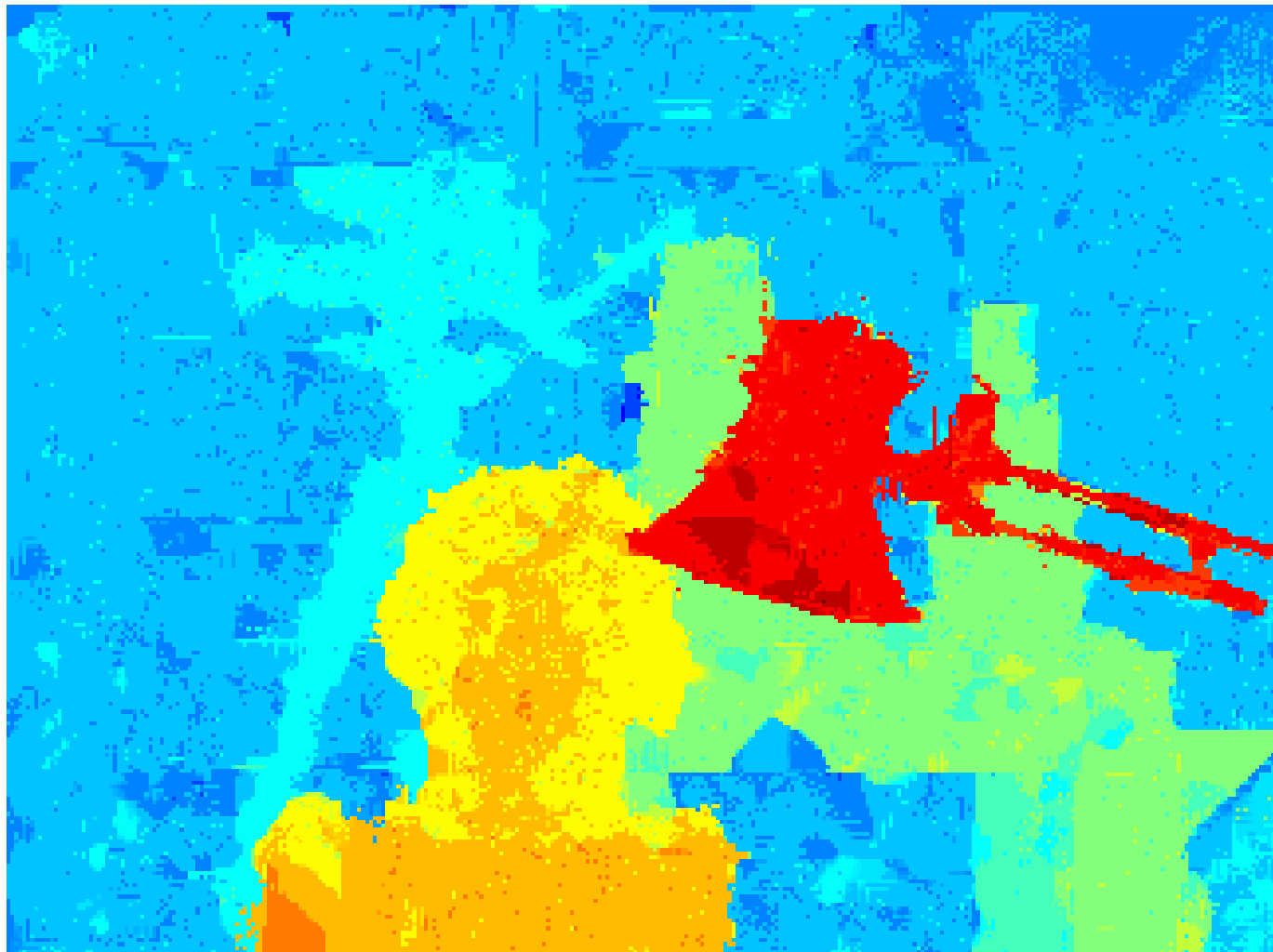


Disparity and stereo



15-463, 15-663, 15-862
Computational Photography
Fall 2021, Lecture 18

Course announcements

- Homework assignment 6 posted.
 - Due on December 5.
- Office hours this week:
 - Monday, 1:00 – 3:00 pm, Yannis.
 - Tuesday, 3:00 – 5:00 pm, Alice.
 - Wednesday, 3:00 – 5:00 pm, Jenny.
- I will post details for *optional* final project checkpoint meetings the week after Thanksgiving.

Overview of today's lecture

- Revisiting triangulation.
- Disparity.
- Revisiting lightfields.
- Structured light.
- Some notes on focusing.

Slide credits

Many of these slides were adapted directly from:

- Kris Kitani (16-385, Spring 2017).
- Srinivasa Narasimhan (16-820, Spring 2017).
- Mohit Gupta (Wisconsin).
- James Tompkin (Brown).

Revisiting triangulation

How would you reconstruct 3D points?

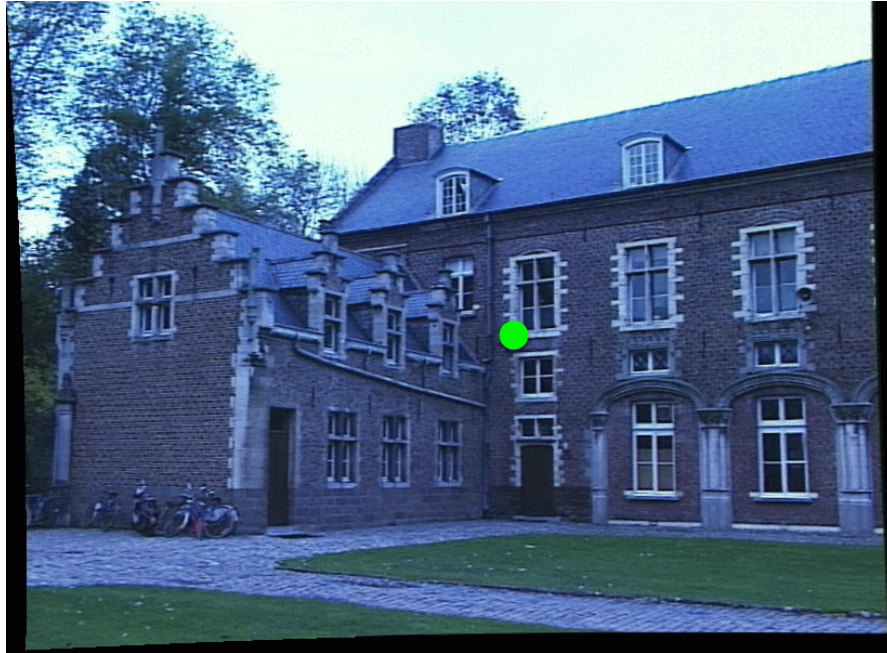


Left image



Right image

How would you reconstruct 3D points?



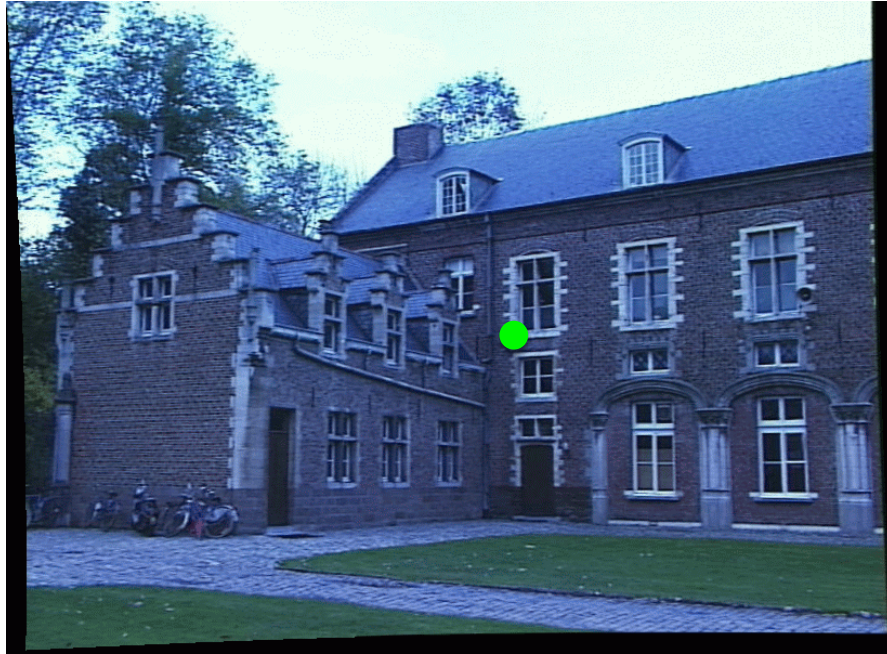
Left image



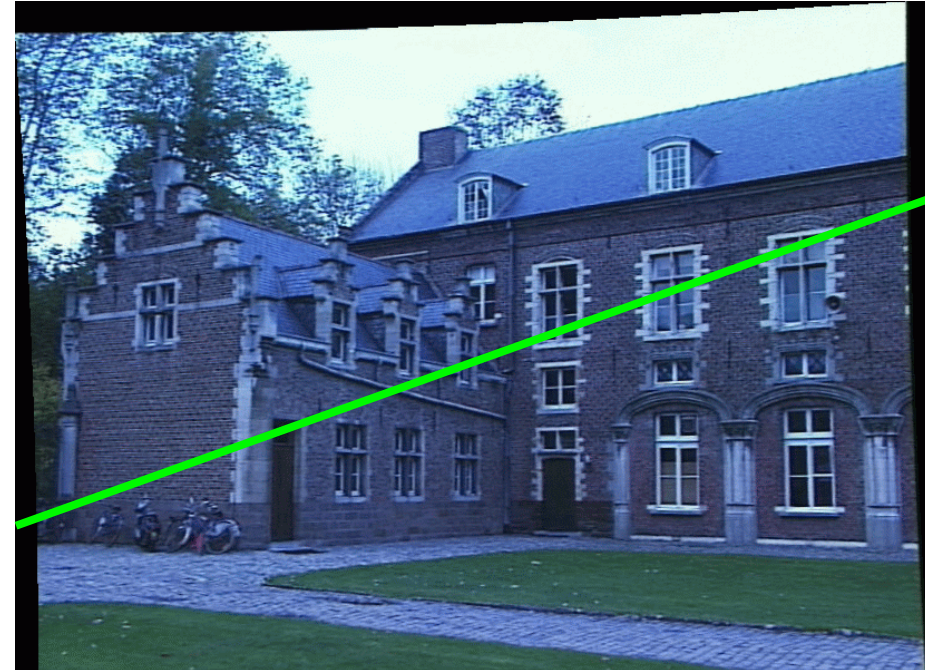
Right image

1. Select point in one image

How would you reconstruct 3D points?



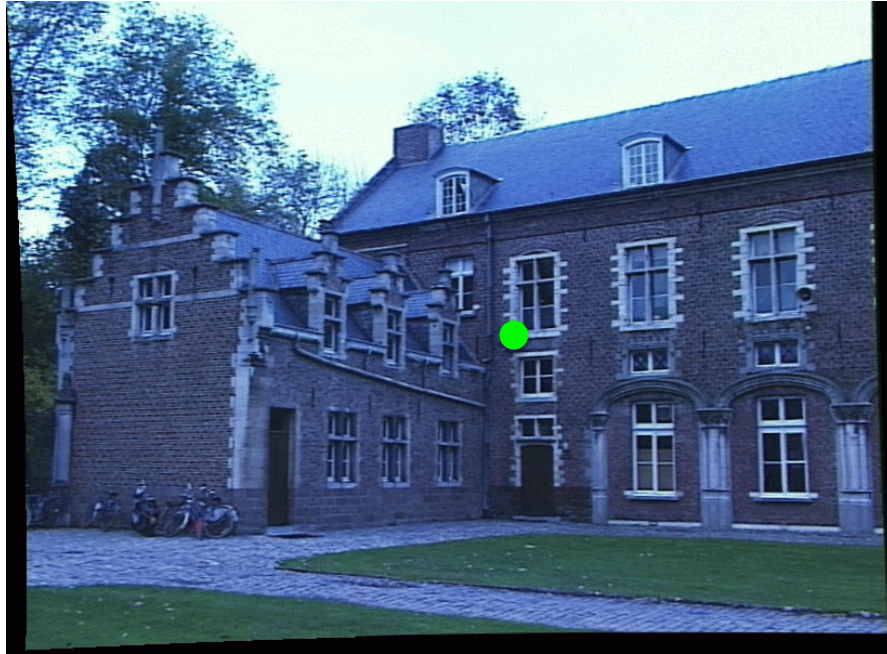
Left image



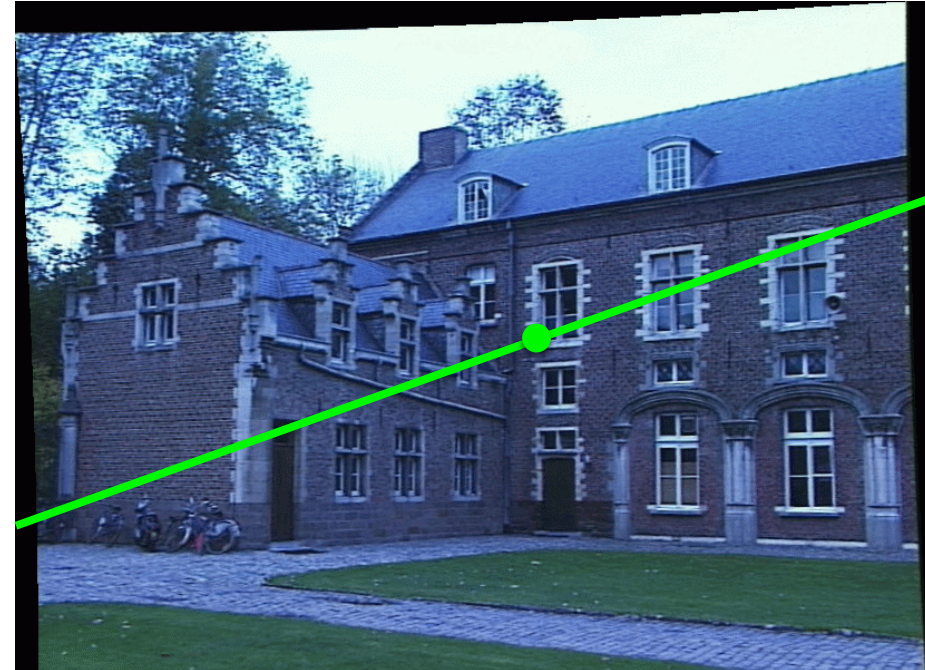
Right image

1. Select point in one image
2. Form epipolar line for that point in second image (how?)

How would you reconstruct 3D points?



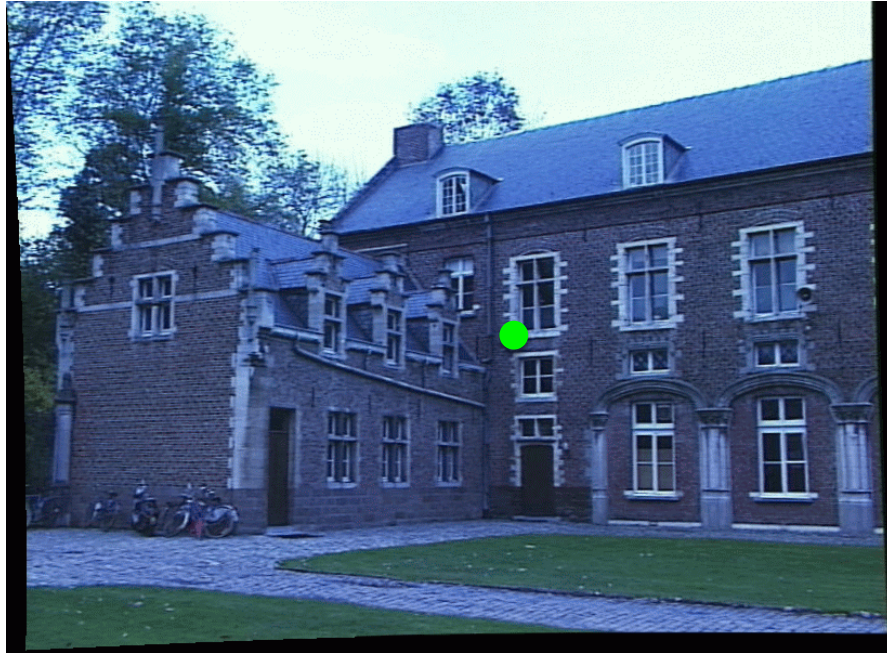
Left image



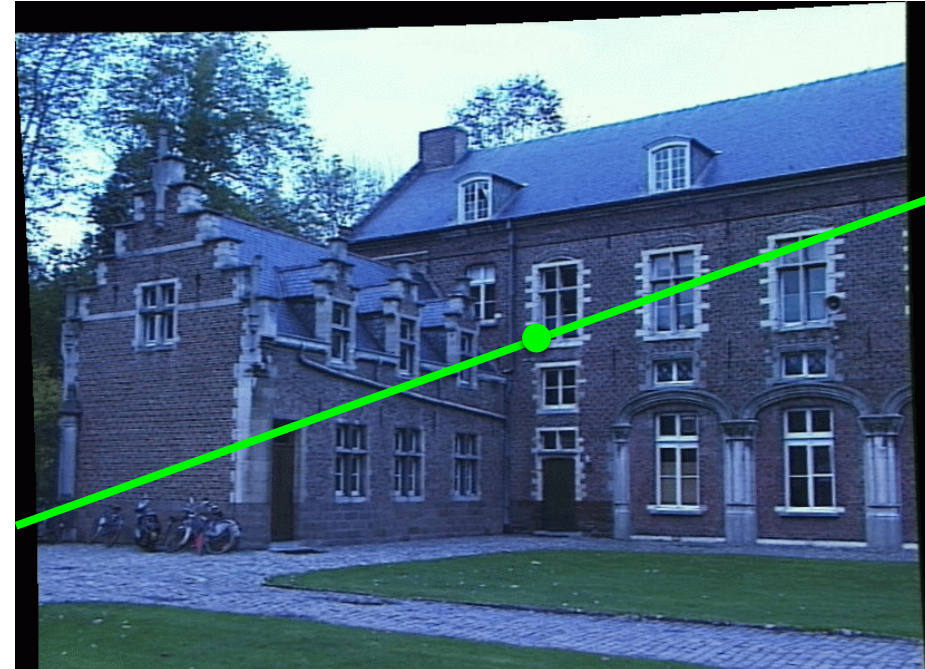
Right image

1. Select point in one image
2. Form epipolar line for that point in second image (how?)
3. Find matching point along line (how?)

How would you reconstruct 3D points?



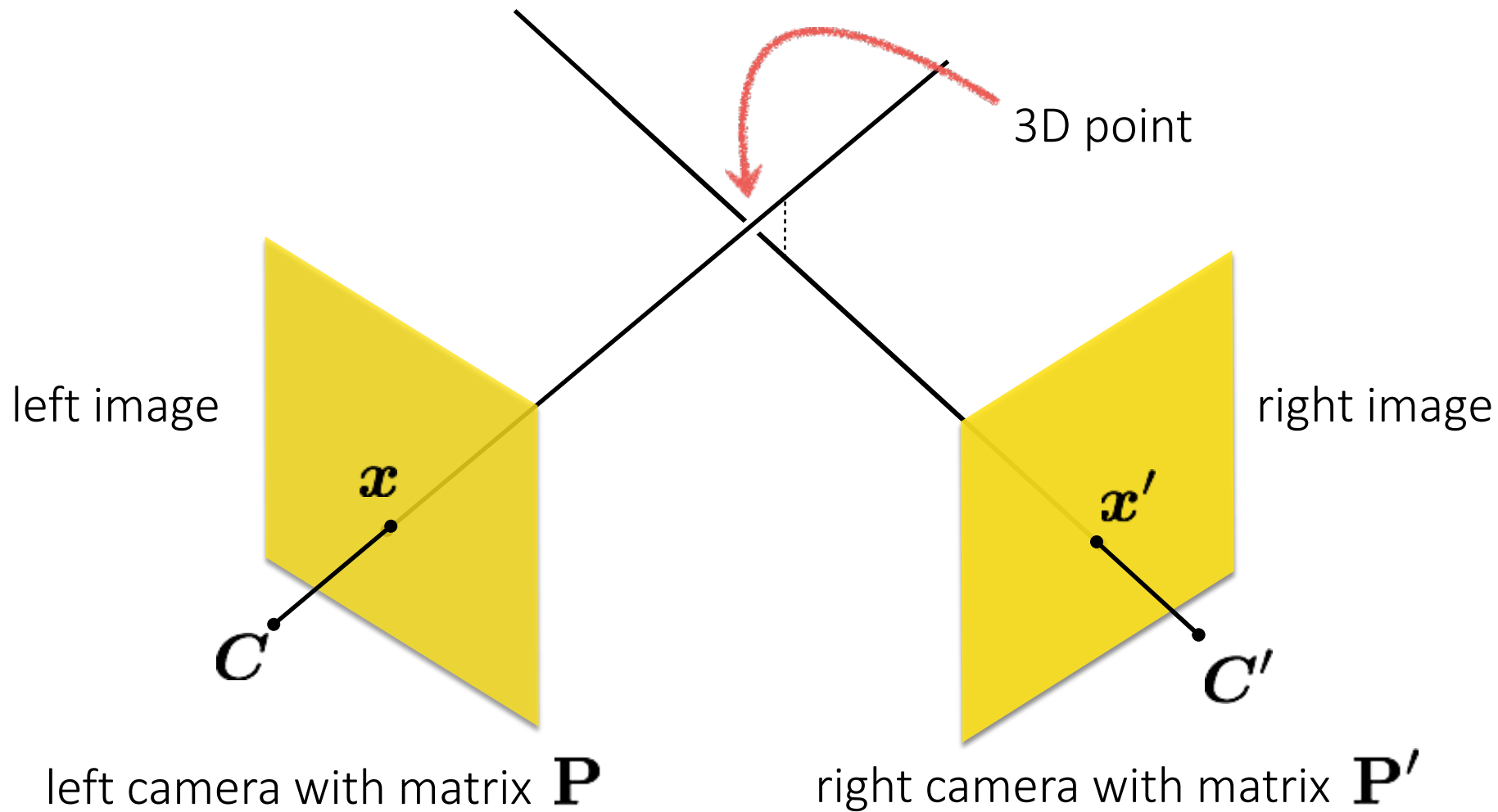
Left image



Right image

1. Select point in one image
2. Form epipolar line for that point in second image (how?)
3. Find matching point along line (how?)
4. Perform triangulation (how?)

Triangulation



Stereo rectification



What's different between these two images?

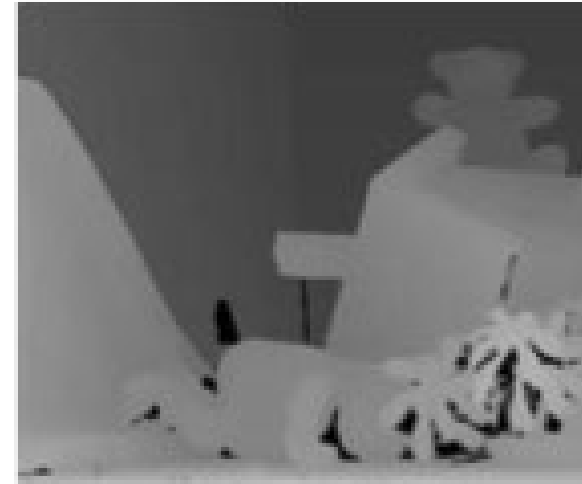




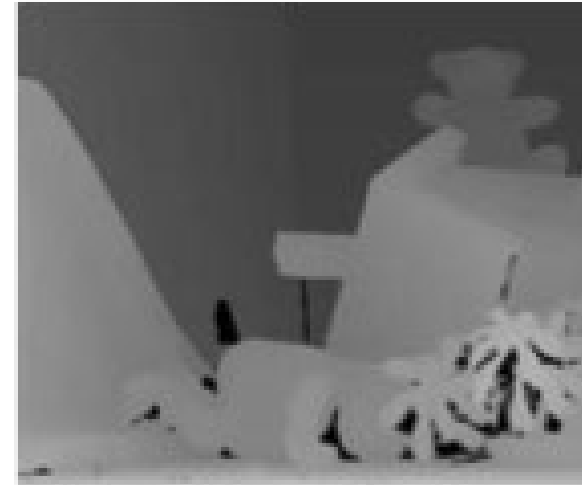


Objects that are close move more or less?

The amount of horizontal movement is
inversely proportional to ...

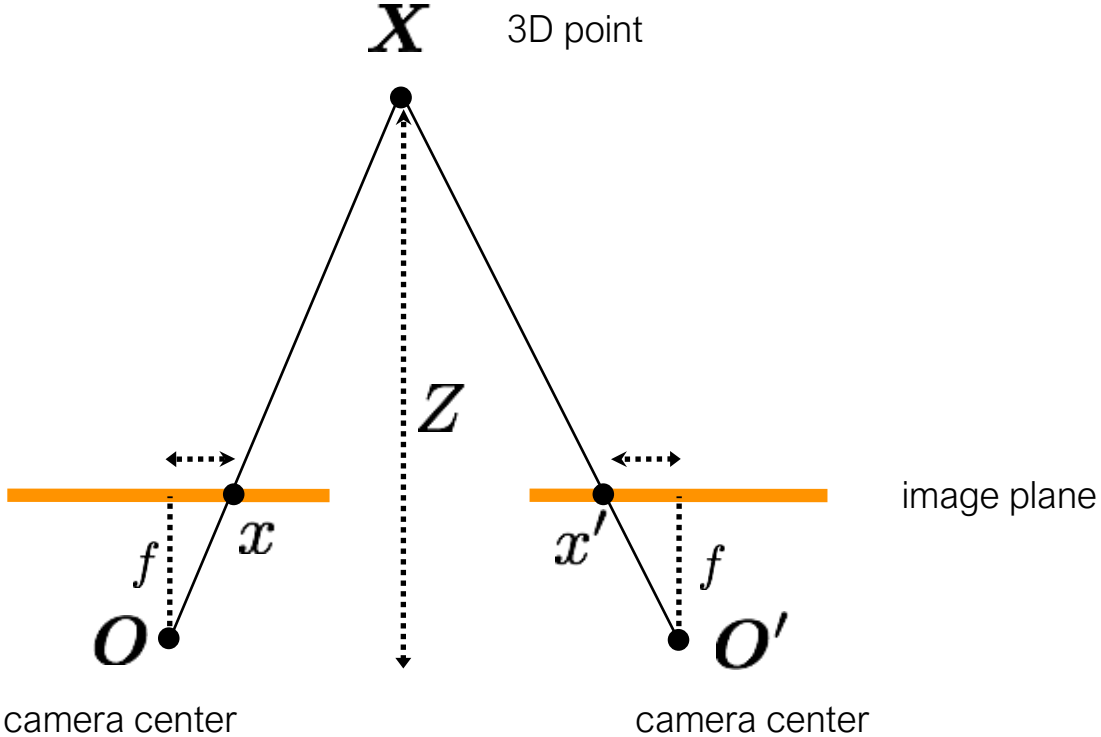


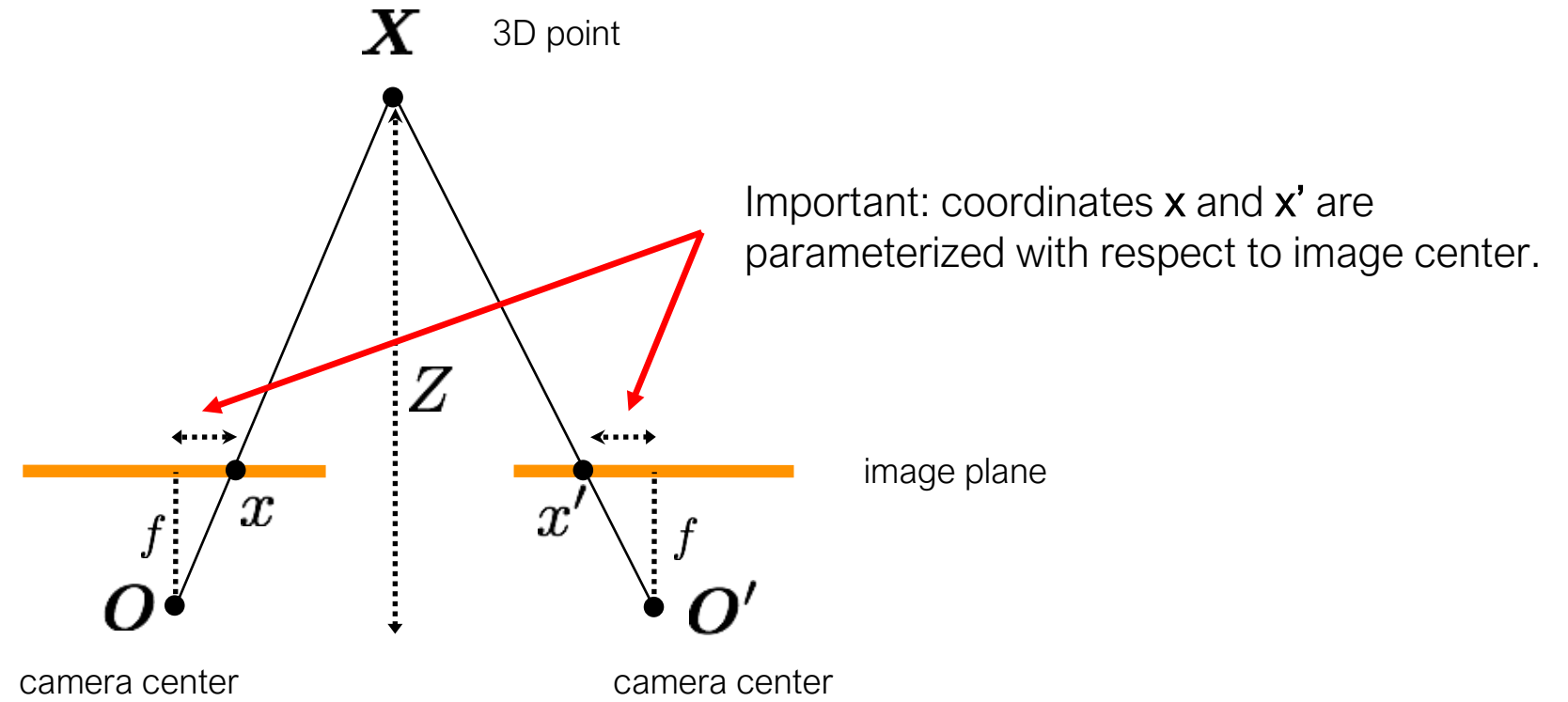
The amount of horizontal movement is
inversely proportional to ...

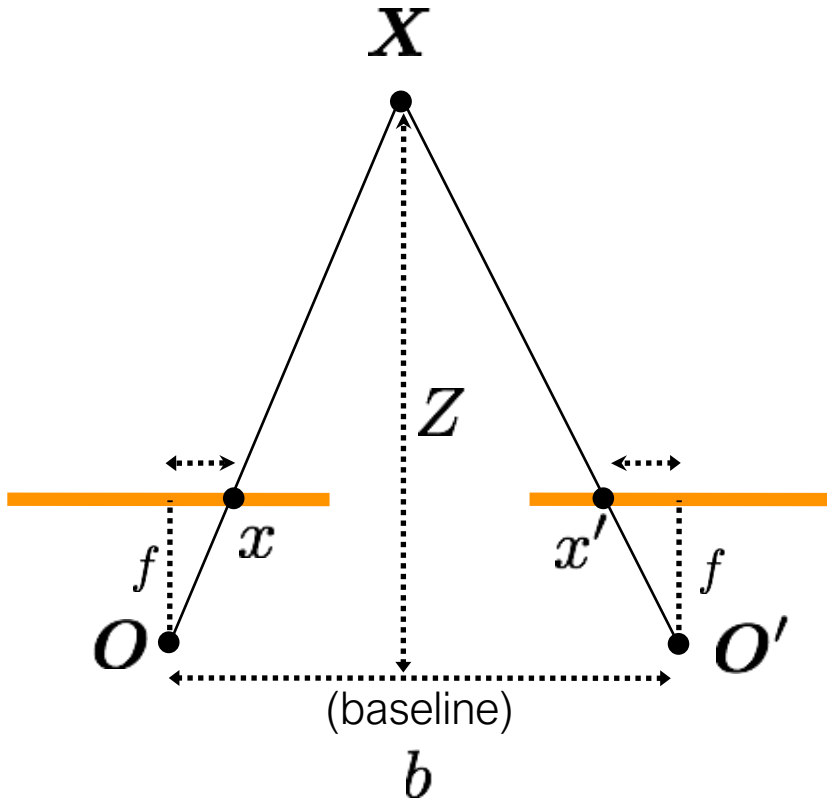


... the distance from the camera.

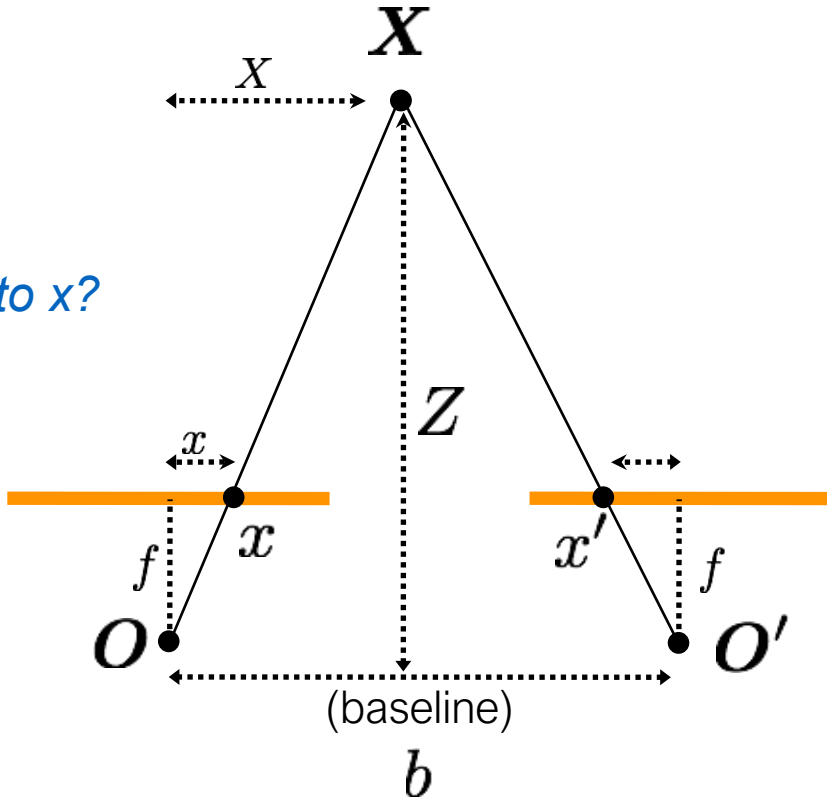
More formally...



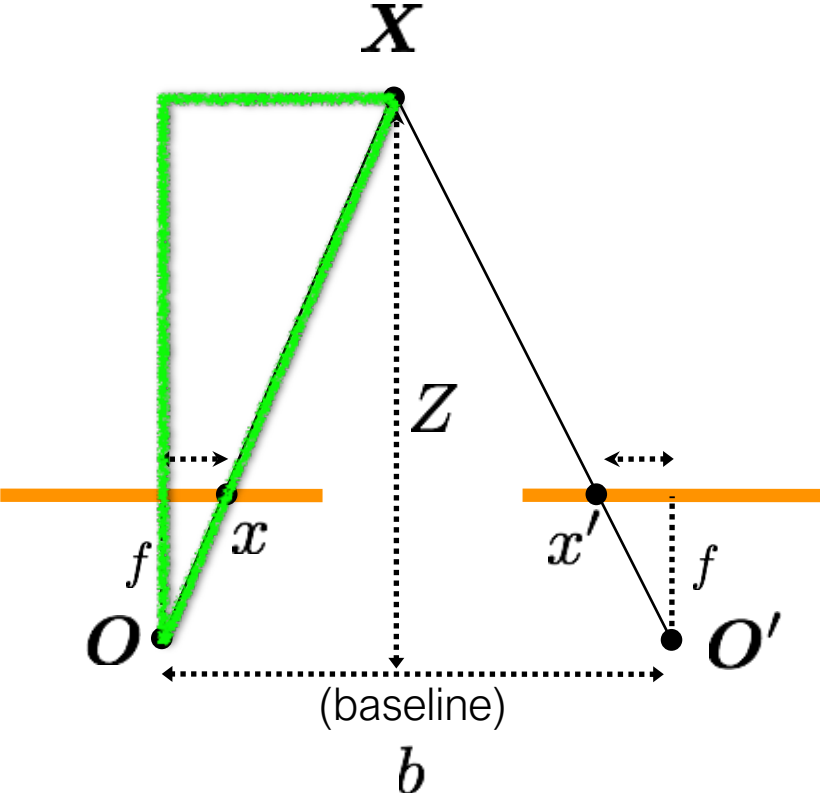




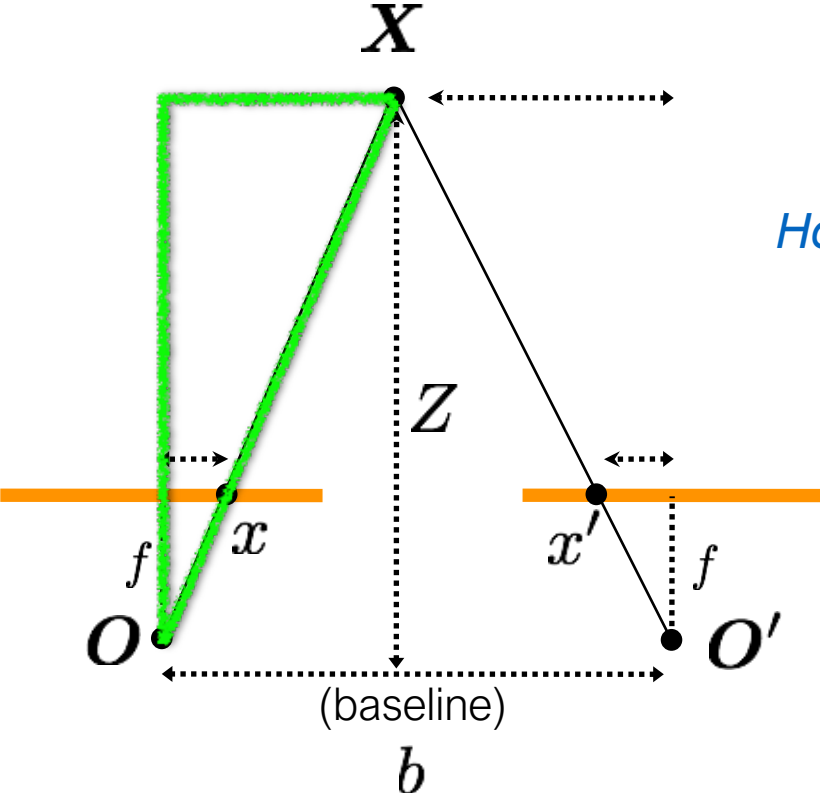
How is X related to x ?



