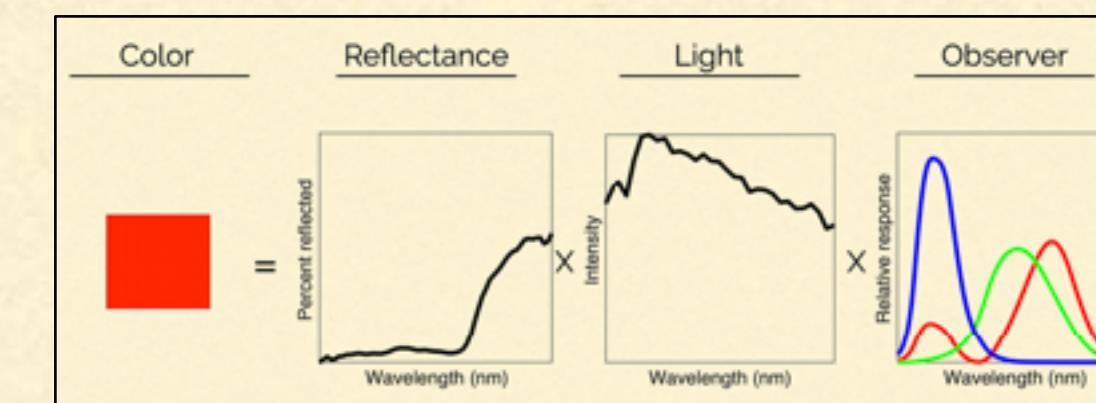


UNDERWATER COLORIMETRY

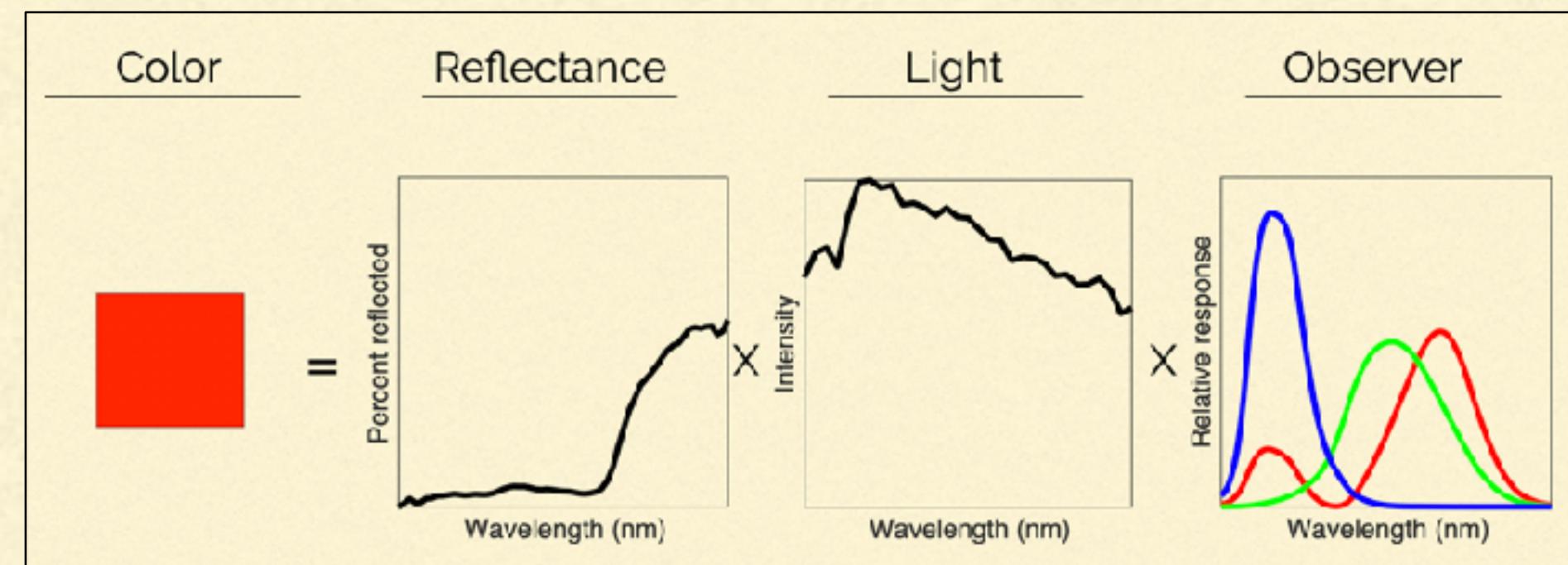


DIGITAL IMAGE FORMATION - I

Dr. Derya Akkaynak | dakkaynak@univ.haifa.ac.il

WHAT HAVE WE LEARNED THUS FAR?

- ▶ Color is complex!
- ▶ The three main components that make up “color”:

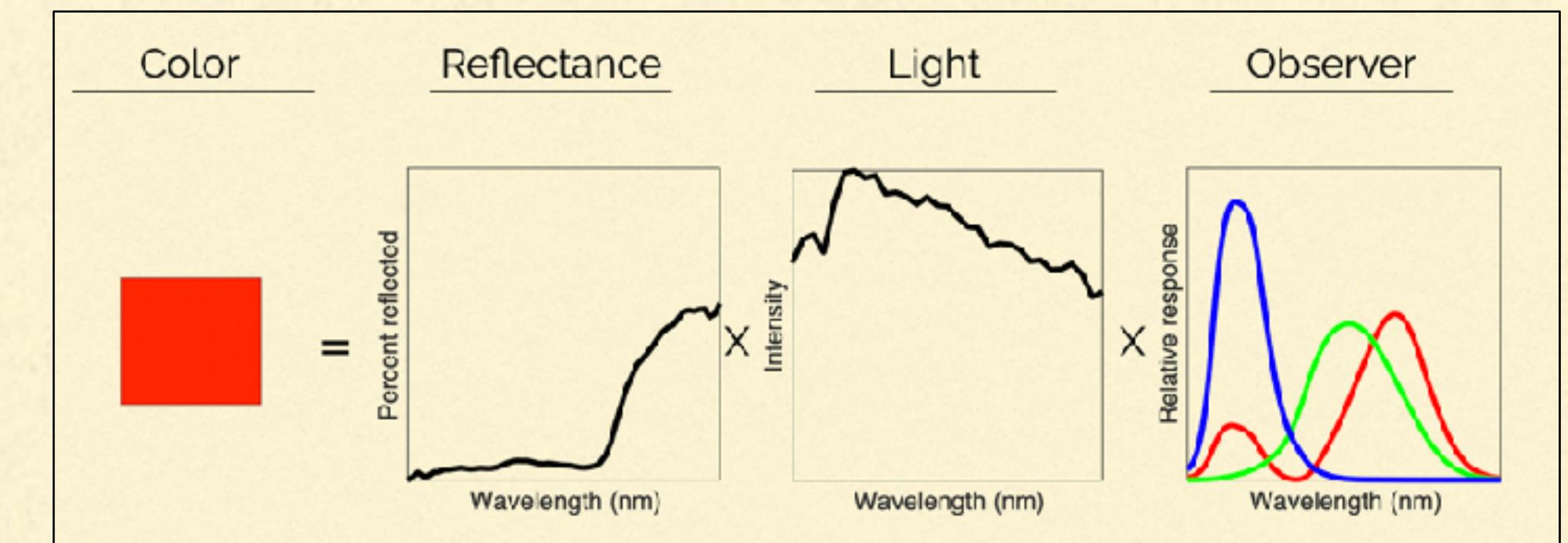


- ▶ **RADIANCE** = **REFLECTANCE** \times **LIGHT**
- ▶ A camera captures **RADIANCE**
- ▶ Pros & Cons of color measuring devices



WHAT WILL WE LEARN IN THIS LECTURE?

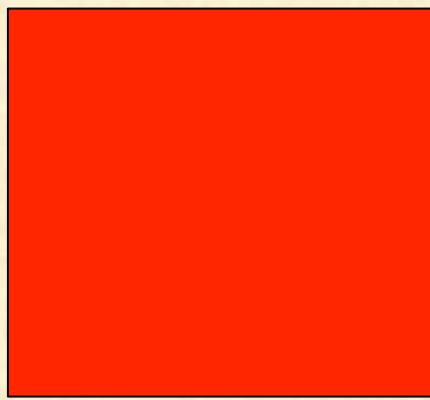
- ▶ What is an **image formation model**?
- ▶ What is a **RAW** image?
- ▶ What is a **JPG** image?
- ▶ Why should you **NEVER** use JPGs in science
- ▶ Real-world tools:
 - ▶ How to process a **RAW** image
 - ▶ How to check for sensor linearity
 - ▶ How simulate an image



What Is Color?

In this course, we are not covering 3D \rightarrow 2D geometric projection of a scene and only focusing on radiometric relations between the scene and an image of the scene.

Color

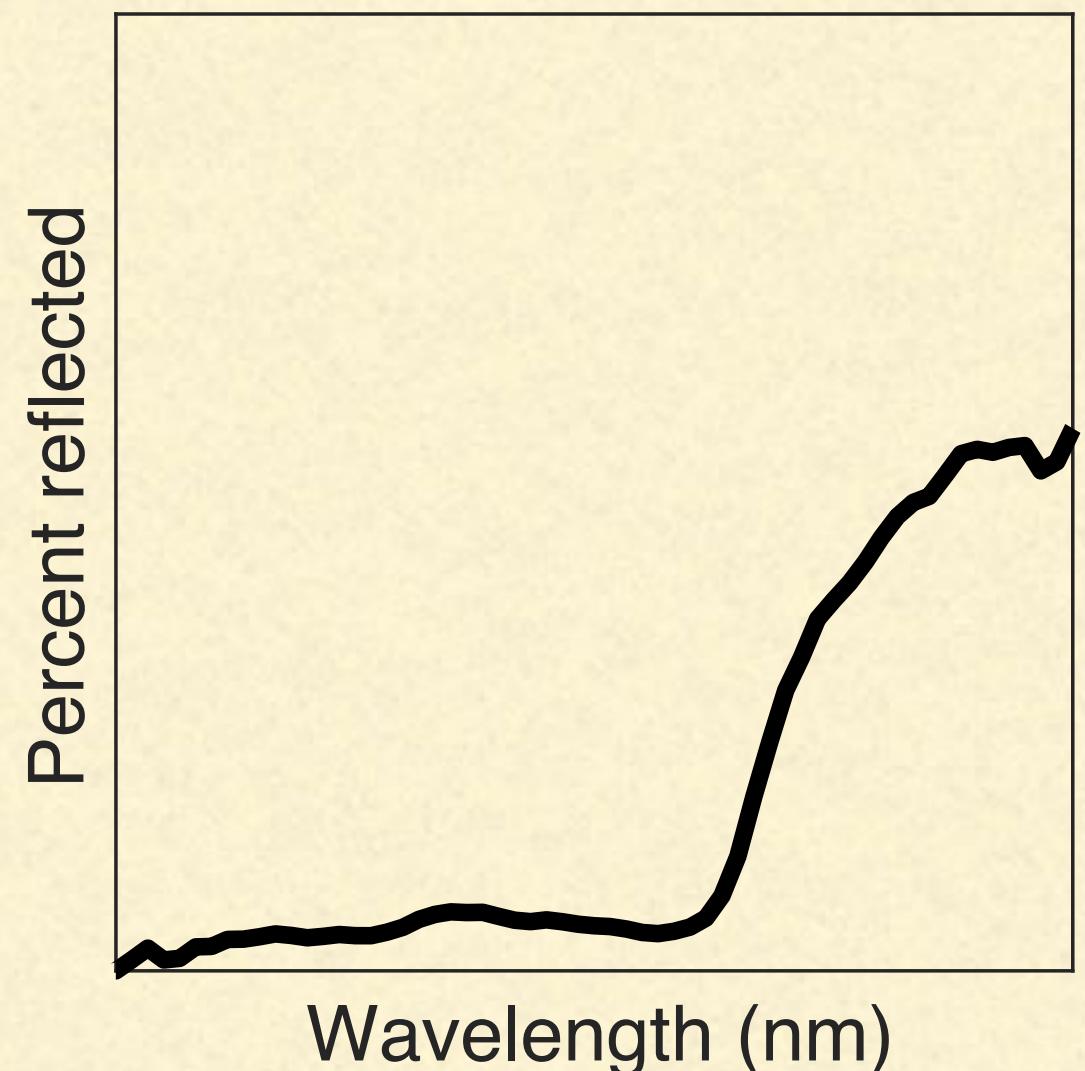


$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

κ : exposure-related constant

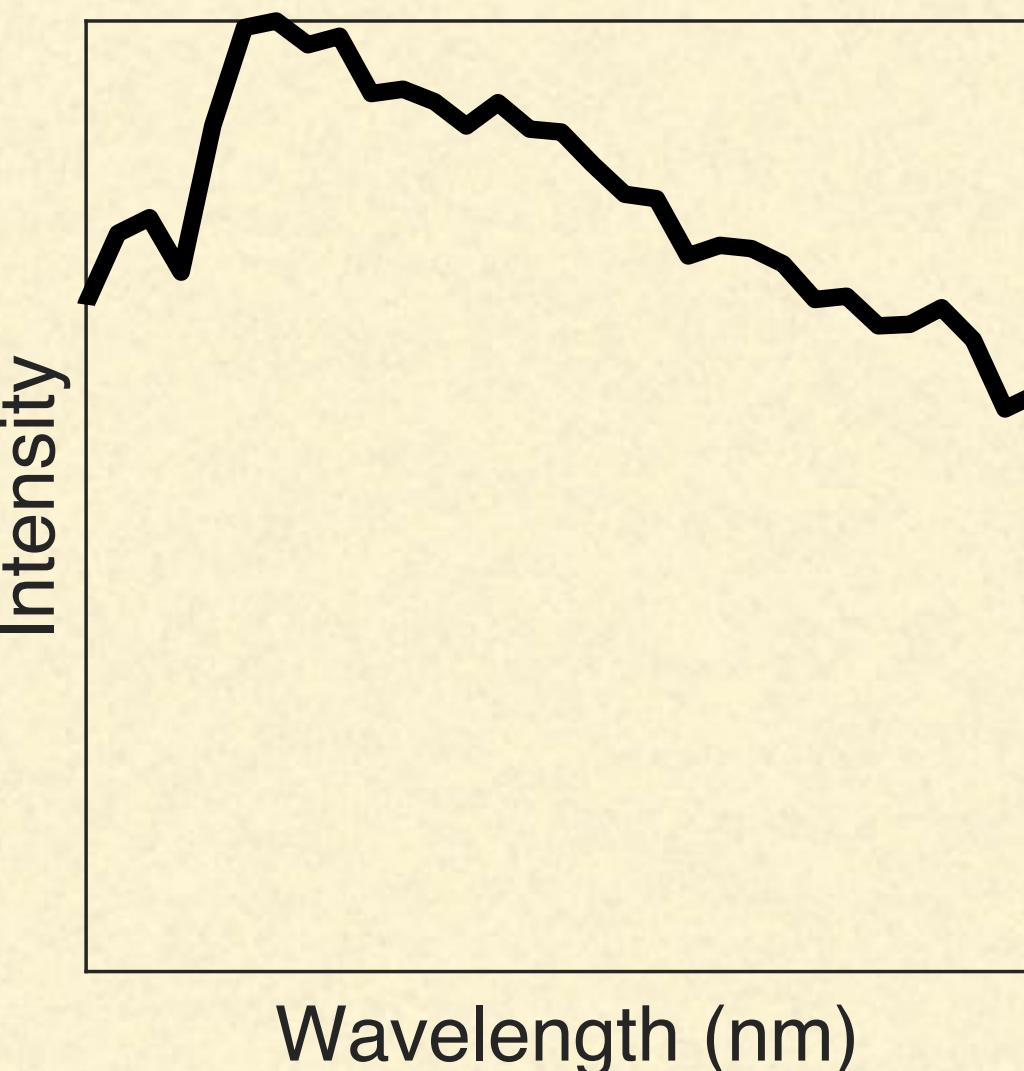
Reflectance

$$\rho(\lambda)$$



Light

$$E(\lambda)$$



Observer

$$S(\lambda)$$

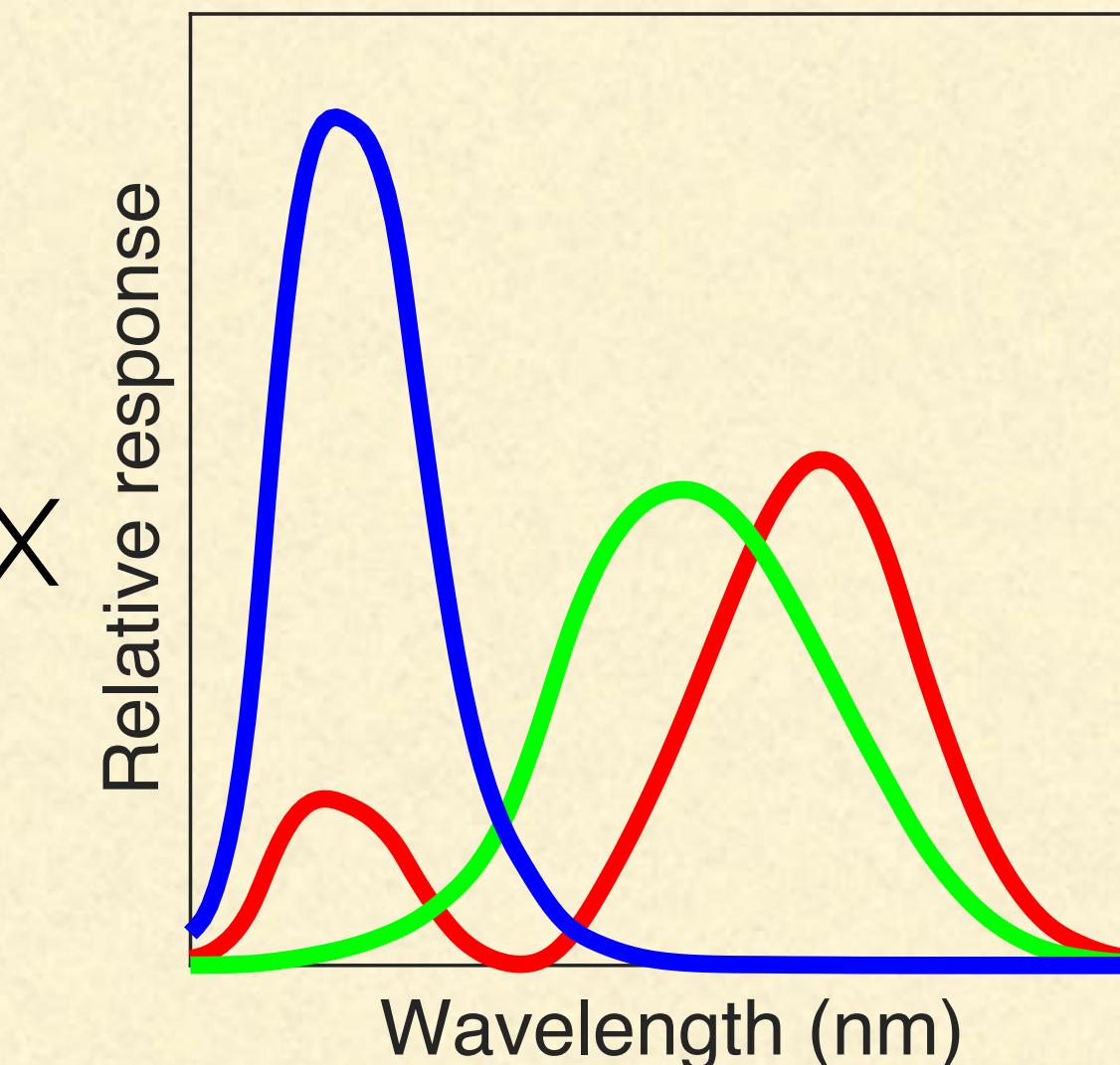


Image Formation Model

In this course, we are not covering 3D \rightarrow 2D geometric projection of a scene and only focusing on radiometric relations between the scene and an image of the scene.

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This is the image formation model for **clear air**.

Image Formation Model

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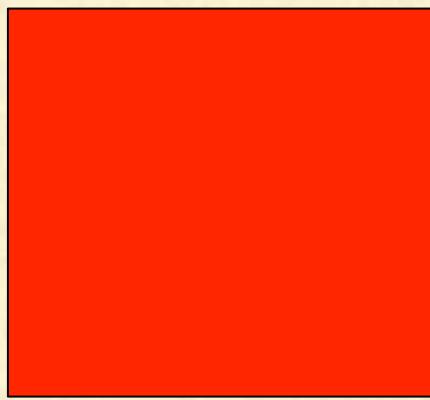
κ : exposure-related constant

This is the image formation model for **clear air**.

Image Formation in Clear Air

$S(\lambda)$:
Spectral response of
the camera

Color

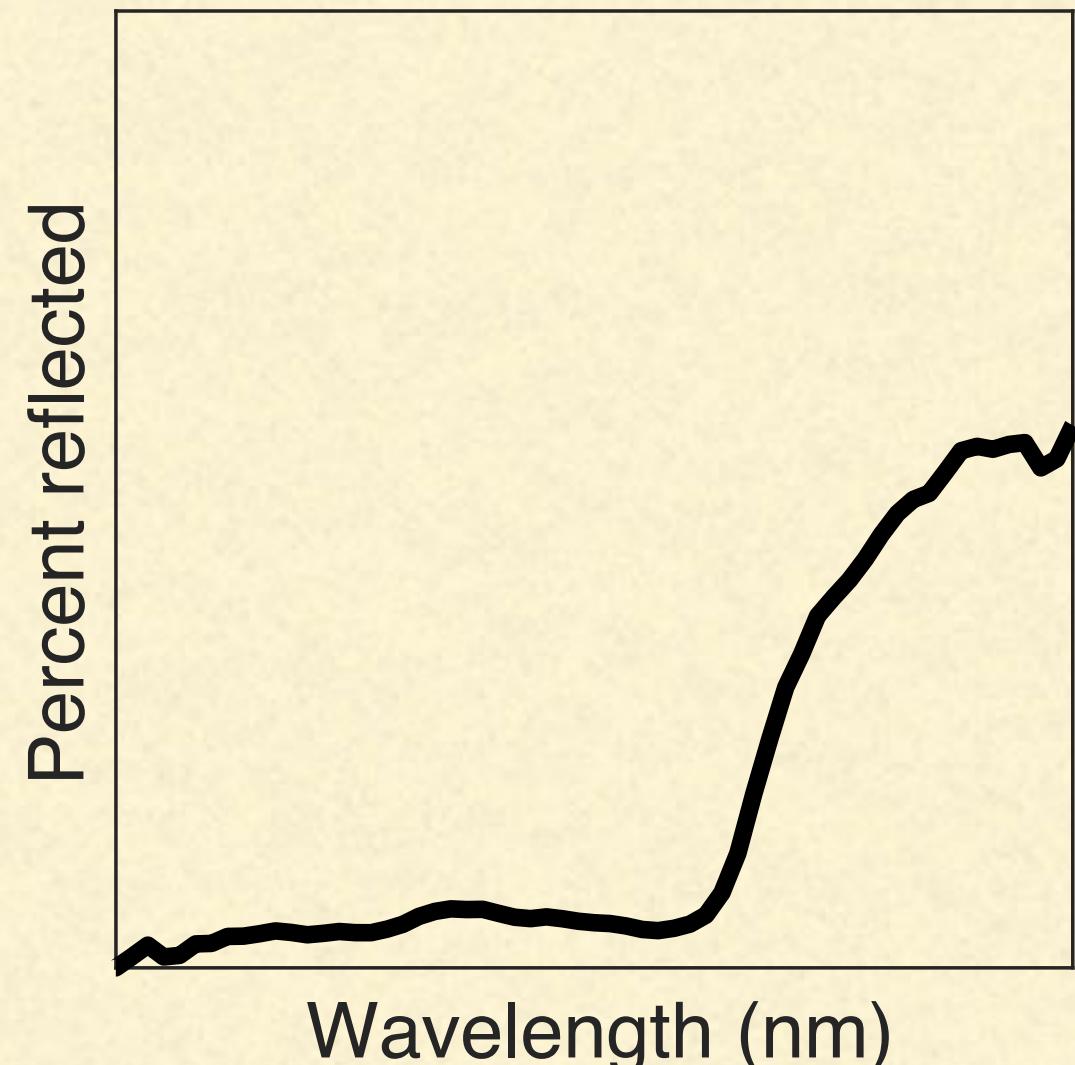


$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

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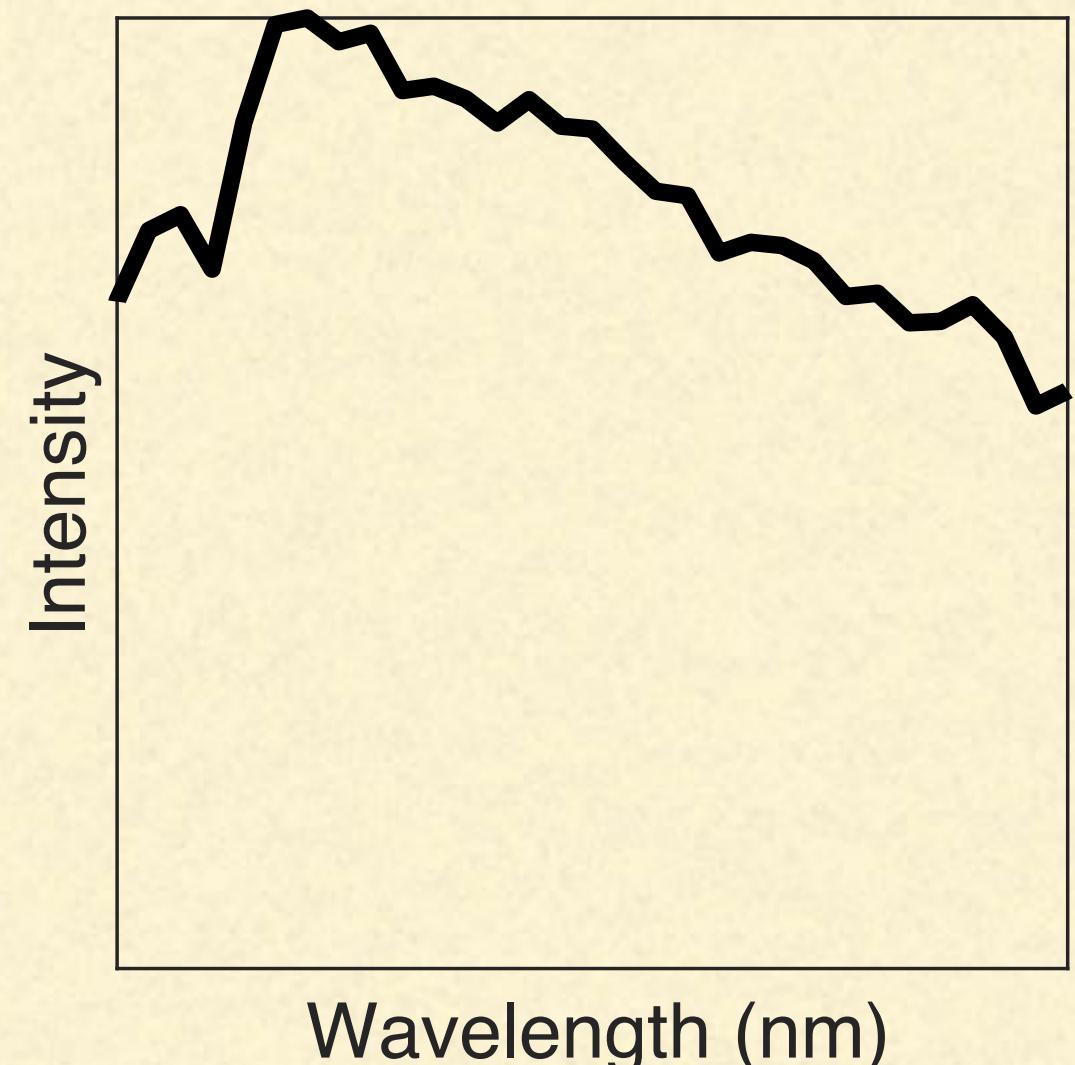
Reflectance

$$\rho(\lambda)$$



Light

$$E(\lambda)$$



Observer

$$S(\lambda)$$

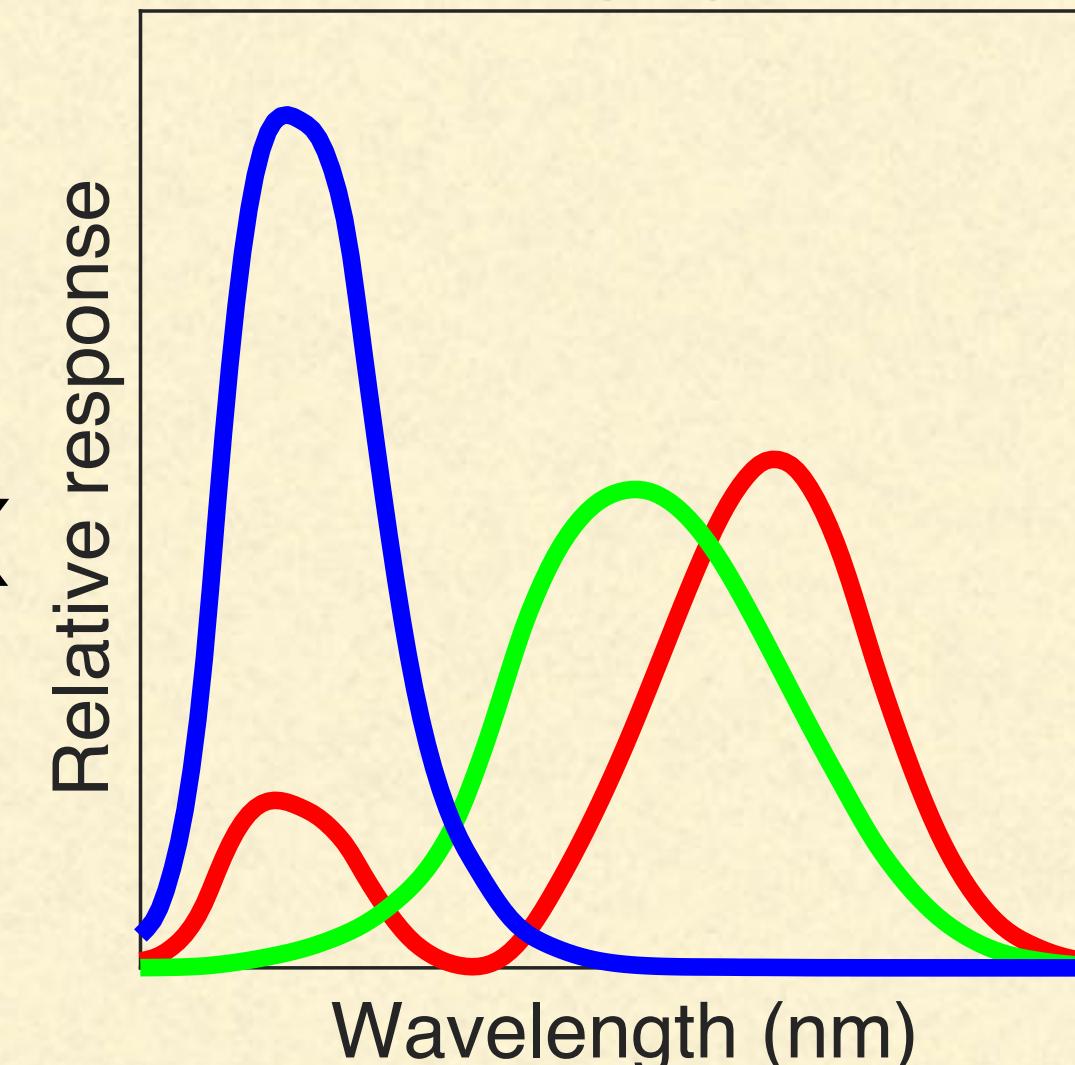
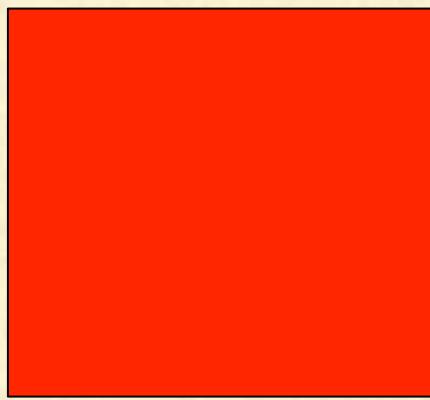


Image Formation in Clear Air

$S(\lambda)$:
Spectral response of
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Color

