Lecture 13:

Camera Image Processing Pipeline: Part II

Visual Computing Systems
CMU 15-869, Fall 2014

Today

- Finish image processing pipeline
- Auto-focus / auto-exposure
- Camera processing elements
- Smart phone processing elements

Simplified image processing pipeline

- Correct for sensor bias (using measurements of optically black pixels)
- Correct pixel defects
- Vignetting compensation
- Dark frame subtract (optional)
- White balance
- Demosaic
- Denoise / sharpen, etc.

lossless compression → RAW file

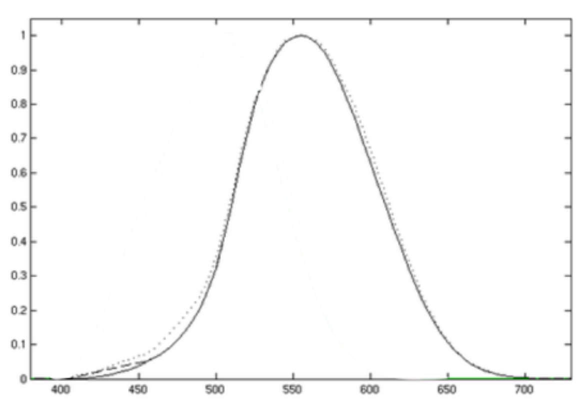
Last time

- Color Space Conversion
- Gamma Correction
- Color Space Conversion (Y'CbCr)
- 4:4:4 to 4:2:2 chroma subsampling
- JPEG compress (lossy)

→ JPEG file

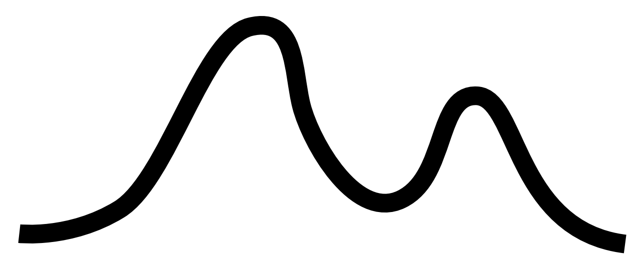
Measurements recorded by sensor depend on the sensor's spectral response

$R = \int_\lambda$



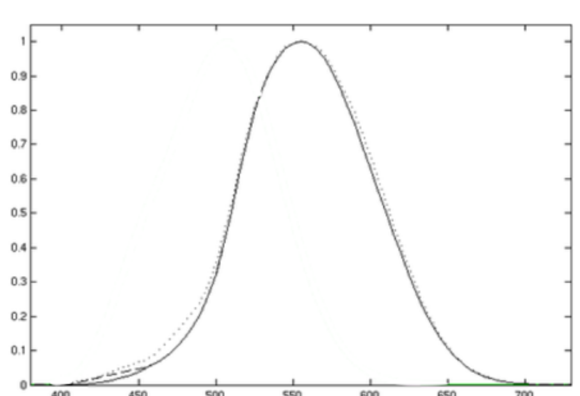
Red pixel spectral sensitivity

$*$



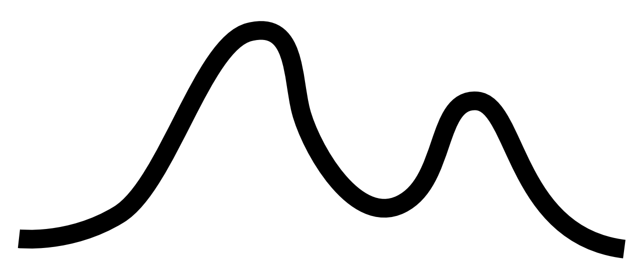
Radiance (energy spectrum from scene)

$G = \int_\lambda$



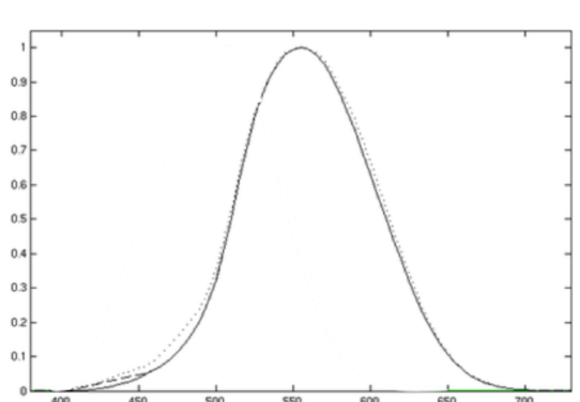
Green pixel spectral sensitivity

$*$



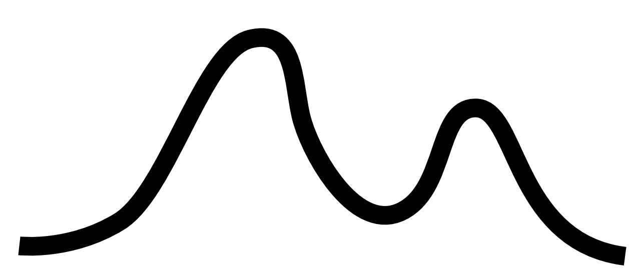
Radiance (energy spectrum from scene)

$B = \int_\lambda$



Blue pixel spectral sensitivity

$*$



Radiance (energy spectrum from scene)

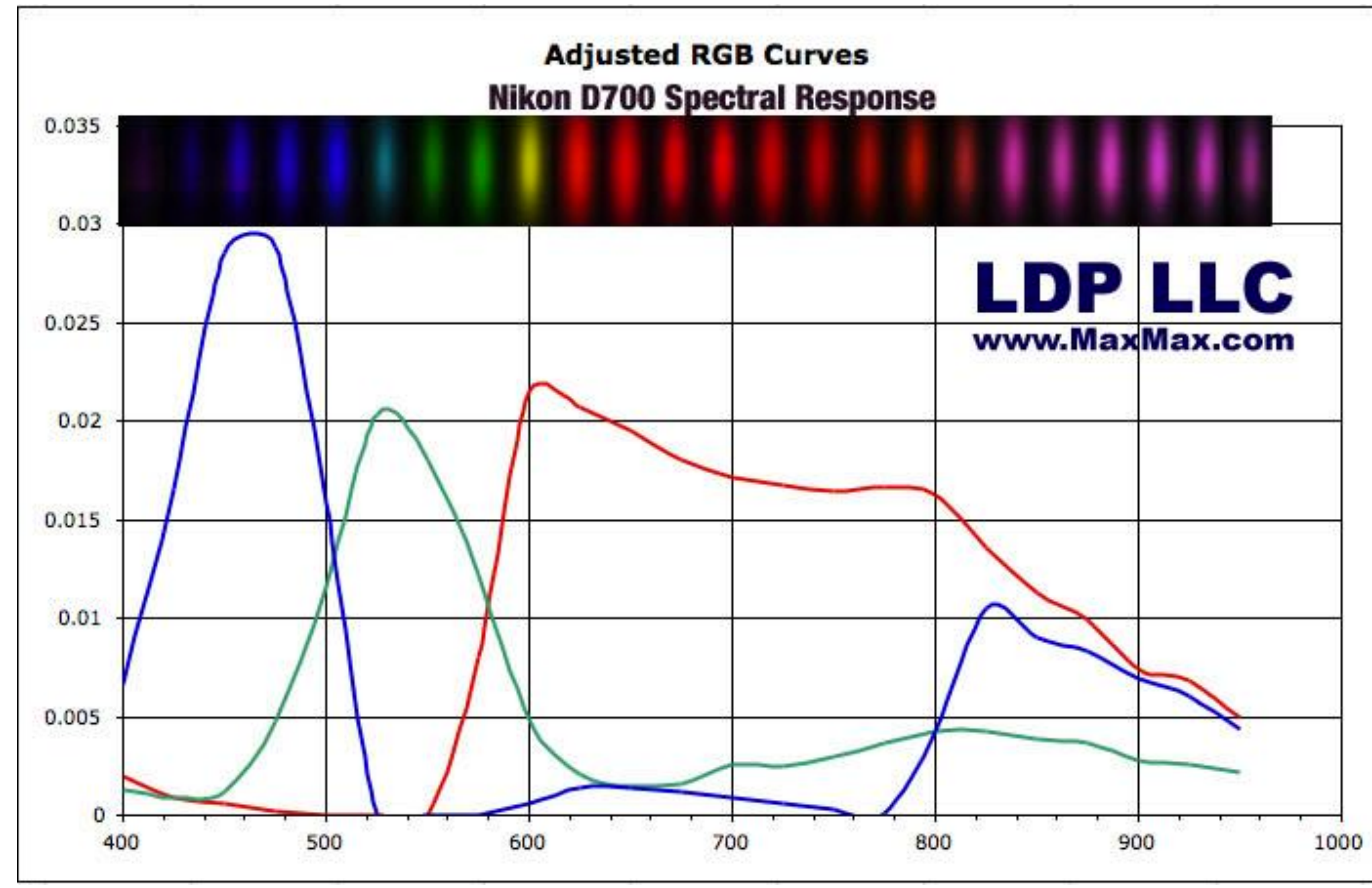
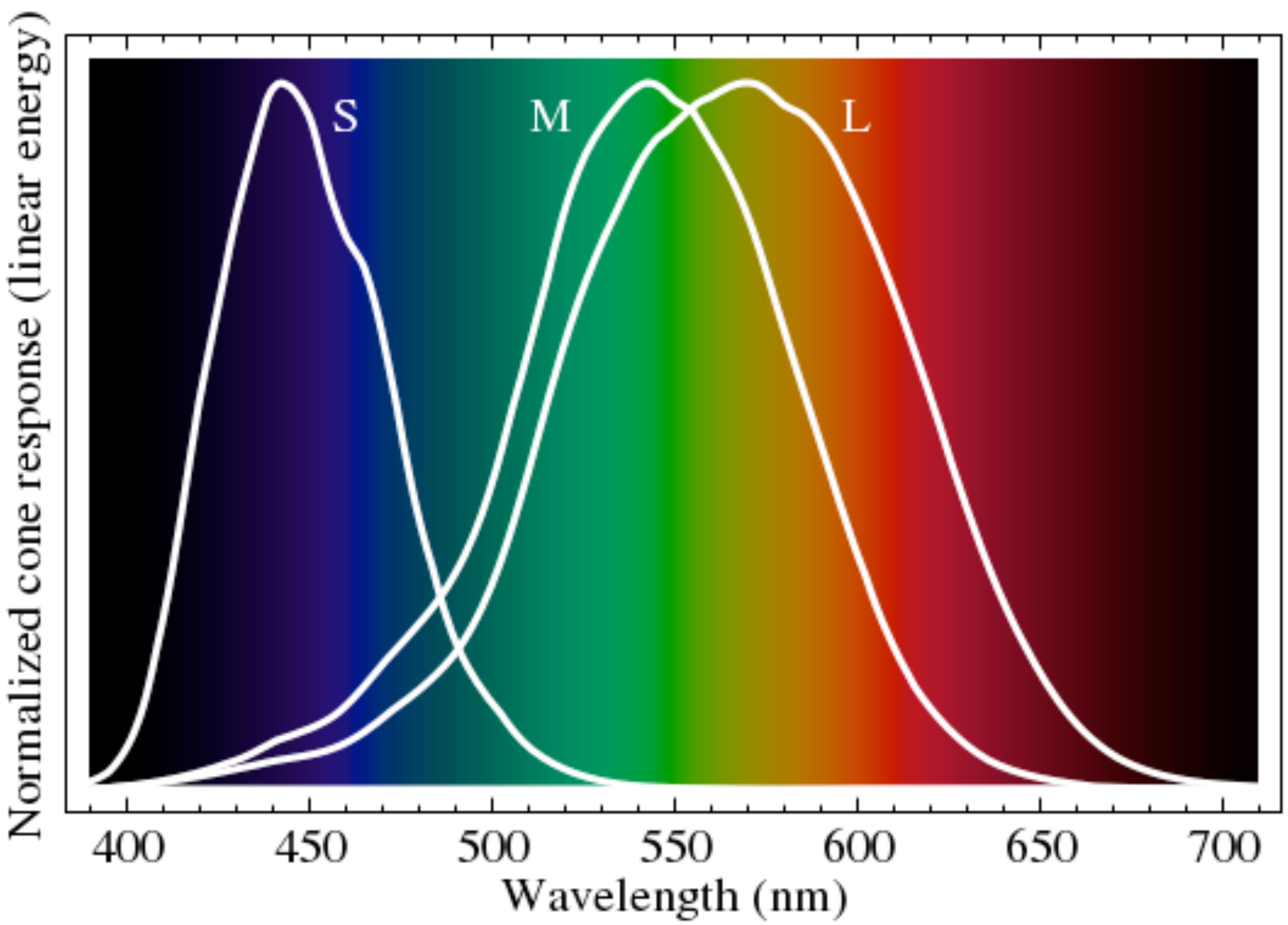
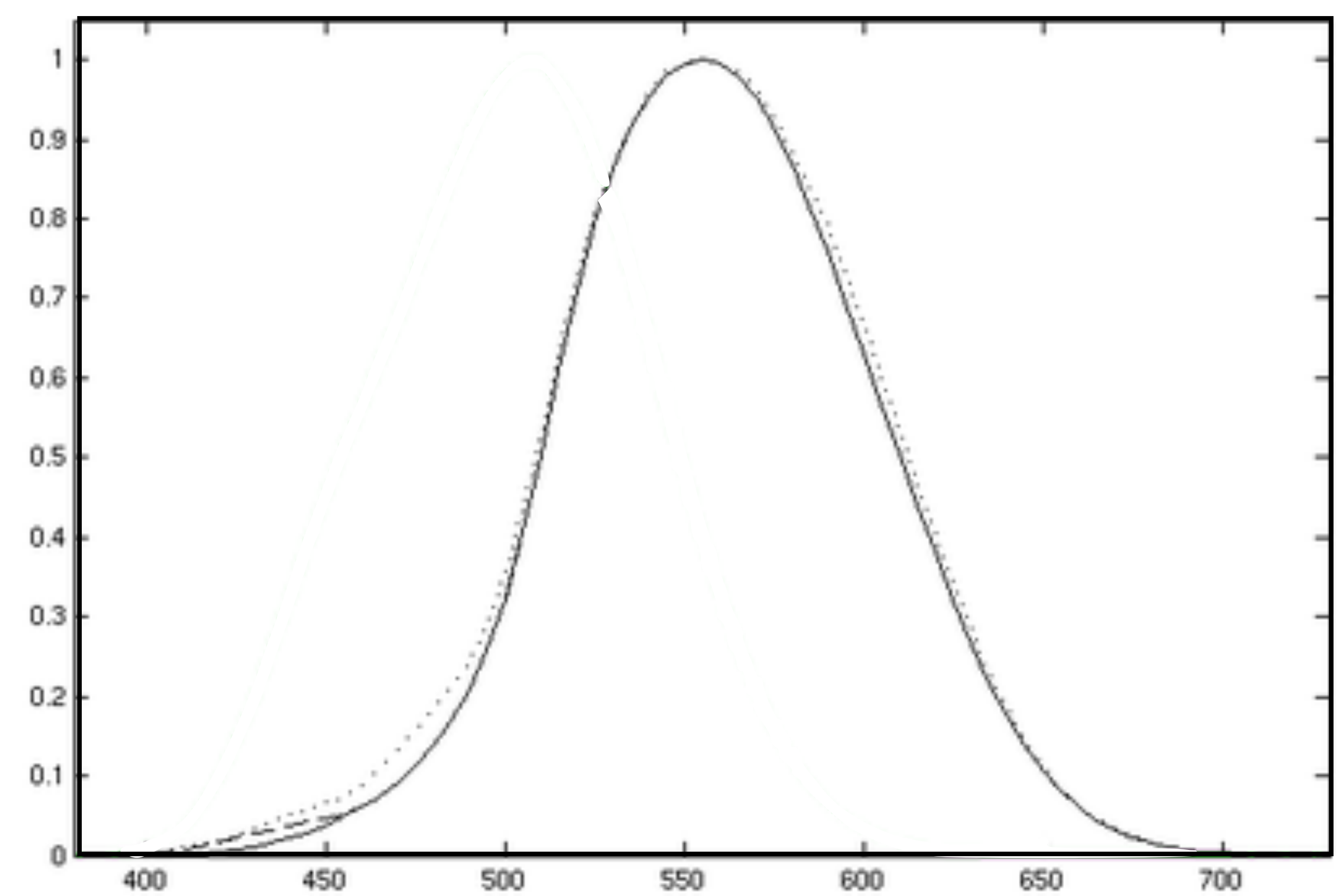