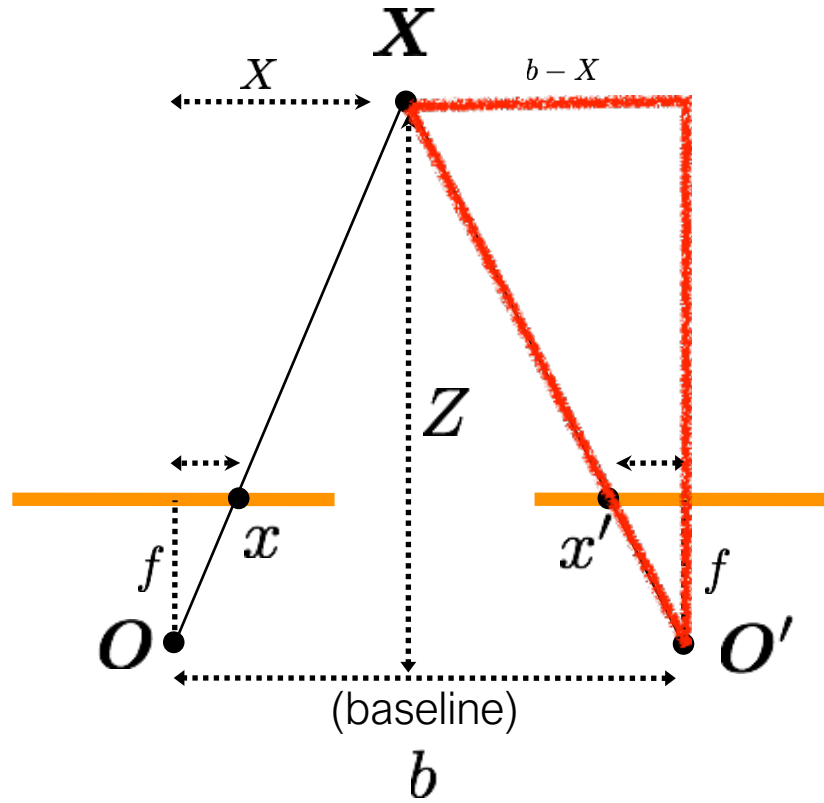
$$\frac{X}{Z} = \frac{x}{f}$$



$$\frac{X}{Z} = \frac{x}{f}$$

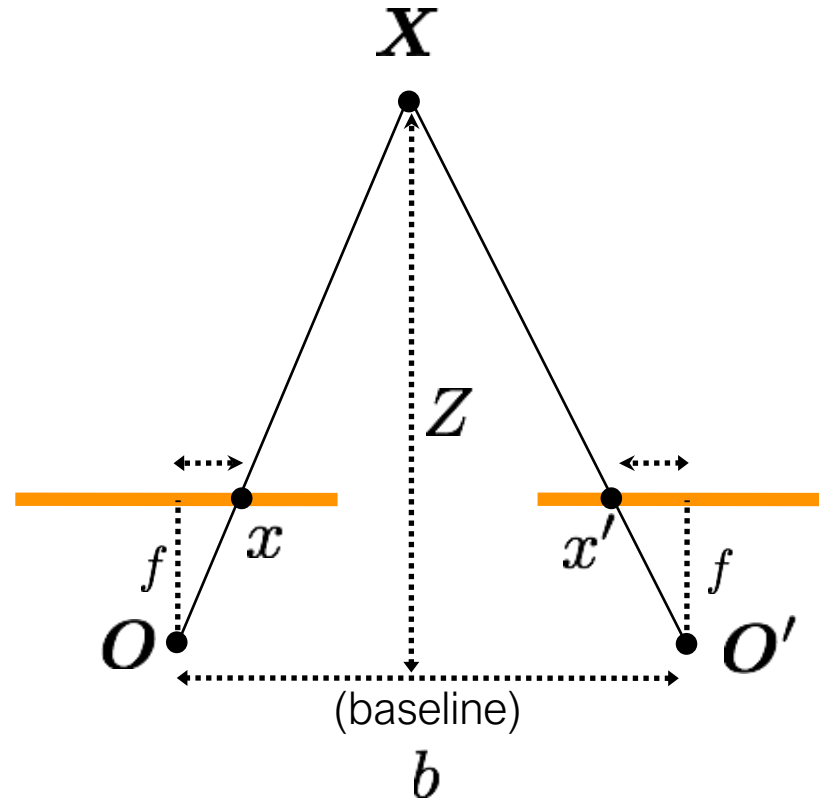


$$\frac{X}{Z} = \frac{x}{f}$$



$$\frac{b - X}{Z} = \frac{-x'}{f}$$

$$\frac{X}{Z} = \frac{x}{f}$$



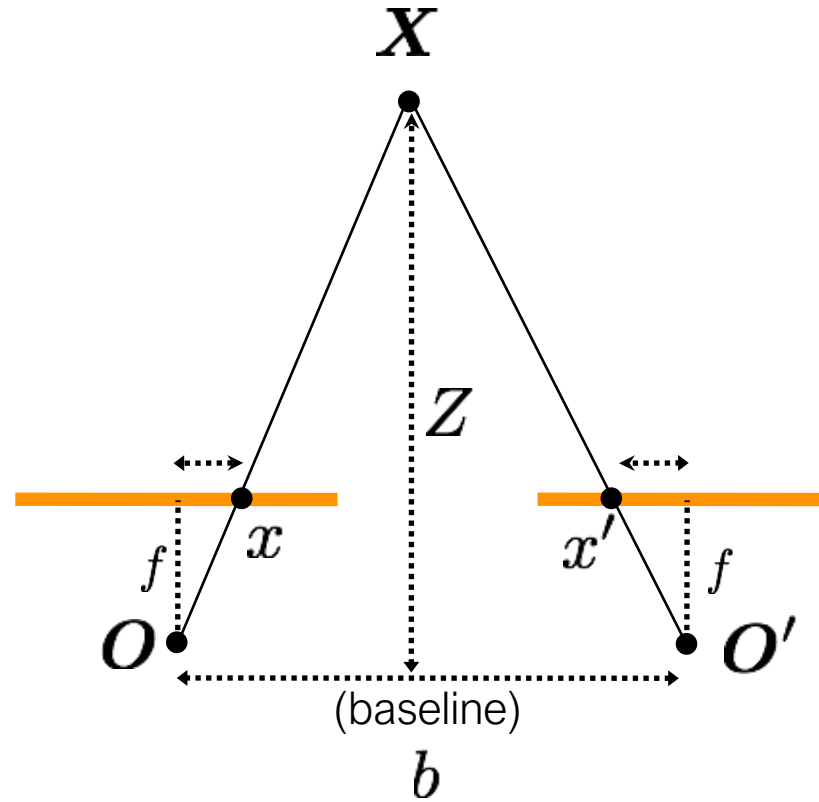
$$\frac{b - X}{Z} = \frac{-x'}{f}$$

Disparity

$$d = x - x' \quad (\text{wrt to camera origin of image plane})$$

$$= \frac{bf}{Z}$$

$$\frac{X}{Z} = \frac{x}{f}$$



$$\frac{b - X}{Z} = \frac{-x'}{f}$$

Disparity

$$d = x - x'$$

$$= \frac{bf}{Z}$$

inversely proportional
to depth

Real-time stereo sensing



Nomad robot searches for meteorites in Antarctica

<http://www.frc.ri.cmu.edu/projects/meteorobot/index.html>



Subaru
Eyesight system

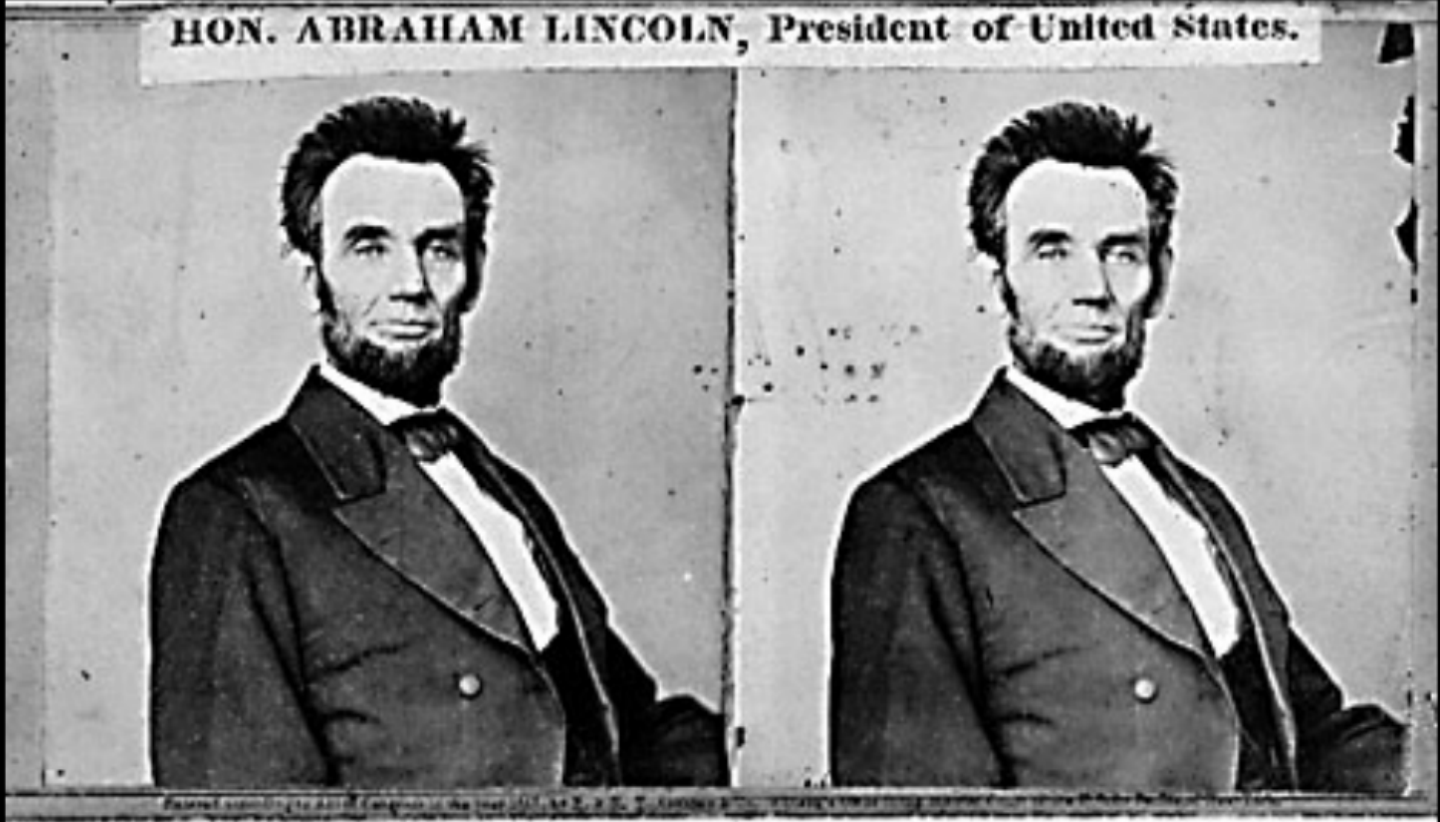
Pre-collision
braking



What other vision system uses disparity for depth sensing?

Stereoscopes: A 19th Century Pastime







Public Library, Stereoscopic Looking Room, Chicago, by Phillips, 1923





Teesta suspension bridge-Darjeeling, India





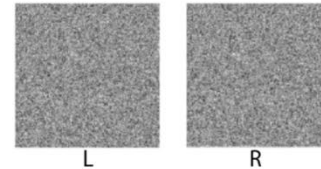
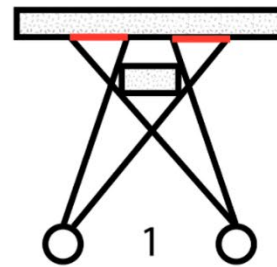
Mark Twain at Pool Table", no date, UCR Museum of Photography



Simple stereoscope

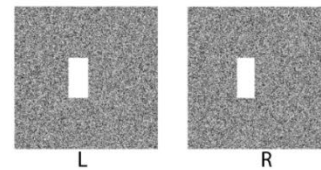


Google cardboard

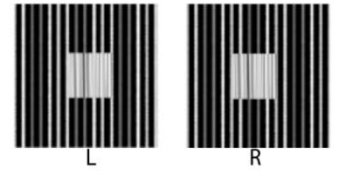
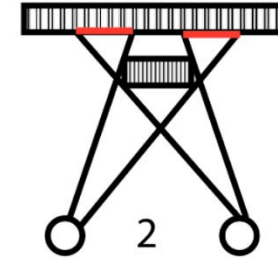


Planar (Julesz, 1960)

One

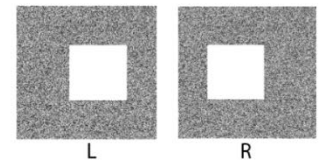
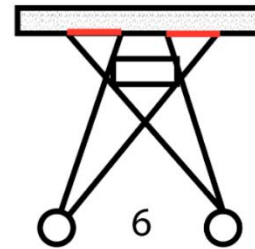


Textureless Middle Plane
(Tsirlin et al, 2010)



Textured Planes

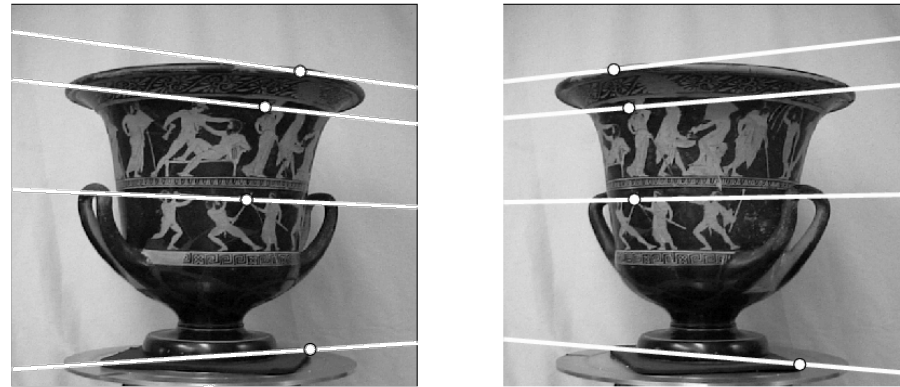
Two



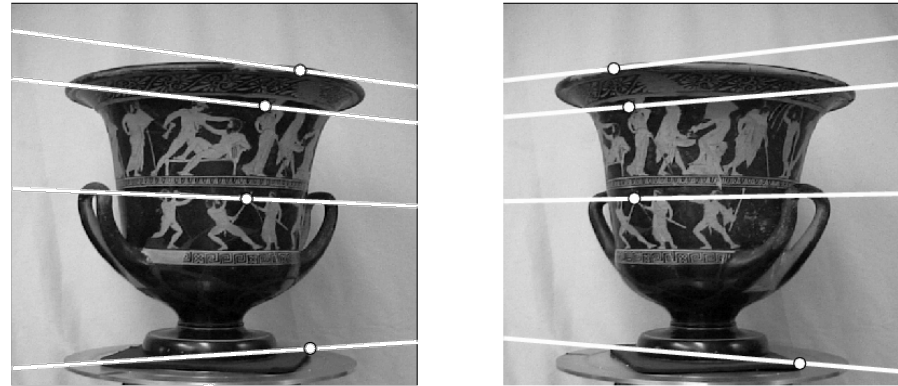
Textureless Plane

Fun patterns: random dot stereograms

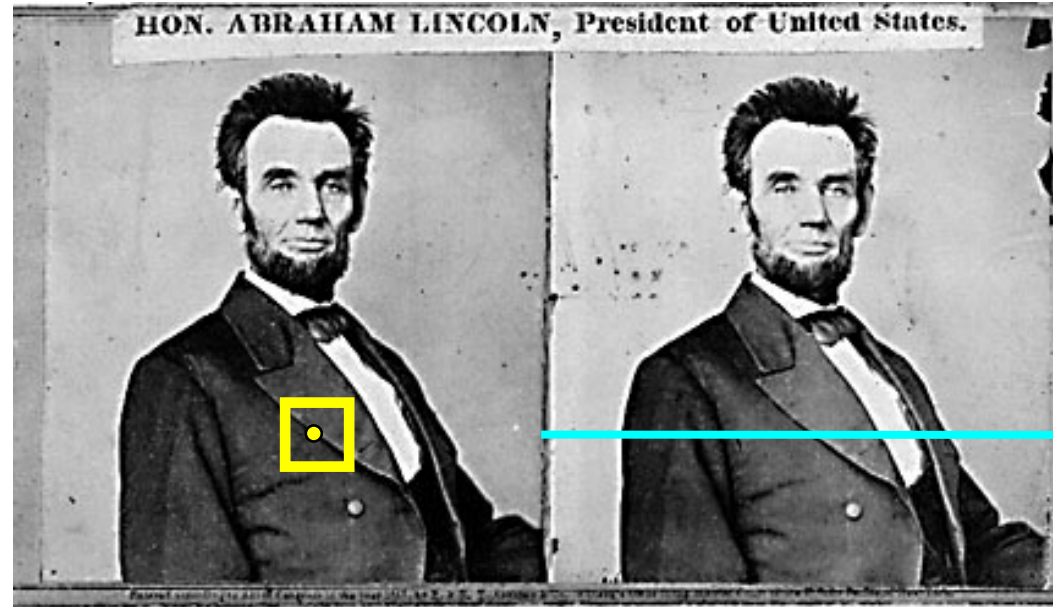
So can I compute depth using disparity from any two images of the same object?



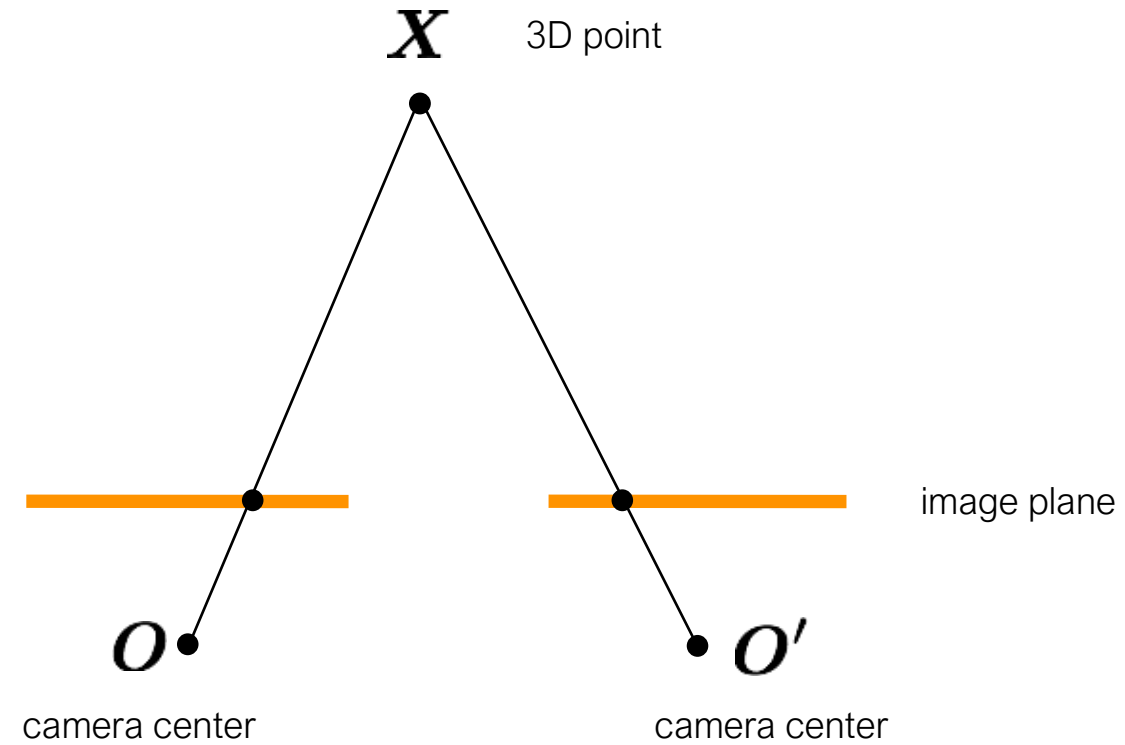
*So can I compute depth using disparity
from any two images of the same object?*



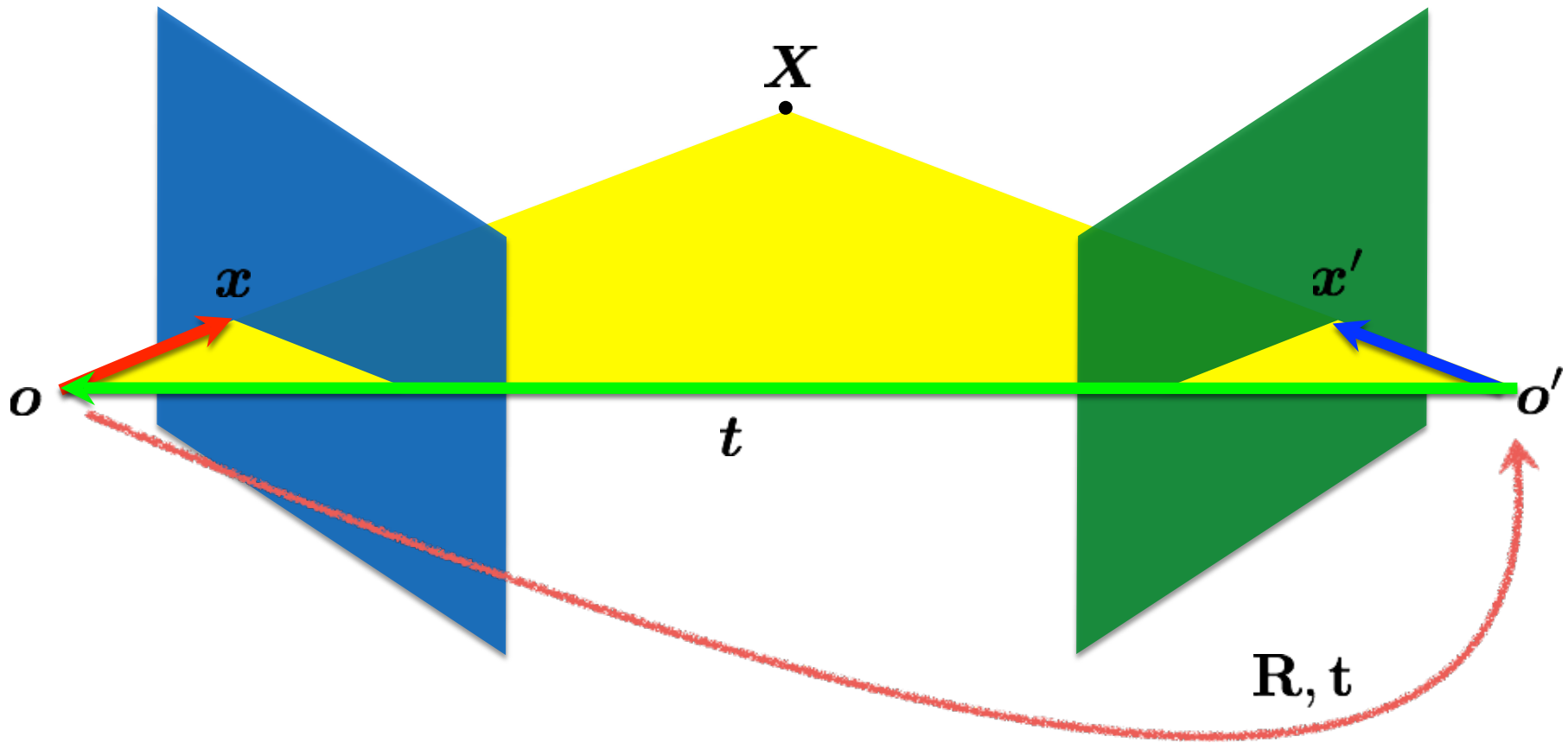
1. Need sufficient baseline
2. Images need to be 'rectified' first (make epipolar lines horizontal)



How can you make the epipolar lines horizontal?

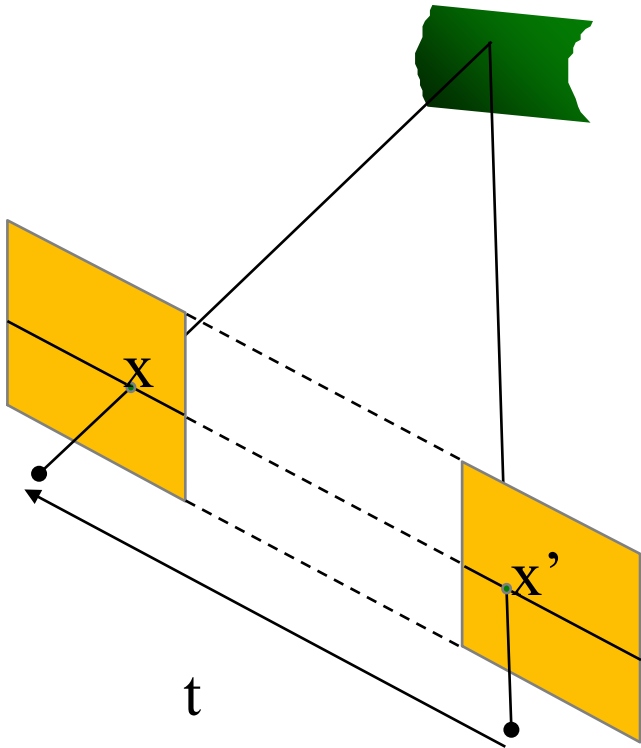


What's special about these two cameras?



$$x' = \mathbf{R}(x - t)$$

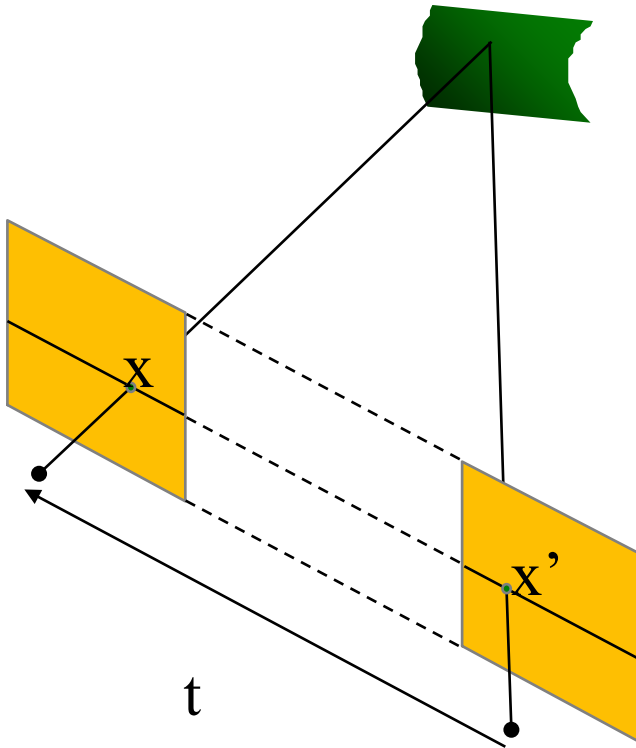
When are epipolar lines horizontal?



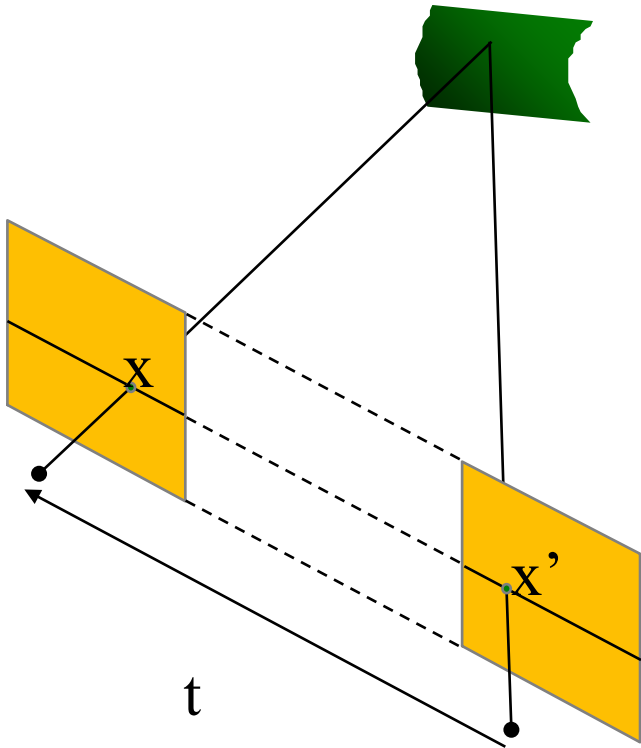
When are epipolar lines horizontal?

When this relationship holds:

$$R = I \quad t = (T, 0, 0)$$



When are epipolar lines horizontal?



When this relationship holds:

$$R = I \quad t = (T, 0, 0)$$

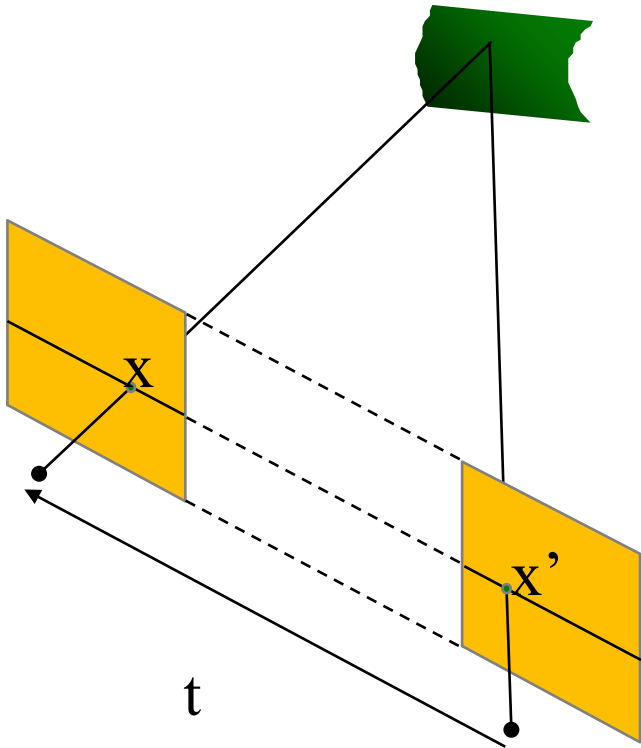
Let's try this out...

$$E = t \times R = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T \\ 0 & T & 0 \end{bmatrix}$$

This always has to hold:

$$x^T E x' = 0$$

When are epipolar lines horizontal?



When this relationship holds:

$$R = I \quad t = (T, 0, 0)$$

Let's try this out...

$$E = t \times R = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T \\ 0 & T & 0 \end{bmatrix}$$

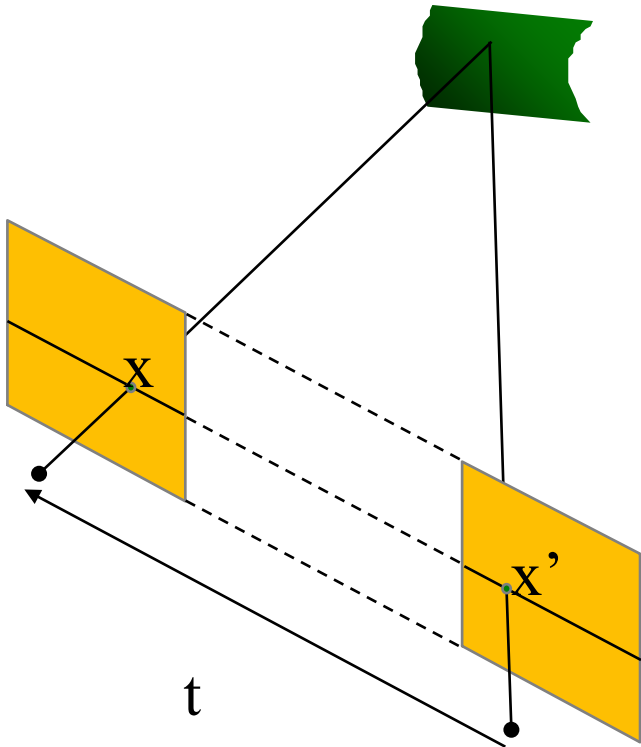
This always has to hold:

$$x^T E x' = 0$$

Write out the constraint

$$(u \quad v \quad 1) \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T \\ 0 & T & 0 \end{bmatrix} \begin{pmatrix} u' \\ v' \\ 1 \end{pmatrix} = 0 \quad (u \quad v \quad 1) \begin{pmatrix} 0 \\ -T \\ Tv' \end{pmatrix} = 0$$

When are epipolar lines horizontal?



Write out the constraint

$$\begin{pmatrix} u & v & 1 \end{pmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T \\ 0 & T & 0 \end{bmatrix} \begin{pmatrix} u' \\ v' \\ 1 \end{pmatrix} = 0$$

$$\begin{pmatrix} u & v & 1 \end{pmatrix} \begin{pmatrix} 0 \\ -T \\ Tv' \end{pmatrix} = 0$$

$Tv = Tv'$
y coordinate is
always the same!