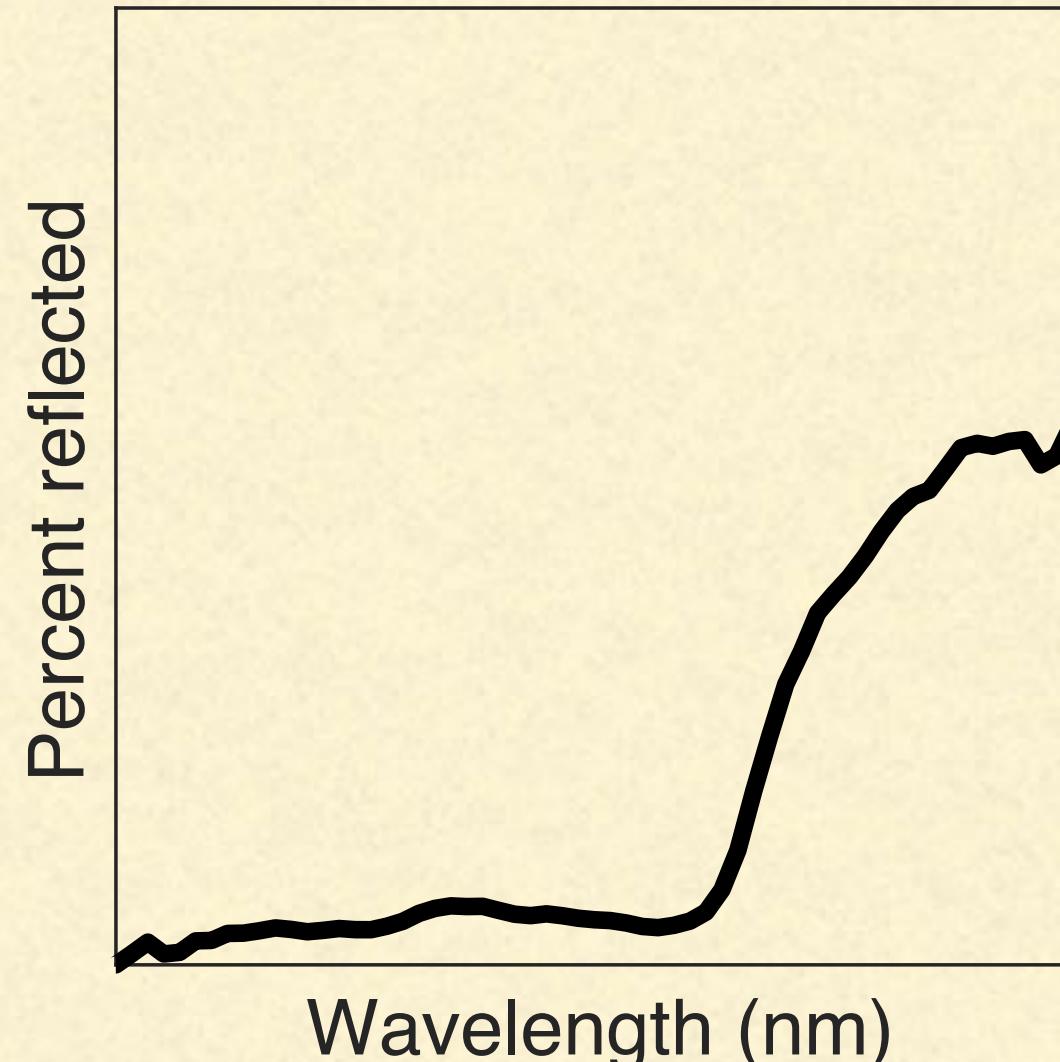


$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

κ : exposure-related constant

Reflectance

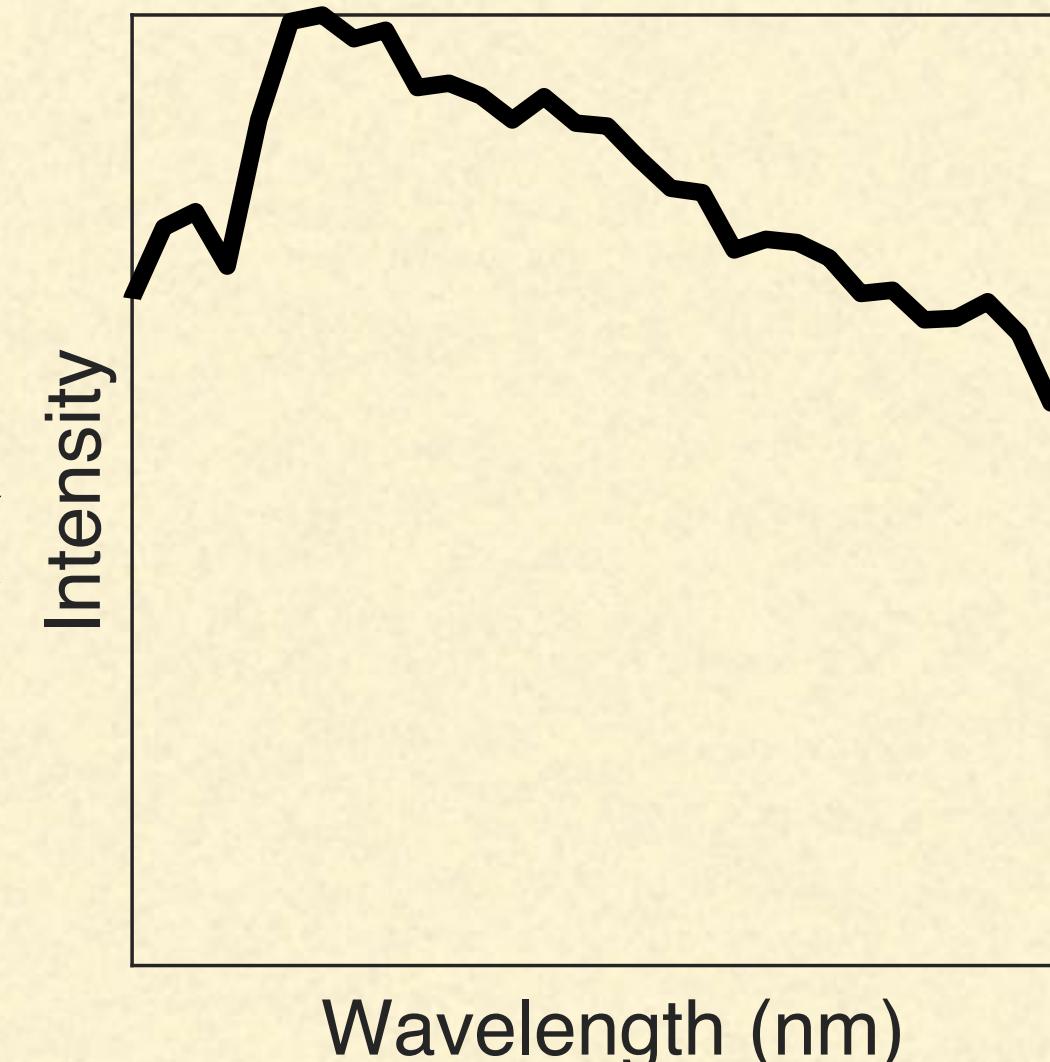
$$\rho(\lambda)$$



||

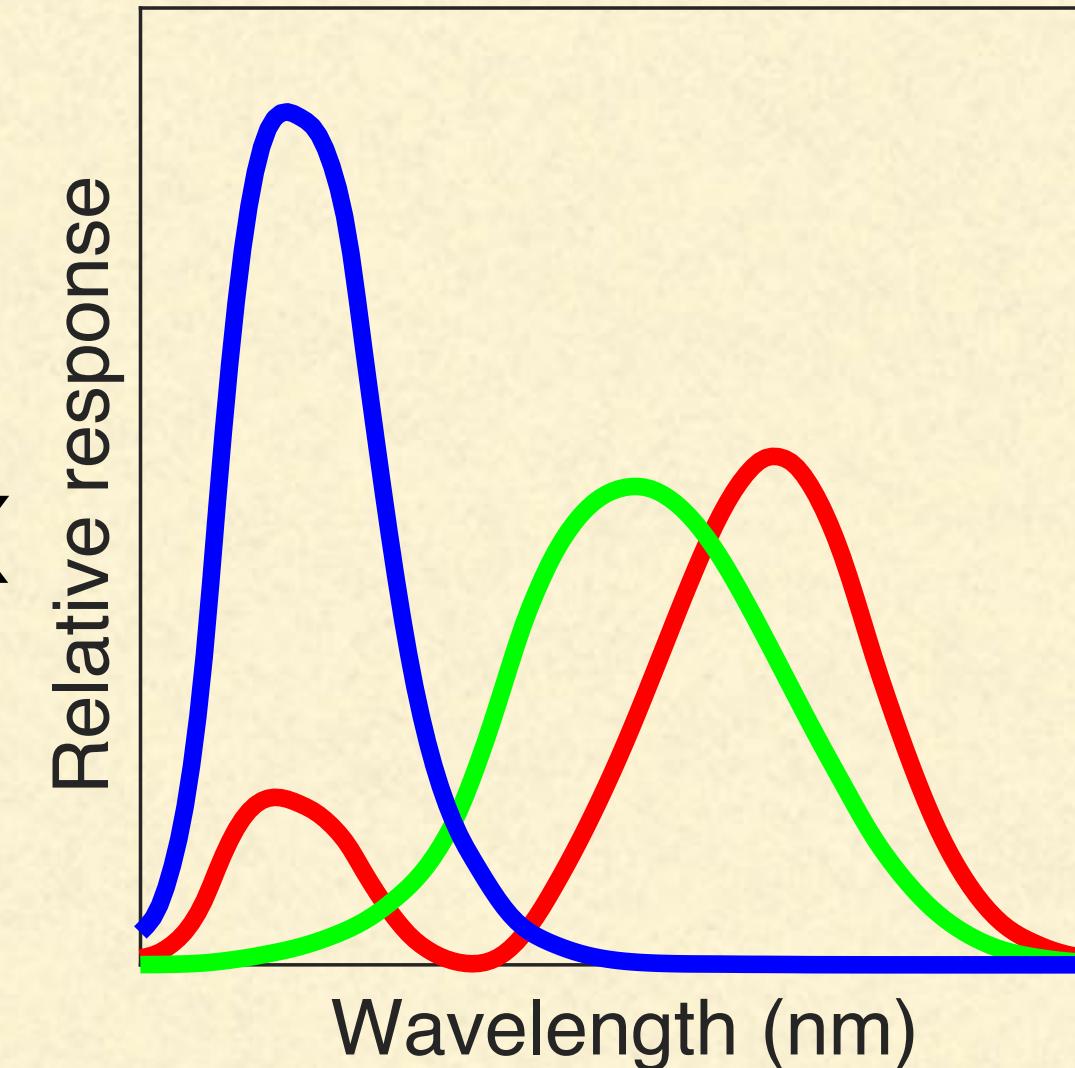
Light

$$E(\lambda)$$

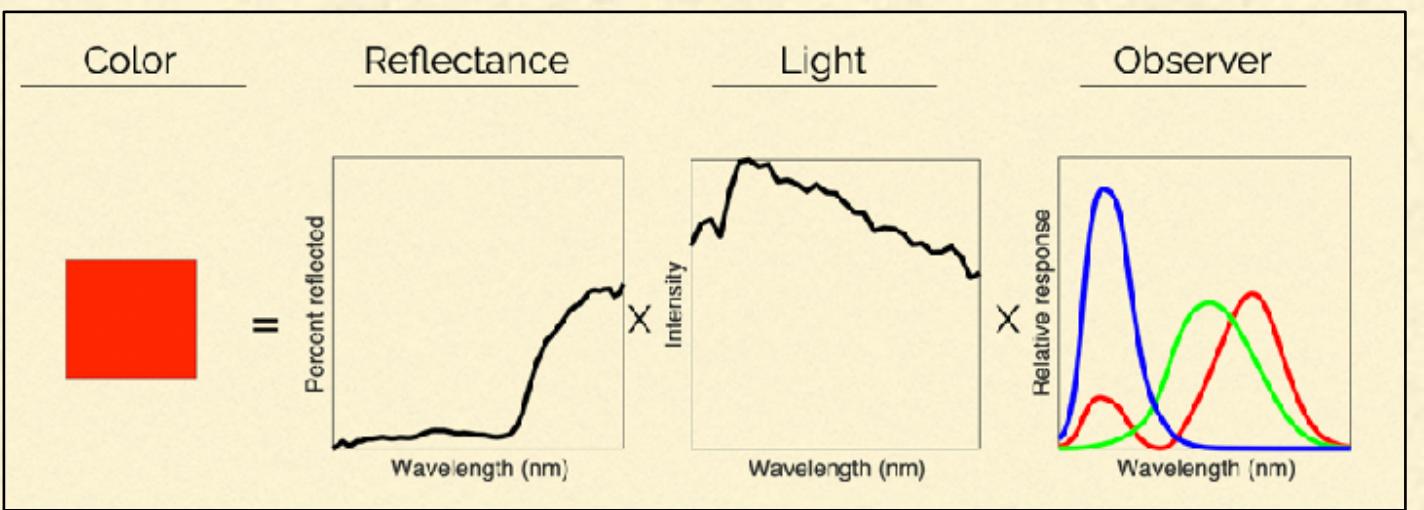


Camera

$$S(\lambda)$$



Cameras



DSLR



Mirrorless



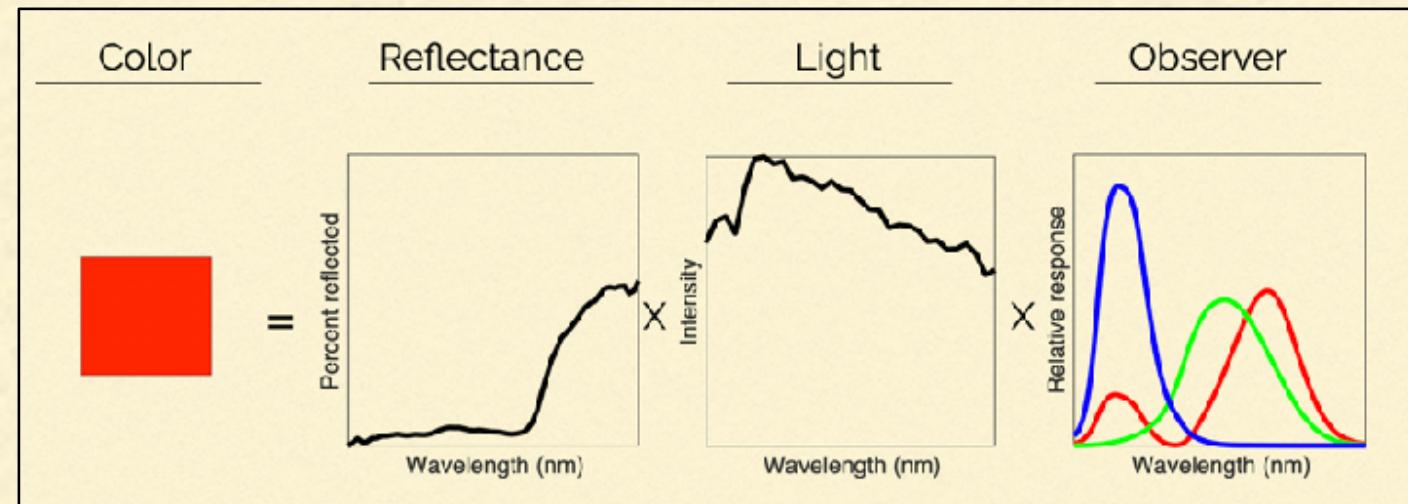
Compact



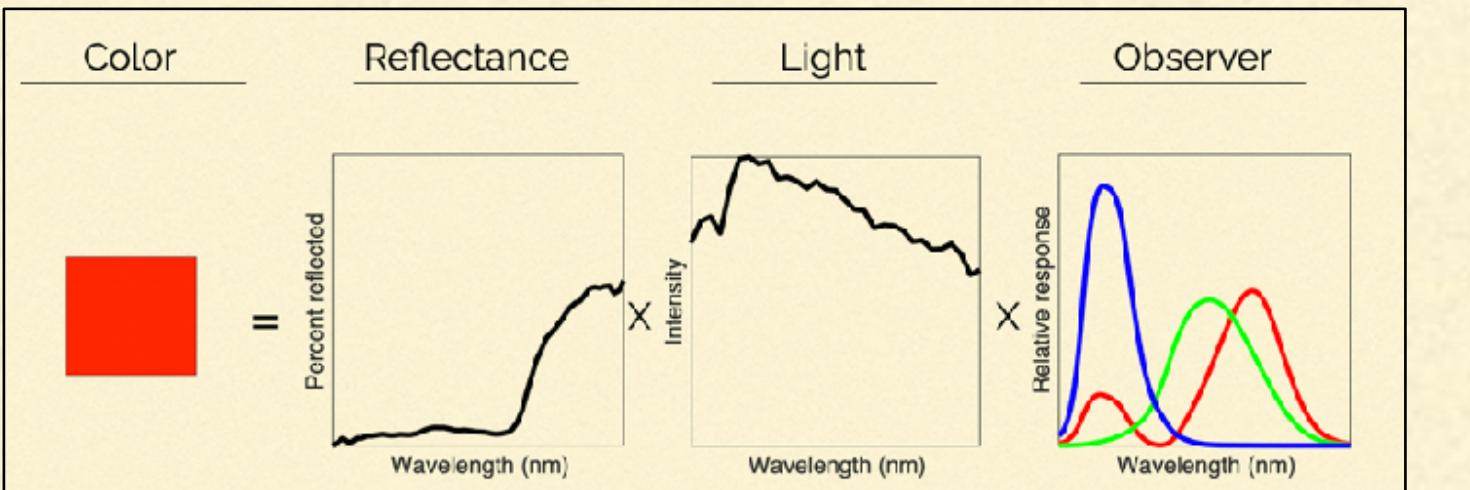
Cell Phone

In this course, we are working with commercial-off-the-shelf (COTS) cameras, also called consumer or RGB cameras, which have sensitivities in the Red, Green, Blue parts of the spectrum.

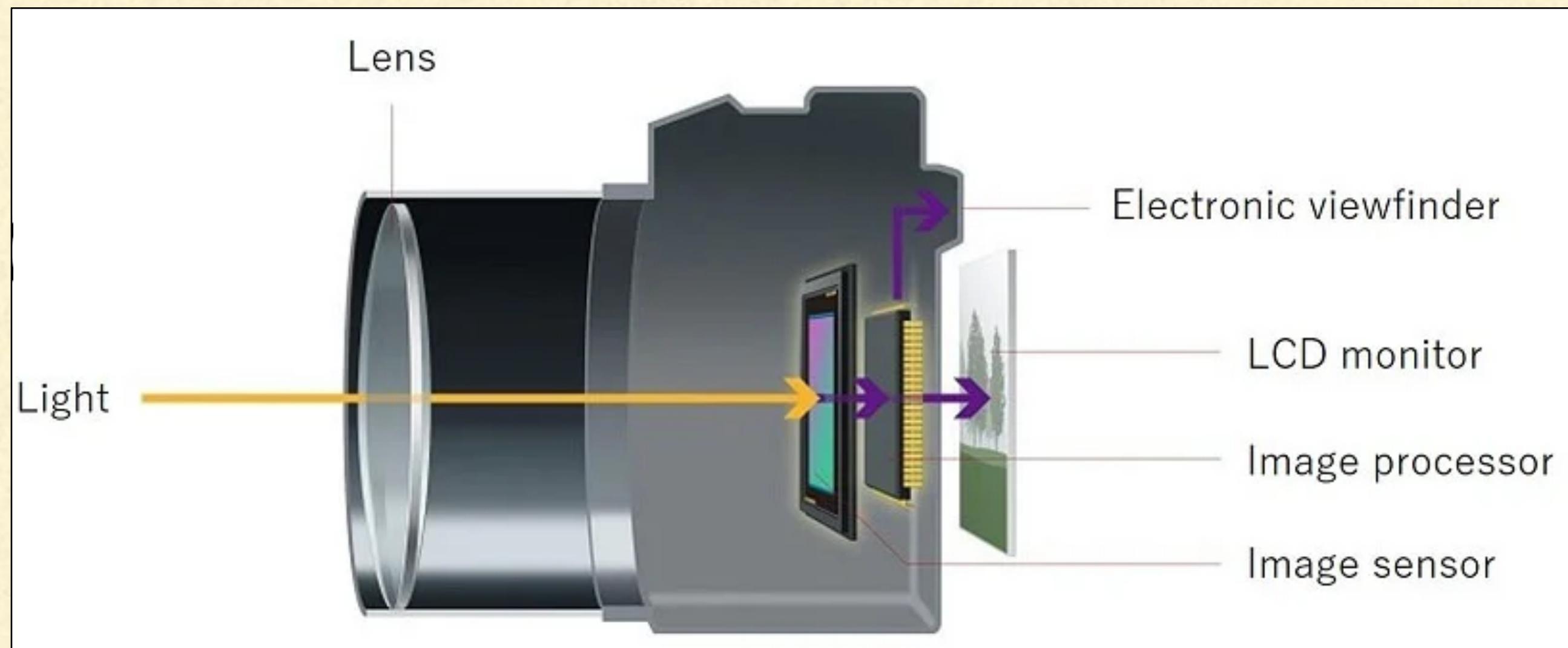
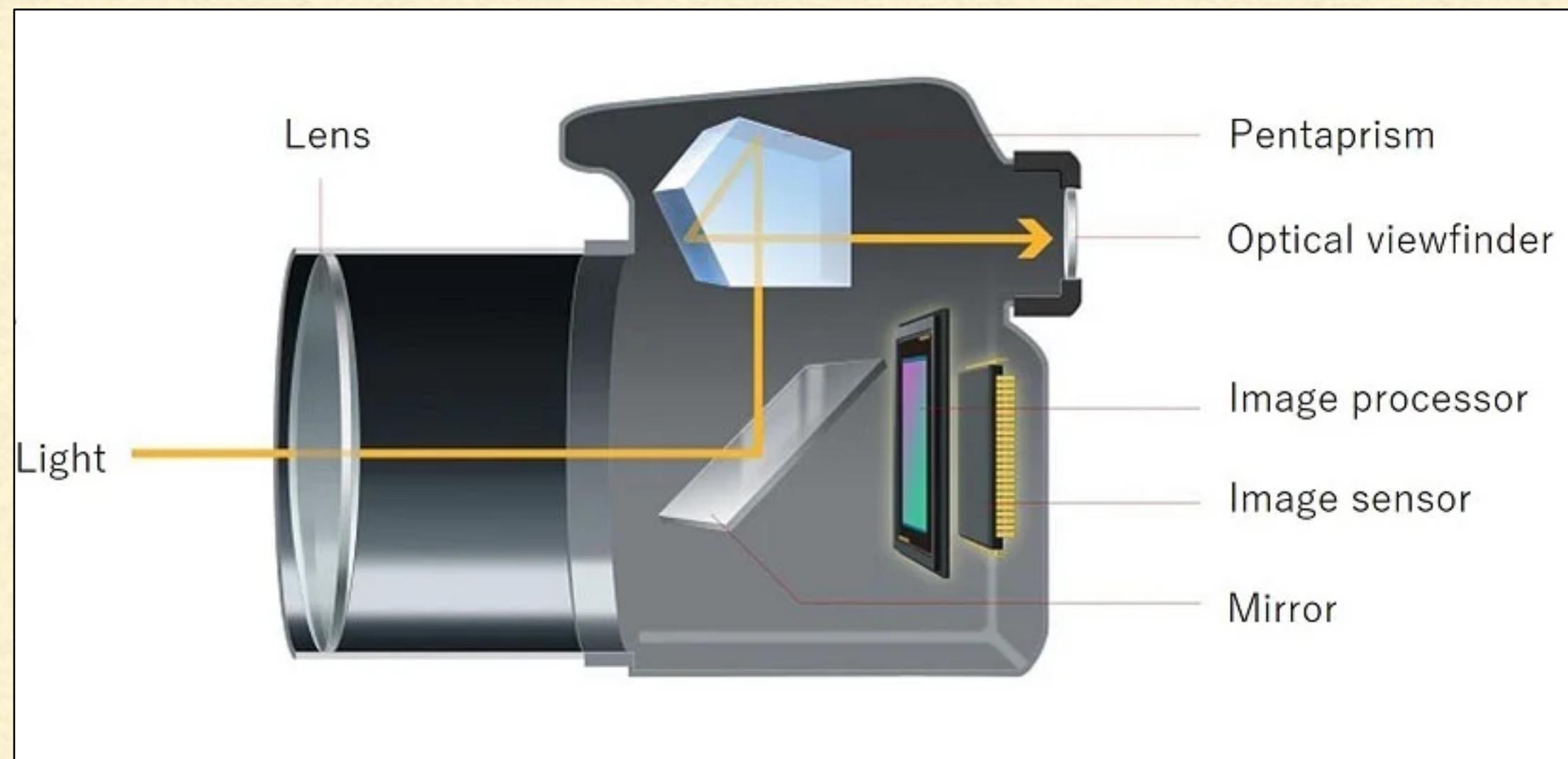
Cameras



Cameras

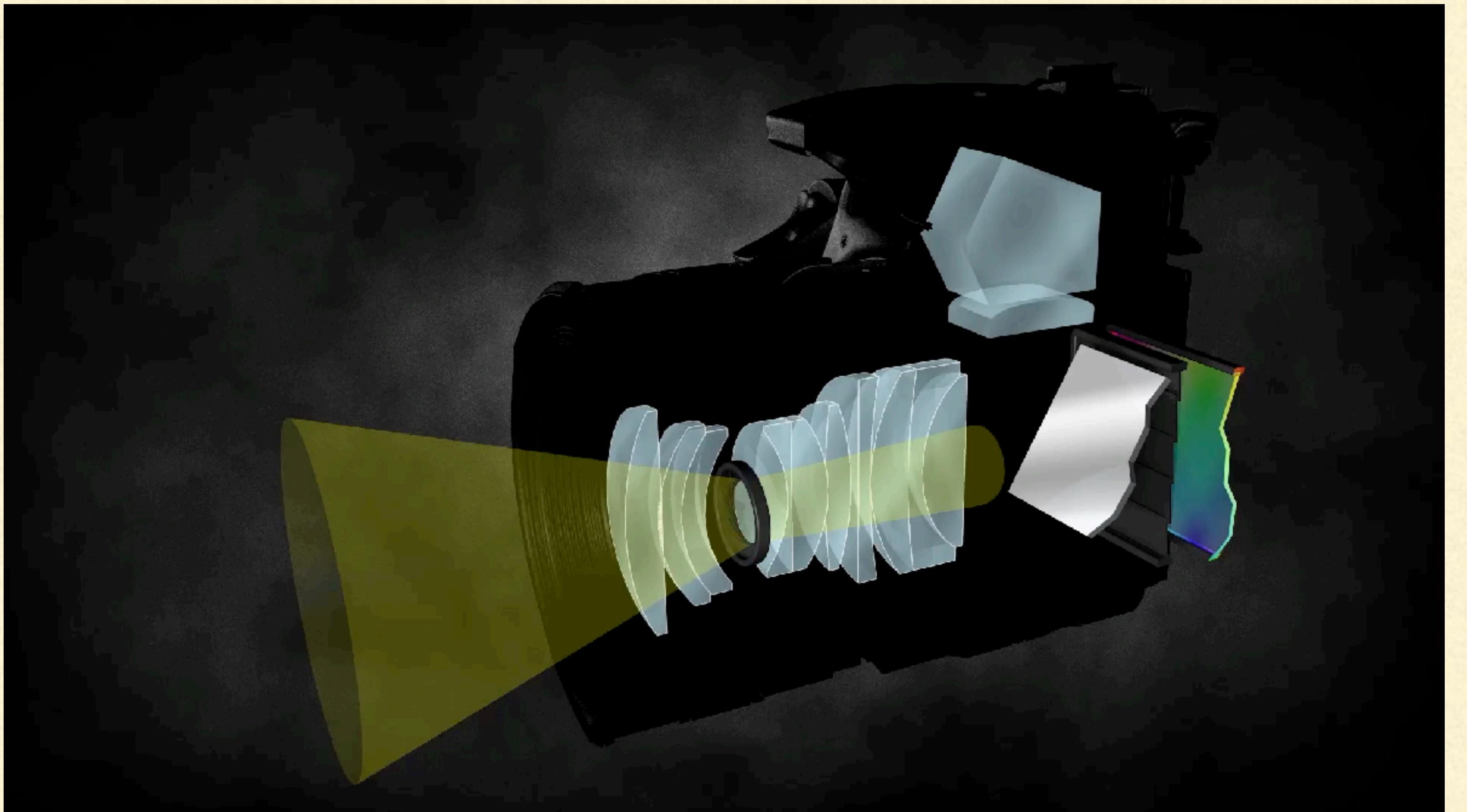
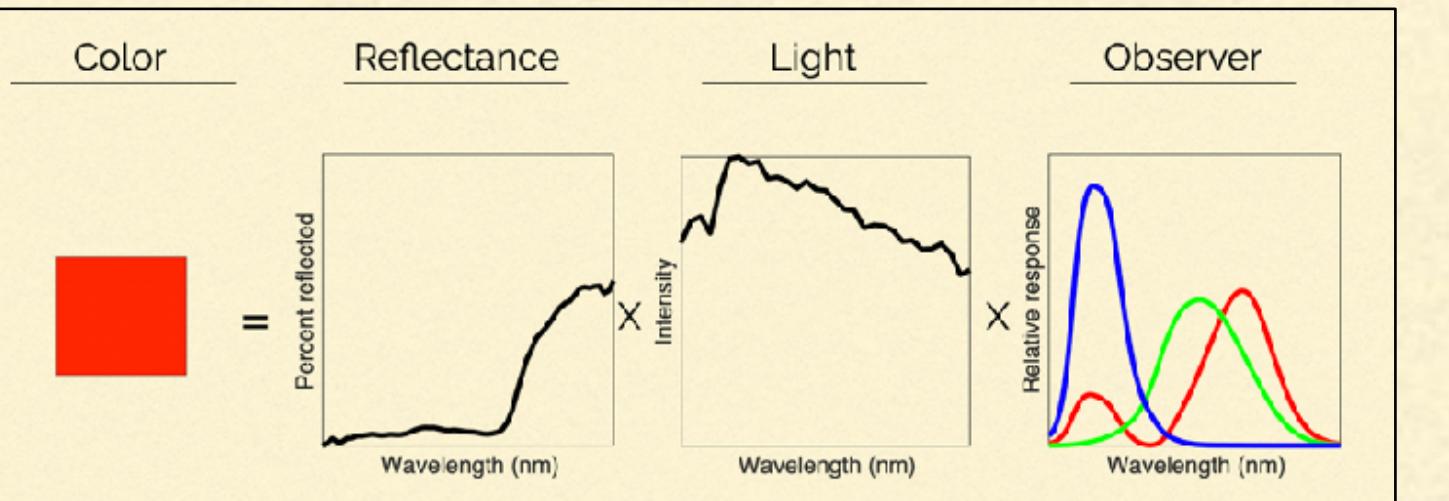


Digital Single Lens Reflex (DSLR)

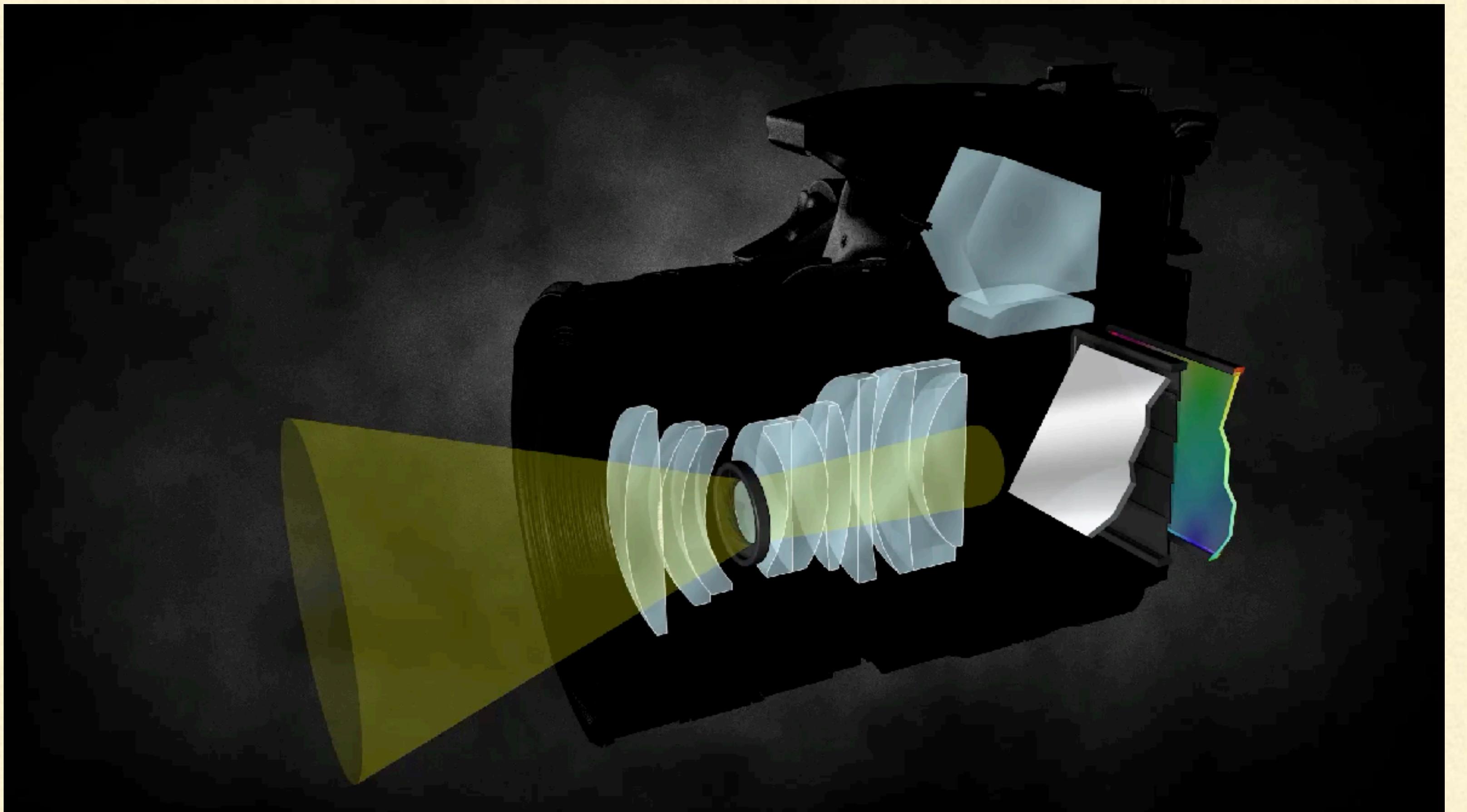
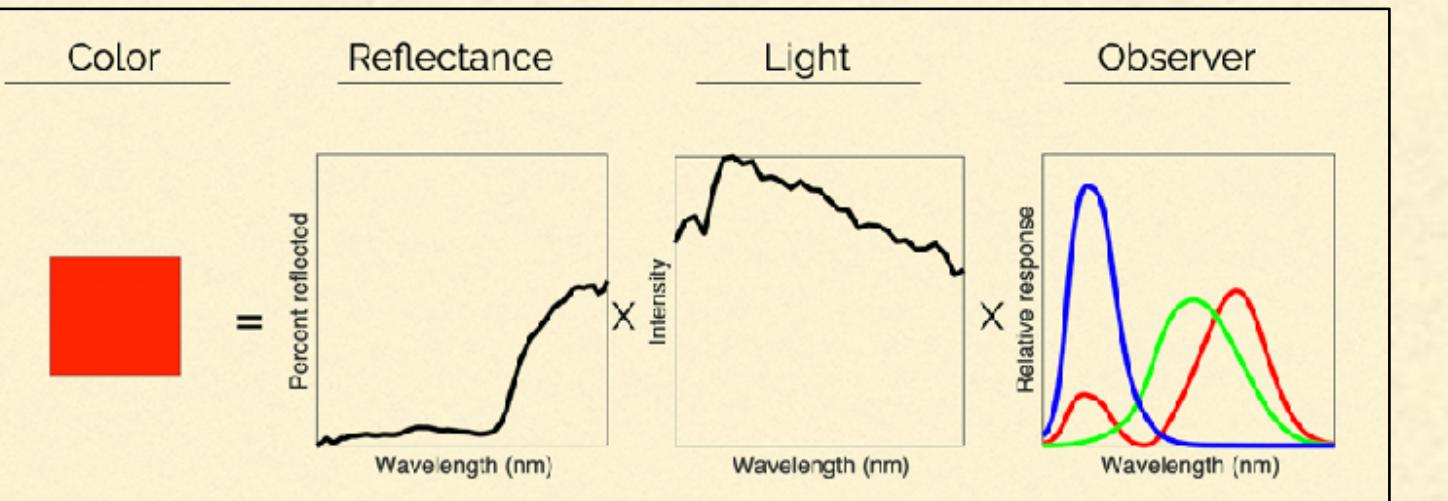


