Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

Georgia Tech College of Computing

Light Fields

* Introducing the Concepts of a Light Field and the Plenoptic Function
* How can we capture a Light Field?

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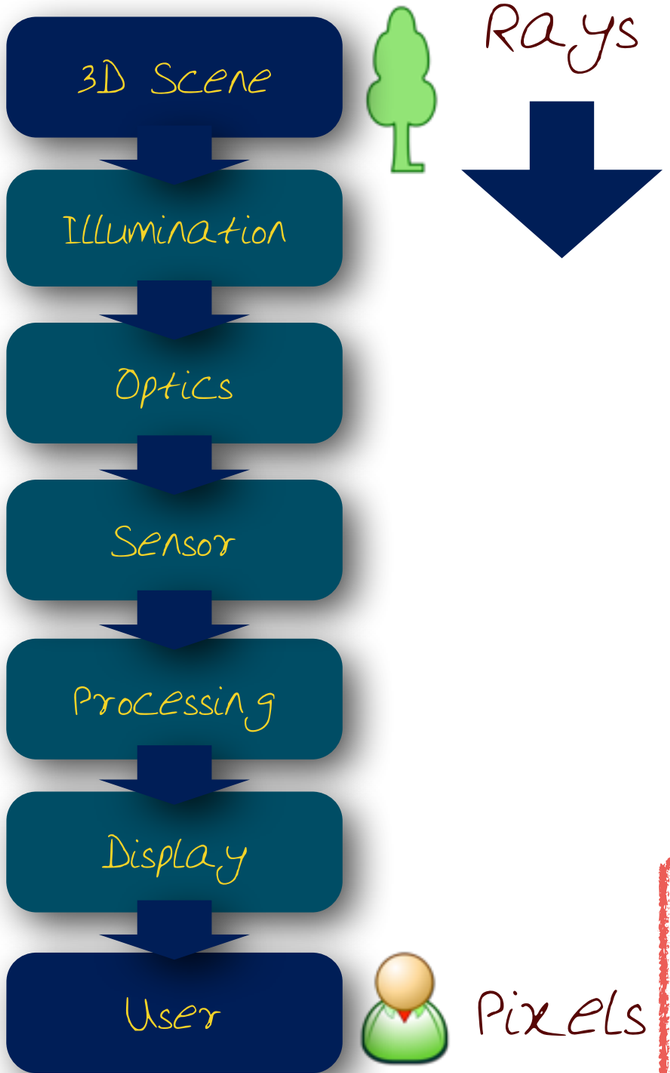
Lesson Objectives

1. Concept of a Light Field
2. Seven parameters of the Plenoptic Function
3. Different types of Light Fields

Lesson Objectives

4. Scene viewed from a pinhole and a lens system
5. Use of an eccentric aperture on a simple lens system
6. An array of pinhole cameras
7. A 4D Light Field camera

Recall: Photography (Light Rays)

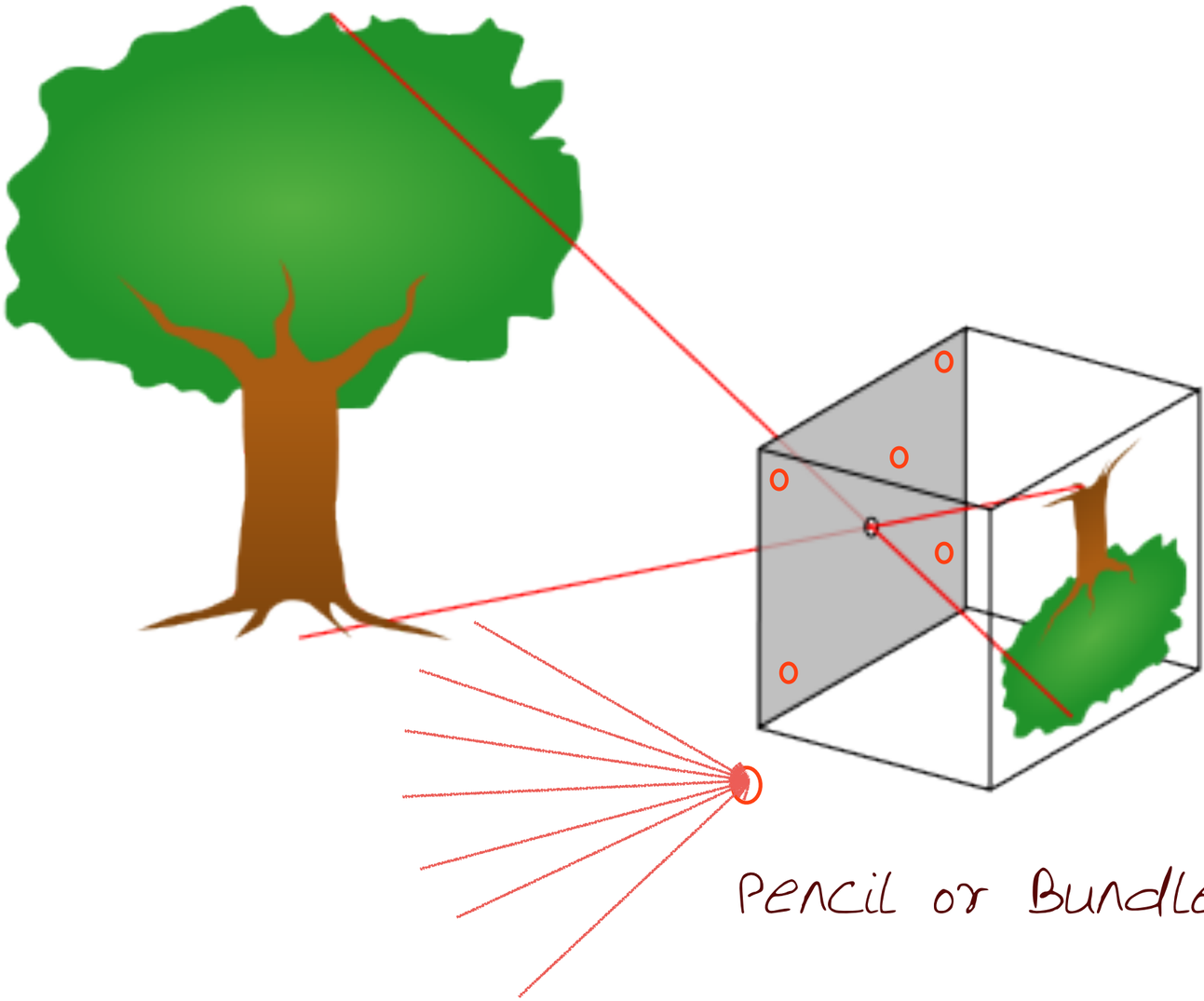


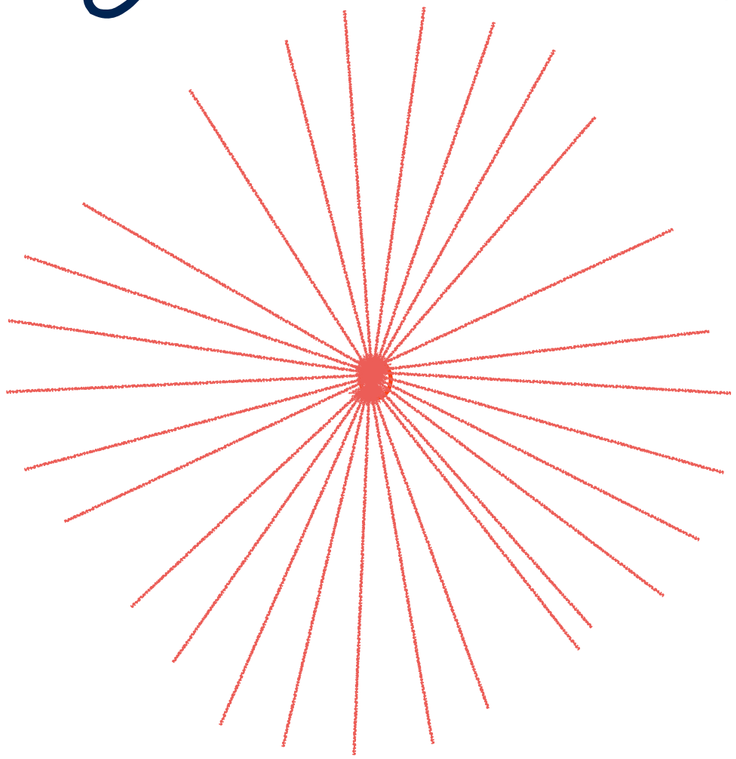
* Image of a scene using 2D array of pixel
* Rays of Light are the fundamental primitives
* Illumination (Light Rays) follows a path from the scene to the sensor
* Computation adaptively controls the parameters of the optics, sensor and illumination

Is this limiting?

Can we not be just stuck with pixels at the end?

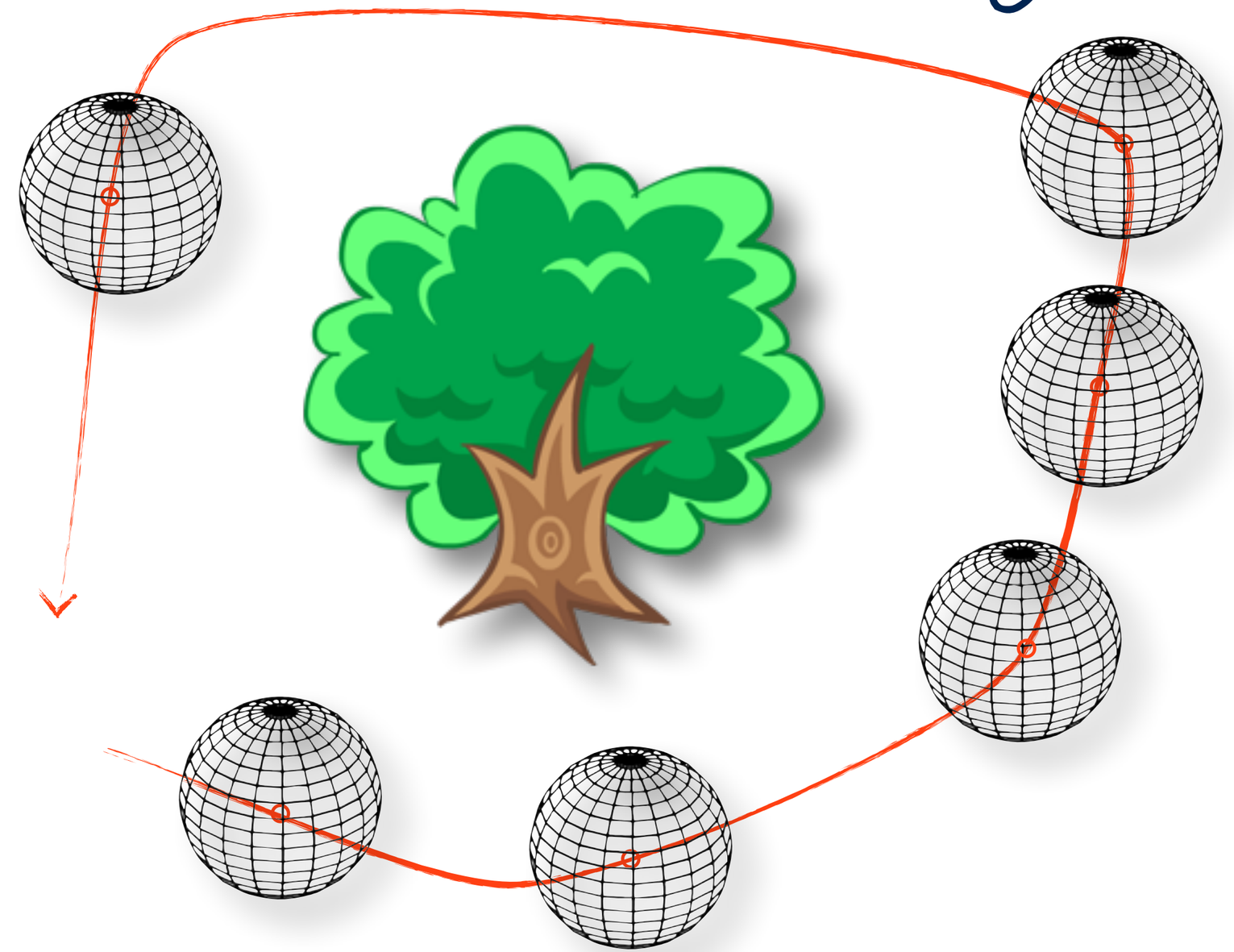
Pinhole Camera and a Light Field





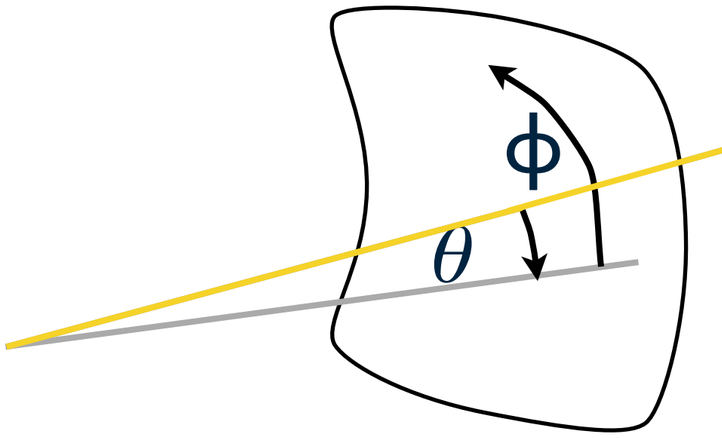
Pencil or Bundle of Light Rays

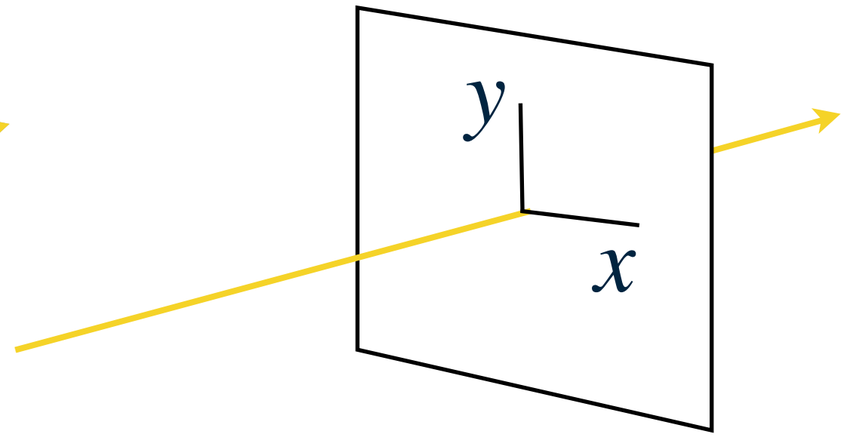
Pinhole Camera and a Light Field

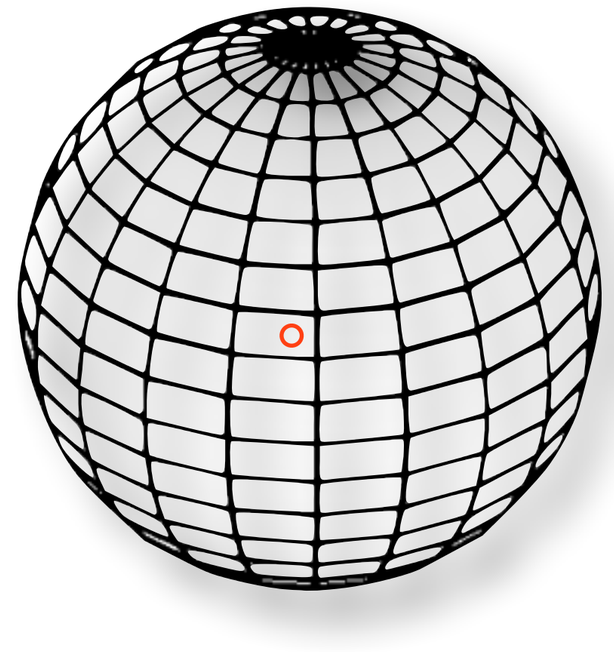


Parameterizing the Light Field

Say **P** is the intensity distribution at that point







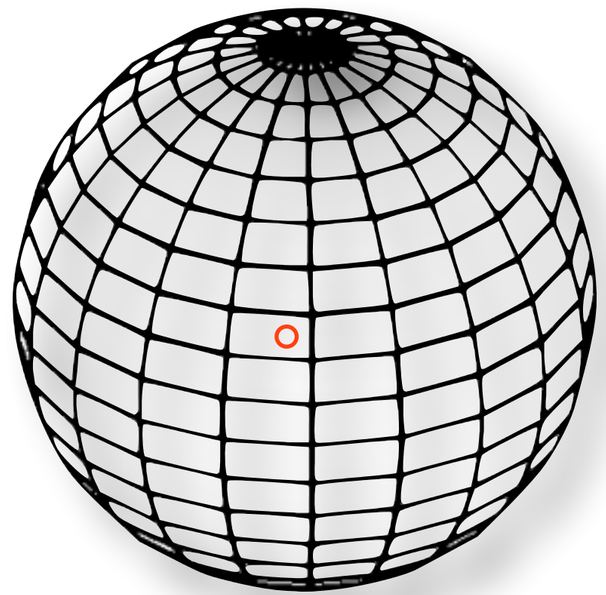
$P(\theta,\phi)$ $\qquad$ $P(x,y)$

Light has color (wavelength), so need λ

And, scenes change over time, so need **t**

$P(\theta,\phi,\lambda,t)$ $\qquad$ $P(x,y,\lambda,t)$

Parameterizing the Light Field



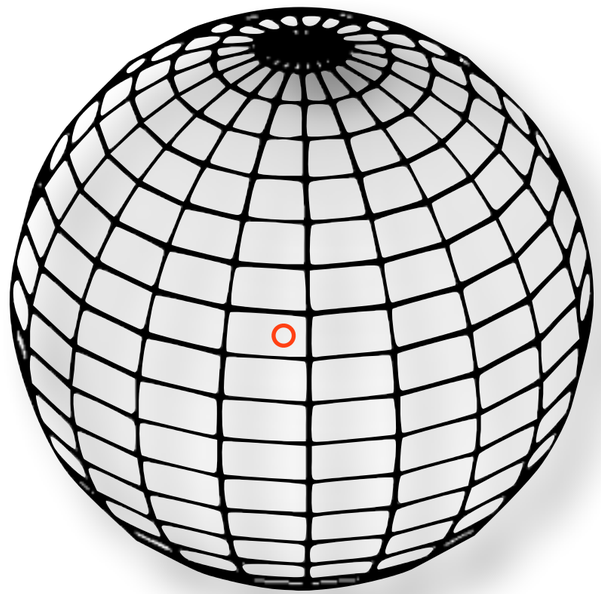
Say V_x, V_y, V_z is the position of the viewing point

$$P(\theta,\phi,\lambda,t,V_x,V_y,V_z) \qquad P(x,y,\lambda,t,V_x,V_y,V_z)$$

$$P(\theta,\phi,\lambda,t) \qquad P(x,y,\lambda,t)$$

The Plenoptic Function

Introducing the Plenoptic Function, P_f

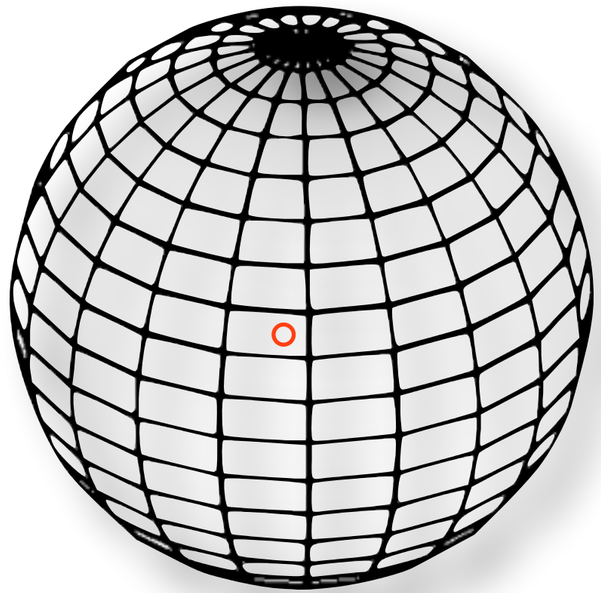


$P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ $\quad$ $P(x,y,\lambda,t,V_x,V_y,V_z)$

The Plenoptic Function, P_f, is measured in an idealized manner by placing an eye at every possible location in the scene (V_x, V_y, V_z) and recording intensity of light rays, wavelength λ, at time t, at every possible angles (θ,ϕ) (around V_z) or in terms of (x,y)

Adelson and Bergen (1991)

The Plenoptic Function



$P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ $\quad$ $P(x,y,\lambda,t,V_x,V_y,V_z)$

Plenoptic: (Latin) plenus (full) + optic

"Of or relating to all the light, traveling in every direction in a given space."

Plenoptic OR Light-field Camera

A camera that can capture a Light-Field, and render to Pixels as needed

Adelson and Bergen (1991)

Light Fields (7-D)

$$P(\theta, \phi, \lambda, t, V_x, V_y, V_z)$$

* 7 Dimensions
* Complete scene; holographic video

Star Wars (1977)

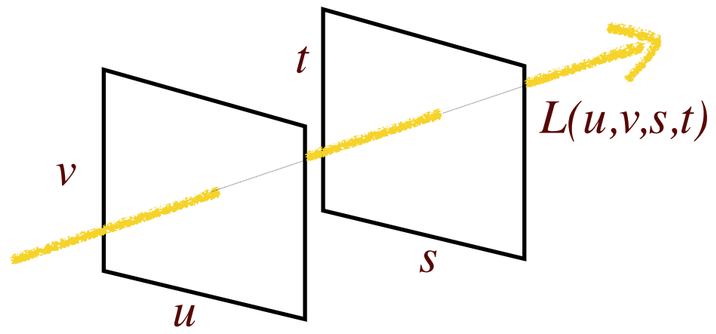
Light Fields (5-D)

$$P(\theta, \phi, V_x, V_y, V_z)$$

* 5 Dimensions
* Ignore time and wavelength
* Capture only viewpoint and direction

Light Fields (4-D)

$$P(\theta, \phi, V_x, V_y, V_z)$$

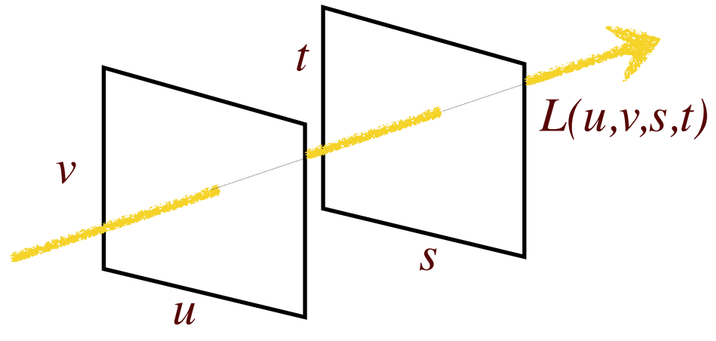


* 4 Dimensions
* Within a bounding box. (Space of all lines in 2D space is 4D)
* No occluding objects, with viewpoint and direction

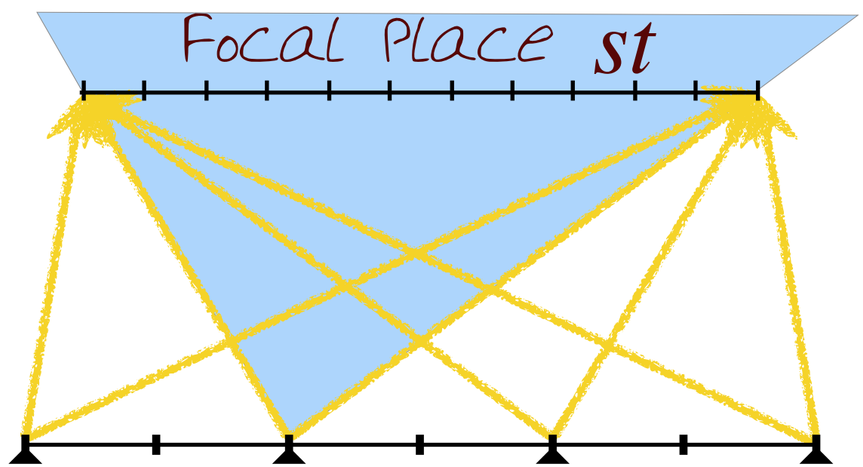
Any point within a scene is represented by a 5D plenoptic function.
Outside of a scene (outside of the sphere of a snow globe) light from the scene does not get occluded by objects, and is represented, as a 4D light field.

Light Fields (4-D)

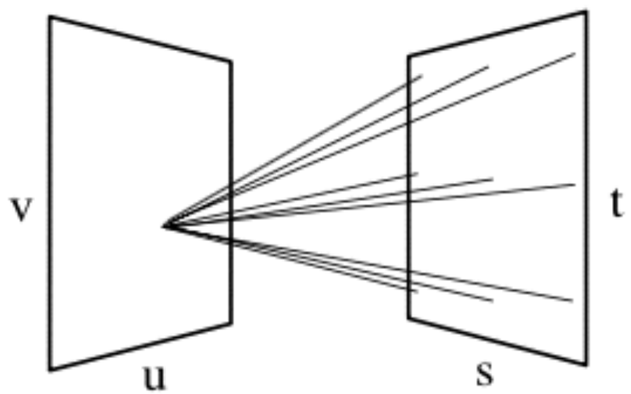
$P(\theta, \phi, V_x, V_y, V_z)$



* Two plane Parameterization for Light Slab/Beam
* Light flows from ***uv*** to ***st*** plane
* Parameters ***uv*** and ***st*** between ***0*** and ***1***



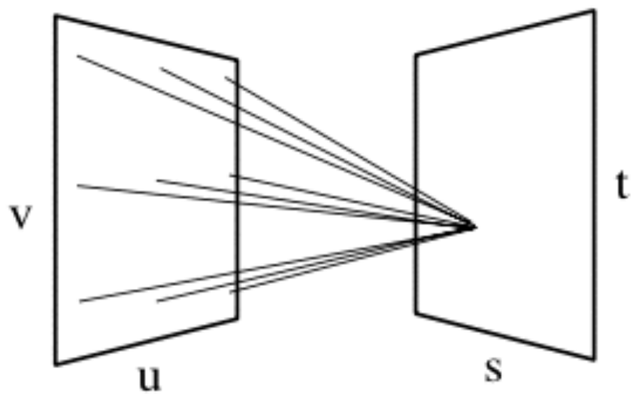
Visualization of a Light-Field (a)



Rays arriving at one point on the **uv** plane from all points on the **st** plane

Levoy & Hanrahan (1996)

Visualization of a Light-Field (b)



Rays leaving at one point on the **st** plane bound for all points on the **uv** plane

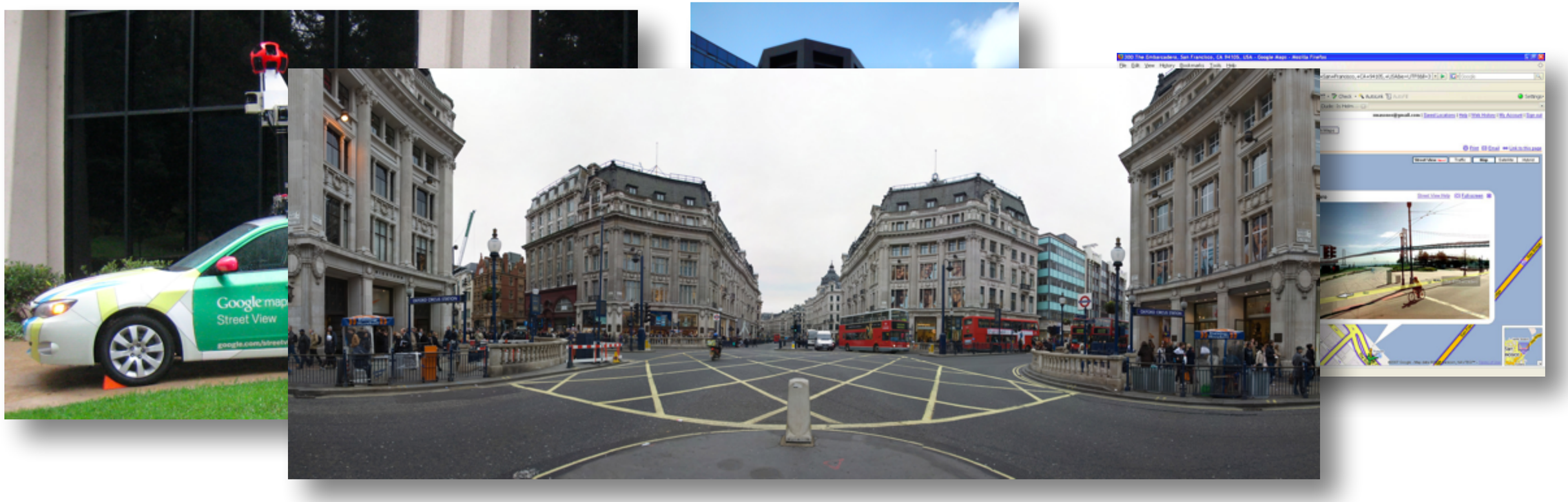
Levoy & Hanrahan (1996)

Capture a Light-field, Store and Render

$P(\theta,\phi)$

* 2 Dimensions
* At the same viewpoint
* Panorama

Examples

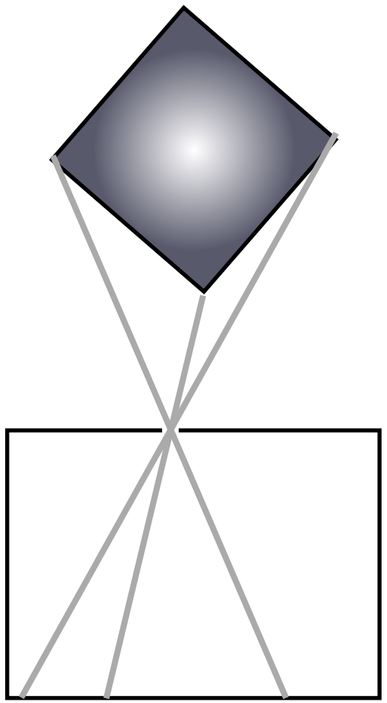


Google Street Views

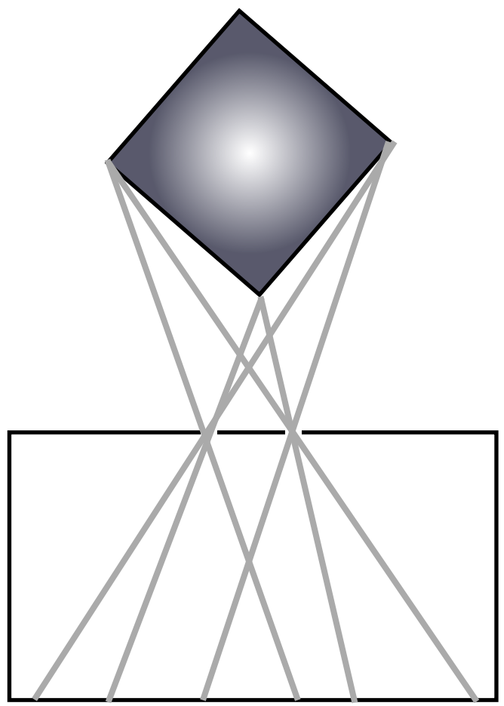
But not just images, they use Geometry too.

