Post-processing pipeline

CS 178, Spring 2013

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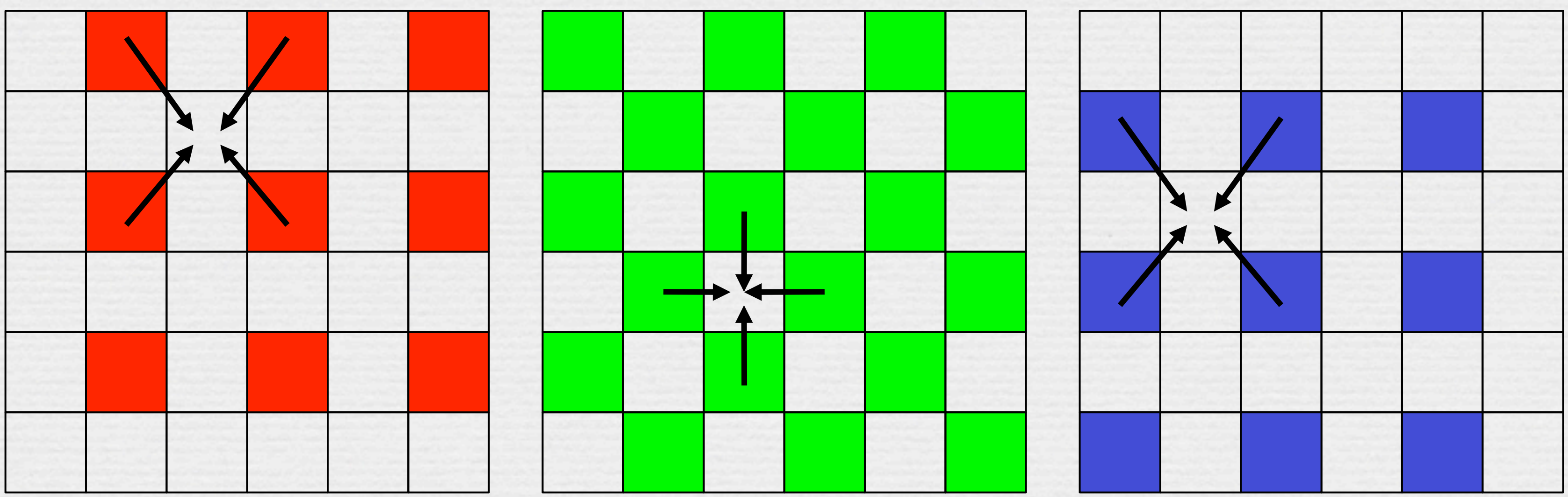
Camera pixel pipeline

sensor → analog to digital conversion (ADC) → processing: demosaicing, tone mapping & white balancing, denoising & sharpening, compression → storage

- every camera uses different algorithms
- the processing order may vary
- most of it is proprietary

Demosaicing (review)

- linear interpolation
  - average of the 4 nearest neighbors of the same color
- cameras typically use more complicated scheme
  - try to avoid interpolating across feature boundaries
  - demosaicing is often combined with denoising, sharpening...

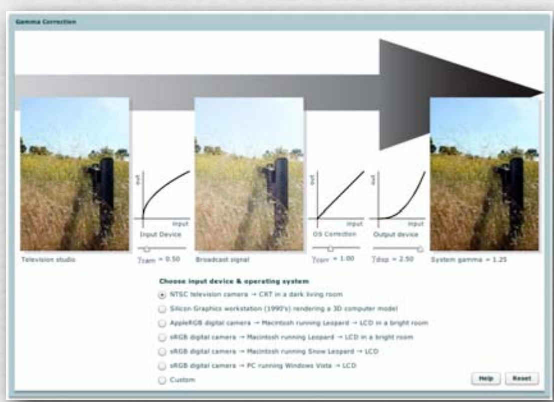


Camera pixel pipeline

sensor → analog to digital conversion (ADC) → processing: demosaicing, tone mapping & white balancing, denoising & sharpening, compression → storage

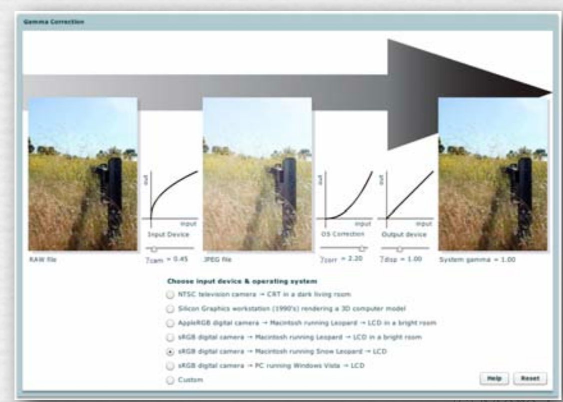
Gamma and gamma correction

- the goal of digital imaging is to accurately reproduce <u>relative</u> scene luminances on a display screen
  - absolute luminance is impossible to reproduce
  - humans are sensitive to relative luminance anyway
- in some workflows, pixel value is made proportional to scene luminance, in other systems to perceived brightness
  - in CRTs luminance was proportional to voltage$^{\gamma}$ with $\gamma \approx 2.5$, so TV cameras were designed to output voltage $\propto$ scene luminance$^{1/\gamma}$
  - pixel value $\propto$ luminance$^{1/2.5}$ is roughly perceptually uniform, so in CG and digital photography it's a good space for quantization, JPEG, etc.



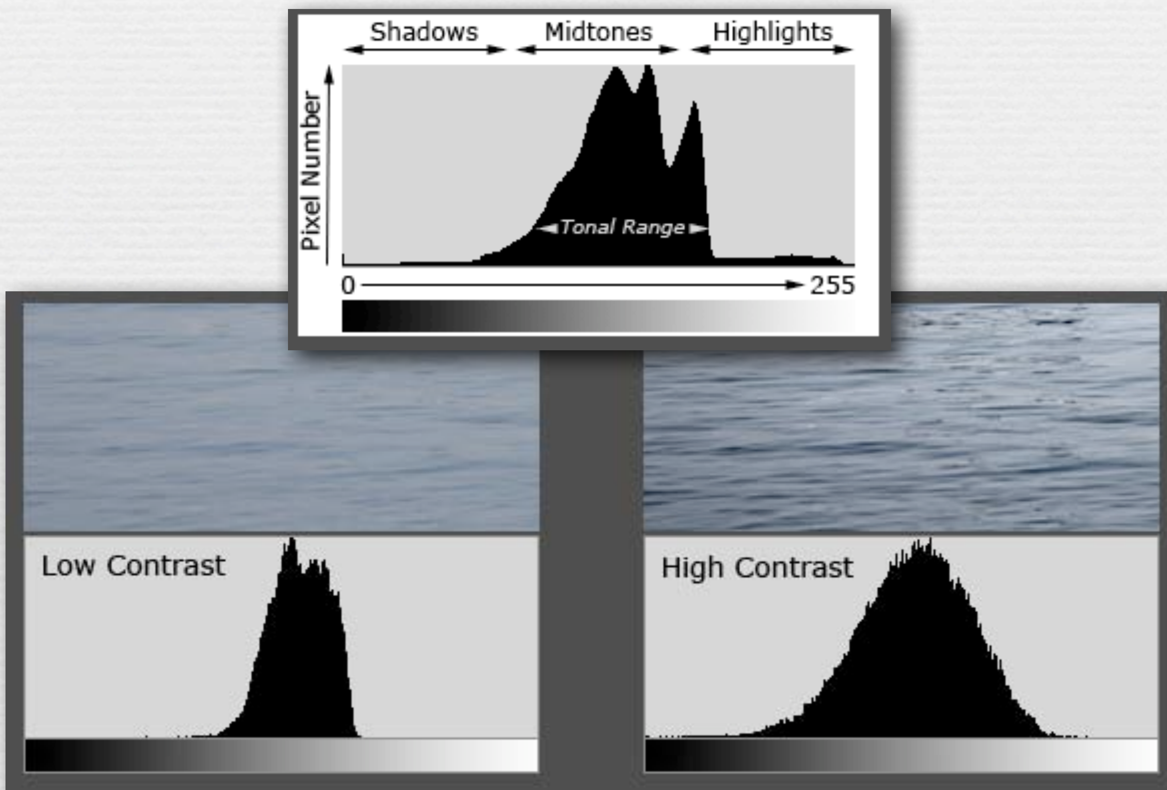
(FLASH DEMO)

http://graphics.stanford.edu/courses/cs178/applets/gamma.html



Contrast correction (a.k.a. tone mapping)

- manual editing
  - capture image in RAW mode, then fiddle with histogram in Photoshop, `dcraw`, Canon Digital Photo Professional, etc.



(cambridgeincoulour.com)

Contrast correction (a.k.a. tone mapping)

- manual editing
  - capture image in RAW mode, then fiddle with histogram in Photoshop, `dcraw`, Canon Digital Photo Professional, etc.
- gamma transform (in addition to RAW→JPEG gamma)
  - output = input$^{\gamma}$ (for $0 \le I_i \le 1$)
  - simple but crude

original

$\gamma = 0.5$

$\gamma = 2.0$

Contrast correction (a.k.a. tone mapping)

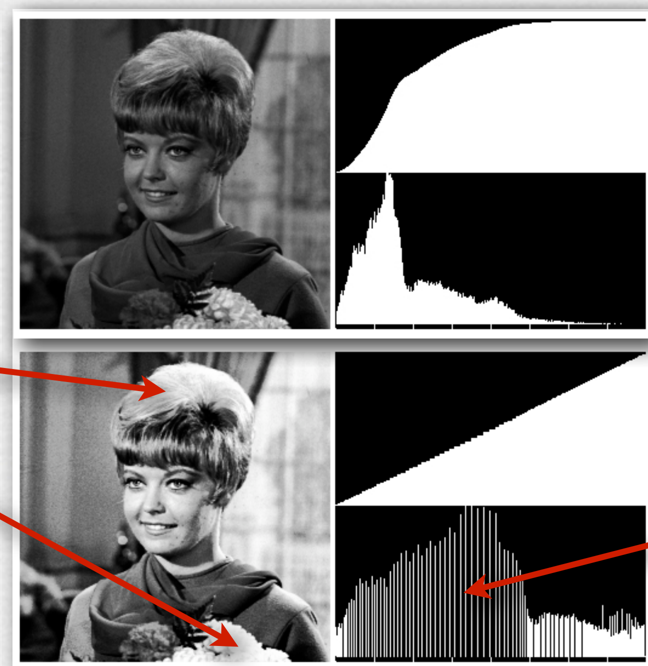
- manual editing
  - capture image in RAW mode, then fiddle with histogram in Photoshop, `dcraw`, Canon Digital Photo Professional, etc.
- gamma transform (in addition to RAW→JPEG gamma)
  - output = input$^{\gamma}$ (for $0 \le I_i \le 1$)
  - simple but crude
- histogram equalization

Histogram equalization

1. convert image to range [0,1]
2. calculate histogram of intensity, i.e. $pdf(i) = \dfrac{N_i}{N}$
   where N_i is the number of pixels of intensity i,
   and N is the total number of pixels
3. calculate cumulative density function $cdf(i) = \sum_{j=0}^{i} pdf(j)$
4. re-map each pixel using $I_{out} = cdf(I_{in}) \times 255 / N$ (for 8-bit pixels)

input

output



cdf

pdf

overexposed

leaves gaps

Histogram equalization

1. convert image to range [0,1]
2. calculate histogram of intensity, i.e. $pdf(i) = \frac{N_i}{N}$
   where N_i is the number of pixels of intensity i,
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4. re-map each pixel using $I_{out} = cdf(I_{in}) \times 255 \,/\, N$ (for 8-bit pixels)

input

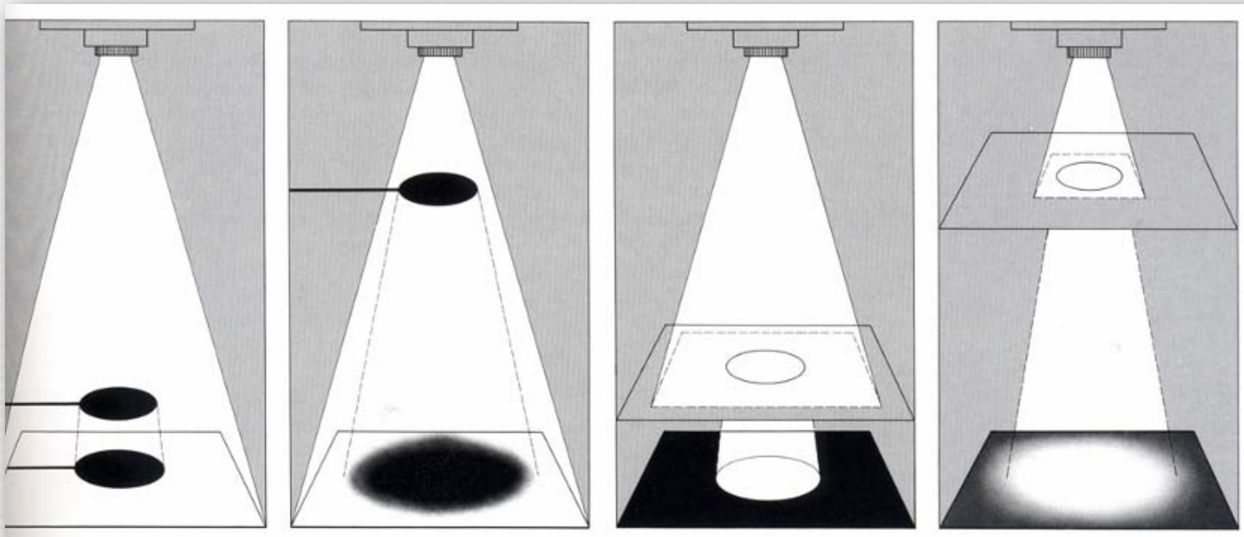
output

works better on this example

Contrast correction (a.k.a. tone mapping)

- manual editing
  - capture image in RAW mode, then fiddle with histogram in Photoshop, `dcraw`, Canon Digital Photo Professional, etc.
- gamma transform (in addition to RAW→JPEG gamma)
  - output = input$^{\gamma}$ (for $0 \le I_i \le 1$)
  - simple but crude
- histogram equalization
- global versus local transformations

Traditional dodging and burning

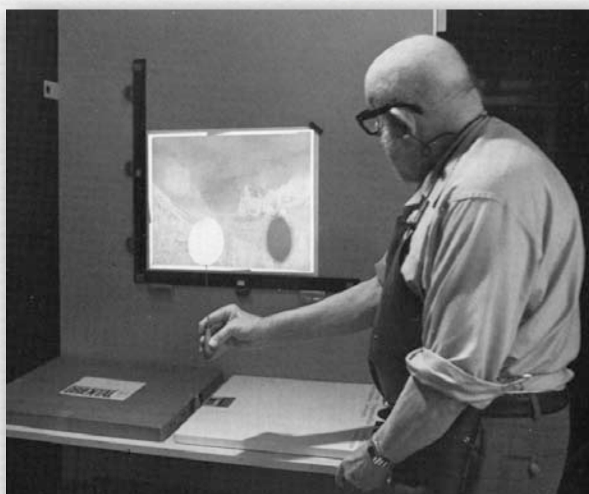


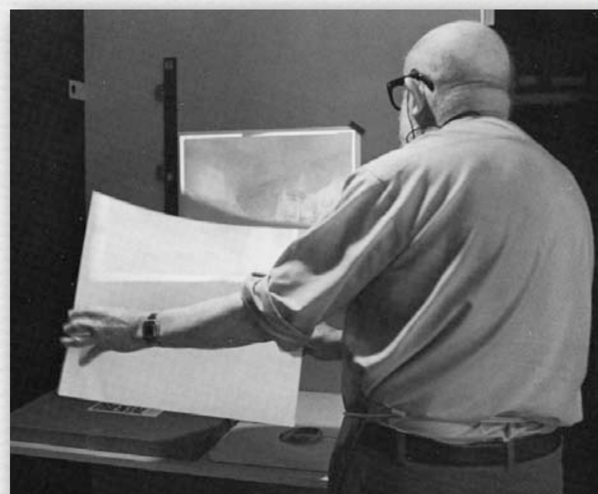
(Rudman)

dodging
(leaves print lighter)

burning
(makes print darker)

Ansel Adams in his darkroom





(Adams)

straight
print

Ansel Adams, Clearing Winter Storm, 1942

toned print

Ansel Adams, Clearing Winter Storm, 1942

Recap

- in CRTs luminance = voltage$^{\gamma}$ where $\gamma \approx 2.5$, so television cameras output luminance$^{1/\gamma}$ to compensate
  - NTSC cameras use luminance$^{0.5}$, yielding a *system gamma*, to compensate for human *dark adaptation* during viewing
- digital cameras also gamma transform sensed pixels before storing them in JPEG files
  - while this matches television cameras, another good reason is perceptual uniformity, thereby reducing quantization artifacts
  - for sRGB cameras, $\gamma = 1/2.2$
- *tone mapping* methods may include
  - contrast expansion
  - additional gamma mapping
  - histogram equalization
  - local methods, like dodging & burning

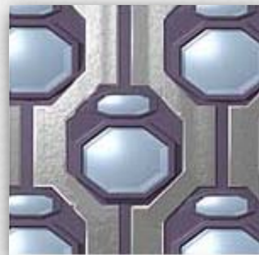
Questions?