Image credit: maxmax.com
https://www.maxmax.com/camera_technical.htm

Spectral response of human eye



Eye Spectral Response (S, M, L cones)



Avg. eye spectral sensitivity (daytime-adapted)

Uneven distribution of cone types
~64% of cones are L cones, ~ 32% M cones

Image credit: Wikipedia

Aside: web links on color matching

Color-space conversion

- Measurements of sensor depend on sensor's spectral response
  - Response depends on bandwidths filtered by color filter array
- Convert representation to sensor-independent basis: e.g., sRGB
  - 3 x 3 matrix multiplication

```
output_rgb_pixel = COLOR_CONVERSION_MATRIX * input_rgb_pixel
```

Represented in standard color space (e.g., sRGB)

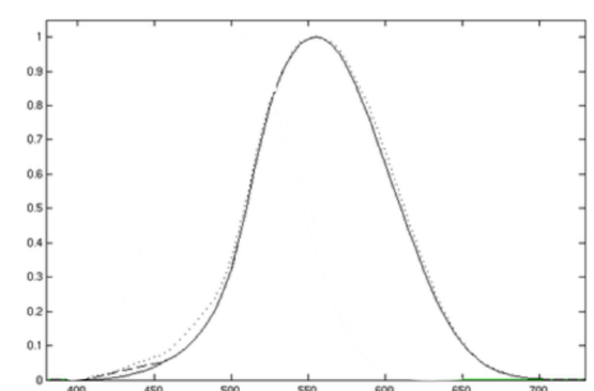
Represented in sensor-specific basis

Aside: web links on human visual system

Lightness (perceived brightness)

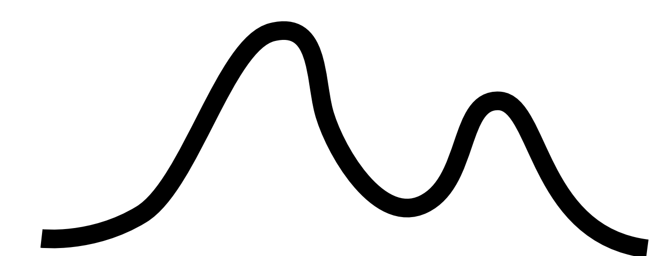
Perceived — **Physical Response**

Lightness (L*) $\xleftarrow{?}$ Luminance (L) $= \int_{\lambda}$



Eye spectral sensitivity

$*$



Radiance
(energy spectrum
from scene)

Dark adapted eye: $L^* \propto L^{0.4}$

Bright adapted eye: $L^* \propto L^{0.5}$

So what does a pixel's value mean?

Gamma (old motivation)

Old CRT display:

1. Frame buffer contains value X
2. CRT display converts digital signal to voltage V(x) (linear relationship)
3. Beam voltage converted to light: (non-linear relationship)

   $L \propto V^{\gamma}$

   Where $\gamma \sim 2.5$

So if pixels store L, what happens?

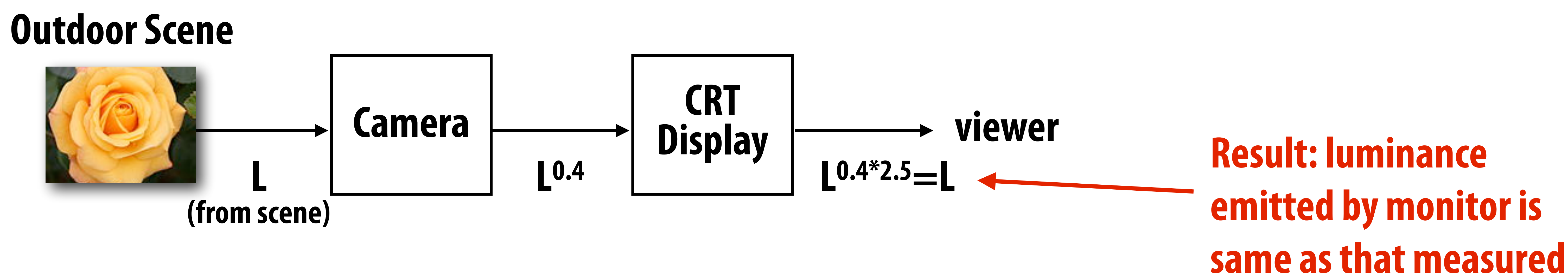
Observed image   Desired Image

Image credit: http://creativebits.org/mac_os_x/windows_vs_mac_monitor_gamma

Gamma correction

Goal: want viewer to <u>perceive</u> luminance differences as if they were present in the environment where a picture is taken (keep in mind: reproducing the absolute values of L is not practical)

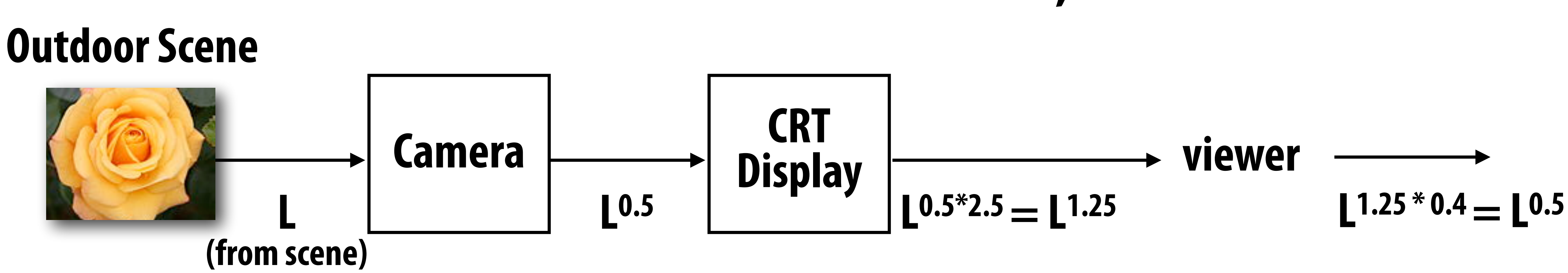
Can set TV camera to record L, but store $L^{1/2.5} = L^{0.4}$ to compensate for CRT effect



But scene is bright (viewer bright adapted) and living room is dark (TV viewer dark adapted)