Mirrorless

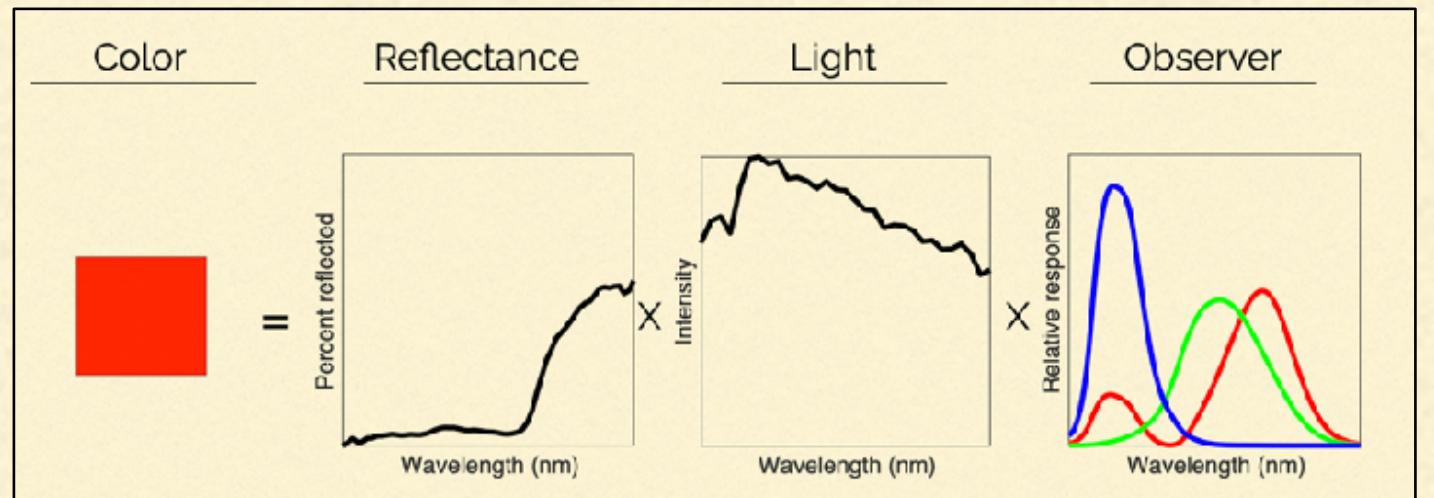
Cameras



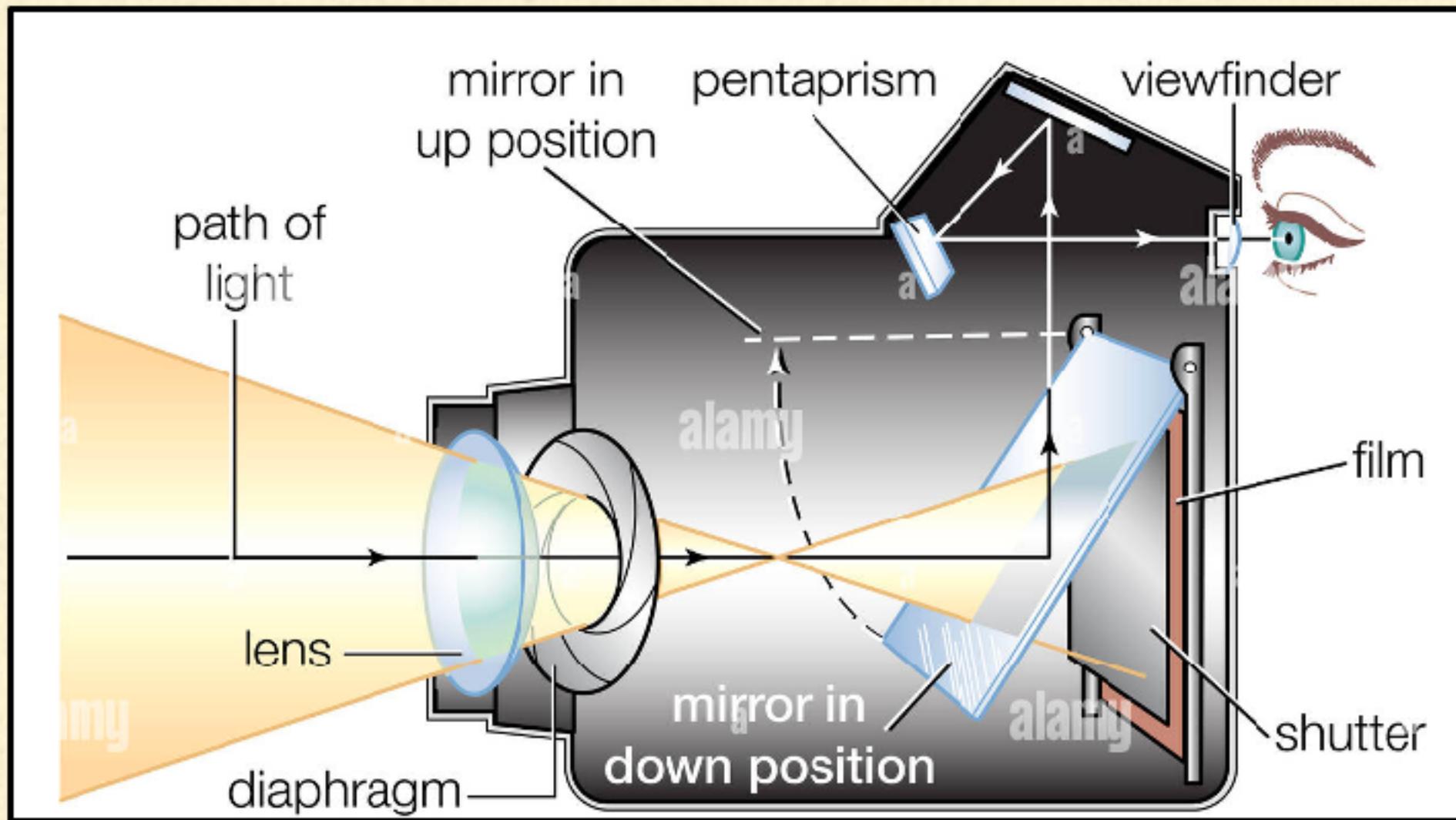
Cameras



Cameras



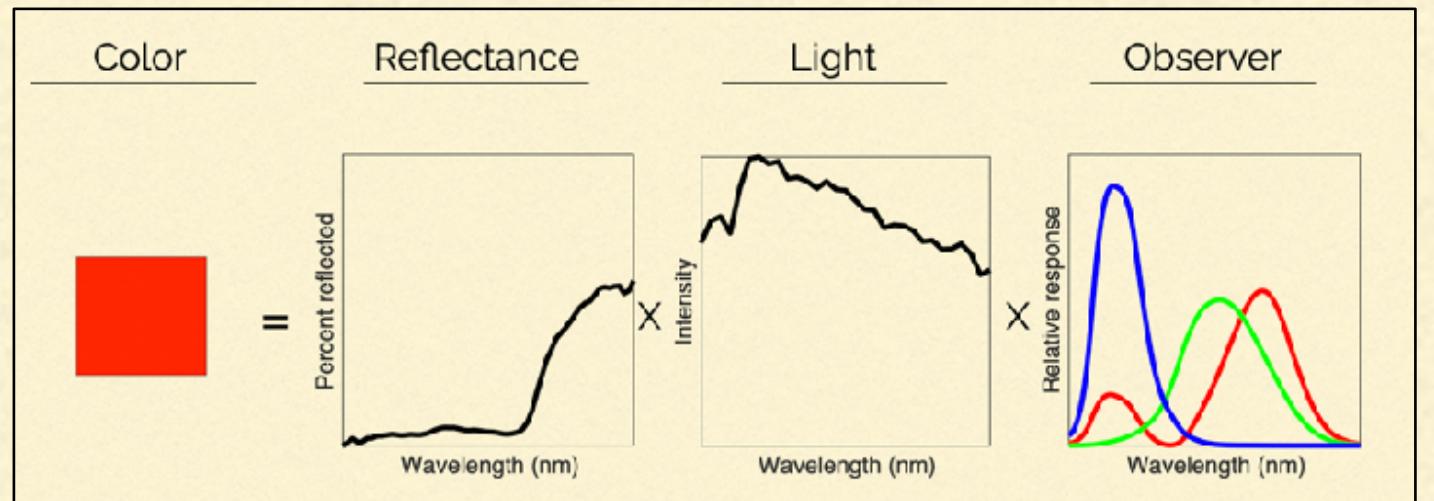
Not Digital Single Lens Reflex (SLR)



Not Digital Twin Lens Reflex (TLR)



Cameras



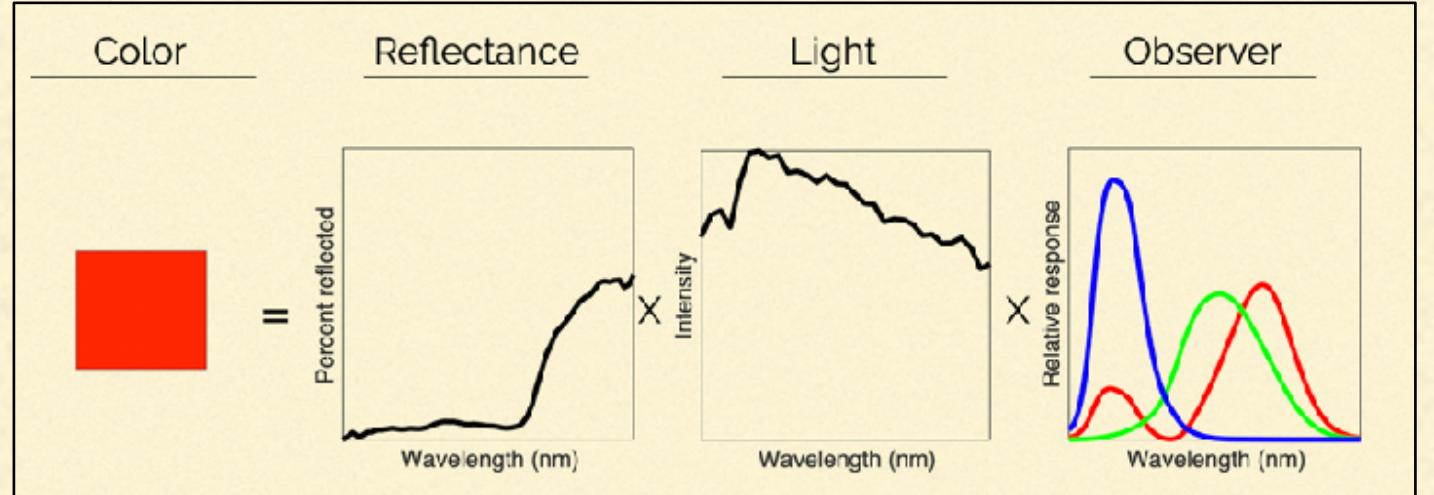
Compact

Cell Phone



Compact cameras and cell phone cameras (usually) do not have interchangeable lenses.

Cameras



Compact

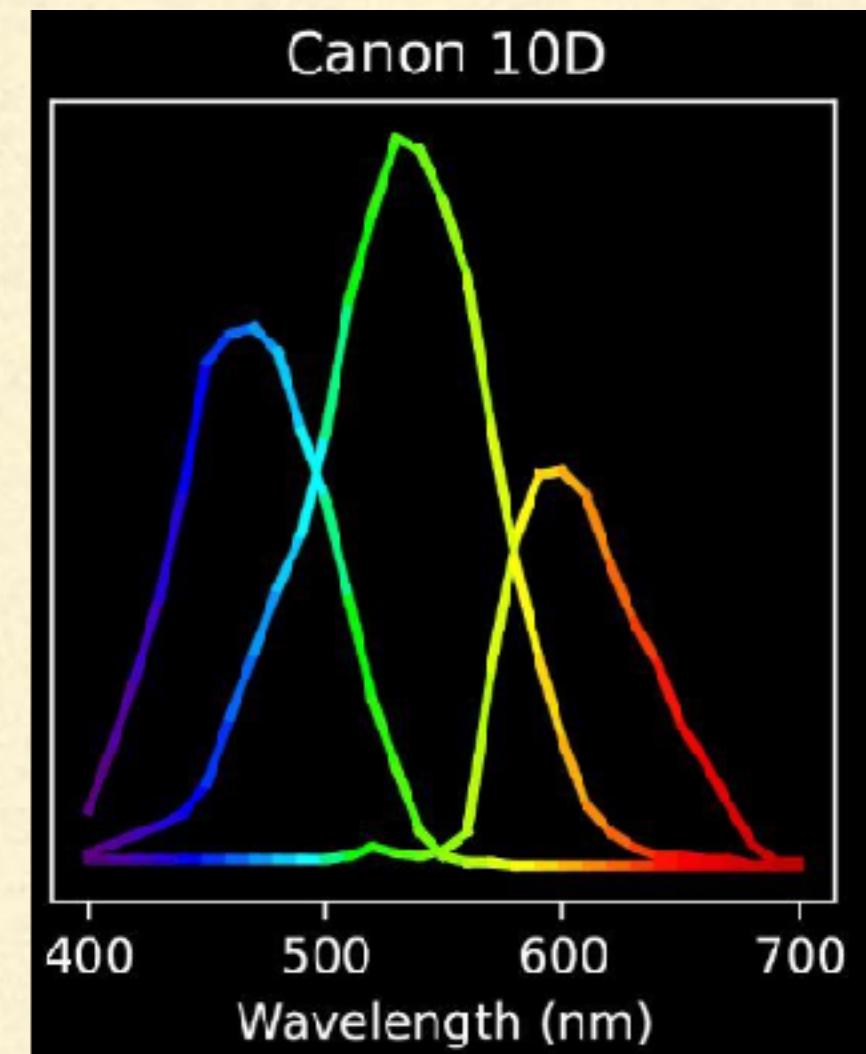
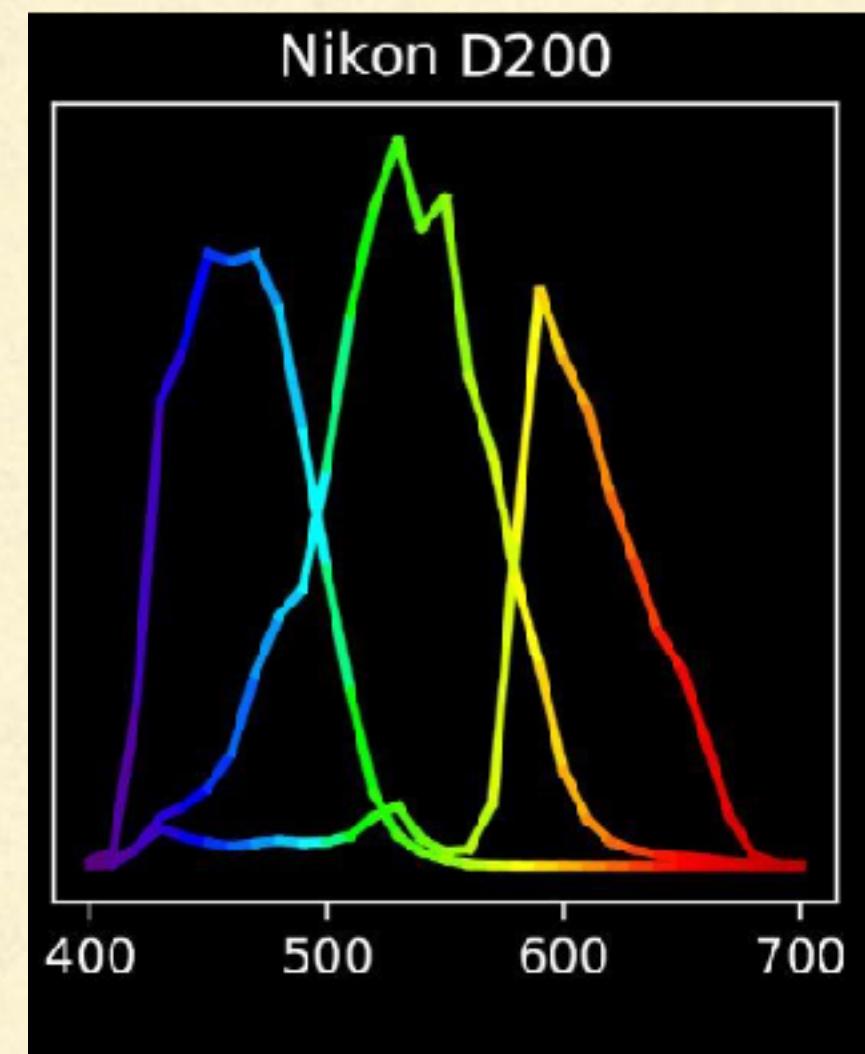
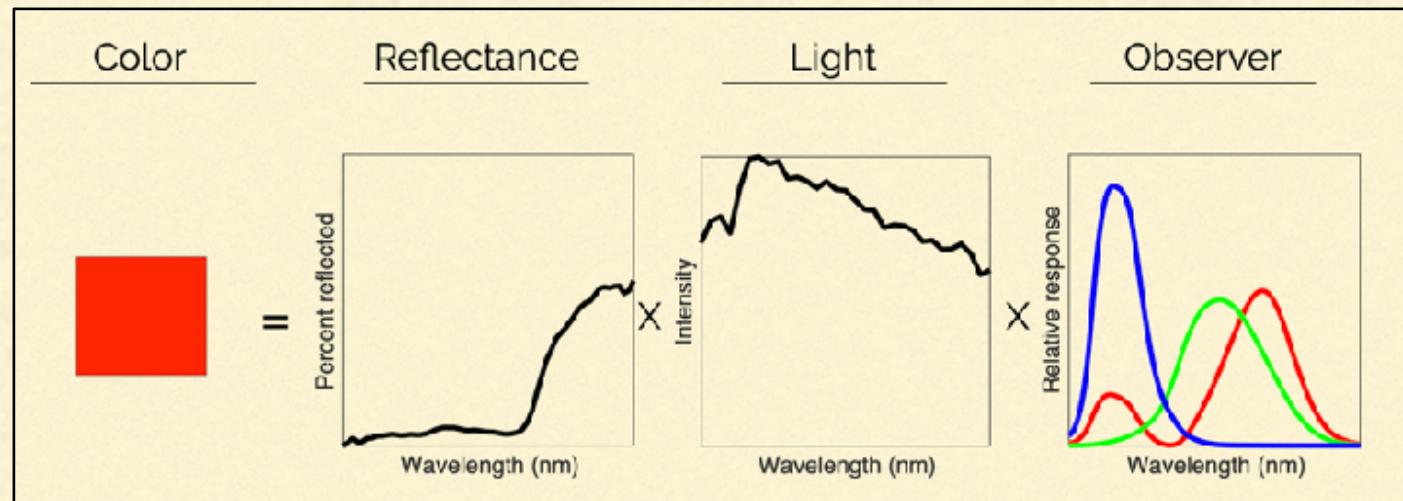


Cell Phone



Compact cameras and cell phone cameras (usually) do not have interchangeable lenses.

Cameras



- ▶ Every camera records colors differently.
- ▶ Manufacturers do not provide the spectral responses of consumer cameras.
- ▶ How can we standardize colors taken with different cameras?

Image Formation

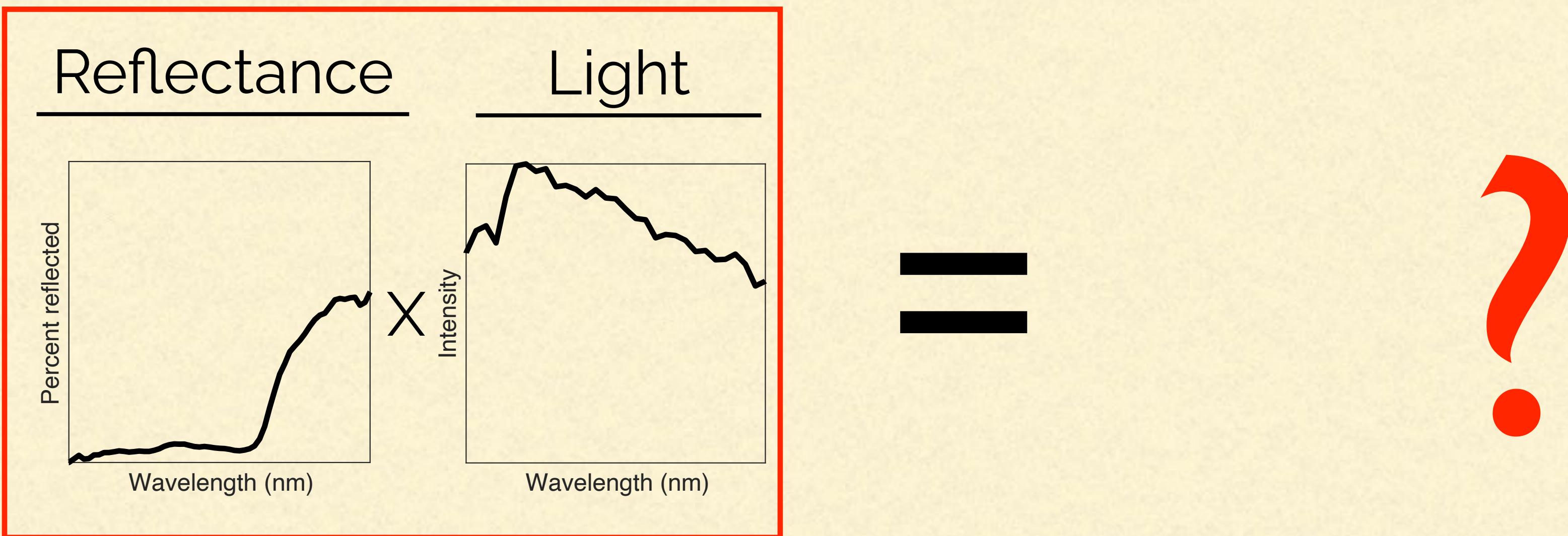
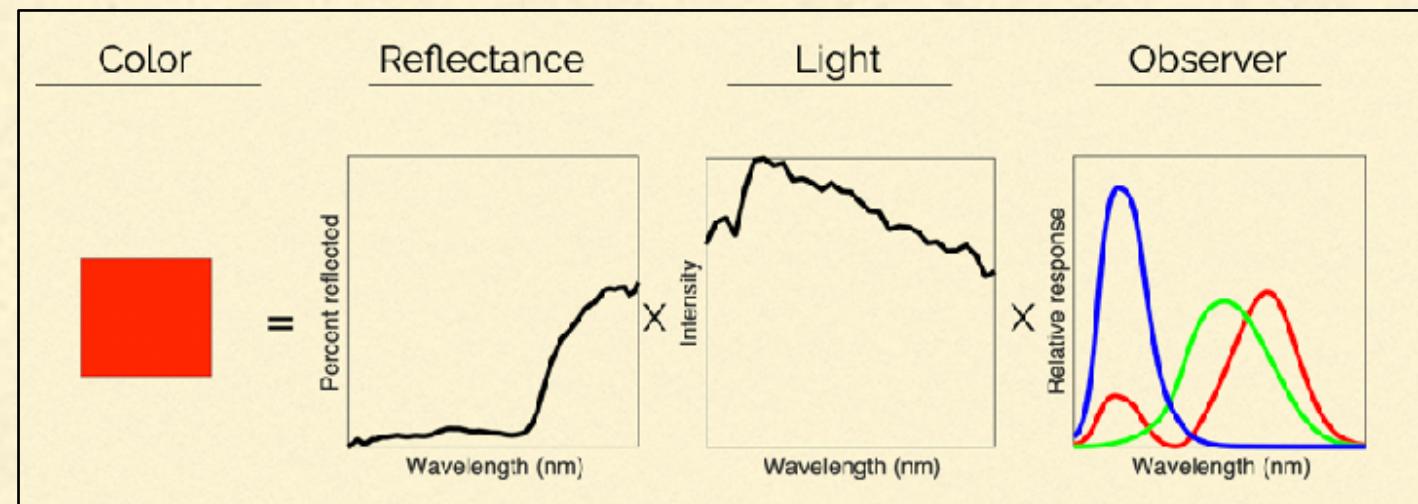


Image Formation

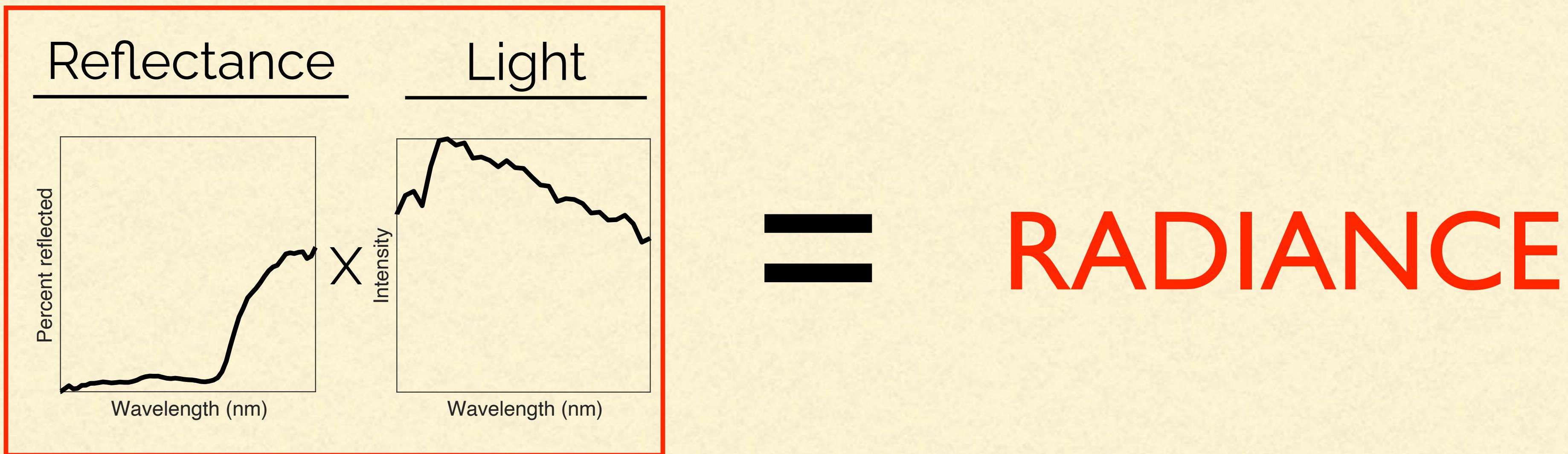
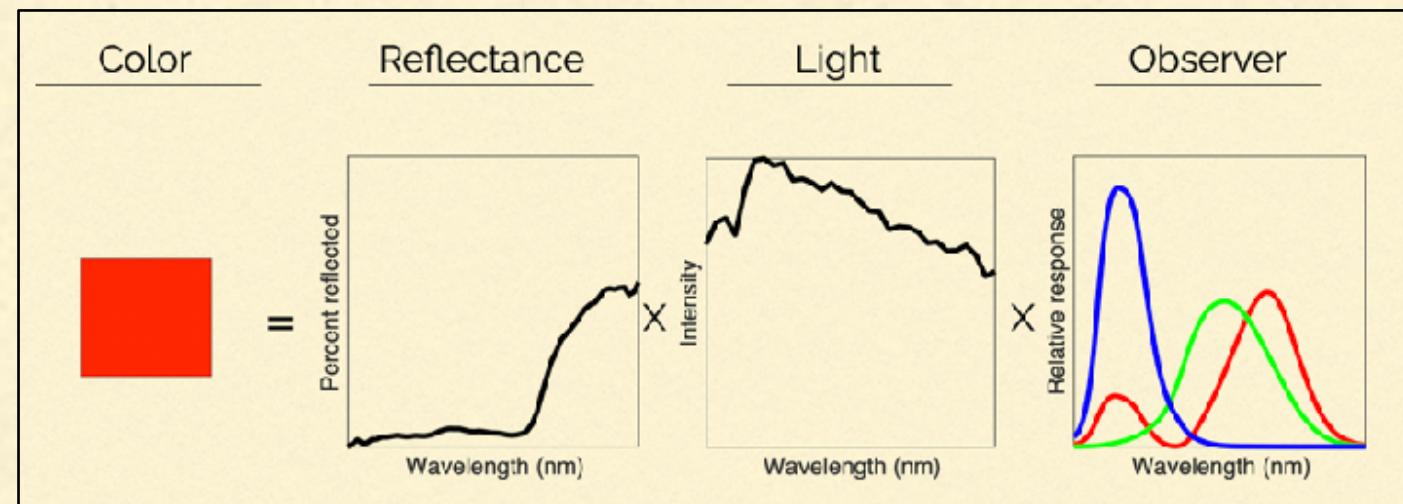
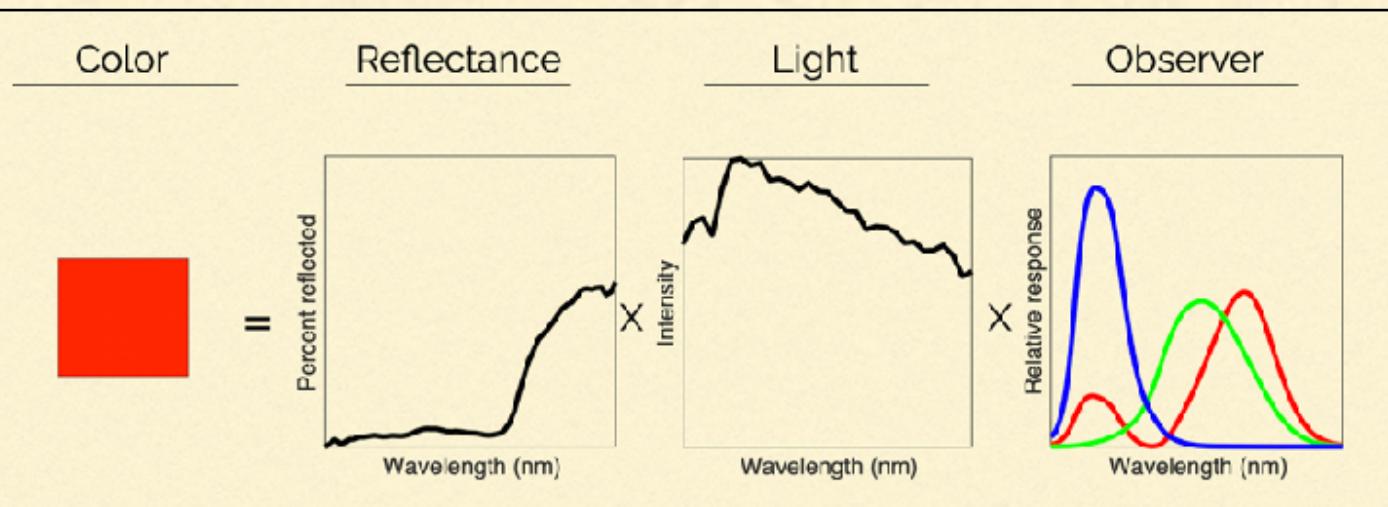


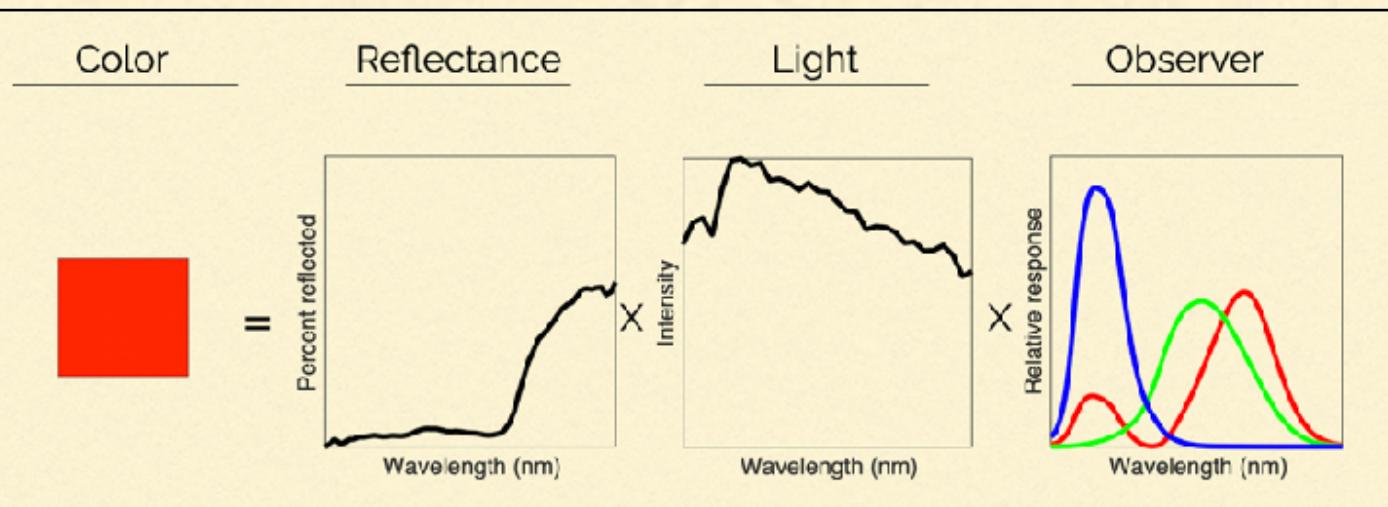
Image Formation



$$\text{Color} = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

κ : exposure-related constant

Image Formation



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Reflectance

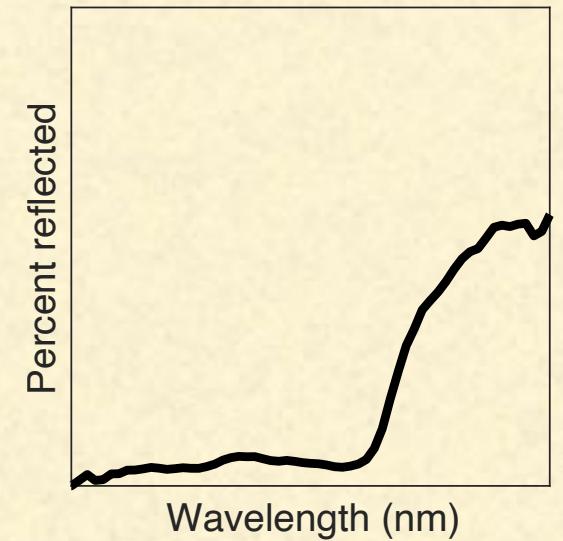
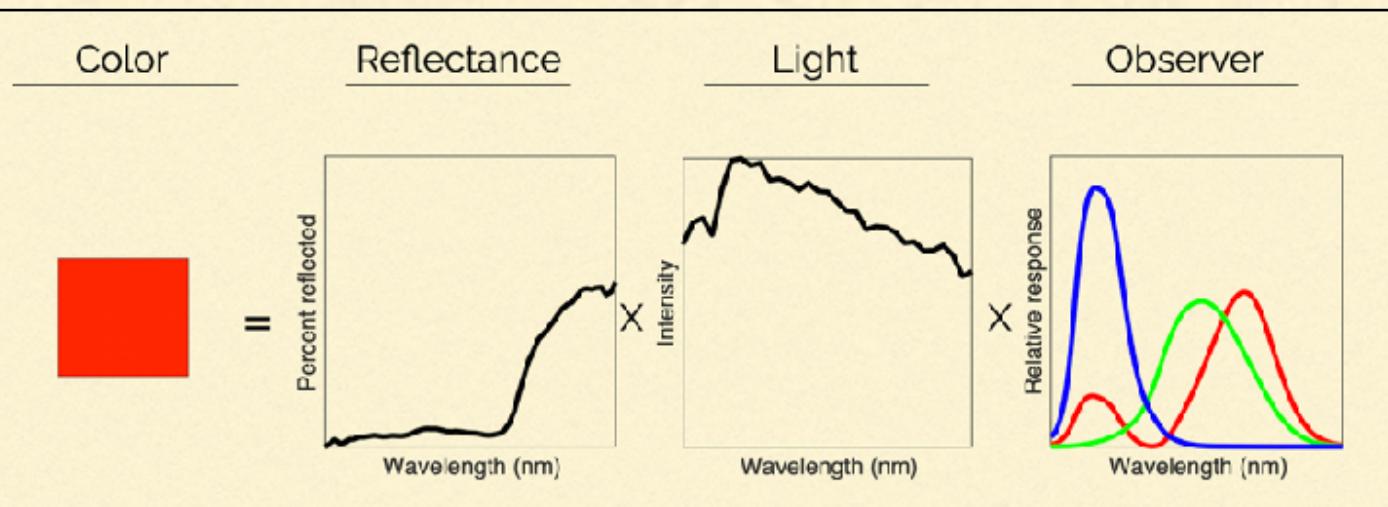


Image Formation



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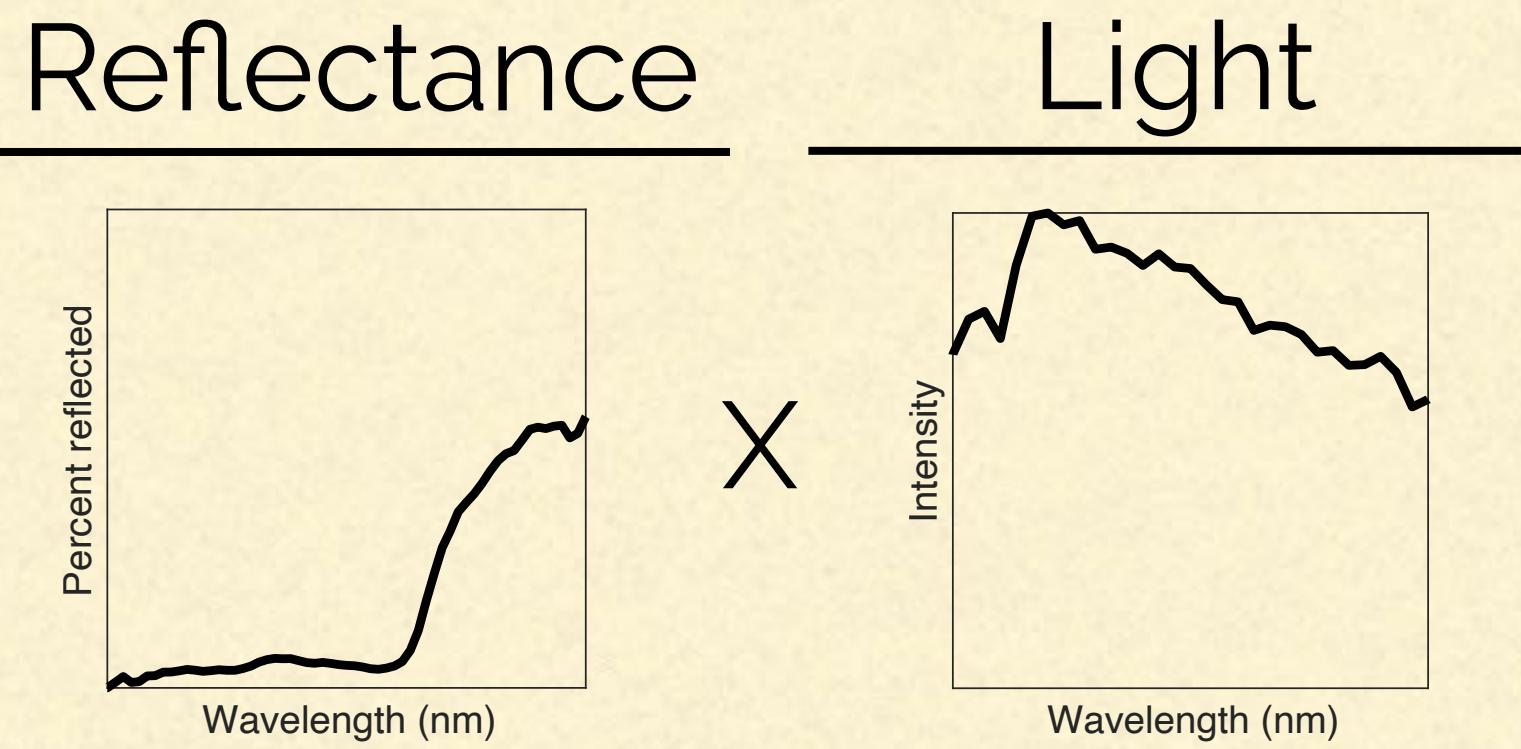
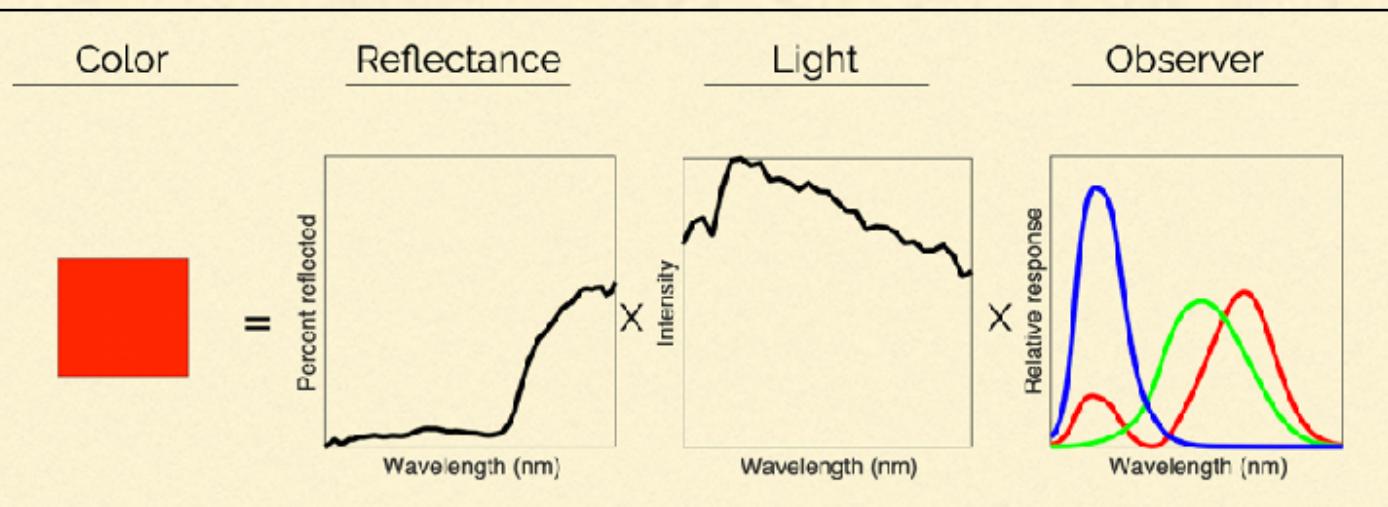


