Georgia Institute of Technology

Computational Photography

Dr. Irfan Essa
Professor
School of Interactive Computing

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

Georgia Institute of Technology

Light Fields: Part 1 of 2 Plenoptic Function

Dr. Irfan Essa
Professor
School of Interactive Computing

Introducing the Concepts of a Light Field and the Plenoptic Function.

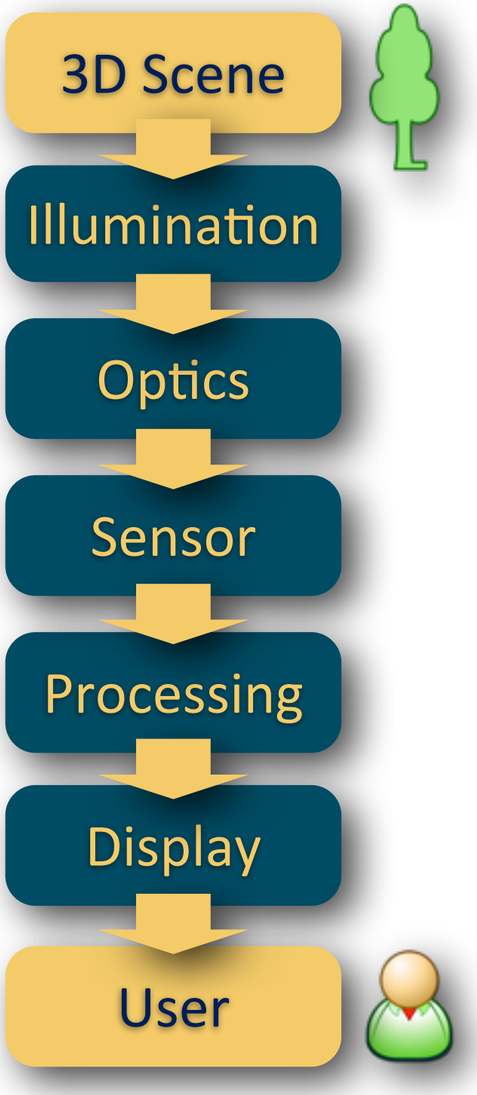
Lesson Objectives

- ★ Descibe in your own words the concept a Light Field.
- ★ Identify in your own words the seven (7) parameters of the Plenoptic Function.
- ★ Describe in your own words the different types of Light Fields in terms of the Dimensions captured.

REVIEW: Photography (Light Rays)

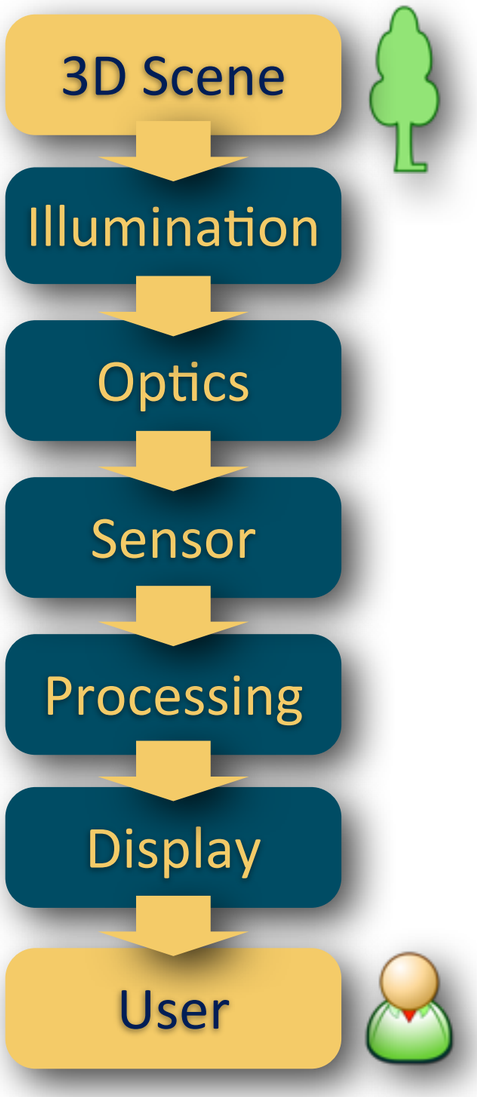
http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

REVIEW: Photography (Light Rays)



http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

REVIEW: Photography (Light Rays)

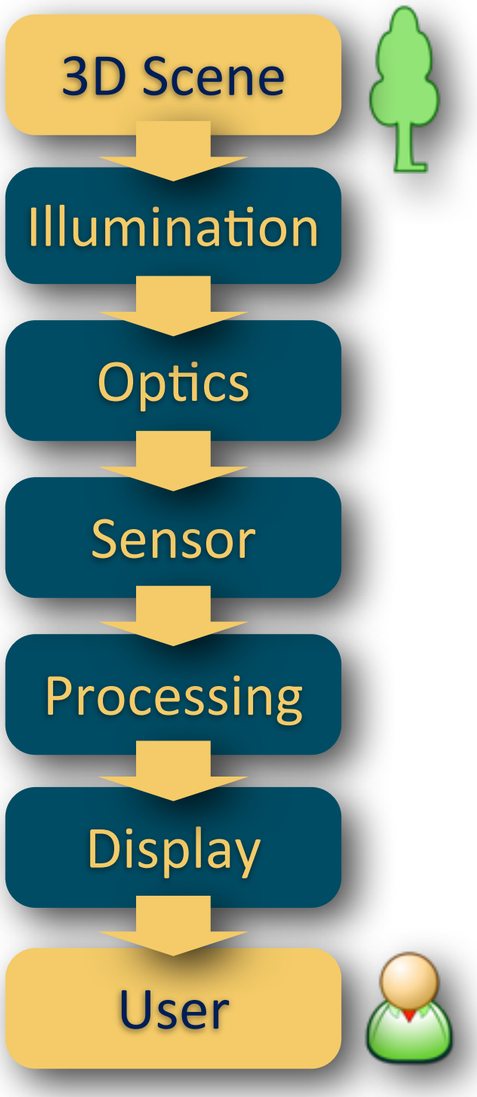


Rays

Pixels

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

REVIEW: Photography (Light Rays)

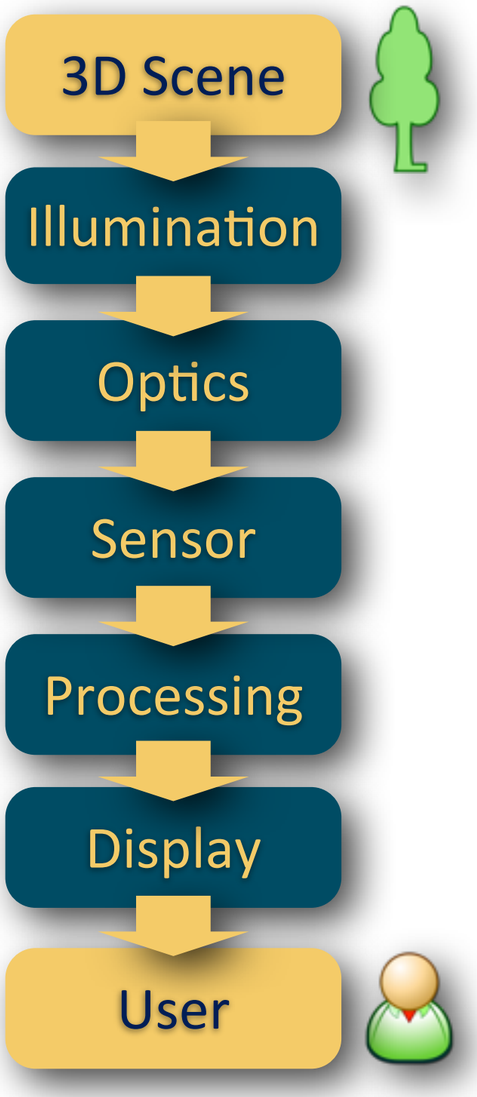


Rays

Pixels

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

REVIEW: Photography (Light Rays)

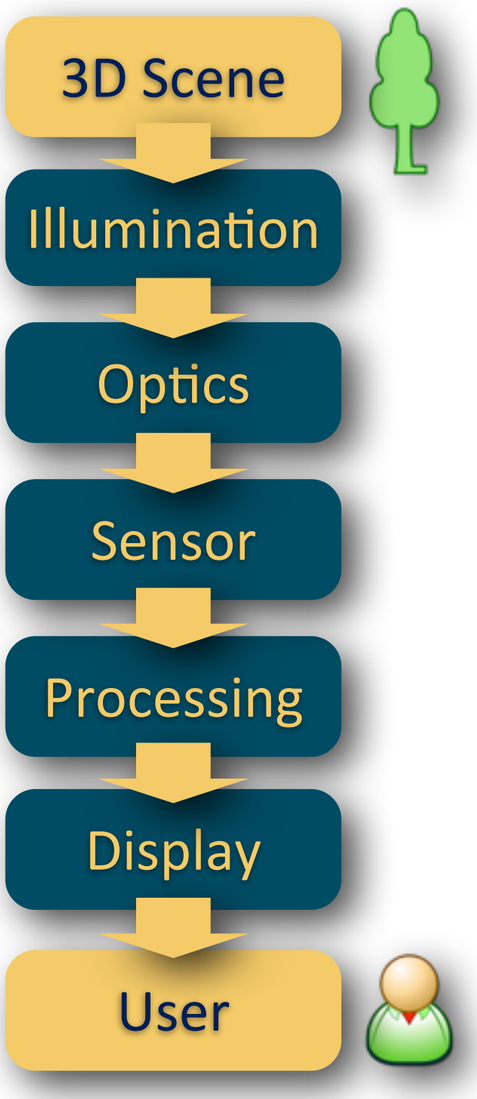


Rays

Pixels

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

REVIEW: Photography (Light Rays)



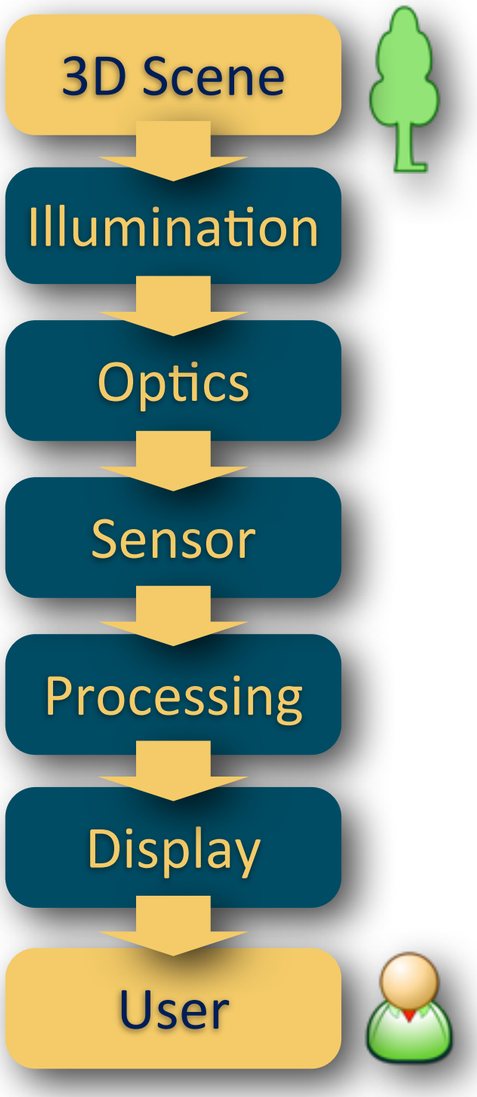
Rays

- Images represent a view of the scene using 2D array of pixels.

Pixels

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

REVIEW: Photography (Light Rays)



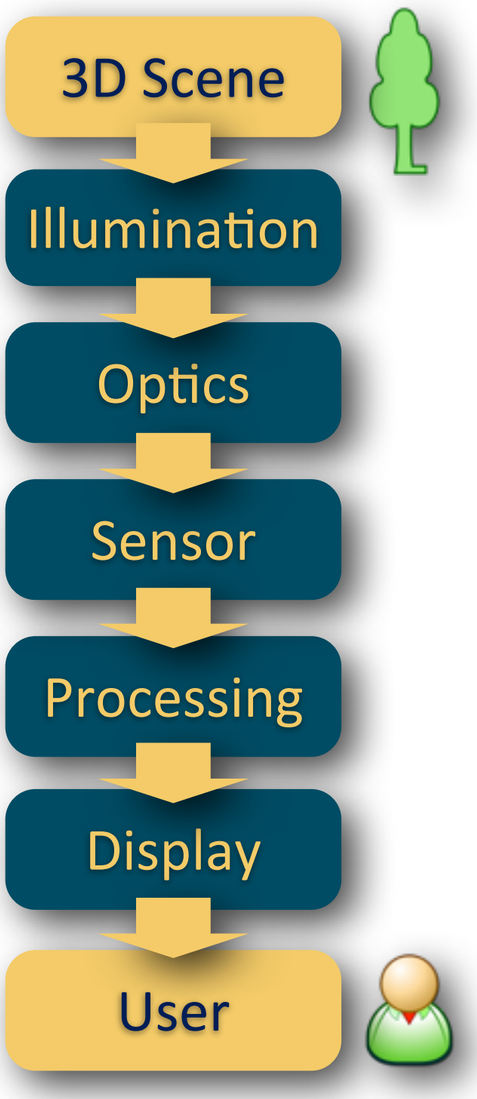
Rays

- ★ Images represent a view of the scene using 2D array of pixels.
- ★ Rays of Light are the fundamental primitives.

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

Pixels

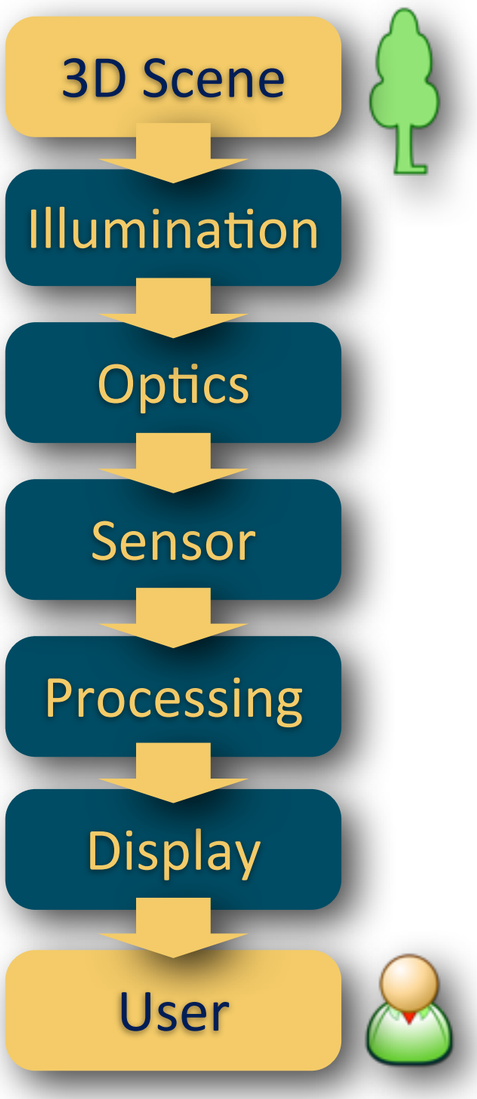
REVIEW: Photography (Light Rays)



- Images represent a view of the scene using 2D array of pixels.
- Rays of Light are the fundamental primitives.
- Illumination (Light Rays) follows a path from the scene to the sensor.

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

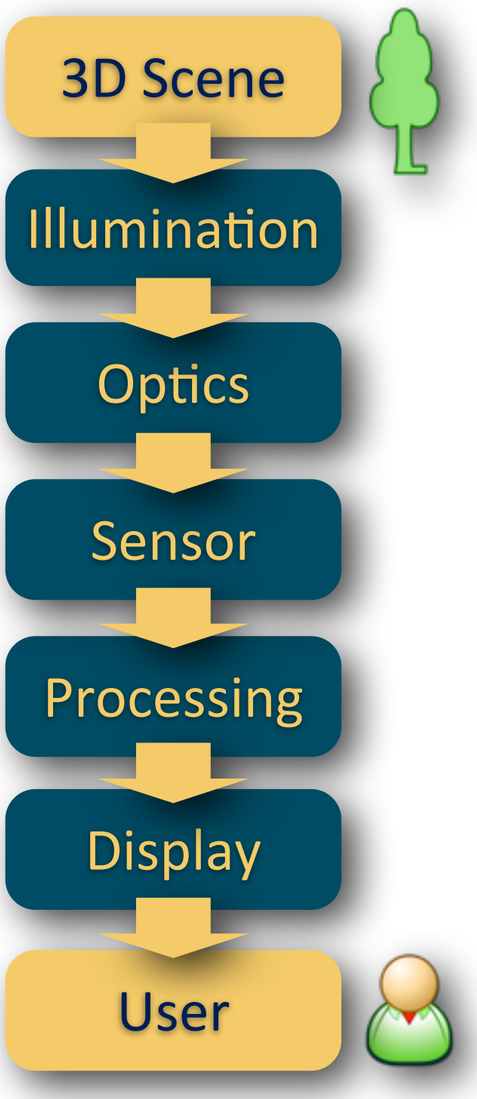
REVIEW: Photography (Light Rays)



- Images represent a view of the scene using 2D array of pixels.
- 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.