High dynamic range (HDR) imaging

- step 1: capturing HDR images
- step 2a: direct display of HDR images, or
- step 2b: tone mapping to create an LDR image for display

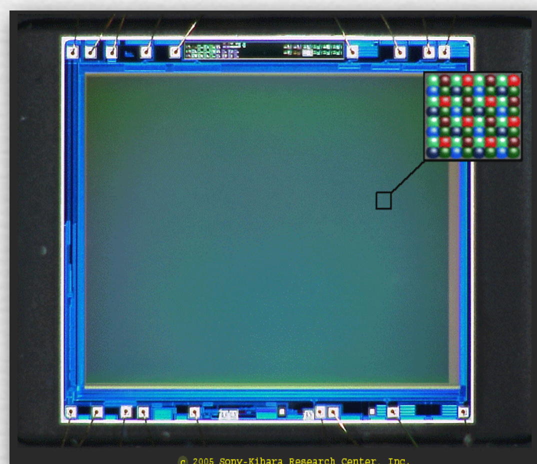
Capturing HDR images

- assorted pixels

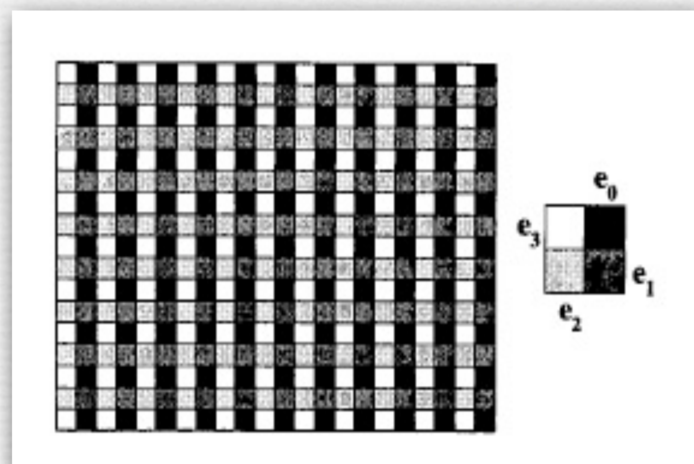


Fuji SuperCCD

- per-pixel neutral density filters
  [Nayar CPVR 2000]
  - throws away photons
  - trades spatial resolution for dynamic range



Sony



Games with ND filters

1/500s, f/5.6, ISO 800

Games with ND filters

1/125s

Games with ND filters

1/30s

Games with ND filters

1/8s

Games with ND filters

1/2s

Games with ND filters

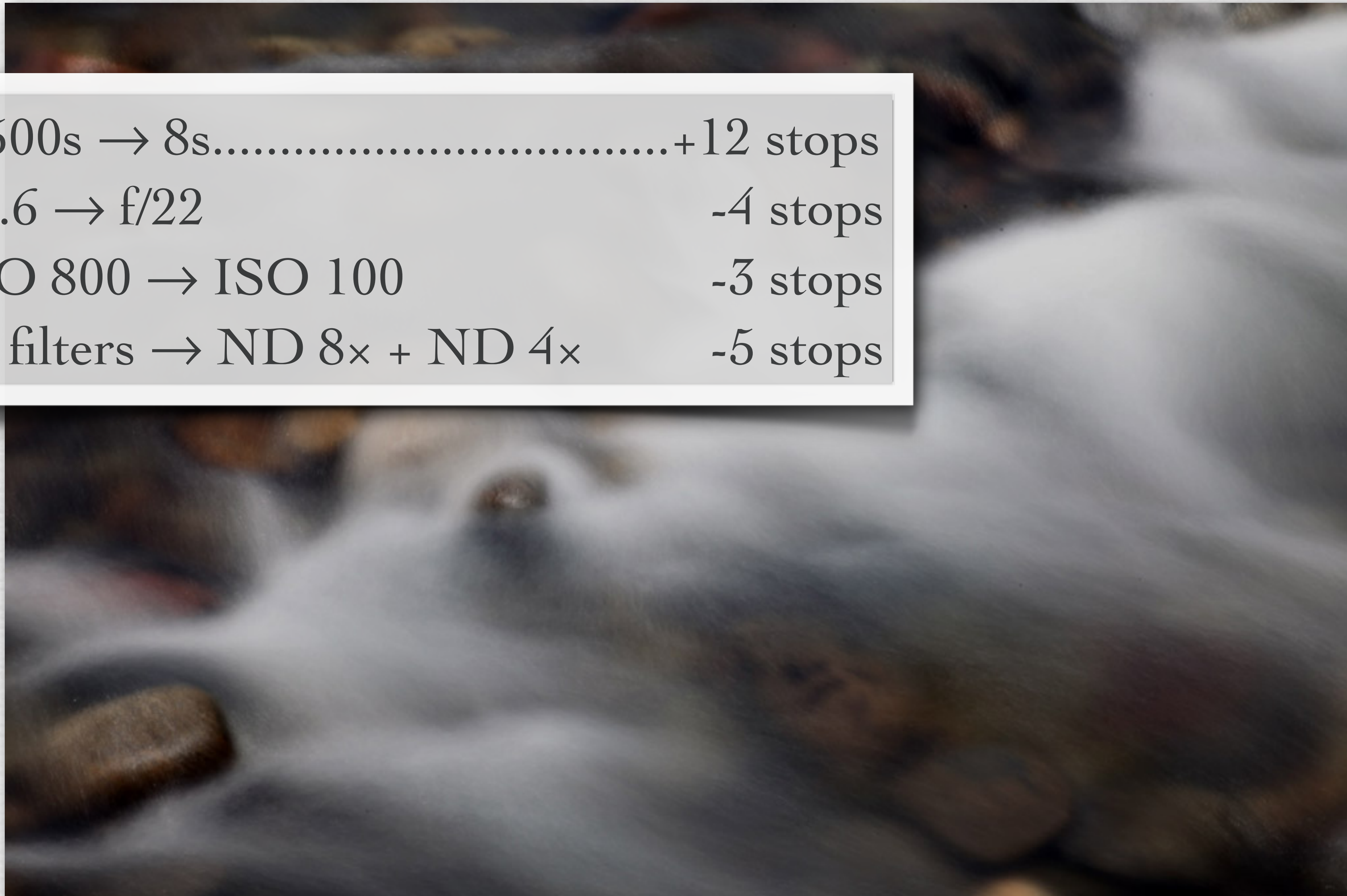
2s

Games with ND filters

8s

Games with ND filters

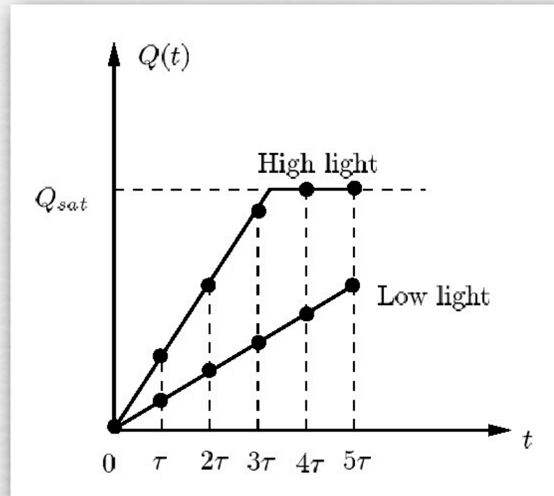
1/500s → 8s	+12 stops
f/5.6 → f/22	-4 stops
ISO 800 → ISO 100	-3 stops
no filters → ND 8× + ND 4×	-5 stops



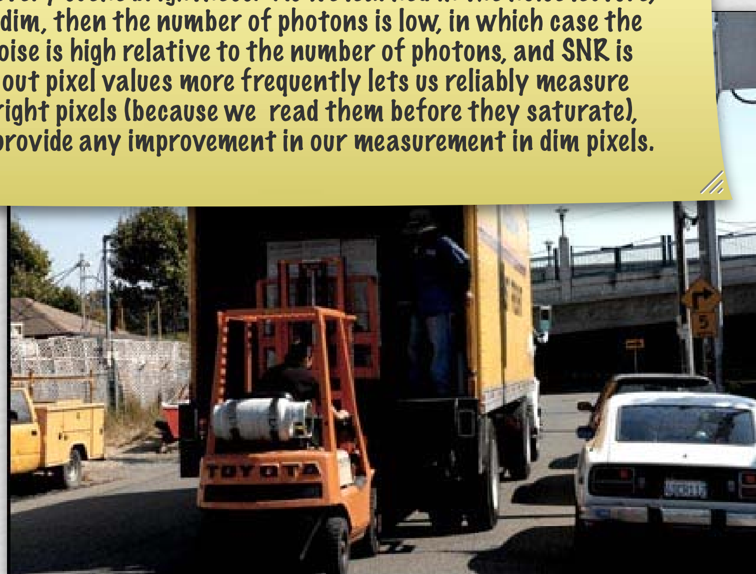
8s

Capturing HDR images

- non-destructive readout of pixels [Gamal 1999]
  - measures light by counting time to saturation
  - improves dynamic range, but SNR at low brightness levels is no better than an ordinary camera



To expand on this last point, remember that SNR is a metric that is different for every scene brightness. As we learned in the noise lecture, if the scene is dim, then the number of photons is low, in which case the photon shot noise is high relative to the number of photons, and SNR is poor. Reading out pixel values more frequently lets us reliably measure intensity in bright pixels (because we read them before they saturate), but it doesn't provide any improvement in our measurement in dim pixels.



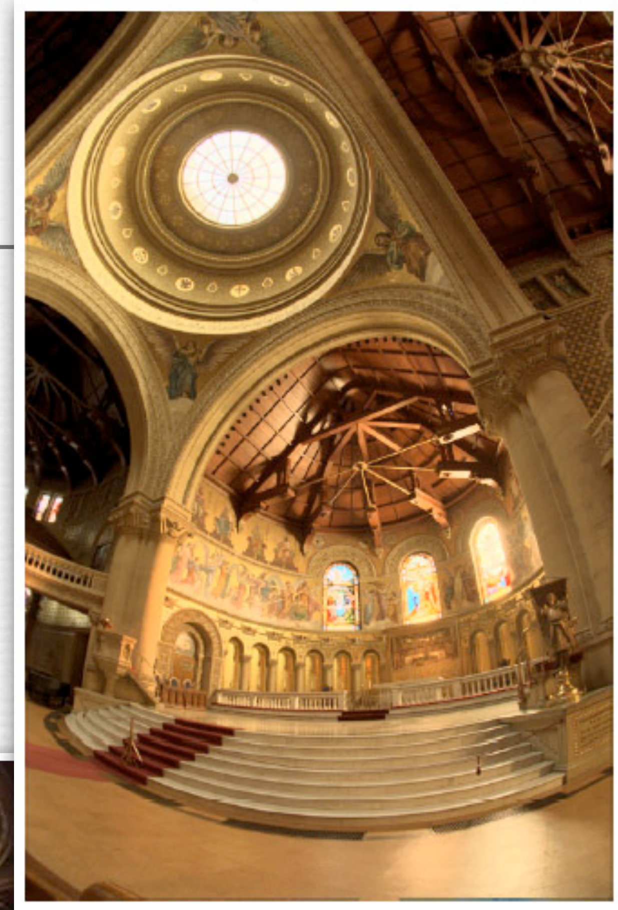
normal

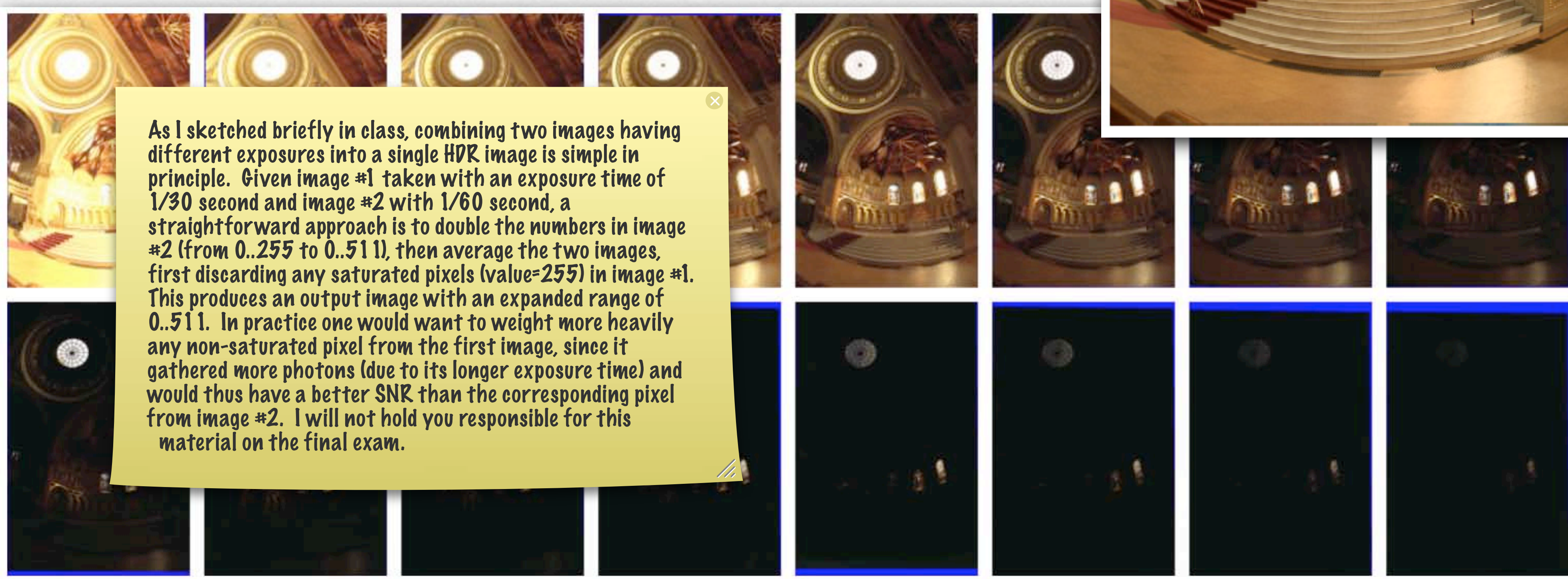
Pixim

Capturing HDR images

- multiple bracketed exposures
  [Debevec SIGGRAPH 1997]
- changing the exposure time is usually better than changing the aperture

