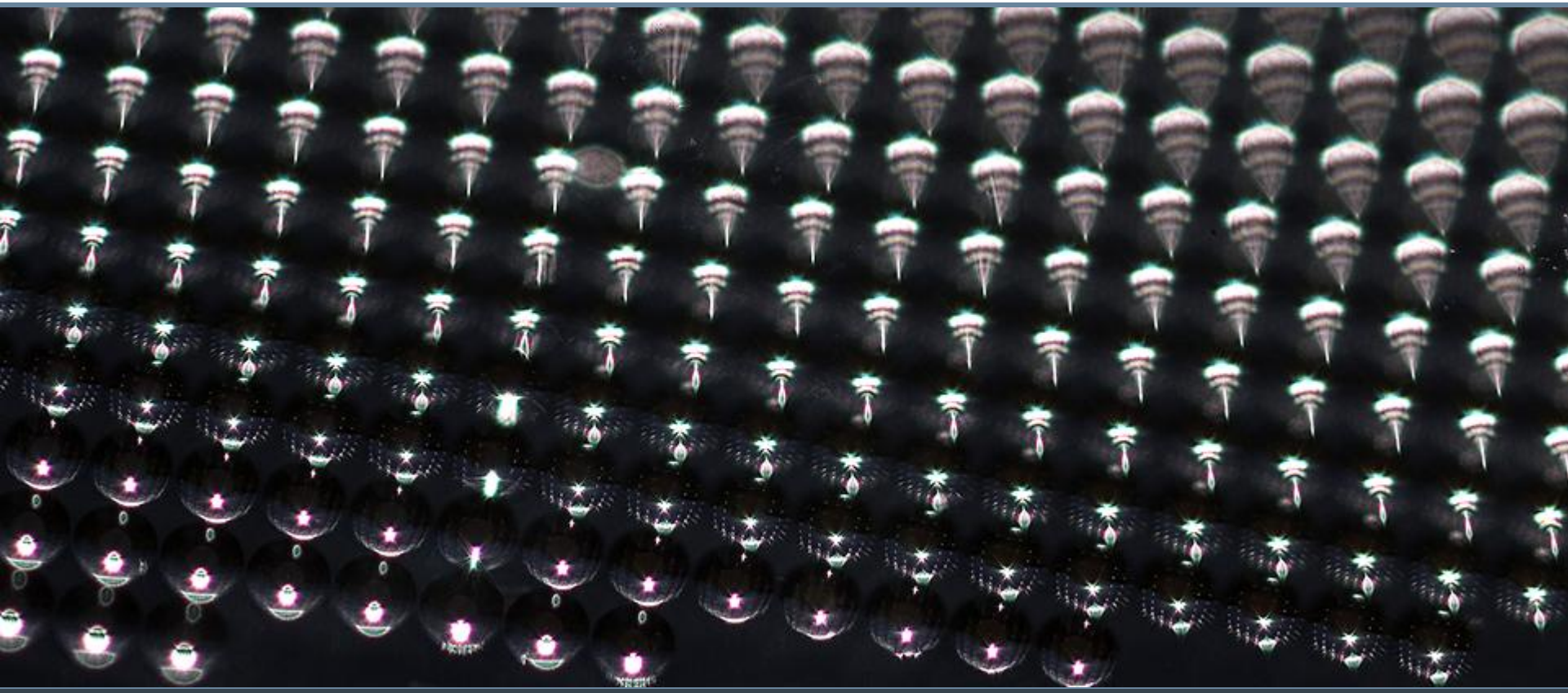
Computational Photography: Real Time Plenoptic Rendering

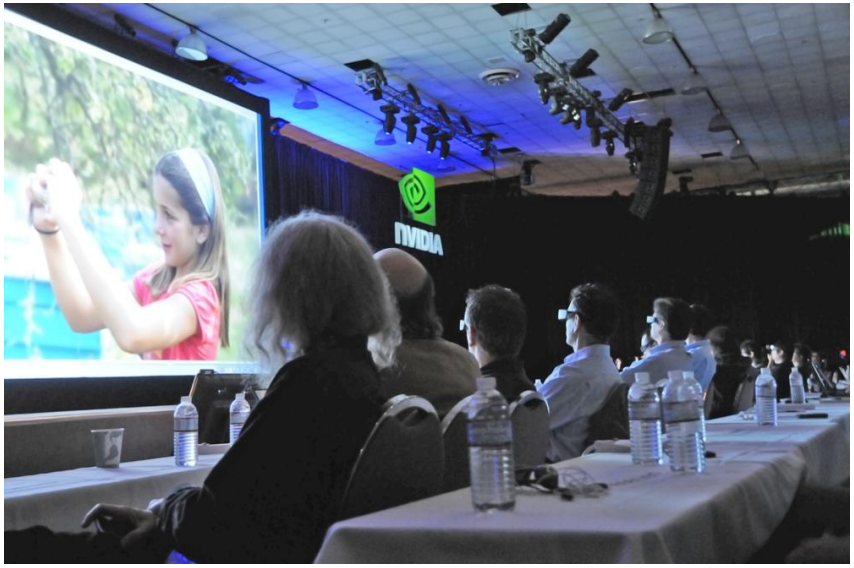
Andrew Lumsdaine, Georgi Chunev | Indiana University

Todor Georgiev | Adobe Systems



Overview

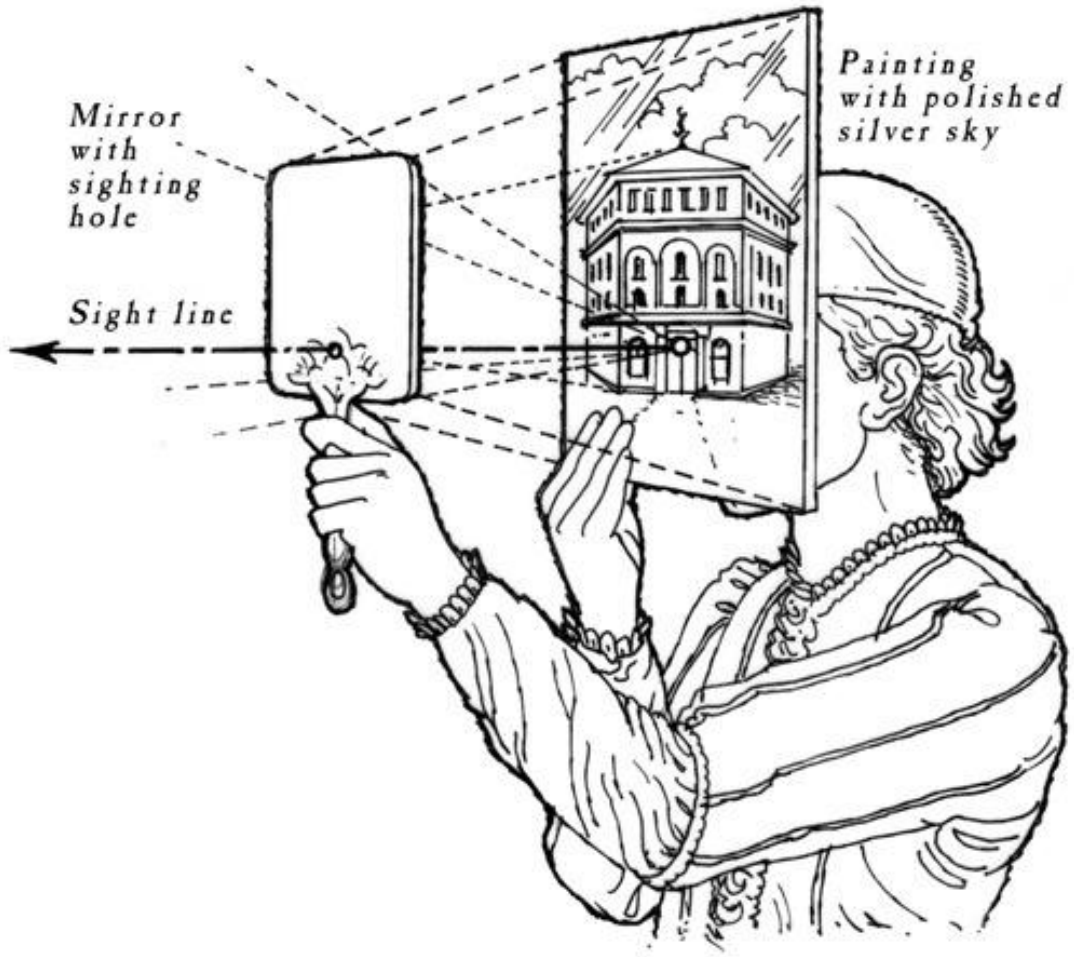
- Plenoptic cameras
- Rendering with GPUs
- Effects
  - Choosing focus
  - Choosing viewpoint (parallax)
  - Stereo
  - Choosing depth of field
  - HDR
  - Polarization
  - Super resolution
- Demos
- Conclusion



Making (and Recreating) Memories

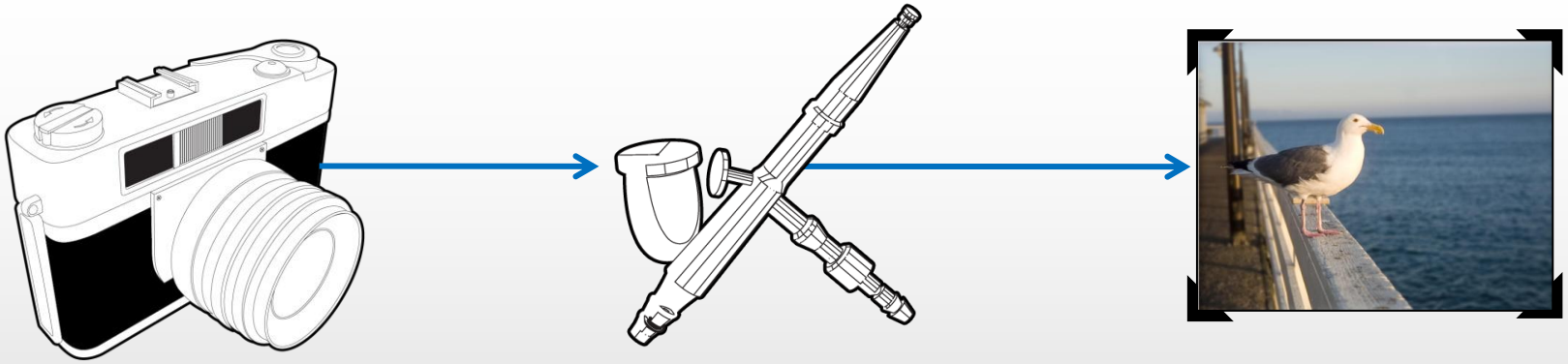
What's Wrong with this Picture?

Perspective



Film

CAPTURE PROCESS VIEW



Color

Exposure

Focus

Color

Exposure

Difficult to Adjust

Along Came Photoshop

CAPTURE

Color

Exposure

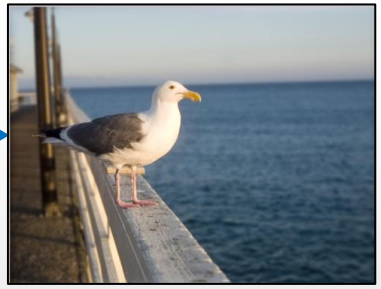
Focus

PROCESS

Color

Exposure

VIEW



Color

Exposure

What's Wrong with This Picture?

Adobe

What's Wrong? It's Only a Picture!

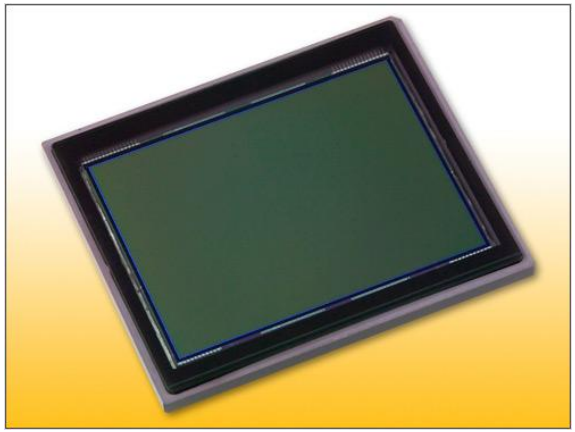
Can We Create More than Pictures?

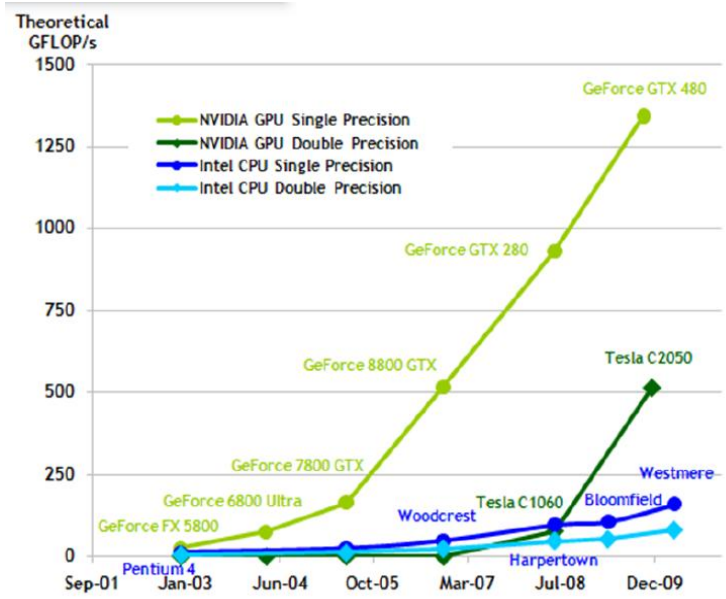
- *Can we request that Photography renders the full variety offered by the direct observation of objects? Is it possible to create a photographic print in such a manner that it represents the exterior world framed, in appearance, between the boundaries of the print, as if those boundaries were that of a window opened on reality.*

Gabriel Lippmann, 1908.

