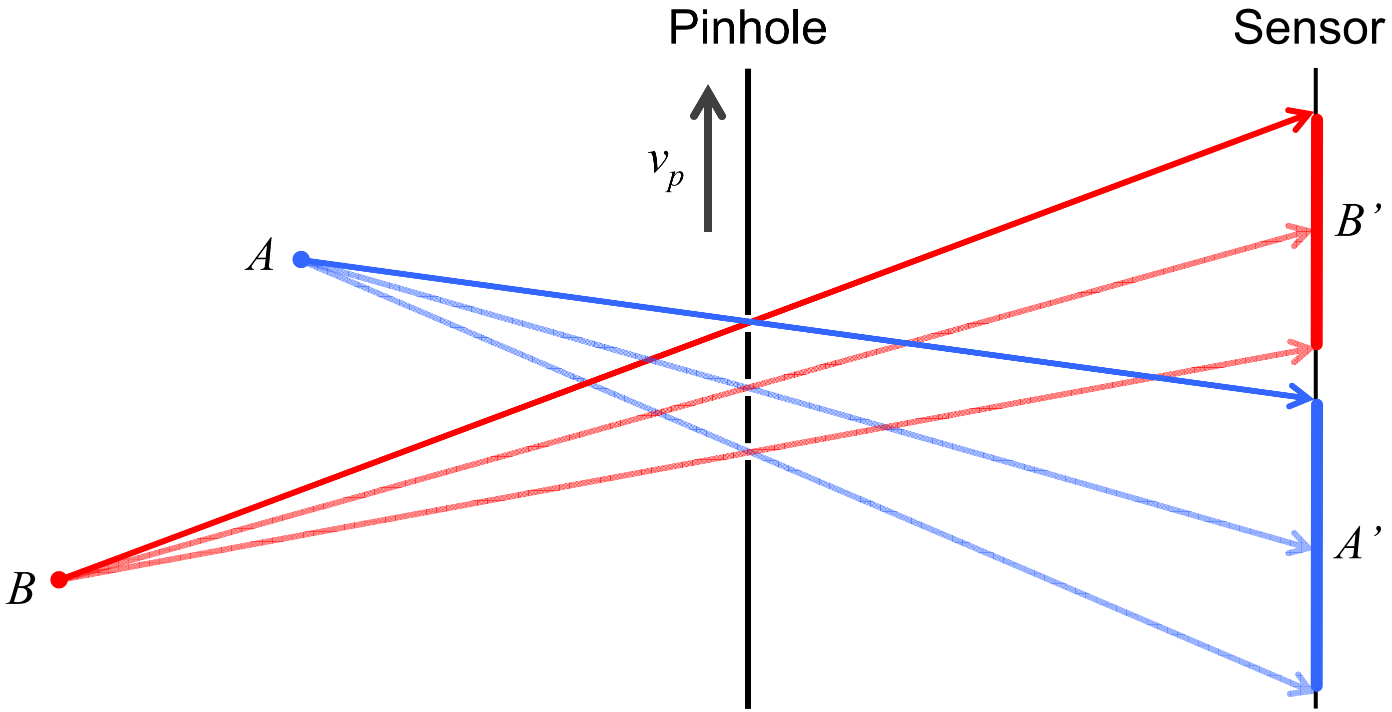
Shifting Pinhole



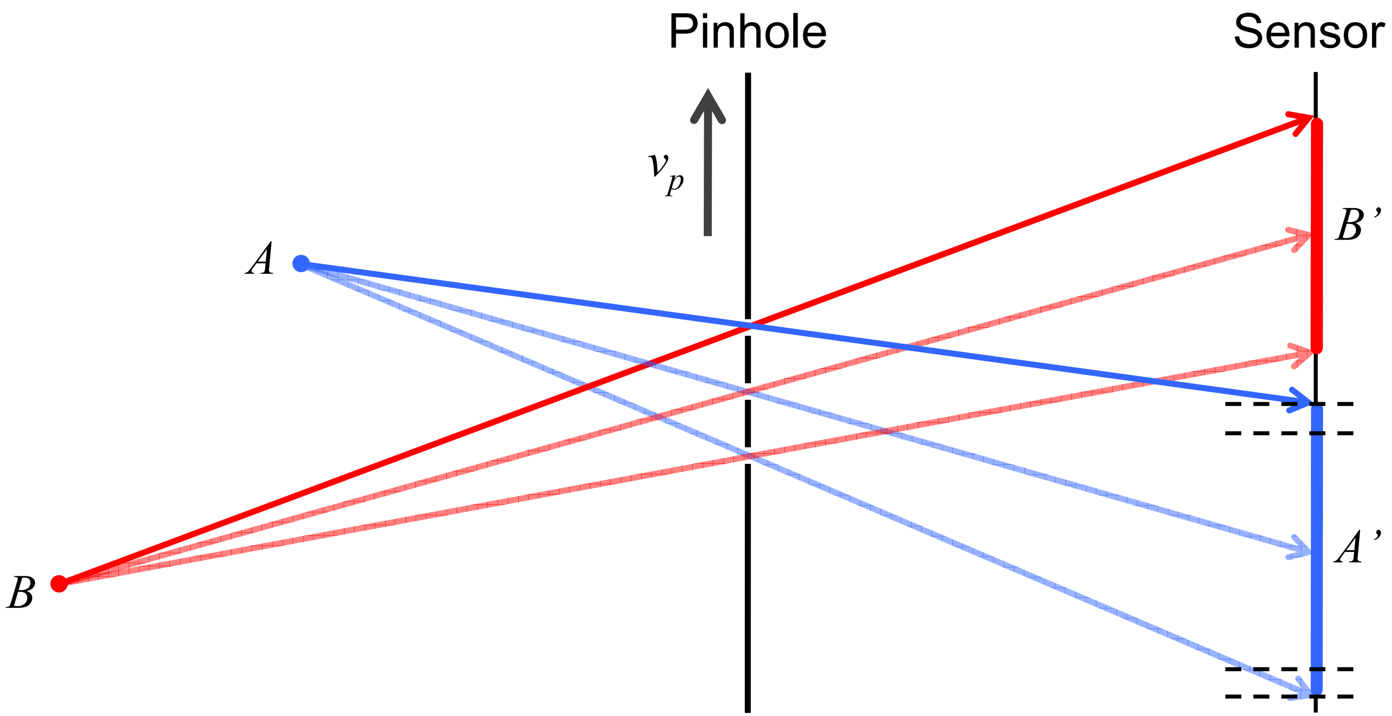
Shifting Pinhole



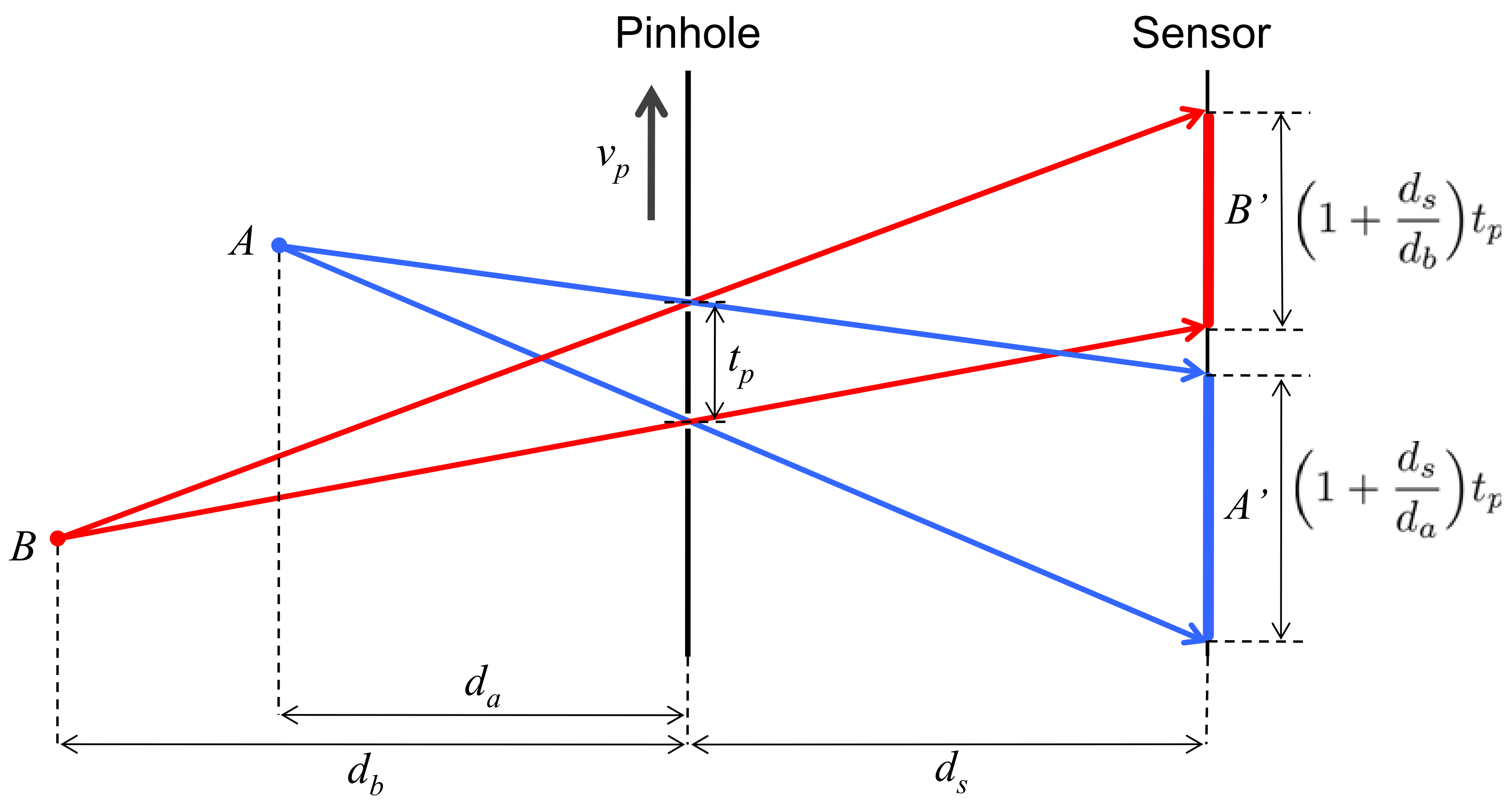