Q. How about changing the ISO?

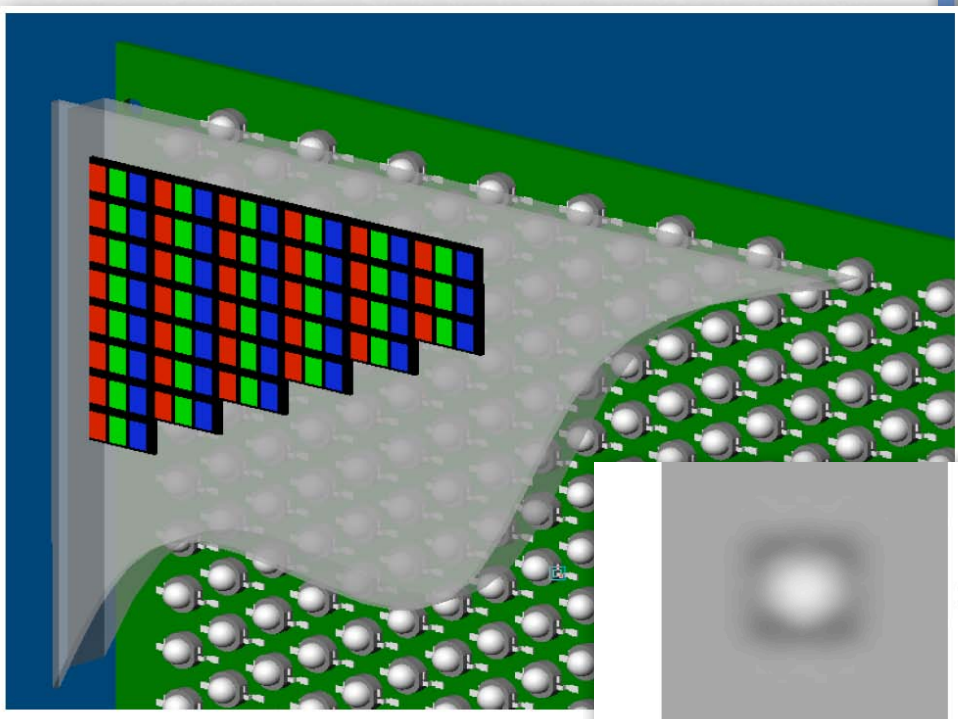


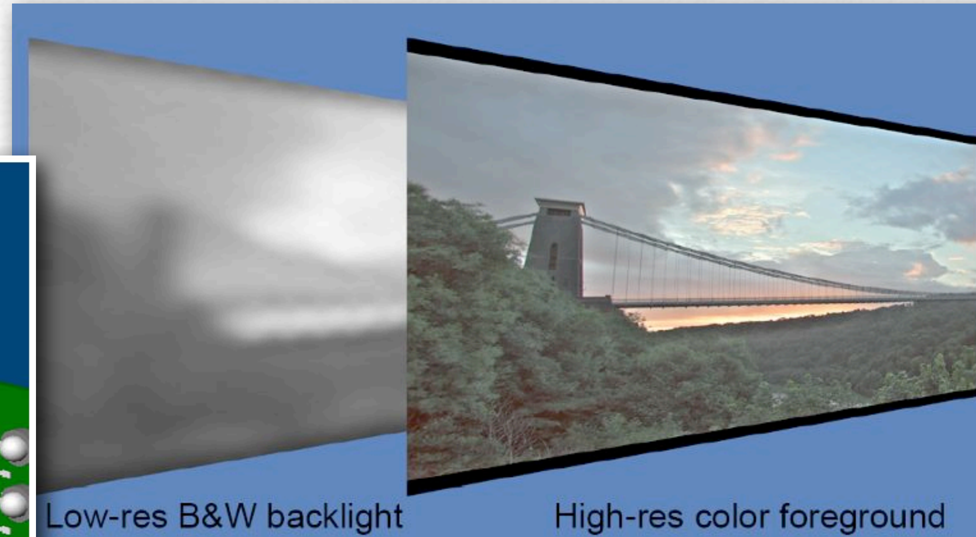


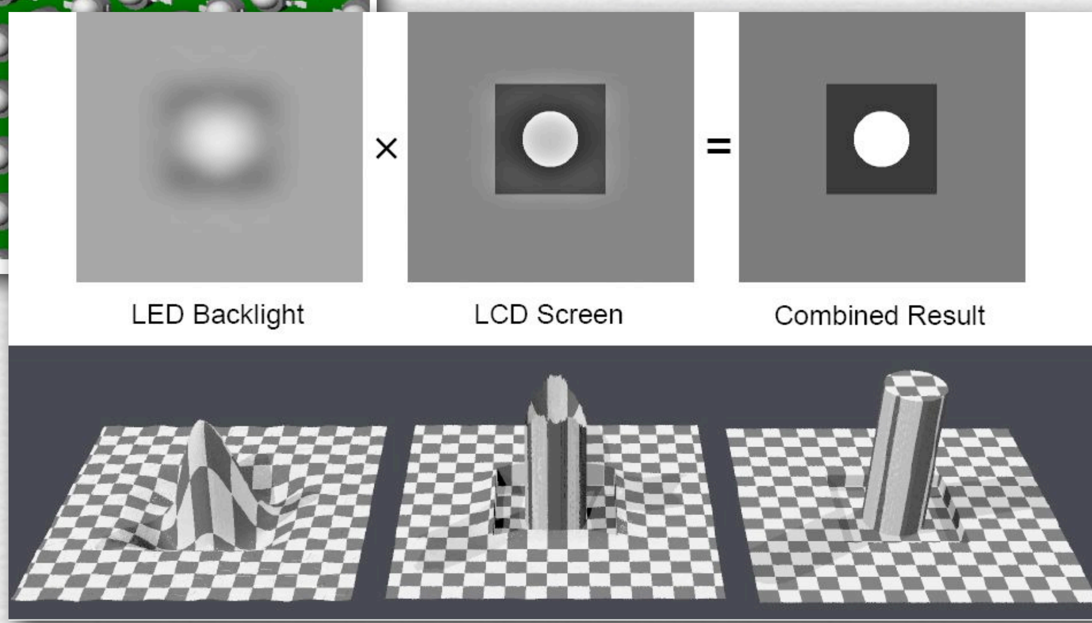
As I sketched briefly in class, combining two images having different exposures into a single HDR image is simple in principle. Given image #1 taken with an exposure time of 1/30 second and image #2 with 1/60 second, a straightforward approach is to double the numbers in image #2 (from 0..255 to 0..511), then average the two images, first discarding any saturated pixels (value=255) in image #1. This produces an output image with an expanded range of 0..511. In practice one would want to weight more heavily any non-saturated pixel from the first image, since it gathered more photons (due to its longer exposure time) and would thus have a better SNR than the corresponding pixel from image #2. I will not hold you responsible for this material on the final exam.

Direct display of HDR images

- Sunnybrook HDR display







Brightside HDR display

High dynamic range (HDR) imaging

- step 1: capturing HDR images
- step 2a: direct display of HDR images, or
- step 2b: tone mapping to create an LDR image for display

you're not responsible for
HDR tone mapping on your final

- goals of HDR → LDR tone mapping
  - squeeze >12 bits of HDR image into 8 bits for JPEG
  - apply mapping for human adaption if scene was very dark
  - or bright...


(Marc Levoy)

(Marc Levoy)

(Marc Levoy)

Cathedral,
Valencia

(Marc Levoy)

tone mapping in Photoshop CS4 by “exposure and gamma” method

Cathedral, Valencia

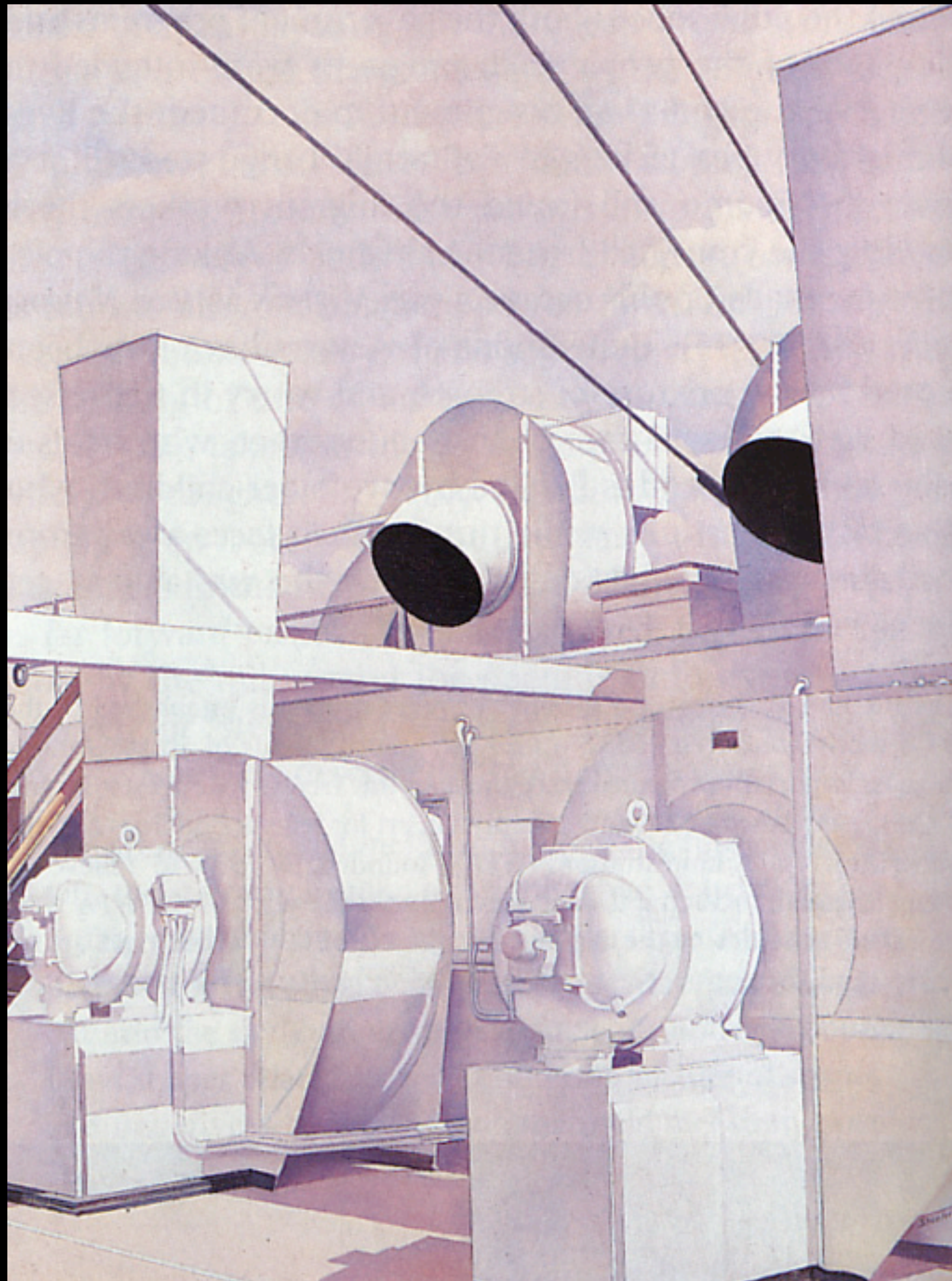
(Marc Levoy)

tone mapping in Photoshop CS4 by "histogram equalization" method

Cathedral, Valencia

(Marc Levoy)

How do artists solve the tone mapping problem?



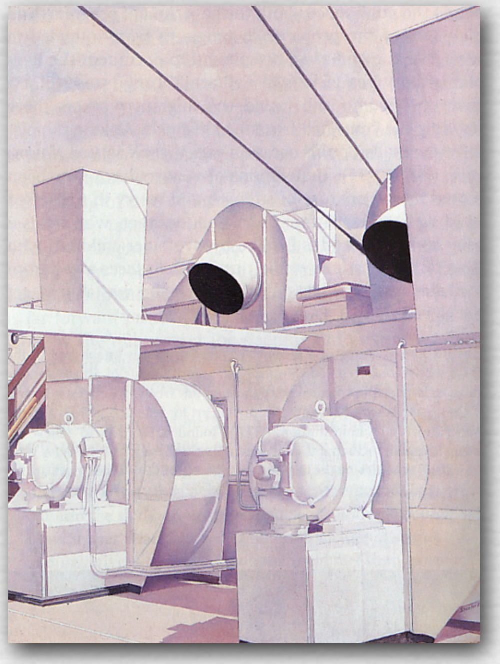
Charles Sheeler,
The Upper Deck
(1929)

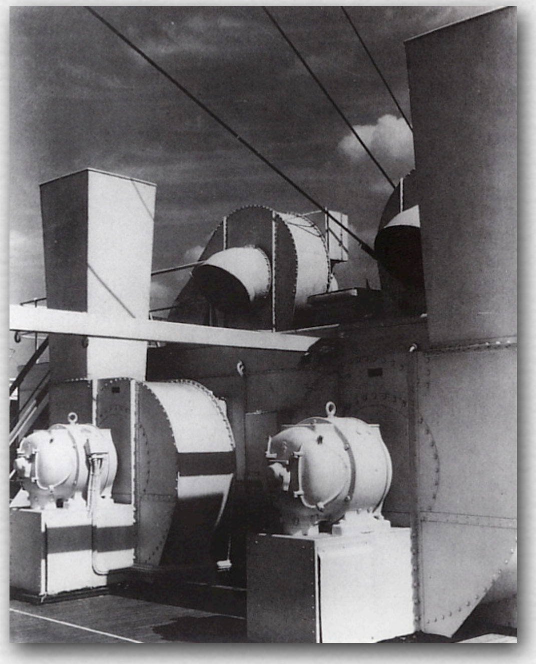
Joseph Wright, The Orrery (1765)

How do artists solve the tone mapping problem?

Hermann von Helmholtz
(1821-1894)
"The relation of optics to painting"

- for bright scenes
  - human vision is dazzled, compressing brightnesses
- for dark scenes
  - shadows are below threshold, so completely black





(Gardner)

(borrowed from lecture on noise)

Tone mapping techniques
(slides from Fredo Durand)

- image has 10,000:1 dynamic range, projector has 1000:1
- how can we compress the image's dynamic range?

A point I should have made clearer in class is that you could trivially reduce an HDR image (for example 10 bits per R,G,B) to an LDR image (for example 8 bits per R,G,B) simply by dividing each pixel value by 4x. However, in a sunset scene like this, most of the 10-bit range is taken up by the sun. The result of doing this naive division is exactly the image shown at right; the cityscape below the horizon is reduced to numbers in the single-digit range (on an 8-bit scale), making it look nearly all black. This is why reducing an HDR image to an LDR image must be accompanied by more intelligent tone mapping.

Global tone mapping operators

- gamma compression, applied independently on R,G,B

  output = input$^\gamma$ (γ = 0.5 here)

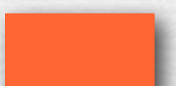
- colors become washed out

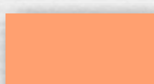
in addition to the gamma transform during RAW → JPEG conversion

input

output

$(1.0, 0.4, 0.2)^{0.5} = (1.0, 0.63, 0.44)$





(try it yourself in Photoshop)

Global tone mapping operators

- gamma compression on intensity only
- saturated but light colors become garish

luminance

(e.g. 0.3R+0.7G+0.01B)

chrominance

(e.g. R/lum, G/lum, B/lum)

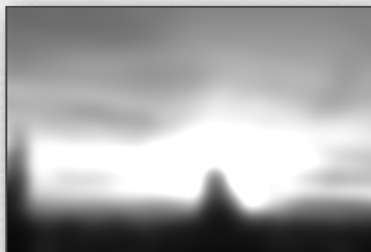
(from our convolution applet)

0.00	-2.00	0.00
-2.00	9.00	-2.00
0.00	-2.00	0.00

Local tone mapping operators

- reduce contrast of low frequencies, while preserving high frequencies [Oppenheim 1968, Chiu et al. 1993]
- produces halos!

low frequency



(e.g. Gaussian blur)

high frequency

(e.g. original minus Gaussian)

chrominance

Local tone mapping operators

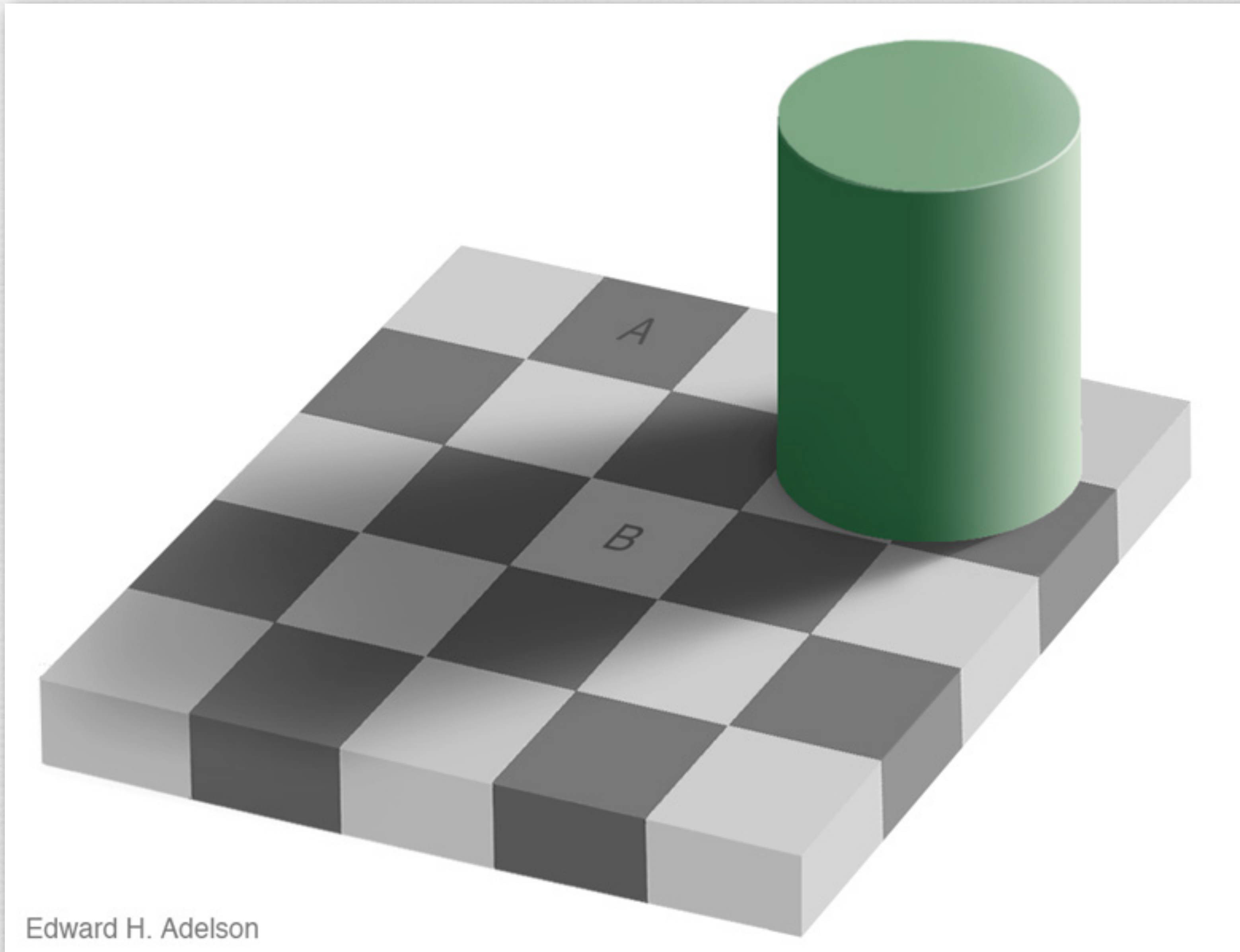
- bilateral filtering to compute large scale image without blurring across edges, remainder is detail image (no halos!); reduce contrast of large scale, while preserving details
  [Durand and Dorsey SIGGRAPH 2002]