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

REVIEW: Photography (Light Rays)



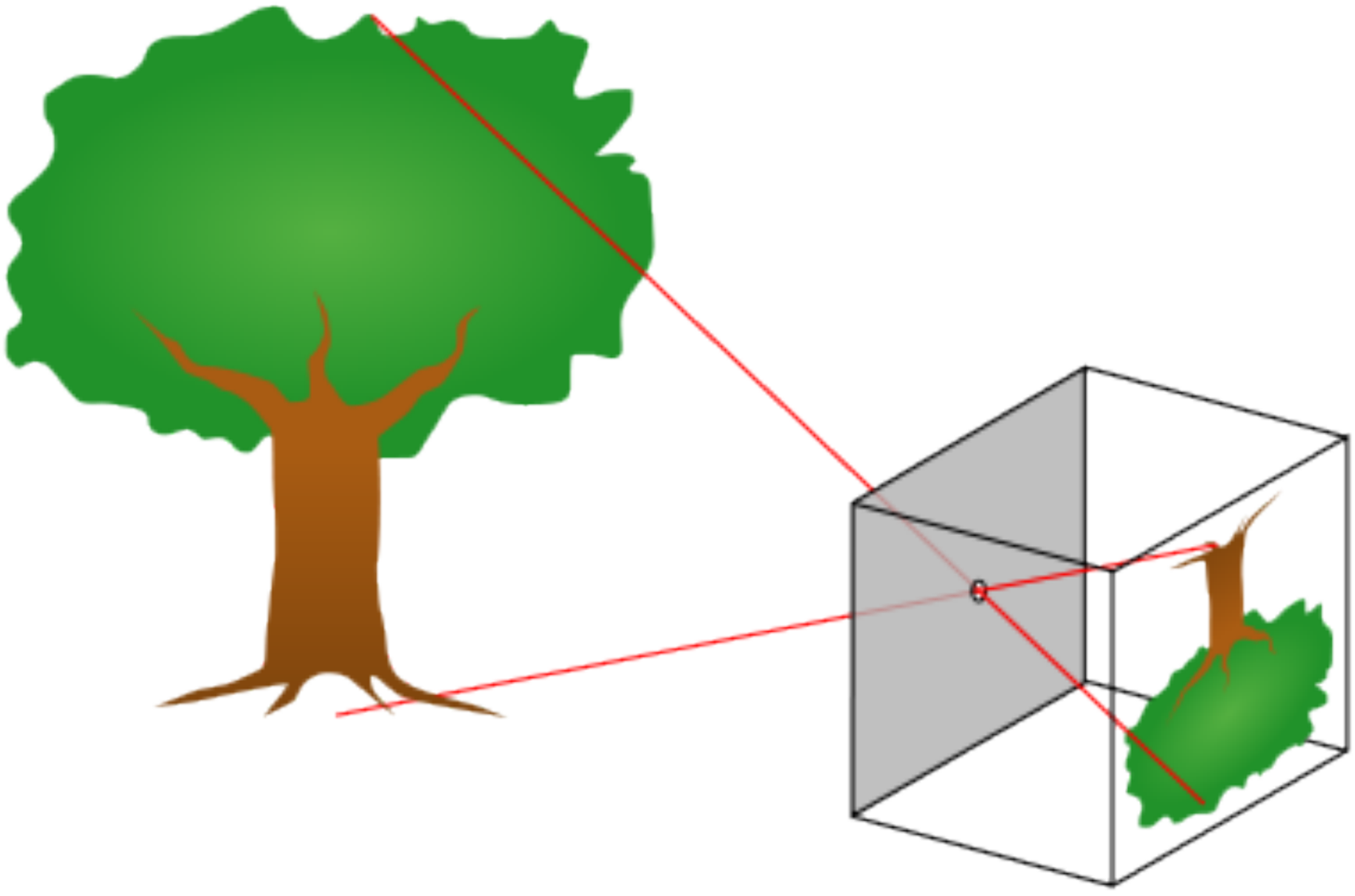
Rays

Pixels

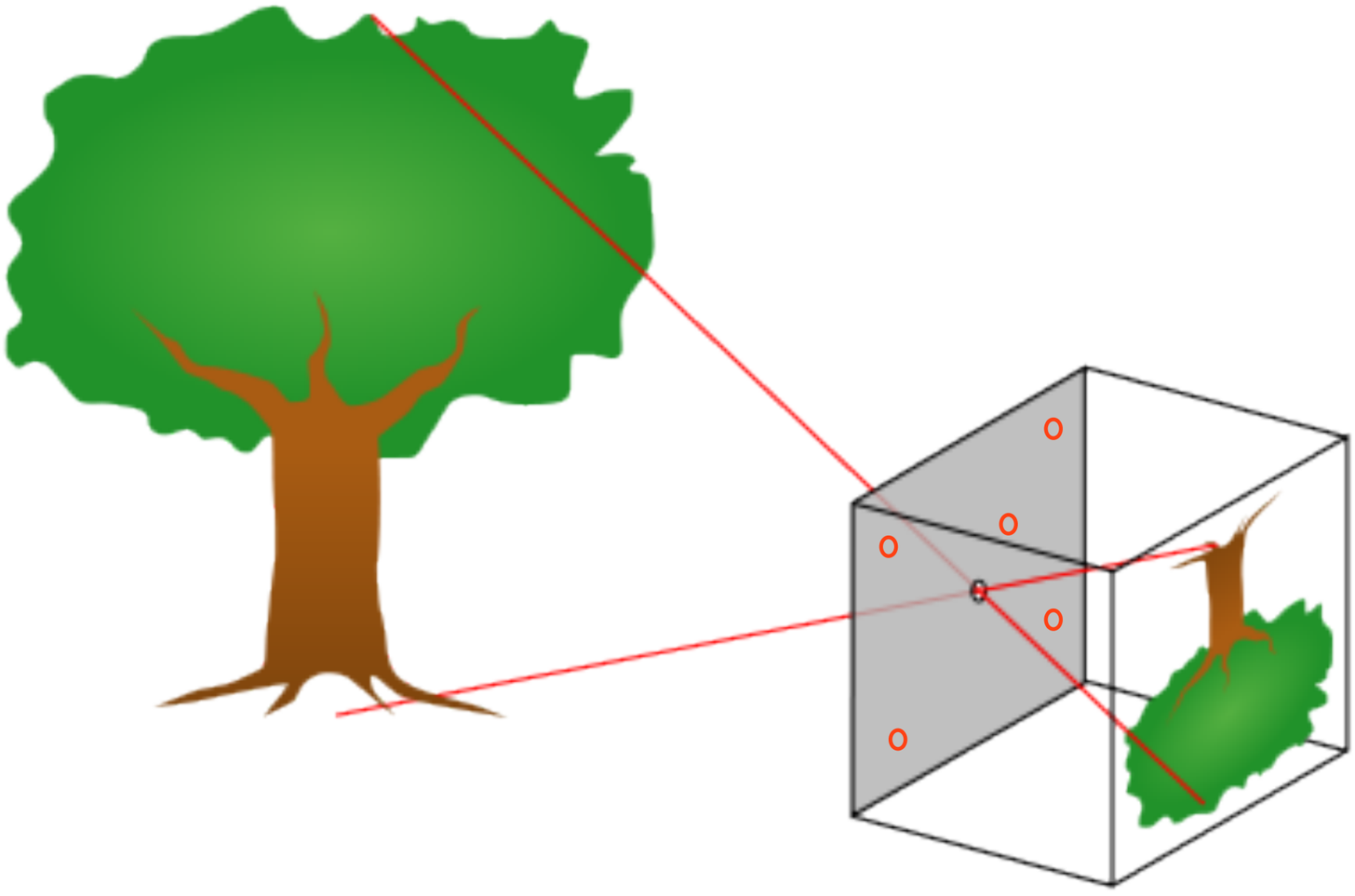
- Images represent a view of the scene using 2D array of pixels.
- Rays of Light are the fundamental primitives.
- Illumination (Light Rays) follows a path from the scene to the sensor.
- Computation adaptively controls the parameters of the optics, sensor and illumination.
- **Is this limiting? Can we not be just stuck with pixels at the end?**