Shifting Pinhole



Shifting Pinhole

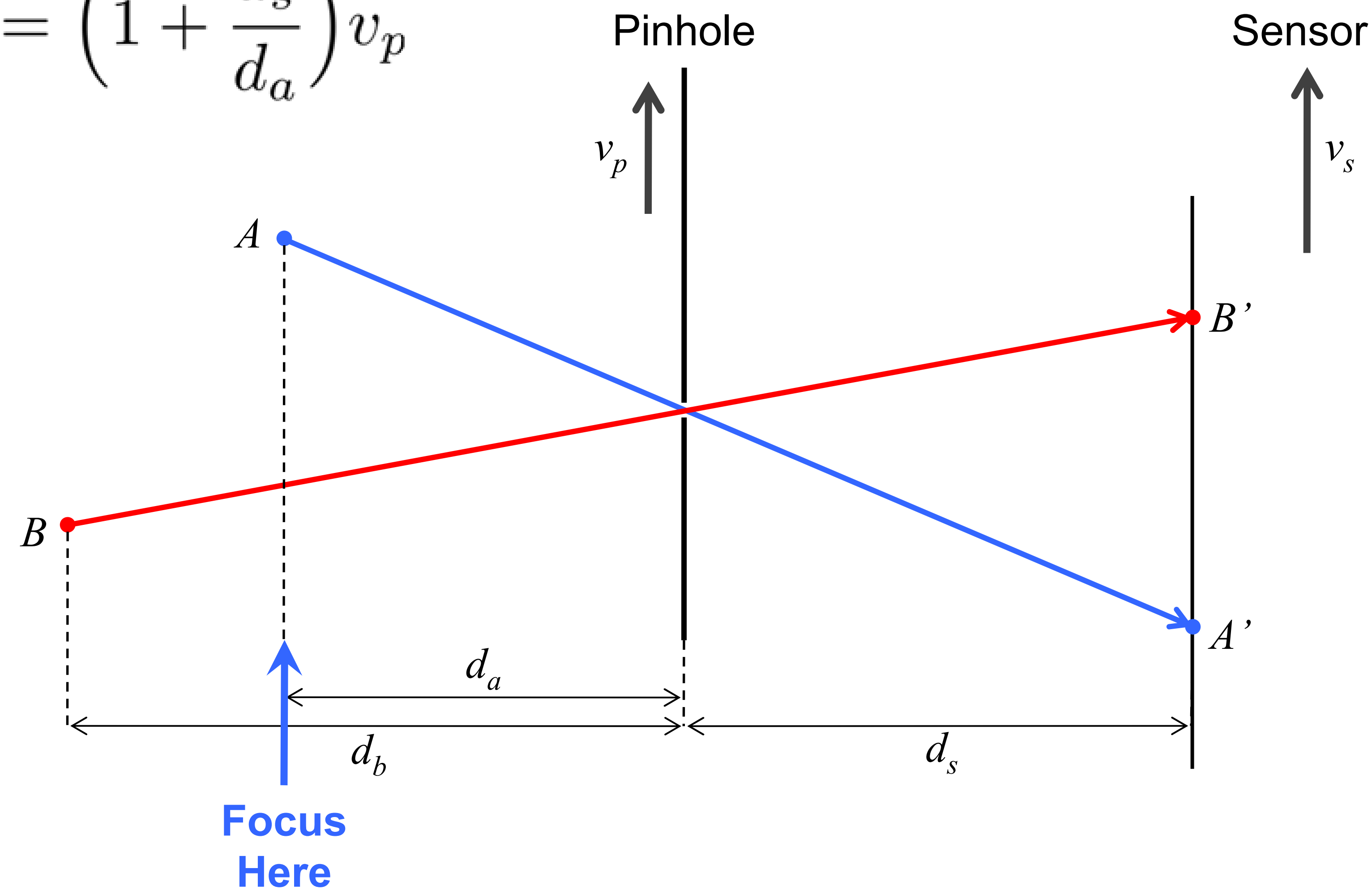


Shifting Pinhole



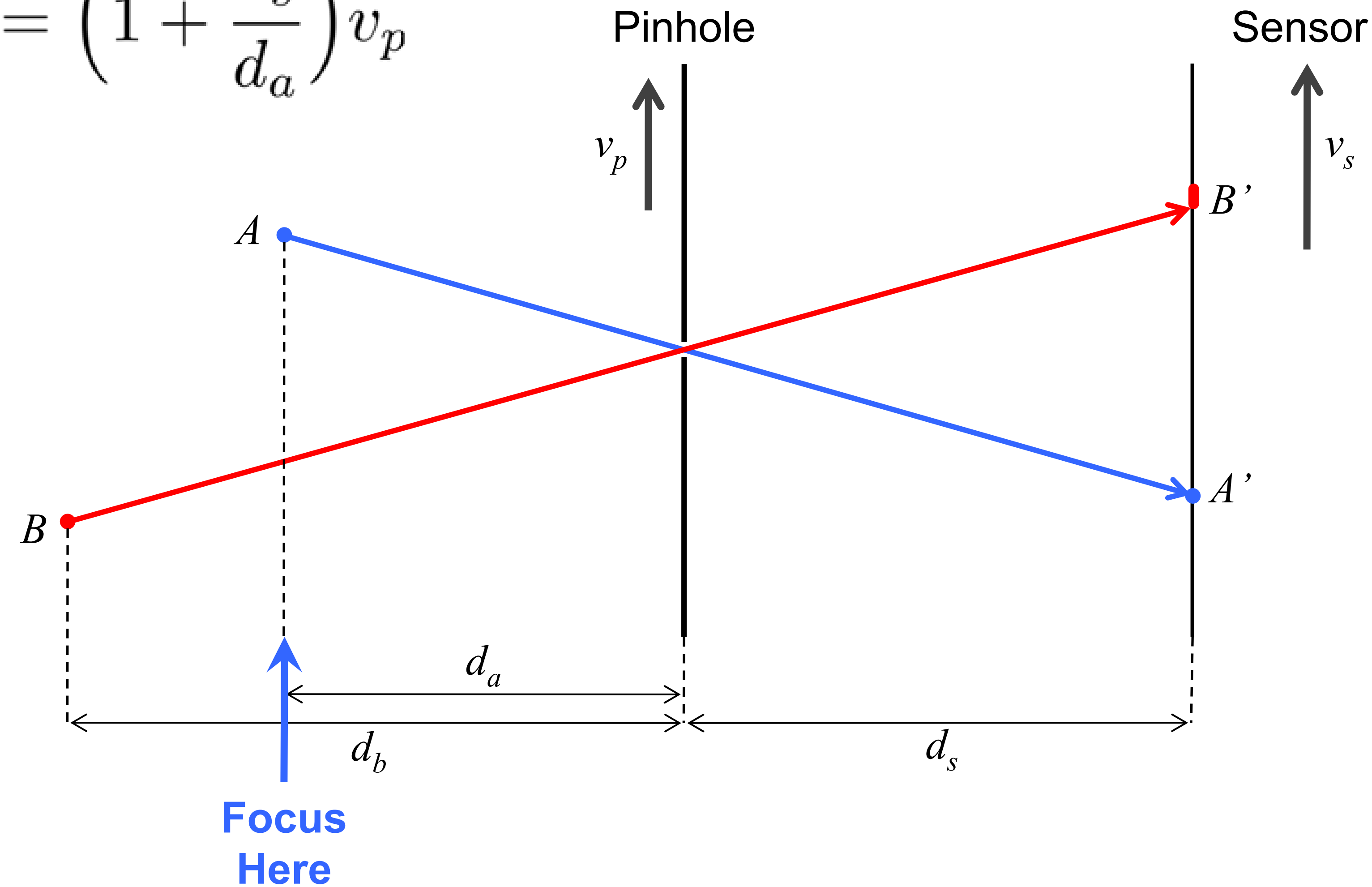
Shifting Pinhole and Sensor