large scale

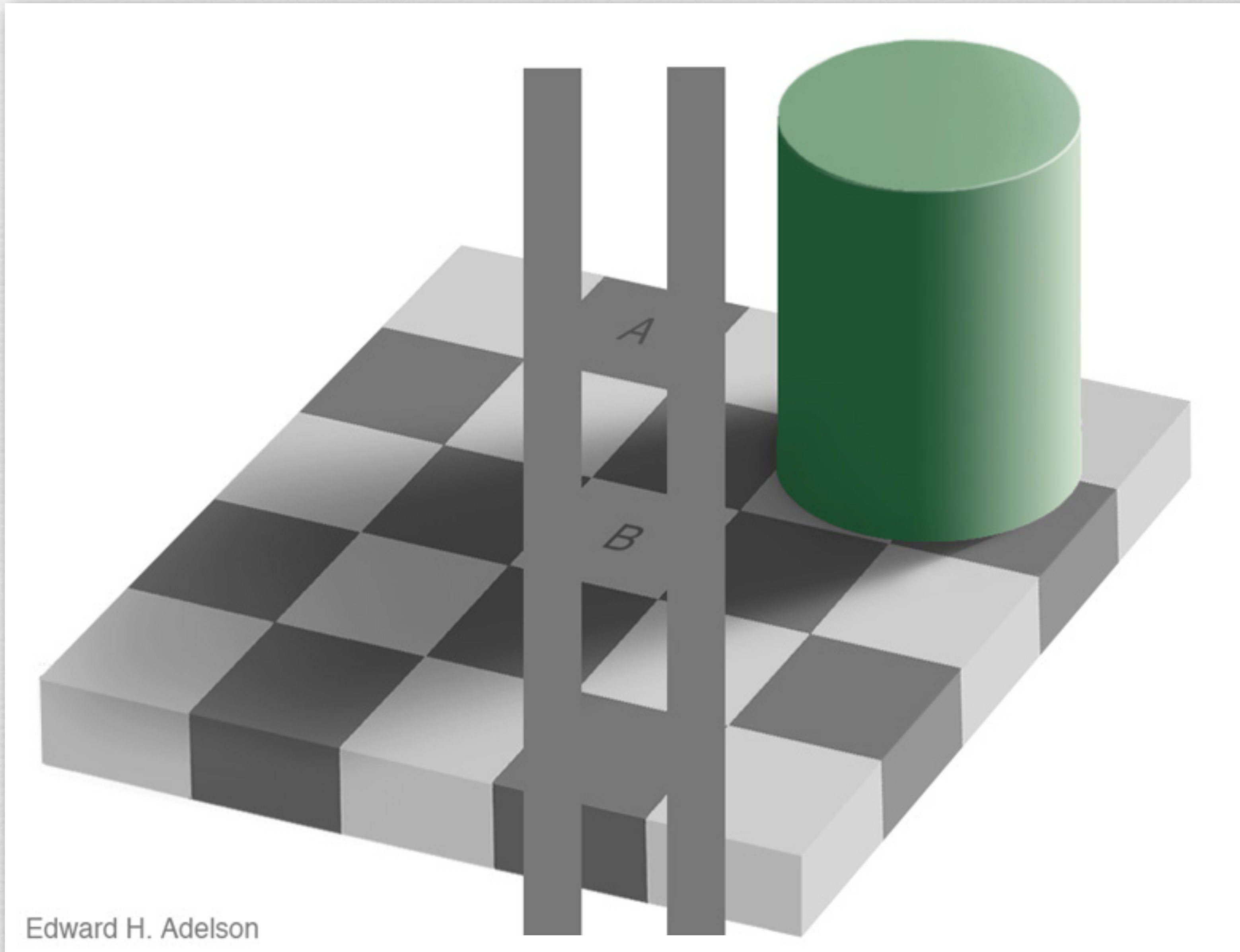
detail

chrominance

The importance of local contrast

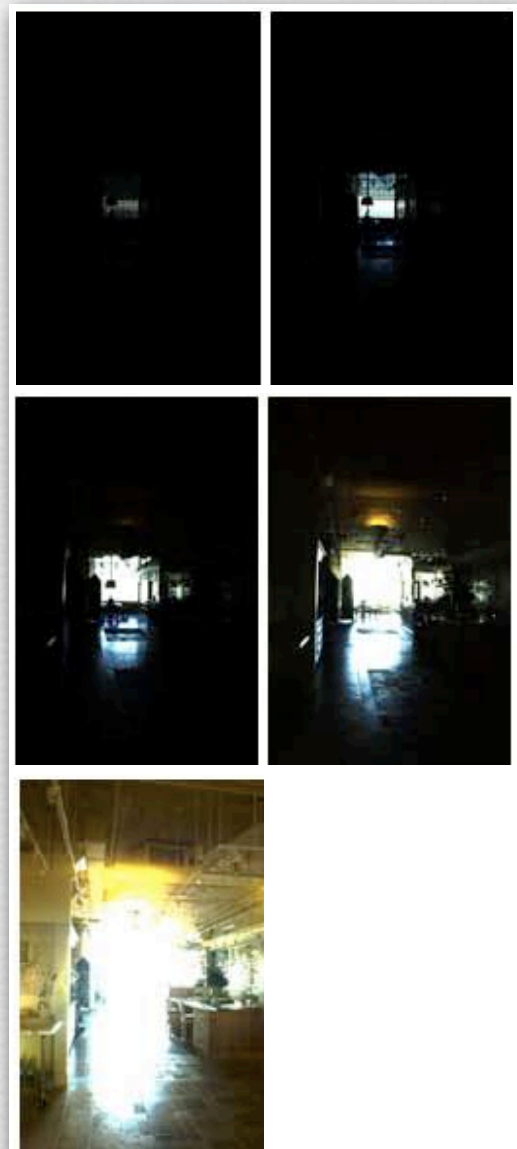


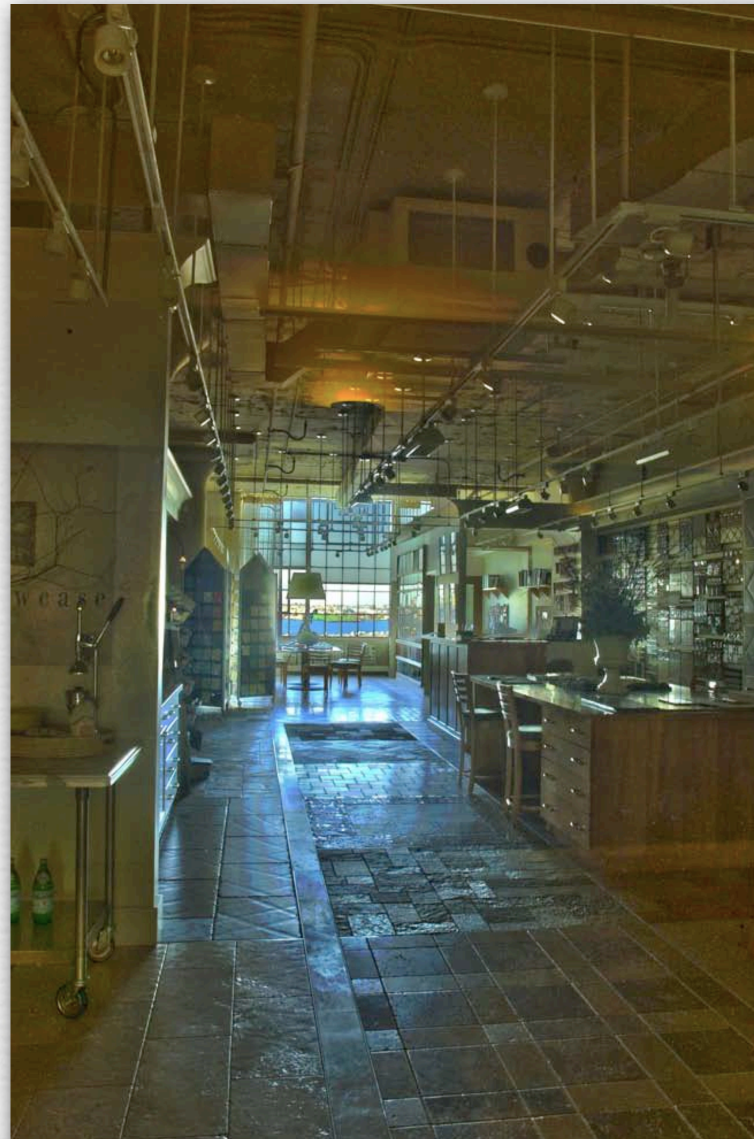
The importance of local contrast



Tone mapping using bilateral filters

[Durand and Dorsey SIGGRAPH 2002]





Commissary,
Fort Ross, CA,
2010

(Panasonic ZS3,
1/30s, ISO 125)

(Marc Levoy)

Commissary,
Fort Ross, CA,
2010

(Panasonic ZS3,
1/30s, ISO 250)

(Marc Levoy)

Commissary,
Fort Ross, CA,
2010

(Panasonic ZS3,
1/25s, ISO 400)

(Marc Levoy)

Commissary,
Fort Ross, CA,
2010

(Panasonic ZS3,
1/13s, ISO 400)

(Marc Levoy)

Commissary, Fort Ross, CA, 2010

(Panasonic ZS3, 1/8s, ISO 400)

(Marc Levoy)

Commissary,
Fort Ross, CA,
2010

(tone mapped HDR using Photomatix v3.3.2's "detail enhancer" algorithm)

(Marc Levoy)

Commissary,
Fort Ross, CA,
2010

(tone mapped HDR using Photomatix v3.3.2's "tone compressor" algorithm)

(Marc Levoy)

Stanford Arcade, 2009 (1/160s, f/6.3, ISO 100)

(Marc Levoy)

Stanford Arcade, 2009 (1/125s, f/5.6, ISO 100)

(Marc Levoy)

Stanford Arcade, 2009 (1/100s, f/5.4, ISO 100)

(Marc Levoy)

Stanford Arcade, 2009 (Photomatix 3.3.2, “tone compressor” algorithm)

(Marc Levoy)

Stanford Arcade, 2009 (1/125s, f/5.6, ISO 100)

(Marc Levoy)

Stanford Arcade, 2009 (Photomatix 3.3.2, "tone compressor" algorithm)

(Marc Levoy)

The HDR "look"

(Trey Ratcliff, http://www.stuckincustoms.com)

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Recap

- high dynamic range (HDR) imaging is useful, and a new aesthetic, but is not necessary in most photographic situations
  - SLRs have more useful dynamic range (~12 bits) than point-and-shoot cameras or cell phones, i.e. w/o shadows being noisy
- low dynamic range (LDR) tone mapping methods apply to HDR, but reducing 12 bits to 8 bits using only global methods is hard
  - the reduction is needed for JPEG, display, and printing
- successful methods reduce large-scale luminance changes (across the image) while preserving *local contrast* (across edges)
  - use bilateral filtering to isolate large-scale luminance changes

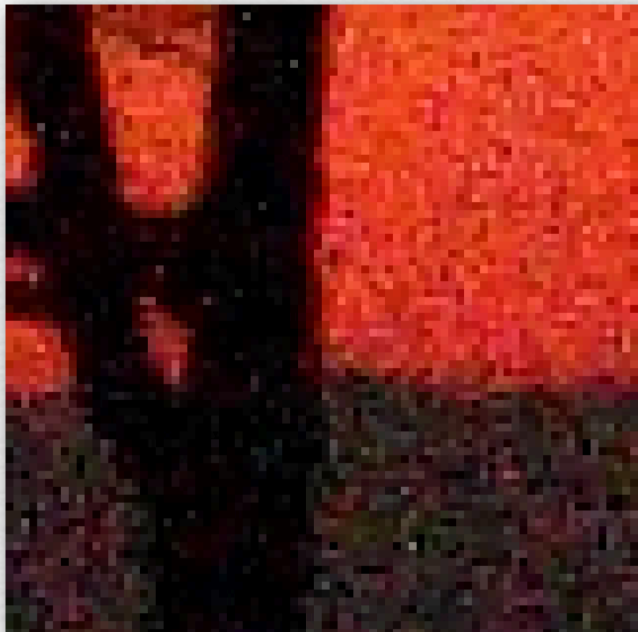
Questions?

Camera pixel pipeline

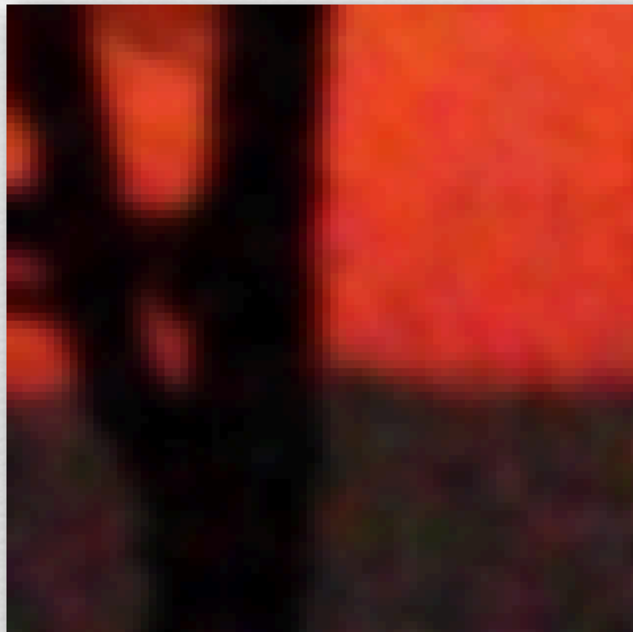
sensor → analog to digital conversion (ADC) → processing: demosaicing, tone mapping & white balancing, denoising & sharpening, compression → storage

Canon 5D II at dusk

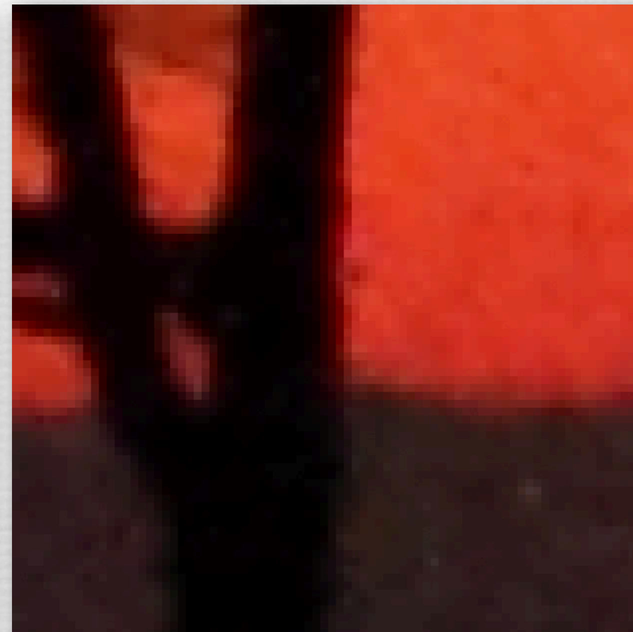
Denoising



RAW (ISO 6400)



Gaussian blur, radius = 1.3



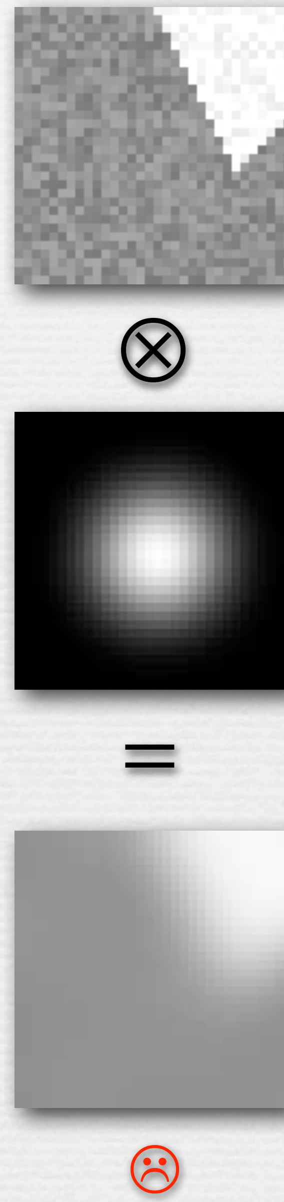
Canon denoising

- goal is to remove sensor noise
  - blurring works, but also destroys edges
  - I don't know what Canon does,
    but here's something that works...