Can you think of others?

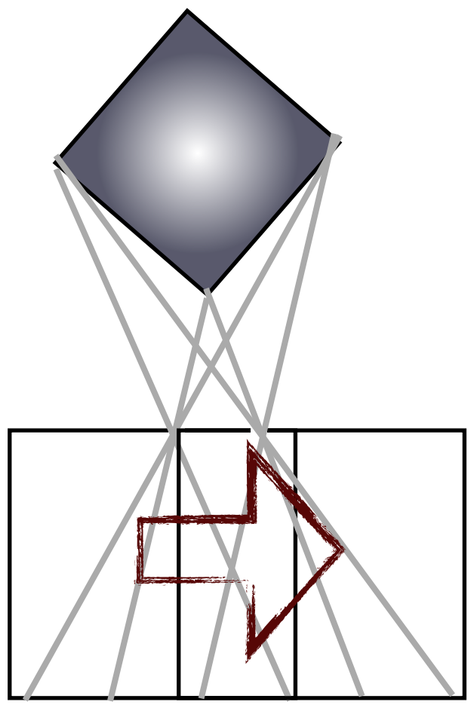
Light field via a PinHole Camera



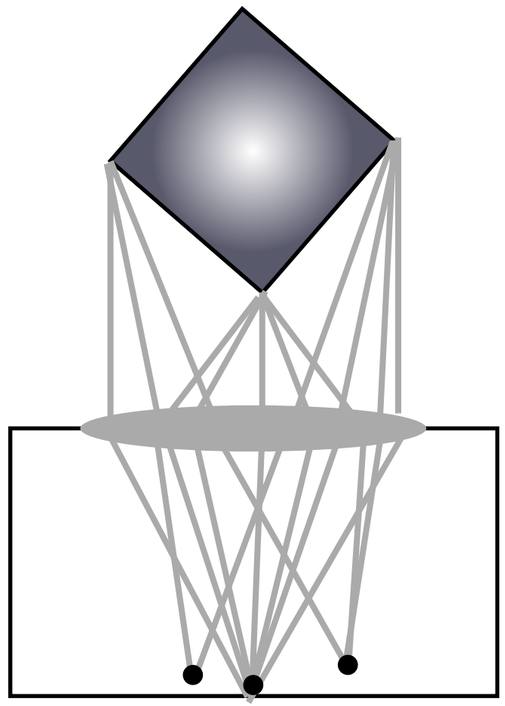
Single Pinhole



Double Pinholes

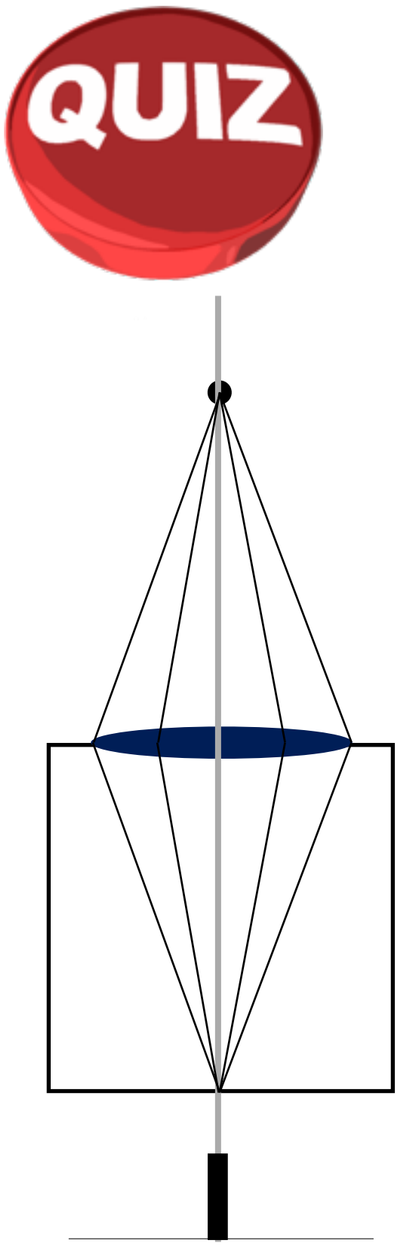


Motion Parallax



With Lens

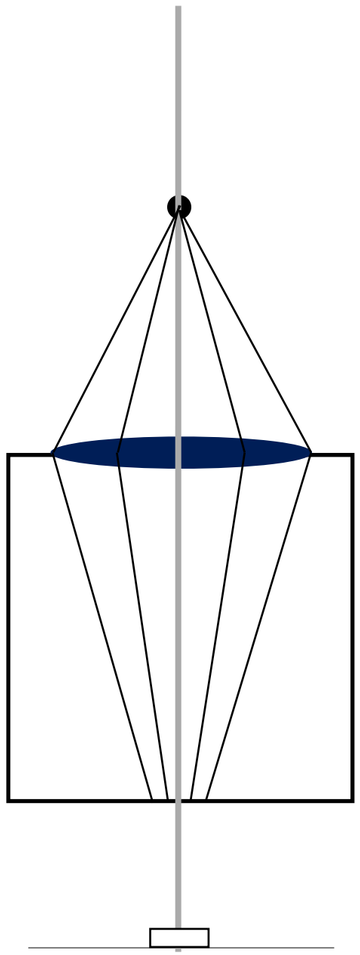
Adelson and Wang (1991)



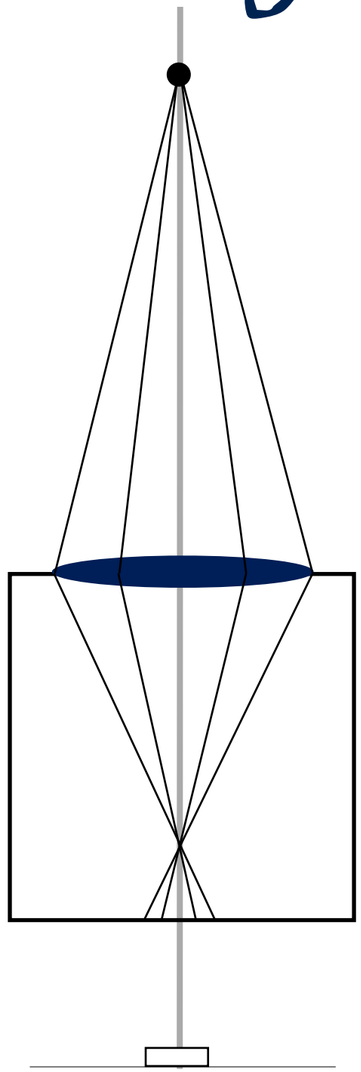
Single Lens System (1)

Point Light Source

(1)



(2)



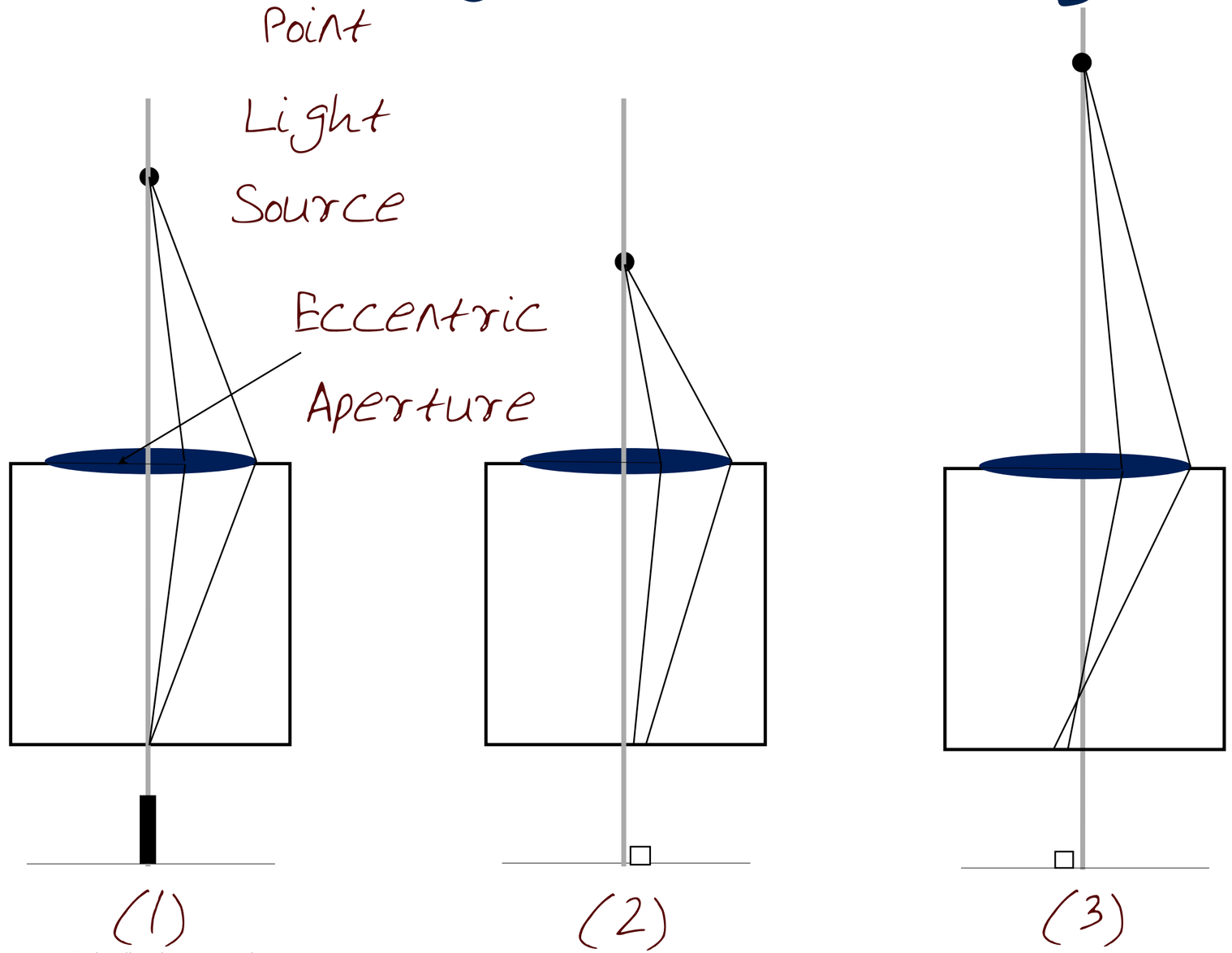
(3)

☐ Near object; blurred

☐ Far object; blurred

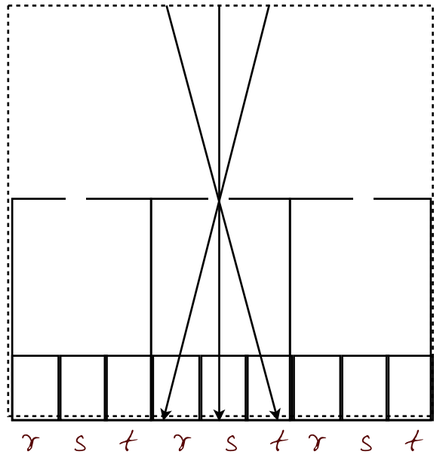
☐ In-focus object; point image

Single Lens System (2)

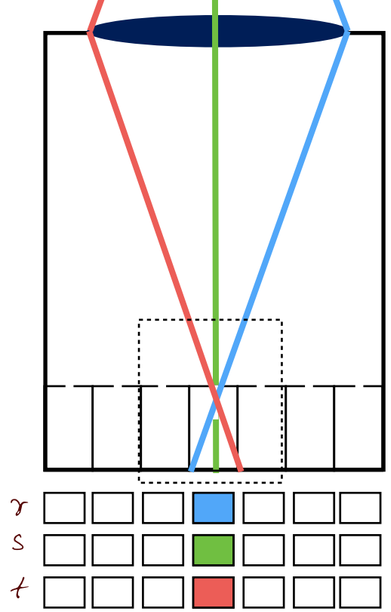


1. In-focus object; forms a Point Image
2. Near object; blurred, to the right
3. Far object; blurred, to the left

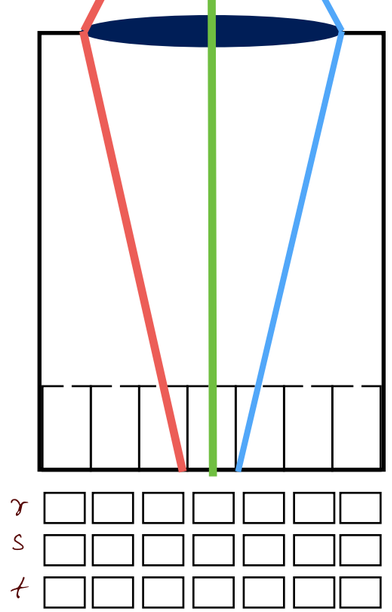
QUIZ Encode Direction and Intensity



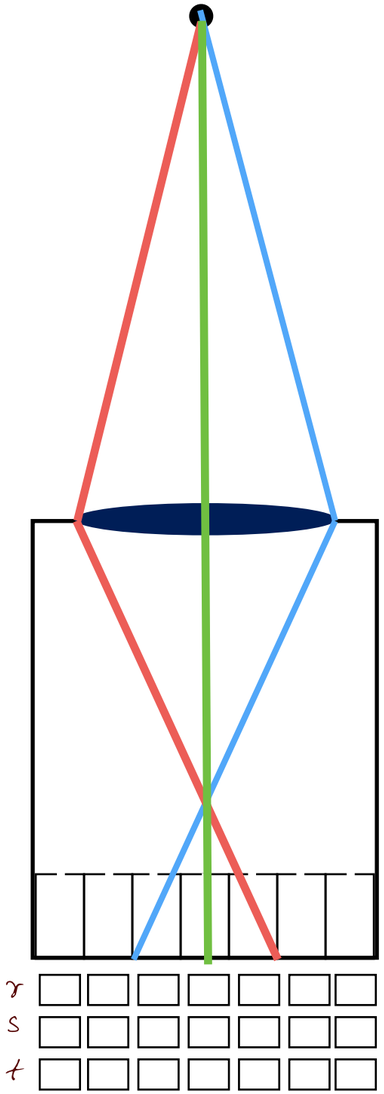
(1)



(2)

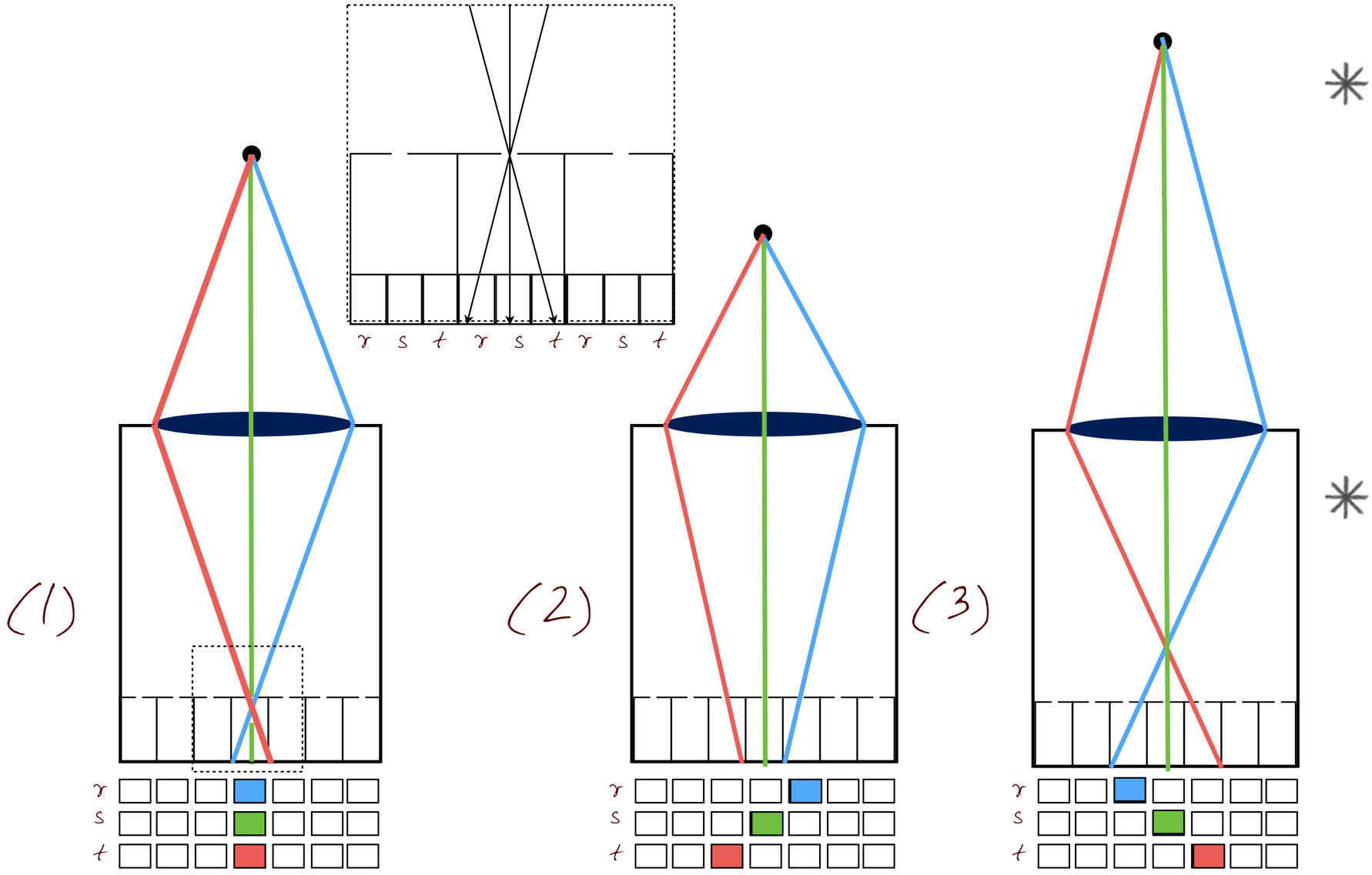


(3)



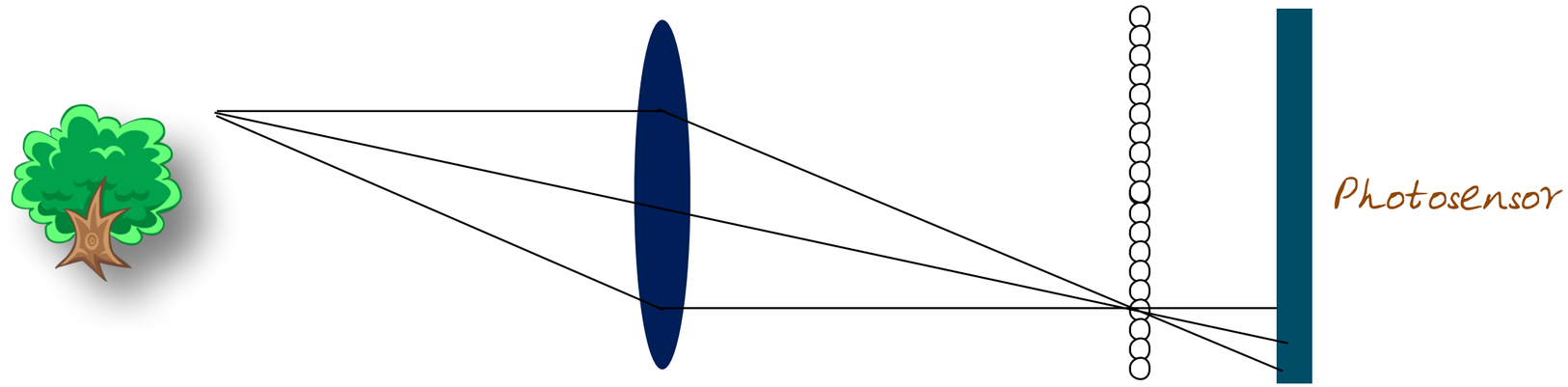
Select which rst will be highlighted for (2) and (3)?

Encode Direction and Intensity



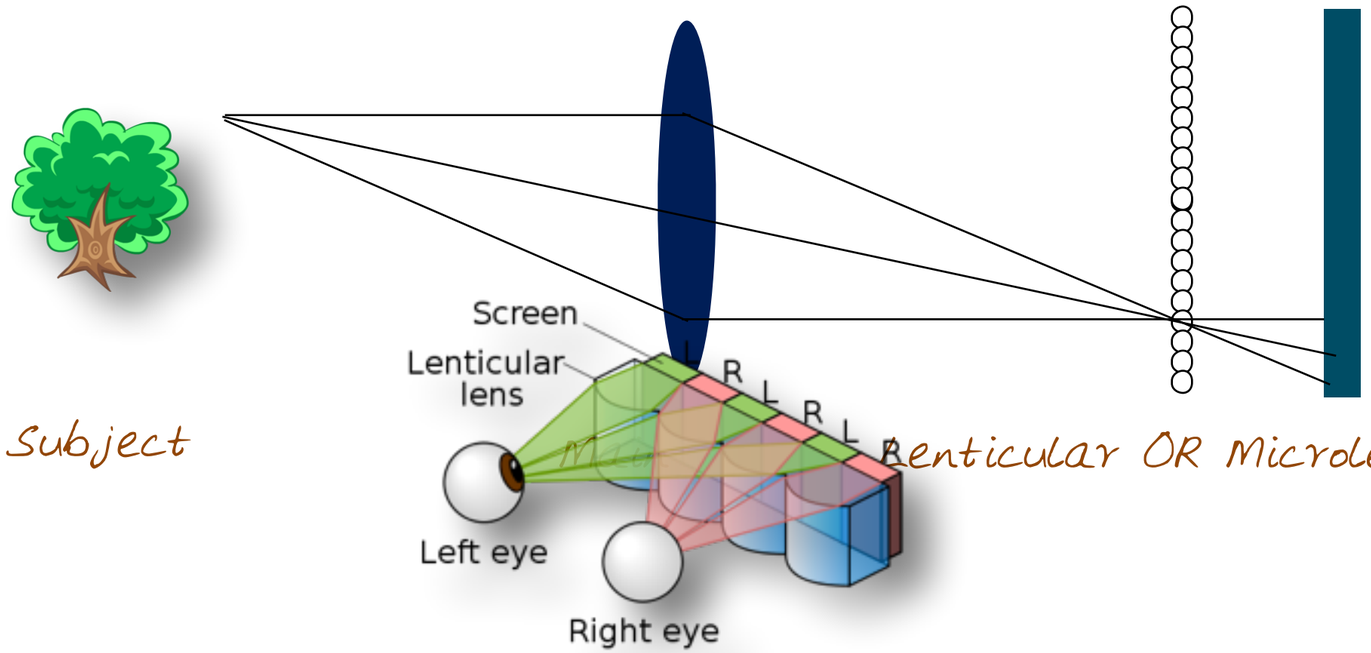
* We add a miniature pinhole at the image plane
* Analyzes the structure of light at each macro-pixel.