When this relationship holds:

$$R = I \quad t = (T, 0, 0)$$

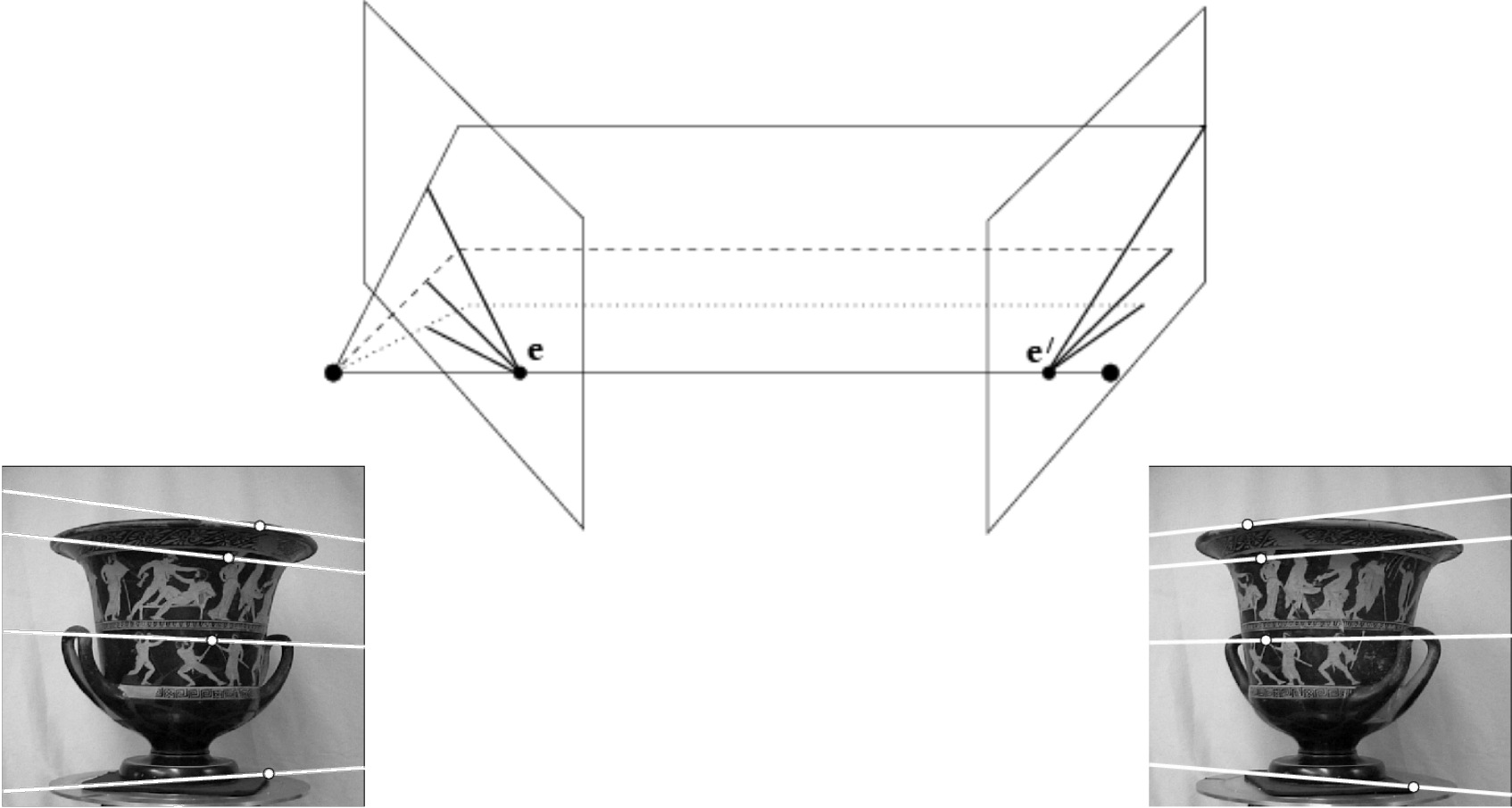
Let's try this out...

$$E = t \times R = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T \\ 0 & T & 0 \end{bmatrix}$$

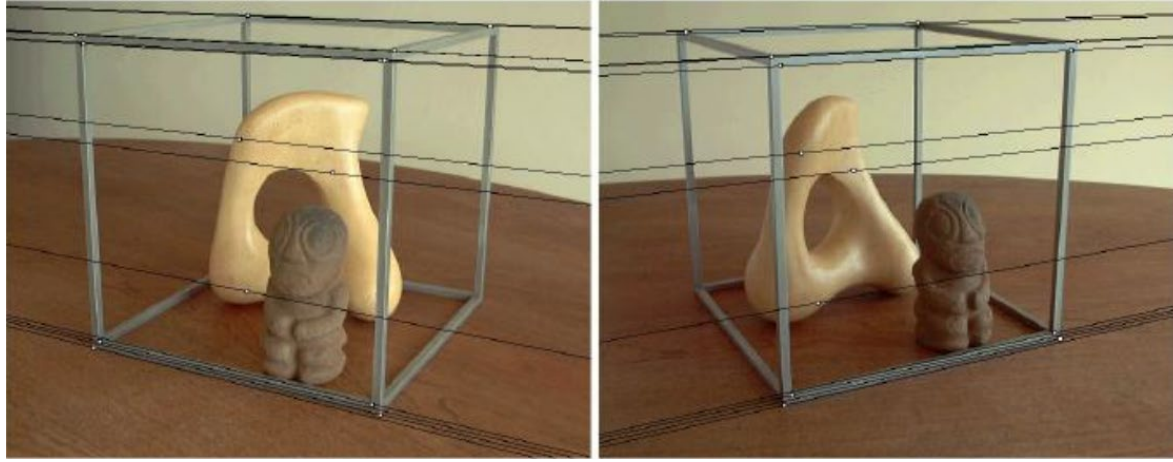
This always has to hold:

$$x^T E x' = 0$$

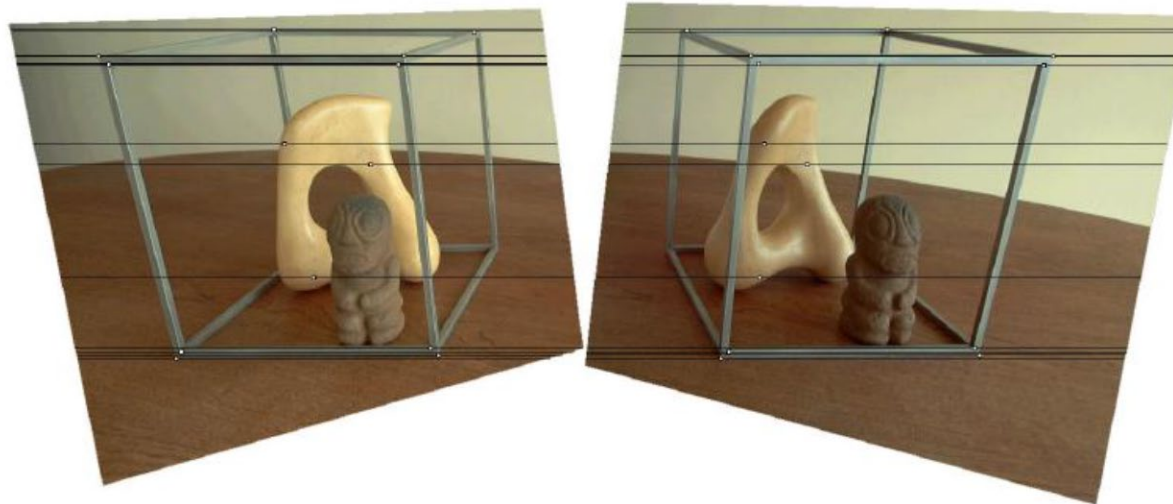
The image of a 3D point will
always be on the same
horizontal line

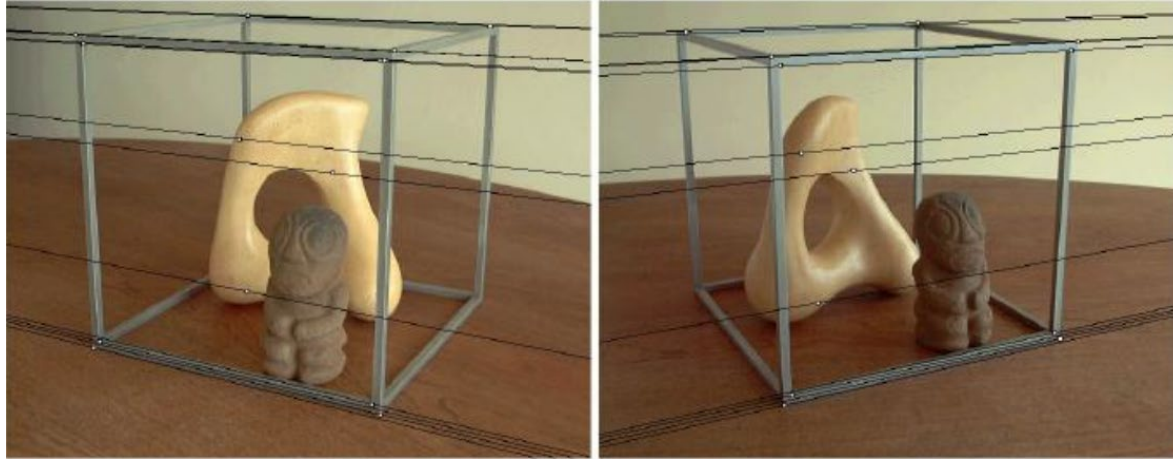


It's hard to make the image planes exactly parallel

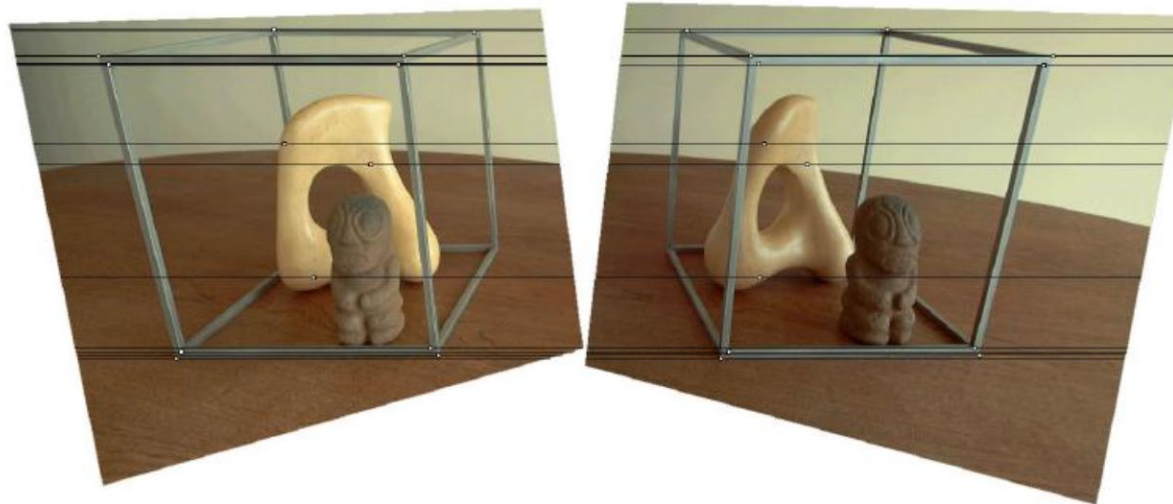


How can you make the epipolar lines horizontal?

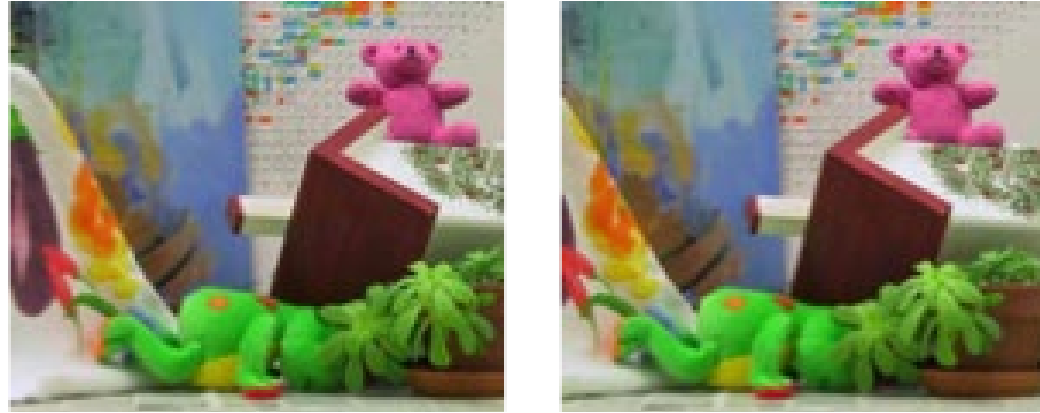




Use stereo rectification

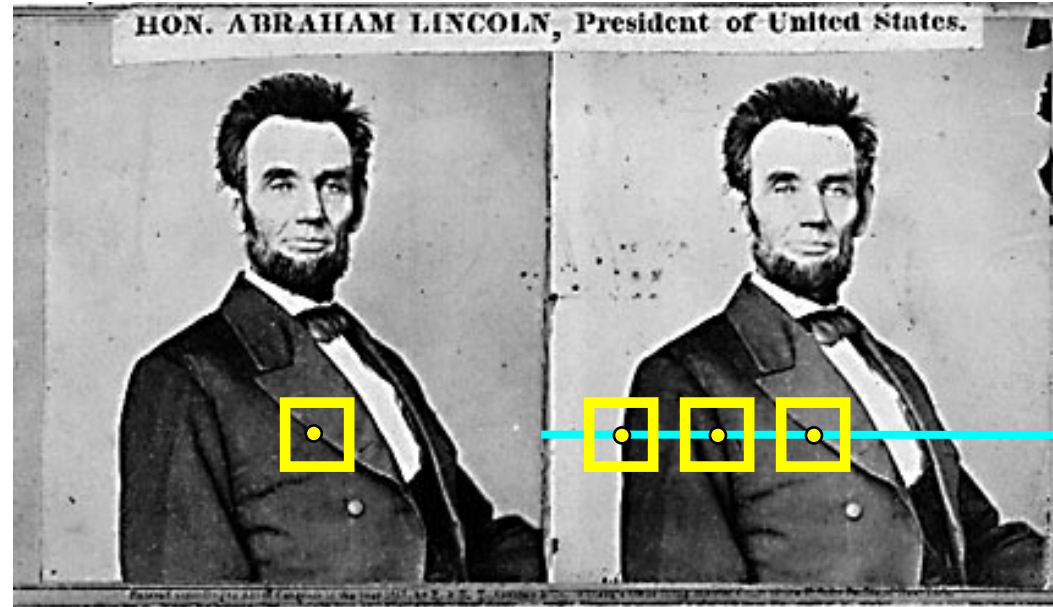


Stereo matching



Depth Estimation via Stereo Matching





1. Rectify images
(make epipolar lines horizontal)
2. For each pixel
 - a. Find epipolar line
 - b. Scan line for best match
 - c. Compute depth from disparity

How would you do this?

$$Z = \frac{bf}{d}$$

When are correspondences difficult?

When are correspondences difficult?

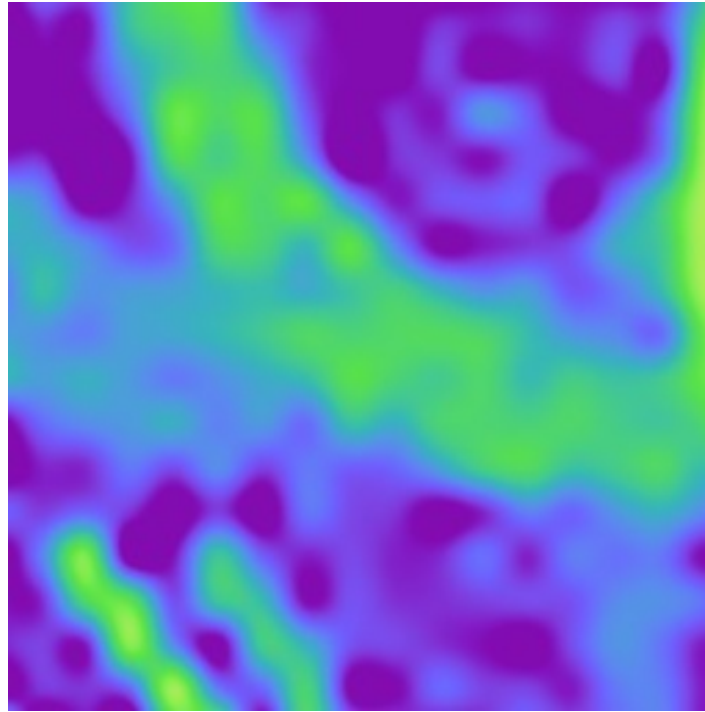


Depth discontinuities

What is the problem here?



One of two input images



Depth from disparity



Groundtruth depth

Depth discontinuities

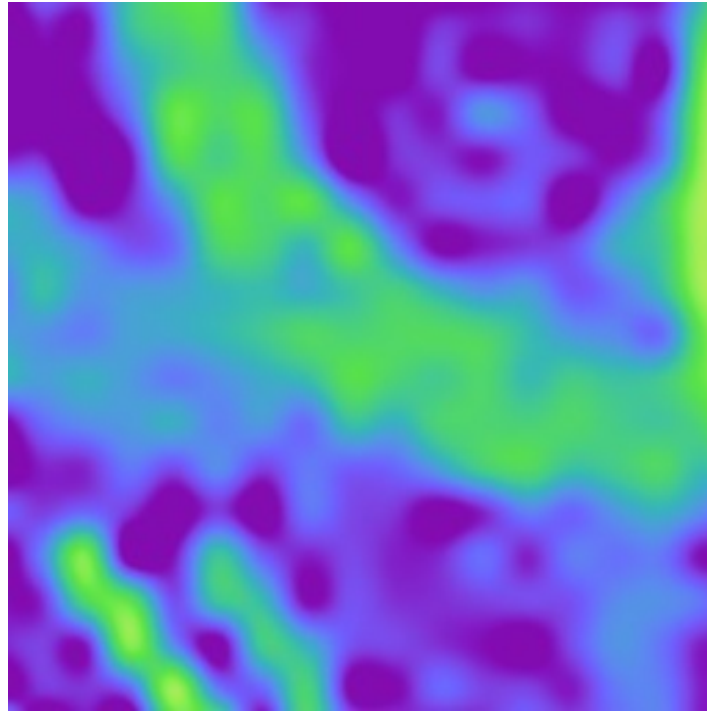
What is the problem here?

- (Patch-wise) stereo matching blurs along the edges.

How can we fix this?



One of two input images



Depth from disparity



Groundtruth depth

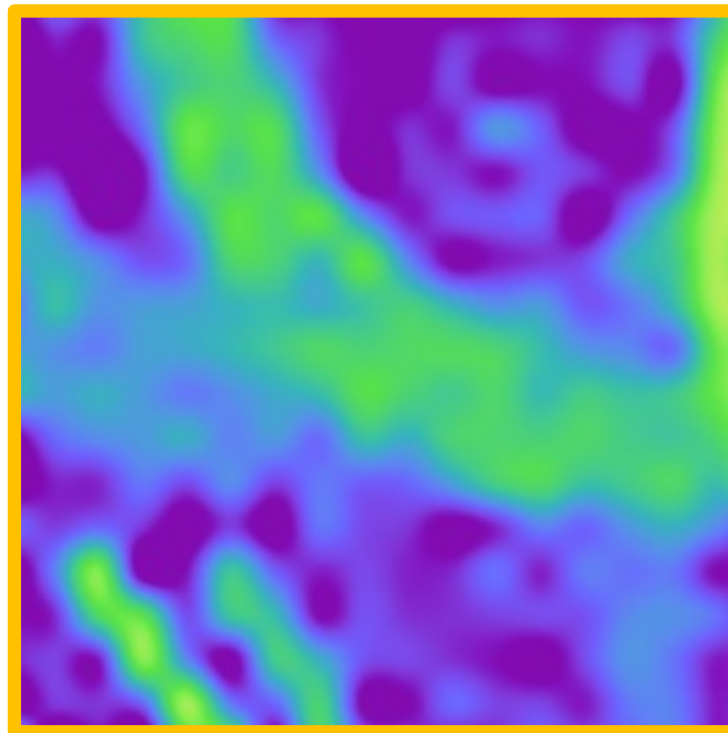
Edge-aware depth denoising

$$A_{p(col)} = \frac{1}{k(p(col))} \sum_{p' \in \Omega} g_d(|p - p'|) g_r(F_{p(col)} - F_{p'(col)}) A_{p'(col)}$$

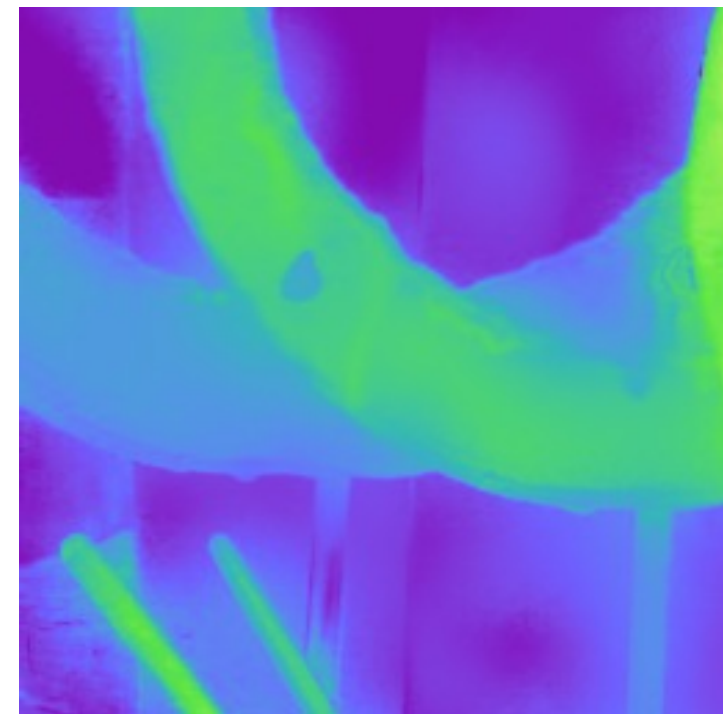
Use joint bilateral filtering, with the input image as guide.



One of two input images



Depth from disparity



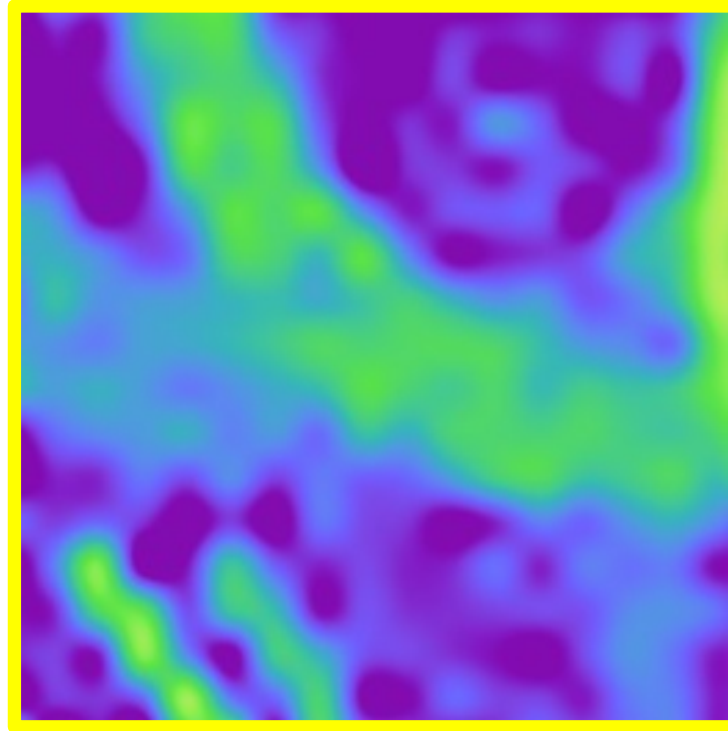
Guided filtering

Fast bilateral solver

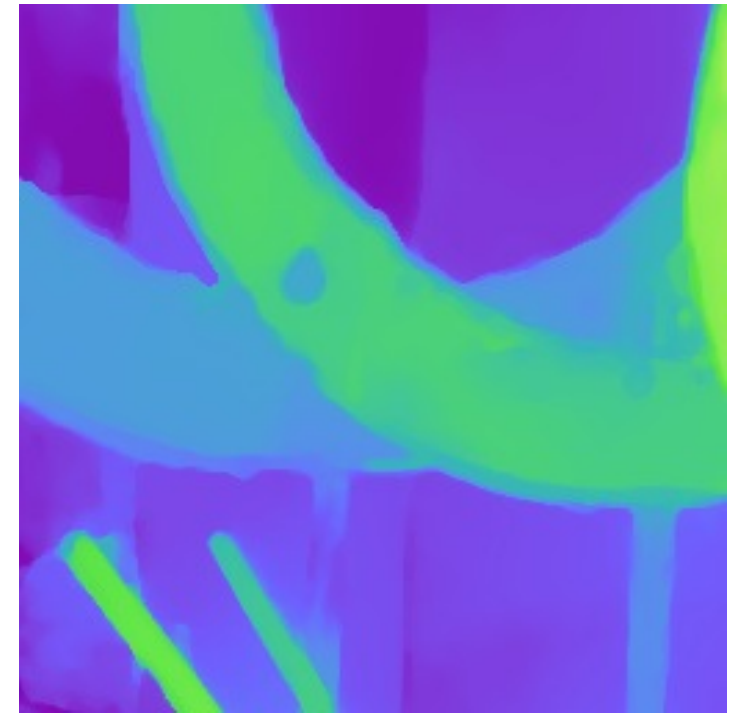
Possible to *combine* edge-enforcement and matching in a single optimization problem, instead of just filtering in post-processing.



One of two input images



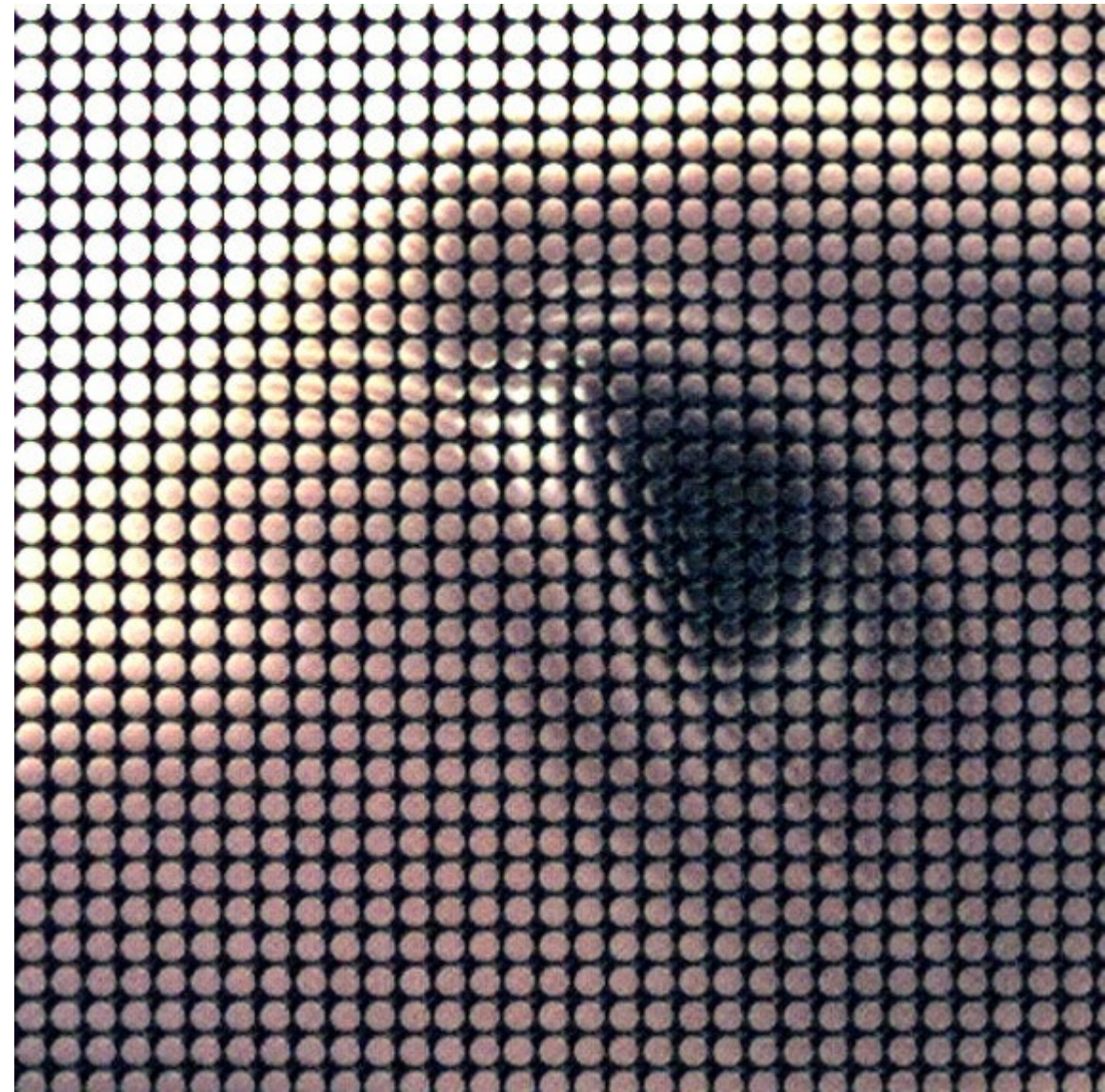
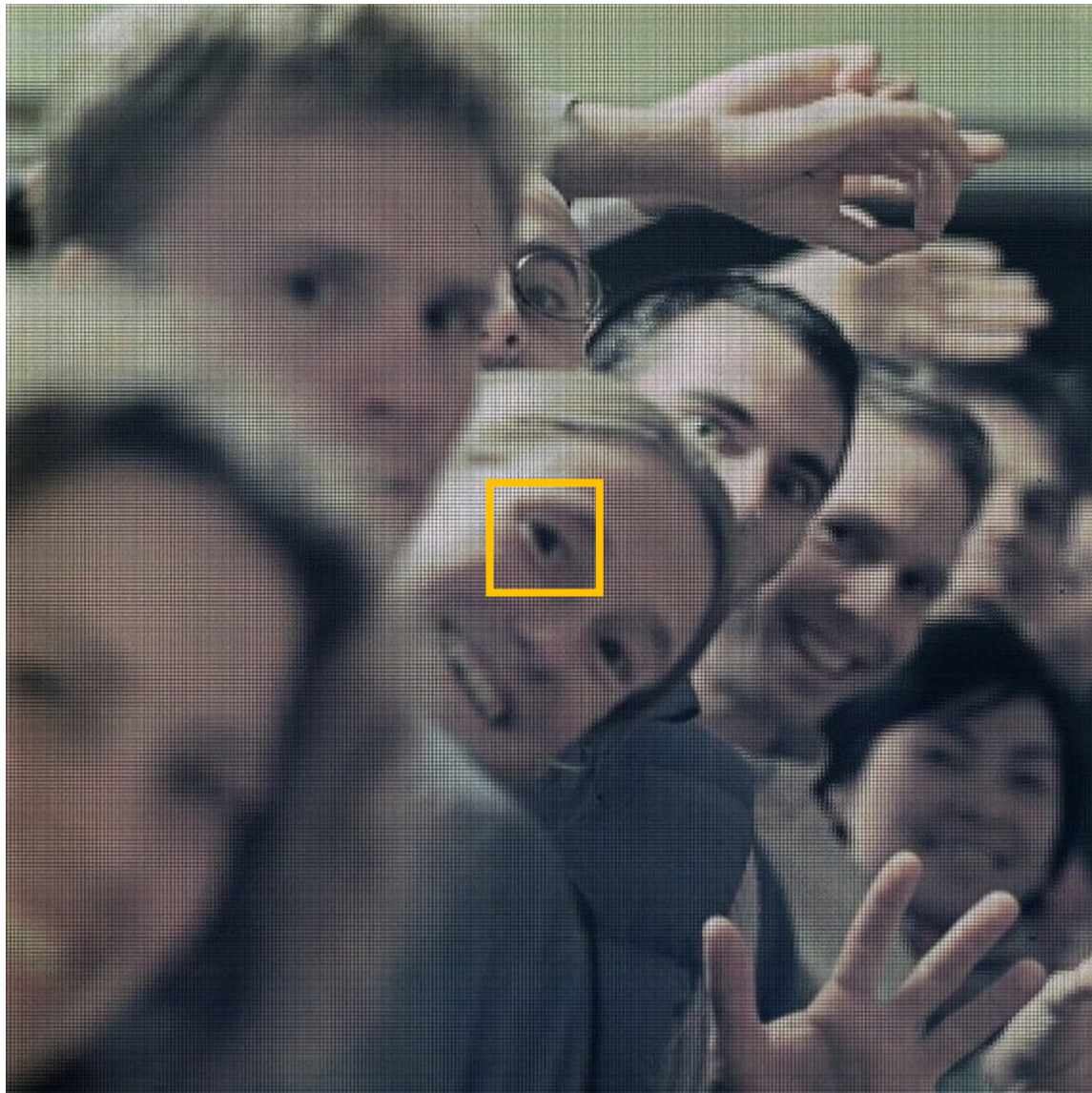
Depth from disparity



Bilateral stereo matching

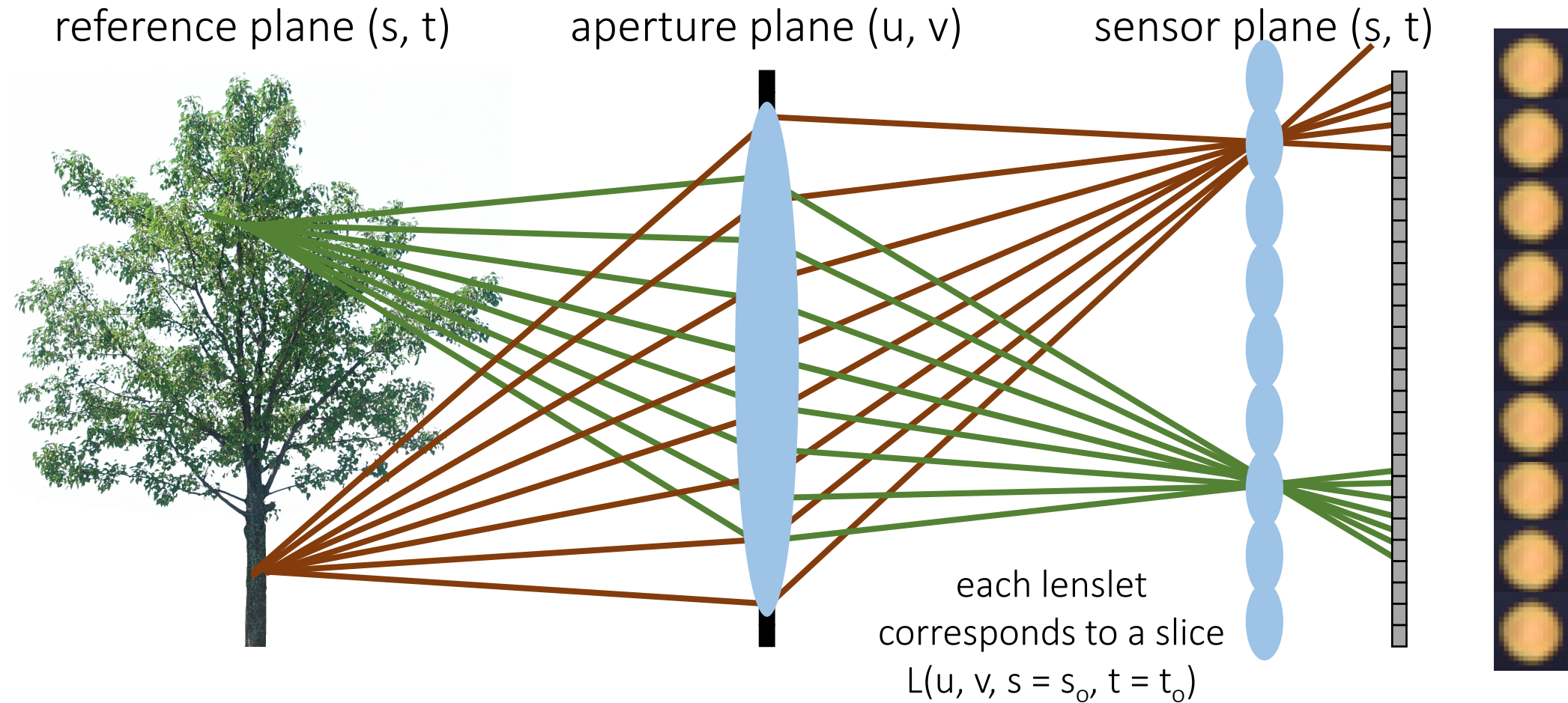
Disparity and lightfields

Reminder: a plenoptic “image”



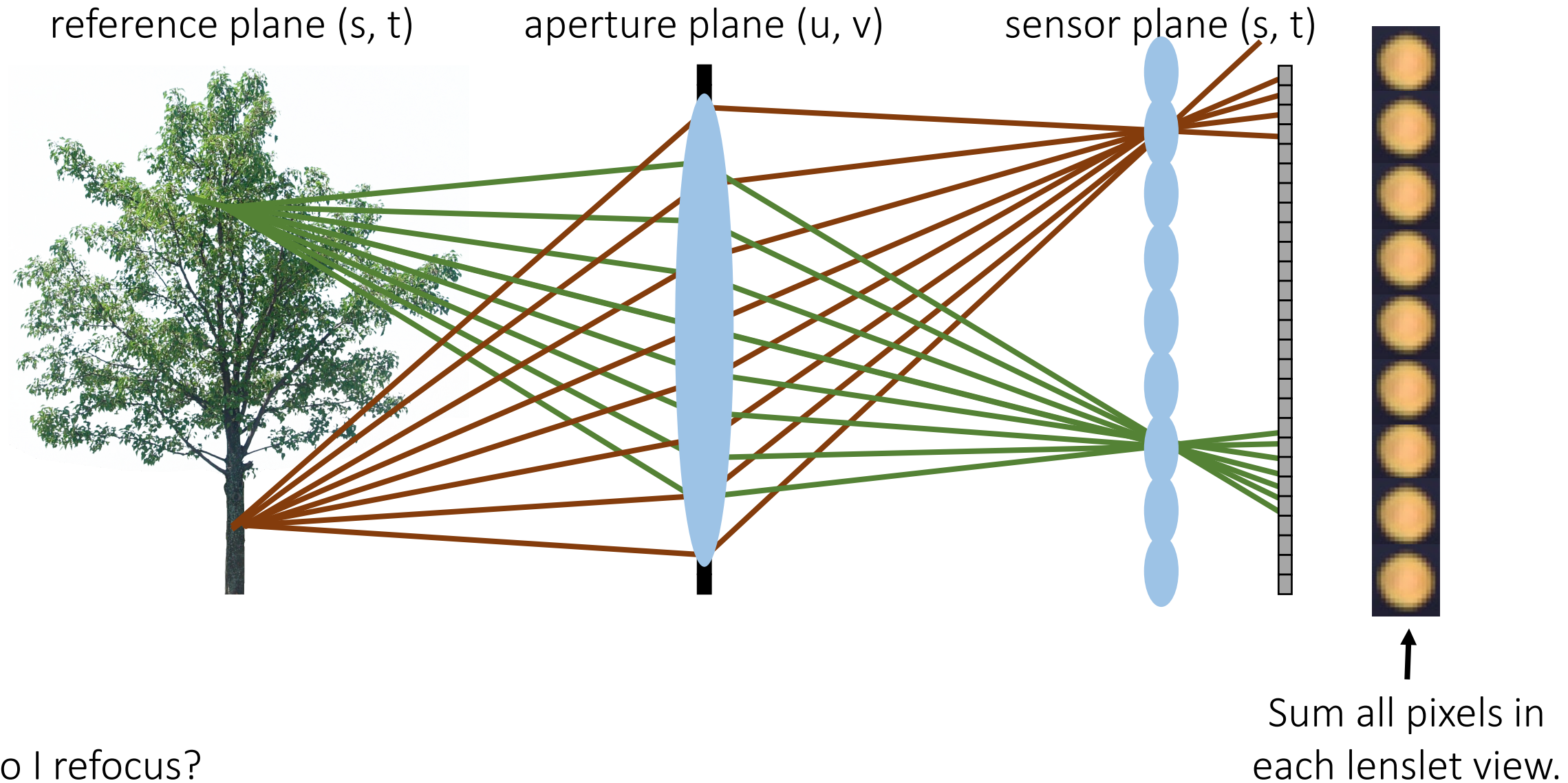
What are these circles?