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

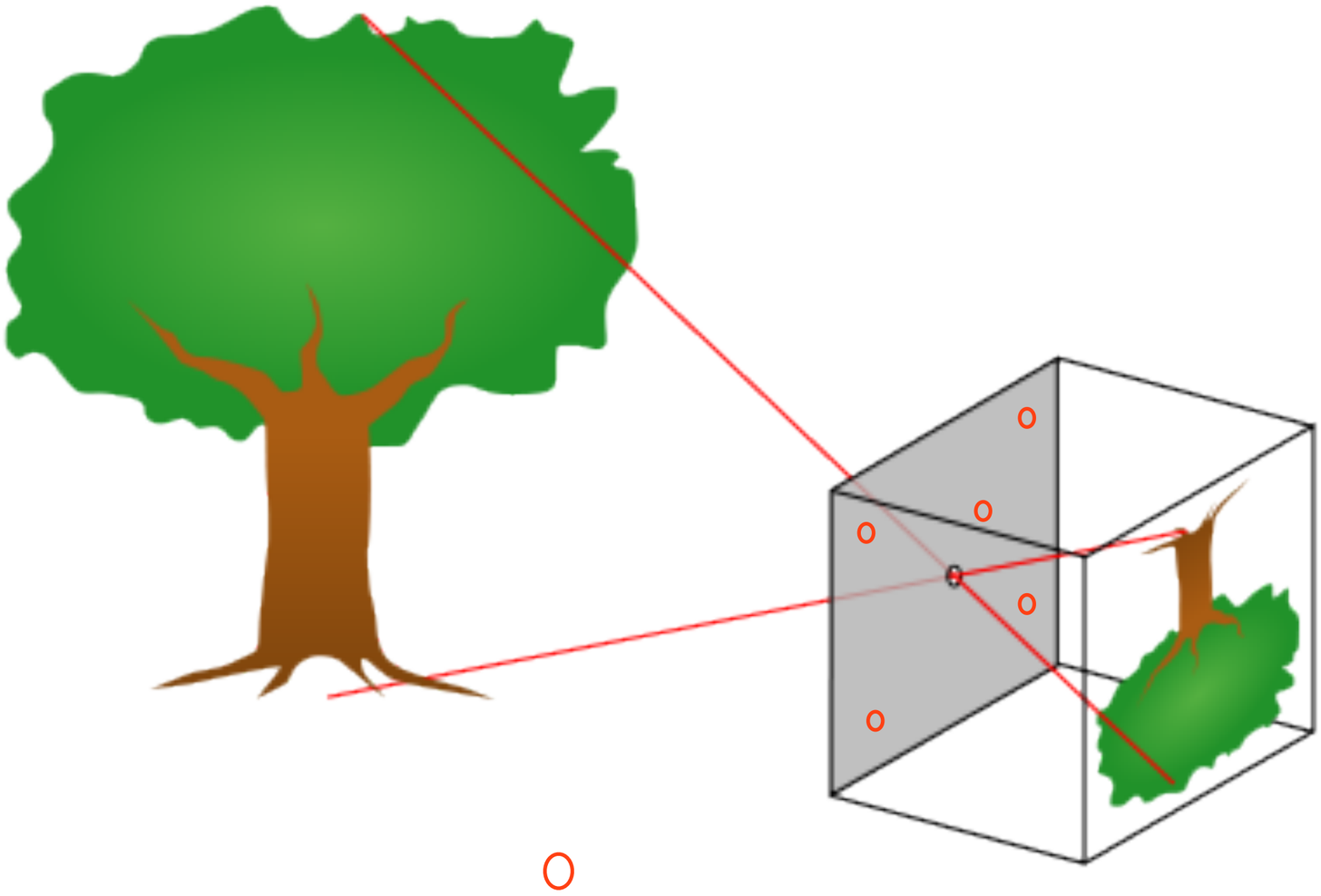
Pinhole Camera and a Light Field



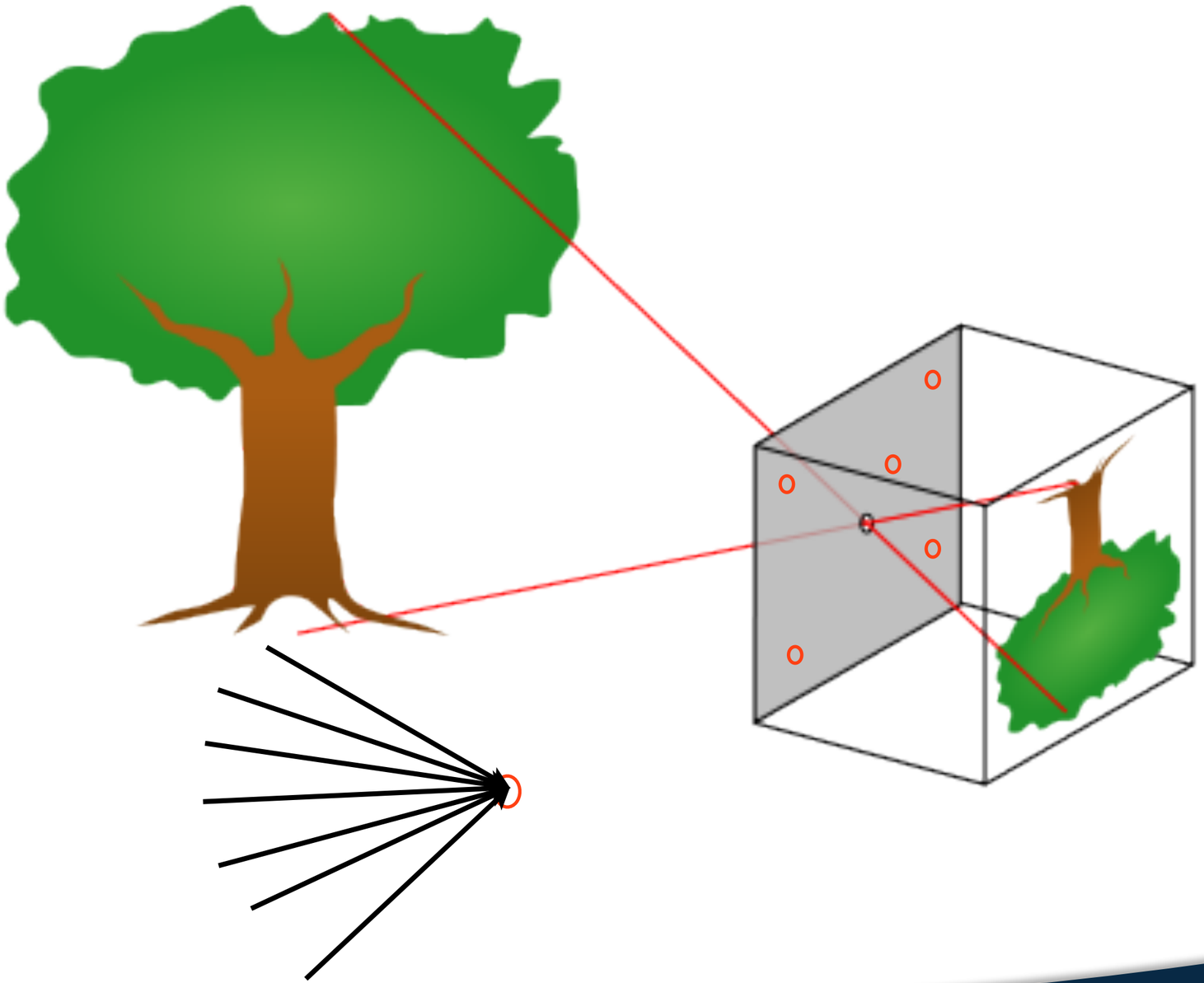
Pinhole Camera and a Light Field



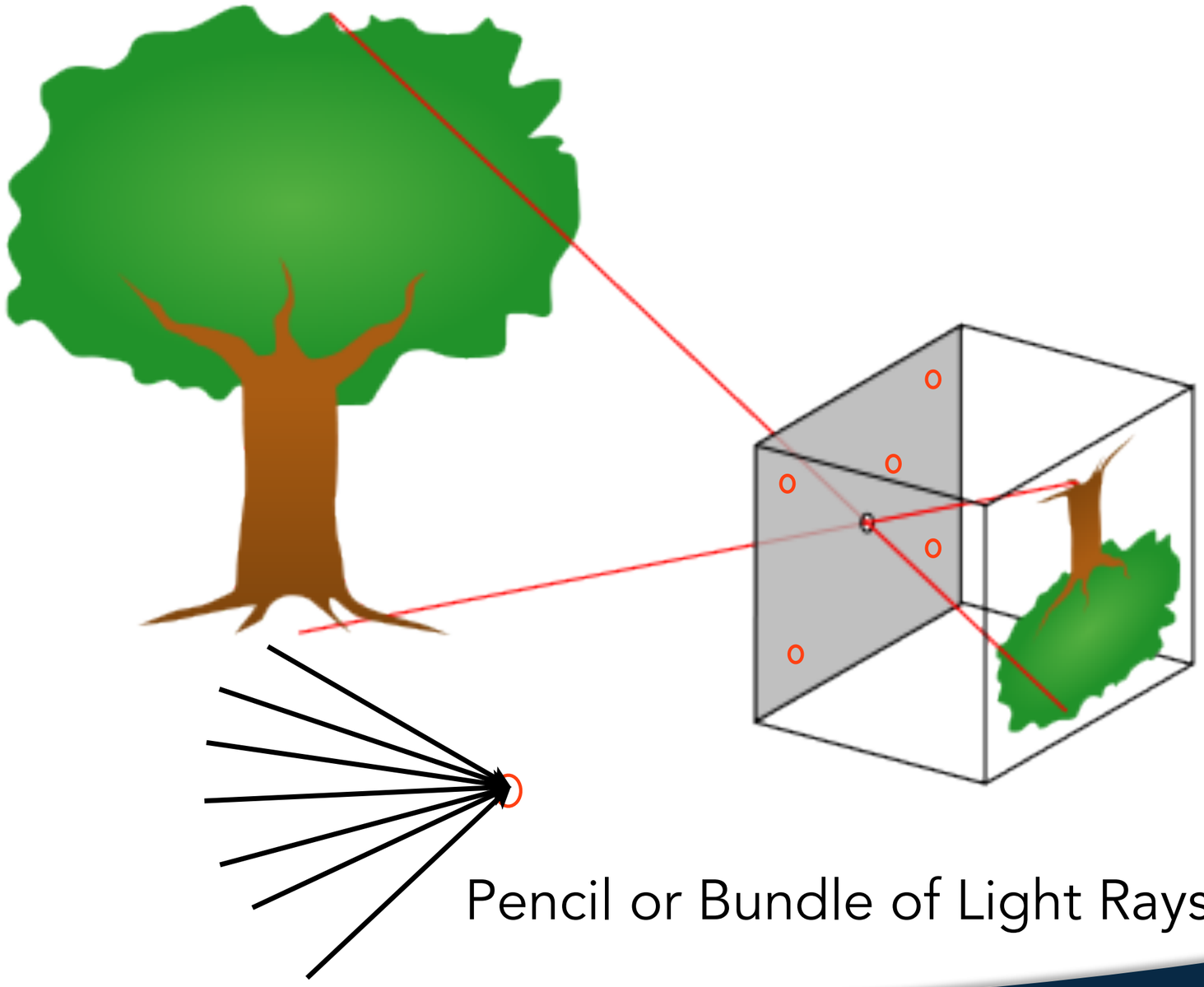
Pinhole Camera and a Light Field



Pinhole Camera and a Light Field

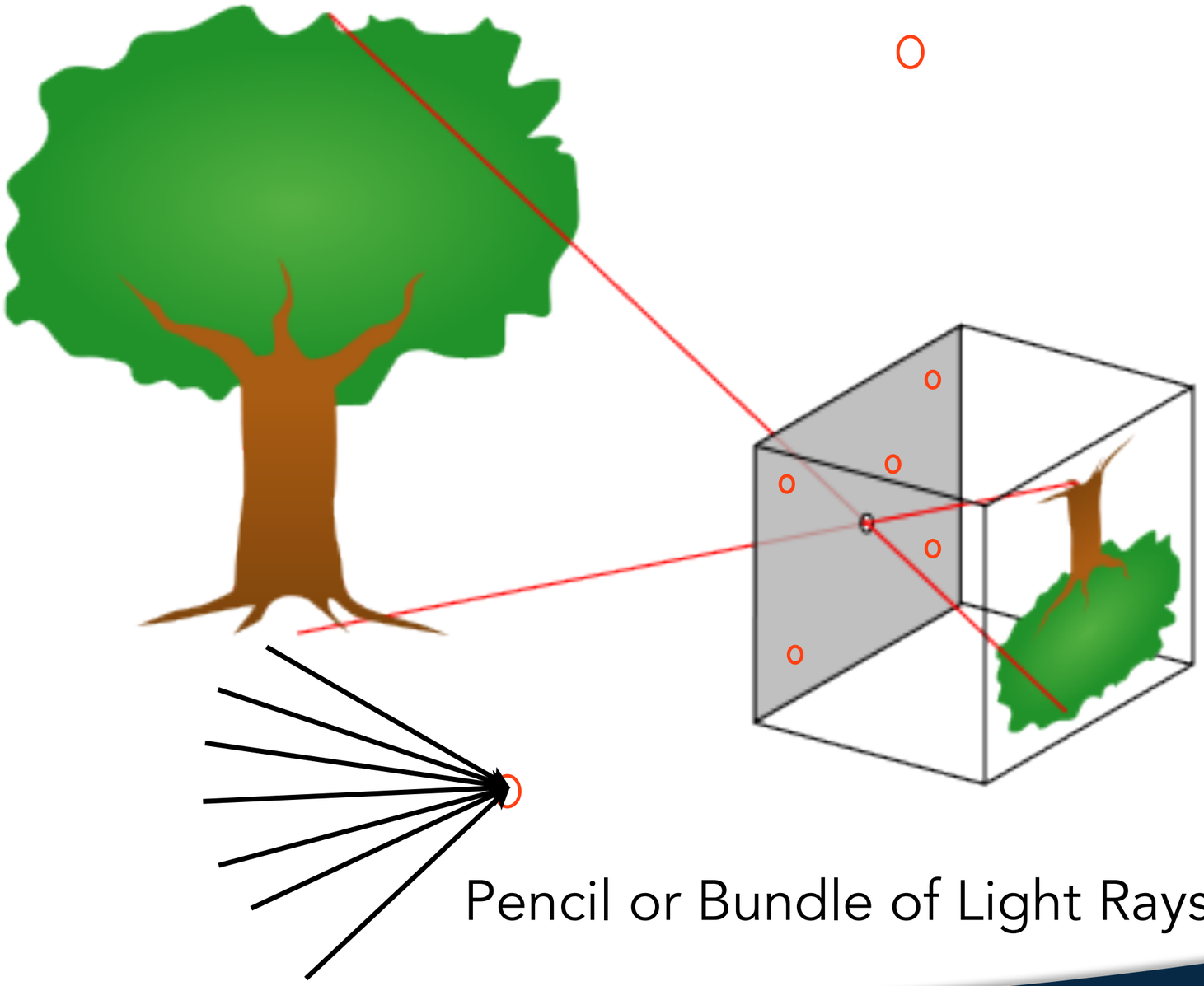


Pinhole Camera and a Light Field



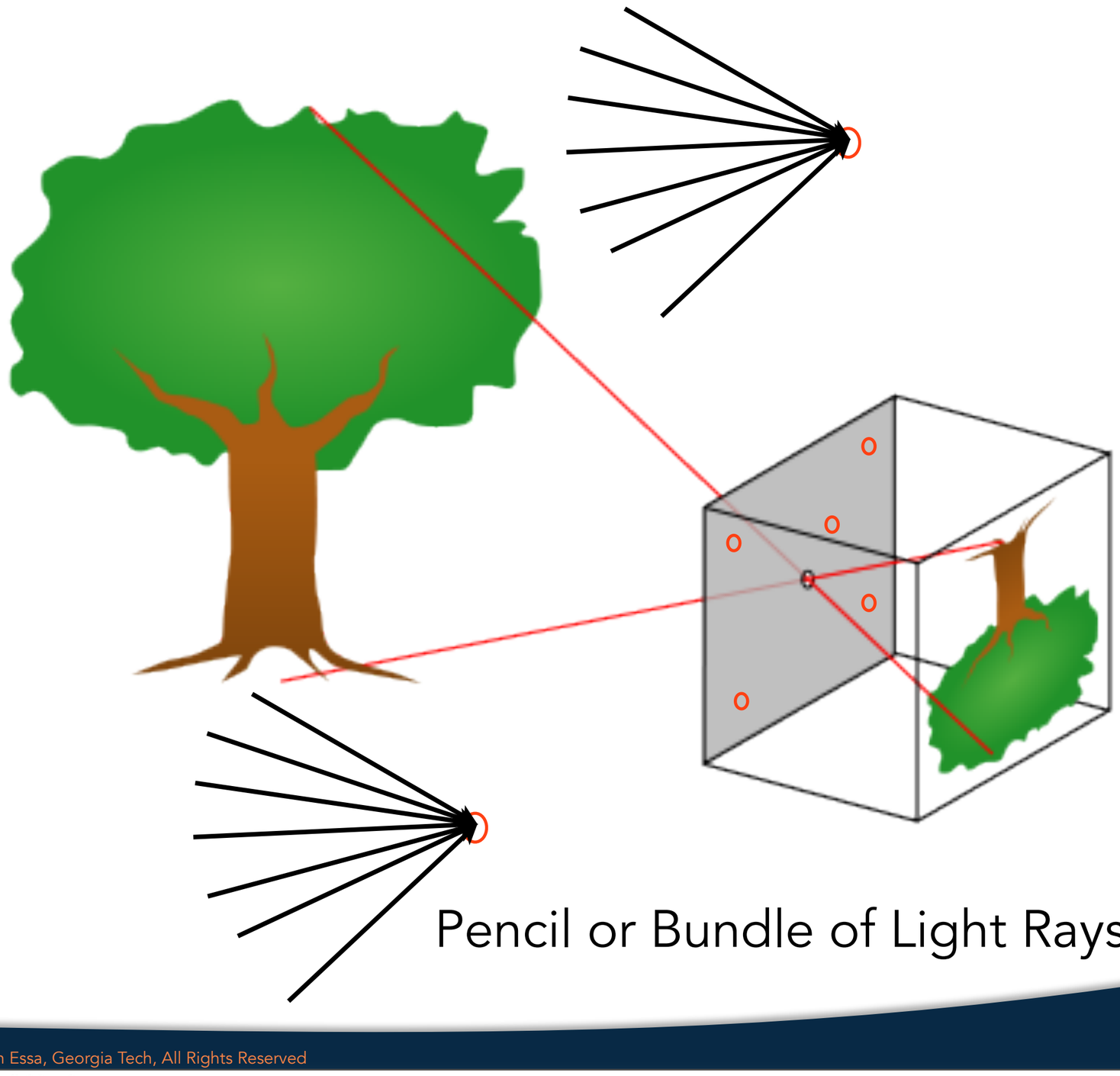
Pencil or Bundle of Light Rays

Pinhole Camera and a Light Field



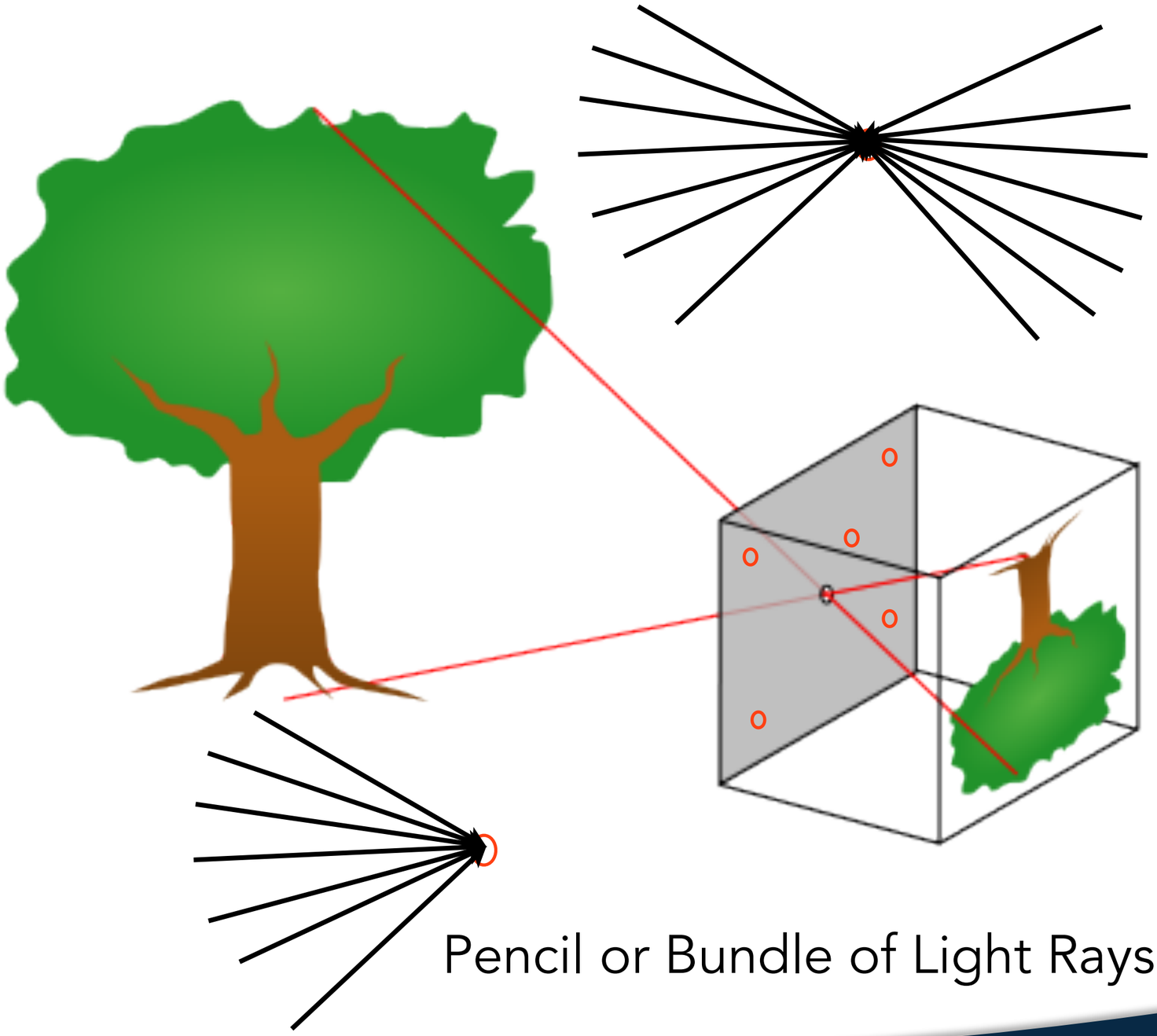
Pencil or Bundle of Light Rays

Pinhole Camera and a Light Field



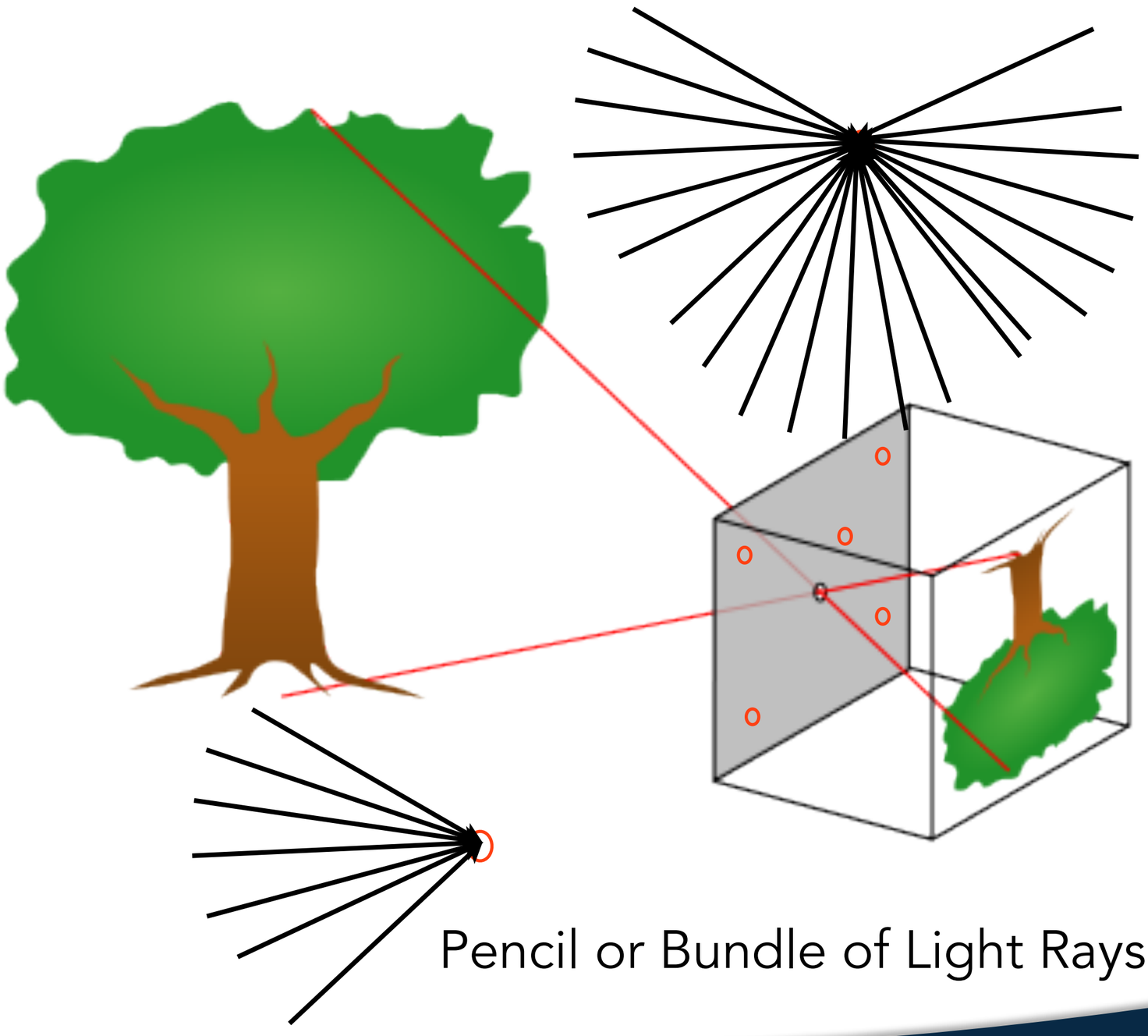
Pencil or Bundle of Light Rays

Pinhole Camera and a Light Field



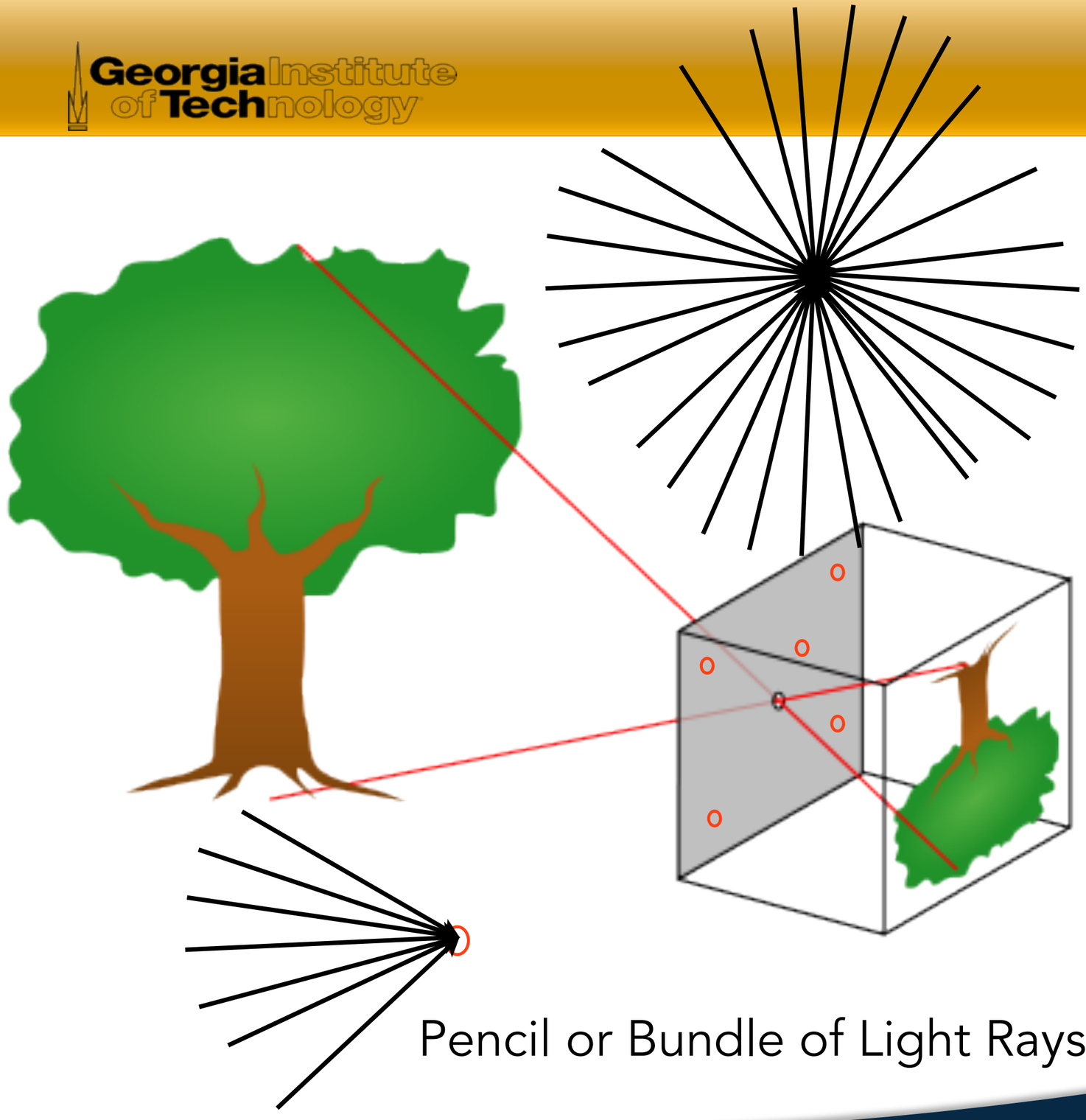
Pencil or Bundle of Light Rays

Pinhole Camera and a Light Field



Pencil or Bundle of Light Rays

