Lecture 4:

Finishing up the Camera Pipeline + Frankencamera Discussion

Visual Computing Systems
Stanford CS348K, Spring 2023

Picking up from last time…
(The HDR part of HDR+)

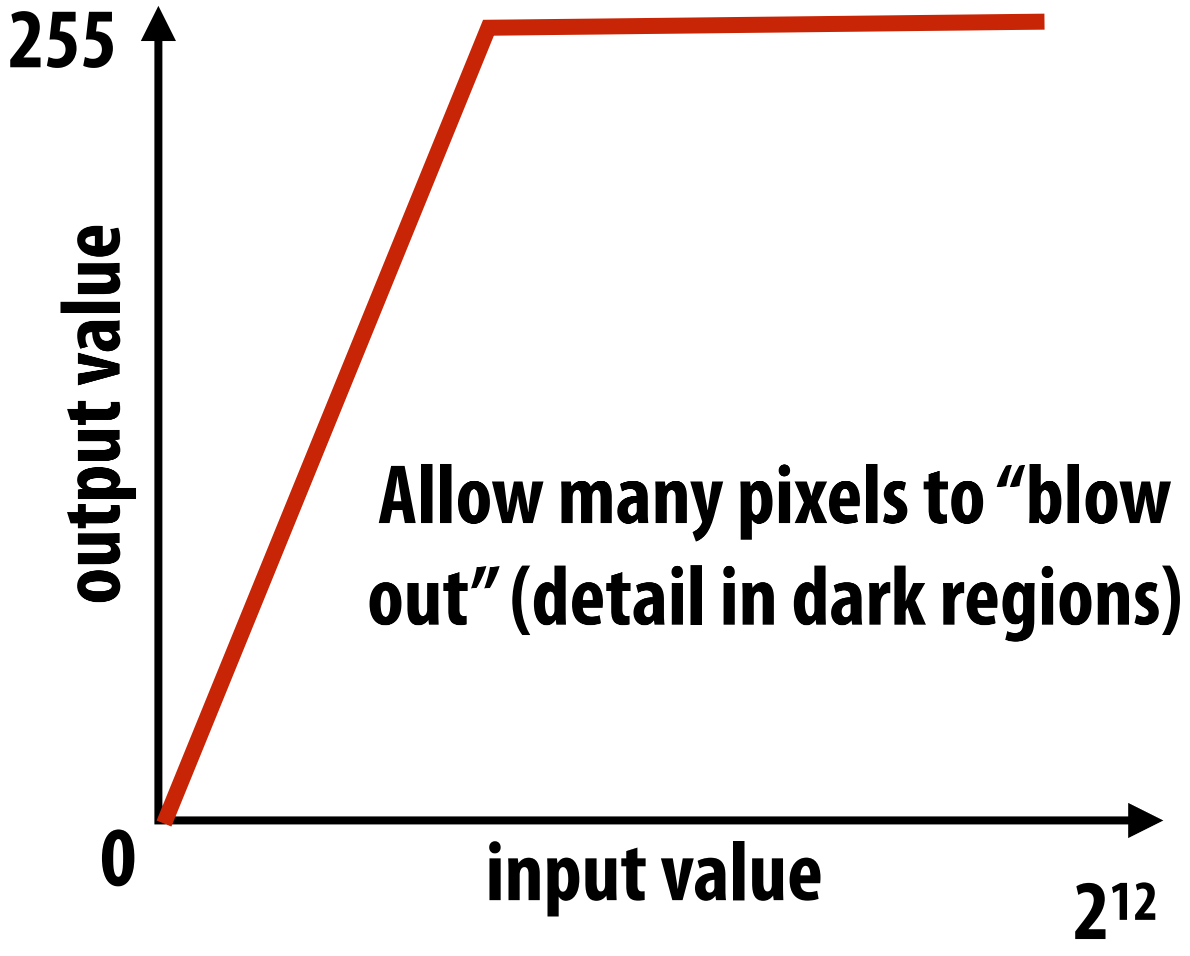
Saturated pixels

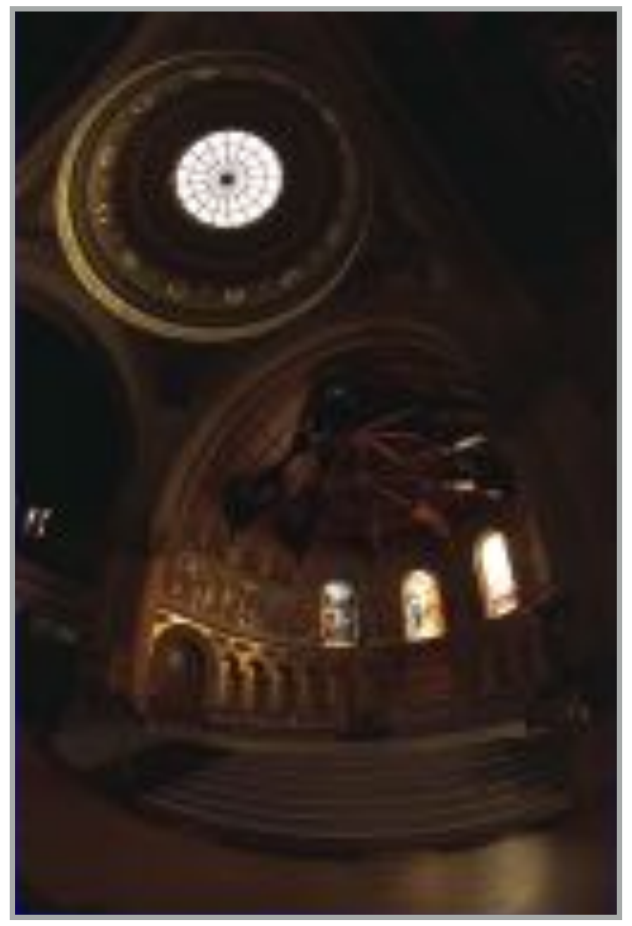
Saturated pixels

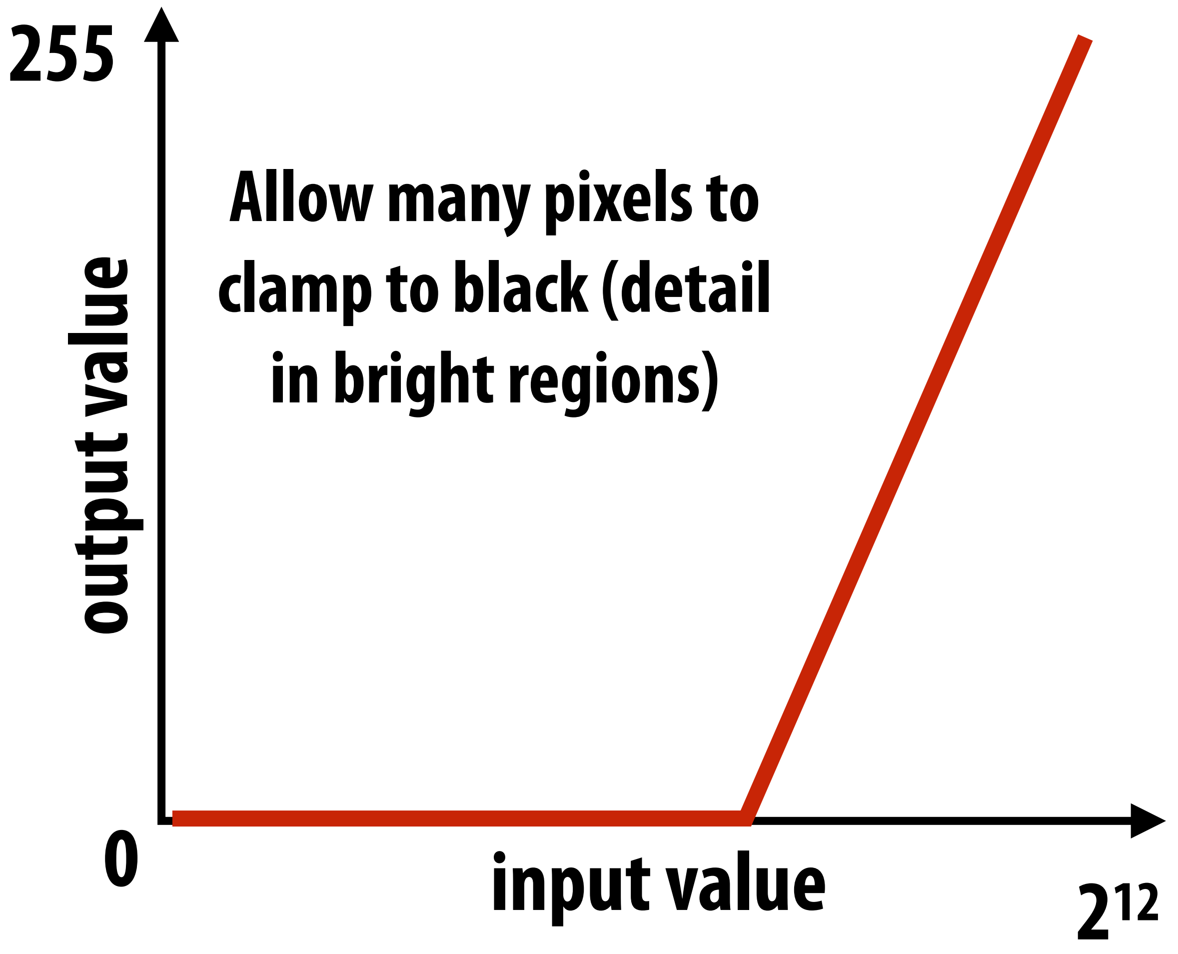
Credit: P. Debevec

Global tone mapping

- Measured image values (by camera's sensor): 10-12 bits / pixel, but common image formats are 8-bits/pixel
- How to convert 12 bit number to 8 bit number?







High dynamic range image (HDR)
Detail in dark and light images

Image credit: Wikipedia

Local tone adjustment

Pixel values

Weights

Improve picture's aesthetics by locally adjusting contrast, boosting dark regions, decreasing bright regions

(no physical basis for this)

Combined image
(unique weights per pixel)

Image credit: Mertens 2007

Challenge of merging images

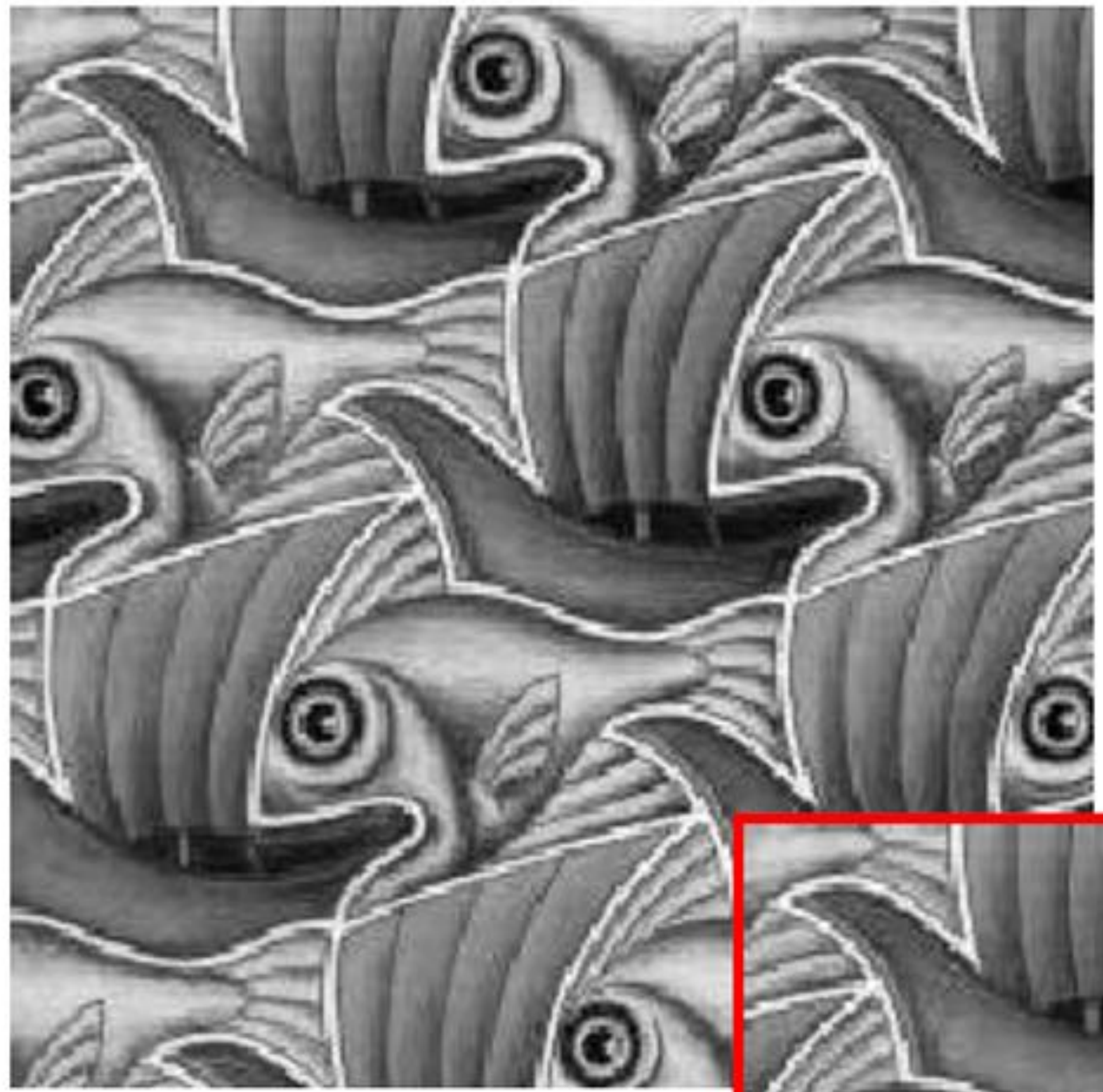
Four exposures (weights not shown)