Reminder: a plenoptic camera

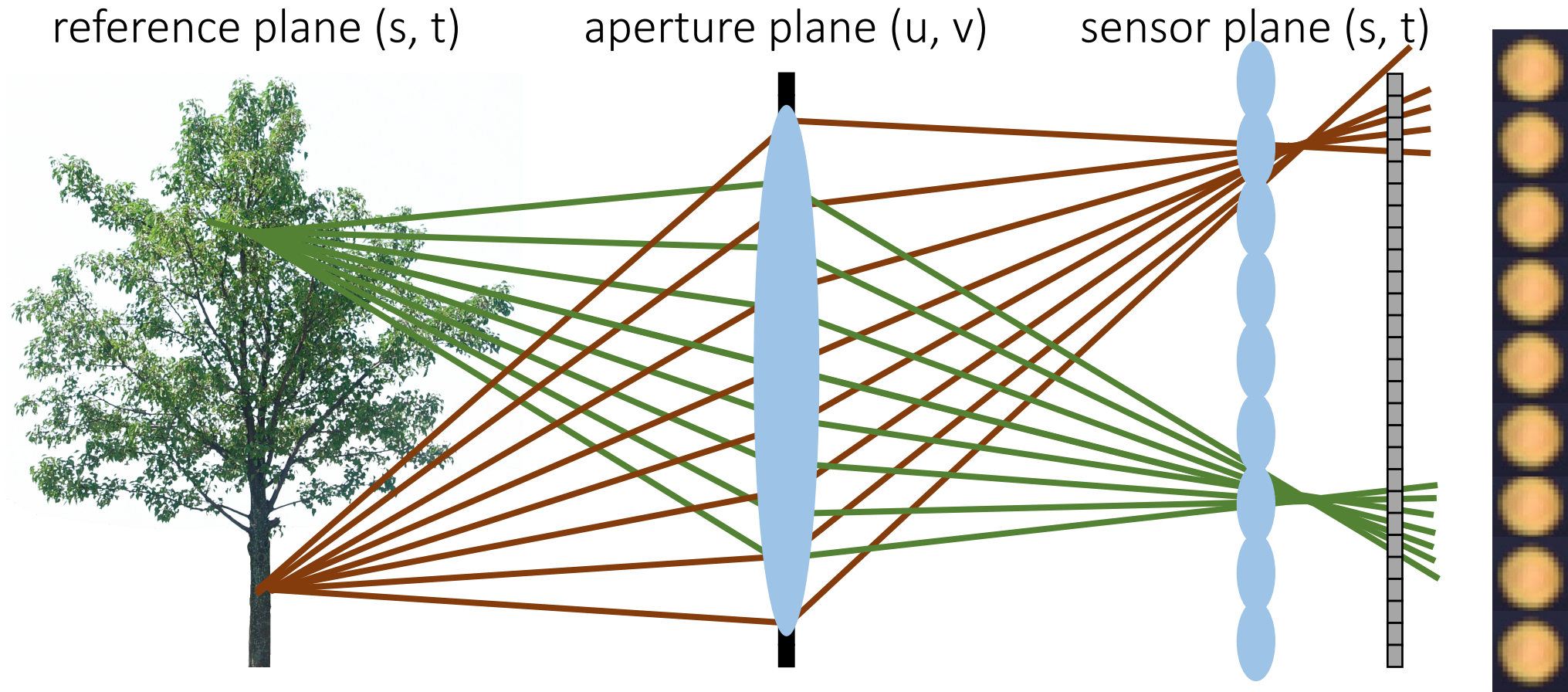


Lightfield $L(u, v, s, t)$

Reminder: form lens image



Reminder: form lens image



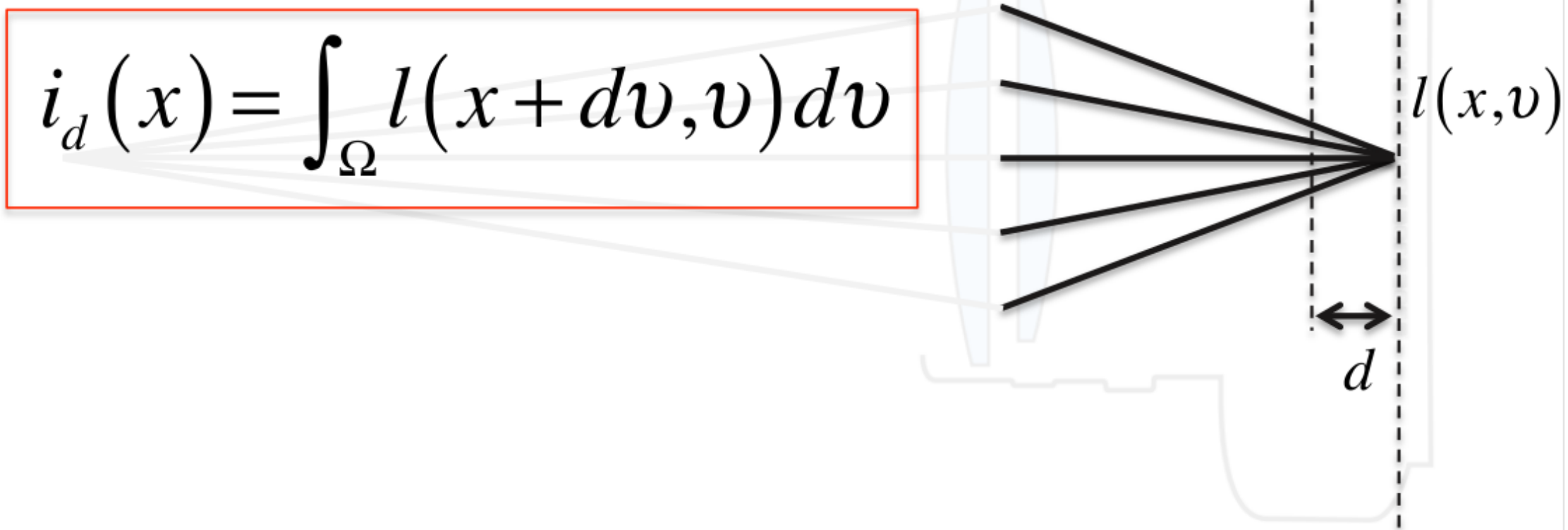
How do I refocus?

- Need to move sensor plane to a different location.

↑
Sum all pixels in
each lenslet view.

Understanding Refocus

- consider light field inside camera
- synthesize image on sensor $i_{d=0}(x) = \int_{\Omega} l(x, v) dv$

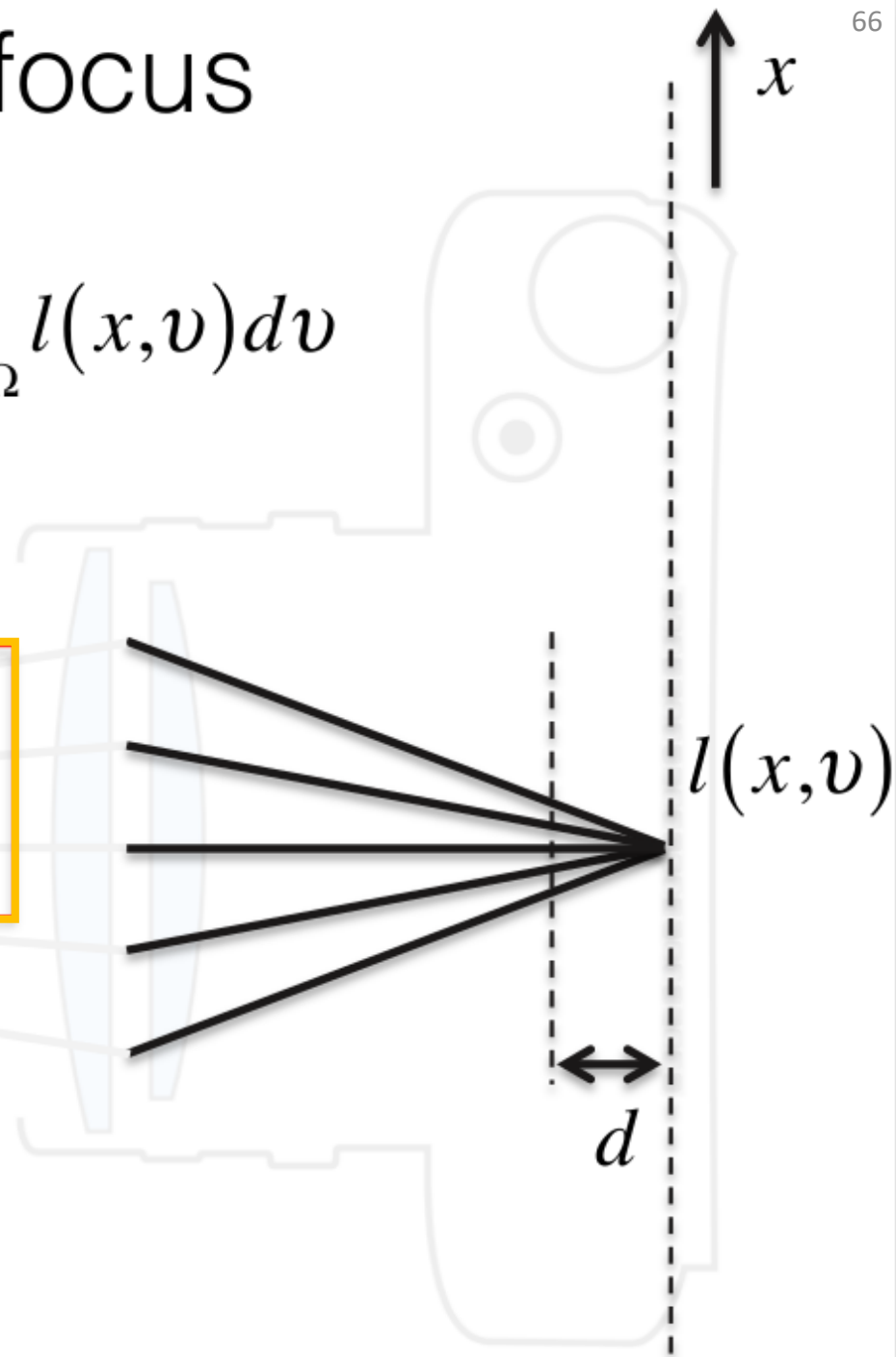


Understanding Refocus

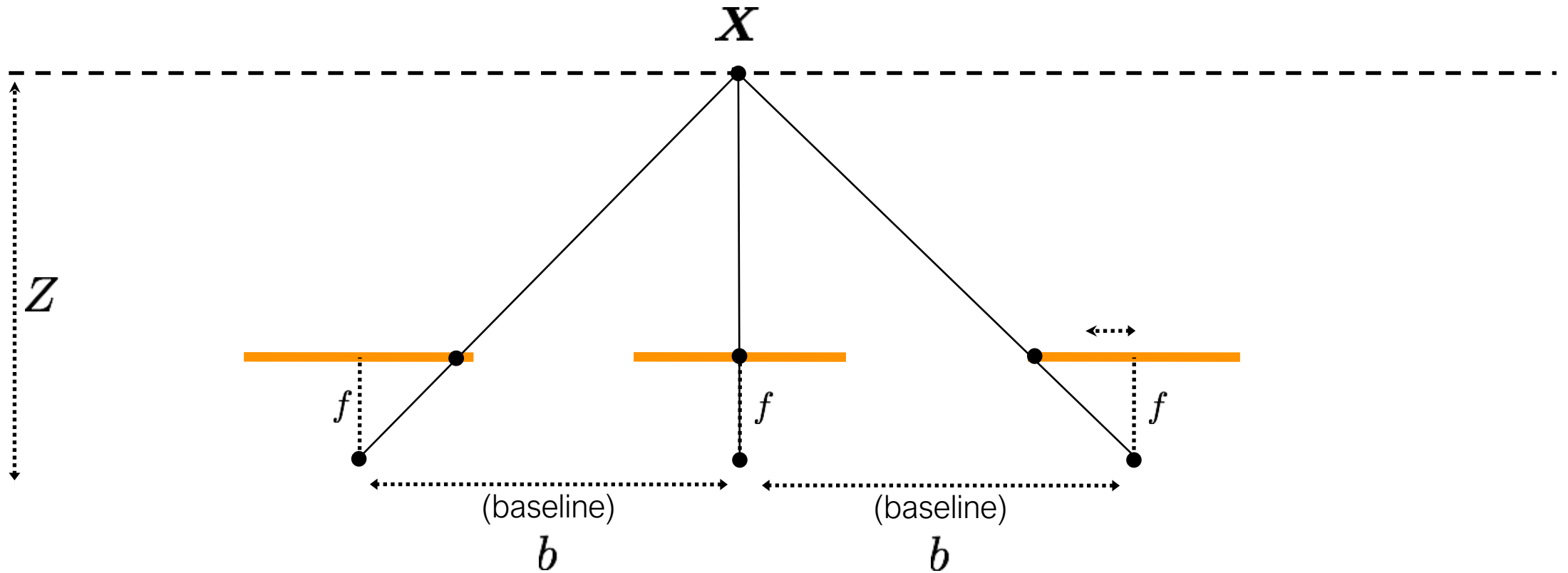
- consider light field inside camera
- synthesize image on sensor $i_{d=0}(x) = \int_{\Omega} l(x, v) dv$

$$i_d(x) = \int_{\Omega} l(x + dv, v) dv$$

Where did this equation come from?

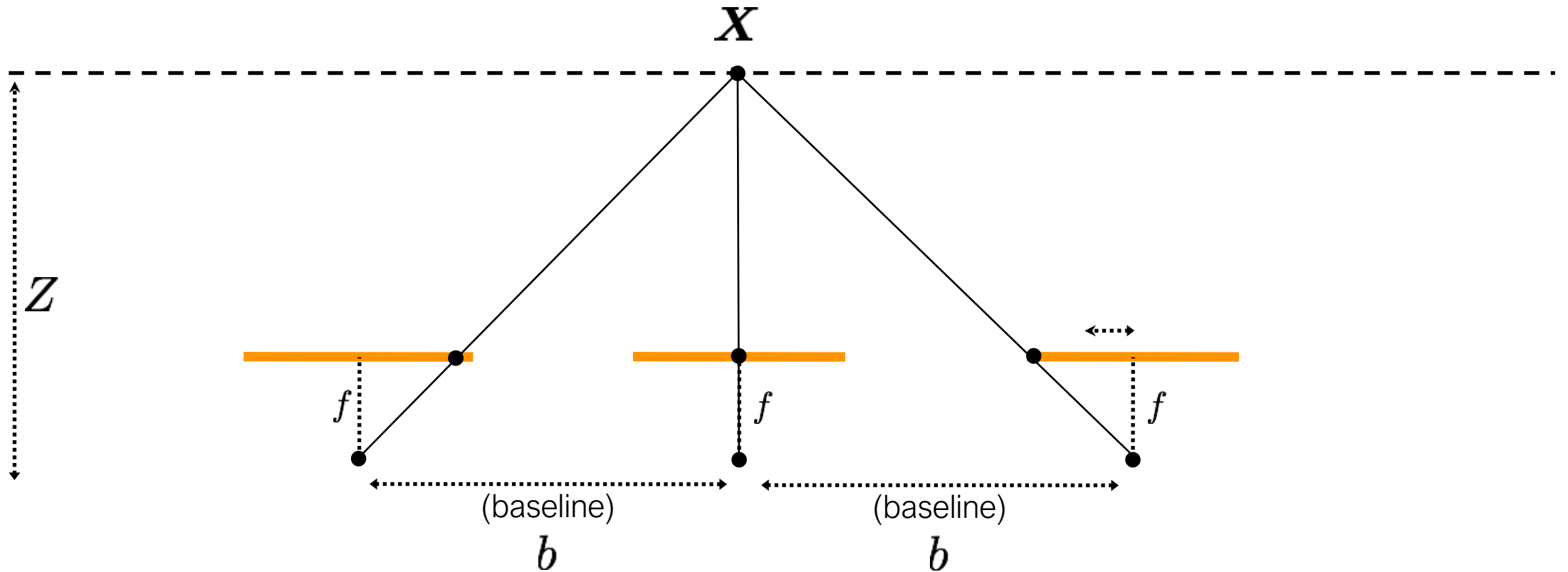


Stereo view of a lightfield camera



What are the different “cameras” in the lightfield case?

Stereo view of a lightfield camera

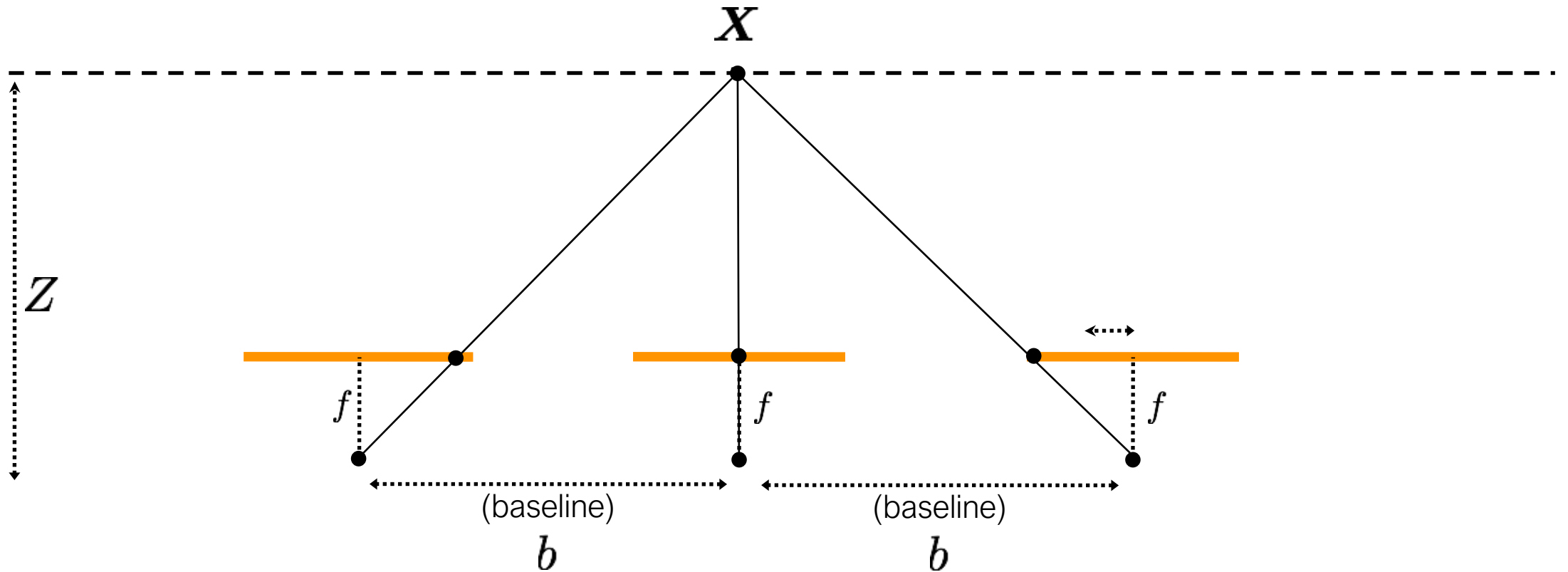


What are the different “cameras” in the lightfield case?

- Different aperture views $L(u = u_o, v = v_o, s, t)$.

By how much do I need to shift each aperture to focus (i.e., *align*) at depth Z ?

Stereo view of a lightfield camera



What are the different “cameras” in the lightfield case?

- Different aperture views $L(u = u_o, v = v_o, s, t)$.

By how much do I need to shift each aperture to focus (i.e., *align*) at depth Z ?

- By an amount equal to the disparity relative to the center view for depth Z .

Refocusing example



Refocusing example



Refocusing example

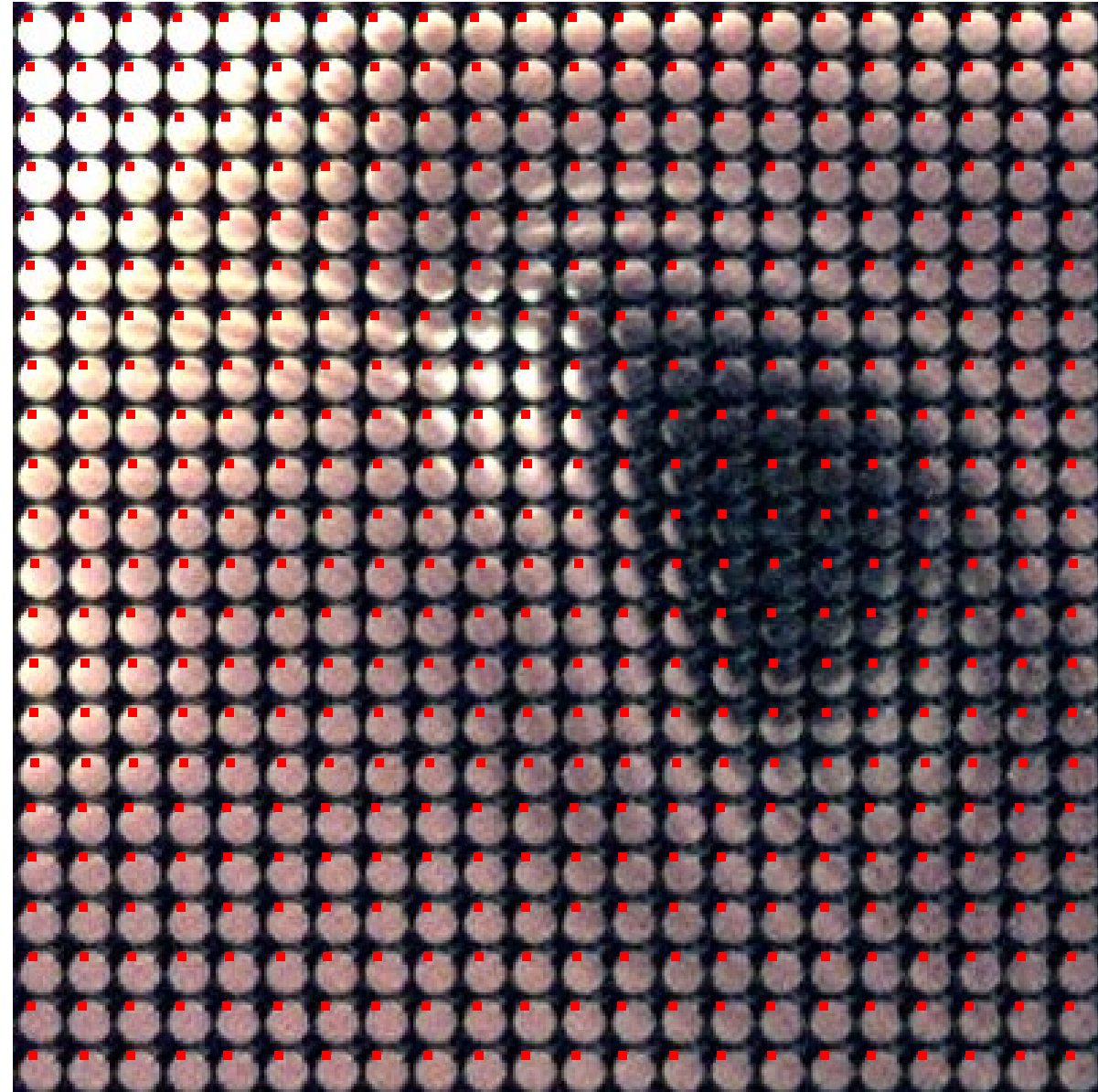


3D from lightfield

Simulate different viewpoints?

- Pick same pixel within each aperture view

Can we use different viewpoints for stereo?



3D from lightfield

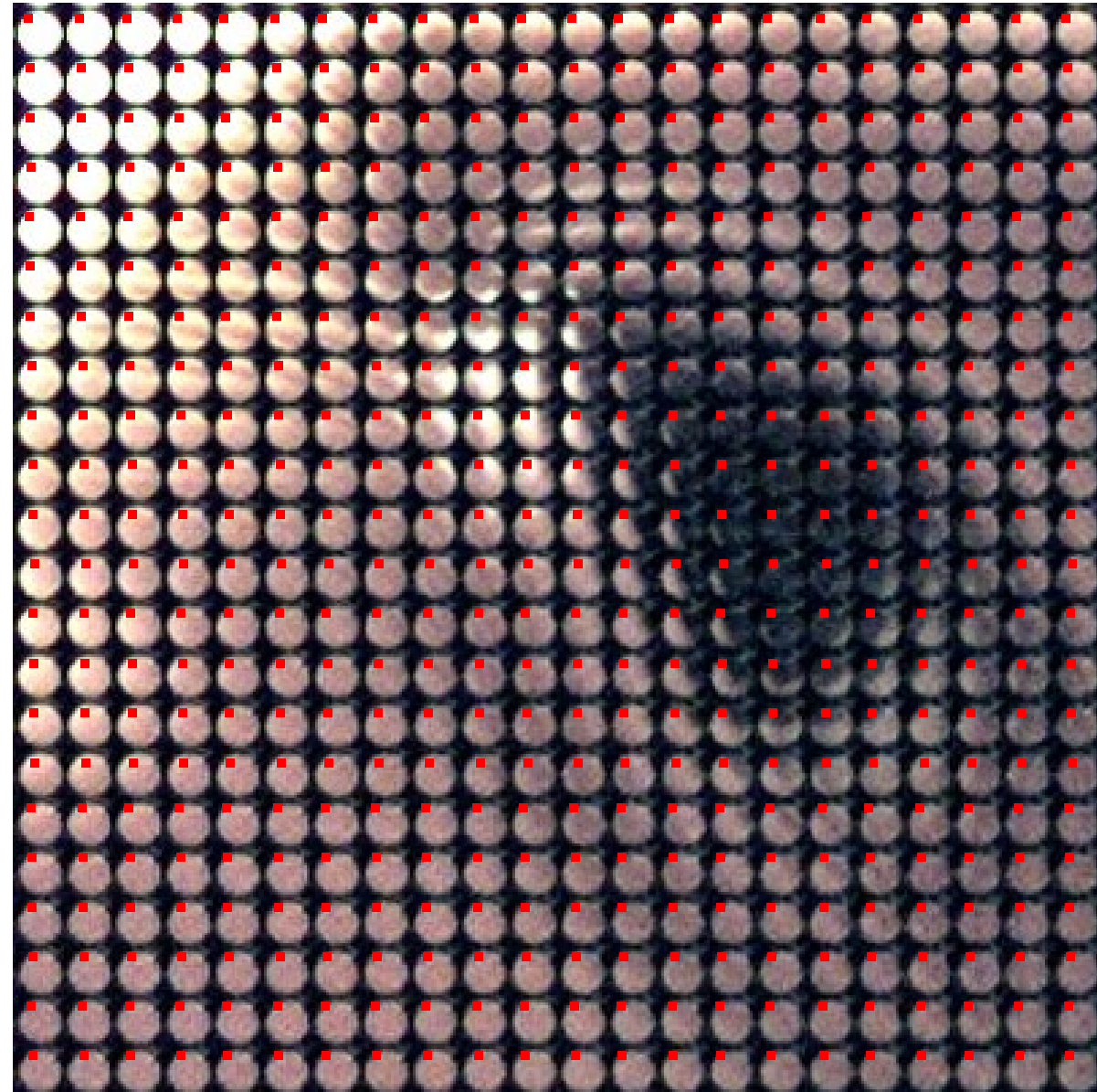
Simulate different viewpoints?

- Pick same pixel within each aperture view

Can we use different viewpoints for stereo?

- Very small baseline to use disparity algorithm.
- Standard algorithm only works with two views.

Can we do something better?



3D from lightfield

Simulate different viewpoints?

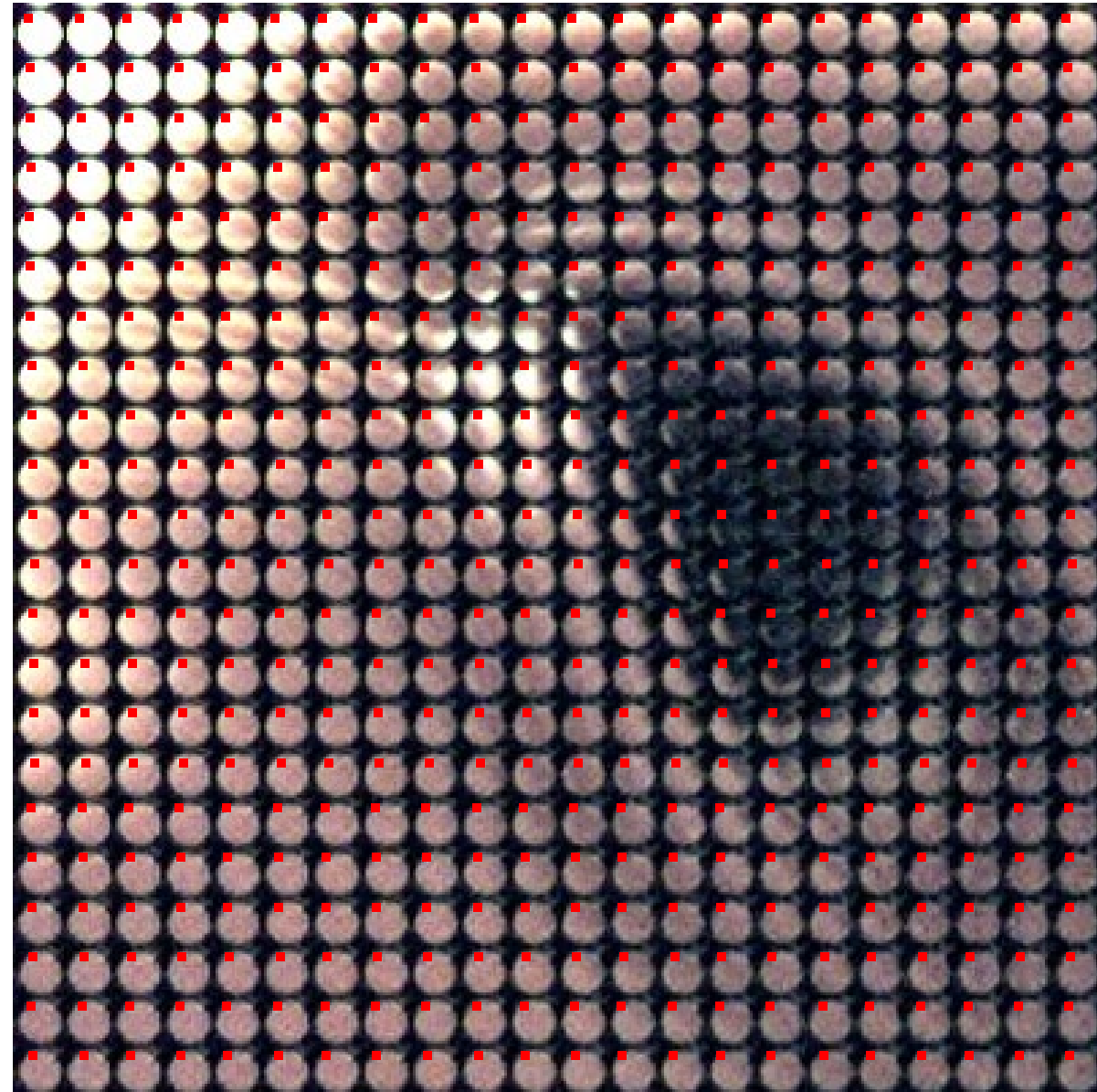
- Pick same pixel within each aperture view

Can we use different viewpoints for stereo?

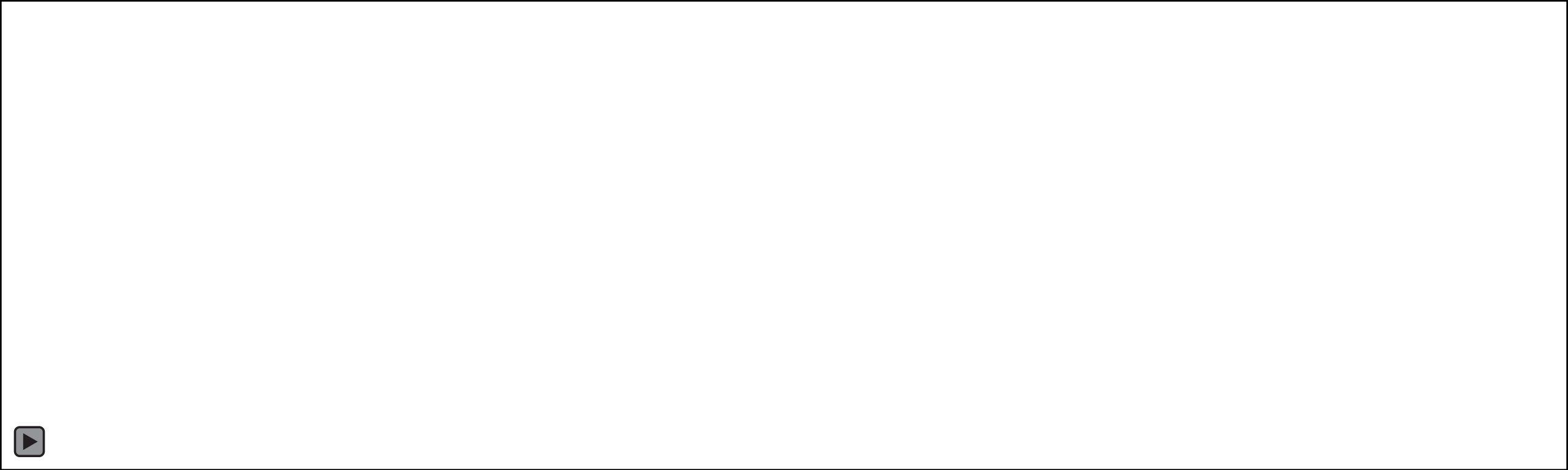
- Very small baseline to use disparity algorithm.
- Standard algorithm only works with two views.

Can we do something better?

- Take advantage of *dense* set of views.
- Use disparity to explain changes in views.

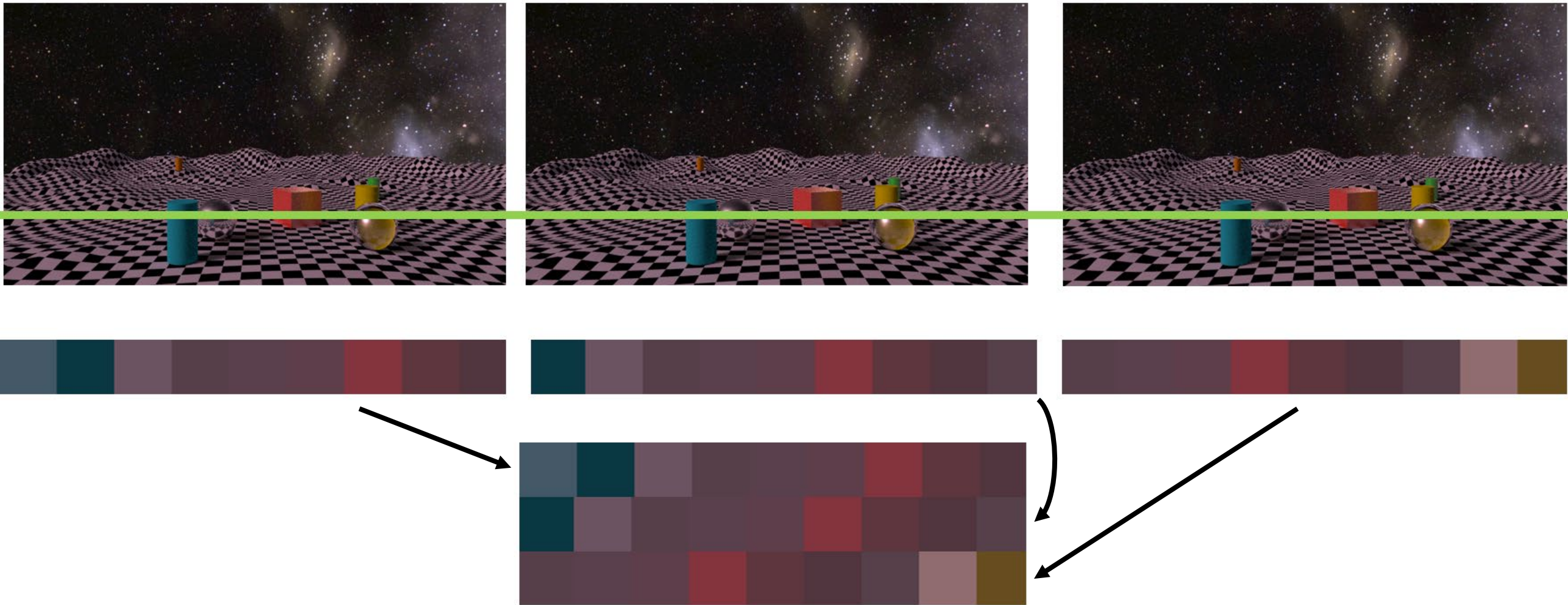


Epipolar plane images (EPIs)



Use lightfield to synthesize images for all aperture views on a horizontal line (*scanline*).

