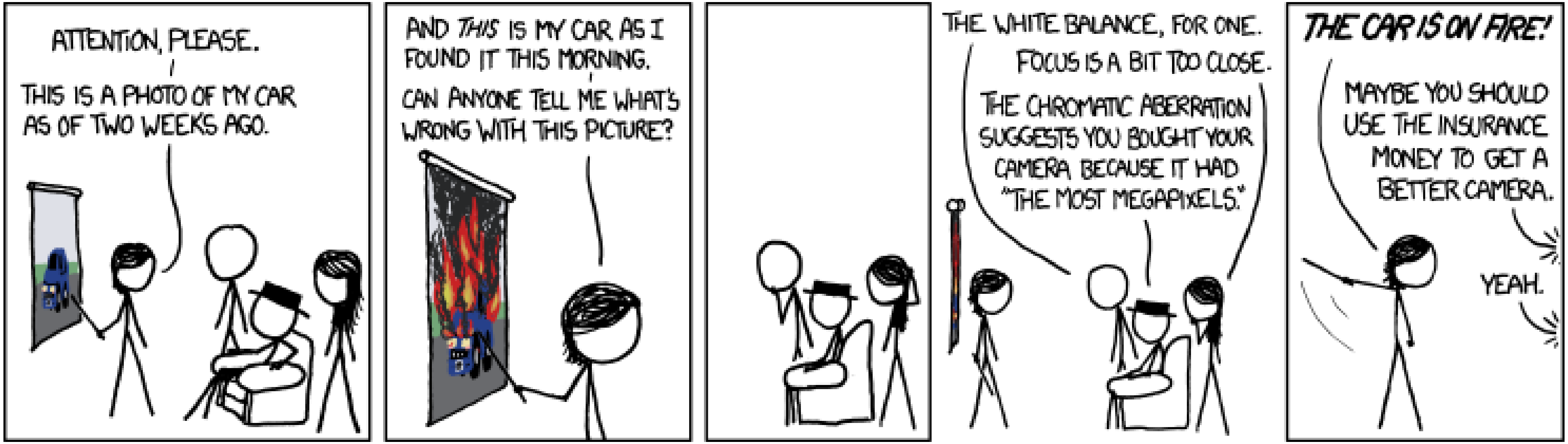
Digital photography



15-463, 15-663, 15-862
Computational Photography
Fall 2018, Lecture 2

http://graphics.cs.cmu.edu/courses/15-463

Course announcements

- To the 26 students who took the start-of-semester survey: Thanks!
- The other 14 students who didn't: Please do so before the next lecture!
- Waitlist issues will (probably) be resolved next week.
- No lecture on Monday (Labor day).
- Homework 1 will be posted on Friday, will be due September 14^{th} at midnight.
- Readings will be listed on slides as references.
- Office hours *for this week only* (will finalize them after more people have taken the survey):
  Alankar – Thursday 2-4 pm, Smith Hall 220.
  Yannis – Friday 3-5 pm, Smith Hall 225.

Course announcements

- Is there anyone not on Piazza?

  https://piazza.com/class/jl5ah6igcqo1ez

- Is there anyone not on Canvas?

  https://canvas.cmu.edu/courses/7047

Overview of today's lecture

- Imaging sensor primer.
- Color primer.
- In-camera image processing pipeline.
- Some general thoughts on the image processing pipeline.

Take-home message: The values of pixels in a photograph and the values output by your camera's sensor are two very different things.

Slide credits

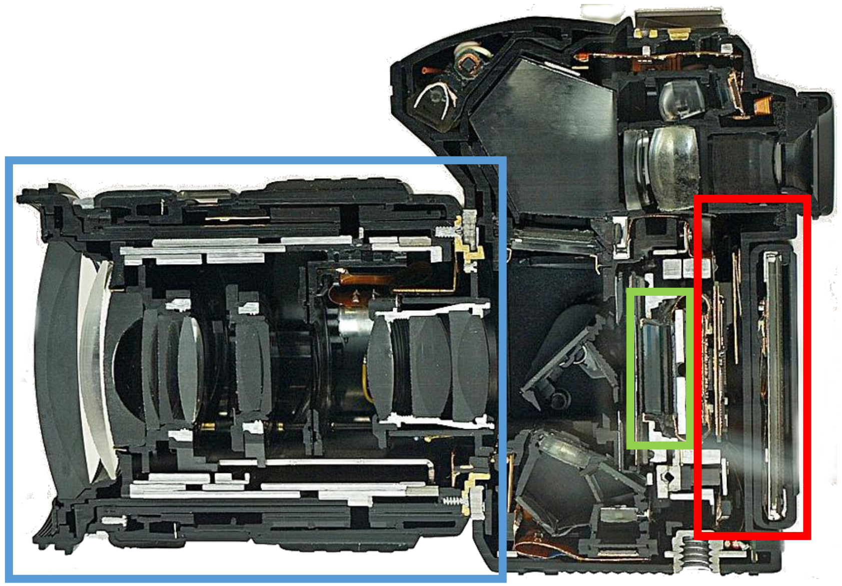
A lot of inspiration and quite a few examples for these slides were taken directly from:

- Kayvon Fatahalian (15-769, Fall 2016).
- Michael Brown (CVPR 2016 Tutorial on understanding the image processing pipeline).

The modern photography pipeline

The modern photography pipeline

post-capture processing
(lectures 5-10)



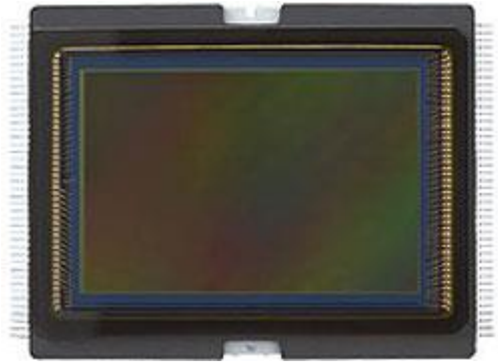
optics and optical controls → sensor, analog front-end, and color filter array → in-camera image processing pipeline

(lectures 2-3, 11-20) (today, lecture 23) (today)

Imaging sensor primer

Imaging sensors

- Very high-level overview of digital imaging sensors.
- We could spend an entire course covering imaging sensors.
- Lecture 23 will cover sensors and noise issues in more detail.

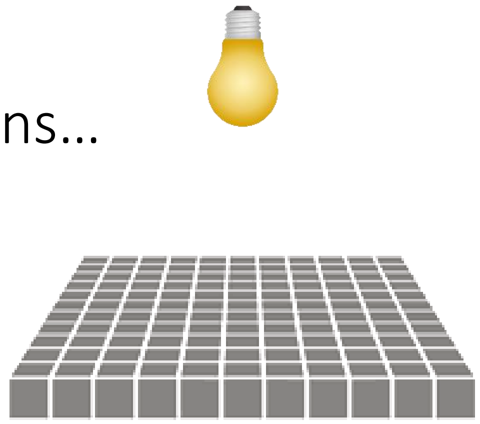


Canon 6D sensor
(20.20 MP, full-frame)

What does an imaging sensor do?

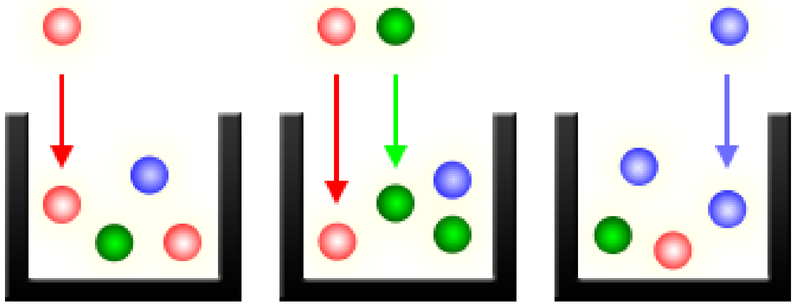
When the camera shutter opens…

… exposure begins…



array of photon buckets

photons

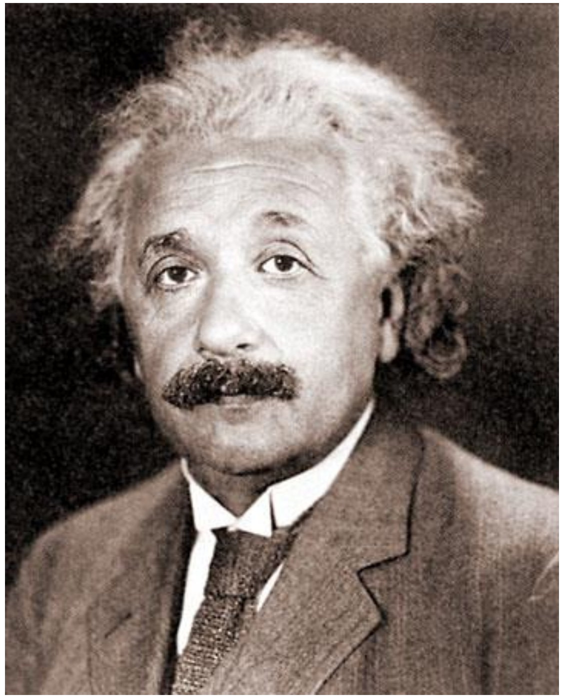


close-up view of photon buckets

… photon buckets begin to store photons...

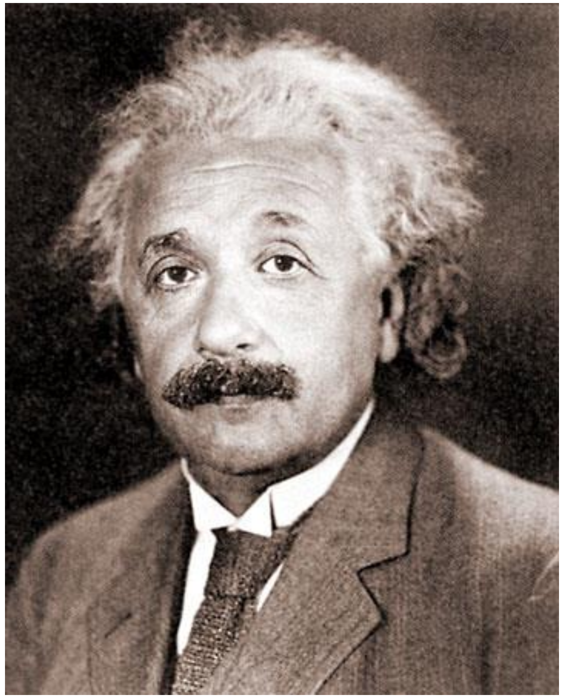
… until the camera shutter closes. Then, they convert stored photons to intensity values.

Nobel Prize in Physics



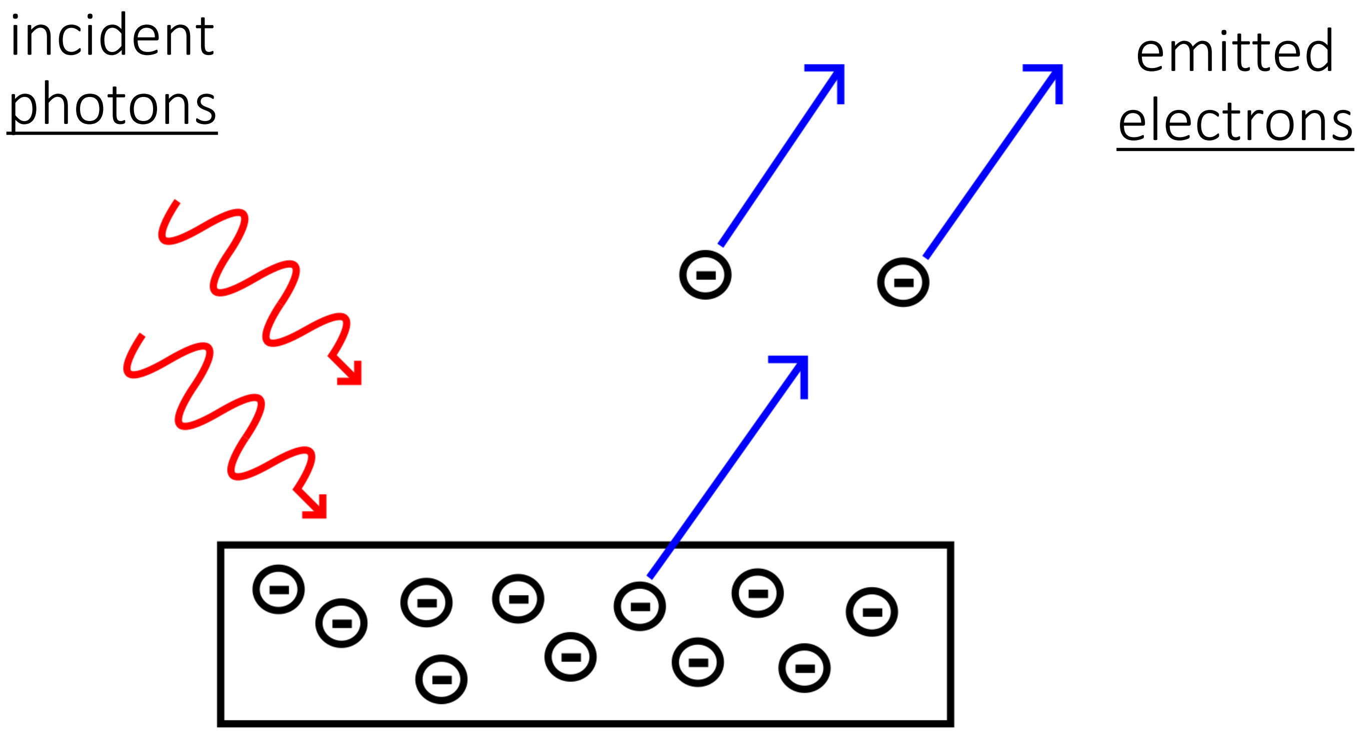
Who is this?

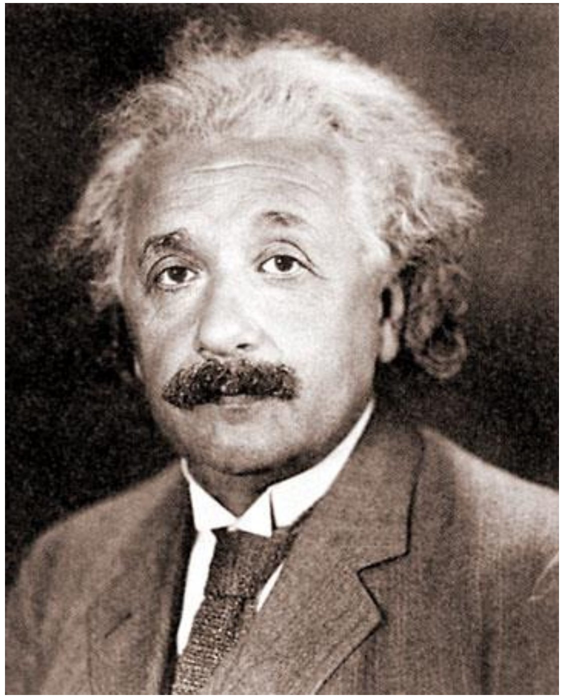
Nobel Prize in Physics



What is he known for?

Photoelectric effect

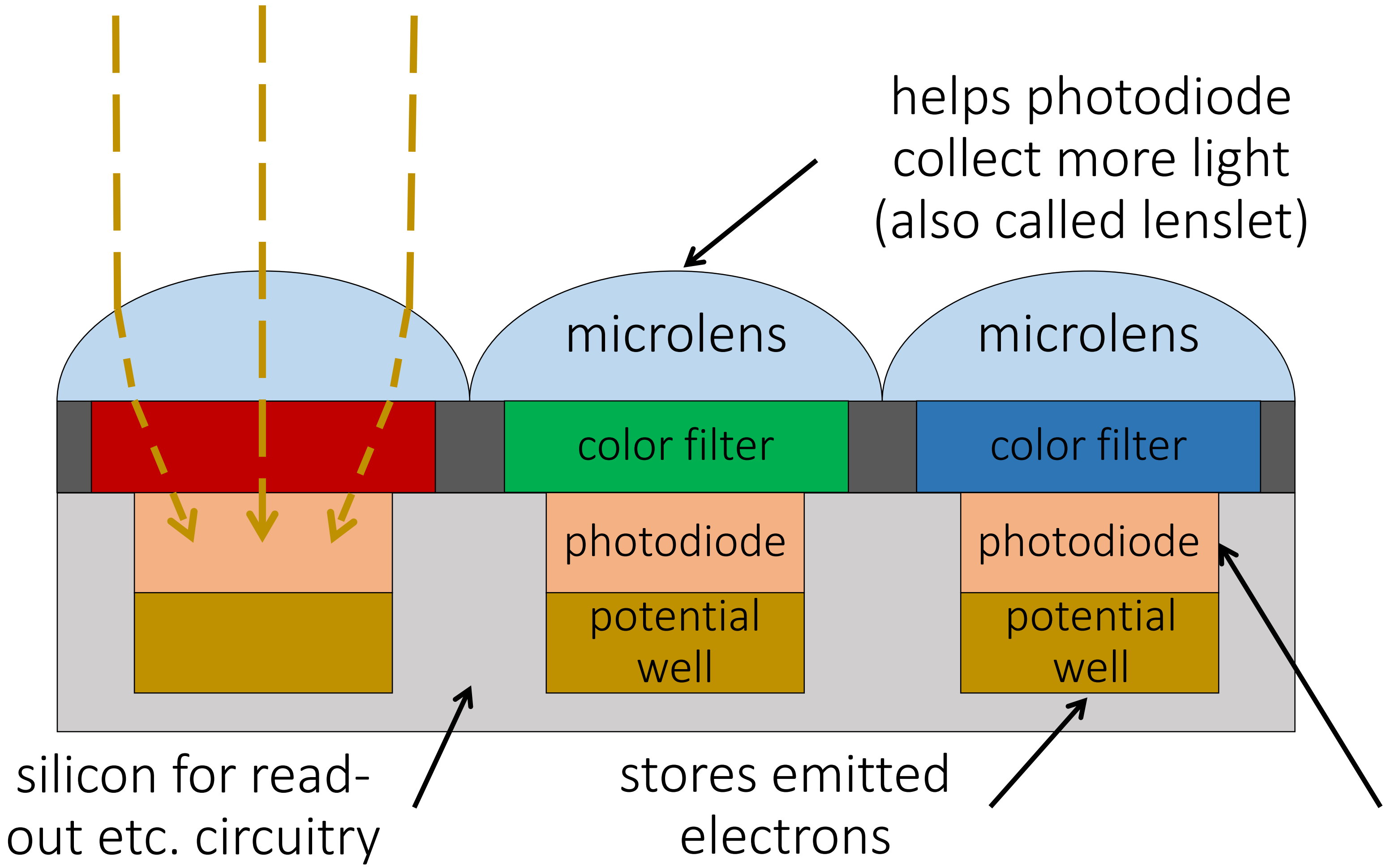




Albert Einstein

Einstein’s Nobel Prize in 1921 “for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect”

Basic imaging sensor design



- Lenslets also filter the image to avoid resolution artifacts.
- Lenslets are problematic when working with coherent light.
- Many modern cameras do not have lenslet arrays.

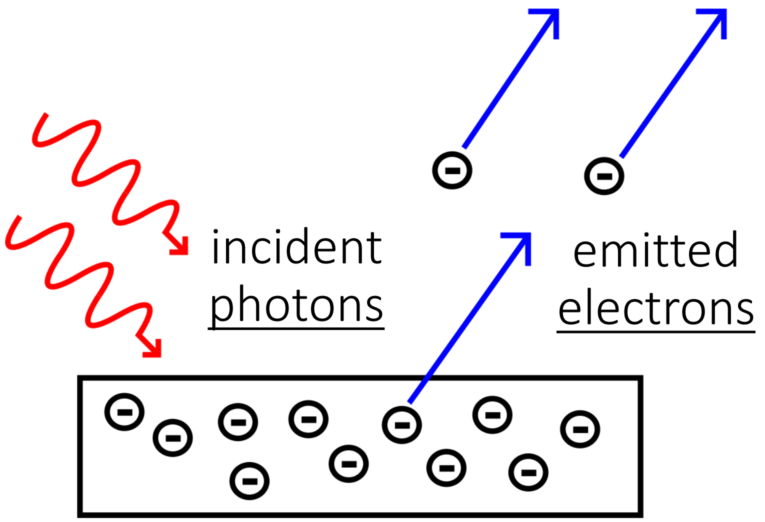
We will discuss these issues in more detail at a later lecture.

We will see what the color filters are for later in this lecture.