Image Formation



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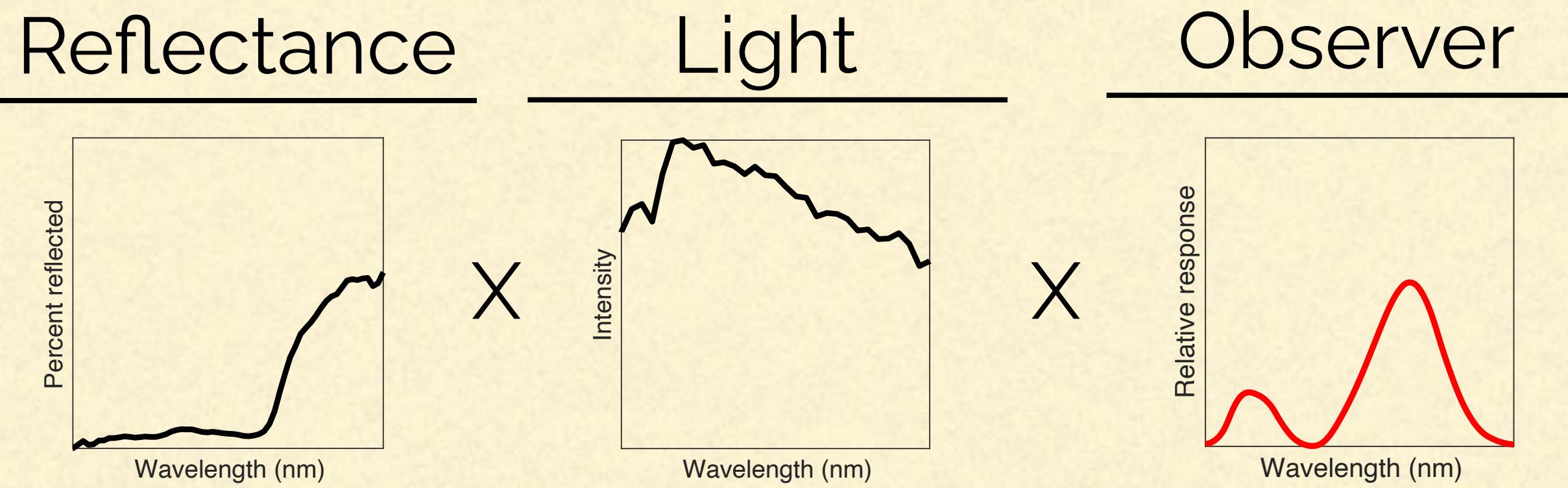
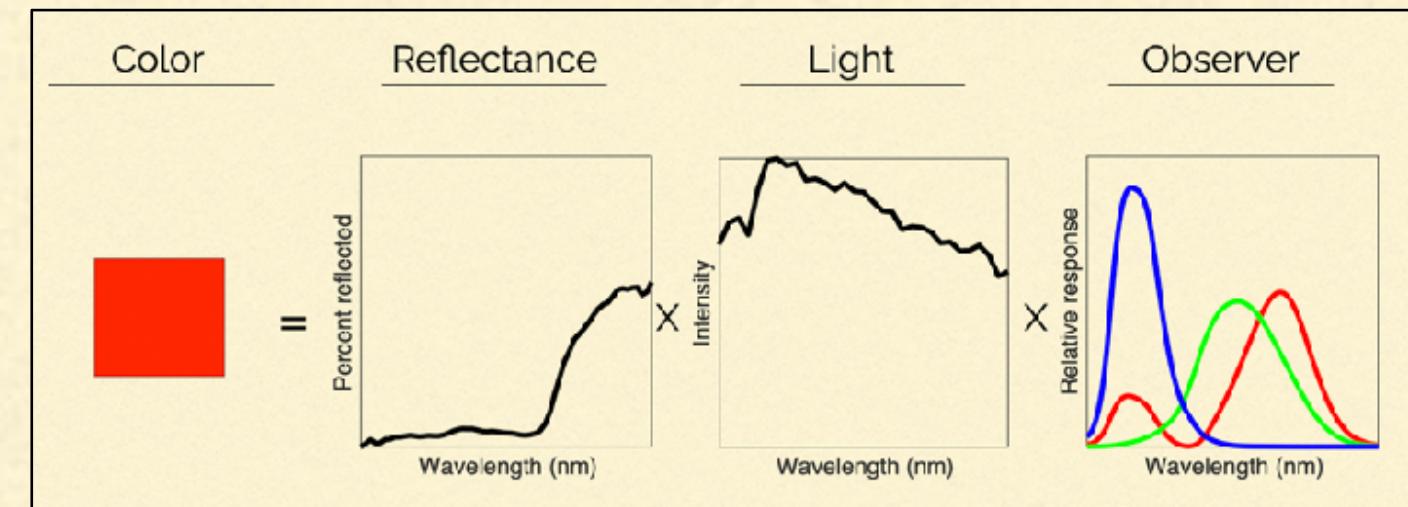


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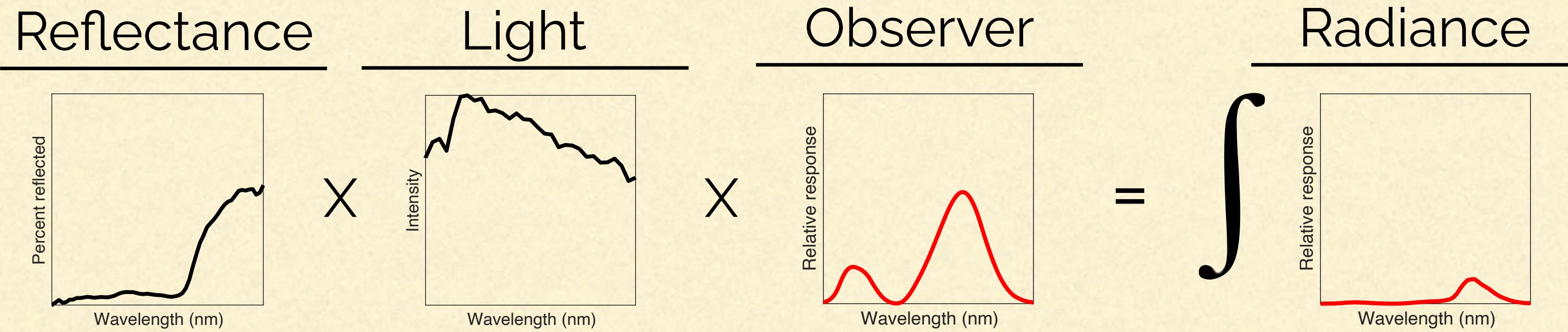
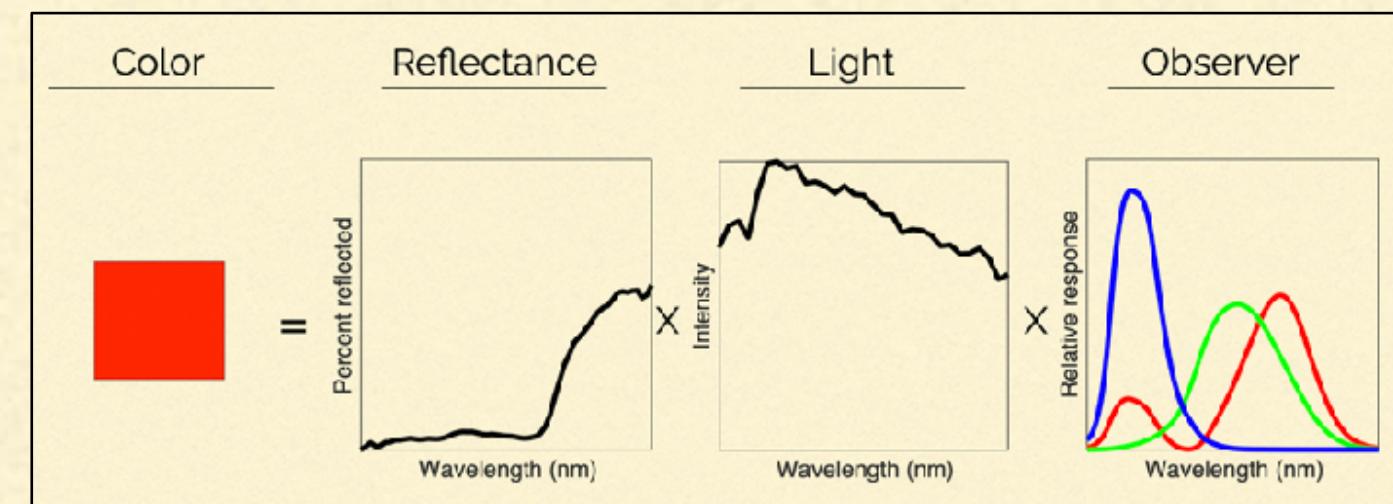


Image Formation



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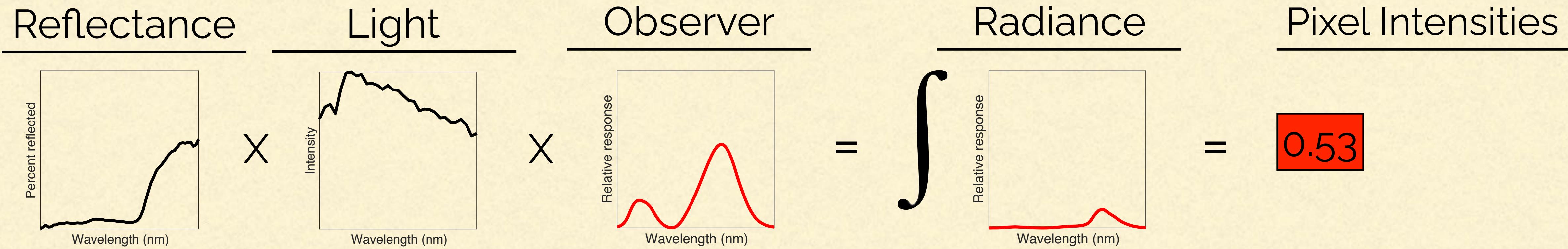
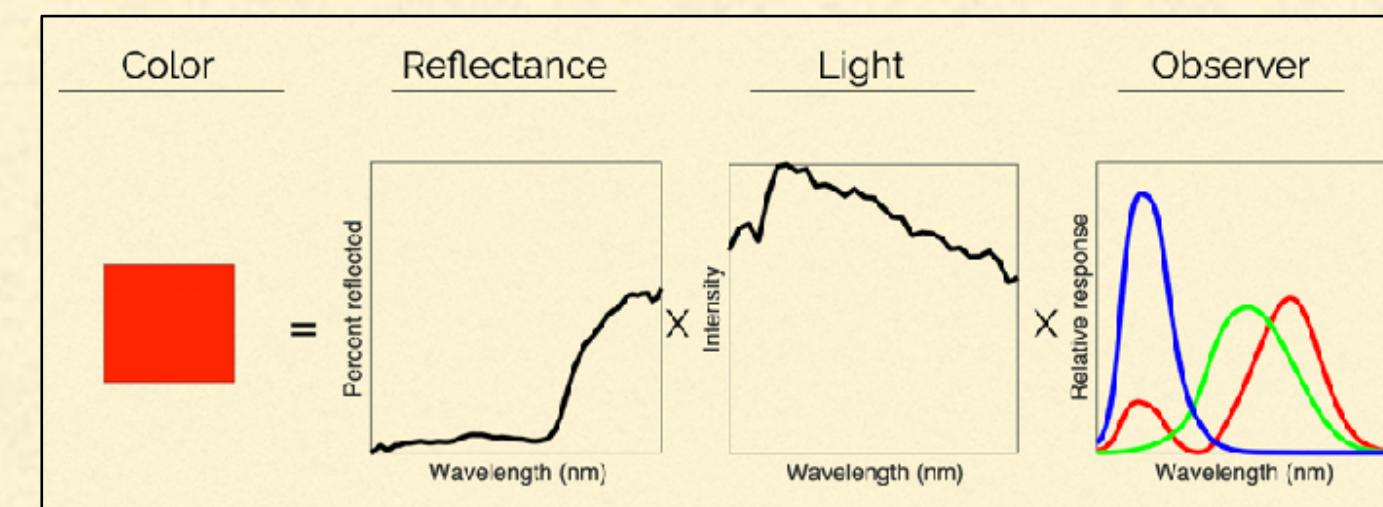


Image Formation



$$\text{Color} = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

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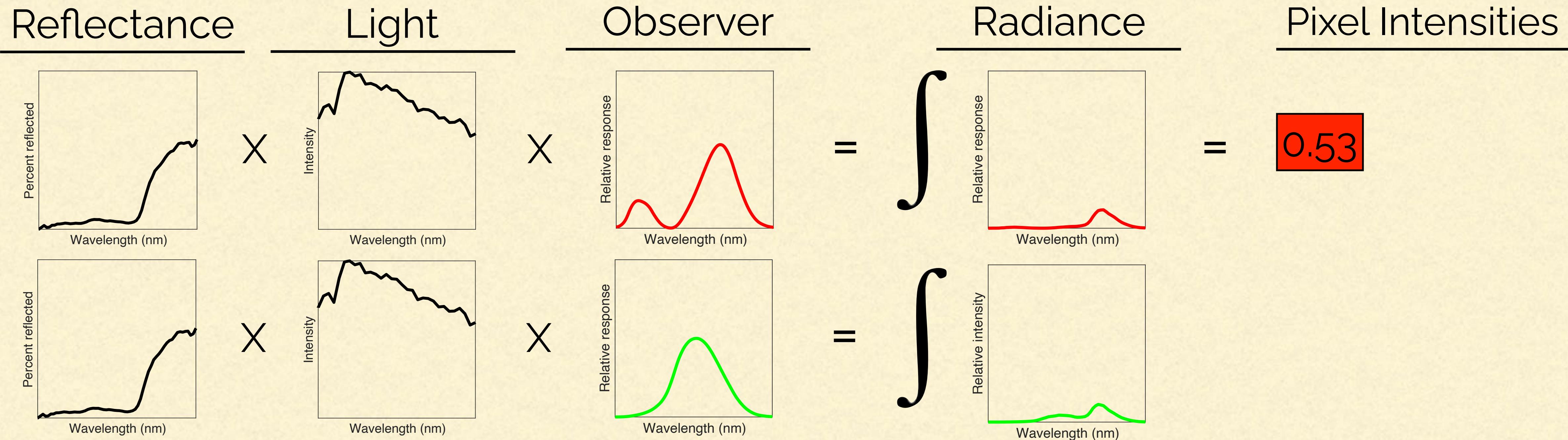
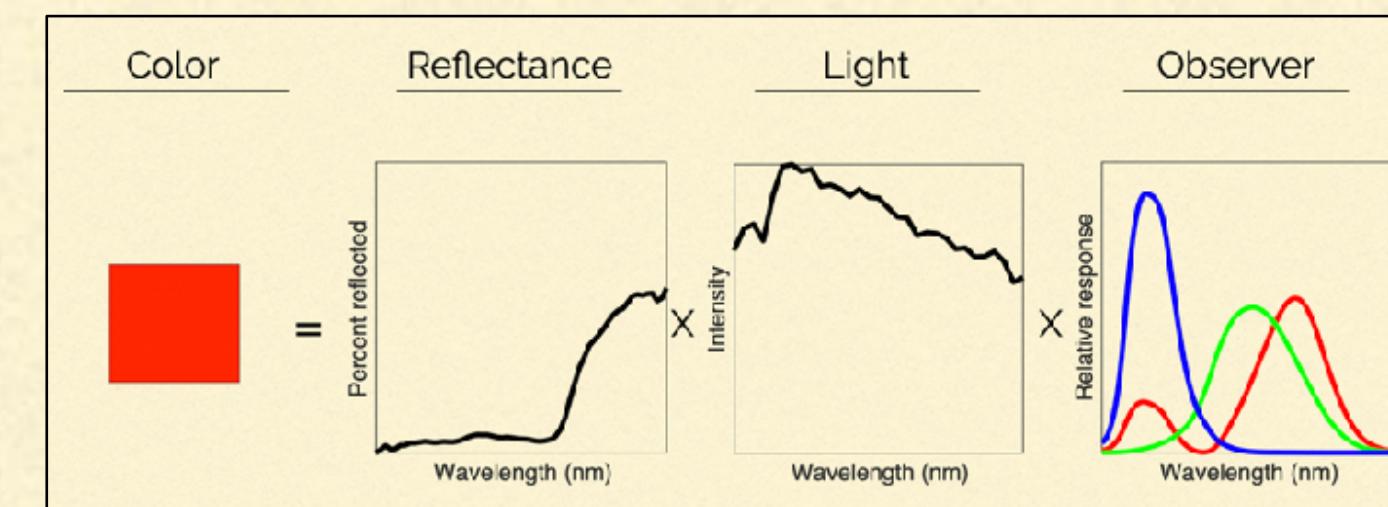


Image Formation



$$\text{Color} = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

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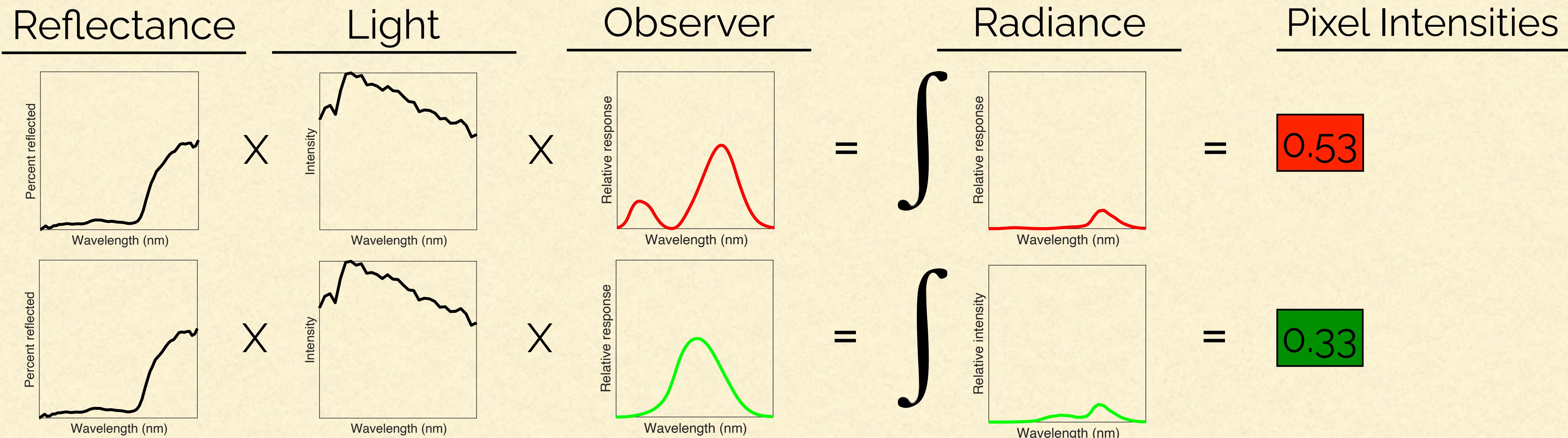
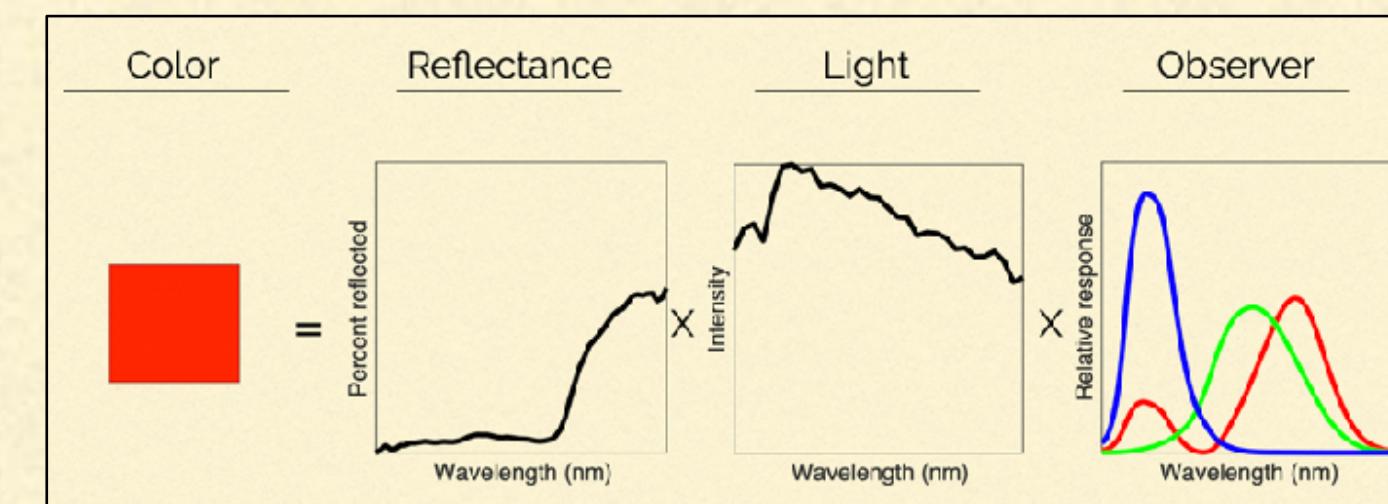


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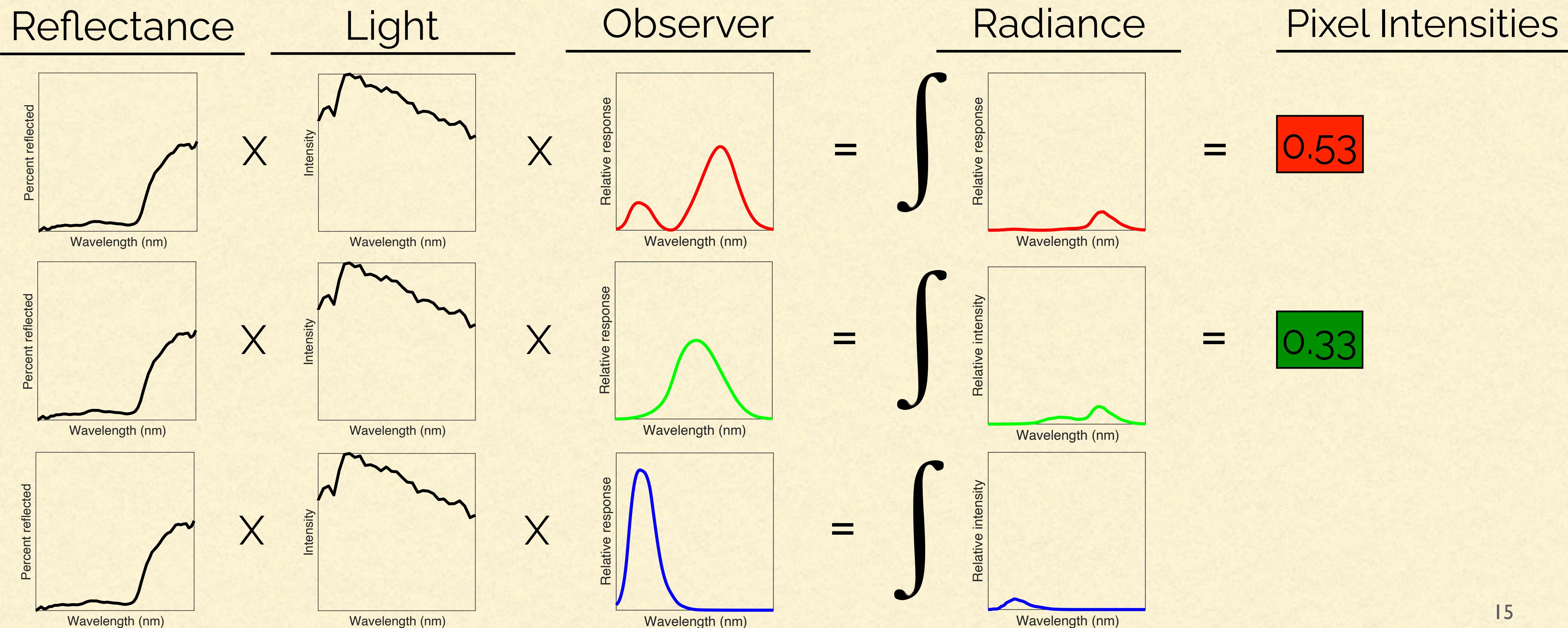
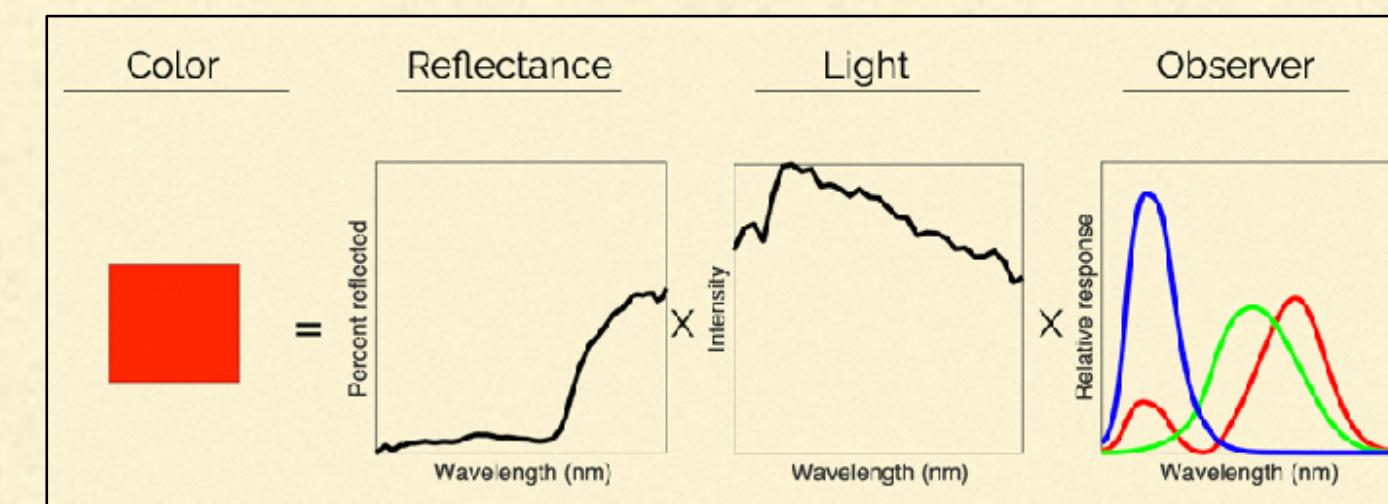


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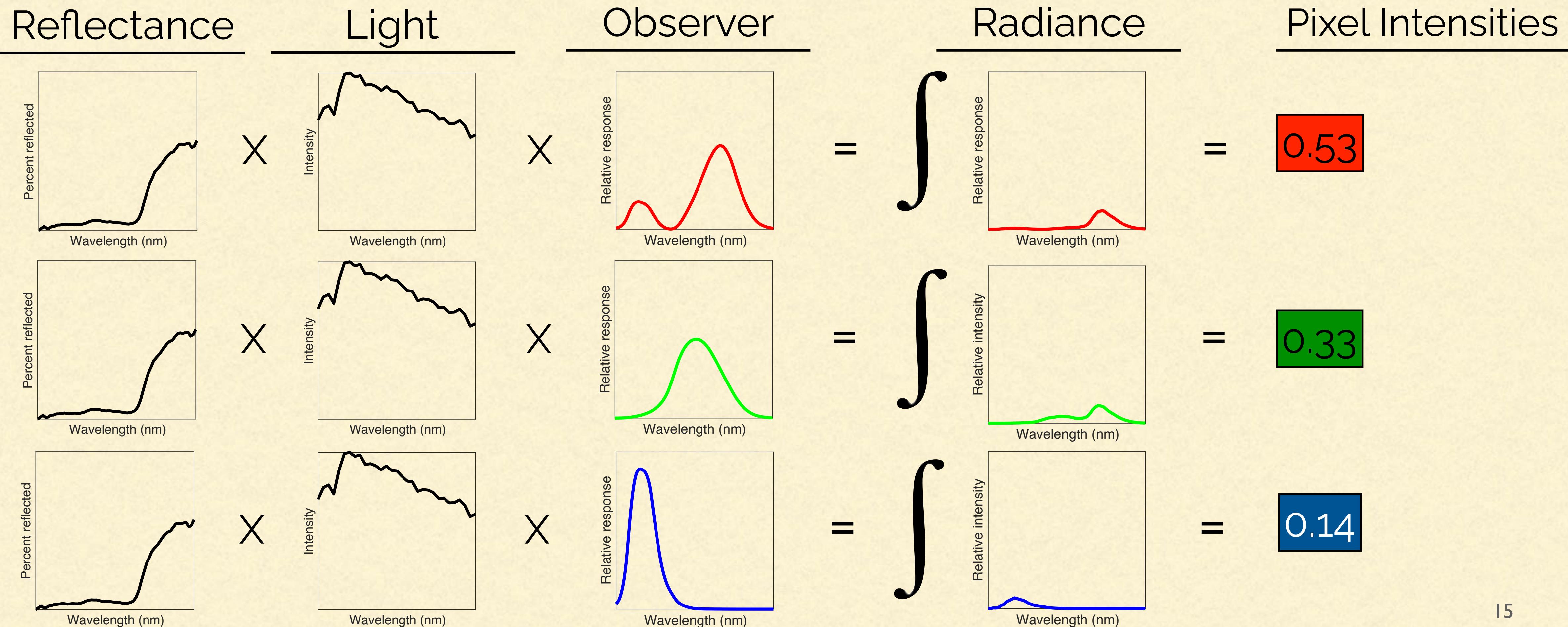
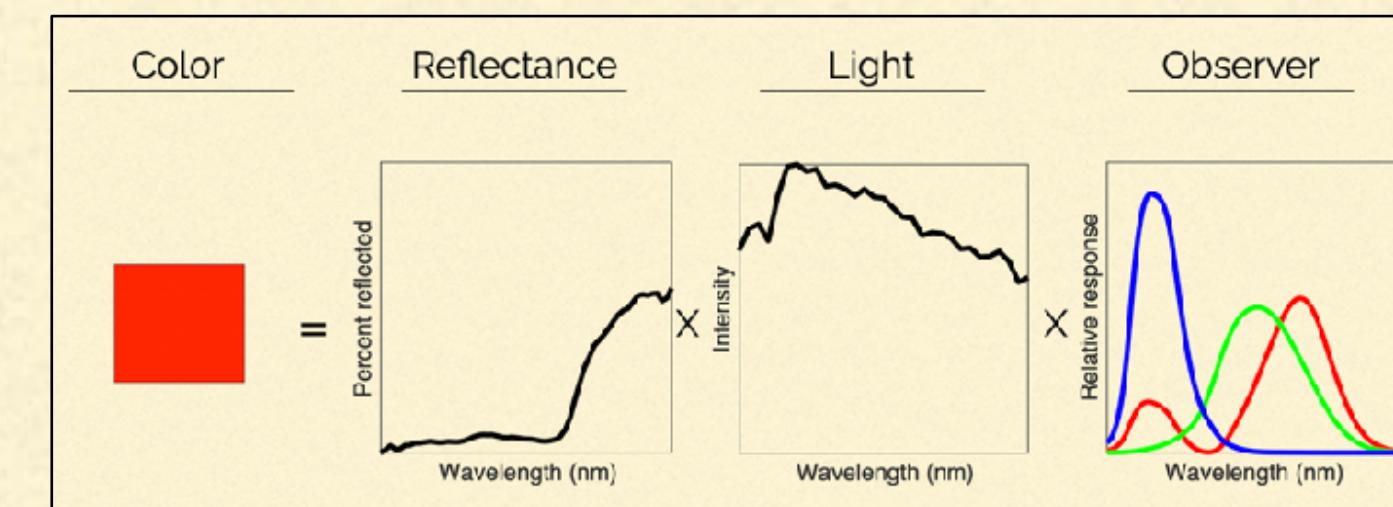
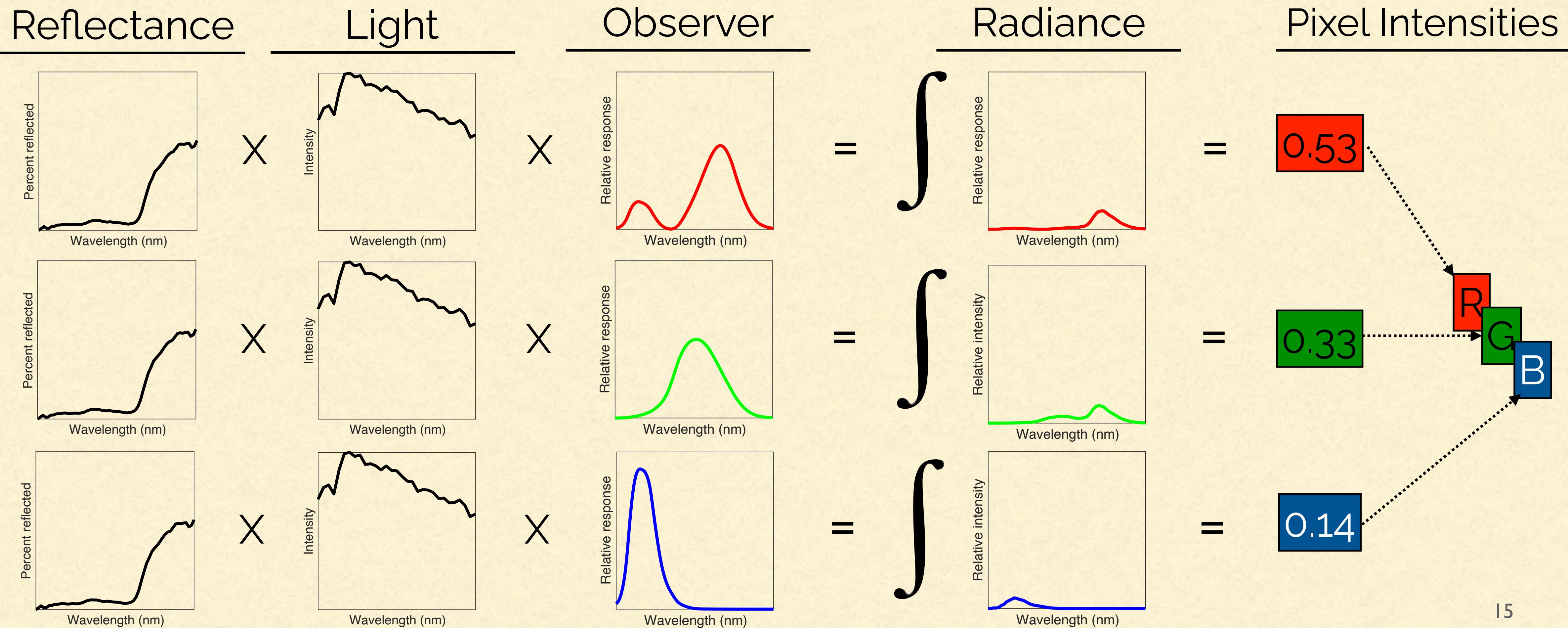