Pixels and Cores

- Moore's Law: Megapixels keep growing
  - 7.2 MP = 8 by 10 at 300dpi
  - Available on cell phones
- 60MP sensors available now
  - Larger available soon (can a use be found?)
- Use pixels to capture richer information about a scene
- Computationally process captured data
  - GPU power also riding Moore's Law curve





Infinite Variety (Focusing)

Adobe

Focusing

Focusing

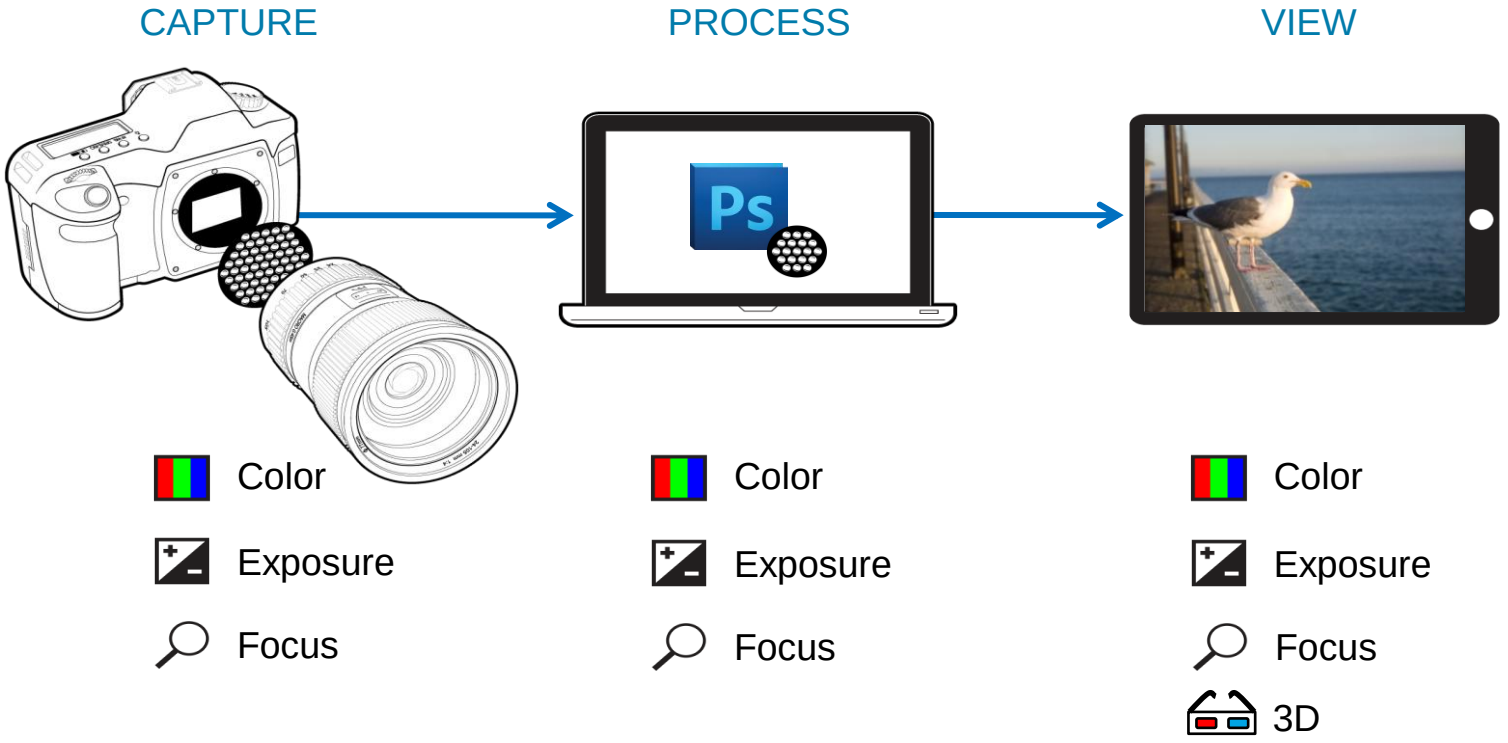
Different Views

Different Views

Different Views

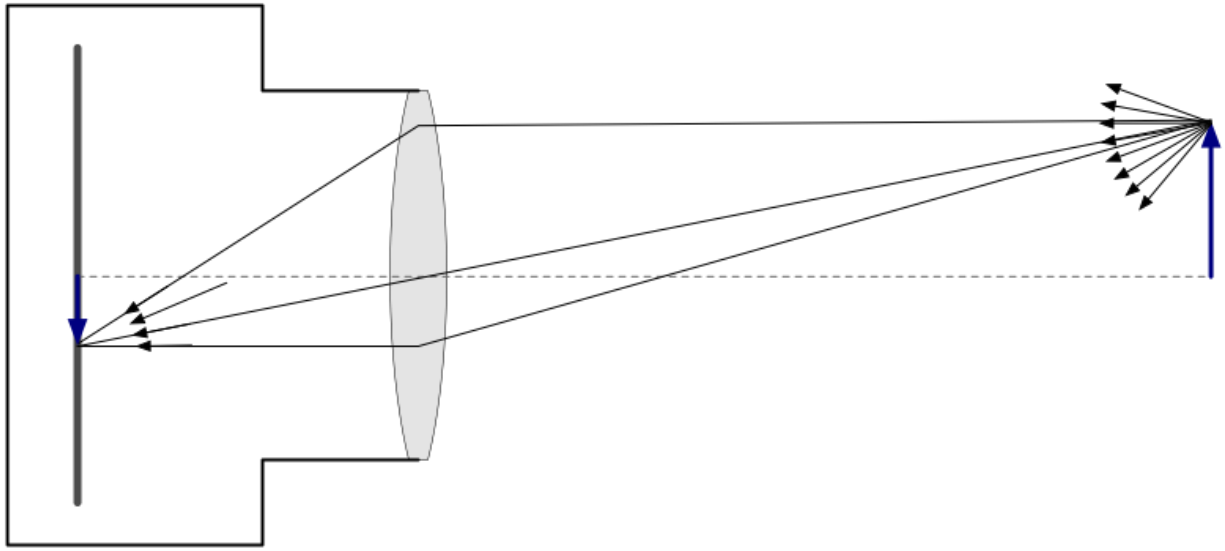
Computational Photography

- With traditional photography light rays in a scene go through optical elements and are captured by a sensor
- With computational photography, we capture the light rays and apply optical elements computationally



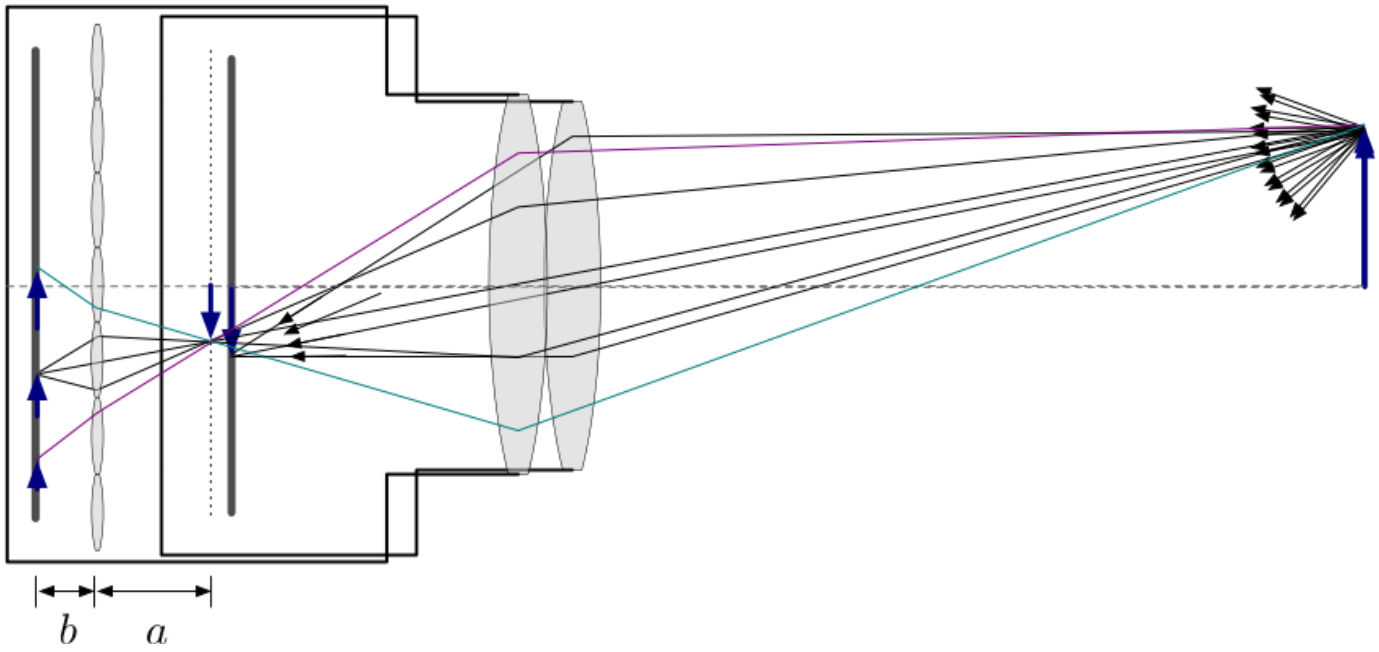
Taking Pictures

- A traditional camera places optical elements into the light rays in a scene
- A pixel on the sensor is illuminated by rays from all directions
- The sensor records the intensity of the ***sum*** of those rays
- We lose all of the information about individual rays



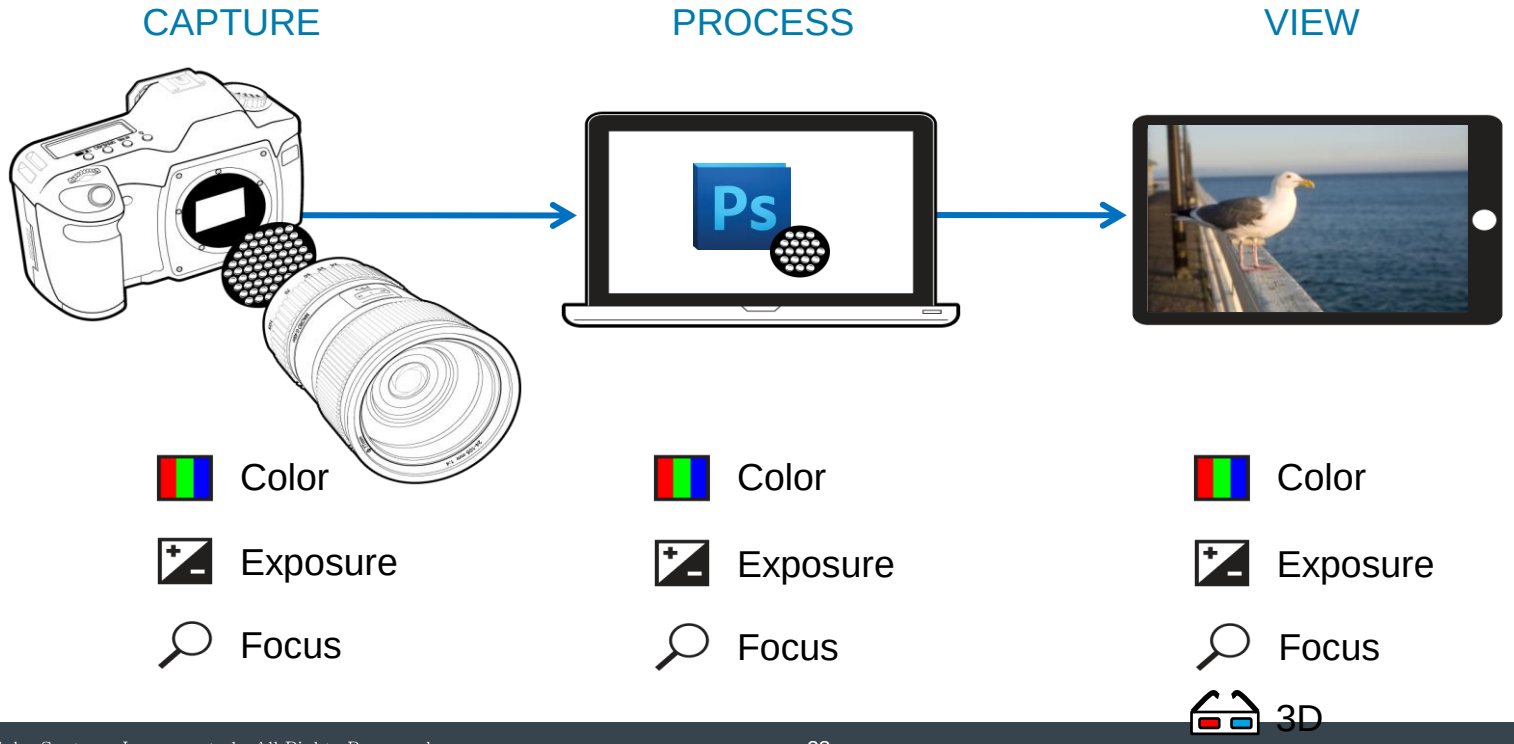
Radiance (Plenoptic Function, Lightfield)

- Instead of integrating rays from all directions, capture the rays themselves (the radiance)
- Record ***all*** the information about the scene