Pinhole Camera and a Light Field

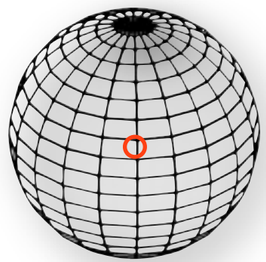


Pencil or Bundle of Light Rays

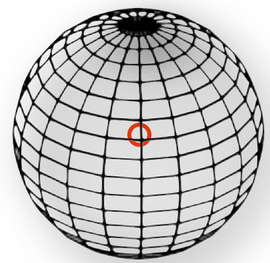
Pinhole Camera and a Light Field

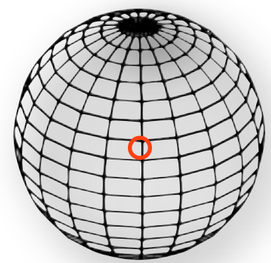
Pinhole Camera and a Light Field

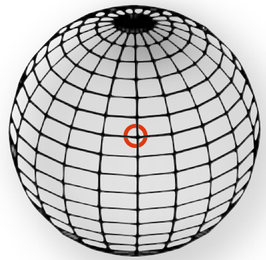
Pinhole Camera and a Light Field

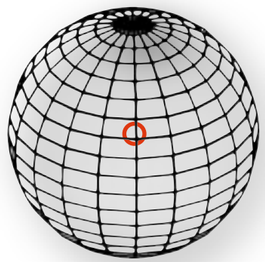


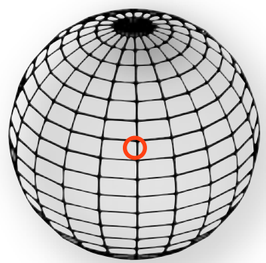
Pinhole Camera and a Light Field





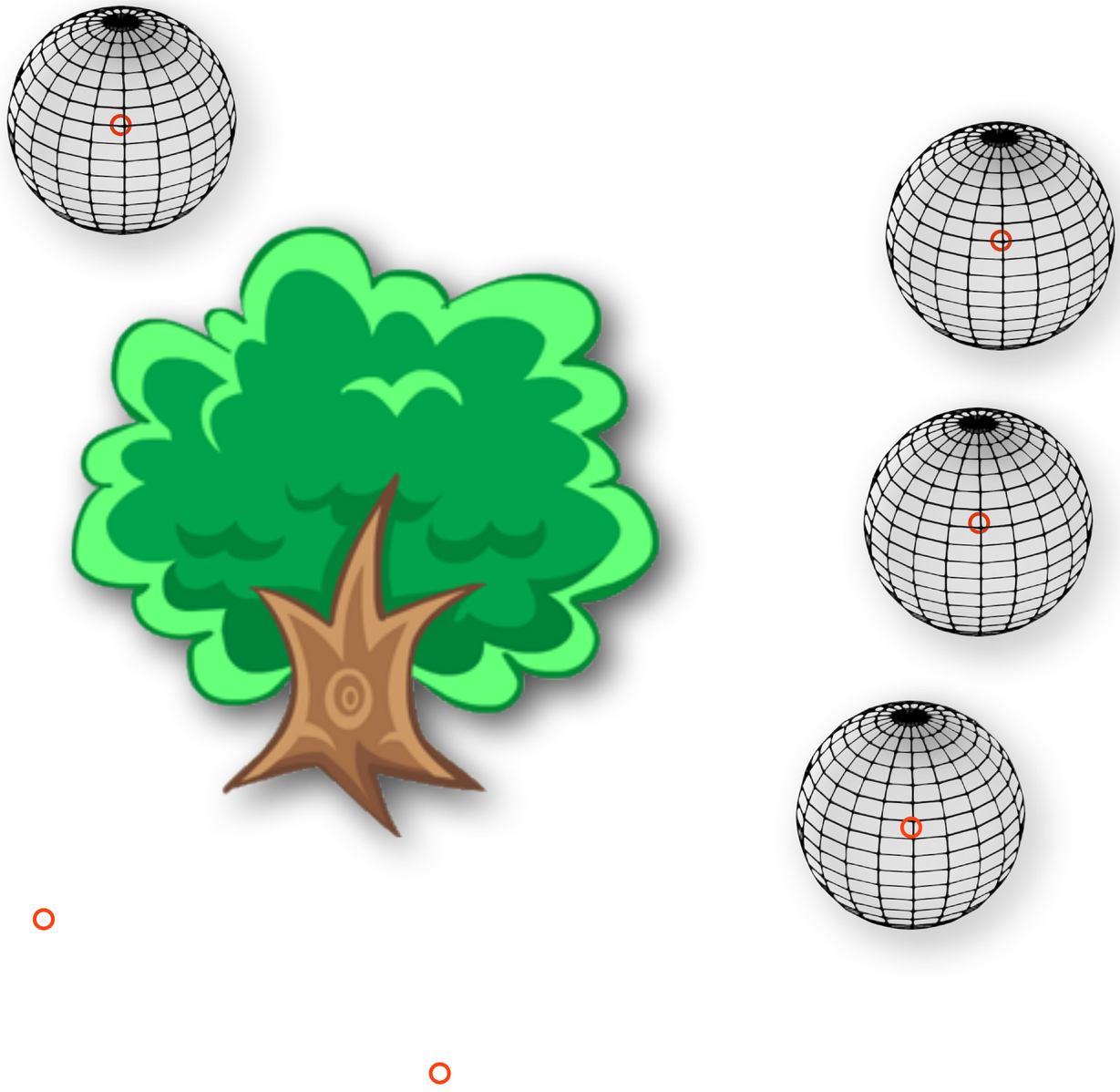






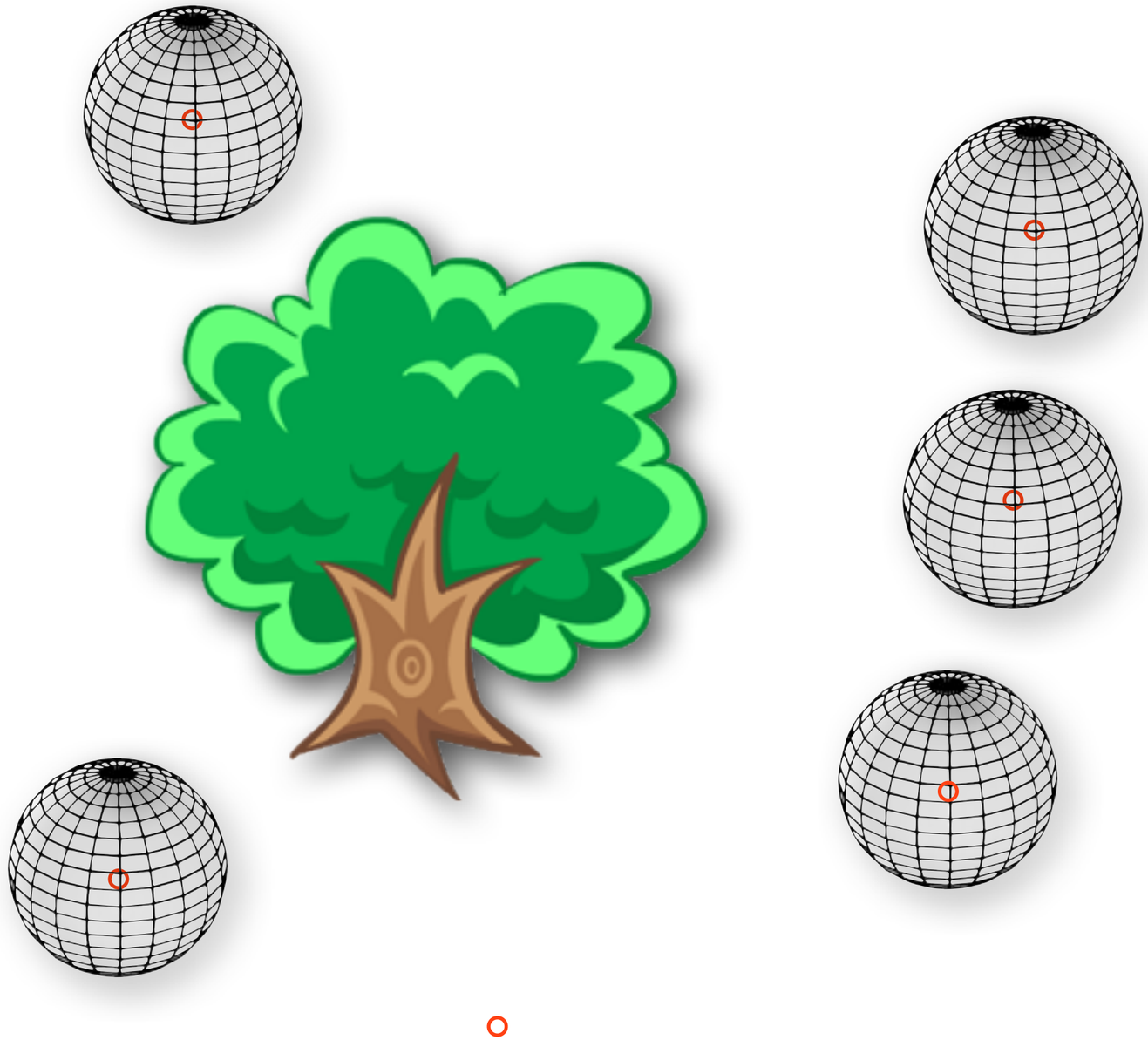
Pinhole Camera and a Light Field

6

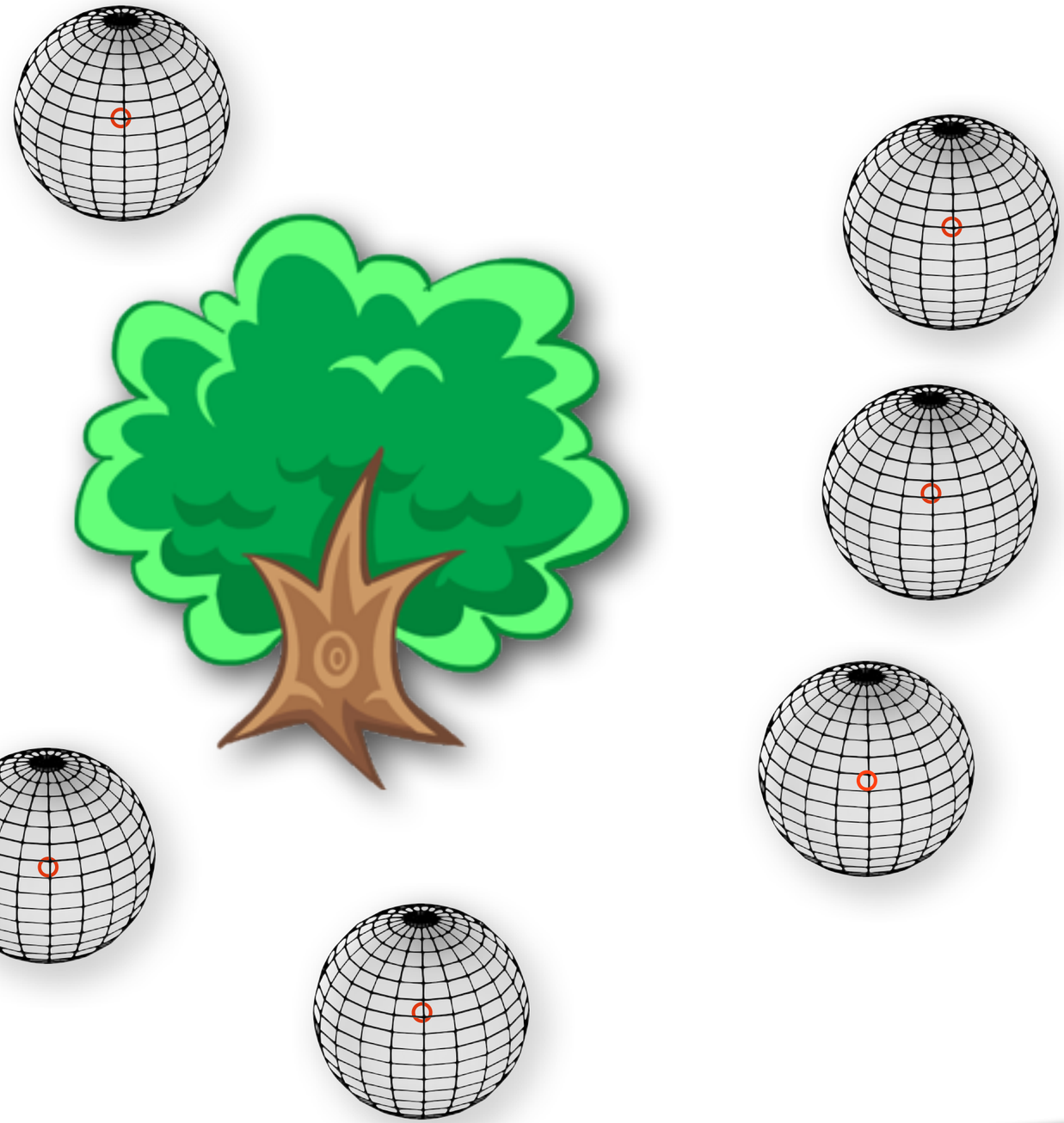


Pinhole Camera and a Light Field

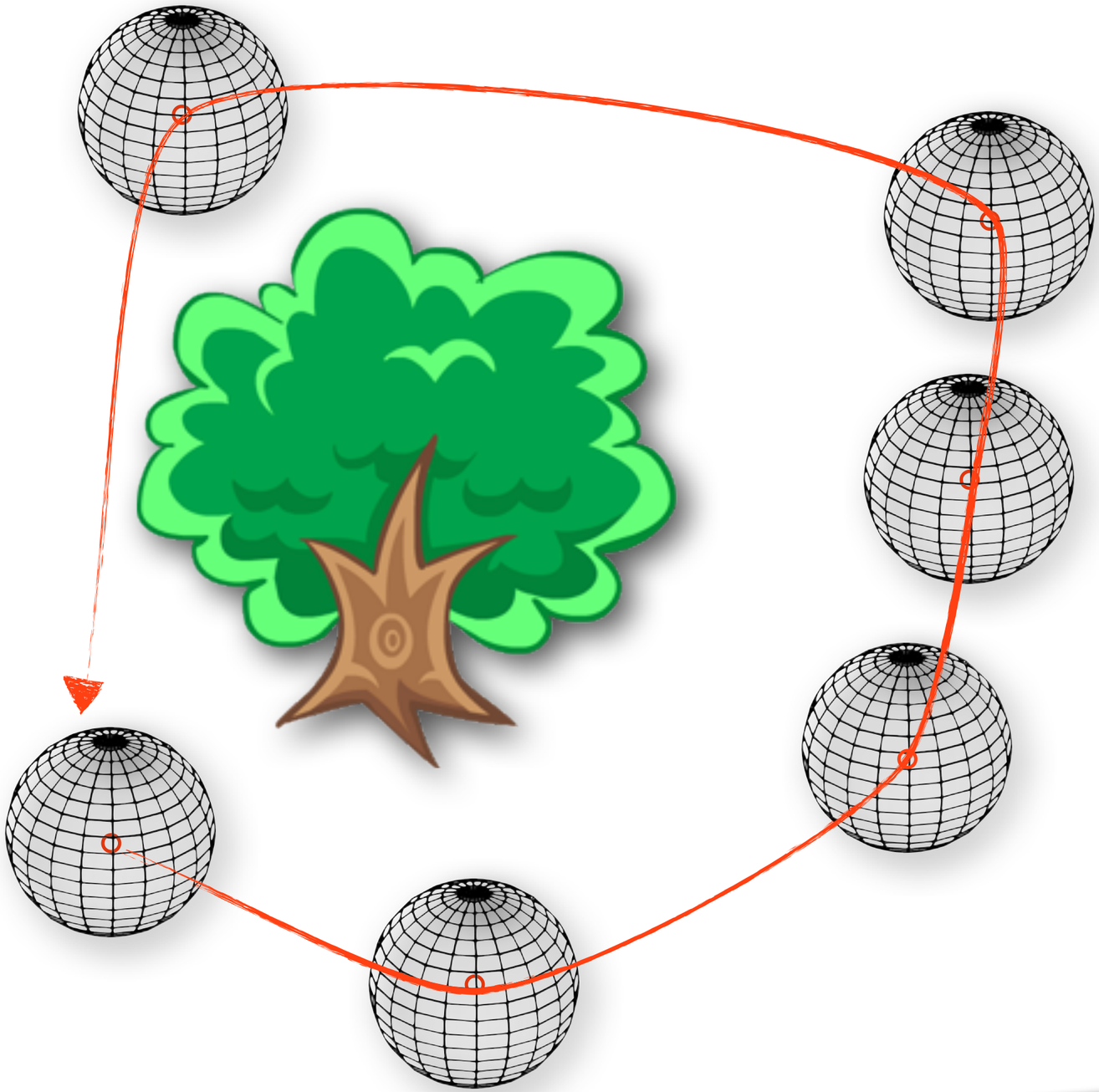
6



Pinhole Camera and a Light Field



Pinhole Camera and a Light Field



Pinhole Camera and a Light Field

Parameterizing the Light Field