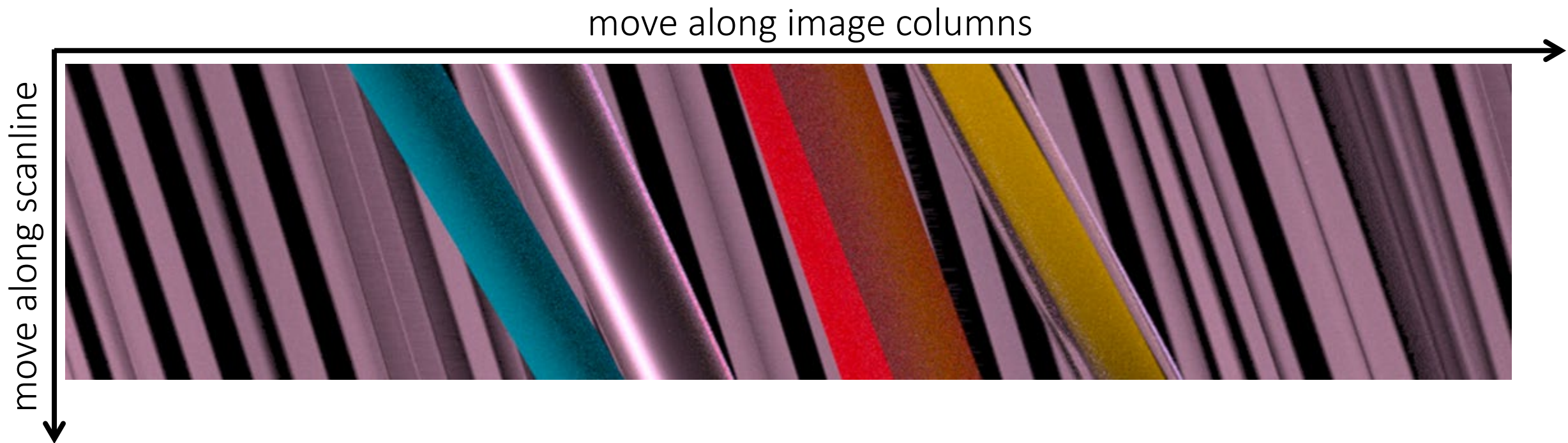
Epipolar plane images (EPIs)



Take the same row out of all images in a scanline, and stack these rows in a new 2D image.

Epipolar plane images (EPIs)

Why do we see straight lines?



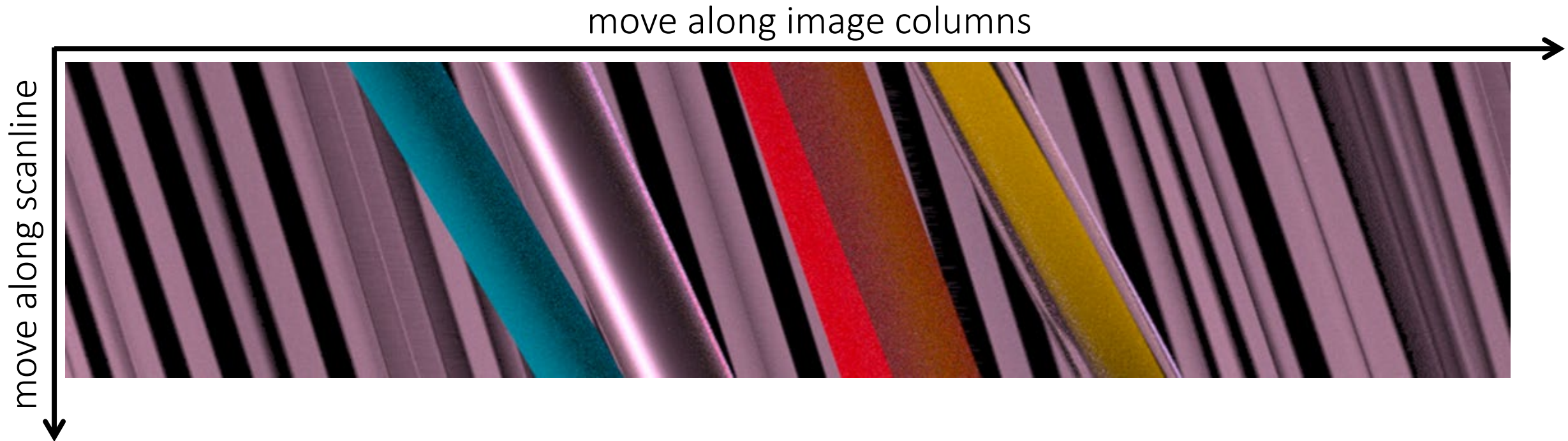
Take the same row out of all images in a scanline, and stack these rows in a new 2D image.

Epipolar plane images (EPIs)

Why do we see straight lines?

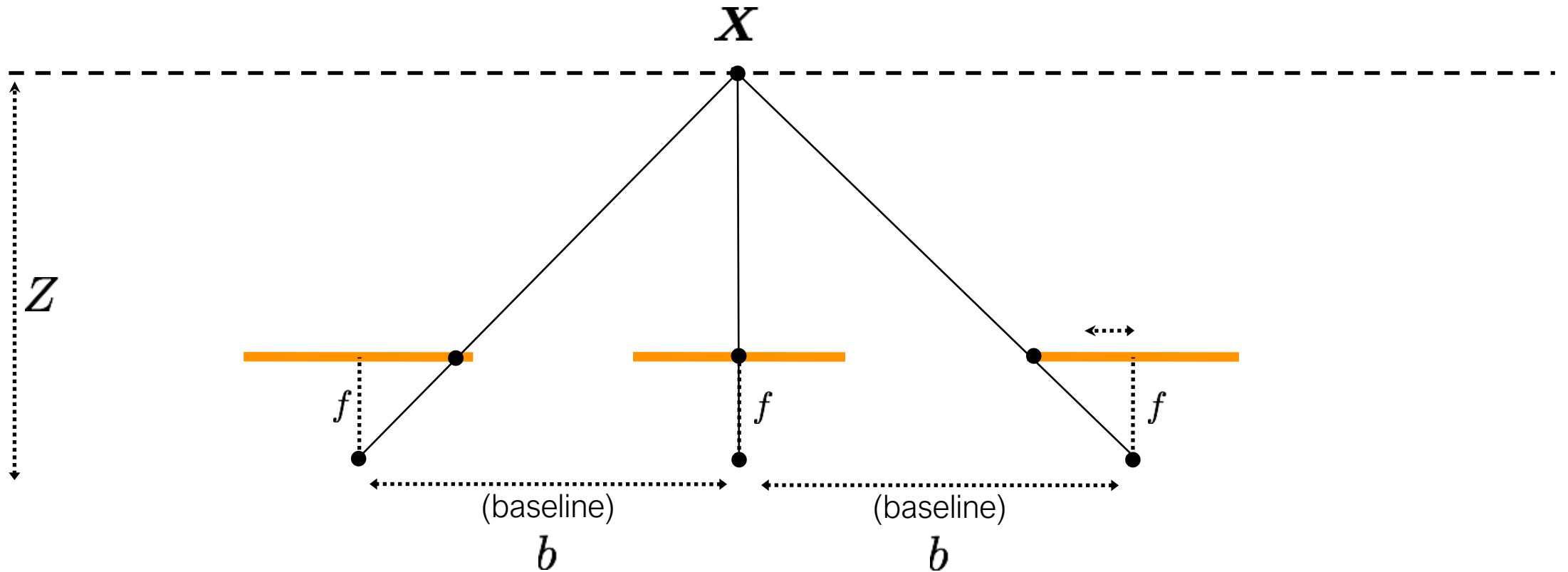
- Same 3D point changes location as viewpoint changes (i.e., *disparity*).

What does the slope of each line correspond to?



Take the same row out of all images in a scanline, and stack these rows in a new 2D image.

Stereo view of a lightfield camera



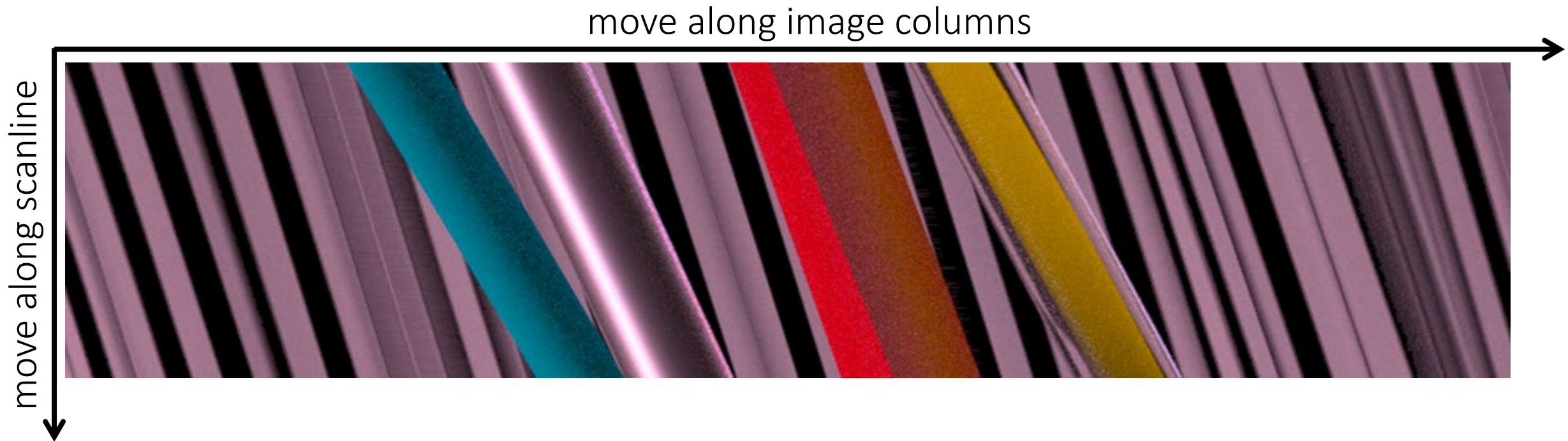
Disparity relationship:

$$d = x - x' \\ = \frac{bf}{Z}$$

- Changing baseline b corresponds to moving along the scanline.
- Projections x of X are on a line of slope inversely proportional to depth.

Epipolar plane images (EPIs)

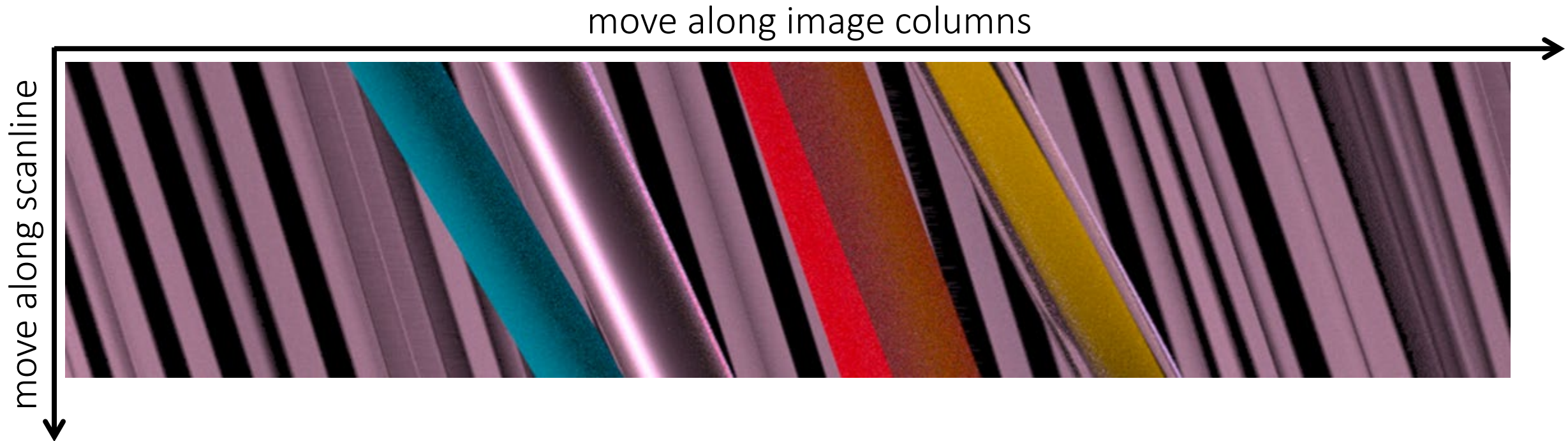
Per-pixel depth detection through line fitting and slope estimation.



Take the same row out of all images in a scanline, and stack these rows in a new 2D image.

Epipolar plane images (EPIs)

Per-pixel depth detection through line fitting and slope estimation.



Take the same row out of all images in a scanline, and stack these rows in a new 2D image.

Epipolar plane images (EPIs)

Scene Reconstruction from High Spatio-Angular Resolution Light Fields

Changil Kim^{1,2}

Henning Zimmer^{1,2}

Yael Pritch¹

Alexander Sorkine-Hornung¹

Markus Gross^{1,2}

¹Disney Research Zurich

²ETH Zurich

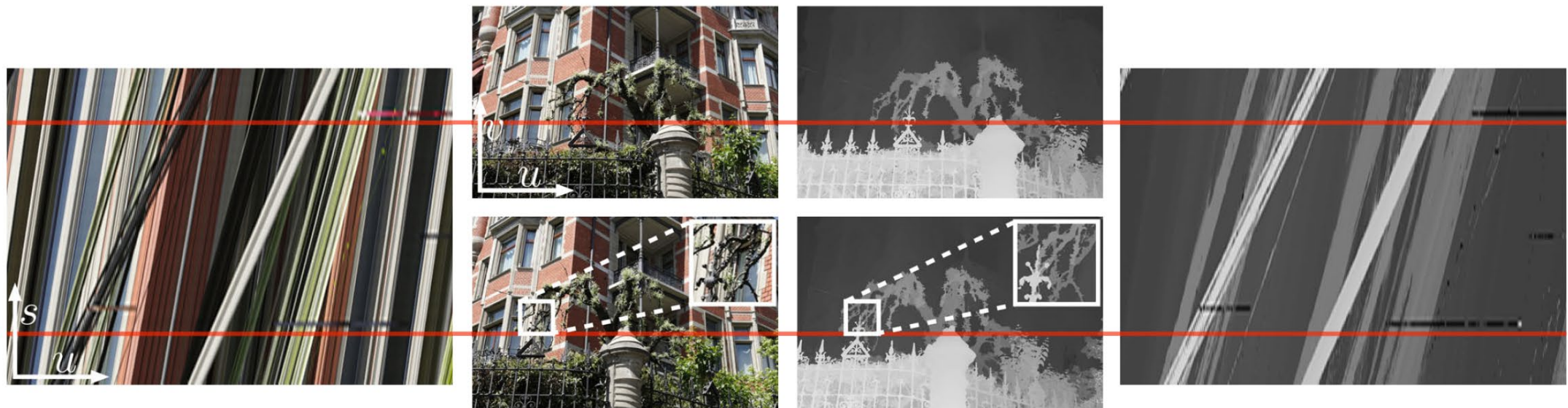
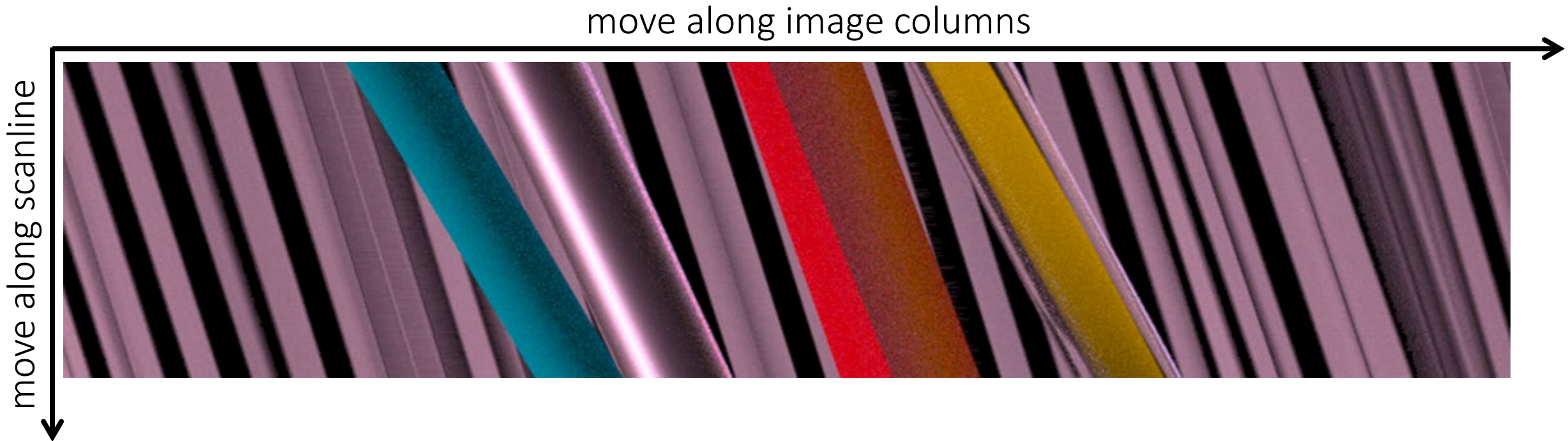


Figure 1: Our method reconstructs accurate depth from light fields of complex scenes. The images on the left show a 2D slice of a 3D input light field, a so called epipolar-plane image (EPI), and two out of one hundred 21 megapixel images that were used to construct the light field. Our method computes 3D depth information for all visible scene points, illustrated by the depth EPI on the right. From this representation, individual depth maps or segmentation masks for any of the input views can be extracted as well as other representations like 3D point clouds. The horizontal red lines connect corresponding scanlines in the images with their respective position in the EPI.

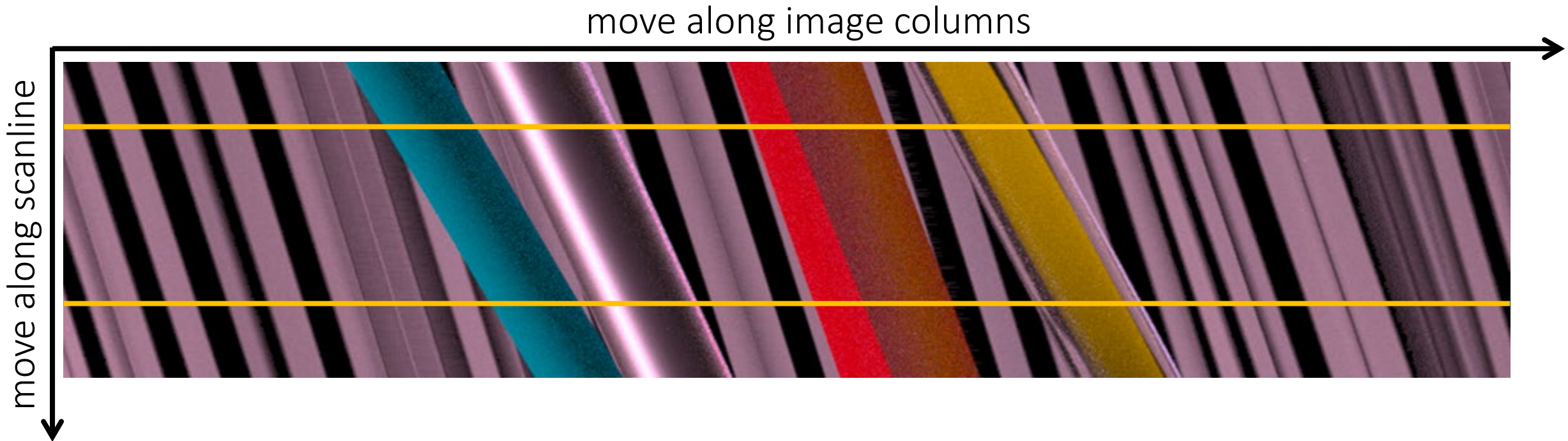
Aside: different types of cameras

What part of the EPI is captured when we use a stereo pair of cameras?



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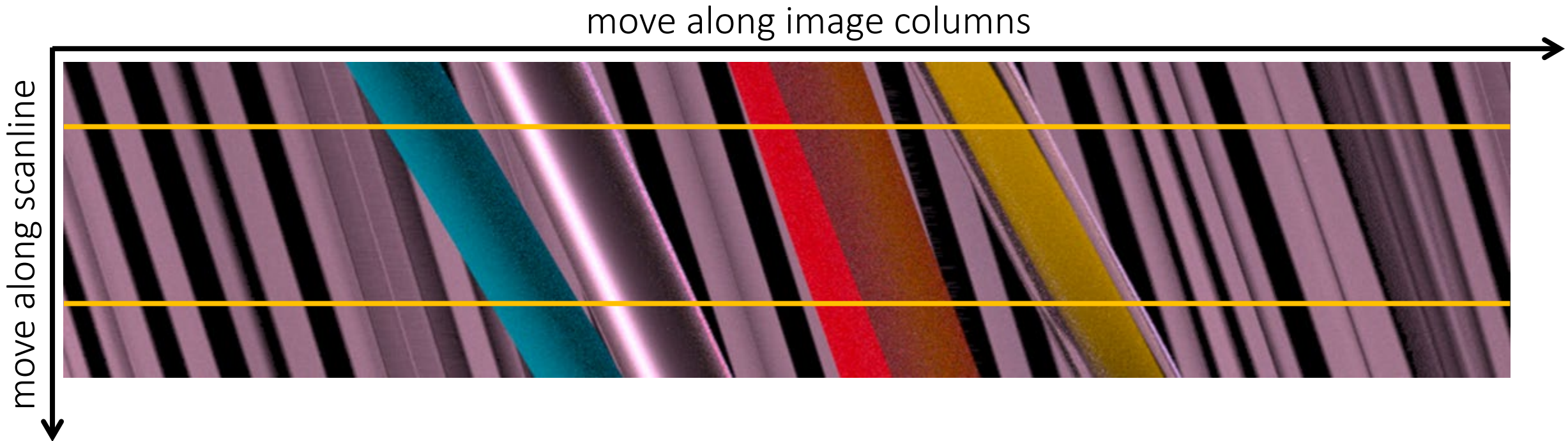


Aside: different types of cameras

What part of the EPI is captured when we use a stereo pair of cameras?

- Two horizontal lines.

When are these two views sufficient to infer depth?



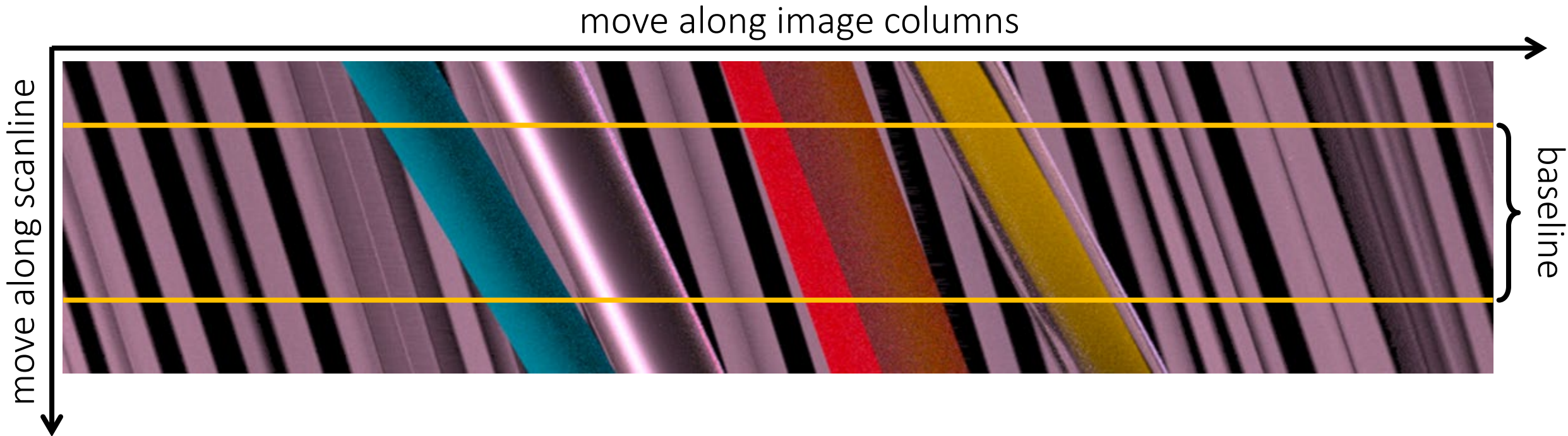
Aside: different types of cameras

What part of the EPI is captured when we use a stereo pair of cameras?

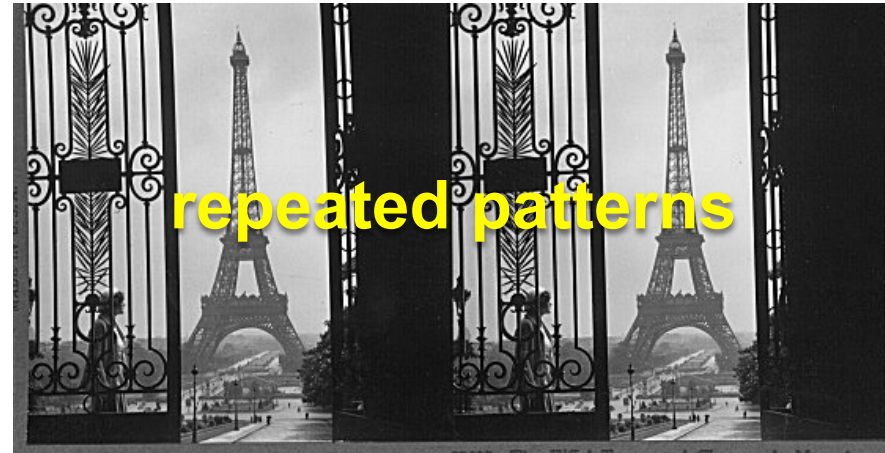
- Two horizontal lines.

When are these two views sufficient to infer depth?

- When their *baseline* is large enough to infer the slope of the lines in EPIs.



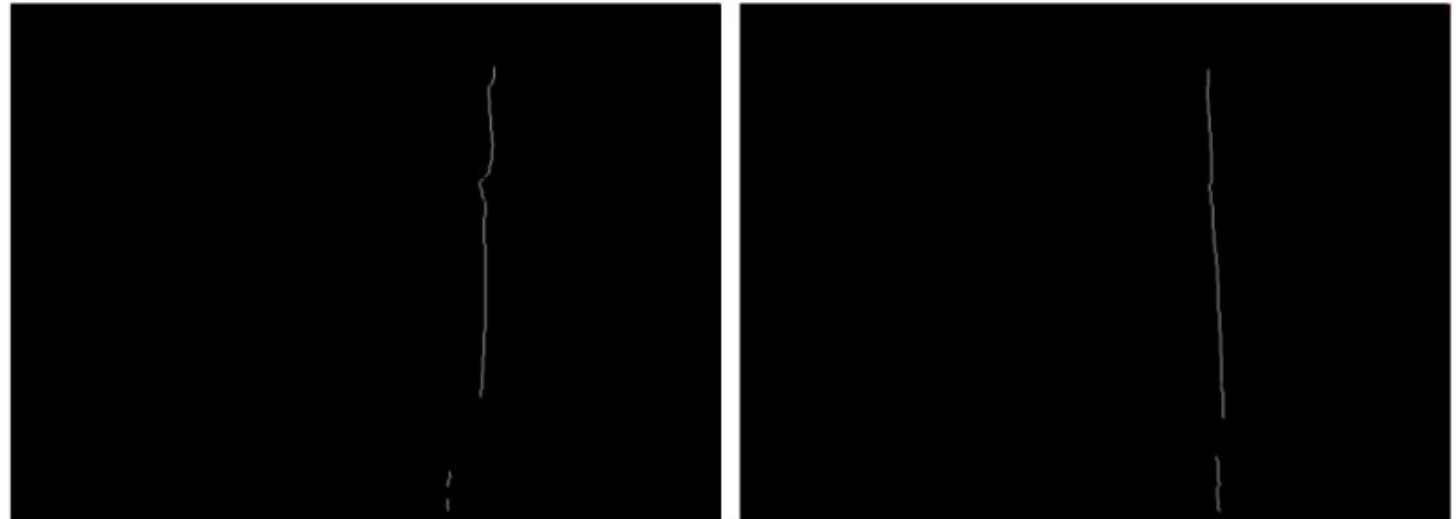
When are correspondences difficult?



Structured light

Use controlled (“structured”) light to make correspondences easier

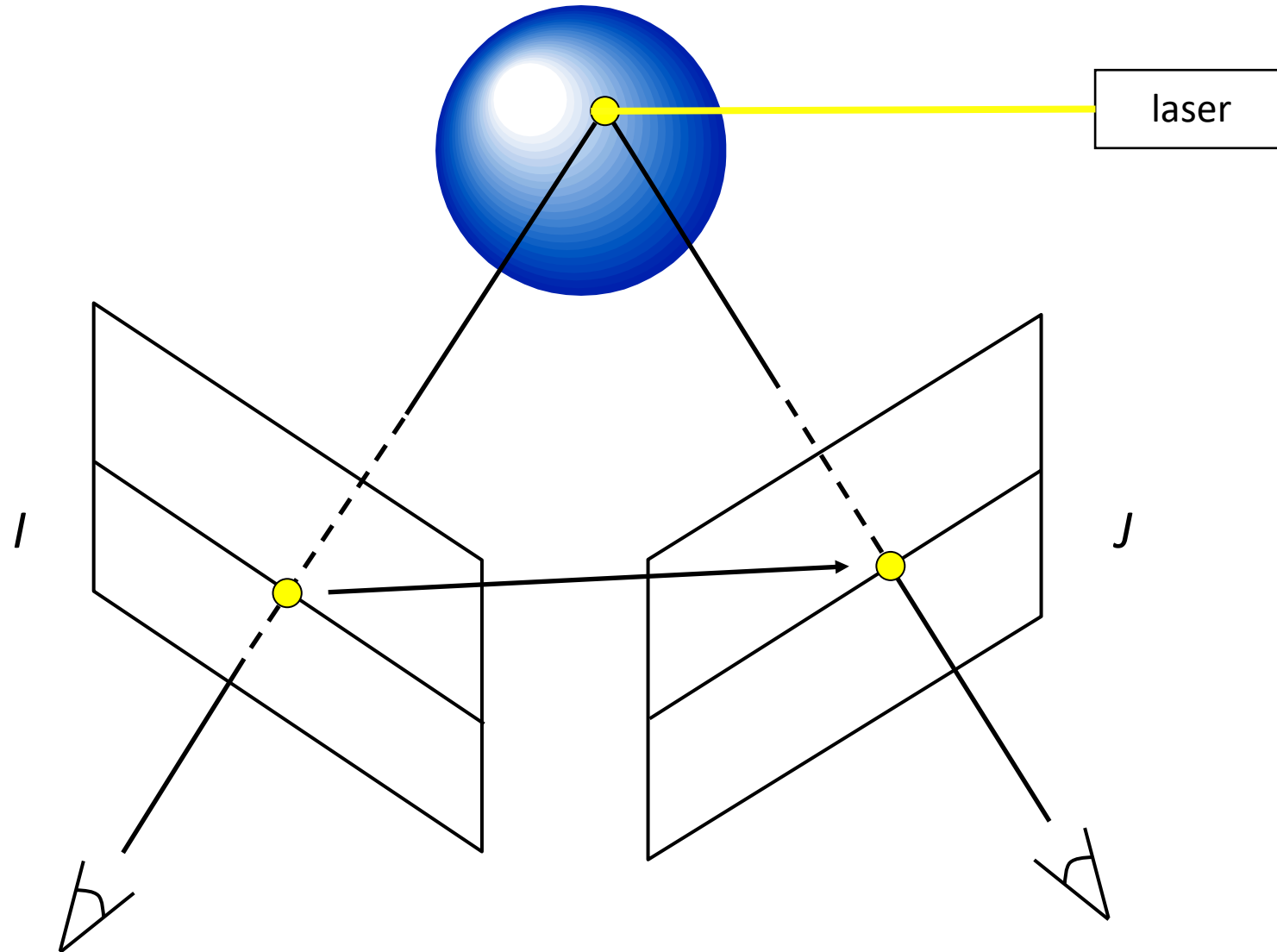
Disparity between laser points on the same scanline in the images determines the 3-D coordinates of the laser point on object



Use controlled (“structured”) light to make correspondences easier

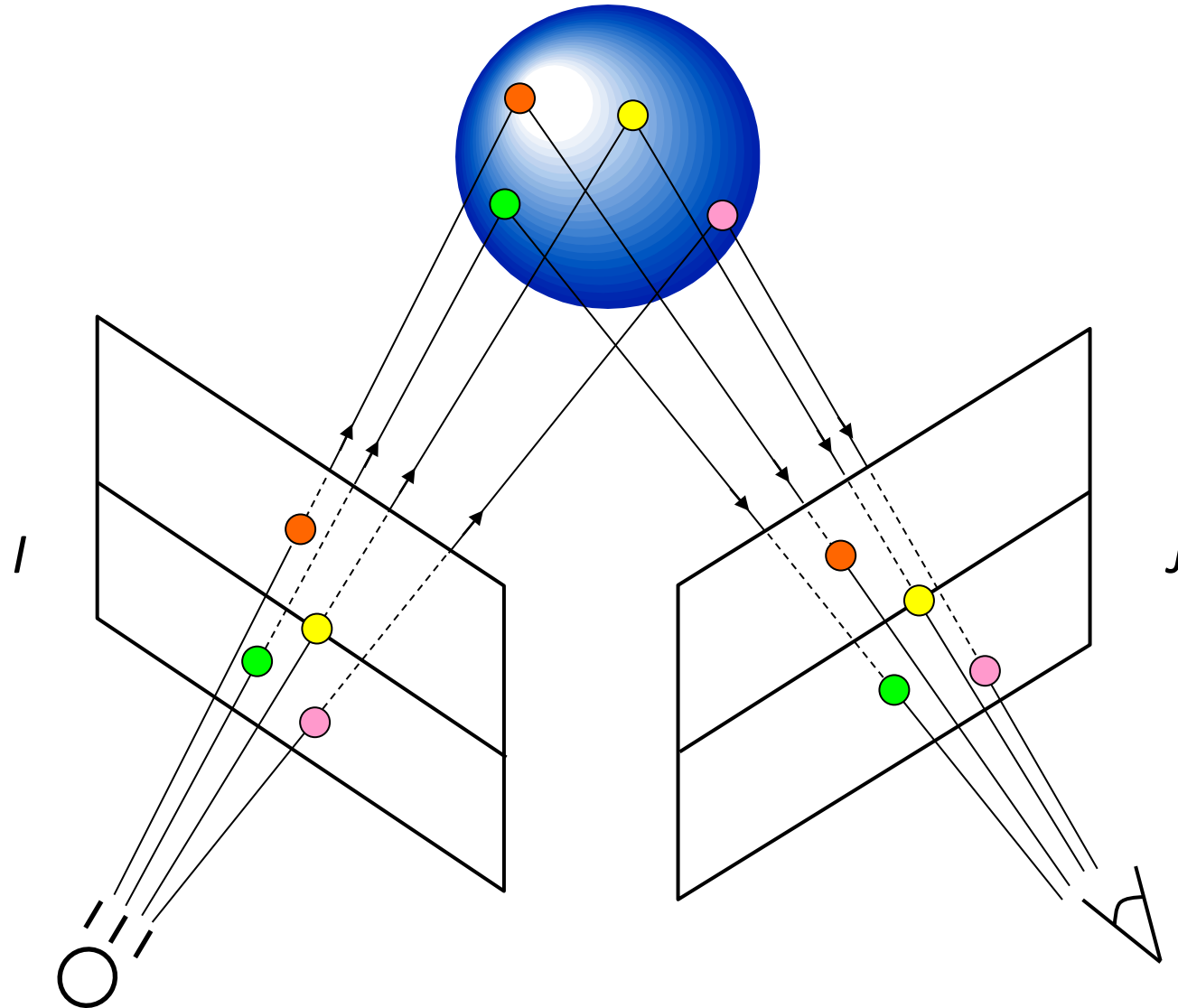


Structured light and two cameras

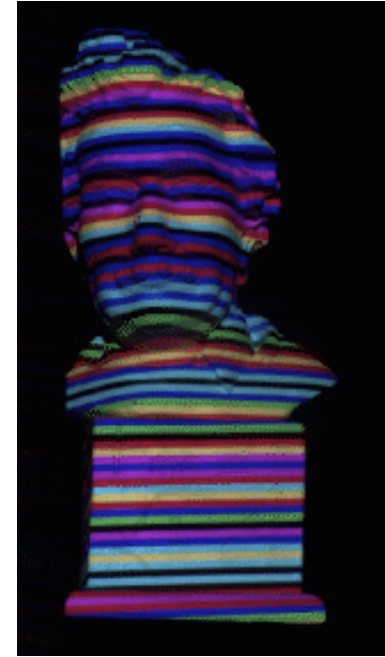


Structured light and one camera

Projector acts like
"reverse" camera

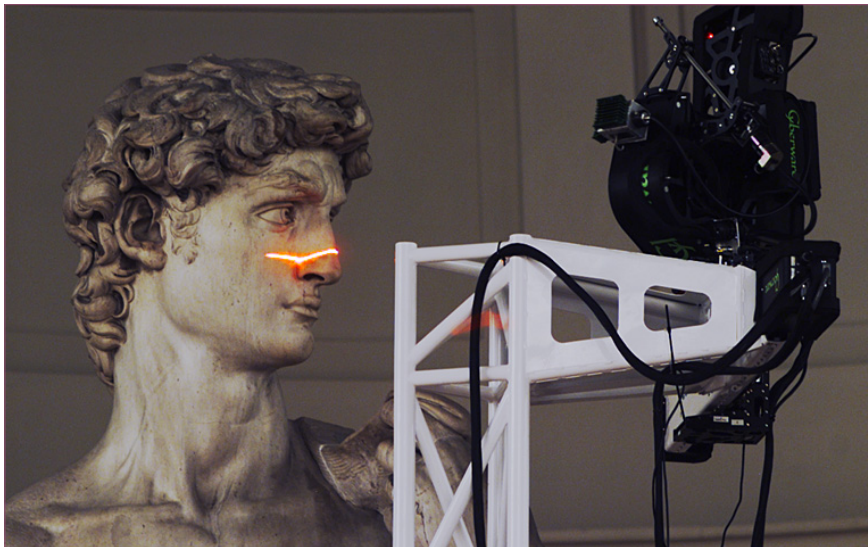


Structured Light



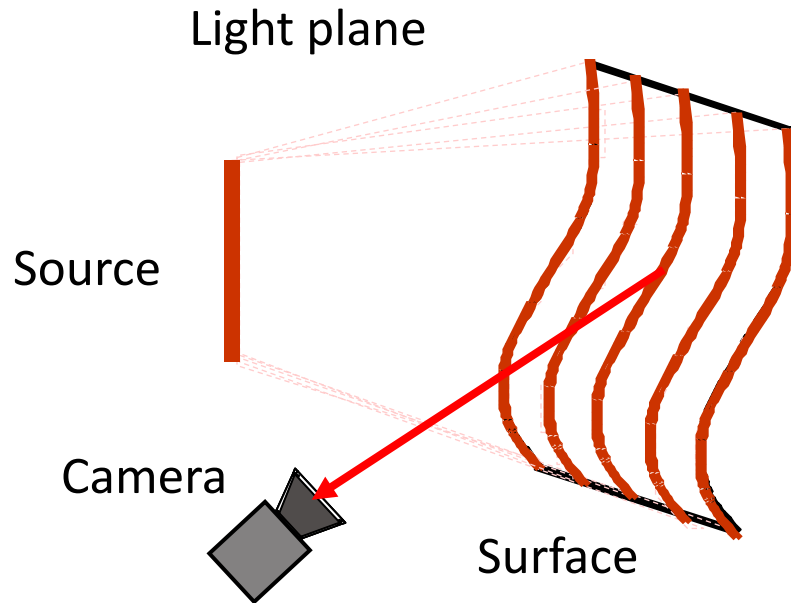
- Any spatio-temporal pattern of light projected on a surface (or volume).
- Cleverly illuminate the scene to extract scene properties (eg., 3D).
- Avoids problems of 3D estimation in scenes with complex texture/BRDFs.
- Very popular in vision and successful in industrial applications (parts assembly, inspection, etc).