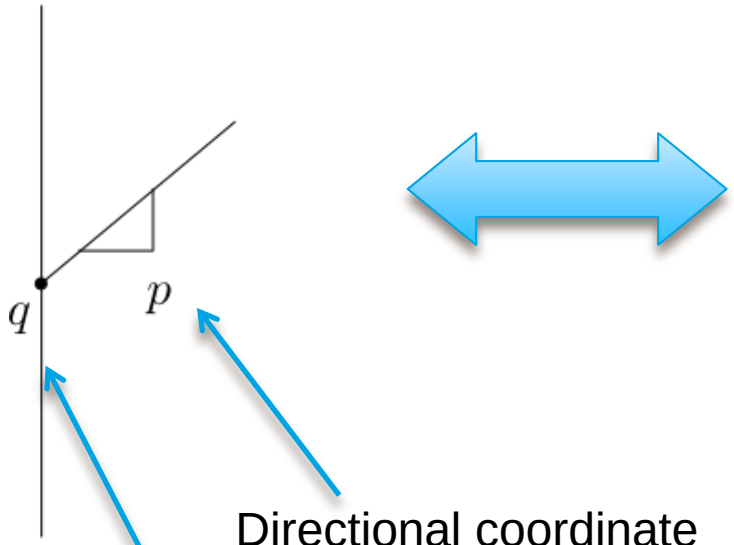
Computational Photography – The Basic Idea

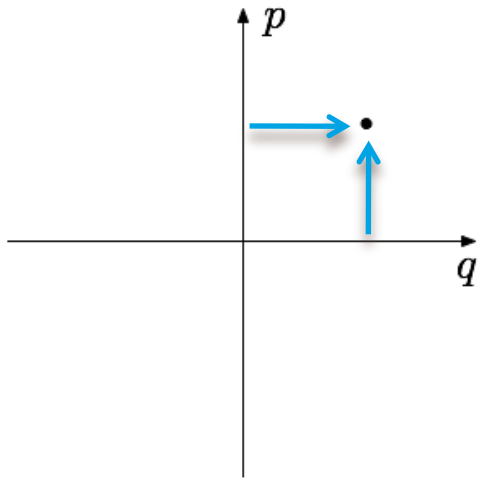
- Using radicance, we can “take the picture” computationally
- Choose and apply optical elements computationally
- Render computationally
- Explore the “full variety” computationally and interactively



Radiance (and Transformations)

- The radiance $r(q,p)$ is a density function over 4D ray space
- Each ray is a point in 4D ray space



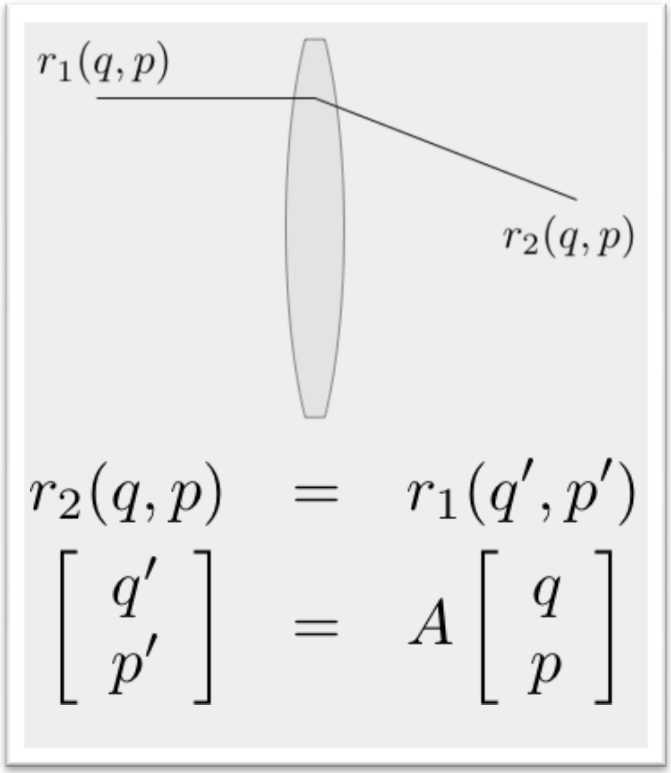


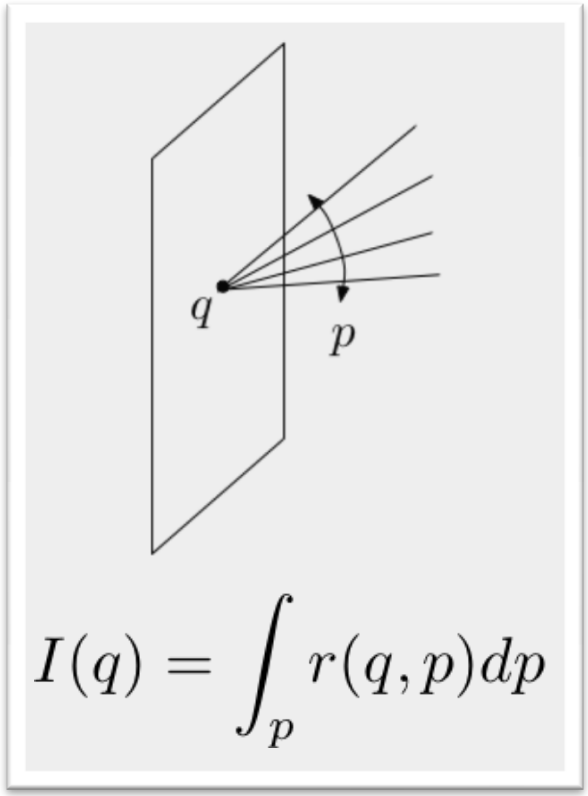
2D phase space

(2D diagrams shown because they are easier to draw.)

Radiance (and Transformations)

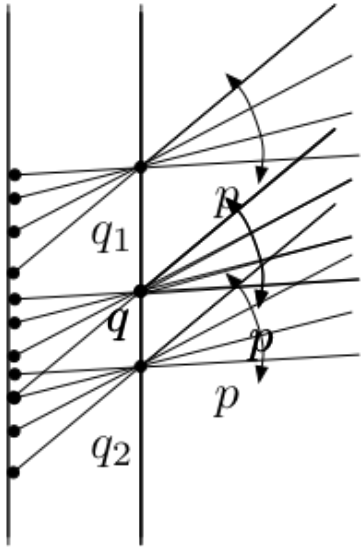
- The radiance $r(q,p)$ is a density function over 4D ray space
- Effects of optical elements (lenses, free space) are linear transformations
- Rendering (taking a picture) is integration over all p at a given q

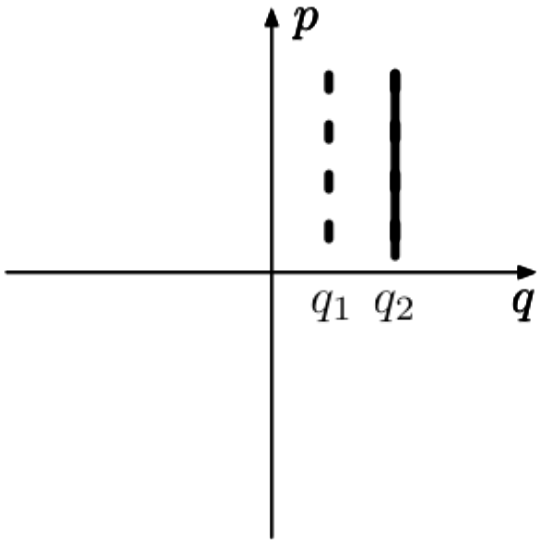




Capturing the 4D radiance with a 2D sensor

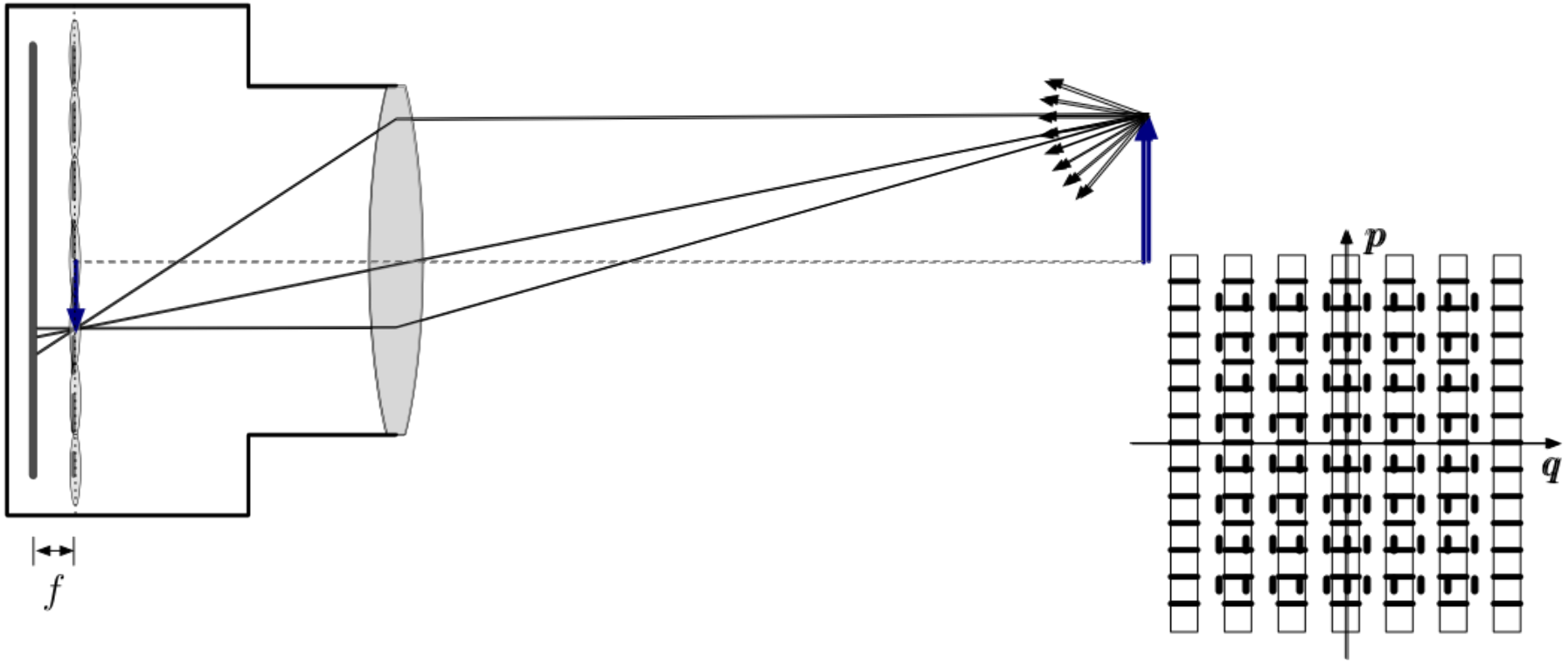
- To capture individual rays, first we have to separate them
- At a particular spatial point, we have a set of rays at all directions
- If we let those rays travel through a pinhole, they will separate into distinguishable individual rays
- Two pinholes will sample two positions





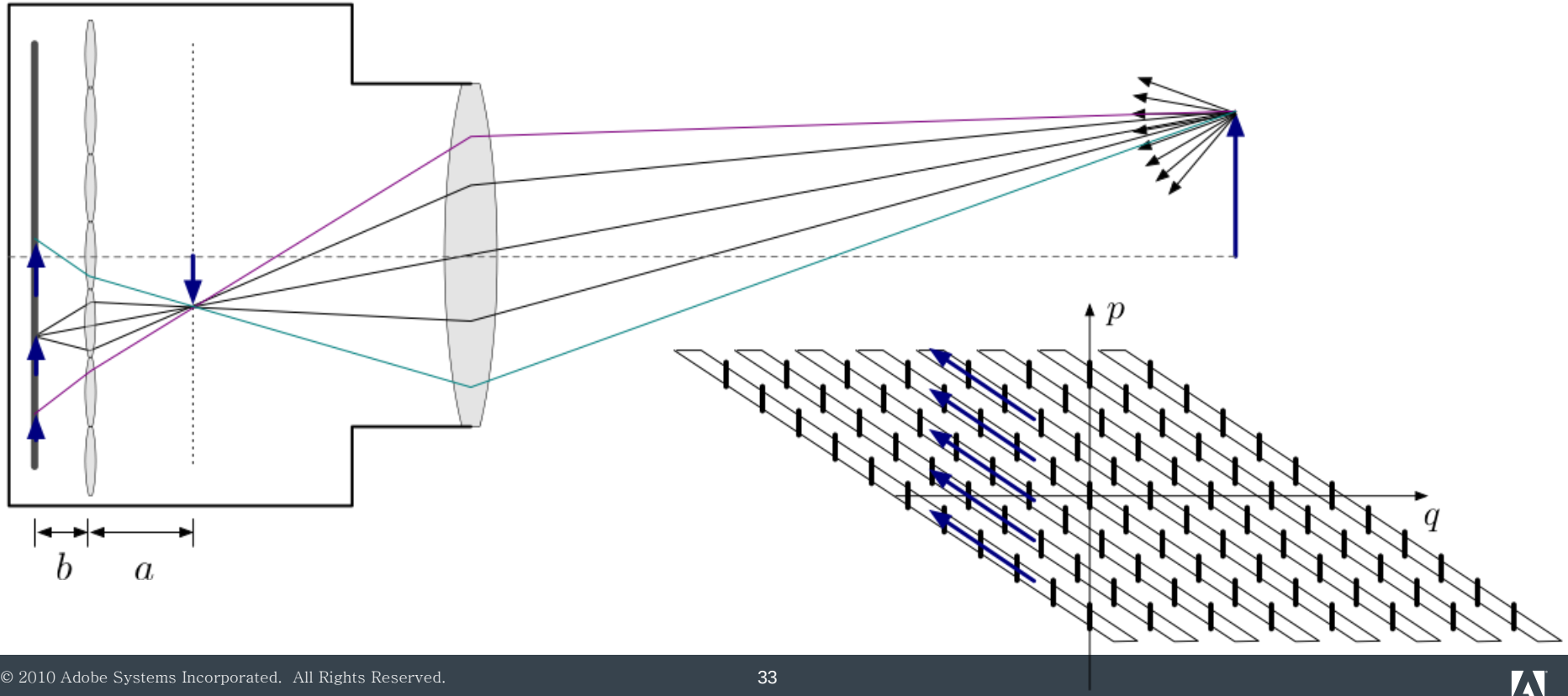
A plenoptic camera

- A camera with an array of pinholes will capture an image that represents the 4D radiance
- In practice, one might use a microlens array to capture more light
  - (cf Ng et al “Handheld Plenoptic Camera”)