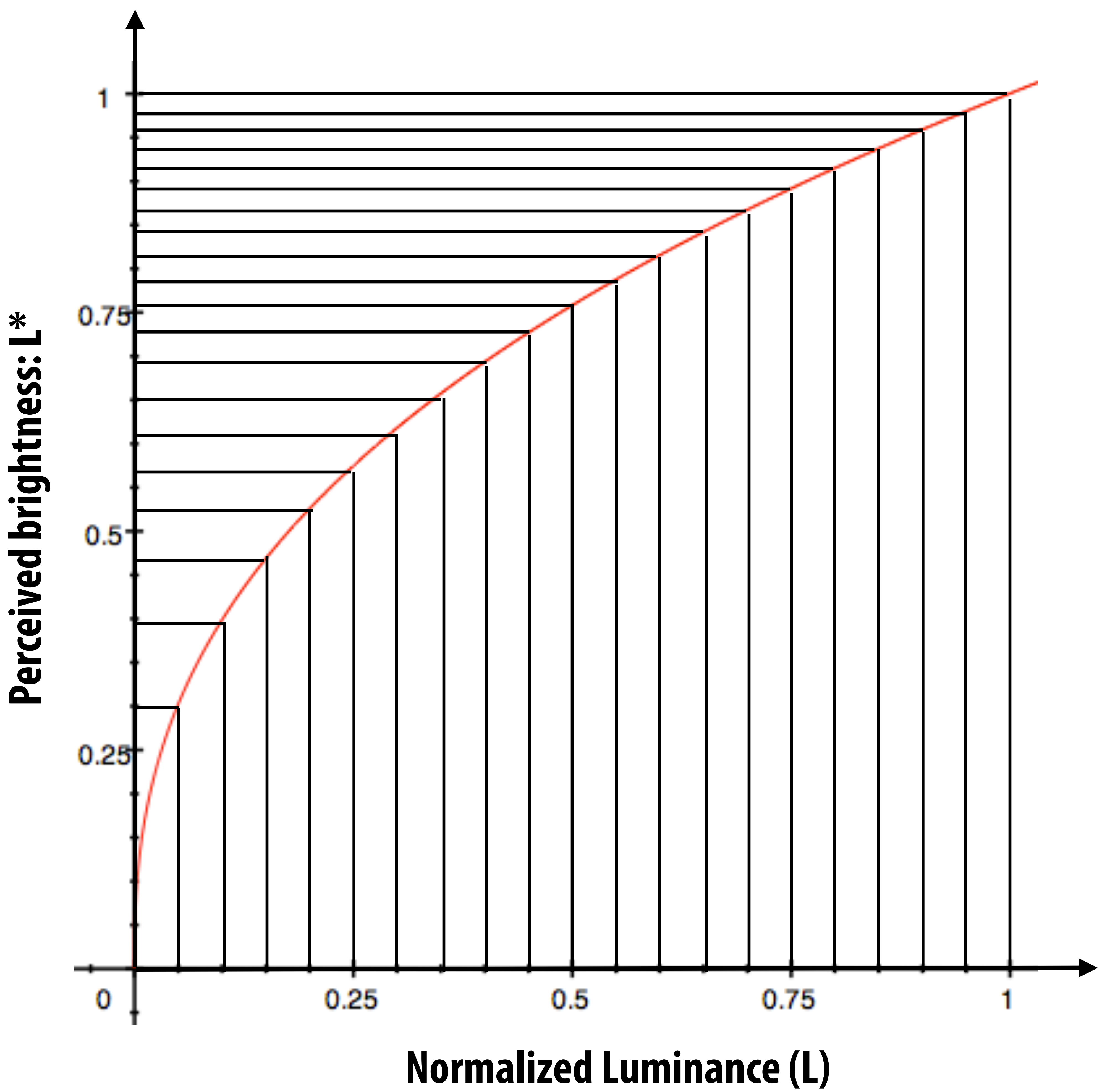
So TV viewer perceives $L^{0.4}$ in the living room instead of $L^{0.5}$ (not the same as if viewer was "there")

Solution: TV cameras record L, store $L^{0.5}$



Credit: Marc Levoy, Stanford CS178

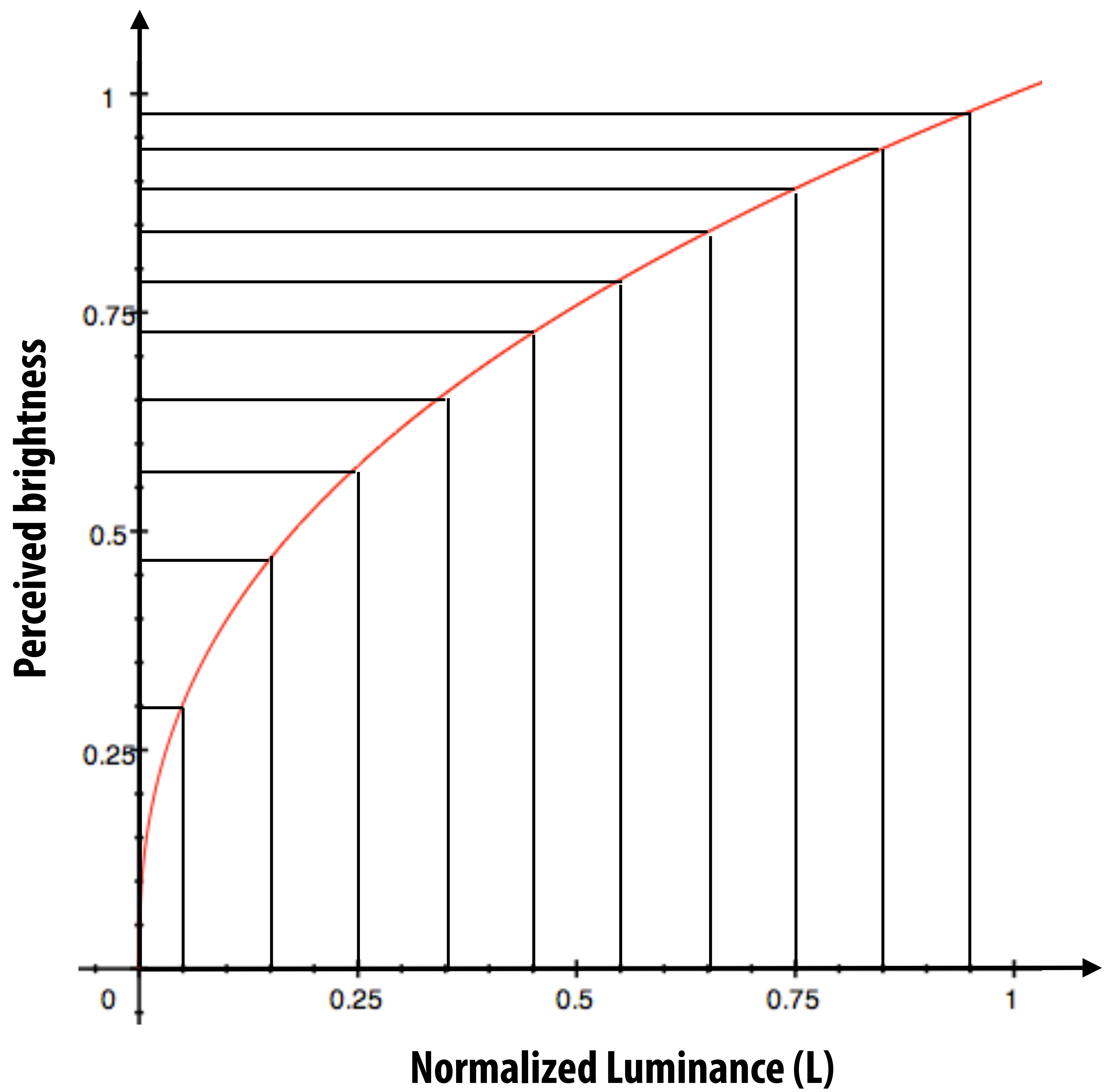
Power law



12 bit sensor pixel:
Can represent 4096 luminance values
Values are ~ linear in luminance

Problem: quantization error

Insufficient (perceived) precision in darker regions of image

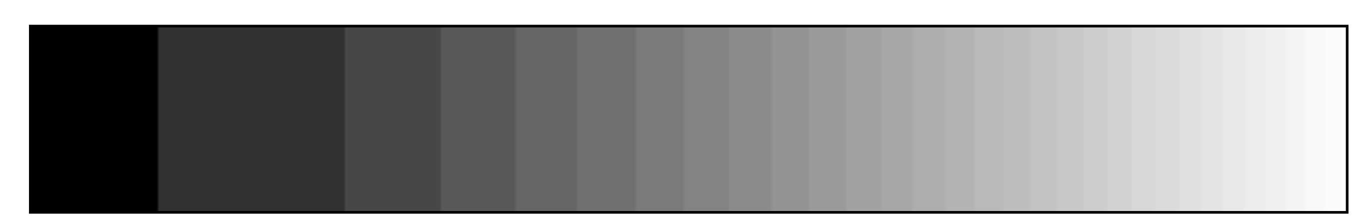


12 bit sensor pixel:
4096 representable luminance values
Values are ~ linear in luminance

Most images are not RAW files

8 bits per channel (256 unique values)
Risks quantization dark areas of image

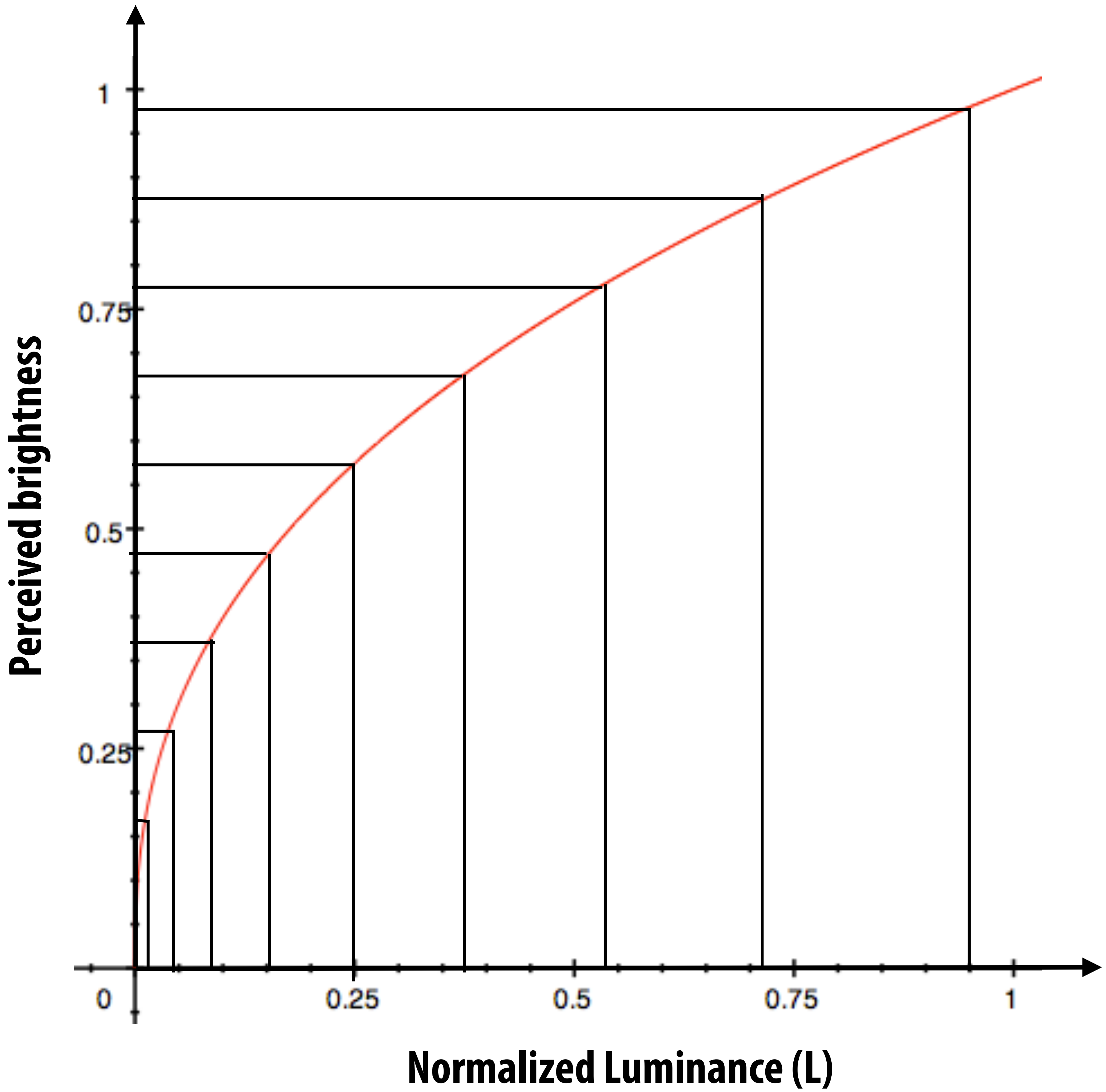
High bit depth pixels



5 bits/pixel (32 grays)
Pixel stores L

Store values linear in brightness, not luminance

Evenly distribute values over perceptible range
(Make better use of available bits)