3D Scanning using structured light



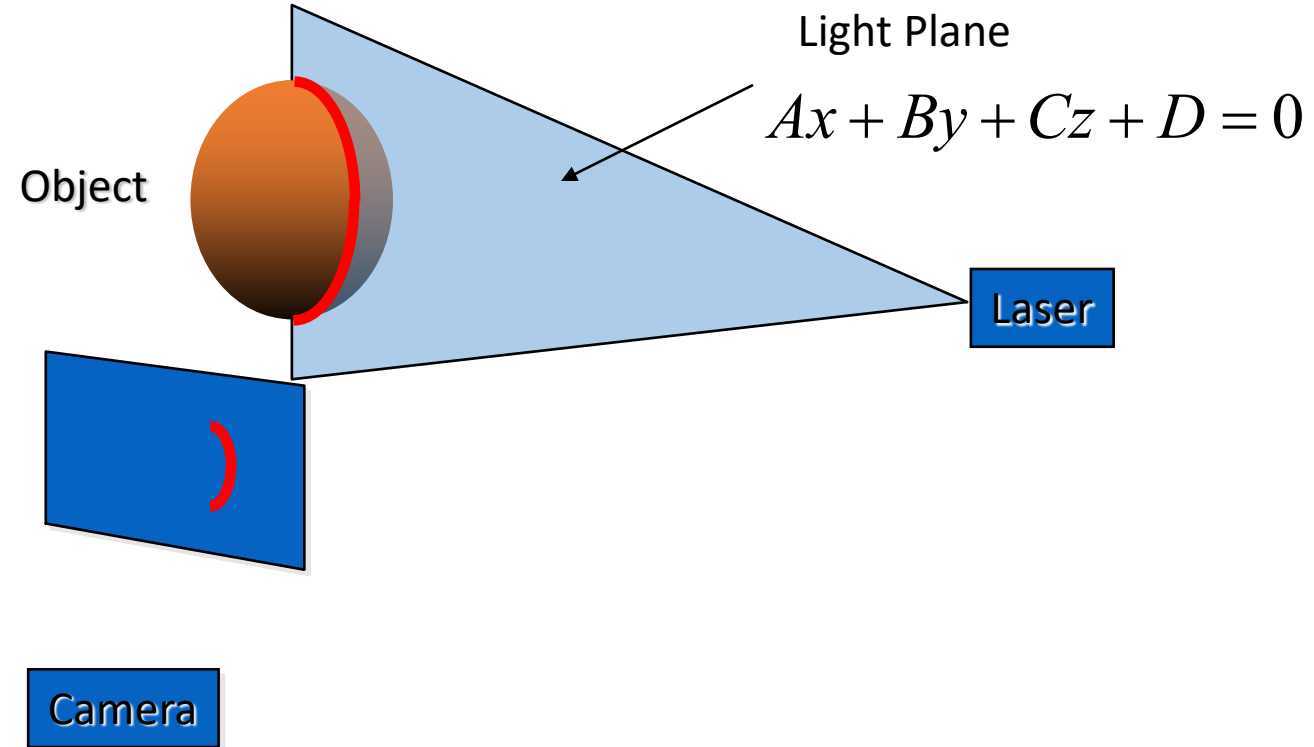
Do we need to illuminate the scene point by point?

Light Stripe Scanning – Single Stripe



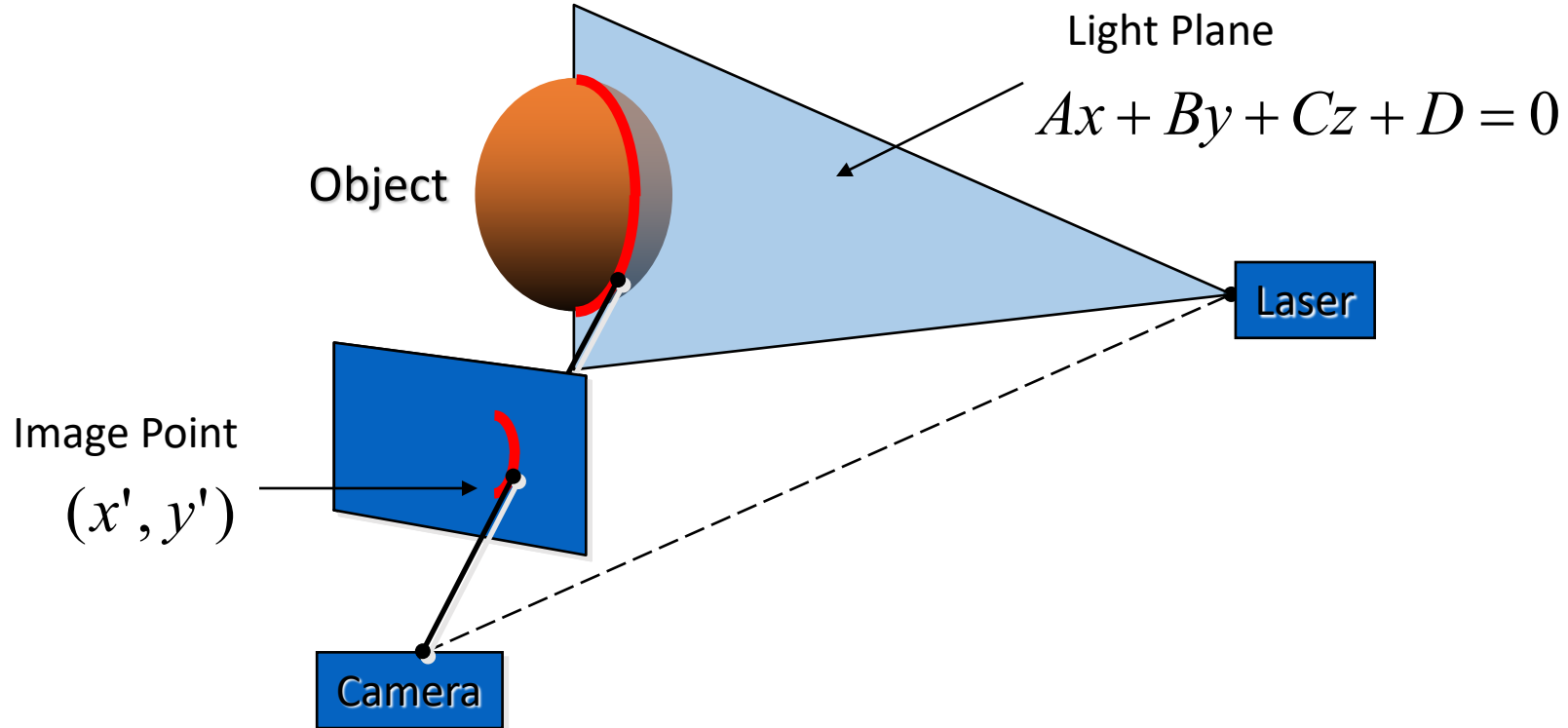
- Faster optical triangulation:
 - Project a single stripe of laser light
 - Scan it across the surface of the object
 - This is a very precise version of structured light scanning
 - Good for high resolution 3D, but still needs many images and takes time

Triangulation



- Project laser stripe onto object

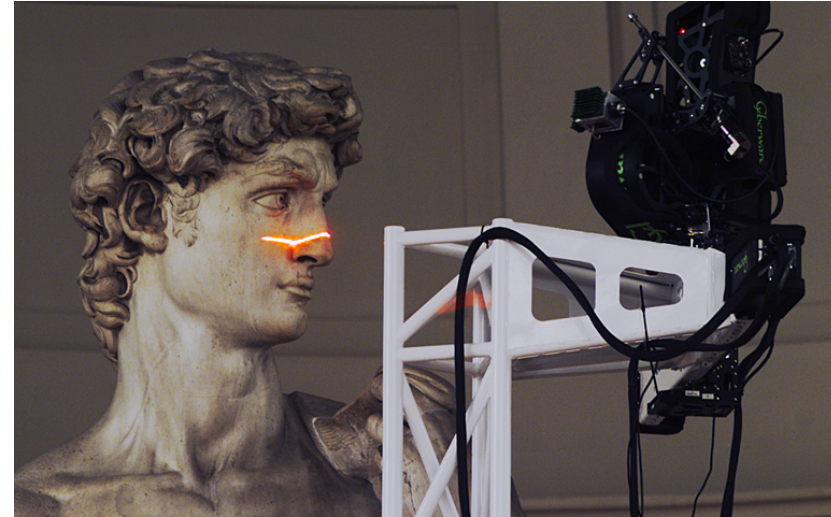
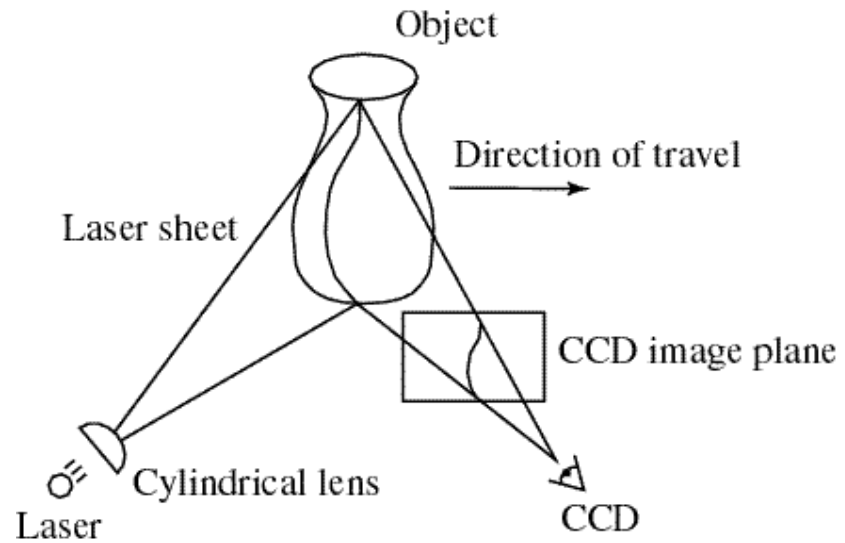
Triangulation



- Depth from ray-plane triangulation:
 - Intersect camera ray with light plane

$$\begin{aligned} x &= x' z / f \\ y &= y' z / f \end{aligned} \quad z = \frac{-Df}{Ax' + By' + Cf}$$

Example: Laser scanner



Digital Michelangelo Project

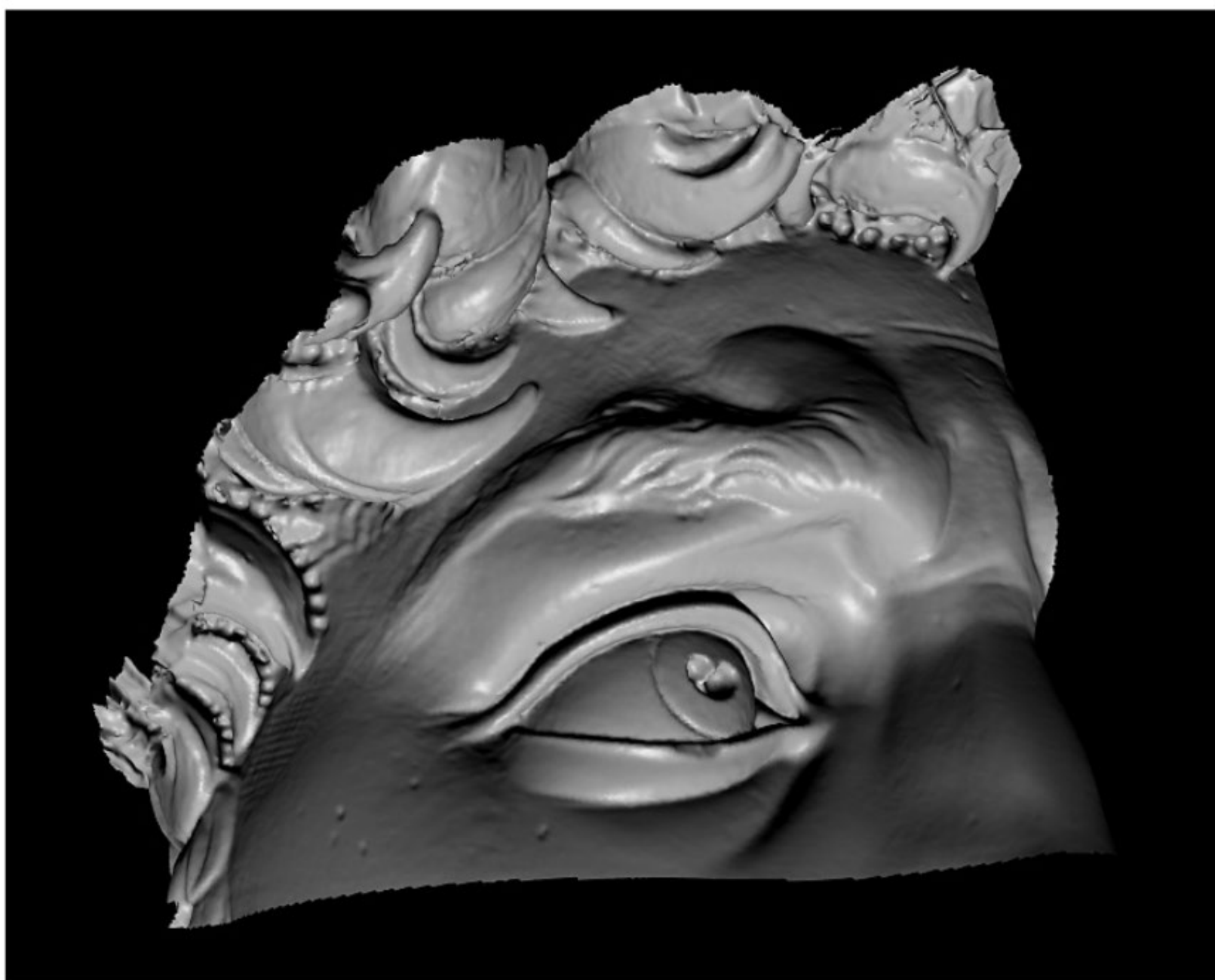
<http://graphics.stanford.edu/projects/mich/>



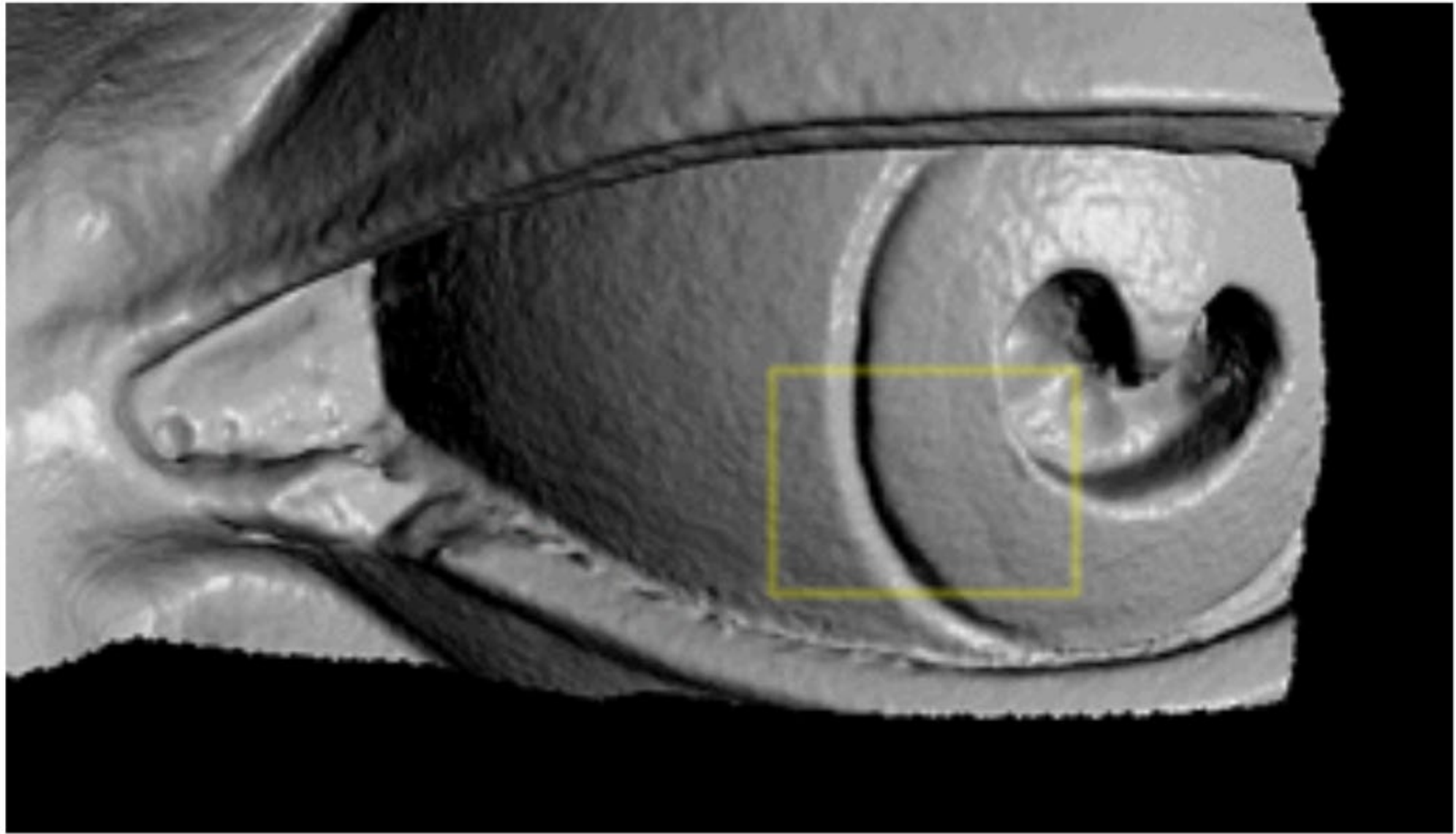
The Digital Michelangelo Project, Levoy et al.



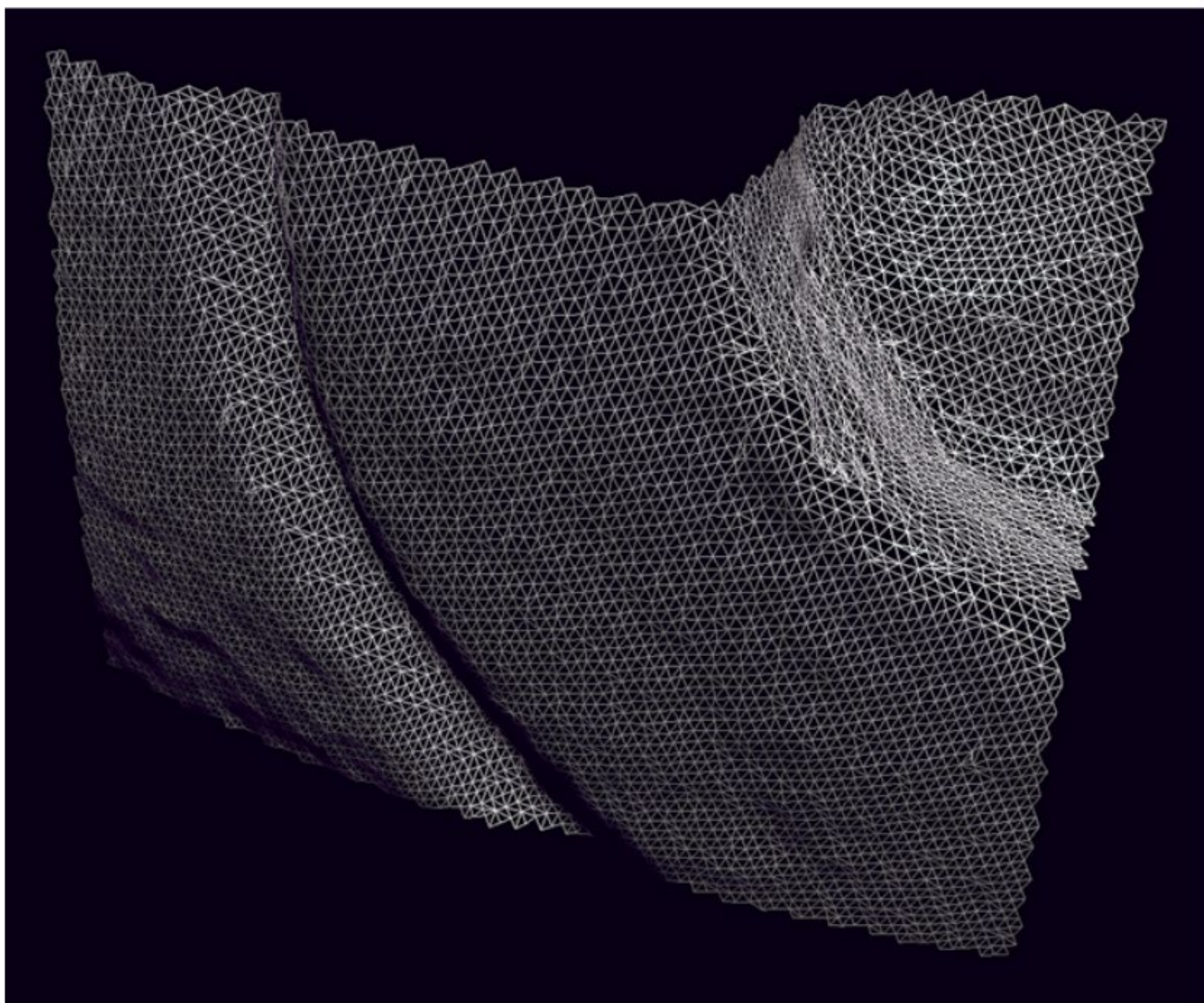
The Digital Michelangelo Project, Levoy et al.



The Digital Michelangelo Project, Levoy et al.



The Digital Michelangelo Project, Levoy et al.



The Digital Michelangelo Project, Levoy et al.

Binary coding

Faster Acquisition?

Faster Acquisition?

- Project multiple stripes simultaneously
- What is the problem with this?

Faster Acquisition?

- Project multiple stripes simultaneously
- Correspondence problem: which stripe is which?
- Common types of patterns:
 - Binary coded light striping
 - Gray/color coded light striping

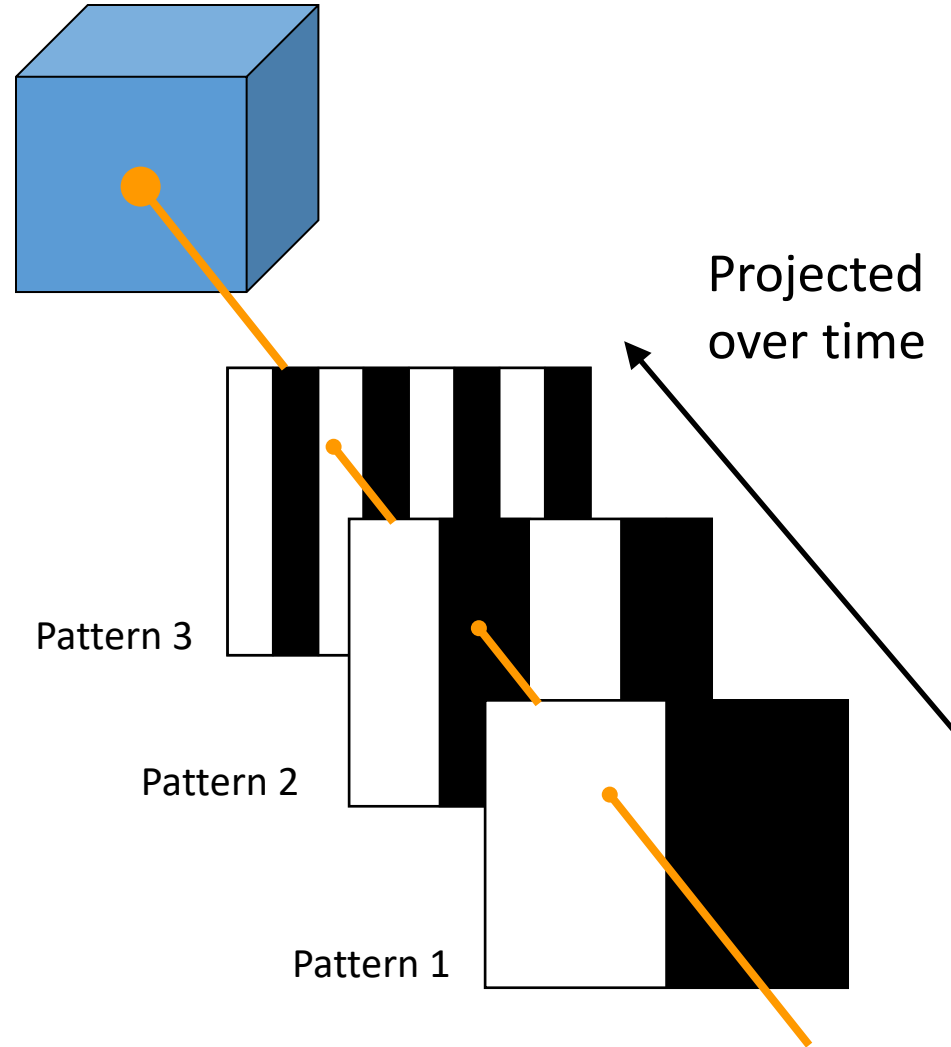
Binary Coding

Faster:

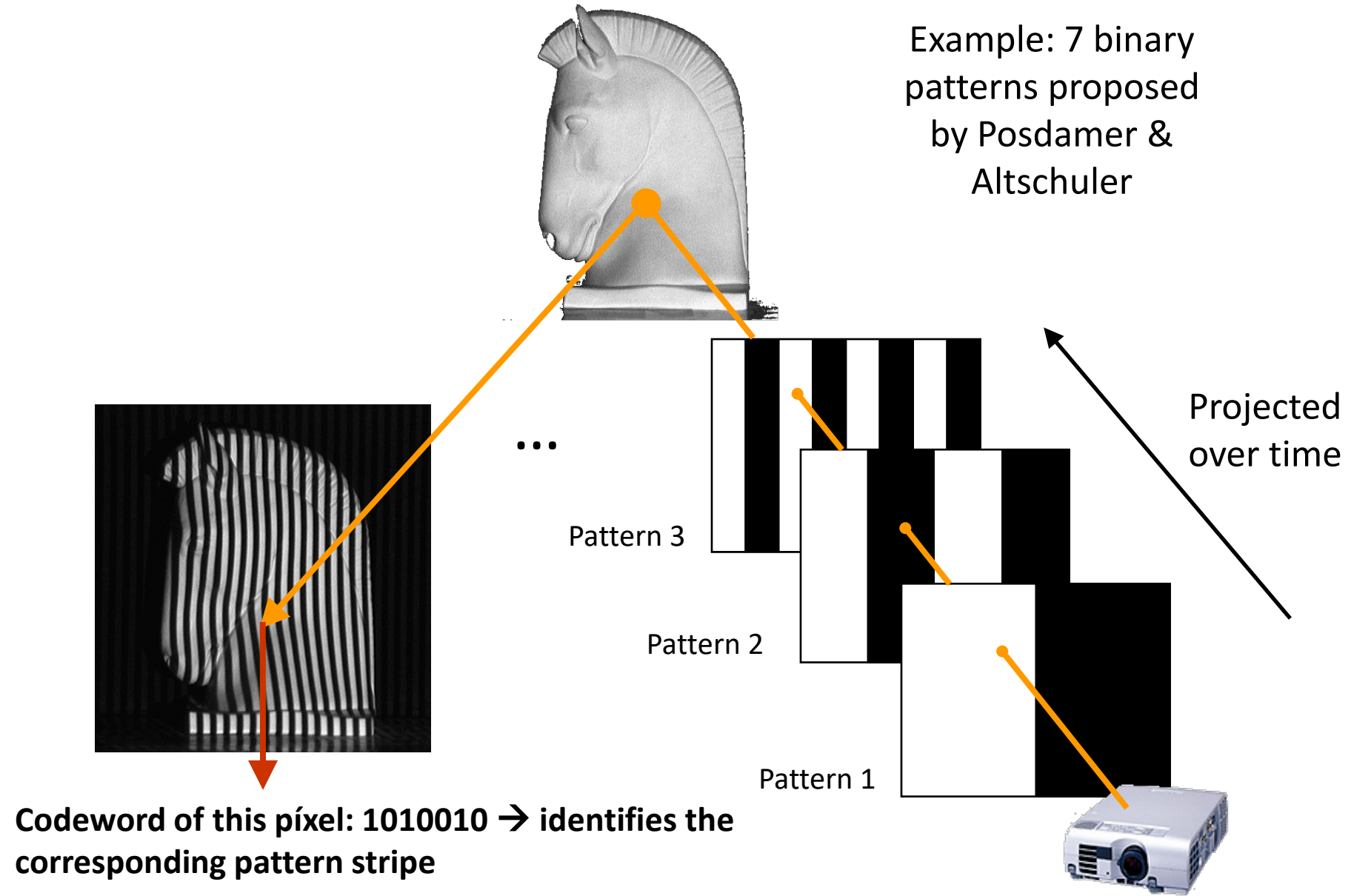
$2^n - 1$ stripes in n images.