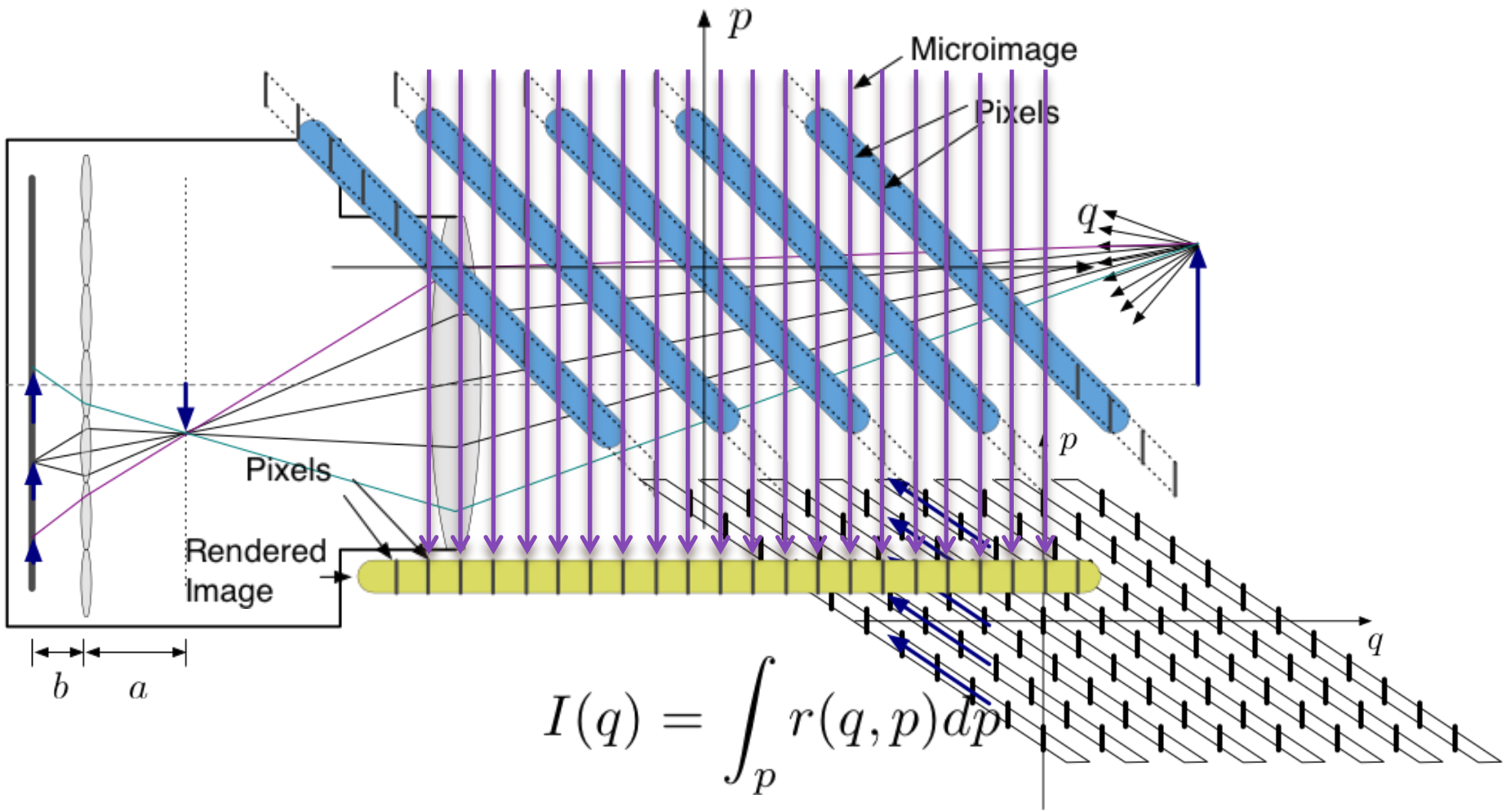
The focused plenoptic camera

- With the Adobe camera, we make one important modification
- We use the microlenses to create an array of relay cameras to sample the plenoptic function with higher spatial resolution
  - Note that image plane can also be behind the sensor (virtual image is captured)



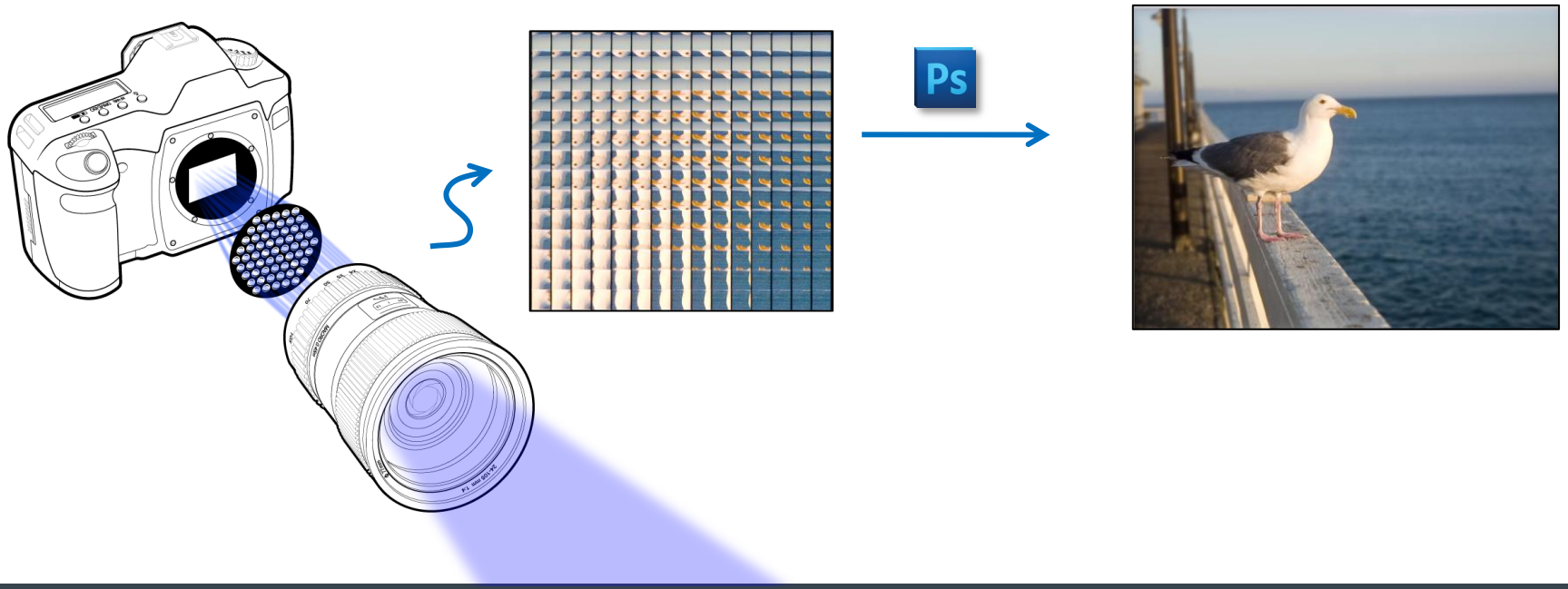
Rendering: Taking a Computational Picture

- To take a picture (render) we integrate over all directions p



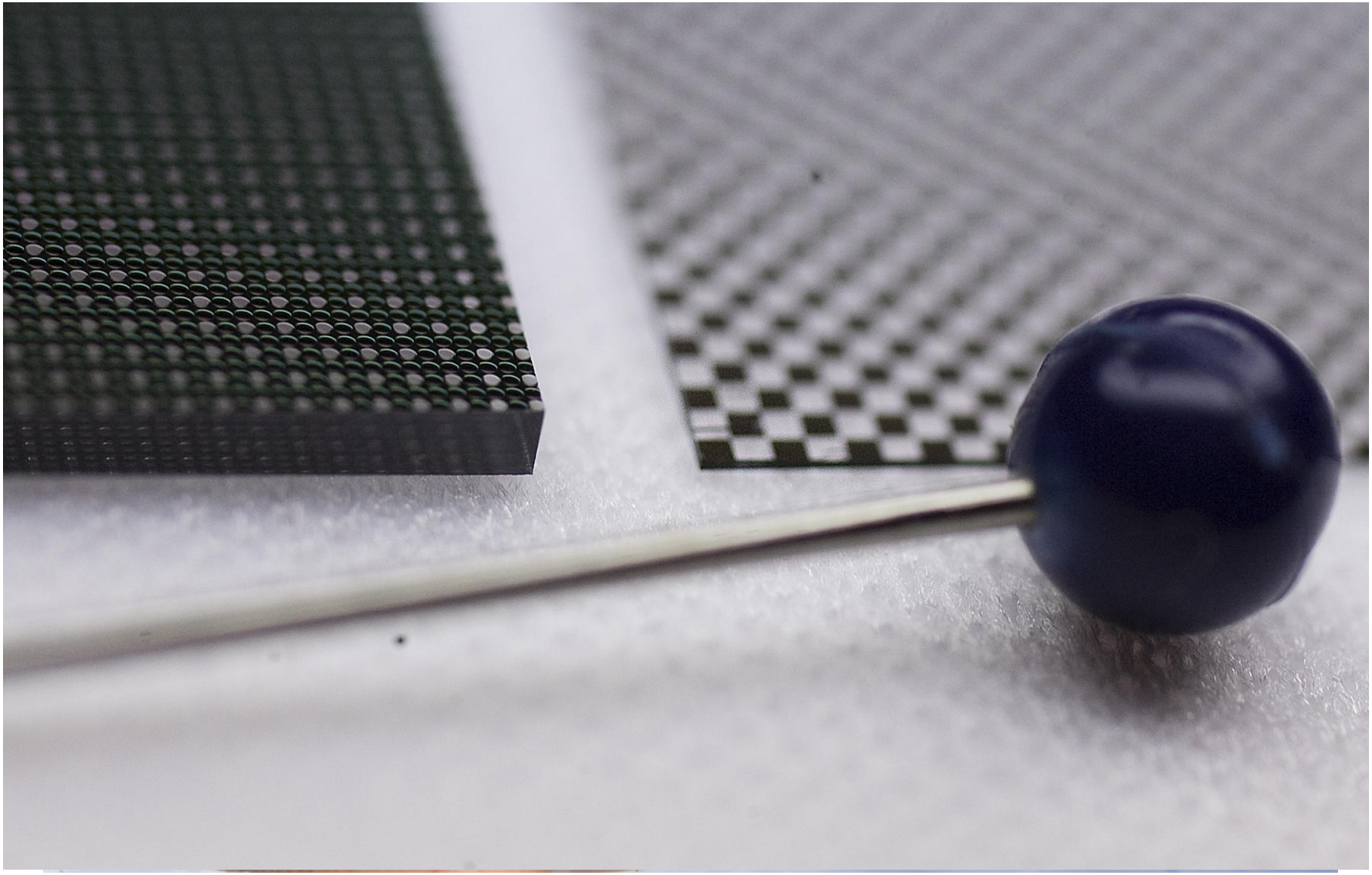
The Story So Far

- A plenoptic camera takes a 2D picture – radiance image (or “flat”)
- The pixels are samples of the radiance in the 4D ray space
- Optical elements (lenses, space) transform the ray space
- We take a picture by rendering (computationally)
- We adjust the picture by transforming the ray space (computationally)