$$v_s = \left(1 + \frac{d_s}{d_a}\right) v_p$$



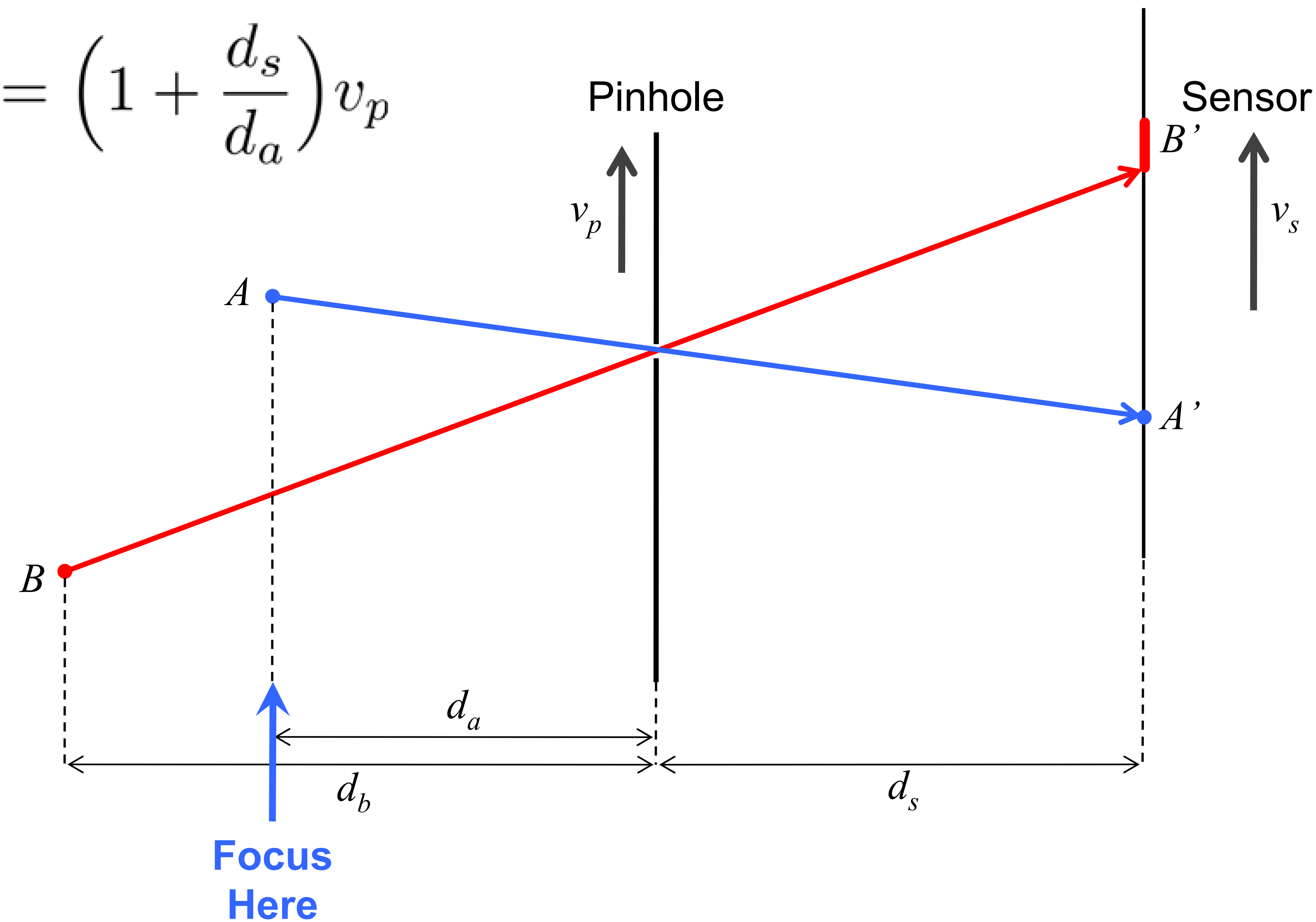
Shifting Pinhole and Sensor

$$v_s = \left(1 + \frac{d_s}{d_a}\right) v_p$$



