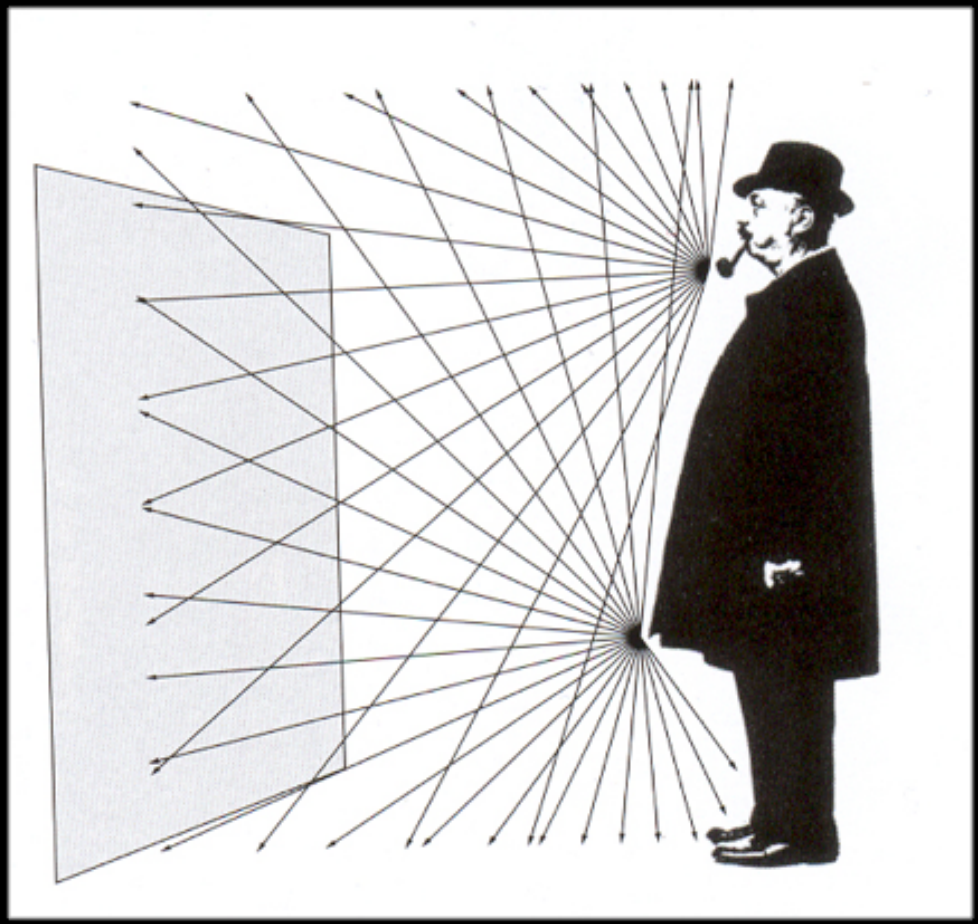
Camera Processing Pipeline

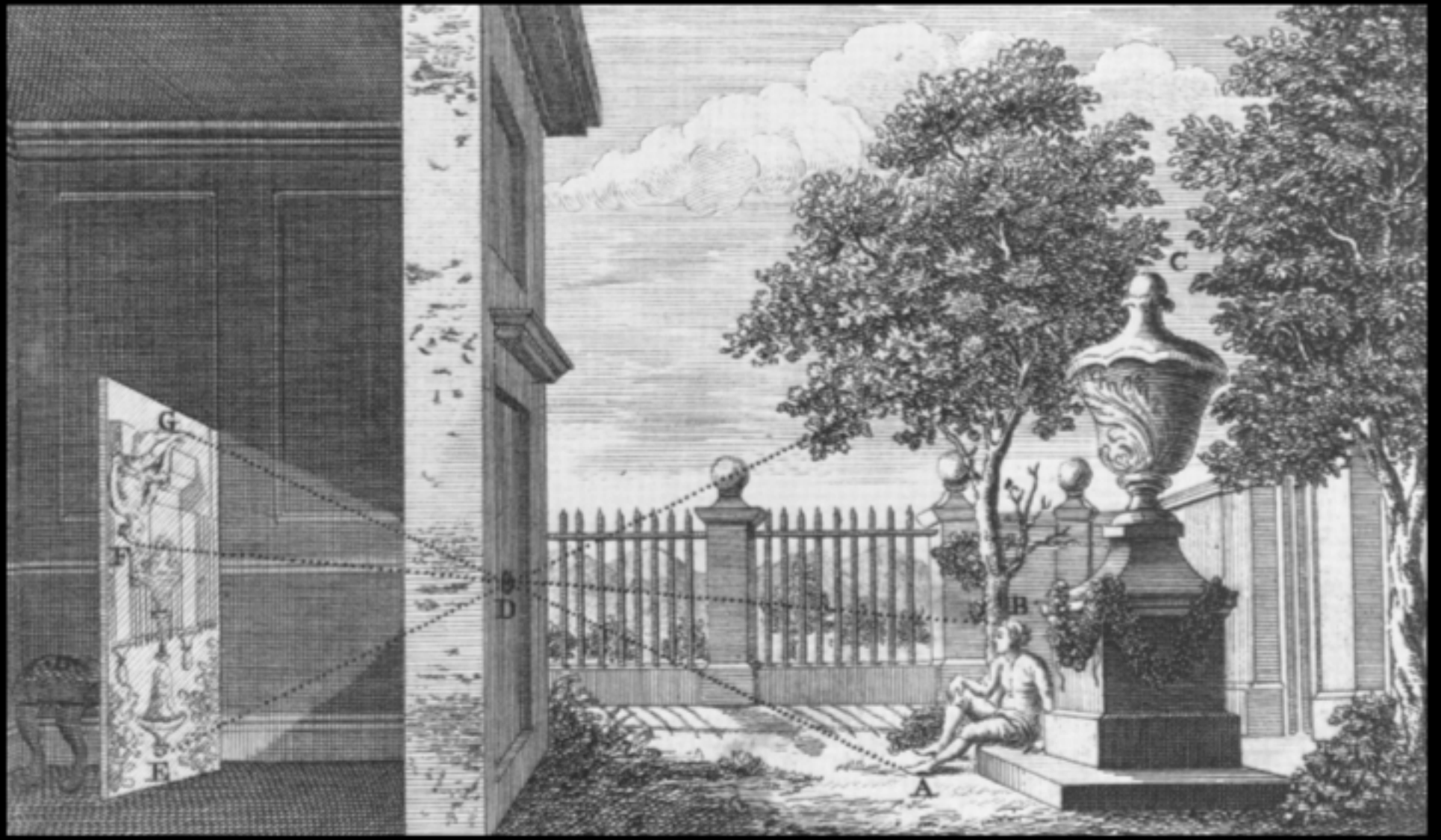
Kari Pulli
VP Computational Imaging
Light

Imaging without optics?

- Each point on sensor
  - would record the integral of light
  - arriving from every point on subject
- All sensor points would record similar colors



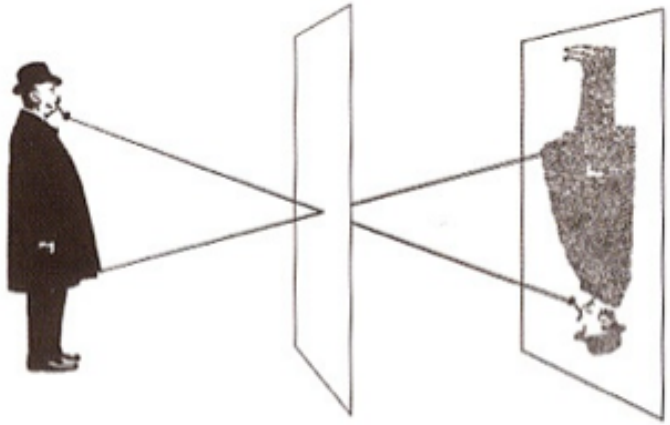
Pinhole camera (a.k.a. camera obscura)



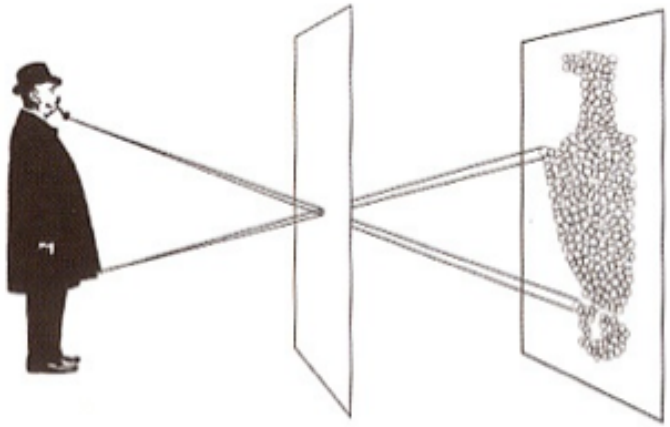
Linear perspective with viewpoint at pinhole

Effect of pinhole size

Photograph made with small pinhole

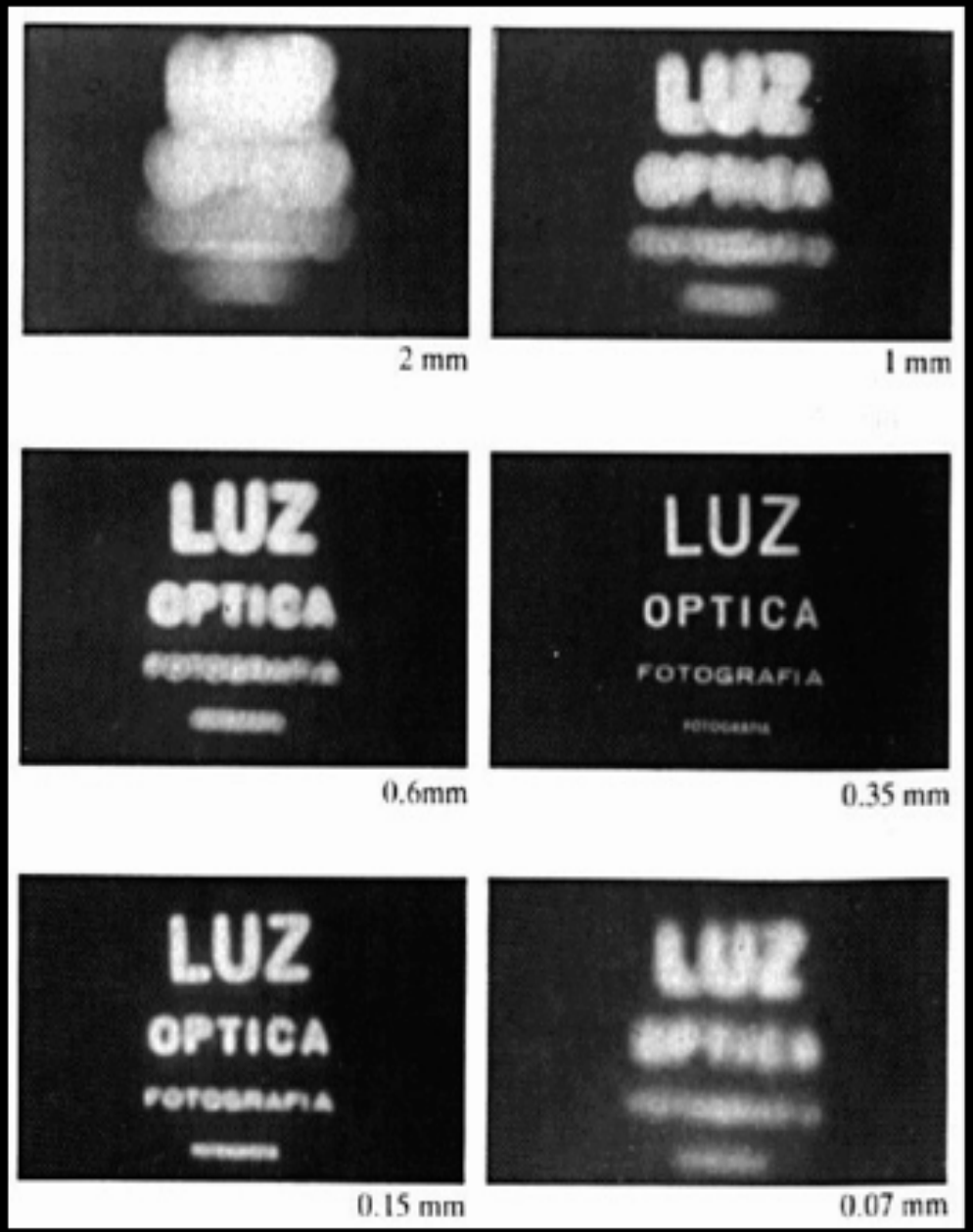


Photograph made with larger pinhole



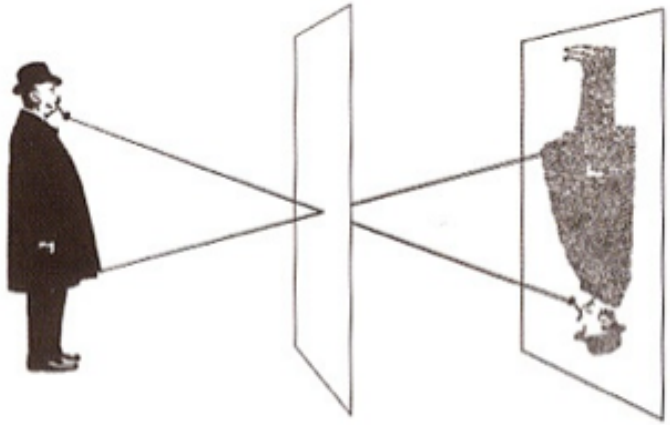
Stopping down the pinhole

- Large pinhole
  - geometric blur
- Optimal pinhole
  - too little light
- Small pinhole
  - diffraction blur

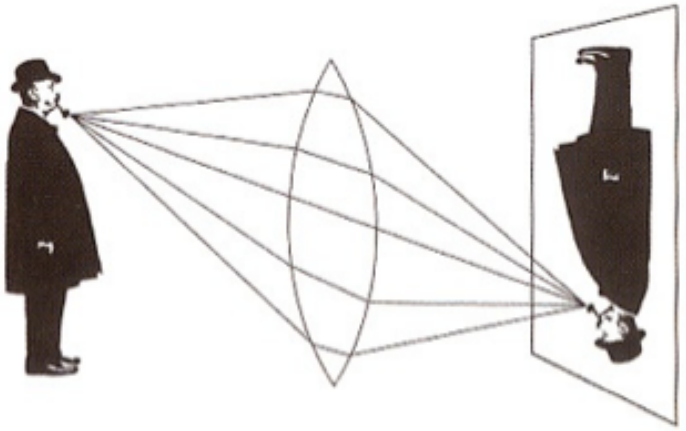


Add a lens to get more light

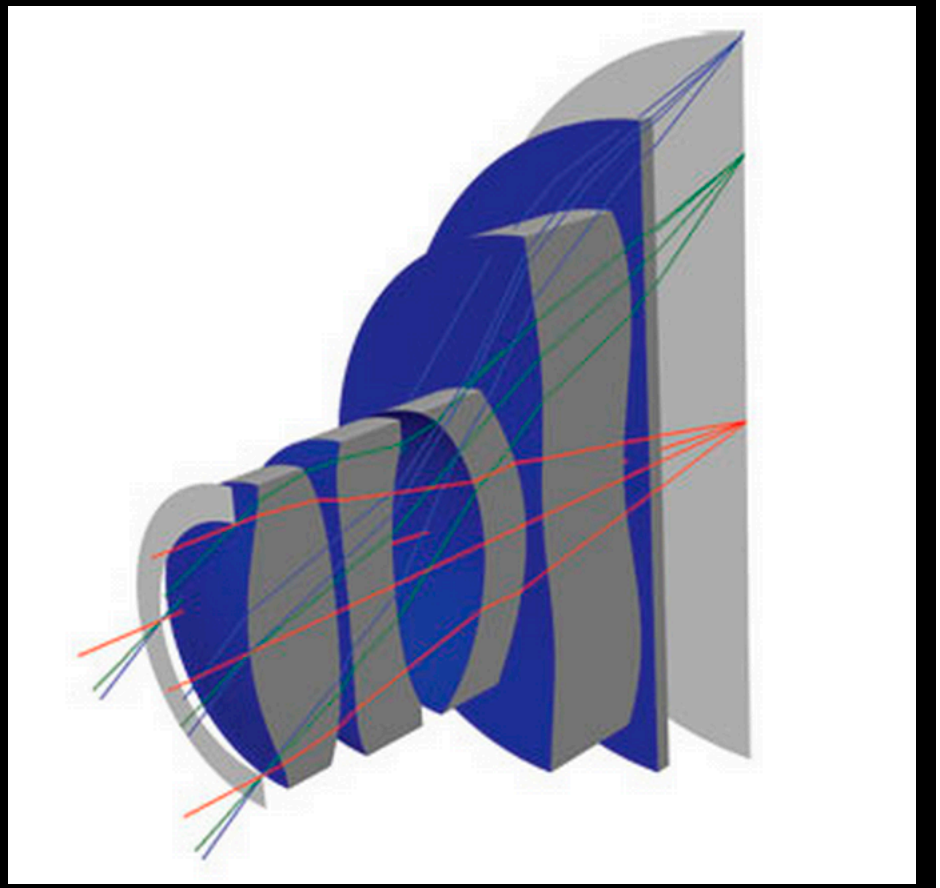
Photograph made with small pinhole

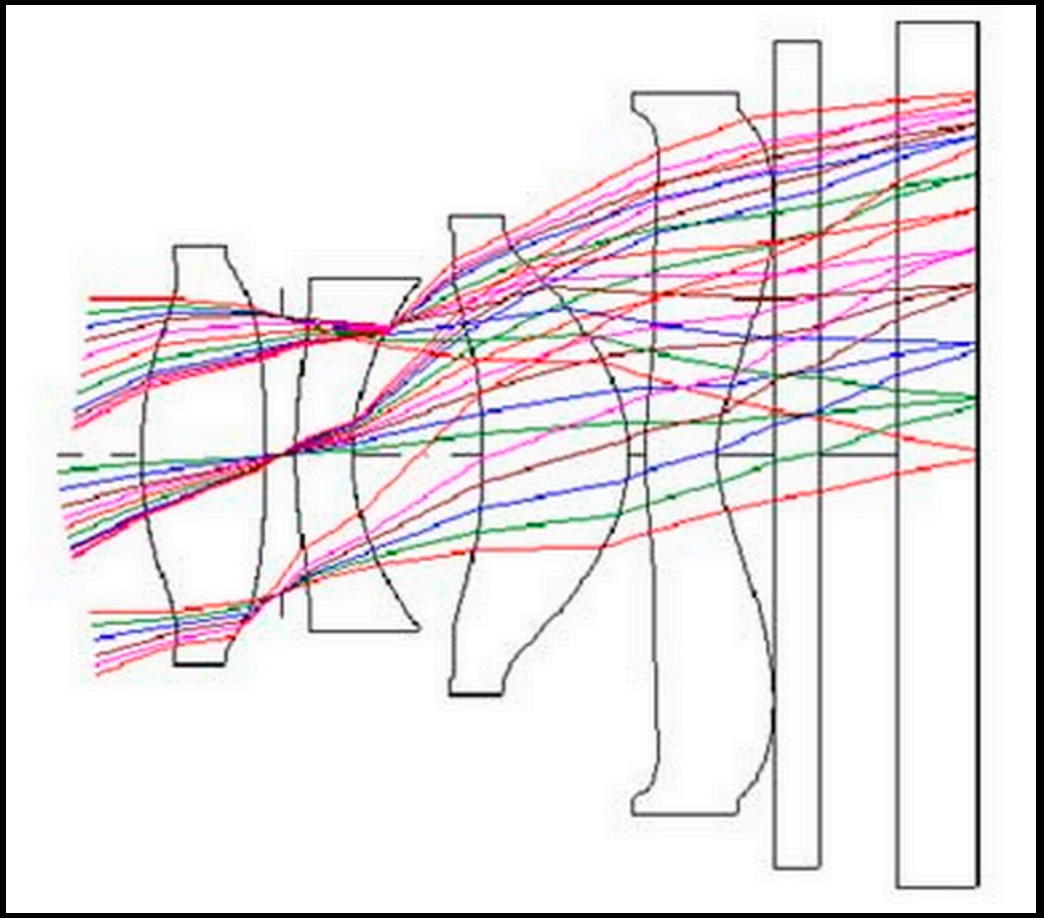


Photograph made with lens

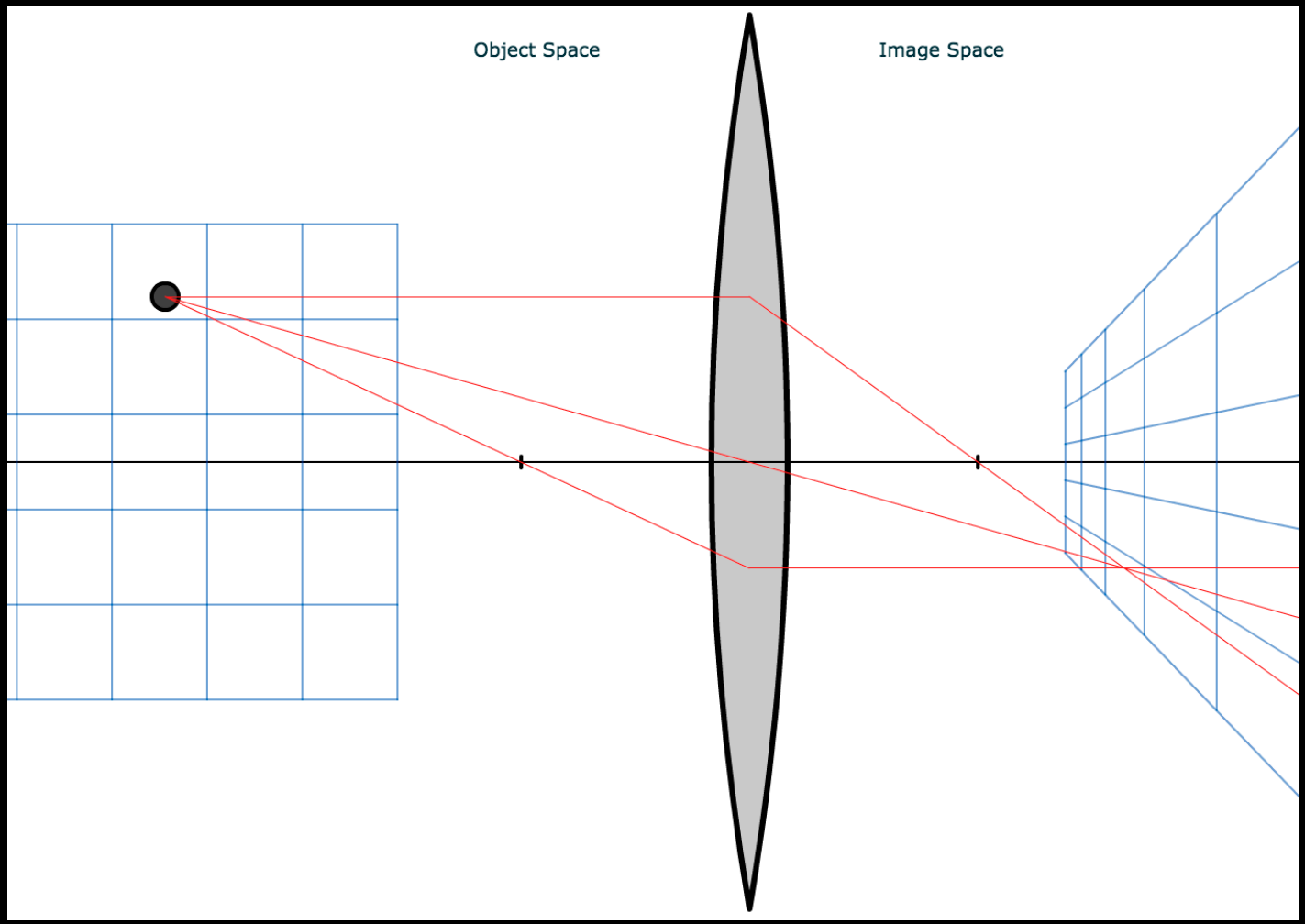


Real lenses are complex





Thin lens approximation: Gauss's ray diagram

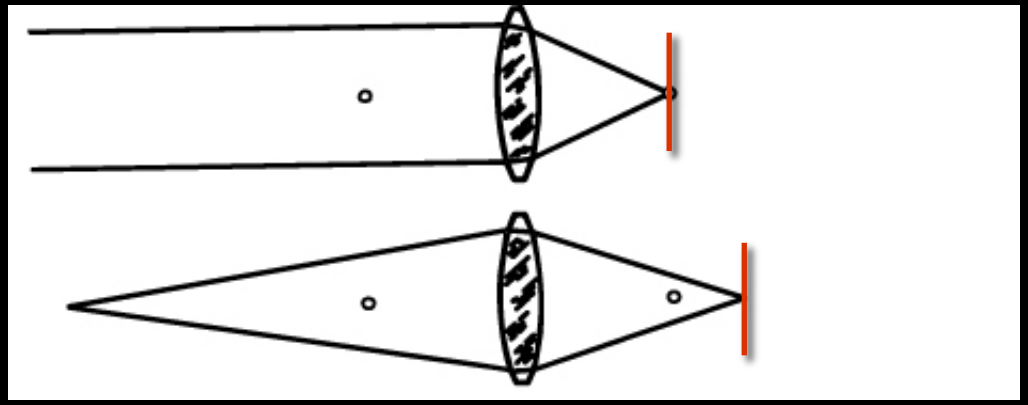


http://graphics.stanford.edu/courses/cs178/applets/thinlens.html

Changing the focus distance

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

- To focus on objects at different distances
  - move sensor relative to the lens