Photodiode quantum efficiency (QE)

How many of the incident photons will the photodiode convert into electrons?

$$QE = \frac{\#\ \text{electrons}}{\#\ \text{photons}}$$



- Fundamental optical performance metric of imaging sensors.
- Not the only important optical performance metric!
- We will see a few more later in the lecture.

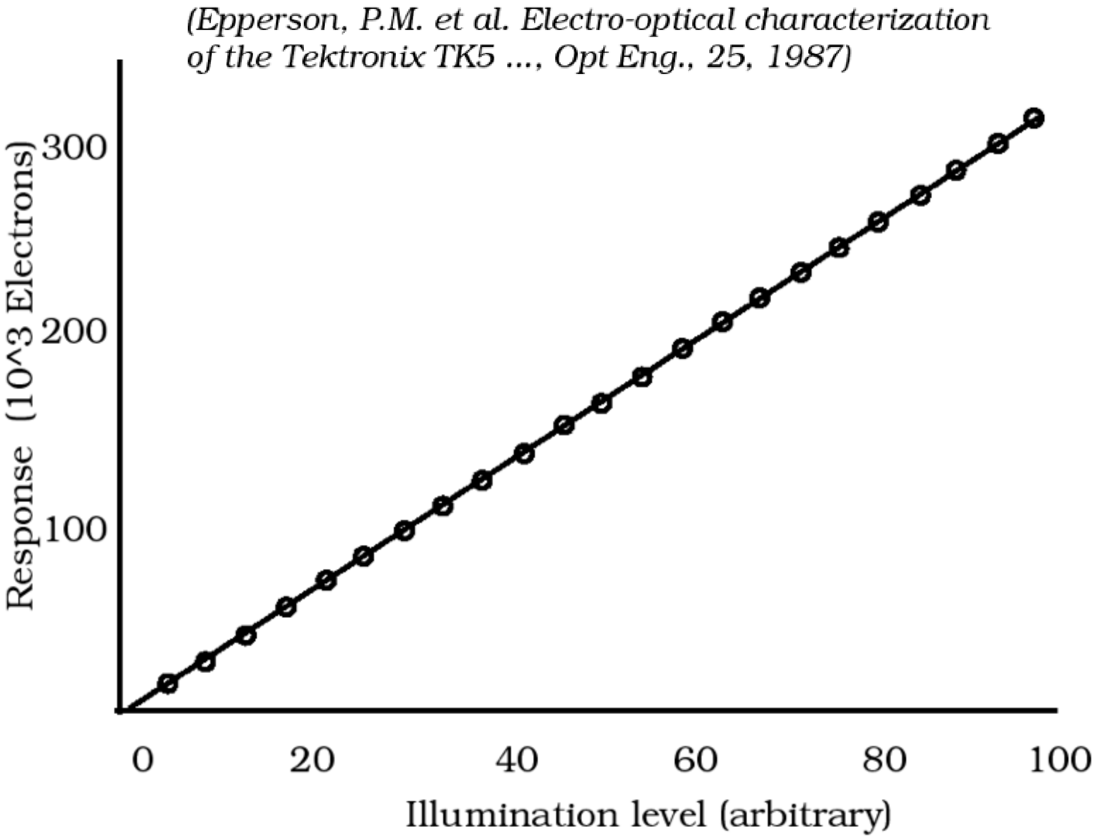
Photodiode response function

For silicon photodiodes, usually linear, but:

- non-linear when potential well is saturated (over-exposure)

- non-linear near zero (due to noise)

We will see how to deal with these issues in a later lecture (high-dynamic-range imaging).

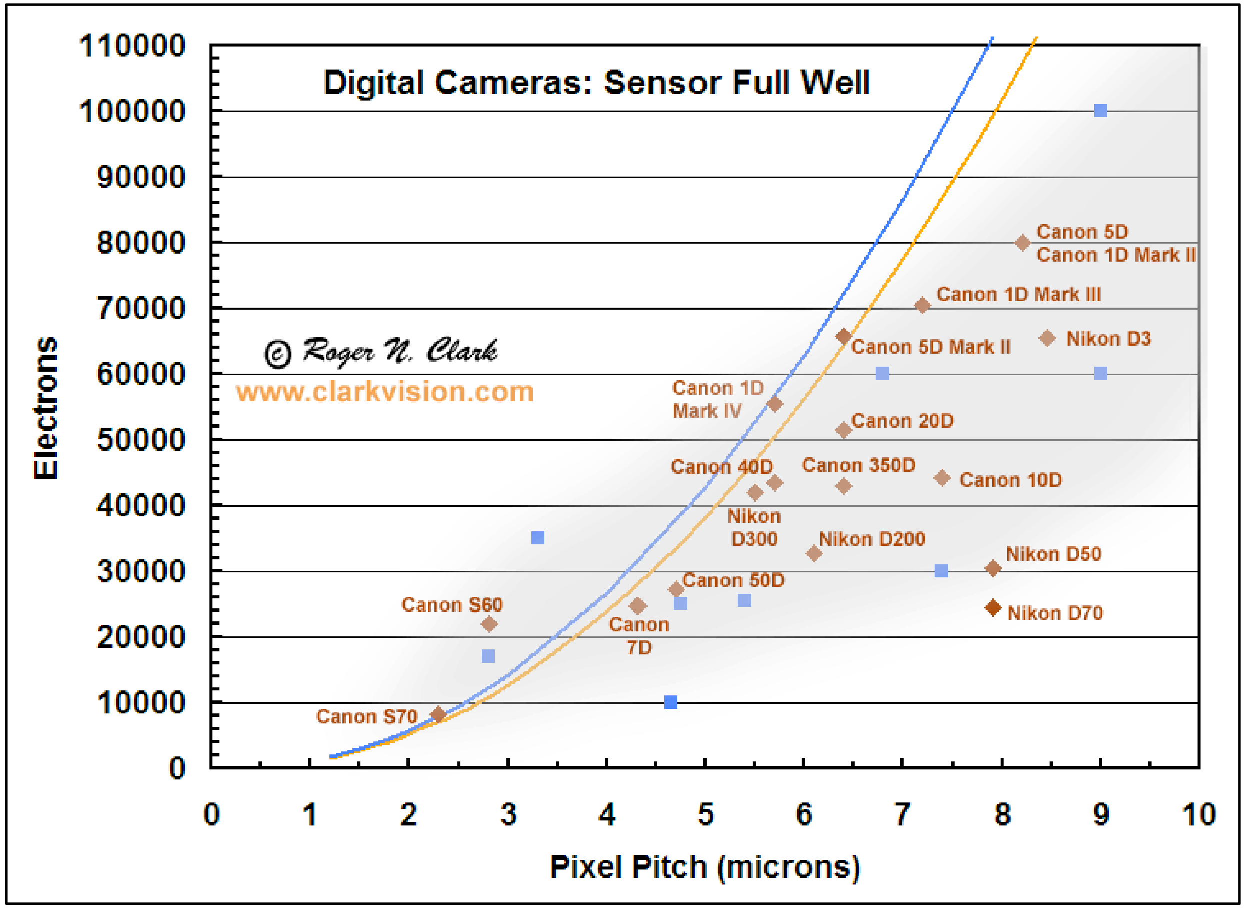


under-exposure (non-linearity due to sensor noise)

over-exposure (non-linearity due to sensor saturation)

Photodiode full well capacity

How many electrons can photodiode store before saturation?

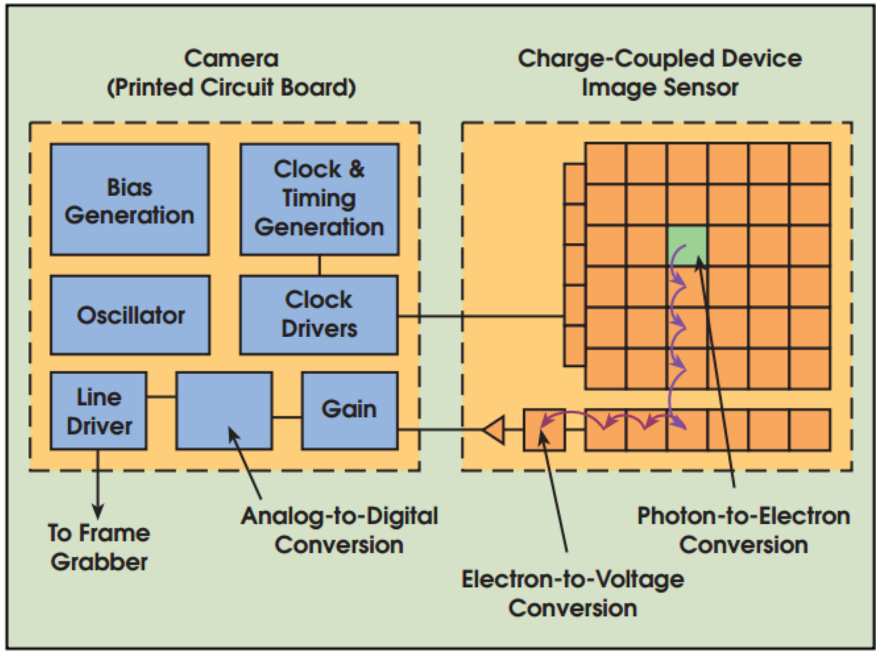


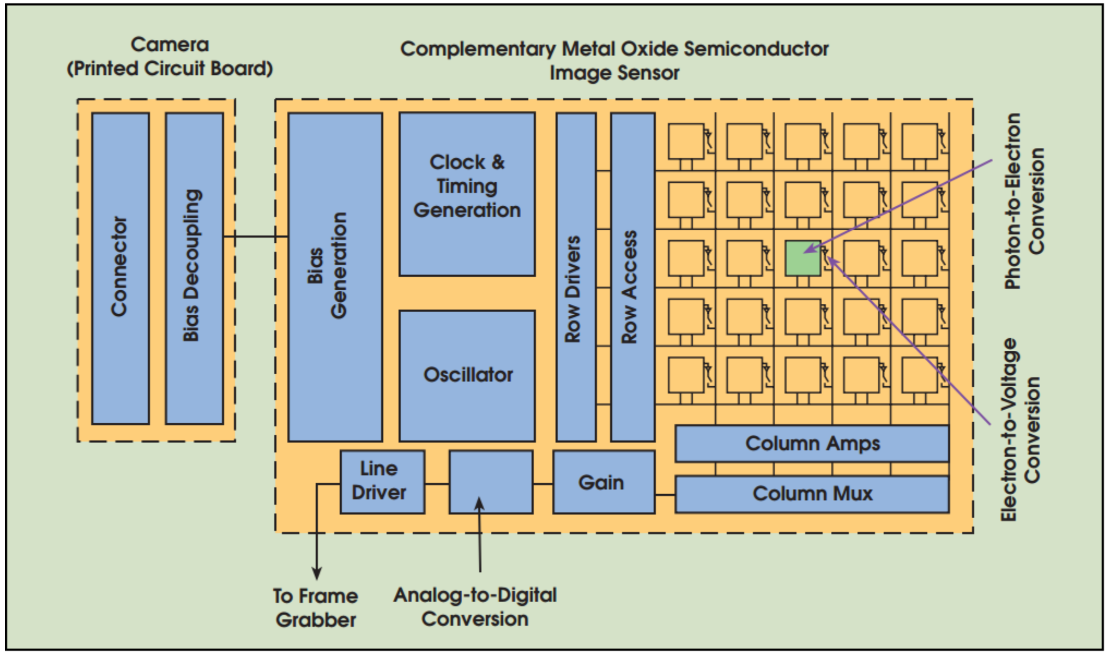
- Another important optical performance metric of imaging sensors.

Two main types of imaging sensors

Do you know them?

Two main types of imaging sensors



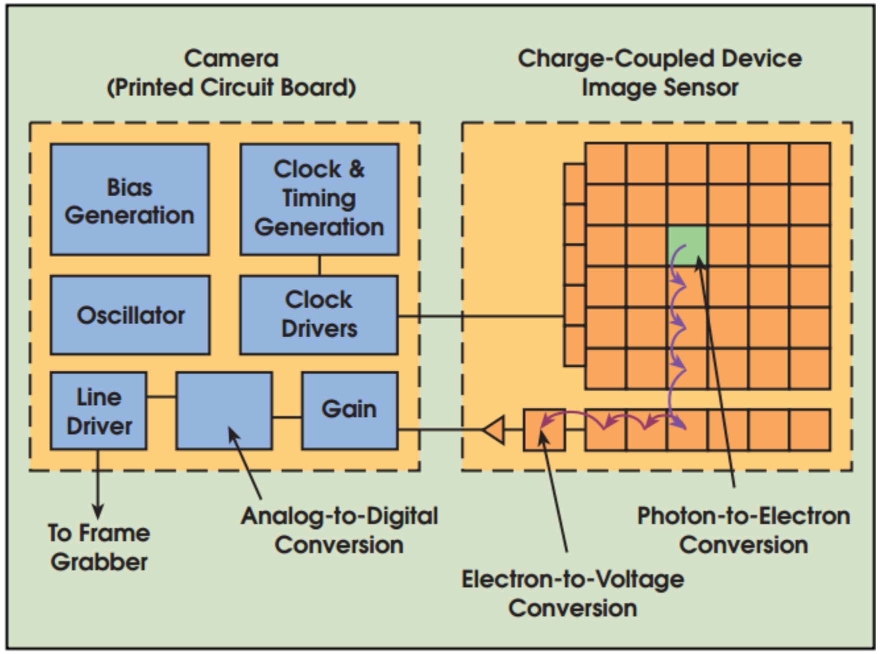


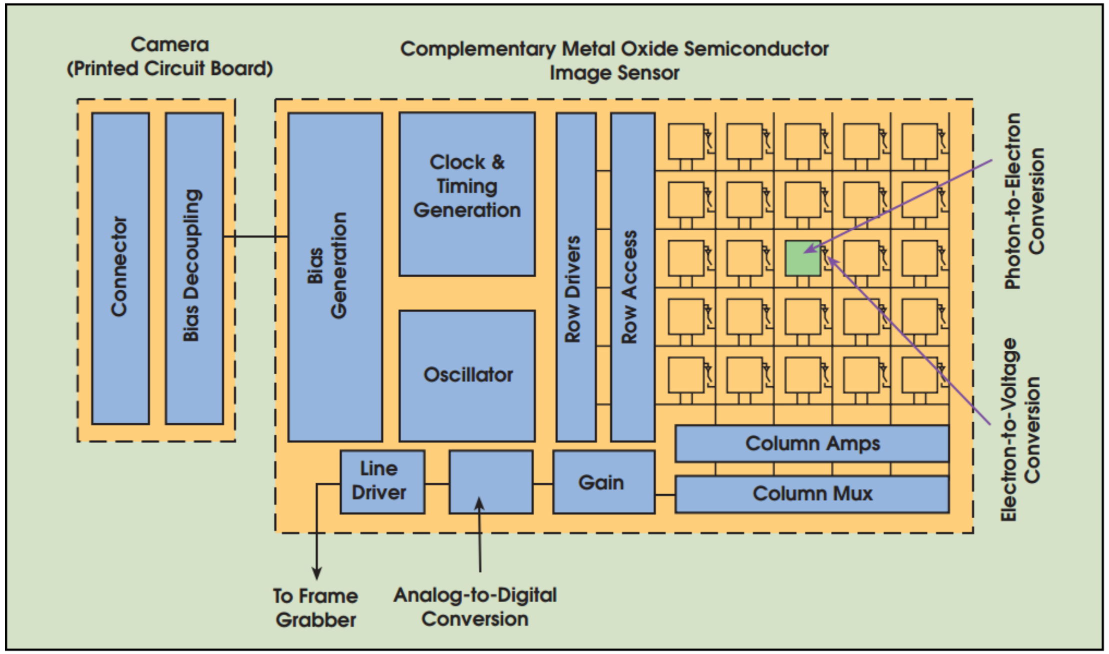
Charged Coupled Device (CCD): converts electrons to voltage using readout circuitry separate from pixel

Complementary Metal Oxide Semiconductor (CMOS): converts electrons to voltage using per-pixel readout circuitry

Can you think of advantages and disadvantages of each type?

Two main types of imaging sensors





Charged Coupled Device (CCD): converts electrons to voltage using readout circuitry separate from pixel

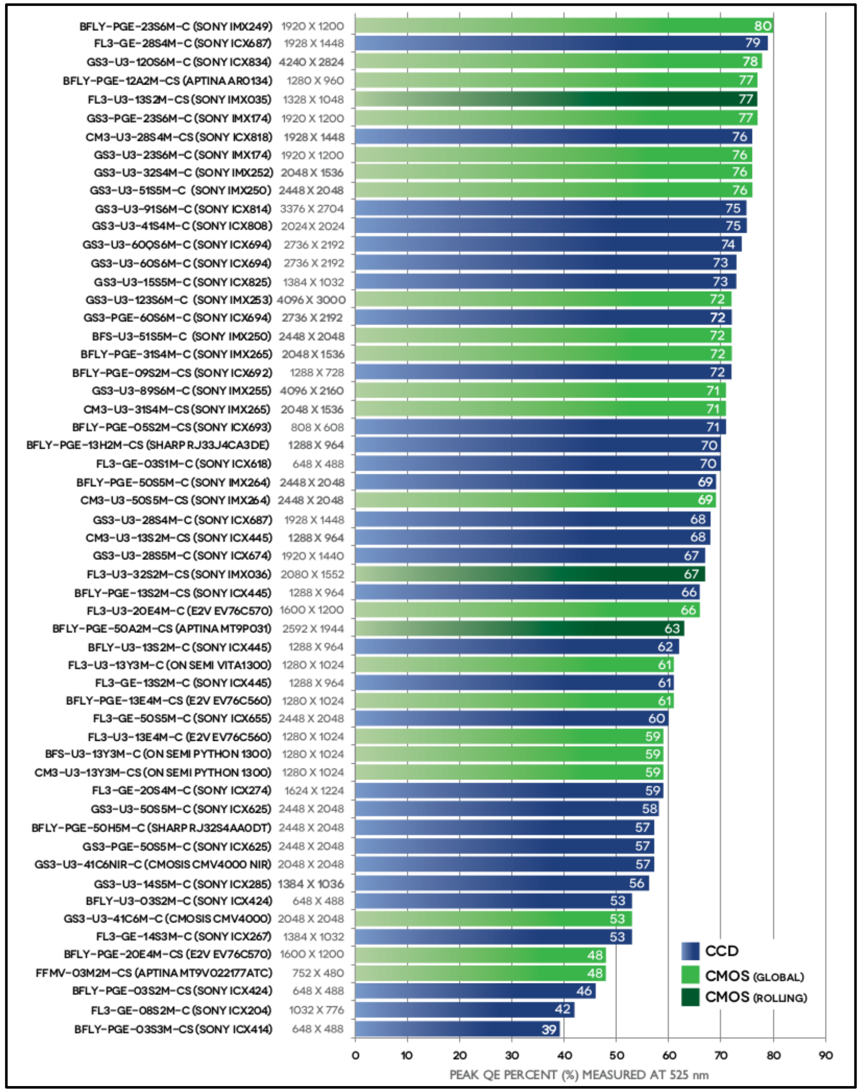
Complementary Metal Oxide Semiconductor (CMOS): converts electrons to voltage using per-pixel readout circuitry