Rule of thumb: human eye cannot differentiate differences in luminance less than 1%

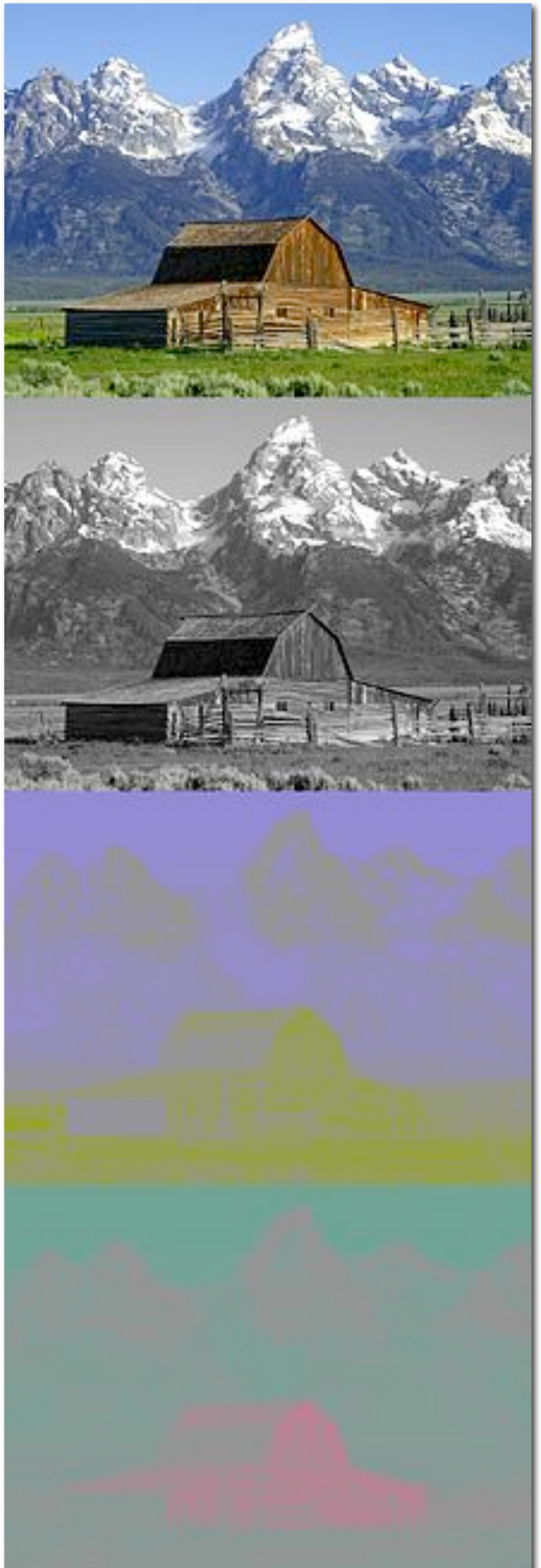
High bit depth pixels

5 bits/pixel (32 grays)
Pixel stores L

5 bits/pixel (32 grays)
Pixel stores $L^{0.45}$
Must compute $(\text{pixel\_value})^{2.2}$ prior to display

Take caution with subsequent pixel processing operations: should blending images average brightness or luminance?

Y′CbCr color space



Y′

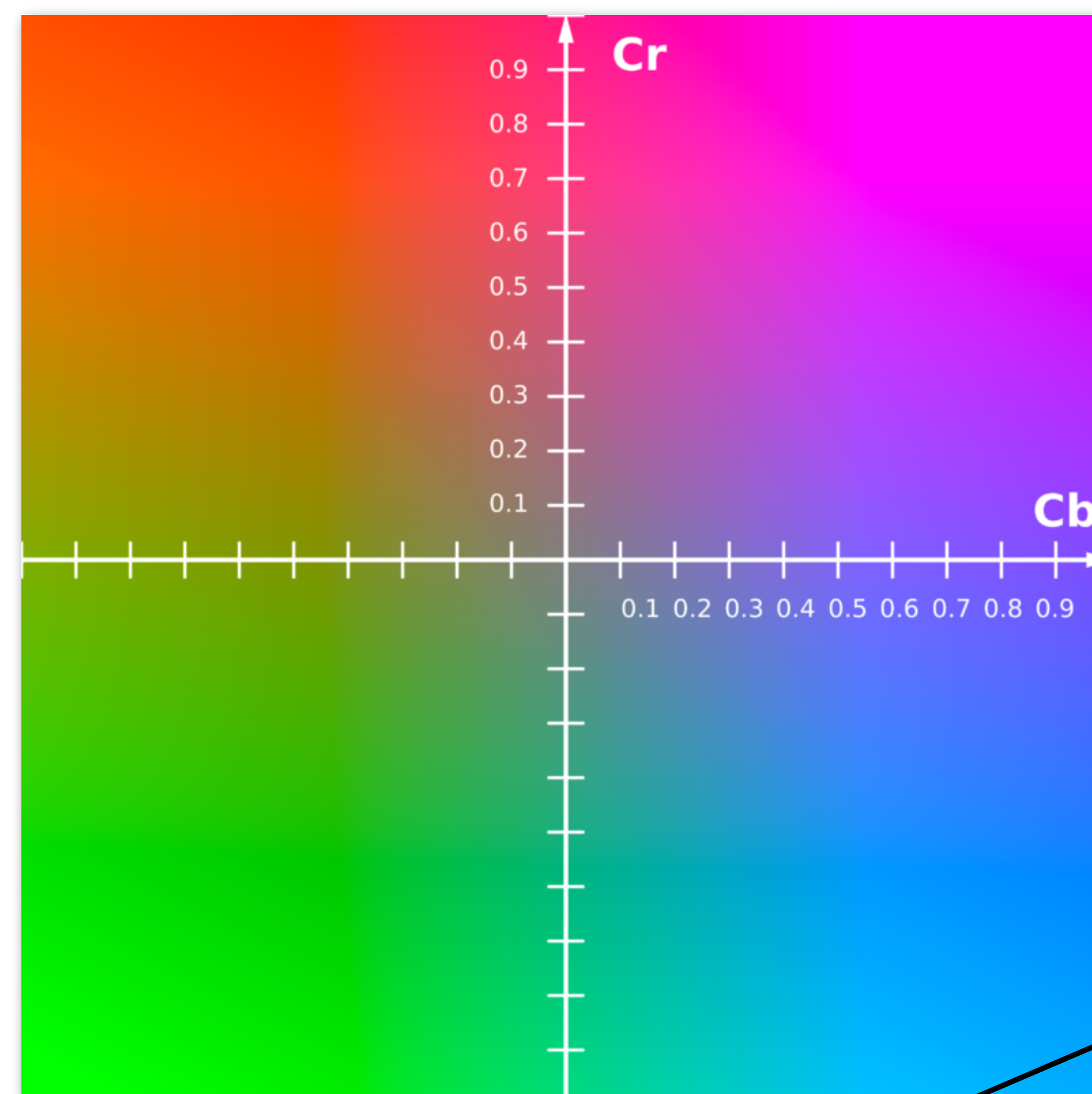
Cb

Cr

Y′ = luma: perceived (gamma corrected) luminance

Cb = blue-yellow deviation from gray

Cr = red-cyan deviation from gray



Gamma corrected RGB (primed notation indicates perceptual (non-linear) space)

Conversion from R′G′B′ to Y′CbCr:

$$Y' = 16 + \frac{65.738 \cdot R'_D}{256} + \frac{129.057 \cdot G'_D}{256} + \frac{25.064 \cdot B'_D}{256}$$

$$C_B = 128 + \frac{-37.945 \cdot R'_D}{256} - \frac{74.494 \cdot G'_D}{256} + \frac{112.439 \cdot B'_D}{256}$$

$$C_R = 128 + \frac{112.439 \cdot R'_D}{256} - \frac{94.154 \cdot G'_D}{256} - \frac{18.285 \cdot B'_D}{256}$$

Image credit: Wikipedia

Chroma subsampling

Y'CbCr is an efficient storage (and transmission) representation because Y' can be stored at higher resolution than CbCr without much loss in perceived visual quality

4:2:2 representation:

Store Y' at full resolution

Store Cb, Cr at full vertical resolution, but half horizontal resolution

Y'_{00} Cb_{00} Cr_{00}	Y'_{10}	Y'_{20} Cb_{20} Cr_{20}	Y'_{30}
Y'_{01} Cb_{01} Cr_{01}	Y'_{11}	Y'_{21} Cb_{21} Cr_{21}	Y'_{31}

JPG Compression

JPG compression observations

- Low-frequency content is predominant in images of the real world

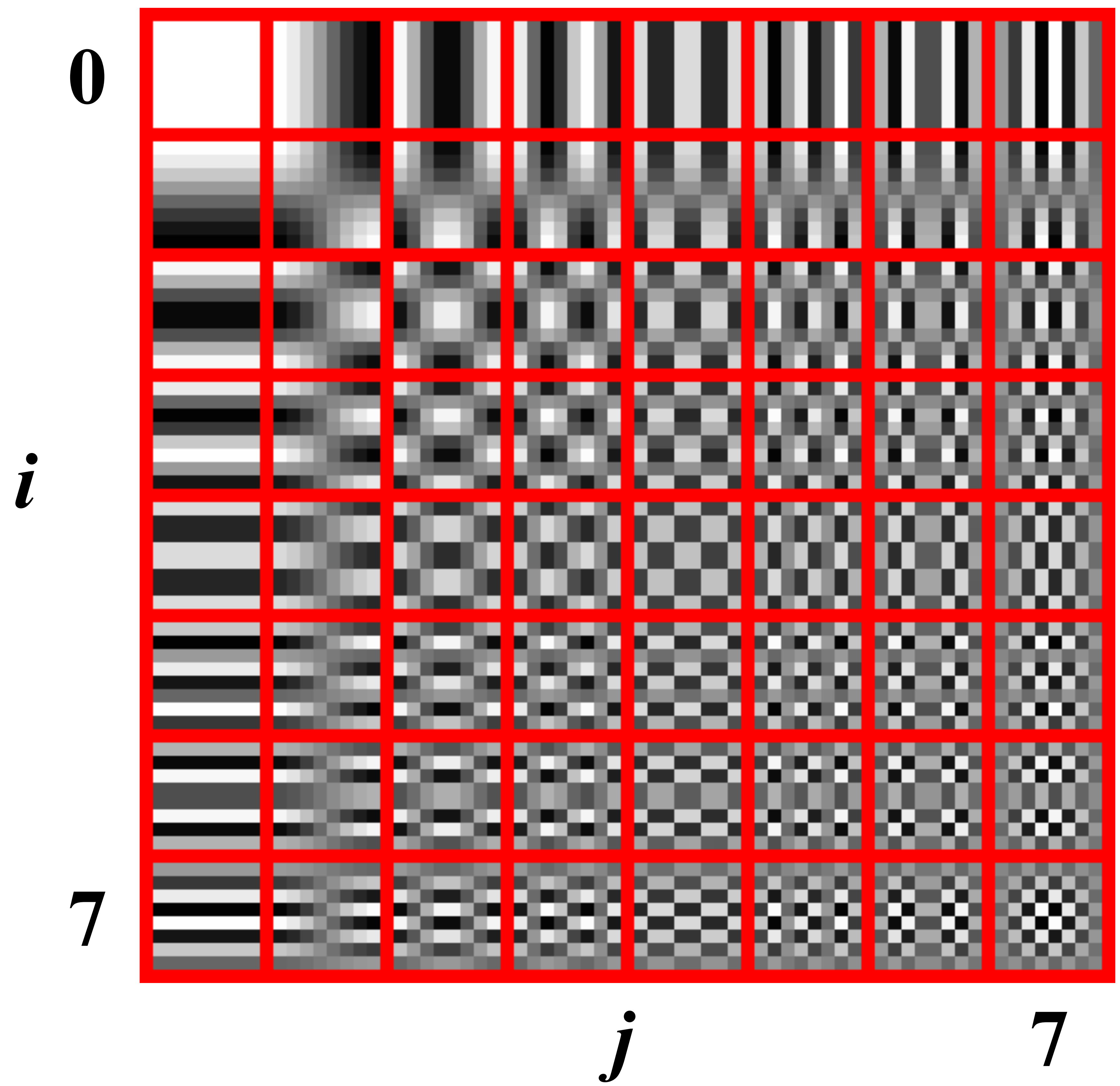
- The human visual system is less sensitive to high frequency sources of error