Image Formation



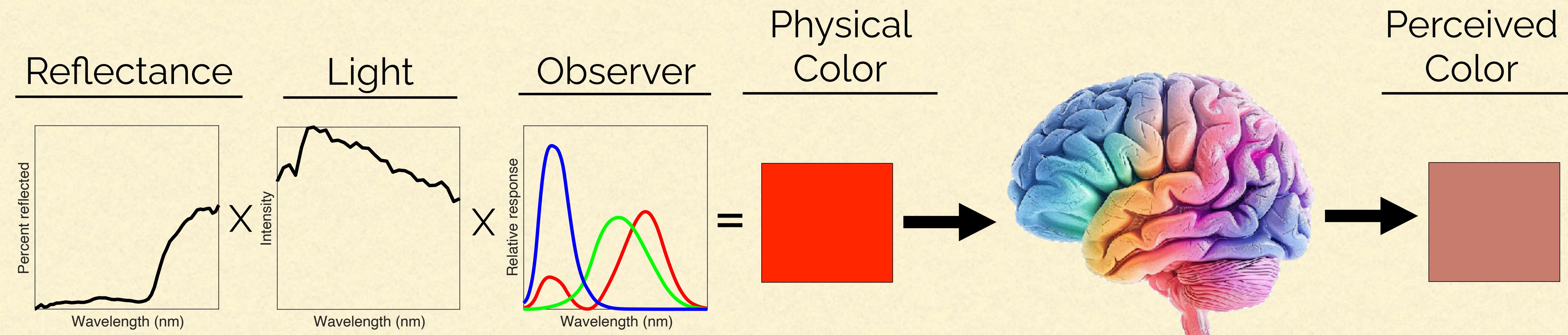
$$\text{Color} = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

κ : exposure-related constant



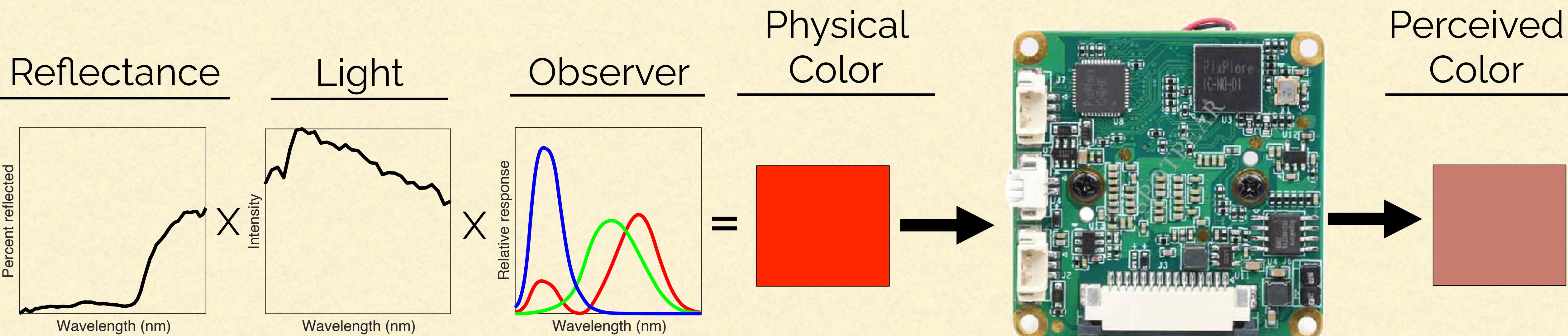
Color is a subjective phenomenon

Color Perception by a Camera



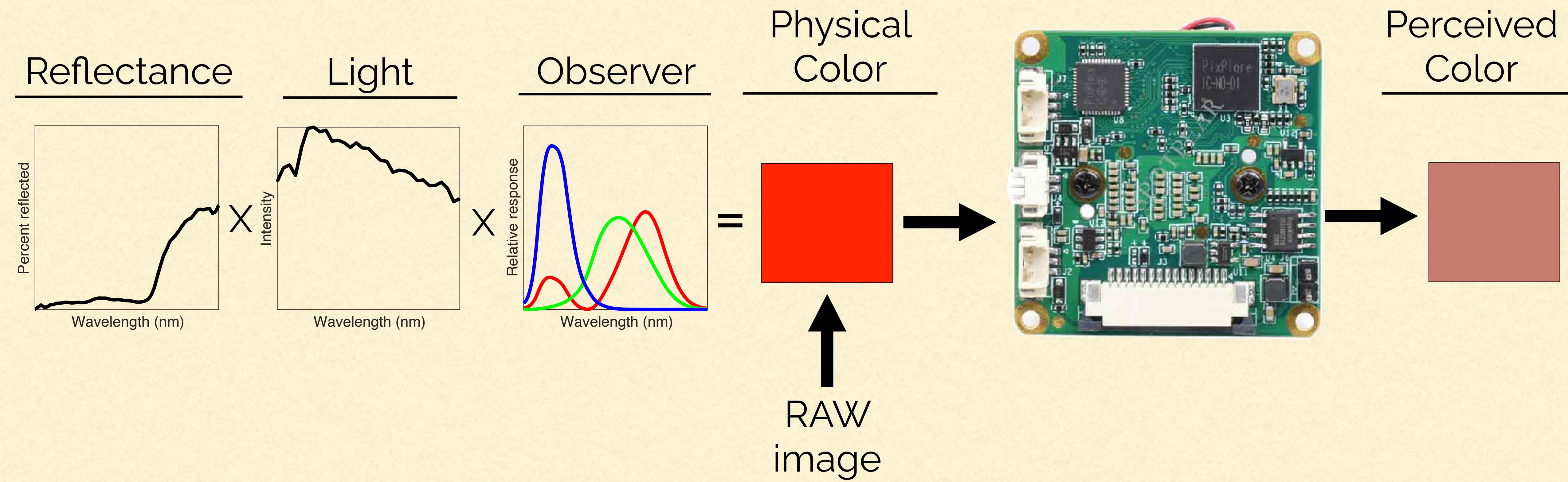
Color is a subjective phenomenon

Color Perception by a Camera



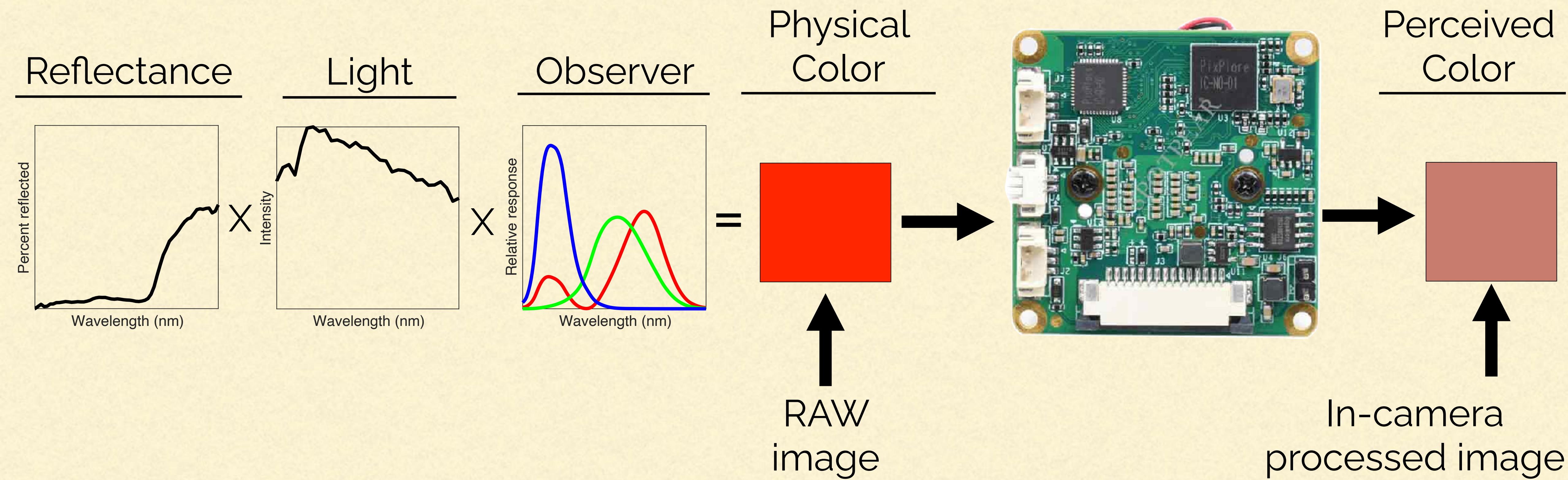
Color Perception by a Camera

Color is a subjective phenomenon



Color is a subjective phenomenon

Color Perception by a Camera

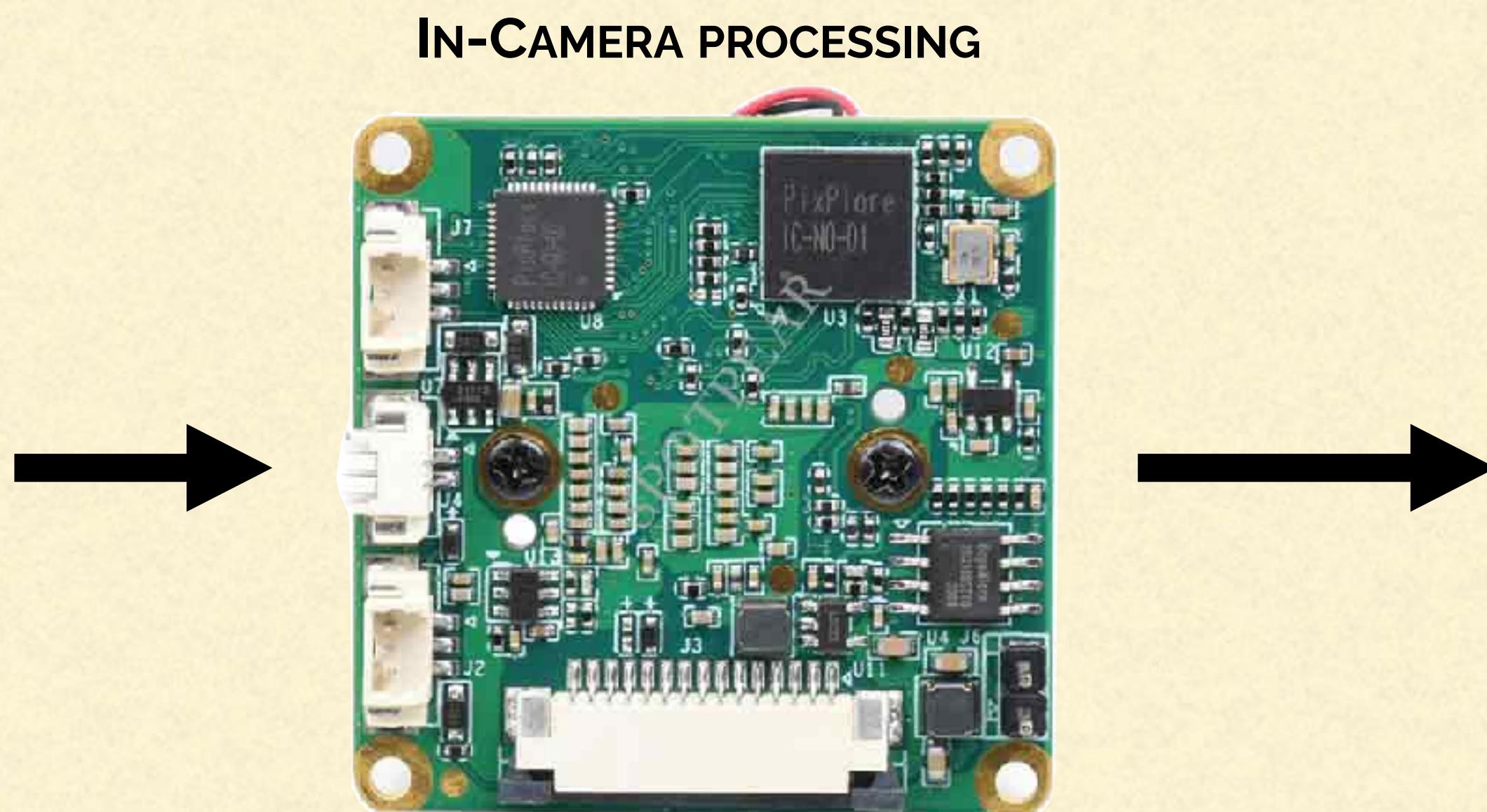


Color Perception by a Camera

Consumer cameras are not scientific instruments!

Cameras have built-in modules to enhance images, but they introduce irreversible color biases and artifacts.

RAW image



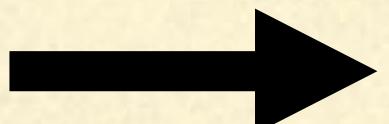
In-camera
processed image

Color Perception by a Camera

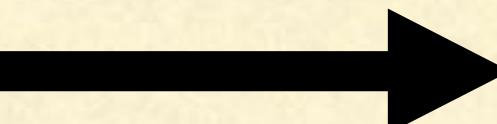
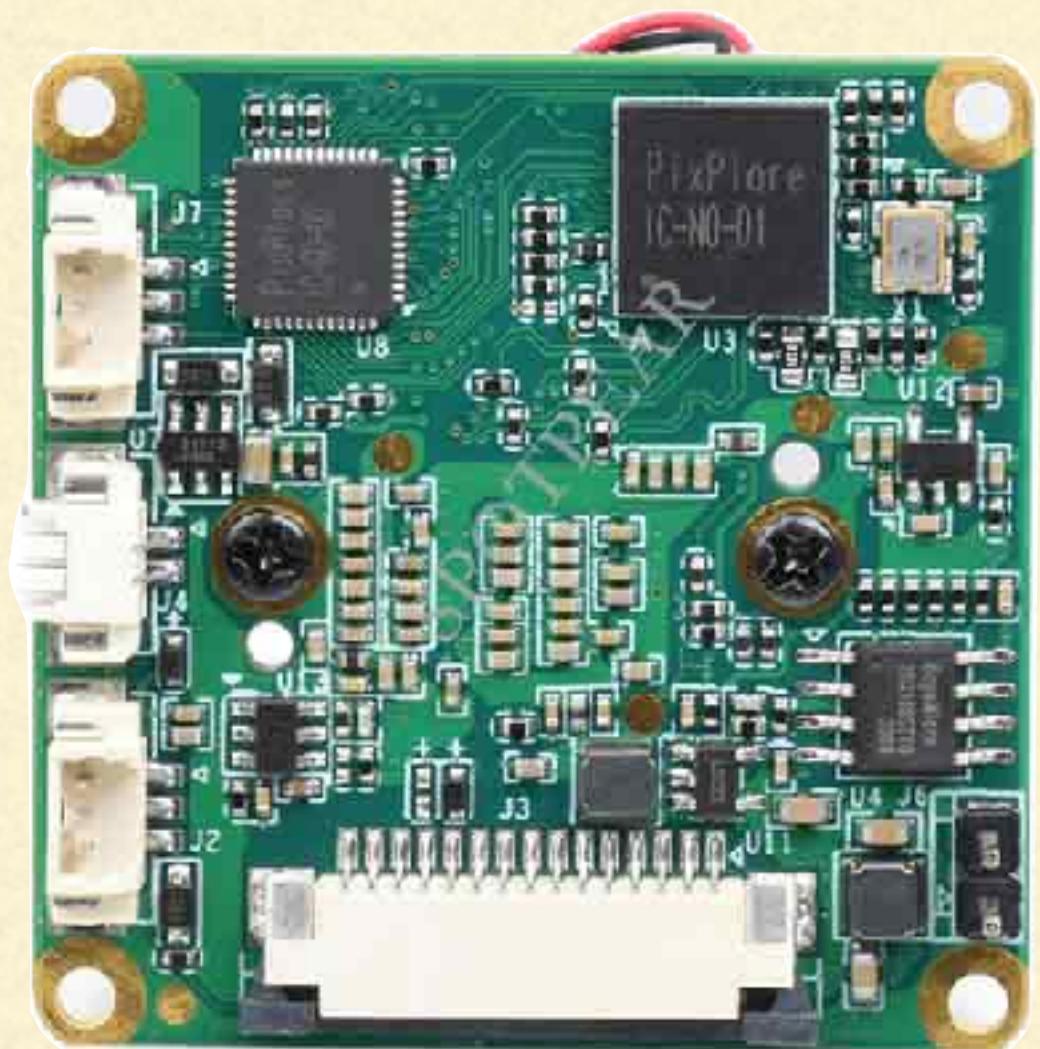
Consumer cameras are not scientific instruments!

Cameras have built-in modules to enhance images, but they introduce irreversible color biases and artifacts.

RAW image



IN-CAMERA PROCESSING



In-camera
processed image

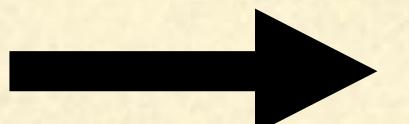
- .CR2 (Canon), .NEF (Nikon), .GPR (GoPro), etc

Color Perception by a Camera

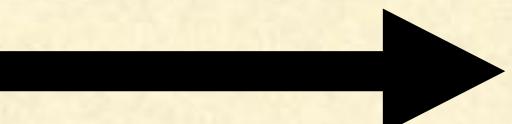
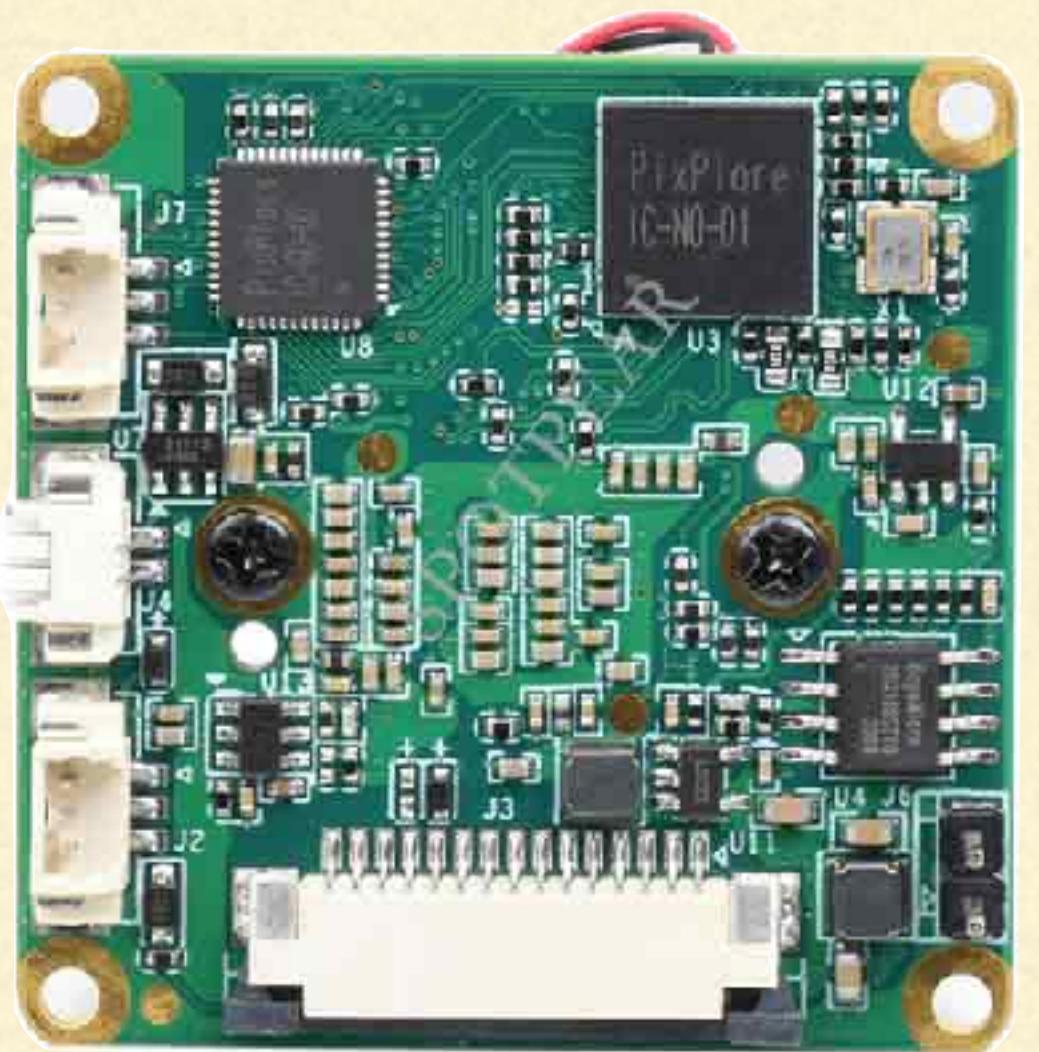
Consumer cameras are not scientific instruments!

Cameras have built-in modules to enhance images, but they introduce irreversible color biases and artifacts.

RAW image



IN-CAMERA PROCESSING



In-camera
processed image

- .CR2 (Canon), .NEF (Nikon), .GPR (GoPro), etc
- **Linear**

Color Perception by a Camera

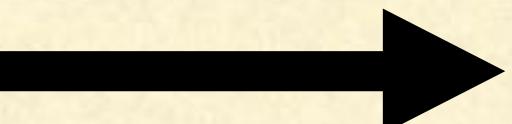
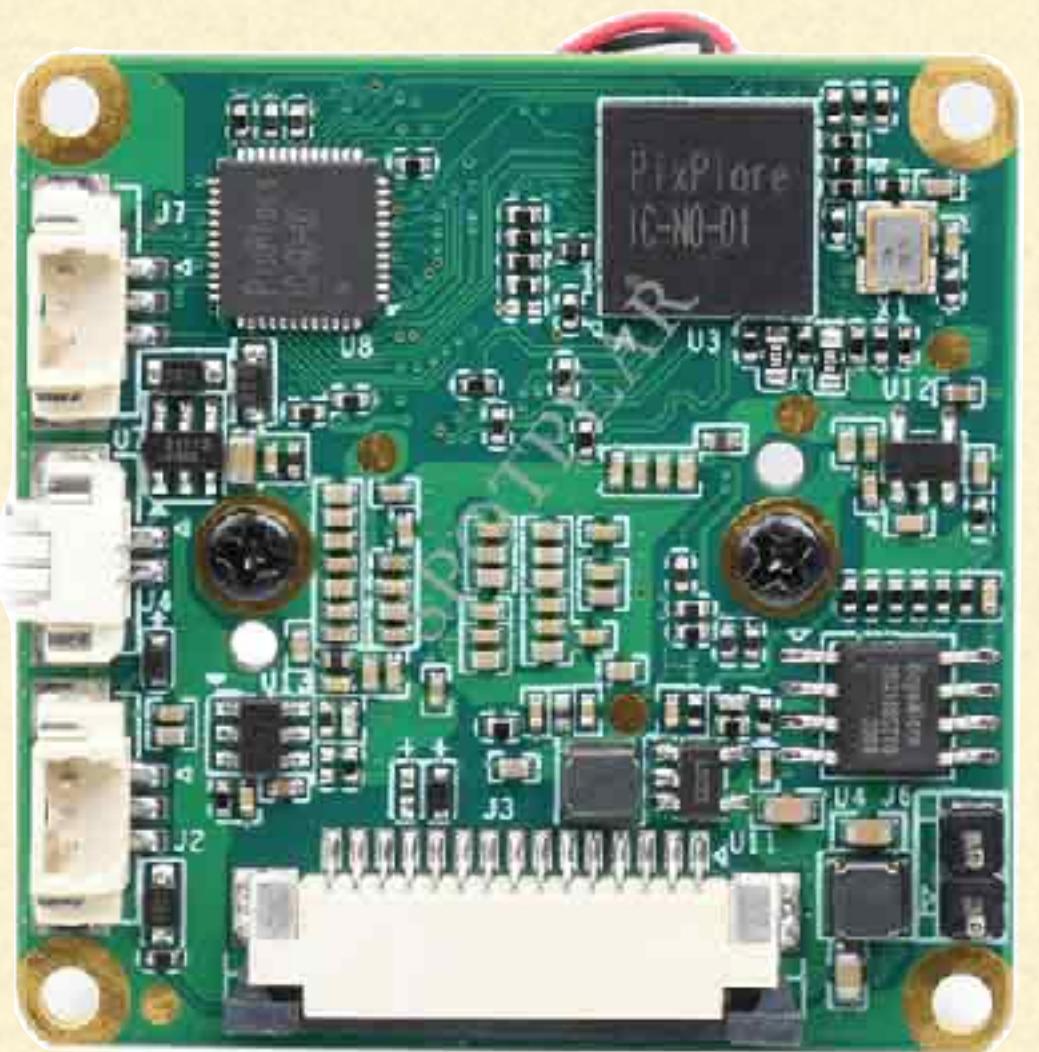
Consumer cameras are not scientific instruments!

Cameras have built-in modules to enhance images, but they introduce irreversible color biases and artifacts.

RAW image



IN-CAMERA PROCESSING



In-camera processed image

- .CR2 (Canon), .NEF (Nikon), .GPR (GoPro), etc
- **Linear**
- Uncompressed

Color Perception by a Camera

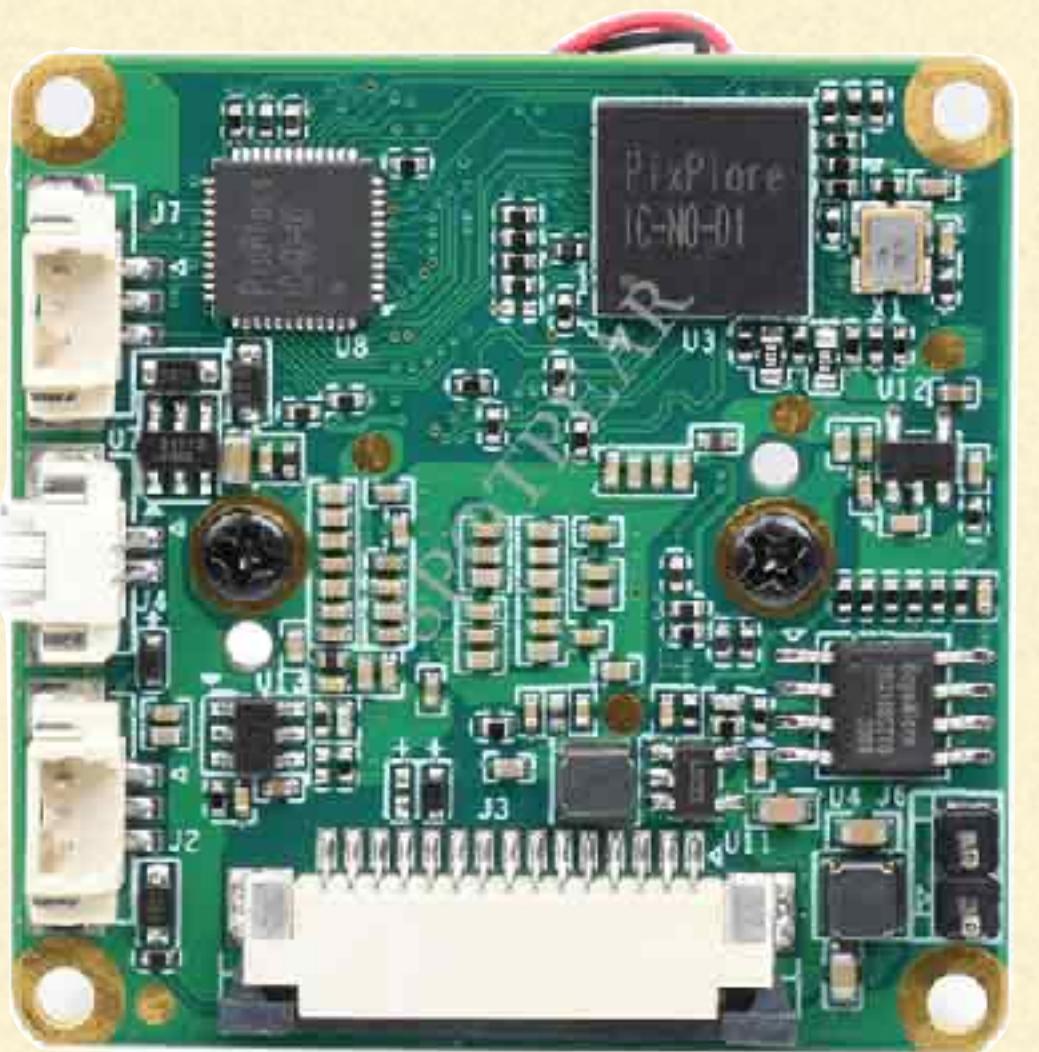
Consumer cameras are not scientific instruments!

Cameras have built-in modules to enhance images, but they introduce irreversible color biases and artifacts.

RAW image



IN-CAMERA PROCESSING



In-camera
processed image

- .CR2 (Canon), .NEF (Nikon), .GPR (GoPro), etc
- **Linear**
- Uncompressed
- Can be used for color science

Color Perception by a Camera

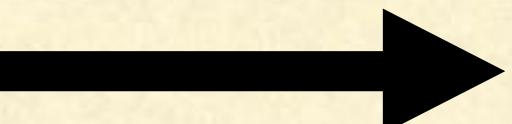
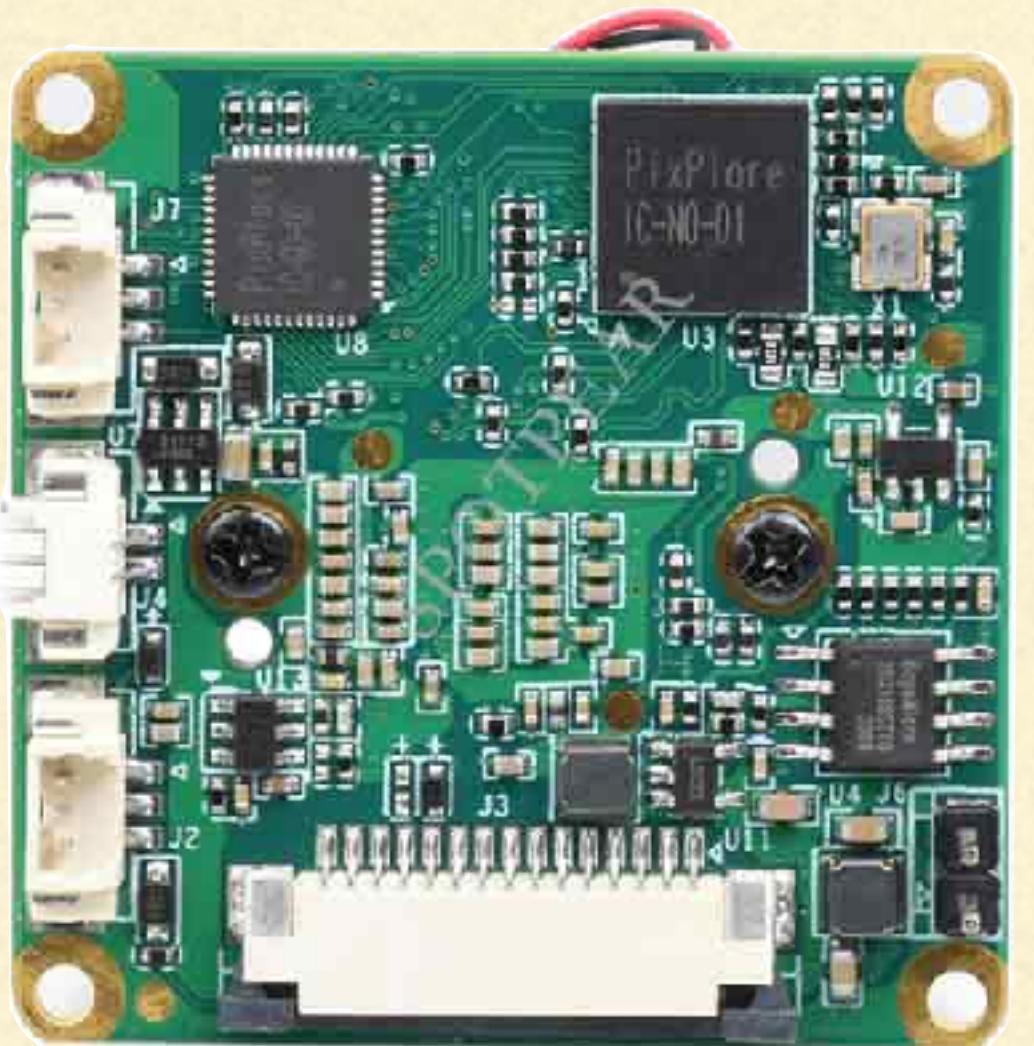
Consumer cameras are not scientific instruments!

Cameras have built-in modules to enhance images, but they introduce irreversible color biases and artifacts.