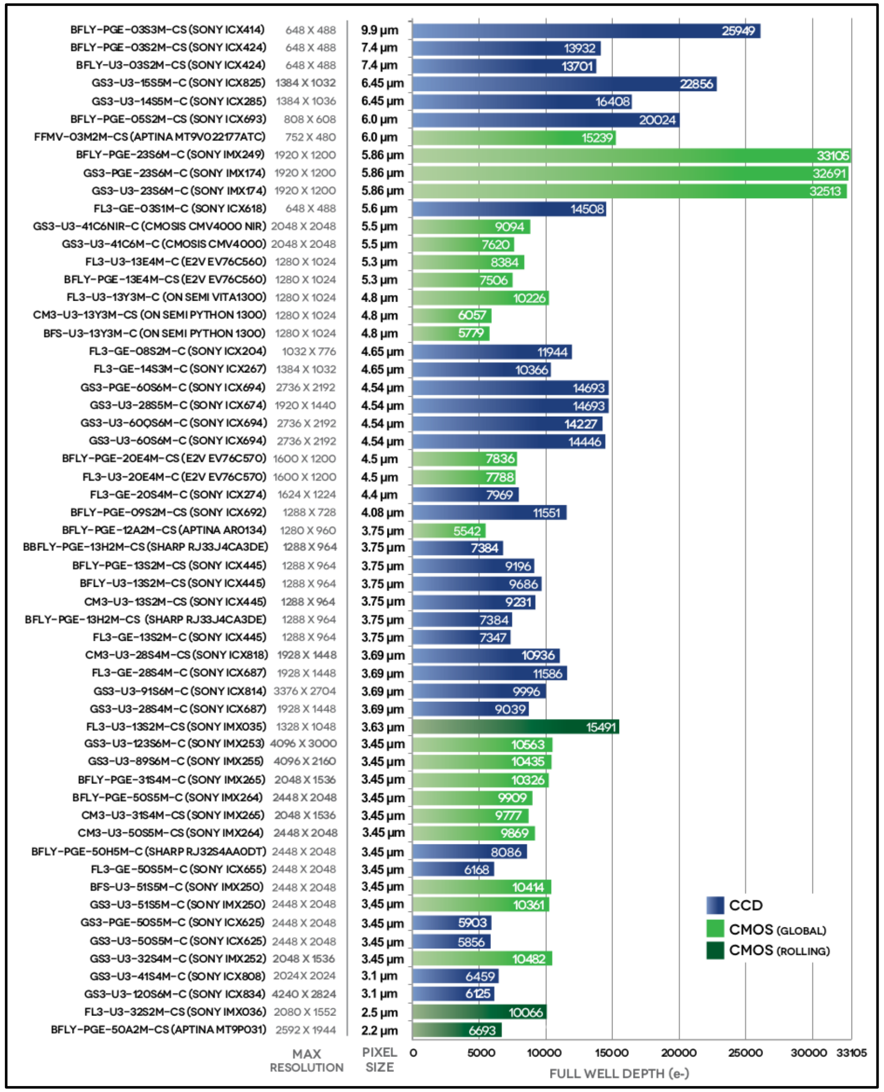
- ✓ higher sensitivity
- ✓ lower noise

- ✓ faster read-out
- ✓ lower cost

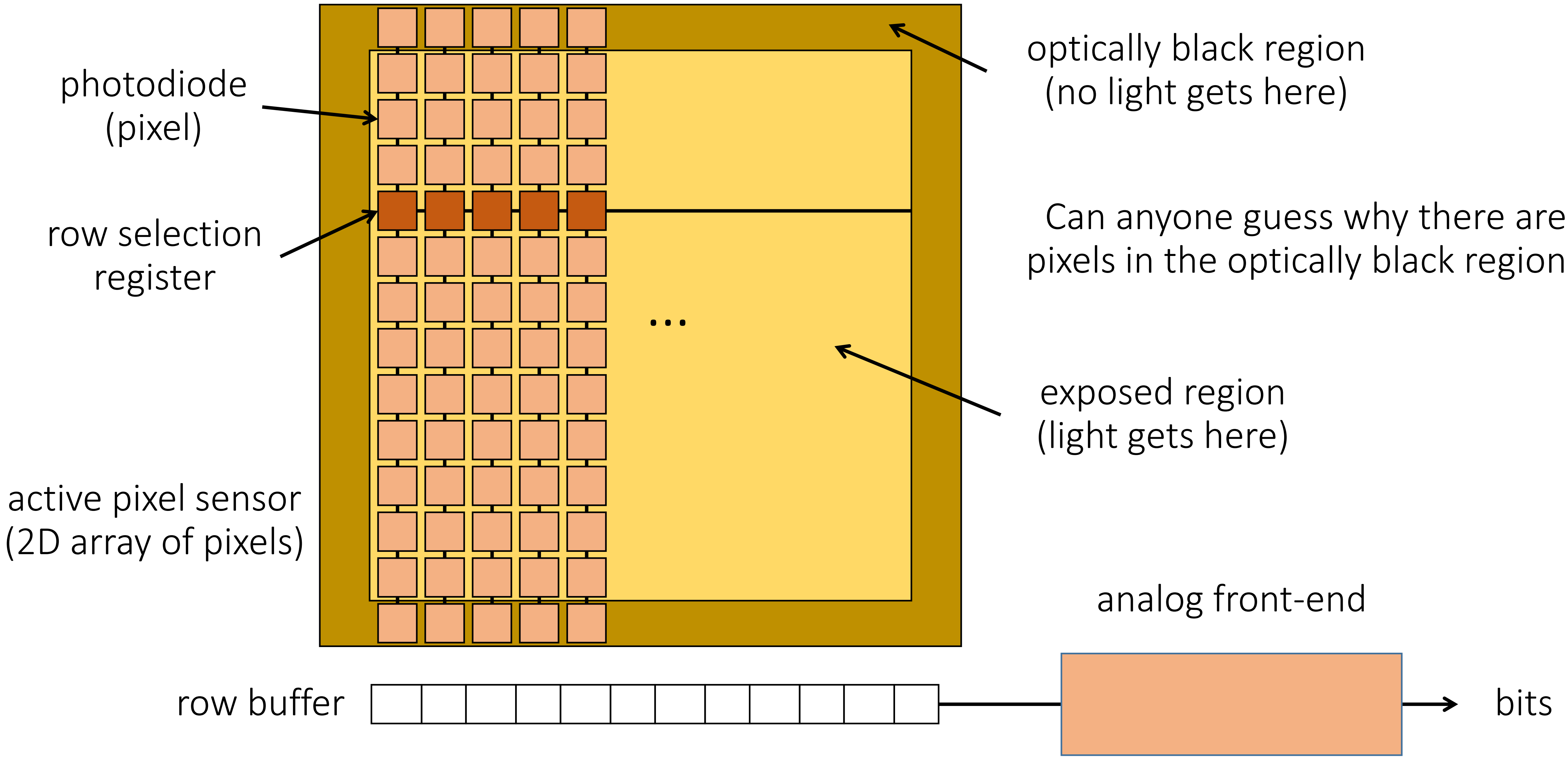
CCD vs CMOS

- Modern CMOS sensors have optical performance comparable to CCD sensors.
- Most modern commercial and industrial cameras use CMOS sensors.



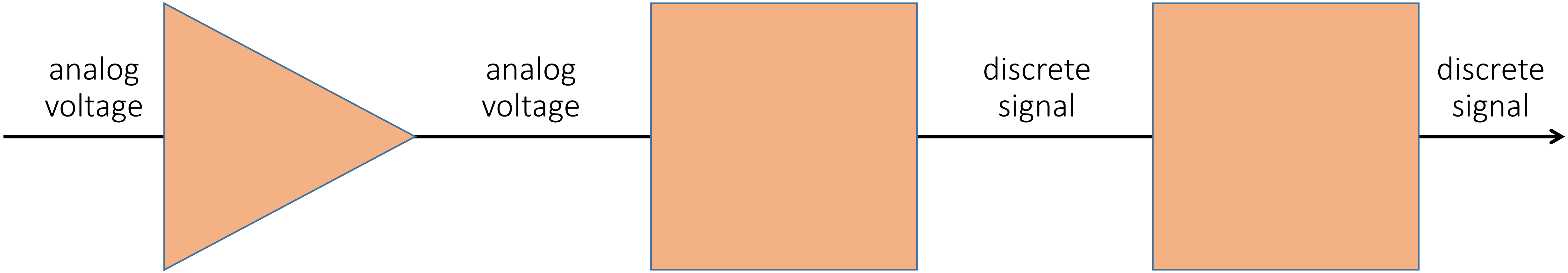


CMOS sensor (very) simplified layout



Can anyone guess why there are pixels in the optically black region?

Analog front-end



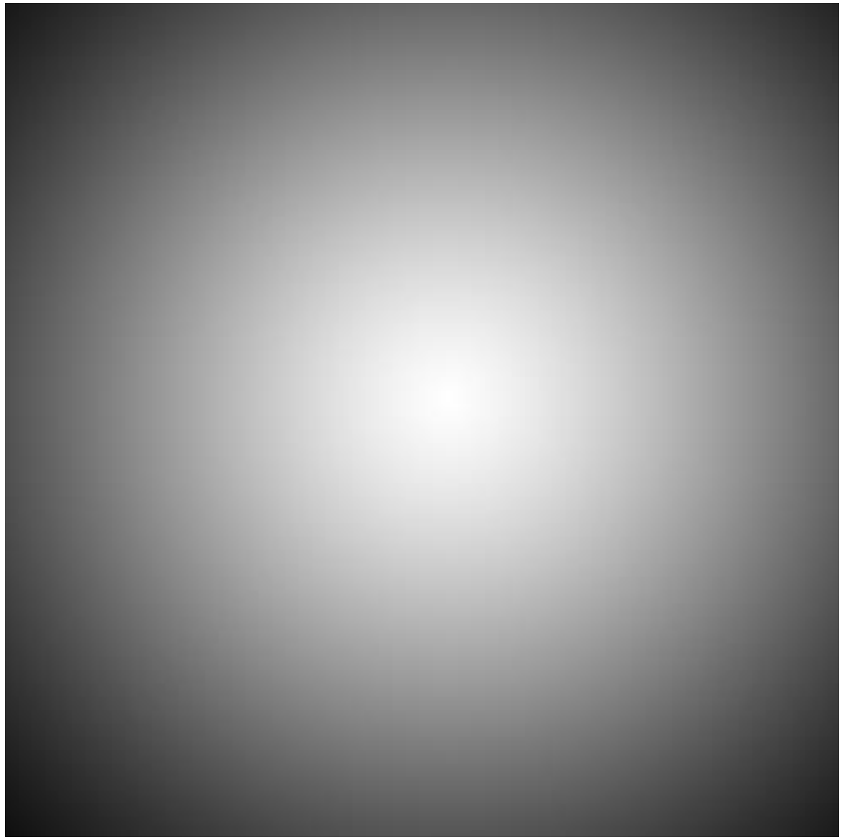
<u>analog amplifier (gain)</u>:
- gets voltage in range needed by A/D converter.
- accommodates ISO settings.
- accounts for <u>vignetting</u>.

<u>analog-to-digital converter (ADC)</u>:
- depending on sensor, output has 10-16 bits.
- most often (?) 12 bits.

<u>look-up table (LUT)</u>:
- corrects non-linearities in sensor's response function (within proper exposure).
- corrects defective pixels.

Vignetting

Fancy word for: pixels far off the center receive less light



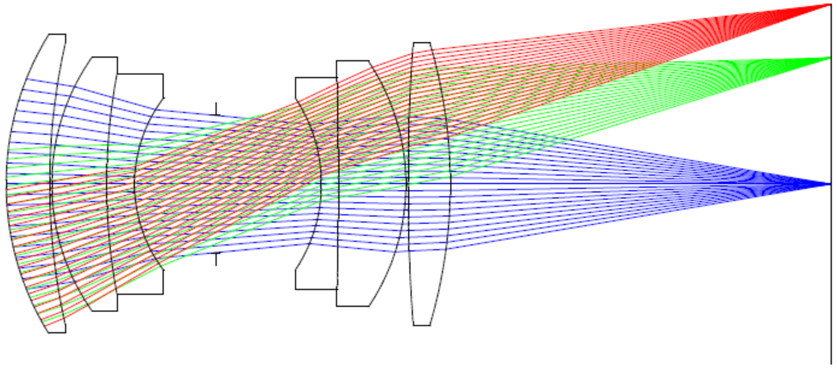
white wall under uniform light

more interesting example of vignetting

Vignetting

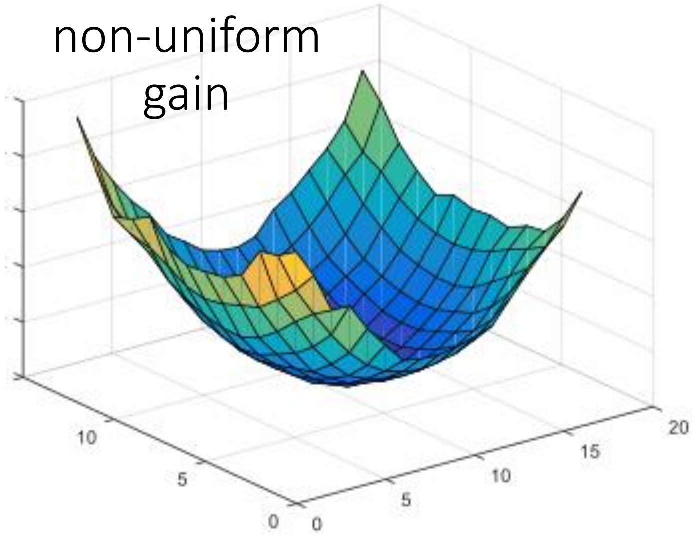
Four types of vignetting:

- Mechanical: light rays blocked by hoods, filters, and other objects.
- Lens: similar, but light rays blocked by lens elements.
- Natural: due to radiometric laws (“cosine fourth falloff”).
- Pixel: angle-dependent sensitivity of photodiodes.



→

non-uniform gain



→

What does an imaging sensor do?

When the camera shutter opens, the sensor:

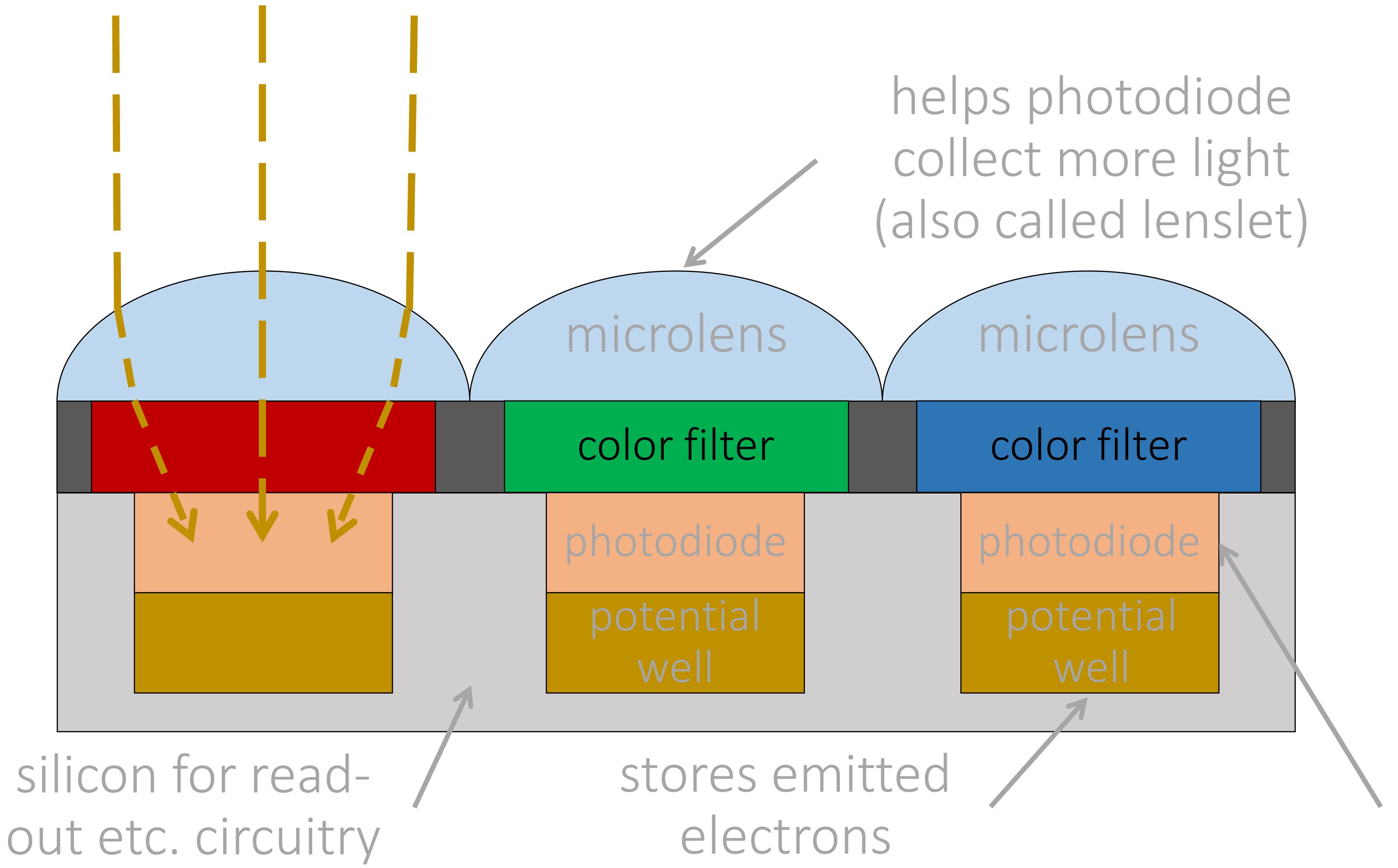
- at every photodiode, converts incident photons into electrons
- stores electrons into the photodiode's potential well while it is not full

… until camera shutter closes. Then, the analog front-end:

- reads out photodiodes' wells, row-by-row, and converts them to analog signals
- applies a (possibly non-uniform) gain to these analog signals
- converts them to digital signals
- corrects non-linearities

… and finally returns an image.

Remember these?



- Lenslets also filter the image to avoid resolution artifacts.
- Lenslets are problematic when working with coherent light.
- Many modern cameras do not have lenslet arrays.

We will discuss these issues in more detail at a later lecture.

We will see what the color filters are for later in this lecture.

Color primer

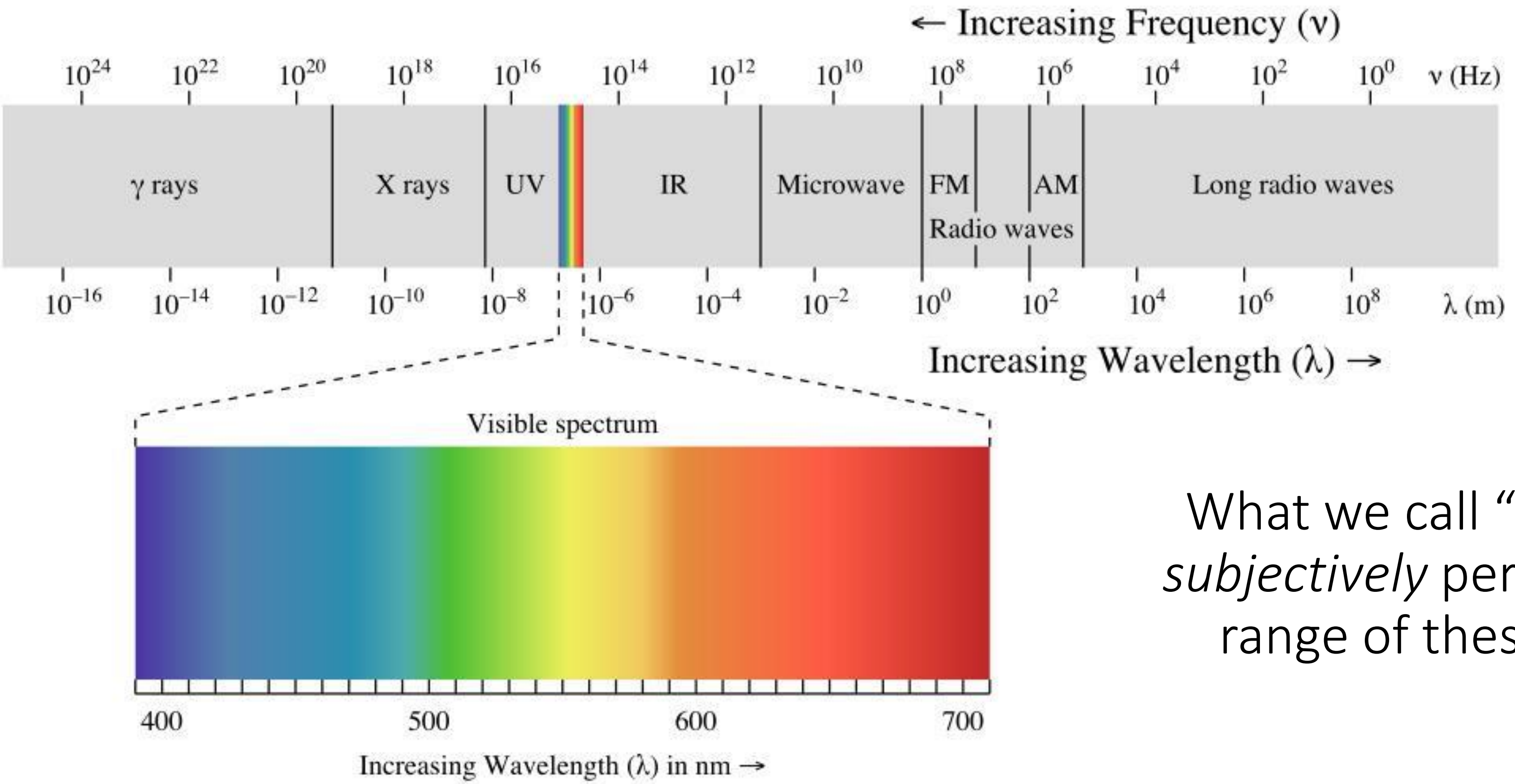
Color

- Very high-level of color as it relates to digital photography.
- We could spend an entire course covering color.
- We will discuss color in more detail in a later lecture.

color is complicated

Color is an artifact of human perception

- "Color" is not an *objective* physical property of light (electromagnetic radiation).
- Instead, light is characterized by its wavelength.