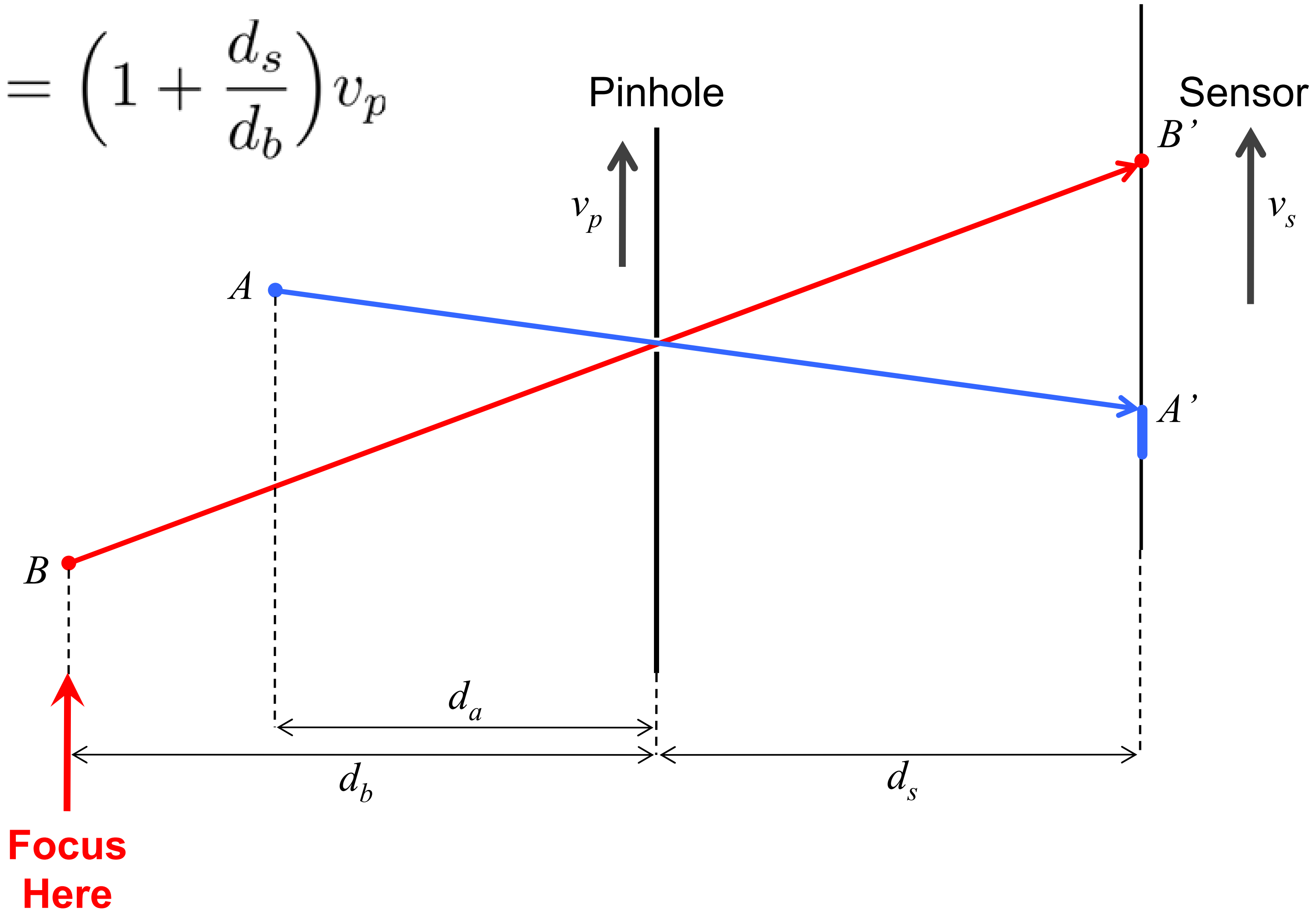
Shifting Pinhole and Sensor

$$v_s = \left(1 + \frac{d_s}{d_a}\right) v_p$$



Shifting Pinhole and Sensor

$$v_s = \left(1 + \frac{d_s}{d_b}\right) v_p$$