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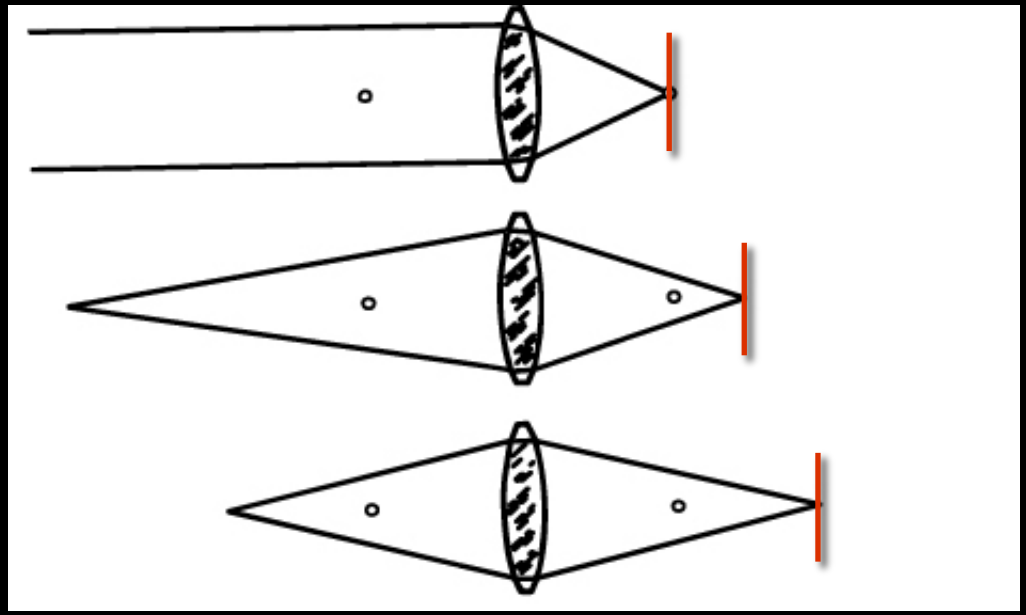


- At $s_o = s_i = 2f$ we get 1:1 imaging (macro) because

$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$

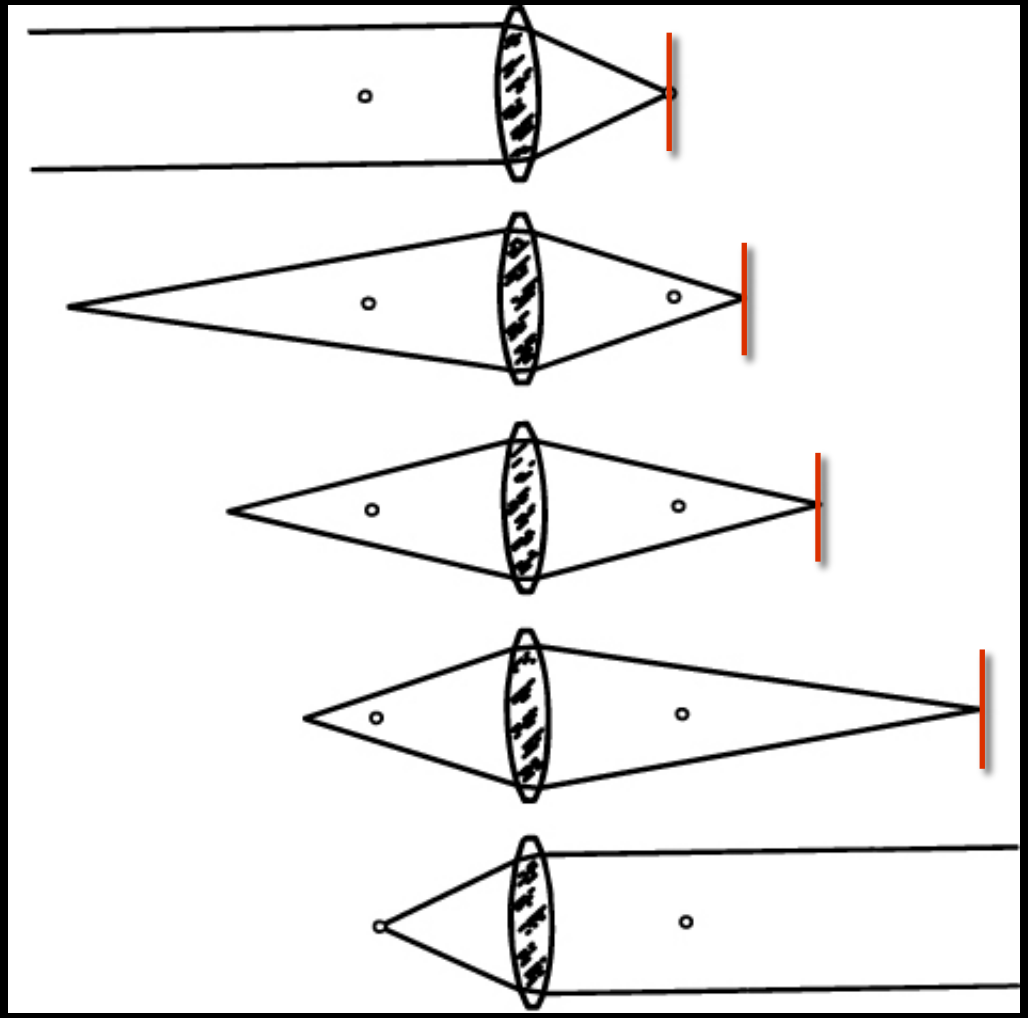
Changing the focus distance

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

- To focus on objects at different distances
  - move sensor relative to the lens
- At $s_o = s_i = 2f$ we get 1:1 imaging (macro) because

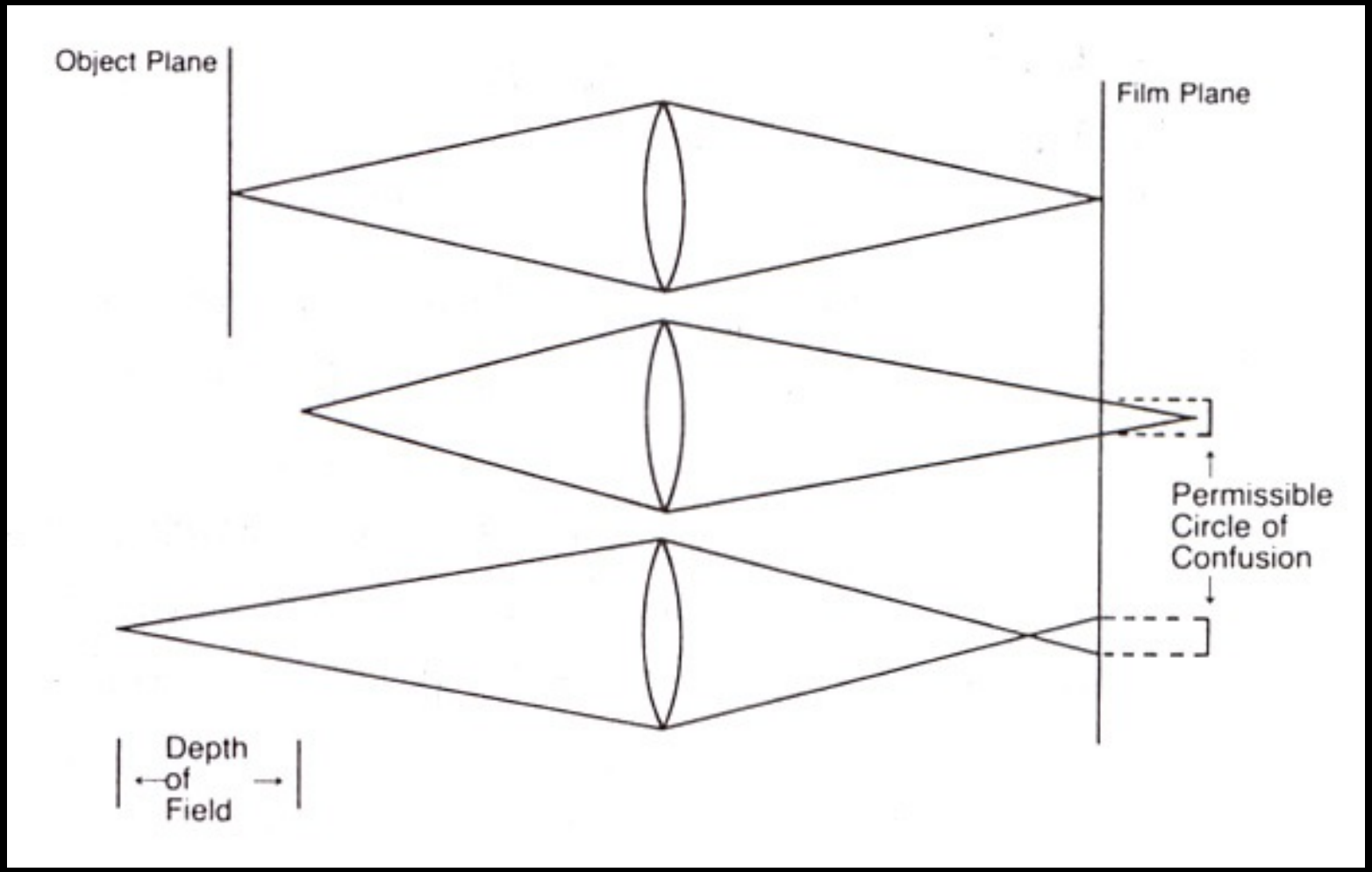
$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$

- Can't focus on objects closer to the lens than *f*

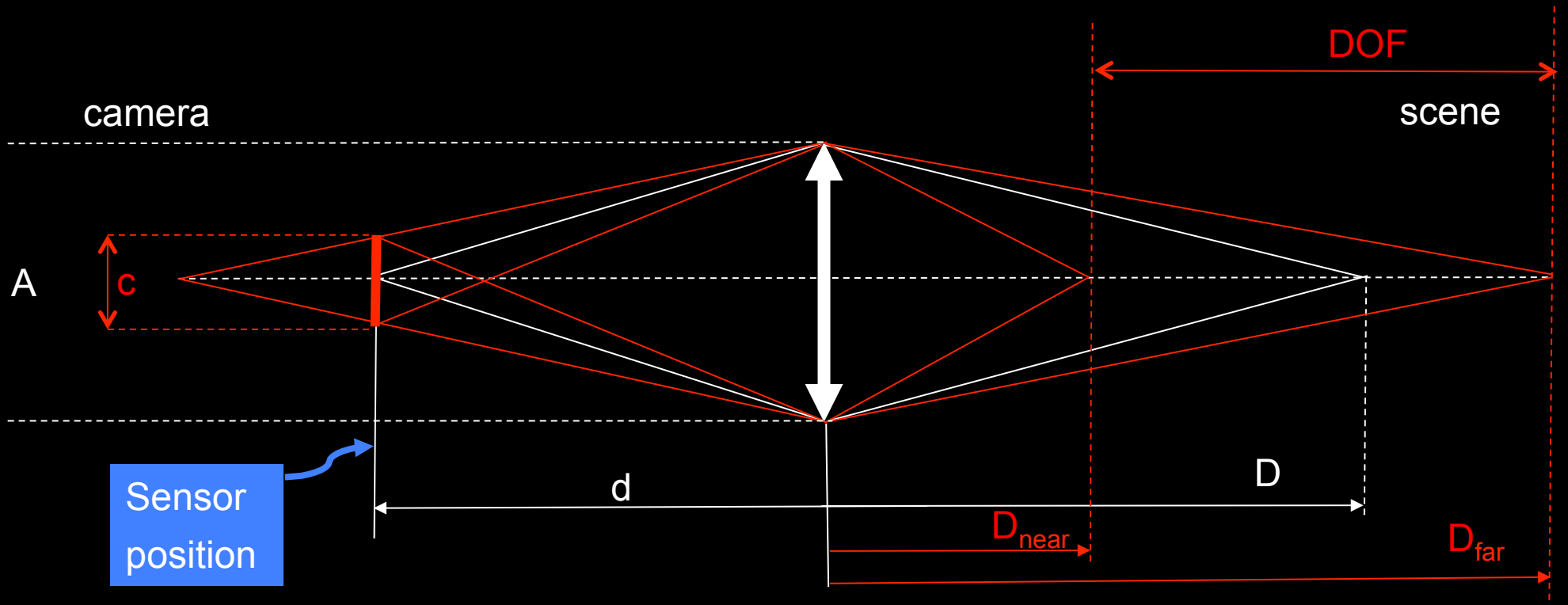


http://graphics.stanford.edu/courses/cs178/applets/gaussian.html

Circle of confusion



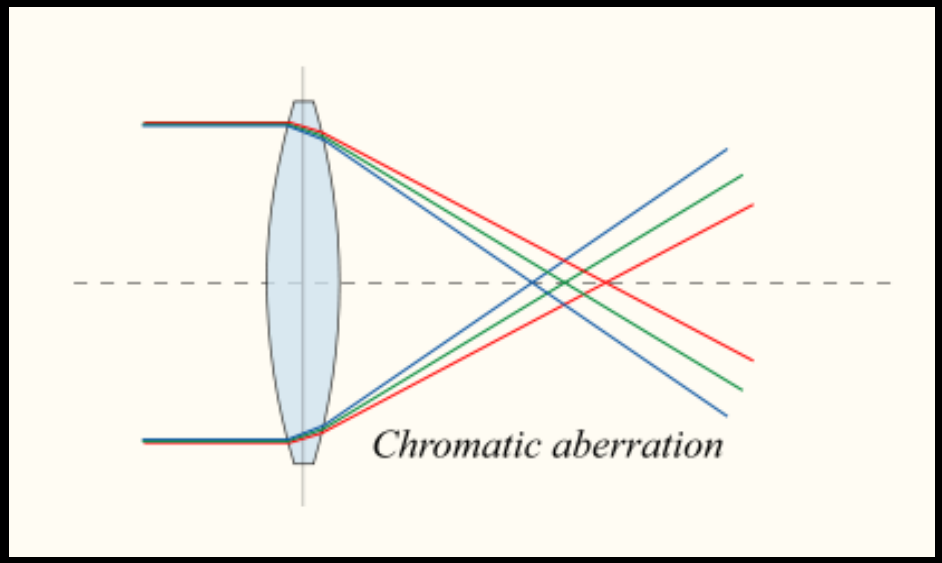
Focusing

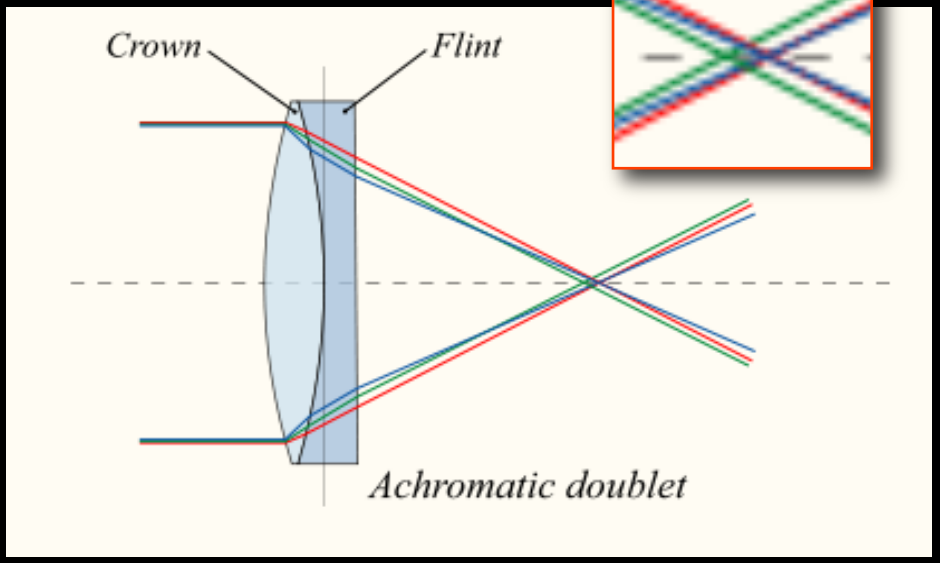


- Depth of field (DOF) = the range of distances that are in focus

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

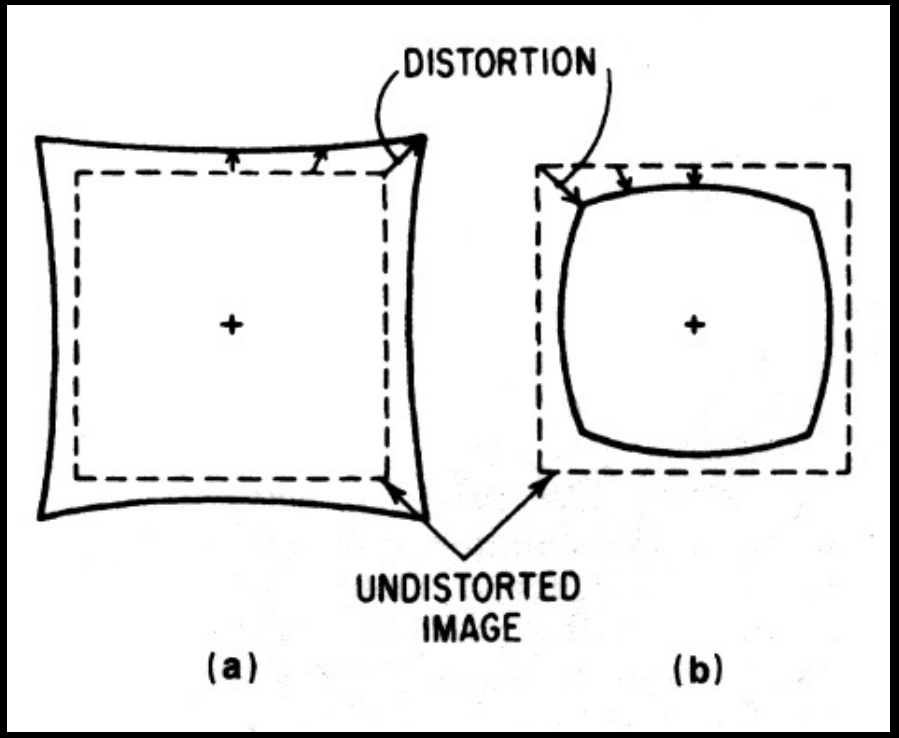
Chromatic aberration





- Different wavelengths refract at different rates
  - so have different focal lengths
- Correct with achromatic doublet
  - strong positive lens + weak negative lens
    = weak positive compound lens
  - align red and blue

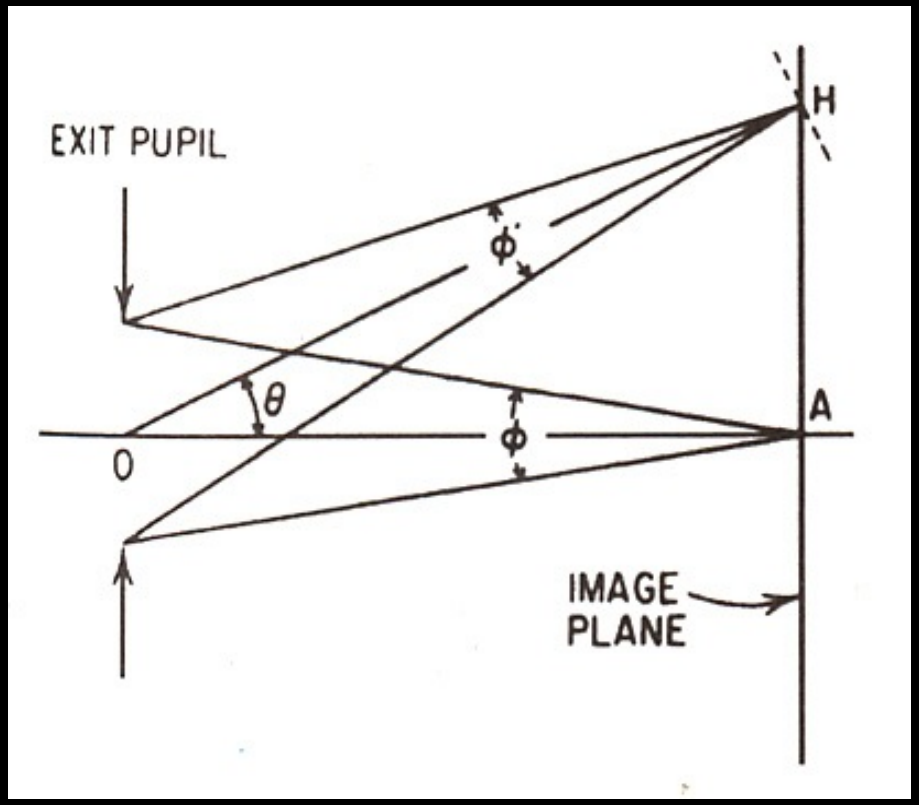
Lens distortion



- Radial change in magnification
  - (a) pincushion
  - (b) barrel distortion

Vignetting

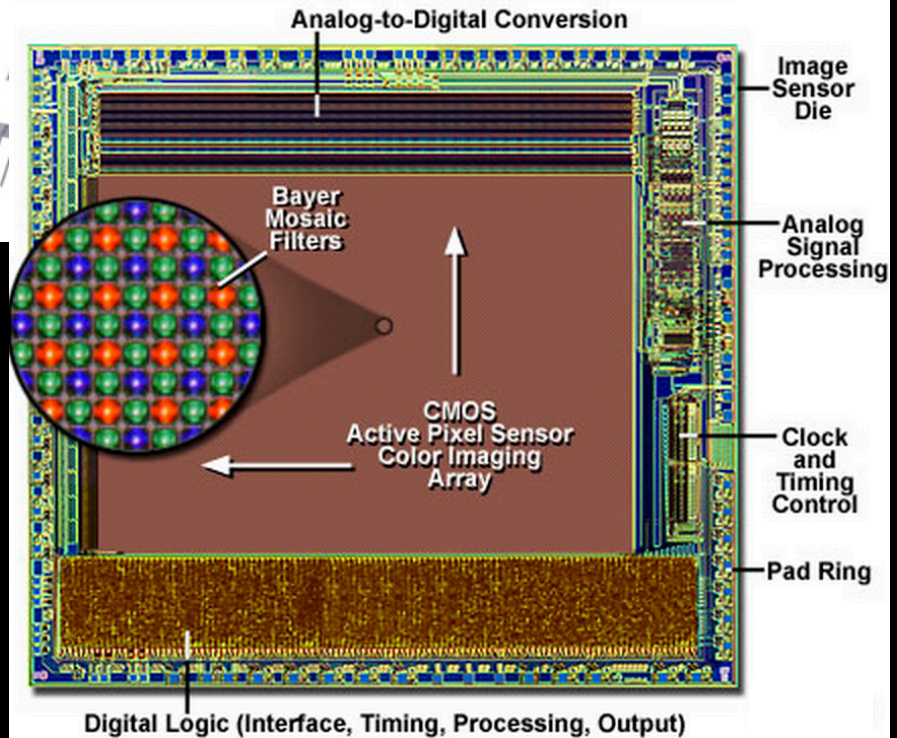
- Irradiance is proportional to
  - projected area of aperture as seen from pixel
  - projected area of pixel as seen from aperture
  - distance^2 from aperture to pixel
- Combining all these
  - each ~ a factor of cos θ
  - light drops as cos^4 θ