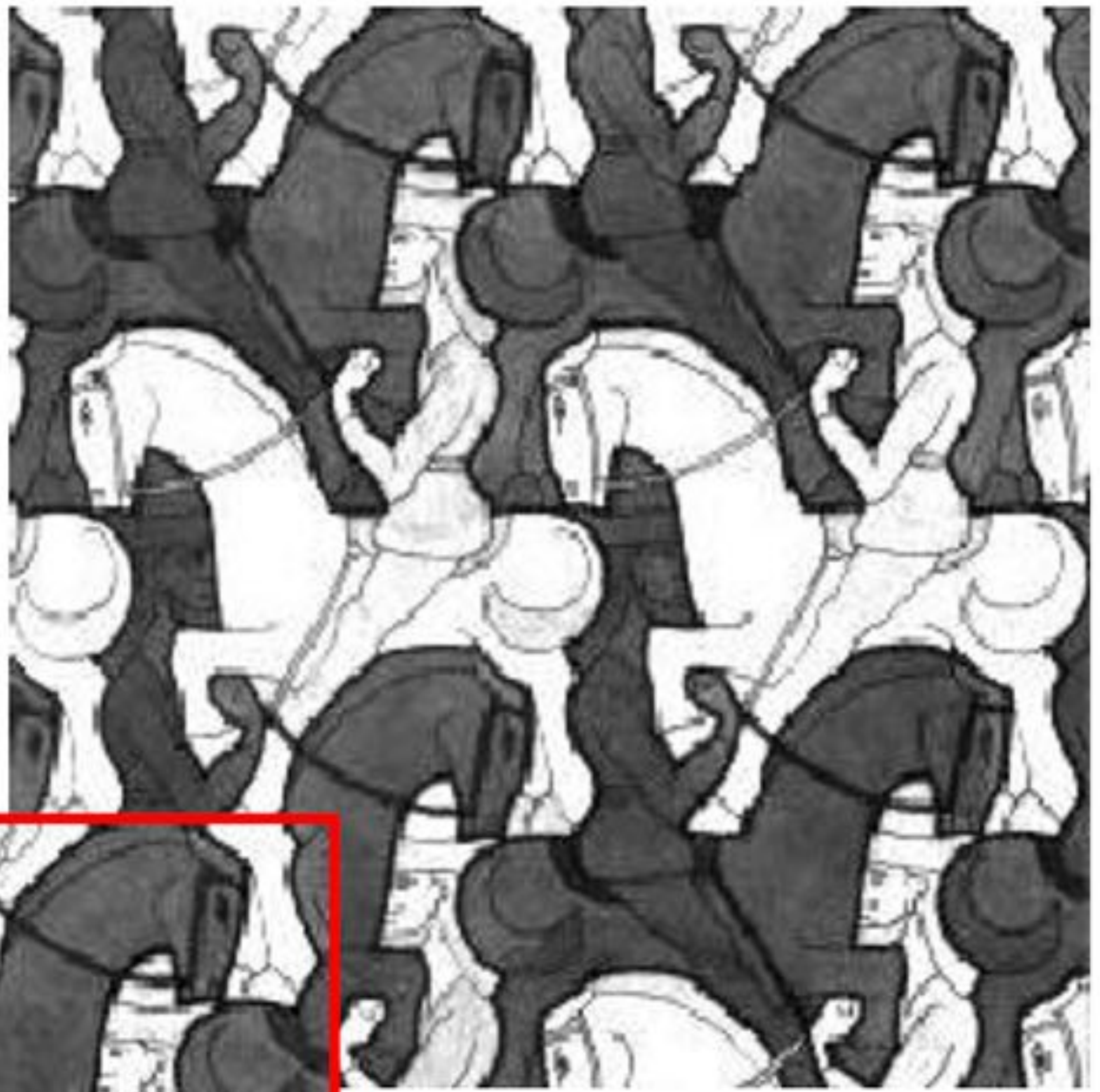
Merged result (based on weight masks)
Notice heavy “banding” since absolute intensity of different exposures is different

Merged result
(after blurring weight mask)
Notice “halos” near edges

Image blending

Consider a simple case where we want to blend two patterns:



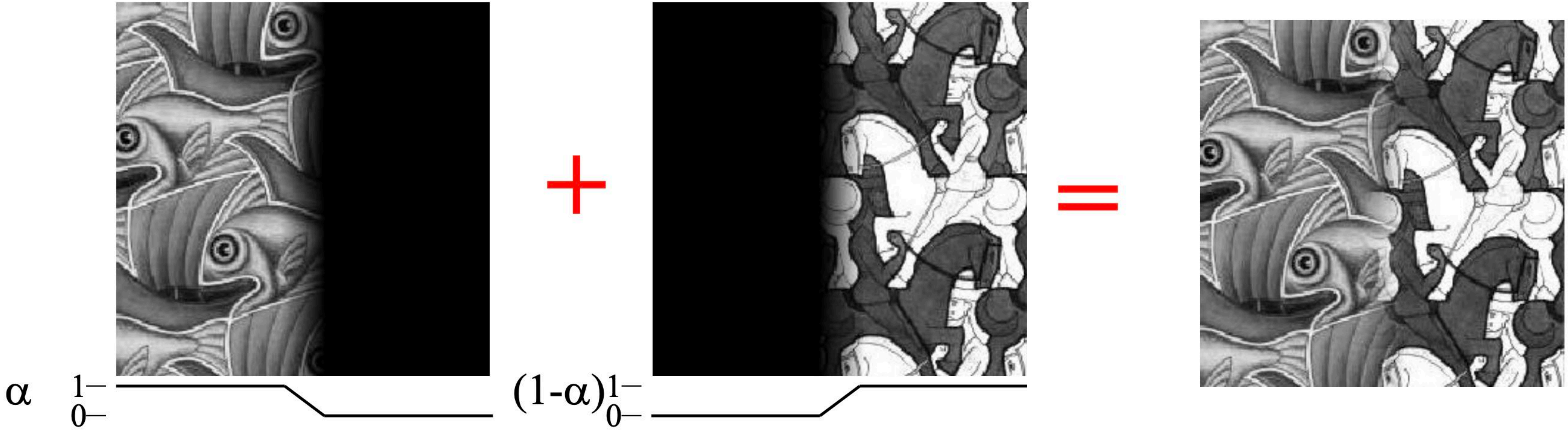


Problem: not "smooth"

Slide credit: Efros

“Feather” the alpha mask

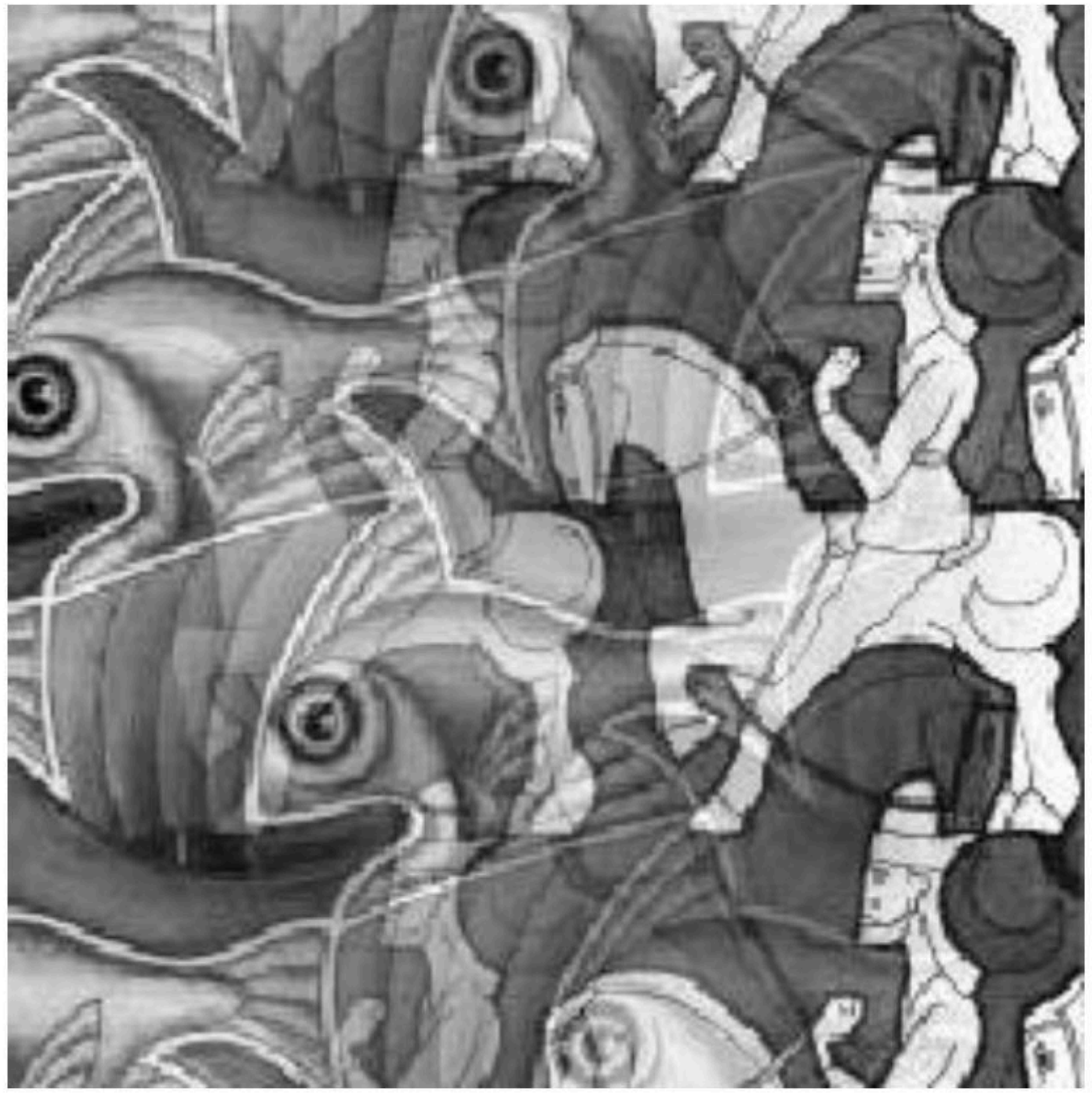
For a “smoother” look…

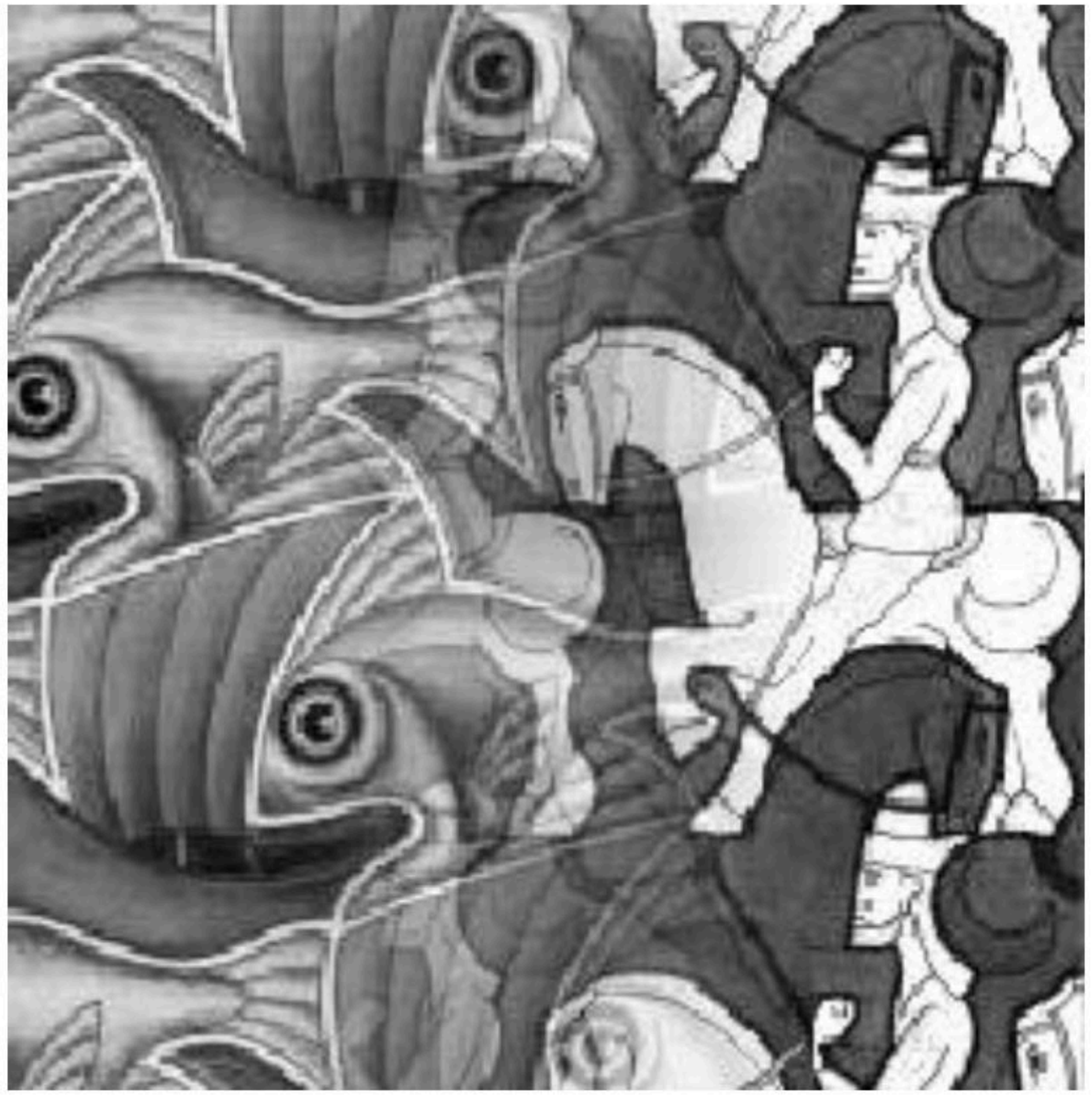


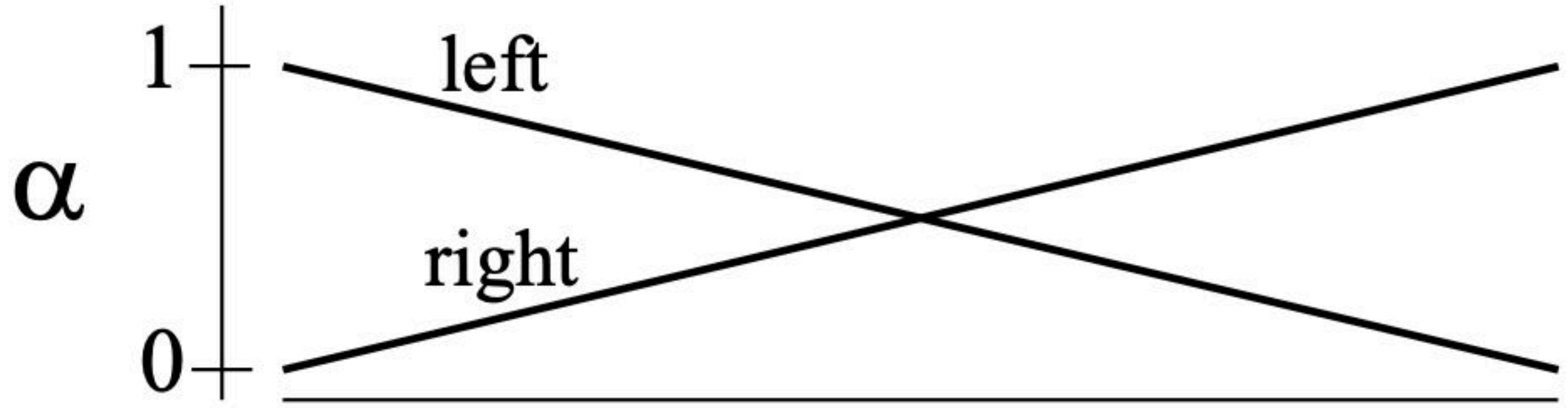
$$\mathrm{I}_{\mathrm{blend}} = \alpha\, \mathrm{I}_{\mathrm{left}} + (1 - \alpha)\, \mathrm{I}_{\mathrm{right}}$$