A Lens in Time!

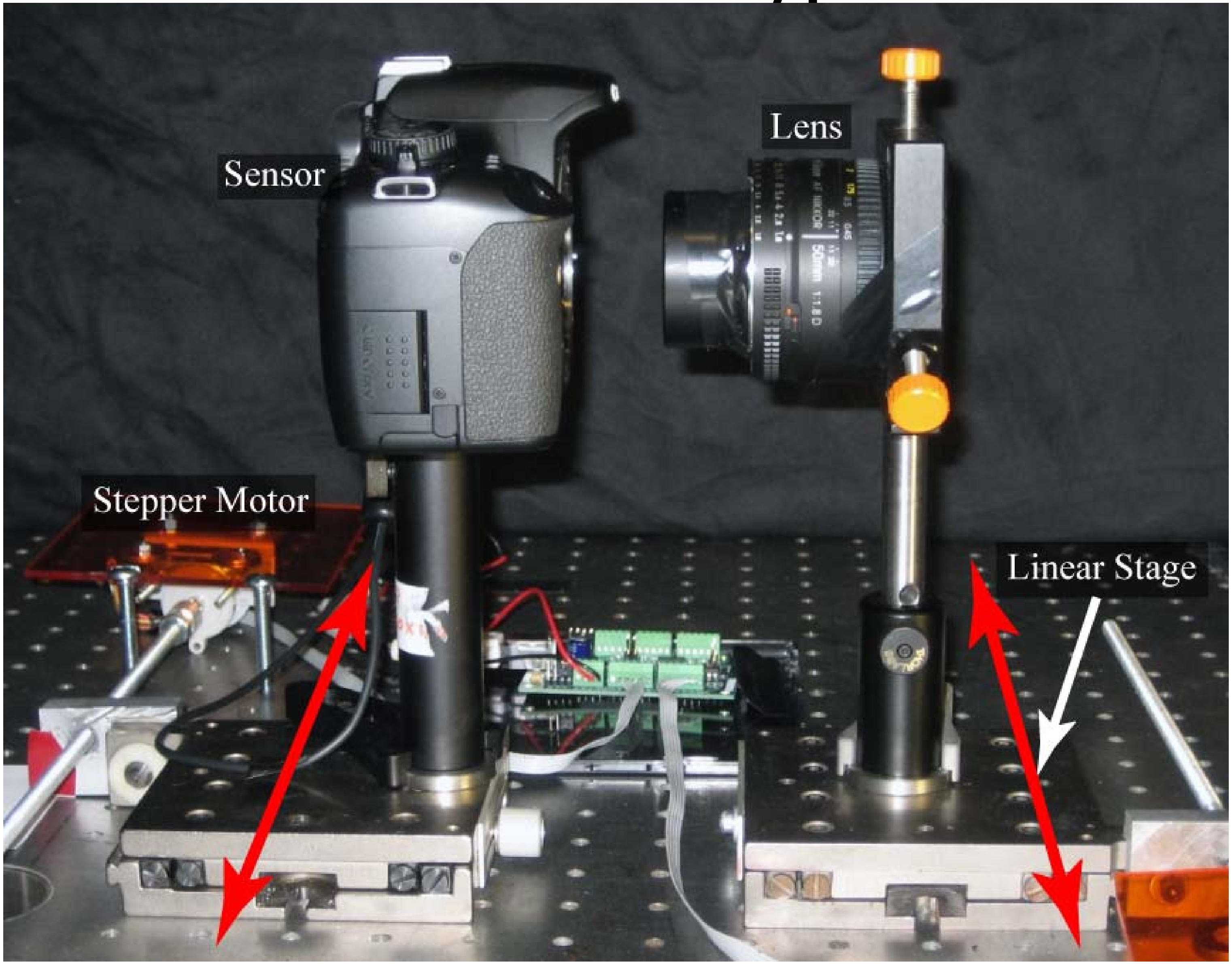
Lens Equation: $$\frac{1}{f_P} = \frac{1}{u} + \frac{1}{v}$$

Virtual Focal Length: $$f_P = \left(\frac{v_p}{v_s}\right) d_s$$

Virtual F-Number: $$N_P = \left(\frac{v_p}{v_s}\right)\left(\frac{d_s}{t_p}\right)$$

Analogous to *shift and sum* based Light field re-focusing.