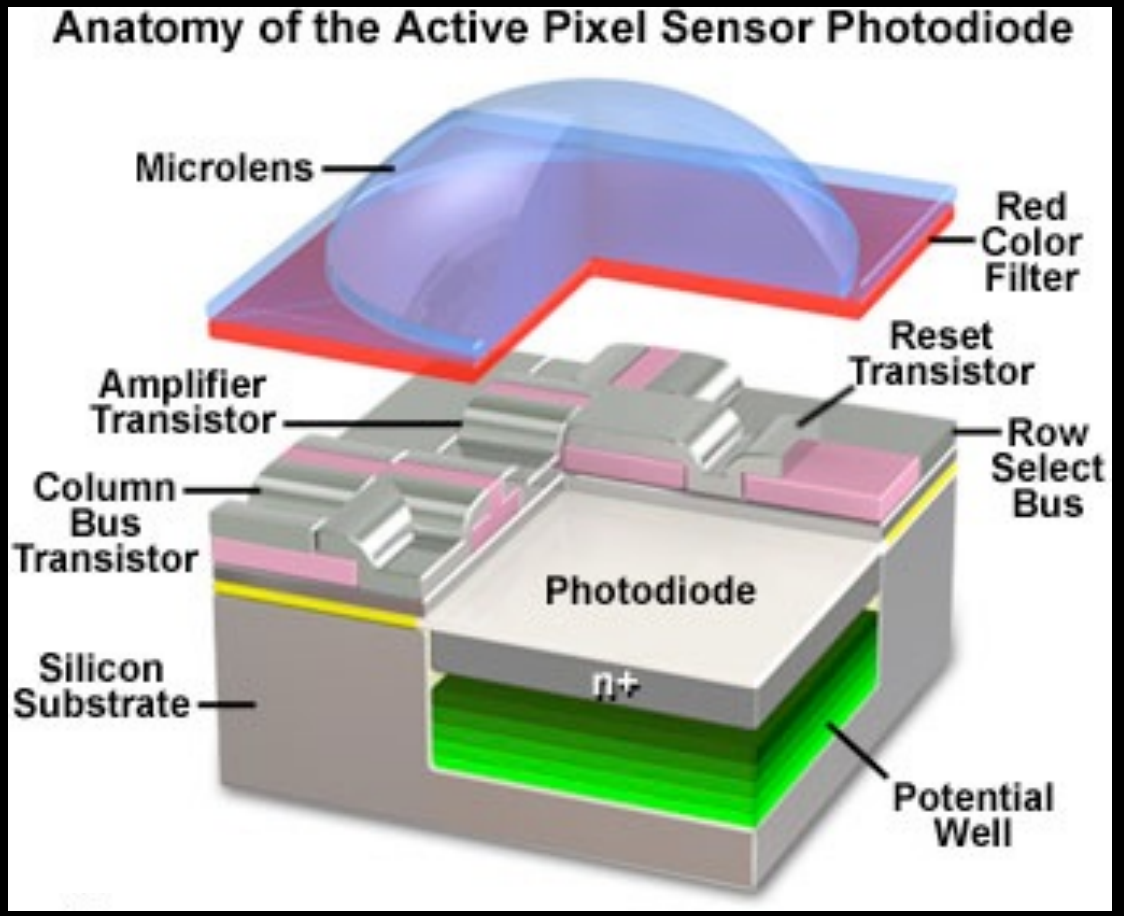


- Fix by calibrating
  - take a photo of a uniformly white object
  - the picture shows the attenuation, divide the pixel values by it

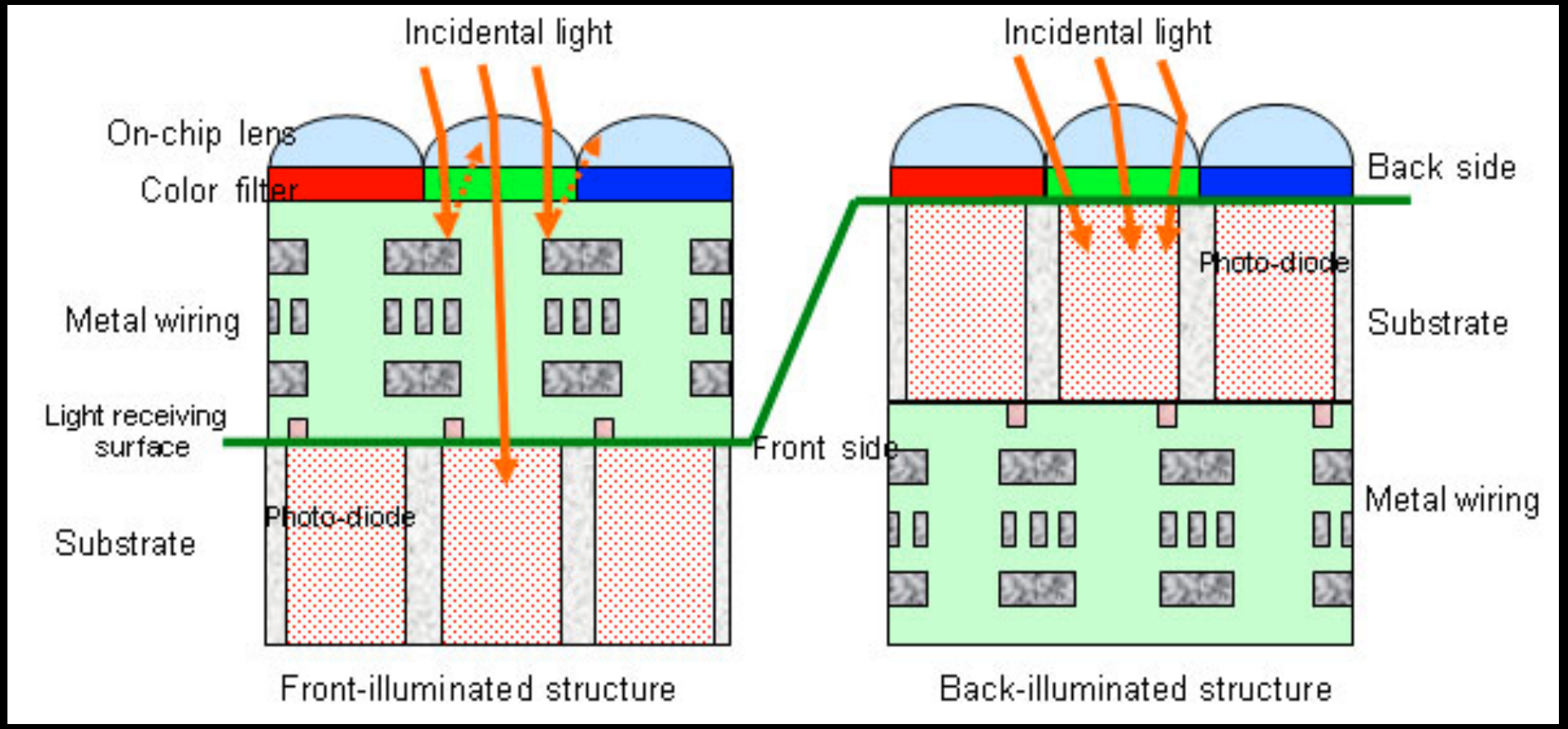
CMOS sensor

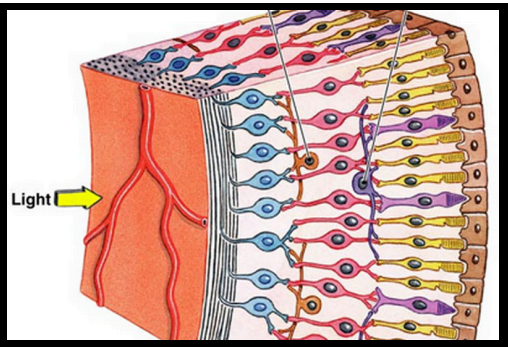
CMOS Image Sensor Integrated Circuit Architecture

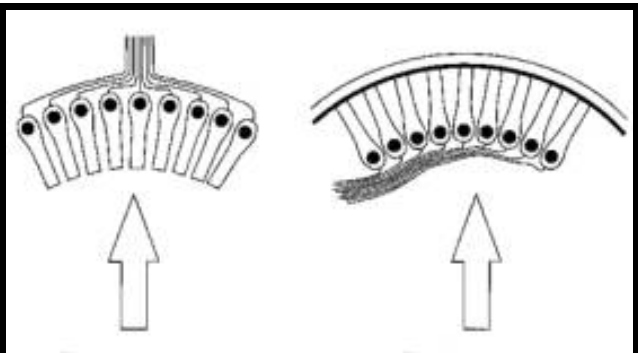




Front- vs. Back-illuminated sensor



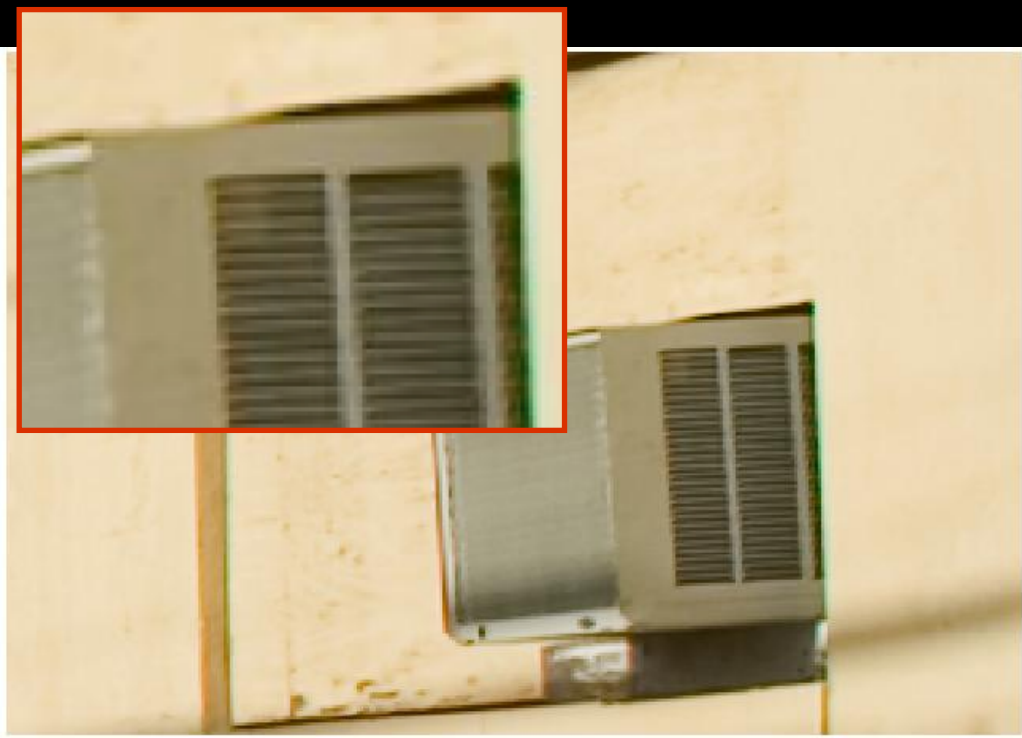




Anti-aliasing filter

- Two layers of birefrigent material
  - splits one ray into 4 rays

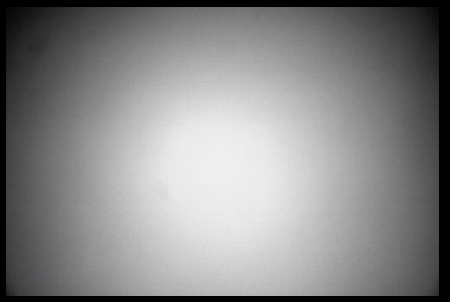
anti-aliasing filter removed



normal

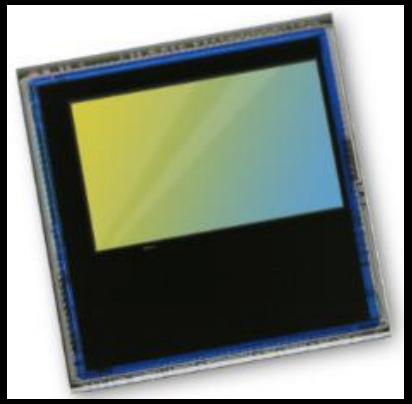
From “raw-raw” to RAW

- Pixel Non-Uniformity
  - each pixel has a slightly different sensitivity to light
    - typically within 1% to 2%
  - reduce by calibrating an image with a flat-field image
    - also eliminate the effects of vignetting and other optical variations



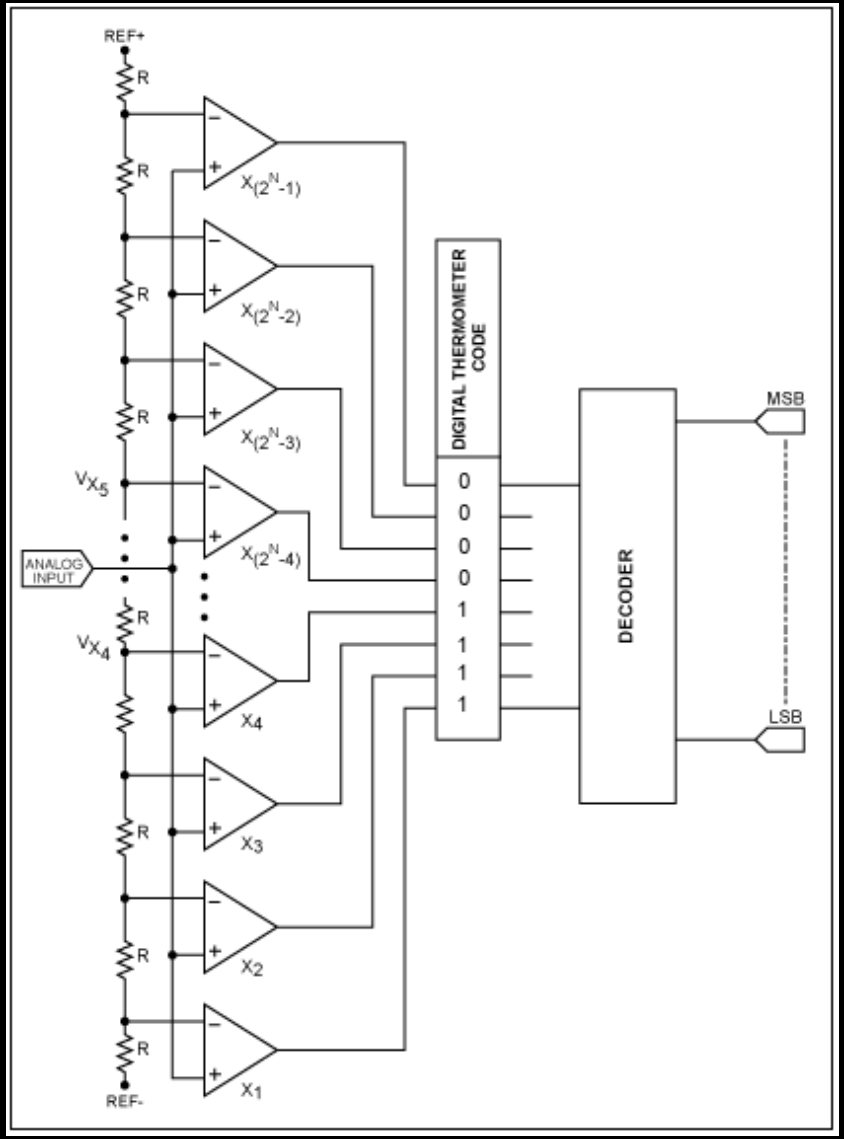
- Stuck pixels
  - some pixels are turned always on or off
  - identify, replace with filtered values

- Dark floor
  - temperature adds noise
  - sensors usually have a ring of covered pixels around the exposed sensor, subtract their signal



AD Conversion

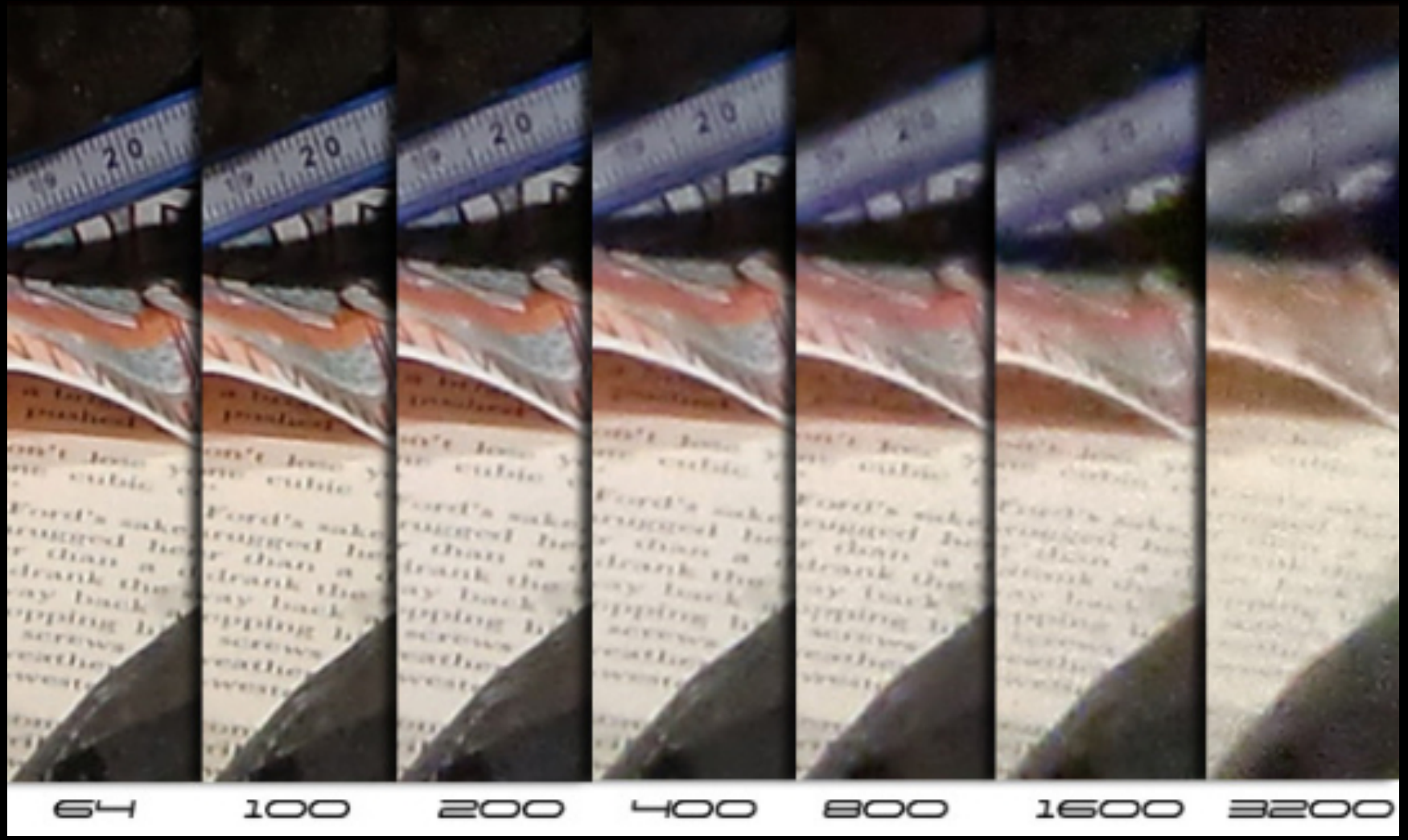
- Sensor converts the continuous light signal to a continuous electrical signal
- The analog signal is converted to a digital signal
  - at least 10 bits (even on cell phones), often 12 or more
  - (roughly) linear sensor response



ISO = amplification in AD conversion

- Before conversion the signal can be amplified
  - ISO 100 means no amplification
  - ISO 1600 means 16x amplification
  - +: can see details in dark areas better
  - -: noise is amplified as well; sensor more likely to saturate

ISO



From “raw-raw” to RAW

- Pixel Non-Uniformity
  - each pixel in a CCD has a slightly different sensitivity to light, typically within 1% to 2% of the average signal
  - can be reduced by calibrating an image with a flat-field image
  - flat-field images are also used to eliminate the effects of vignetting and other optical variations
- Stuck pixels
  - some pixels are turned always on or off
  - identify, replace with filtered values
- Dark floor
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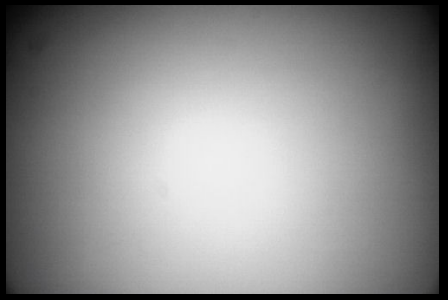
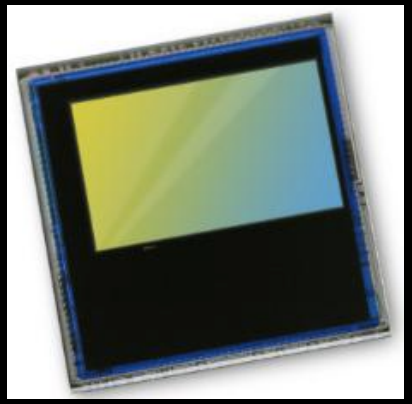
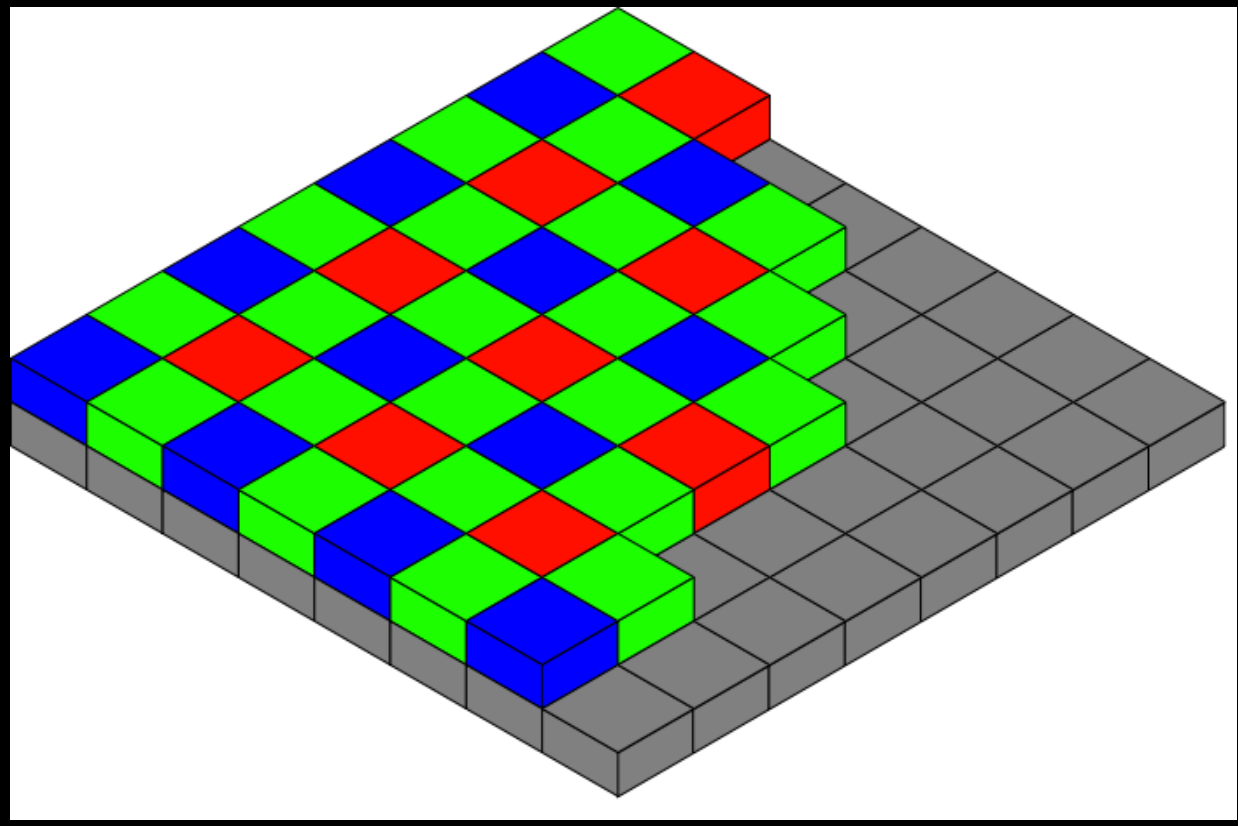