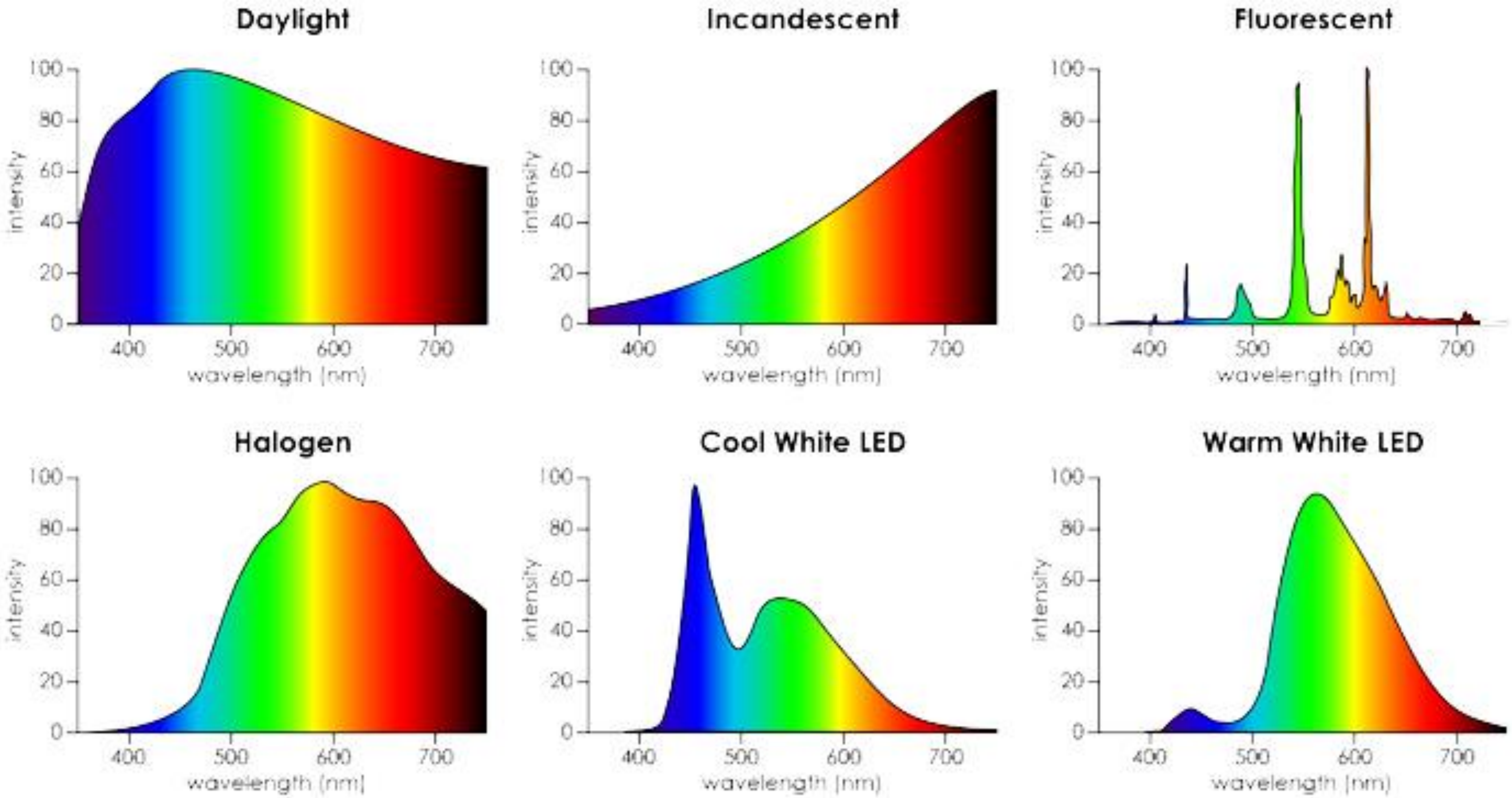
electromagnetic spectrum

What we call "color" is how we *subjectively* perceive a very small range of these wavelengths.

Spectral Power Distribution (SPD)

- Most types of light “contain” more than one wavelengths.
- We can describe light based on the distribution of power over different wavelengths.

We call our sensation of all of these distributions “white”.



Spectral Sensitivity Function (SSF)

- *Any* light sensor (digital or not) has different sensitivity to different wavelengths.
- This is described by the sensor's *spectral sensitivity function* $f(\lambda)$.
- When measuring light of a some SPD $\Phi(\lambda)$, the sensor produces a *scalar* response:

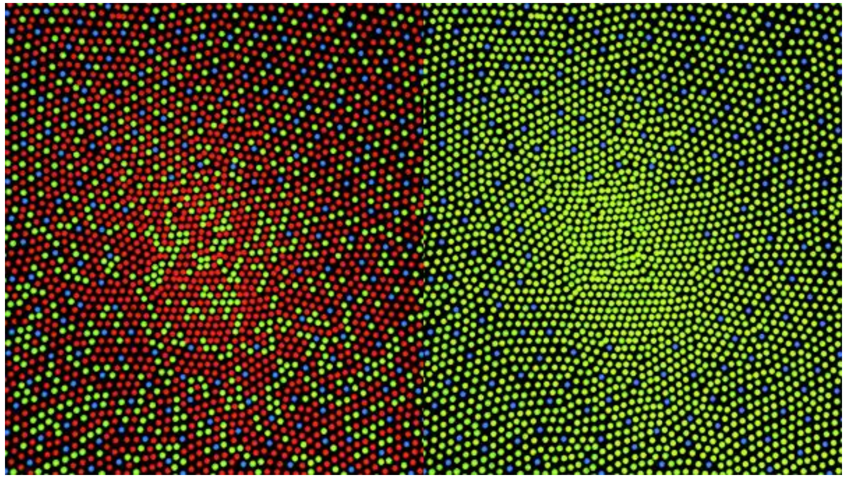
light SPD   sensor SSF

sensor response ⟶
$$R = \int_\lambda \Phi(\lambda) f(\lambda) d\lambda$$

Weighted combination of light's SPD: light contributes more at wavelengths where the sensor has higher sensitivity.

Spectral Sensitivity Function of Human Eye

- The human eye is a collection of light sensors called cone cells.
- There are three types of cells with different spectral sensitivity functions.
- Human color perception is three-dimensional (*tristimulus color*).

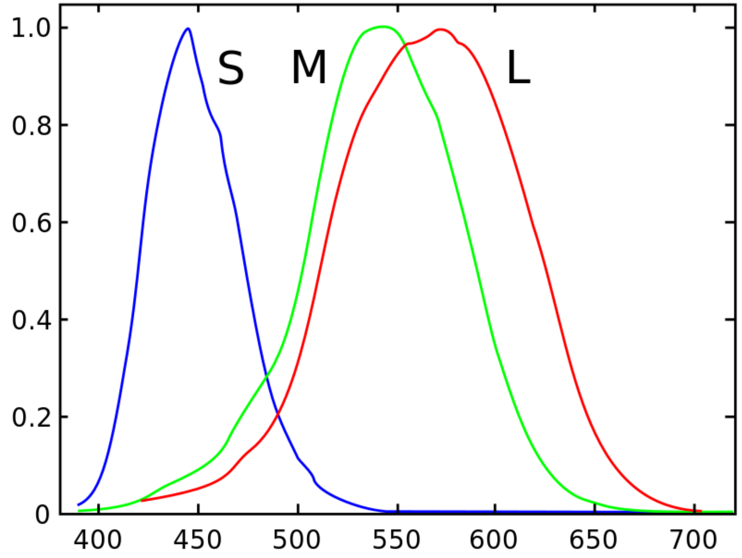


cone distribution
for normal vision
(64% L, 32% M)

"short" $$S = \int_\lambda \Phi(\lambda) S(\lambda) d\lambda$$

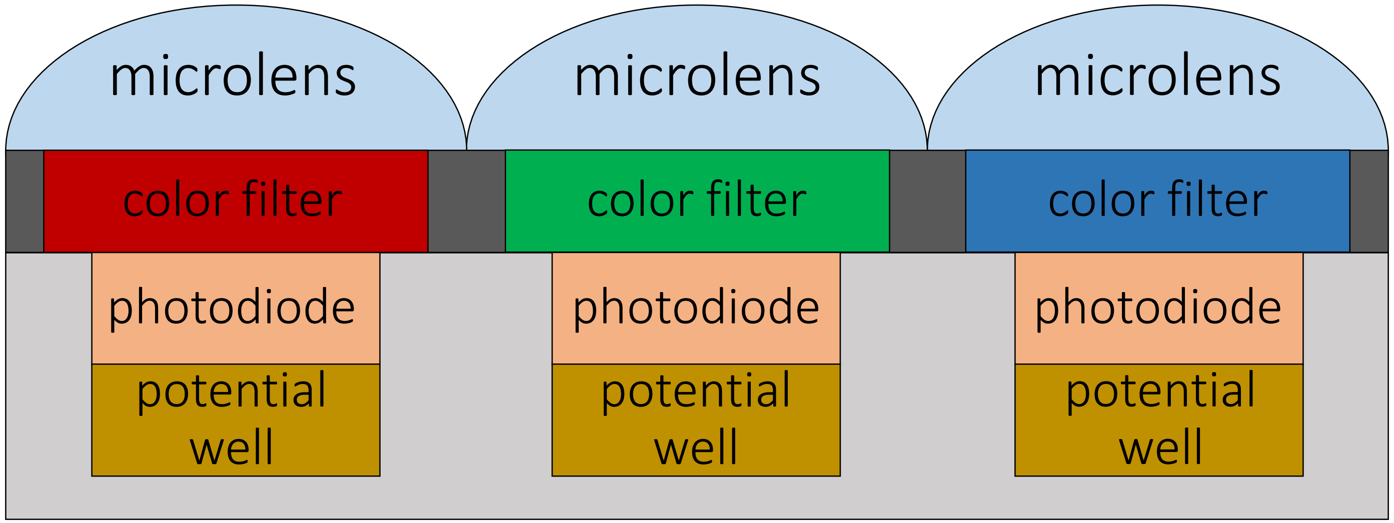
"medium" $$M = \int_\lambda \Phi(\lambda) M(\lambda) d\lambda$$

"long" $$L = \int_\lambda \Phi(\lambda) L(\lambda) d\lambda$$



Color filter arrays (CFA)

- To measure color with a digital sensor, mimic cone cells of human vision system.
- “Cones” correspond to pixels that are covered by different color filters, each with its own spectral sensitivity function.

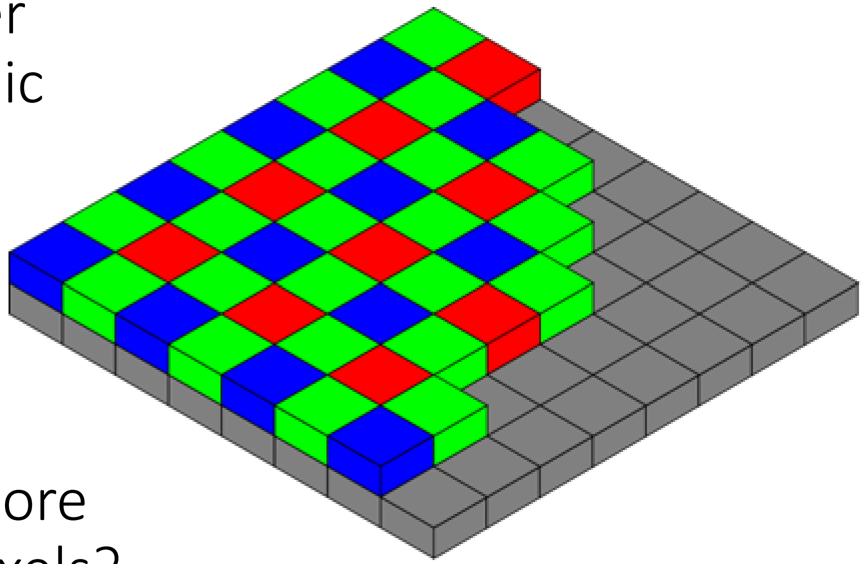


What color filters to use?

Two design choices:

- What spectral sensitivity functions $f(\lambda)$ to use for each color filter?
- How to spatially arrange ("mosaic") different color filters?

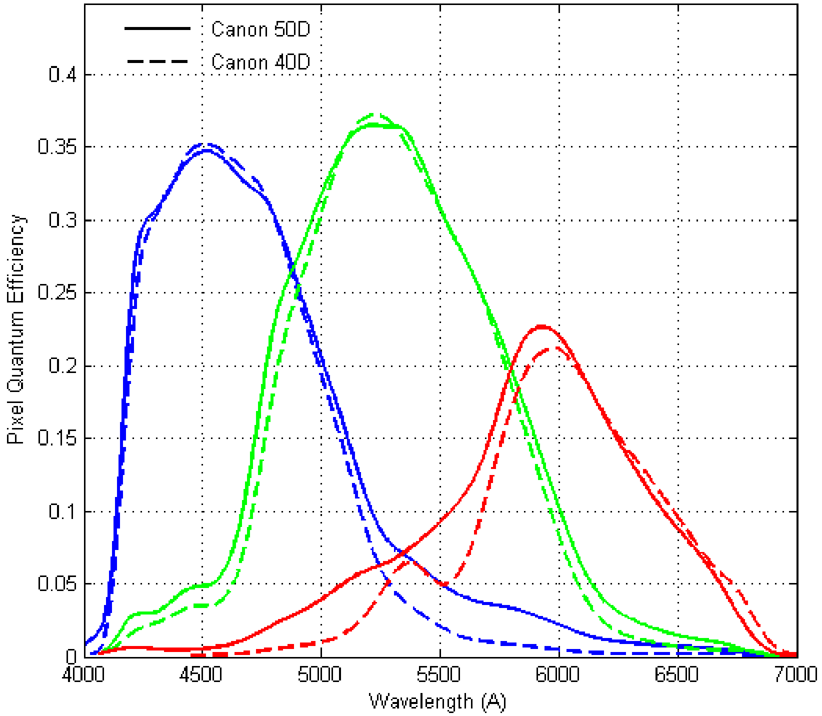
Bayer mosaic



Why more green pixels?

SSF for Canon 50D

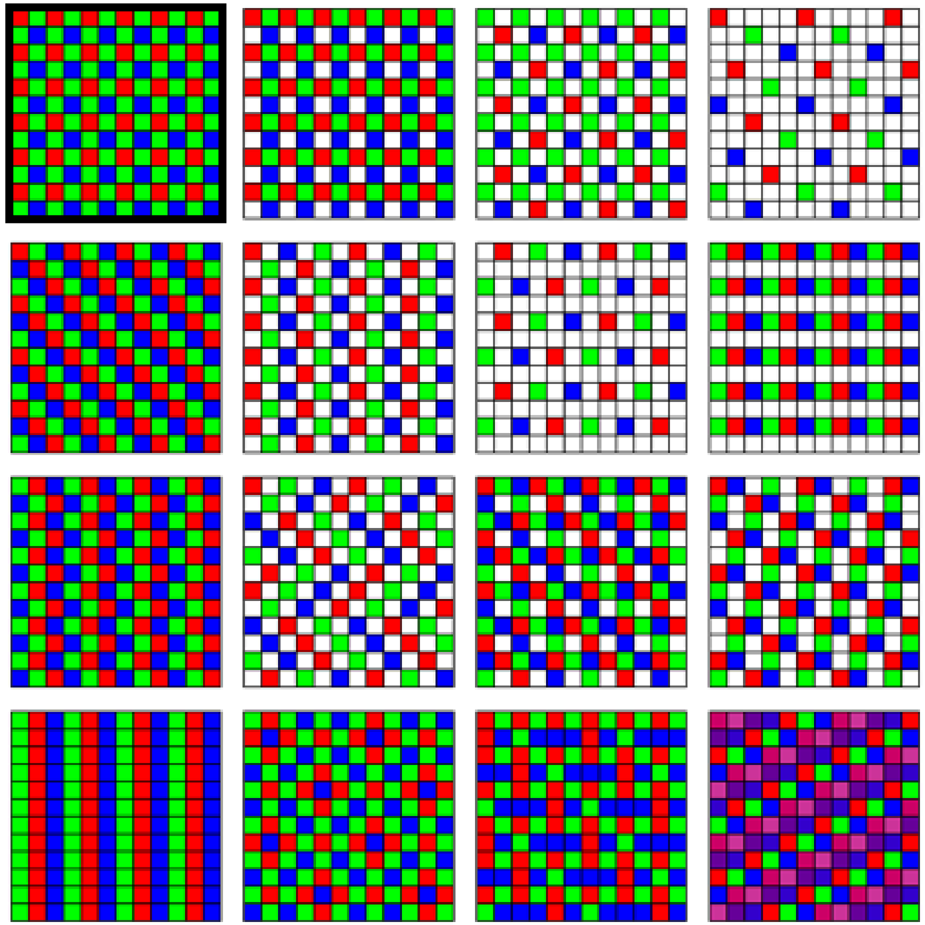
Generally do not match human LMS.

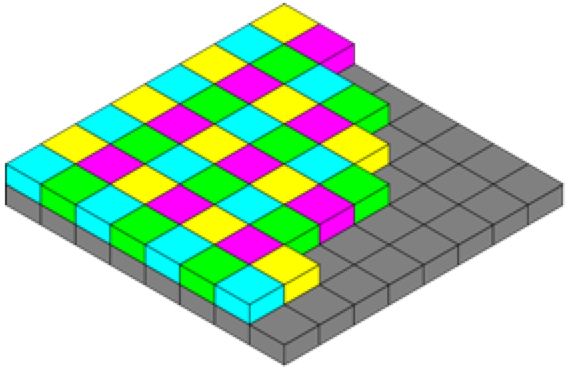


$f(\lambda)$

Many different CFAs

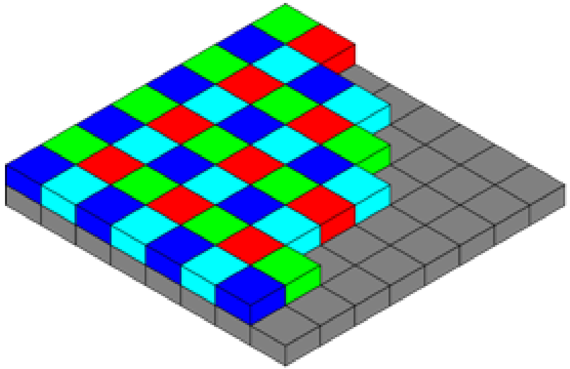
Finding the "best" CFA mosaic is an active research area.