Our Prototype



Adjusting the Focus Plane

all-in-focus pinhole image

Defocus Exaggeration

destabilization simulates a reduced f-number

Large apertures with tiny lenses?

Benefits

- No *time* or *light* inefficiency wrt cheap cameras
- Exploits unused area around the lens
- Compact design
- With near-pinhole apertures (*mobile phones*) many possibilities

Photo courtesy of Wikipedia User: Lipton_sale.

Limitations

- Coordinated mechanical movement required
- Diffraction (due to small aperture) cannot be eliminated

  [Zhang and Levoy, tomorrow]

  [Our group: augmented LF for wave analysis]
- Scene motion during exposure

Figure by MIT OpenCourseWare.

Increasing Spatial Resolution

- Superresolution
- Panoramas over time
- Panoramas over sensors

Capturing Gigapixel Images

[Kopf et al, SIGGRAPH 2007]

Image removed due to copyright restrictions.
See Fig. 4b in Kopf, J., et al. "Capturing and Viewing Gigapixel Images."
Proceedings of SIGGRAPH 2007.

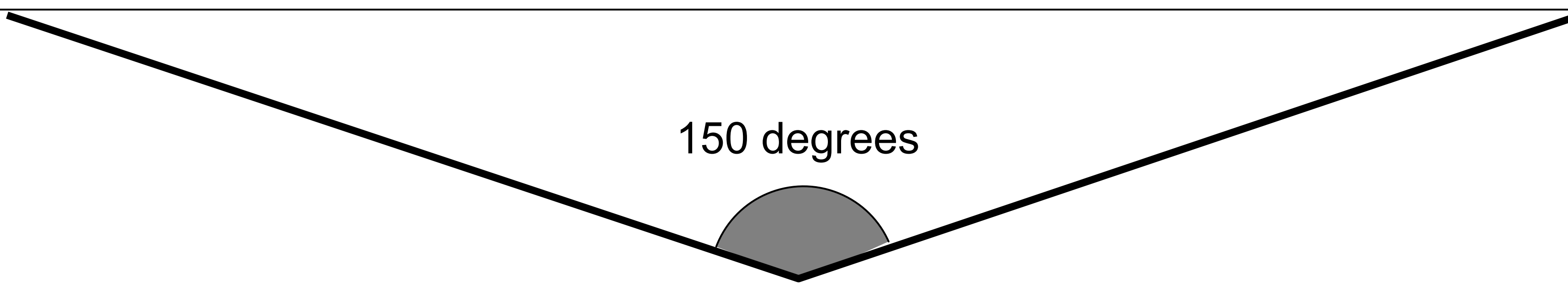
3,600,000,000 Pixels

Created from about 800 8 MegaPixel Images

Capturing Gigapixel Images

[Kopf et al, 2007]

Image removed due to copyright restrictions.
See Fig. 4b in Kopf, J., et al. "Capturing and Viewing Gigapixel Images."
Proceedings of SIGGRAPH 2007.



"Normal" perspective projections cause distortions.

Capturing Gigapixel Images

[Kopf et al, 2007]

Image removed due to copyright restrictions.
See Fig. 4b in Kopf, J., et al. "Capturing and Viewing Gigapixel Images."
Proceedings of SIGGRAPH 2007.

100X variation in Radiance

High Dynamic Range

A tiled camera array

Photo removed due to copyright restrictions.
See
http://graphics.stanford.edu/projects/array/images/tiled-side-view-cessh.jpg
(Figure 1a in Wilburn, B., et al. SIGGRAPH 2005)

- 12 × 8 array of VGA cameras
- abutted: 7680 × 3840 pixels
- overlapped 50%: half of this
- total field of view = 29° wide
- (seamless mosaicing isn't hard)
- cameras individually metered
- Approx same center-of-proj.

Tiled panoramic image
(before geometric or color calibration)

Photo removed due to copyright restrictions.

Tiled panoramic image (after geometric or color calibration)

Photo removed due to copyright restrictions.

Three images removed due to copyright restrictions.
Similar to Fig. 6 and 7 in Wilburn, B., et al. "High Performance Imaging Using Large Camera Arrays." *Proceedings of SIGGRAPH 2005*.