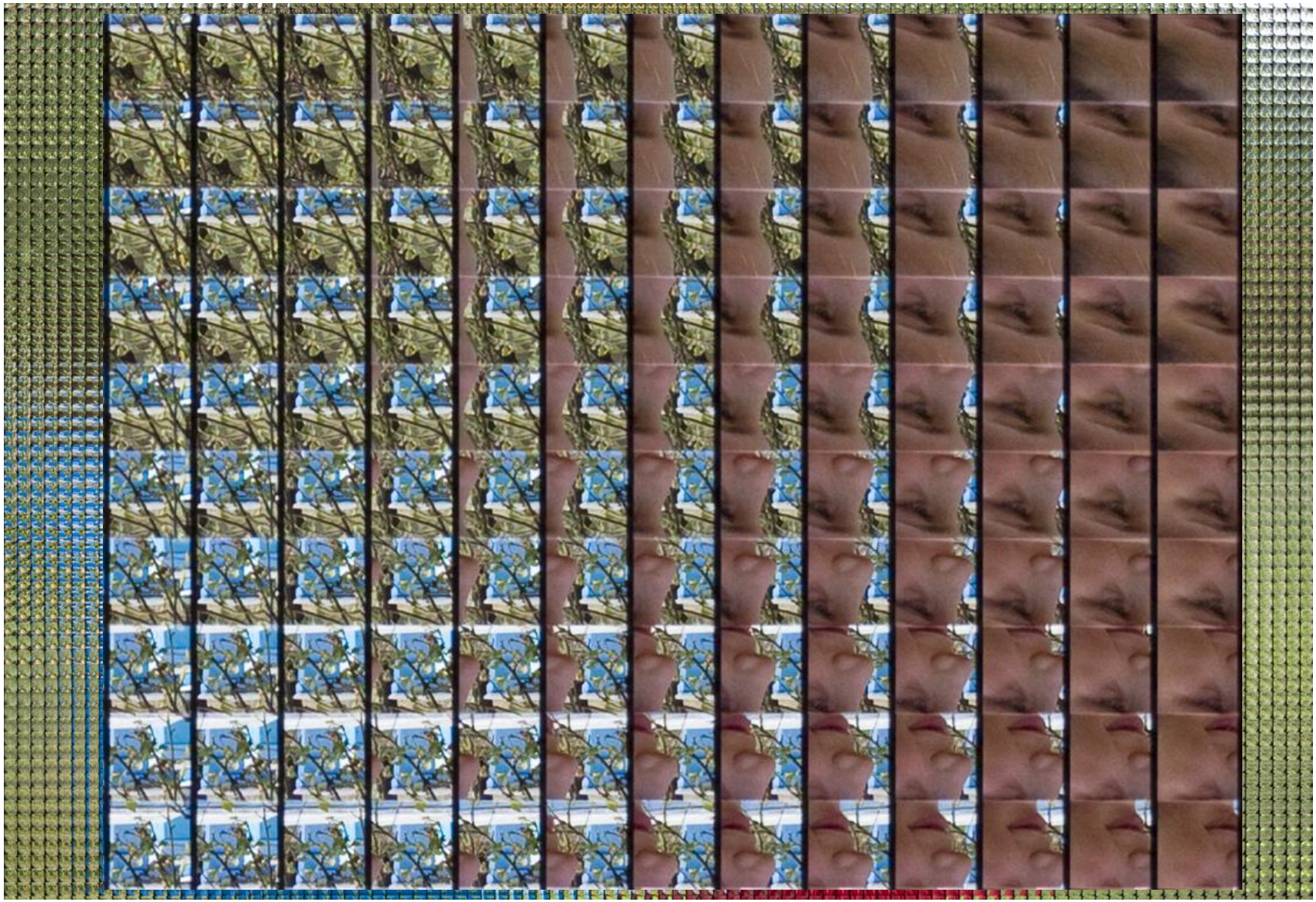


The Part of the Talk Where we Reveal the Magic

First, the Camera

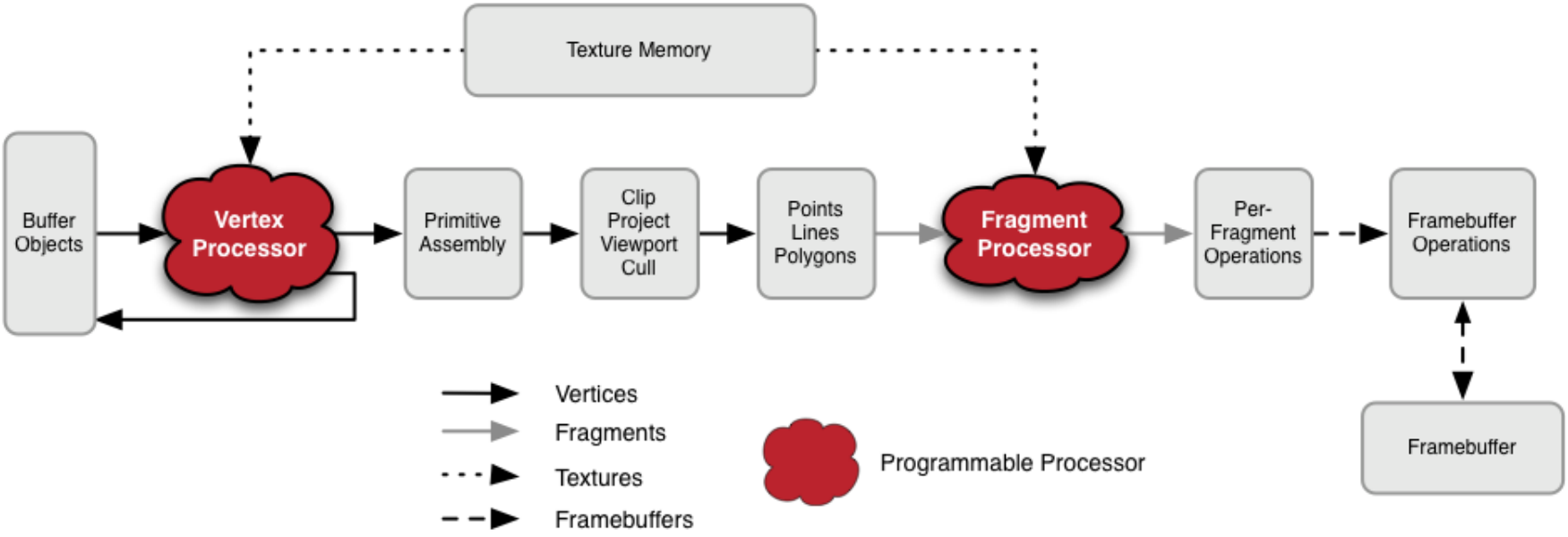


Plenoptic Image (Flat)



GPU Programming

- Basic alternatives for programming GPU: General purpose (CUDA) or graphics-based (GLSL)
- Open GL Shader Language (GLSL) a natural fit
  - Texture mapping

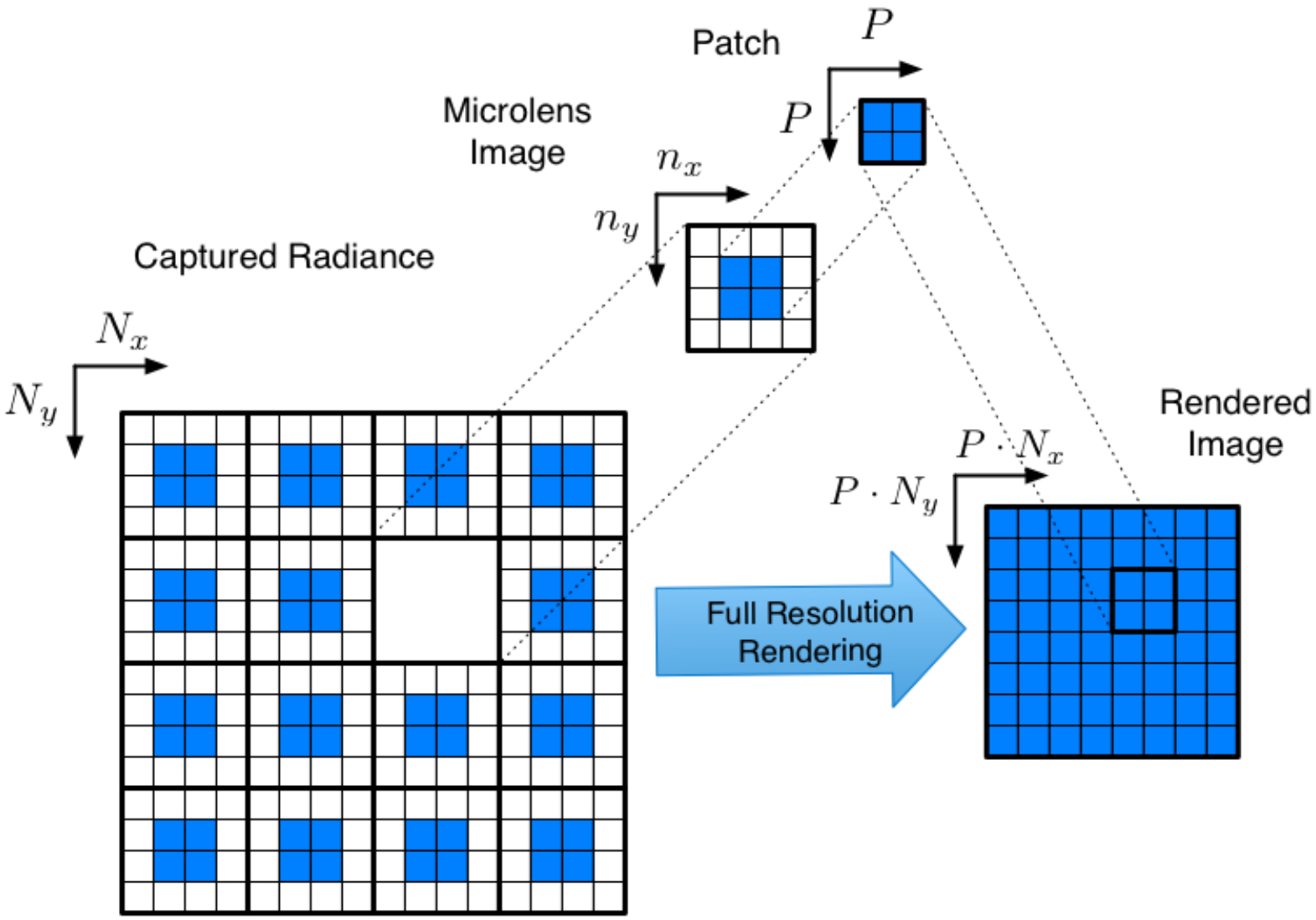


Rendering with GPU using Open GL

- Read in plenoptic radiance image
- Create 2D texture object for radiance
- Serialize image data to Open GL compatible format
- Define the texture to OpenGL

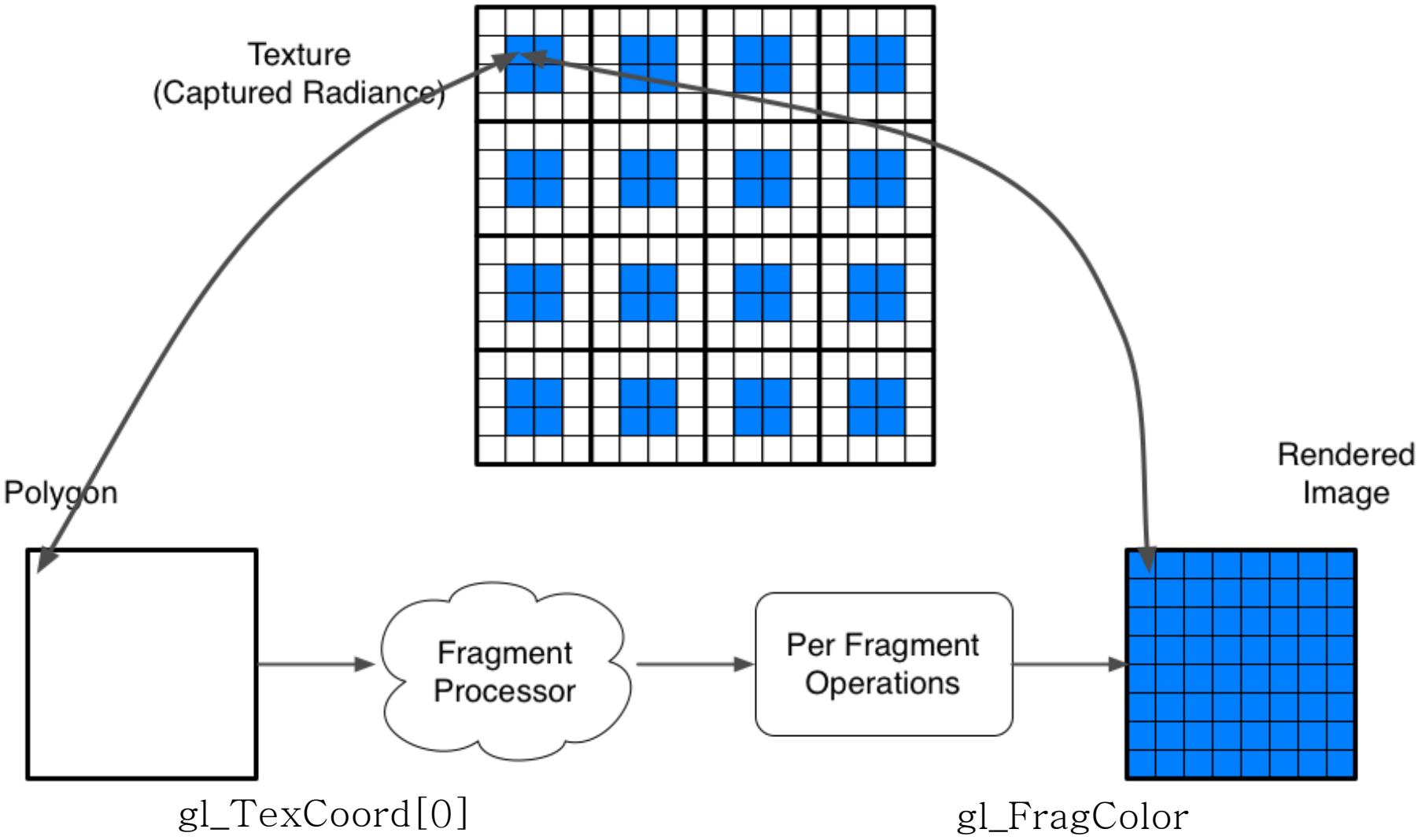
```
image = Image.open("lightfield.png")

str_image = image.tostring("raw", "RGBX", 0, 1)

glActiveTexture(GL_TEXTURE0)
lfTexture = glGenTextures(1)
glBindTexture(GL_TEXTURE_RECTANGLE_ARB, lfTexture)
glTexImage2D(GL_TEXTURE_RECTANGLE_ARB, 0, 3,
                        image.size[0], image.size[1], 0,
                        GL_RGBA,GL_UNSIGNED_BYTE, str_image)
```