Lens and Microlens



A Light-field / Plenoptic Camera (Ng et al. 2005)

Lens and Microlens



Subject

Photosensor

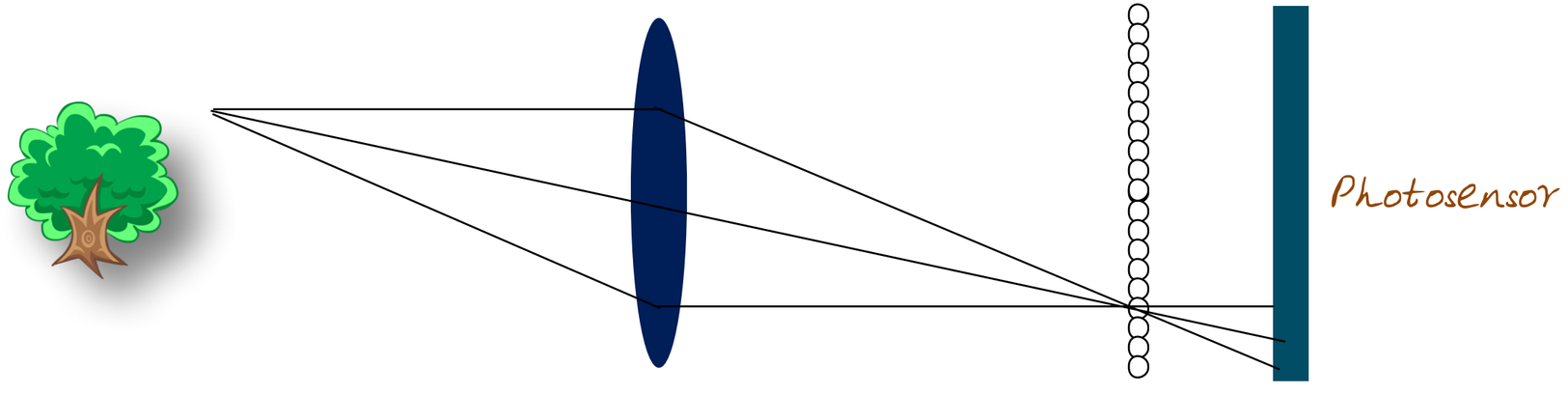
Lenticular OR Microlens Array

Lectincular Array
used in lenticular printed cards

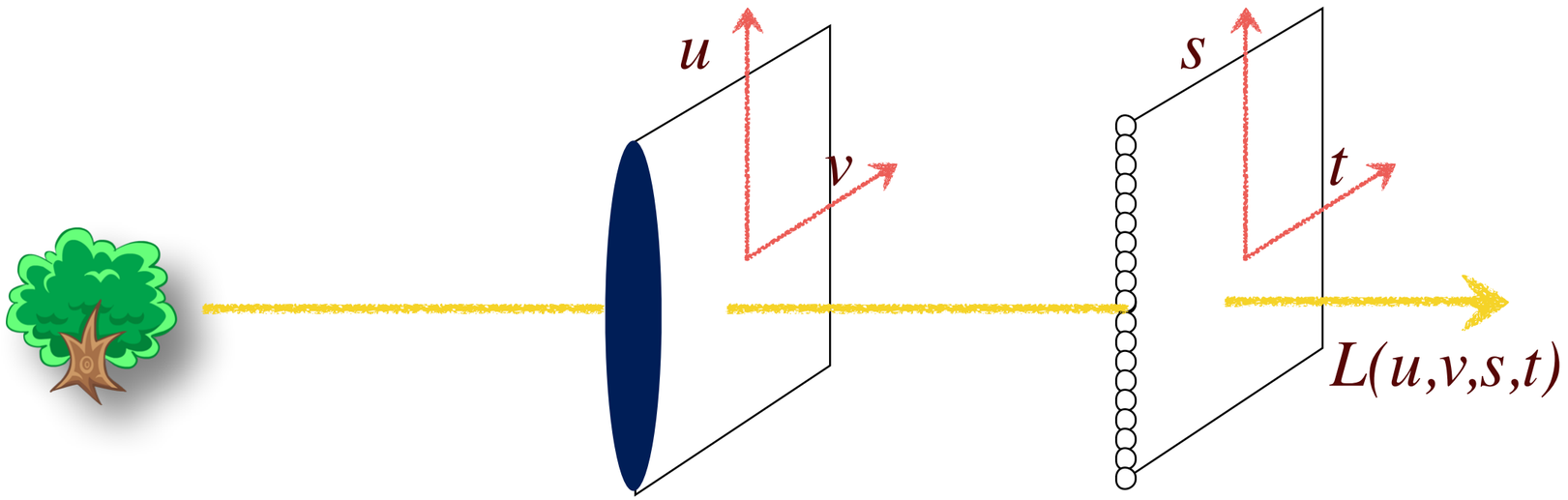
A Light-field / Plenoptic Camera (al. 2005)

Cylindrical lenses to form a Lenticular Array

Lens and Microlens



A Light-field / Plenoptic Camera (Ng et al. 2005)



History of Light Field Camera

- 1908: Lippmann proposed one that used integral photography
  - A Nobel laureate in physics for a method to reproduce colors photographically based on interference
- 1930: Ives constructed Parallax Panoramagrams
- 1992: Adelson and Wang proposed a plenoptic camera and used it to generate stereo from a single lens
- 1990s (mid): Graphics researchers explored Light fields for Image-based Rendering
- 2005: Ng et al. proposed a hand-held Plenoptic Camera
- 2012: Lytro available (lytro.com)

http://en.wikipedia.org/wiki/Light-field_camera

4D Light Field
(Lytro)

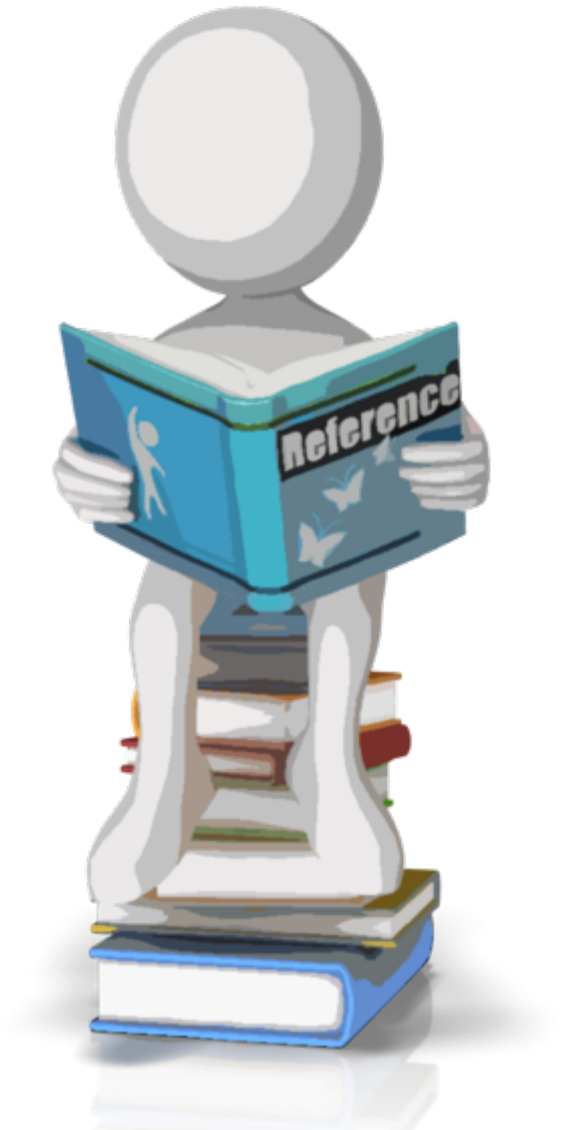
Summary (1)

* Concept a Light Field
* Plenoptic function and its seven (7) parameters
* Different types of Light Fields in terms of the Dimensions captured

Summary (2)

* Uses of a pinhole and a lens system to analyze the scene
* Eccentric aperture on a simple lens system
* A lens with an array of pinhole camera to encode direction and intensity of the rays of light
* 4D Light Field camera

Further Reading



* Adelson and Bergen (1991), "The Plenoptic Function and the Elements of Early Vision" Computational models of visual processing [PDF]
* Adelson and Wang (1992) "Single lens stereo with a plenoptic camera", IEEE PAMI 14(2) [PDF]
* Levoy and Hanrahan (1996) "Light field Rendering", ACM SIGGRAPH 1996 [PDF]
* Gorler, Grzeszczuk, Szeliski, Cohen (1996) "The Lumigraph" ACM SIGGRAPH 1996 [PDF]
* Ng, Levoy, et al. (2005), "Light field photography with a hand-held plenoptic camera" Stanford Tech Report CTSR 2005-02, 2005 [PDF]

Credits

* For more information, see
  * Richard Szeliski (2010) Computer Vision: Algorithms and Applications, Springer
* Lytro.com

Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

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Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

Georgia Tech College of Computing

Projector Camera Systems

* Combing a Controllable Camera and a Light Source

1. Basics of Controlled Illumination
2. Use of a Projector as a controlled Light Source
3. Projector-Camera System
4. Projector Calibration
5. Examples of PROCAMS

Recall: Computational Photography

3D Scene

Illumination

Optics

Sensor

Processing

Display

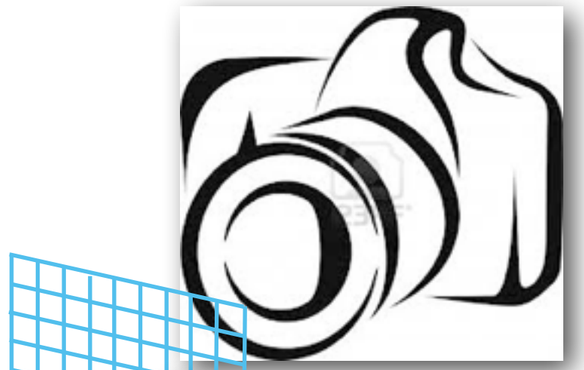
User

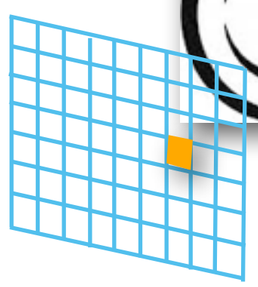
Projector (Controllable Light Source)

Modulator (Controllable Aperture)

3D Scene

Camera





Modulator (Controllable Aperture)

Controlled Illumination

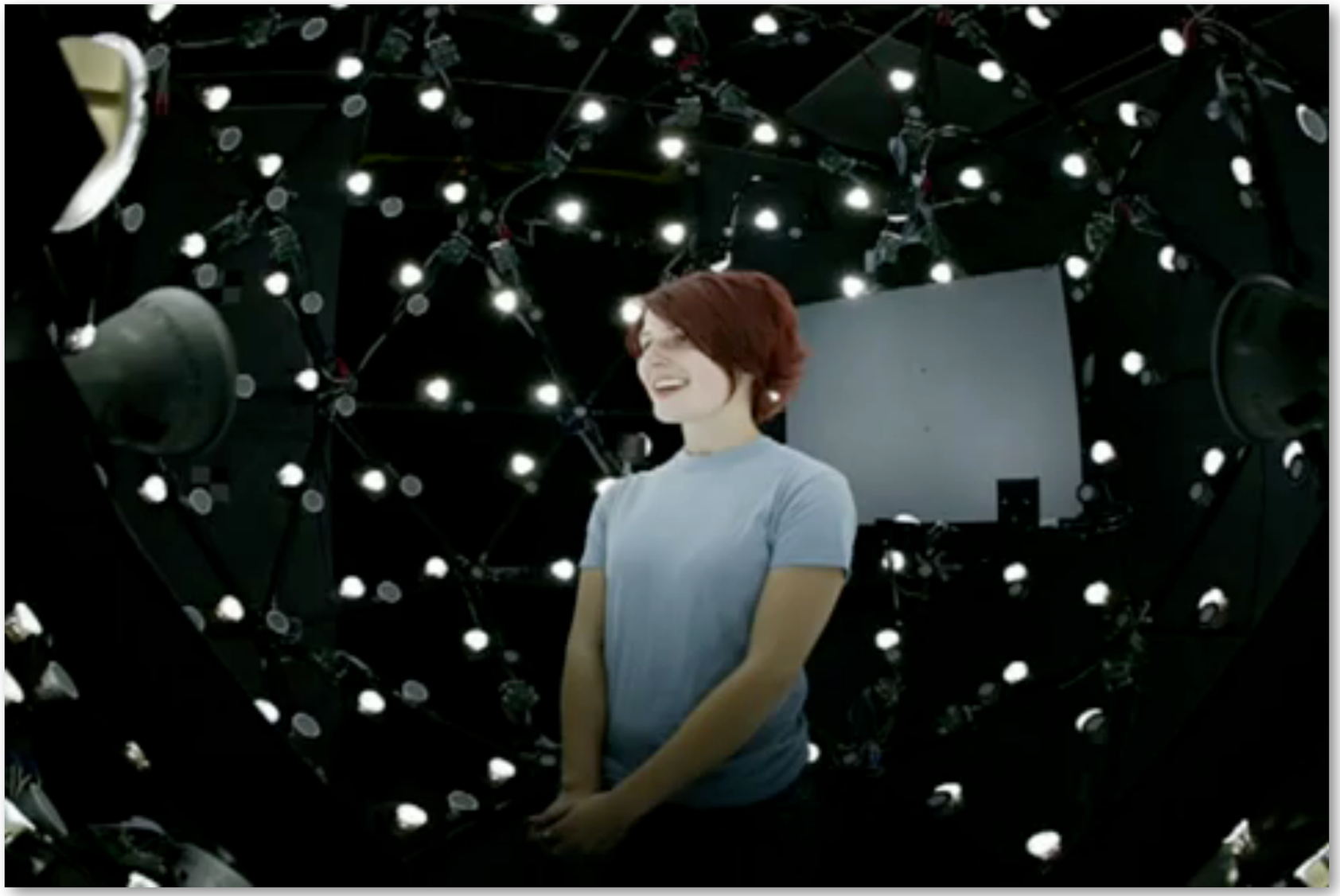
Projector
(Controllable
Light Source)

Modulator
(Controllable
Aperture)

Lightstage,
USC/ICT

Trimensional
Schindler

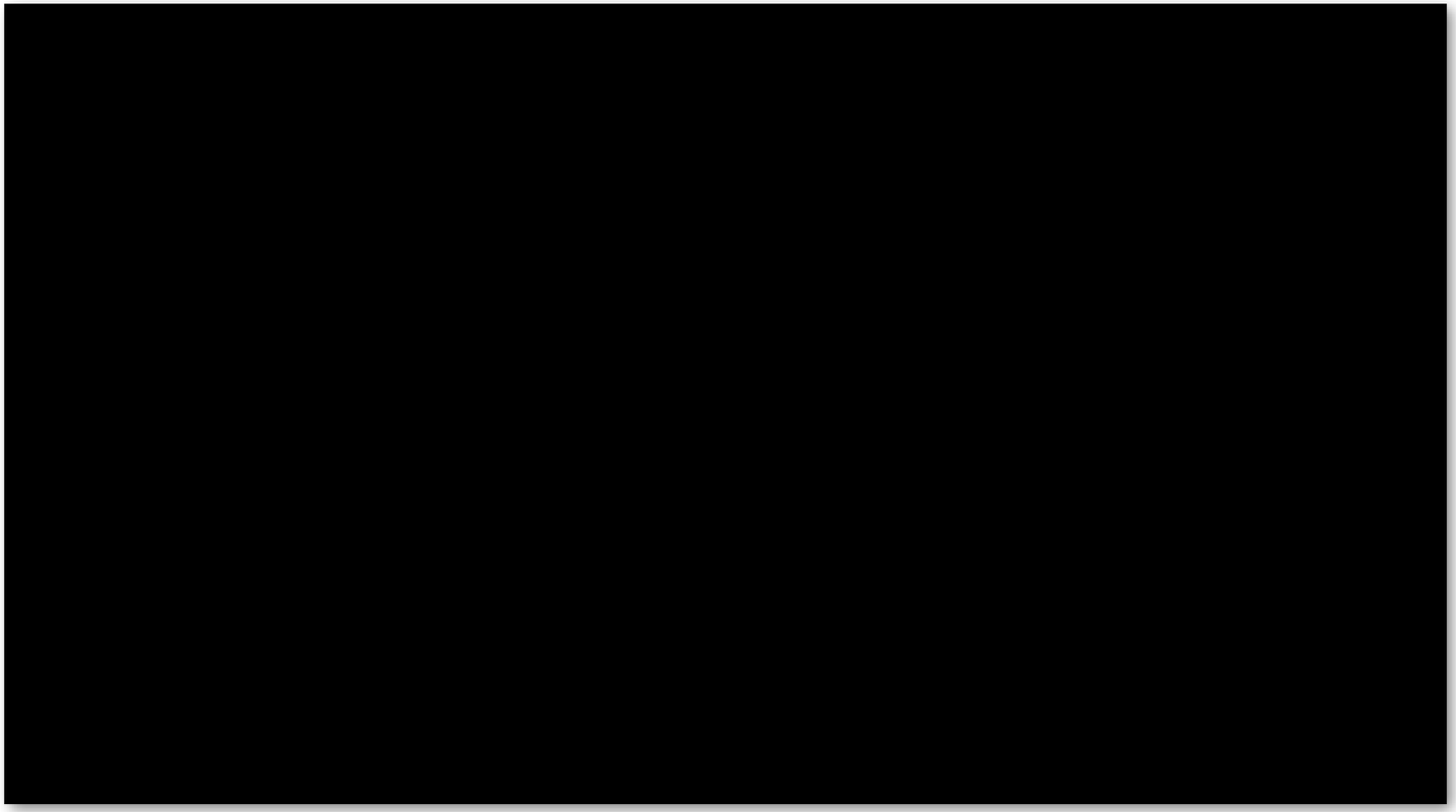
Lightstage



http://gl.ict.usc.edu/LightStages/

Debevec (2012)

Lightstage



http://gl.ict.usc.edu/LightStages/

Debevec (2012)

3D Scanning on Mobile Phone

Controlled Illumination

* Given a controlled light source, we can:
  * Scan
  * Relight

* How can we computer control light?
  * Projectors are computer controlled light sources!

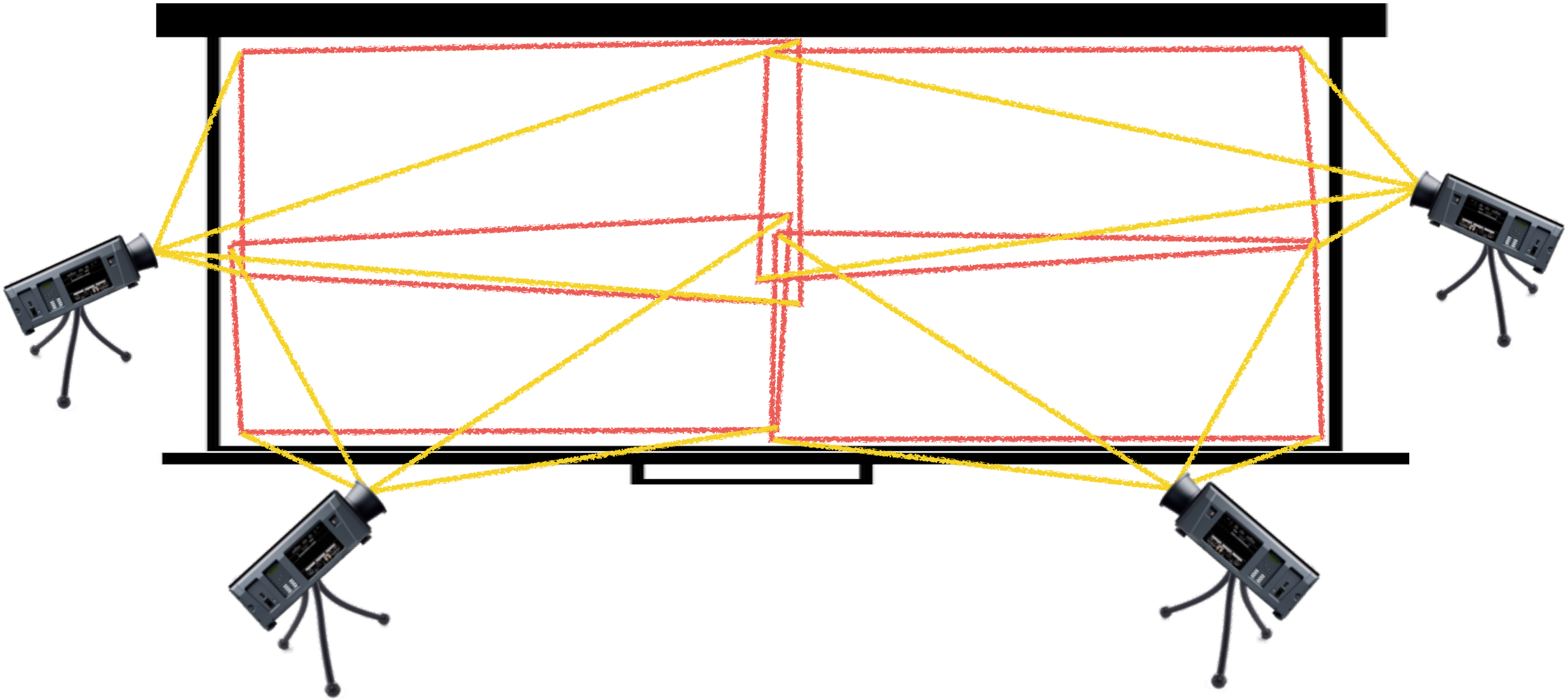
Projector Calibration

How do we <u>automatically</u> get a perfectly rectangular image on the display of the exact aspect ratio of the original image?

- ☐ Move the screen
- ☐ Move the Projector
- ☐ Use a Camera to "see" the displayed image and transform the image on the projector

Projector Calibration

Projector Calibration



Projector Calibration

http://wearables.unisa.edu.au/

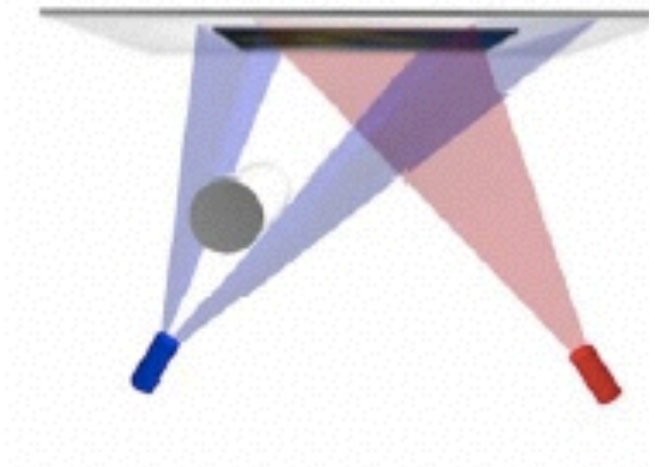
Marner, Smith, Walsh, Thomas (2014)

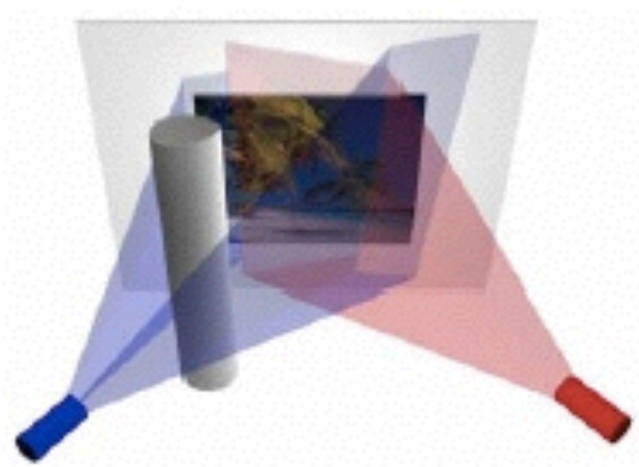
Projector Calibration with 1 Pixel Sensor

* Low resolution cameras can be used with structured light
* A single "pixel"

Lee, Dietz, Aminzade, and Hudson, (2004)

Light that is Aware of Obstructions





Summet, Flagg, et al. (2007)

Programable Headlights

Tamburo, Nurvitadhi, Chugh, Chen, Rowe, Kanade and Narasimhan (2014)

http://www.cs.cmu.edu/smartheadlight/

Room Alive

Jones, Sodhi, Murdock, Mehra, Benko, Wilson, Ofek,, MacIntyre, Shapira, (2104) http://projection-mapping.org/roomalive-uist/

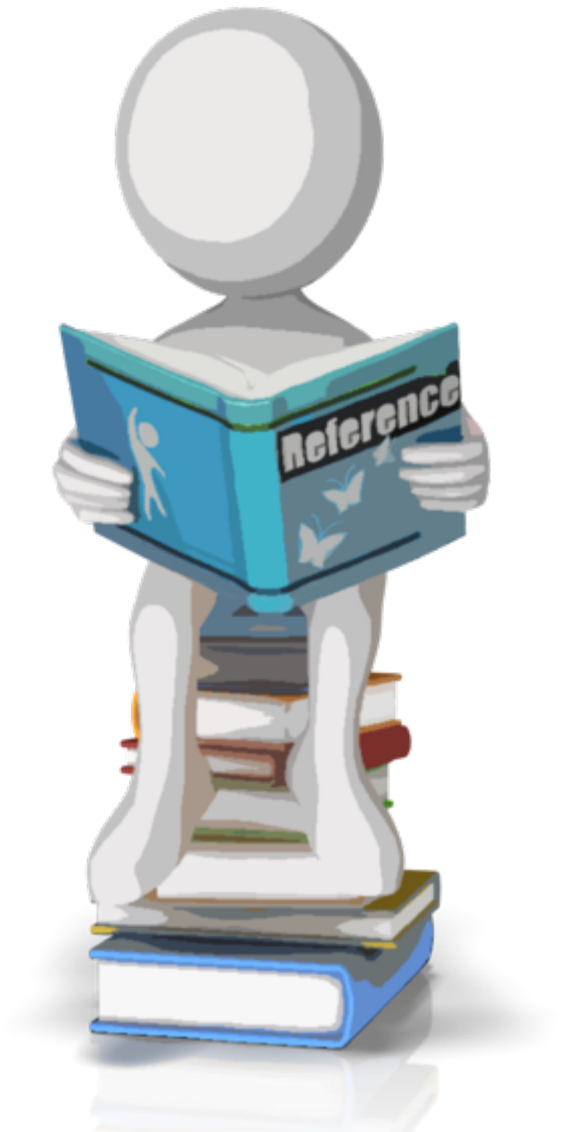
Summary

* Introduced systems where a controlled light source is coupled with a camera
* PROCAMS

Further Reading

* Debevec (2012), "The Light Stages and Their Applications to Photoreal Digital Actors", SIGGRAPH Asia 2012 Technical Briefs [PDF]
* Marner, Smith, Walsh, Thomas (2104), "Spatial User Interfaces for Large Scale Projector-Based Augmented Reality", in IEEE CGA 2014 [PDF]
* Summet, Flagg, Cham, Rehg and Sukthankar (2007) "Shadow Elimination and Blinding Light Suppression for Interactive Projected Displays" IEEE TVCG 2007 [PDF]

Further Reading



* Lee, Dietz, Aminzade, and Hudson, (2004) "Automatic Projector Calibration using Embedded Light Sensors", ACM UIST 2004 [PDF]
* Tamburo, Nurvitadhi, Chugh, Chen, Rowe, Kanade and Narasimhan (2014) "Programmable Automotive Headlights" ECCV 2014 [PDF]
* Jones, Sodhi, Murdock, Mehra, Benko, Wilson, Ofek,, MacIntyre, Shapira, (2104) "RoomAlive: Magical Experiences Enabled by Scalable, Adaptive Projector-Camera Units" ACM UIST, 2014 [PDF]

Credits

* https://www.youtube.com/watch?v=xgUWRN8QNM
* https://www.youtube.com/watch?v=IW4tZGXA4VQ
* https://www.youtube.com/watch?v=XgrGjJUBF_I
* https://www.youtube.com/watch?v=dolJHDkwDss
* http://www.cs.cmu.edu/smartheadlight/
* http://projection-mapping.org/roomalive-uist/
* Thanks to Jay Summet for slides

Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

Georgia Tech College of Computing

Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

Georgia Tech College of Computing

Coded Photography

* Cameras that capture additional information about a scene, by using controlled patterns built into the imaging process

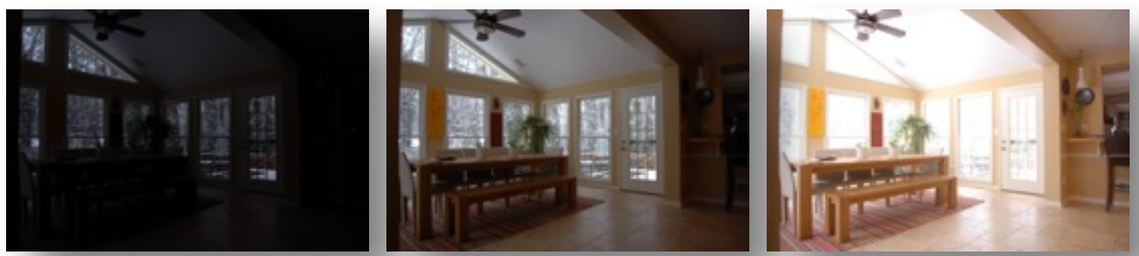
Georgia Tech College of Computing

Lesson Objectives

1. From Epsilon Photography to Coded Photography
2. Concept/Ideals of Coded Photography
3. Coded Aperture
4. Flutter Shutter Camera

Recall: Epsilon Photography

exposure



viewpoint

focus

* Multiple sequential photos
  * Changing some parameters
    * Fusing the photos to create a richer representation
* Synthesizing novel pictures by multiple captures of single images

Recall: Computational Photography

3D Scene

Illumination

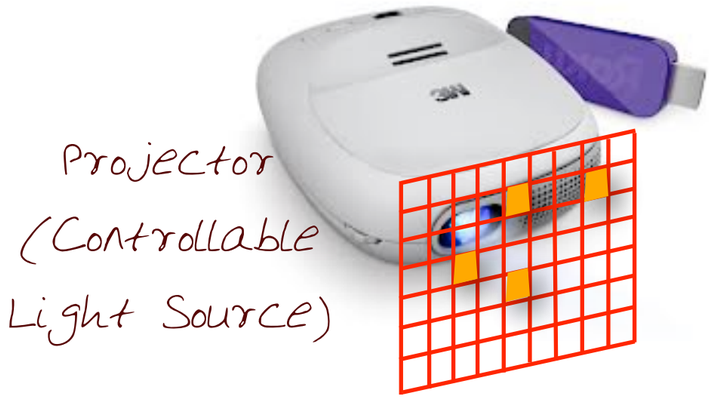
Optics

Sensor

Processing

Display

User

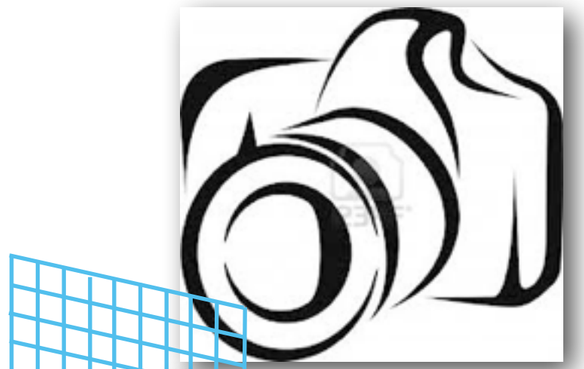


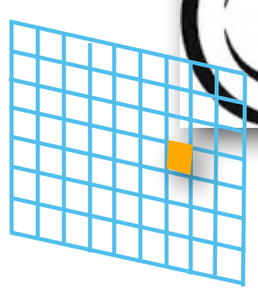
Projector (Controllable Light Source)