Slide credit: Pat Hanrahan

Discrete cosine transform (DCT) for 8x8 block of pixels

Project image from pixel basis into cosine basis

$$\text{basis}[i,j] = \cos\left[\pi \frac{i}{N}\left(x+\frac{1}{2}\right)\right] \times \underset{j}{\cos}\left[\pi \frac{j}{N}\left(y+\frac{1}{2}\right)\right]$$



Visualization of 64 basis functions for an 8x8 pixel block: (basis[i, j])

Slide credit: Wikipedia, Pat Hanrahan

Quantization

$$\begin{bmatrix} -415 & -30 & -61 & 27 & 56 & -20 & -2 & 0 \\ 4 & -22 & -61 & 10 & 13 & -7 & -9 & 5 \\ -47 & 7 & 77 & -25 & -29 & 10 & 5 & -6 \\ -49 & 12 & 34 & -15 & -10 & 6 & 2 & 2 \\ 12 & -7 & -13 & -4 & -2 & 2 & -3 & 3 \\ -8 & 3 & 2 & -6 & -2 & 1 & 4 & 2 \\ -1 & 0 & 0 & -2 & -1 & -3 & 4 & -1 \\ 0 & 0 & -1 & -4 & -1 & 0 & 1 & 2 \end{bmatrix} \Big/ \begin{bmatrix} 16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\ 12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\ 14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\ 14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\ 18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\ 24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\ 49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\ 72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \end{bmatrix}$$

DCT **Quantization Matrix**

$$= \begin{bmatrix} -26 & -3 & -6 & 2 & 2 & -1 & 0 & 0 \\ 0 & -2 & -4 & 1 & 1 & 0 & 0 & 0 \\ -3 & 1 & 5 & -1 & -1 & 0 & 0 & 0 \\ -4 & 1 & 2 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Quantized DCT

Quantization produces small values for coefficients (only few bits per coefficient)

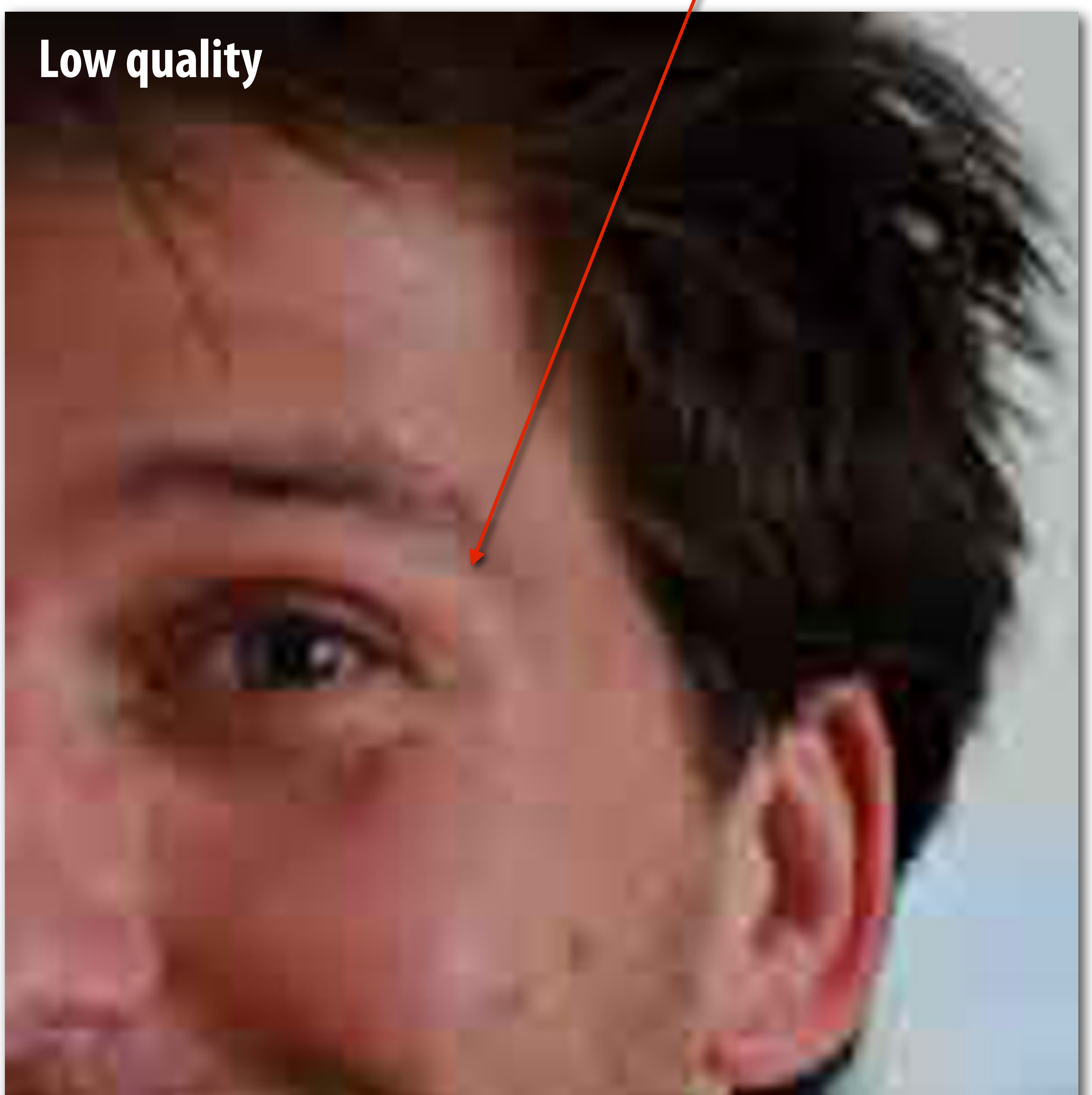
Quantization zeros out many coefficients

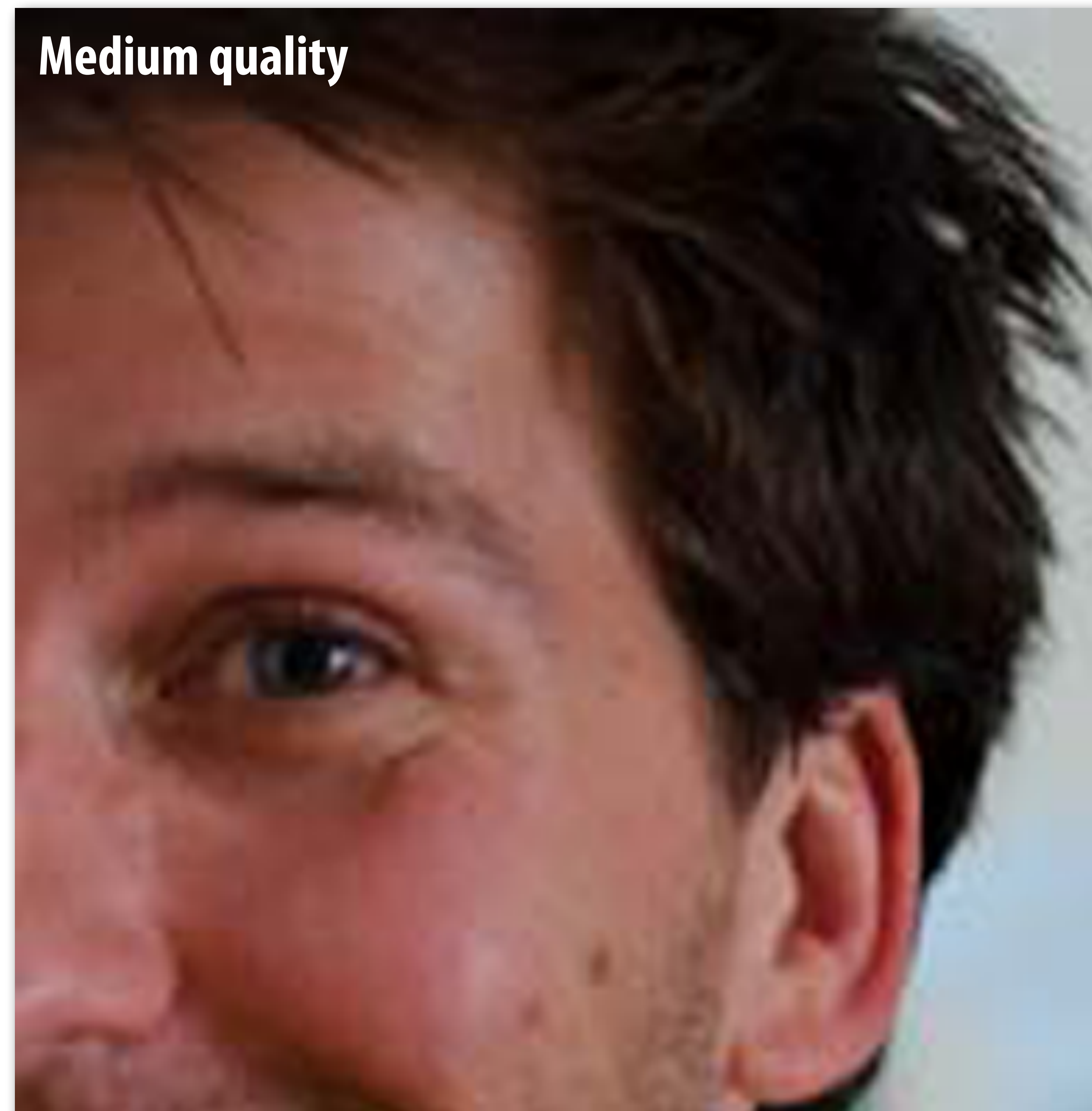
Application's JPEG quality setting scales quantization matrix