GLSL Implementation of Rendering



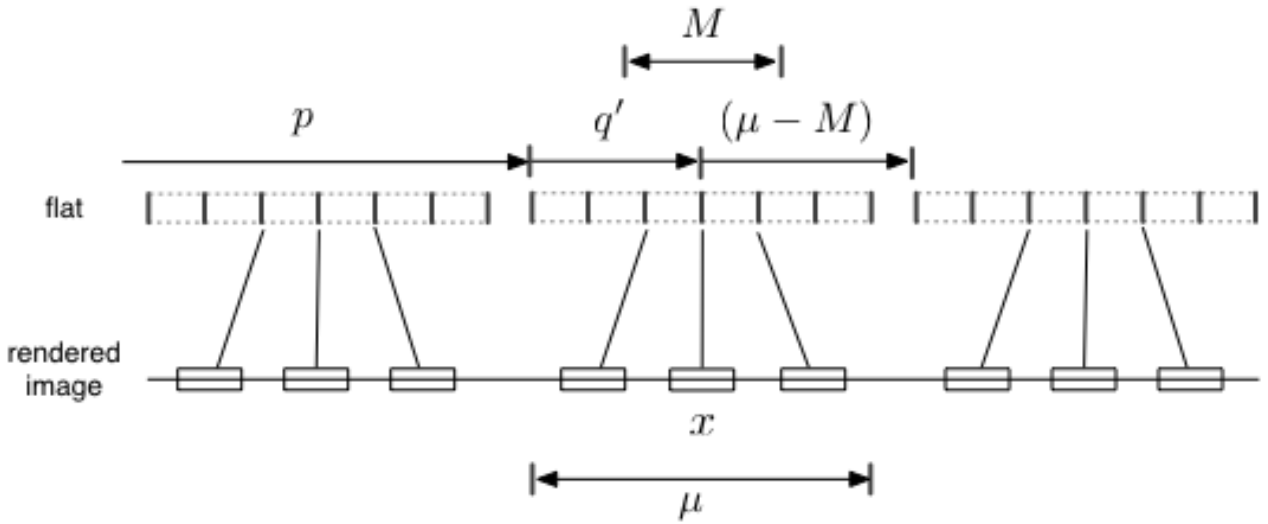
Adobe

GLSL Implementation of Rendering



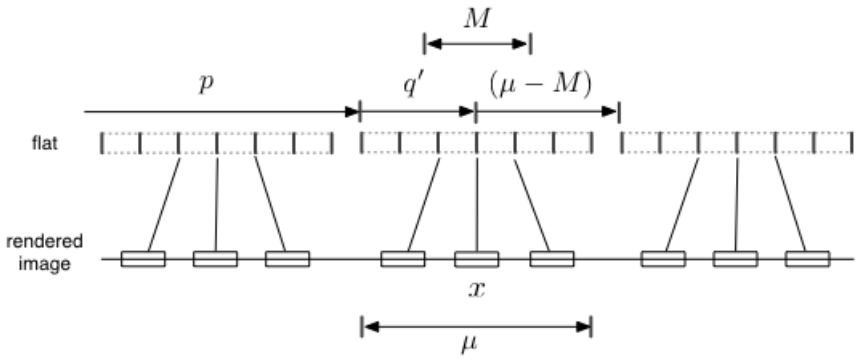
GLSL Implementation of Rendering

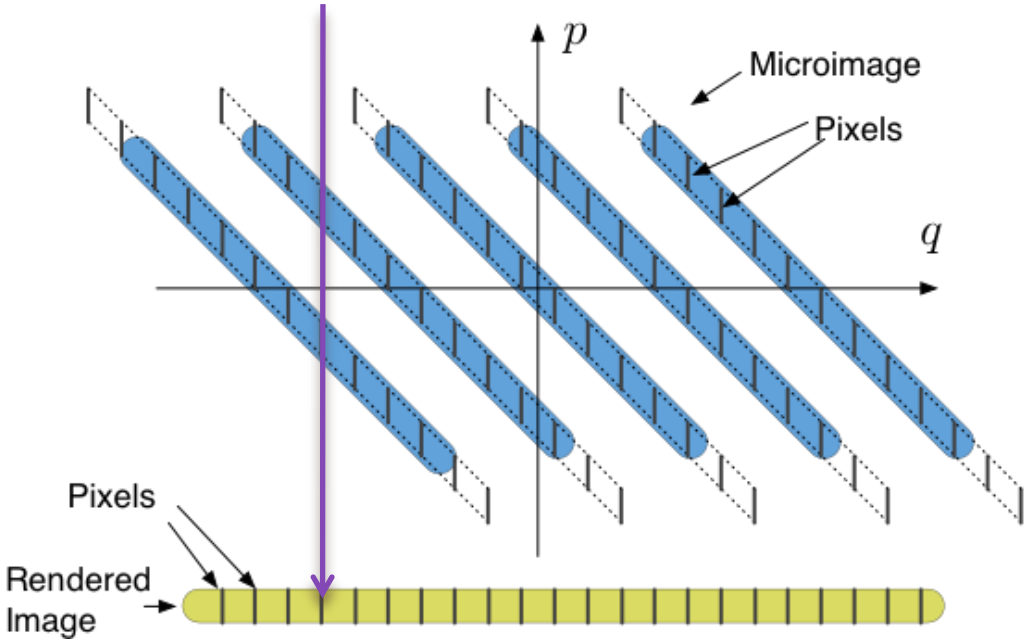
- Given output pixel coordinate gl_TexCoord[0].st
- Find relevant microimage $p = \lfloor \frac{x}{\mu} \rfloor$
- Find offset within $q = \left(x - \lfloor \frac{x}{\mu} \rfloor \mu\right) \frac{M}{\mu} = \left(\frac{x}{\mu} - p\right) M$
- Center $q' = q + \frac{\mu - M}{2} = \left(\frac{x}{\mu} - p\right) M + \frac{\mu - M}{2}$



GLSL Rendering

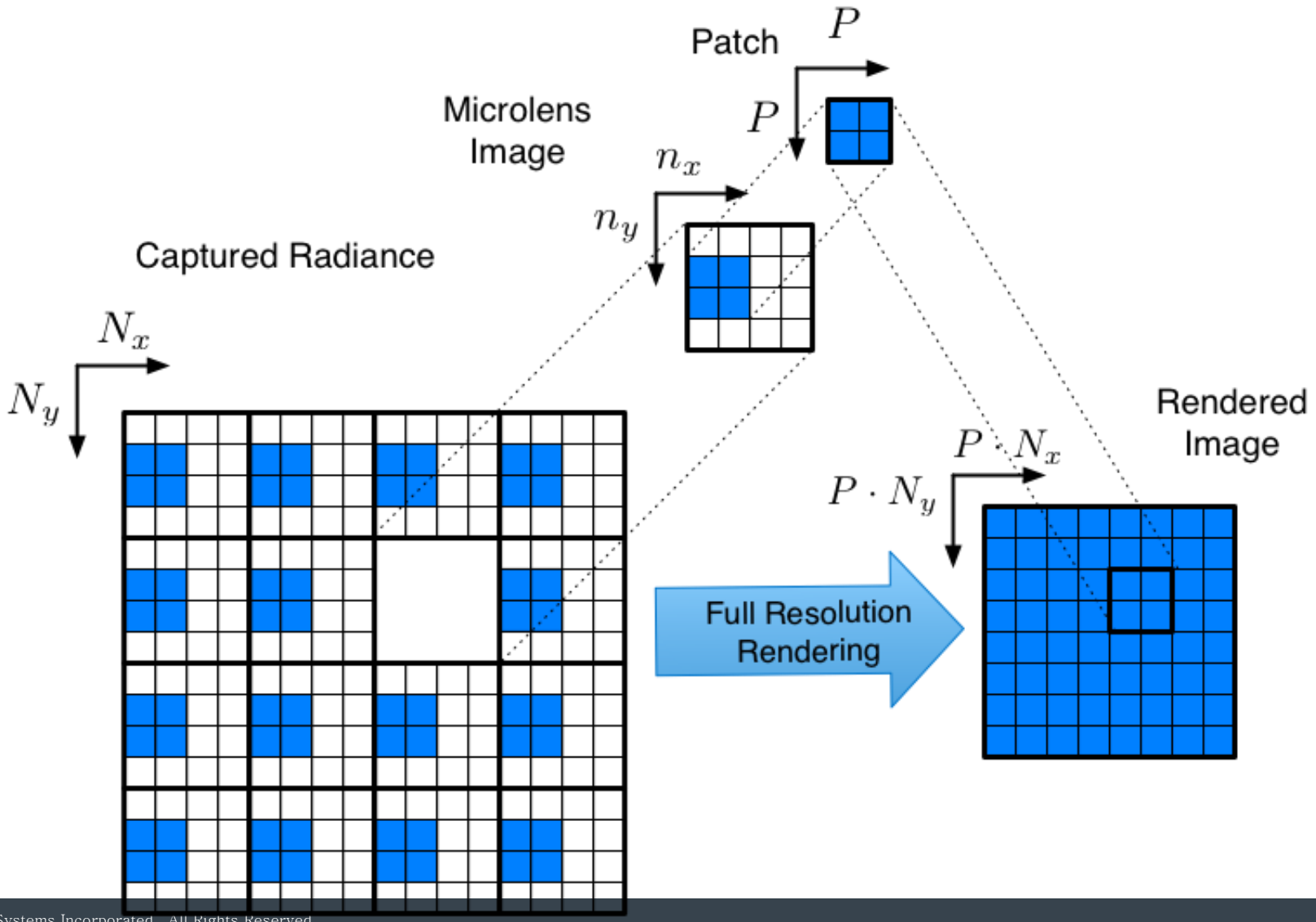
```
uniform sampler2DRect flat;

uniform float M, mu;

void main()
{
  vec2 x_mu = gl_TexCoord[0].st/mu;  // x/μ
  vec2 p = floor(x_mu);              // p = ⌊x/μ⌋
  vec2 q = (x_mu - p) * M;           // (x/μ - p)M
  vec2 qp = q + 0.5*(mu - M);        // q' = q + (μ - M)/2

  vec4 colXY = vec4(0.0);
  for (int i = -1; i <= 1; ++i) {
    for (int j = -1; j <= 1; ++j) {

      vec2 ij = vec2(float(i), float(j));
      vec2 dq = qp - ij * M;
      vec2 fx = (p + ij)*mu + dq;

      colXY += texture2DRect(flat, fx);
    }
  }
  gl_FragColor = colXY / 5.0;
}
```