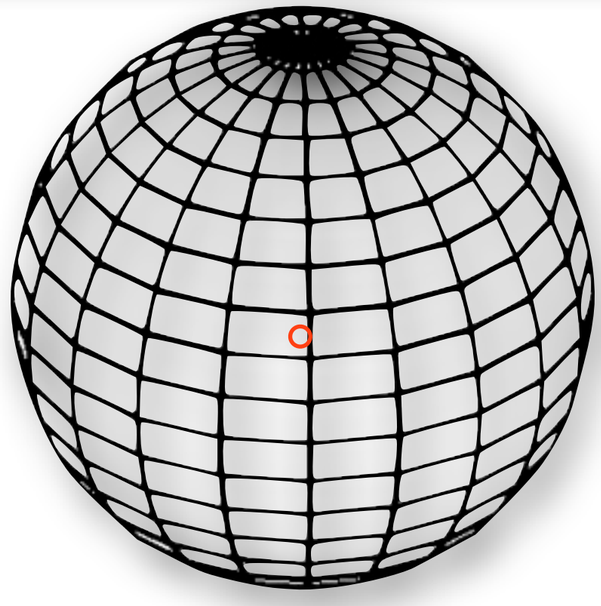
Let's say *P* is the intensity distribution at that point.

Parameterizing the Light Field

Let's say *P* is the intensity distribution at that point.

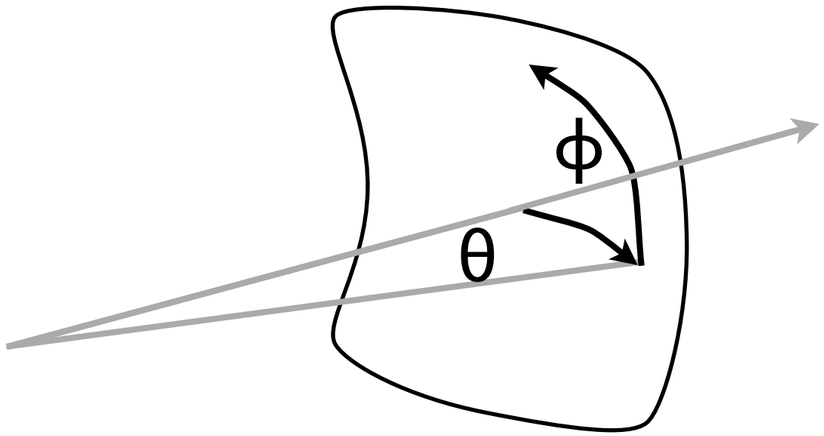
Parameterizing the Light Field

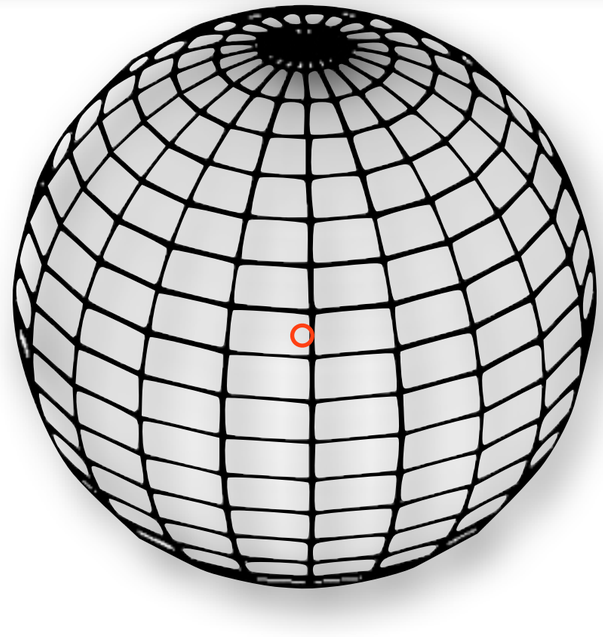
Let's say *P* is the intensity distribution at that point.



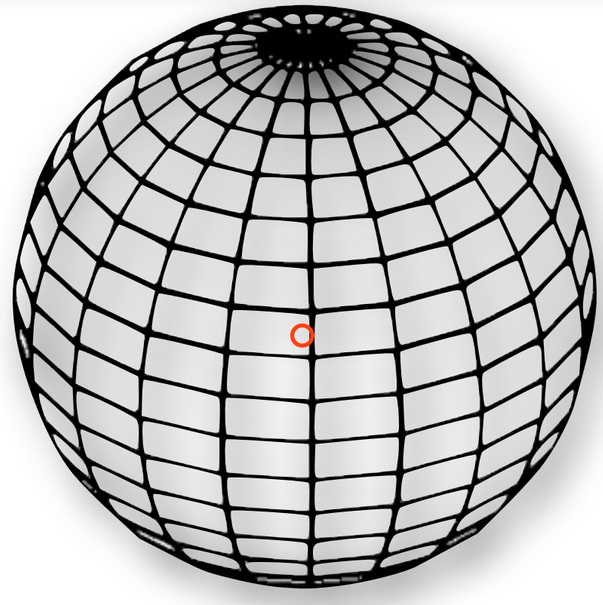
Parameterizing the Light Field

Let's say *P* is the intensity distribution at that point.

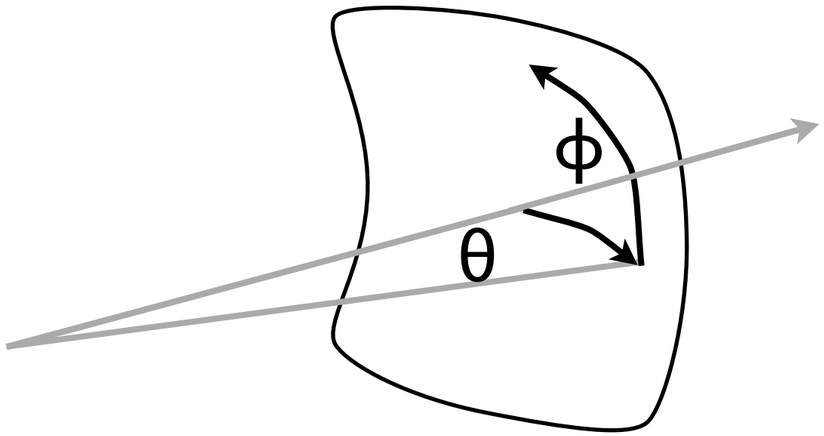




Parameterizing the Light Field



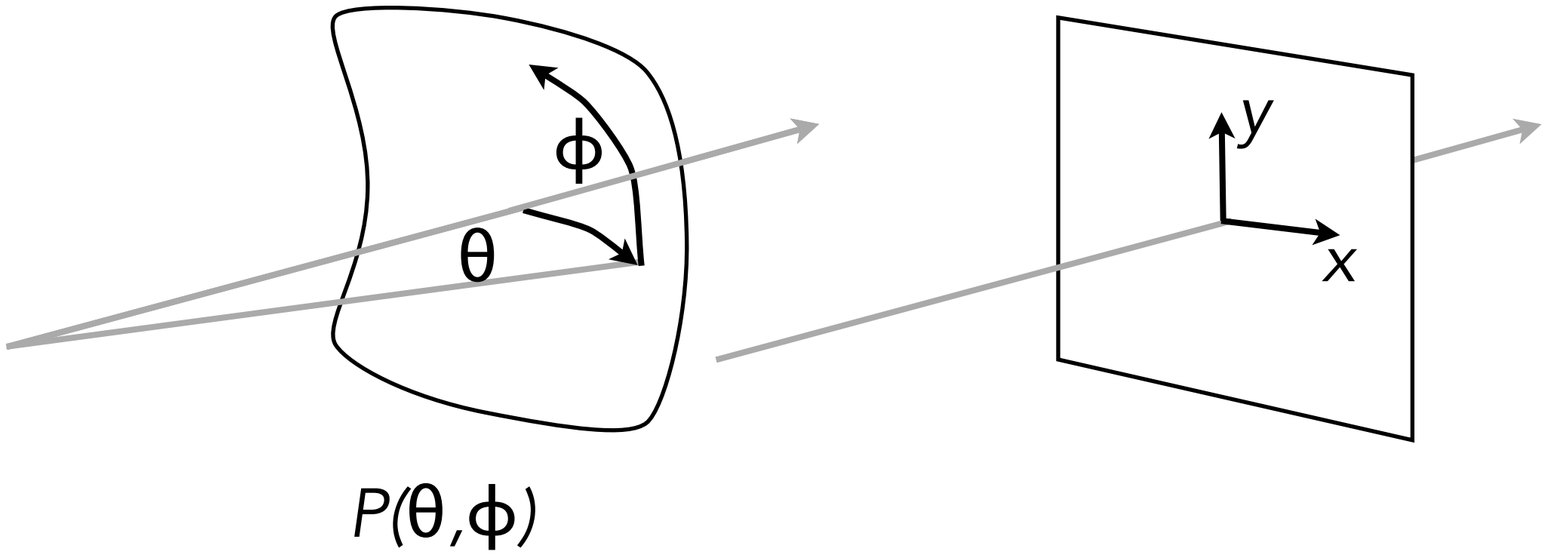
Let's say *P* is the intensity distribution at that point.

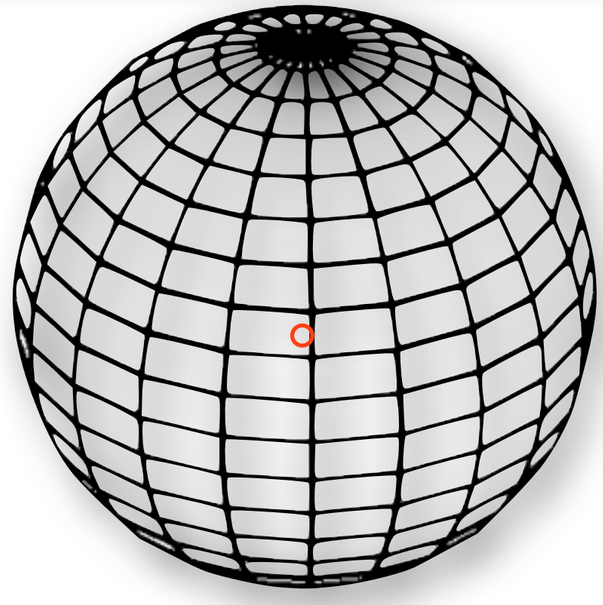


$P(\theta,\phi)$

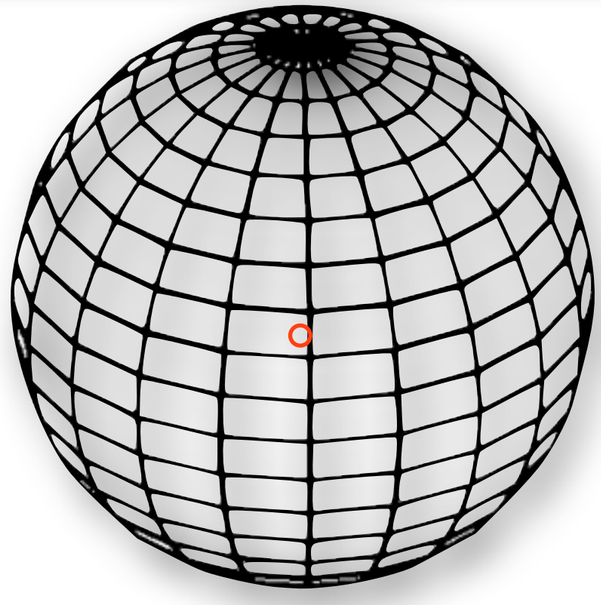
Parameterizing the Light Field

Let's say *P* is the intensity distribution at that point.