CYGM

Canon IXUS, Powershot



RGBE

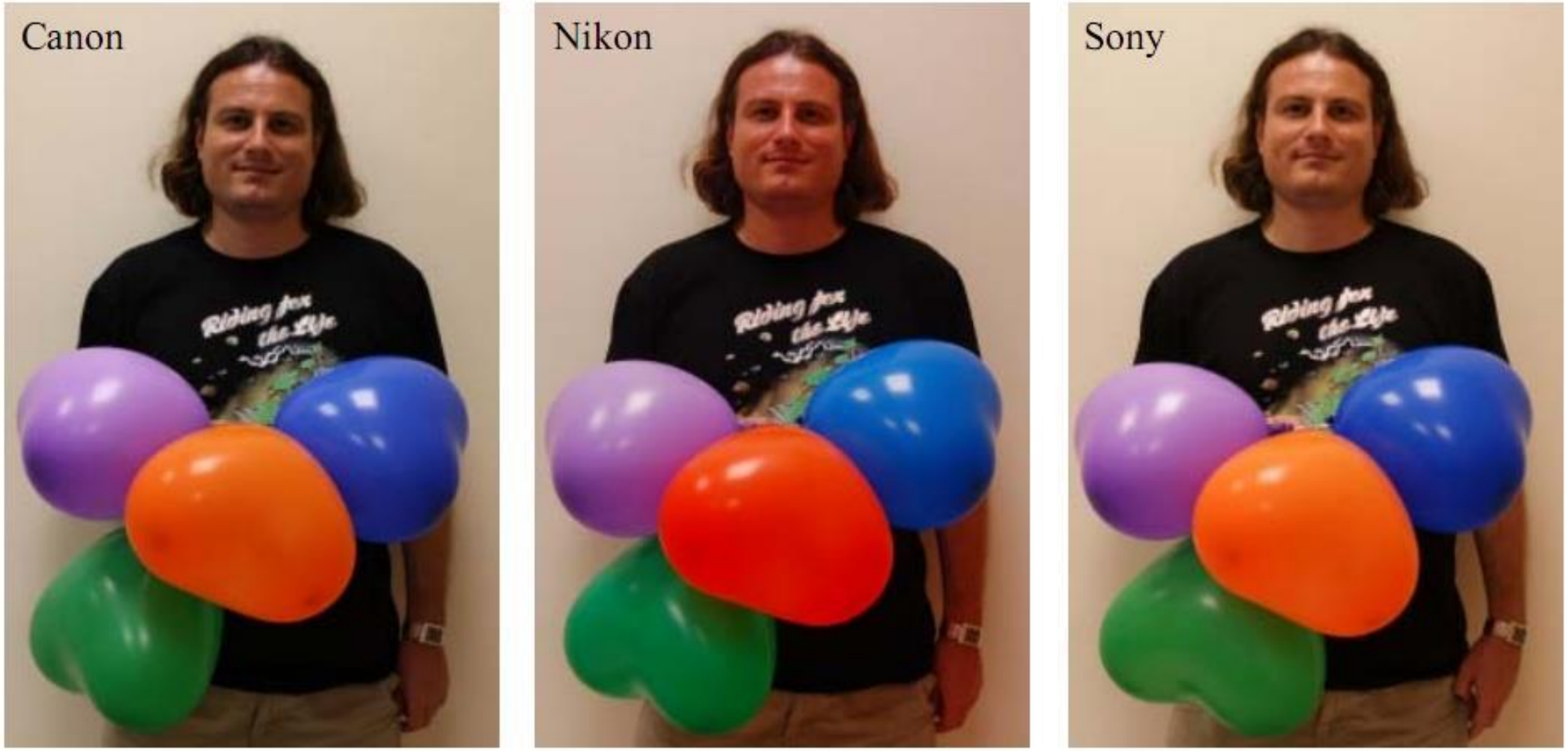
Sony Cyber-shot

How would you go about designing your own CFA? What criteria would you consider?

Many different spectral sensitivity functions

Each camera has its more or less unique, and most of the time *secret*, SSF.

- Makes it very difficult to correctly reproduce the color of sensor measurements.
- We will see more about this in the color lecture.



Images of the same scene captured using 3 different cameras with identical settings.

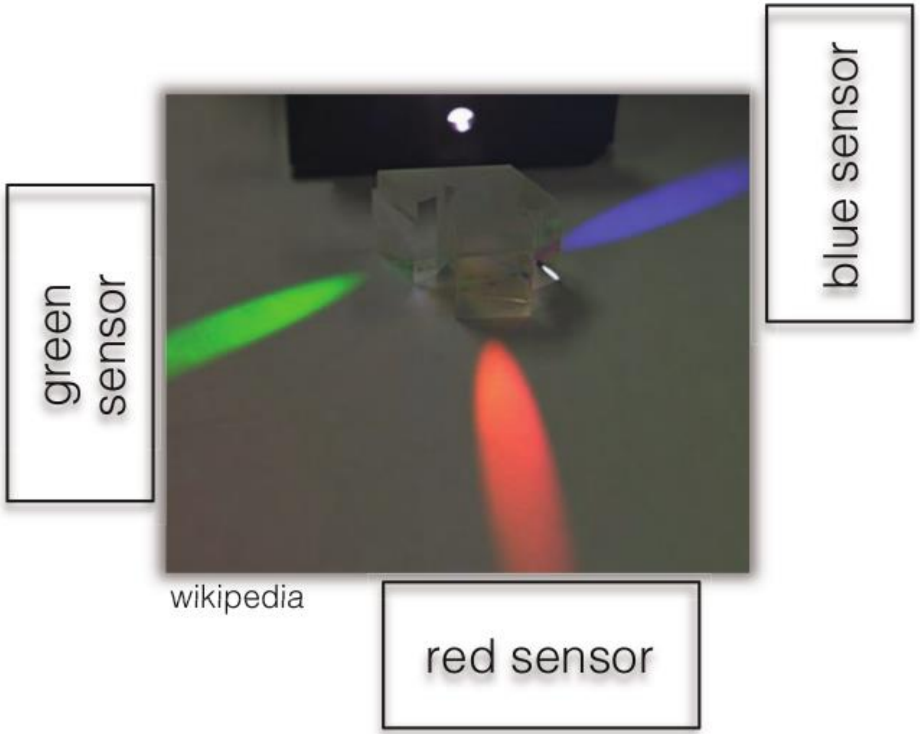
Aside: can you think of other ways to capture color?

Aside: can you think of other ways to capture color?

field sequential

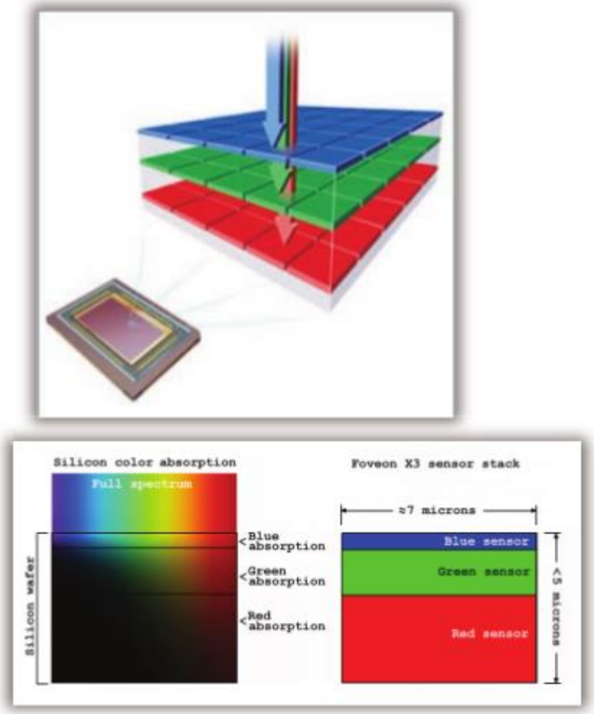
Prokudin-Gorsky

multiple sensors



wikipedia

vertically stacked



Foveon X3

[Slide credit: Gordon Wetzstein]

What does an imaging sensor do?

When the camera shutter opens, the sensor:

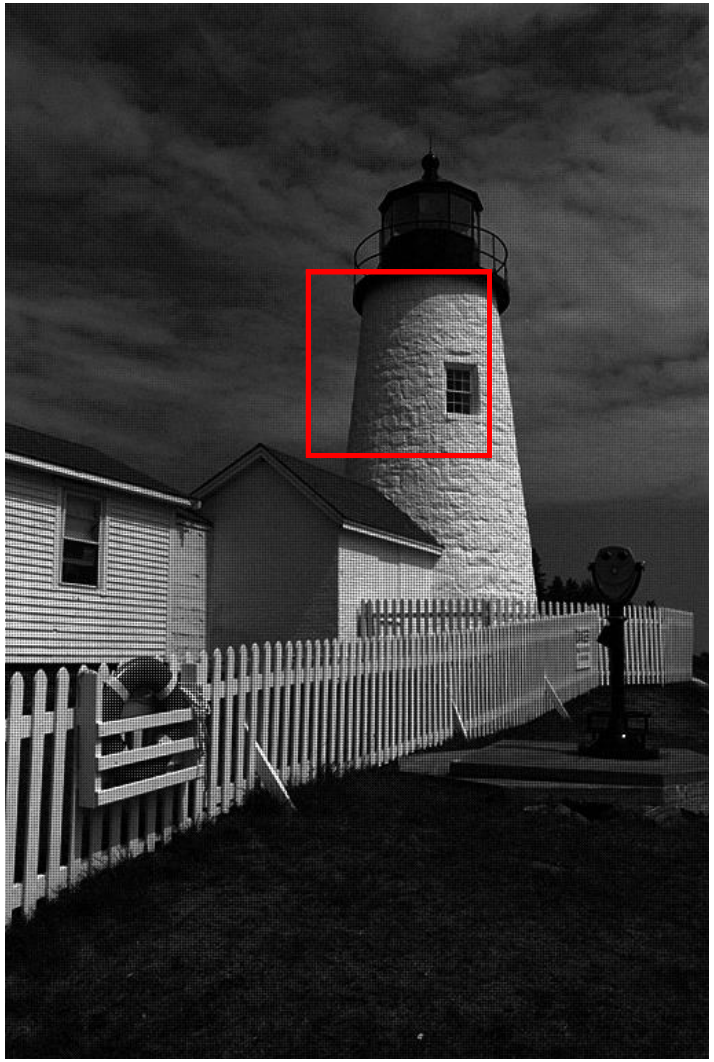
- at every photodiode, converts incident photons into electrons using mosaic's SSF
- stores electrons into the photodiode's potential well while it is not full

… until camera shutter closes. Then, the analog front-end:

- reads out photodiodes' wells, row-by-row, and converts them to analog signals
- applies a (possibly non-uniform) gain to these analog signals
- converts them to digital signals
- corrects non-linearities

… and finally returns an image.

After all of this, what does an image look like?



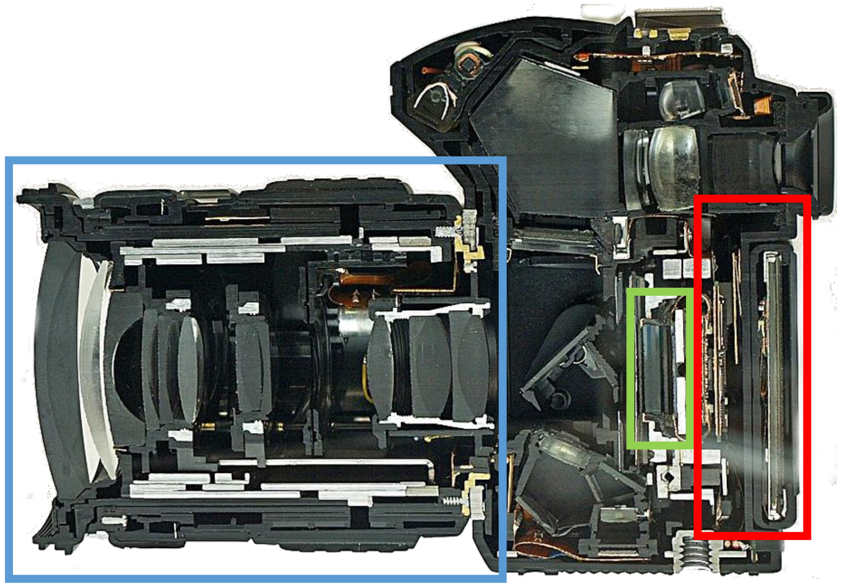
lots of noise

mosaicking artifacts

- Kind of disappointing.
- We call this the *RAW* image.

The modern photography pipeline

post-capture processing
(lectures 5-10)



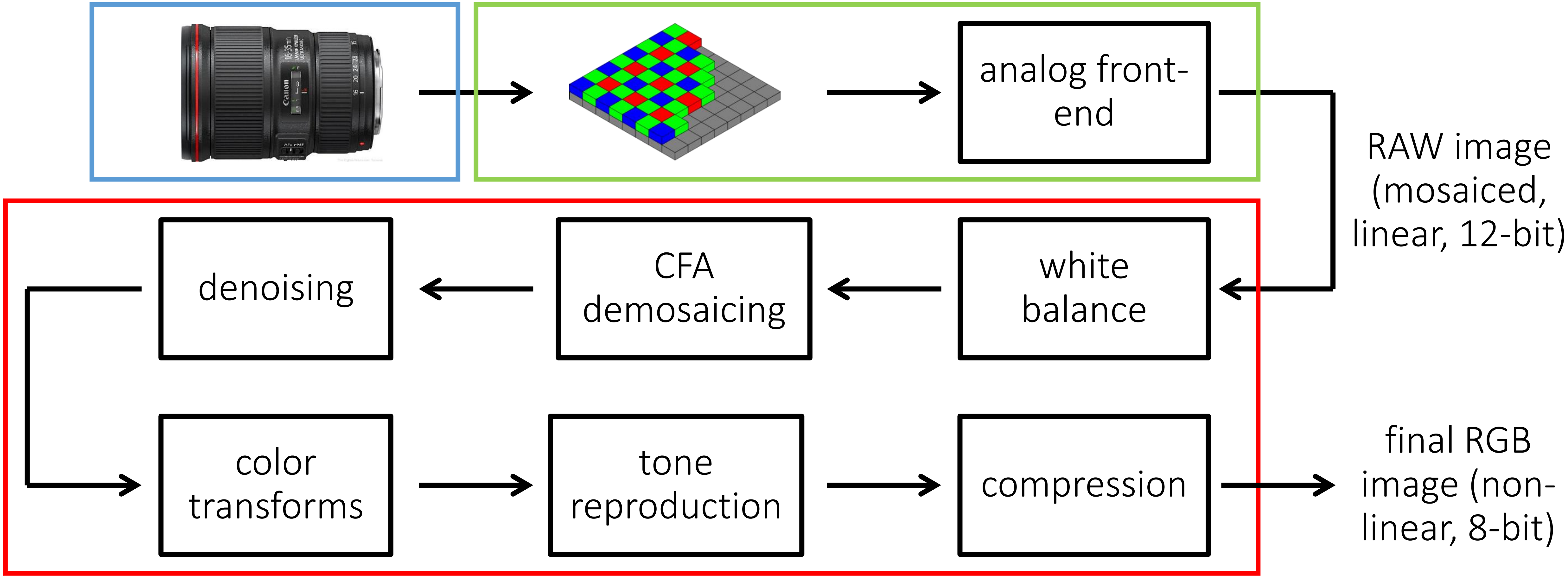
optics and optical controls → sensor, analog front-end, and color filter array → in-camera image processing pipeline

(lectures 2-3, 11-20) (today, lecture 23) (today)

The in-camera image processing pipeline

The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



Quick notes on terminology

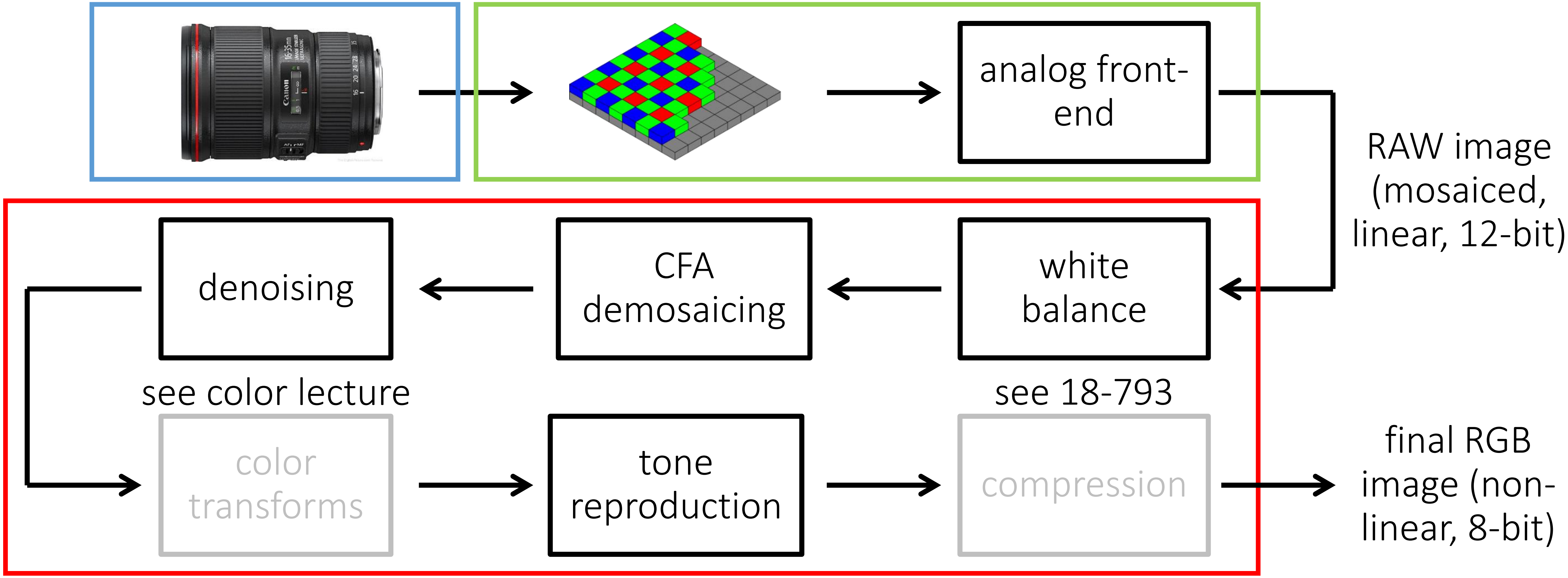
- Sometimes the term *image signal processor* (ISP) is used to refer to the image processing pipeline itself.

- The process of converting a RAW image to a “conventional” image is often called *rendering* (unrelated to the image synthesis procedure of the same name in graphics).

- The inverse process, going from a “conventional” image back to RAW is called *derendering*.

The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



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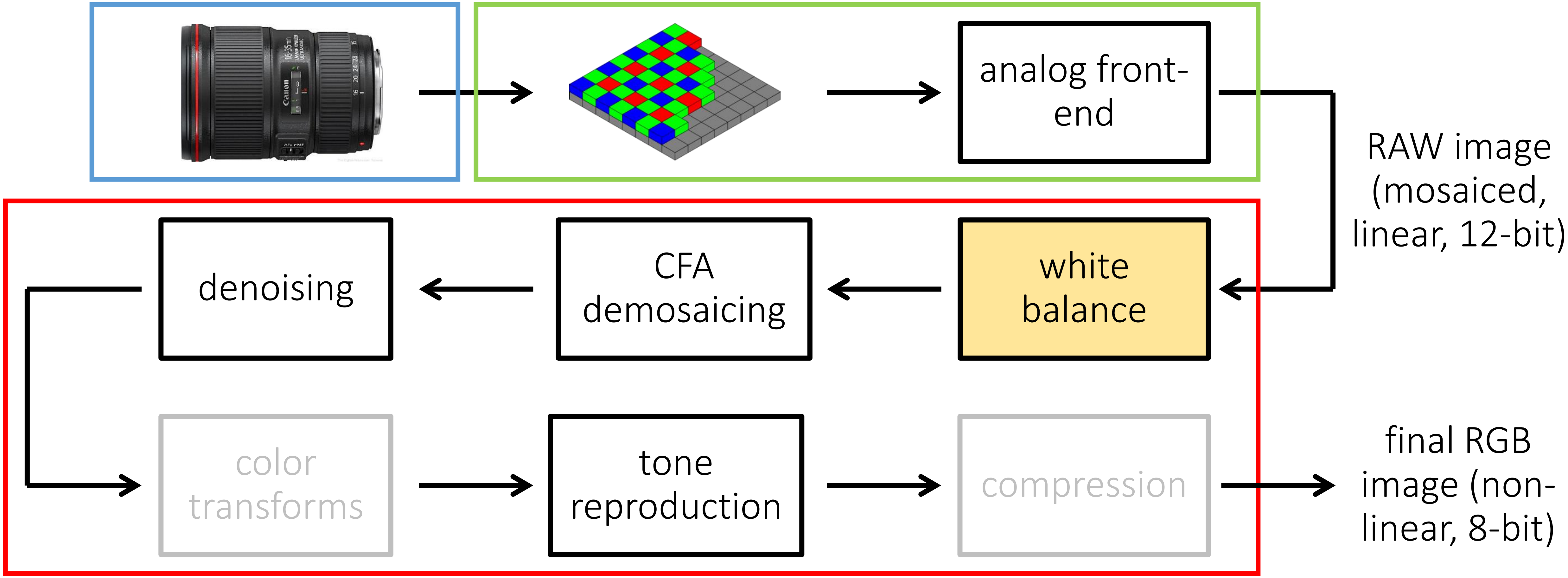


White balancing

Human visual system has *chromatic adaptation*:

- We can perceive white (and other colors) correctly under different light sources.

[Slide credit: Todd Zickler]

White balancing

Human visual system has *chromatic adaptation*:

- We can perceive white (and other colors) correctly under different light sources.

Retinal vs perceived color.

[Slide credit: Todd Zickler]

White balancing

Human visual system has *chromatic adaptation*:

- We can perceive white (and other colors) correctly under different light sources.
- Cameras cannot do that (there is no "camera perception").

White balancing: The process of removing color casts so that colors that we would *perceive* as white are *rendered* as white in final image.

different whites

image captured under fluorescent

image white-balanced to daylight

White balancing presets

Cameras nowadays come with a large number of presets: You can select which light you are taking images under, and the appropriate white balancing is applied.