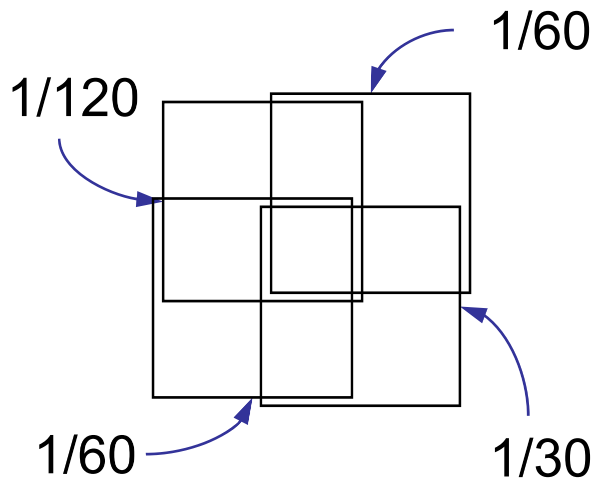
same exposure in all cameras

1/60	1/60
1/60	1/60

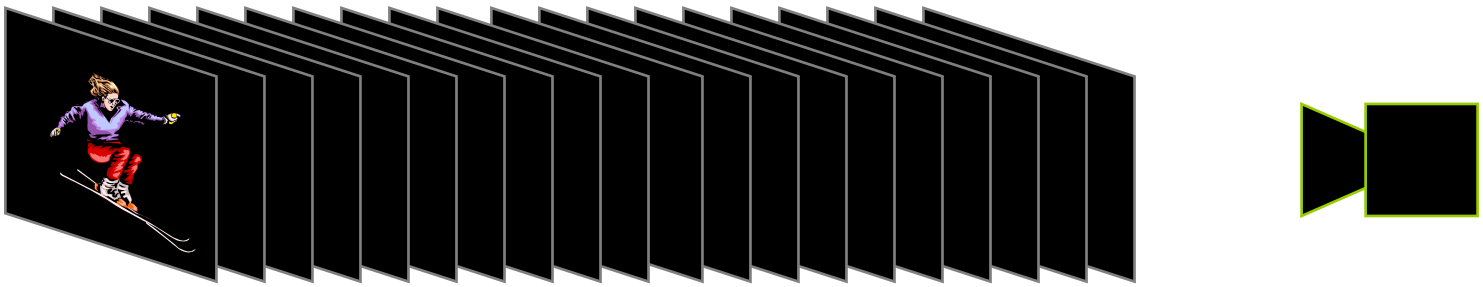
individually metered

1/120	1/60
1/60	1/30

same and overlapped 50%



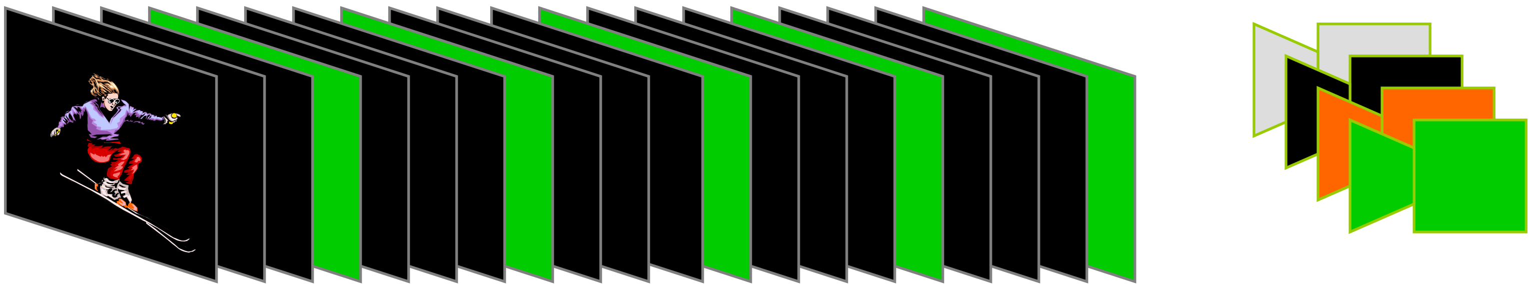
Increasing Temporal Resolution



Say you want 120 frame per second (fps) video.

- You could get one camera that runs at 120 fps
- Or…

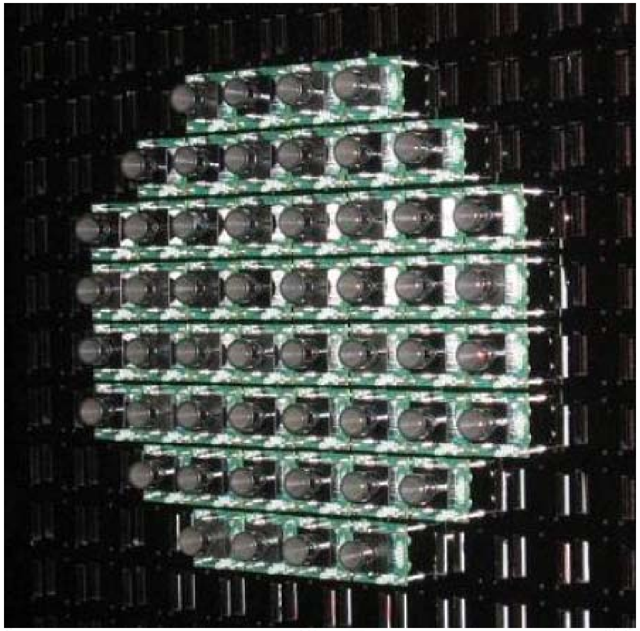
Increasing Temporal Resolution



Say you want 120 frame per second (fps) video.

- You could get one camera that runs at 120 fps
- Or… get 4 cameras running at 30 fps.

Increasing Temporal Resolution



High Speed Video Using a Dense Camera Array [Wilburn et al, CVPR 2004]

1560fps video of popping balloon

Epsilon Photography

Modify …

- Exposure settings
- Spectrum/color settings
- Focus settings
- Camera position
- Scene illumination

… over …

- time (bracketing)
- sensors (SAMP, camera arrays)
- pixels (bayer)