RAW image



IN-CAMERA PROCESSING



In-camera processed image

- .CR2 (Canon), .NEF (Nikon), .GPR (GoPro), etc
- **Linear**
- Uncompressed
- Can be used for color science

- .JPG for still images

Color Perception by a Camera

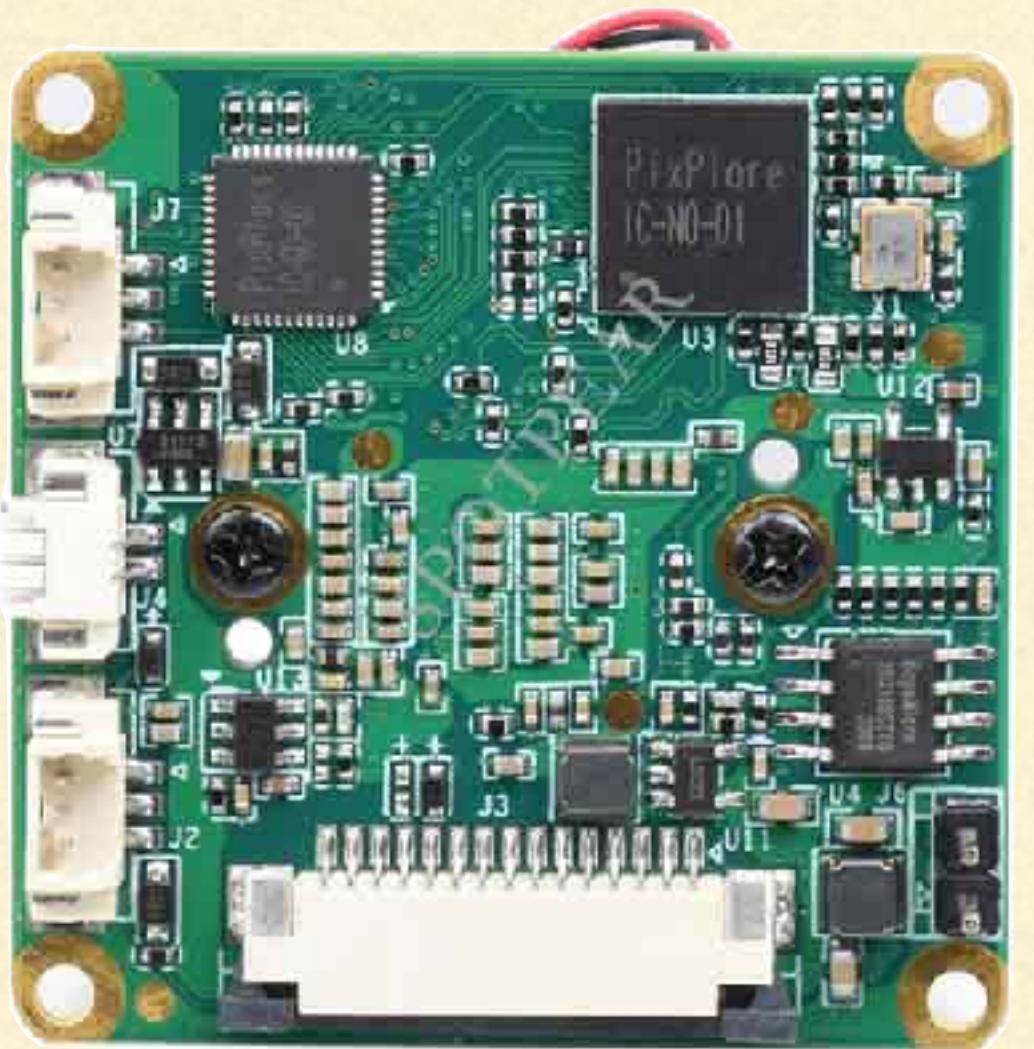
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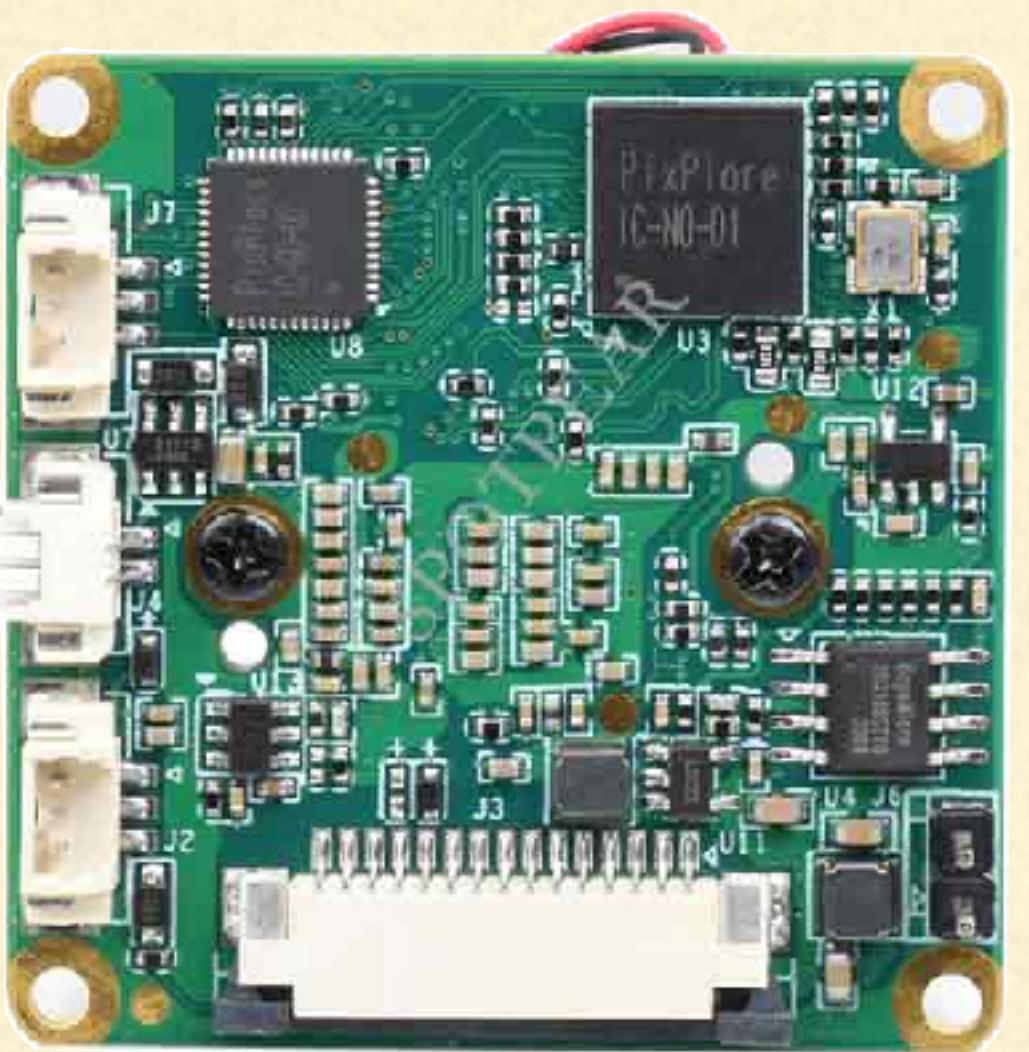
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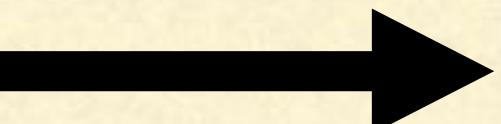
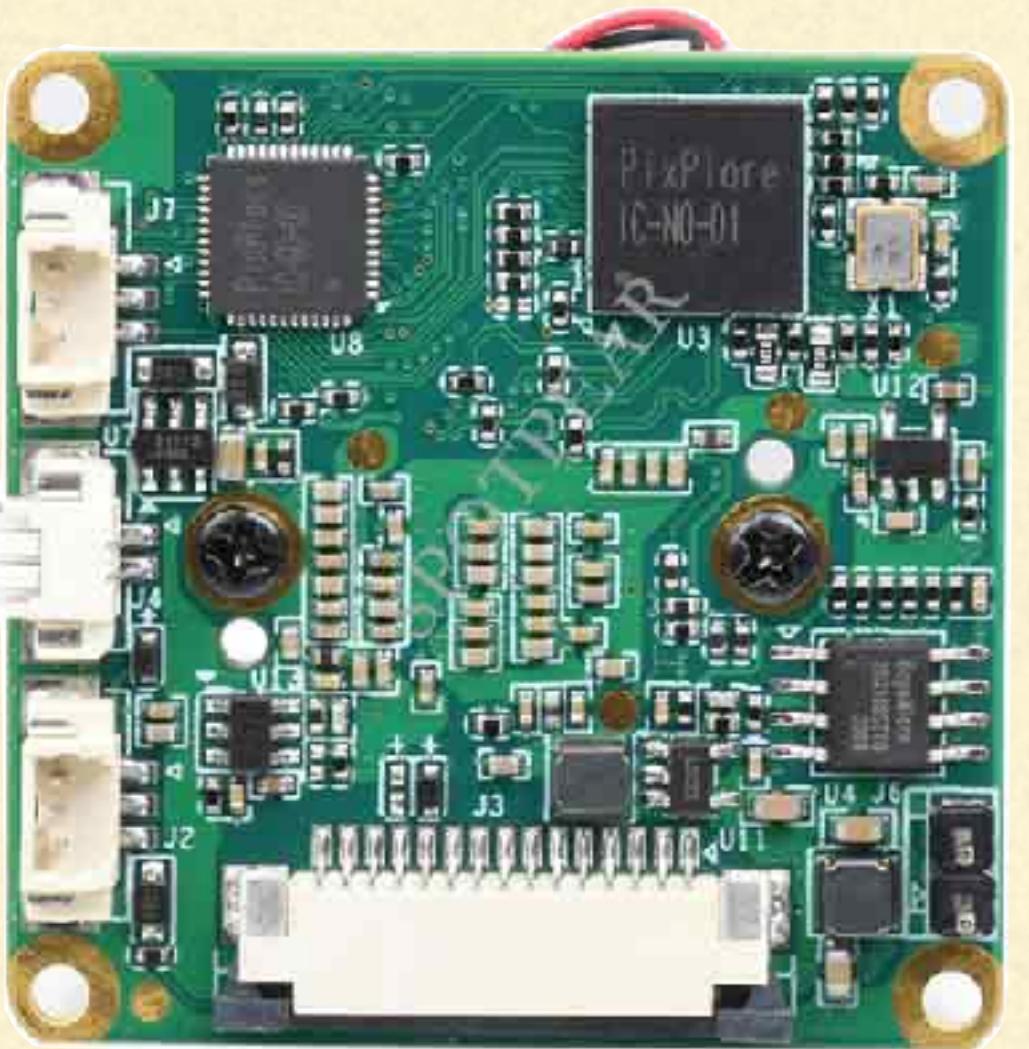
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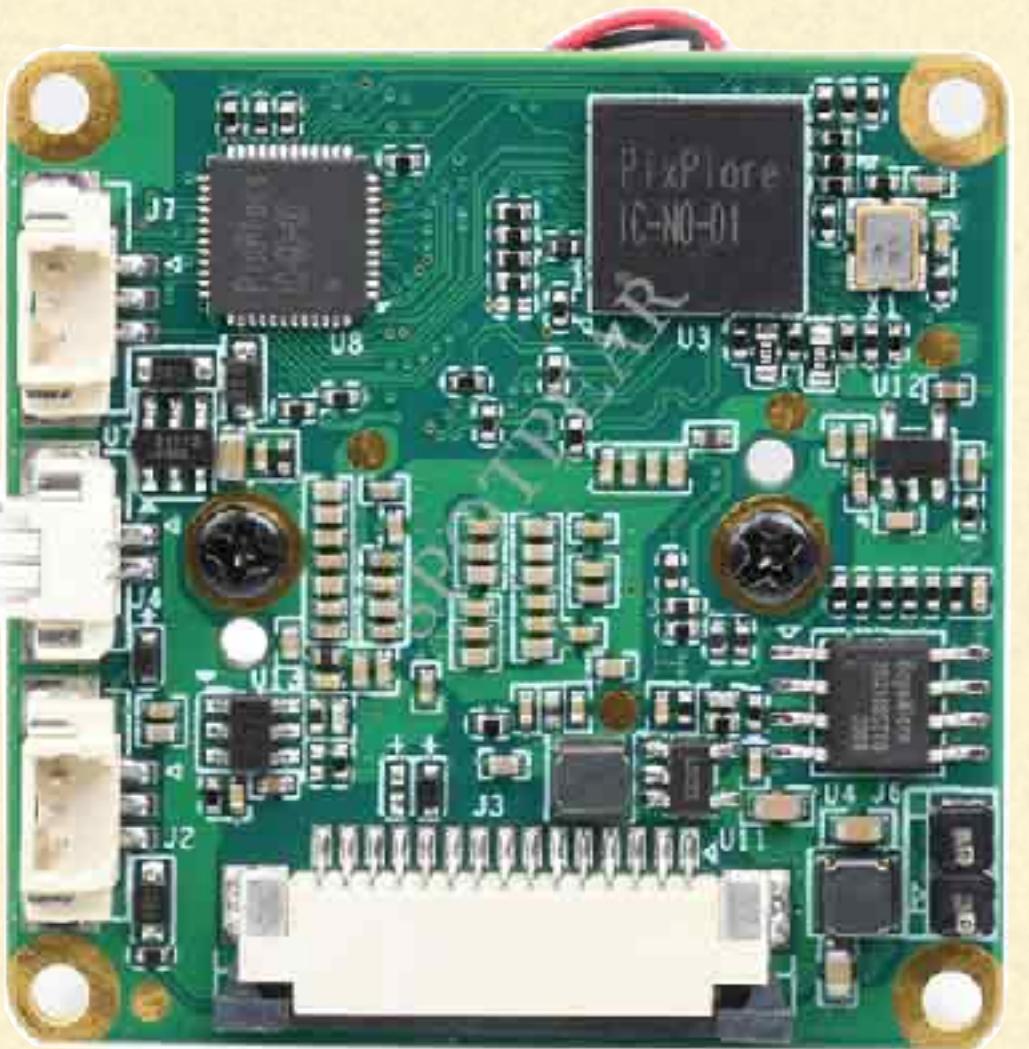
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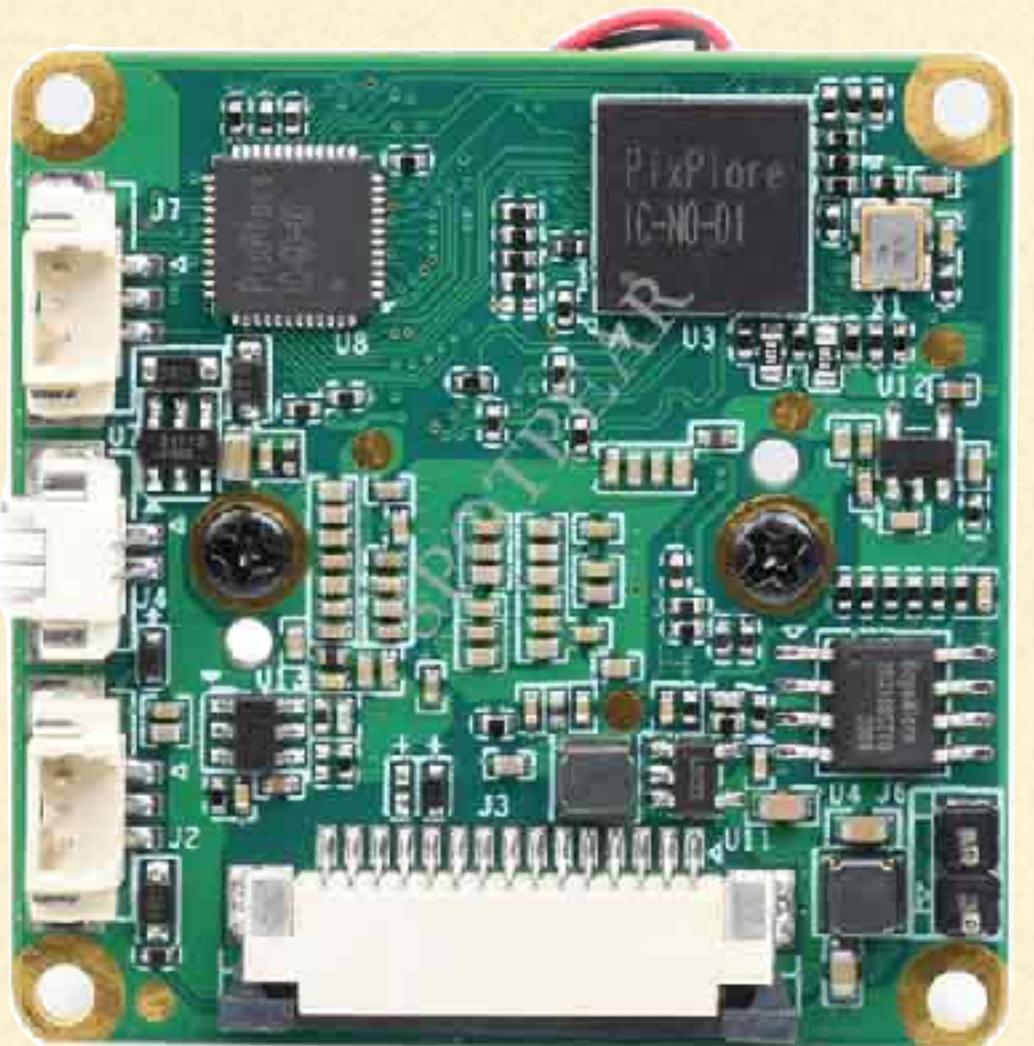
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- Make & model specific
- Undocumented
- Proprietary
- **Non-linear**
- Irreversible

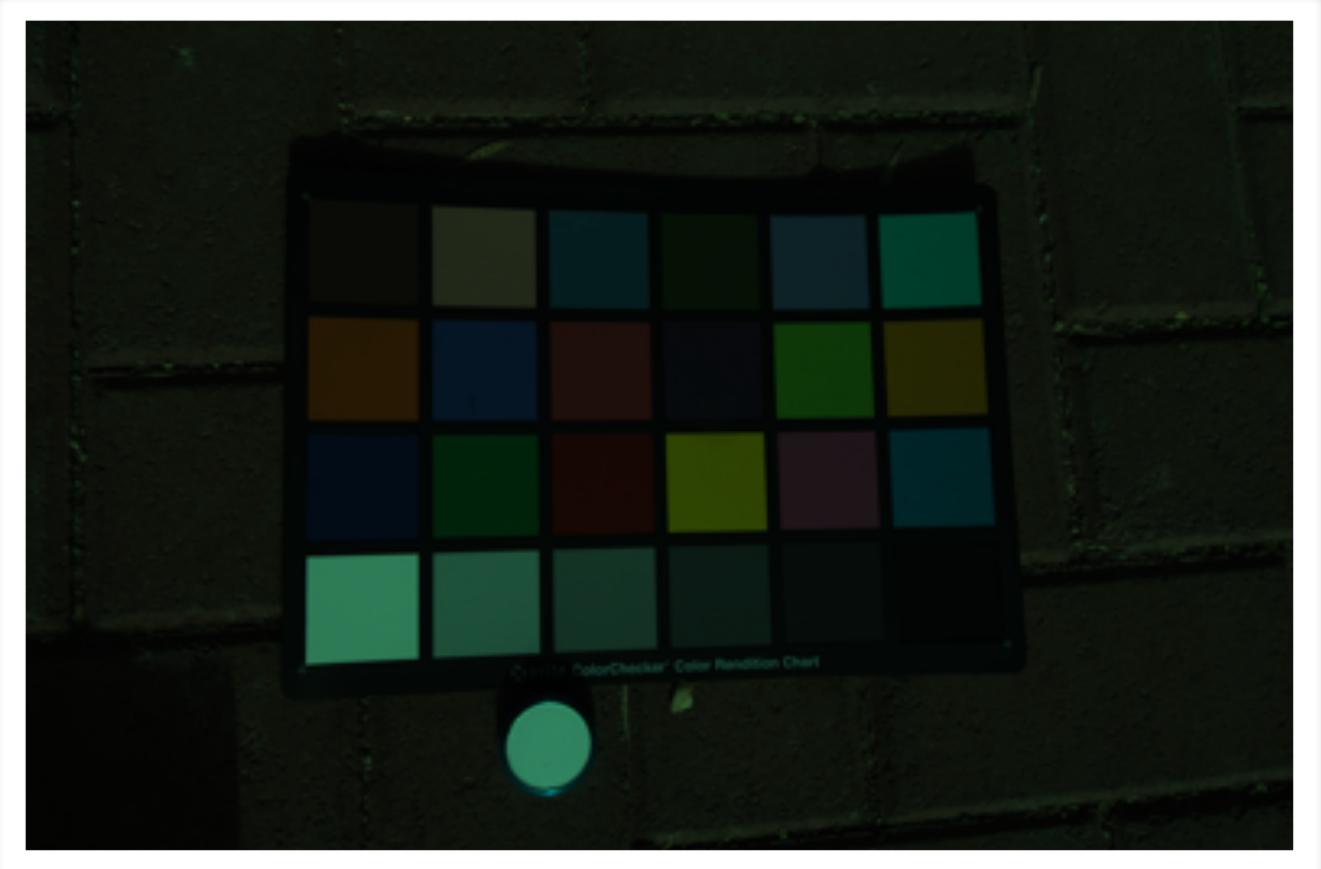
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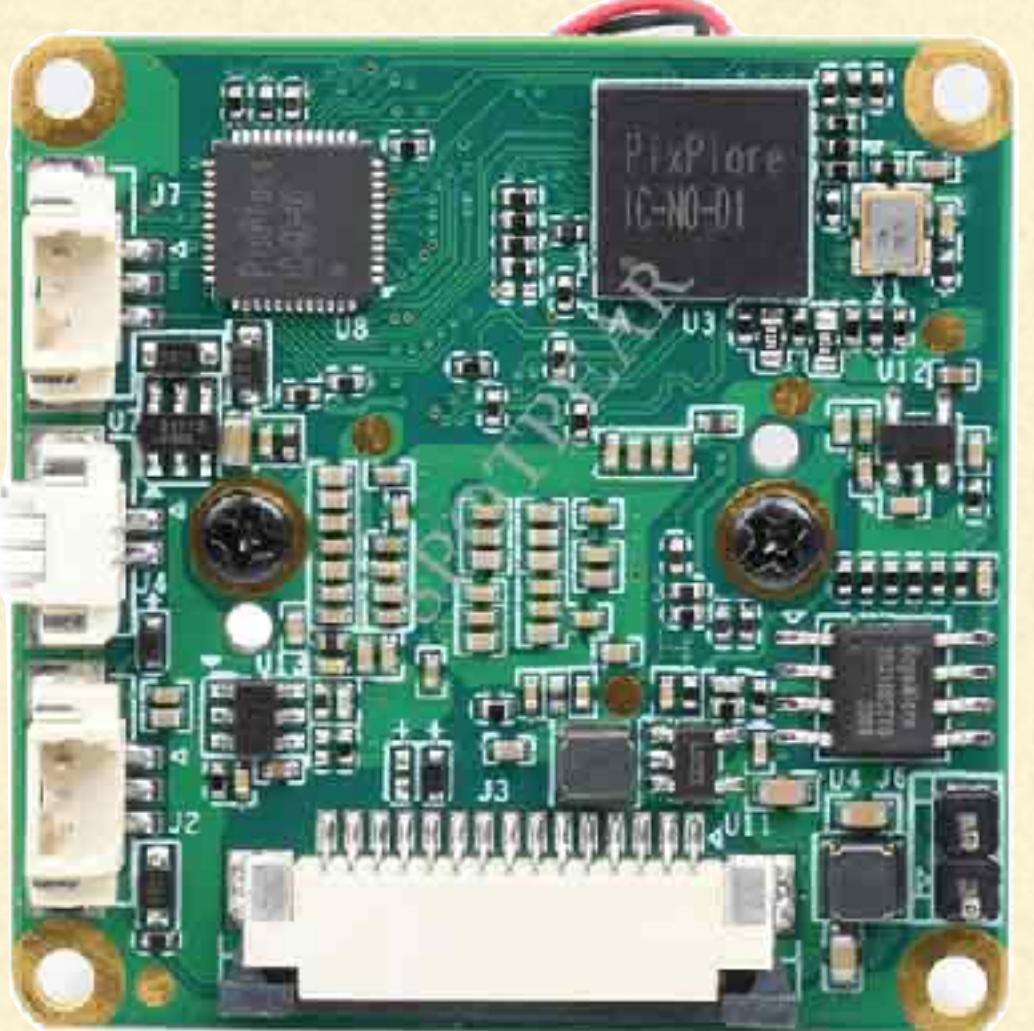
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RAW IMAGE



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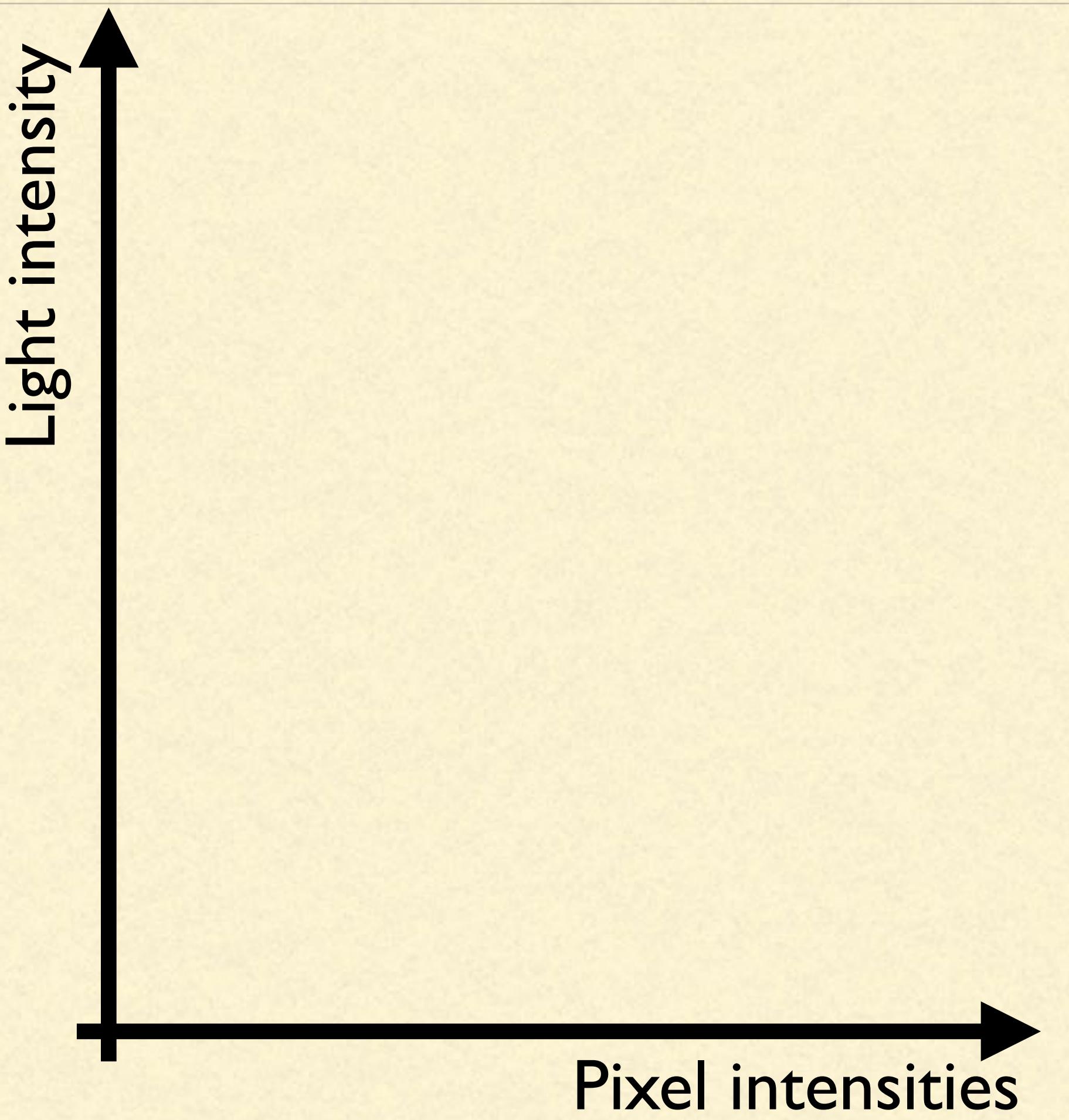
An image is linear
if pixel intensities
are linearly related
to light intensity.