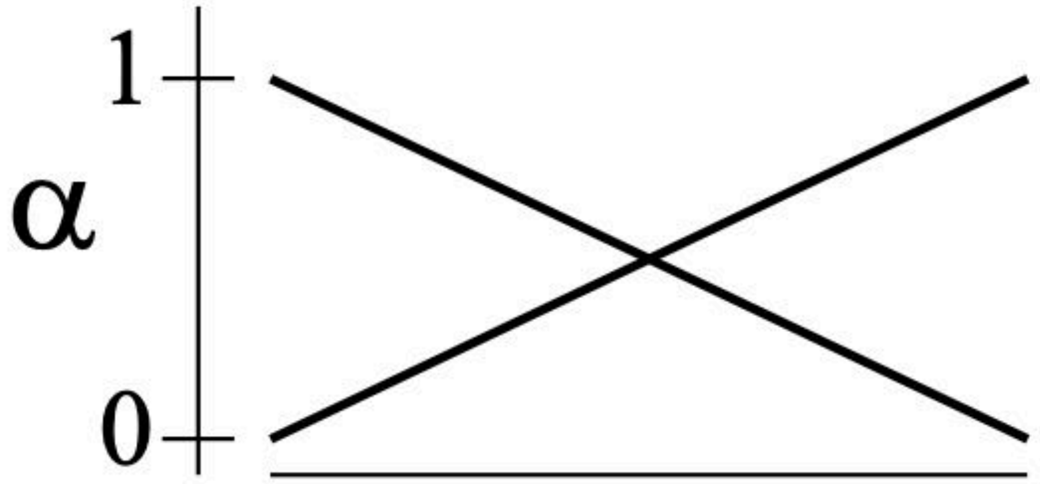
Slide credit: Efros

Effect of feather window size





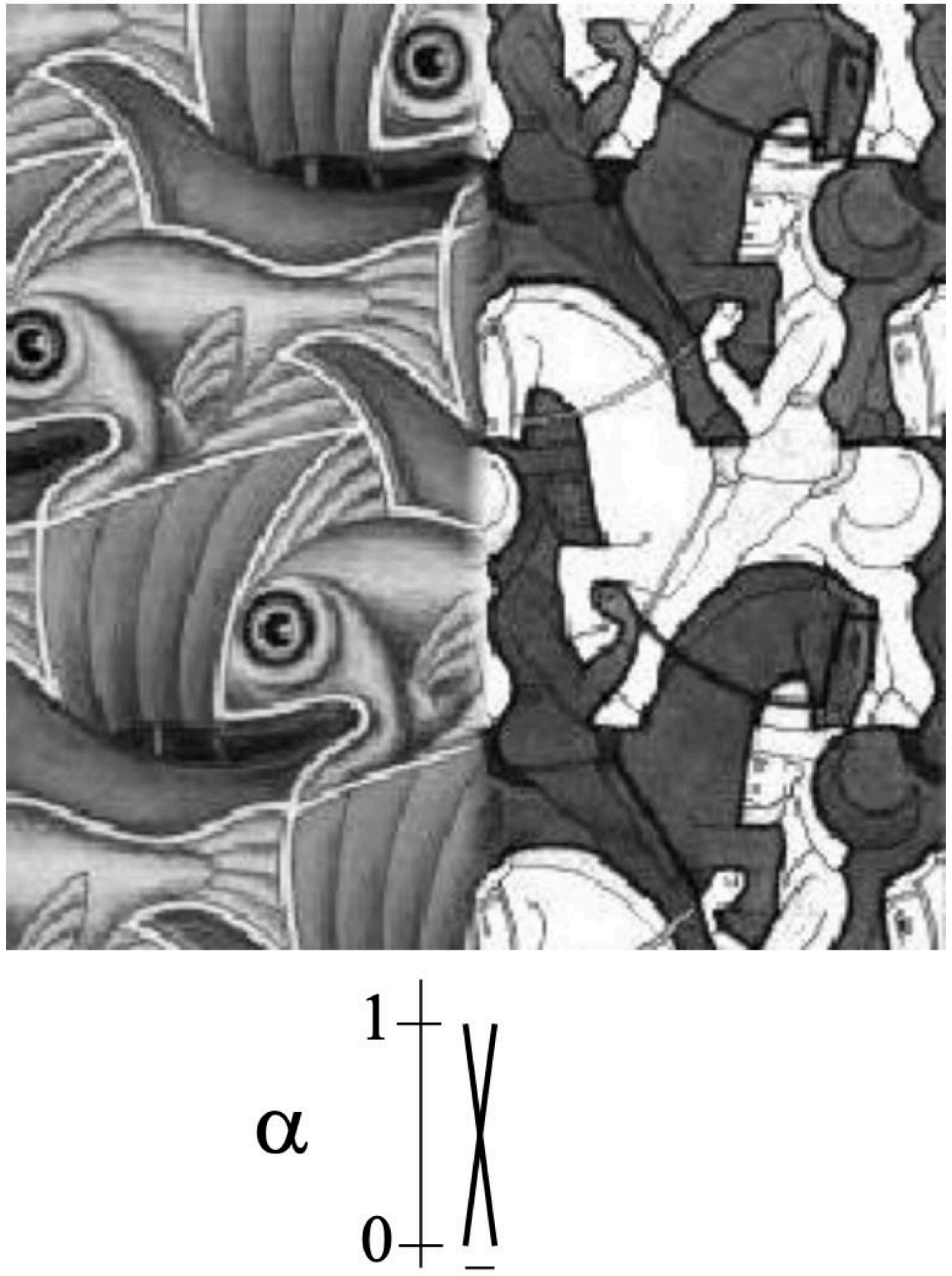


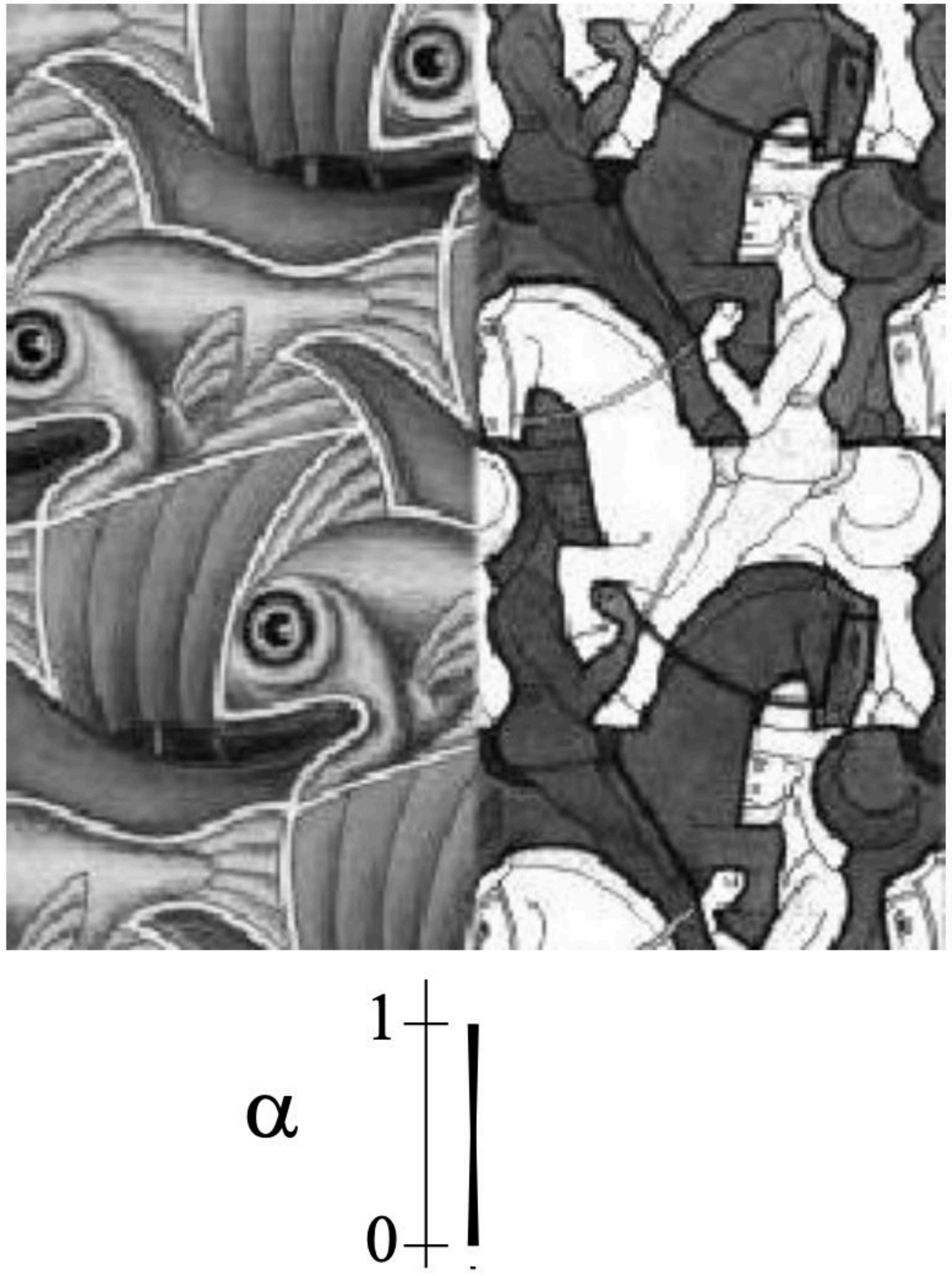


"Ghosting" visible if the feather window (transition) is too large

Slide credit: Efros

Effect of feather window size





Seams visible if the feather window (transition) is too small

Slide credit: Efros

What do we want

- To avoid seams, transition window should be >= size of largest prominent feature
- To avoid ghosting, transition window should be smaller than ~ 2X smallest prominent feature
- In other words, the largest and smallest features need to be within a factor of two for feathering to generate good results
- Intuition:
    - Coarse structure of images (large features) should transition slowly between images
    - Fine structure should blend quickly

Slide credit: Efros, Guerzhoy

Gaussian pyramid

G_0 = image

G_1 = down(G_0)

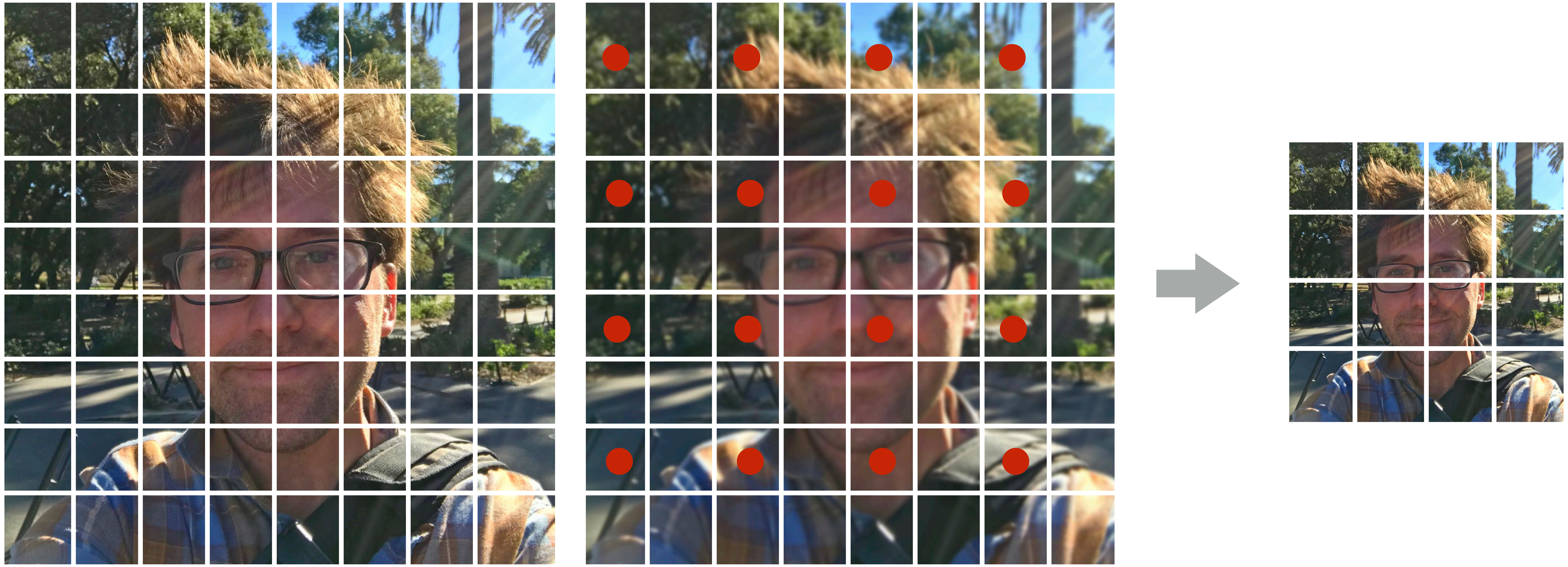
G_2 = down(G_1)