WB SETTINGS	COLOR TEMPERATURE	LIGHT SOURCES
	10000 - 15000 K	Clear Blue Sky
	6500 - 8000 K	Cloudy Sky / Shade
	6000 - 7000 K	Noon Sunlight
	5500 - 6500 K	Average Daylight
	5000 - 5500 K	Electronic Flash
	4000 - 5000 K	Fluorescent Light
	3000 - 4000 K	Early AM / Late PM
	2500 - 3000 K	Domestic Lightning
	1000 - 2000 K	Candle Flame

Manual vs automatic white balancing

Manual white balancing:

- Select a camera preset based on lighting.

Can you think of any other way to do manual white balancing?

Manual vs automatic white balancing

Manual white balancing:

- Select a camera preset based on lighting.
- Manually select object in photograph that is color-neutral and use it to normalize.

How can we do automatic white balancing?

Manual vs automatic white balancing

Manual white balancing:

- Select a camera preset based on lighting.
- Manually select object in photograph that is color-neutral and use it to normalize.

Automatic white balancing:

- Grey world assumption: force average color of scene to be grey.
- White world assumption: force brightest object in scene to be white.
- Sophisticated histogram-based algorithms (what most modern cameras do).

Automatic white balancing

Grey world assumption:

- Compute per-channel average.
- Normalize each channel by its average.
- Normalize by green channel average.

white-balanced RGB → $$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} G_{avg}/R_{avg} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & G_{avg}/B_{avg} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$ ← sensor RGB

White world assumption:

- Compute per-channel maximum.
- Normalize each channel by its maximum.
- Normalize by green channel maximum.

white-balanced RGB → $$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} G_{max}/R_{max} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & G_{max}/B_{max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$ ← sensor RGB

Automatic white balancing example

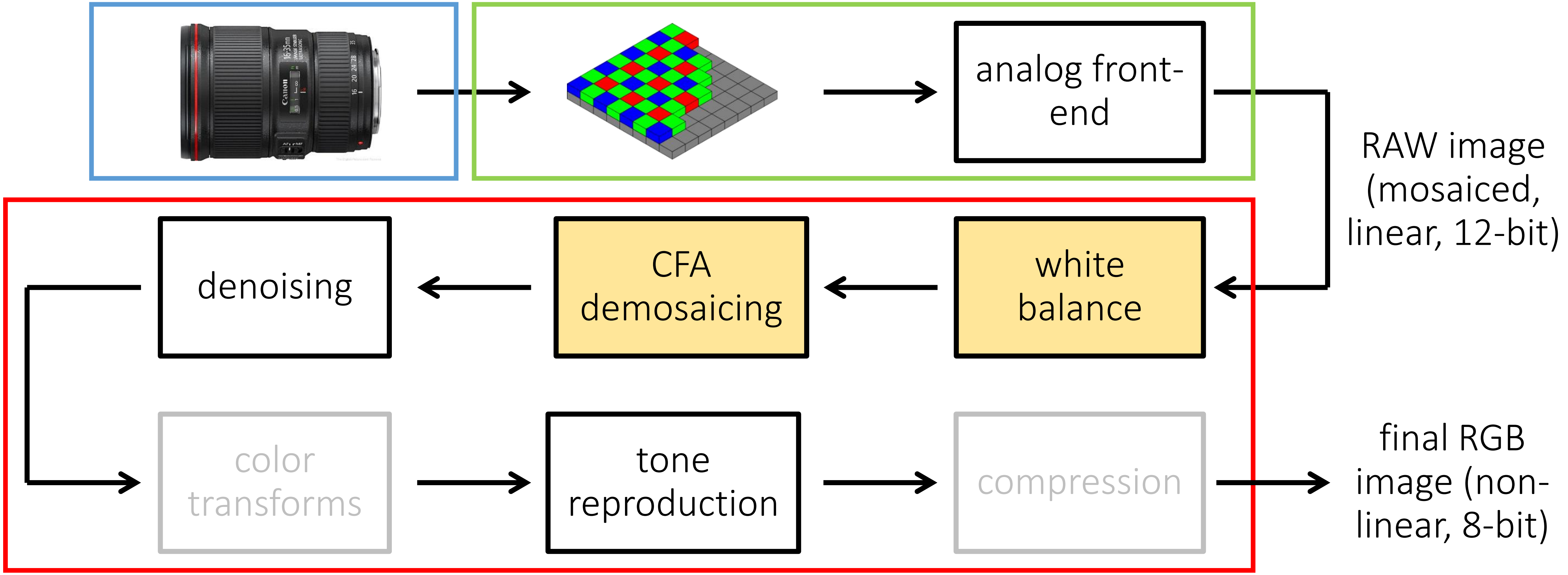
input image

grey world

white world

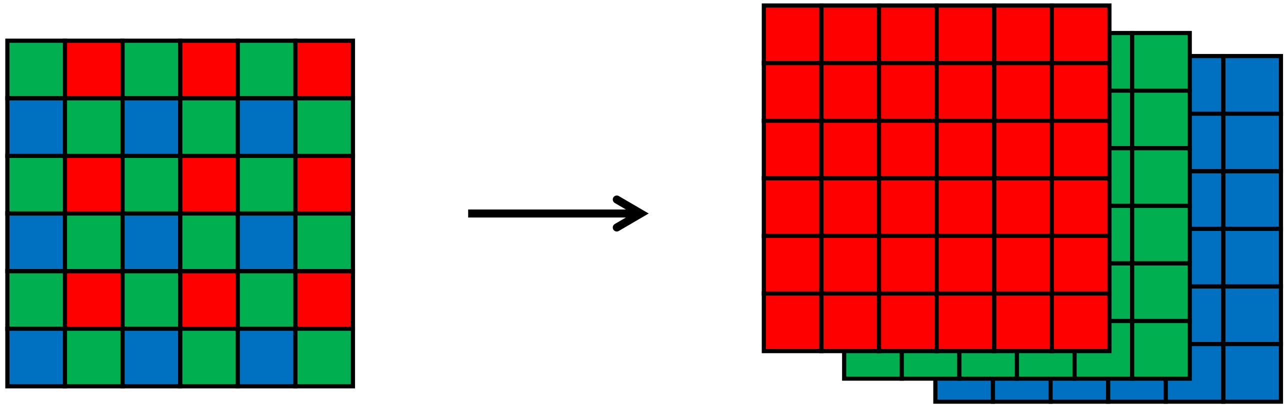
The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



CFA demosaicing

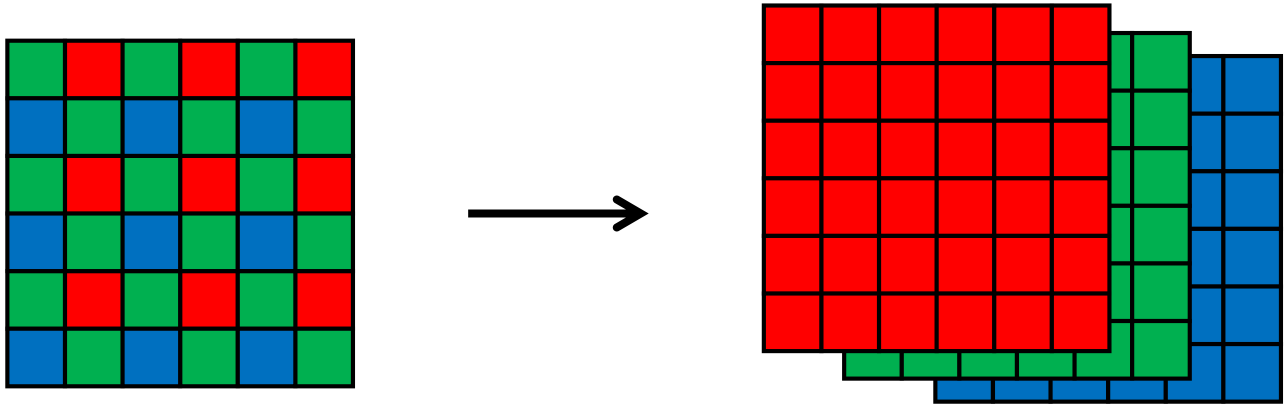
Produce full RGB image from mosaiced sensor output.



Any ideas on how to do this?

CFA demosaicing

Produce full RGB image from mosaiced sensor output.

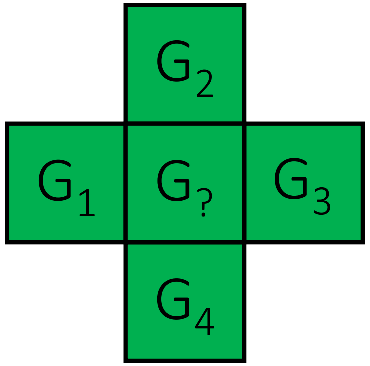


Interpolate from neighbors:

- Bilinear interpolation (needs 4 neighbors).
- Bicubic interpolation (needs more neighbors, may overblur).
- Edge-aware interpolation (more on this later).

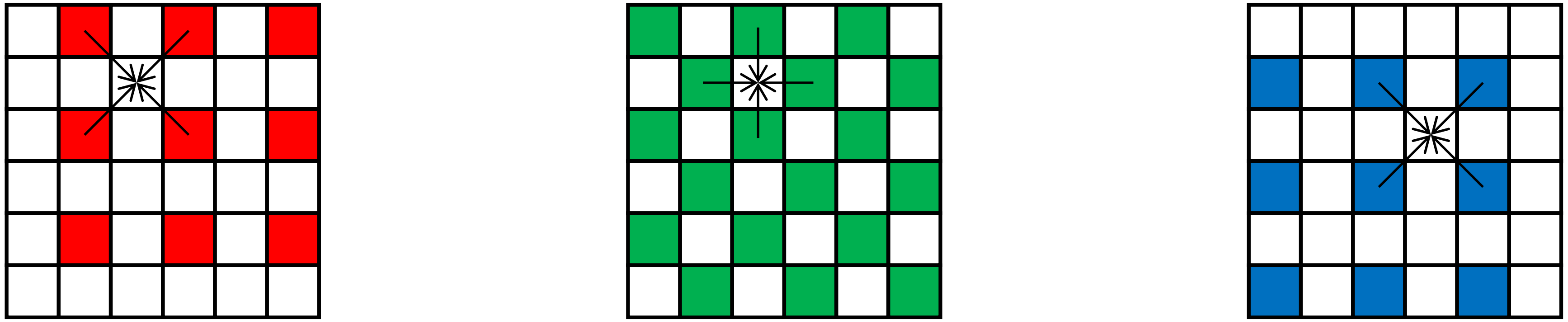
Demosaicing by bilinear interpolation

Bilinear interpolation: Simply average your 4 neighbors.



$$G_? = \frac{G_1 + G_2 + G_3 + G_4}{4}$$

Neighborhood changes for different channels:



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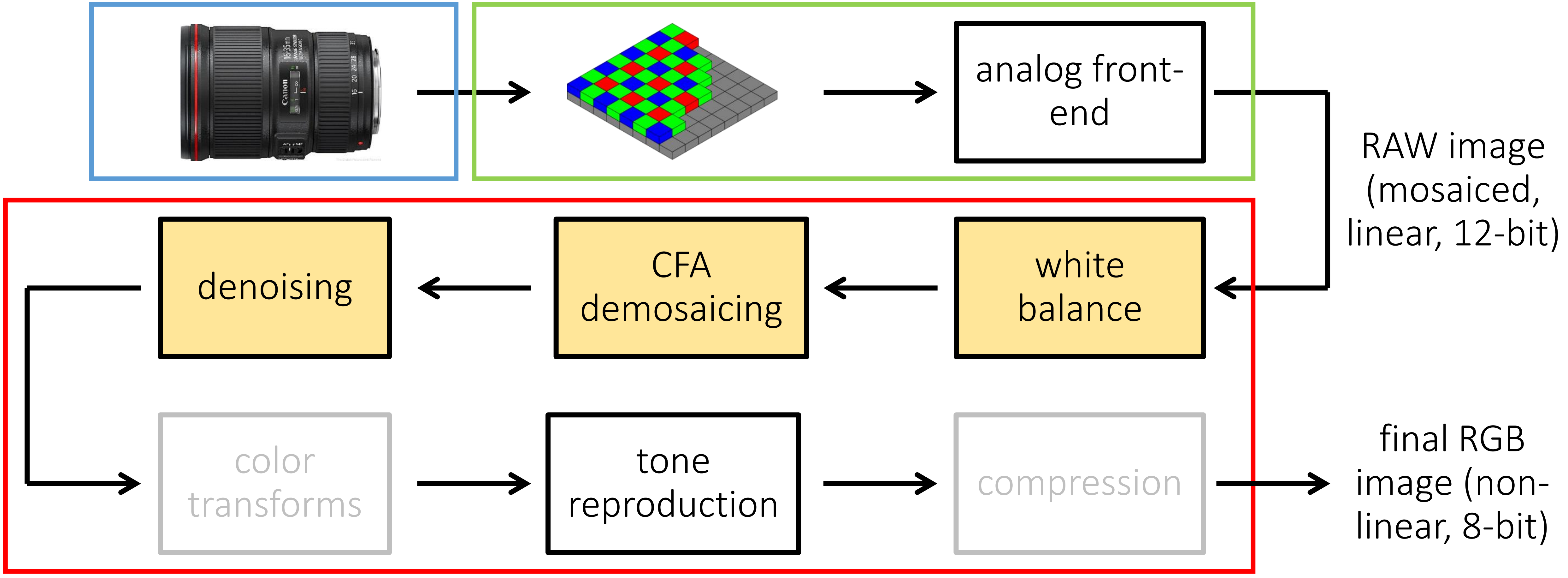
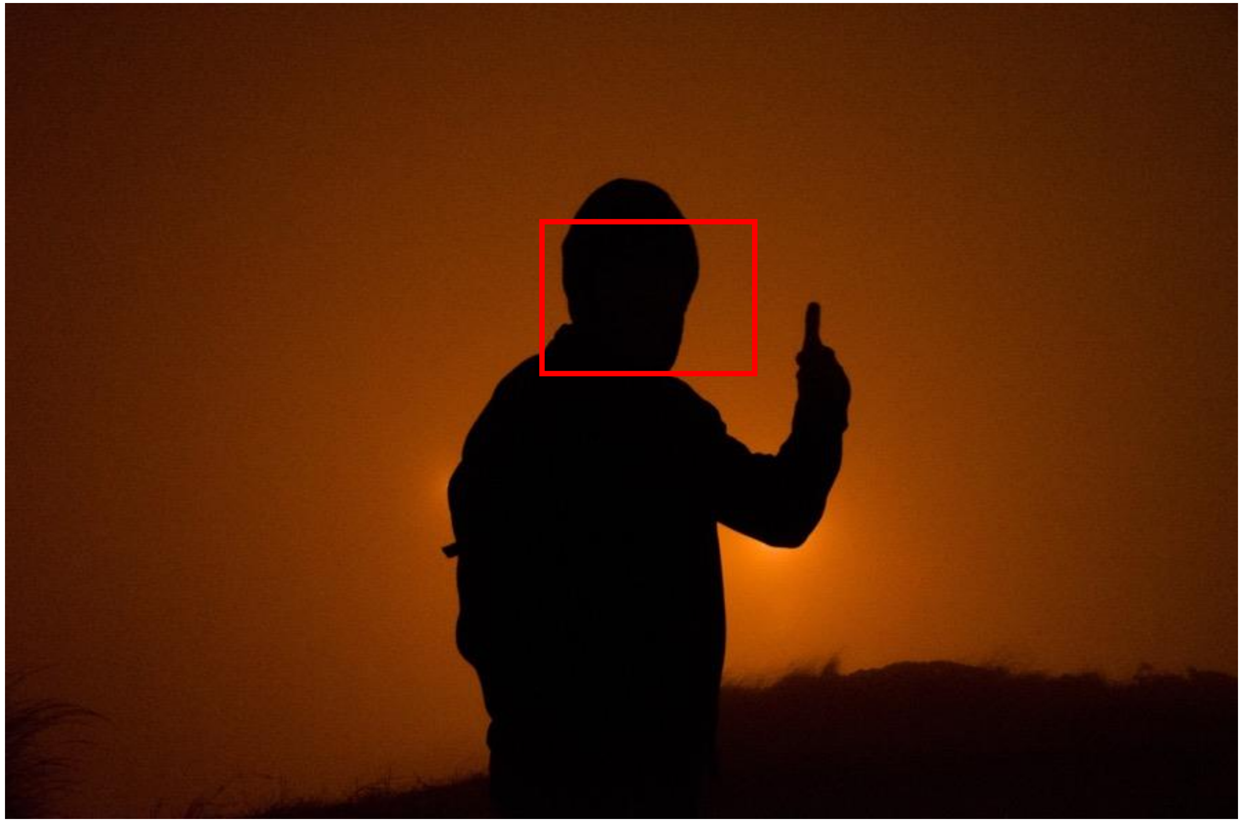


Noise in images

Can be very pronounced in low-light images.



Three types of sensor noise

1) (Photon) shot noise:

- Photon arrival rates are a random process (Poisson distribution).
- The brighter the scene, the smaller the variance of the distribution.

2) Dark-shot noise:

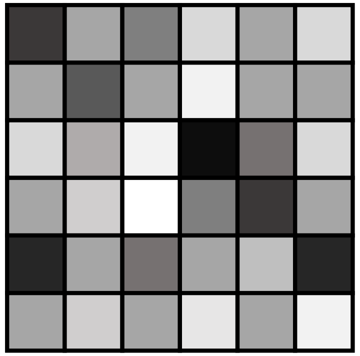
- Emitted electrons due to thermal activity (becomes worse as sensor gets hotter.)

3) Read noise:

- Caused by read-out and AFE electronics (e.g., gain, A/D converter).

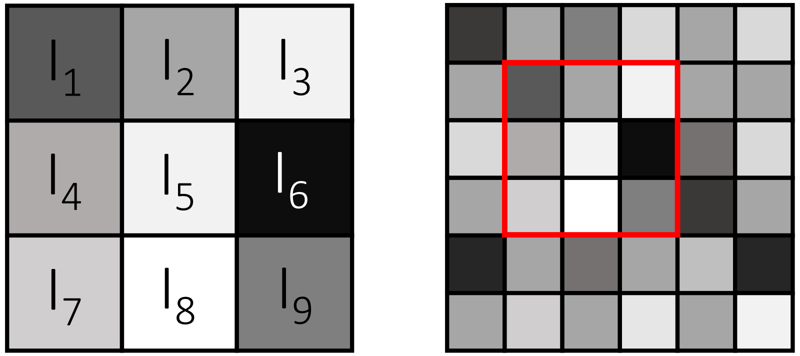
Bright scene and large pixels: photon shot noise is the main noise source.

How to denoise?



How to denoise?

Look at the neighborhood around you.



- Mean filtering (take average):

$$I'_5 = \frac{I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7 + I_8 + I_9}{9}$$

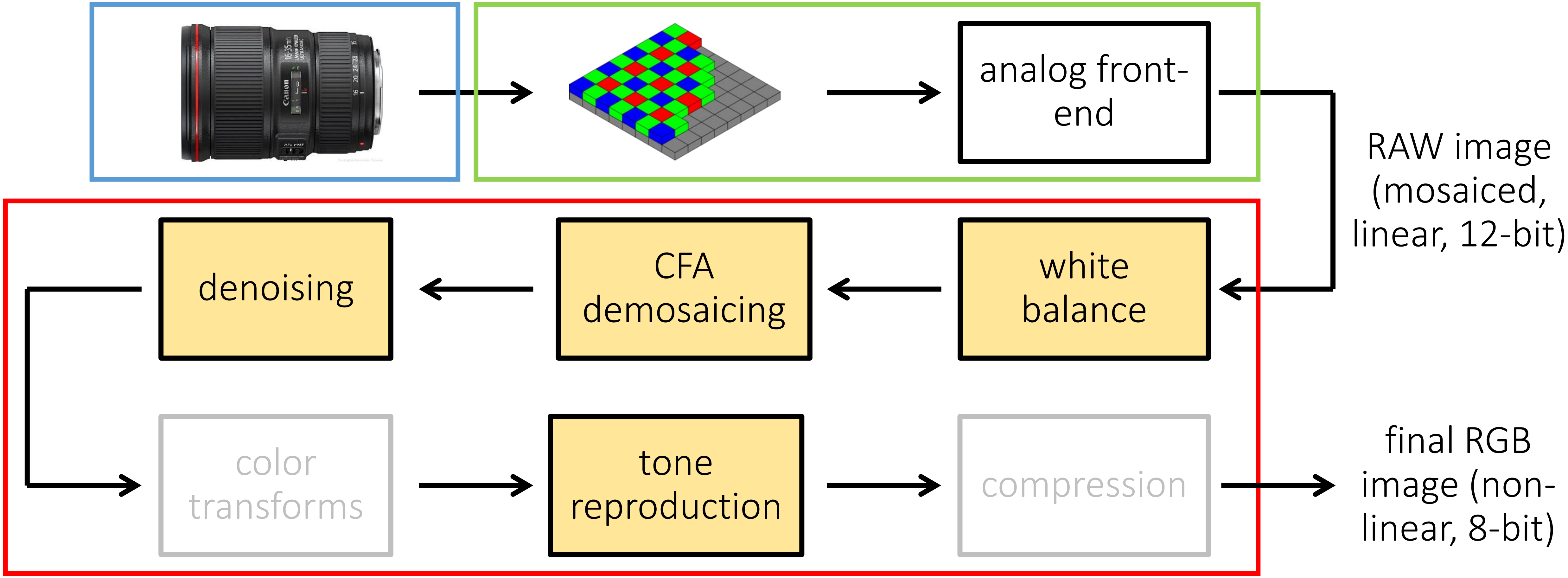
- Median filtering (take median):

$$I'_5 = \text{median}(I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8, I_9)$$

Large area of research. We will see some more about filtering in a later lecture.