Modulator (Controllable Aperture)

3D Scene

Camera



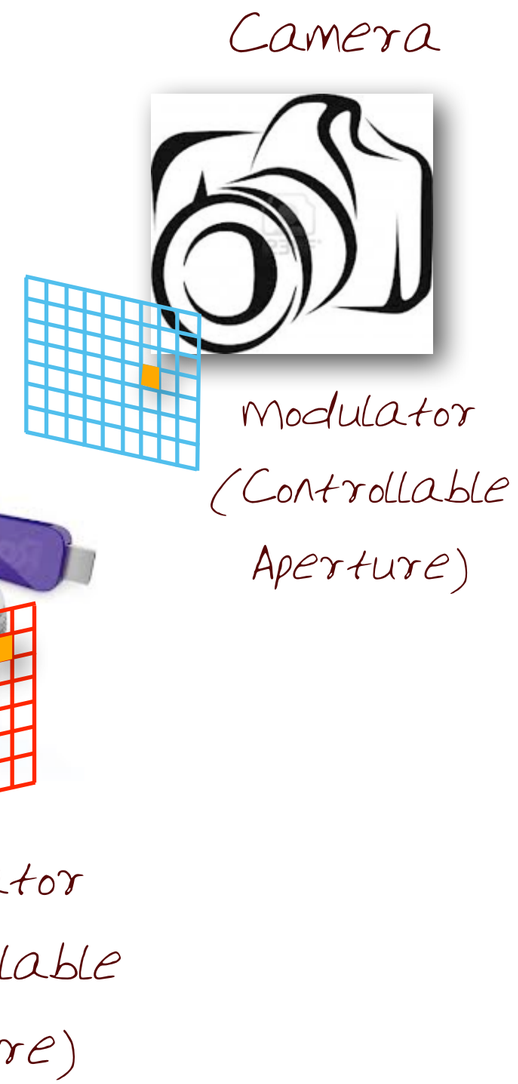


Modulator (Controllable Aperture)

Coded Photography

* Coded Exposure
  - Control light in time
* Coded aperture
  - Control light near the sensor
* Coded illumination
  - Control light in the scene
* Coded sensing
  - Control intensities

Raskar 2009

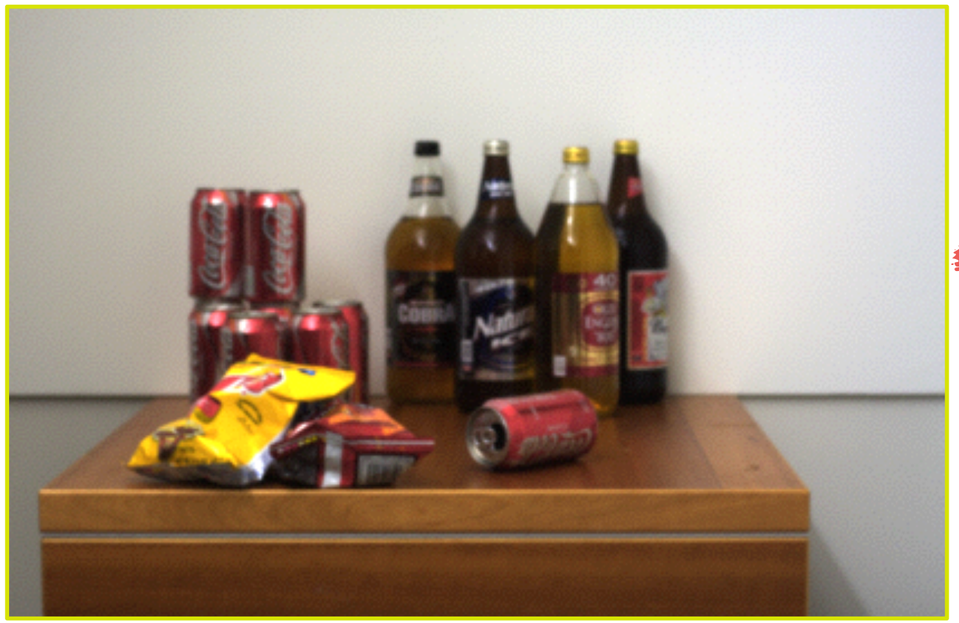


Epsilon ⟺ Coded Photography

- Coded photography encodes the photographic signal and post-capture decoding for improved scene analysis
- Epsilon Photography: successive frames may have different variations
- Coded Photography: neighborhood pixels may have different variations
  - Controlling light over time or space
  - Preserve details about the scene in the recorded photograph
- Coded photography ⟺ Epsilon photography

Raskar 2009

Coded Photography



Single input image

Output #1: Depth map

Levin et al. 2007

Coded Photography

Single input image

Output #2: All-focused image

Levin et al. 2007

Lens and defocus

Lens' aperture

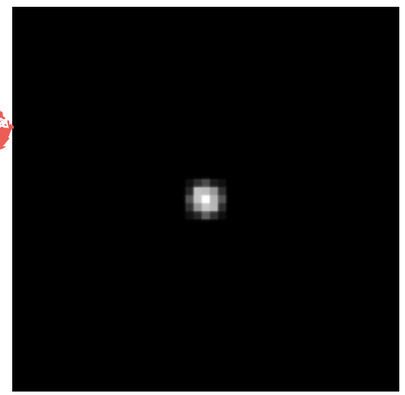
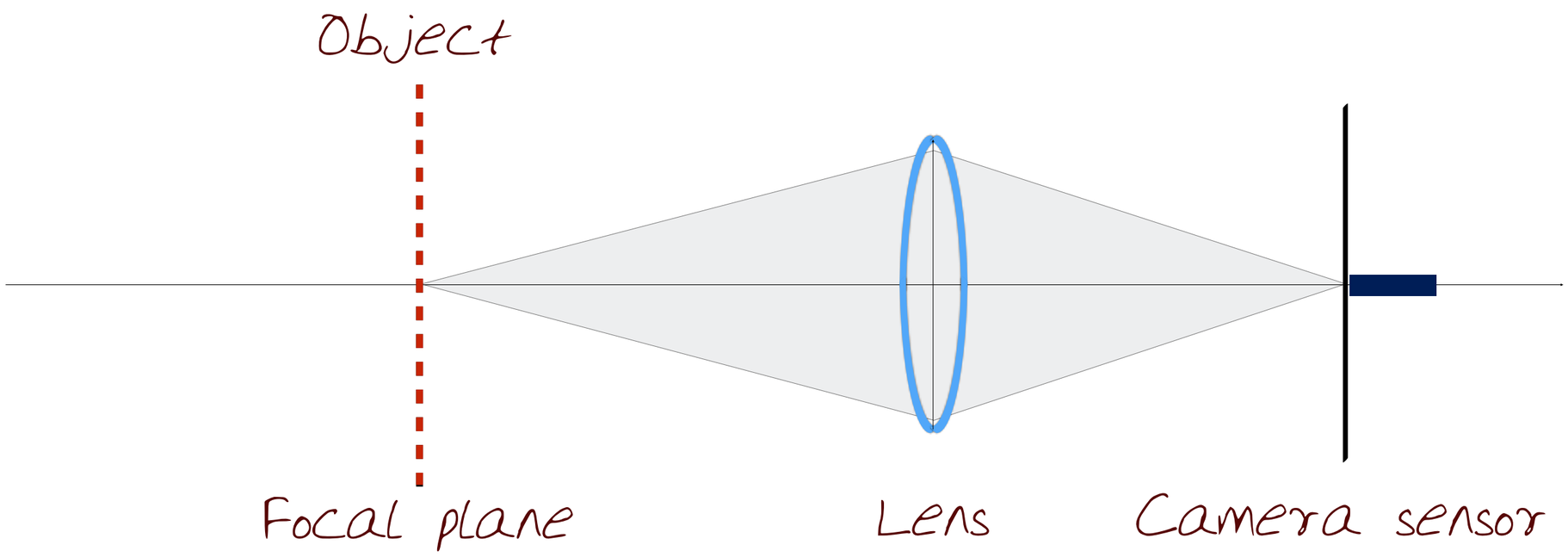


Image of a point light source



Point spread function

Lens and defocus

Lens' aperture

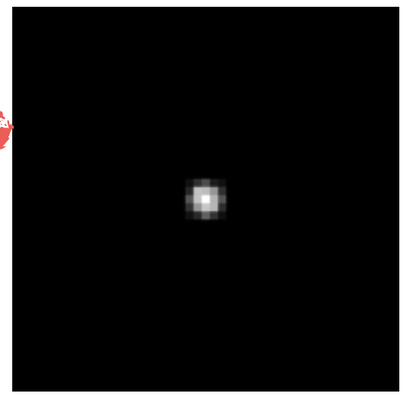
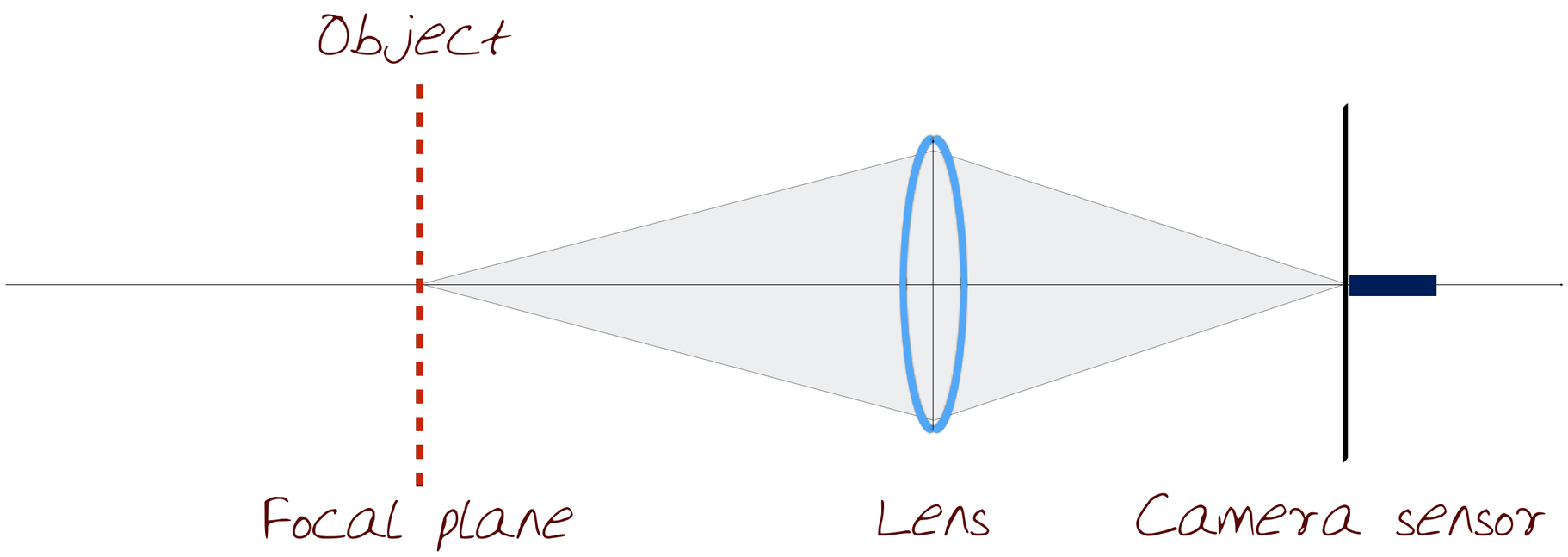


Image of a point light source



Point spread function

Lens and defocus

Lens' aperture

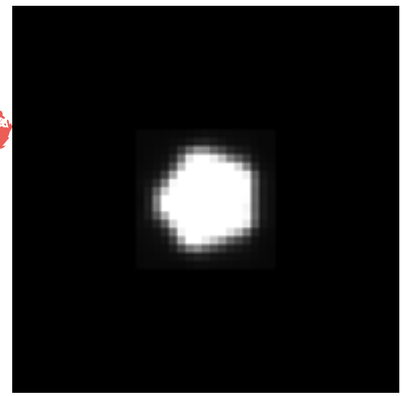
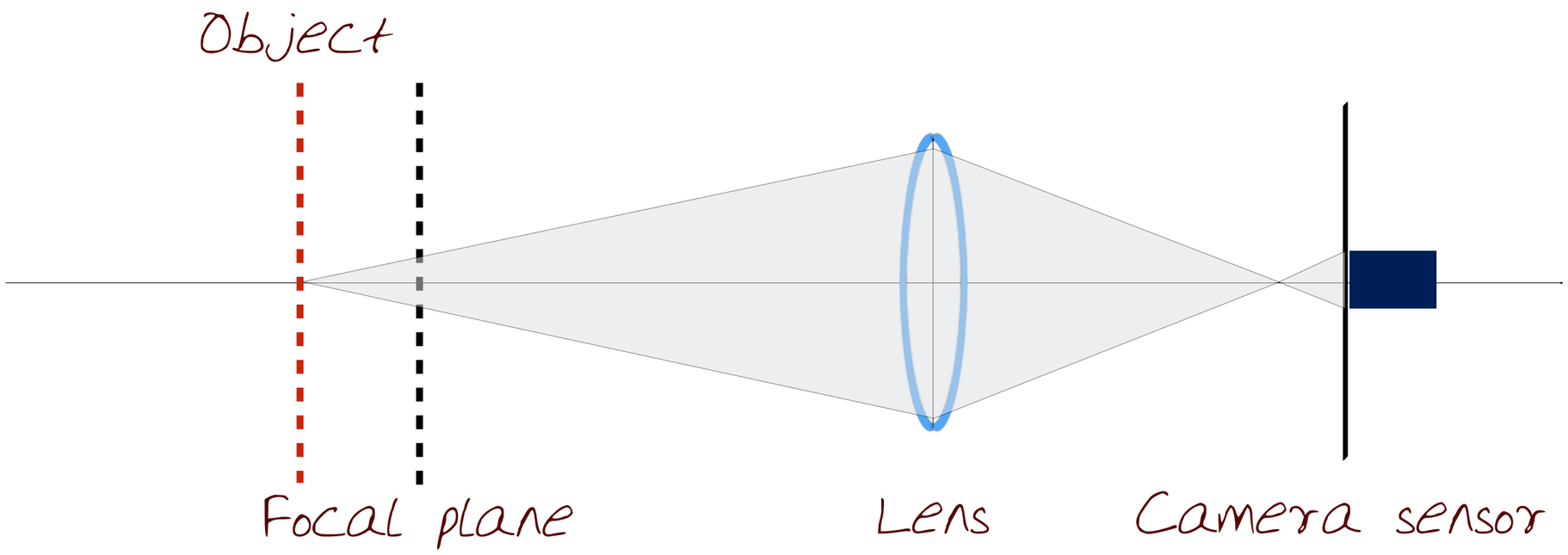


Image of a defocused point light source



Point spread function

Lens and defocus

Lens' aperture

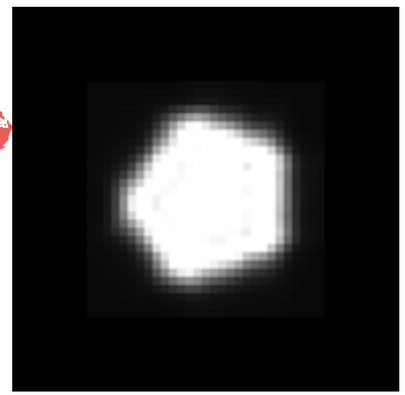
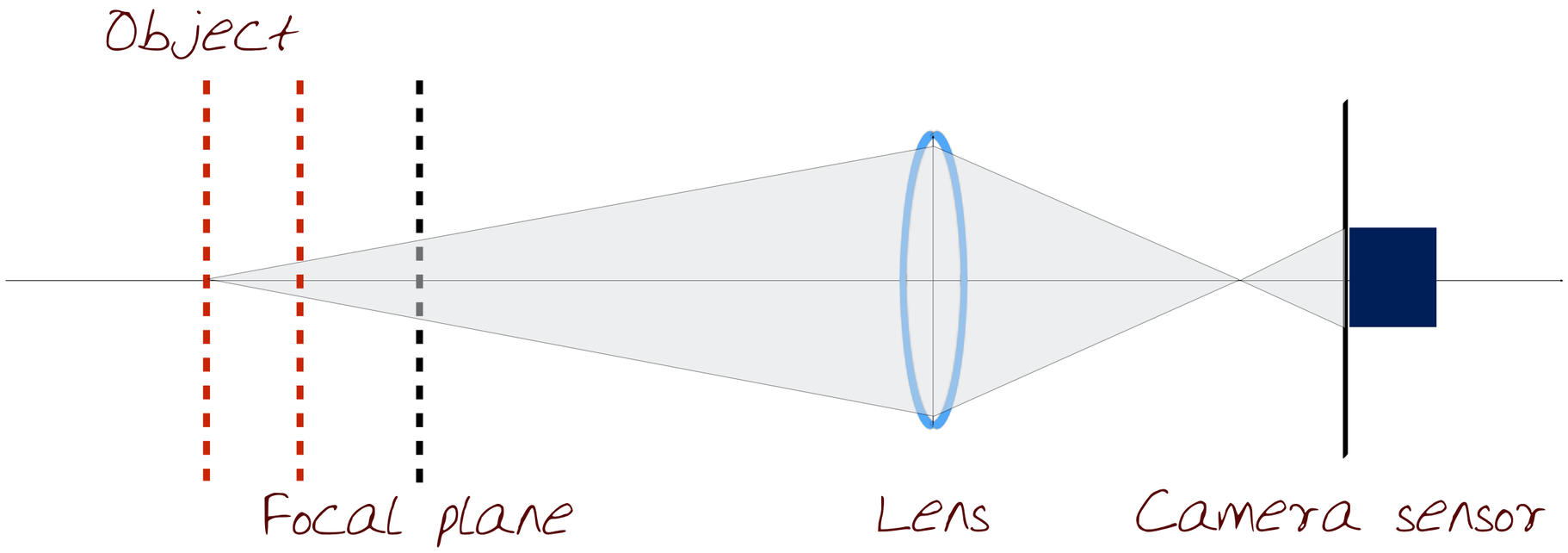


Image of a defocused point light source



Point spread function

Lens and defocus

Lens' aperture

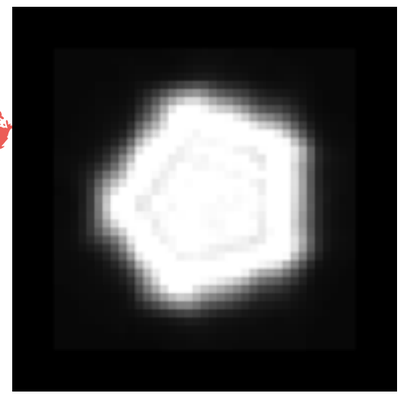
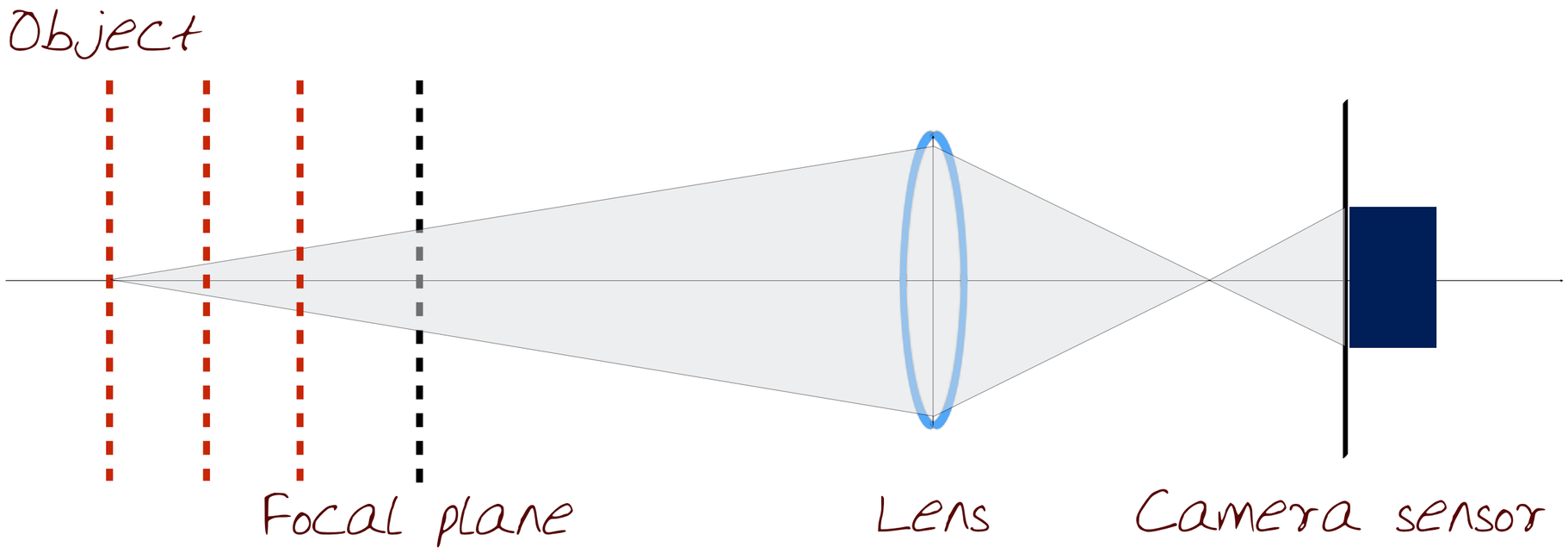


Image of a defocused point light source



Point spread function

Lens and defocus

Lens' aperture

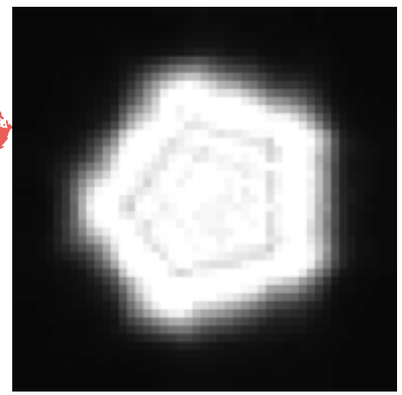
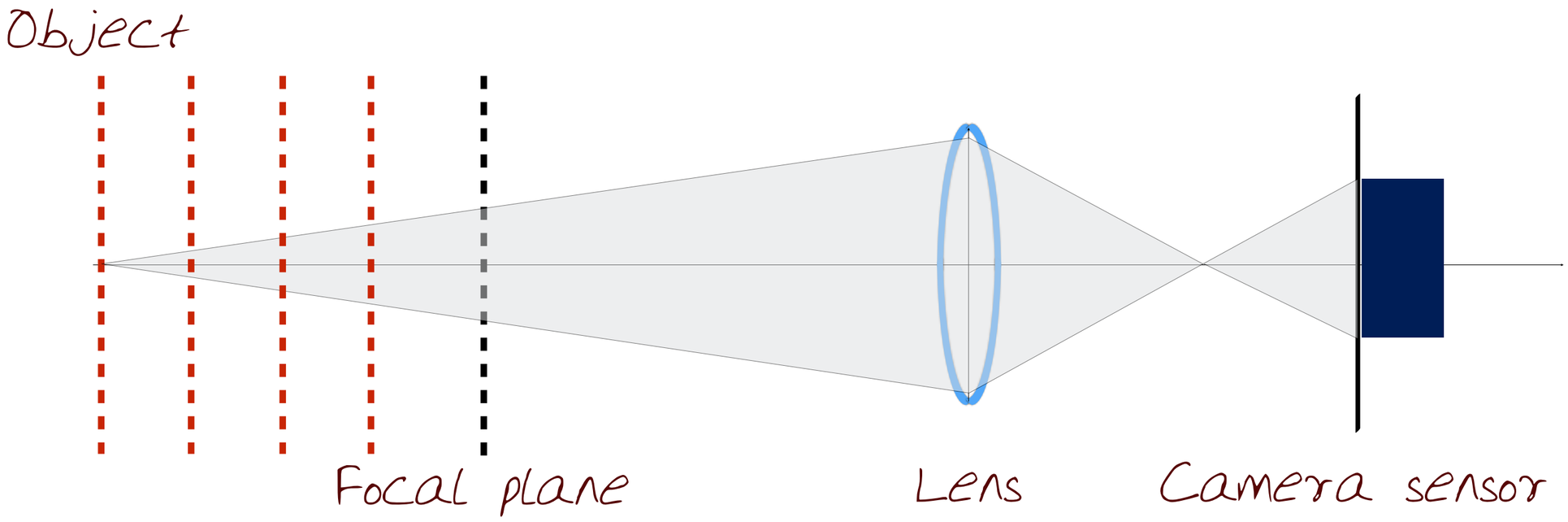
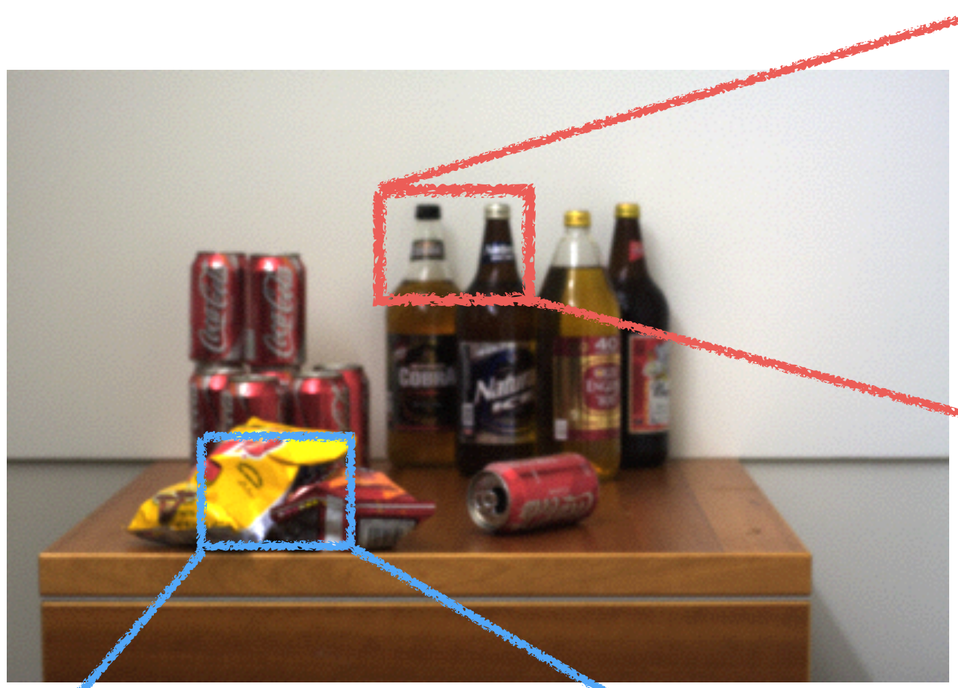


Image of a defocused point light source



Point spread function

Depth and defocus



Out of focus

In focus

ill-posed

Depth from defocus:
Infer depth by
analyzing local scale
of defocus blur

Depth and defocus: Challenges

* Hard to discriminate a smooth scene from defocus blur
* Hard to undo defocus blur

Out of focus?