Each image in pyramid contains increasingly low-pass filtered signal

down() = image downsample operation

Downsample

- Step 1: Remove high frequency detail (blur)
- Step 2: Sparsely sample pixels (in this example: every other pixel)



Downsample

- Step 1: Remove high frequency detail (blur)
- Step 2: Sparsely sample pixels (in this example: every other pixel)

```
float input[(WIDTH+2) * (HEIGHT+2)];
float output[WIDTH/2 * HEIGHT/2];

float weights[] = {1/64, 3/64, 3/64, 1/64,    // 4x4 blur (approx Gaussian)
                   3/64, 9/64, 9/64, 3/64,
                   3/64, 9/64, 9/64, 3/64,
                   1/64, 3/64, 3/64, 1/64};

for (int j=0; j<HEIGHT/2; j++) {
   for (int i=0; i<WIDTH/2; i++) {
      float tmp = 0.f;
      for (int jj=0; jj<4; jj++)
         for (int ii=0; ii<4; ii++)
            tmp += input[(2*j+jj)*(WIDTH+2) + (2*i+ii)] * weights[jj*3 + ii];
      output[j*WIDTH/2 + i] = tmp;
  }
}
```

Gaussian pyramid

G_0

Gaussian pyramid

G_1

Gaussian pyramid

G_2

Gaussian pyramid

G_3

Gaussian pyramid

G_4

Gaussian pyramid

G_5

Upsample

Via bilinear interpolation of samples from low resolution image

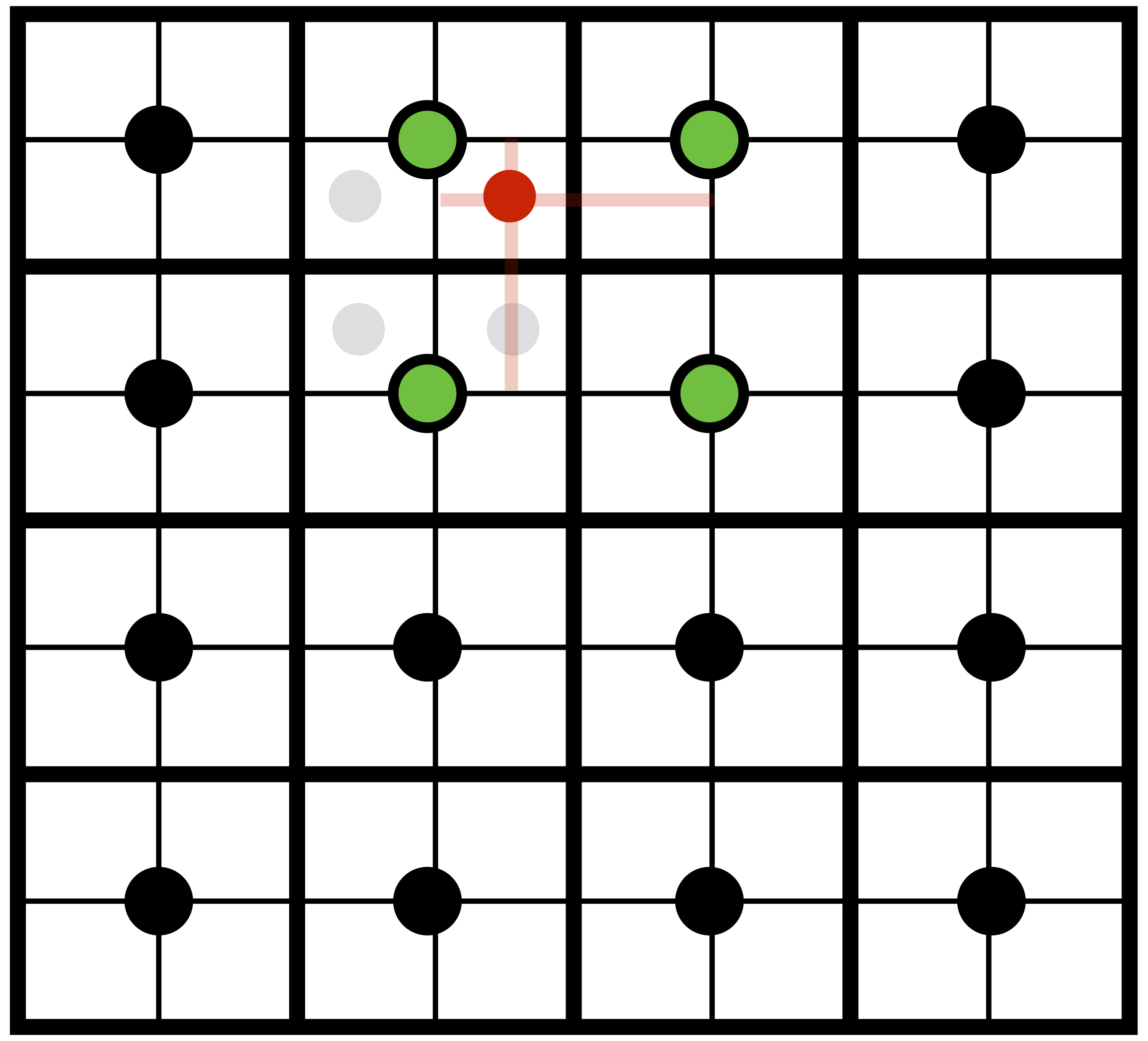
Upsample

Via bilinear interpolation of samples from low resolution image

```
float input[WIDTH * HEIGHT];
float output[2*WIDTH * 2*HEIGHT];

for (int j=0; j<2*HEIGHT; j++) {
   for (int i=0; i<2*WIDTH; i++) {
      int row = j/2;
      int col = i/2;
      float w1 = (i%2) ? .75f : .25f;
      float w2 = (j%2) ? .75f : .25f;

      output[j*2*WIDTH + i] = w1 * w2 * input[row*WIDTH + col] +
                              (1.0-w1) * w2 * input[row*WIDTH + col+1] +
                              w1 * (1-w2) * input[(row+1)*WIDTH + col] +
                              (1.0-w1)*(1.0-w2) * input[(row+1)*WIDTH + col+1];
  }
}
```



Laplacian pyramid

$L_0 = G_0 - \mathrm{up}(G_1)$

G_0

$G_1 = \mathrm{down}(G_0)$

Each (increasingly numbered) level in Laplacian pyramid represents a band of (increasingly lower) frequency information in the image

down() = image downsample operation

up() = image upsample operation

[Burt and Adelson 83]

Laplacian pyramid

$L_0 = G_0 - up(G_1)$

$L_1 = G_1 - up(G_2)$

Laplacian pyramid

$L_0 = G_0 - up(G_1)$

$L_1 = G_1 - up(G_2)$

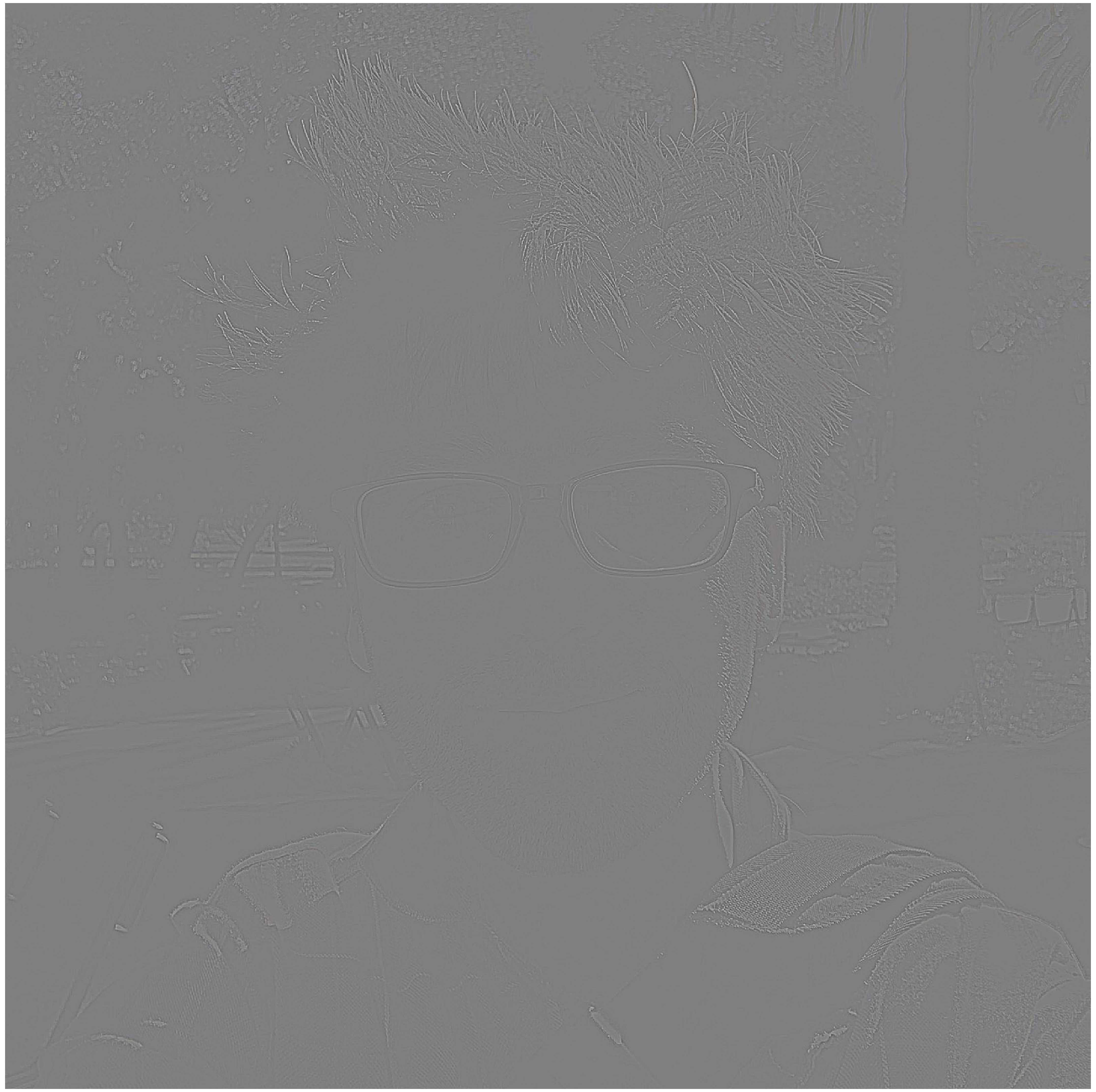
$L_2 = G_2 - up(G_3)$

$L_3 = G_3 - up(G_4)$

$L_4 = G_4$

Question: how do you reconstruct original image from its Laplacian pyramid?

Laplacian pyramid



$L_0 = G_0 - \mathrm{up}(G_1)$

Laplacian pyramid

$L_1 = G_1 - up(G_2)$

Laplacian pyramid

$L_2 = G_2 - up(G_3)$

Laplacian pyramid

$L_3 = G_3 - up(G_4)$

Laplacian pyramid

$L_4 = G_4 - \mathrm{up}(G_5)$

Laplacian pyramid

$L_5 = G_5$

Gaussian/Laplacian pyramid summary

- **Gaussian and Laplacian pyramids are image representations where each pixel maintains information about frequency content in a region of the image**

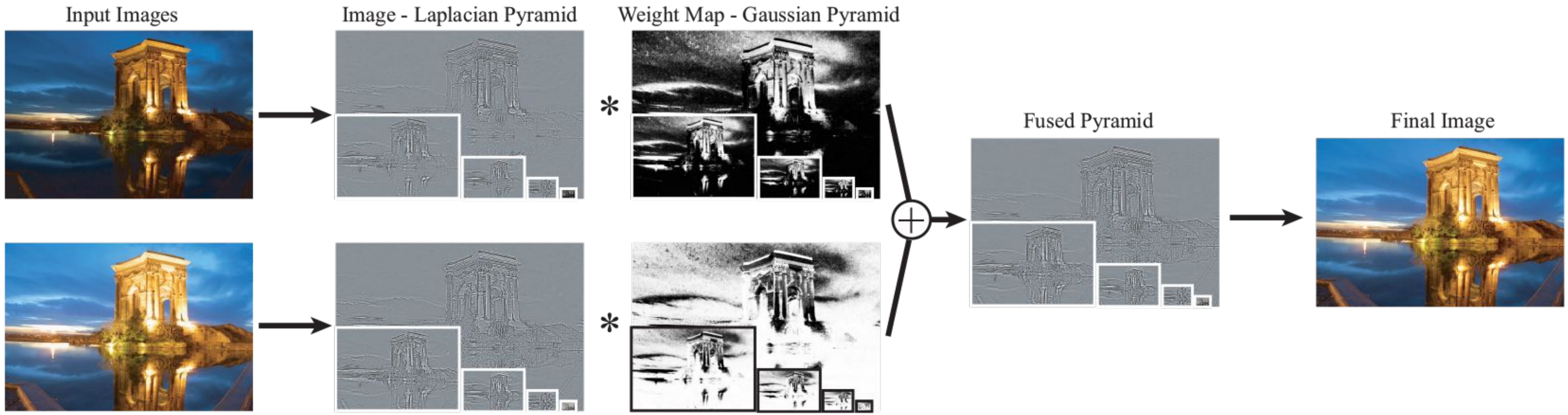
- **$G_i(x,y)$ — frequencies up to limit given by *i***

- **$L_i(x,y)$ — frequencies added to G_{i+1} to get G_i**

- **Notice: to boost the band of frequencies in image around pixel (x,y), increase coefficient $L_i(x,y)$ in Laplacian pyramid**

Use of Laplacian pyramid in local tone mapping

- Build Gaussian pyramid of weight map
- Merge laplacian pyramids (image features) not image pixels according to weight pyramid
- "Flatten" merged laplacian pyramid to get final image



Merging Laplacian pyramids

Four exposures (weights not shown)

Merged result
(after blurring weight mask)
Notice “halos” near edges

Merged result
(based on multi-resolution pyramid merge)

Why does merging Laplacian pyramids work better than merging image pixels?