Slide credit: Wikipedia, Pat Hanrahan

JPEG compression artifacts

8x8 pixel block boundaries

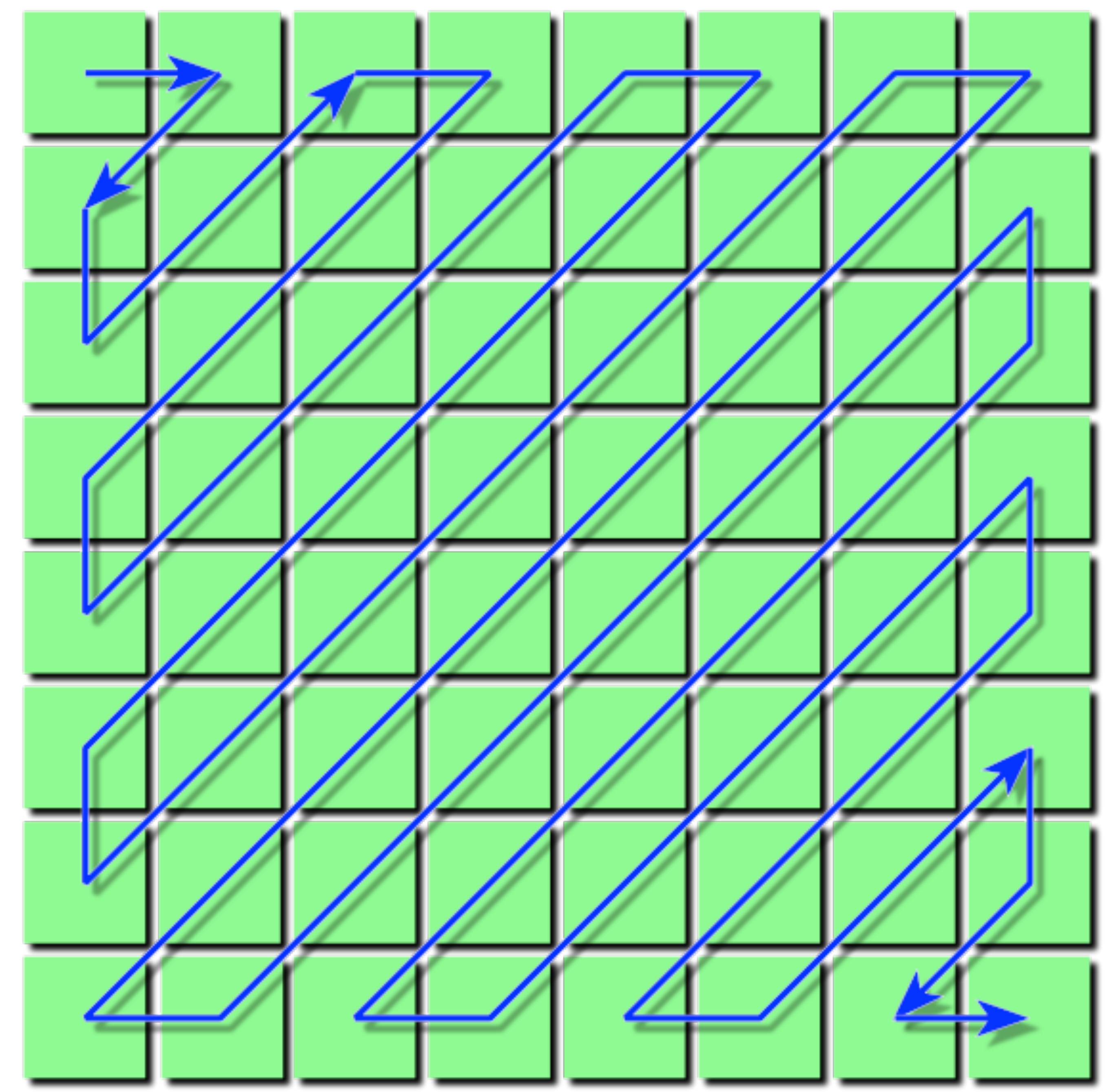




Lossless compression of quantized DCT values

$$\begin{bmatrix} -26 & -3 & -6 & 2 & 2 & -1 & 0 & 0 \\ 0 & -2 & -4 & 1 & 1 & 0 & 0 & 0 \\ -3 & 1 & 5 & -1 & -1 & 0 & 0 & 0 \\ -4 & 1 & 2 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Quantized DCT Values



Reordering

Entropy encoding: (lossless)

- **Reorder values**
- **RLE encode 0's**
- **Huffman encode non-zero values**

Image credit: Wikipedia

JPG compression summary

For each image channel

- For each 8x8 image block
  - Compute DCT
  - Quantize results (lossy)
  - Reorder values
  - RLE encode 0-spans
  - Huffman encode non-zero values

Summary: exploiting characteristics of human perception to build efficient image processing systems

- Encode pixel values linearly in perceived brightness, not in luminance
- Y'CrCb representation allows reduced resolution in color channels (4:2:2)
- JPEG compression reduces file size at cost of quantization errors in high spatial frequencies (human brain tolerates these high frequency errors more than low frequency ones)

Simplified image processing pipeline

- Correct for sensor bias (using measurements of optically black pixels)
- Correct pixel defects
- Vignetting compensation
- Dark-frame subtract (optional)
- White balance
- Demosaic

12-bits per pixel
1 intensity per pixel
Pixel values linear in energy

- Denoise / sharpen, etc.
- Color Space Conversion
- Gamma Correction

3x12-bits per pixel
RGB intensity per pixel
Pixel values linear in energy

- Color Space Conversion (Y'CbCr)
- 4:4:4 to 4:2:2 chroma subsampling
- JPEG compression

3x8-bits per pixel
(until 4:2:2 subsampling)
Pixel values perceptually linear

Nikon D7000

- Sensor made by Sony
  - 16 MP
  - Pixel size 4.78 x 4.78 um
  - 14 bit ADC

- 6 full-resolution JPG compressed shots / sec

- Note: RAW to JPG conversation in Adobe Lightroom on my MacBook Pro: 6 sec / image (36 times slower)

Auto Focus / Auto Exposure

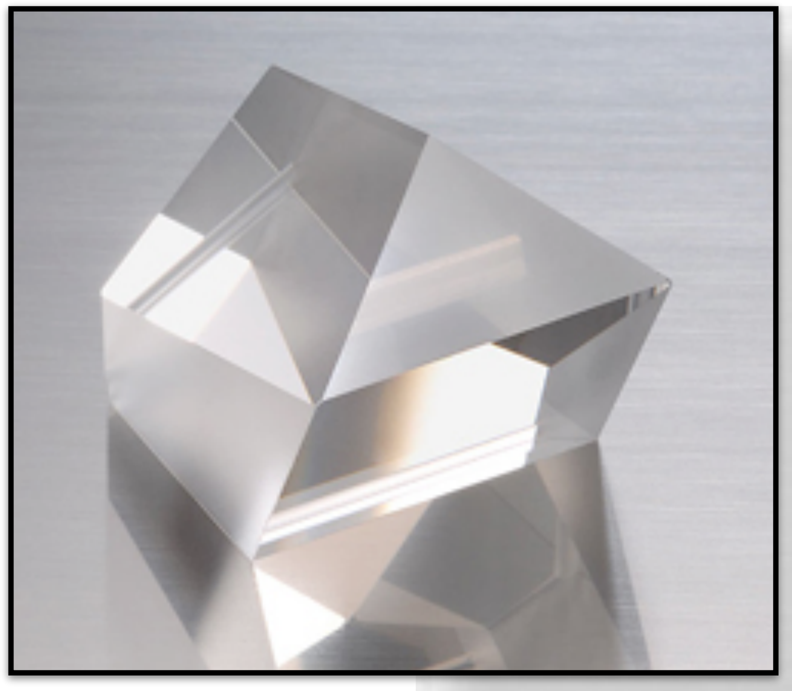
Autofocus demos

- Phase-detection auto focus
  - Common in SLRs

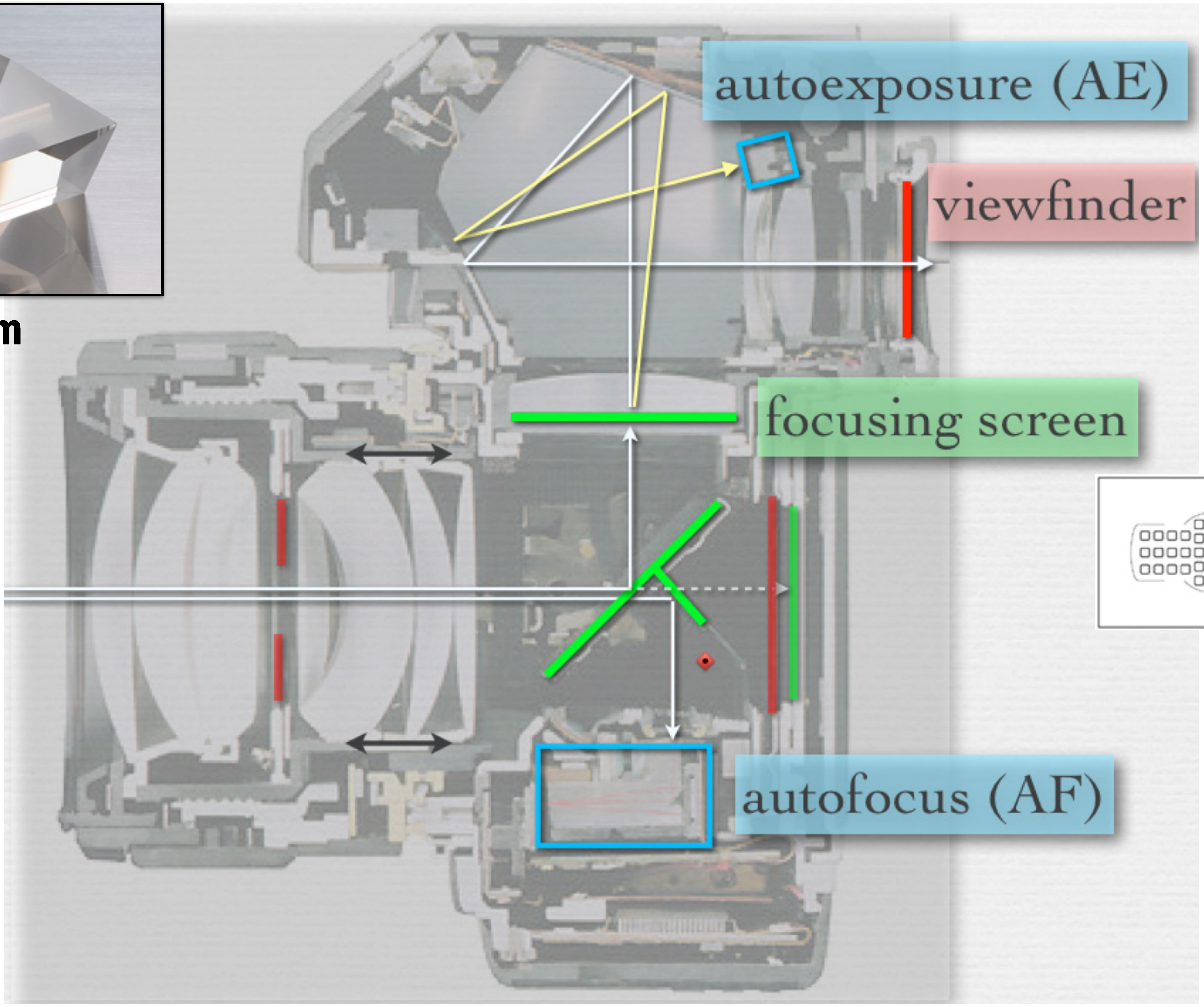
- Contrast-detection auto focus
  - Point-and-shoots, smart-phone cameras

Demo credits: Marc Levoy and Stanford CS178 course staff

SLR Camera



Pentaprism



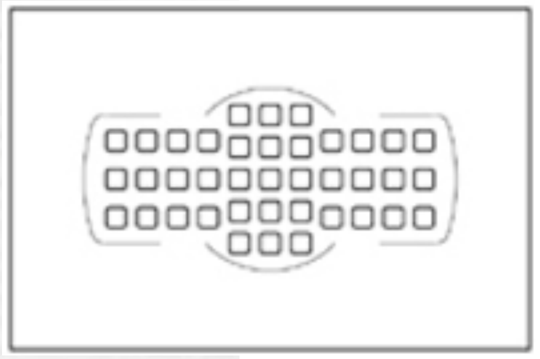
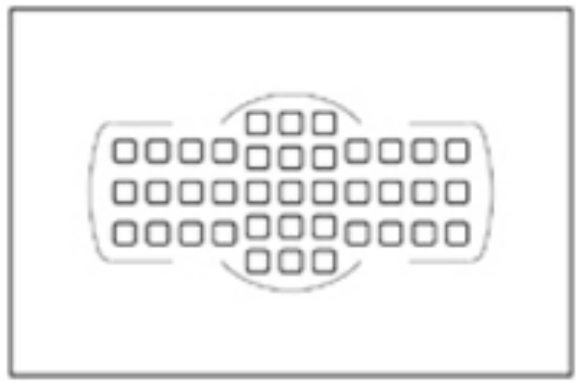
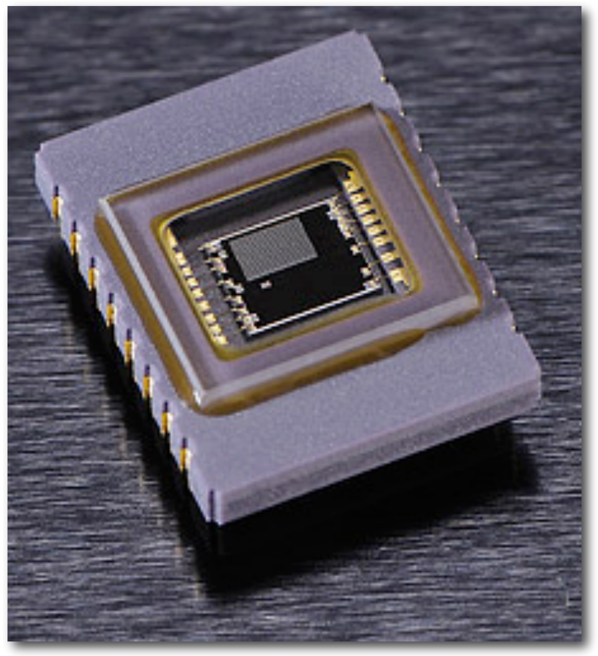