Given this image

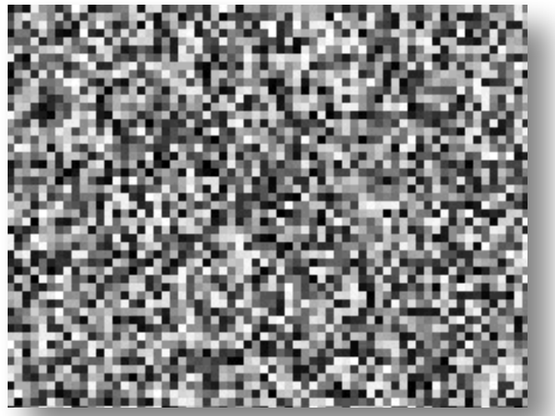
Conventional de-blurring algorithm

Lucy-Richardson Deconvolution 1972-74

Possible Approaches

* Levin et al 2007
* Exploit prior on natural images
  * Improve deconvolution
  * Improve depth discrimination
* make defocus patterns different from natural images and easier to discriminate
* Coded aperture (mask inside lens)

Natural

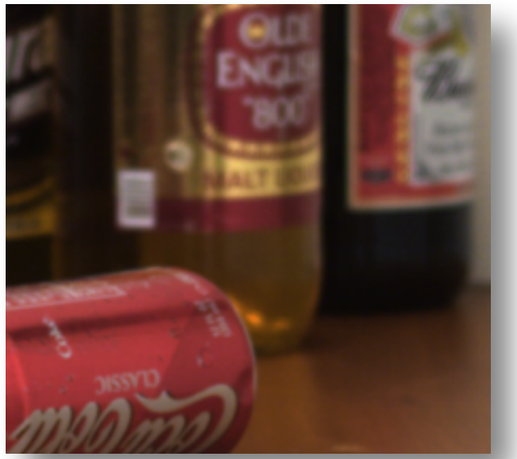


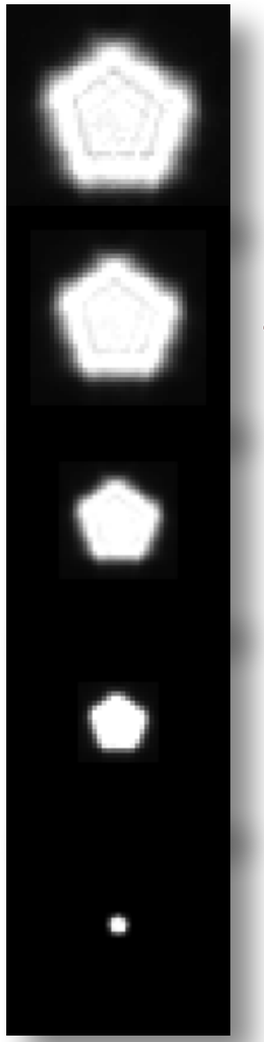
Unnatural

Levin et al 2007, Lucy-Richardson Deconvolution 1972-74

Defocus as Local Convolution

Input defocused image



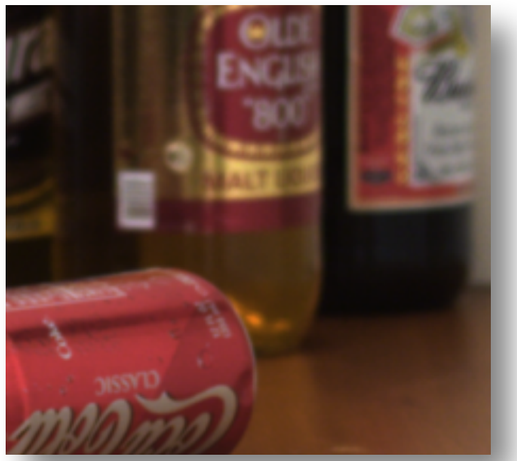


Calibrated blur kernels at different depths

Levin et al 2007

Defocus as Local Convolution

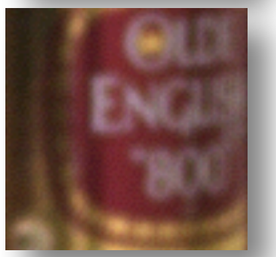
Input defocused image



Local sub-window y_k

Depth $k=1$

Depth $k=2$

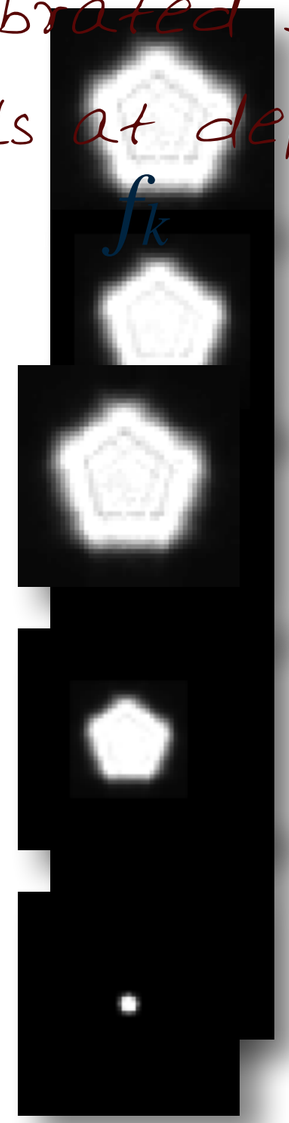


Depth $k=3$

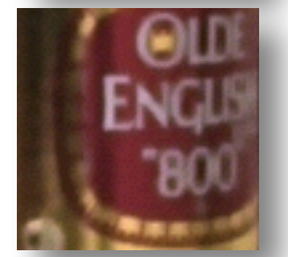
$$y_k = f_k \star x$$

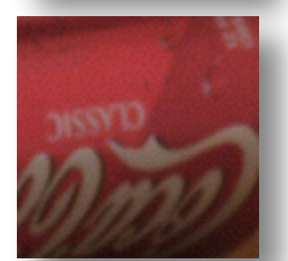
Calibrated blur kernels at depth k

f_k



Sharp sub-window x



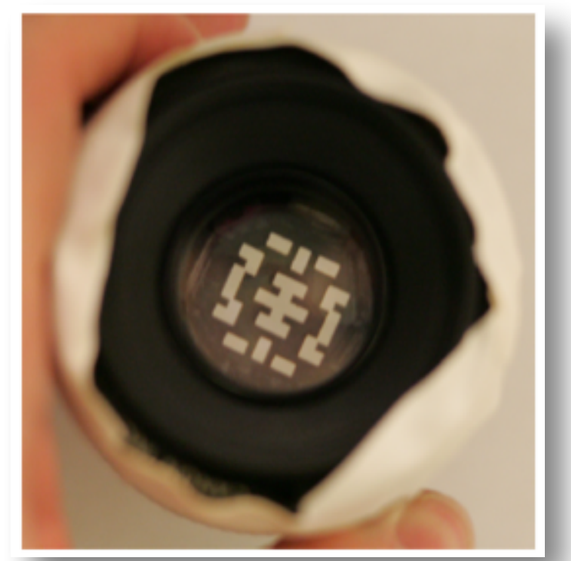


Levin et al 2007

Coded Aperture

* mask (code) in aperture plane
* make defocus patterns different and easier to discriminate

Conventional aperture



Our coded aperture

Levin et al 2007

Lens and defocus

Lens' aperture

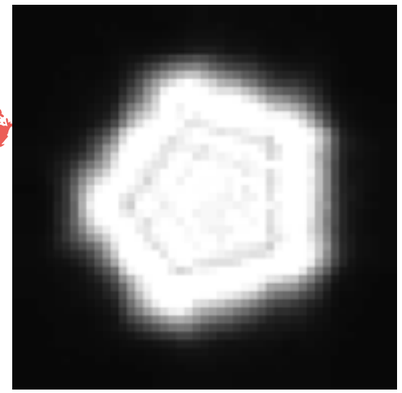
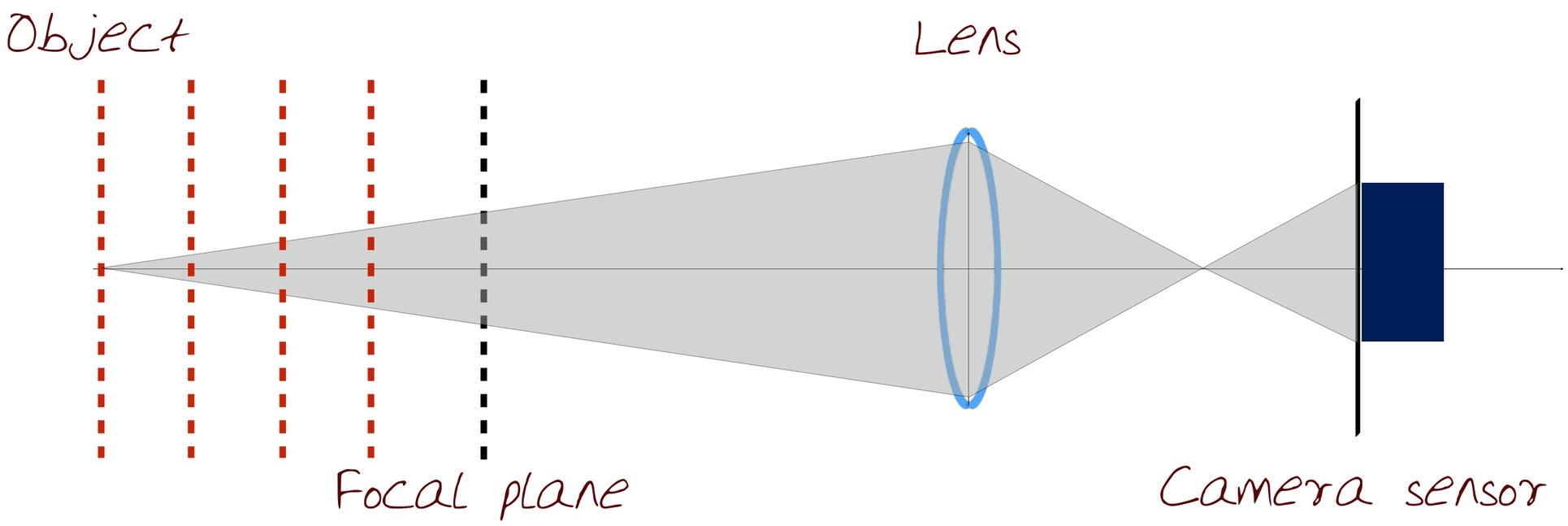


Image of a defocused point light source



Point spread function

Coded Lens and Defocus

Lens with coded aperture

Lens with coded Aperture

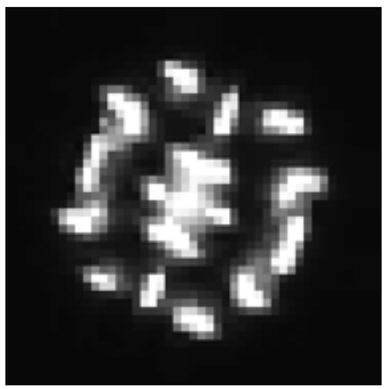
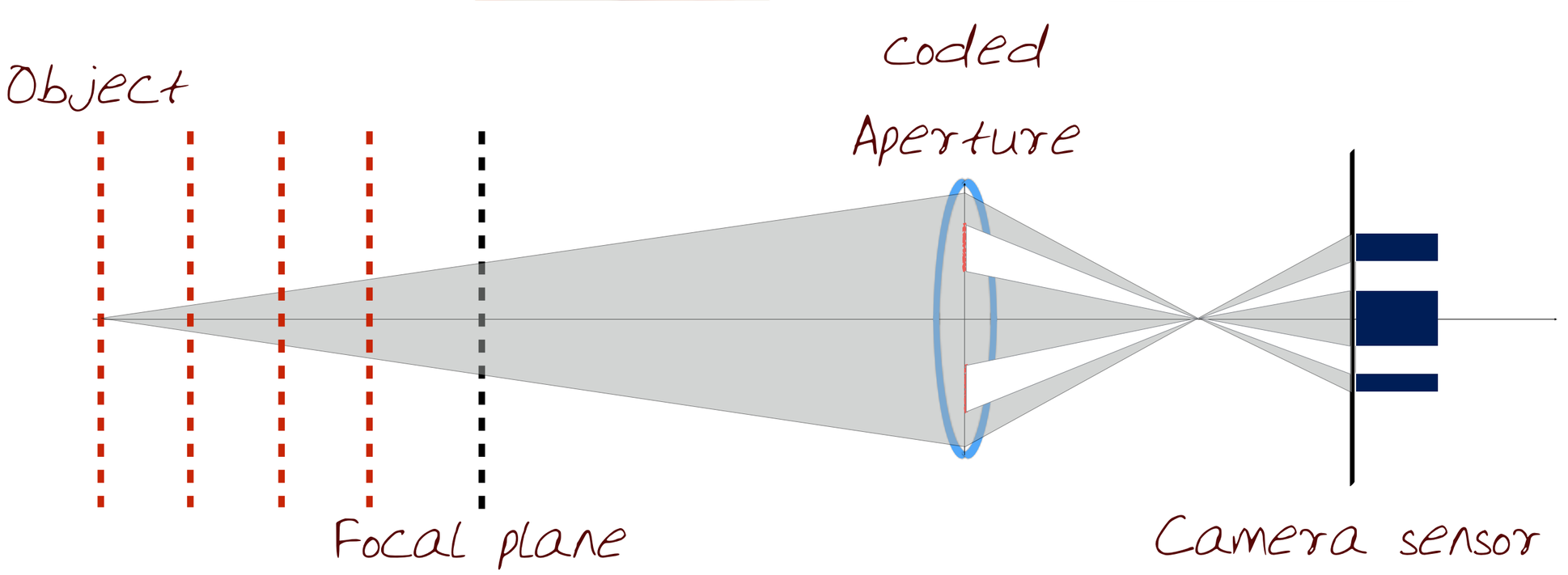


Image of a defocused point light source



Coded Lens and Defocus

Lens with coded aperture

Lens with coded Aperture

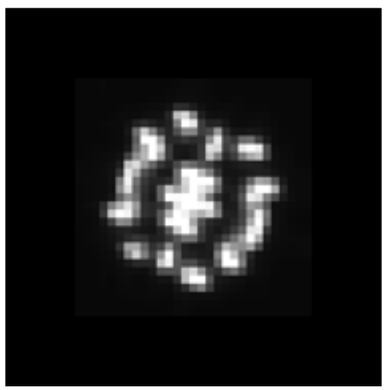
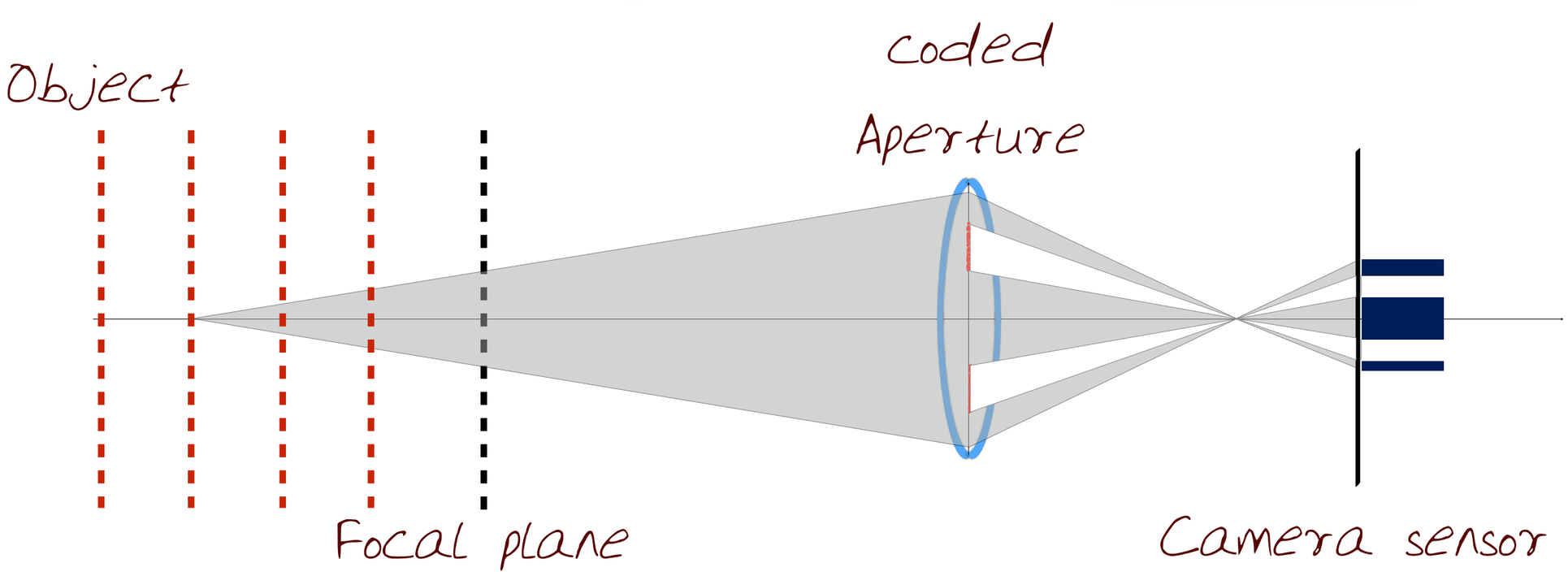


Image of a defocused point light source



Point spread function

Coded Lens and Defocus

Lens with coded aperture

Lens with coded Aperture

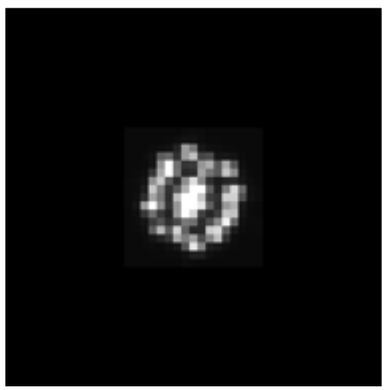
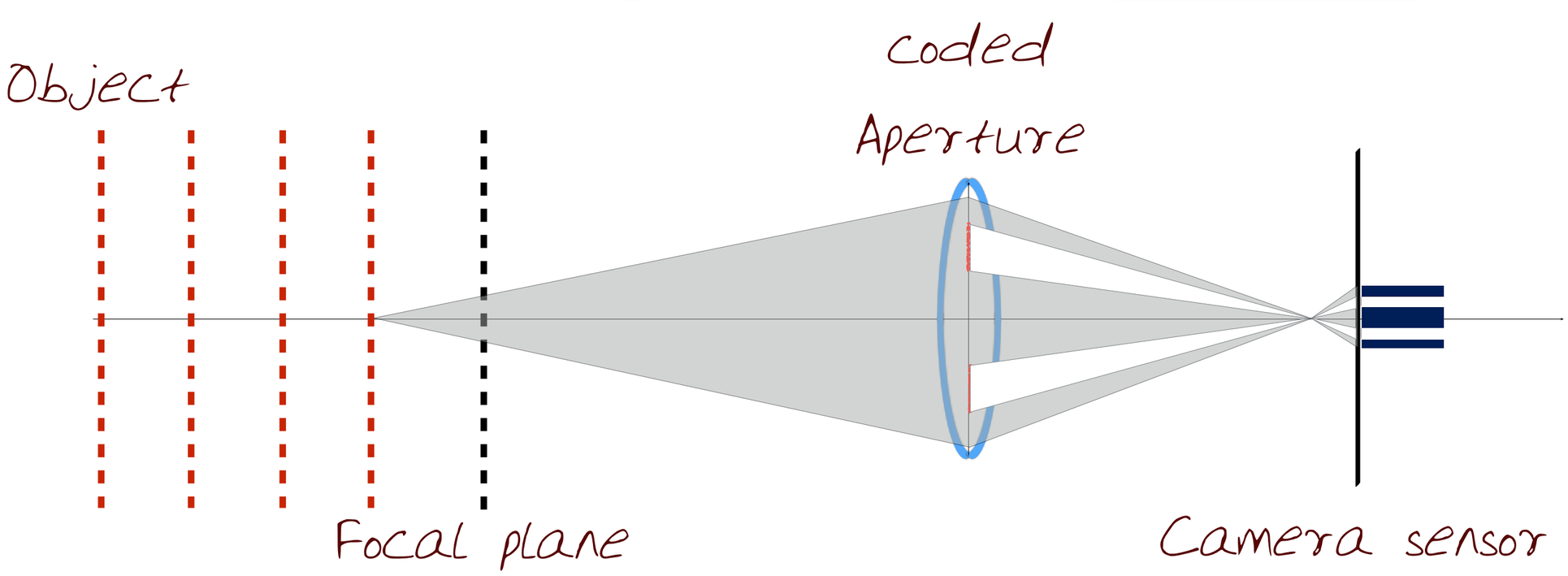


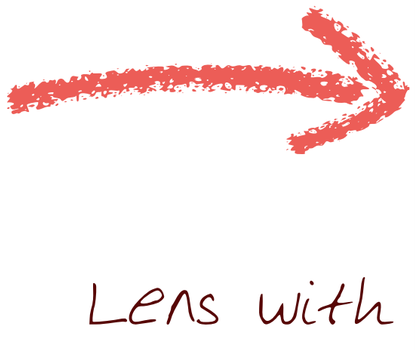
Image of a defocused point light source



Point spread function

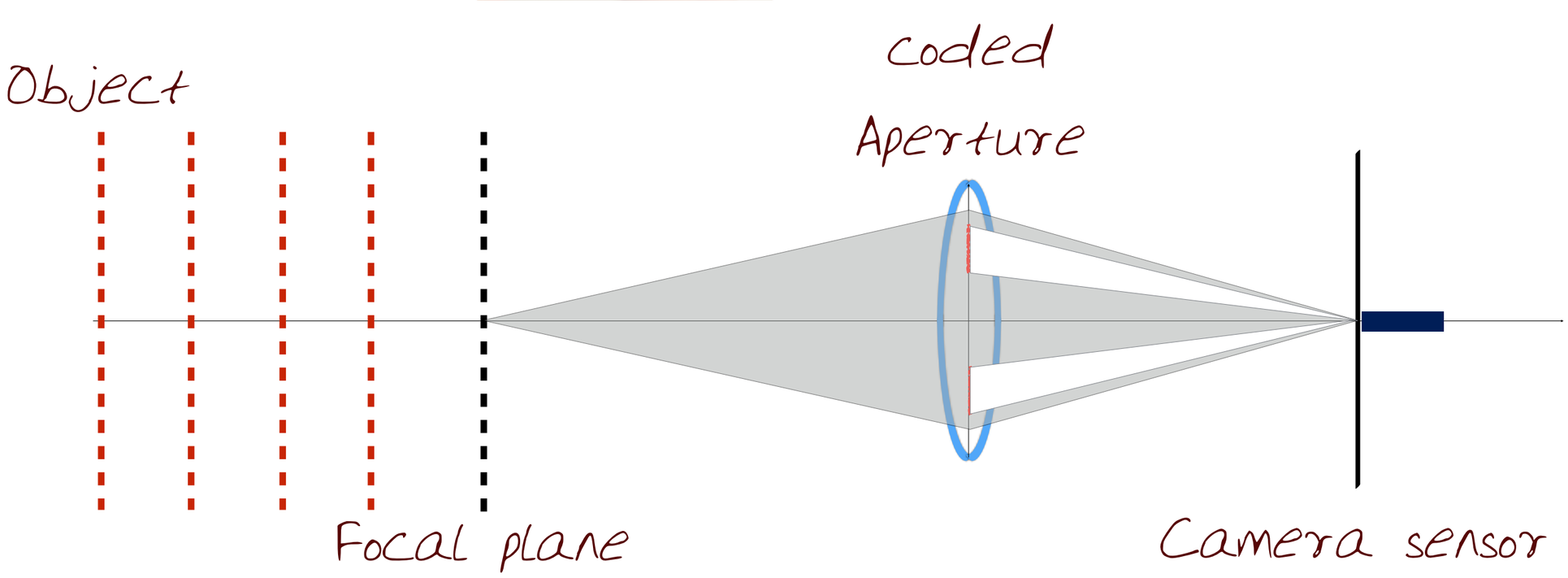
Coded Lens and Defocus

Lens with coded aperture



Lens with coded Aperture

Image of a defocused point light source



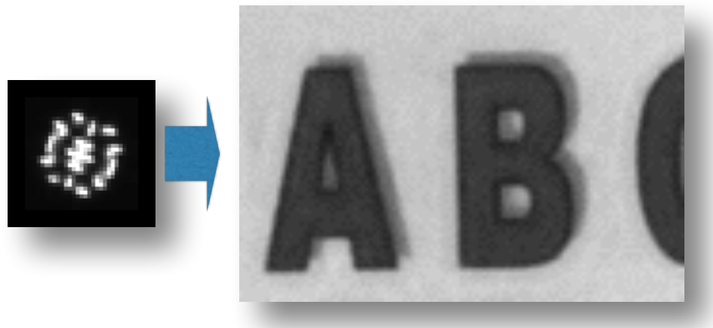
Benefits of Coded Aperture

Conventional

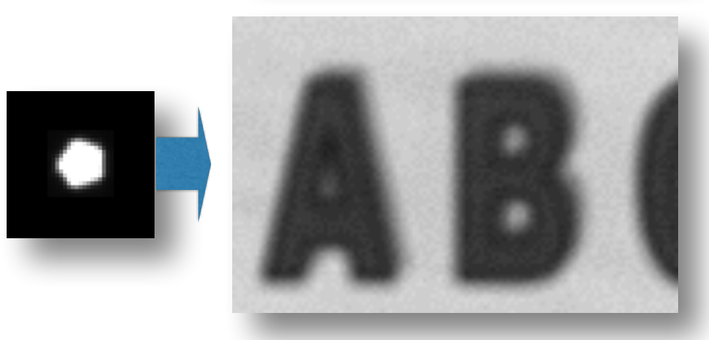
Coded

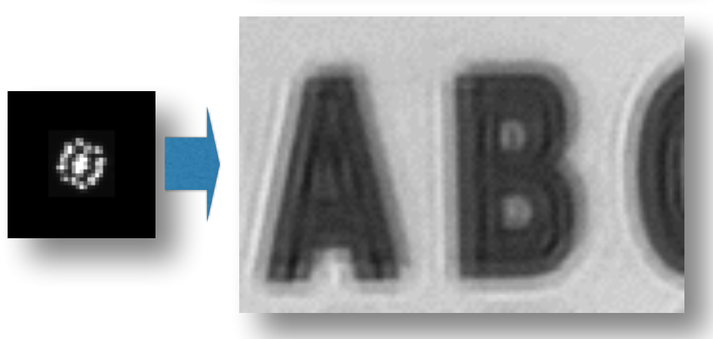
Larger scale

Correct scale



Smaller scale





Lucy-Richardson Deconvolution

Aperture Occluder!