Summary: simplified image processing pipeline

- Correct pixel defects
- Align and merge (to create high signal to noise ration RAW image)
- Correct for sensor bias (using measurements of optically black pixels)
- Vignetting compensation
- White balance

(10-12 bits per pixel)
1 intensity value per pixel
Pixel values linear in energy

- Demosaic
- Denoise
- Gamma Correction (non-linear mapping)

3x10 bits per pixel
RGB intensity per pixel
Pixel values linear in energy

- Local tone mapping
- Final adjustments sharpen, fix chromatic aberrations, hue adjust, etc.

3x8-bits per pixel
Pixel values perceptually linear

Frankencamera
(Discussion)

Choosing the "right" representation for the job

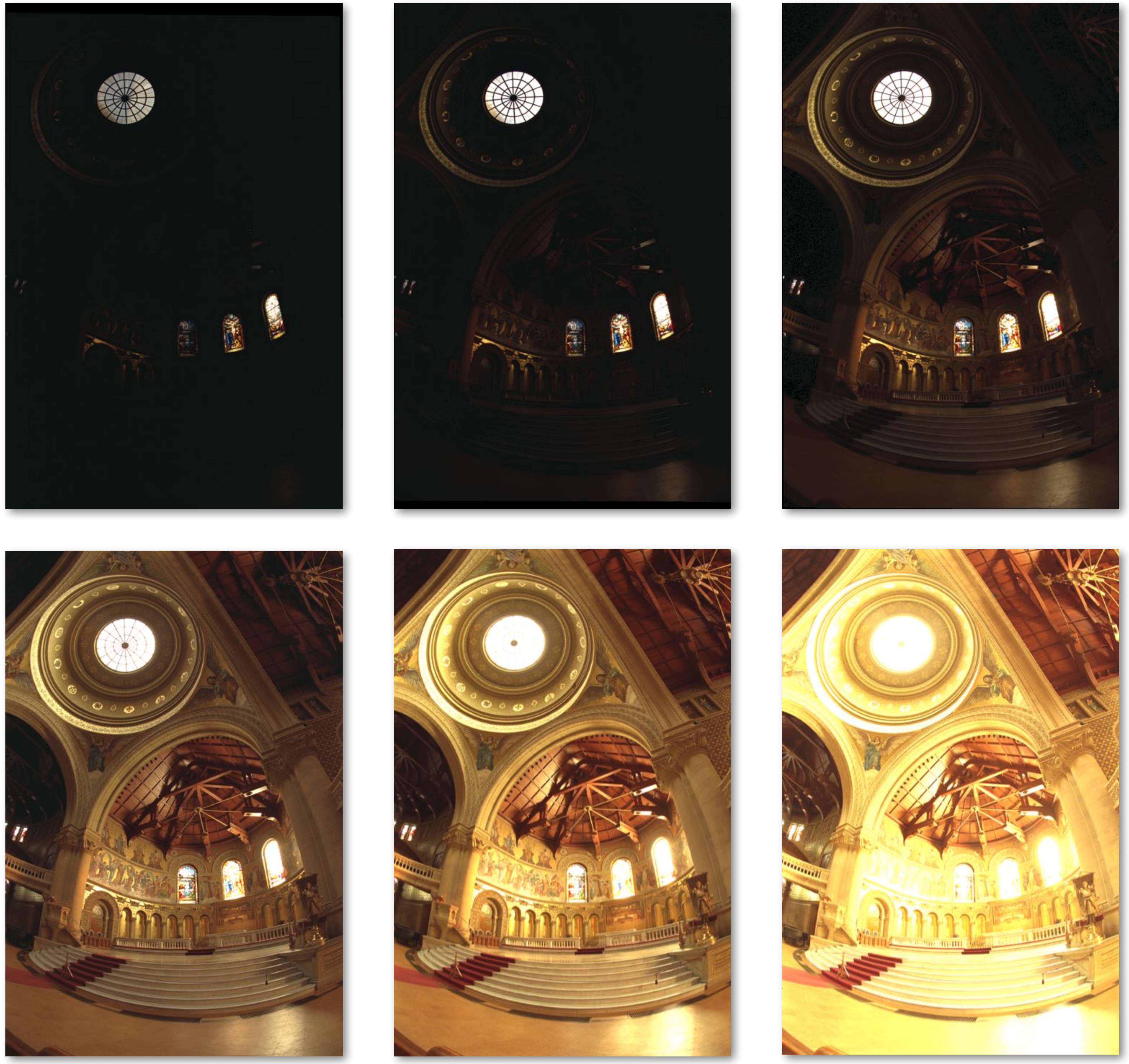
- Good representations are productive to use:
  - They embody the natural way of thinking about a problem

- Good representations enable the system to provide the application developer useful services:
  - Validating/providing certain guarantees (correctness, resource bounds, conversation of quantities, type checking)
  - Performance optimizations (parallelization, vectorization, use of specialized hardware)
  - Implementations of common, difficult-to-implement functionality (texture mapping and rasterization in 3D graphics, auto-differentiation in ML frameworks)

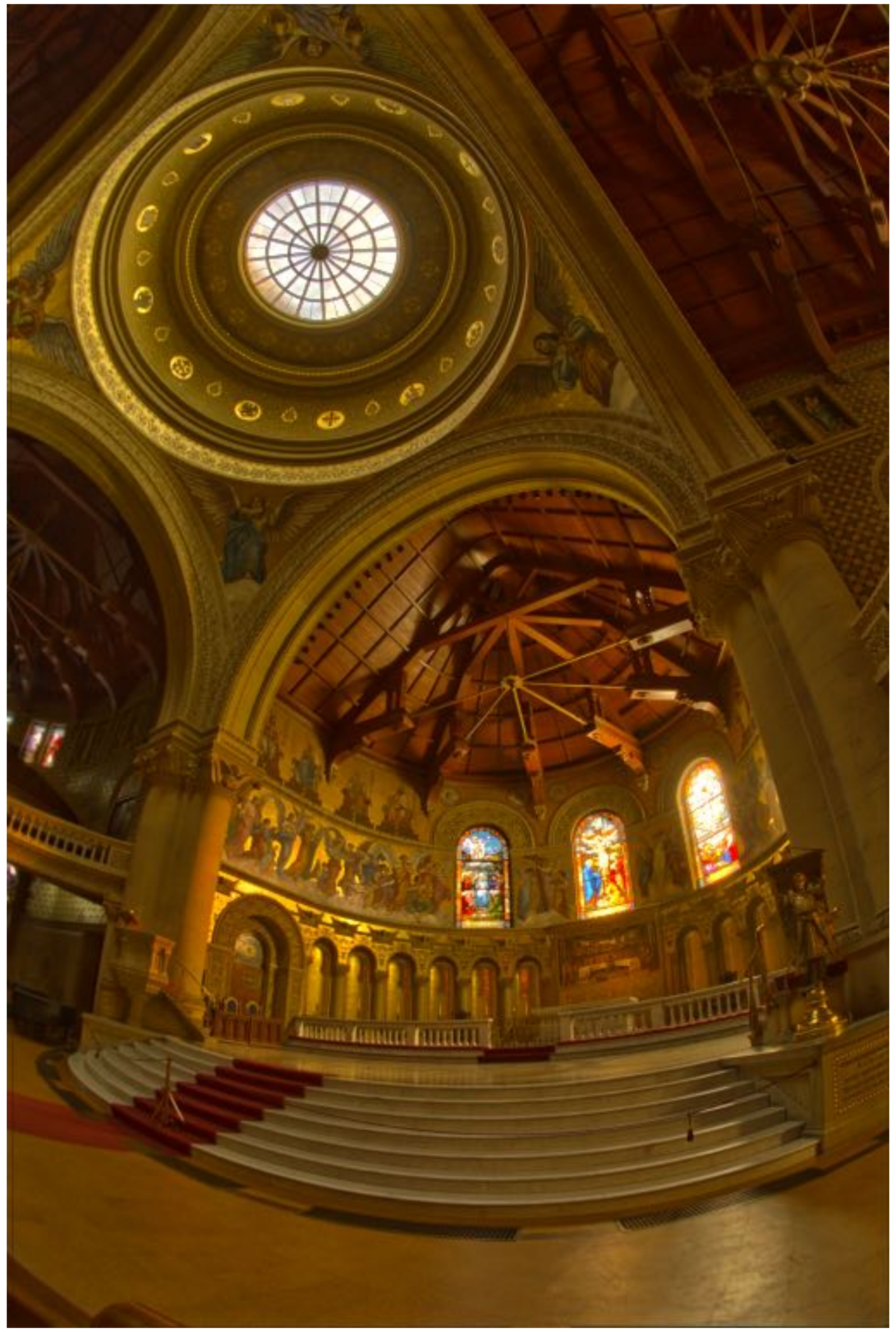
Frankencamera: some 2010 context

- Cameras were becoming increasingly cheap and ubiquitous
- Cameras featured increasing processing capability
- Significant graphics research focus on developing techniques for combining multiple photos to overcome deficiencies of traditional camera systems

Multi-shot photography example: high dynamic range (HDR) images



Source photographs: each photograph has different exposure



Tone mapped HDR image

Credit: Debevec and Malik

More multi-shot photography examples

"Lucky" imaging

Take several photos in rapid succession: likely to find one without camera shake

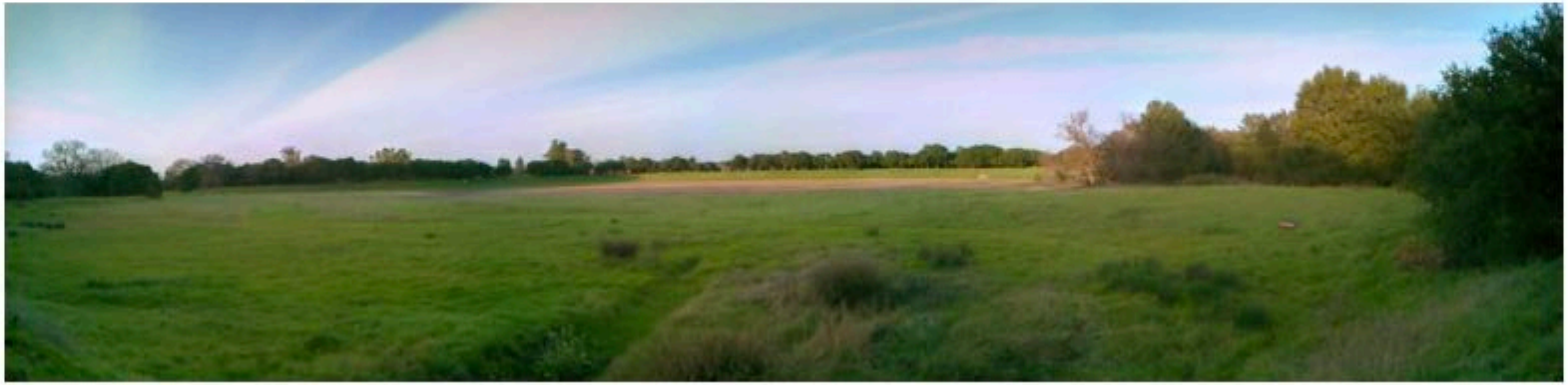
no-flash flash result

Flash-no-flash photography [Eisemann and Durand]
(use flash image for sharp, colored image, infer room lighting from no-flash image)

More multi-shot photography examples

Panorama capture

individual images



extended dynamic range panorama

Frankencamera: some 2010 context

- Cameras were becoming increasingly cheap and ubiquitous
- Cameras featured increasing processing capability
- Significant graphics research focus on developing techniques for combining multiple photos to overcome deficiencies of traditional camera systems

- Problem: the ability to implement multi-shot techniques on cameras was limited by camera system programming abstractions
  - Programmable interface to camera was very basic
  - Echoed physical button interface to a point-and-shoot camera:
    - `take_photograph(parameters, output_jpg_buffer)`
  - Result: on most camera implementations, latency between two photos was high, mitigating utility of multi-shot techniques (large scene movement or camera shake between shots)

Frankencamera (F-cam) goals

[Adams et al. 2010]

1. Create open, handheld computational camera platform for researchers

2. Define system architecture for computational photography applications
   - Motivated by impact of OpenGL on graphics application and graphics hardware development (portable apps despite highly optimized GPU implementations)
   - Motivated by proliferation of smart-phone apps

F2 Reference Implementation

Note: Apple was not involved in Frankencamera's industrial design. ;-)

Nokia N900 Smartphone Implementation

F-cam scope

- F-cam provides a set of abstractions that allow for manipulating configurable camera components
  - Timeline-based specification of actions
  - Feed-forward system: no feedback loops

- F-cam architecture performs image processing, but...
  - This functionality as presented by the architecture is <u>not programmable</u>
  - Hence, F-cam does not provide an image processing language (it's like fixed-function OpenGL)
  - Other than work performed by the image processing stage, F-cam applications perform their own image processing (e.g., on smartphone/camera's CPU or GPU resources)