What Is a Linear Image? **(and with what is it linear?)**



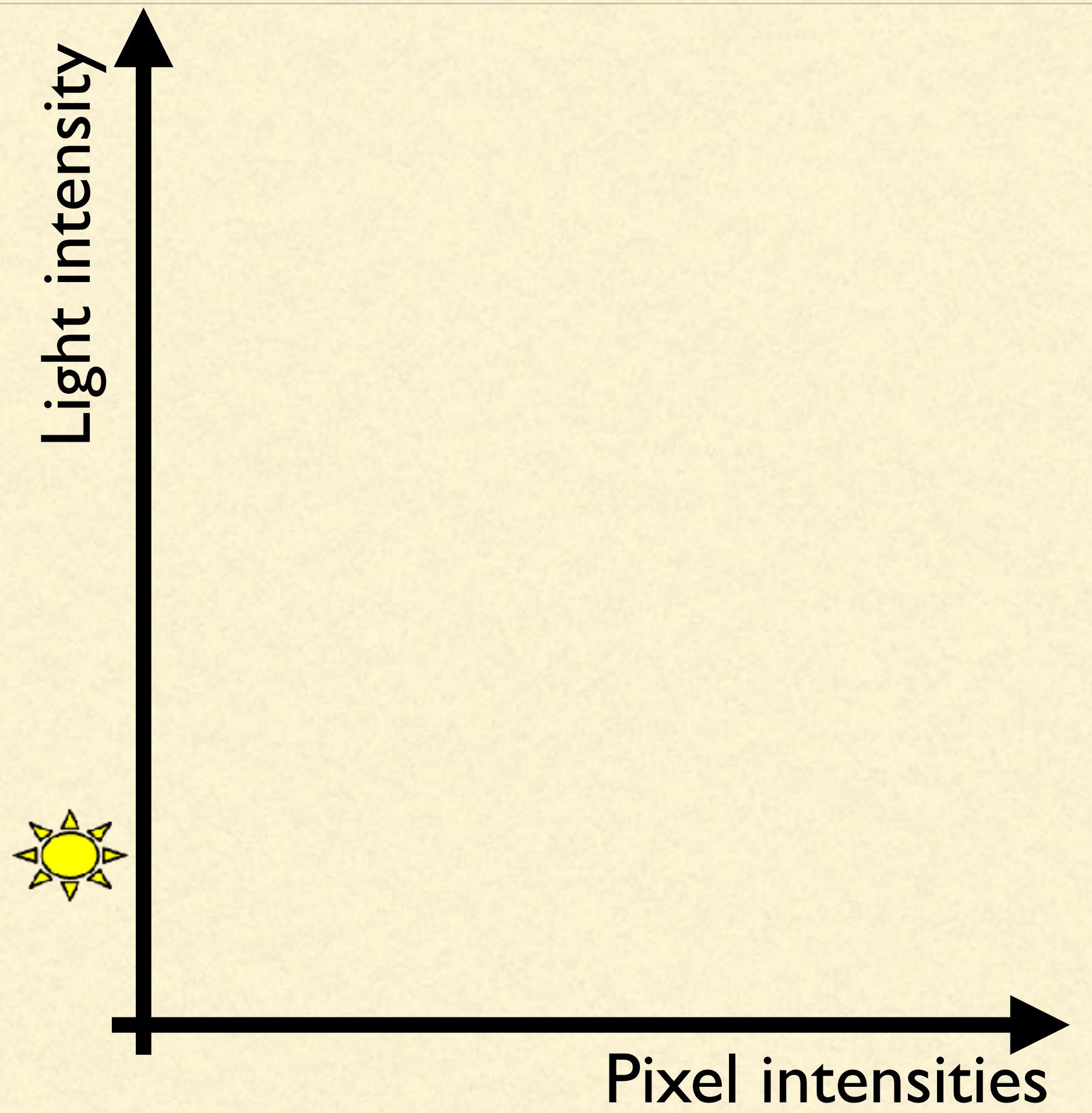
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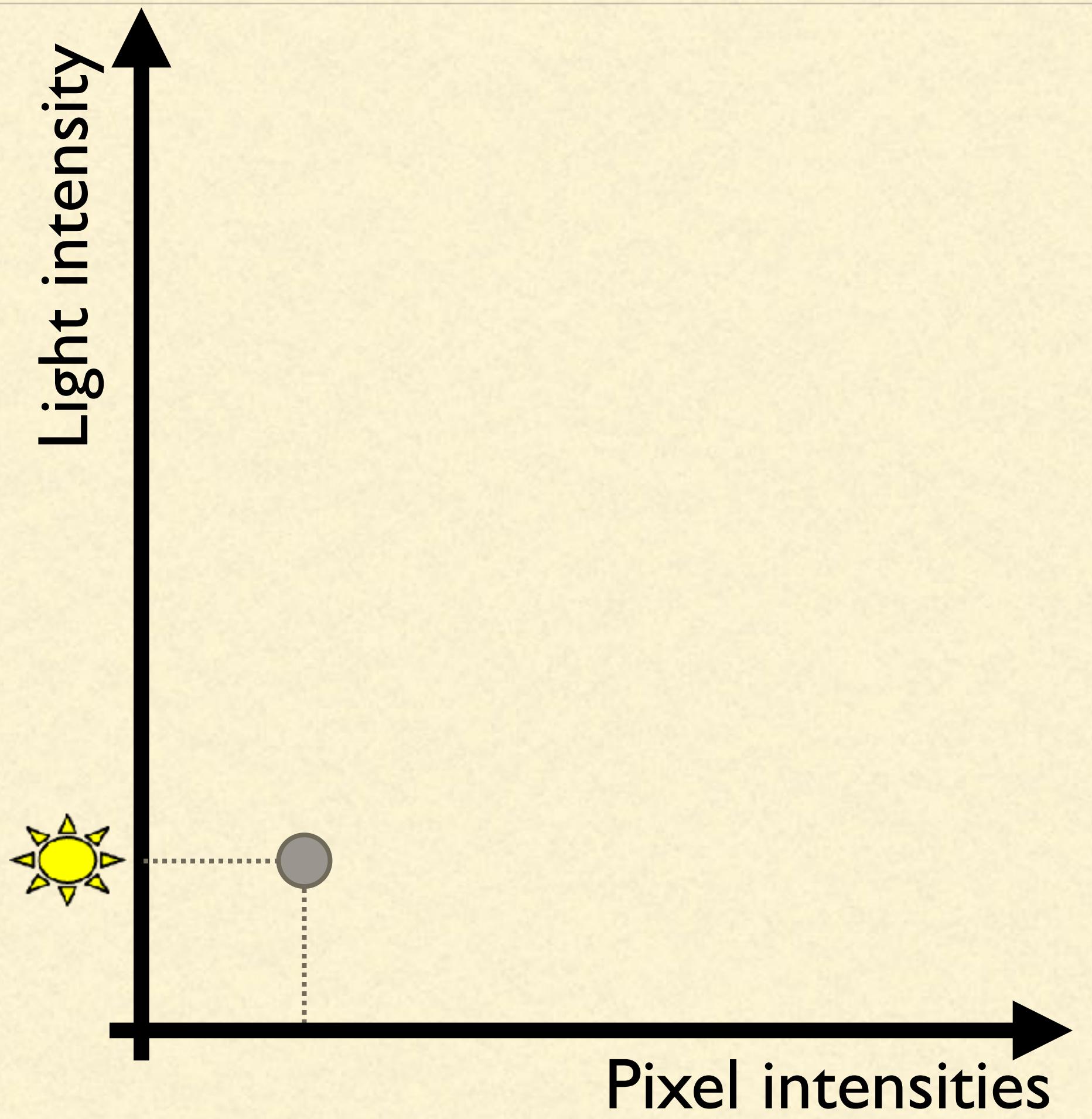
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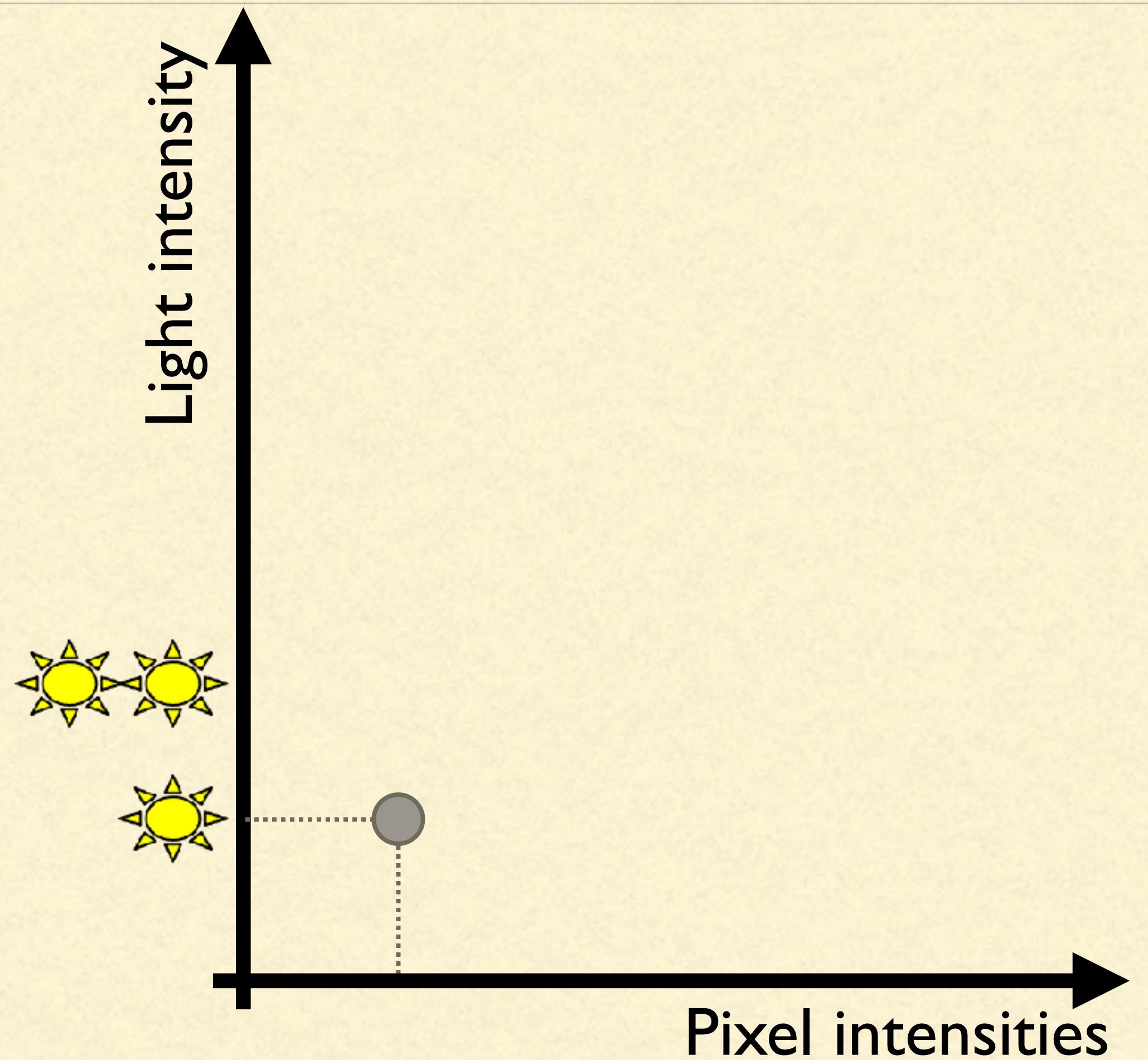
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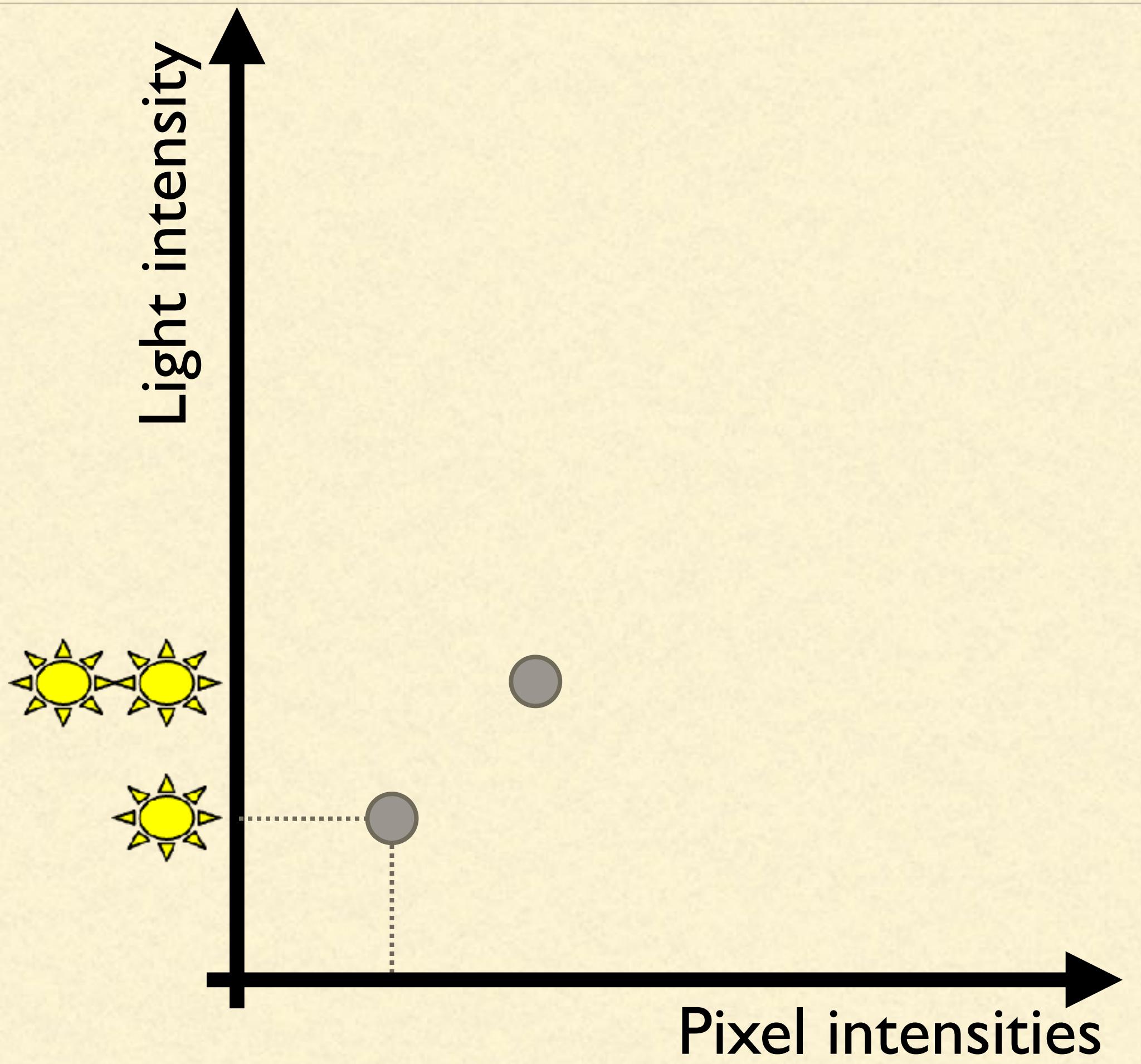
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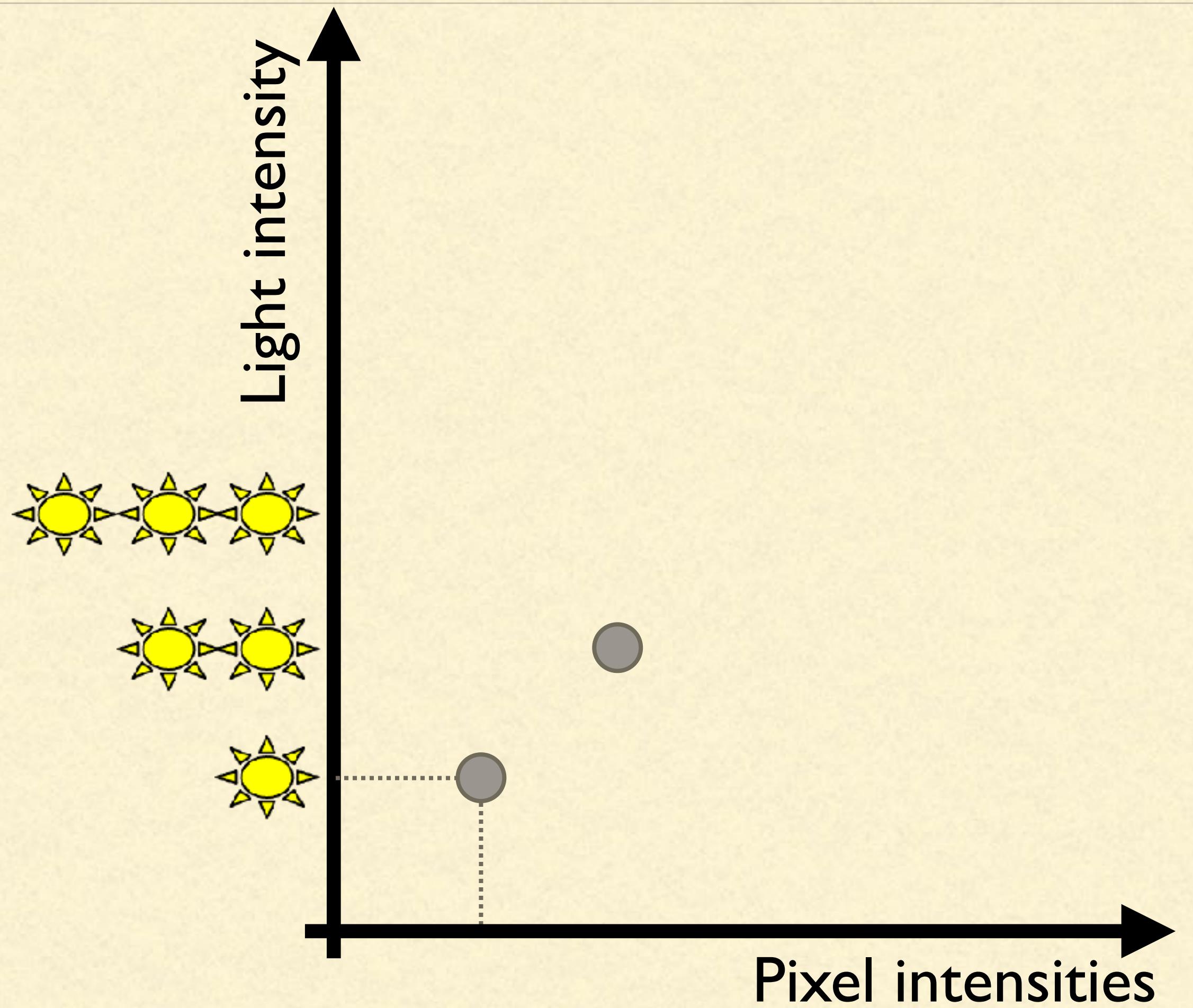
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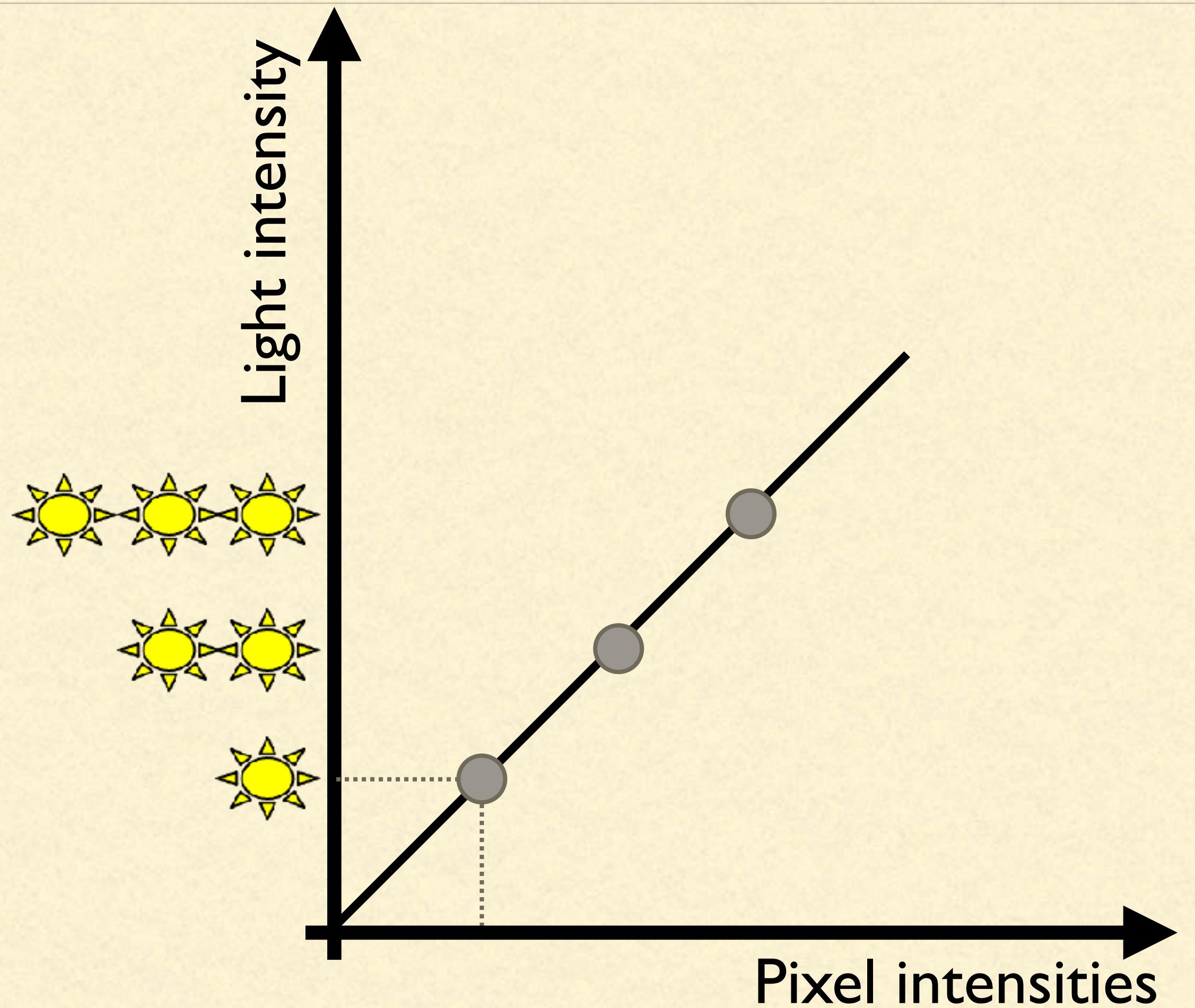
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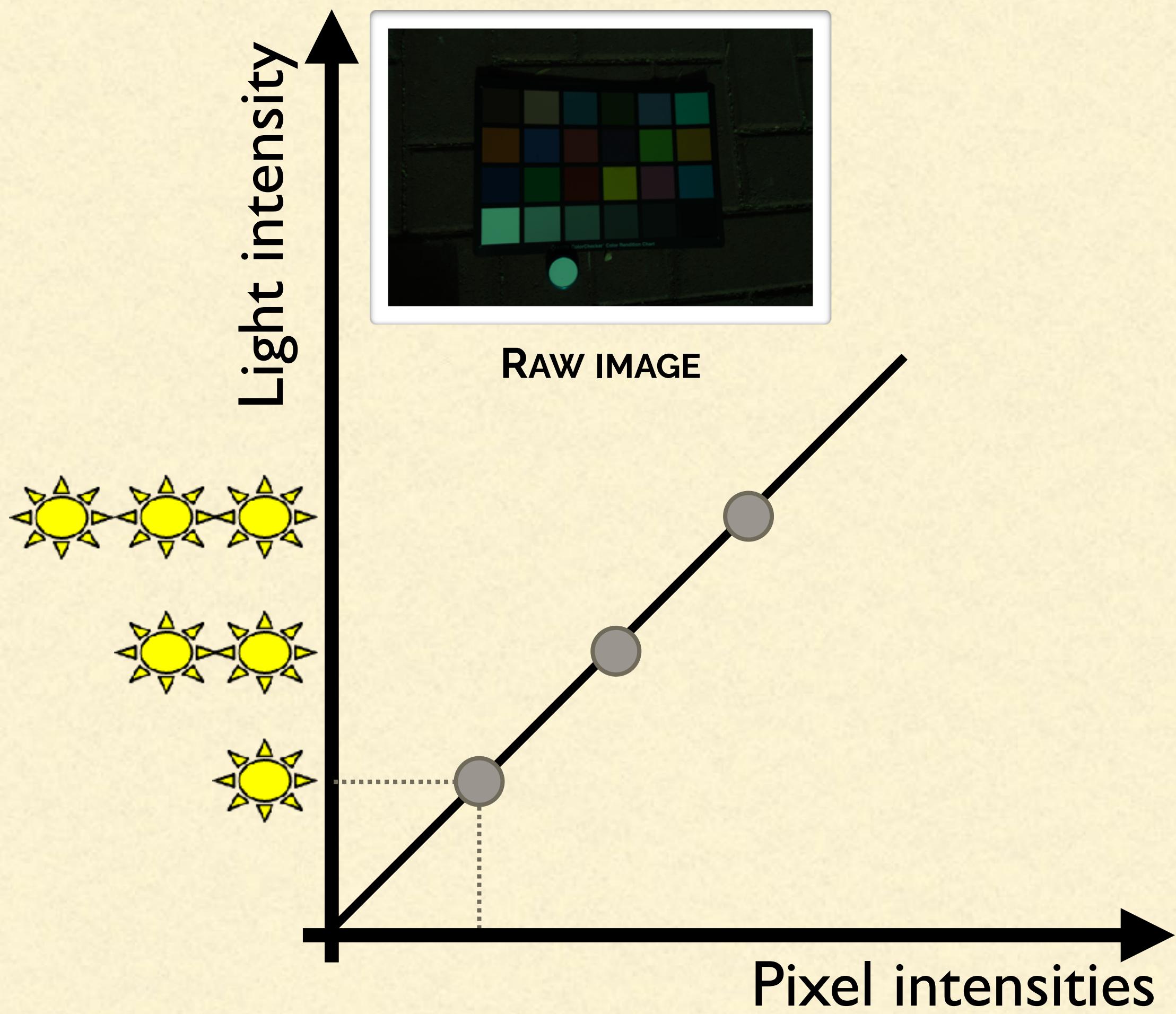
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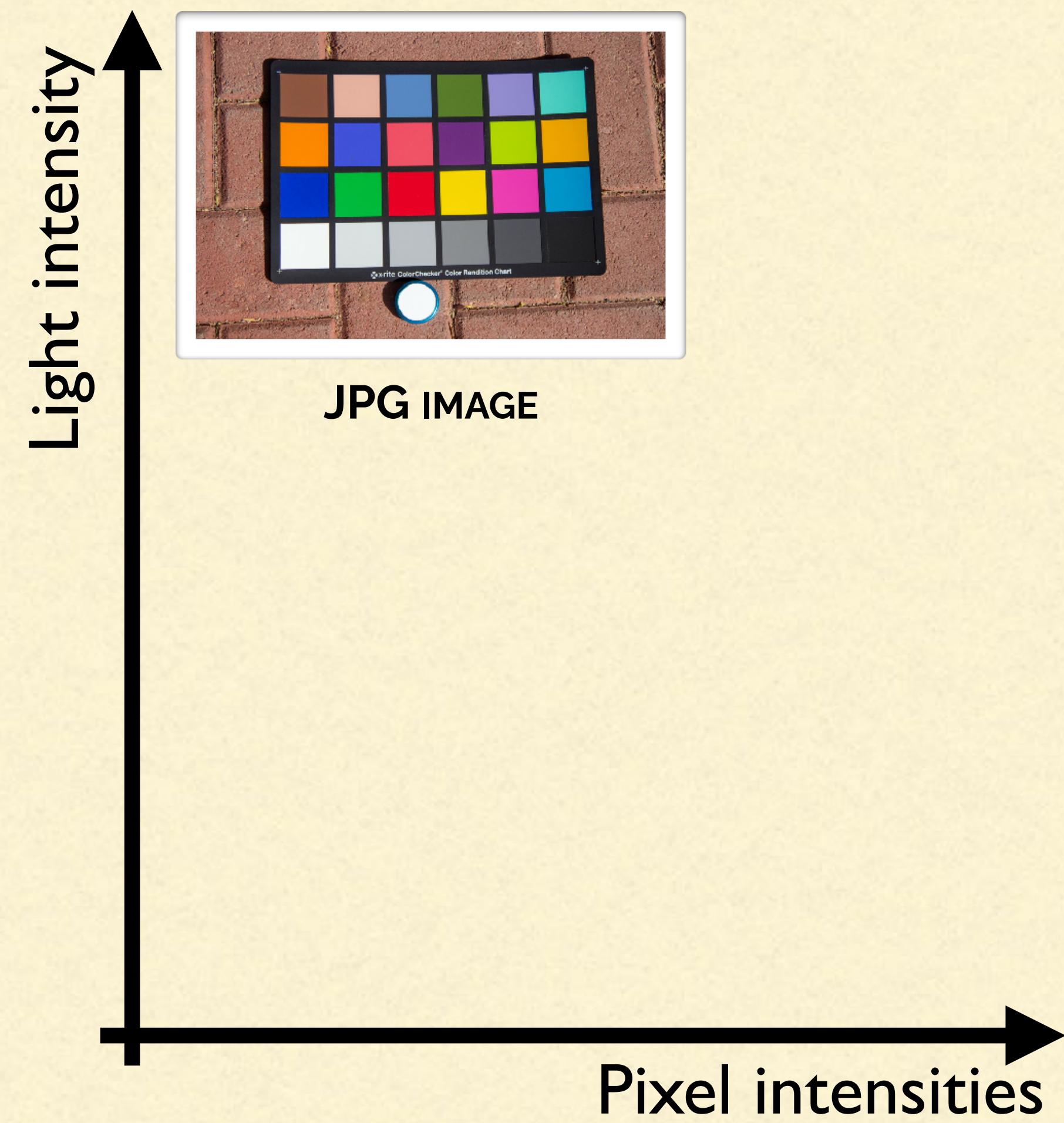
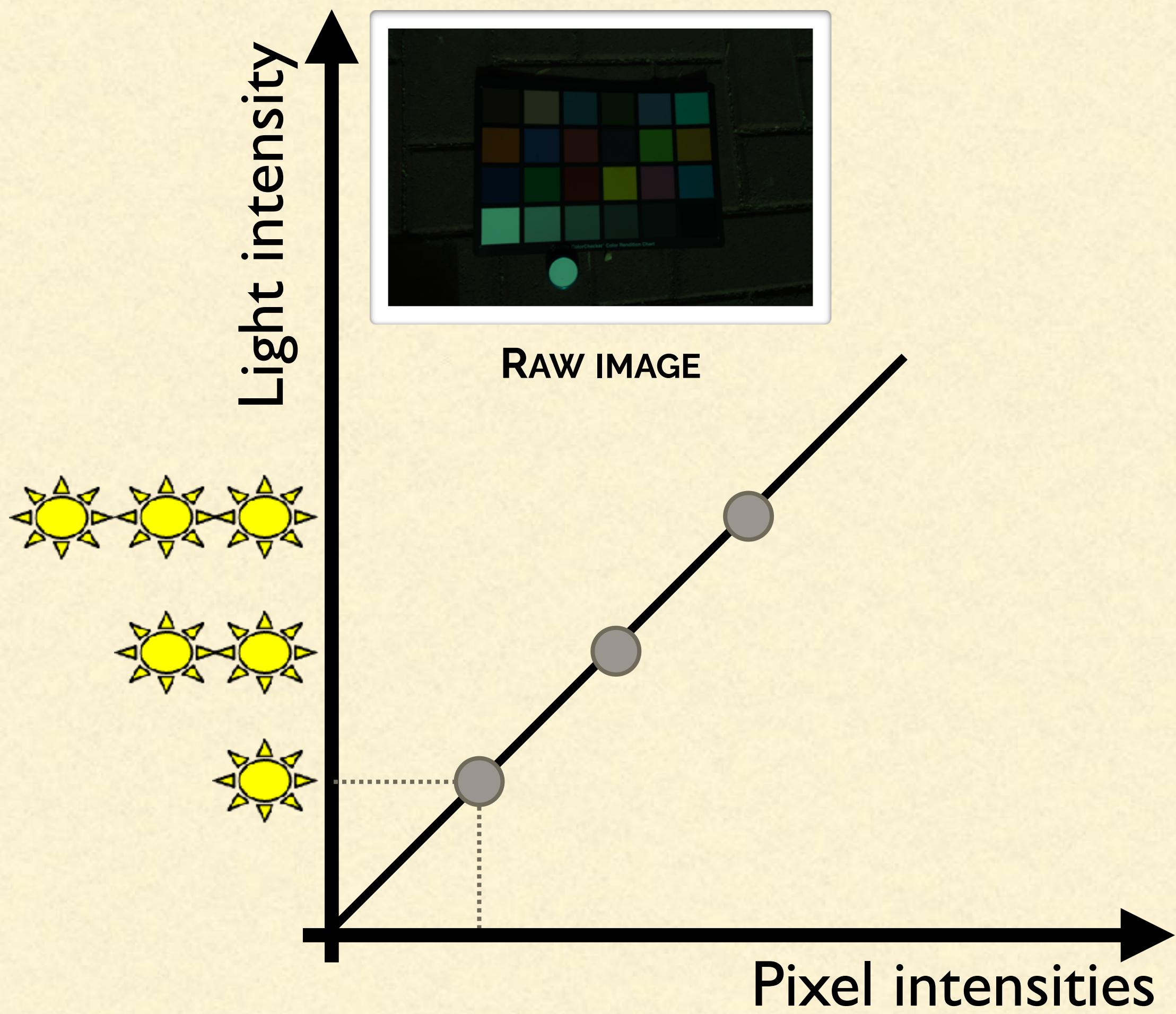
What Is a Linear Image? (and with what is it linear?)

Most modern sensors produce images that have a linear relationship with scene radiance.