Example:

3 binary-encoded patterns which allows the measuring surface to be divided in 8 sub-regions



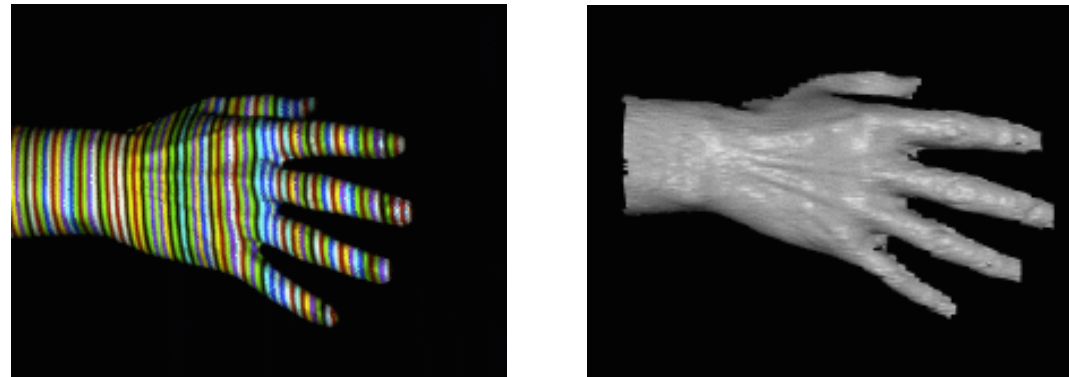
Binary Coding



More complex patterns



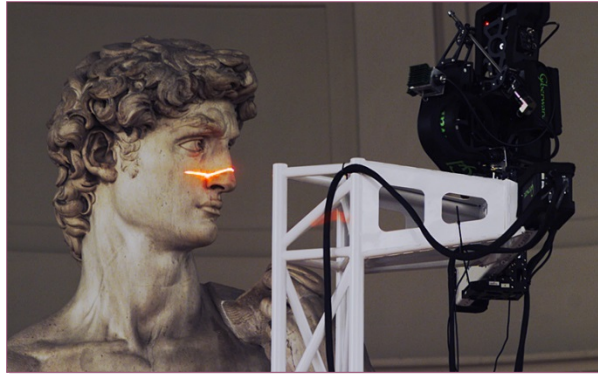
Works despite complex appearances



Works in real-time and on dynamic scenes

- Need very few images (one or two).
- But needs a more complex correspondence algorithm

Continuum of Triangulation Methods



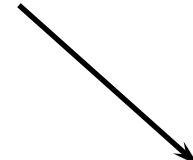
Single-stripe



Multi-stripe
Multi-frame



Single-frame

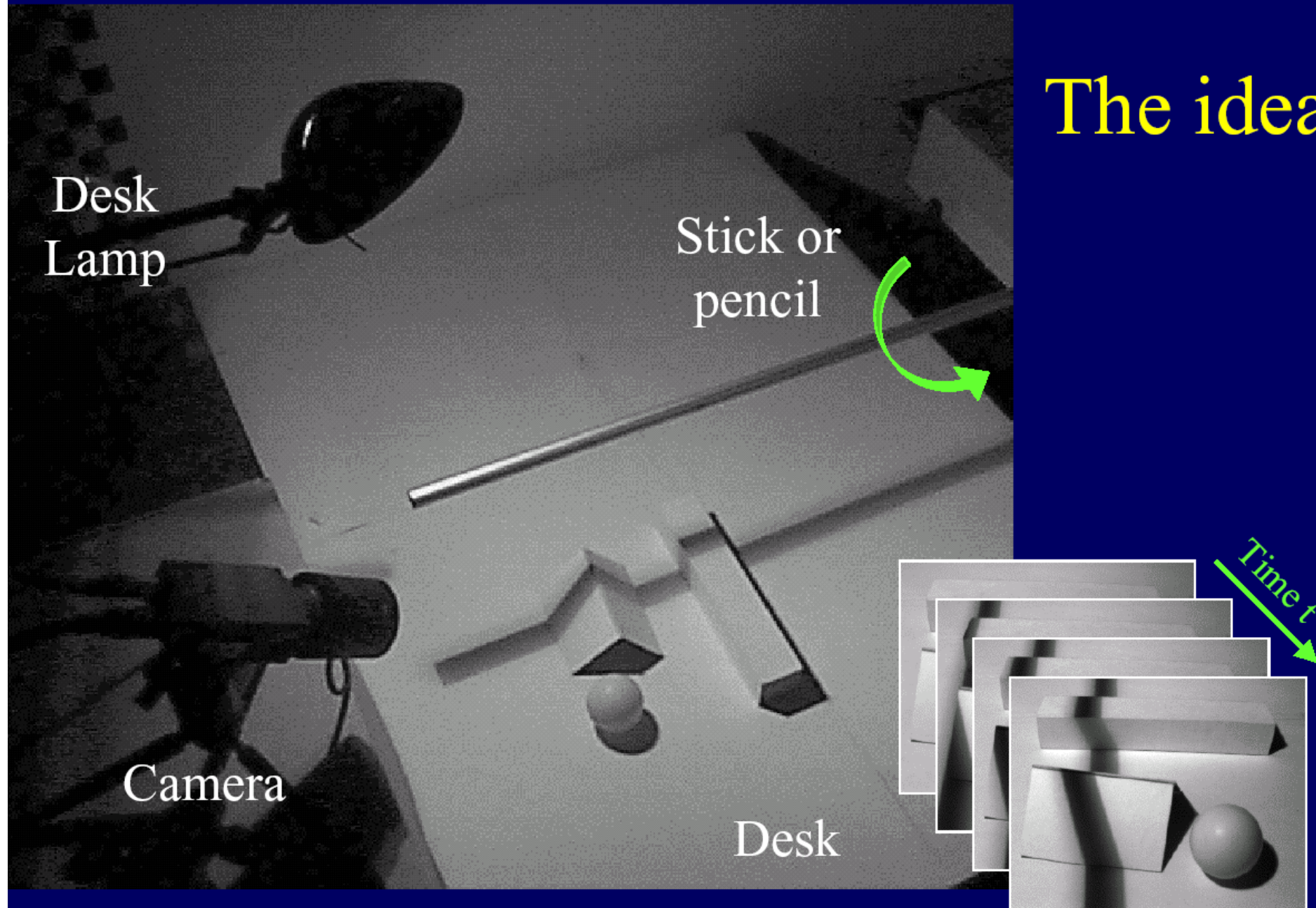


Slow, robust

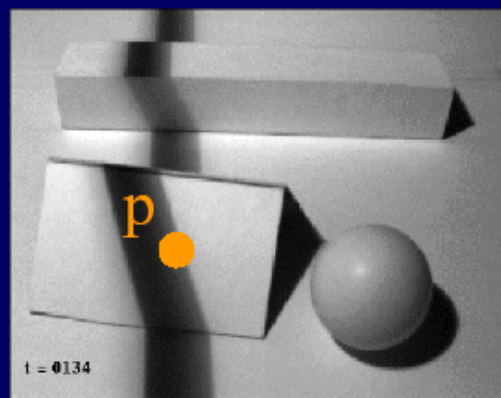
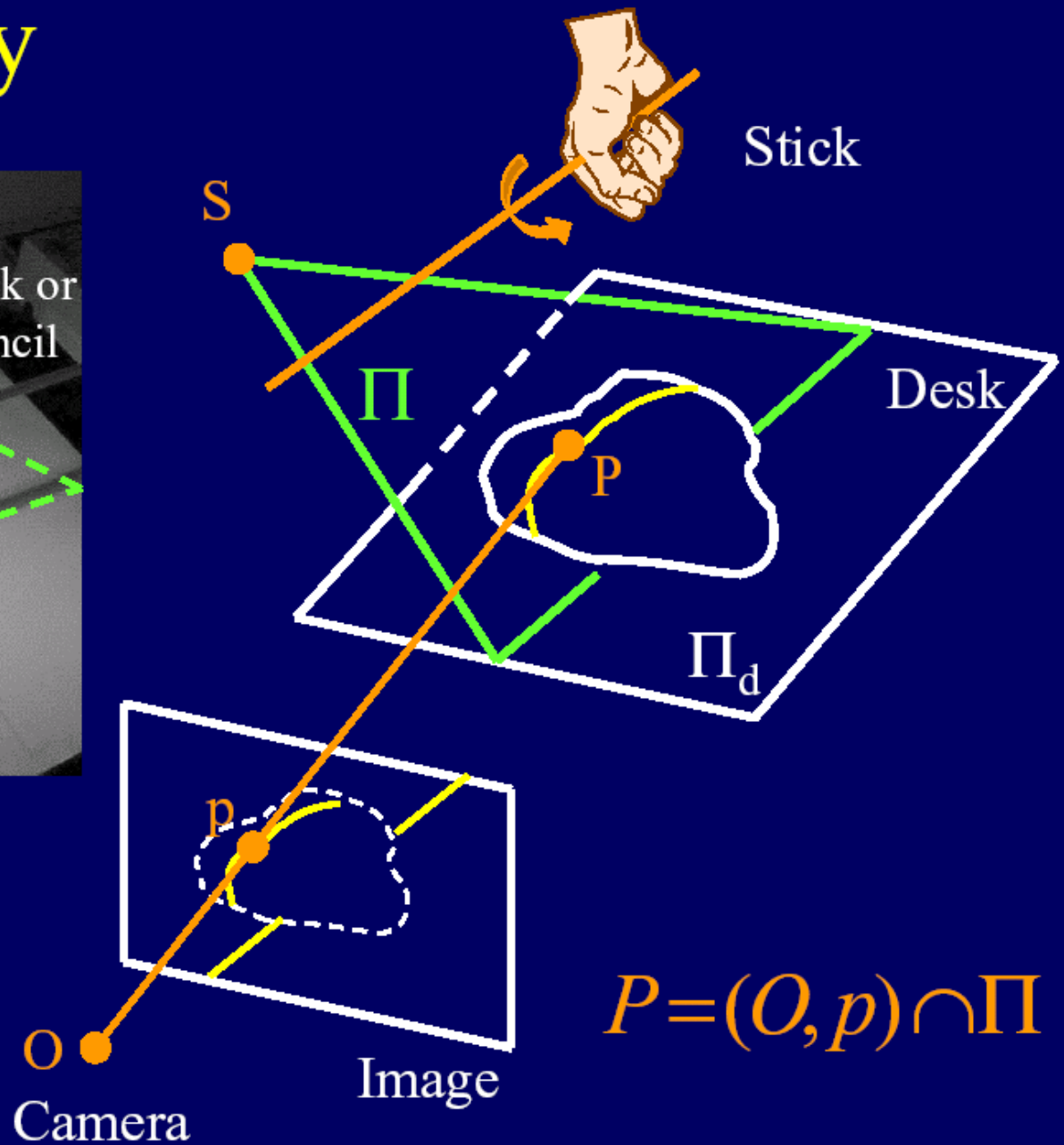
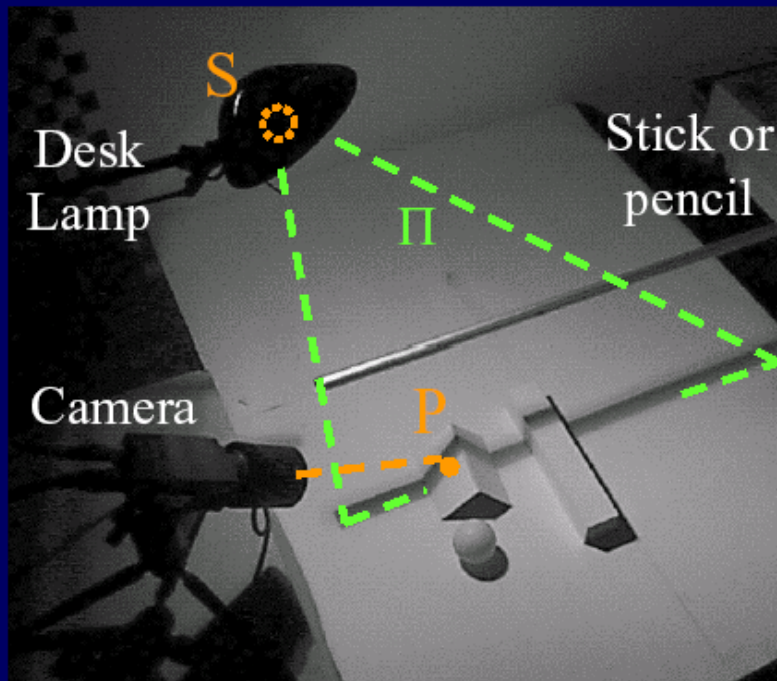
Fast, fragile

Using shadows

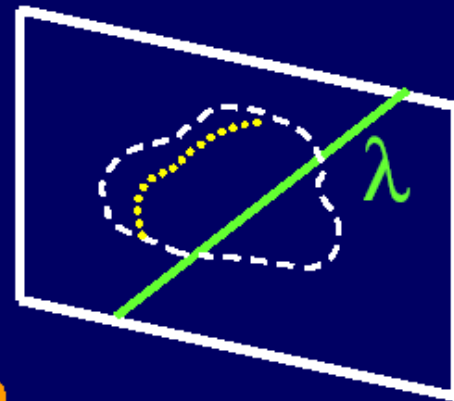
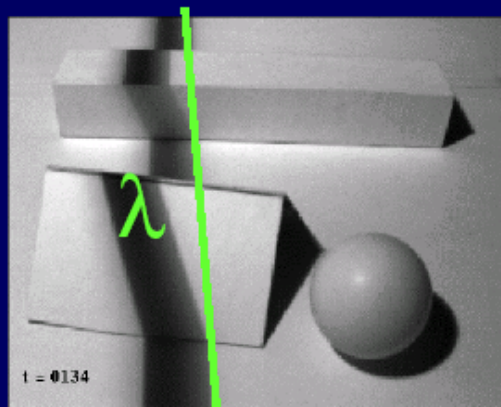
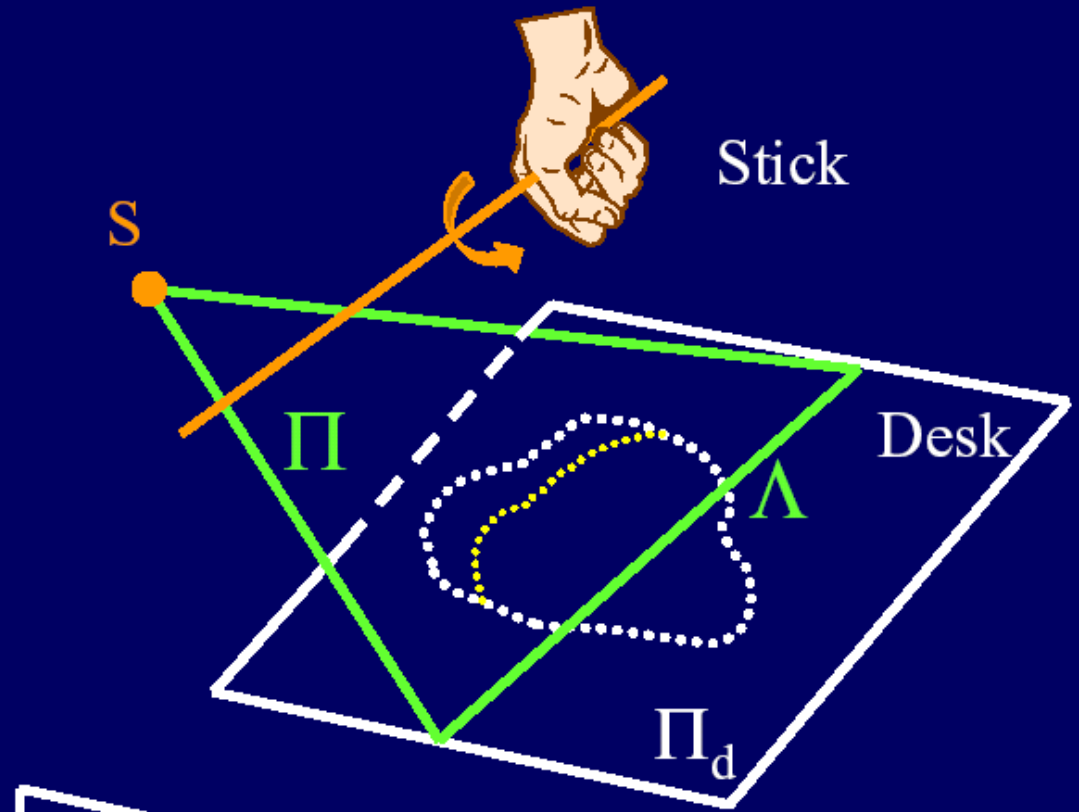
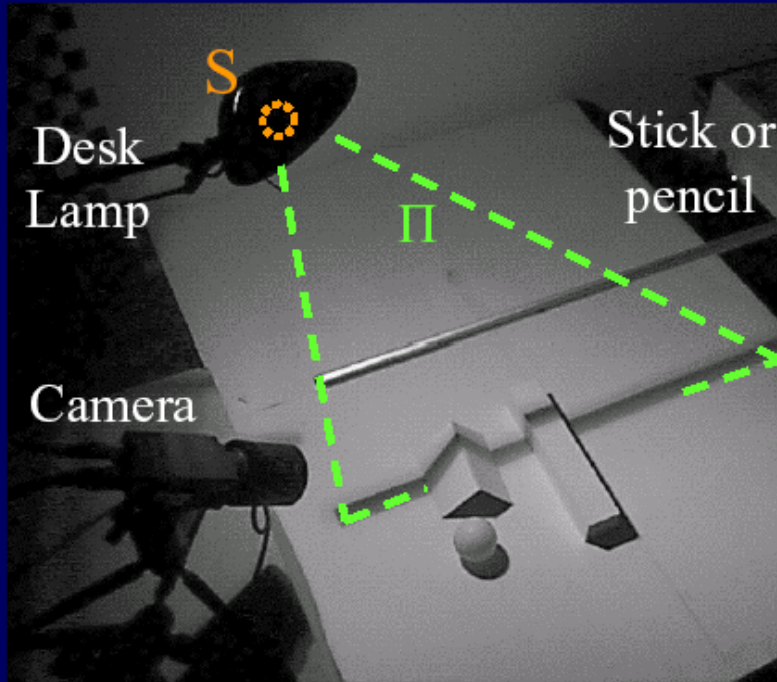
The idea



The geometry



The geometry



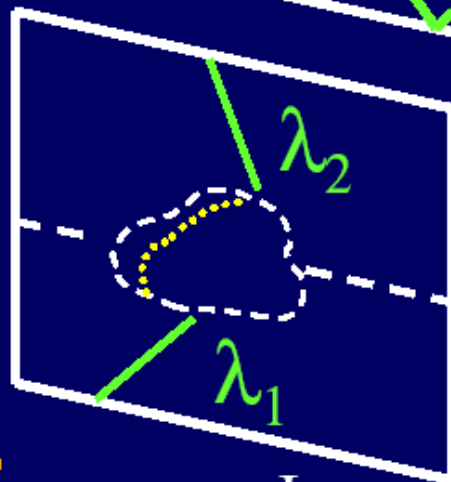
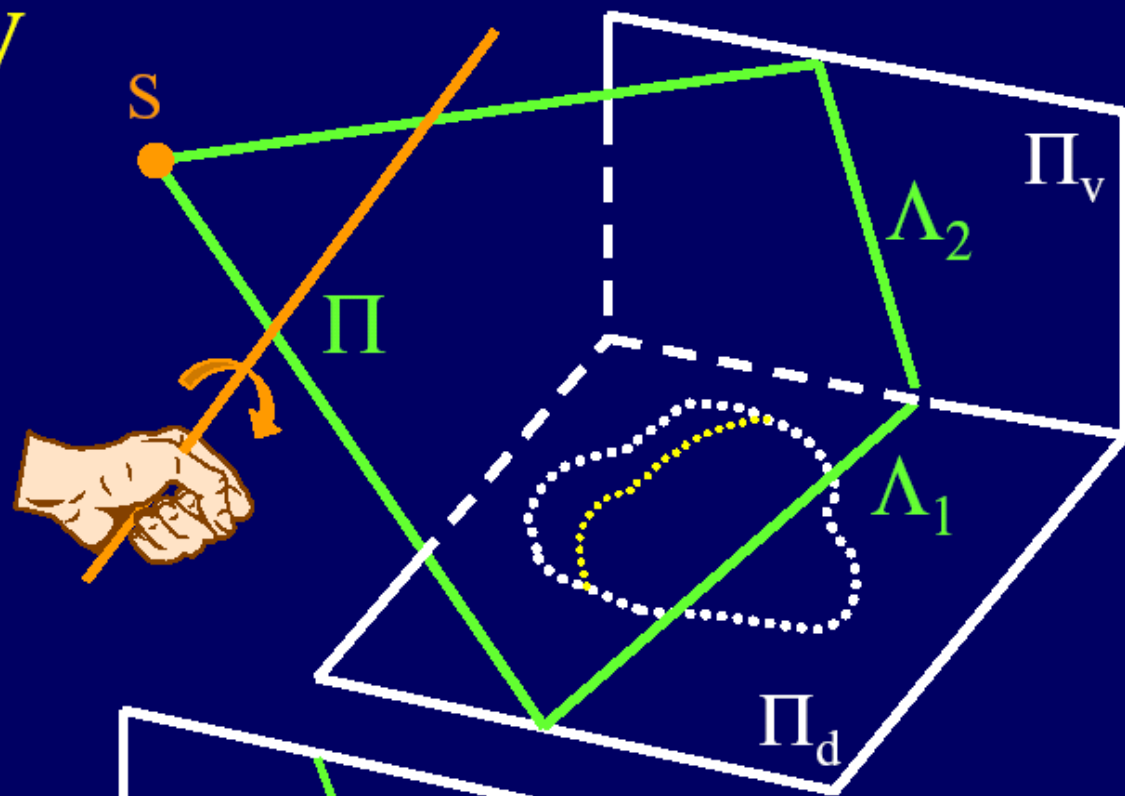
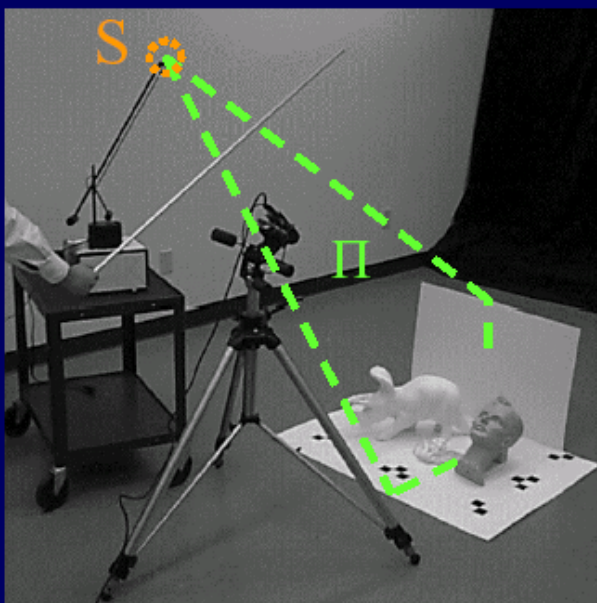
Image

○ ●
Camera

$$\Lambda = (O, \lambda) \cap \Pi_d$$

$$\Pi = (S, \Lambda)$$

The geometry



● ●
Camera

Image

$$\Lambda_1 = (O, \lambda_1) \cap \Pi_d$$

$$\Lambda_2 = (O, \lambda_2) \cap \Pi_v$$

$$\Pi = (\Lambda_1, \Lambda_2)$$

Angel experiment



Accuracy: 0.1mm over 10cm  ~ 0.1% error

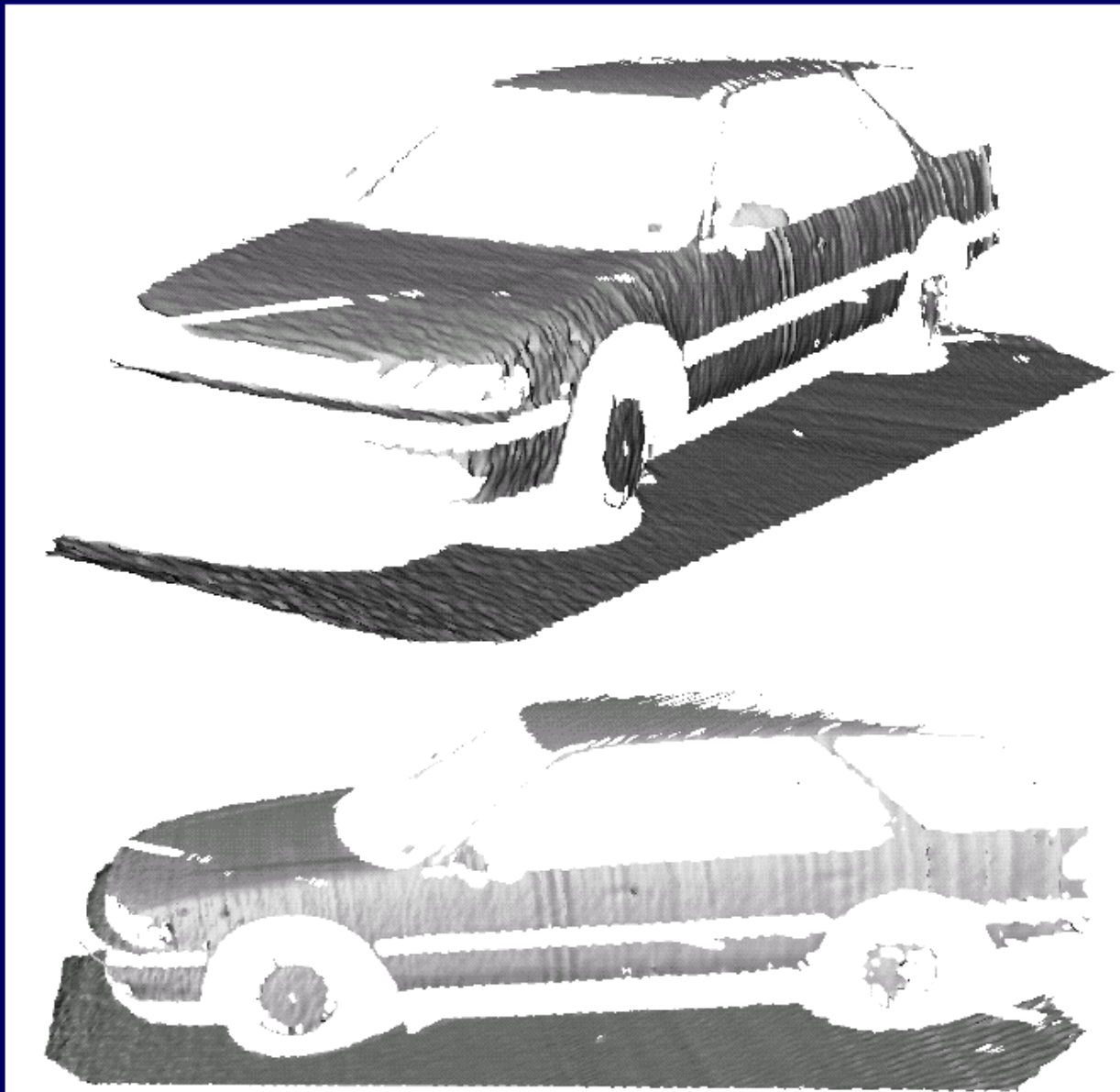
Scanning with the sun



Accuracy: 1cm over 2m



~ 0.5% error



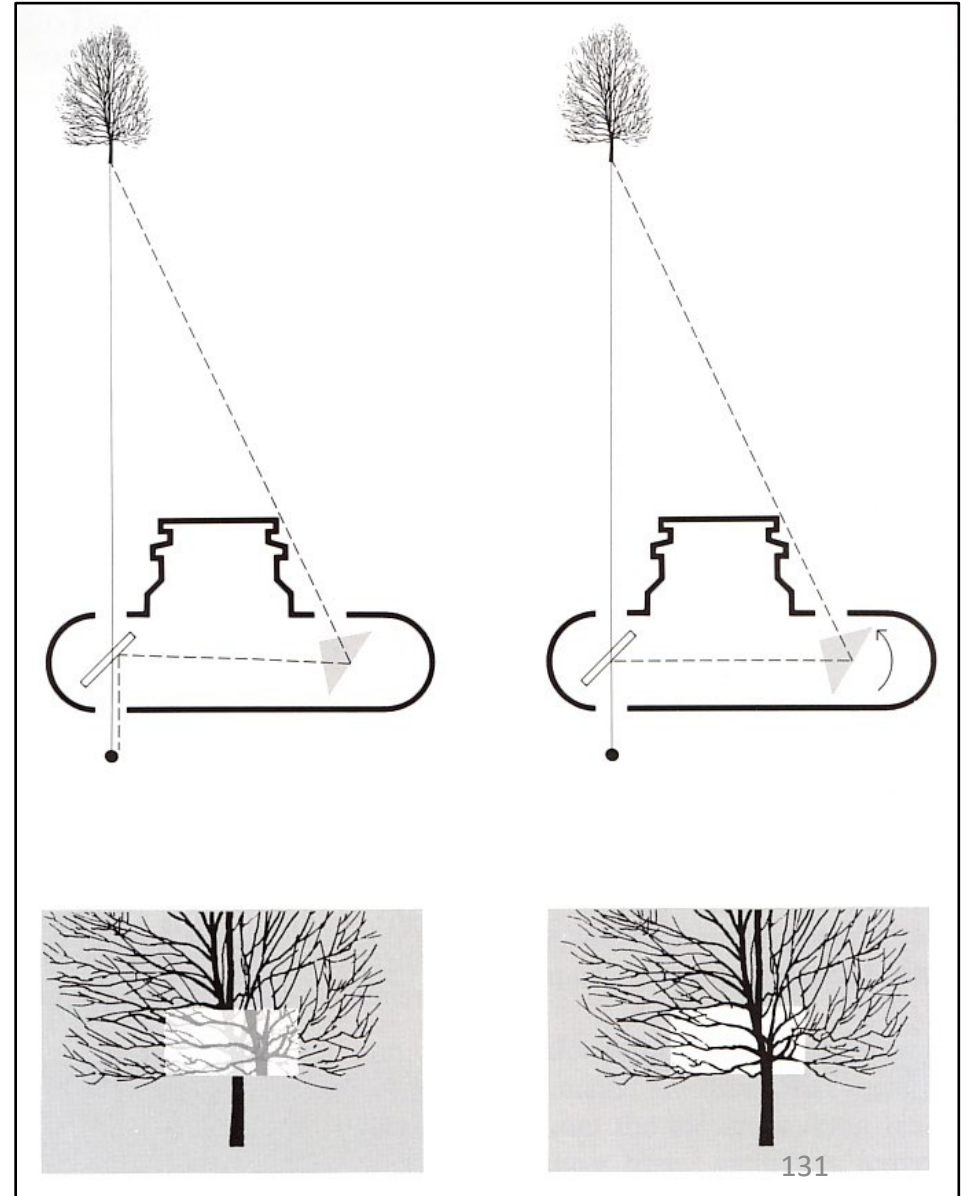
Some notes on (auto-)focusing

Different cameras have different focusing processes

Manual focus in rangefinder cameras

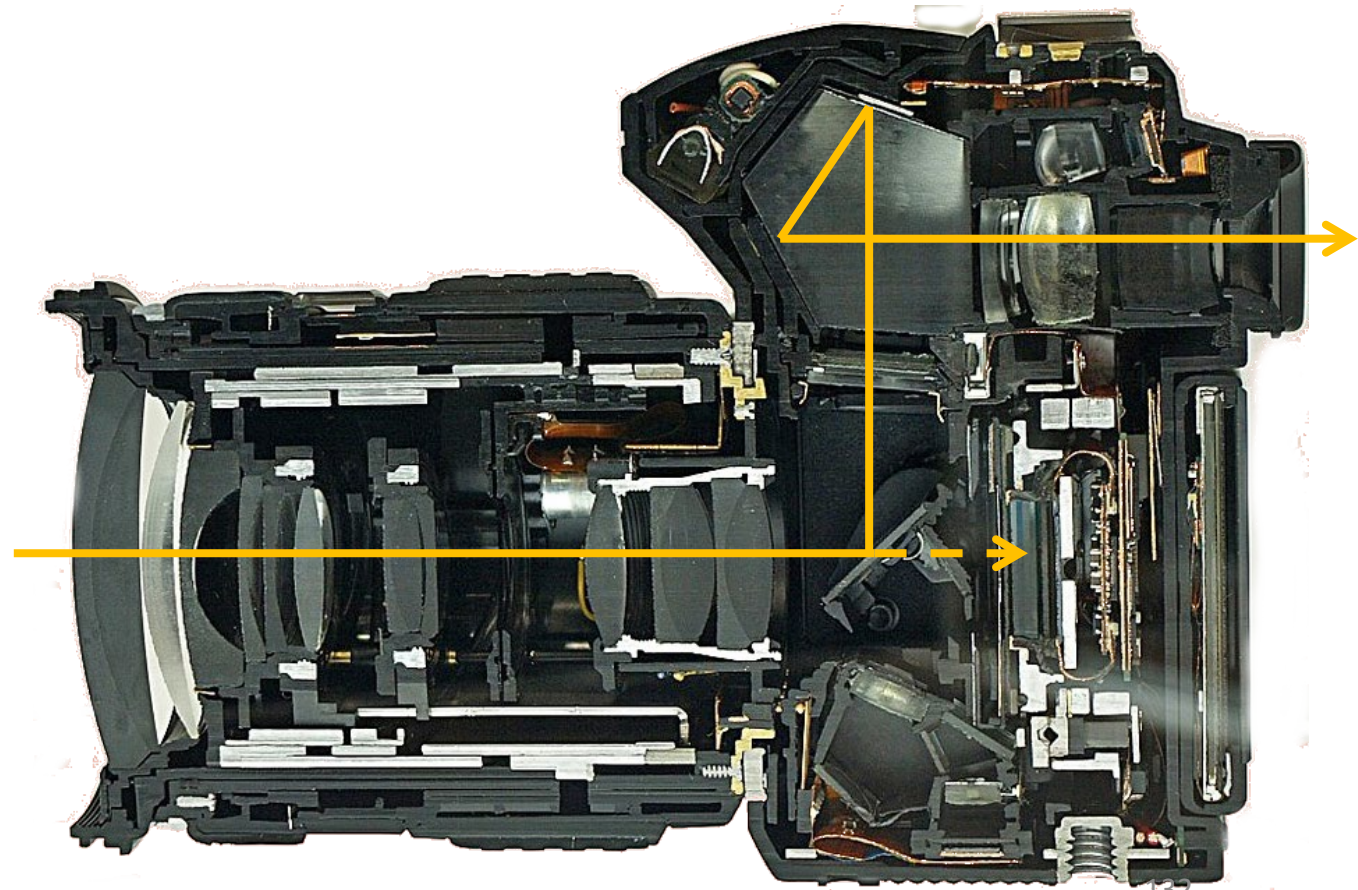
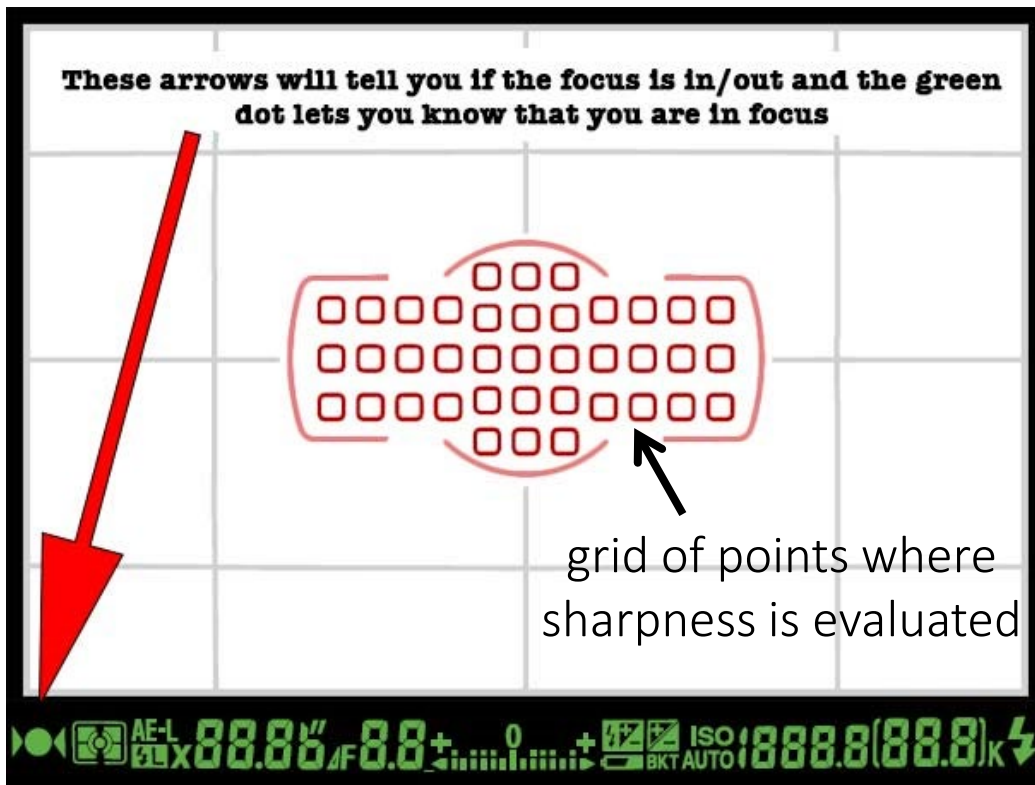
- Focusing based on triangulation: when the image is in focus, you will see the two copies aligned.
- Very accurate but very painstaking.
- Different perspective than that of the main lens.

standard in
Leica cameras



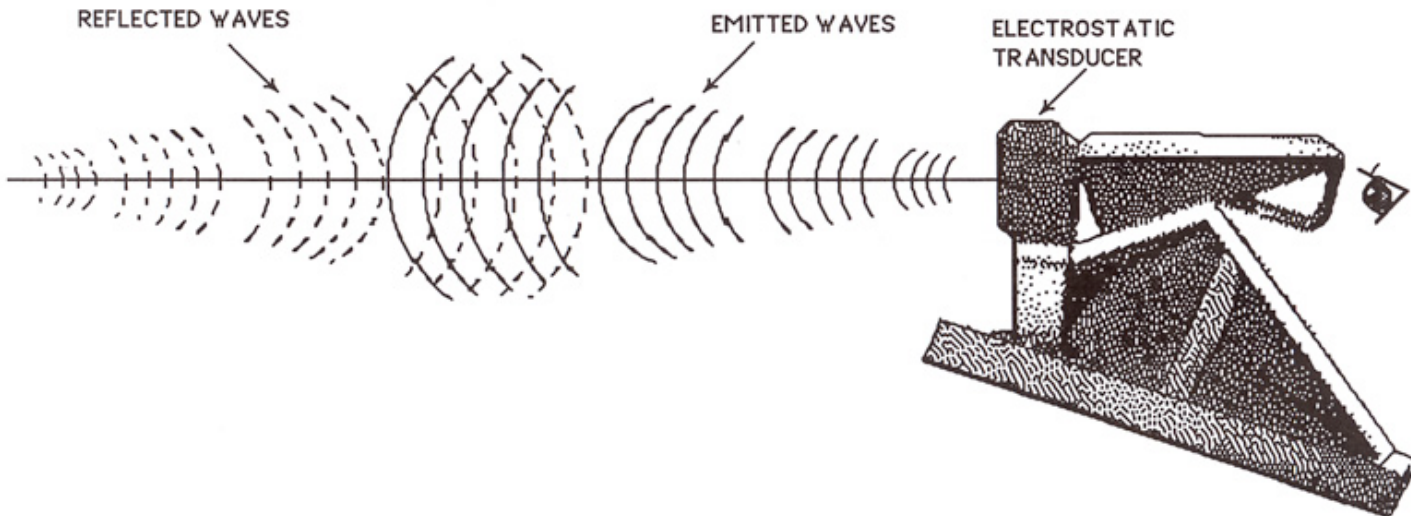
Manual focus in (D)SLR cameras

- Same view as main lens.
- Just rotate the focusing ring until you are satisfied by the sharpness.
- Viewfinder indicators can help this process.