Android Camera2 API

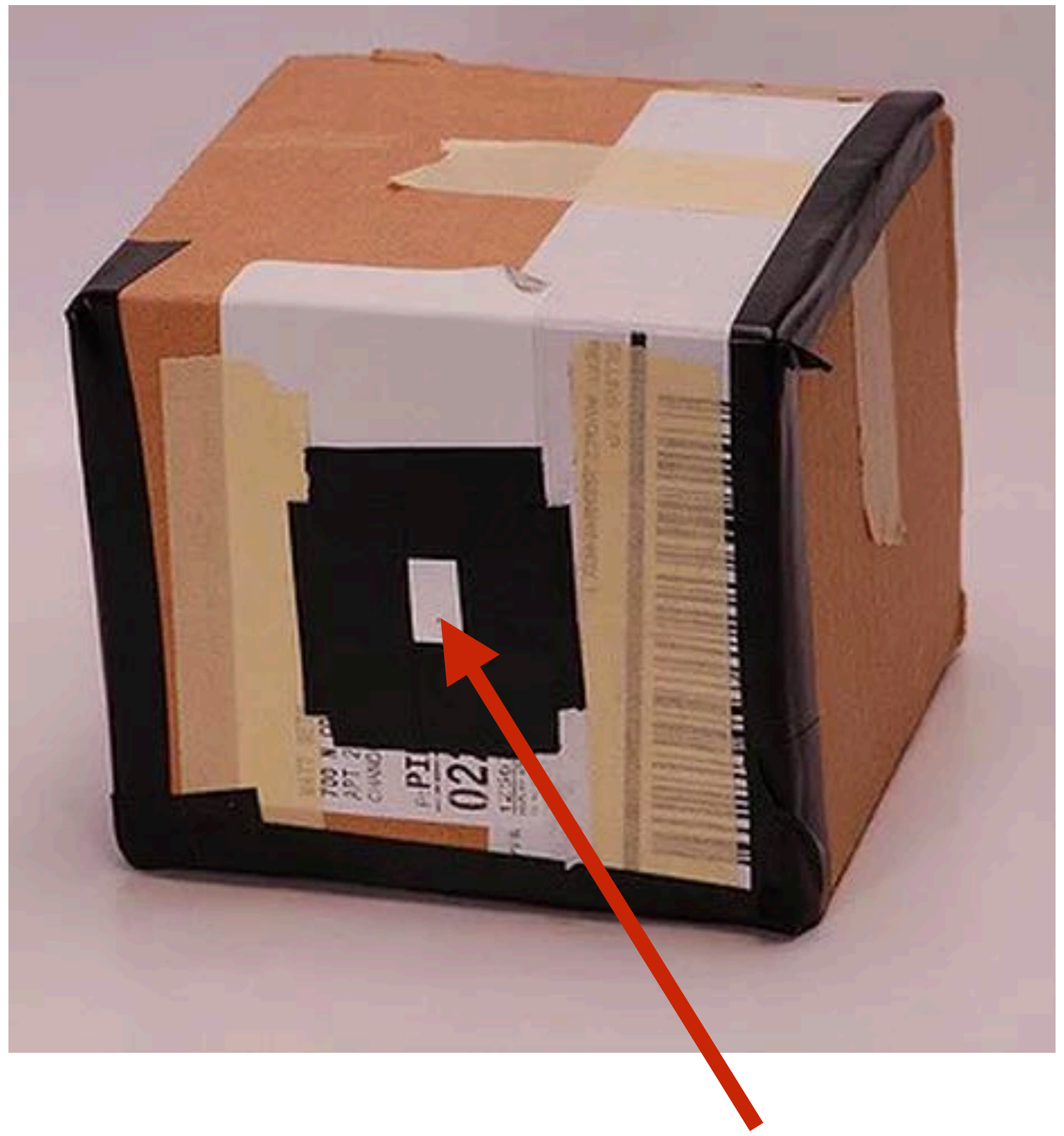
- **Take a look at the documentation of the Android Camera2 API, and you'll see influence of F-Cam.**

Modern smartphone cameras perform advanced image analysis functions

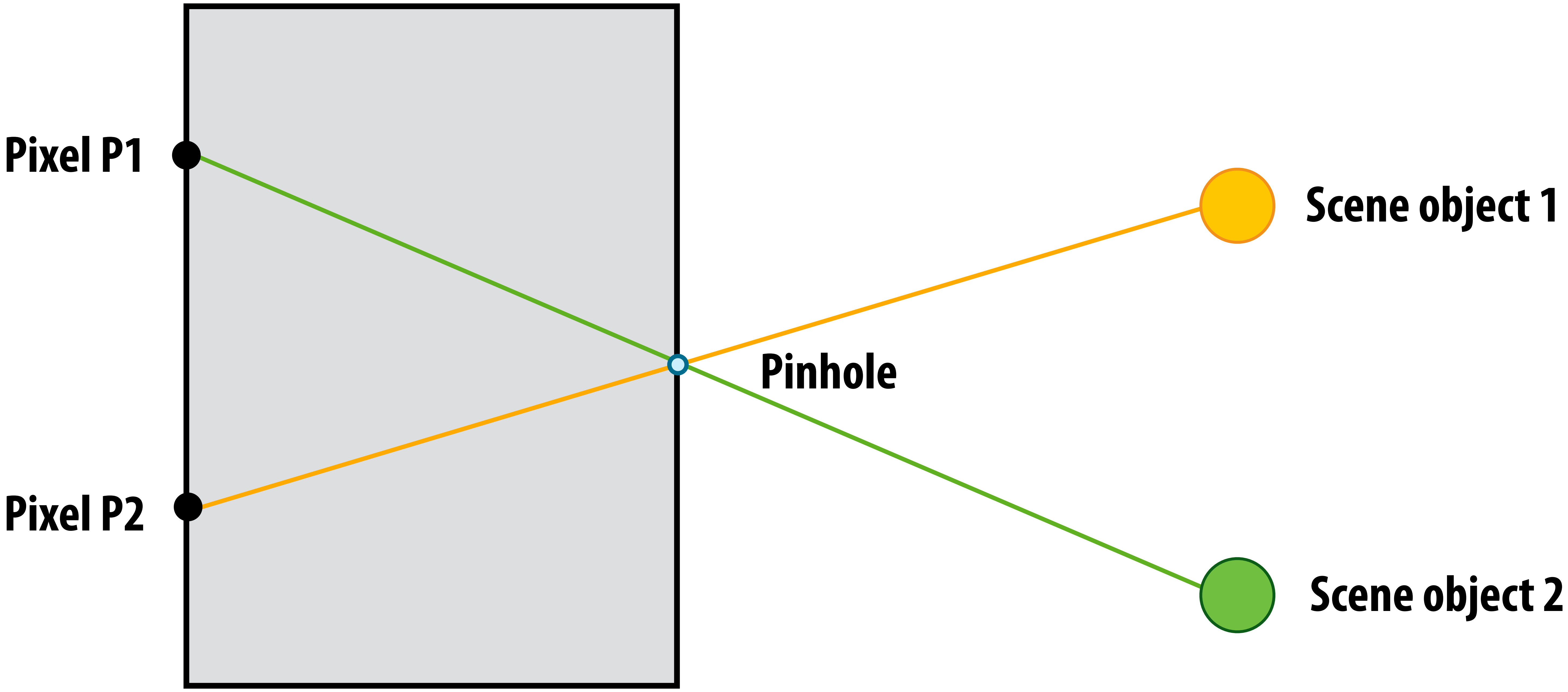
Image analysis examples from prior lectures:
auto white balance, auto exposure, image denoising

Auto Focus

Pinhole camera (no lens)



Pinhole



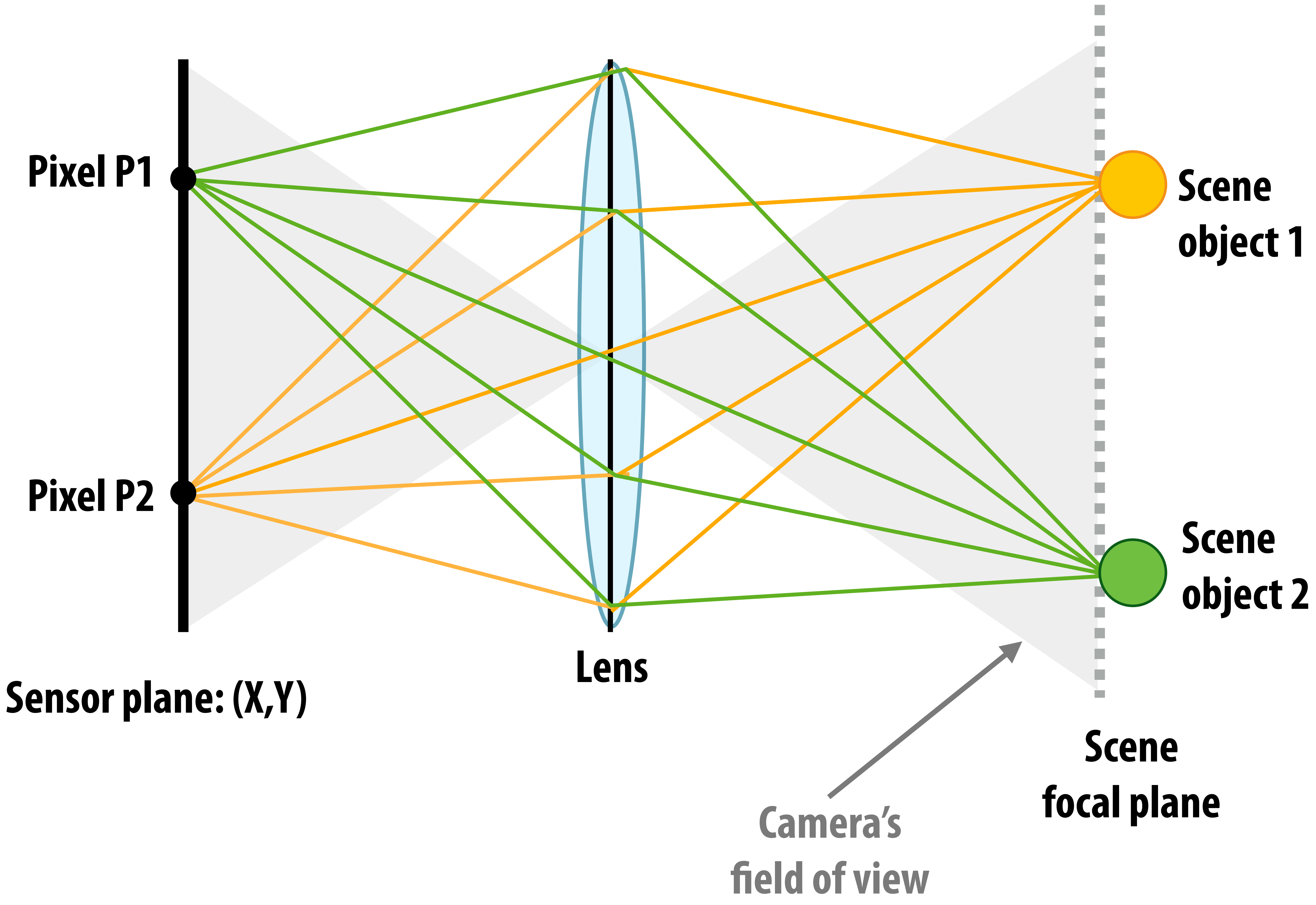
Sensor plane: (X,Y)

What does a lens do?

A lens refracts light.

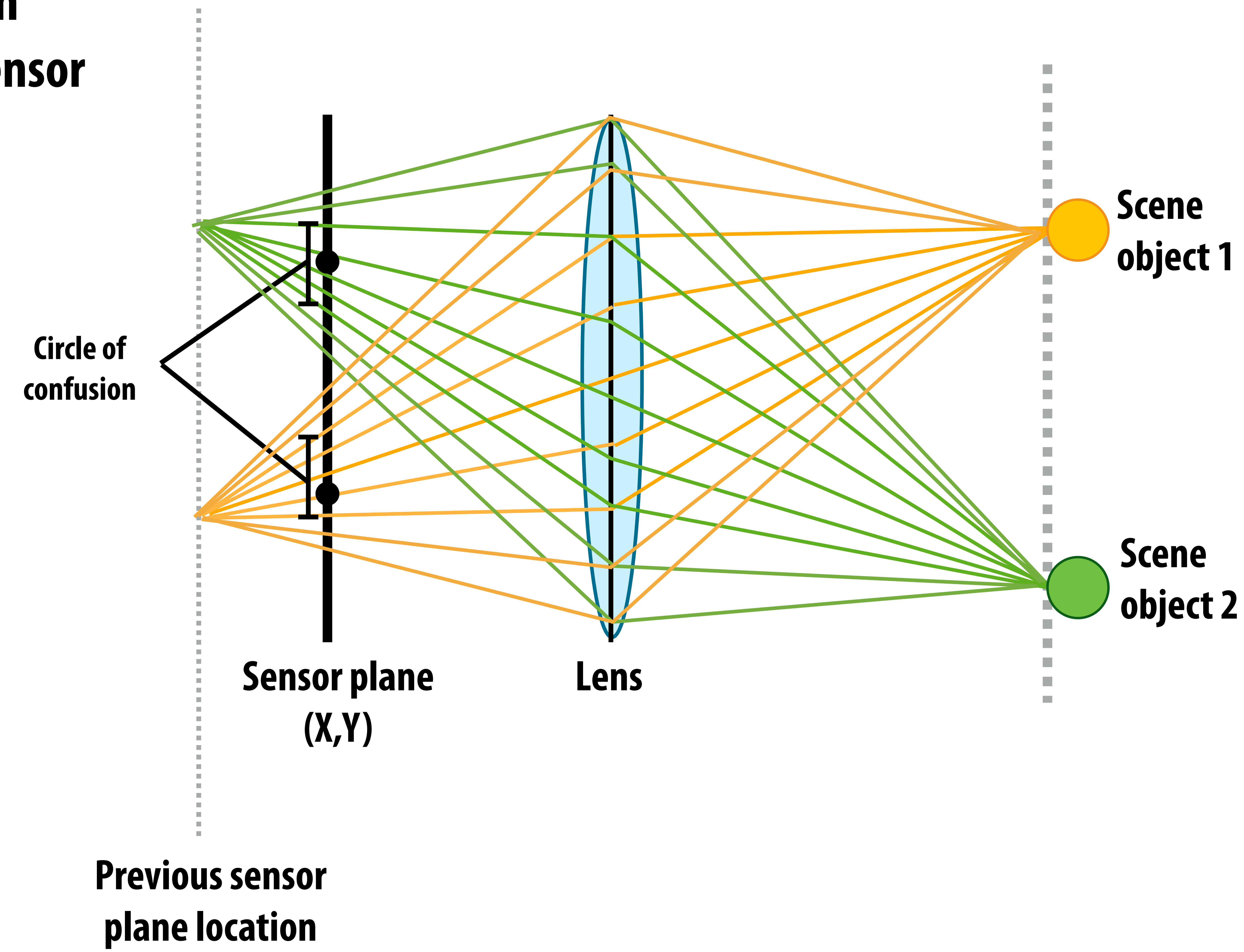
Camera with lens: every pixel accumulates all rays of light that pass through lens aperture and refract toward that pixel