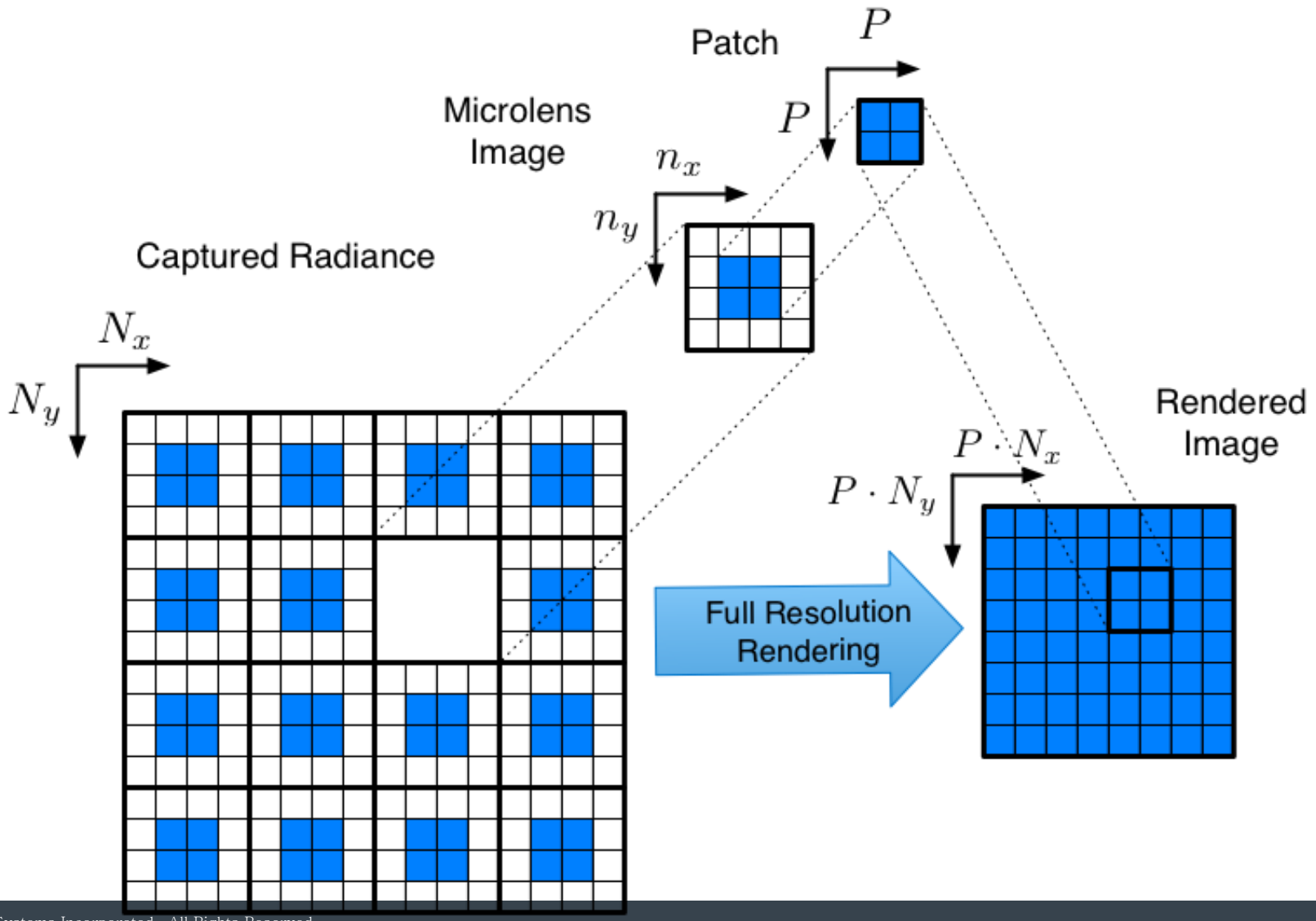
Adobe

Choosing View



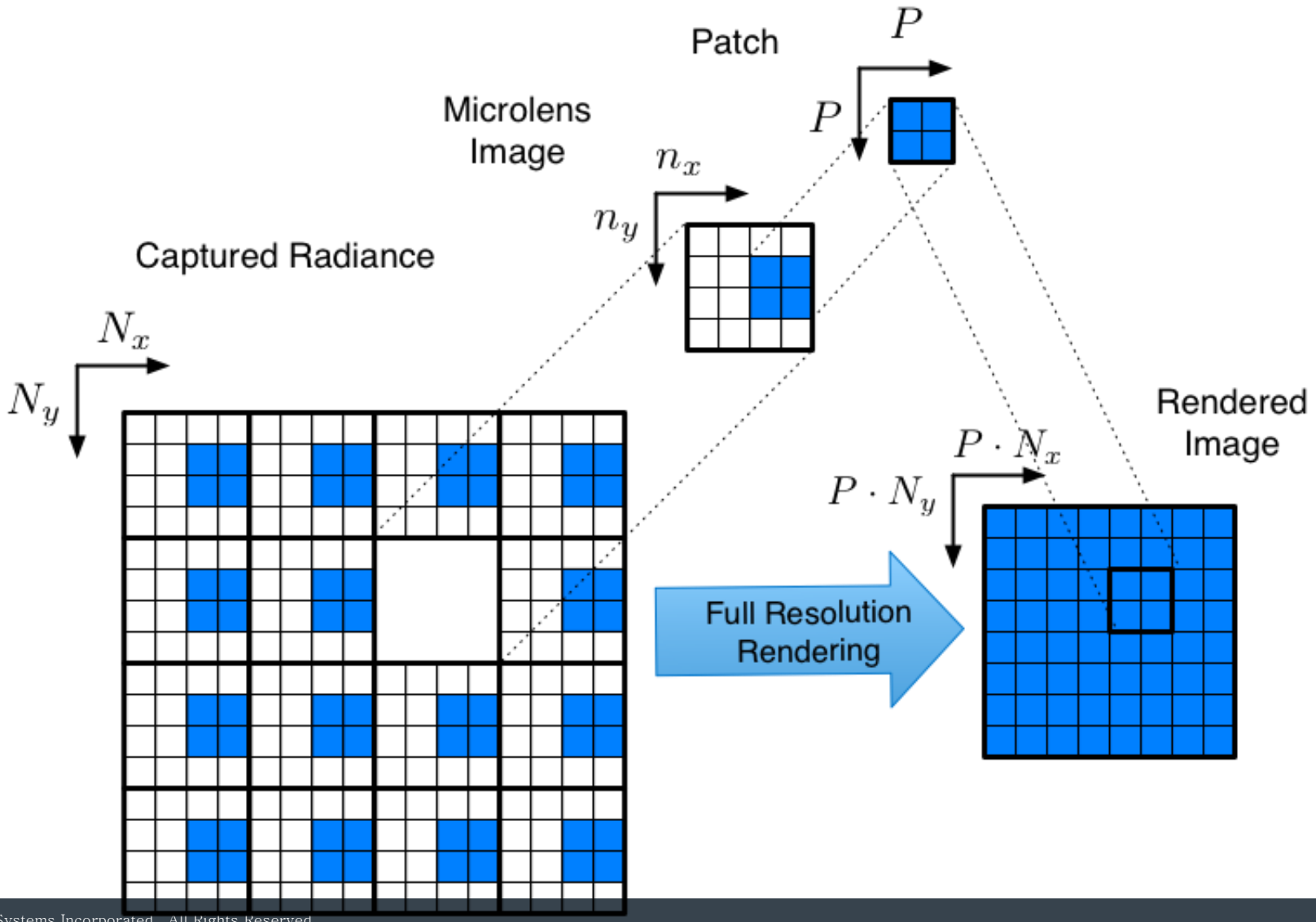
Adobe

Choosing View



Adobe

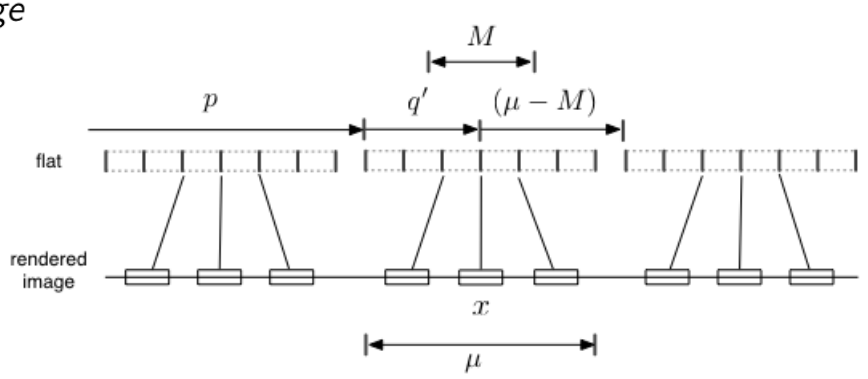
Choosing View

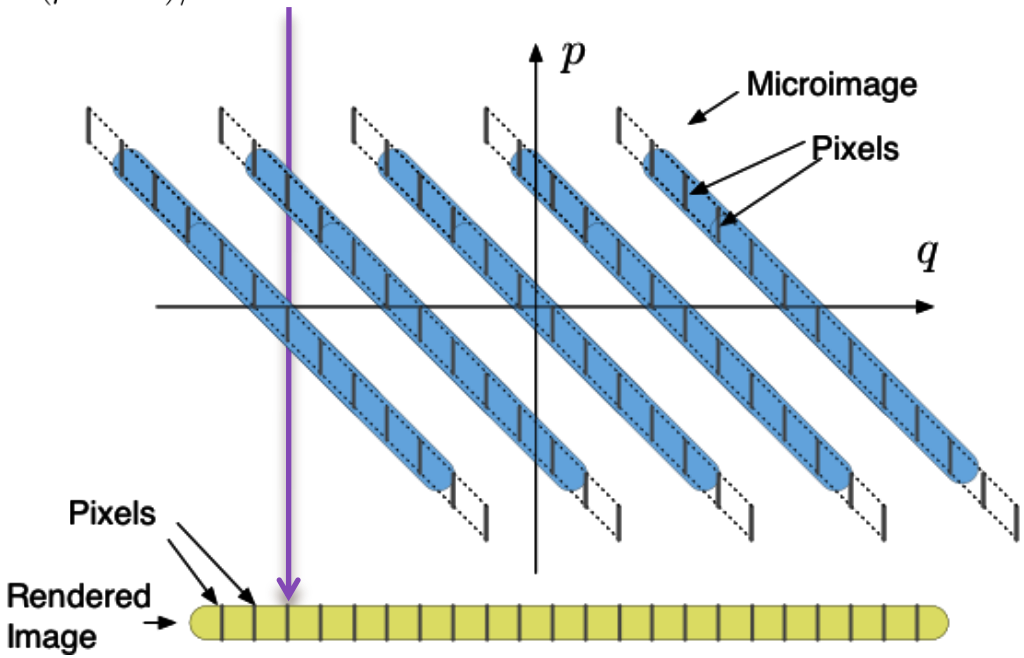


Adobe

GLSL Rendering

```
uniform sampler2DRect flat;                // Plenoptic image
uniform sampler2DRect flat;

uniform float M, mu;
uniform float M, mu;
uniform vec2 offset;

void main()
void main()
{
  vec2 x_mu = gl_TexCoord[0].st/mu;  // x/μ
  vec2 x_mu = gl_TexCoord[0].st/mu;  // x/μ
  vec2 p = floor(x_mu);              // p = ⌊x/μ⌋
  vec2 p = floor(x_mu);              // p = ⌊x/μ⌋
  vec2 q = (x_mu - p) * M;           // (x/μ − p)M
  vec2 q = (x_mu - p) * M;           // (x/μ − p)M
  vec2 qp = q + 0.5*(mu - M);        // q' = q + (μ − M)/2
  vec2 qp = q + 0.5*(mu - M);        // q' = q + (μ − M)/2

  vec4 colXY = vec4(0.0);
  vec4 colXY = vec4(0.0);
  for (int i = -1; i <= 1; ++i) {
  for (int i = -1; i <= 1; ++i) {
    for (int j = -1; j <= 1; ++j) {
    for (int j = -1; j <= 1; ++j) {

      vec2 ij = vec2(float(i), float(j));
      vec2 ij = vec2(float(i), float(j));
      vec2 dq = qp - ij * M;
      vec2 dq = qp - ij * M;
      vec2 fx = (p + ij)*mu + dq;
      vec2 fx = (p + ij)*mu + dq + offset;

      colXY += texture2DRect(flat, fx);
      colXY += texture2DRect(flat, fx);
    }
    }
  }
  }
  gl_FragColor = colXY / 5.0;
}
  gl_FragColor = colXY / 5.0;
}
```





Adobe

Choosing View

Adobe

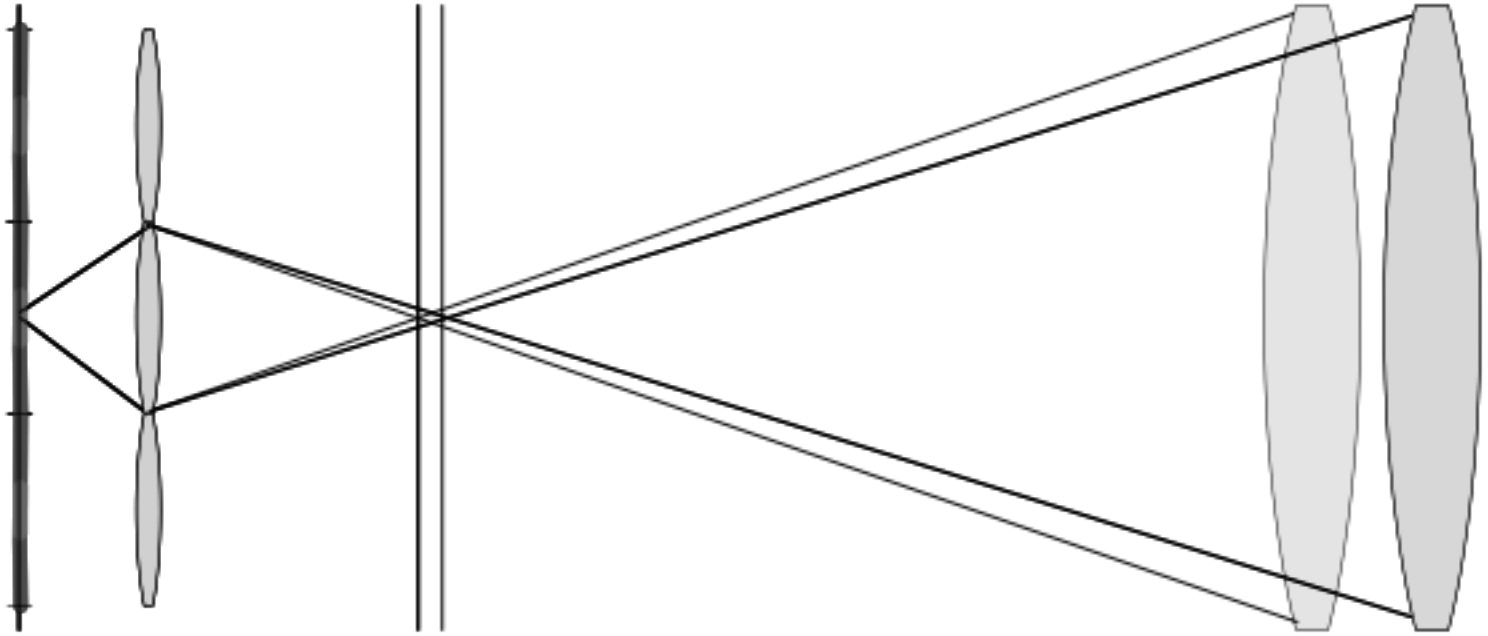
Choosing View

Adobe

Choosing View

Adobe

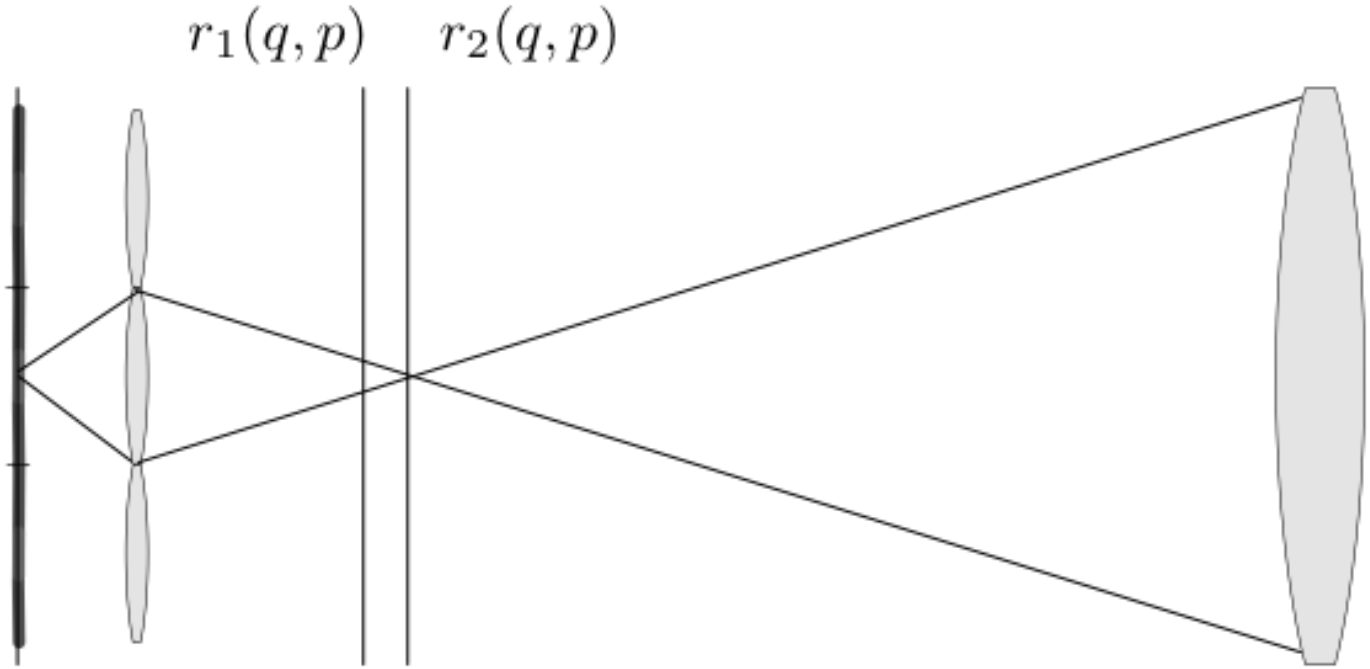
Computational Refocusing



- What does the sensor capture with different focal planes?
- What is this in terms of phase space?