Analytically search for a pattern maximizing discrimination between images at different defocus scales

Score

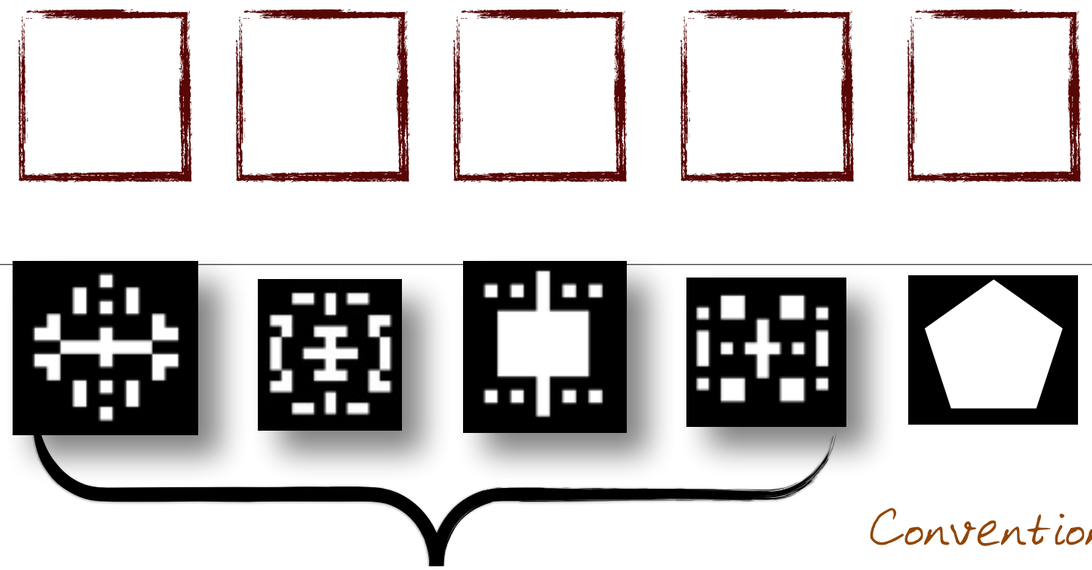
Enter relative discrimination:

1 = least,

5 = most

More discrimination

Less discrimination

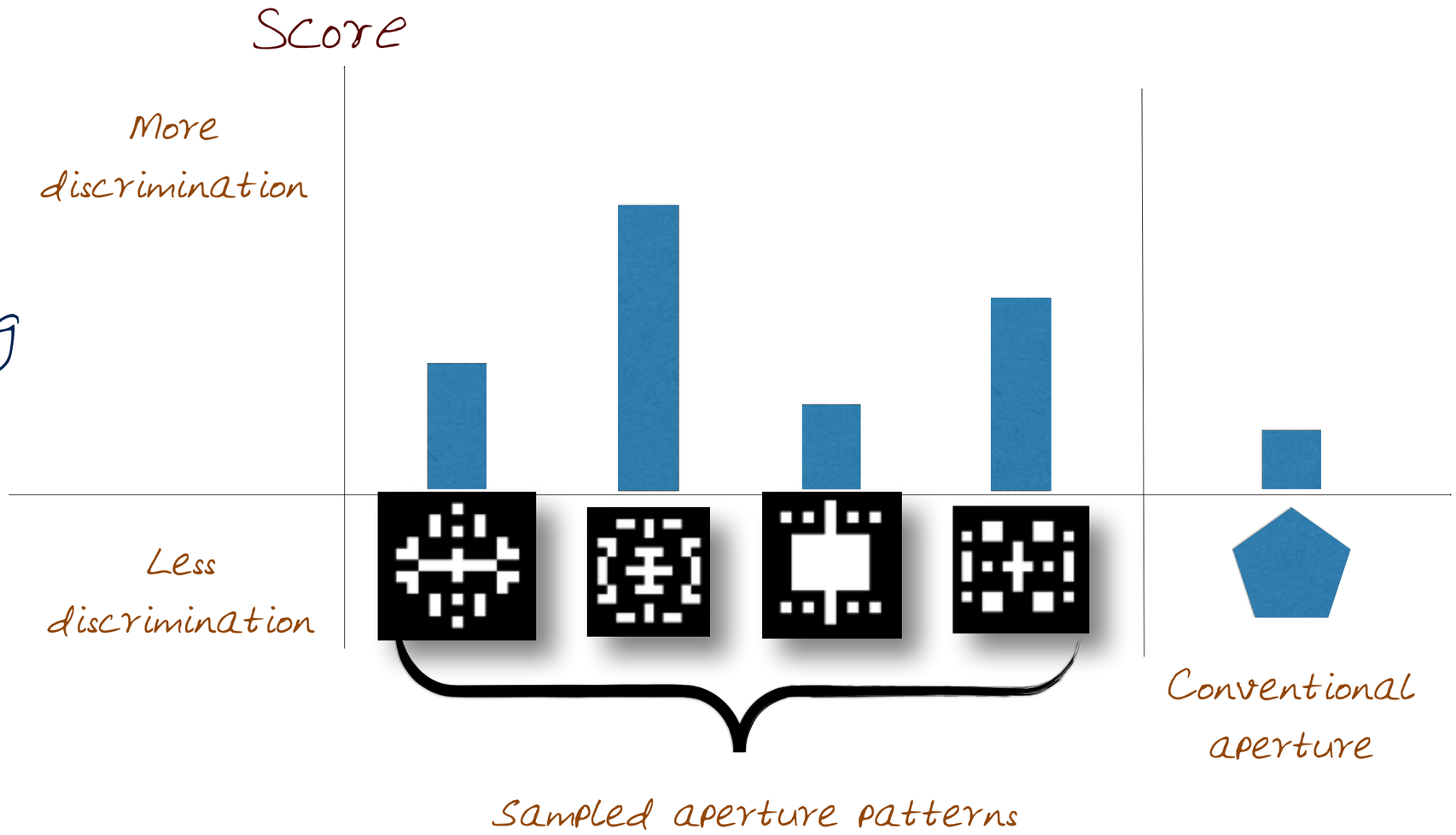


Sampled aperture patterns

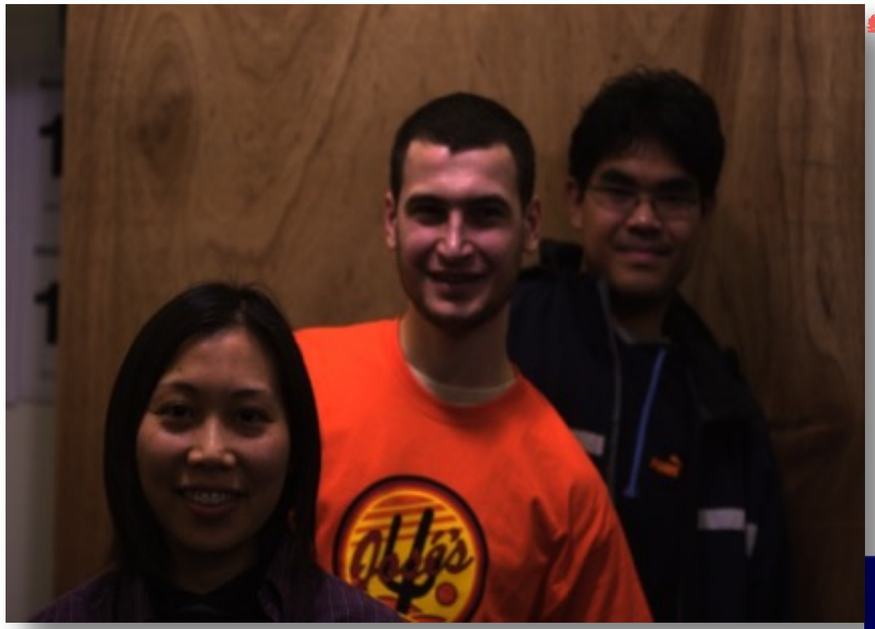
Conventional aperture

Aperture Occluder!

Analytically search for a pattern maximizing discrimination between images at different defocus scales

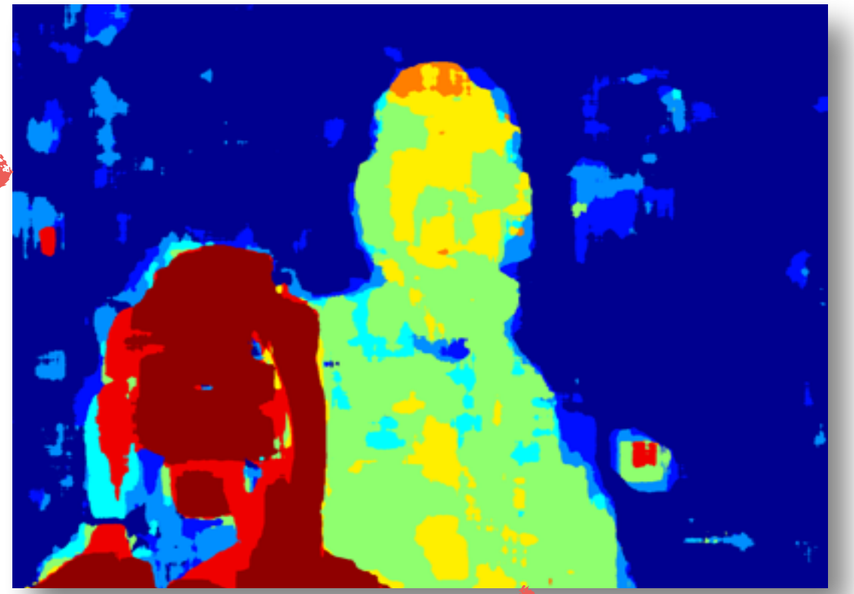


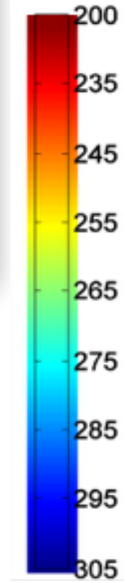
Depth Estimation

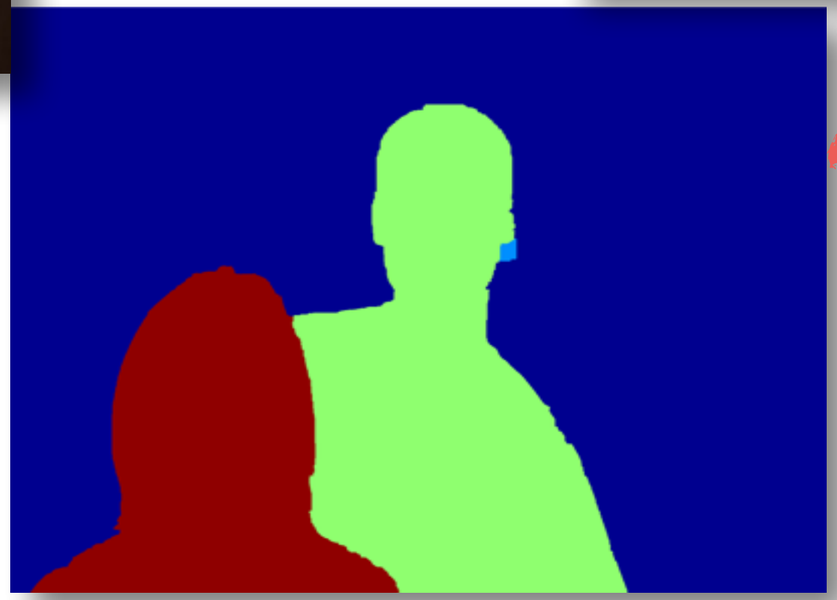


Input

Local depth estimation







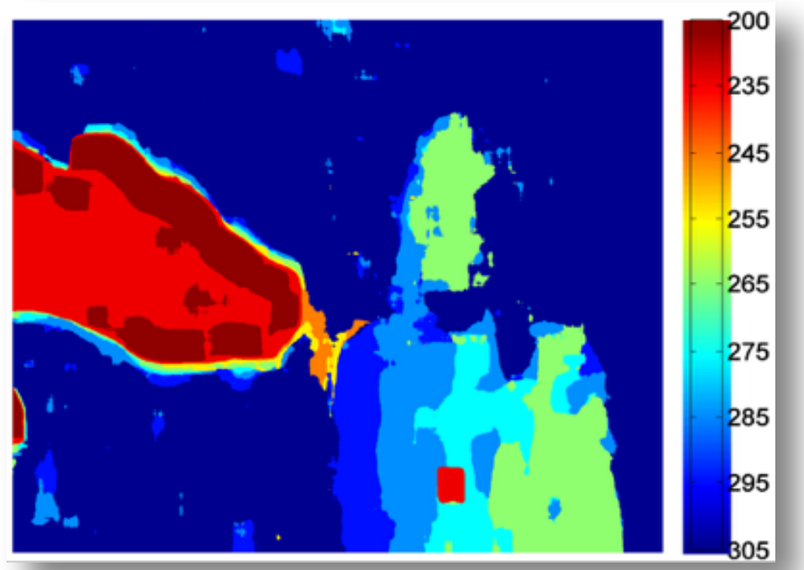
Regularized depth

Levin et al 2007

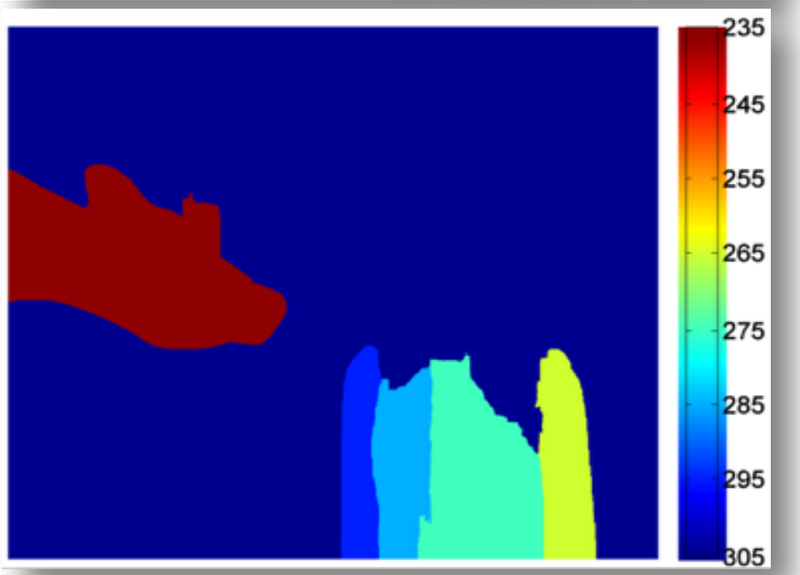
Depth

Input

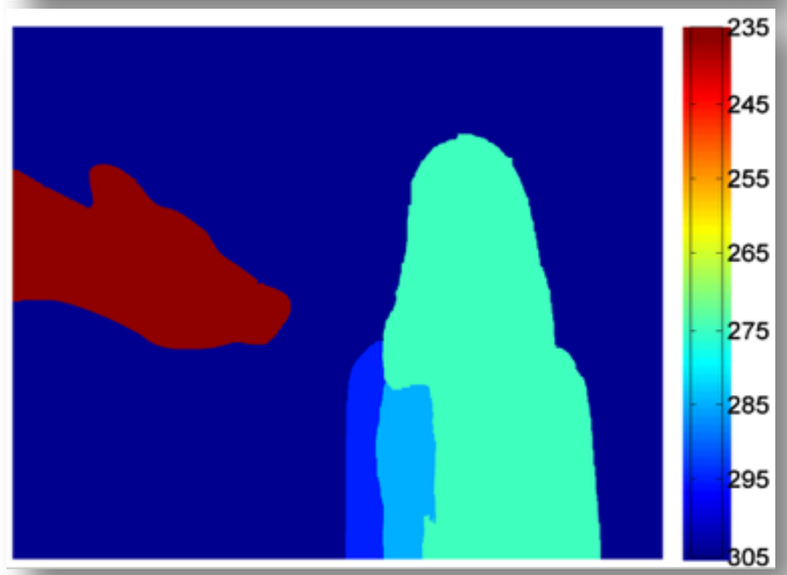
Local depth estimation



Regularized depth



After user corrections



Levin et al 2007

Focus Corrections: Input

All-focused (deconvolved)

Levin et al 2007

Focus Corrections' Input

All-focused (deconvolved)

Levin et al 2007

Focussed Images

Original image

All-focus image

Levin et al 2007

Input

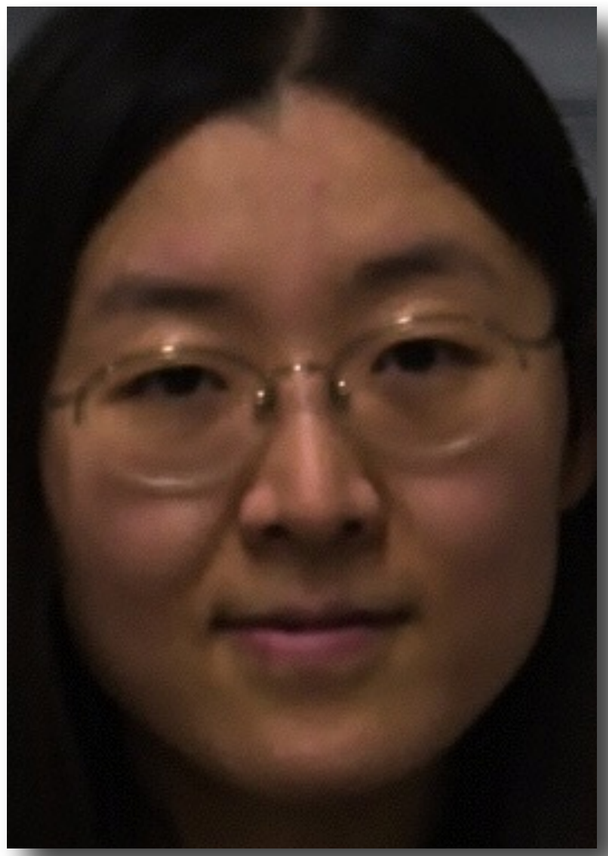
Levin et al 2007

All-focused (deconvolved)