In-focus camera: all rays of light from a point in the scene arrive at a point on sensor plane



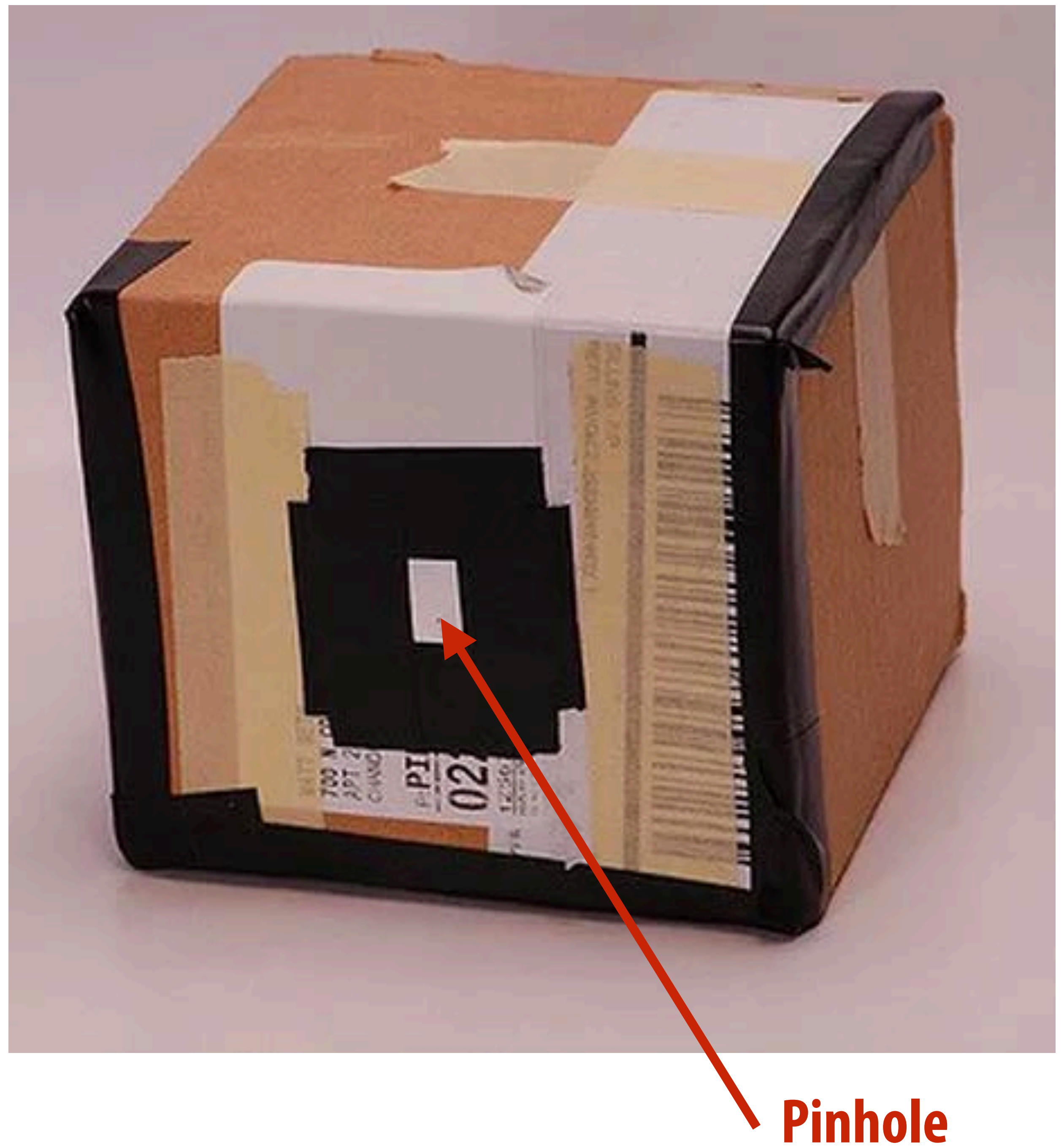
Out of focus camera

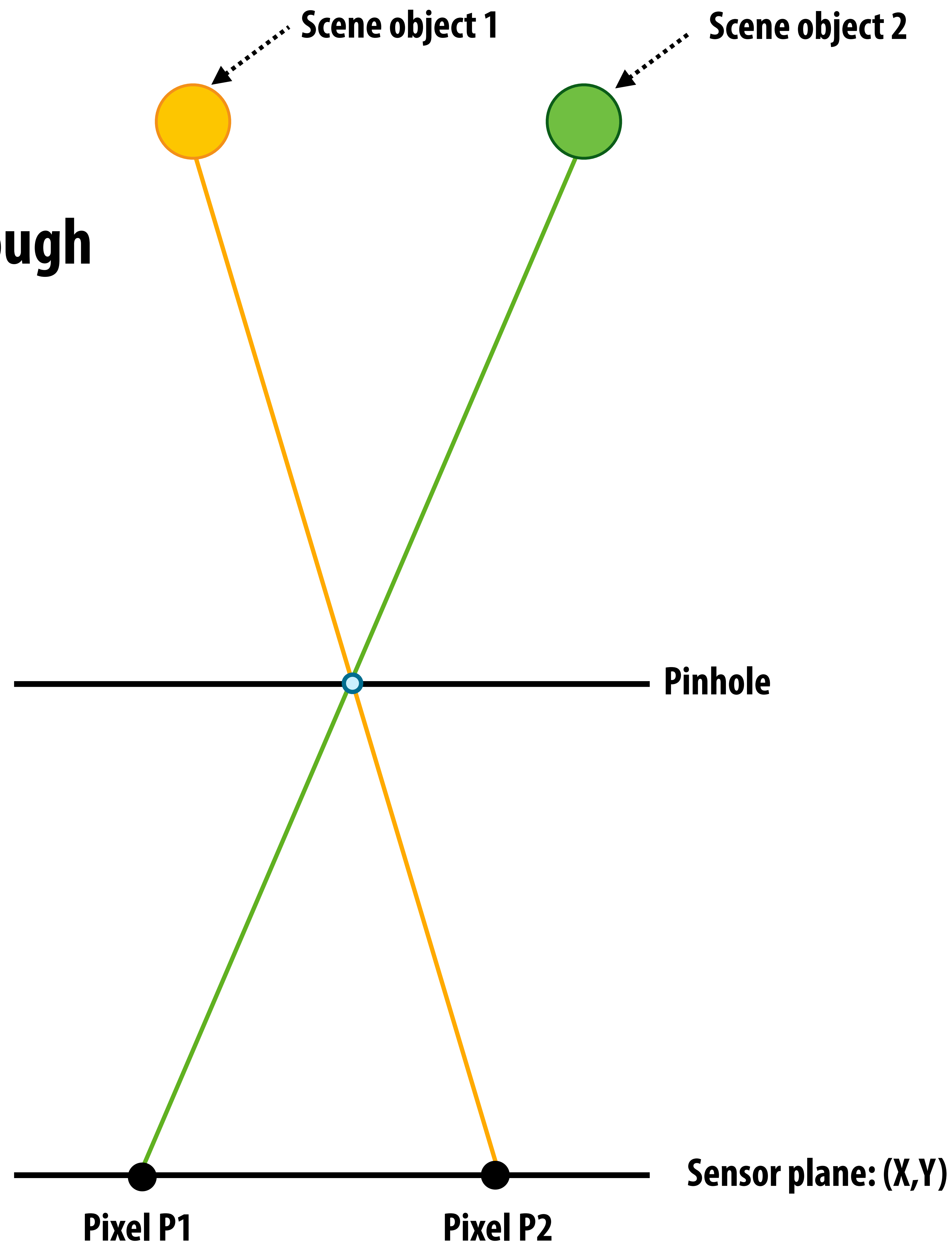
Out of focus camera: rays of light from one point in scene do not converge to the same point on the sensor



What does a lens do?

Recall: pinhole camera you may have made in science class
(every pixel measures ray of light passing through pinhole and arriving at pixel)





Bokeh

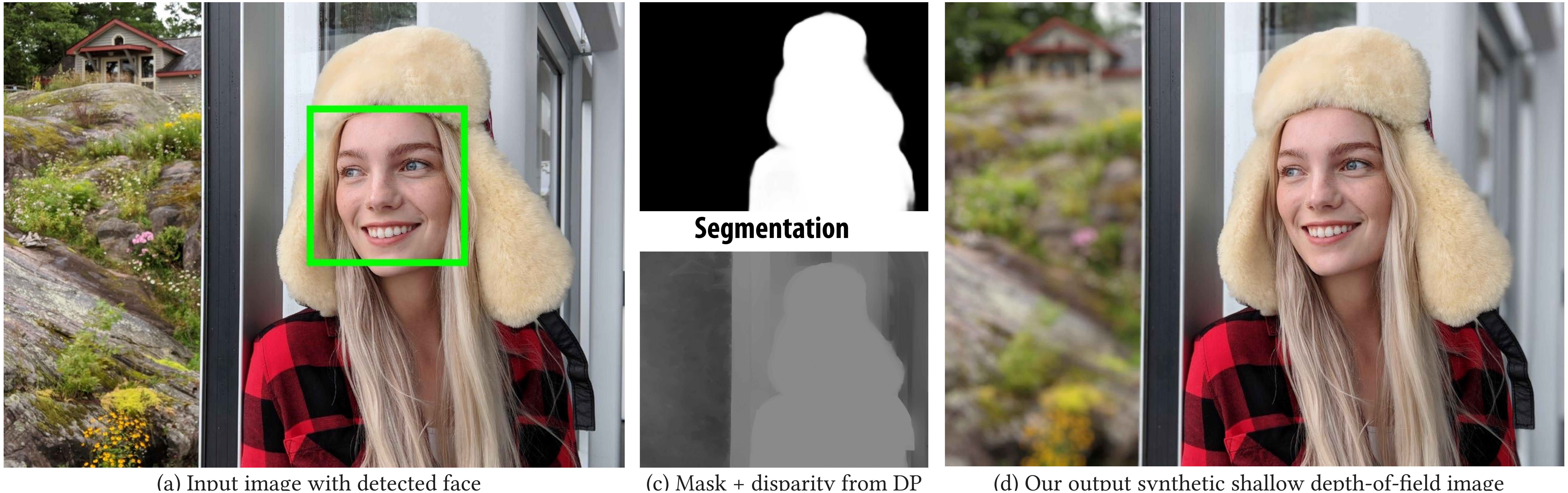
Sharp foreground, defocused background

Common technique to emphasize subject in a photo

Cell phone camera lens(es)
(small aperture)

Portrait mode in modern smartphones

- Smart phone cameras have small apertures
  - Good: thin, lightweight lenses, often fast focus
  - Bad: cannot physically create aesthetically please photographs with nice bokeh, blurred background
- Answer: simulate behavior of large aperture lens (hallucinate image formed by large aperture lens)



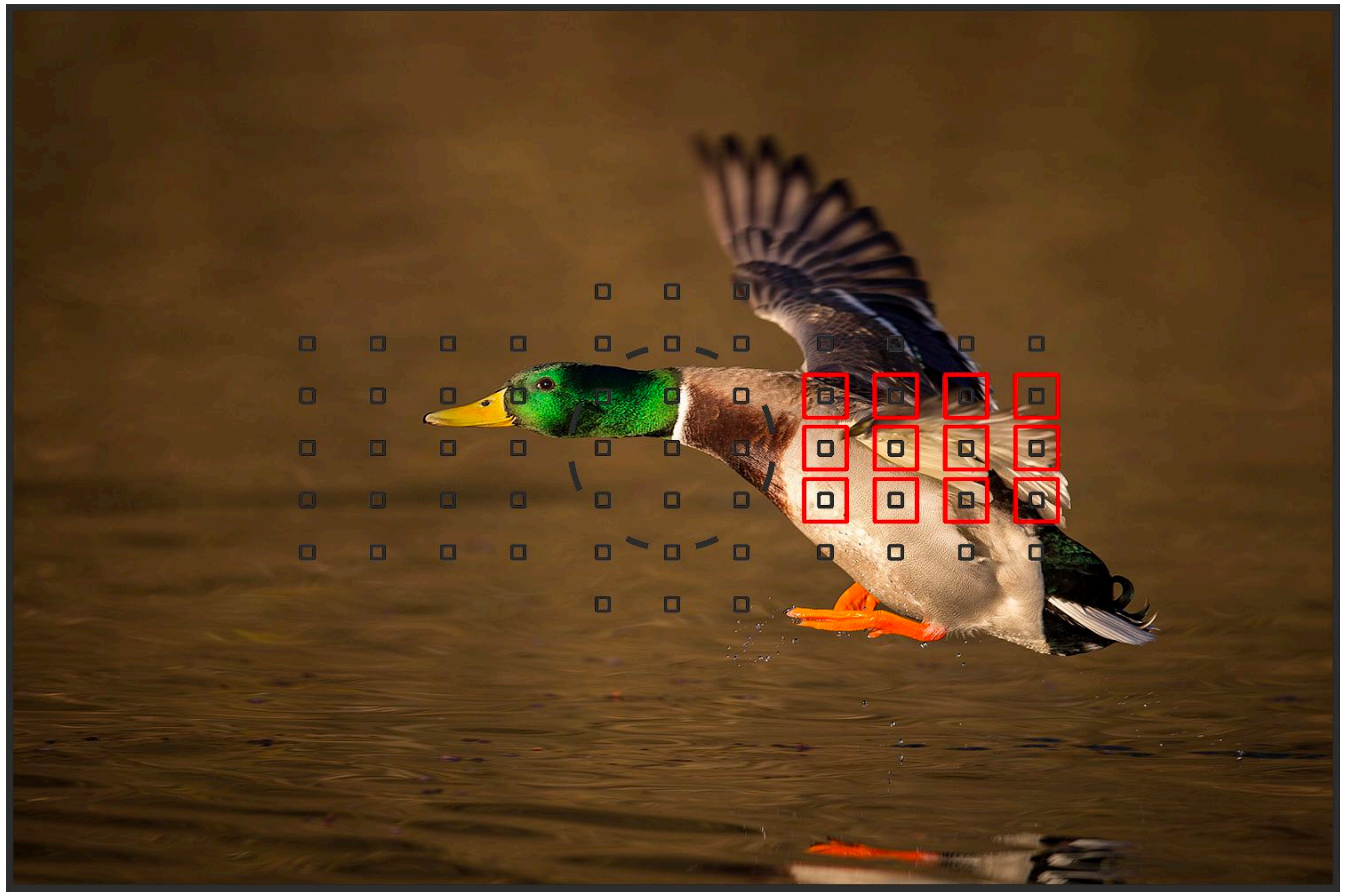
Input image /w detected face

Scene Depth
Estimate

Generated image
(note blurred background.
Blur increases with depth)

Image credit: [Wadha 2018]

What part of image should be in focus?