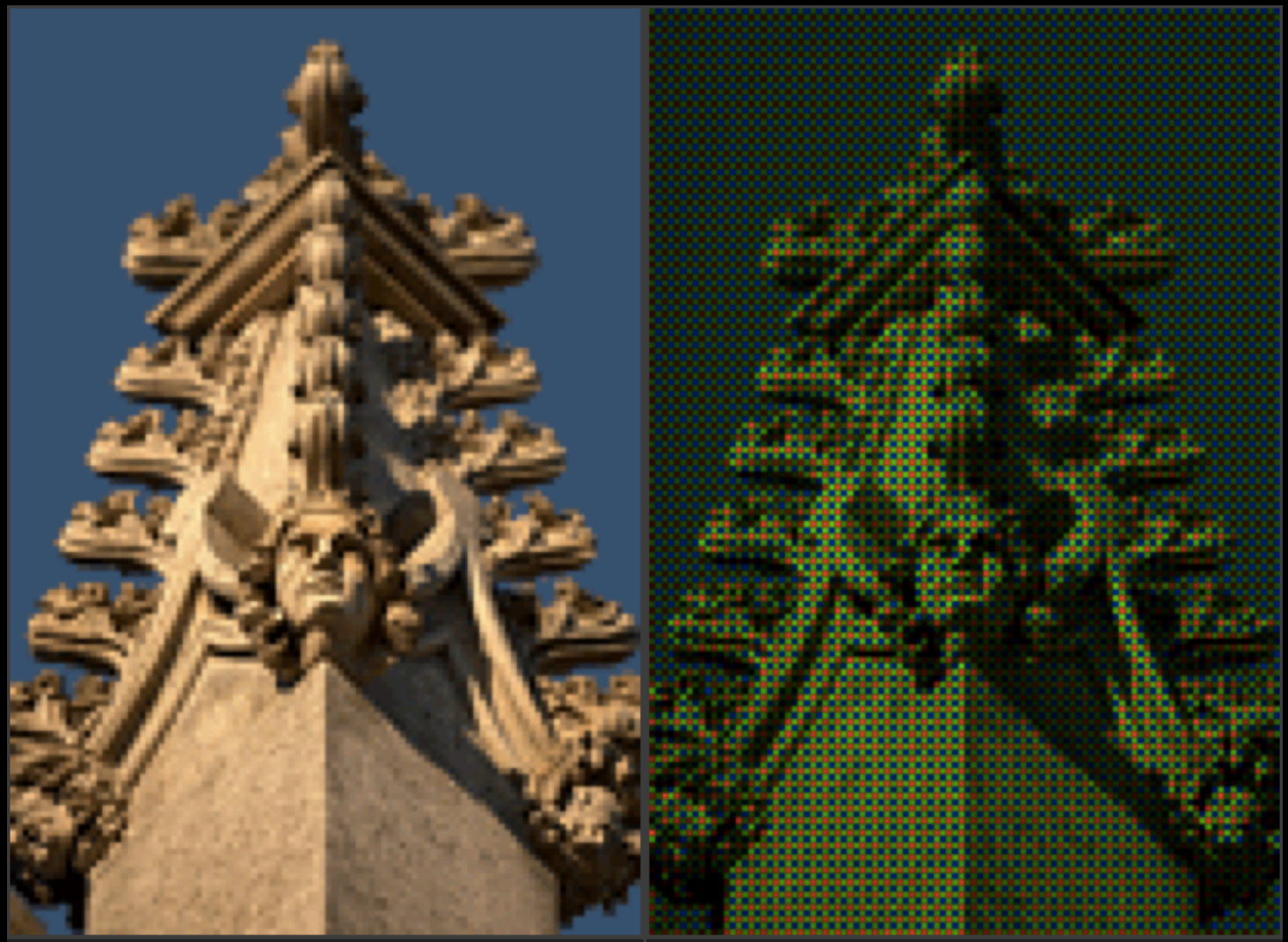


Color filter array

- Bayer pattern



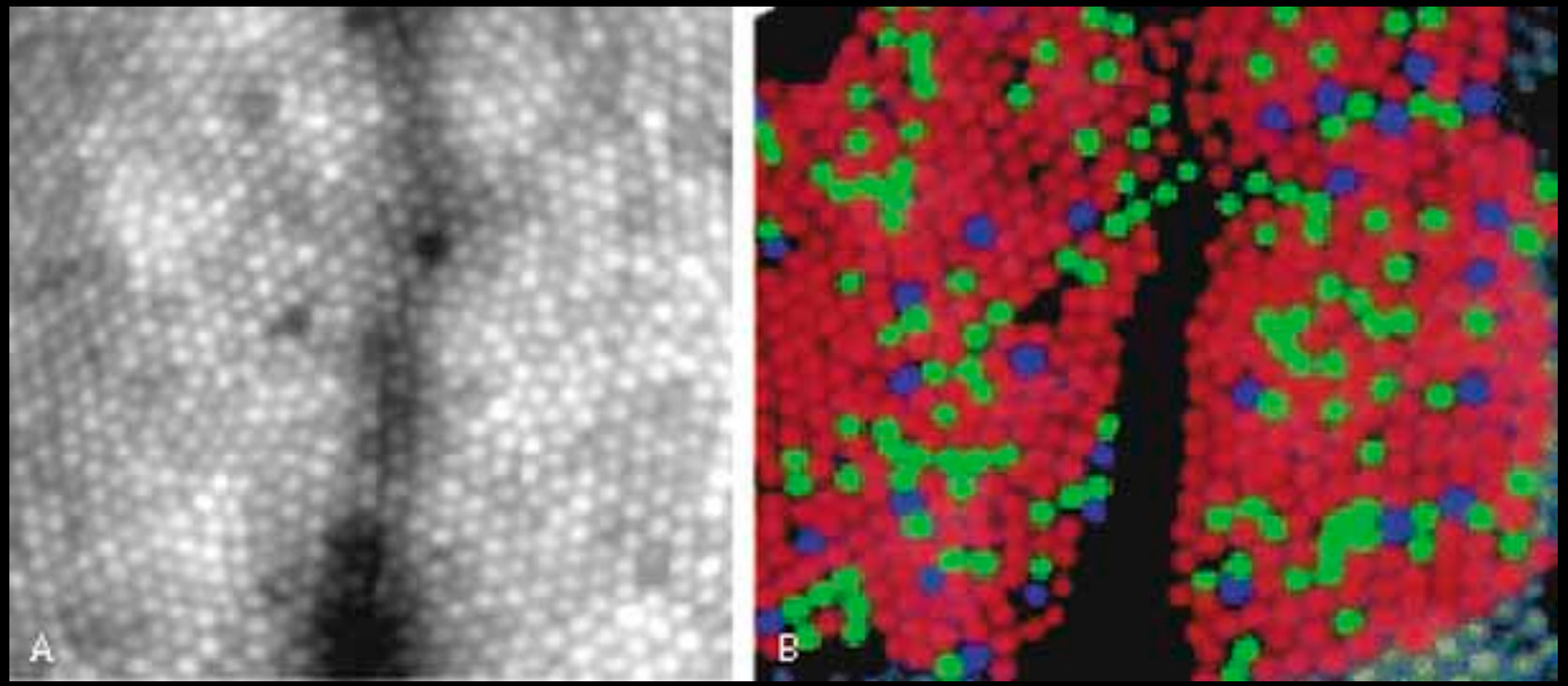
Demosaicking

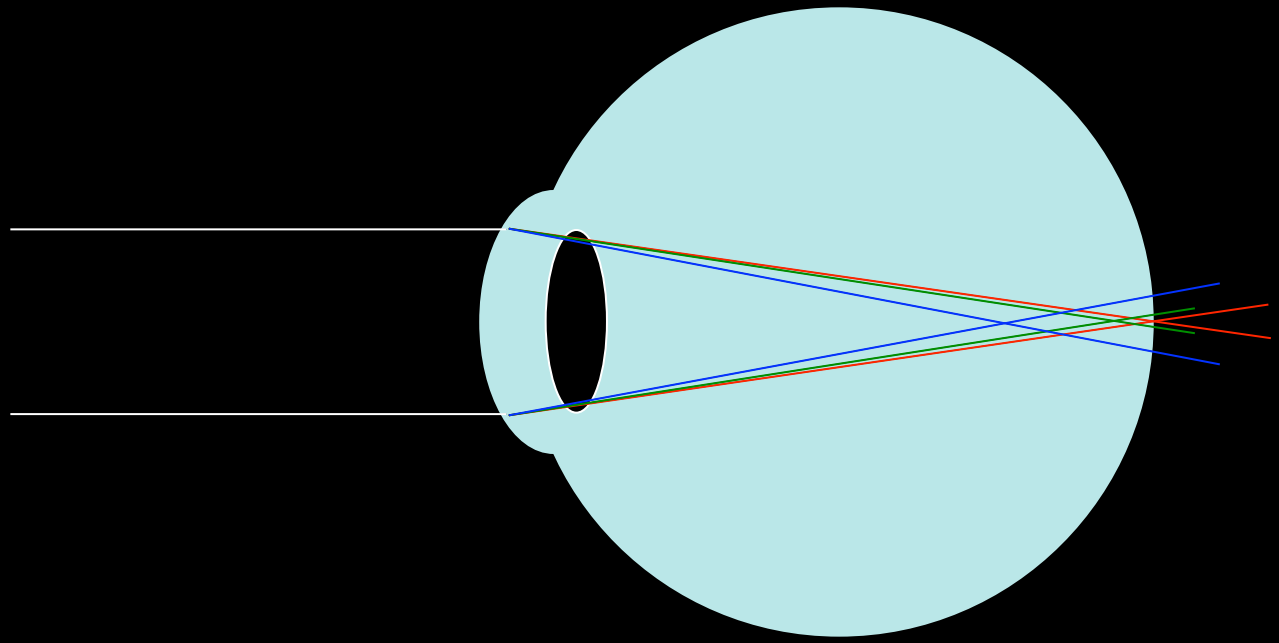


Original Scene
(shown at 200%)

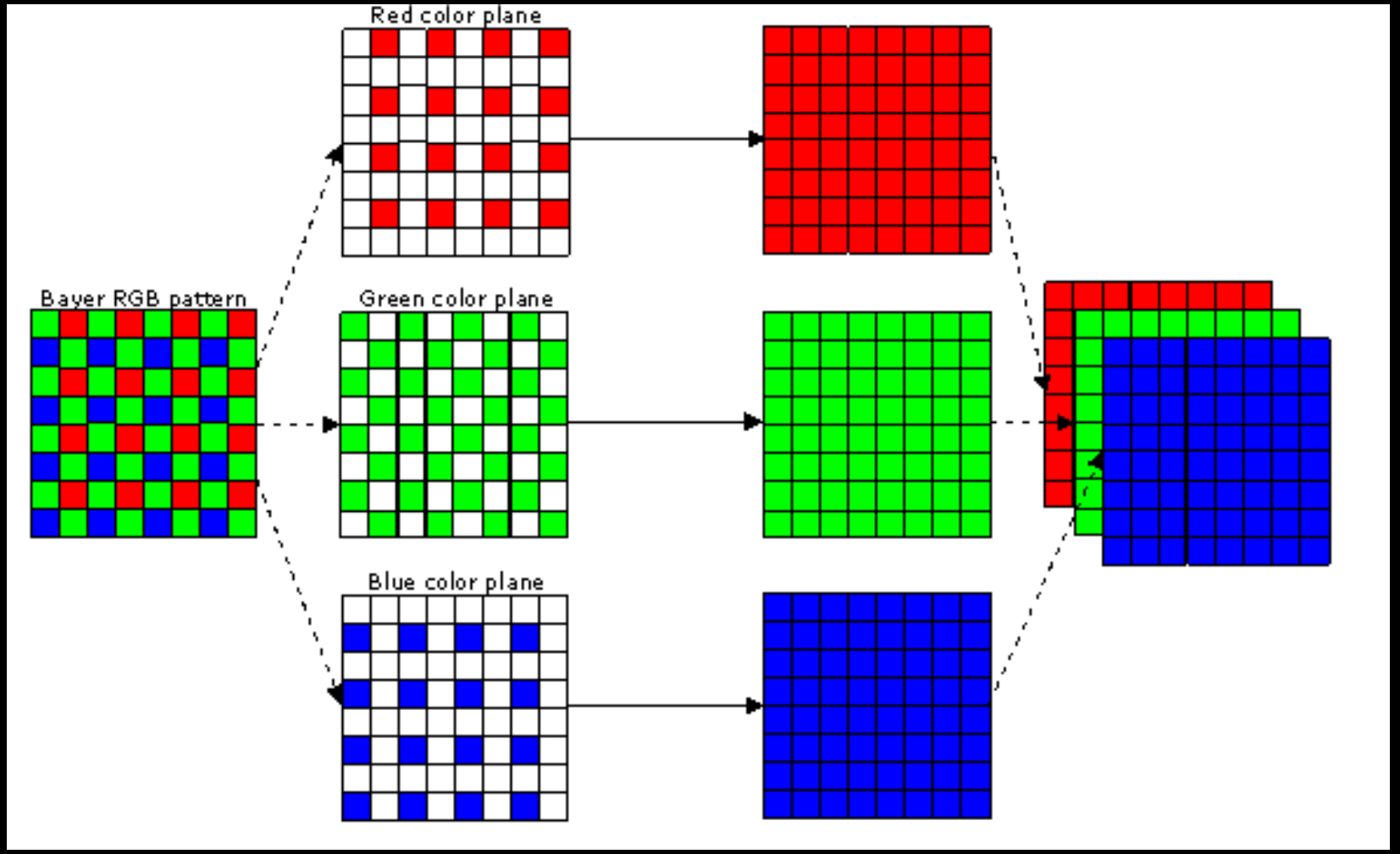
What Your Camera Sees
(through a Bayer array)

Your eyes do it too…



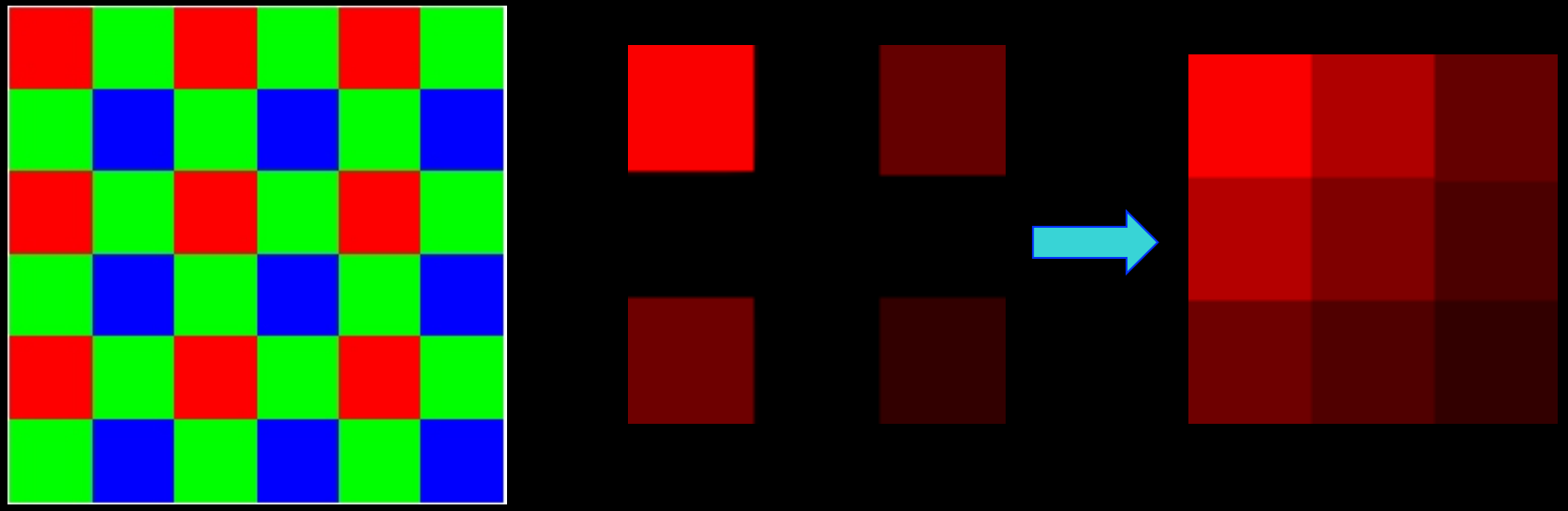


Demosaicking

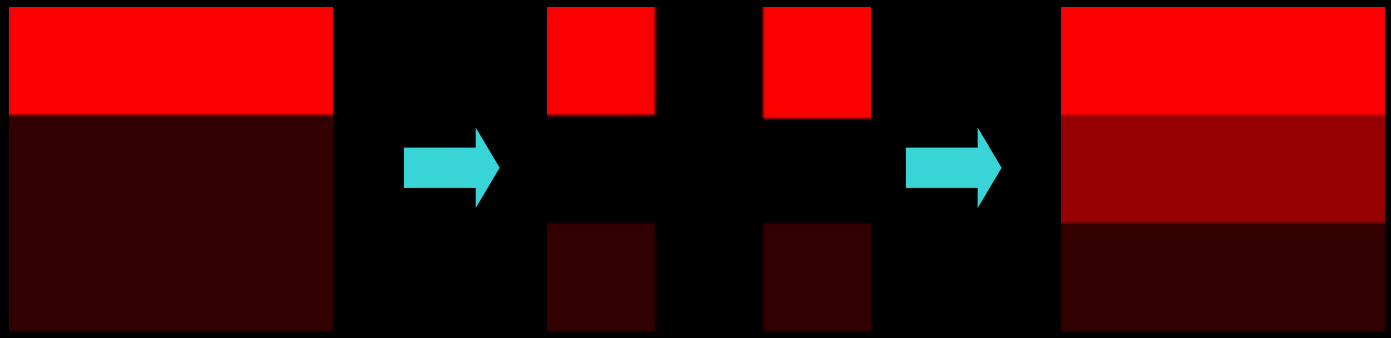


First choice: bilinear interpolation

- Easy to implement



- But fails at sharp edges



Take edges into account

- **Use bilateral filtering**
  - **avoid interpolating across edges**

ADAPTIVE DEMOSAICKING
Ramanath, Snyder, JEI 2003

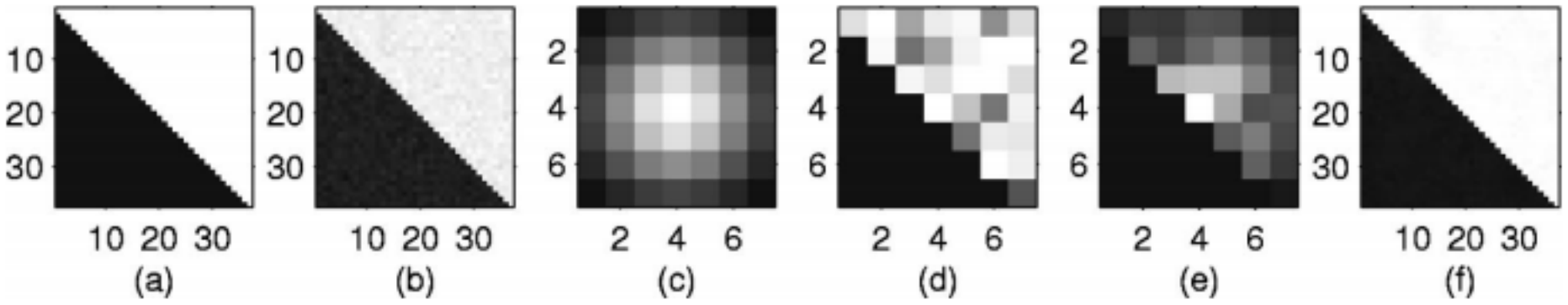


Fig. 3 Bilateral filtering: (a) original image, (b) image corrupted by Gaussian noise, (c) 7×7 blur kernel, (d) 7×7 similarity kernel at row=18, col=18, (e) 7×7 bilateral filter kernel, and (f) resulting image (denoised and sharpened).

Take edges into account

- Predict edges and adjust
  - assumptions
    - luminance correlates with RGB
    - edges = luminance change
- When estimating G at R
  - if the R differs from bilinearly estimated R
    - → luminance changes
- Correct the bilinear estimate
  - by the difference between the estimate and real value

$$\hat{G}(i,j) = \hat{G}(i,j) + \alpha\Delta_{\hat{R}}(i,j)$$

HIGH-QUALITY LINEAR INTERPOLATION FOR DEMOSAICING OF BAYER-PATTERNED COLOR IMAGES

Malvar, He, Cutler, ICASSP 2004

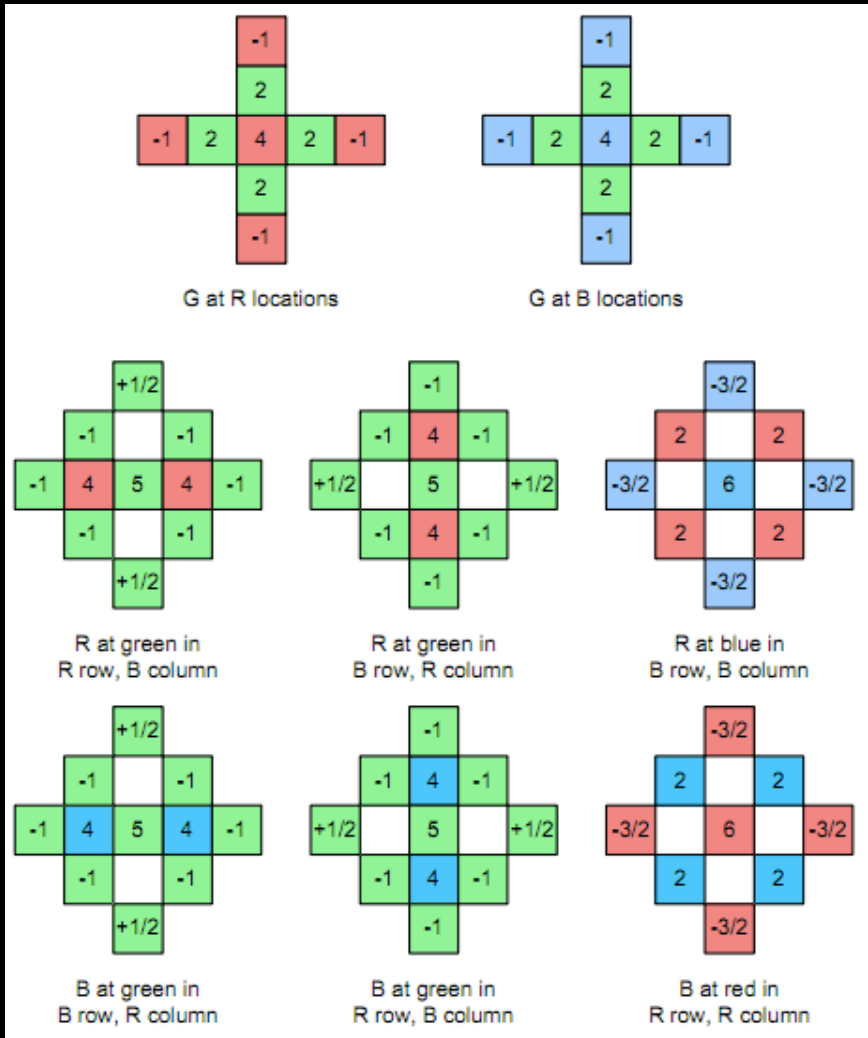


Figure 2. Filter coefficients for our proposed linear

Denoising using non-local means

- Most image details occur repeatedly
- Each color indicates a group of squares in the image which are almost indistinguishable
- Image self-similarity can be used to eliminate noise
  - it suffices to average the squares which resemble each other