Image credits: Nikon, Marc Levoy

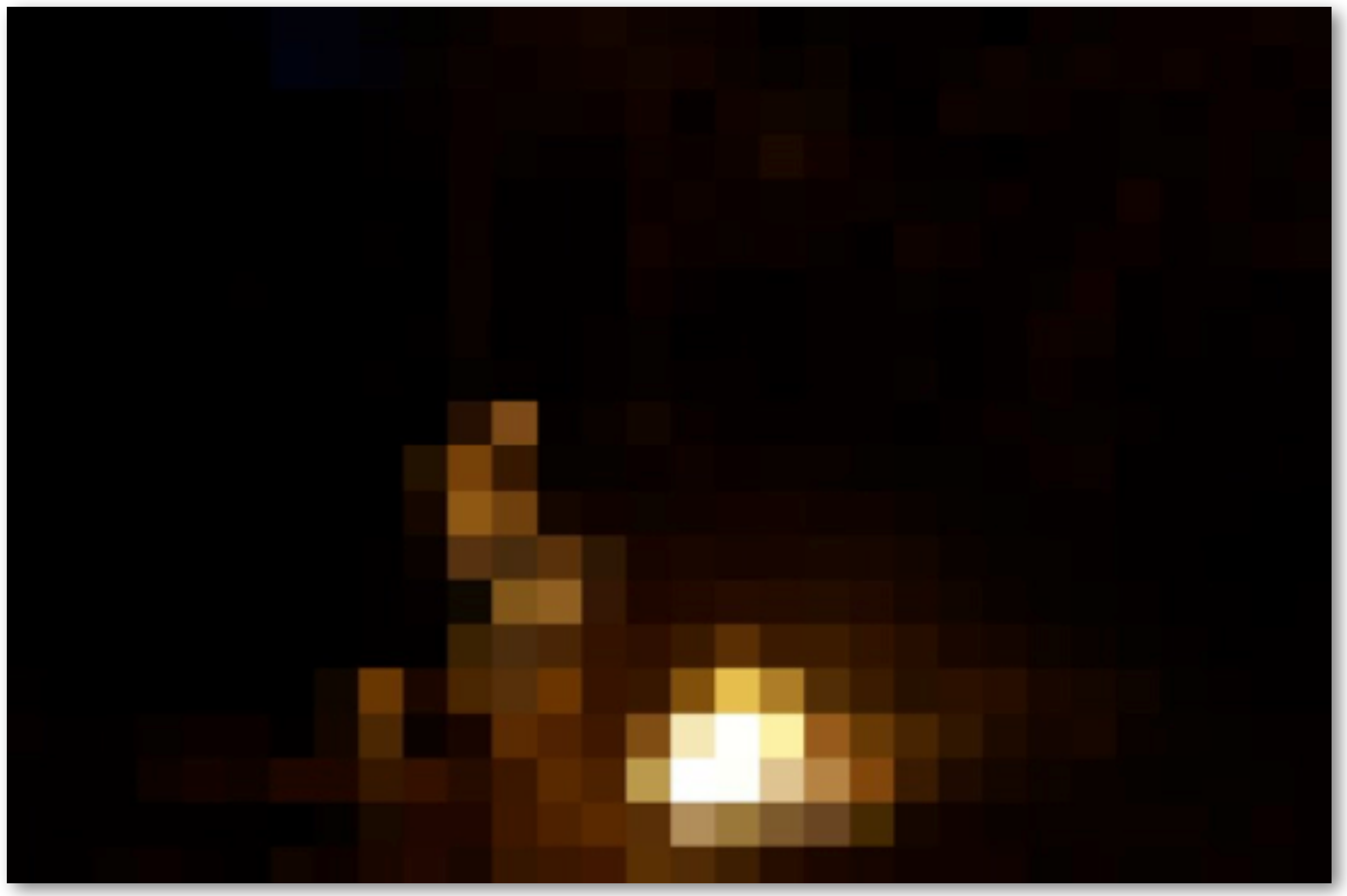
Nikon D7000

- Auto-focus sensor: 39 regions
- Metering sensor: 2K pixels
  - Auto-exposure
  - Auto-white-balance
  - Subject tracking to aid focus (predicts movement)
- Shutter lag ~ 50ms





Auto exposure



Low resolution metering sensor capture

Metering sensor pixels are large
(higher dynamic range than main sensor)

How do we set exposure?

What if a camera doesn't have a separate metering sensor?

Image credits: Marc Levoy, Andrew Adams

AF/AE summary

- DSLRs have additional sensing/processing hardware to assist with the "3A's" (auto-focus, auto-exposure, auto-white-balance)
  - Phase-detection AF: optical system directs light to AF sensor
  - Example: Nikon metering sensor: large pixels to avoid over-saturation
- Point-and-shoots/smartphone cameras make these measurements by performing image processing operations on data from the main sensor
  - Contrast-detection AF: search for lens position that produces large image gradients
  - Exposure metering: if pixels are saturating, meter again with lower exposure
- In general, implementing AF/AE/AWB is an image understanding problem ("computer vision")
  - Understand the scene well enough to set the camera's image capture and image processing parameters to best approximate the image a human would <u>perceive</u>
  - As processing/sensing capability increases, algorithms are becoming more sophisticated