Bilateral filtering [Tomasi ICCV 1998]

- images are often piecewise constant with noise added
  - in this case, nearby pixels are often a different noisy measurement of the same data
- simple blurring doesn't work
  - because it also blurs the edges
- we should blur only within each constant-colored scene region
  - not across edges between regions

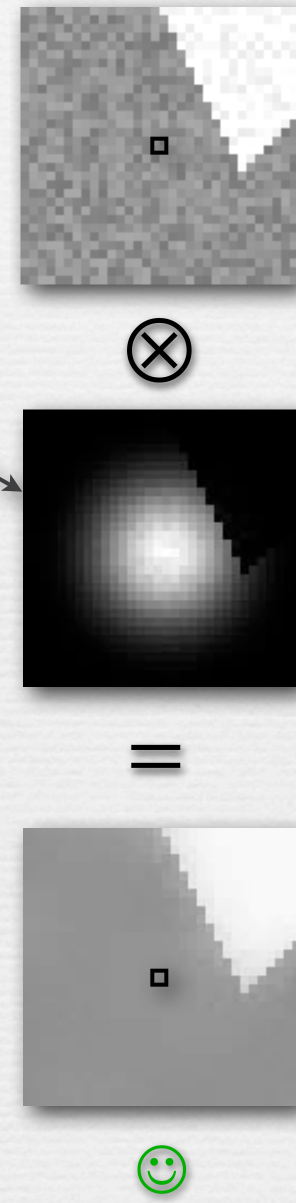
(simulated)



Bilateral filtering

- if the pixels are similar in intensity, they are probably from the same region of the scene

effective filter weights are thus different for each pixel of input



- so perform a convolution where the weight applied to nearby pixels in the summation falls off
  - with increasing *(x,y)* distance from the pixel being blurred, and
  - with increasing intensity difference from the pixel being blurred
- i.e. blur in *domain* and *range* dimensions!

Example of bilateral filtering

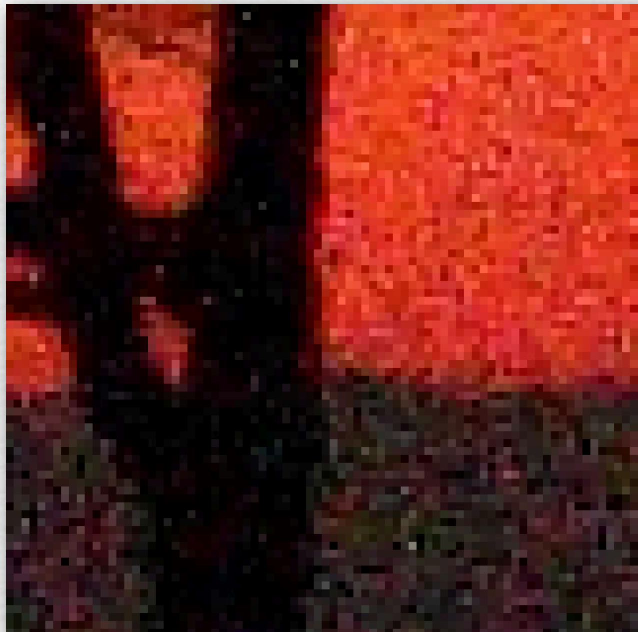
Women's gymnastics

(Canon 7D, 1/1000 sec, ISO 3200, f/1.8, 85mm)

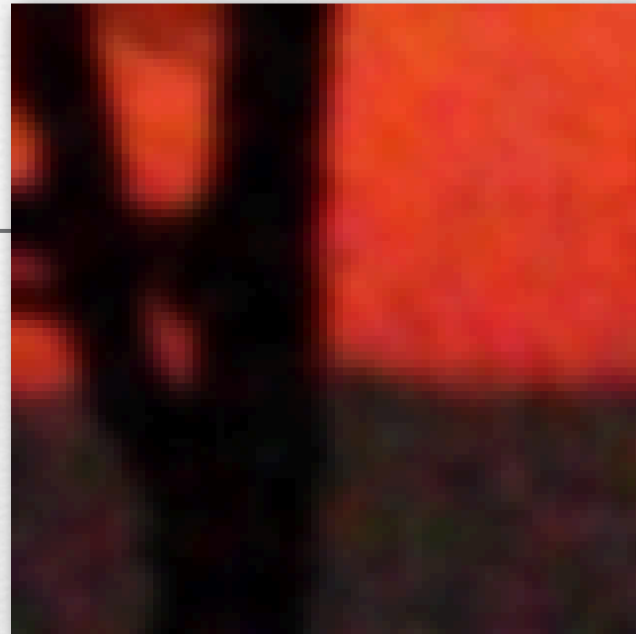
original

denoised in Noise Ninja

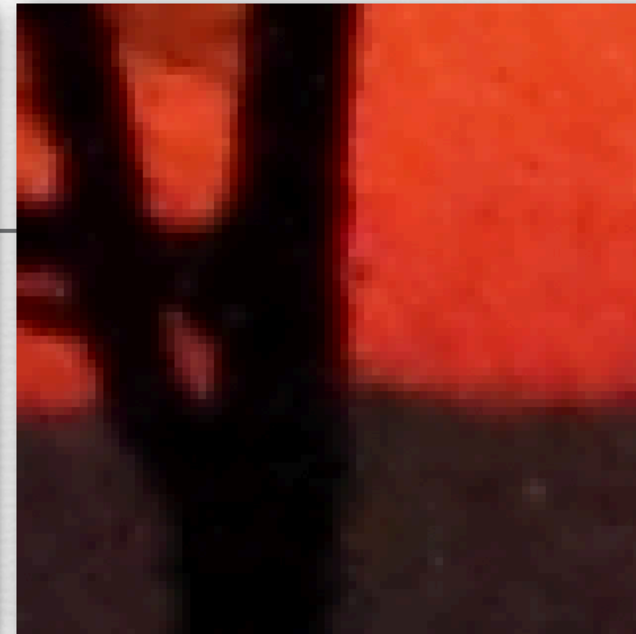
Denoising



RAW (ISO 6400)

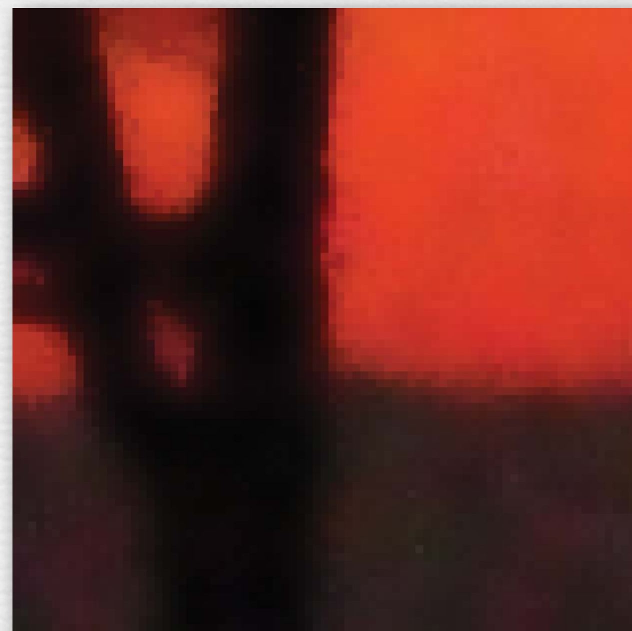


Gaussian blur, radius = 1.3



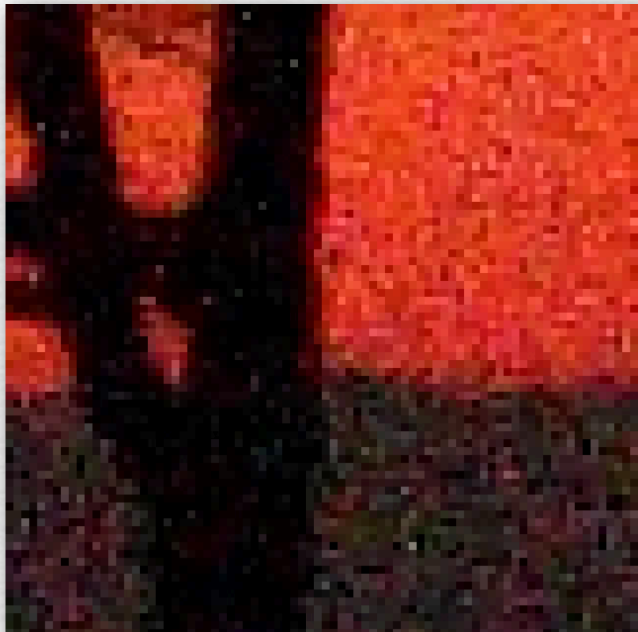
Canon denoising

- bilateral filtering removes sensor noise without blurring edges
- can easily be extended to RGB

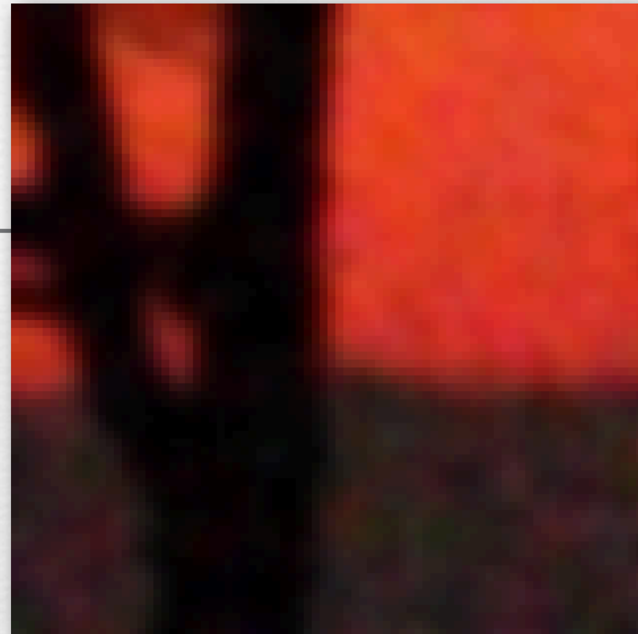


bilateral filtering

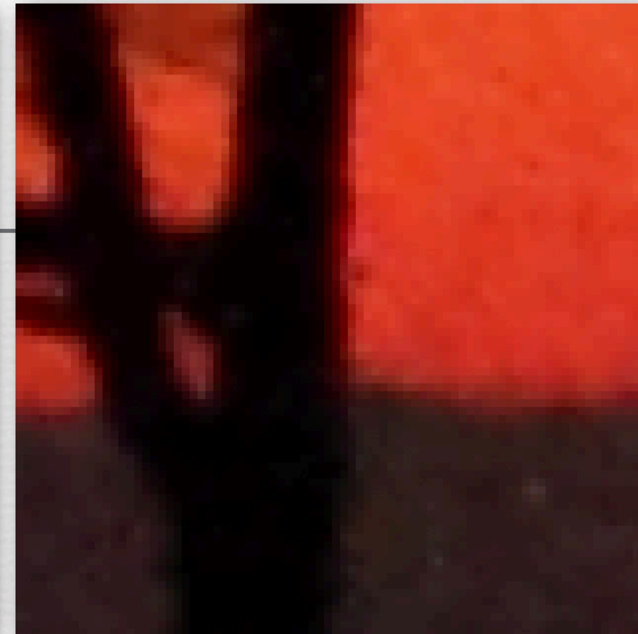
Denoising



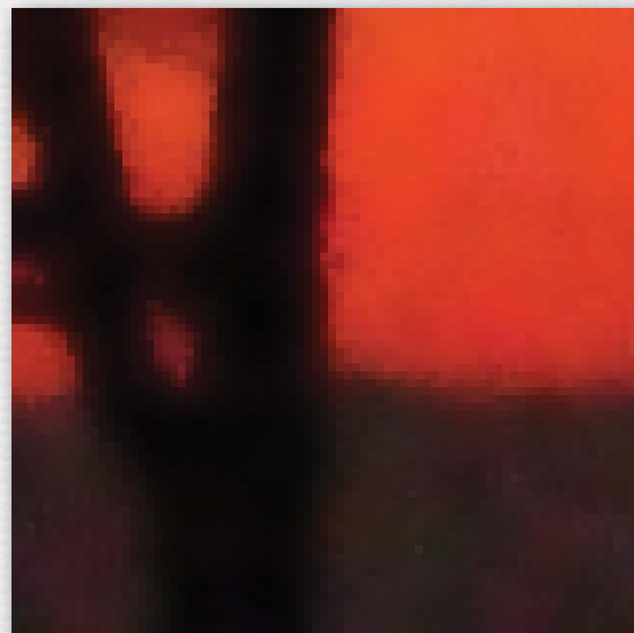
RAW (ISO 6400)



Gaussian blur, radius = 1.3



Canon denoising



bilateral filtering

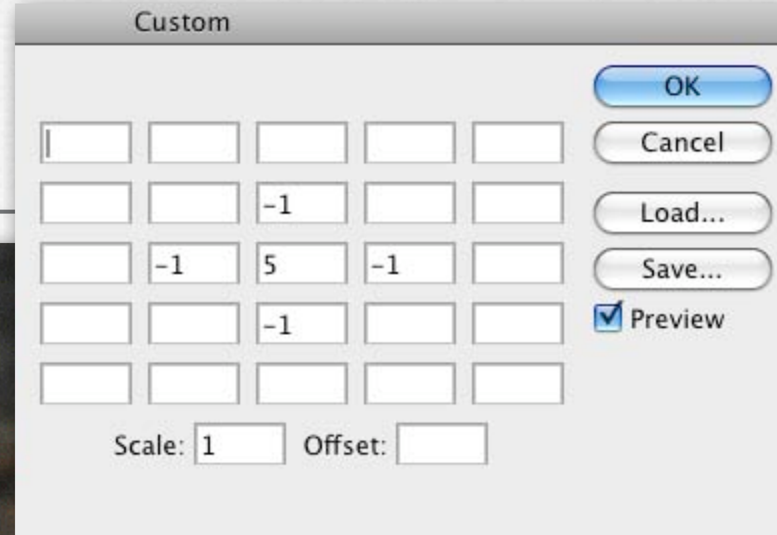
- can be applied more (or less) strongly to chrominance than luminance
- can be combined with demosaicing
- active area of research…

Sharpening

original

(Marc Levoy)

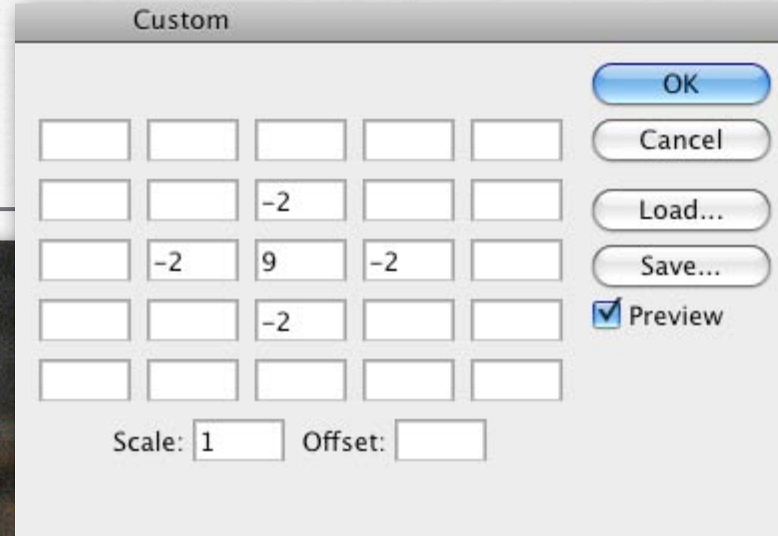
Sharpening



Filter/Other/Custom in Photoshop CS4

(Marc Levoy)

Sharpening



Filter/Other/Custom in Photoshop CS4

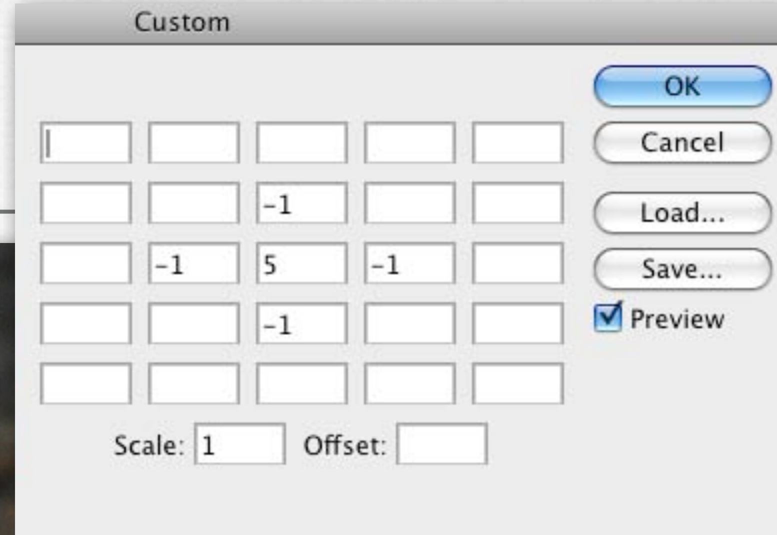
(Marc Levoy)

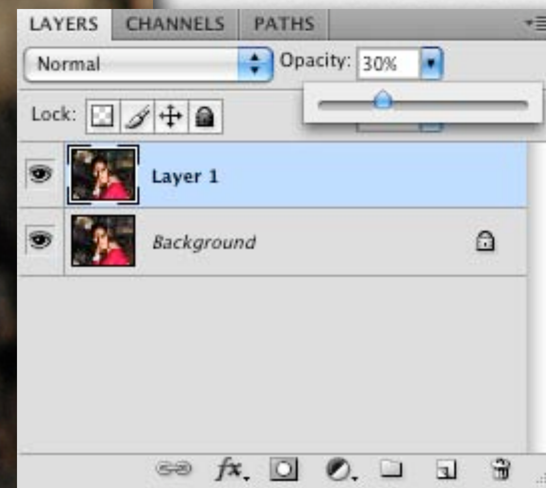
Sharpening

original

(Marc Levoy)