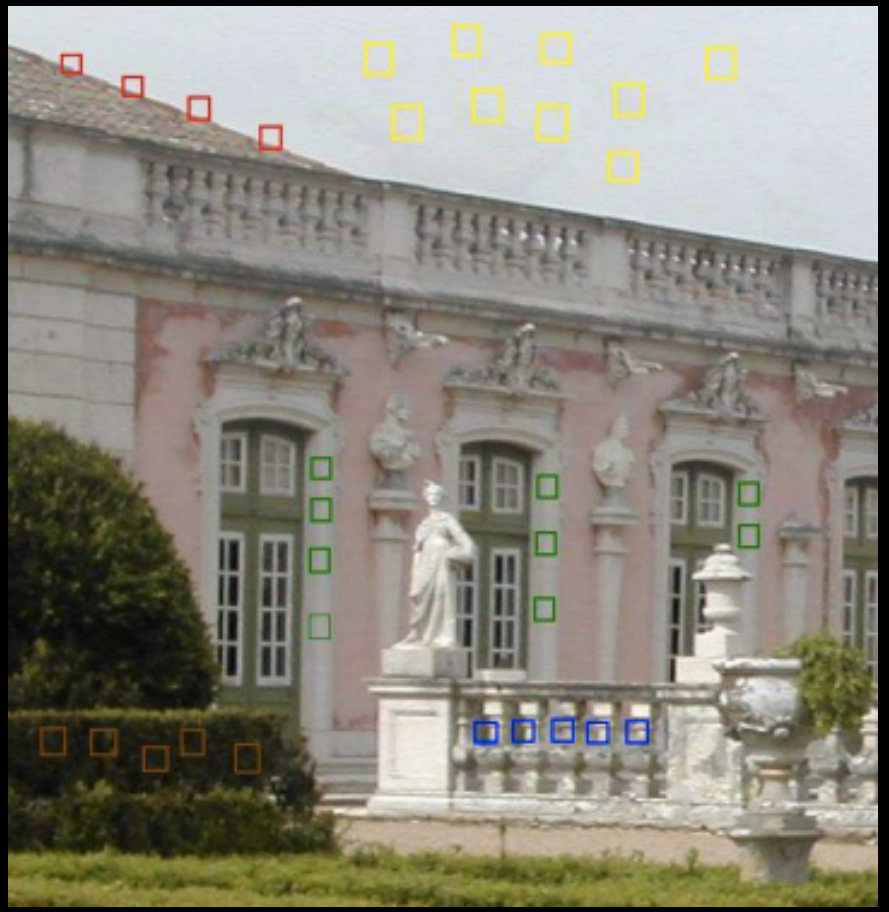


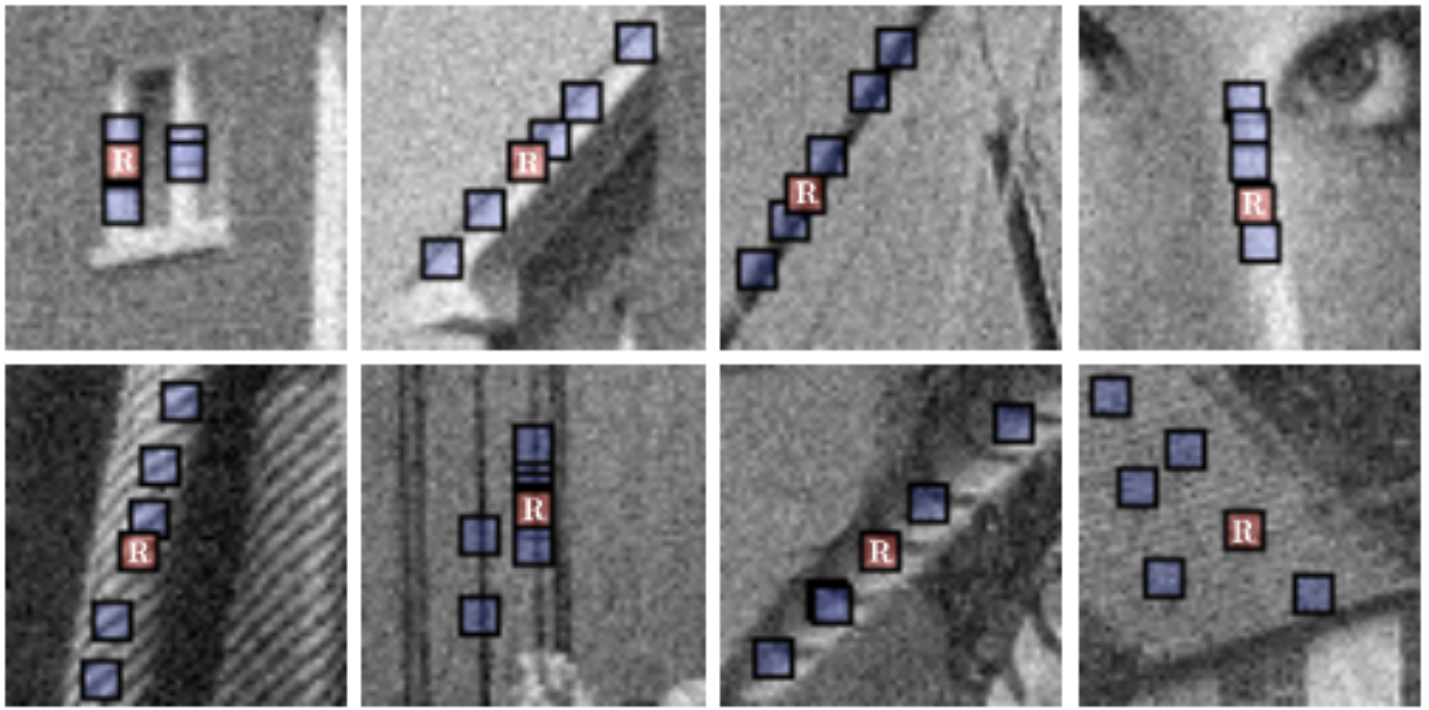
Image and movie denoising by nonlocal means
Buades, Coll, Morel, IJCV 2006

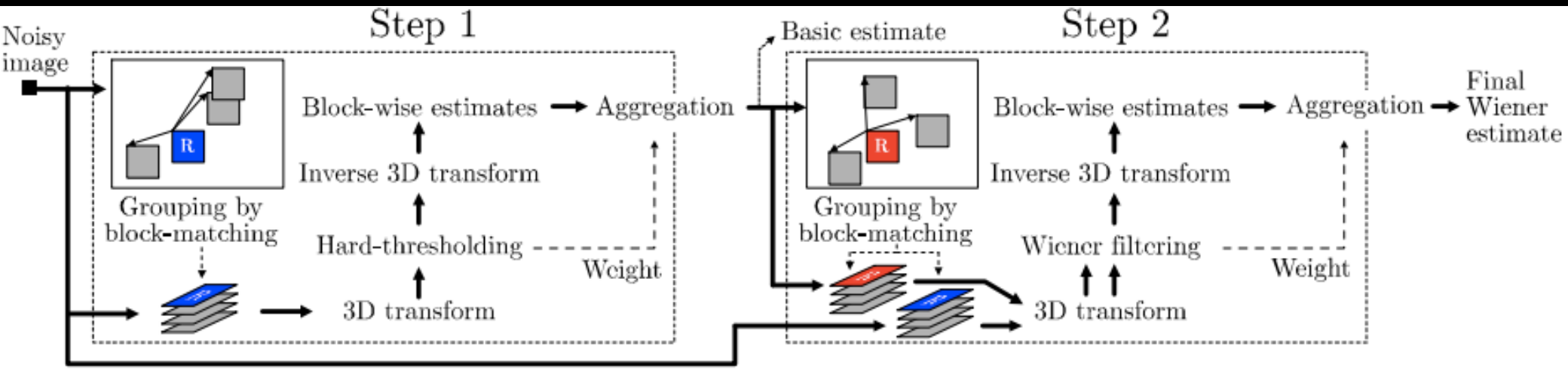
BM3D (Block Matching 3D)

ACCEPTED. TO APPEAR IN IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 16, NO. 8, AUGUST 2007.

Image denoising by sparse 3D transform-domain collaborative filtering

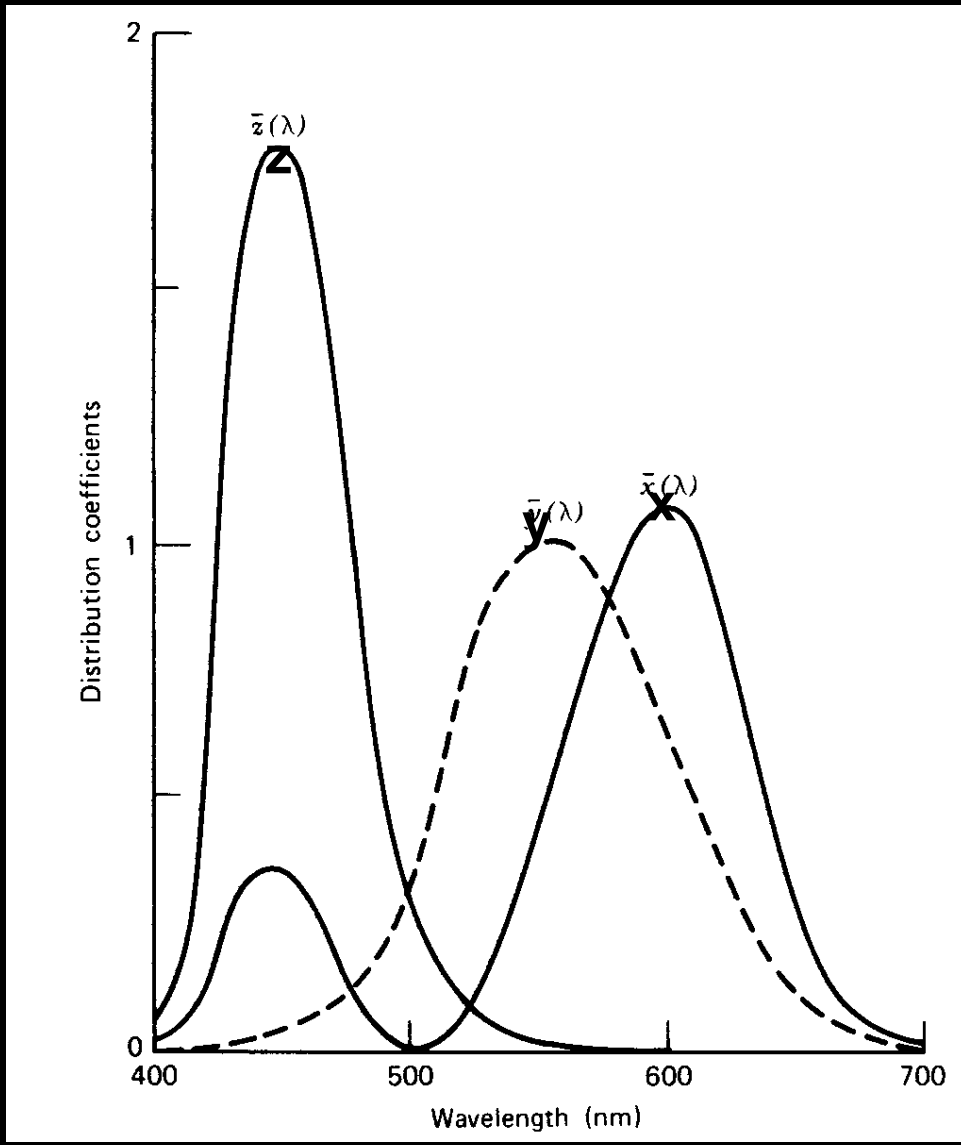
Kostadin Dabov, Alessandro Foi, Vladimir Katkovnik, and Karen Egiazarian, *Senior Member, IEEE*





The CIE *XYZ* System

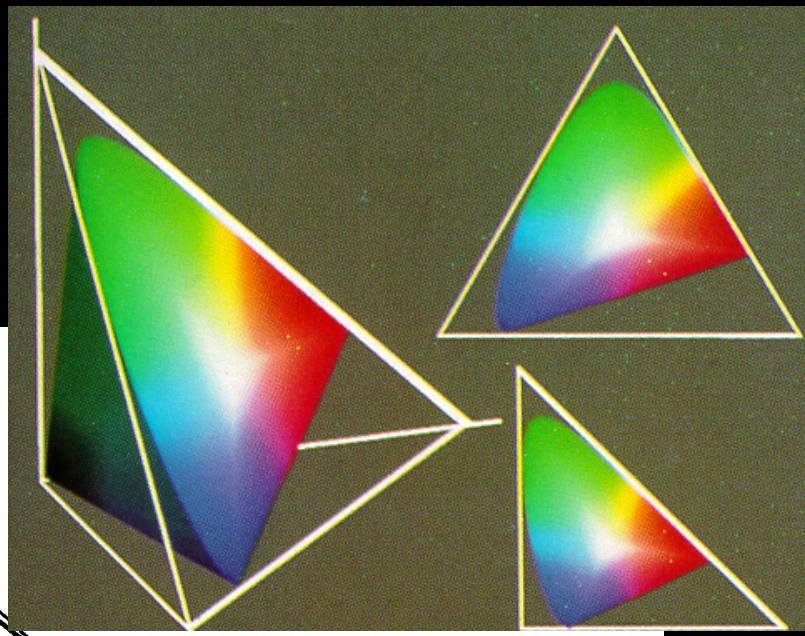
- A standard created in 1931 by CIE
  - Commission Internationale de L'Eclairage
- Defined in terms of three color matching functions
- Given an emission spectrum, we can use the CIE matching functions to obtain the *x, y* and *z* coordinates
  - y corresponds to luminance perception

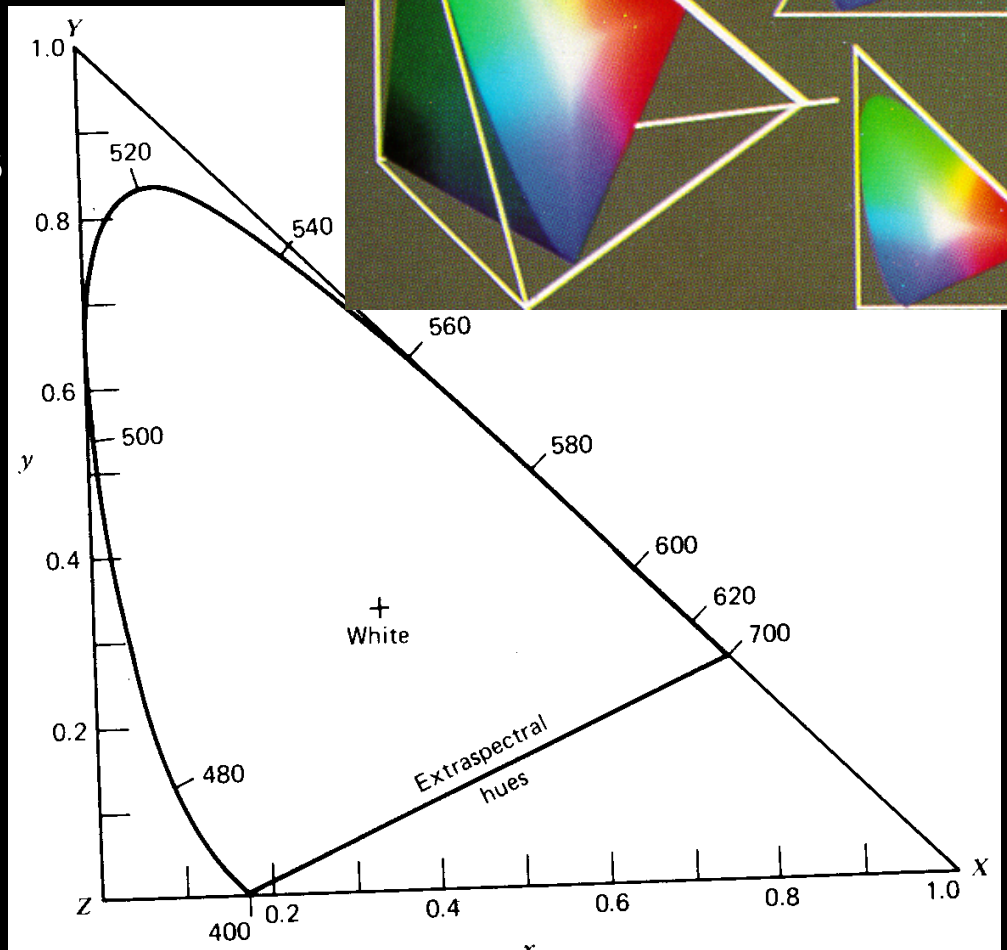


http://graphics.stanford.edu/courses/cs178/applets/threedgamut.html

The CIE Chromaticity Diagram

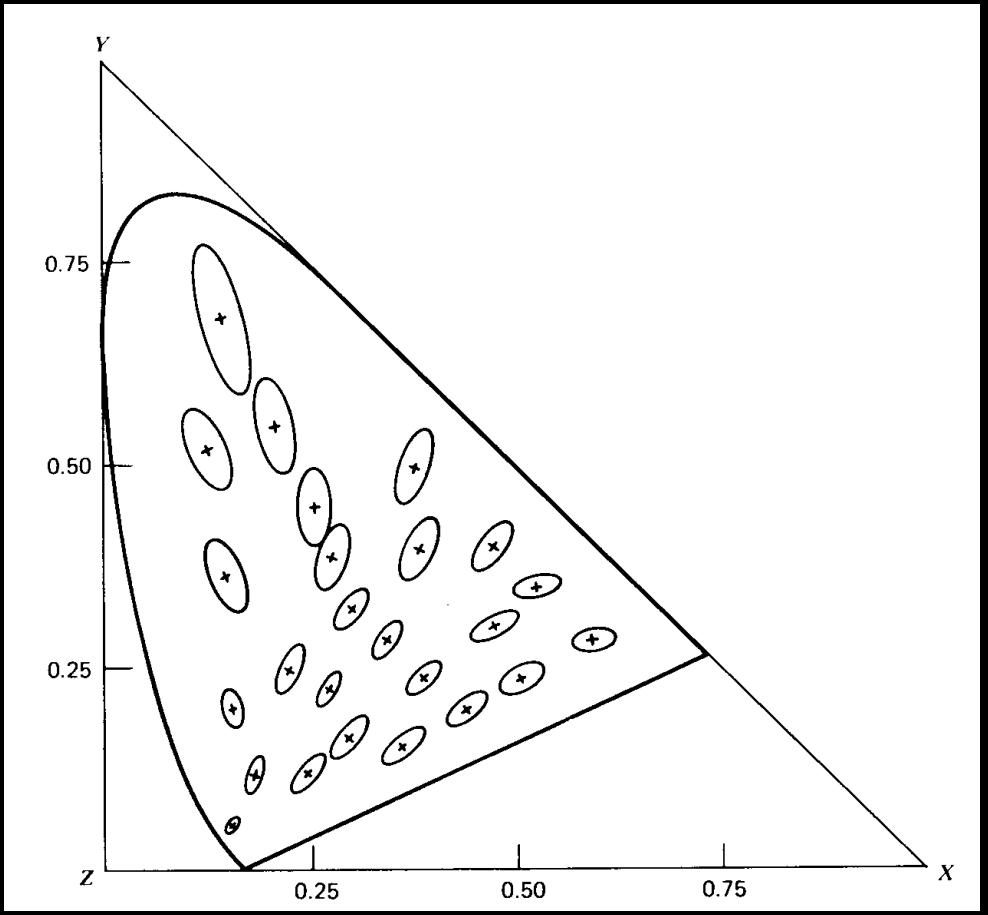
- Intensity is measured as the distance from origin
  - black = (0, 0, 0)
- *Chromaticity coordinates* give a notion of color independent of brightness
- A projection of the plane $x + y + z = 1$ yields a *chromaticity* value dependent on
  - *dominant wavelength (= hue)*, and
  - *excitation purity (= saturation)*
    - the distance from the white at (1/3, 1/3, 1/33)





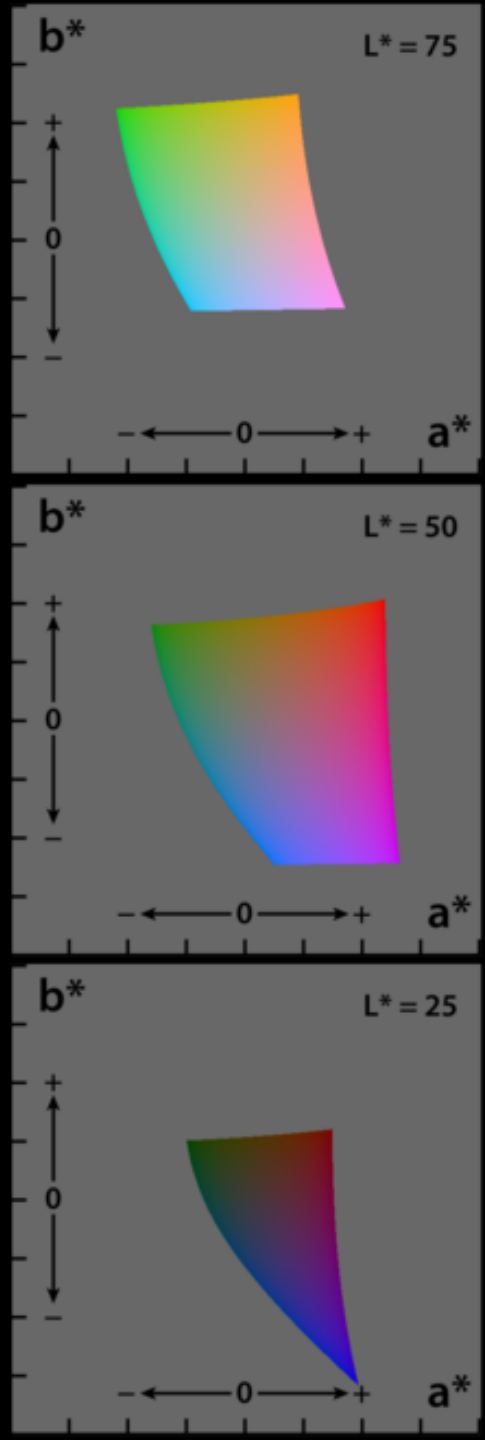
Perceptual (non-)uniformity

- The *XYZ* color space is not perceptually uniform!
- Enlarged ellipses of constant color in XYZ space



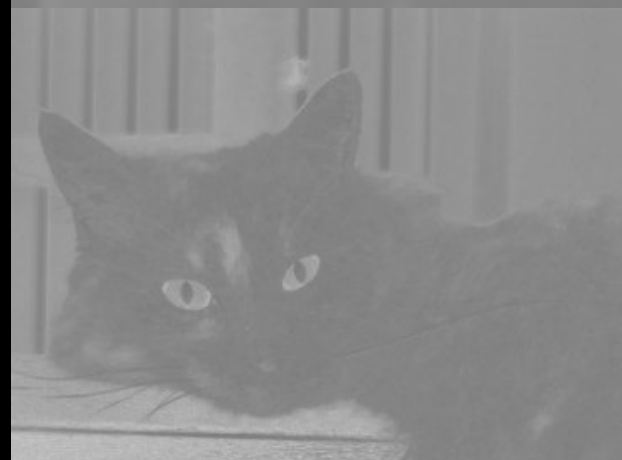
CIE L*a*b*: uniform color space

- Lab is designed to approximate human vision
  - it aspires to perceptual uniformity
  - L component closely matches human perception of lightness
- A good color space for image processing



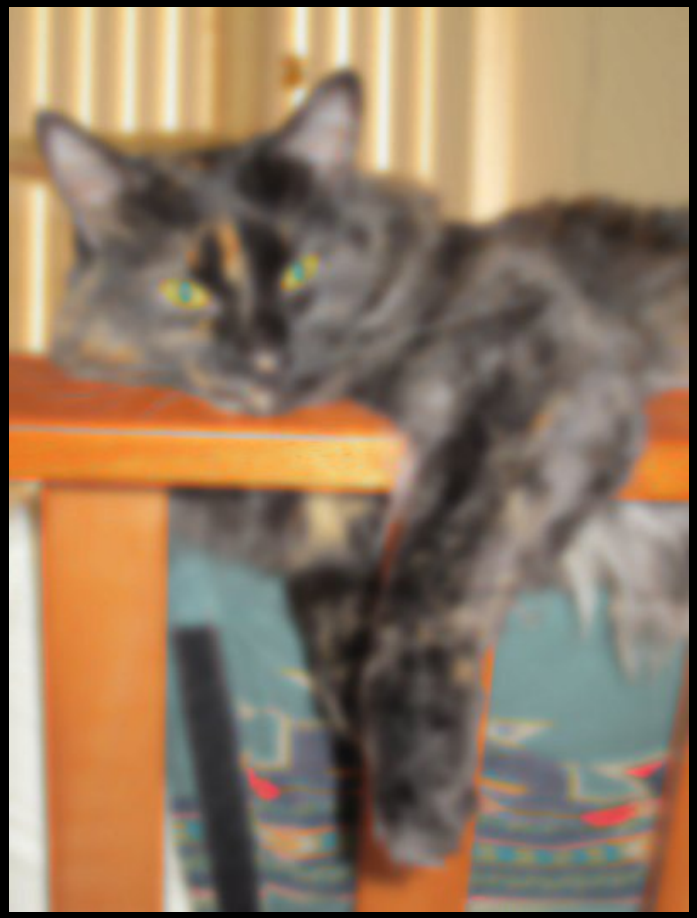
Break RGB to Lab channels

Blur “a” channel (red-green)

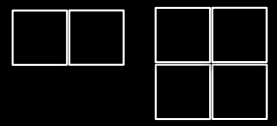


Blur “b” channel (blue-yellow)

Blur “L” channel



YUV, YCbCr, …

- Family of color spaces for video encoding
  - Uses the fact that eye is sensitive to luminance
  - Filters colors down (2:1, 4:1) 
- Channels
  - Y = luminance [linear]; Y’ = luma [gamma corrected]
  - CbCr / UV = chrominance [always linear]
- Y′CbCr is not an absolute color space
  - it is a way of encoding RGB information
  - the actual color depends on the RGB primaries used

How many bits are needed for smooth shading?