Consider possible heuristics:

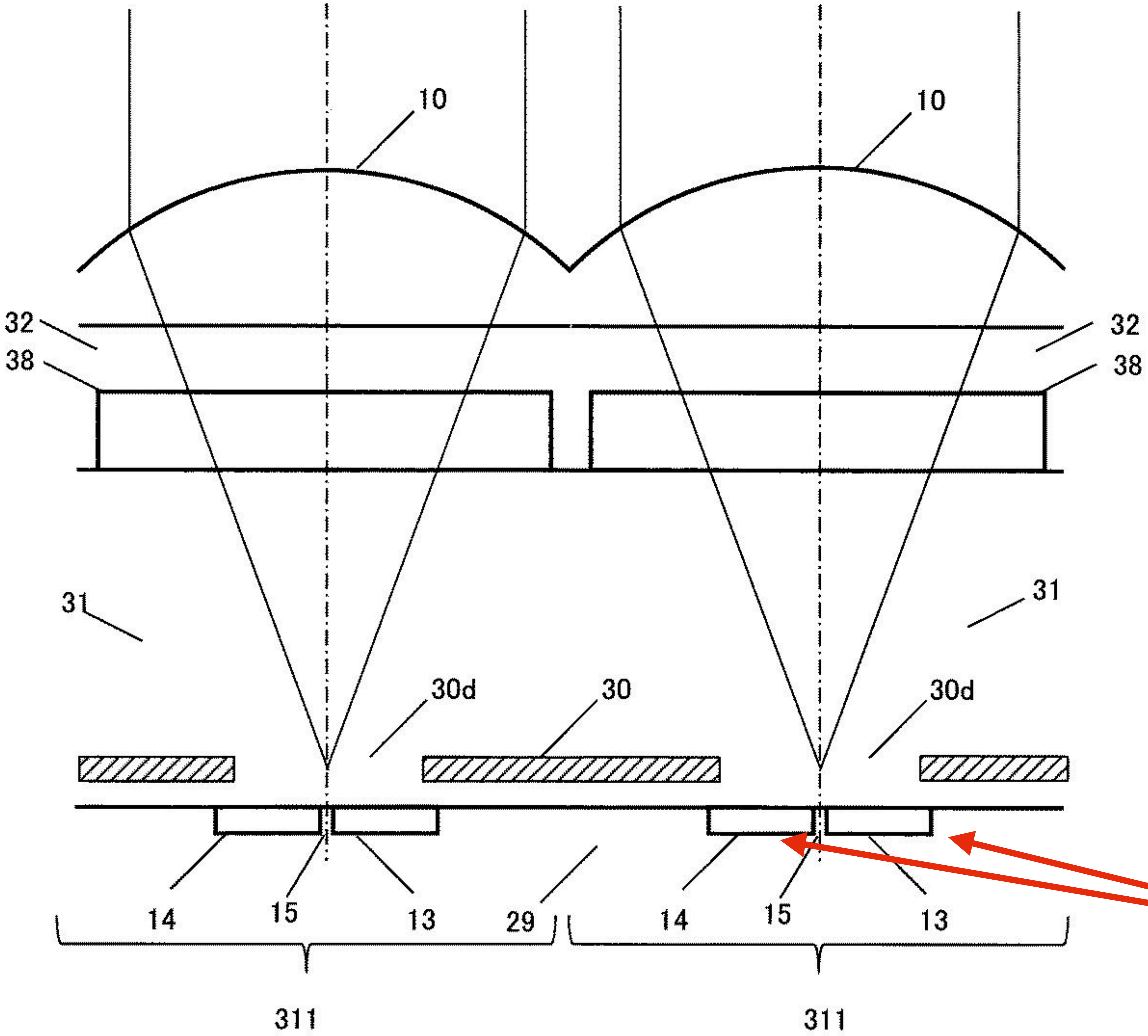
Focus on closest scene region

Put center of image in focus

Detect faces and focus on closest/largest face

Image credit: DPReview:
https://www.dpreview.com/articles/9174241280/configuring-your-5d-mark-iii-af-for-fast-action

Split pixel sensor



When both pixels have the same response, camera is in focus, why?

Now two pixels under each microlens (not one)

Image credit: Nikon

Estimating depth

Additional sensing modalities

Fuse information from all modalities to obtain best estimate of depth

iPhone Xr depth estimate
with lights ON in room

iPhone Xr depth estimate
with lights OFF in room
(No help from RGB)

Image credit: https://blog.halide.cam/iphone-xr-a-deep-dive-into-depth-47d36ae69a81

Magic eraser

(Feature in recent Google Pixel phones)

Summary

Summary

- Computation now a fundamental part of producing a pleasing photograph
- Used to compensate for physical constraints (demosaic, denoise, lens corrections, portrait mode)
- Used to analyze image to estimate system parameters (autofocus, autoexposure, white balance, depth estimation)
- Used to make non-physically plausible images that have aesthetic merit

Sensor output ("RAW")

Computation

Beautiful image that impresses your friends on Instagram

Image processing workload characteristics

- "Pointwise" operations
  - output_pixel = f(input_pixel)
- "Stencil" computations (e.g., convolution, demosaic, etc.)
  - Output pixel (x,y) depends on fixed-size local region of input around (x,y)
- Lookup tables
  - e.g., contrast s-curve
- Multi-resolution operations (upsampling/downsampling)
- Fast-Fourier transforms
  - We didn't talk about Fourier domain techniques in class (but Hasinoff 16 reading has many examples)
- Long pipelines of these operations

Next class: efficiently mapping these workloads to modern processors

Abstractions for authoring image processing pipelines

Choosing the "right" representation for the job (again)

- This was the theme of our Frankencamera discussion

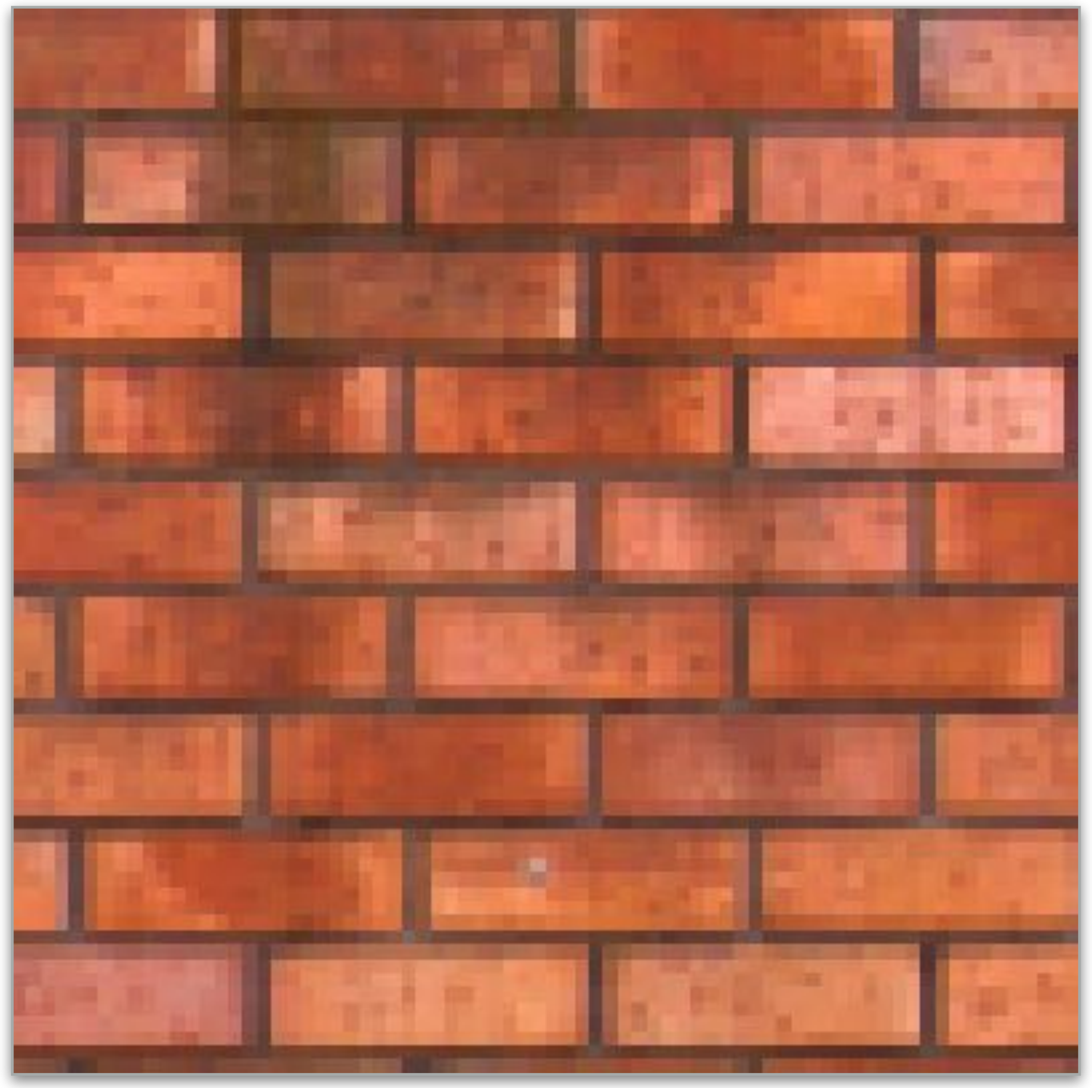
- Good representations are productive to use:
  - They embody the natural way of thinking about a problem

- Good representations enable the system to provide the application developer useful services:
  - Validating/providing certain guarantees (correctness, resource bounds, conversation of quantities, type checking)
  - Performance optimizations (parallelization, vectorization, use of specialized hardware)
  - Implementations of common, difficult-to-implement functionality (texture mapping and rasterization in 3D graphics, auto-differentiation in ML frameworks)

Consider a single task: sharpen an image

Example: sharpen an image

$$F = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$$



Input

Output

Four different representations of sharpen

1

```
Image input;
Image output = sharpen(input);
```

2

$$F = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$$

```
Image input;
Image output = convolve(input, F);
```

3

```
Image input;
Image output;
output[i][j]
    = F[0][0] * input[i-1][j-1] +
      F[0][1] * input[i-1][j]   +
      F[0][2] * input[i-1][j+1] +
      F[1][0] * input[i][j-1]   +
      F[1][1] * input[i][j]     +
      ...
```

4

```
float input[(WIDTH+2) * (HEIGHT+2)];
float output[WIDTH * HEIGHT];

float weights[] = {0., -1., 0.,
                   -1., 5, -1.,
                   0., -1., 0.};

for (int j=0; j<HEIGHT; j++) {
  for (int i=0; i<WIDTH; i++) {
    float tmp = 0.f;
    for (int jj=0; jj<3; jj++)
      for (int ii=0; ii<3; ii++)
        tmp += input[(j+jj)*(WIDTH+2) + (i+ii)]
                 * weights[jj*3 + ii];
    output[j*WIDTH + i] = tmp;
  }
}
```

Image processing tasks from previous lectures

Sobel Edge Detection

$$\mathrm{G_x} = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \mathrm{I}$$

$$\mathrm{G_y} = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} * \mathrm{I}$$

$$\mathrm{G} = \sqrt{\mathrm{G_x}^2 + \mathrm{G_y}^2}$$

3x3 Gaussian blur

$$\mathbf{F=} \begin{bmatrix} .075 & .124 & .075 \\ .124 & .204 & .124 \\ .075 & .124 & .075 \end{bmatrix}$$

2x2 downsample (via averaging)

```
output[x][y] = (input[2x][2y]   + input[2x+1][2y] +
                input[2x][2y+1] + input[2x+1][2y+1]) / 4.f;
```

Gamma Correction

```
output[x][y] = pow(input[x][y], 0.5f);
```

LUT-based correction

```
output[x][y] = lookup_table[input[x][y]];
```

Local Pixel Clamp

```
float f(image input) {
   float min_value = min( min(input[x-1][y], input[x+1][y]),
                          min(input[x][y-1], input[x][y+1]) );
   float max_value = max( max(input[x-1][y], input[x+1][y]),
                          max(input[x][y-1], input[x][y+1]) );
output[x][y] = clamp(min_value, max_value, input[x][y]);
output[x][y] = f(input);
```

Histogram

```
bin[input[x][y]]++;
```

New goals (setting up for next class)

- Be expressive: facilitate intuitive expression of a broad class of image processing applications
  - e.g., all the components of a modern camera RAW pipeline
- Be high performance: want to generate code that efficiently utilizes the multi-core and SIMD processing resources of modern CPUs and GPUs, and is memory bandwidth efficient