Sharpening

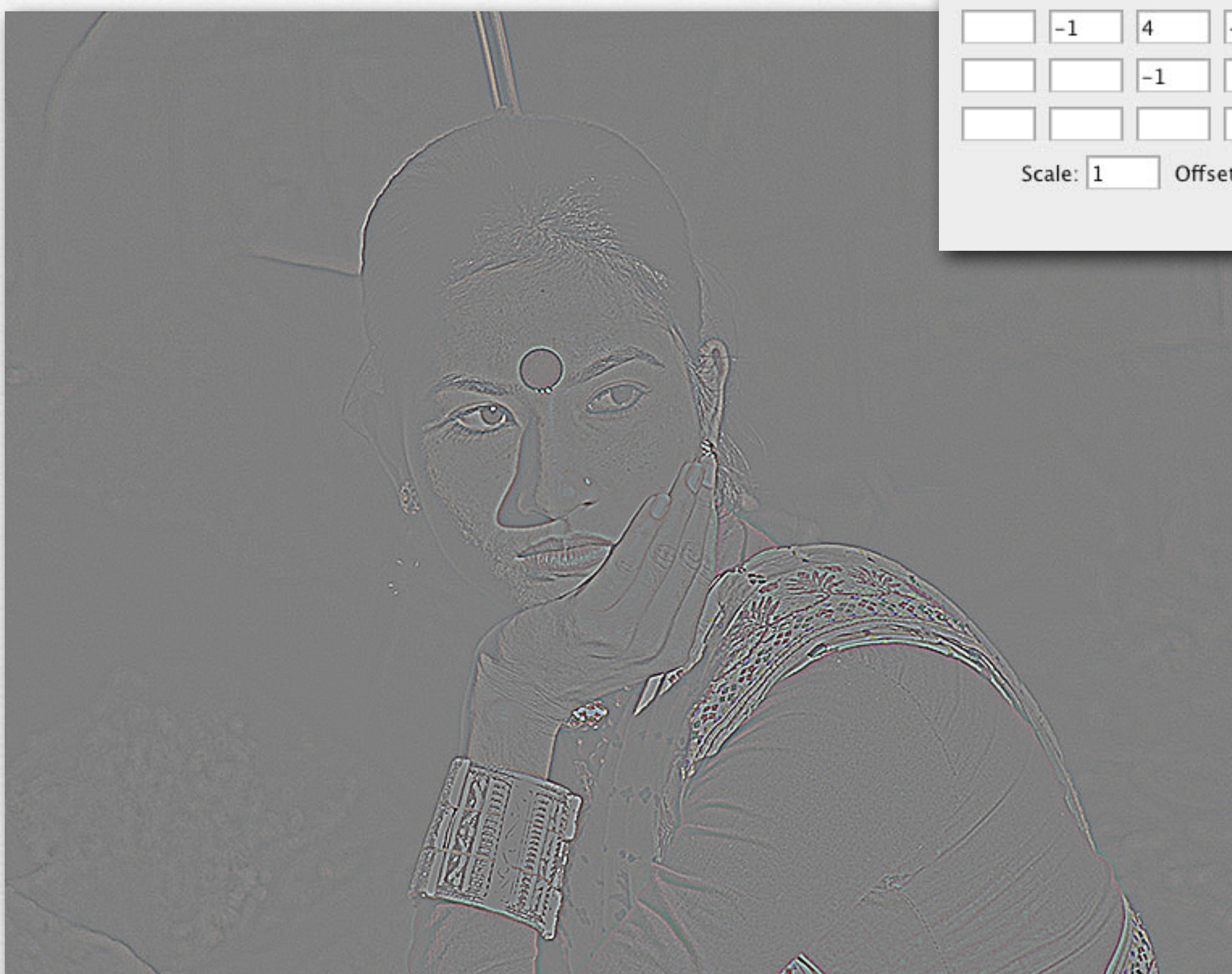


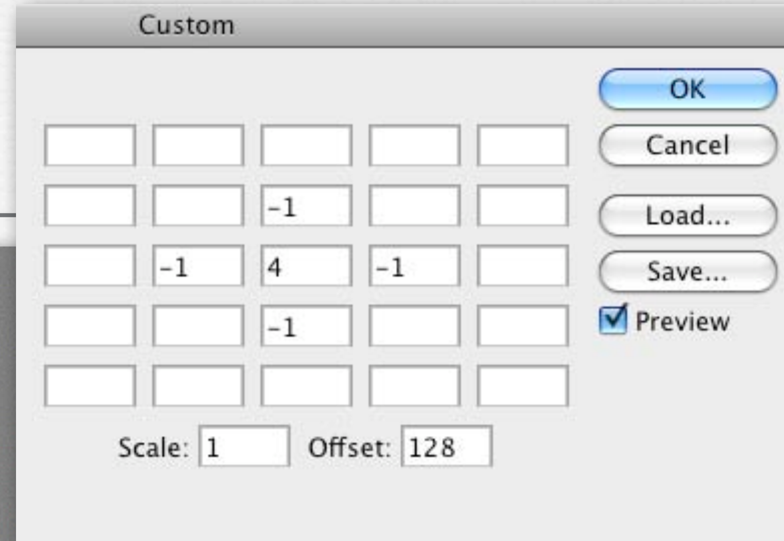


1^{st} layer is original,
2^{nd} layer is sharpened,
blend w. 30% opacity

(Marc Levoy)

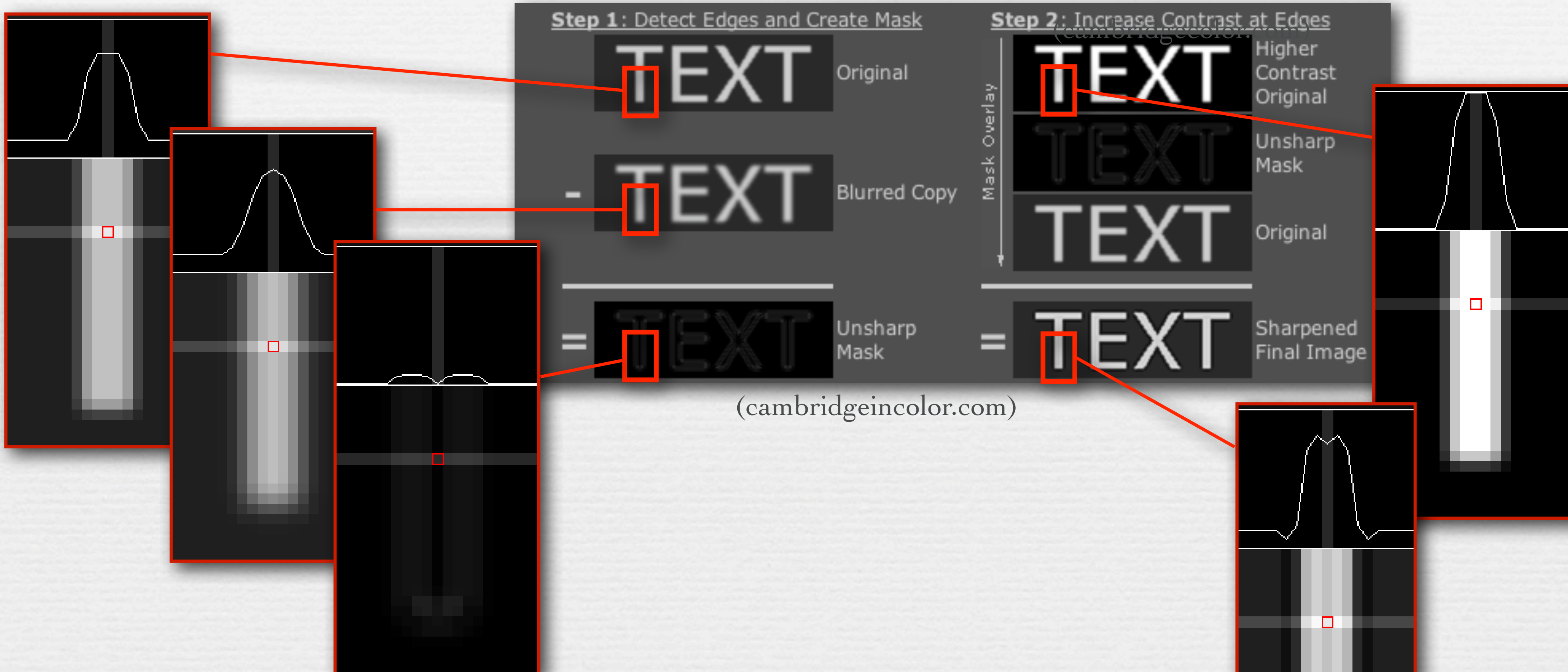
Sharpening

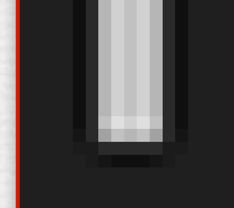




Filter/Other/Custom
in Photoshop CS4

Unsharp masking

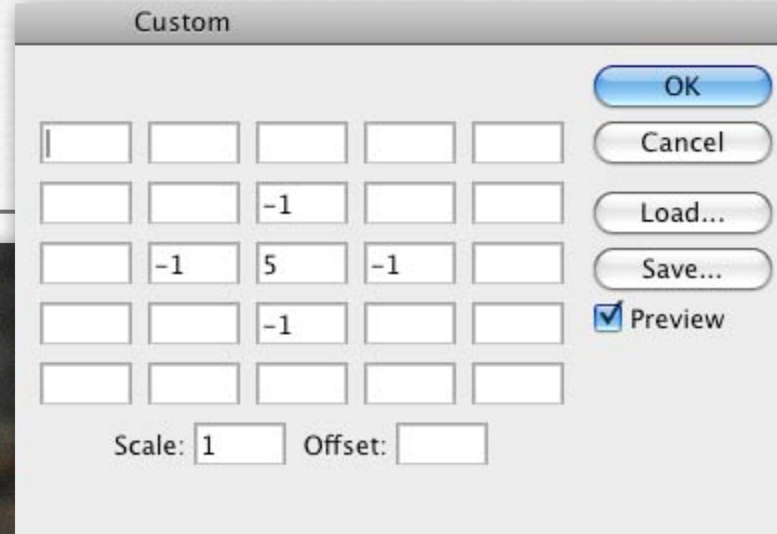




(cambridgeincolor.com)

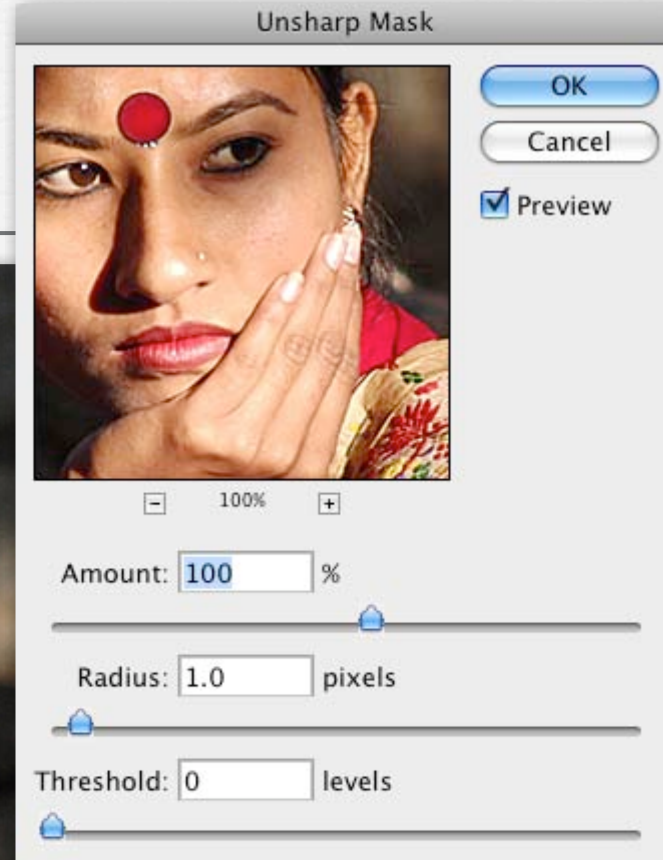
- blend between original and high-contrast version, controlled by a mask that represents scene edges
- dropping (thresholding) the darkest mask pixels avoids sharpening noise, and makes the filter non-linear

Sharpening



Filter/Other/Custom
in Photoshop CS4

Sharpening



Filter/Sharpen/
Unsharp Mask in CS4

Sharpening

original

Recap

- *bilateral filtering* reduces noise while preserving edges
  - replaces each pixel with a weighted sum of its neighbors, where the weight drops with increasing distance from the pixel in X and Y and with increasing intensity difference
- *unsharp masking* sharpens edges but doesn't sharpen noise
  - replaces each pixel with a weighted sum of the original and a contrast-enhanced version, using the latter along edges, where the edge mask is `threshold(original-blur(original))`
- both are non-linear filters
  - i.e. they are not convolutions by a spatially invariant filter kernel

Questions?

Camera pixel pipeline

sensor → analog to digital conversion (ADC) → processing: demosaicing, tone mapping & white balancing, denoising & sharpening, compression → storage

JPEG files

- Joint Photographic Experts Group
  - organized 1986, standard adopted 1994
- defines how an image is to be compressed (*codec*) into a stream of bytes, and the file format for storing that stream
  - file format is JFIF, but people use .JPG or .JPEG extensions
- good for compressing images of natural scenes
  - not so good for compressing drawings or graphics
- *lossy*, so loses quality <u>each</u> time you open → edit → save
  - especially if you crop or shift pixels (hence block boundaries)
  - for *lossless* compression, use PNG or TIFF

EXIF data

- Exchangeable Image File Format
  - created by Japan Electronic Industries Development Assoc.
- used by nearly every digital camera manufactured today
  - actually a file format
  - JPEG or TIFF file + metadata about the camera and shot
  - .JPG or .JPEG extension is used, not .EXIF

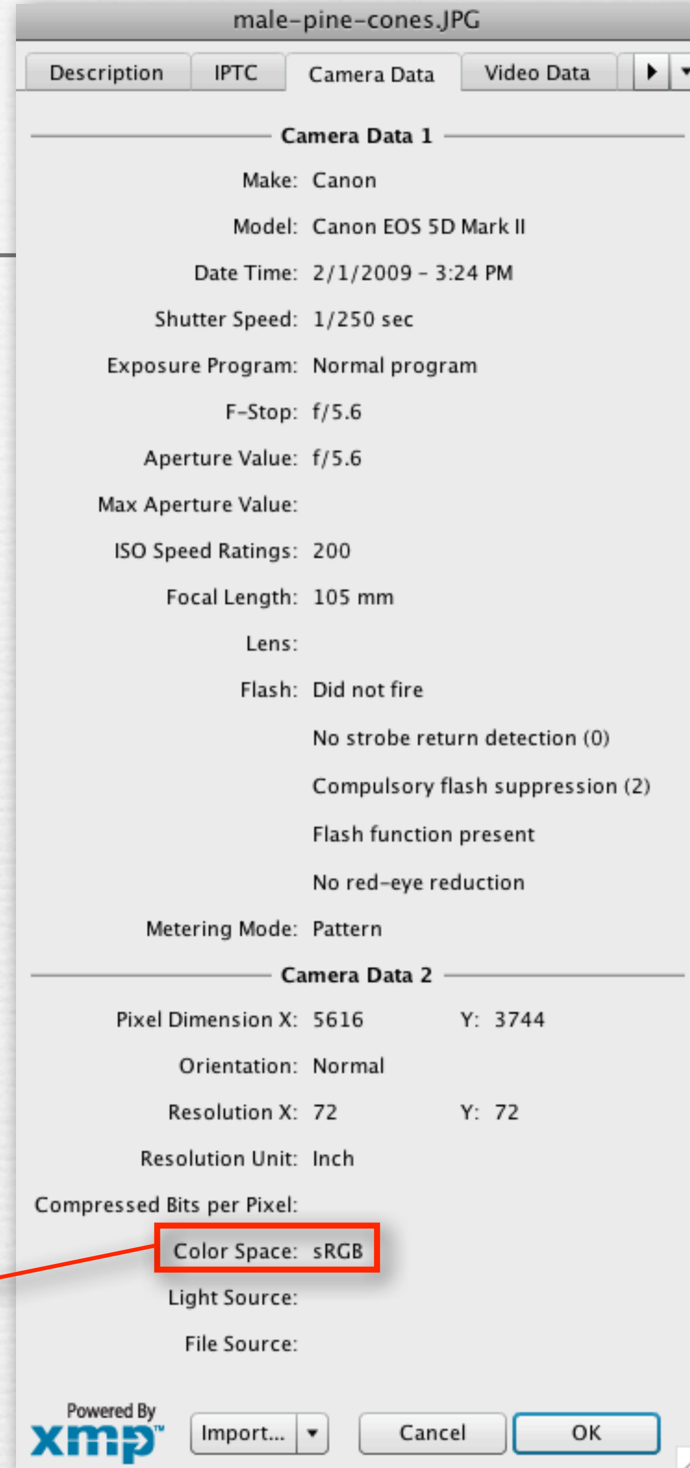
EXIF data

File/File Info in Photoshop CS4

(Marc Levoy)