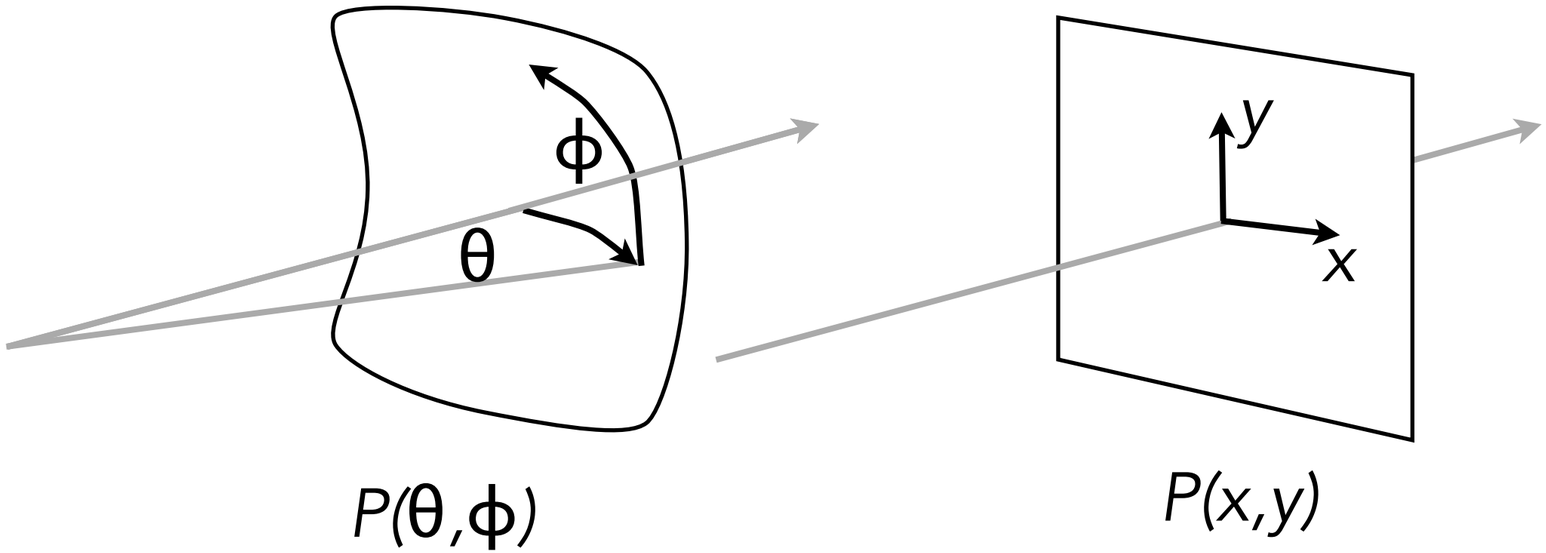




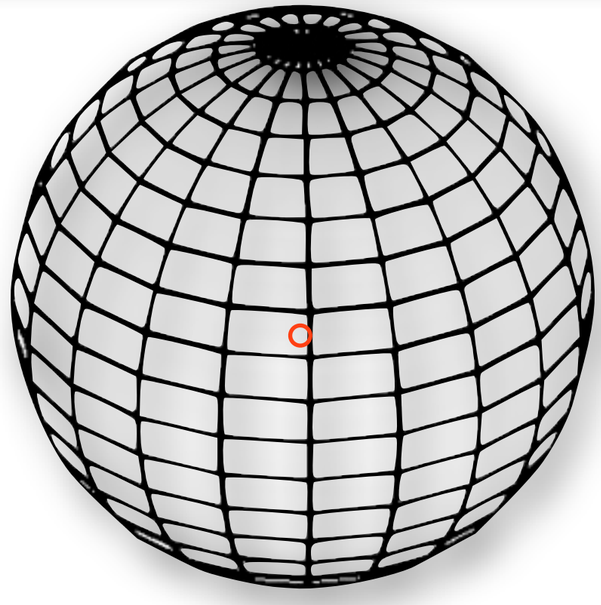
Parameterizing the Light Field



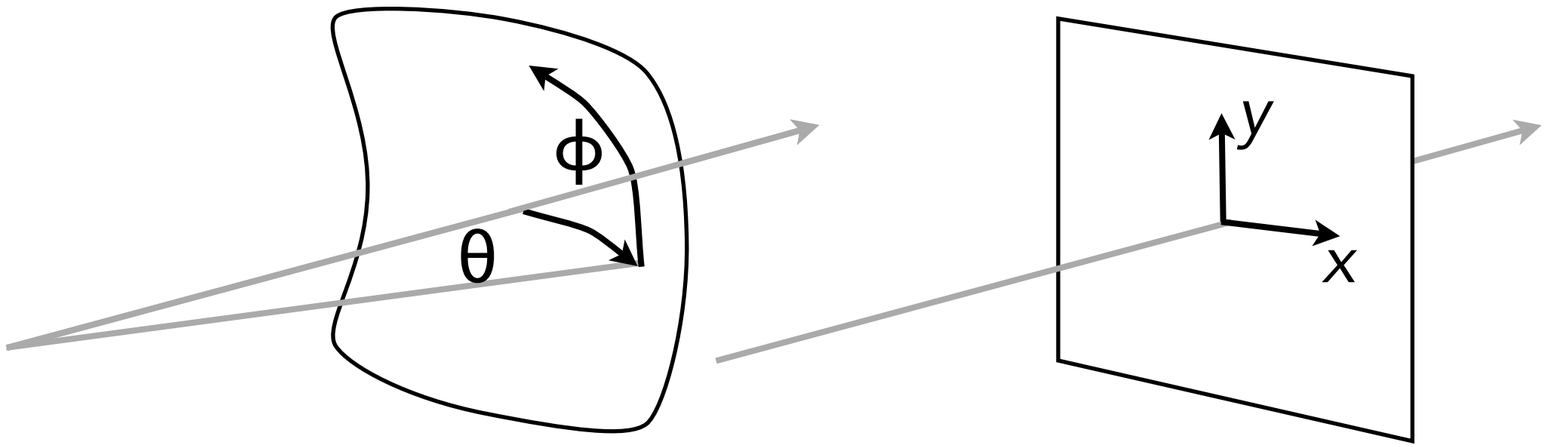
Let's say *P* is the intensity distribution at that point.



Parameterizing the Light Field



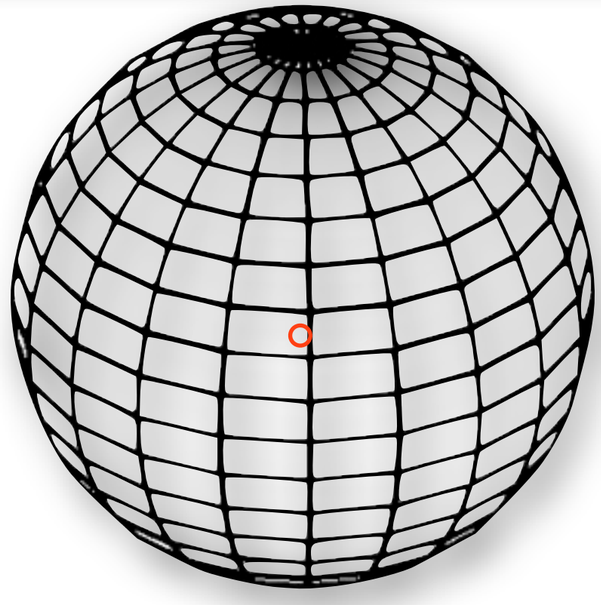
Let's say *P* is the intensity distribution at that point.



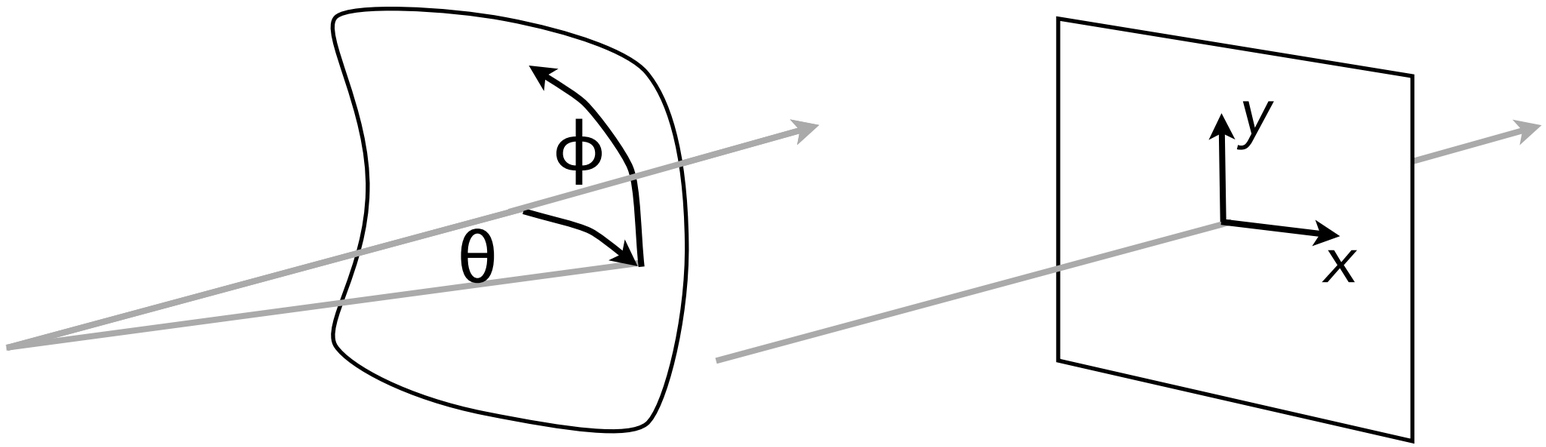
Light has color (wavelength), so need λ

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

Parameterizing the Light Field



Let's say *P* is the intensity distribution at that point.



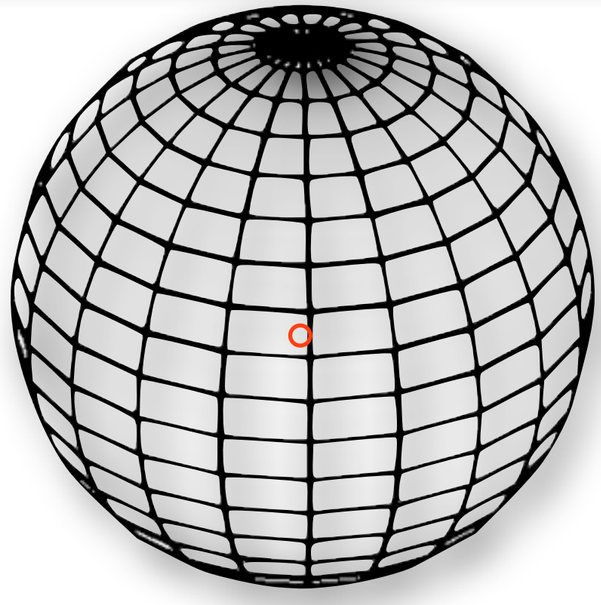
$P(\theta,\phi)$ $P(x,y)$

Light has color (wavelength), so need λ

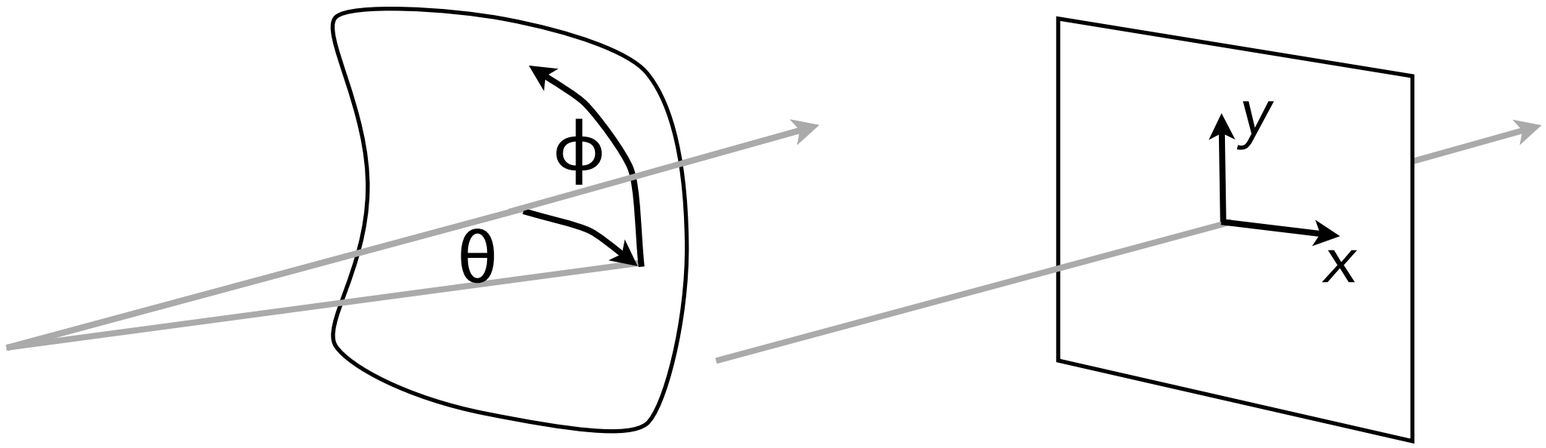
And, scenes change over time, so need t

$P(\theta,\phi,\lambda,t)$

Parameterizing the Light Field



Let's say *P* is the intensity distribution at that point.