- With a given adaptation, human vision has contrast sensitivity ~1%
  - call black 1, white 100
  - you can see differences
    - 1, 1.01, 1.02, … needed step size ~ 0.01
    - 98, 99, 100 needed step size ~ 1
  - with linear encoding
    - delta 0.01
      - 100 steps between 99 & 100 → wasteful
    - delta 1
      - only 1 step between 1 & 2 → lose detail in shadows
  - instead, apply a non-linear power function, gamma
    - provides adaptive step size

Gamma encoding

- With the “delta” ratio of 1.01
  - need about 480 steps to reach 100
  - takes almost 9 bits
- 8 bits, nonlinearly encoded
  - sufficient for broadcast quality digital TV
  - contrast ratio ~ 50 : 1
- With poor viewing conditions or display quality
  - fewer bits needed

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

Luminance from RGB

- If three sources of same radiance appear R, G, B:
  - green will appear the brightest, it has high luminous efficiency
  - red will appear less bright
  - blue will be the darkest
- Luminance by NTSC: 0.2990 R + 0.5870 G + 0.1140 B
  - based on phosphors in use in 1953
- Luminance by CIE: 0.2126 R + 0.7152 G + 0.0722 B
  - based on contemporary phosphors
- Luminance by ITU: 0.2125 R + 0.7154 G + 0.0721 B
- 1/4 R + 5/8 G + 1/8 B works fine
  - quick to compute: R>>2 + G>>1 + G>>3 + B>>3
    - range is [0, 252]

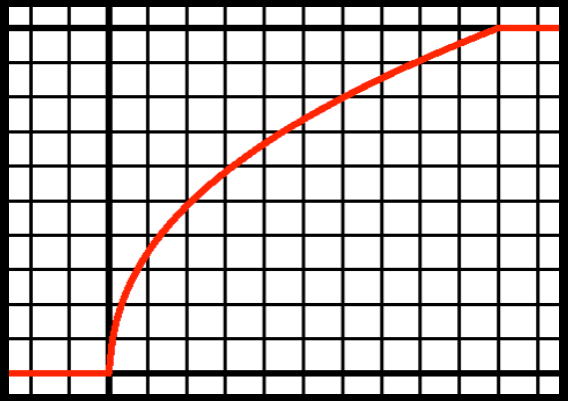
Cameras use sRGB

- sRGB is a standard RGB color space (since 1996)
  - uses the same primaries as used in studio monitors and HDTV
  - and a gamma curve typical of CRTs
  - allows direct display

- First need to map from sensor RGB to standard
  - need calibration

sRGB from XYZ

XYZ → matrix(3x3) → RGB_{sRGB}



RGB_{sRGB} → RGB'_{sRGB} → RGB_{8Bit}

$R_{sRGB} < 0.0031308$

$R'_{sRGB} = 12.92\ R_{sRGB}$

$R_{sRGB} > 0.0031308$

$R'_{sRGB} = 1.055\ R_{sRGB}^{(1/2.4)} - 0.055$

$R_{8Bit} = \text{round}[255\ R'_{sRGB}]$

linear relation between XYZ und sRGB:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{pmatrix} \begin{pmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{pmatrix}$$

red green blue

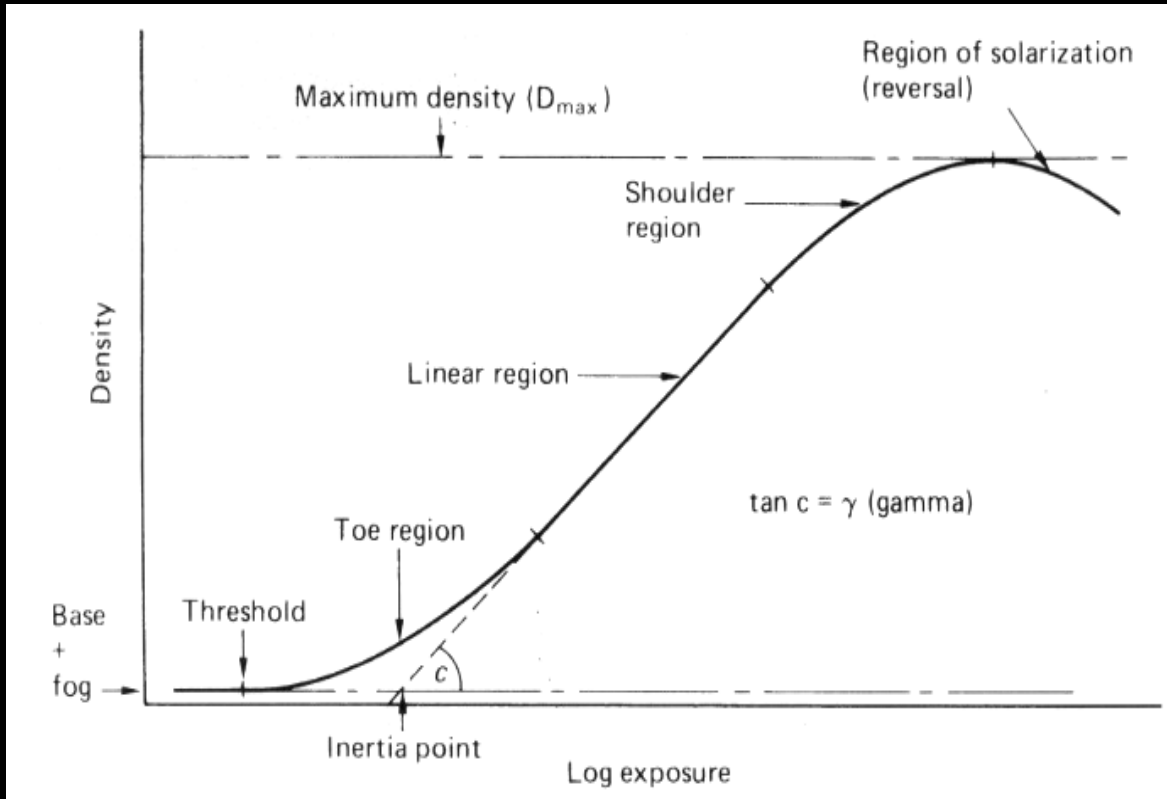
Primaries according to ITU-R BT.709.3

Image processing in linear or non-linear space?

- Simulating physical world
  - use linear light
  - a weighted average of gamma-corrected pixel values is not a linear convolution!
    - Bad for antialiasing
  - want to numerically simulate lens?
    - Undo gamma first
- Dealing with human perception
  - using non-linear coding allows minimizing perceptual errors due to quantization

Film response curve

- Toe region
  - the chemical process is just starting
- Middle
  - follows a power function
  - if a given amount of light turned half of the grain crystals to silver, the same amount more turns half of the rest
- Shoulder region
  - close to saturation

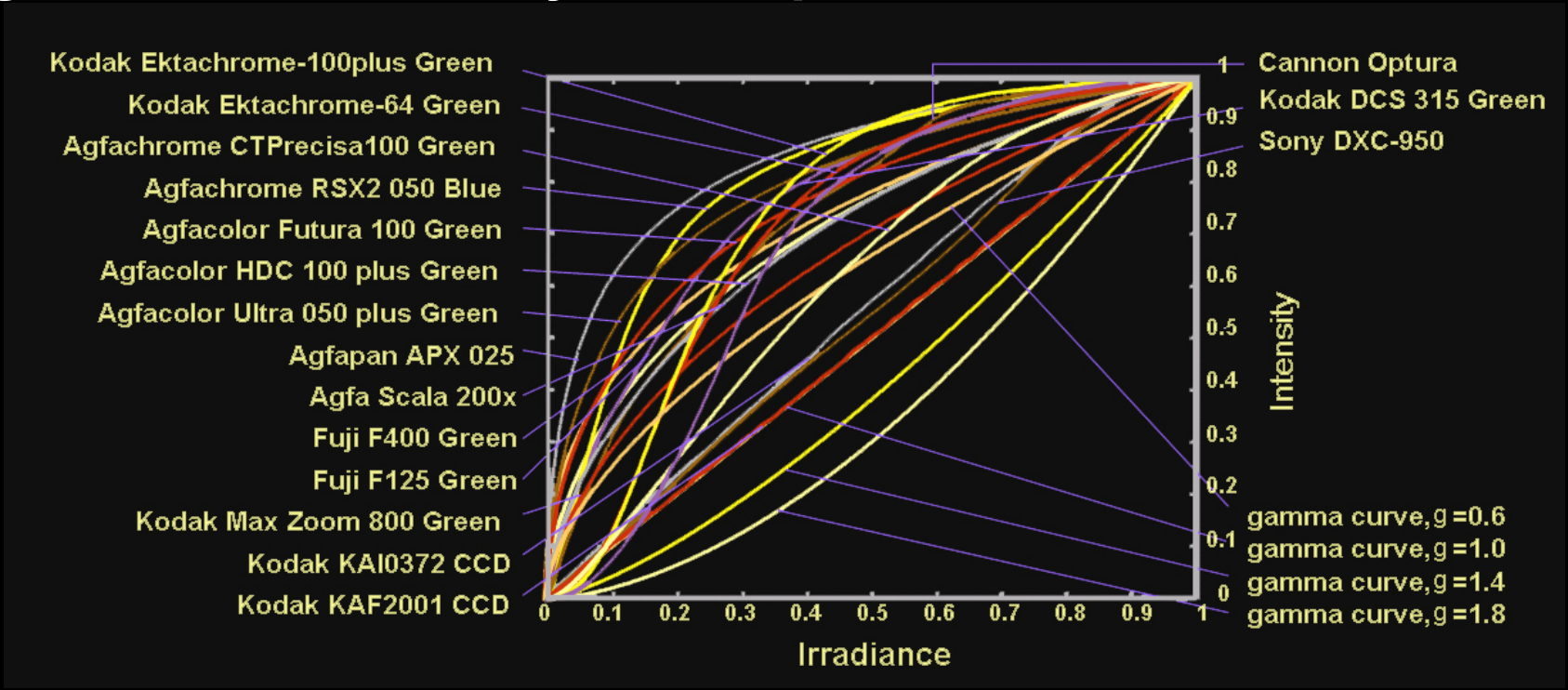


The 'geography' of the characteristic curve of a negative material

- Toe and shoulder preserve more dynamic range at dark and bright areas
  - at the cost of reduced contrast
- Film has more dynamic range than print
  - ~12bits

Digital camera response curve

- Digital cameras modify the response curve



- May use different response curves at different exposures
  - impossible to calibrate and invert!

3A

- Automated selection of key camera control values
  - auto-focus
  - auto-exposure
  - auto-white-balance

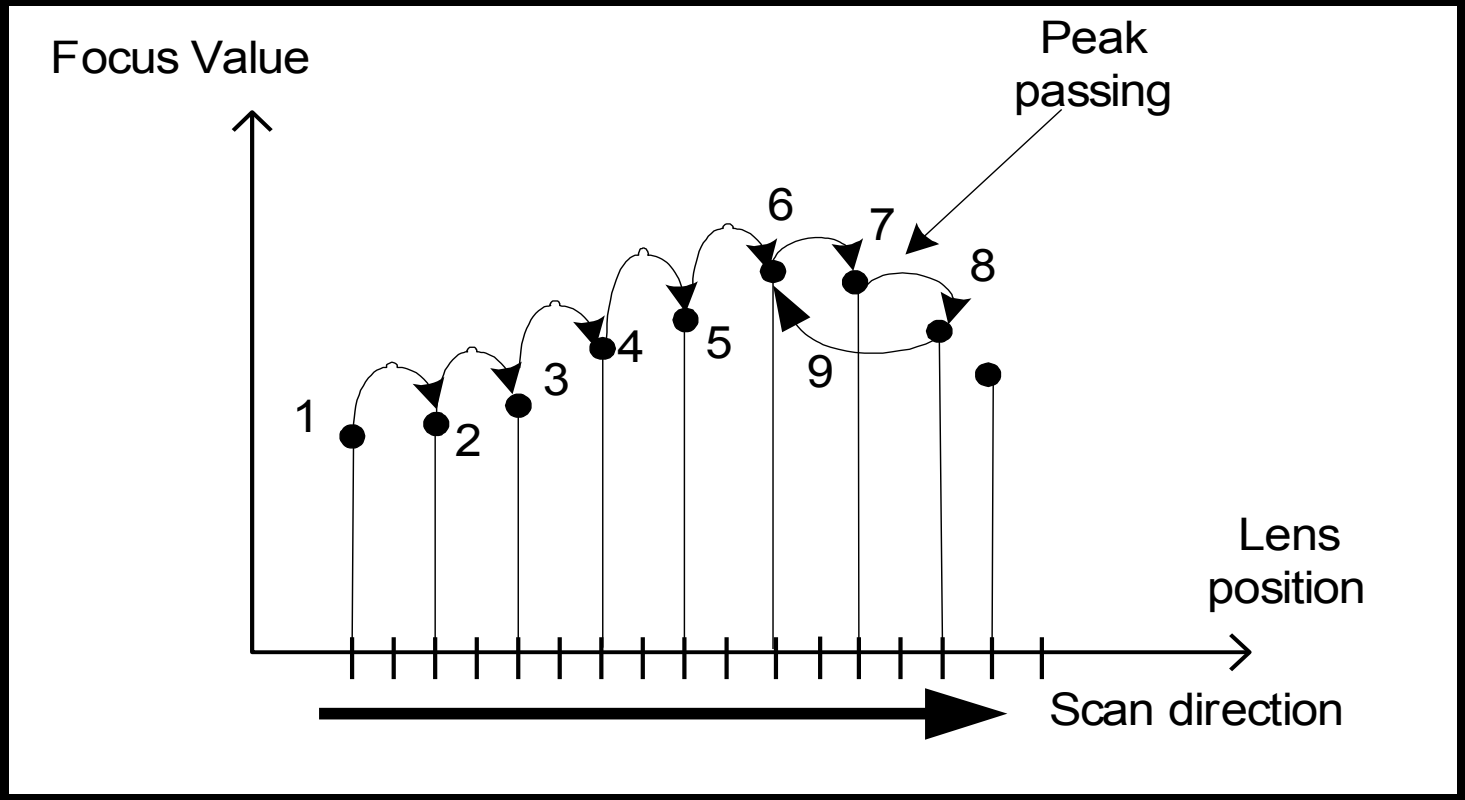
Contrast-based auto-focus

- ISP can filter pixels with configurable IIR filters
  - to produce a low-resolution sharpness map of the image
- The sharpness map helps estimate the best lens position
  - by summing the sharpness values (= Focus Value)
    - either over the entire image
    - or over a rectangular area

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

Hunt for the peak

- First coarse search
  - back up after peak, do a finer search



Auto-White-Balance

- The dominant light source (*illuminant*) produces a color cast that affects the appearance of the scene objects
- The color of the illuminant determines the color normally associated with white by the human visual system
- Auto-white-balance
  - Identify the illuminant color
  - Neutralize the color of the illuminant

(source: www.cambridgeincolour.com)

Identify the color of the illuminant

- Prior knowledge about the ambient light
  - Candle flame light (1850^0K)
  - Sunset light (2000^0K)
  - Summer sunlight at noon (5400^0K)
  - …
- Known reference object in the picture
  - best: find something that is white or gray
- Assumptions about the scene
  - Gray world assumption (gray in sRGB space!)

Best way to do white balance

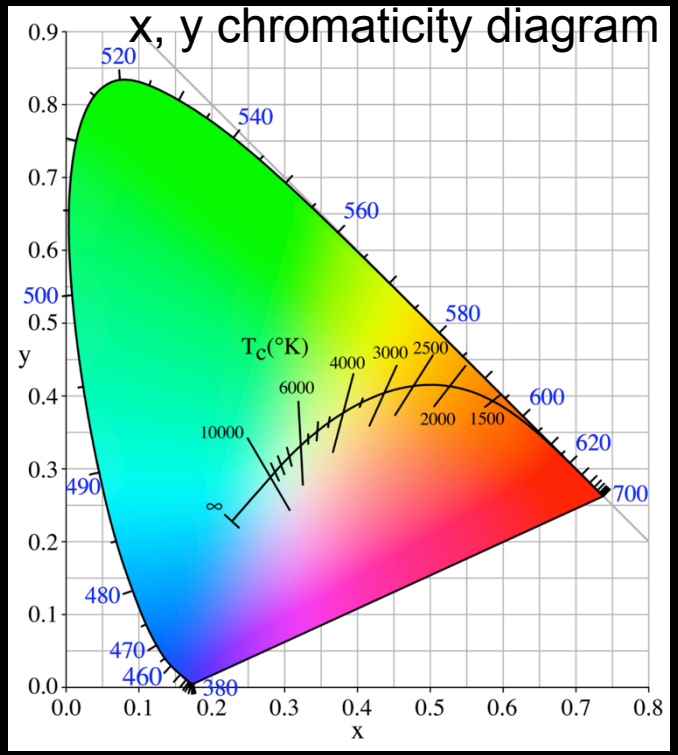
- Grey card
  - take a picture of a neutral object (white or gray)
  - deduce the weight of each channel

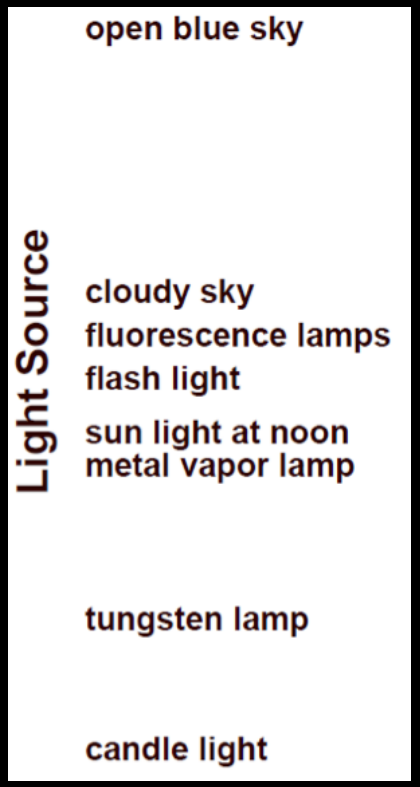
- If the object is recoded as r_w, g_w, b_w
  - use weights k/r_w, k/g_w, k/b_w
    - where k controls the exposure

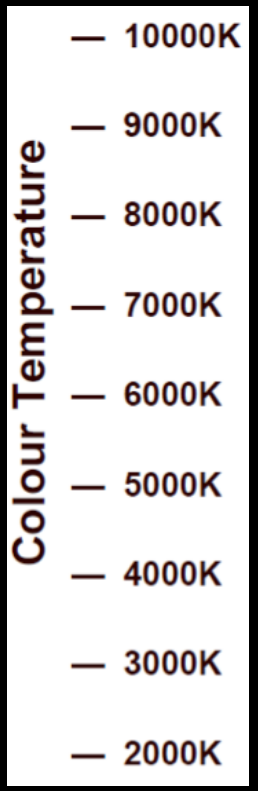
Brightest pixel assumption

- Highlights usually have the color of the light source
  - at least for dielectric materials
- White balance by using the brightest pixels
  - plus potentially a bunch of heuristics
  - in particular use a pixel that is not saturated / clipped

Color temperature







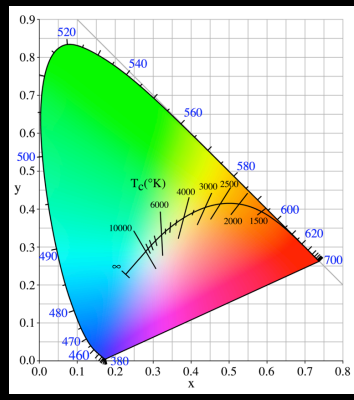
- Colors of a black-body heated at different temperatures fall on a curve (Planckian locus)
- Colors change non-linearly with temperature
  - but almost linearly with reciprocal temperatures 1/T

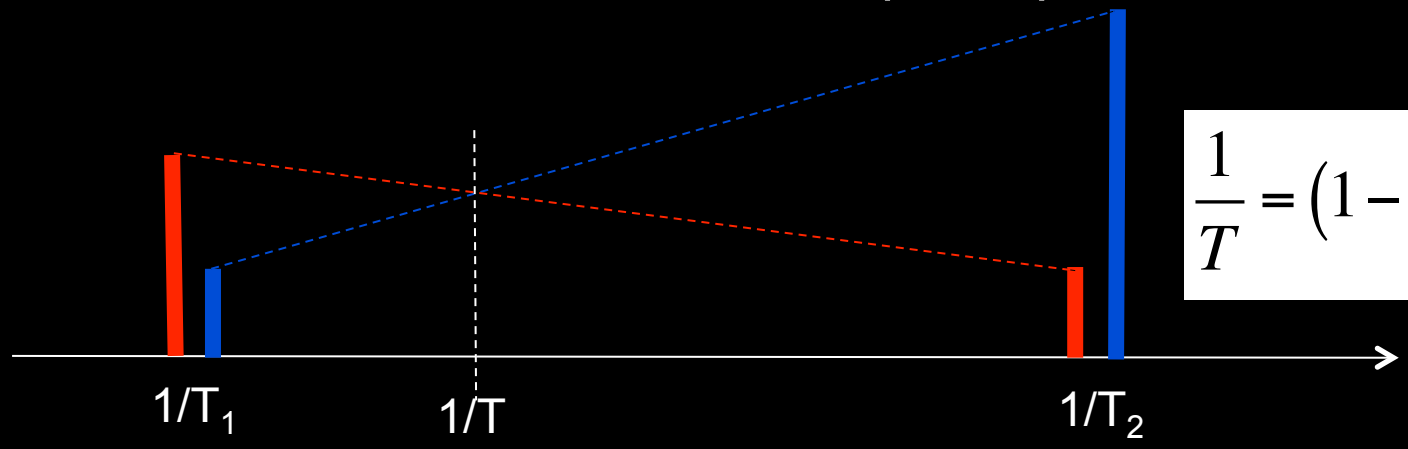
Mapping the colors

- For a given sensor
  - pre-compute the transformation matrices between the sensor color space and sRGB at different temperatures
- Estimate a new transformation
  - by interpolating between pre-computed matrices
  - ISP can apply the linear transformation

Estimating the color temperature

- Use scene mode
- Use gray world assumption (R = G = B) in sRGB space
  - really, just R = B, ignore G
- Estimate color temperature in a given image
  - apply pre-computed matrix to get sRGB for T_1 and T_2
  - calculate the average values R, B
  - solve α, use to interpolate matrices (or 1/T)





$$\frac{1}{T} = (1-\alpha)\frac{1}{T_1} + \alpha\frac{1}{T_2}$$

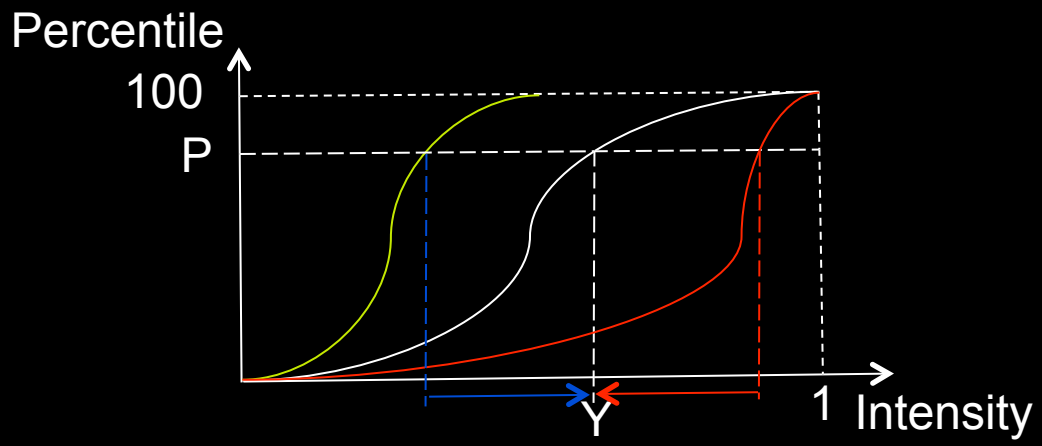
$$R = (1-\alpha)R_1 + \alpha R_2,\ B = (1-\alpha)B_1 + \alpha B_2$$

Auto-exposure

- Goal: well-exposed image (not a very well defined goal!)
- Possible parameters to adjust
  - Exposure time
    - Longer exposure time leads to brighter image, but also motion blur
  - Aperture (f-number)
    - Larger aperture (smaller f-number) lets more light in causing the image to be brighter, also makes depth of field shallower
    - Phone cameras often have fixed aperture
  - Analog and digital gain
    - Higher gain makes image brighter but amplifies noise as well
  - ND filters on some cameras

Exposure metering

- **Cumulative Density Function of image intensity values**
  - ***P* percent of image pixels have an intensity lower than *Y***

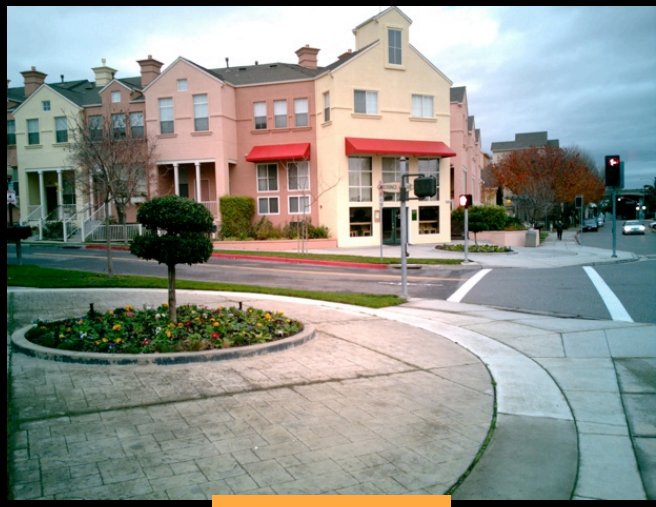


Exposure metering examples

- Adjustment examples
  - P = 0.995, Y = 0.9
    - max 0.5% of pixels are saturated (highlights)
  - P = 0.1, Y = 0.1
    - max 10% of pixels are under-exposed (shadows)
  - Auto-exposure somewhere in between, e.g., P = 0.9, Y = 0.4