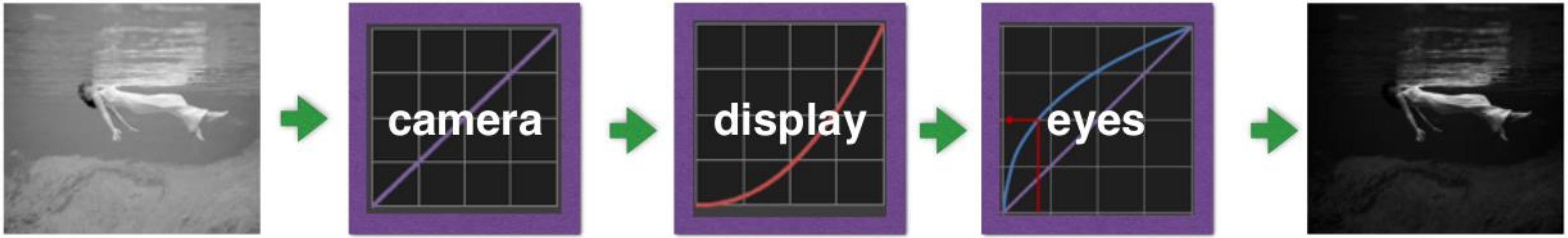
The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



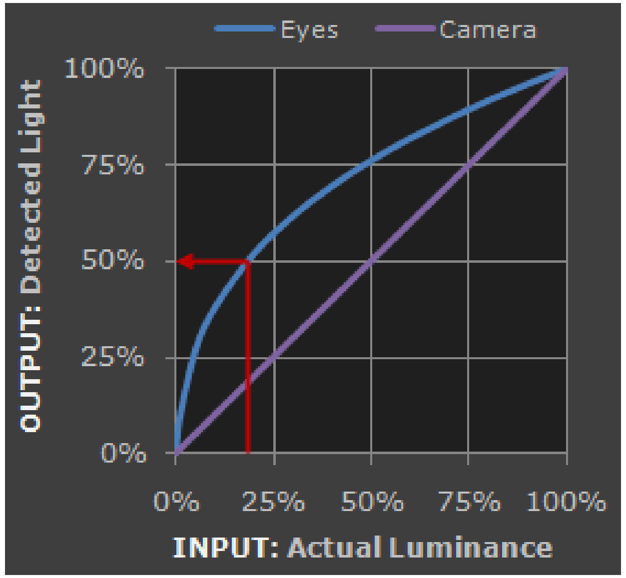
Tone reproduction

- Also known as gamma encoding (and erroneously as gamma correction).
- Without tone reproduction, images look very dark.



Why does this happen?

Perceived vs measured brightness by human eye



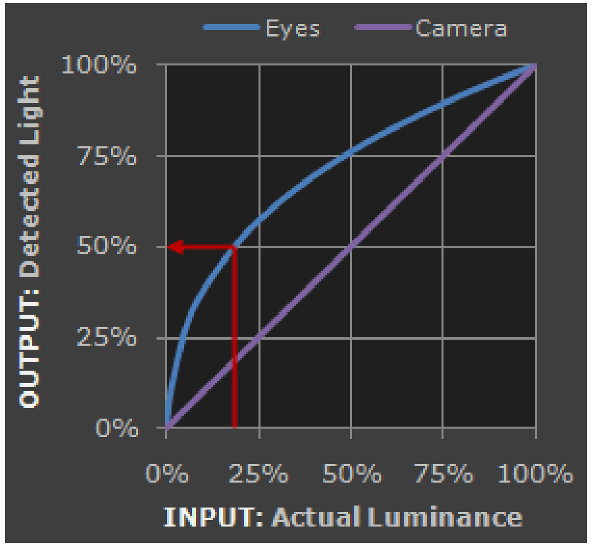
We have already seen that sensor response is linear.

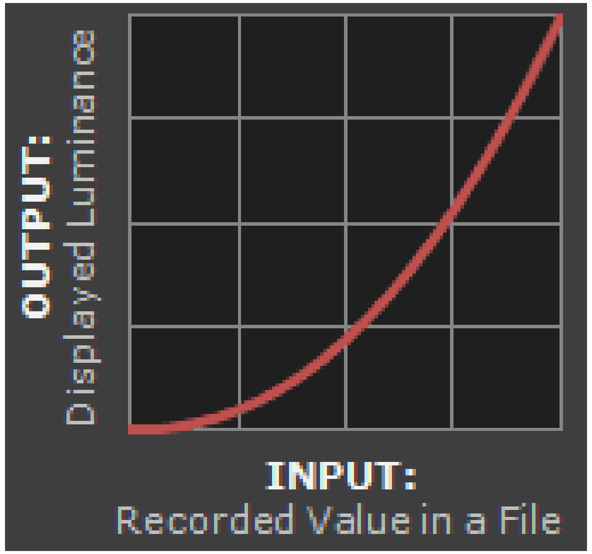
Human-eye *response* (measured brightness) is also linear.

However, human-eye *perception* (perceived brightness) is *non-linear*:

- More sensitive to dark tones.
- Approximately a Gamma function.

What about displays?





We have already seen that sensor response is linear.

Human-eye *response* (measured brightness) is also linear.

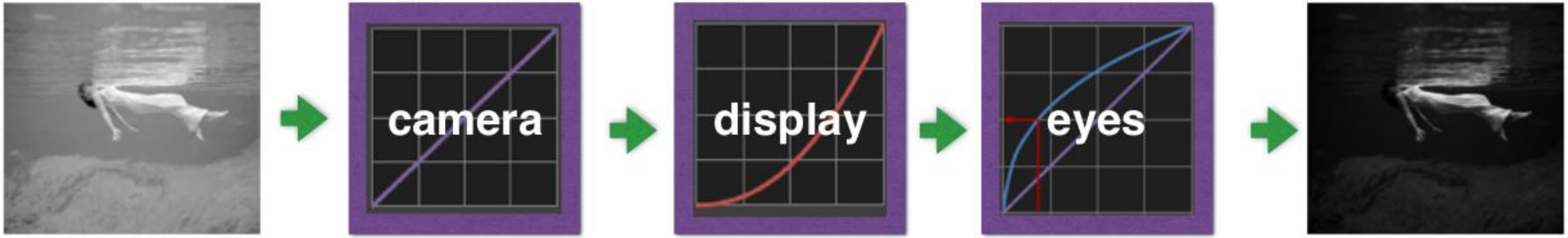
However, human-eye *perception* (perceived brightness) is *non-linear*:

- More sensitive to dark tones.
- Approximately a Gamma function.

Displays have a response opposite to that of human perception.

Tone reproduction

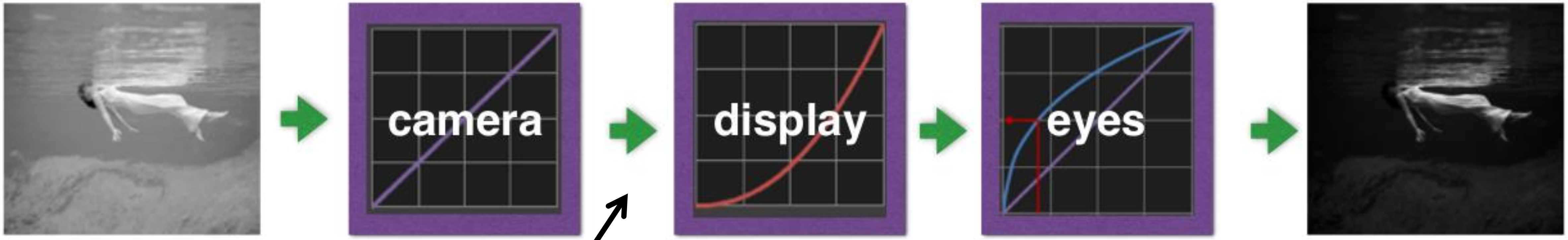
- Because of mismatch in displays and human eye perception, images look very dark.

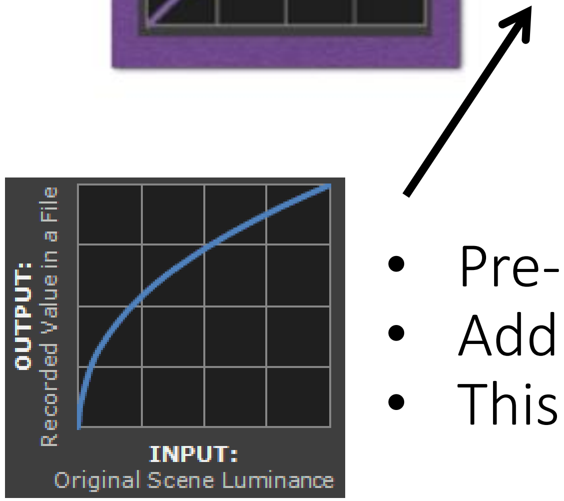


How do we fix this?

Tone reproduction

- Because of mismatch in displays and human eye perception, images look very dark.





- Pre-emptively cancel-out the display response curve.
- Add inverse display transform here.
- This transform is the tone reproduction or gamma correction.

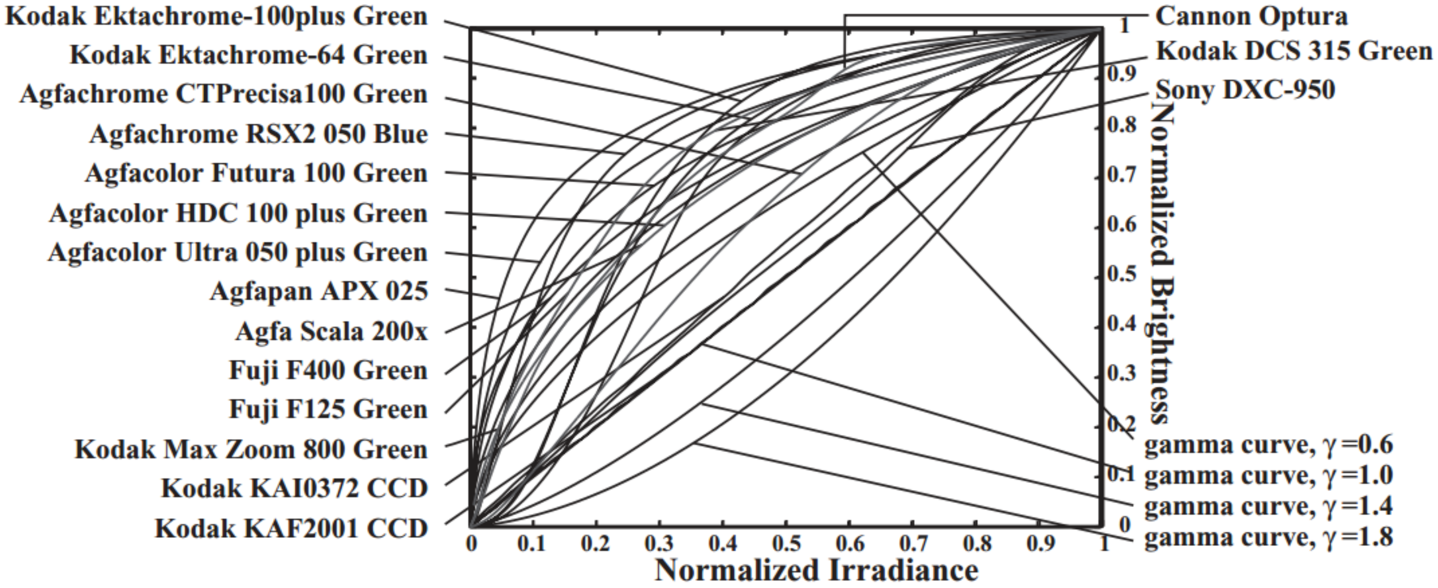
Tone reproduction curves

The exact tone reproduction curve depends on the camera.

- Often well approximated as L^{γ}, for different values of the power γ ("gamma").
- A good default is γ = 2.2.

before gamma

after gamma



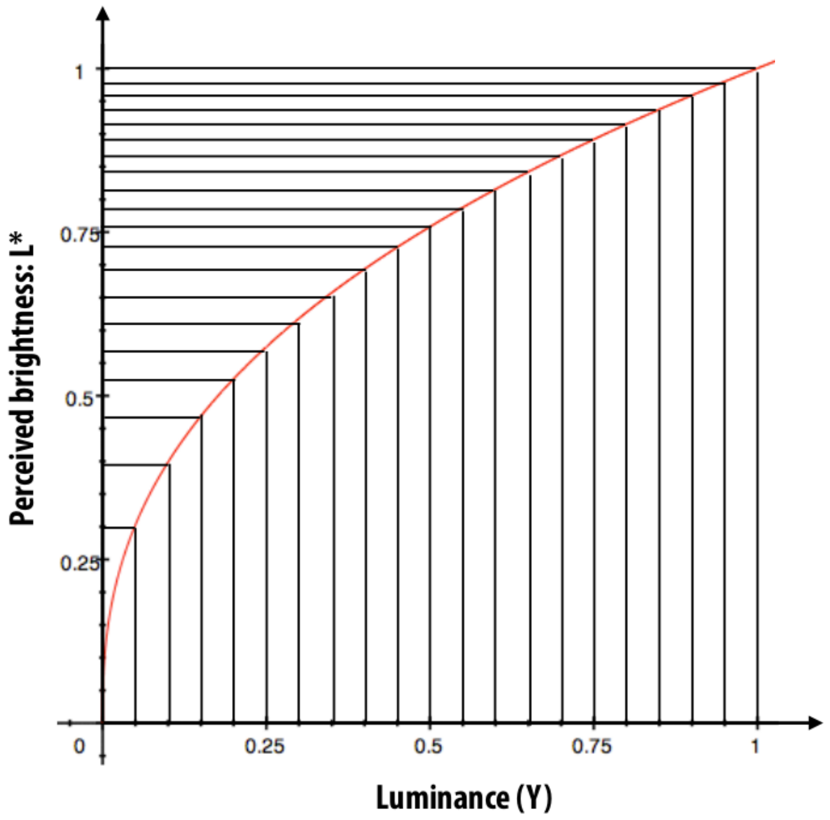
Warning: Our values are no longer linear relative to scene radiance!

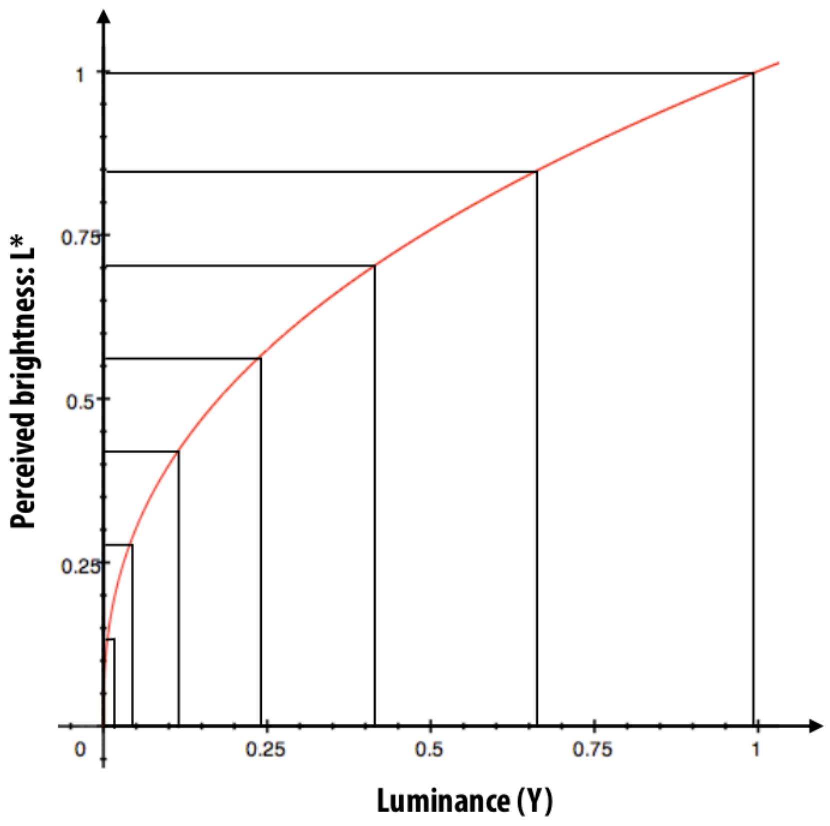
Tone reproduction

Question: Why not just keep measurements linear and do gamma correction right before we display the image?

Tone reproduction

Question: Why not just keep measurements linear and do gamma correction right before we display the image?



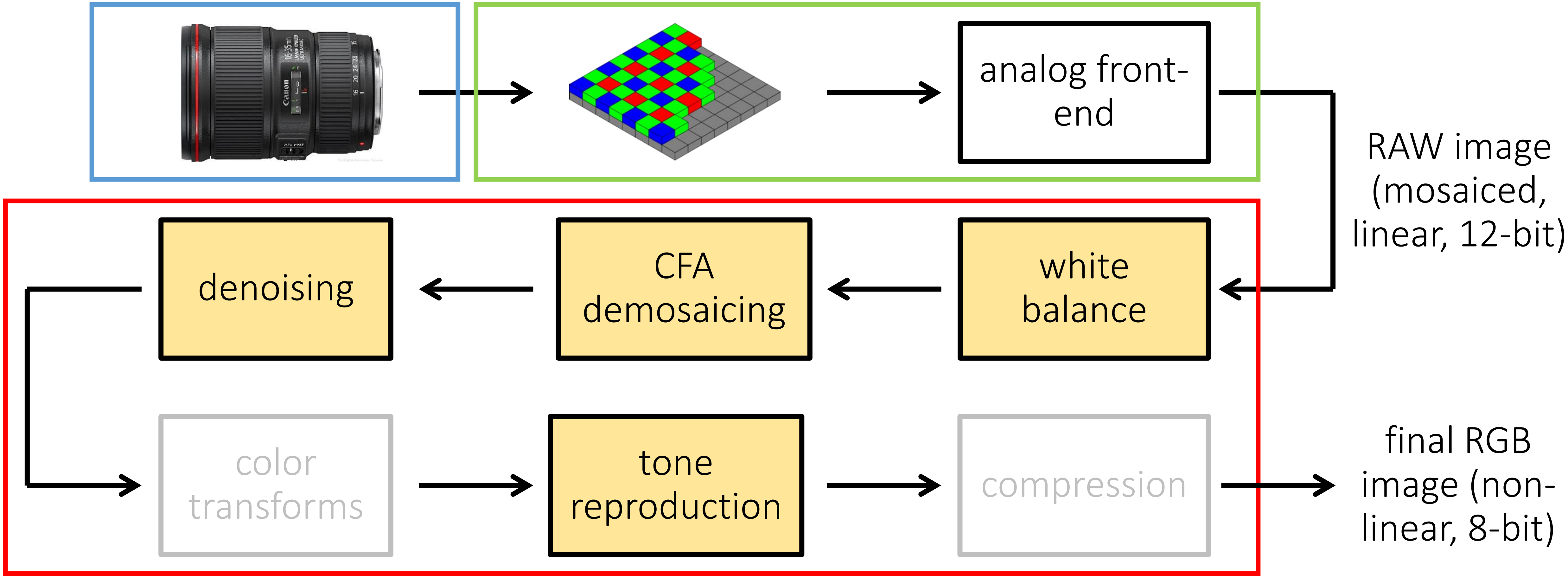


Answer: After this stage, we perform compression, which includes change from 12 to 8 bits.

- Better to use our available bits to encode the information we are going to need.

The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



Some general thoughts on the image processing pipeline

Do I ever need to use RAW?

Do I ever need to use RAW?

Emphatic yes!