Levin et al 2007

Close-up

Original image



All-focus image

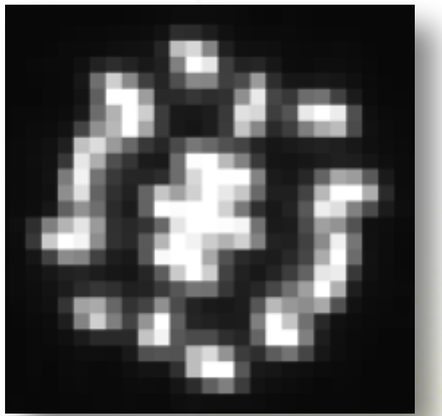
Naive sharpening

Levin et al 2007

Comparison-conventional Aperture Result

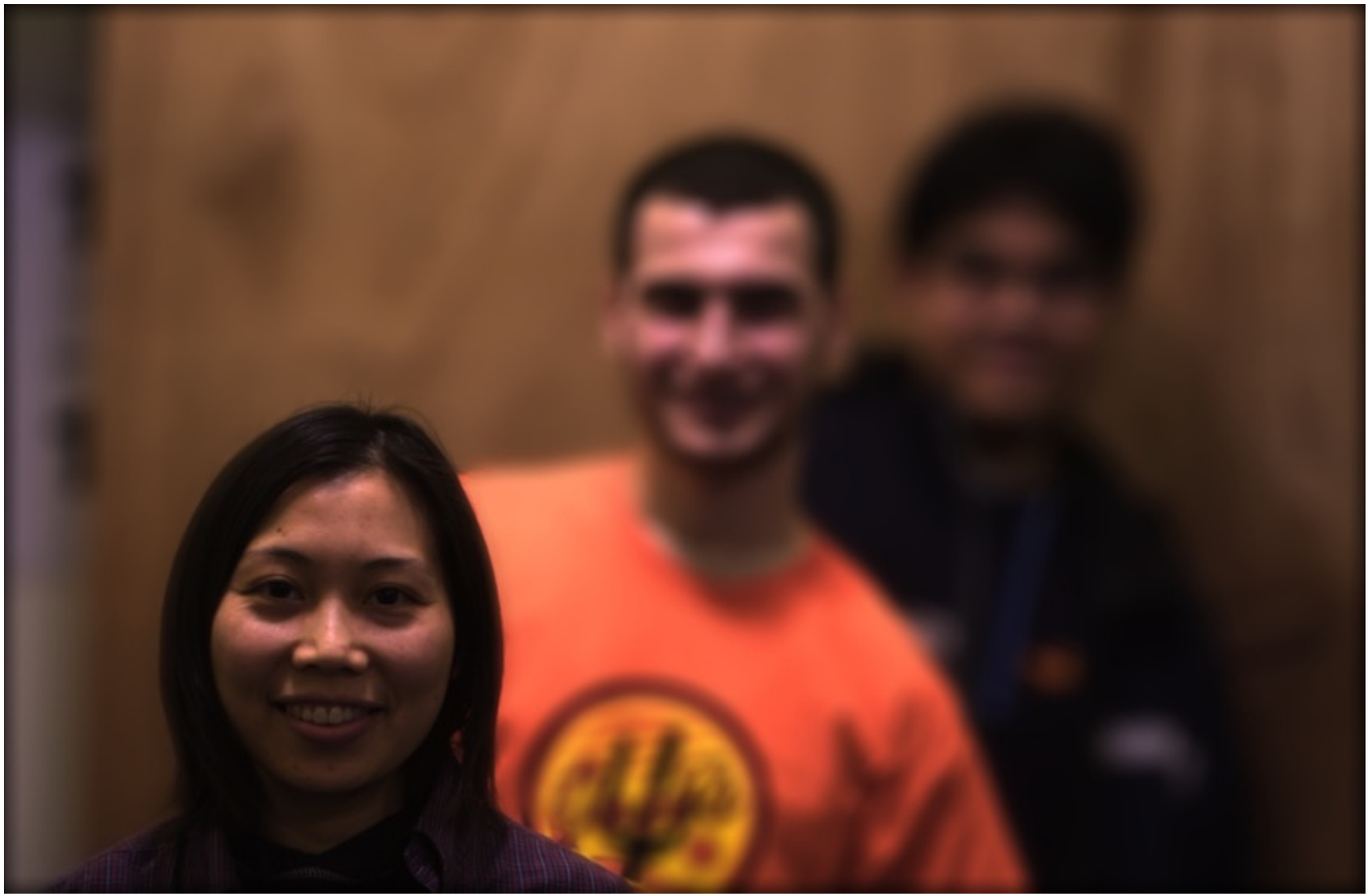
Ringing due to wrong scale estimation

Comparison-coded Aperture Result

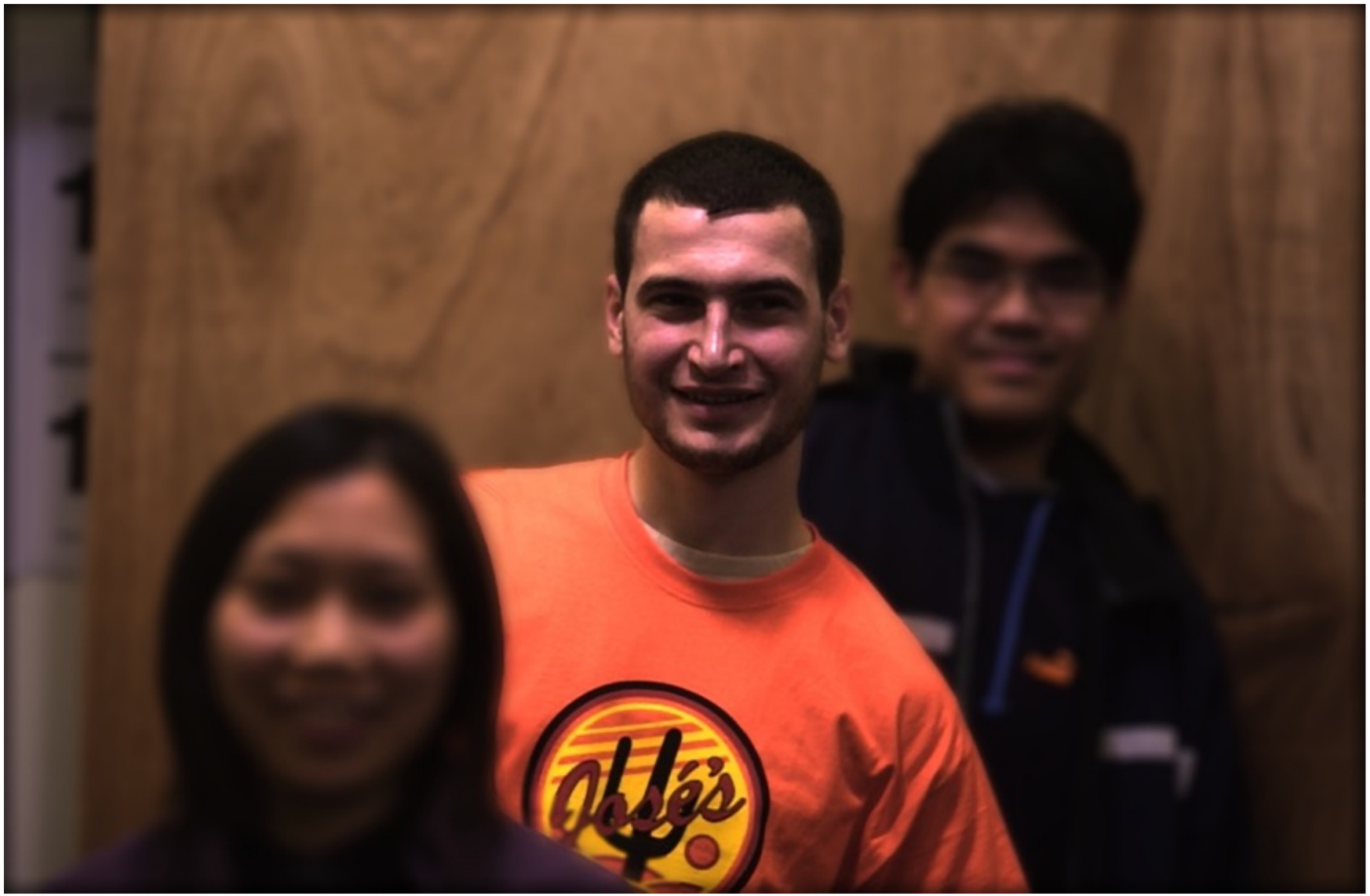


Refocusing from a single image

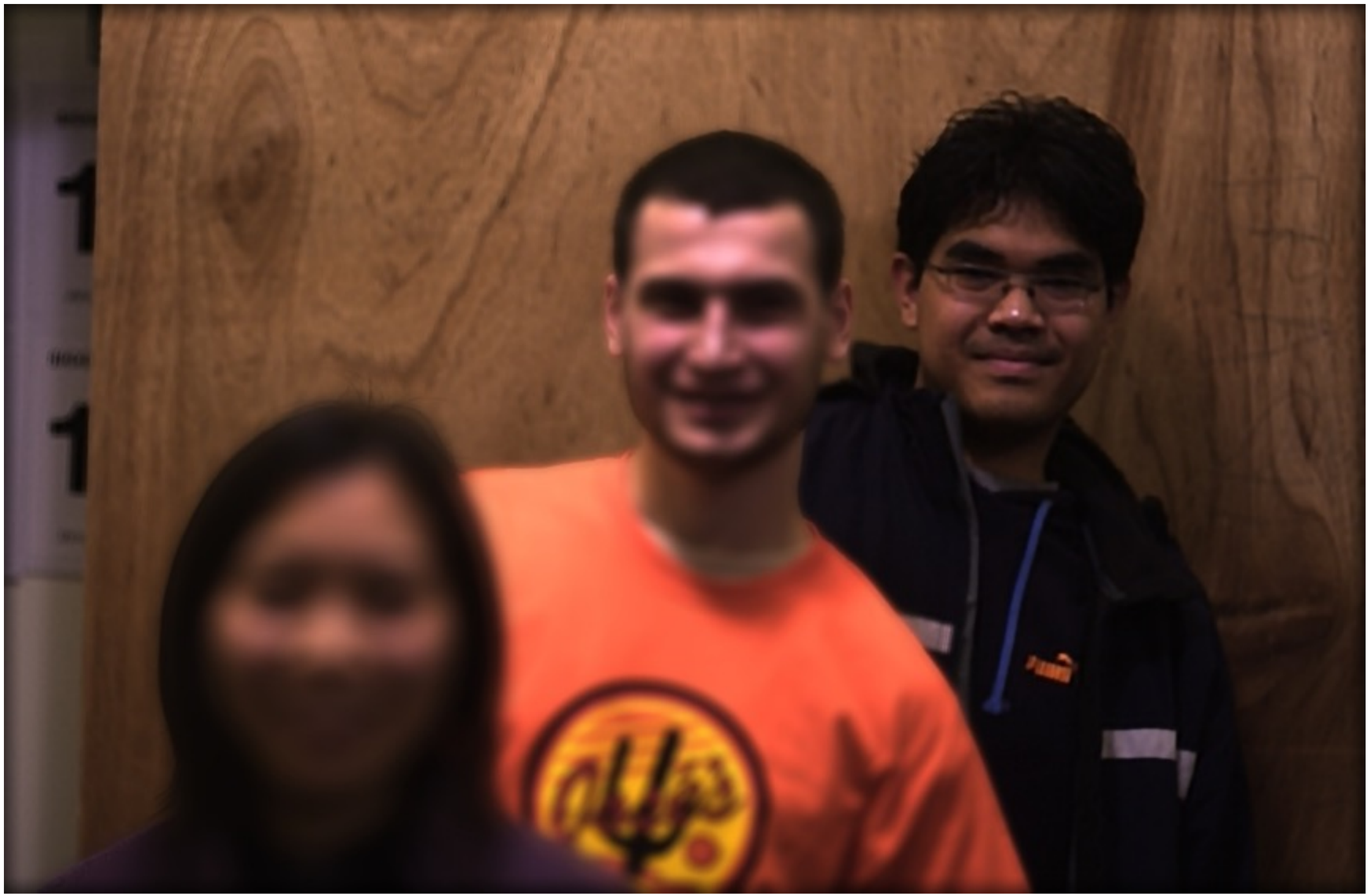
Refocusing from a single image



Refocusing from a single image

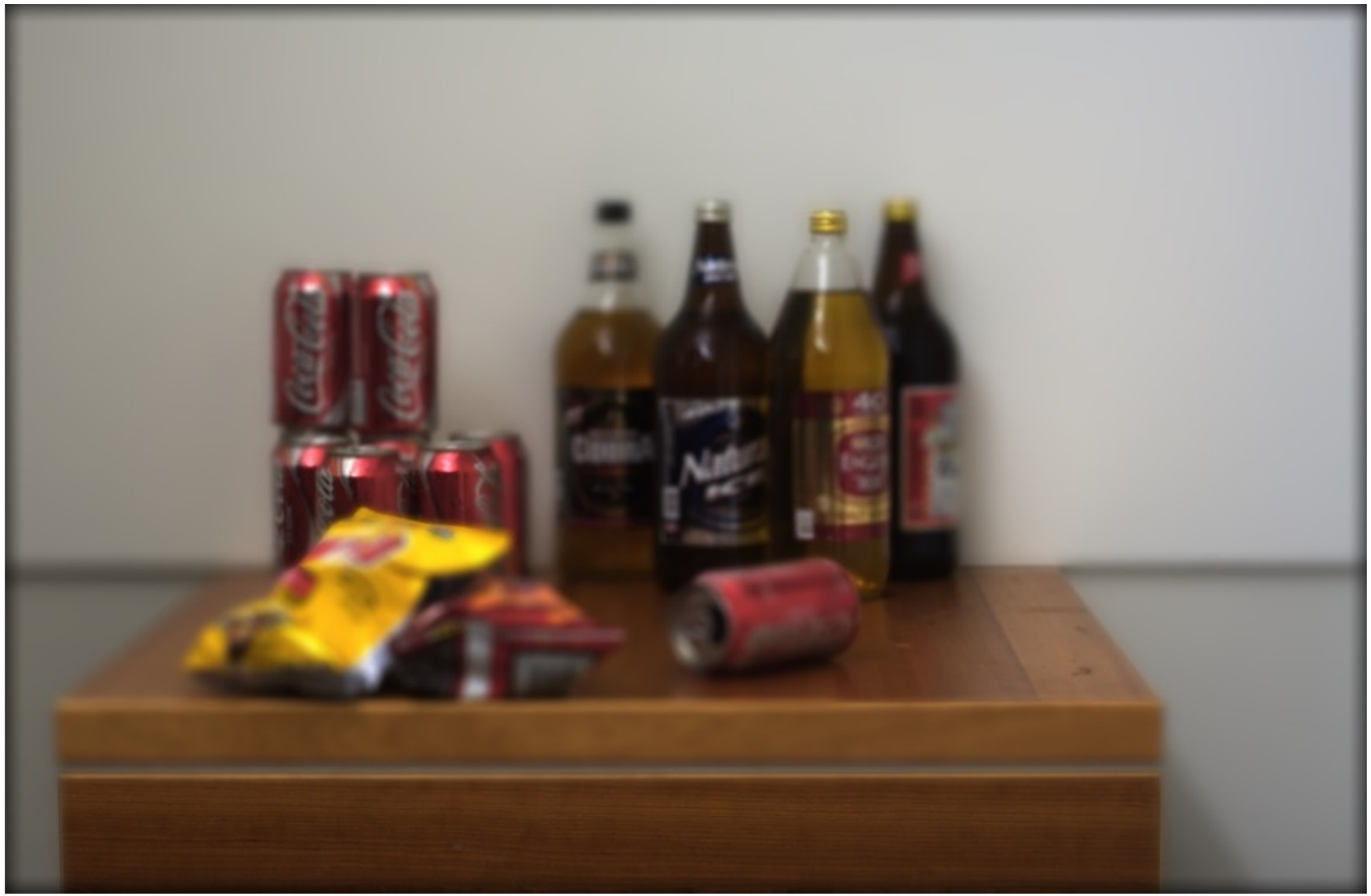


Refocusing from a single image

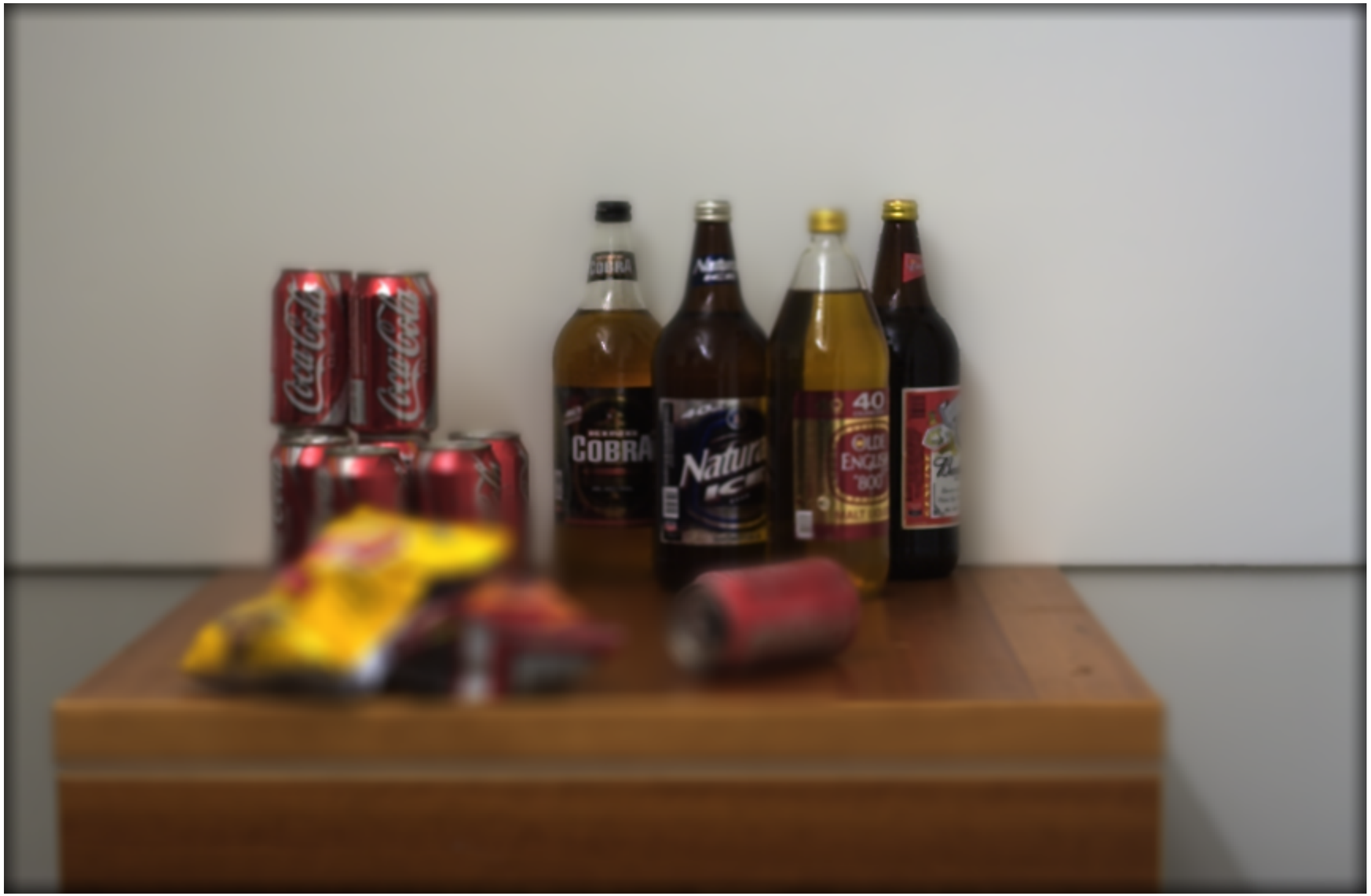


Refocusing from a single image

Refocusing from a single image



Refocusing from a single image



Build your own coded aperture

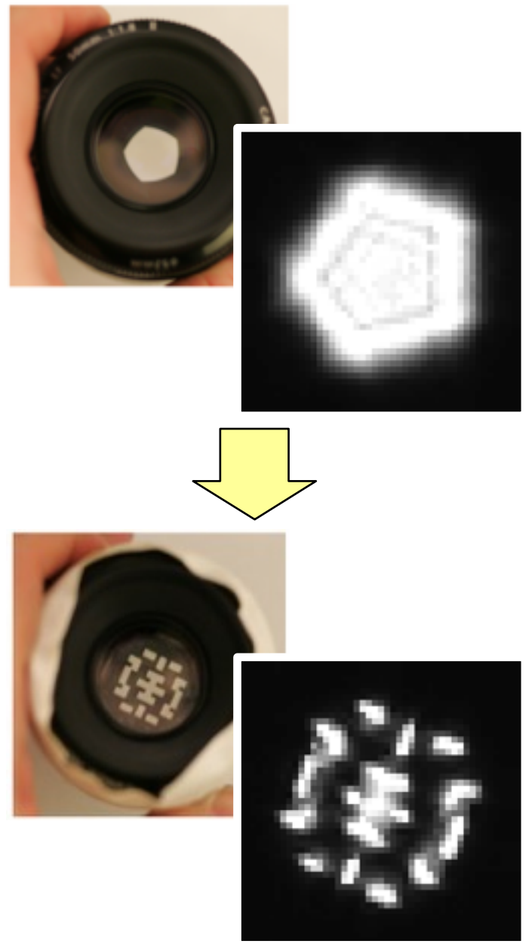
Levin et al. 2007

Voila!

Levin et al. 2007

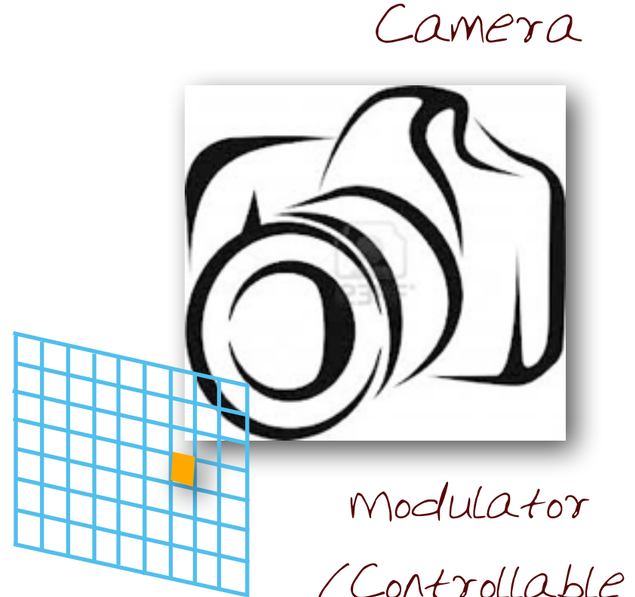
Coded Aperture

- Image AND depth at a single shot +
- No loss of image resolution +
- Simple modification to lens +
- Depth is coarse -
- But depth is a pure bonus +
- Lose some light -
- But deconvolution increases depth of field +

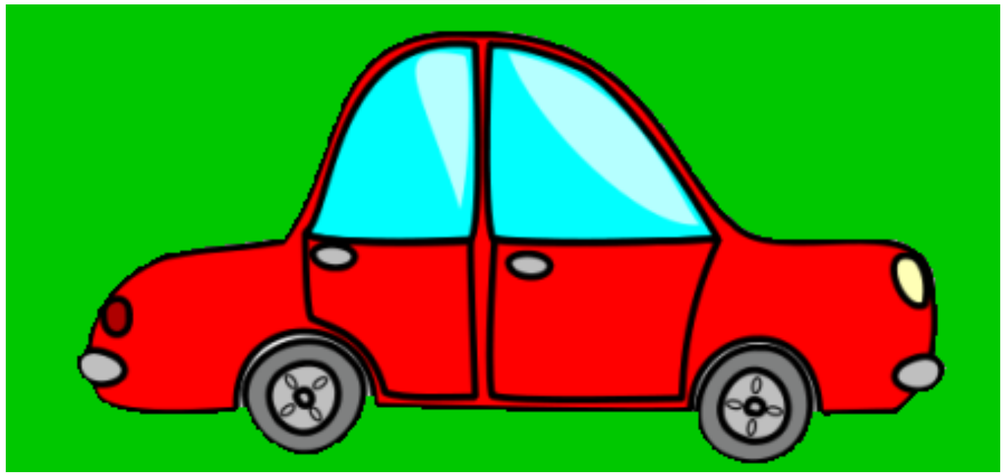


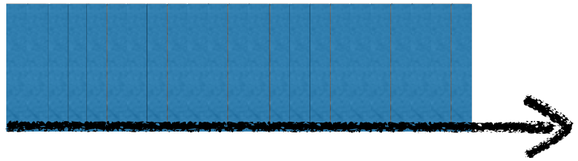
Flutter Shutter Camera

* Coded Aperture: Add "obstructions" to aperture
* Flutter Shutter: Control when the shutter opens/closes



Traditional Camera

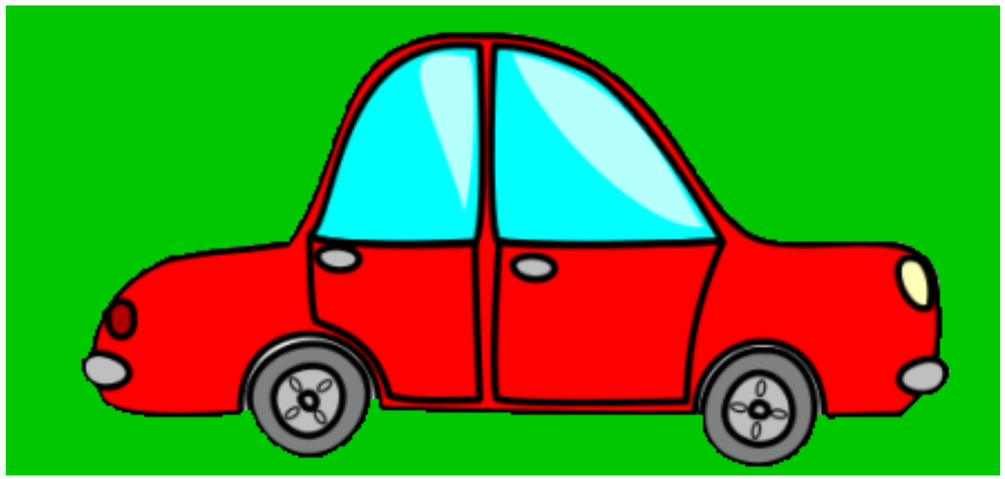


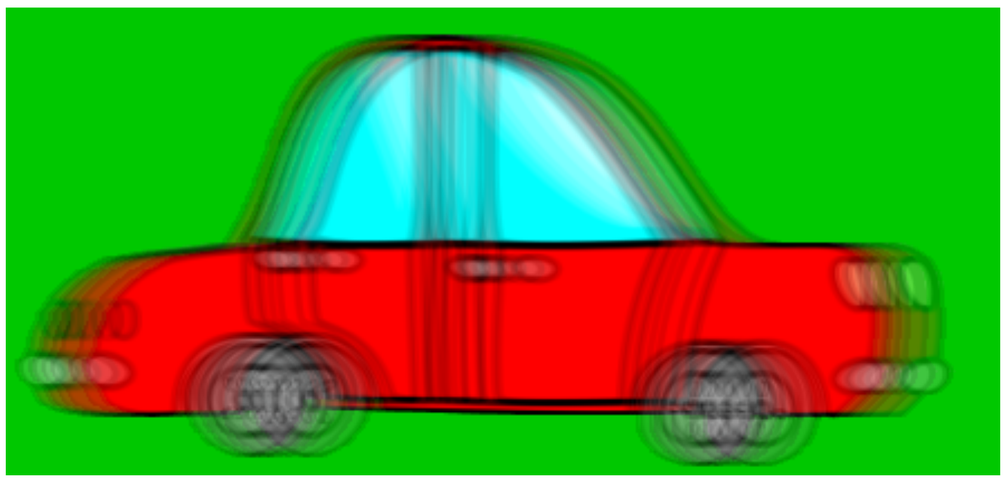


Shutter is OPEN

Raskar et al 2006

Flutter Shutter Camera

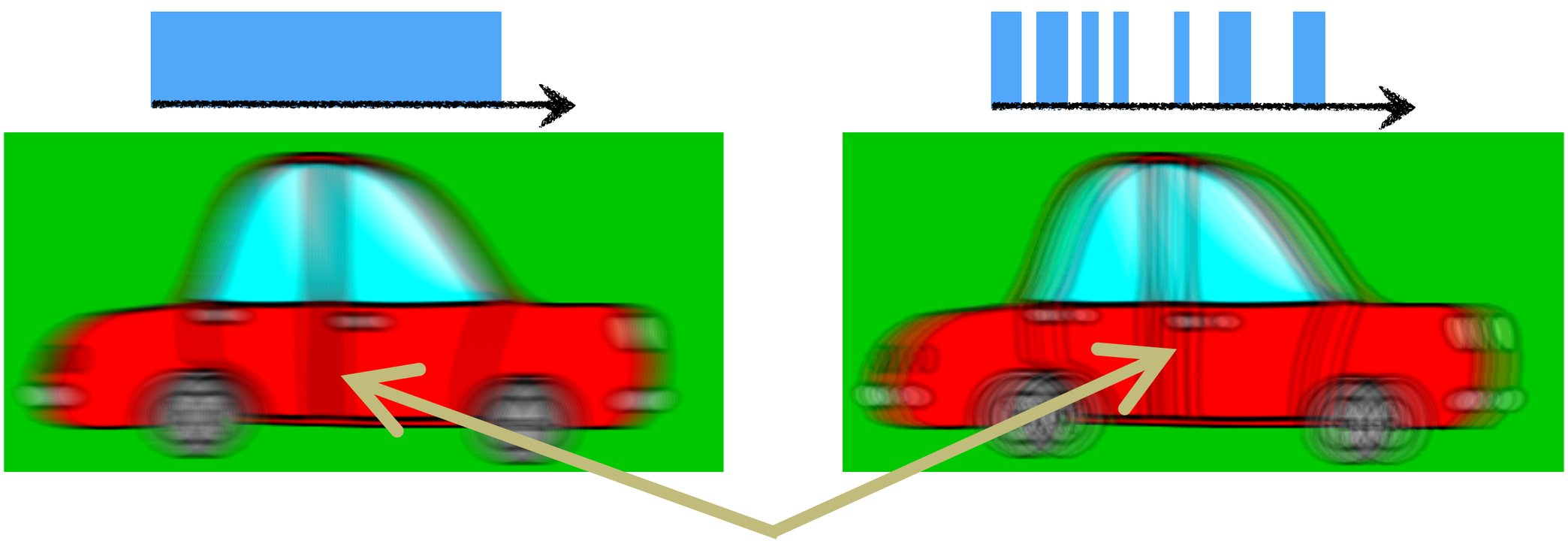




The Shutter opens and closes

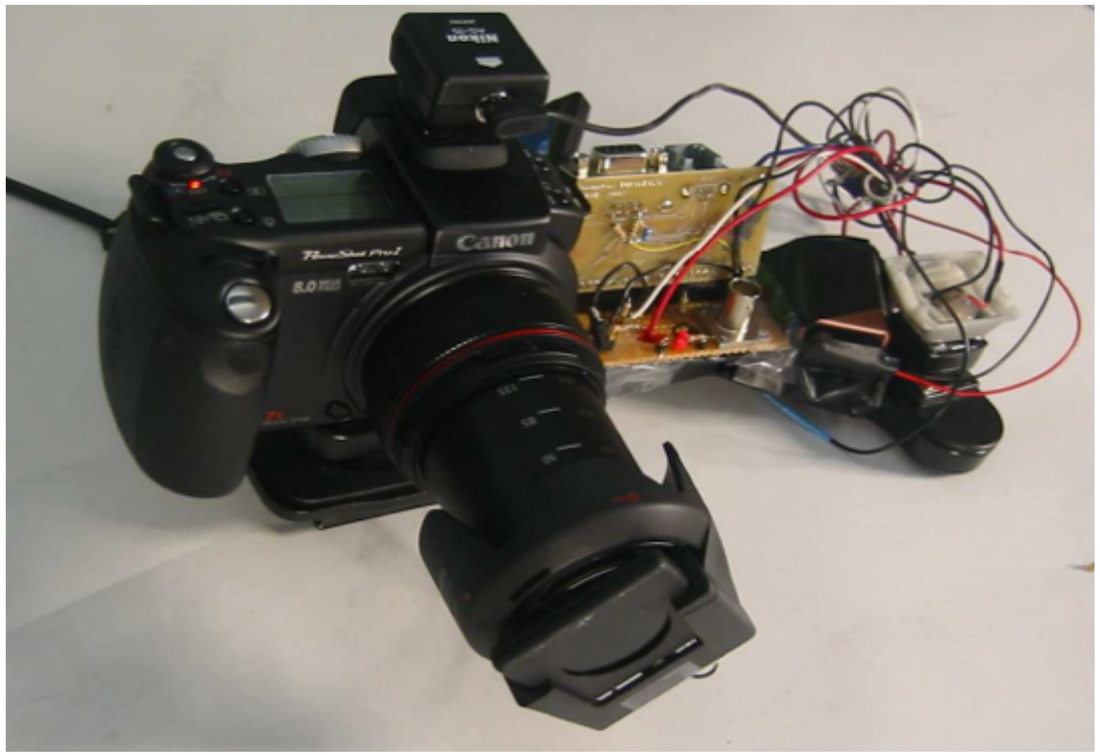
Raskar et al 2006

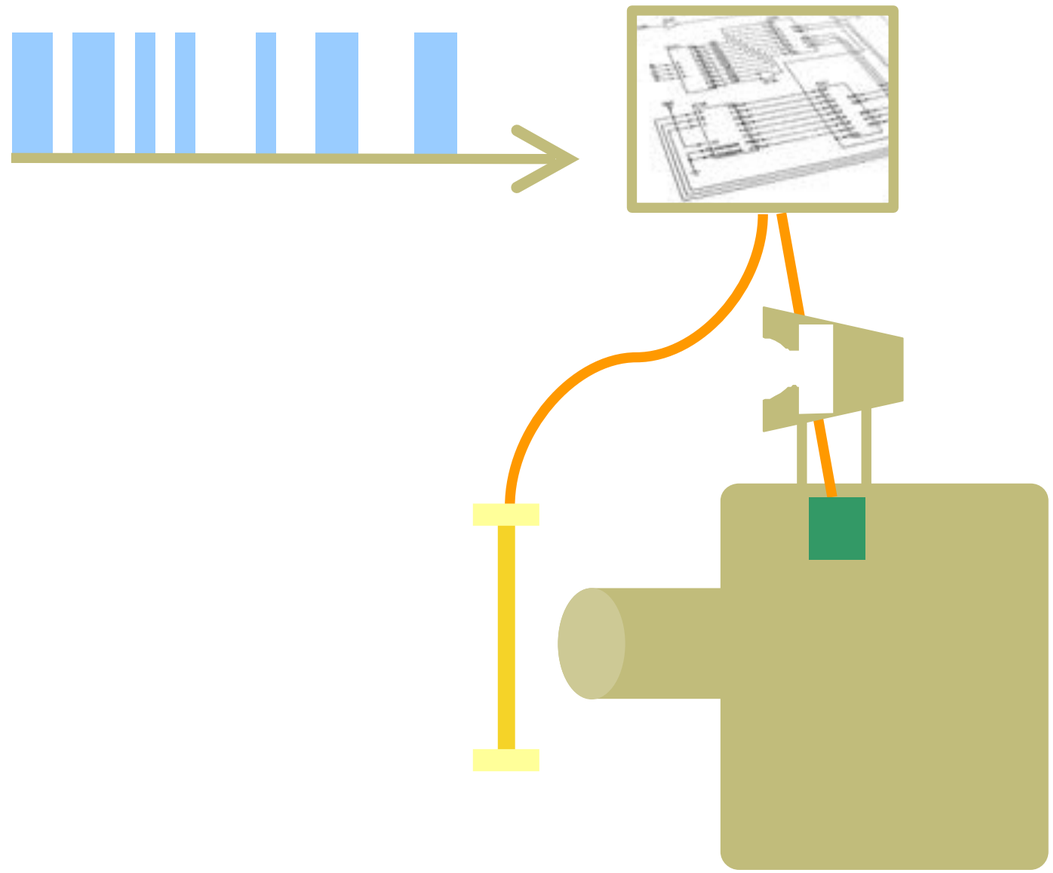
Traditional vs. F-S Camera



Raskar et al 2006

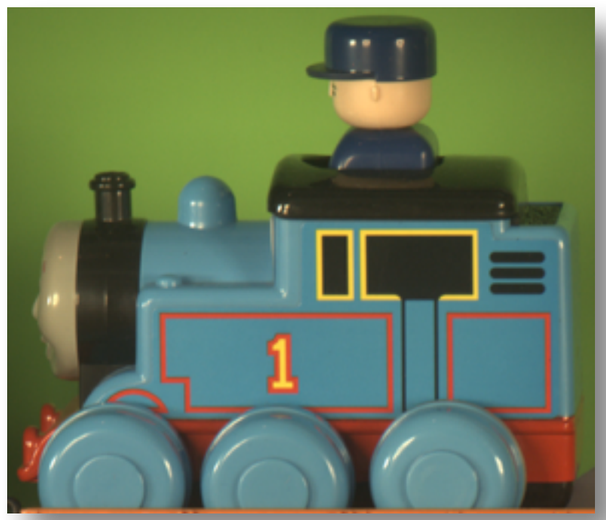
F-S Camera

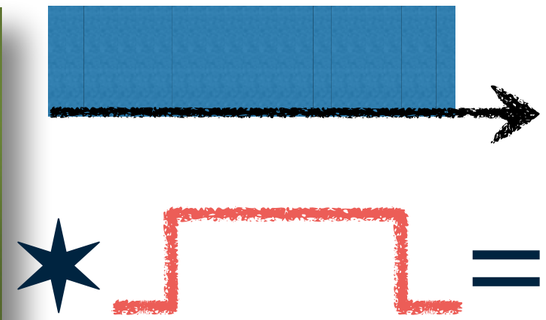




Raskar et al 2006

Traditional Camera: Box Filter





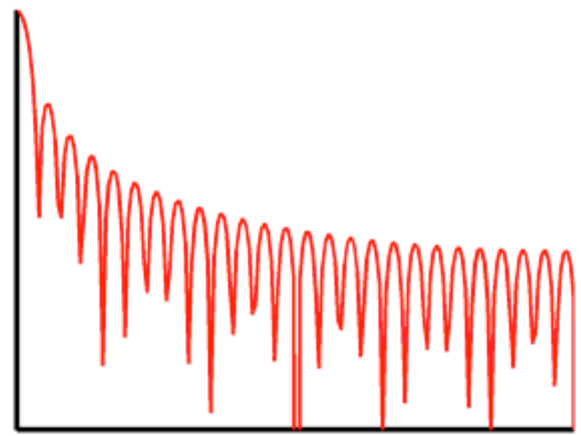
Blurring

==

Convolution

The sinc function is of the general form sin(x)/x and is a sine wave that decays in amplitude as 1/x.