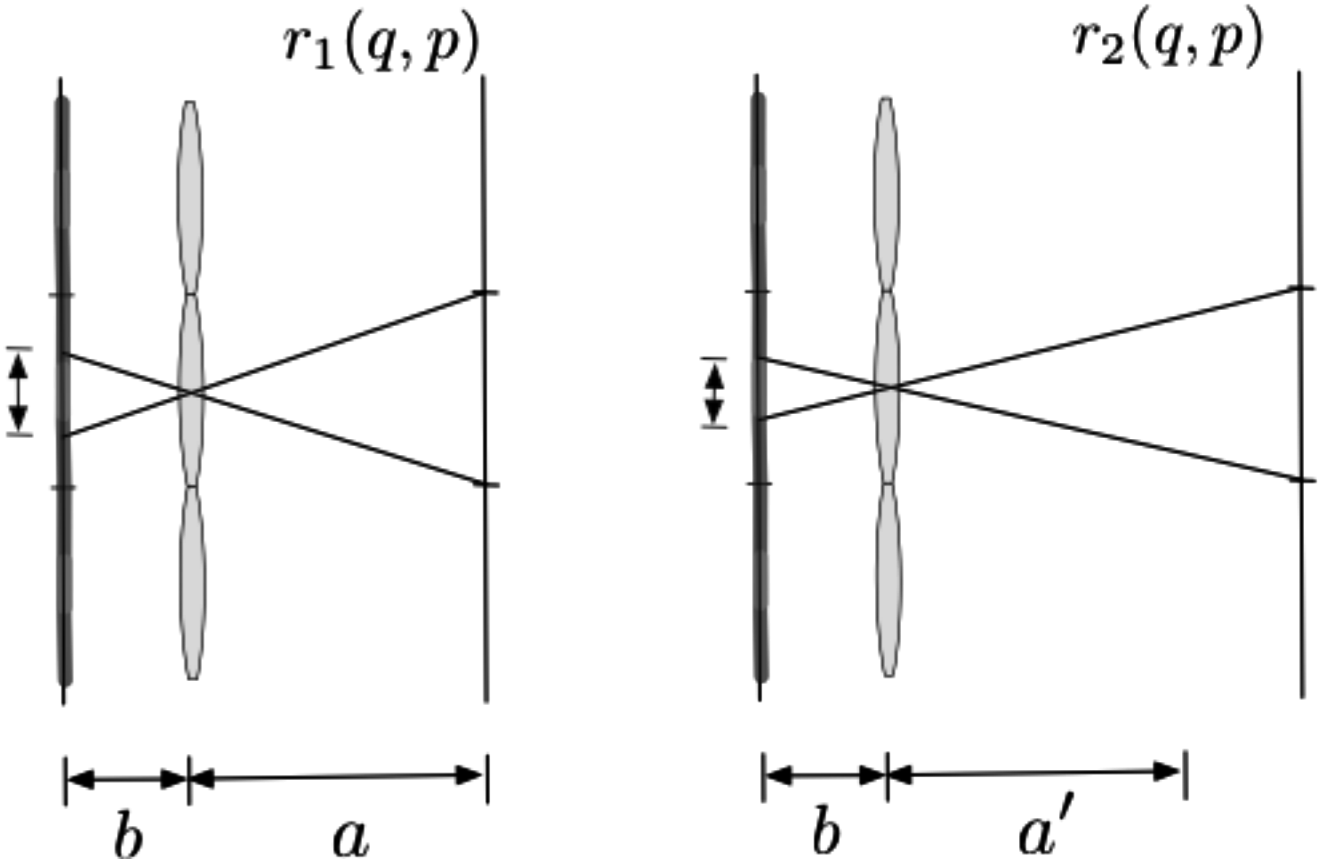
Computational Refocusing

- We capture radiance r_1. How can we compute r_2?
- Apply translation transform of the radiance and render from transformed r
  - Very expensive



Plenoptic 2.0 Refocusing Principle

- Rendering for two different focal planes
- Comments?

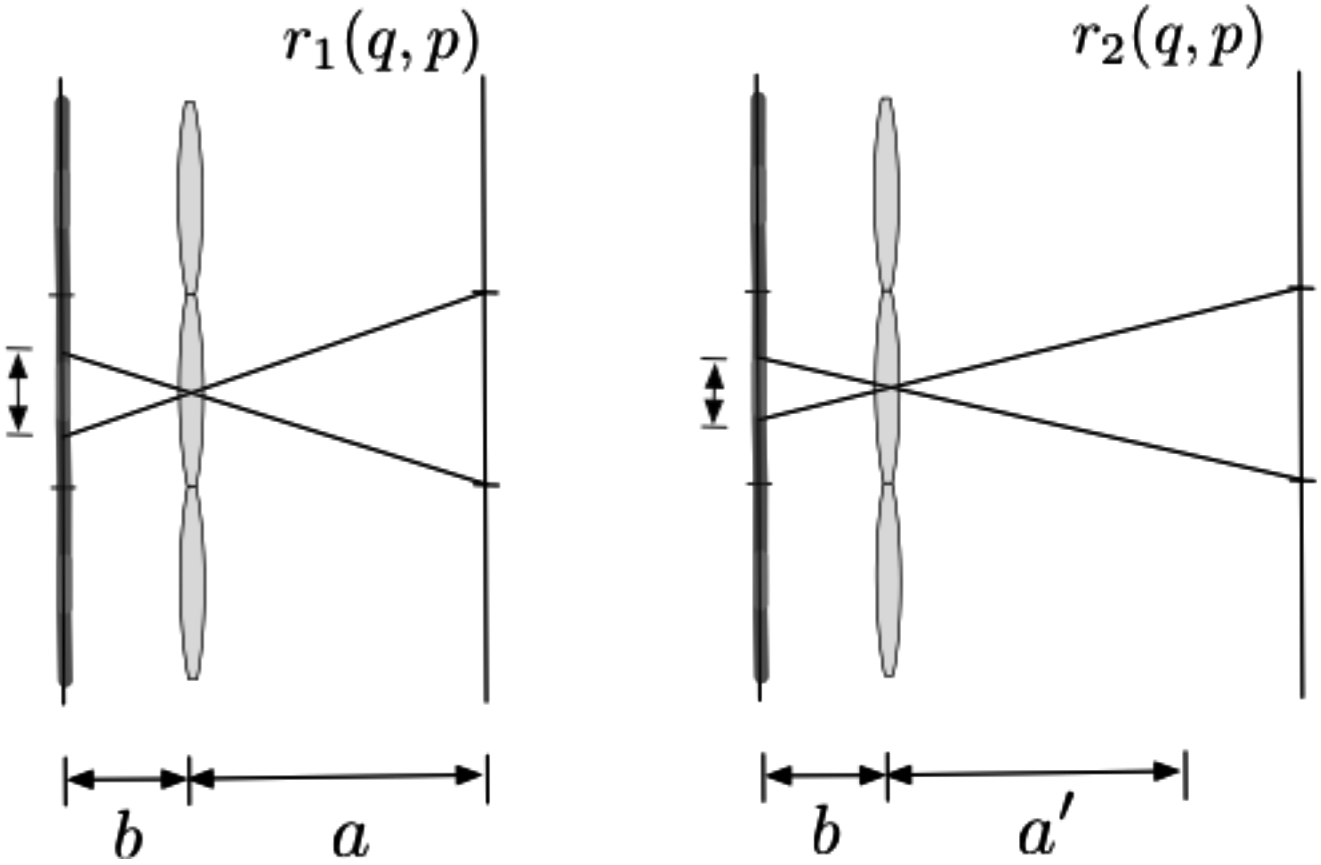


Adobe

Plenoptic 2.0 Refocusing Principle

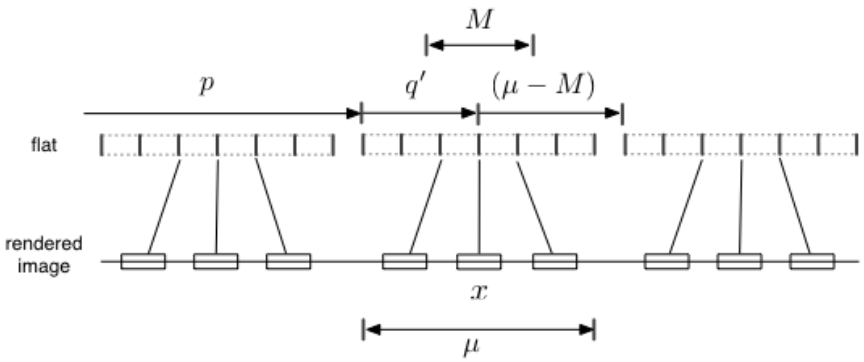
- A new focal plane can be rendered directly from original radiance

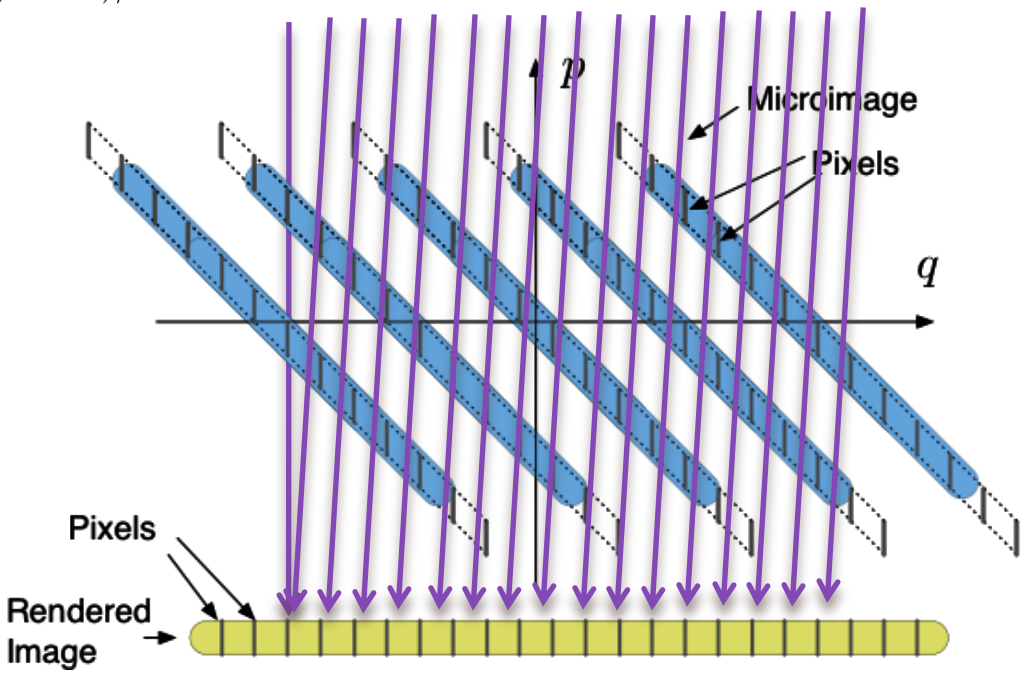
$$I_2(q) = \int_p r_2(q,p)dp = \int_p r_1(q',p')dp$$



GLSL Rendering

```
uniform sampler2DRect flat;

uniform float M, mu;

void main()
{
  vec2 x_mu = gl_TexCoord[0].st/mu;  // x/μ
  vec2 p = floor(x_mu);              // p = ⌊x/μ⌋
  vec2 q = (x_mu - p) * M;           // (x/μ - p)M
  vec2 qp = q + 0.5*(mu - M);        // q' = q + (μ - M)/2

  vec4 colXY = vec4(0.0);
  for (int i = -1; i <= 1; ++i) {
    for (int j = -1; j <= 1; ++j) {

      vec2 ij = vec2(float(i), float(j));
      vec2 dq = qp - ij * M;
      vec2 fx = (p + ij)*mu + dq;

      colXY += texture2DRect(flat, fx);
    }
  }
  gl_FragColor = colXY / 5.0;
}
```





Adobe

Computational Focusing

Adobe

Computational Focusing

Adobe

Computational Focusing

Adobe

To Find Out More

- Georgiev, T., Lumsdaine, A., “Focused Plenoptic Camera and Rendering,” *Journal of Electronic Imaging*, Volume 19, Issue 2, 2010
- http://www.tgeorgiev.net/CVPR2010/

Live Demonstrations


Adobe

GLSL Implementation (Basic Rendering)

```
uniform sampler2DRect flat;          // Plenoptic image

uniform float M, mu;

void main()
{
  vec2 x_mu = gl_TexCoord[0].st/mu;  // x/μ
  vec2 p = floor(x_mu);              // p = ⌊x/μ⌋
  vec2 q = (x_mu - p) * M;           // (x/μ - p)M
  vec2 qp = q + 0.5*(mu - M);        // q' = q + (μ - M)/2

  vec2 fx = p * mu + qp;             // f(x) = pμ + q'

  gl_FragColor = texture2DRect(flat, fx);
}
```