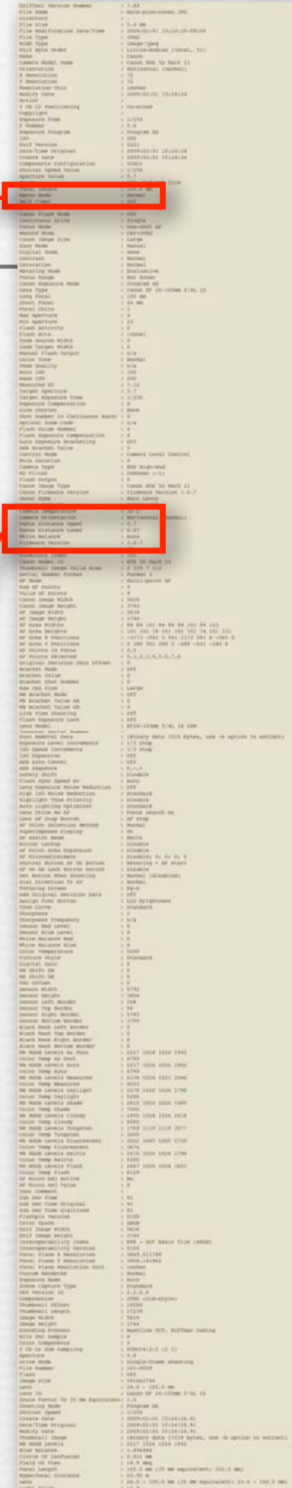
shot with Canon 5D Mark II

Color Space: sRGB



EXIF data

exiftool



```
Focal Length                    : 105.0 mm
```

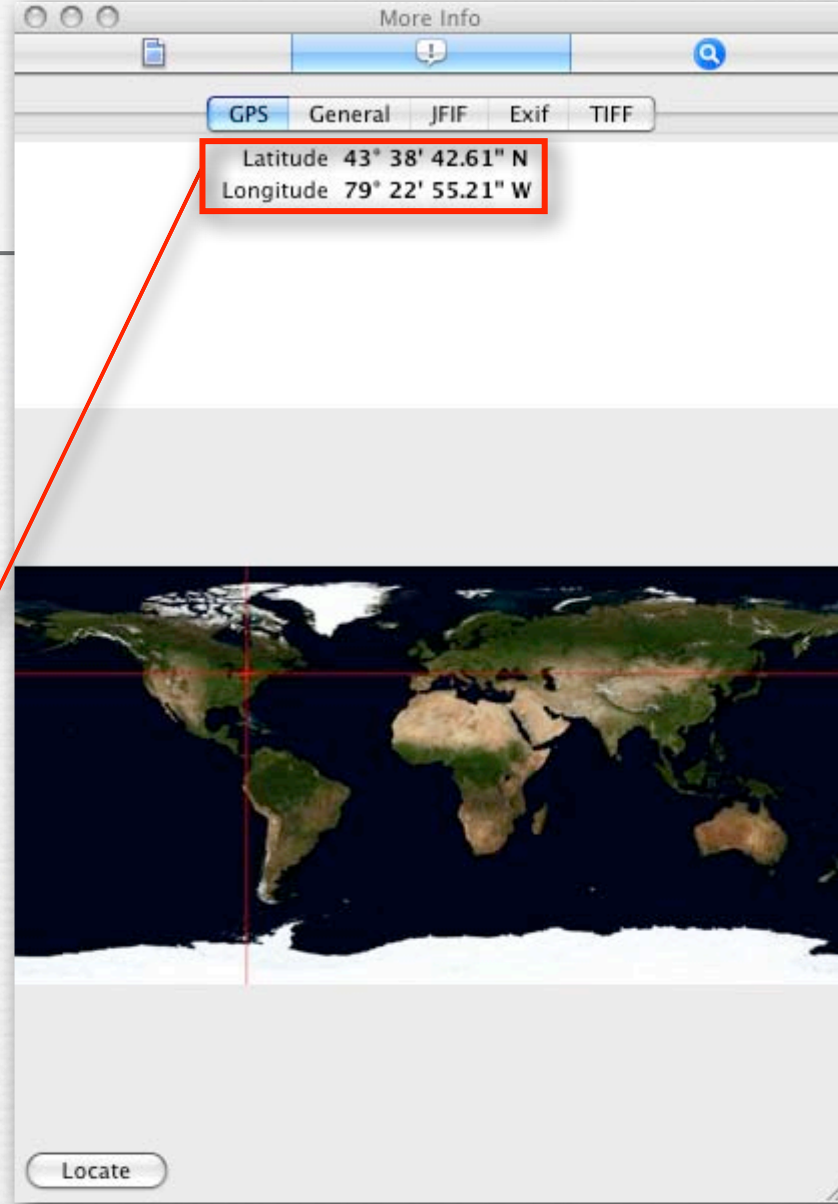
shot with Canon 5D Mark II

```
Focus Distance Upper            : 0.7
Focus Distance Lower            : 0.67
```

EXIF data

Mac Preview

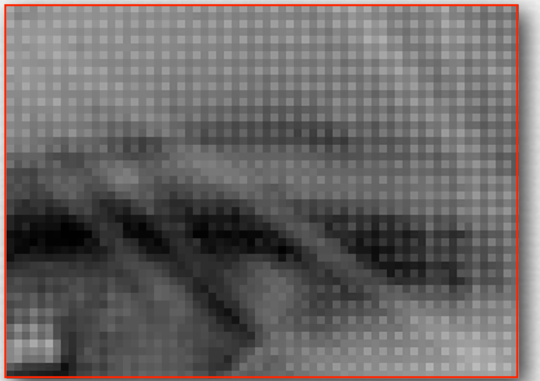
shot with iPhone 3G



Latitude 43° 38' 42.61" N
Longitude 79° 22' 55.21" W

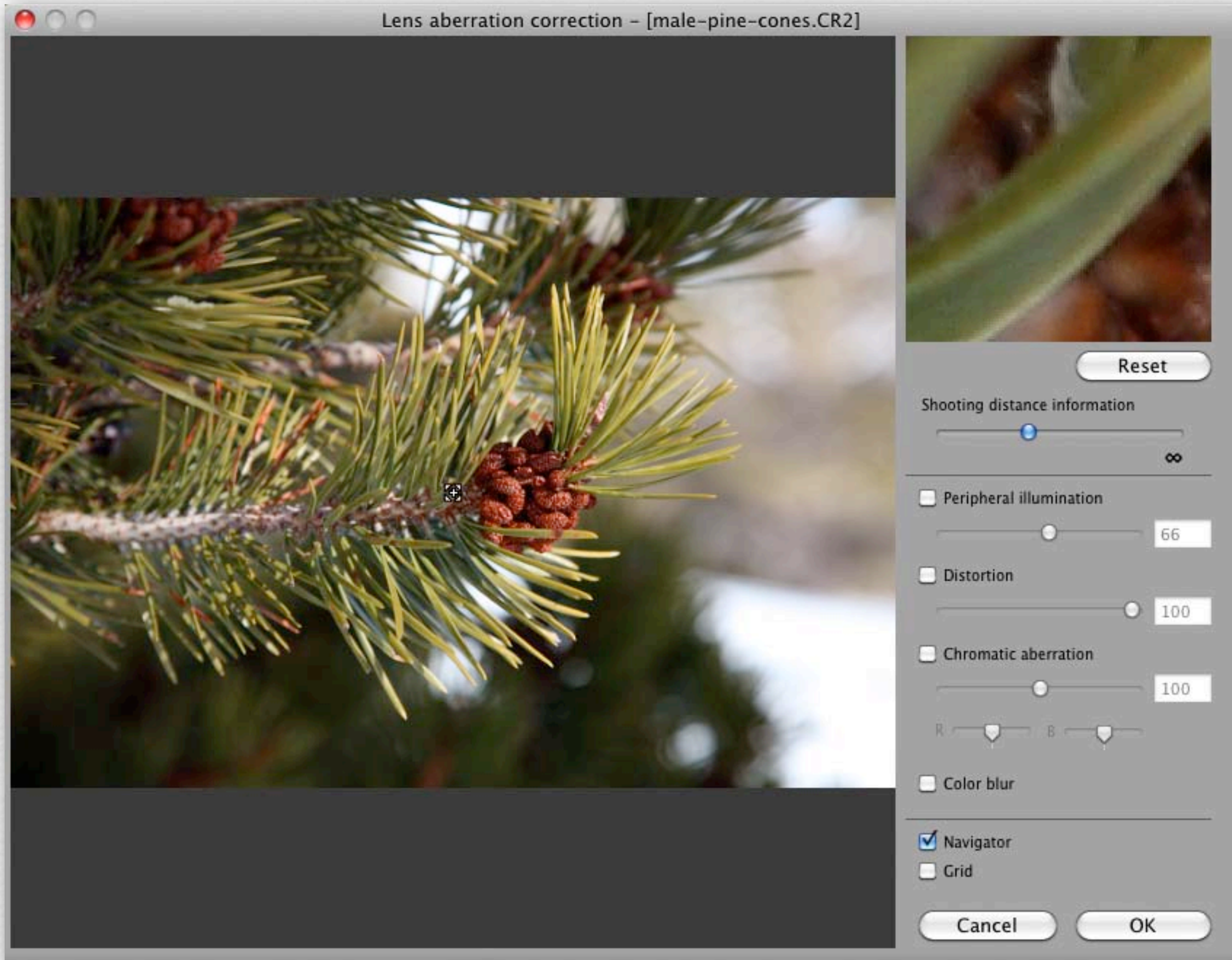
RAW files

- minimally processed images, not even demosaiced
- uncompressed or losslessly compressed
- includes metadata, possibly encrypted
- file format varies by manufacturer
- example extensions: .CR2, .NEF, .RW2, .ARW
- processed and converted to a JPEG file using
  - proprietary software (e.g. Canon Digital Photo Professional)
  - Photoshop or Lightroom (if they support your camera)
  - freeware programs like `dcraw`
  - or in your camera (every time you store a JPEG)
  - but their processing algorithms are all different!