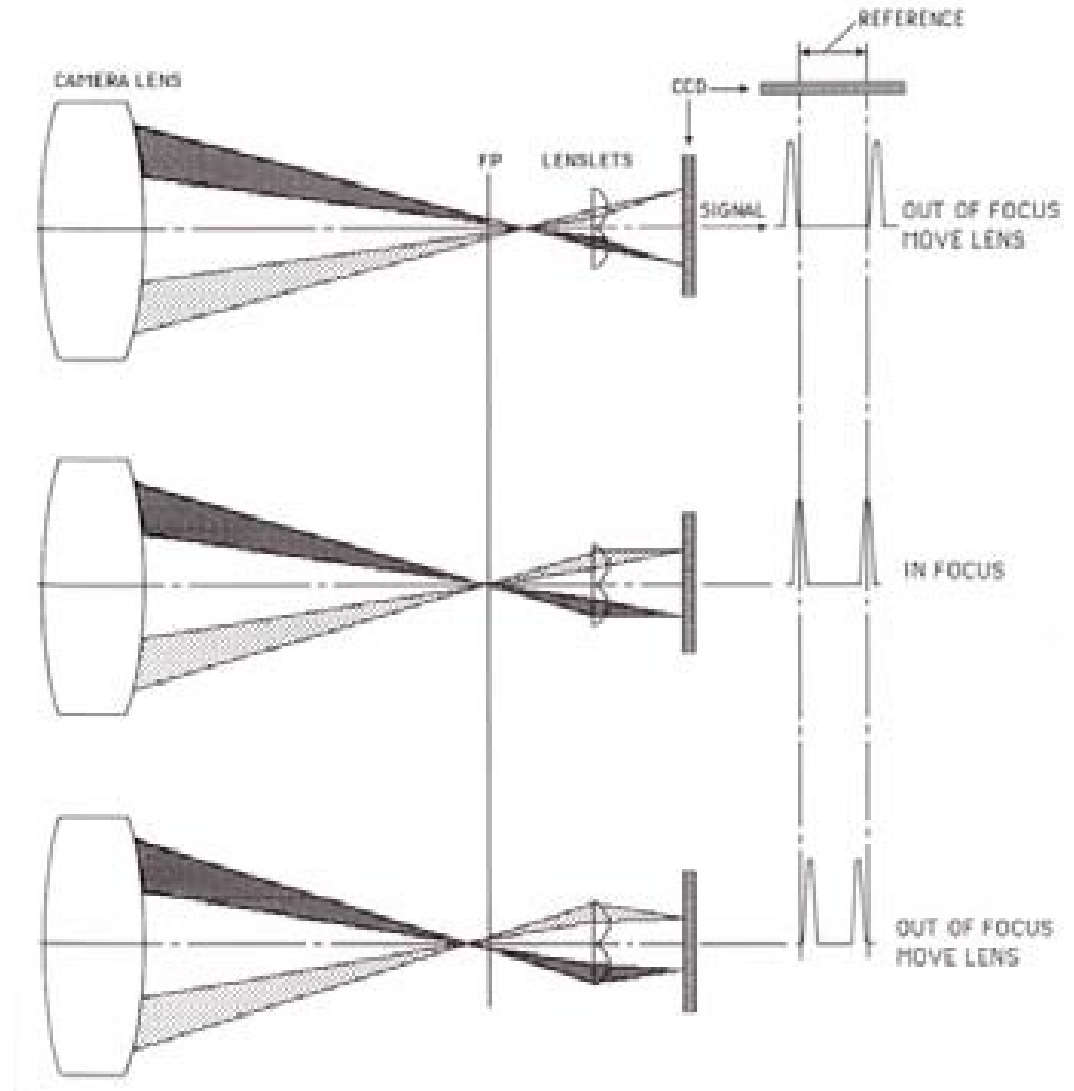
Active auto-focus: time-of-flight sensors

- Basically how SONAR works (we'll also see time-of-flight sensors later in class).
- Method used in Polaroid cameras, which used ultrasound waves.
- Energy inefficient.
- Limited range.
- Multi-path interference (e.g., glass surfaces back-reflected the waves).



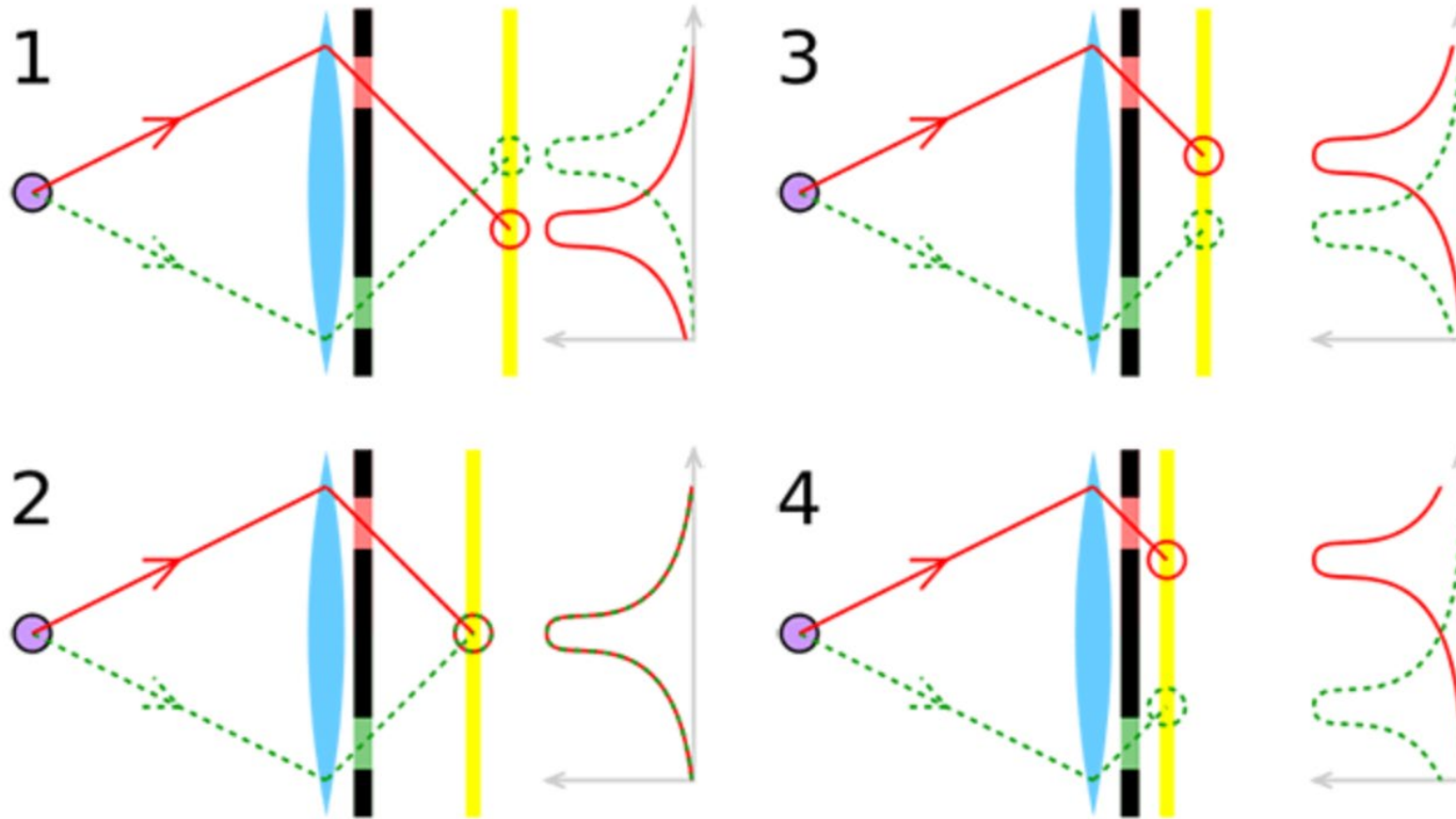
Passive auto-focus: phase detection

- As the lens moves, ray bundles from an object converge to a different point in the camera and change in angle.
- This change in angle causes them to refocus through two lenslets to different positions on a separate AF sensor.
- A certain spacing between these double images indicates that the object is “in focus”.



Demo: <http://graphics.stanford.edu/courses/cs178/applets/autofocuspd.html>

Passive auto-focus: phase detection



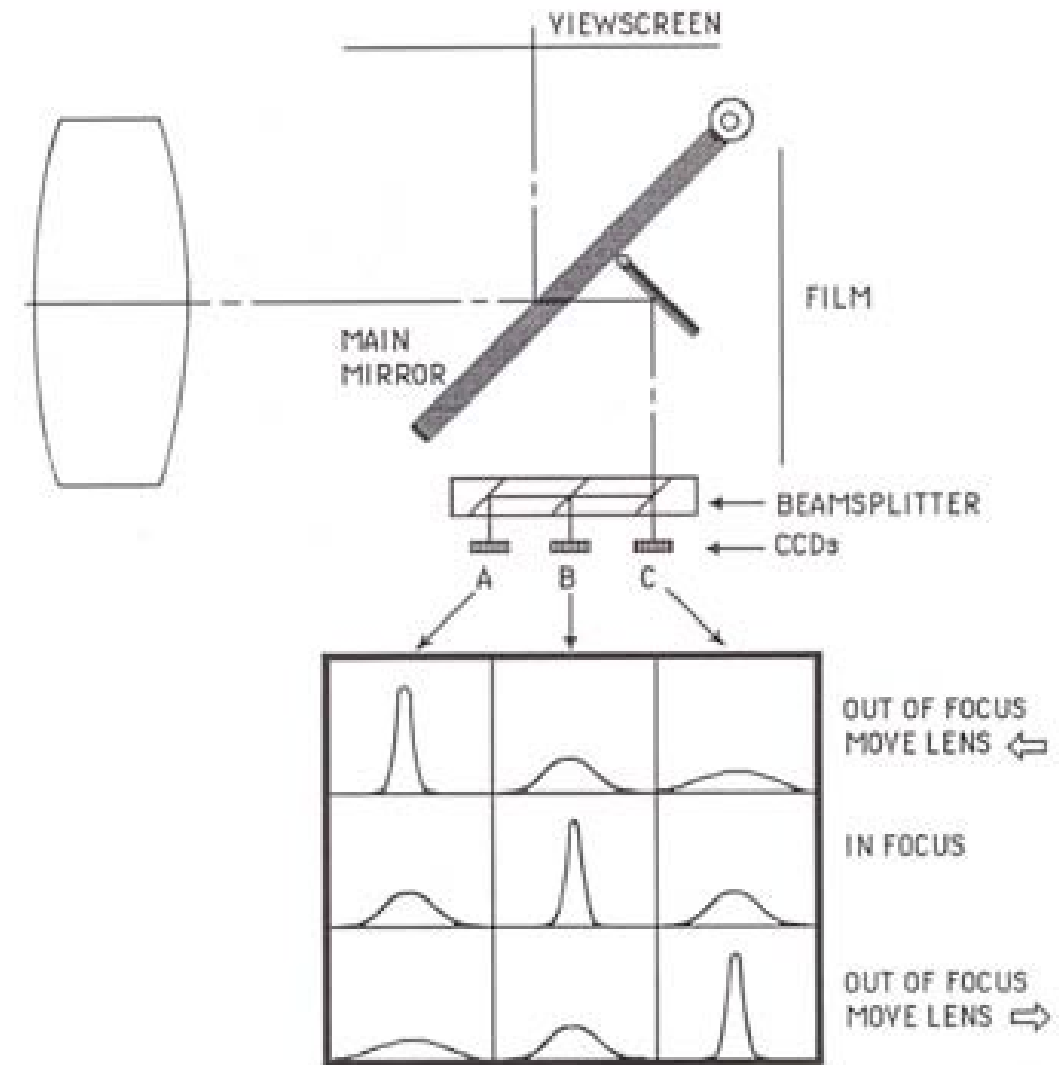
Each yellow box indicates *two* sensors, each measuring light from different parts of the aperture.

- Which one is correct focusing?
- How do you need to move the lens or sensor to get correct focusing?

Passive auto-focus: contrast detection

- Sensors at different image distances will see the same object at high-contrast if it's in focus, or low-contrast if it's not.
- Move the lens until the high-contrast sub-image falls on the middle sensor, which is conjugate to the camera's main sensor.
- Compute contrast using local differences of pixel values.

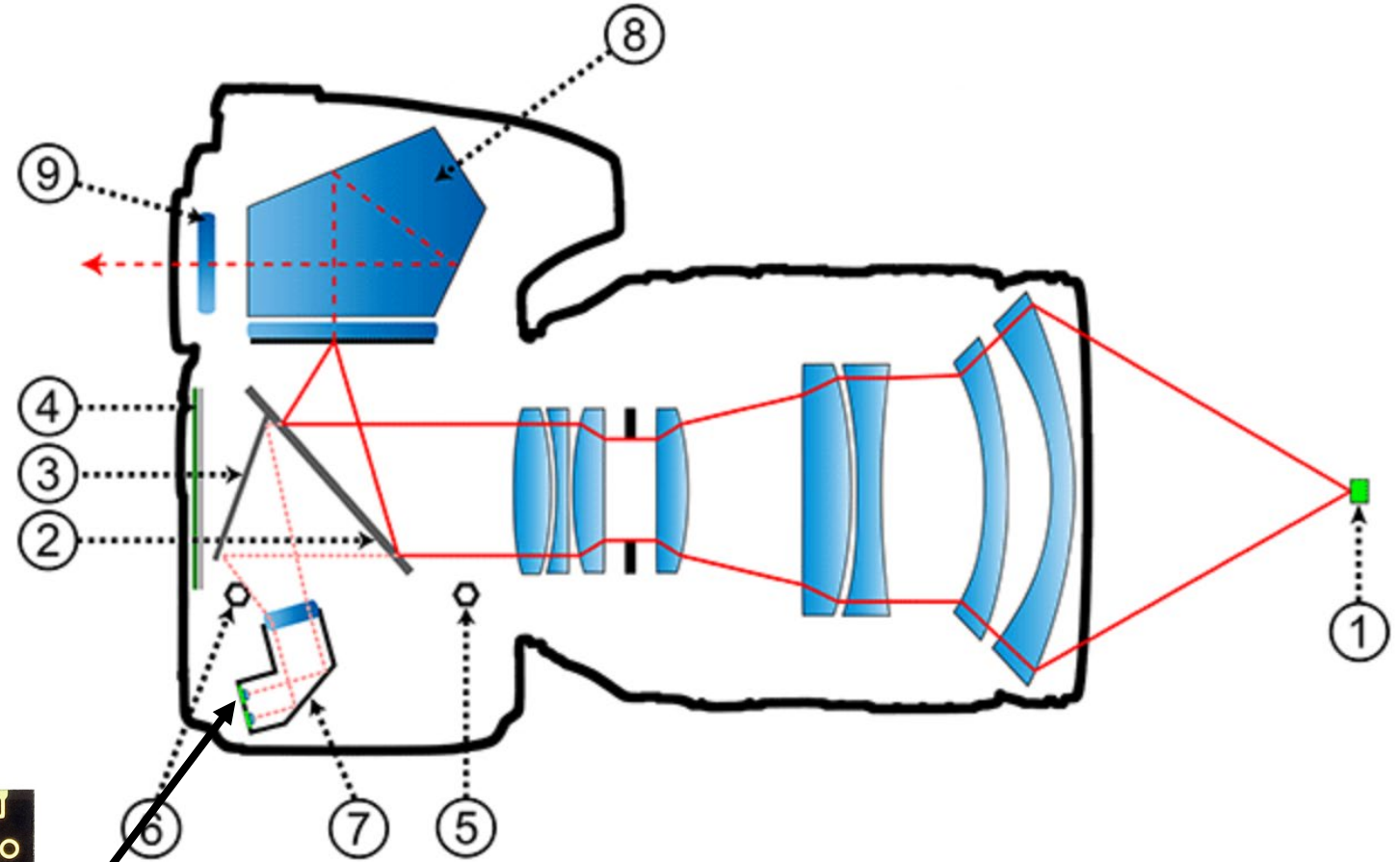
Effectively the same as depth from focus.



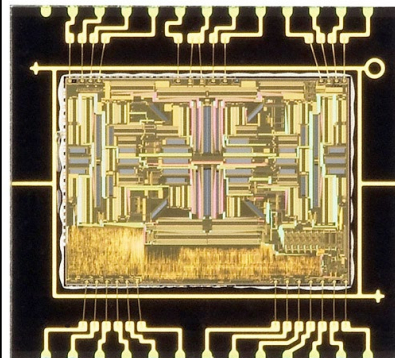
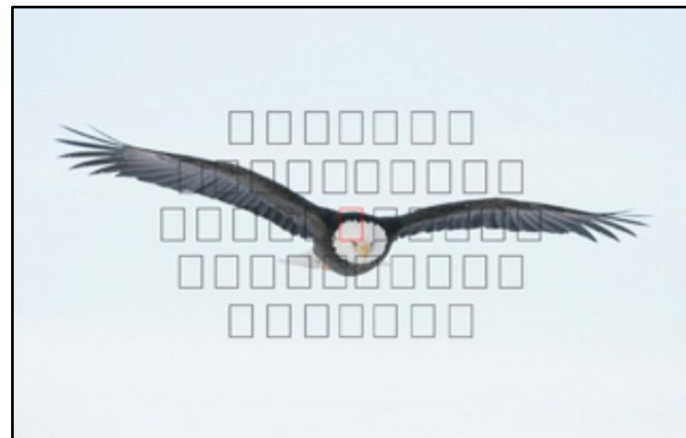
Demo: <http://graphics.stanford.edu/courses/cs178/applets/autofocuscd.html>

High-end DSLRs use phase detection

- Distance between sub-images allows lens to move directly into focus, without hunting
- Many AF points corresponding to different points on imaging sensor, complicated algorithms for choosing among them: generally use closest point, but also consider position in FOV.



DSLR mirror has a translucent part that allows some light to make it to the AF sensor.

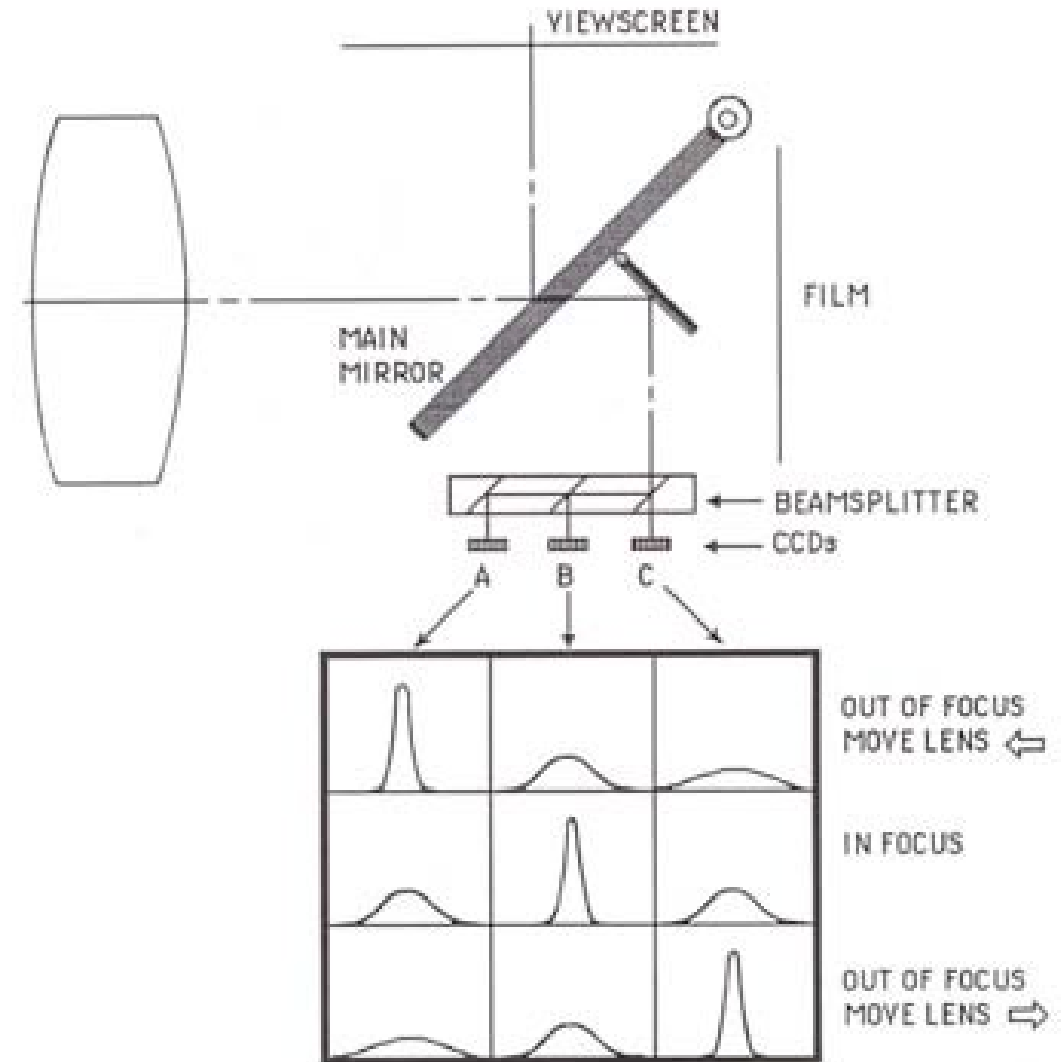


Low-end cameras (and phones) use contrast detection

- Nowadays it is mostly done using main camera sensor instead of dedicated sensors.
- Requires repeated measurements as lens moves, which are captured using the main sensor (an “autofocus stack”).
- Slow, requires hunting, suffers from overshooting.

But

- People have come up with creative uses for the autofocus stack (depth-from-focus on a cell phone, HDR+ on Android).

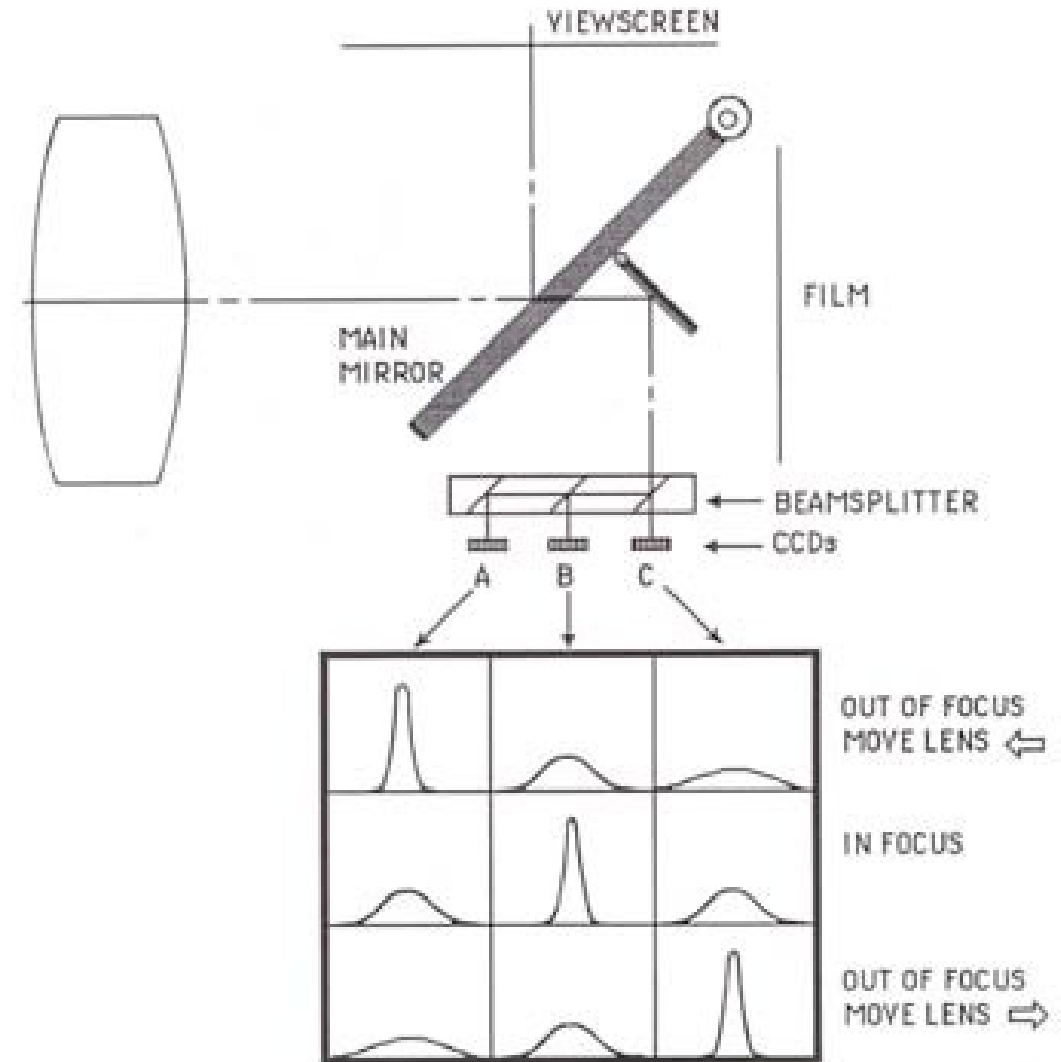


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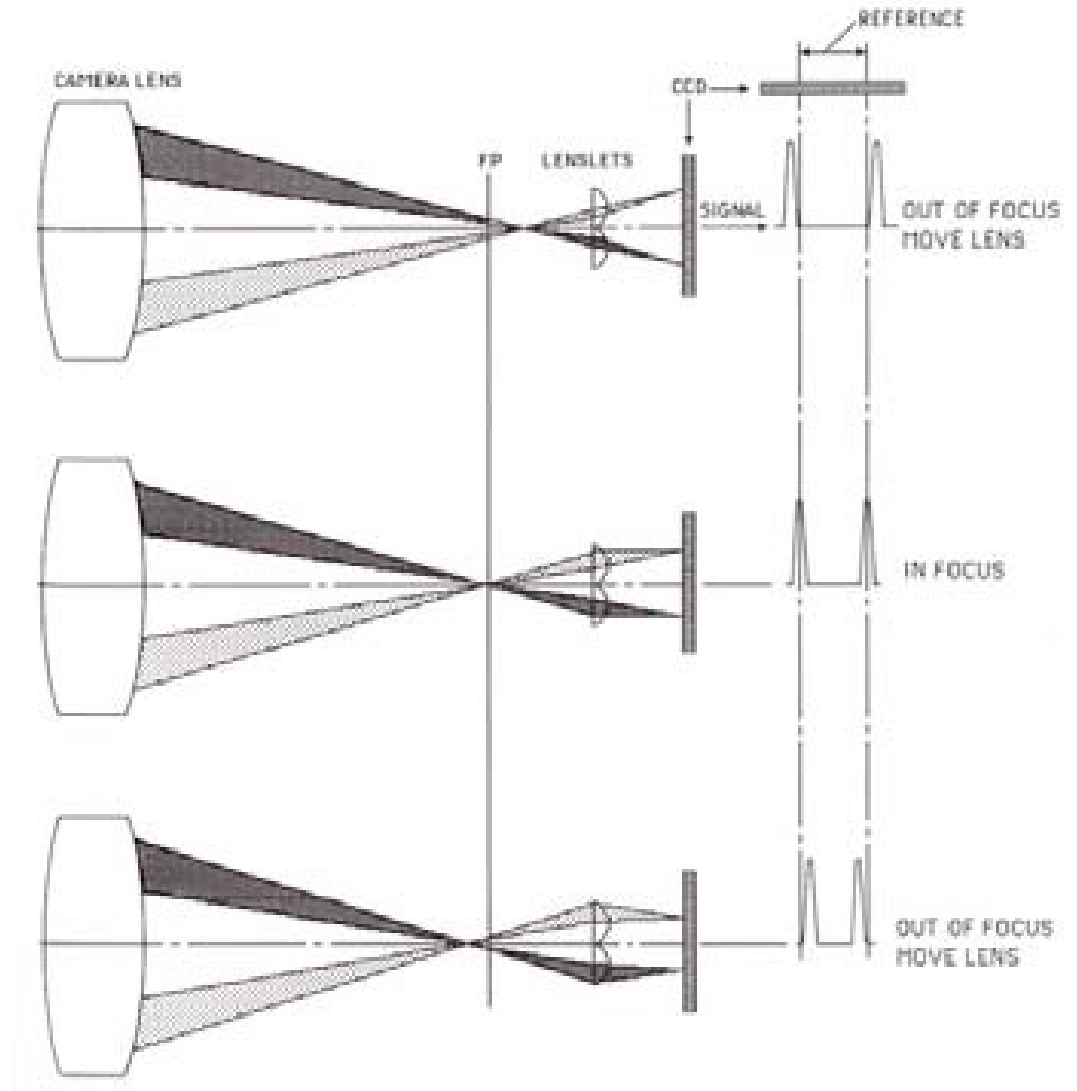
- People have come up with creative uses for the autofocus stack (depth-from-focus on a cell phone, HDR+ on Android).



Modern mirror-less cameras use phase detection

- Dedicate a small number of pixels on the imaging sensor to work for phase detection.
- Do this at different parts of the sensor to be able to autofocus at different parts of the image.

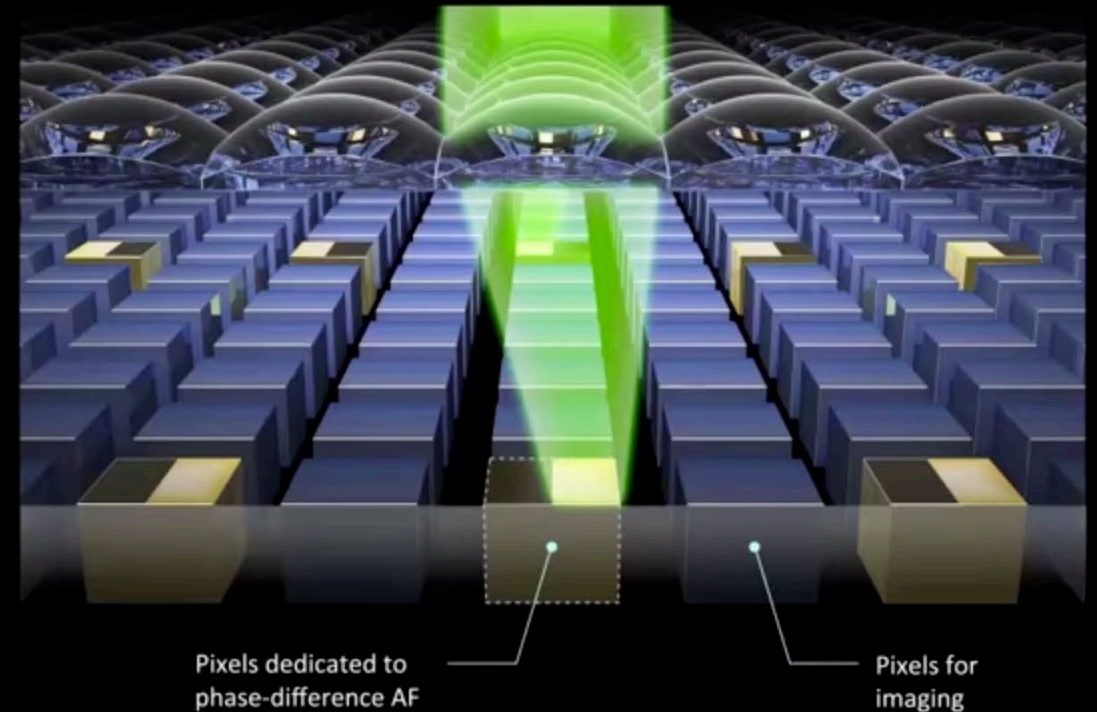
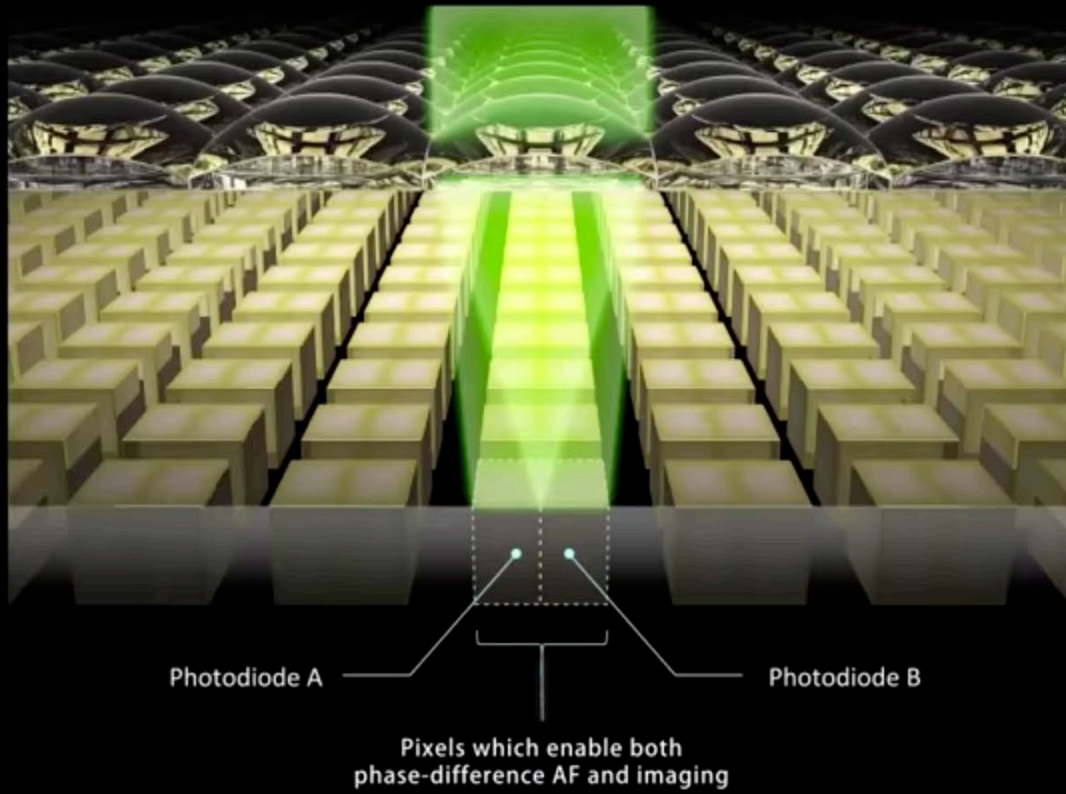
Any downsides?



Dual-pixel phase detection autofocus

- Split each pixel into two independent photodiodes—like a two-view lightfield.
- Use different pixels for phase detection.
- Many other interesting opportunities (depth from stereo/lightfield with a tiny baseline).

All pixels are configured to be used for imaging as well as phase-difference AF*



Should you use autofocus?

Should you use autofocus?

Quick answer: Yes.

More detailed answer: Yes, except for certain special circumstances.

- You are using a lens that does not have an autofocus motor (e.g., vintage or otherwise old lenses, high-end lenses, industrial and machine vision lenses).
- You are trying to capture an image under conditions where autofocus is prone to fail (e.g., macrophotography, poorly-lit scenes, imaging through glass or occluders).
- You intentionally want some part of the scene to be out of focus (e.g., for artistic effect, or because you want a face or other featured to be obscured).
- You are in an once-in-a-lifetime opportunity to photograph something, and you cannot afford to risk autofocus failing. This additionally assumes that:
 - Your scene is static enough that you can take the time to focus manually.
 - You are experienced enough so that the probability of manual focus failing is smaller than the probability of autofocus failing.

References

Basic reading:

- Szeliski textbook, Sections 7.1, 11.1, 12.1.
- Boles et al., “Epipolar-plane image analysis: An approach to determining structure from motion,” IJCV 1987.
 - This classical paper introduces EPIs, and discusses how they can be used to infer depth.
- Lanman and Taubin, “Build Your Own 3D Scanner: Optical Triangulation for Beginners,” SIGGRAPH course 2009.
 - This very comprehensive course has everything you need to know about 3D scanning using structured light, including details on how to build your own.
- Bouguet and Perona, “3D Photography Using Shadows in Dual-Space Geometry,” IJCV 1999.
 - This paper introduces the idea of using shadows to do structured light 3D scanning, and shows an implementation using just a camera, desk lamp, and a stick.

Additional reading:

- Gupta et al., “A Practical Approach to 3D Scanning in the Presence of Interreflections, Subsurface Scattering and Defocus,” IJCV 2013.
 - This paper has a very detailed treatment of standard patterns used for structured light, problems arising due to global illumination, and robust patterns for dealing with these patterns.
- Barron et al., “Fast bilateral-space stereo for synthetic defocus,” CVPR 2015.
- Barron and Poole, “The fast bilateral solver,” ECCV 2016.
 - The above two papers show how to combine edge-aware filtering (and bilateral filtering in particular) with disparity matching for robust stereo. The first paper also shows how the resulting depth maps can be used to create synthetic defocus blur.
- Wanner and Goldluecke, “Globally Consistent Depth Labeling of 4D Light Fields,” CVPR 2012.
- Kim et al., “Scene reconstruction from high spatio-angular resolution light fields,” SIGGRAPH 2013.
 - These two papers show detailed systems for using EPIs to extract depth.
- Levin et al., “Understanding camera trade-offs through a Bayesian analysis of light field projections,” ECCV 2008.
 - This paper uses EPIs to show how different types of imaging systems (pinhole cameras, plenoptic cameras, stereo pairs, lens-based systems, and so on) relate to each other, and analyze their pros and cons for 3D imaging.