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

Light has color (wavelength), so need λ

And, scenes change over time, so need t

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

Parameterizing the Light Field

$P(\theta,\phi,\lambda,t)$

$P(x,y,\lambda,t)$

Adelson and Bergen (1991)

Parameterizing the Light Field

$P(\theta,\phi,\lambda,t)$

$P(x,y,\lambda,t)$

Adelson and Bergen (1991)

Parameterizing the Light Field

$P(\theta,\phi,\lambda,t)$

$P(x,y,\lambda,t)$

Adelson and Bergen (1991)

Parameterizing the Light Field

$P(\theta,\phi,\lambda,t)$

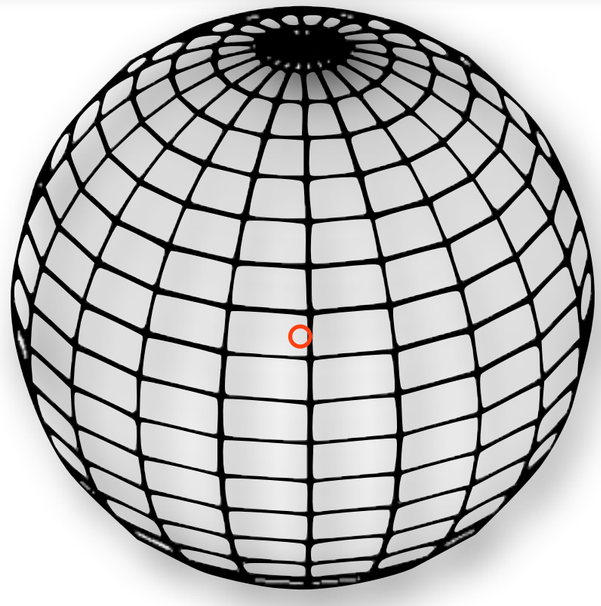
$P(x,y,\lambda,t)$

Adelson and Bergen (1991)

Parameterizing the Light Field

$P(\theta,\phi,\lambda,t)$

$P(x,y,\lambda,t)$



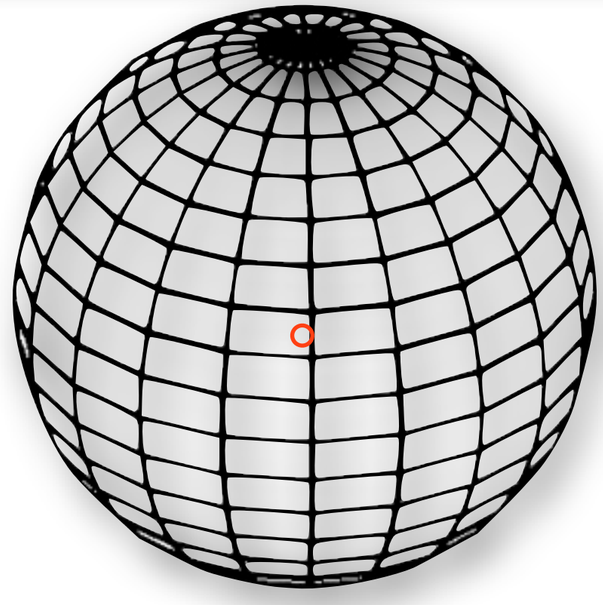
Adelson and Bergen (1991)

8

Parameterizing the Light Field

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

Let's say V_x, V_y, V_z is the position of the viewing point



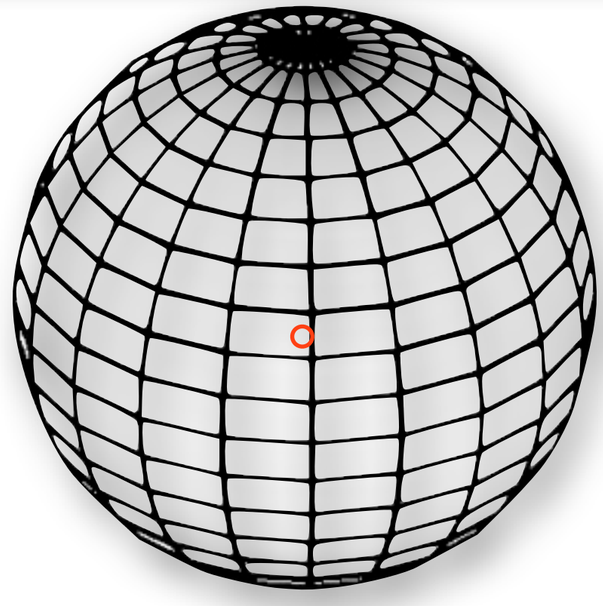
Adelson and Bergen (1991)

Parameterizing the Light Field

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

Let's say V_x, V_y, V_z is the position of the viewing point

Introducing the Plenoptic Function, P_f



Adelson and Bergen (1991)

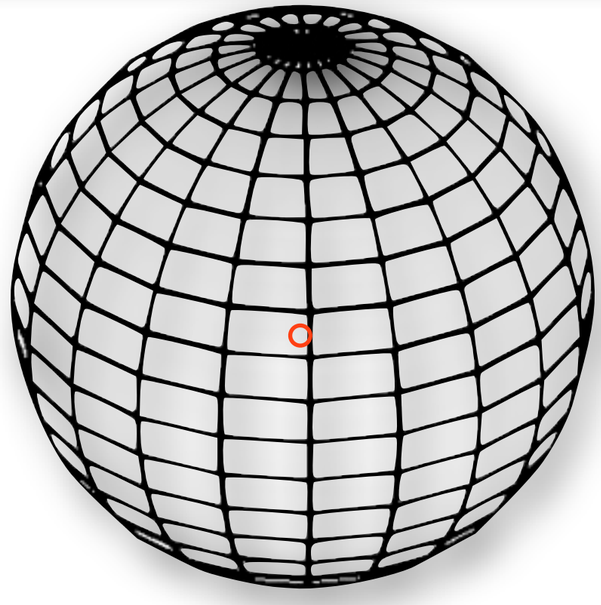
Parameterizing the Light Field

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

Let's say V_x, V_y, V_z is the position of the viewing point

Introducing the Plenoptic Function, P_f

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



Adelson and Bergen (1991)

8

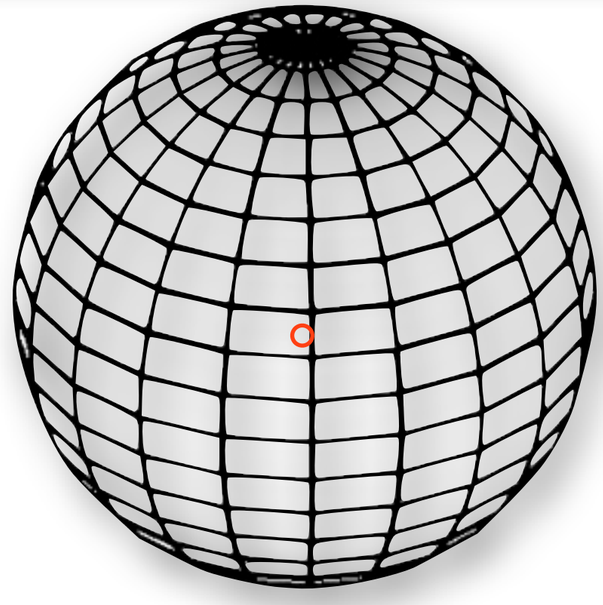
Parameterizing the Light Field

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

Let's say V_x, V_y, V_z is the position of the viewing point

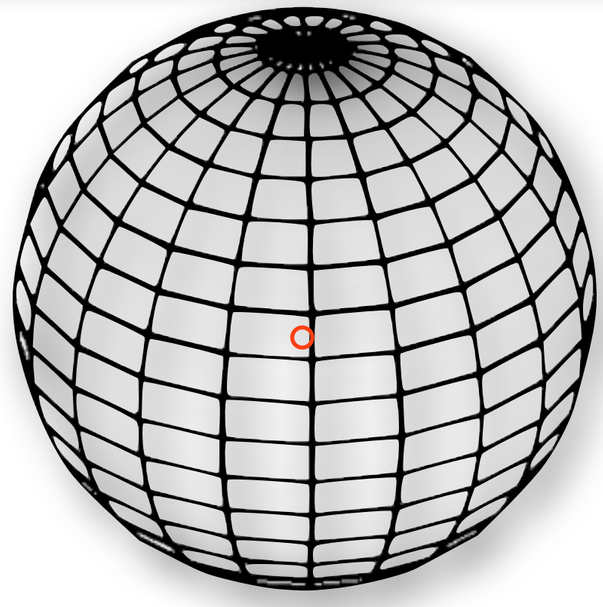
Introducing the Plenoptic Function, P_f

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



Adelson and Bergen (1991)

Parameterizing the Light Field



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

Let's say V_x, V_y, V_z is the position of the viewing point

Introducing the Plenoptic Function, P_f

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

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 or in terms of (x,y).

Adelson and Bergen (1991)

Plenoptic Function

Adelson and Bergen (1991)

Plenoptic Function

Adelson and Bergen (1991)

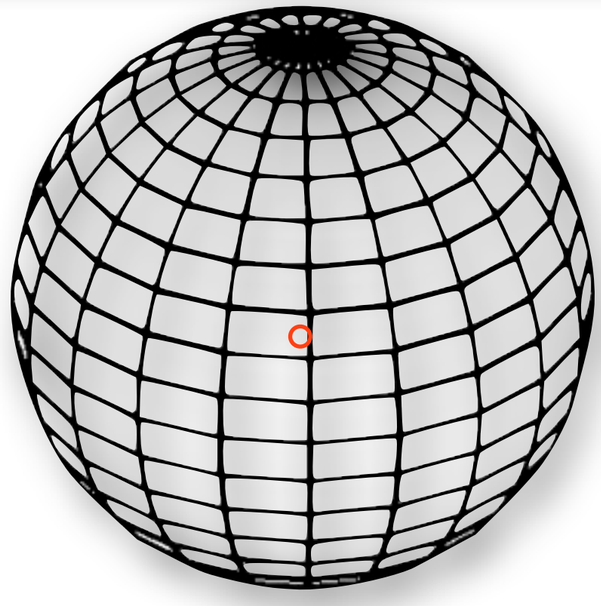
Plenoptic Function

Adelson and Bergen (1991)

Plenoptic Function

Adelson and Bergen (1991)

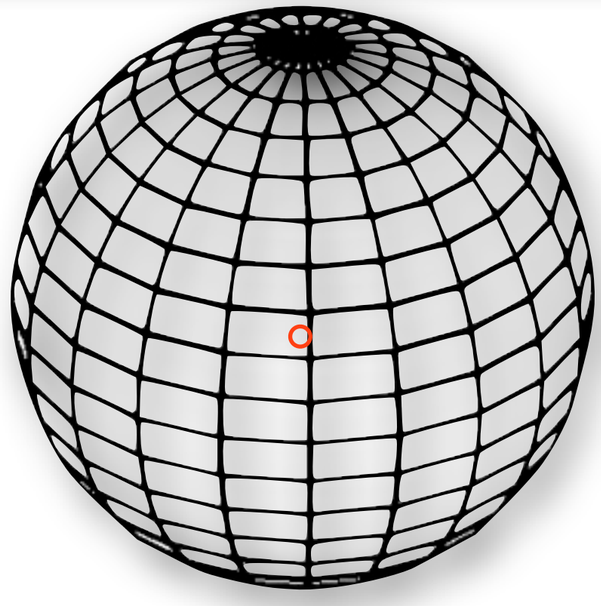
Plenoptic Function



Adelson and Bergen (1991)

Plenoptic Function

Introducing the Plenoptic Function, P_f

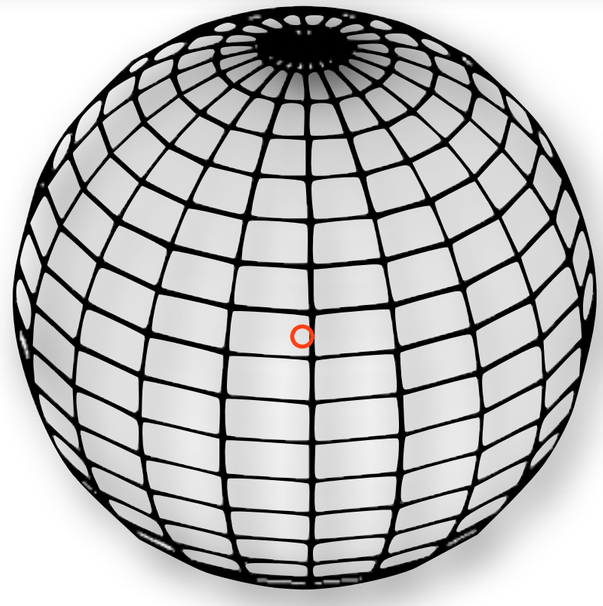


Adelson and Bergen (1991)

Plenoptic Function

Introducing the Plenoptic Function, P_f

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

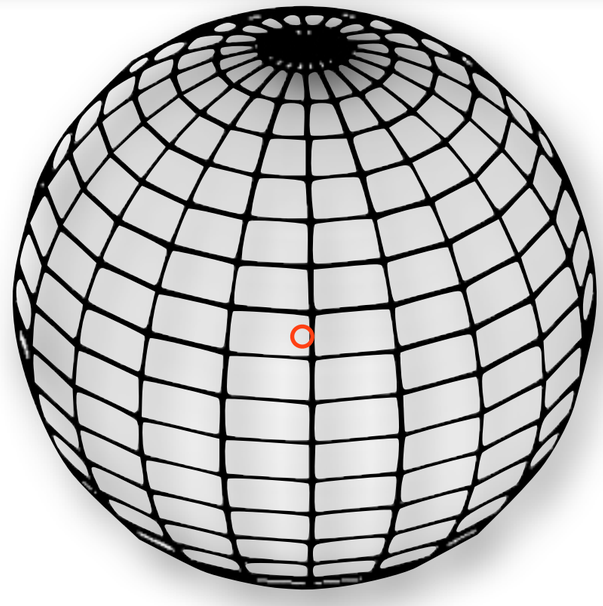


Adelson and Bergen (1991)

Plenoptic Function

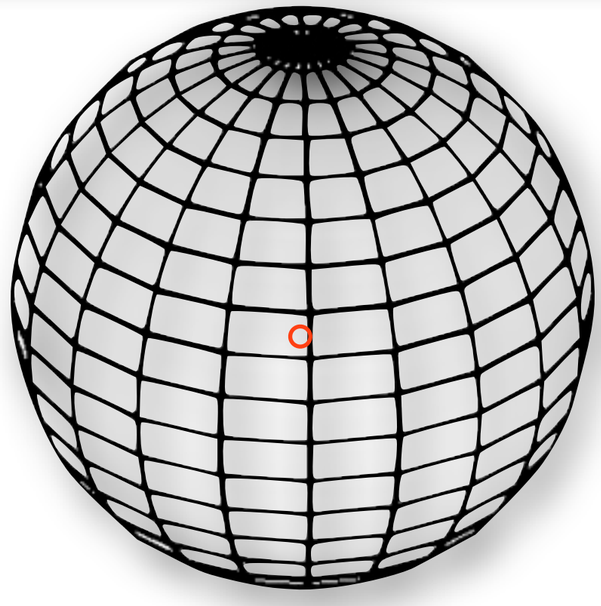
Introducing the Plenoptic Function, P_f

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



Adelson and Bergen (1991)

Plenoptic Function



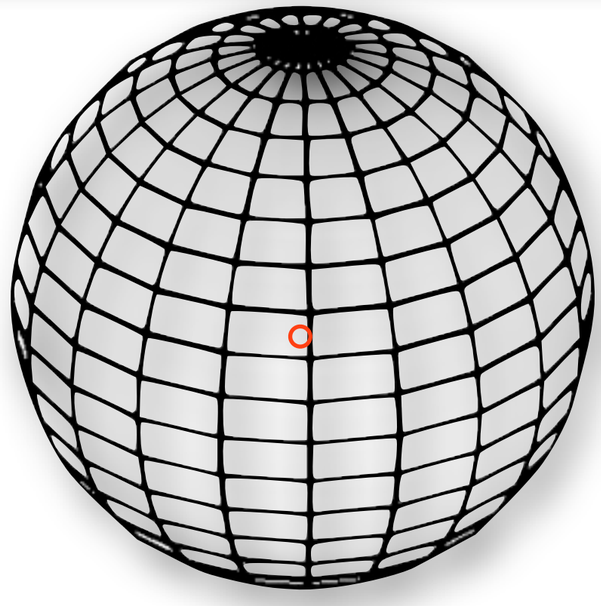
Introducing the Plenoptic Function, P_f

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

Plenoptic: (Latin) plenus (full) + optic
"Of or relating to all the light, traveling in every direction in a given space."