- Every time you use a physics-based computer vision algorithm, you *need linear measurements of radiance*.
- Examples: photometric stereo, shape from shading, image-based relighting, illumination estimation, anything to do with light transport and inverse rendering, etc.
- Applying the algorithms on non-linear (i.e., not RAW) images will produce completely invalid results.

What if I don’t care about physics-based vision?

What if I don’t care about physics-based vision?

You often still *want* (rather than need) to use RAW!

- If you like re-finishing your photos (e.g., on Photoshop), RAW makes your life much easier and your edits much more flexible.

Are there any downsides to using RAW?

Are there any downsides to using RAW?

Image files are *a lot* bigger.

- You burn through multiple memory cards.
- Your camera will buffer more often when shooting in burst mode.
- Your computer needs to have sufficient memory to process RAW images.

Is it even possible to get access to RAW images?

Is it even possible to get access to RAW images?

Quite often yes!

- Most high-end cameras provide an option to store RAW image files.
- Certain phone cameras allow, directly or indirectly, access to RAW.
- Sometimes, it may not be “fully” RAW. The Lightroom app provides images after demosaicking but before tone reproduction.

I forgot to set my camera to RAW, can I still get the RAW file?

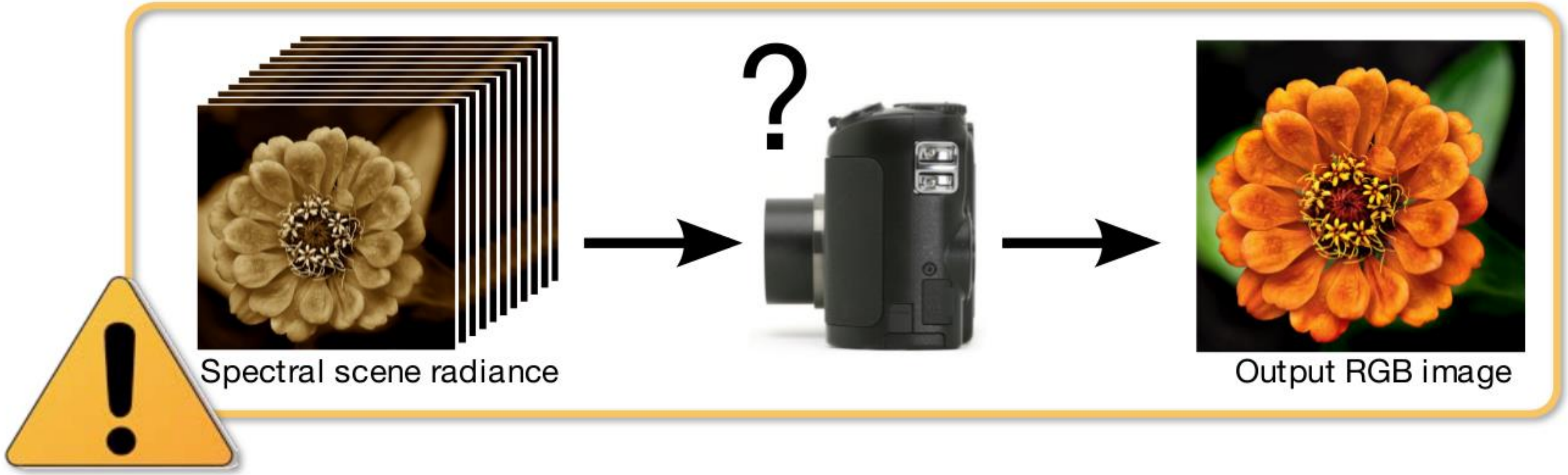
Nope, tough luck.

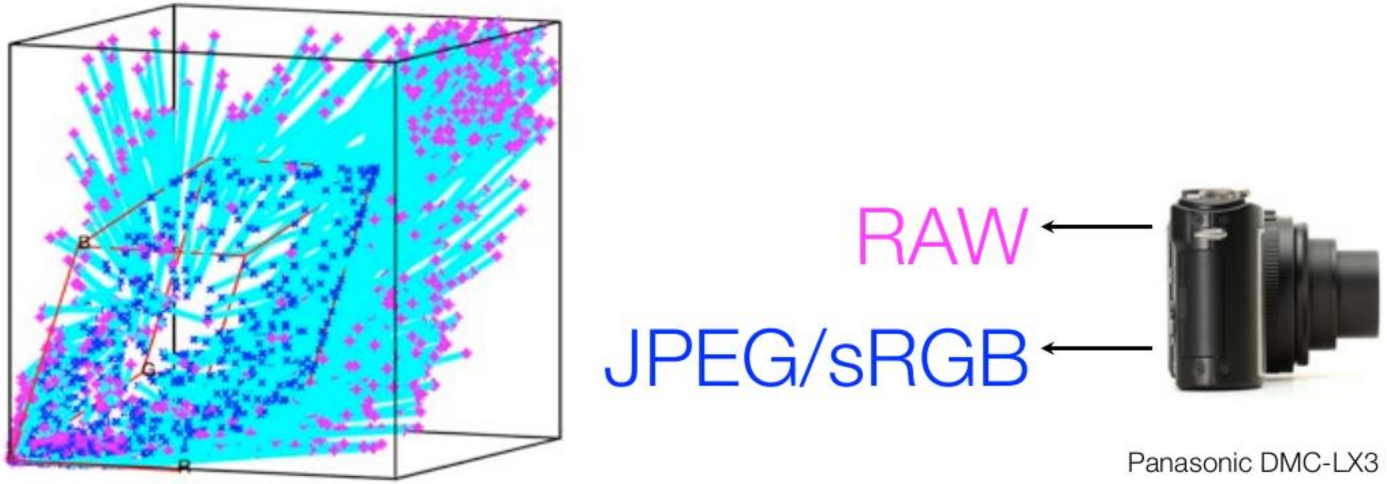
- The image processing pipeline is lossy: After all the steps, information about the original image is lost.

- Sometimes we may be able to reverse a camera's image processing pipeline *if we know exactly what it does* (e.g., by using information from other similar RAW images).

- The conversion of PNG/JPG back to RAW is known as "derendering" and is an active research area.

Derendering





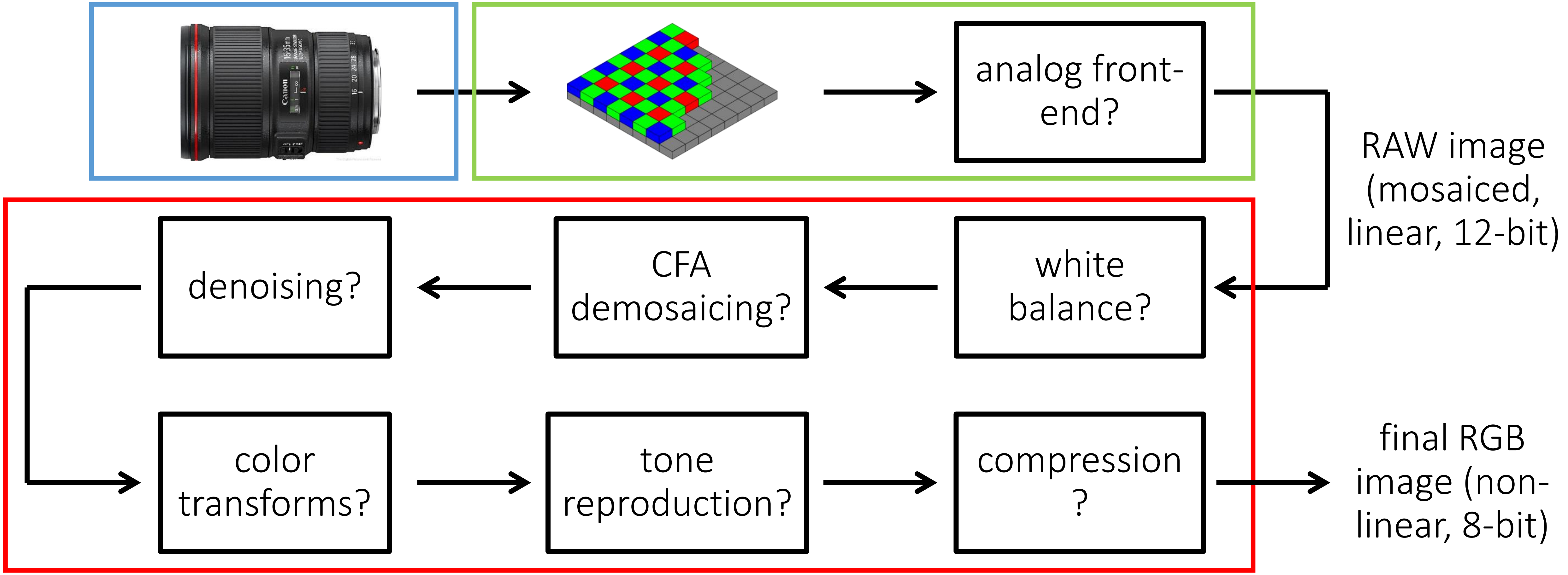
Why did you use italics in the previous slide?

What I described today is an “idealized” version of what we *think* commercial cameras do.

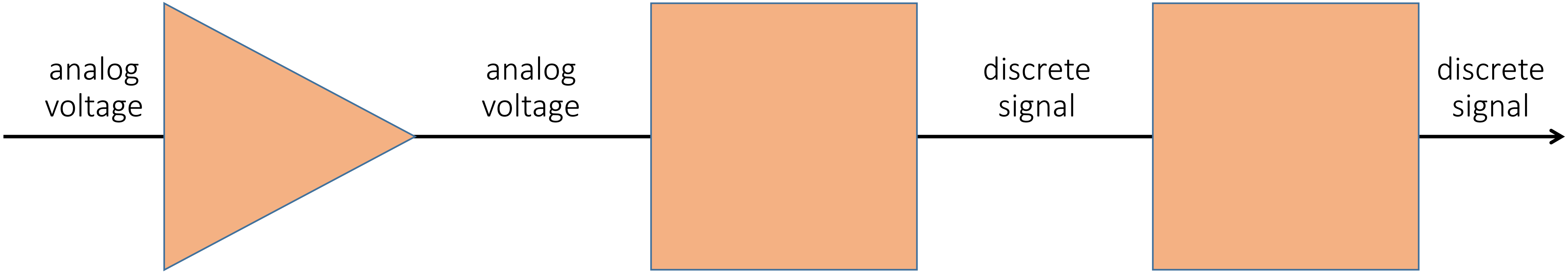
- Almost all of the steps in both the sensor and image processing pipeline I described earlier are camera-dependent.
- Even if we know the basic steps, the implementation details are proprietary information that companies actively try to keep secret.
- I will go back to a few of my slides to show you examples of the above.

The hypothetical image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



The hypothetical analog front-end



analog amplifier (gain):

- gets voltage in range needed by A/D converter?
- accommodates ISO settings?
- accounts for vignetting?

analog-to-digital converter (ADC):

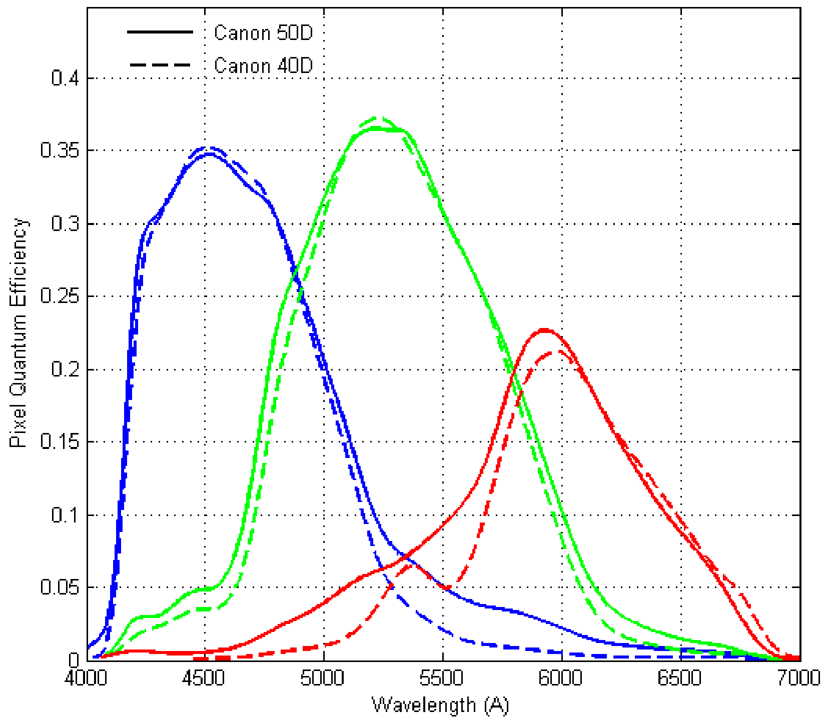
- depending on sensor, output has 10-16 bits.
- most often (?) 12 bits.

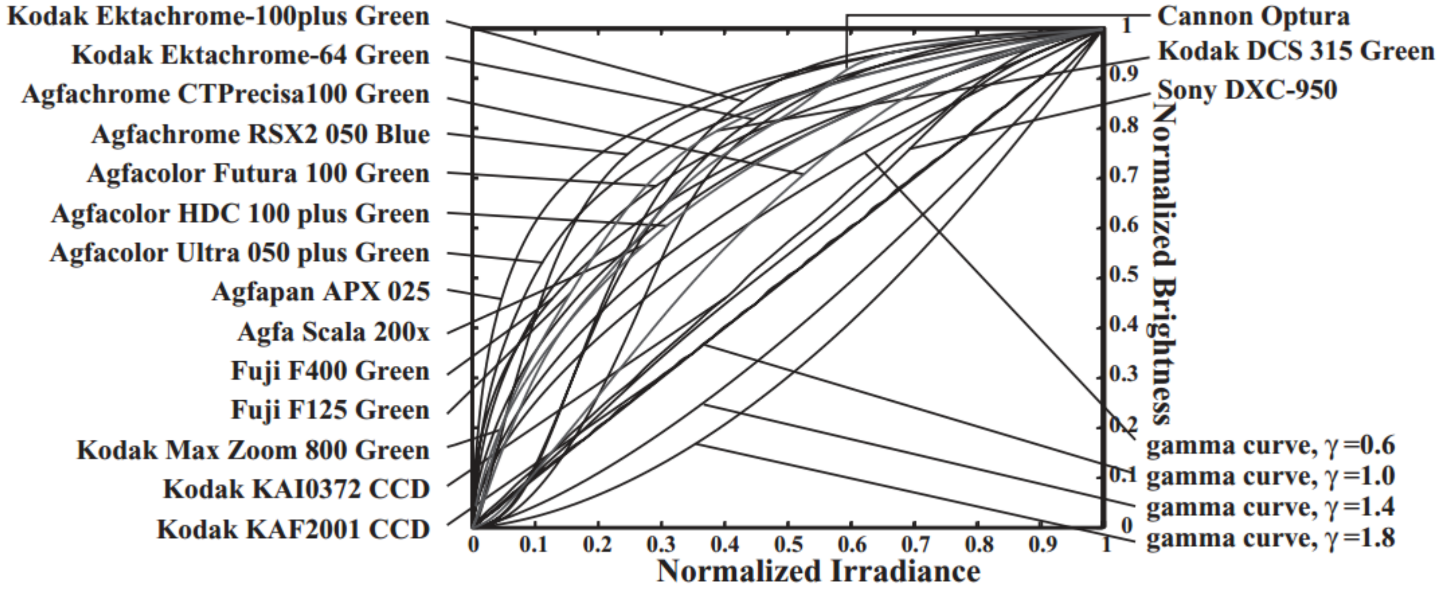
look-up table (LUT):

- corrects non-linearities in sensor's response function (within proper exposure)?
- corrects defective pixels?

Various curves

All of these sensitivity curves are different from camera to camera and kept secret.





Serious inhibition for research

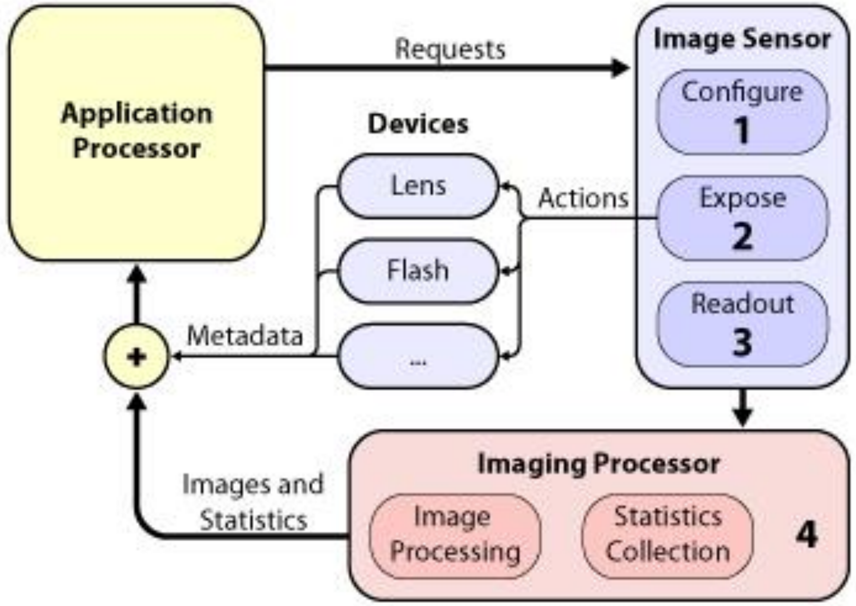
- Very difficult to get access to ground-truth data at intermediate stages of the pipeline.
- Very difficult to evaluate effect of new algorithms for specific pipeline stages.

…but things are getting better

The Frankencamera: An Experimental Platform for Computational Photography

Andrew Adams, Eino-Ville Talvala, Sung Hee Park, David E. Jacobs, Boris Ajdin, Natasha Gelfand, Jennifer Dolson, Daniel Vaquero, Jongmin Baek, Marius Tico, Hendrik P. A. Lensch, Wojciech Matusik, Kari Pulli, Mark Horowitz, Marc Levoy

Presented at SIGGRAPH 2010



…but things are getting better

Camera 2 API Overview

- ● Android.hardware.camera2 API to facilitate fine-grain photo capture and image processing.
- ● The android.hardware.camera2 package provides an interface to individual camera devices connected to an Android device. It replaces the deprecated Camera class.

How do I open a RAW file in Matlab?

You can’t (not easily at least). You need to use one of the following:

- dcraw – tool for parsing camera-dependent RAW files (specification of file formats are also kept secret).

- Adobe DNG – recently(-ish) introduced file format that attempts to standardize RAW file handling.

See Homework 1 for more details.

Is this the best image processing pipeline?

It depends on how you define “best”. This definition is task-dependent.

- The standard image processing pipeline is designed to create “nice-looking” images.
- If you want to do physics-based vision, the best image processing pipeline is no pipeline at all (use RAW).
- What if you want to use images for, e.g., object recognition? Tracking? Robotics SLAM? Face identification? Forensics?

Developing task-adaptive image processing pipelines is an active area of research.

Take-home messages

The values of pixels in a photograph and the values output by your camera's sensor are two very different things.

The relationship between the two is complicated and unknown.

References

Basic reading:

- Szeliski textbook, Section 2.3.
- Michael Brown, "Understanding the In-Camera Image Processing Pipeline for Computer Vision," CVPR 2016, slides available at: http://www.comp.nus.edu.sg/~brown/CVPR2016_Brown.html

Additional reading:

- Adams et al., "The Frankencamera: An Experimental Platform for Computational Photography," SIGGRAPH 2010.
  The first open architecture for the image processing pipeline, and precursor to the Android Camera API.
- Heide et al., "FlexISP: A Flexible Camera Image Processing Framework," SIGGRAPH Asia 2014.
  Discusses how to implement a single-stage image processing pipeline.
- Buckler et al., "Reconfiguring the Imaging Pipeline for Computer Vision," ICCV 2017.
- Diamond et al., "Dirty Pixels: Optimizing Image Classification Architectures for Raw Sensor Data," arXiv 2017.
  Both papers discuss how to adaptively change the conventional image processing pipeline so that it is better suited to various computer vision problems.
- Chakrabarti et al., "Rethinking Color Cameras," ICCP 2014.
  Discusses different CFAs, including ones that have white filters, and how to do demosaicing for them.
- Gunturk et al., "Demosaicking: Color Filter Array Interpolation," IEEE Signal Processing Magazine 2005
  A nice review of demosaicing algorithms.
- Chakrabarti et al., "Probabilistic Derendering of Camera Tone-mapped Images," PAMI 2014.
  Discusses how to (attempt to) derender an image that has already gone through the image processing pipeline of some (partially calibrated) camera.