Highlights

Auto-exposure



Shadows

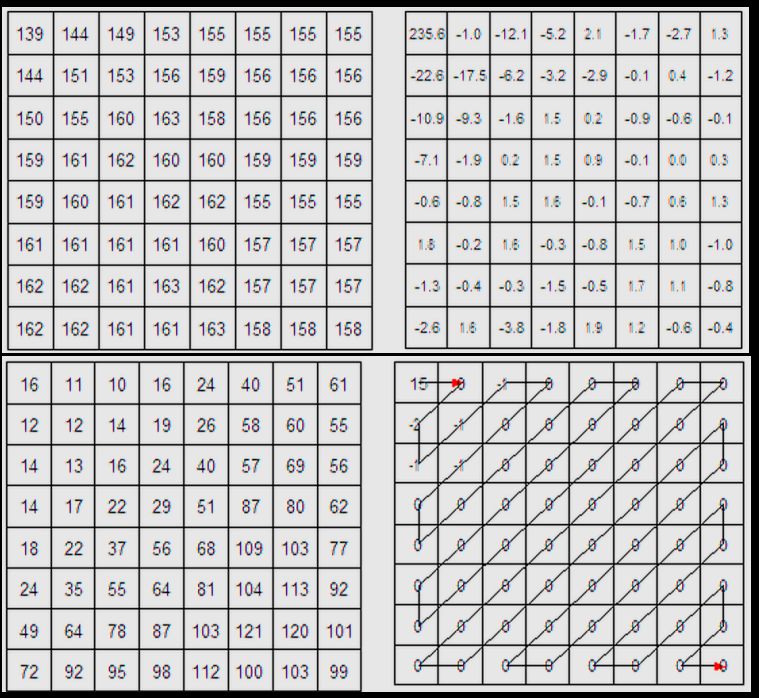
JPEG Encoding

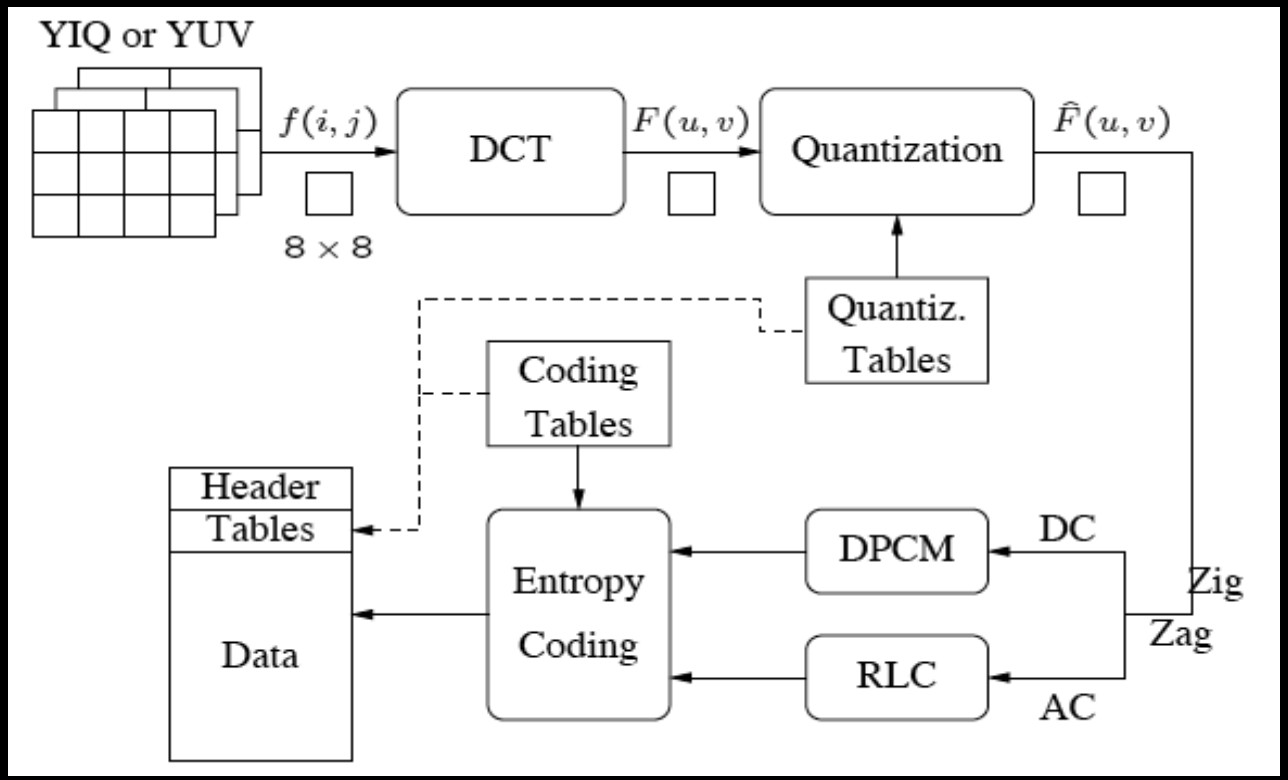
1. Transform RGB to YUV or YIQ and subsample color
2. DCT on 8x8 image blocks
3. Quantization
4. Zig-zag ordering and run-length encoding
5. Entropy coding

139	144	149	153	155	155	155	155
144	151	153	156	159	156	156	156
150	155	160	163	158	156	156	156
159	161	162	160	160	159	159	159
159	160	161	162	162	155	155	155
161	161	161	161	160	157	157	157
162	162	161	163	162	157	157	157
162	162	161	161	163	158	158	158

235.6	-1.0	-12.1	-5.2	2.1	-1.7	-2.7	1.3
-22.6	-17.5	-6.2	-3.2	-2.9	-0.1	0.4	-1.2
-10.9	-9.3	-1.6	1.5	0.2	-0.9	-0.6	-0.1
-7.1	-1.9	0.2	1.5	0.9	-0.1	0.0	0.3
-0.6	-0.8	1.5	1.6	-0.1	-0.7	0.6	1.3
1.8	-0.2	1.6	-0.3	-0.8	1.5	1.0	-1.0
-1.3	-0.4	-0.3	-1.5	-0.5	1.7	1.1	-0.8
-2.6	1.6	-3.8	-1.8	1.9	1.2	-0.6	-0.4

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



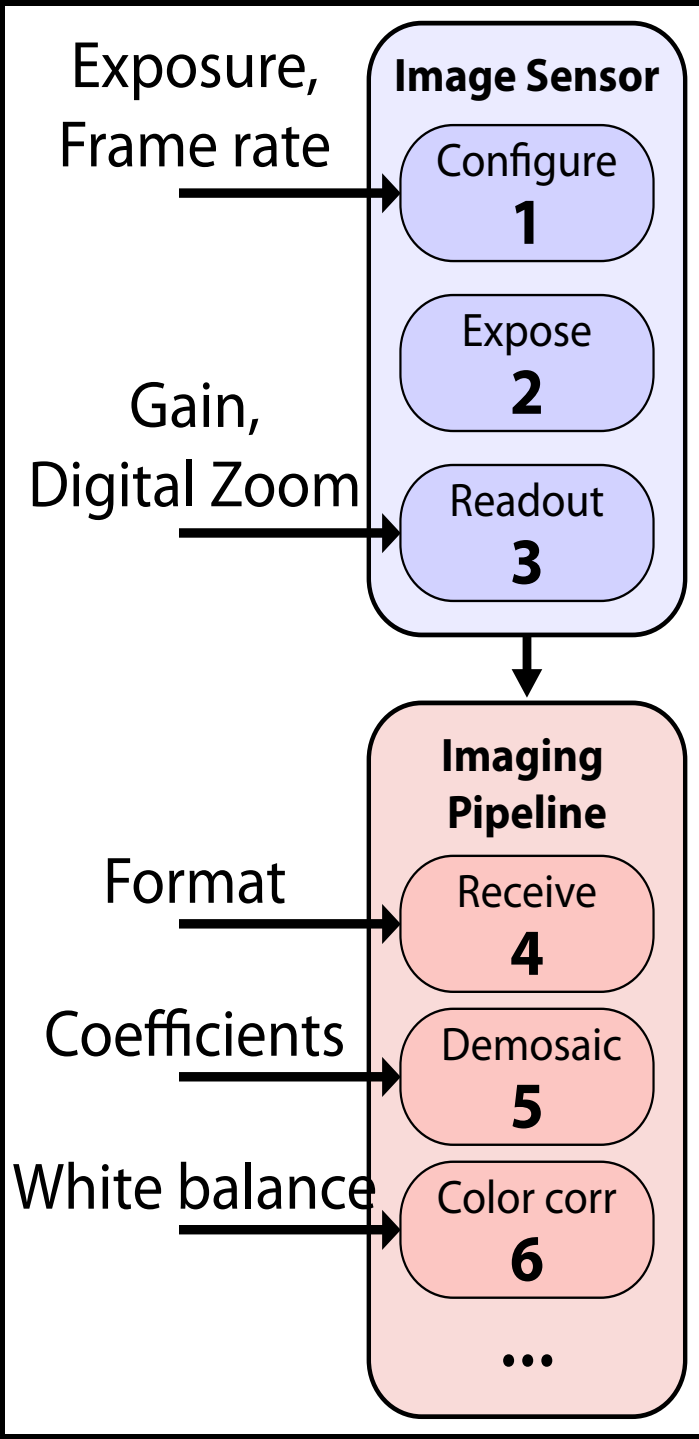


Alternatives?

- JPEG 2000
  - ISO, 2000
  - better compression, inherently hierarchical, random access, …
  - but much more complex than JPEG
- JPEG XR
  - Microsoft, 2006; ISO / ITU-T, 2010
  - good compression, supports tiling (random access without having to decode whole image), better color accuracy (incl. HDR), transparency, compressed domain editing
- But JPEG stays
  - too large an install base

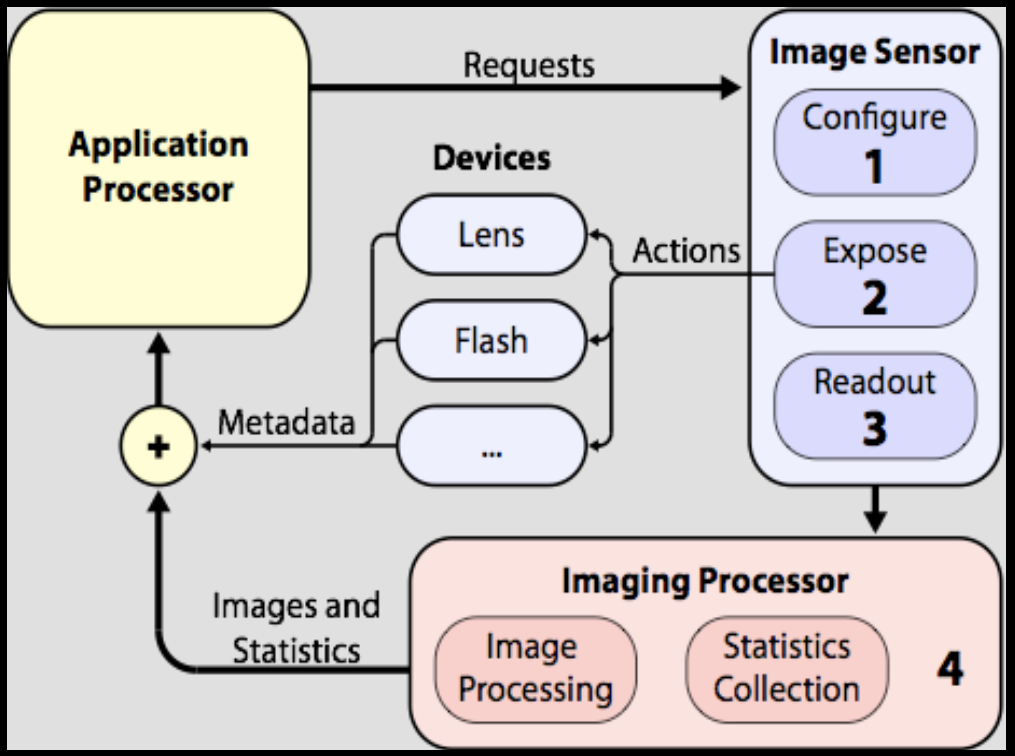
Traditional camera APIs

- Real image sensors are pipelined
  - while one frame exposing
  - next one is being prepared
  - previous one is being read out
- Viewfinding / video mode:
  - pipelined, high frame rate
  - settings changes take effect sometime later
- Still capture mode:
  - need to know which parameters were used
  - → reset pipeline between shots → slow



The FCam Architecture

- A software architecture for programmable cameras
  - that attempts to expose the maximum device capabilities
  - while remaining easy to program



Sensor

- A pipeline that converts requests into images
- No global state
  - state travels in the requests through the pipeline
  - all parameters packed into the requests

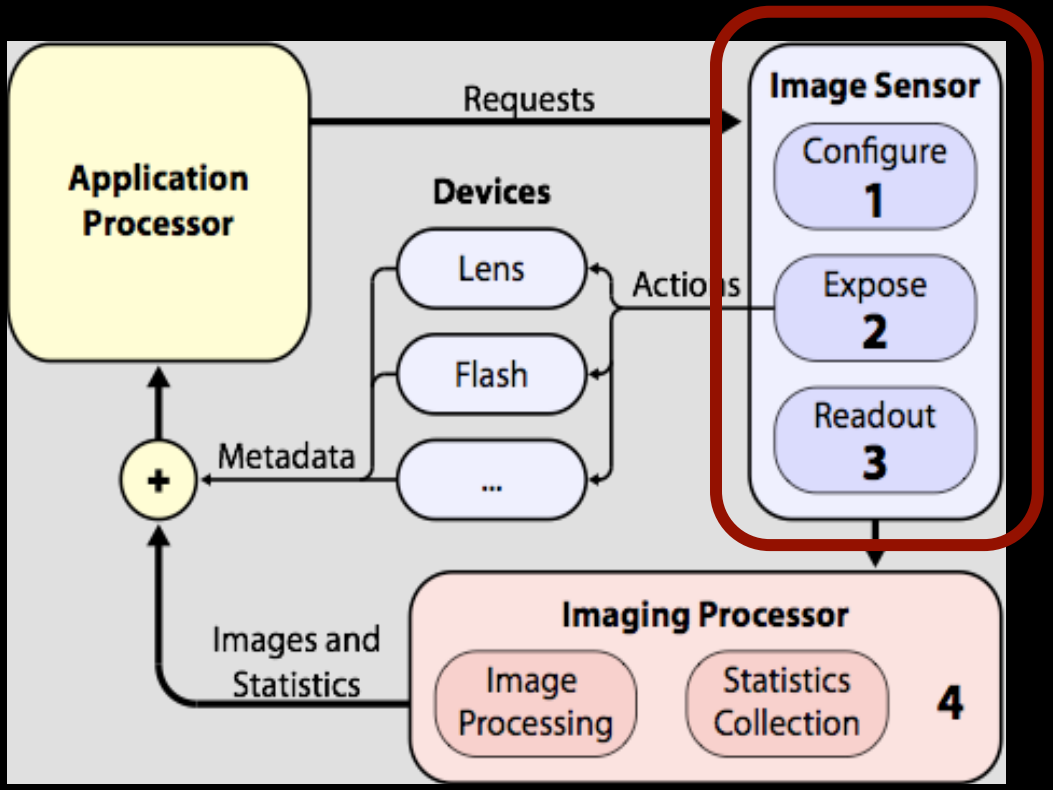
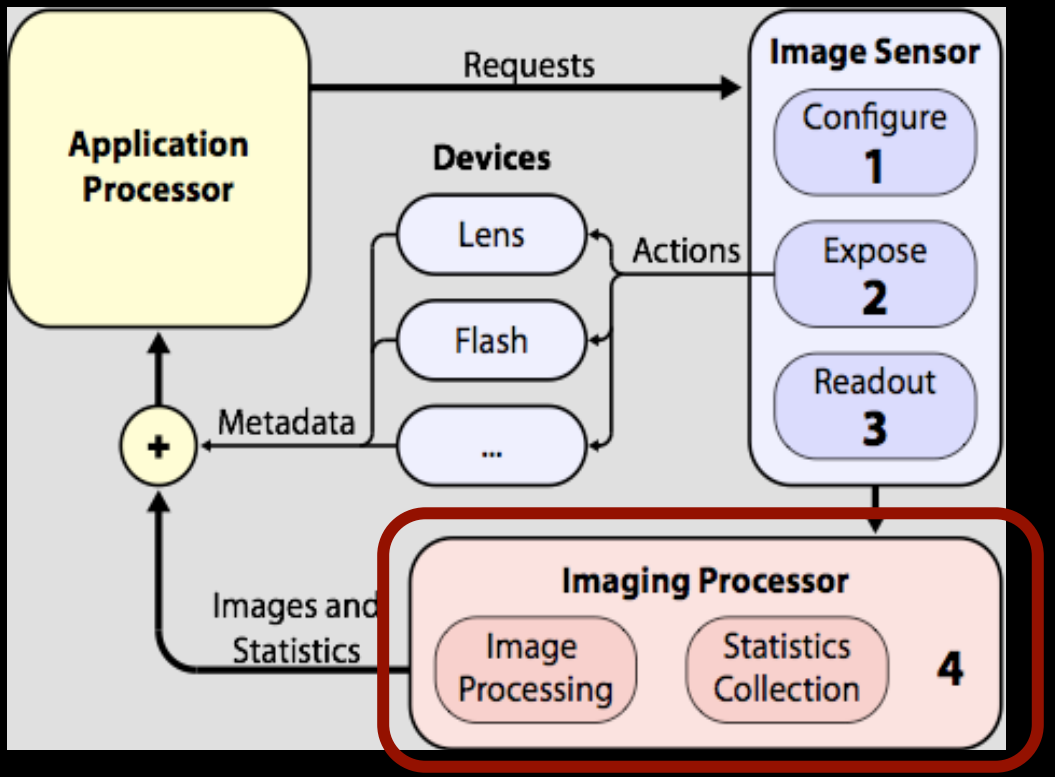


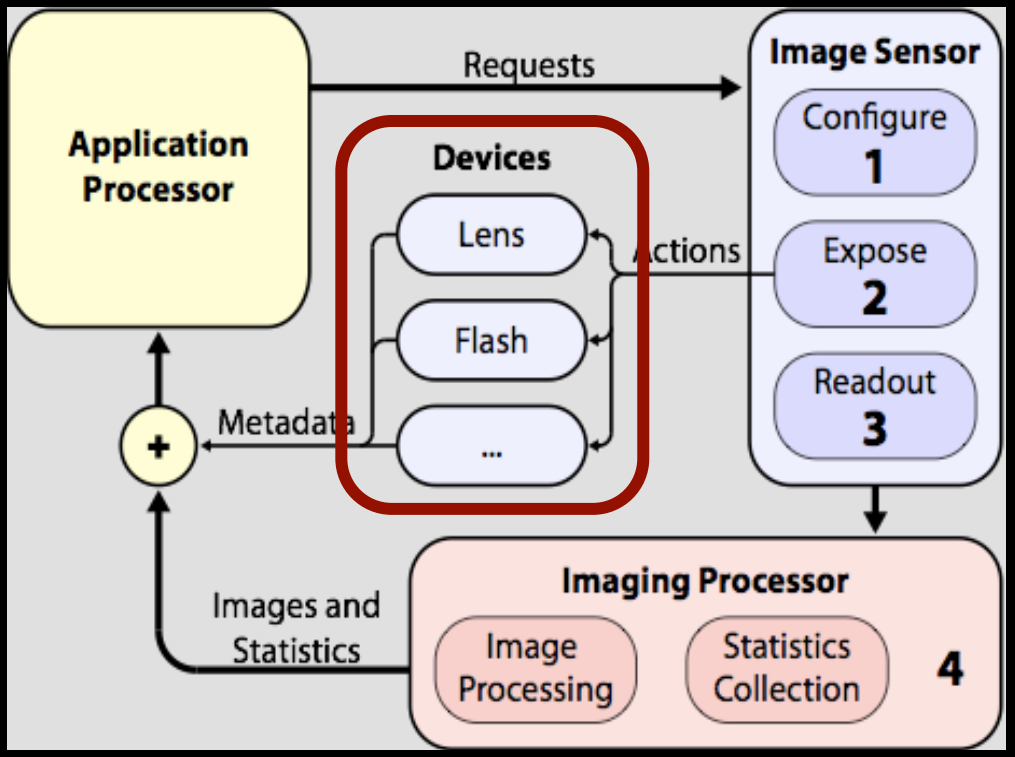
Image Signal Processor (ISP)

- Receives sensor data, and optionally transforms it
  - untransformed raw data must also be available
- Computes helpful statistics
  - histograms, sharpness maps



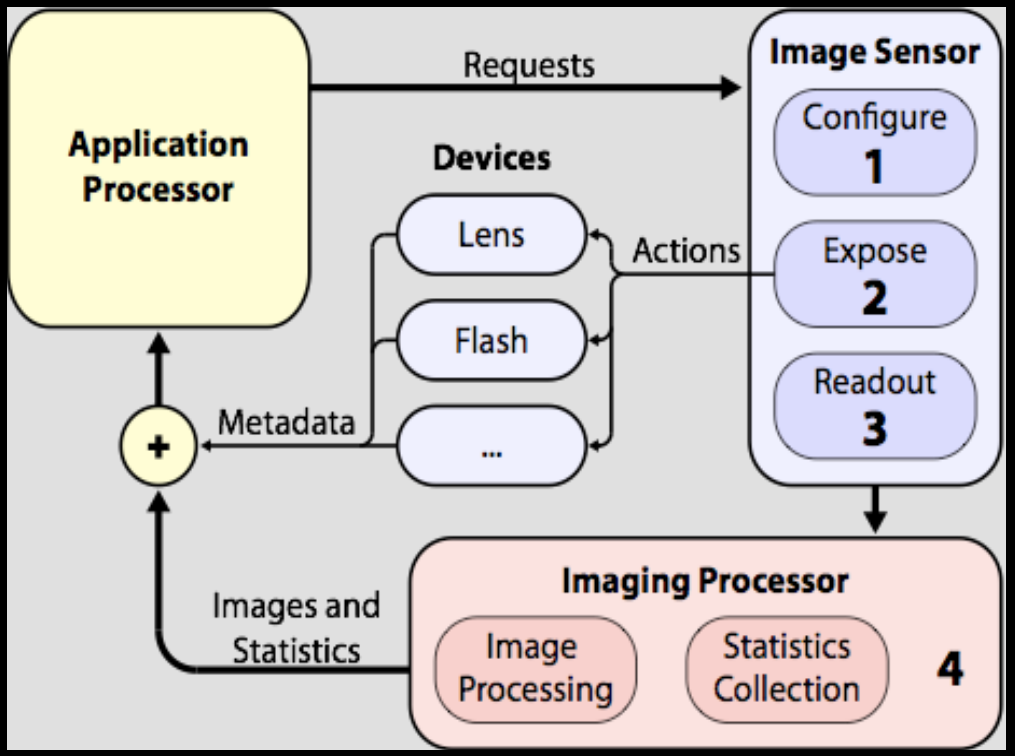
Devices

- Devices (like the Lens and Flash) can
  - schedule Actions
    - to be triggered at a given time into an exposure
  - Tag returned images with metadata



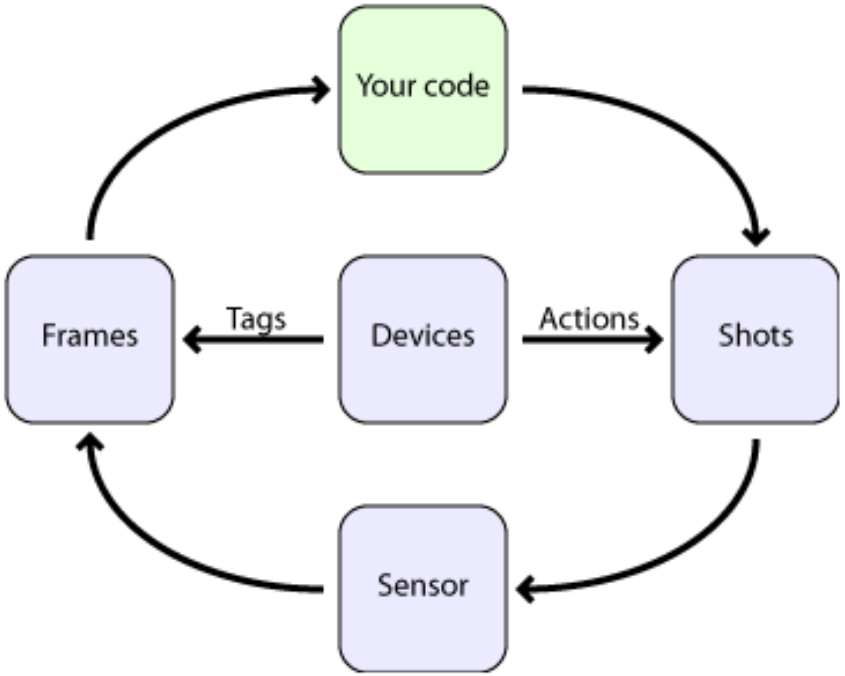
Everything is visible

- Programmer has full control over sensor settings
  - and access to the supplemental statistics from ISP
- No hidden daemon running autofocus/metering
  - nobody changes the settings under you



FCam: An API for controlling computational cameras.