Smarter cameras

Goal: help photographer capture the shot they want

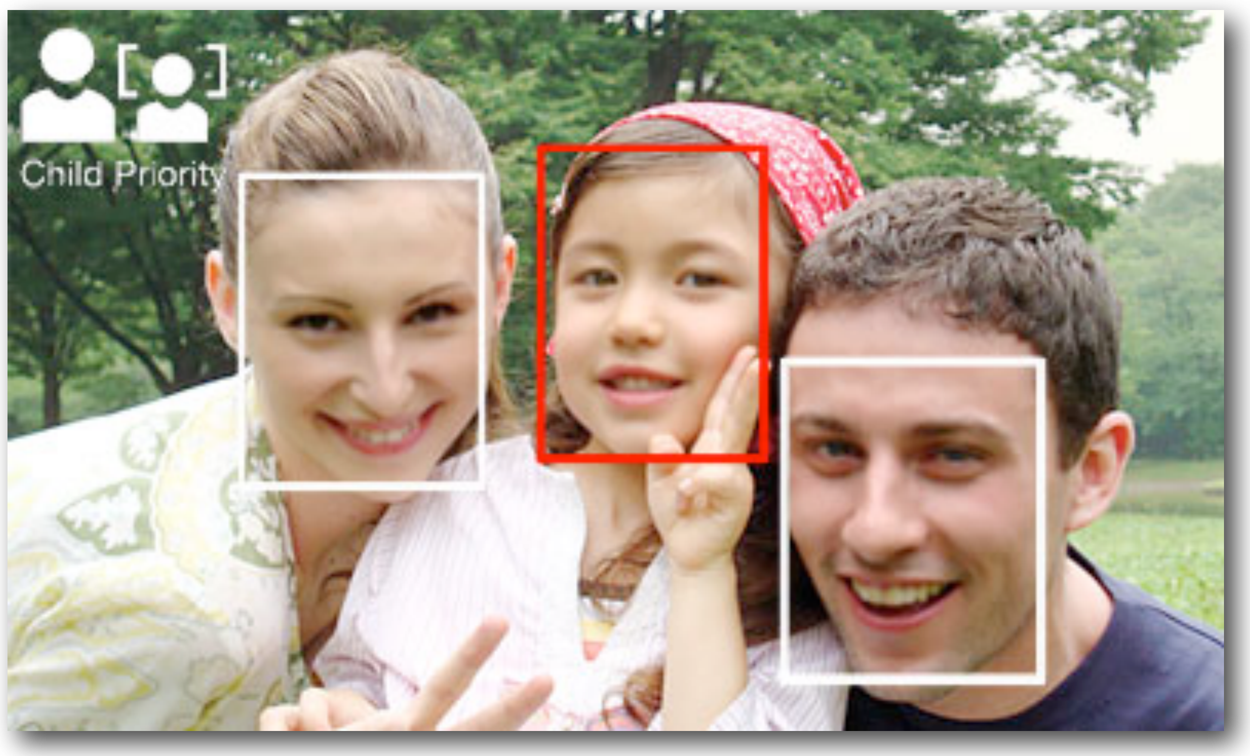


Image credit: Sony

Face detection: camera finds faces: tunes AWB, AE, AF for these regions

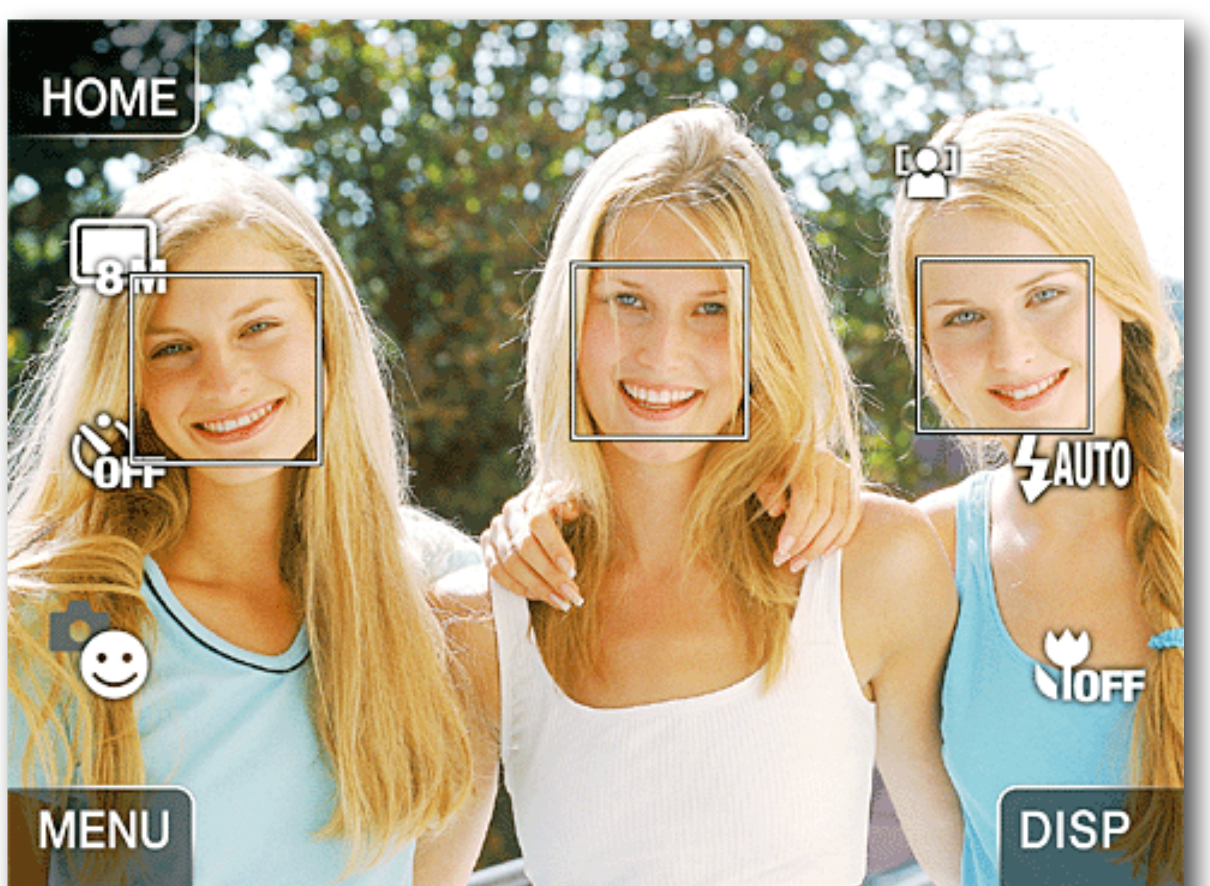


Image credit: Sony

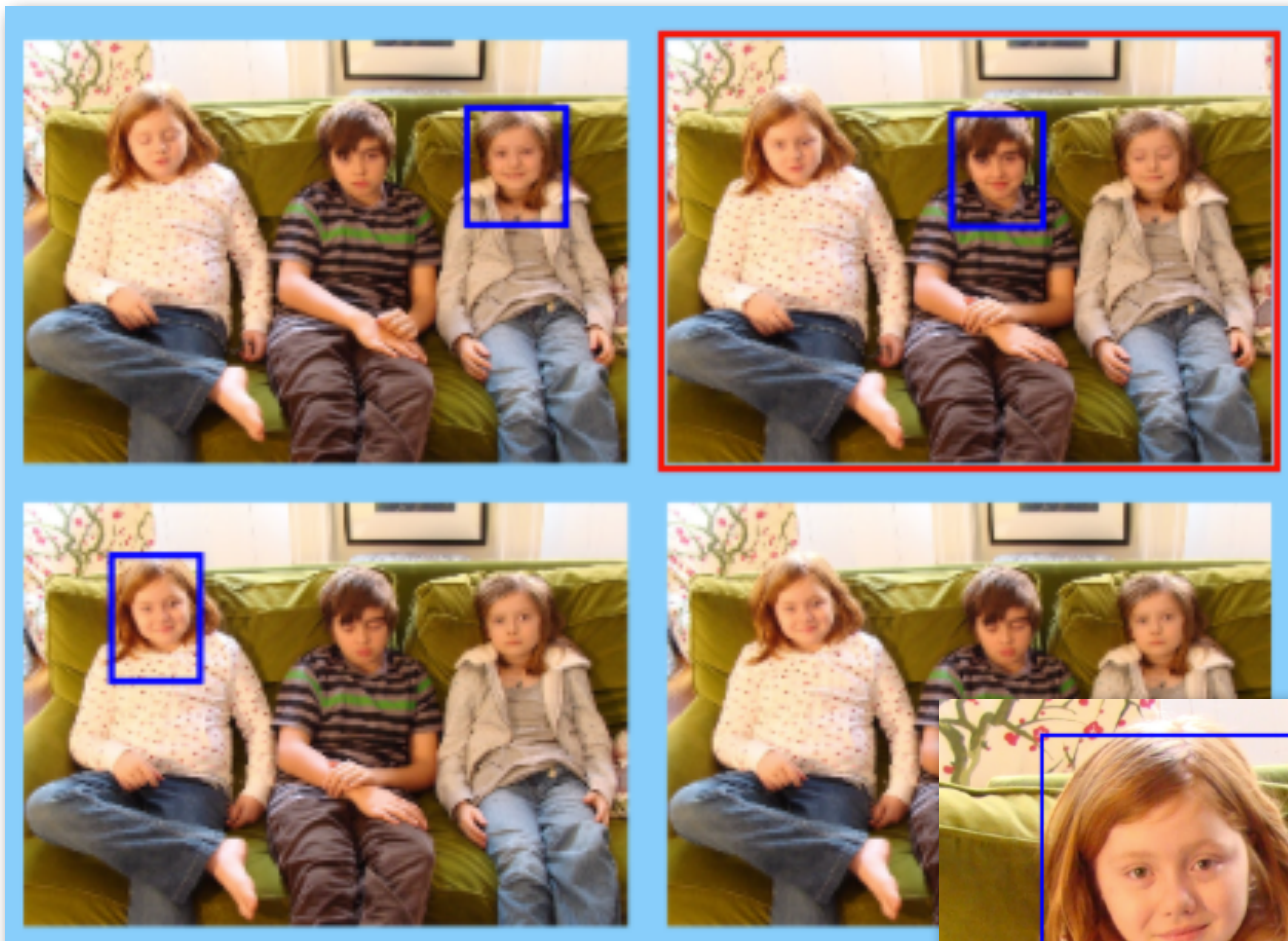
Another example: iPhone burst mode "best" shot selection

Sony's ill-fated "smile shutter"

Camera detects smile and automatically takes picture.

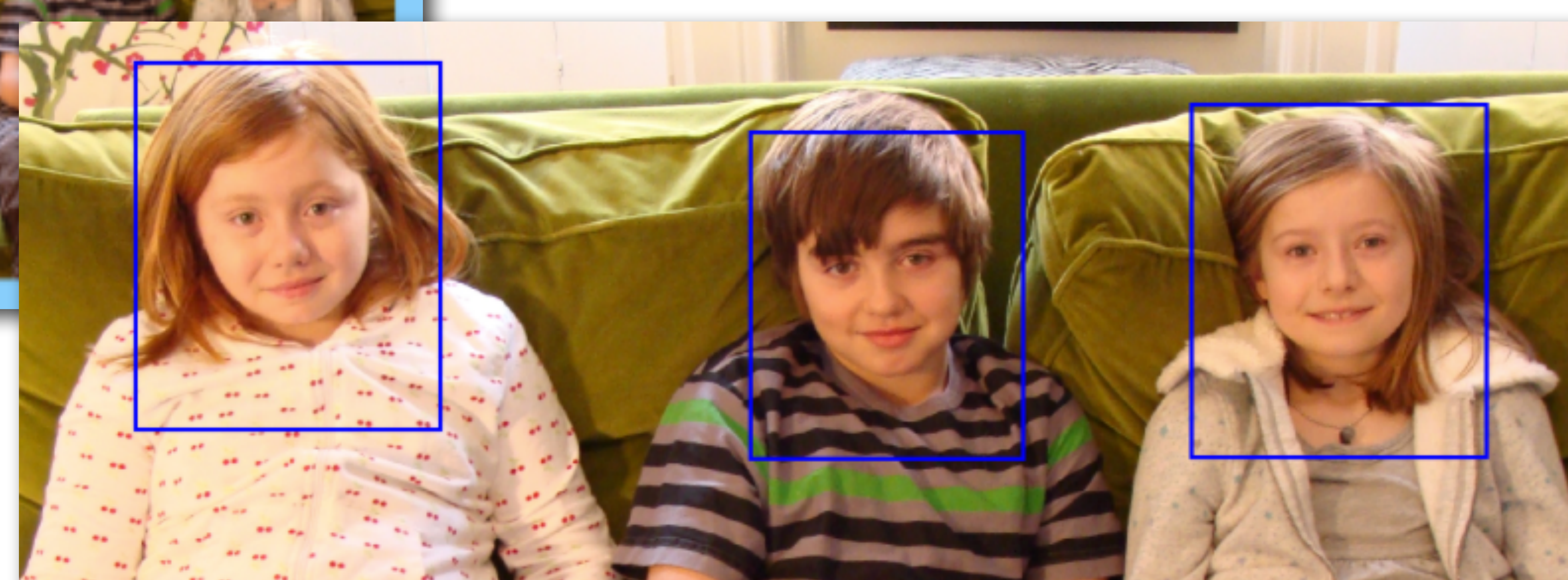
Smarter cameras

- **Future behaviors**
  - Automatic photo framing/cropping?
  - Replace undesirable data with more desirable data acquired previously



Four source photos:
in each shot, at least one child's eyes are closed

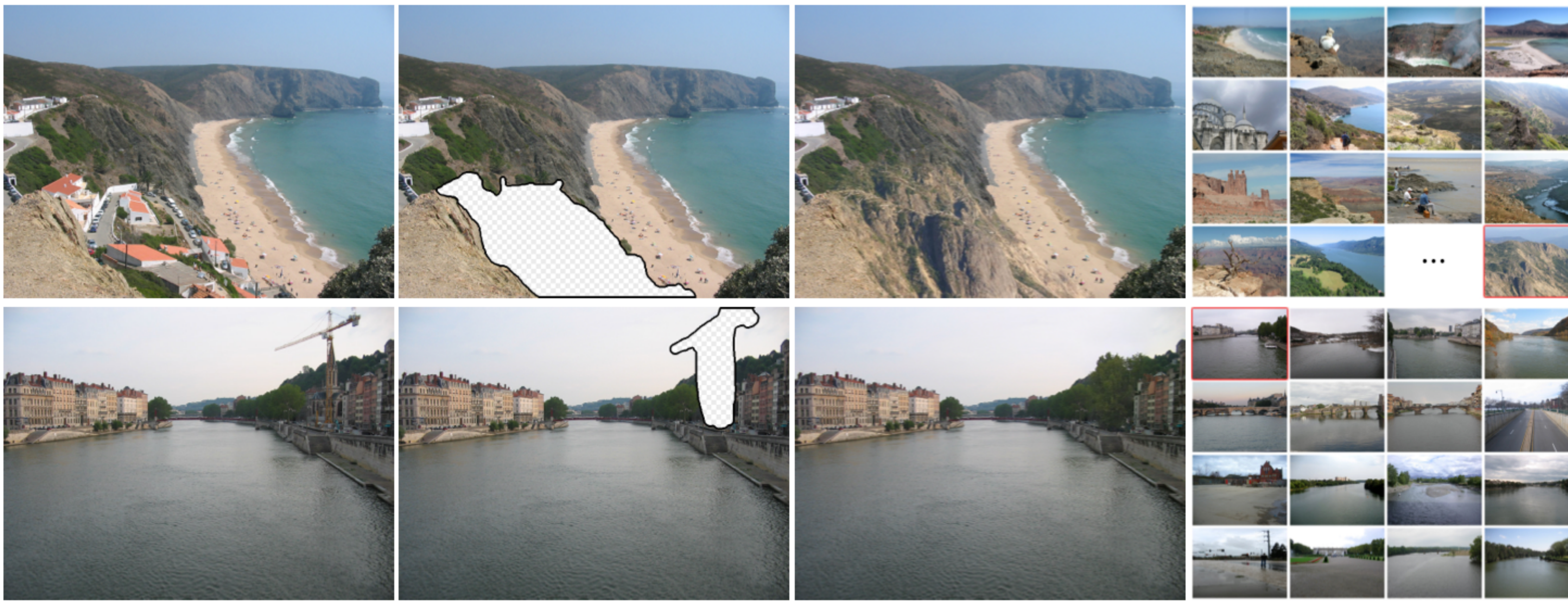
"Face-swapping"
[Bitouk et al. 2008]



Result: Composite image with everyone's eyes open

Smarter cameras

- Future behaviors
  - Automatic photo framing/cropping?
  - Replace undesirable data with more desirable data acquired previously



Original image | Selected "Bad" region | Final Composite | Top Replacement Candidates

Scene Completion Using Millions of Photos
[Hays and Efros 2007]

Camera processing resources

Generic SLR camera

Consider everything that happens from shutter press to image!

Do designers care about latency or throughput?