Adelson and Bergen (1991)

Plenoptic Function



Introducing the Plenoptic Function, P_f

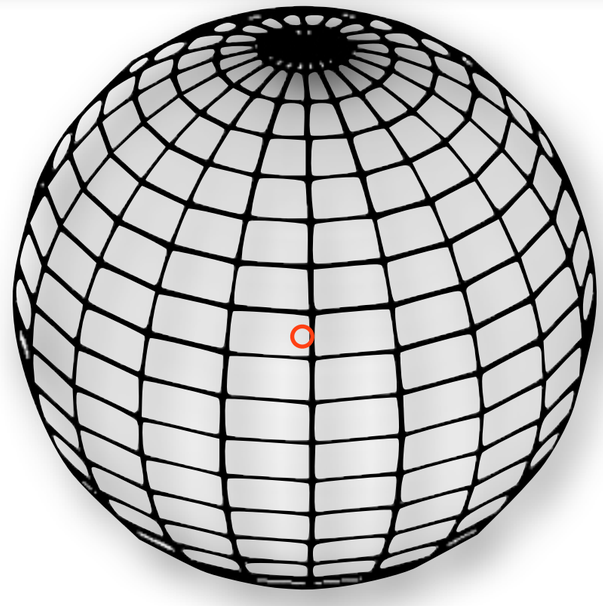
$P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ $P(x,y,\lambda,t,V_x,V_y,V_z)$

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

Adelson and Bergen (1991)

Plenoptic Function



Introducing the Plenoptic Function, P_f

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

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)

9

Capture a Light-field, Store and Render

http://en.wikipedia.org/wiki/Light_field
http://commons.wikimedia.org/wiki/File:Snow_Globe_icon.jpg

Capture a Light-field, Store and Render

- ★ $P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ ➔ *7 Dimensions*
  - Complete scene; holographic video

http://en.wikipedia.org/wiki/Light_field
http://commons.wikimedia.org/wiki/File:Snow_Globe_icon.jpg

Capture a Light-field, Store and Render

- ★ $P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ ➔ *7 Dimensions*
  - Complete scene; holographic video
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *5* Dimensions
  - Ignore time and wavelength
  - Capture only viewpoint and direction

http://en.wikipedia.org/wiki/Light_field
http://commons.wikimedia.org/wiki/File:Snow_Globe_icon.jpg

Capture a Light-field, Store and Render

- ★ $P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ ➔ *7 Dimensions*
  - Complete scene; holographic video
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *5* Dimensions
  - Ignore time and wavelength
  - Capture only viewpoint and direction
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *4* Dimensions
  - Within a bounding box. (Space of all lines in 2D space is 4D)
  - No occluding objects, with viewpoint and direction

http://en.wikipedia.org/wiki/Light_field
http://commons.wikimedia.org/wiki/File:Snow_Globe_icon.jpg

Capture a Light-field, Store and Render

- ★ $P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ ➔ *7 Dimensions*
  - Complete scene; holographic video
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *5* Dimensions
  - Ignore time and wavelength
  - Capture only viewpoint and direction
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *4* Dimensions
  - Within a bounding box. (Space of all lines in 2D space is 4D)
  - No occluding objects, with viewpoint and direction

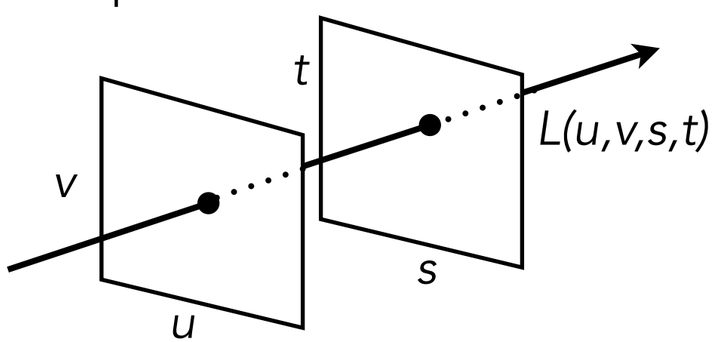
Any point within a scene is represented by a 5D plenoptic function. Outside of a scene (outside of the sphere of a snow globe) light from the scene does not get occluded by objects, and is represented, as a 4D light field.

http://en.wikipedia.org/wiki/Light_field
http://commons.wikimedia.org/wiki/File:Snow_Globe_icon.jpg

Capture a Light-field, Store and Render

- ★ $P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ ➔ *7 Dimensions*
  - Complete scene; holographic video
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *5* Dimensions
  - Ignore time and wavelength
  - Capture only viewpoint and direction
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *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.

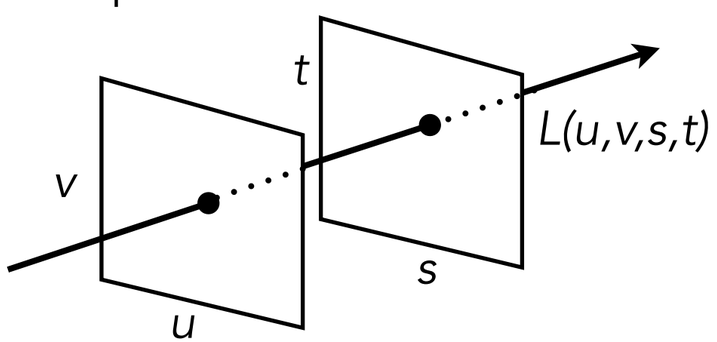


http://en.wikipedia.org/wiki/Light_field
http://commons.wikimedia.org/wiki/File:Snow_Globe_icon.jpg

Capture a Light-field, Store and Render

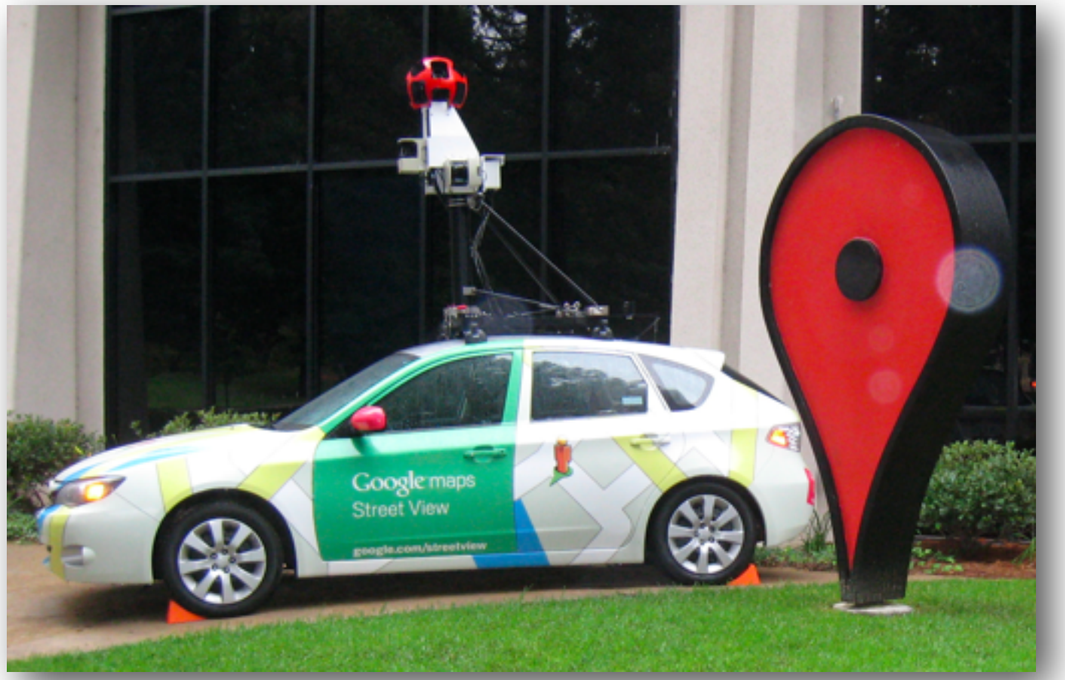
- ★ $P(\theta,\phi,\lambda,t,V_x,V_y,V_z)$ ➔ *7 Dimensions*
  - Complete scene; holographic video
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *5* Dimensions
  - Ignore time and wavelength
  - Capture only viewpoint and direction
- ★ $P(\theta,\phi,V_x,V_y,V_z)$ ➔ *4* Dimensions
  - Within a bounding box. (Space of all lines in 2D space is 4D)
  - No occluding objects, with viewpoint and direction
- ★ $P(\theta,\phi)$ ➔ *2* Dimensions
  - At the same viewpoint
  - Panorama

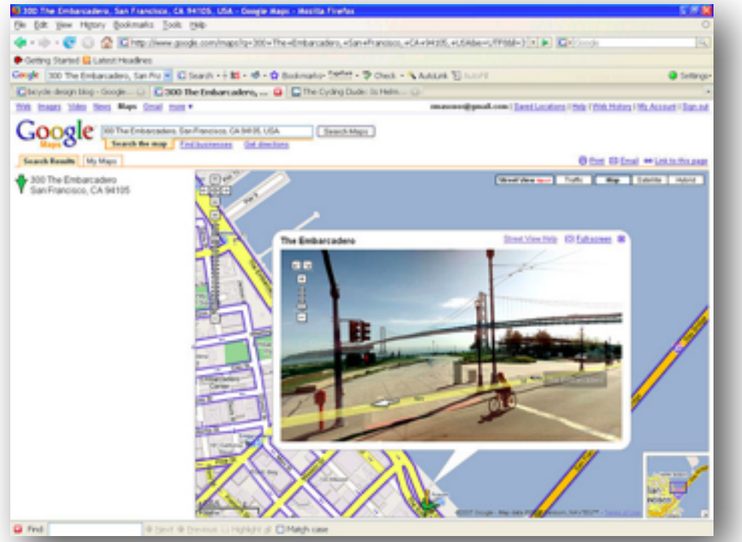
Any point within a scene is represented by a 5D plenoptic function. Outside of a scene (outside of the sphere of a snow globe) light from the scene does not get occluded by objects, and is represented, as a 4D light field.



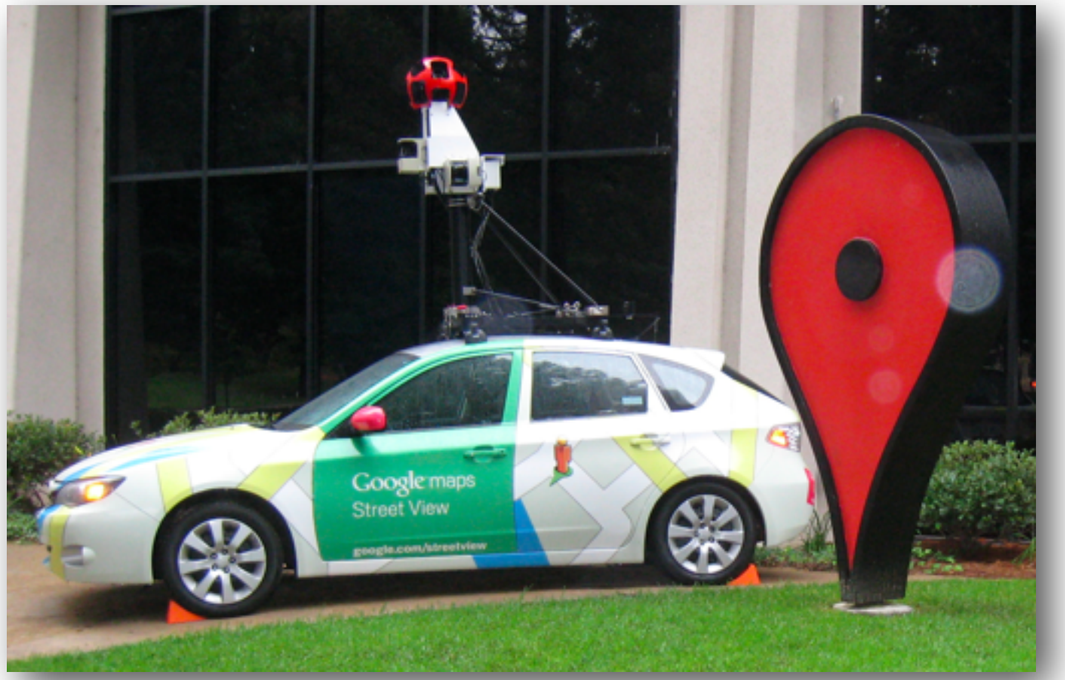
http://en.wikipedia.org/wiki/Light_field
http://commons.wikimedia.org/wiki/File:Snow_Globe_icon.jpg

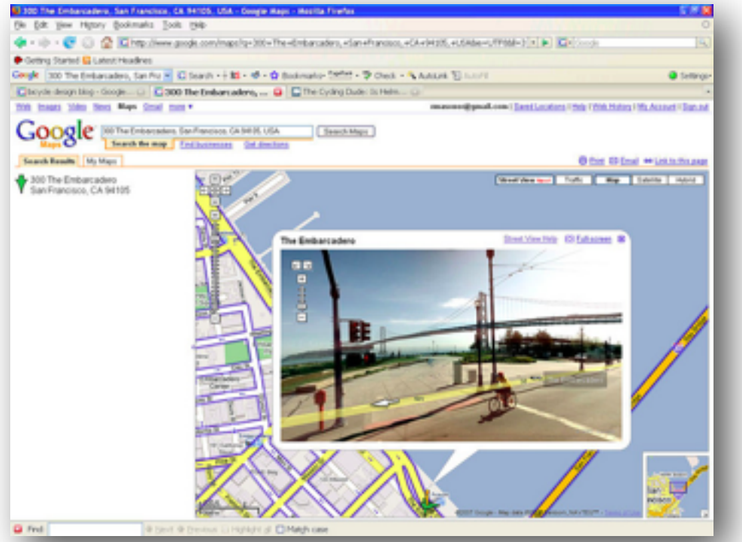
An Example





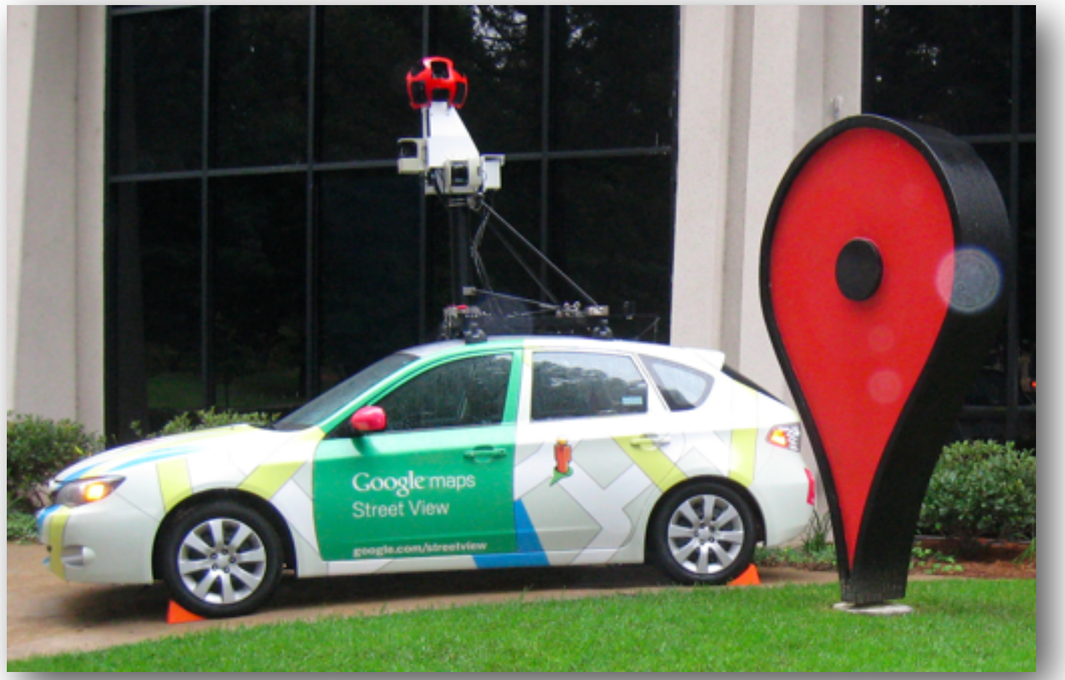
An Example

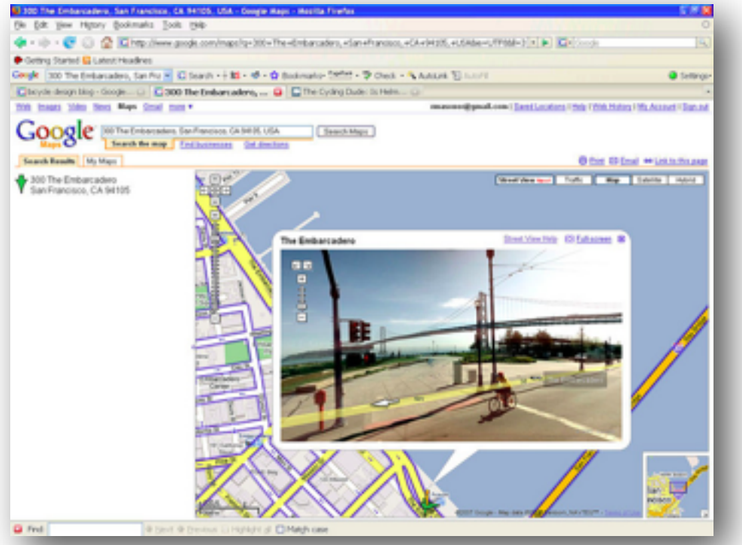




Google Street Views

An Example





Google Street Views

But not just images, they use Geometry too.

11

Google Street Views

But not just images, they use Geometry too.

http://upload.wikimedia.org/wikipedia/commons/4/49/Oxford_Circus_Panorama_March_2006.jpg

Google Street Views

But not just images, they use Geometry too.

Can you think of others?

http://upload.wikimedia.org/wikipedia/commons/4/49/Oxford_Circus_Panorama_March_2006.jpg

Summary

- ★ Introduced the concept a Light Field.
- ★ Introduced the Plenoptic function and its seven (7) parameters.
- ★ Discussed the different types of Light Fields in terms of the Dimensions captured.

https://commons.wikimedia.org

Further Information

★ Adelson and Bergen (1991), "The Plenoptic Function and the Elements of Early Vision" Computational models of visual processing. [PDF]

commons.wikimedia.org/

★

Next Class

★ Light Fields and Plenoptic Cameras

14

Credits

- ★ For more information, see
  - Richard Szeliski (2010) Computer Vision: Algorithms and Applications, Springer.
- ★ Some images retrieved from
  - http://commons.wikimedia.org/.
  - List will be available on website.

www.flickr.com/photos/neneonline/231886965/

Georgia Institute of Technology

Computational Photography

Dr. Irfan Essa
Professor
School of Interactive Computing

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