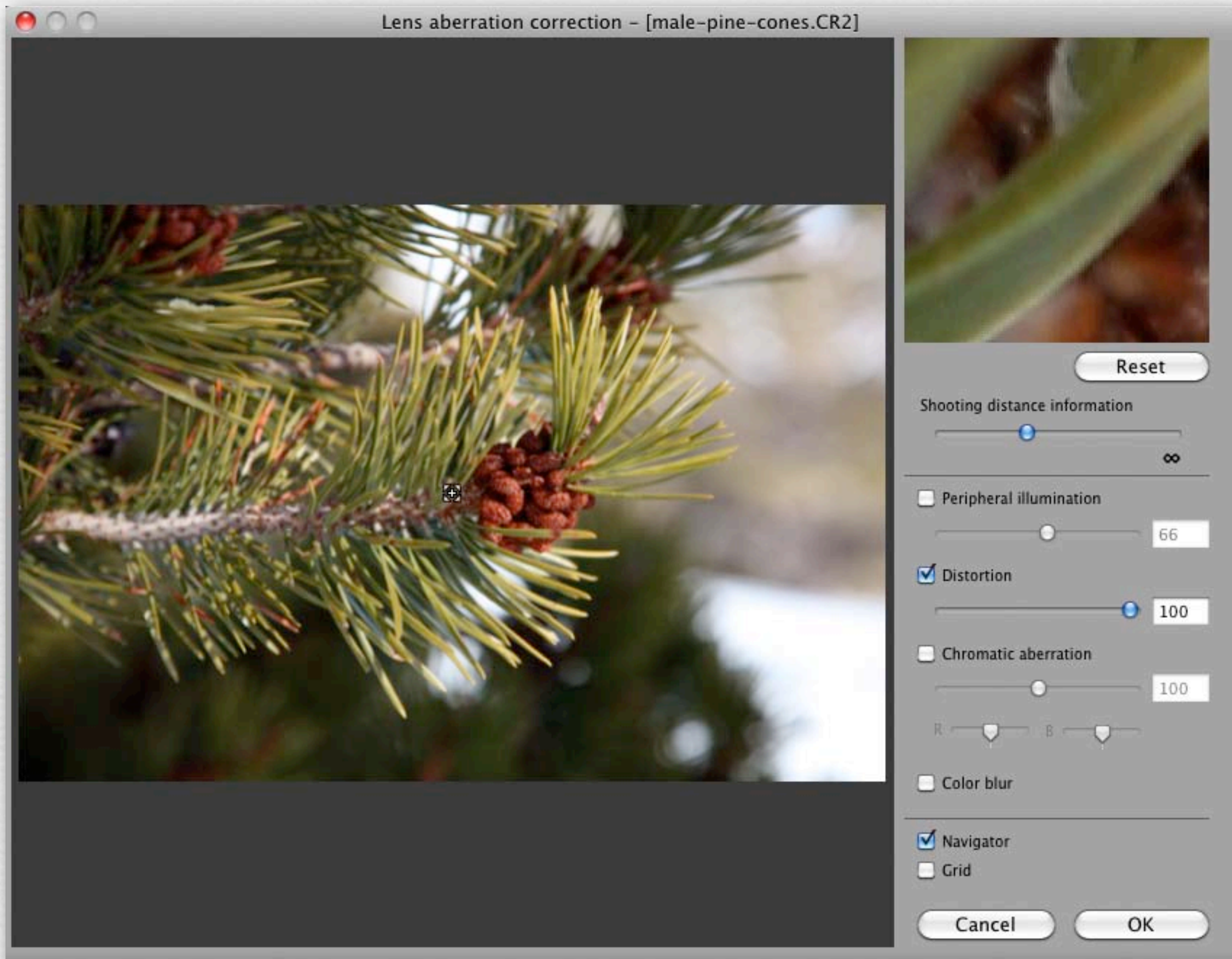
RAW file processor

Lens aberration correction panel in Canon Digital Photo Professional



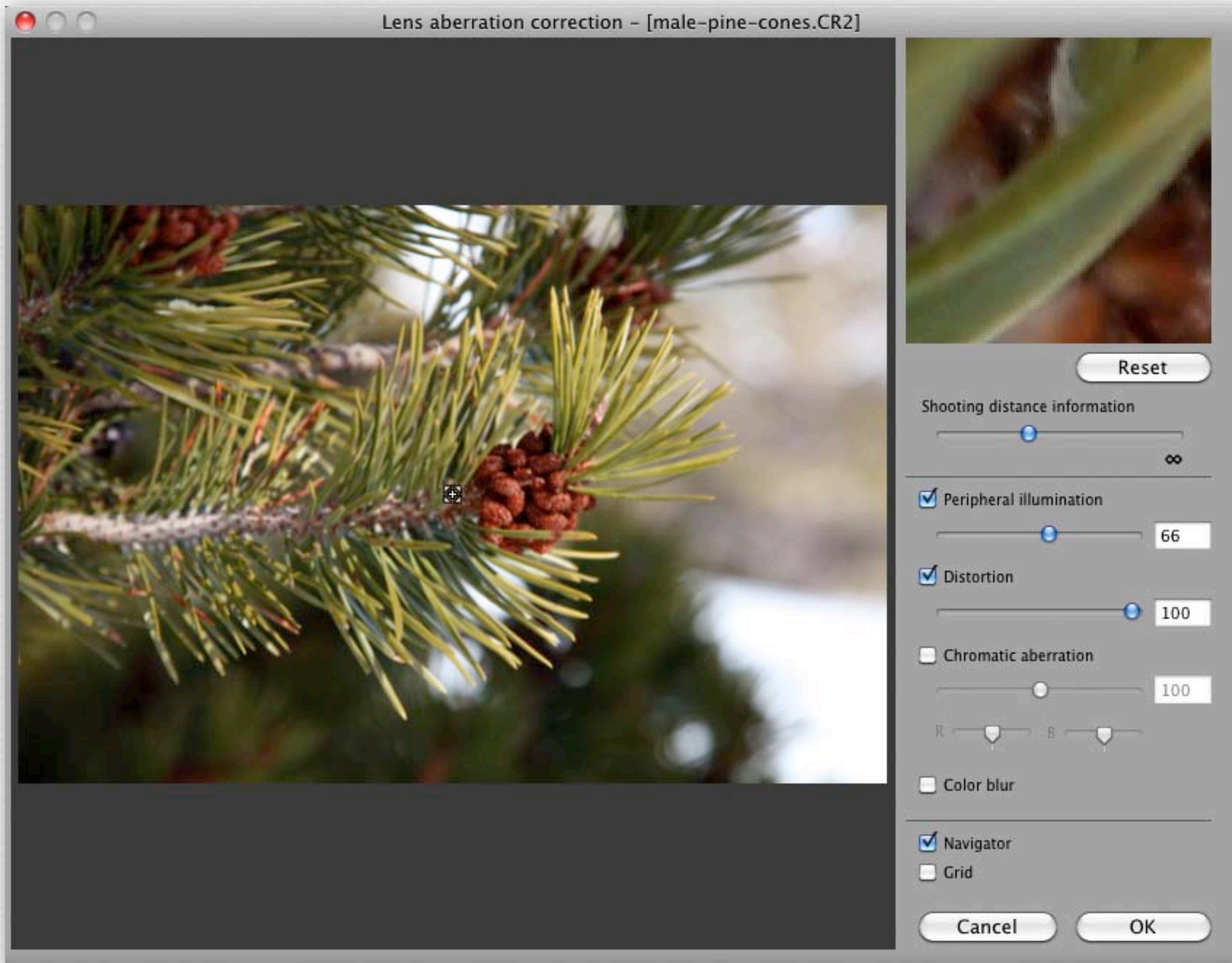
RAW file processor

Lens aberration correction panel in Canon Digital Photo Professional



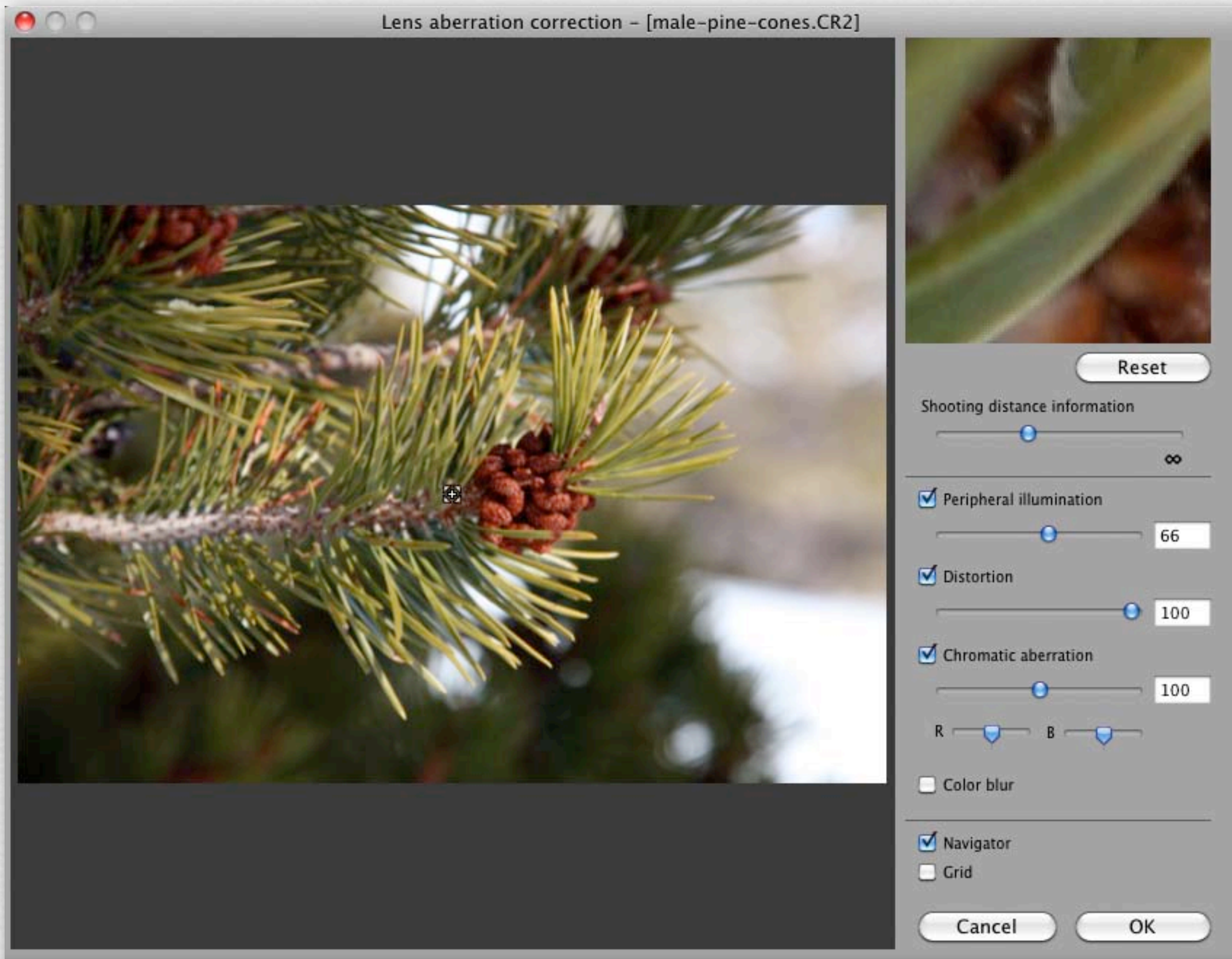
RAW file processor

Lens aberration correction panel in Canon Digital Photo Professional



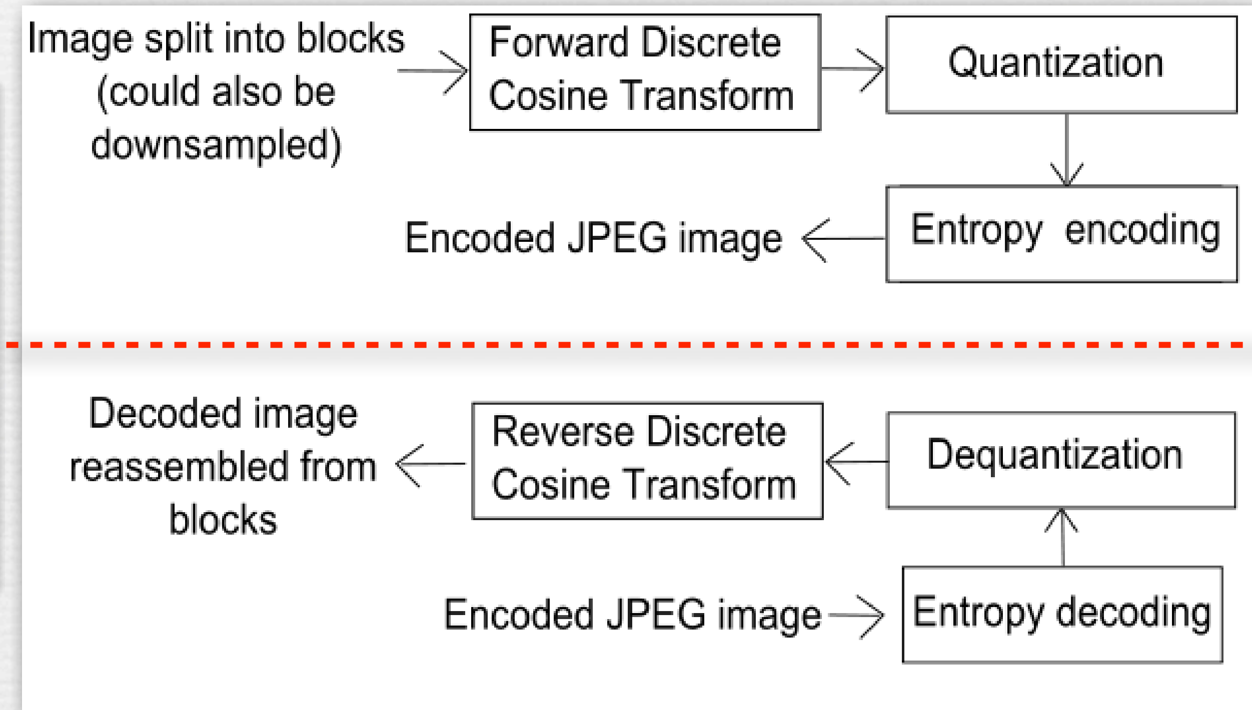
RAW file processor

Lens aberration correction panel in Canon Digital Photo Professional



JPEG image compression

- compression (in camera)



(wikipedia)

- decompression (for display)

- input is Y'CbCr
- Cb and Cr typically downsampled by 2× in X and Y
- each component is compressed separately

JPEG image compression

$$\begin{array}{c c}
x \longrightarrow & \\
\begin{bmatrix}
-76 & -73 & -67 & -62 & -58 & -67 & -64 & -55 \\
-65 & -69 & -73 & -38 & -19 & -43 & -59 & -56 \\
-66 & -69 & -60 & -15 & 16 & -24 & -62 & -55 \\
-65 & -70 & -57 & -6 & 26 & -22 & -58 & -59 \\
-61 & -67 & -60 & -24 & -2 & -40 & -60 & -58 \\
-49 & -63 & -68 & -58 & -51 & -60 & -70 & -53 \\
-43 & -57 & -64 & -69 & -73 & -67 & -63 & -45 \\
-41 & -49 & -59 & -60 & -63 & -52 & -50 & -34
\end{bmatrix} & \Big\downarrow y
\end{array}$$

zero-centered image

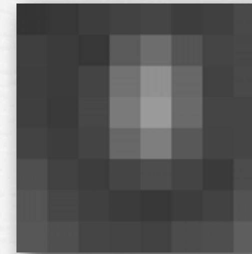
$$\begin{bmatrix}
52 & 55 & 61 & 66 & 70 & 61 & 64 & 73 \\
63 & 59 & 55 & 90 & 109 & 85 & 69 & 72 \\
62 & 59 & 68 & 113 & 144 & 104 & 66 & 73 \\
63 & 58 & 71 & 122 & 154 & 106 & 70 & 69 \\
67 & 61 & 68 & 104 & 126 & 88 & 68 & 70 \\
79 & 65 & 60 & 70 & 77 & 68 & 58 & 75 \\
85 & 71 & 64 & 59 & 55 & 61 & 65 & 83 \\
87 & 79 & 69 & 68 & 65 & 76 & 78 & 94
\end{bmatrix}$$

8-bit image

- step #1: split into 8×8 pixel blocks
- step #2: quantize to 8 bits / pixel
- step #3: convert to zero-centered

8×8 pixel block

JPEG image compression



$$\begin{array}{cc} \xrightarrow{x} & \\ \begin{bmatrix} -76 & -73 & -67 & -62 & -58 & -67 & -64 & -55 \\ -65 & -69 & -73 & -38 & -19 & -43 & -59 & -56 \\ -66 & -69 & -60 & -15 & 16 & -24 & -62 & -55 \\ -65 & -70 & -57 & -6 & 26 & -22 & -58 & -59 \\ -61 & -67 & -60 & -24 & -2 & -40 & -60 & -58 \\ -49 & -63 & -68 & -58 & -51 & -60 & -70 & -53 \\ -43 & -57 & -64 & -69 & -73 & -67 & -63 & -45 \\ -41 & -49 & -59 & -60 & -63 & -52 & -50 & -34 \end{bmatrix} & \Big\downarrow y \end{array} \longrightarrow \begin{array}{cc} \xrightarrow{u} & \\ \begin{bmatrix} -415 & -30 & \boxed{-61} & 27 & 56 & -20 & -2 & 0 \\ 4 & -22 & -61 & 10 & 13 & -7 & -9 & 5 \\ -47 & 7 & 77 & -25 & -29 & 10 & 5 & -6 \\ -49 & 12 & 34 & -15 & -10 & 6 & 2 & 2 \\ 12 & -7 & -13 & -4 & -2 & 2 & -3 & 3 \\ -8 & 3 & 2 & -6 & -2 & 1 & 4 & 2 \\ -1 & 0 & 0 & -2 & -1 & -3 & 4 & -1 \\ 0 & 0 & -1 & -4 & -1 & 0 & 1 & 2 \end{bmatrix} & \Big\downarrow v \end{array}$$

zero-centered image

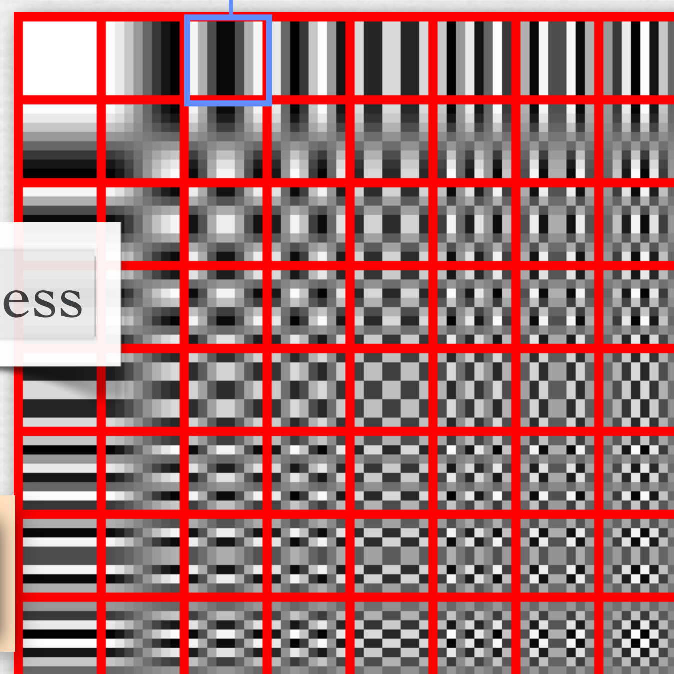
discrete cosine transform (DCT)

- ✦ any 8×8 pixel zero-centered image can be represented by a weighted sum of the 64 8×8 pixel *basis functions* shown at right

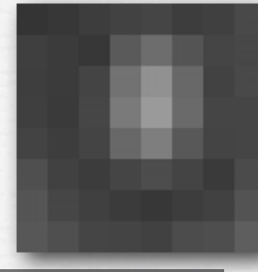
- ✦ step #4: compute the weighting for each basis function using:

lossless

$$G_{u,v} = \alpha(u)\alpha(v) \sum_{x=0}^{7} \sum_{y=0}^{7} g_{x,y} \cos\left[\frac{\pi}{8}\left(x+\frac{1}{2}\right)u\right] \cos\left[\frac{\pi}{8}\left(y+\frac{1}{2}\right)v\right]$$



JPEG image compression



$$\begin{pmatrix}\begin{bmatrix} 16 & 11 & \boxed{10} & 16 & 24 & 40 & 51 & 61 \\ 12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\ 14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\ 14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\ 18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\ 24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\ 49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\ 72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \end{bmatrix}\end{pmatrix}$$

bin size for each coefficient

$$\begin{array}{cc} \overset{u}{\longrightarrow} & \\ \begin{bmatrix} -415 & -30 & \boxed{-61} & 27 & 56 & -20 & -2 & 0 \\ 4 & -22 & -61 & 10 & 13 & -7 & -9 & 5 \\ -47 & 7 & 77 & -25 & -29 & 10 & 5 & -6 \\ -49 & 12 & 34 & -15 & -10 & 6 & 2 & 2 \\ 12 & -7 & -13 & -4 & -2 & 2 & -3 & 3 \\ -8 & 3 & 2 & -6 & -2 & 1 & 4 & 2 \\ -1 & 0 & 0 & -2 & -1 & -3 & 4 & -1 \\ 0 & 0 & -1 & -4 & -1 & 0 & 1 & 2 \end{bmatrix} & \Big\downarrow v \end{array}$$

discrete cosine transform (DCT)

- the human visual system is more sensitive to low & mid frequencies than very high frequencies, so quantize the latter coarsely

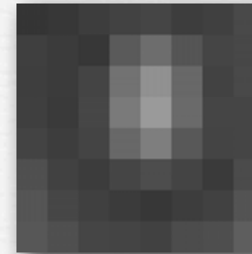
lossy

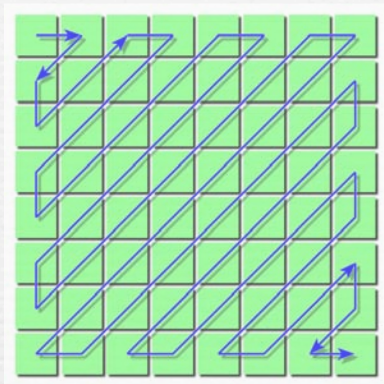
- <u>step #5</u>: quantize the DCT coefficients using bins whose size increases with frequency

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

quantized DCT coefficients

JPEG image compression





zig-zag ordering

-26					
-3	0				
-3	-2	-6			
2	-4	1	-4		
1	1	5	1	2	
-1	1	-1	2	0	0
0	0	0	-1	-1	EOB

- step #6: arrange the non-zero coefficients in zig-zag order

lossless

- step #7: use run-length encoding to remove repeated elements
- step #8: apply Huffman coding to reduce number of bits needed for each coefficient

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

quantized DCT coefficients

JPEG image compression

Q = 100

2.6 : 1

Q = 25

23 : 1

Q = 1

144 : 1

144:1 looks fine if it's displayed small enough

- not easily comparable to Photoshop quality numbers, since Adobe uses its own (proprietary) encoder

Recap

- RAW files is the direct output of the camera sensor
  - not demosaiced, 16 bits per pixel, losslessly compressed
  - contains metadata, usually proprietary
- JPEG files are a standard format for storing images
  - typically 8 bits per pixel, lossy compression
  - contains metadata in EXIF format
- JPEG's compression format is designed to discard details
  - images are partitioned into blocks of 8 × 8 pixels
  - each block is represented by a weighted sum of cosinusoids (DCT)
  - the coefficients of high frequency cosinusoids are heavily quantized, which reduces # of bits, hence file size, but also loses images quality
  - these coefficients are losslessly compressed using Huffman coding

Questions?

Slide credits

- Fredo Durand

- Wandell, B., *Foundations of Vision*, Sinauer, 1995.
- Tanser and Kleiner, *Gardner's Art Through the Ages* (10th ed.), Harcourt Brace, 1996.
- Rudman, T., *Photographer's Master Printing Course*, Focal Press, 1998.
- Adams, A., *The Print*, Little, Brown and Co., 1980.
- Goldstein, B.E., *Sensation and Perception,* Wadsworth, 1999.
- Wolfe, J.M., *Sensation and Perception,* Sinauer, 2006.