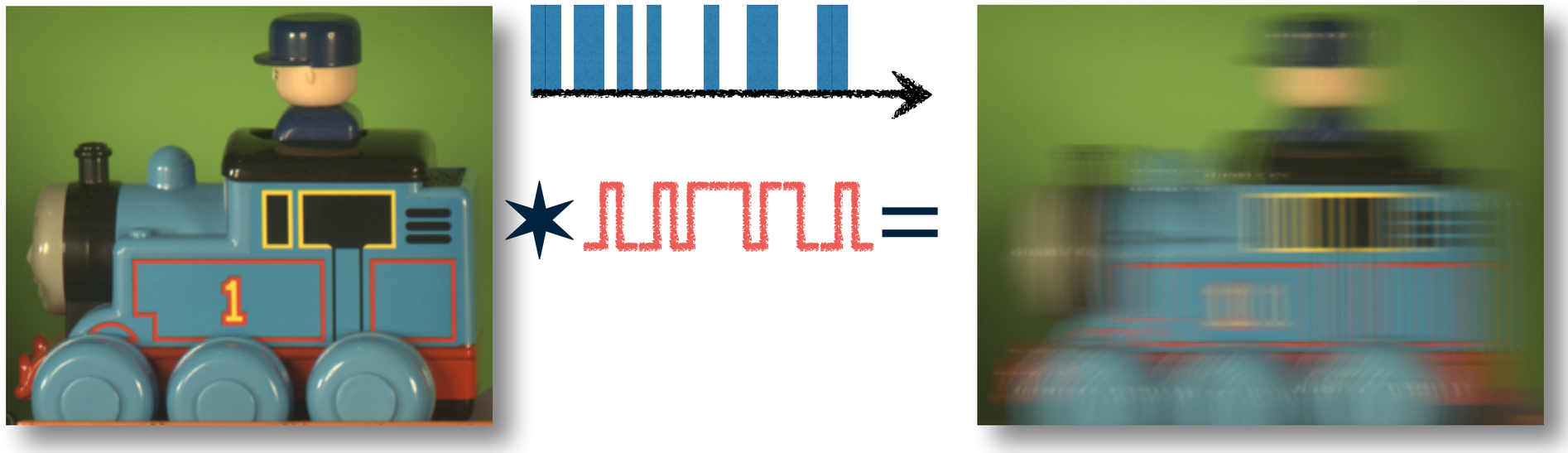
Sinc Function



Raskar et al 2006

Sinc Function: http://www.dspguide.com/ch11/2.htm

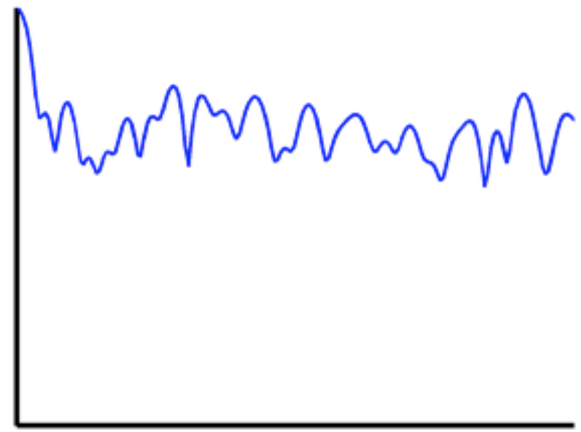
Flutter Shutter: Coded Filter



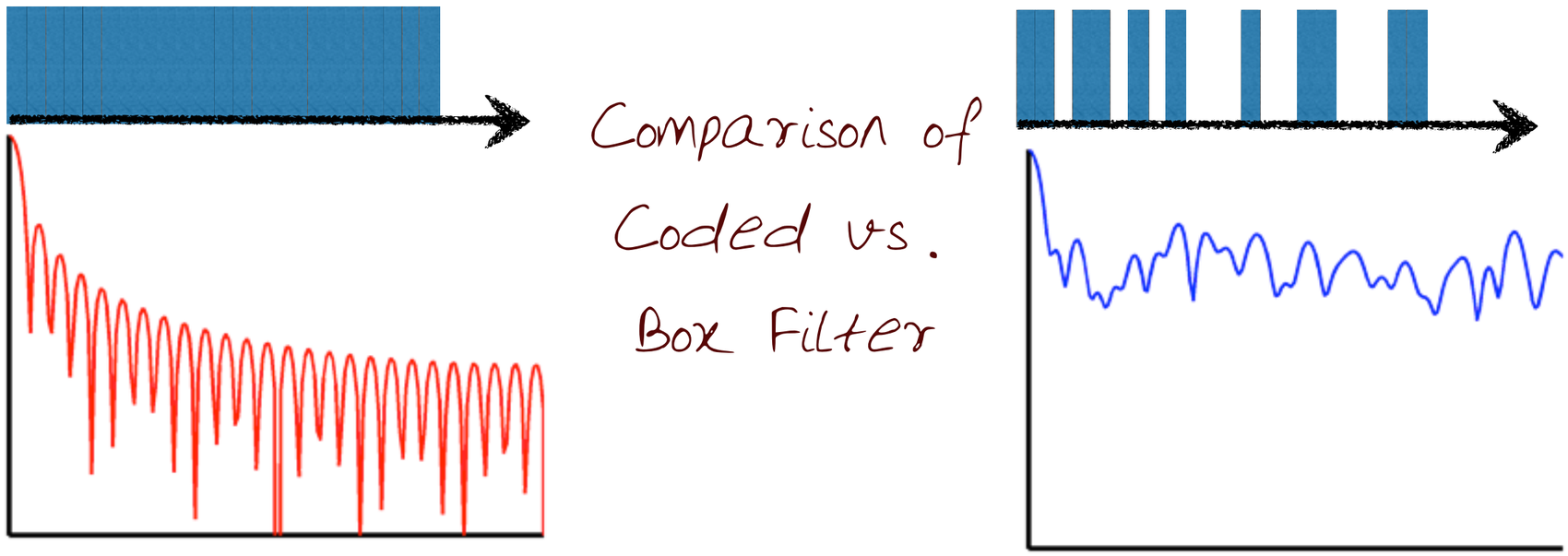
Sinc Function

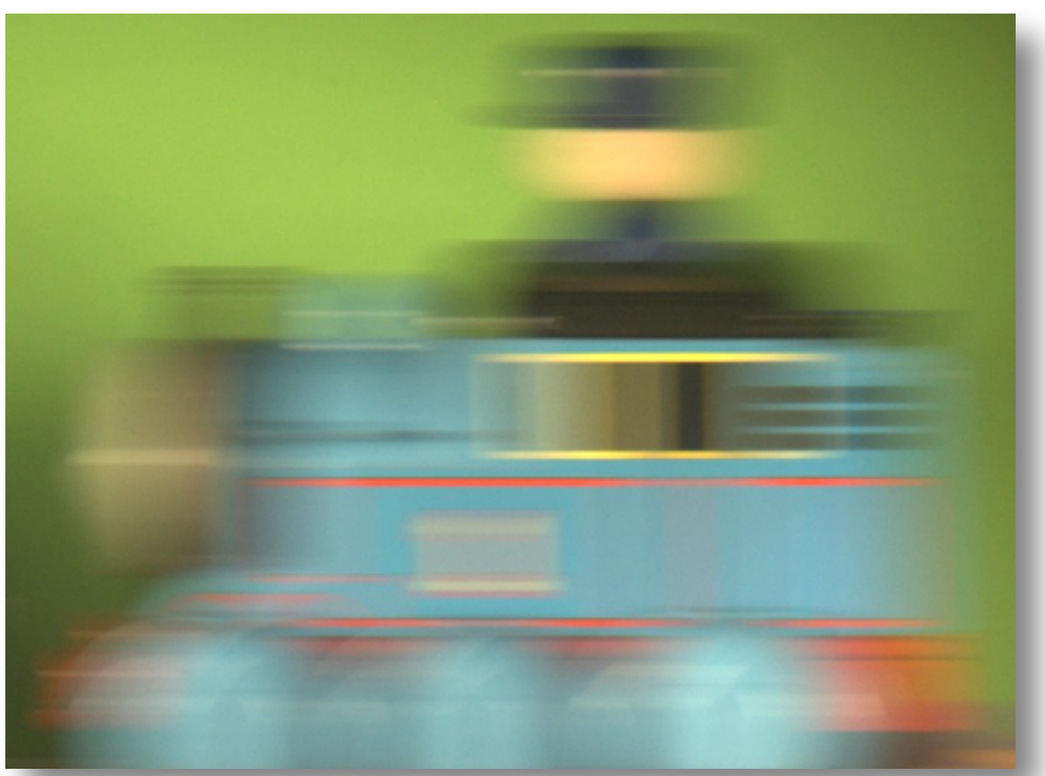
Preserves High

Frequencies!!!

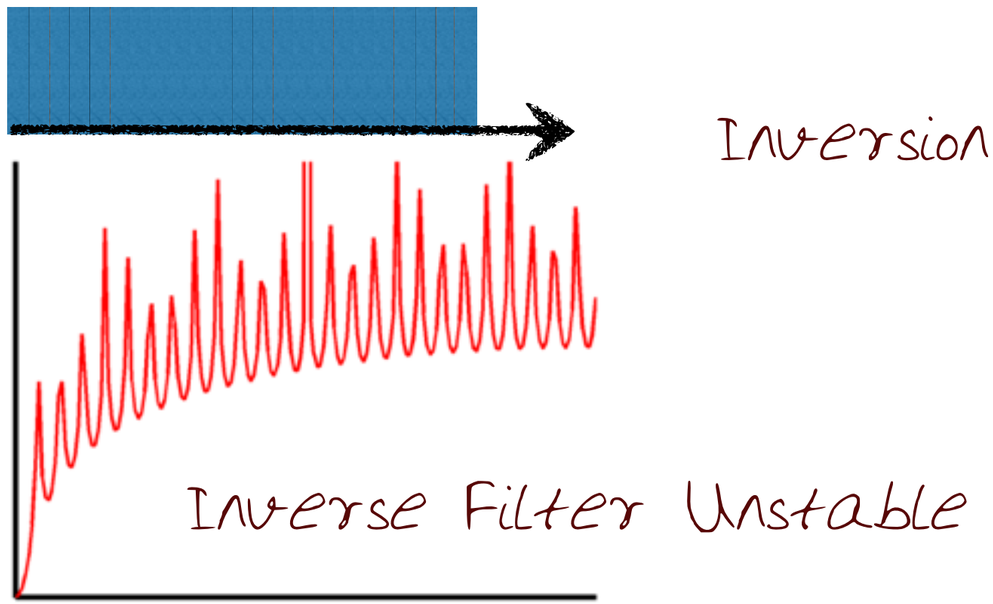


Raskar et al 2006



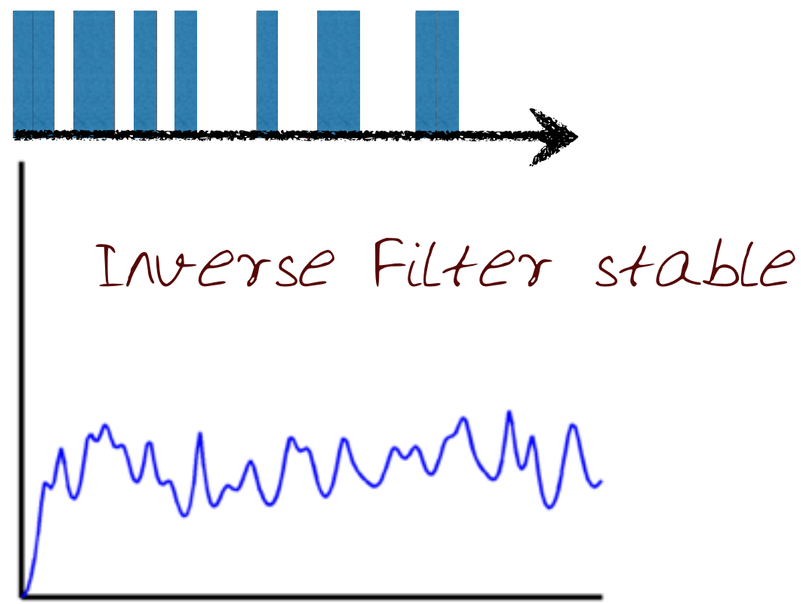


Inverse sinc function for IDFT



Inverse Filter Unstable

Inversion



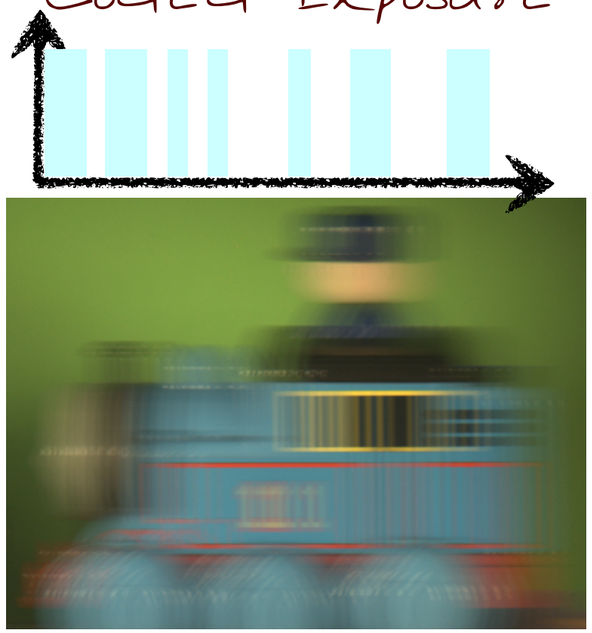
Inverse Filter stable

Long vs. Coded Exposure

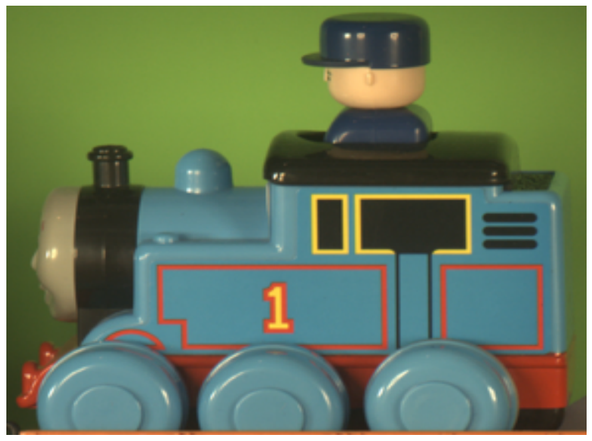
Short Exposure

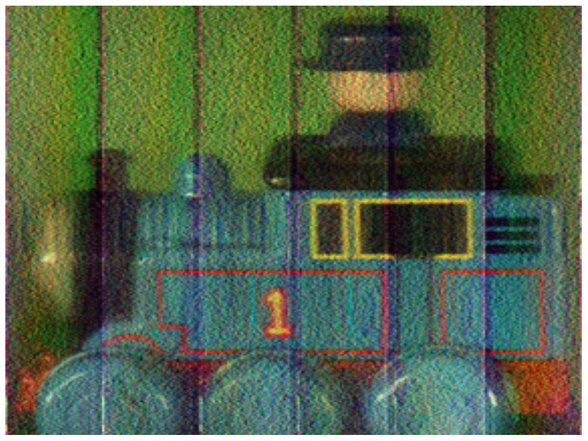
Long Exposure

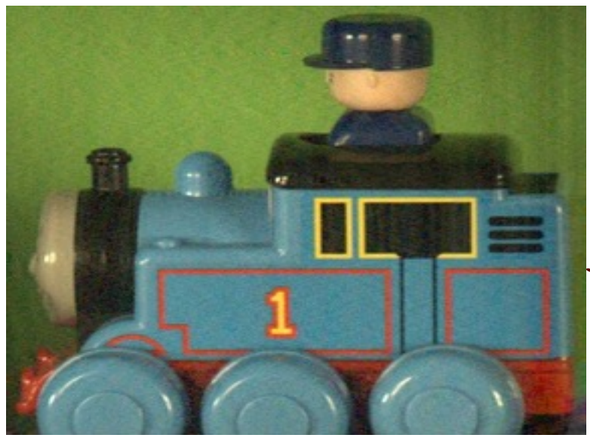
Coded Exposure



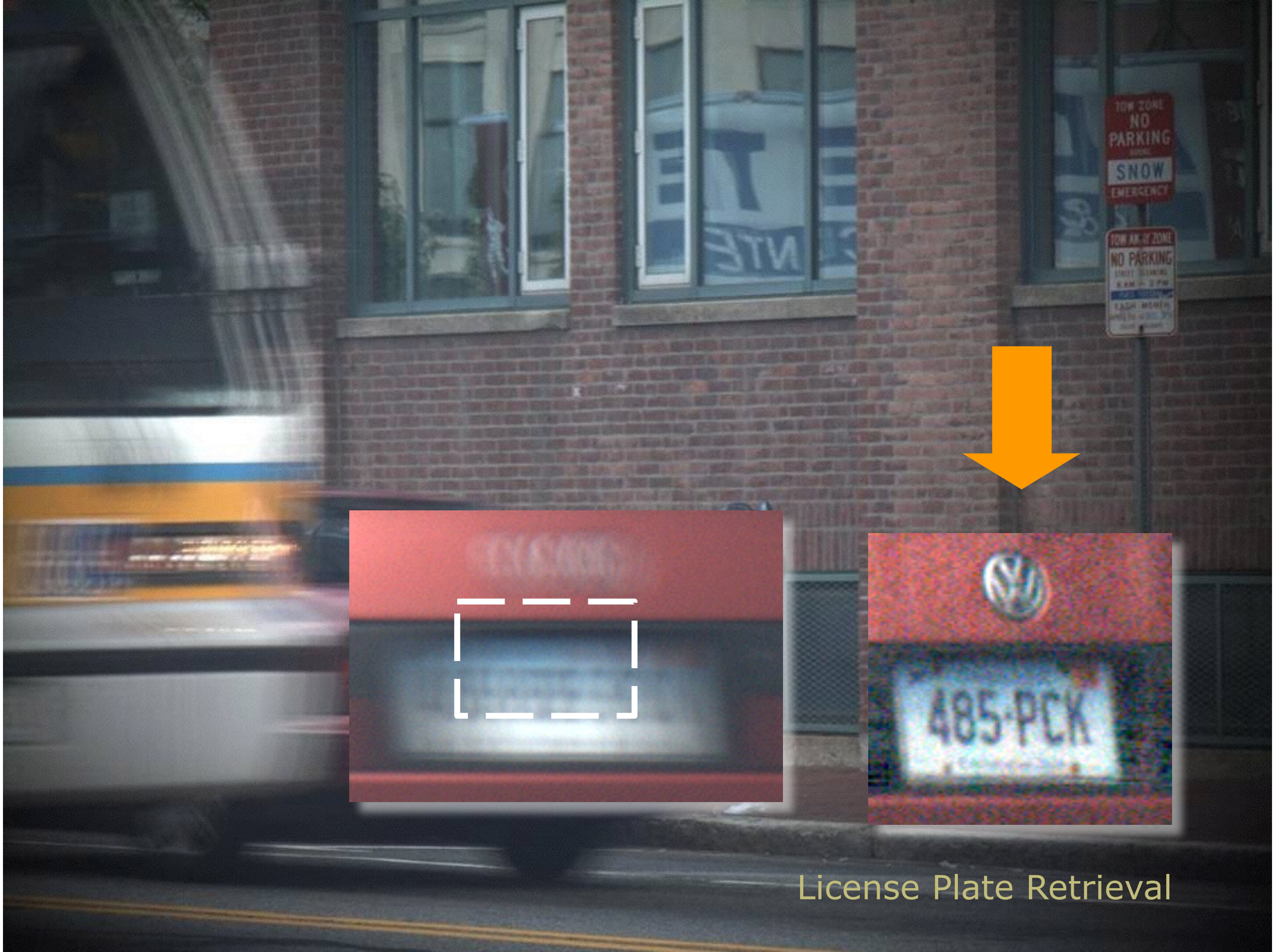
Ground Truth





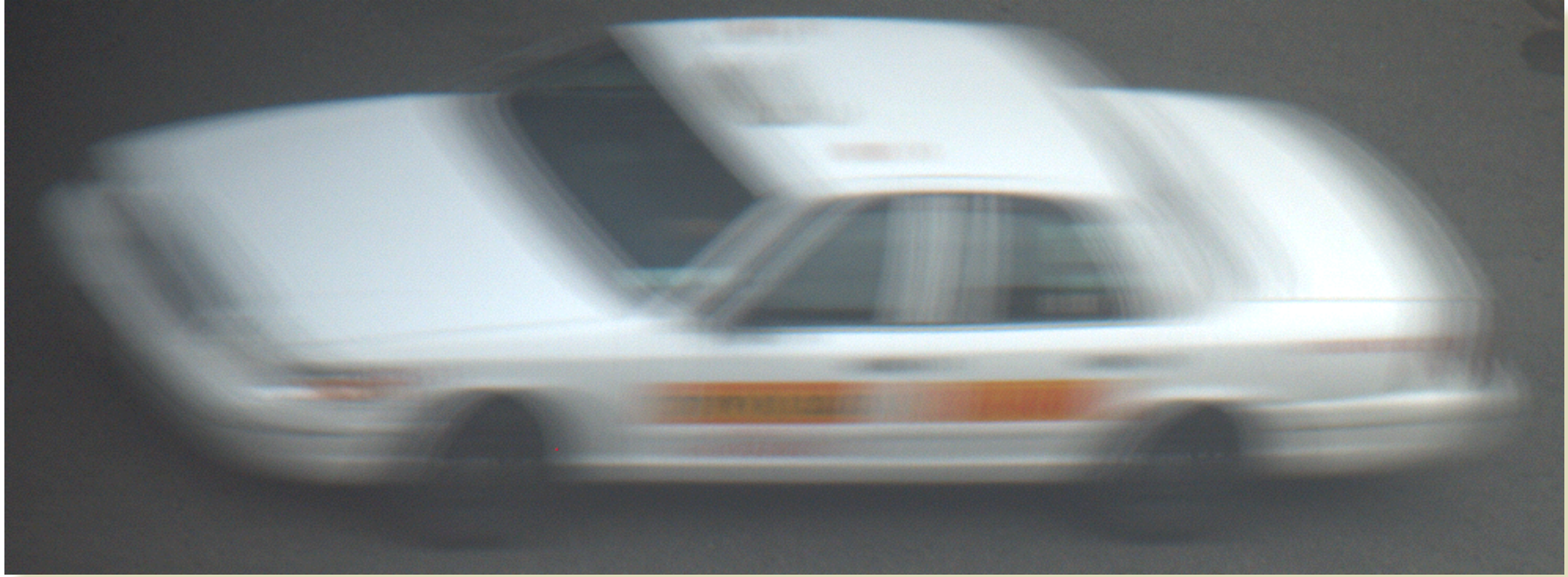


De blurred



License Plate Retrieval


TWO HOUR PARKING
NO PARKING
SNOW
EMERGENCY
NO PARKING
EQ62ZH
License Plate Retrieval




TOP CAB

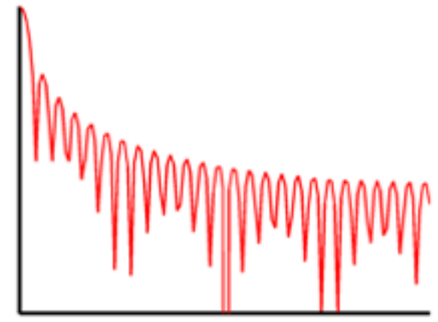

Input Image

Rectified Crop

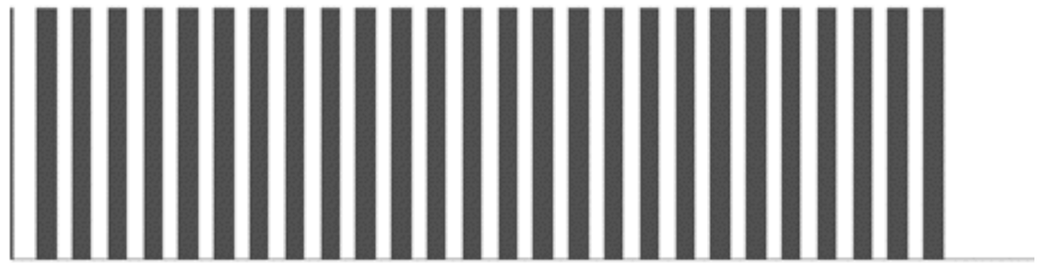
Deblurred Result

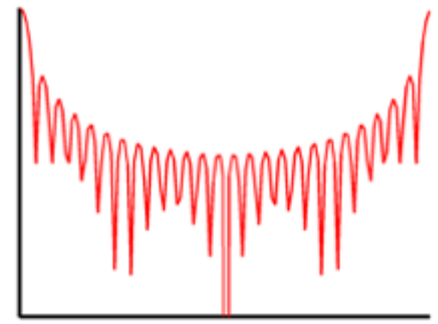
Different Codes

ALL ones

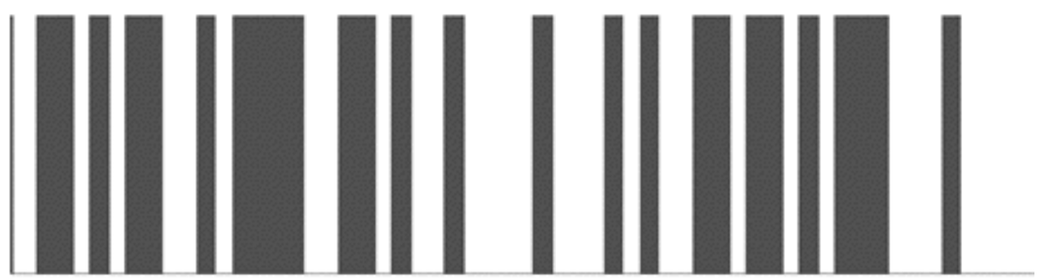


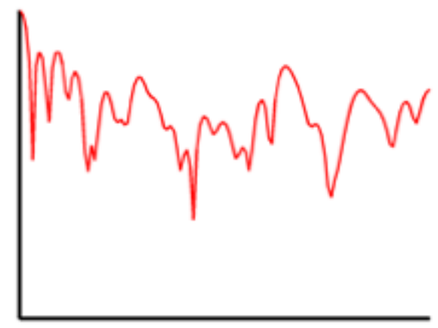
Alternate



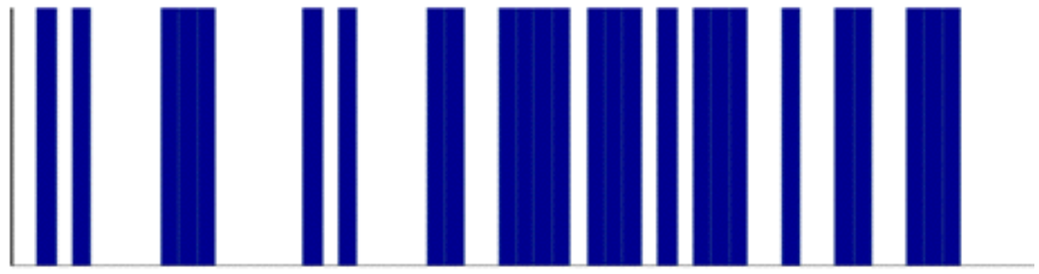


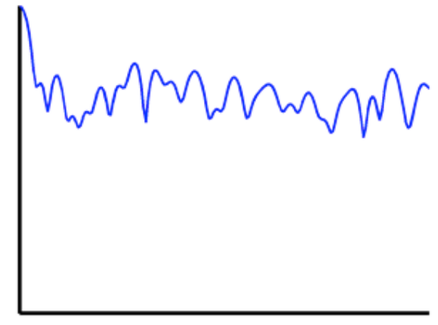
Random





F/S Camera

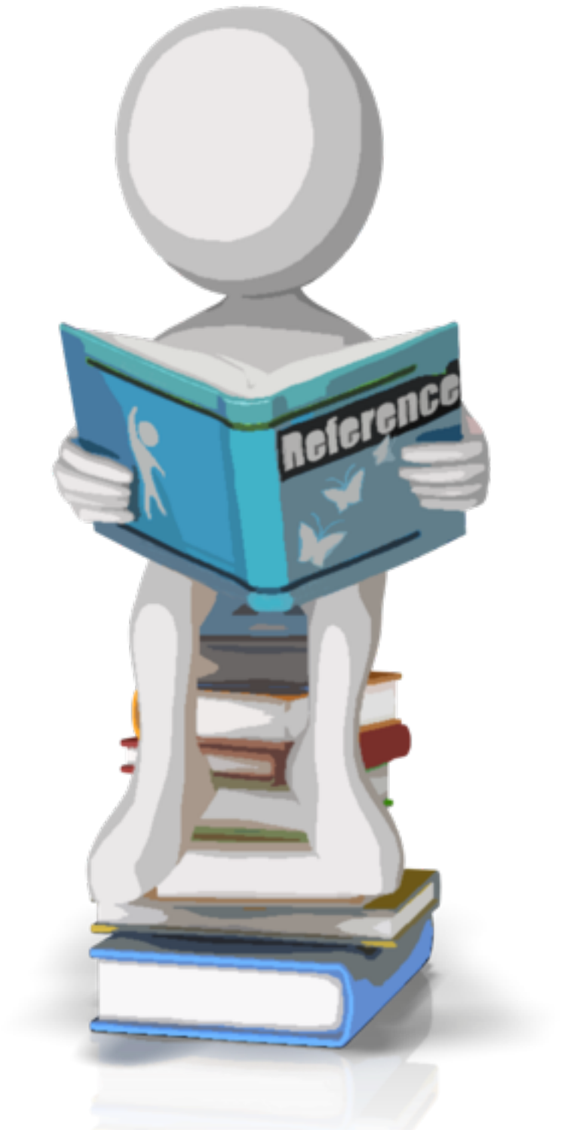




Summary

* Epsilon Photography
* Coded Photography
* Coded Aperture
* Flutter-Shutter Camera

Further Reading



* Raskar (2009) "Computational Photography: Epsilon to Coded Photography", Emerging Trends in Visual Computing, Springer 2009 [PDF]
* Levin, Fergus, Durand, Freeman (2007), "Image and Depth from a Conventional Camera with a Coded Aperture" ACM SIGGRAPH 2007 [PDF]
* Raskar, Agrawal, Tumblin (2006) "Coded Exposure Photography: Motion Deblurring using Fluttered Shutter" ACM SIGGRAPH 2006 [PDF]
* Lucy-Richardson Deconvolution (see wikipedia)
* Smith (1998), The Scientist and Engineer's Guide to Digital Signal Processing (http://www.dspguide.com/)

Credits

- For more information, see
- Richard Szeliski (2010) Computer Vision: Algorithms and Applications, Springer
- http://groups.csail.mit.edu/graphics/CodedAperture/
- http://web.media.mit.edu/~raskar/deblur/
- http://en.wikipedia.org/wiki/Richardson%E2%80%93Lucy_deconvolution
- Sinc Function: http://www.dspguide.com/ch11/2.htm

Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

Georgia Tech College of Computing