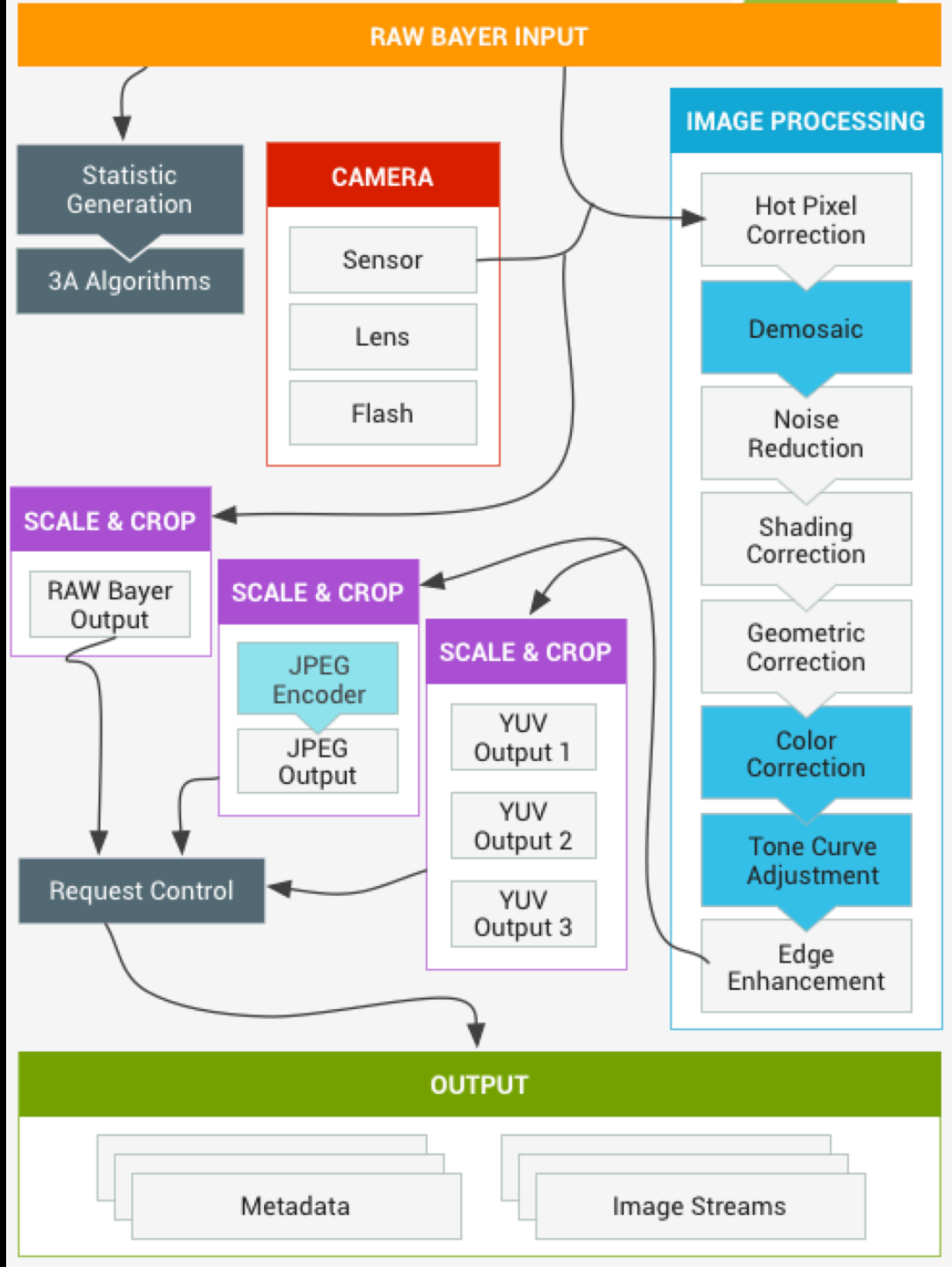
The **FCam** API provides mechanisms to control various components of a camera to facilitate complex photographic applications.



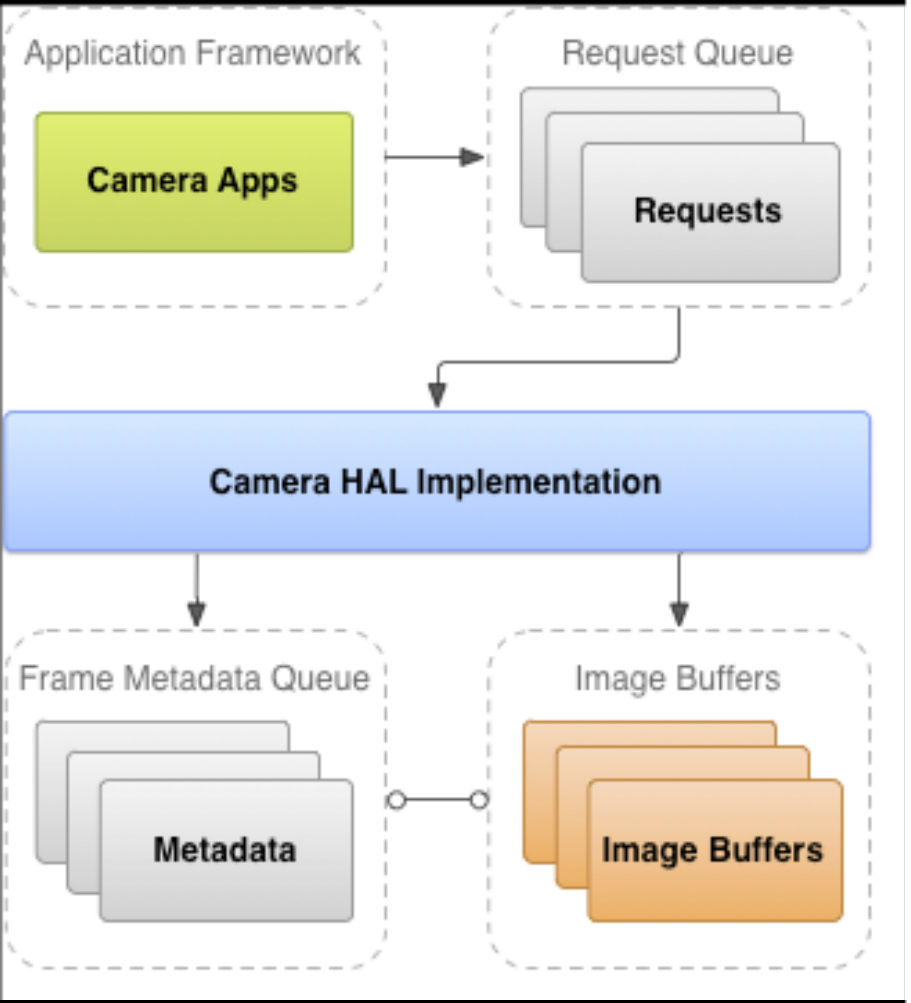
To use the **FCam**, you pass **Shots** to a **Sensor** which asynchronously returns **Frames**. A **Shot** completely specifies the capture and post-processing parameters of a single photograph, and a **Frame** contains the resulting image, along with supplemental hardware-generated statistics like a **Histogram** and **SharpnessMap**. You can tell **Devices** (like **Lenses** or **Flashes**) to schedule **Actions** (like **firing the flash**) to occur at some number of microseconds into a **Shot**. If timing is unimportant, you can also just tell **Devices** to do their thing directly from your code. In either case, **Devices** add tags to returned **Frames** (like the position of the **Lens** for that **Shot**). Tags are key-value pairs, where the key is a string like "focus" and the value is a **TagValue**, which can represent one of a number of types.

Android Camera Architecture

http://source.android.com/devices/camera/index.html

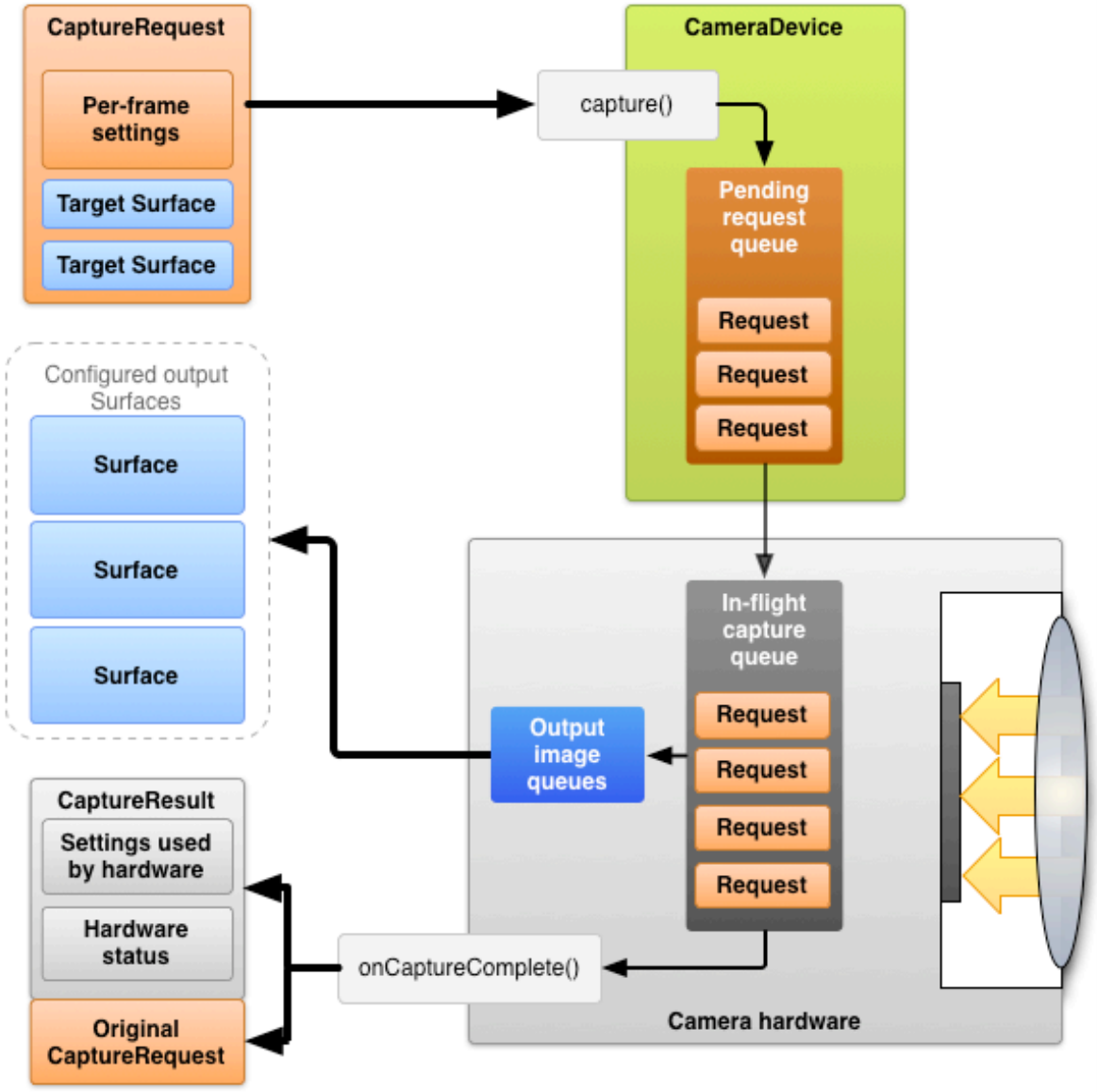


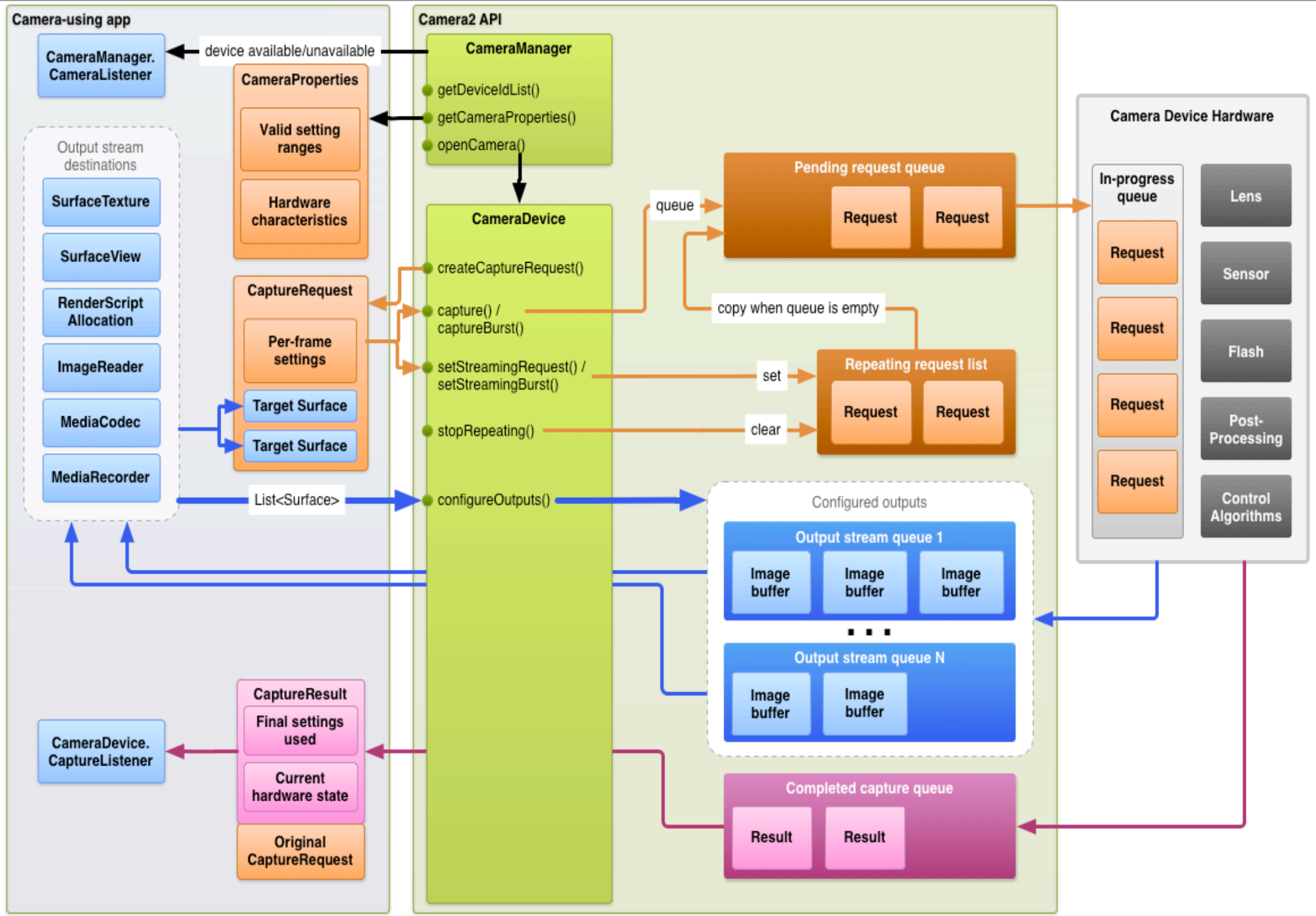
HAL v3

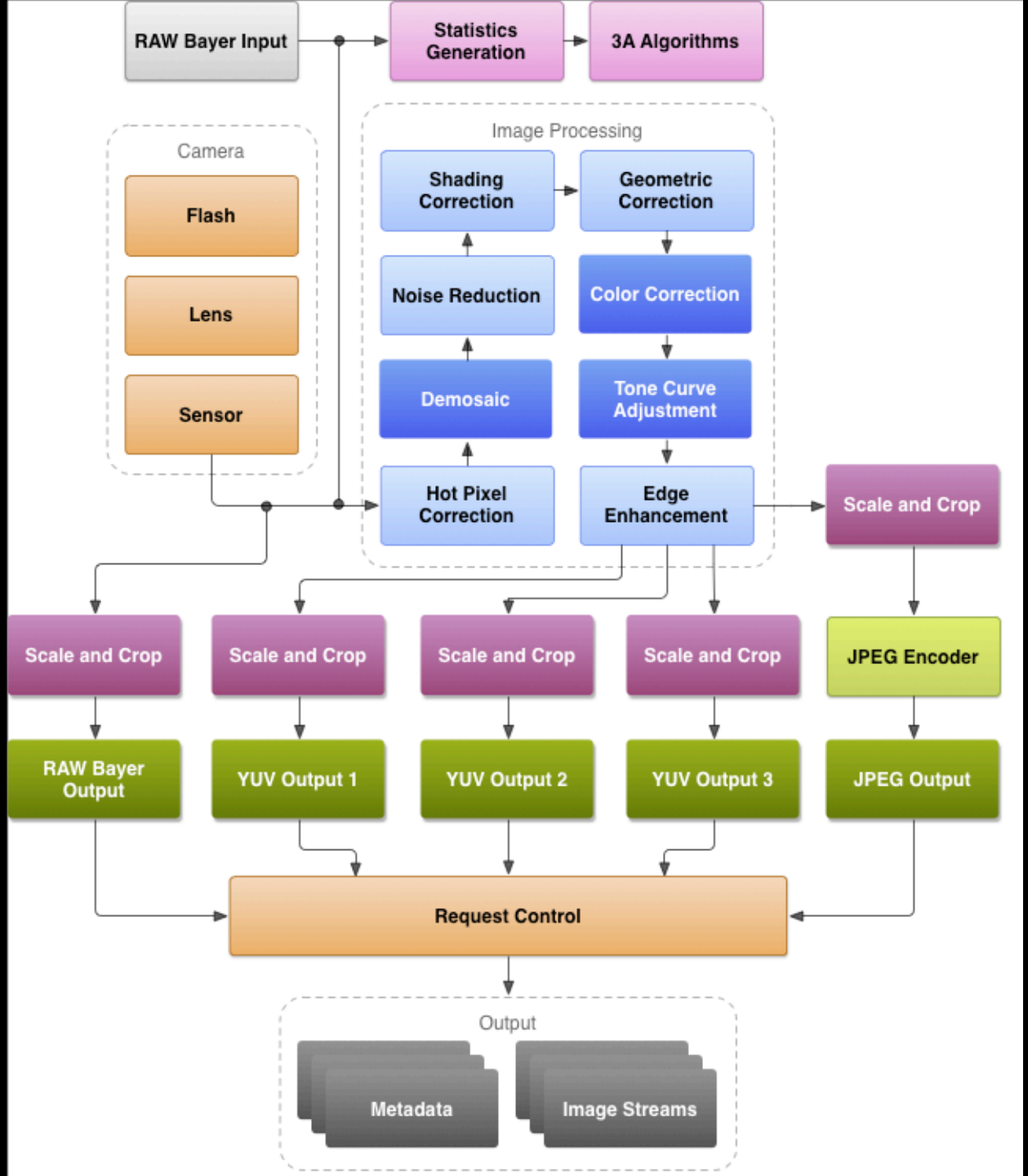


Camera2 API Core Operation Model

1 Request ⟹ 1 image captured ⟹
1 Result metadata + N image buffers




Camera-using app
CameraManager.
CameraListener
device available/unavailable
Camera2 API
CameraManager
getDeviceIdList()
getCameraProperties()
openCamera()
CameraProperties
Valid setting ranges
Hardware characteristics
Output stream destinations
SurfaceTexture
SurfaceView
RenderScript Allocation
ImageReader
MediaCodec
MediaRecorder
CaptureRequest
Per-frame settings
Target Surface
Target Surface
List<Surface>
CameraDevice
createCaptureRequest()
capture() / captureBurst()
setStreamingRequest() / setStreamingBurst()
stopRepeating()
configureOutputs()
queue
Pending request queue
Request
Request
copy when queue is empty
set
clear
Repeating request list
Request
Request
Camera Device Hardware
In-progress queue
Request
Request
Request
Request
Lens
Sensor
Flash
Post-Processing
Control Algorithms
Configured outputs
Output stream queue 1
Image buffer
Image buffer
Image buffer
Output stream queue N
Image buffer
Image buffer
CaptureResult
Final settings used
Current hardware state
Original CaptureRequest
CameraDevice.
CaptureListener
Completed capture queue
Result
Result


RAW Bayer Input
Statistics Generation
3A Algorithms
Camera
Flash
Lens
Sensor
Image Processing
Shading Correction
Geometric Correction
Noise Reduction
Color Correction
Demosaic
Tone Curve Adjustment
Hot Pixel Correction
Edge Enhancement
Scale and Crop
Scale and Crop
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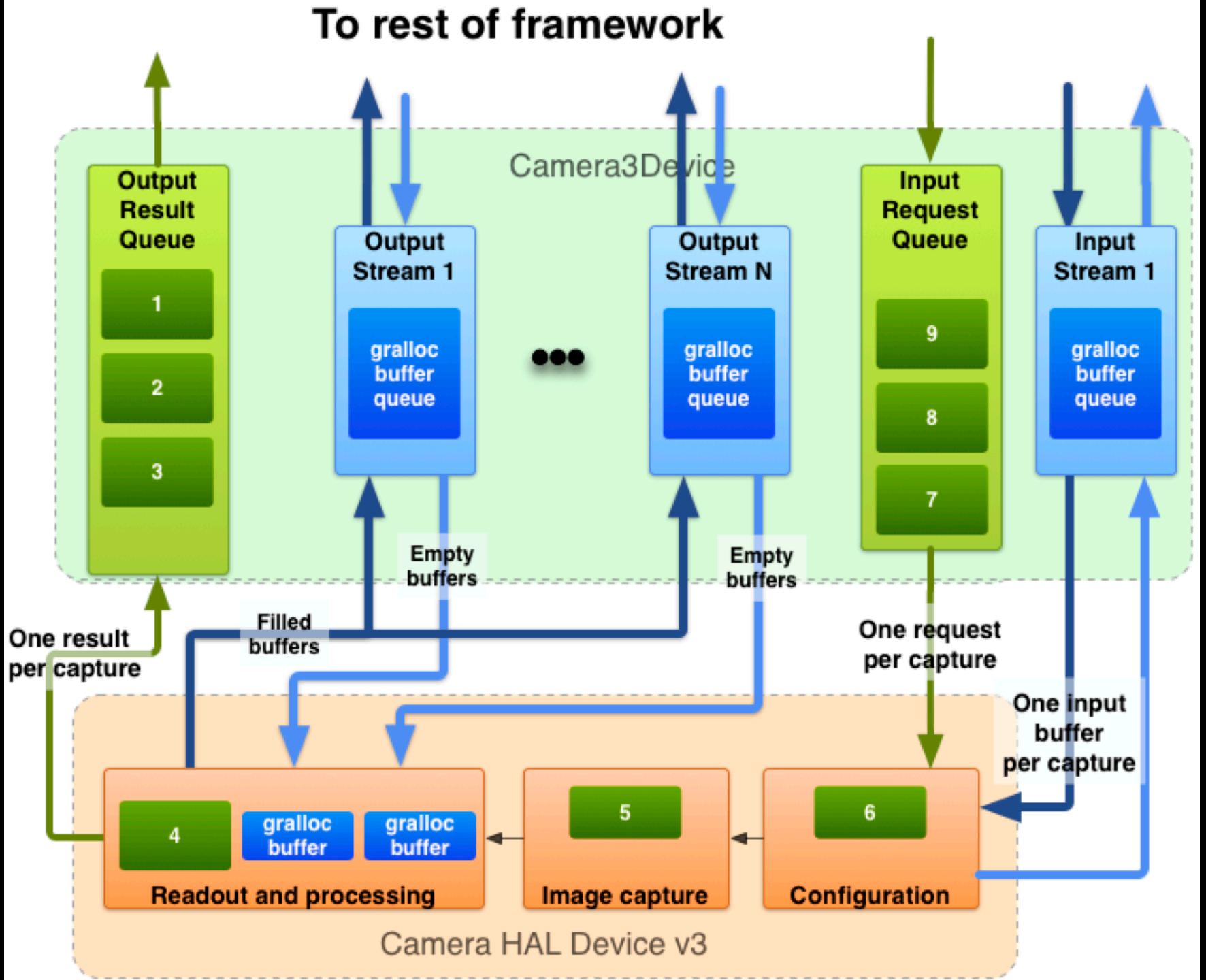
Scale and Crop
Scale and Crop
JPEG Encoder
RAW Bayer Output
YUV Output 1
YUV Output 2
YUV Output 3
JPEG Output
Request Control
Output
Metadata
Image Streams


To rest of framework
Camera3Device
Output Result Queue
1
2
3
Output Stream 1
gralloc buffer queue
Output Stream N
gralloc buffer queue
Input Request Queue
9
8
7
Input Stream 1
gralloc buffer queue
Empty buffers
Empty buffers
Filled buffers
One result per capture
One request per capture
One input buffer per capture
4
gralloc buffer
gralloc buffer
Readout and processing
5
Image capture
6
Configuration
Camera HAL Device v3