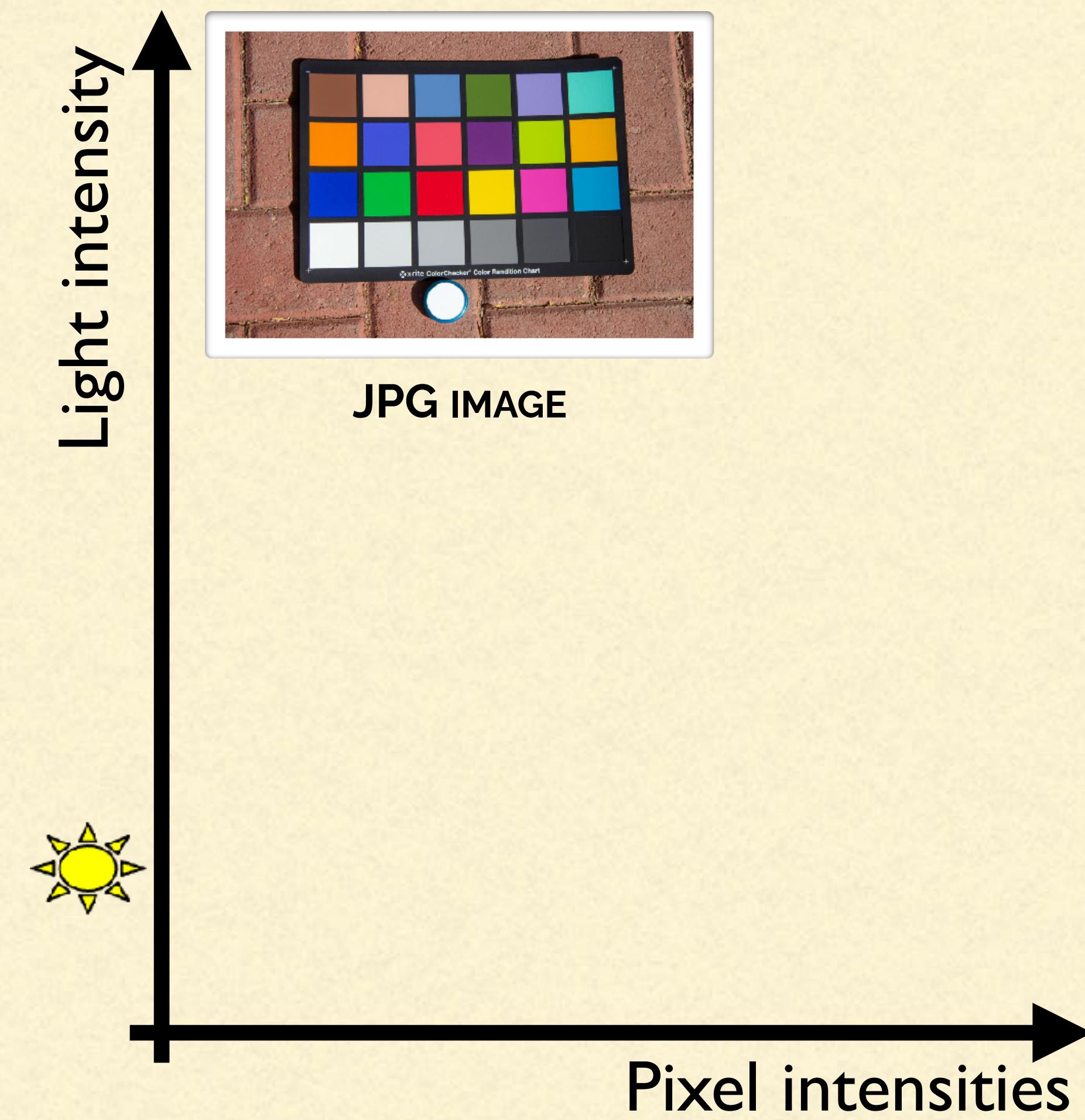
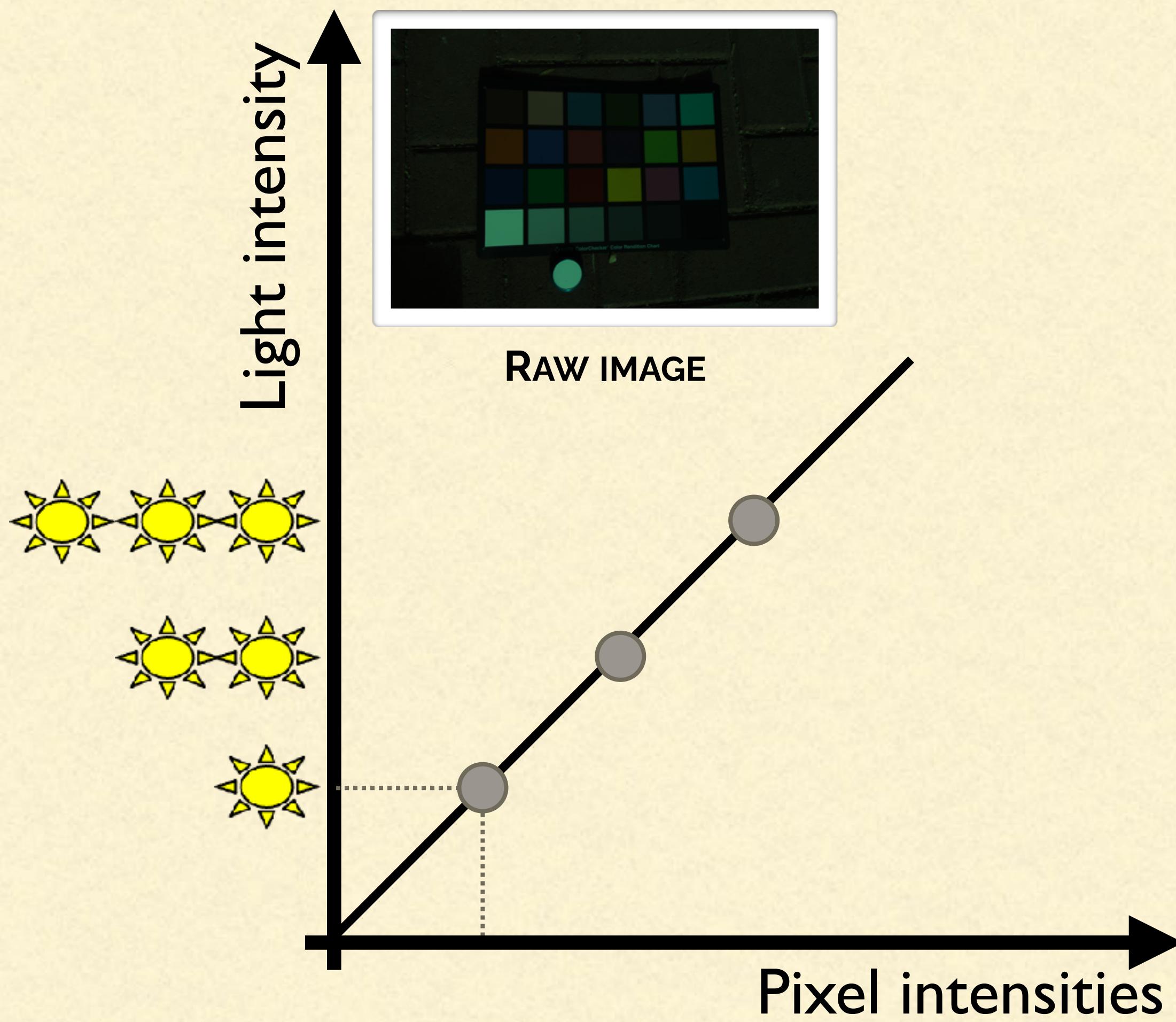
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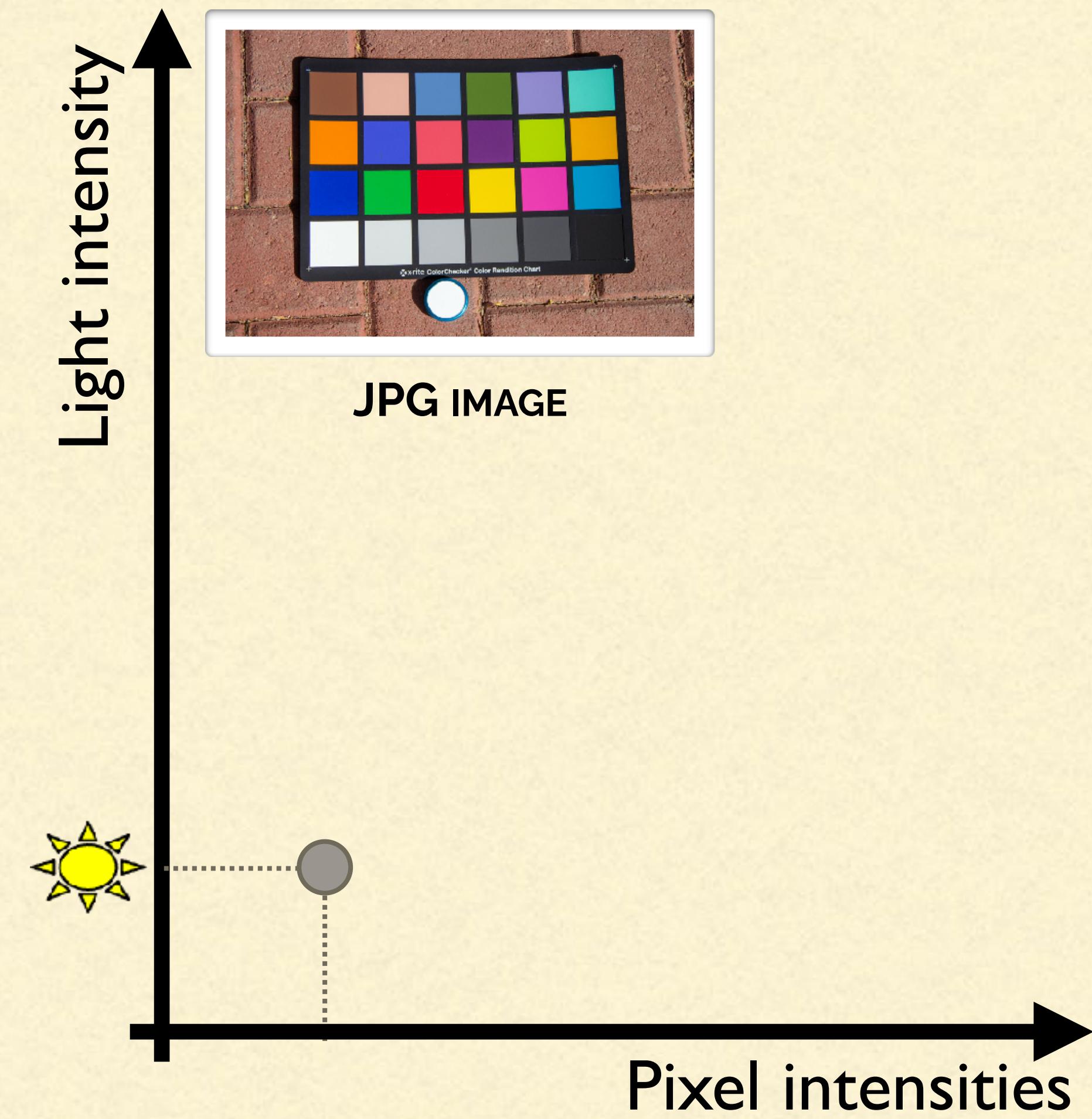
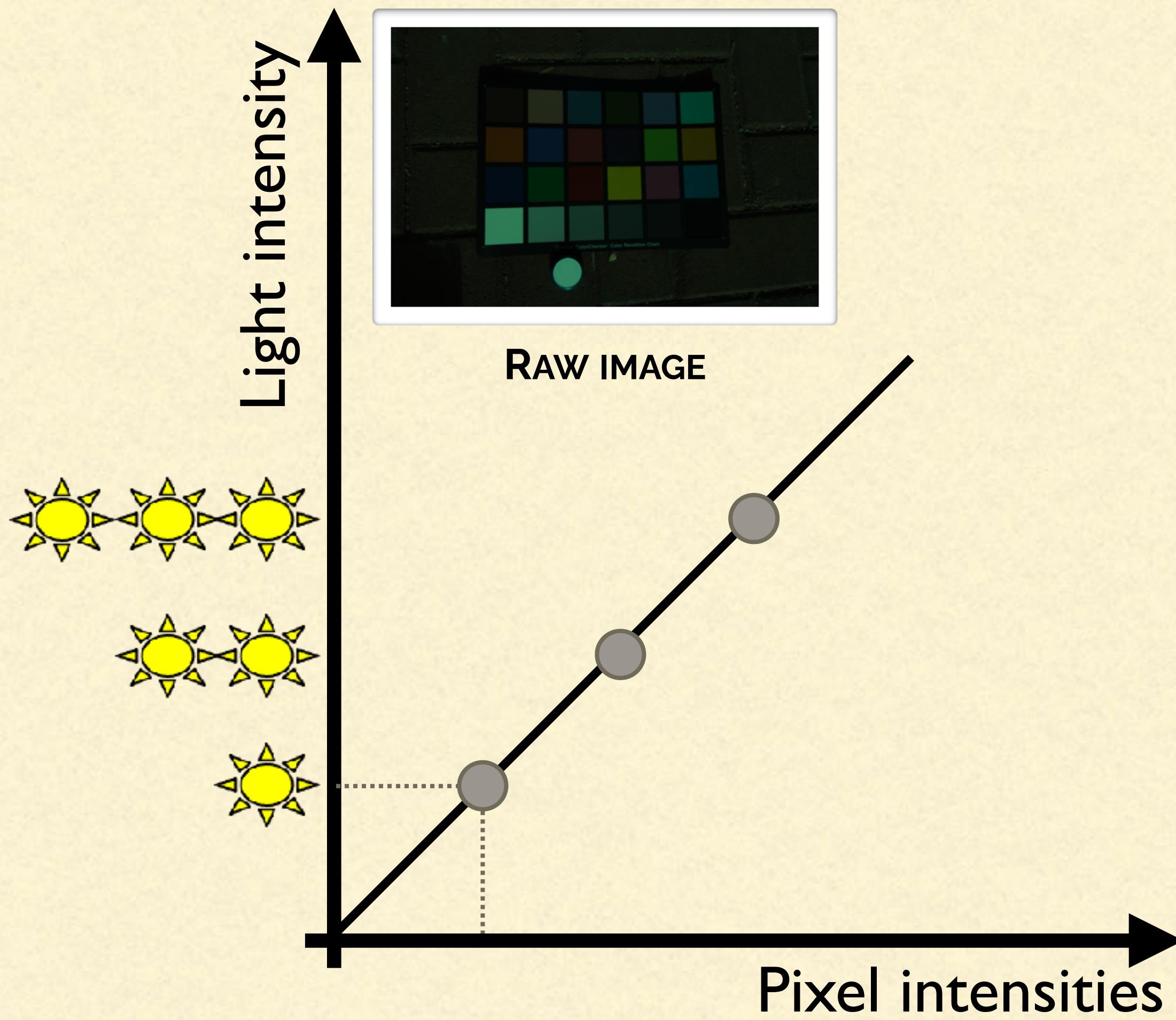
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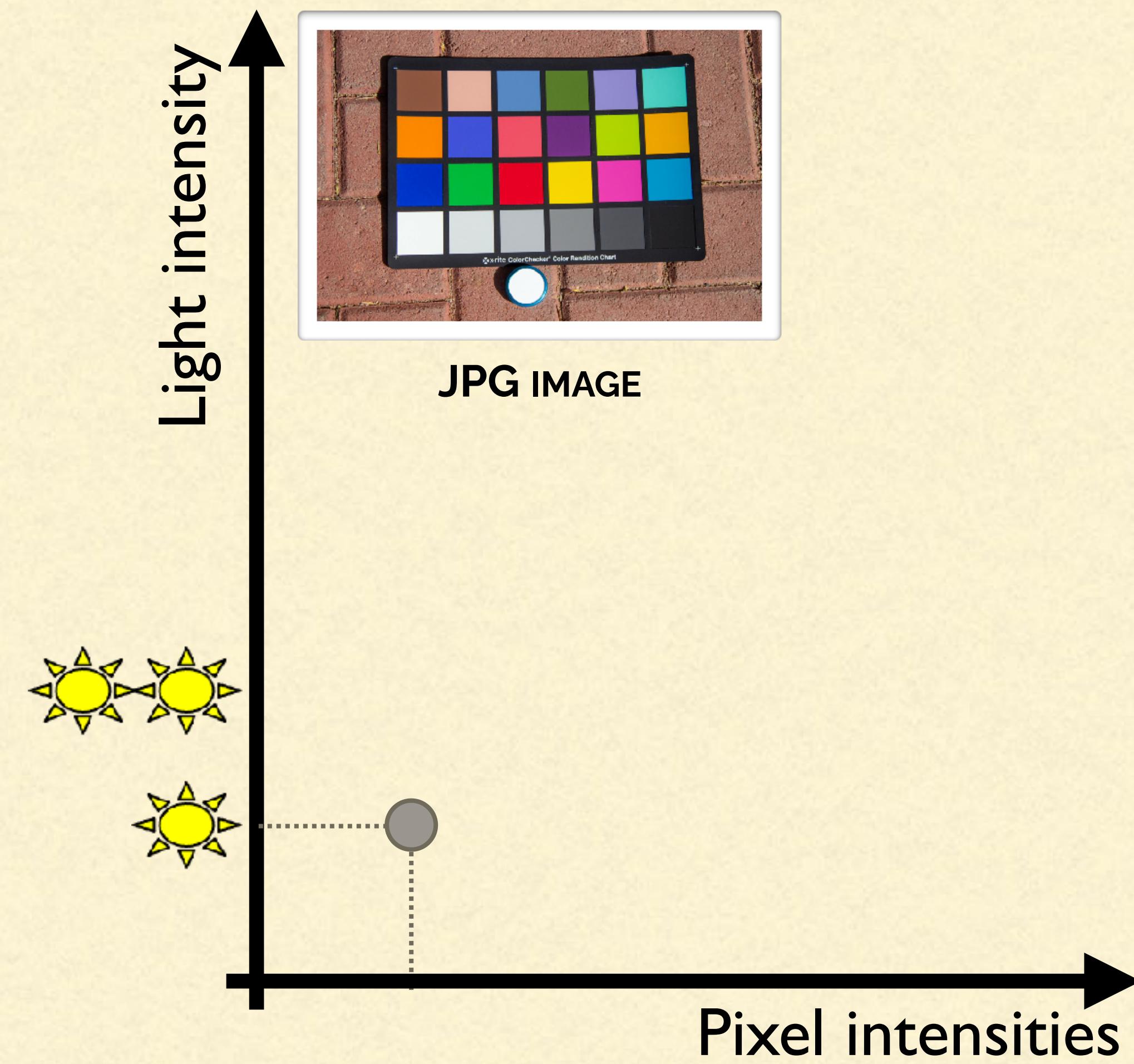
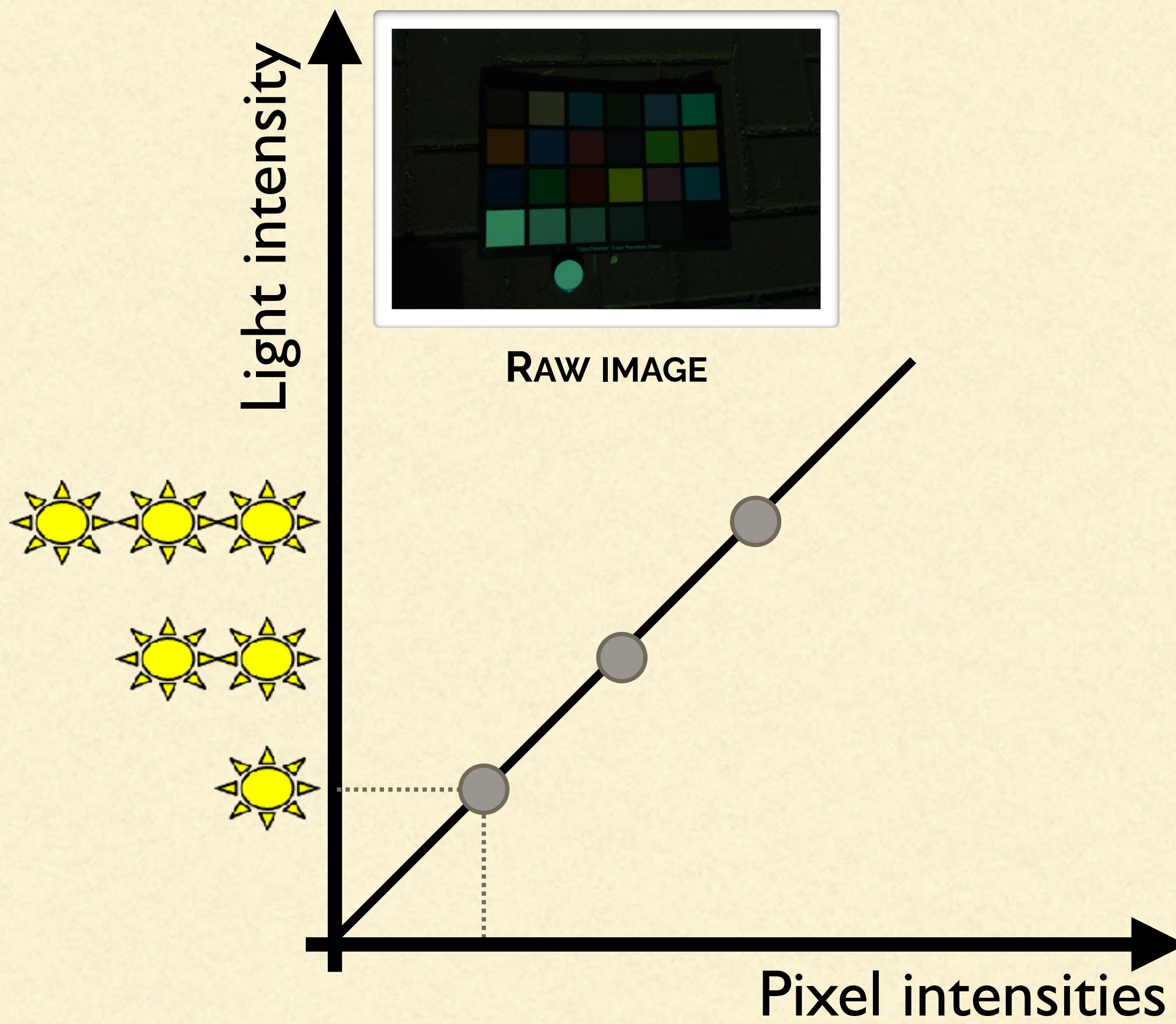
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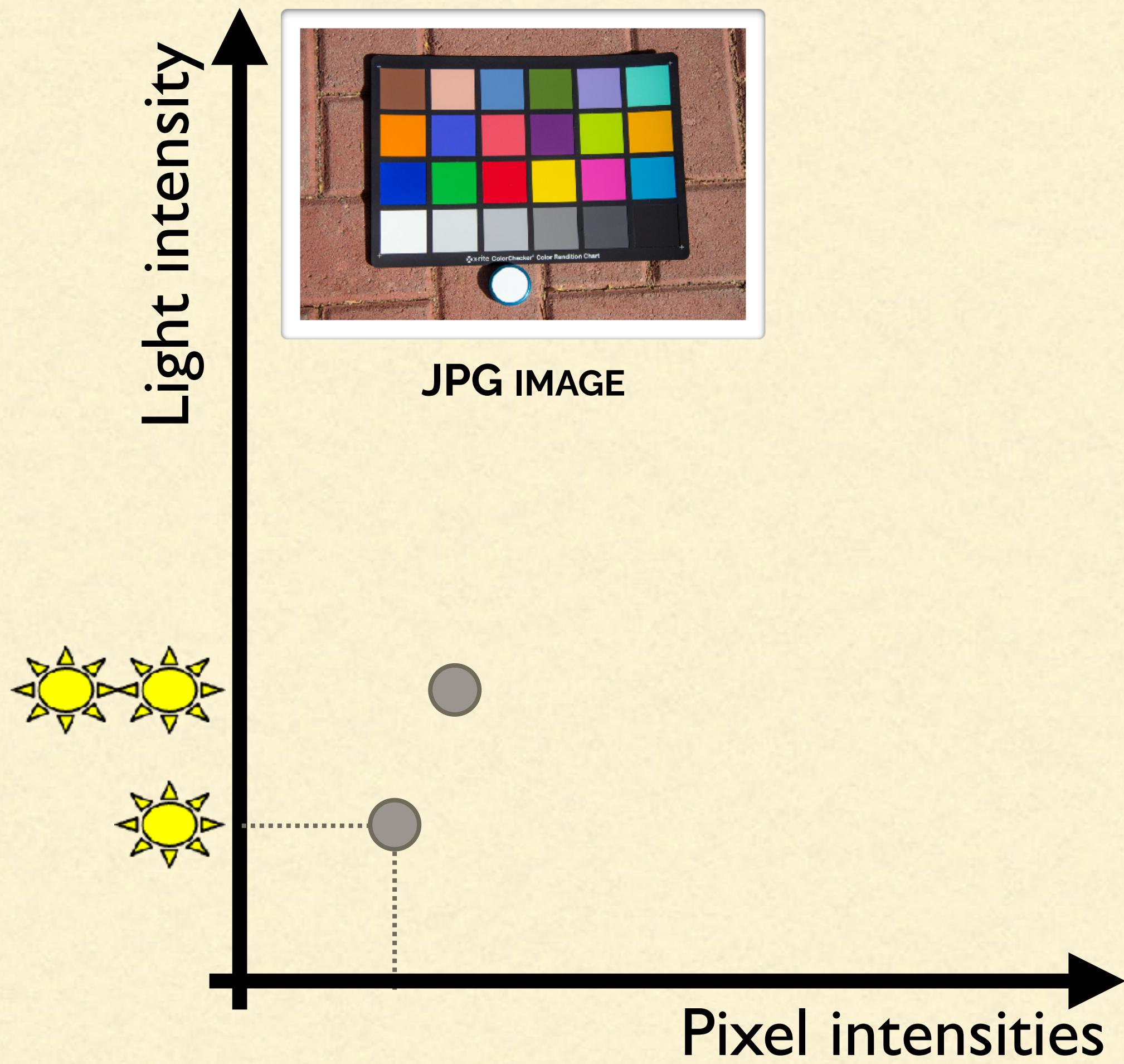
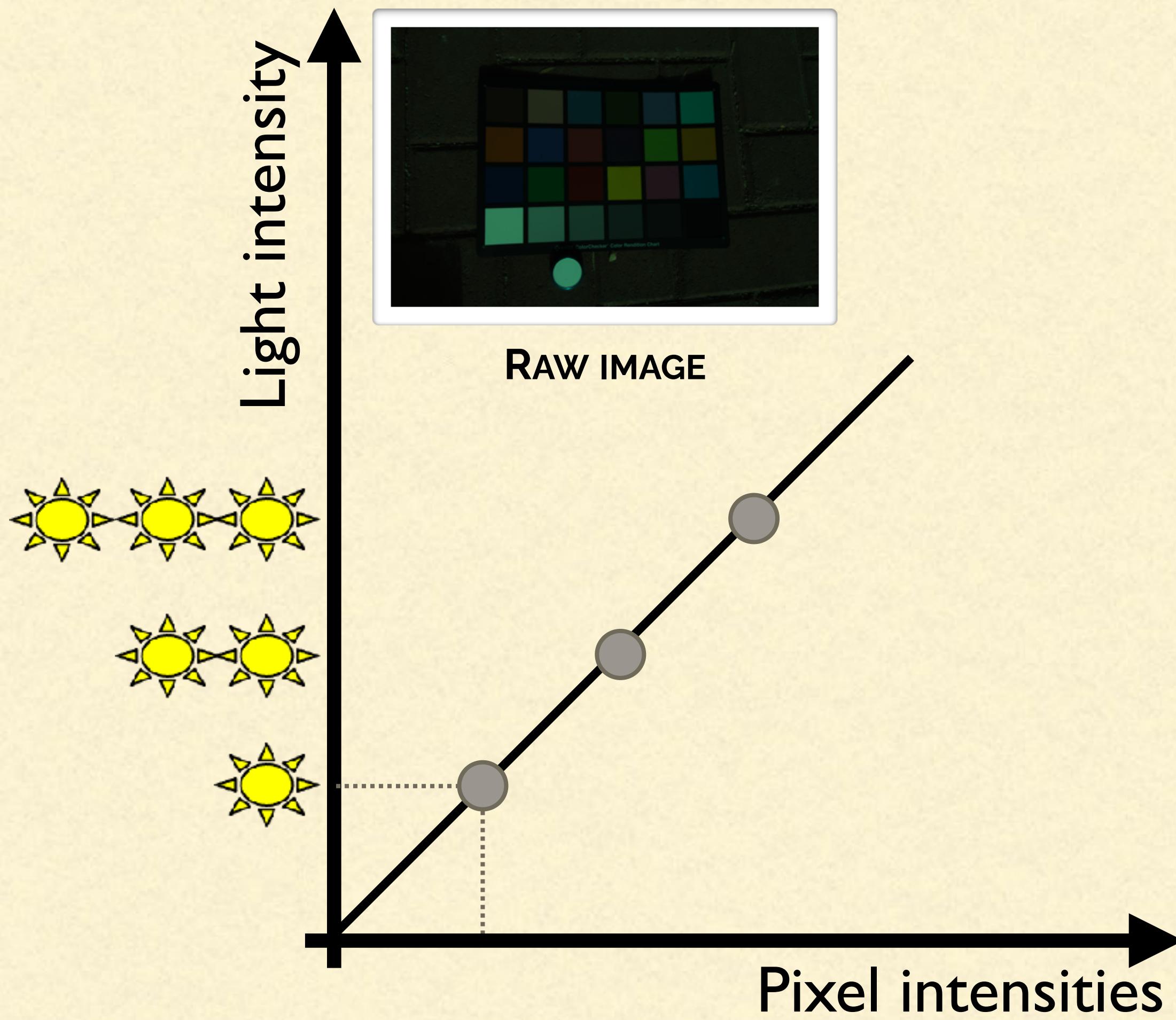
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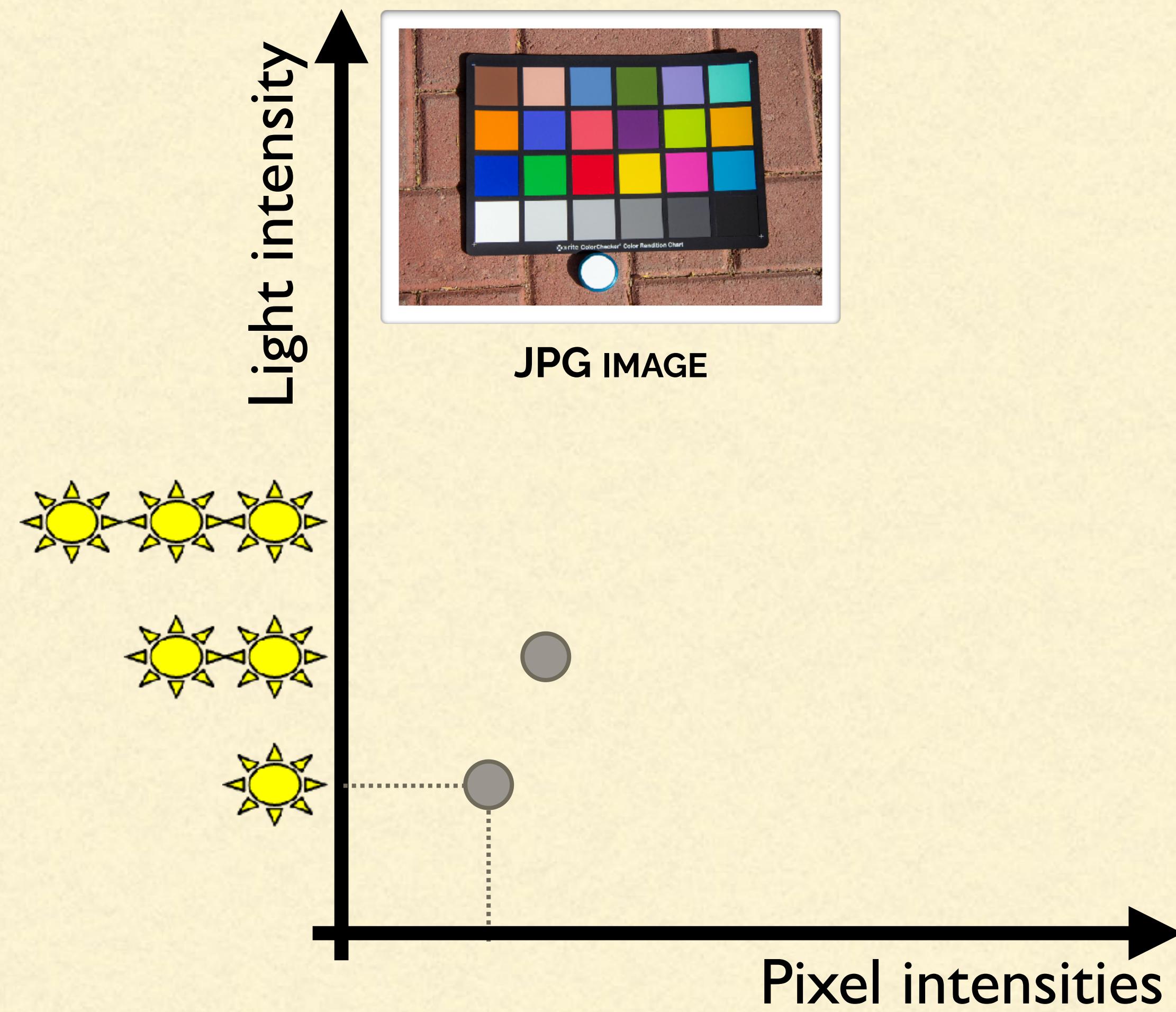
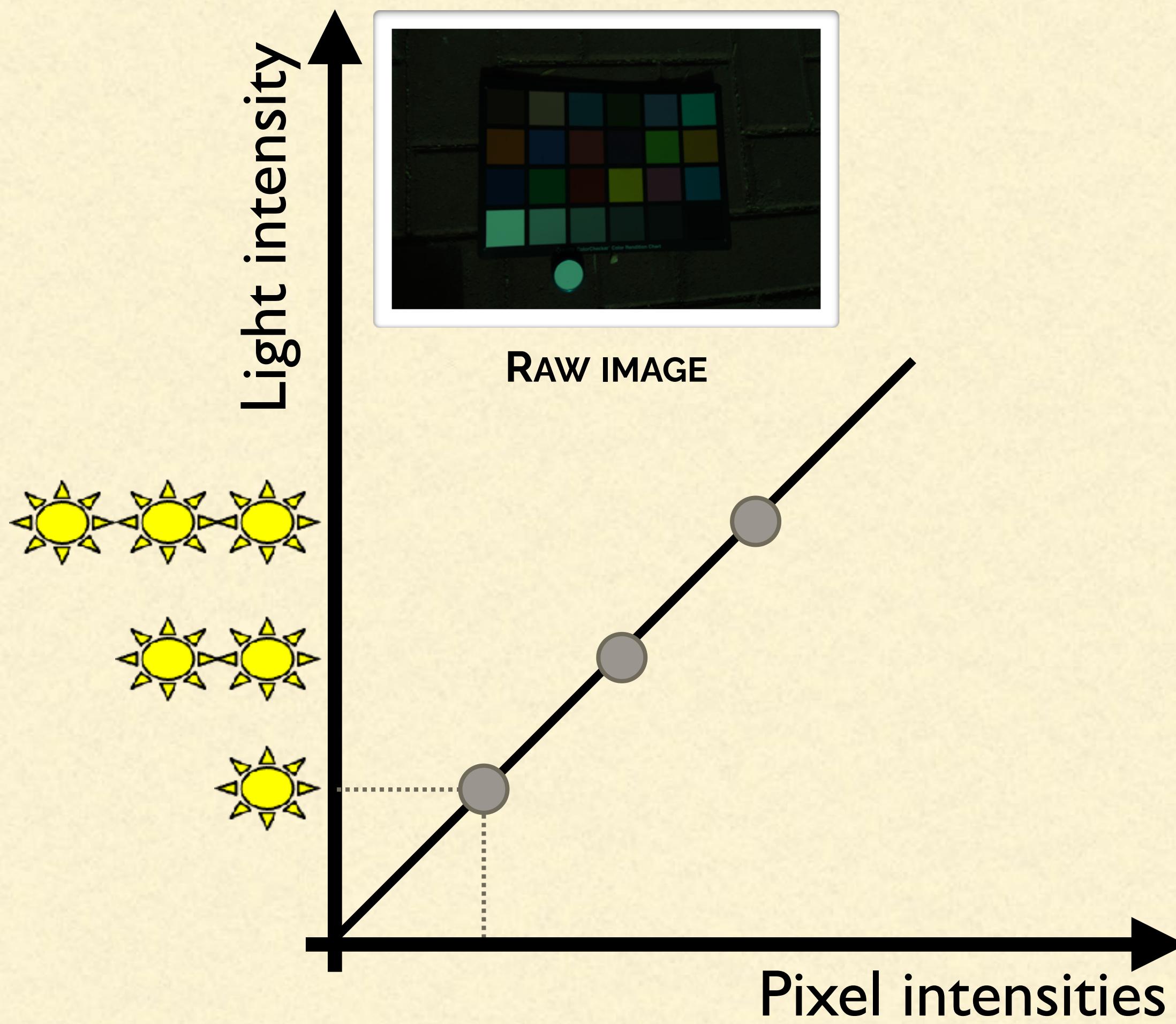
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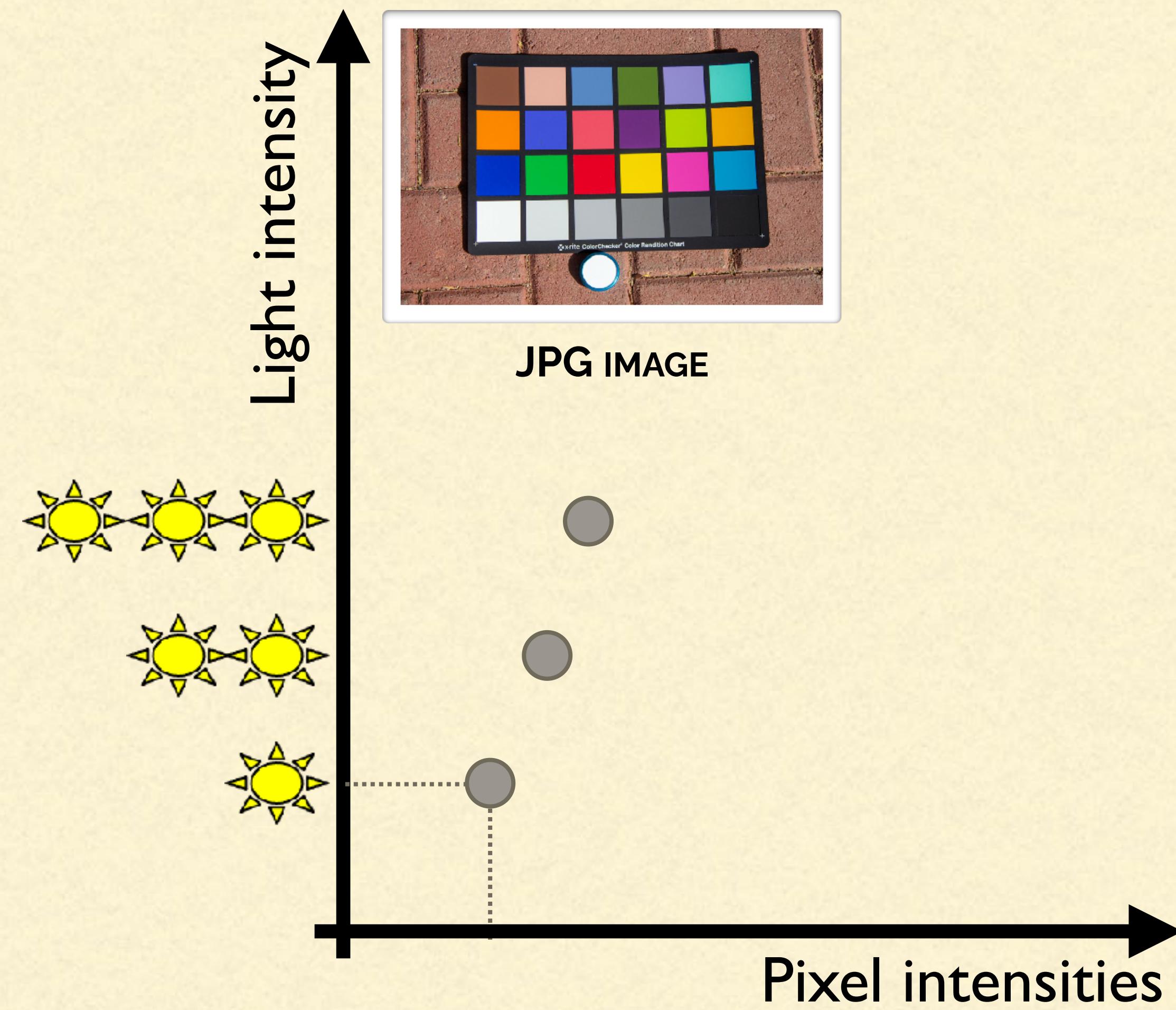
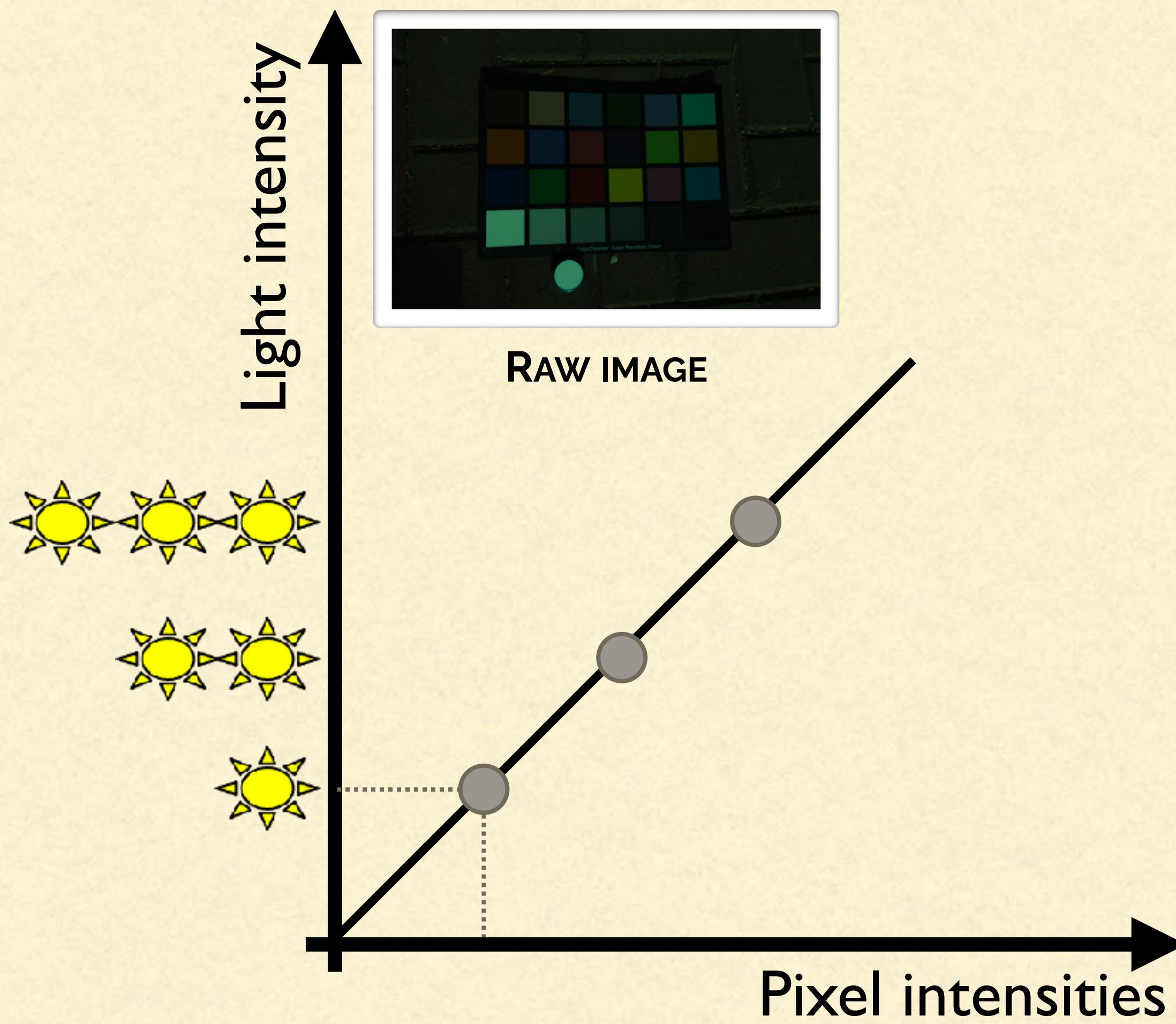
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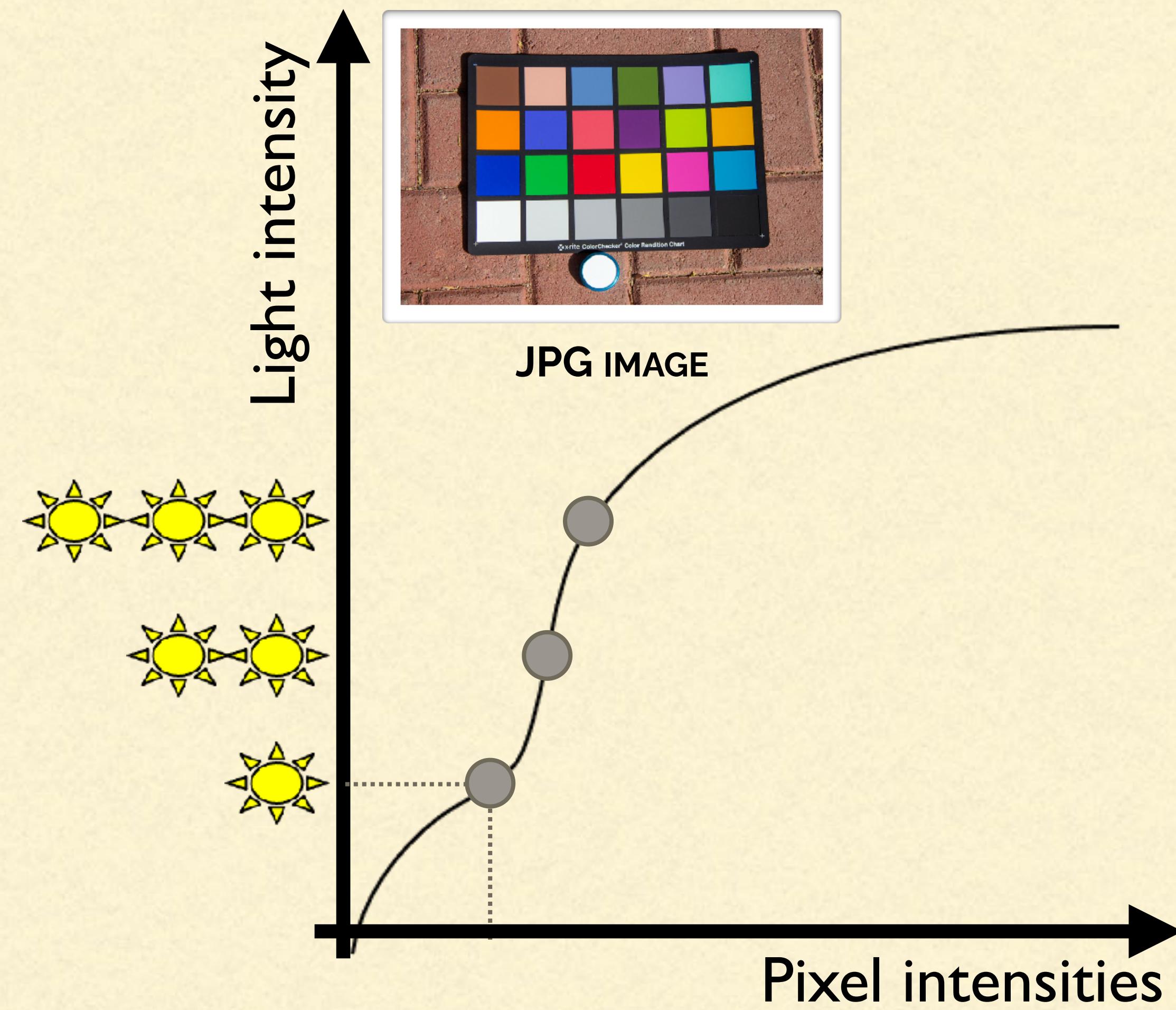
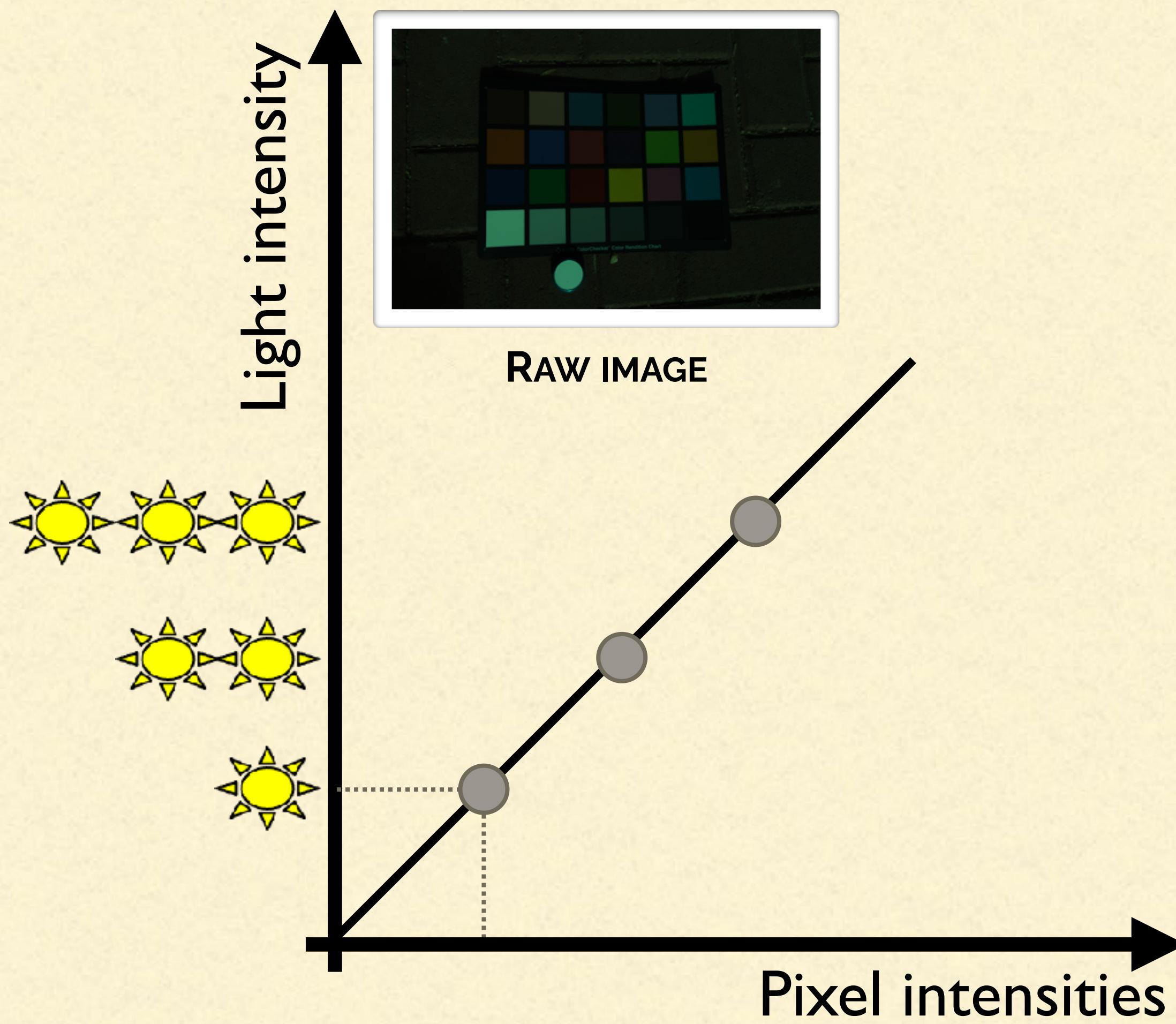
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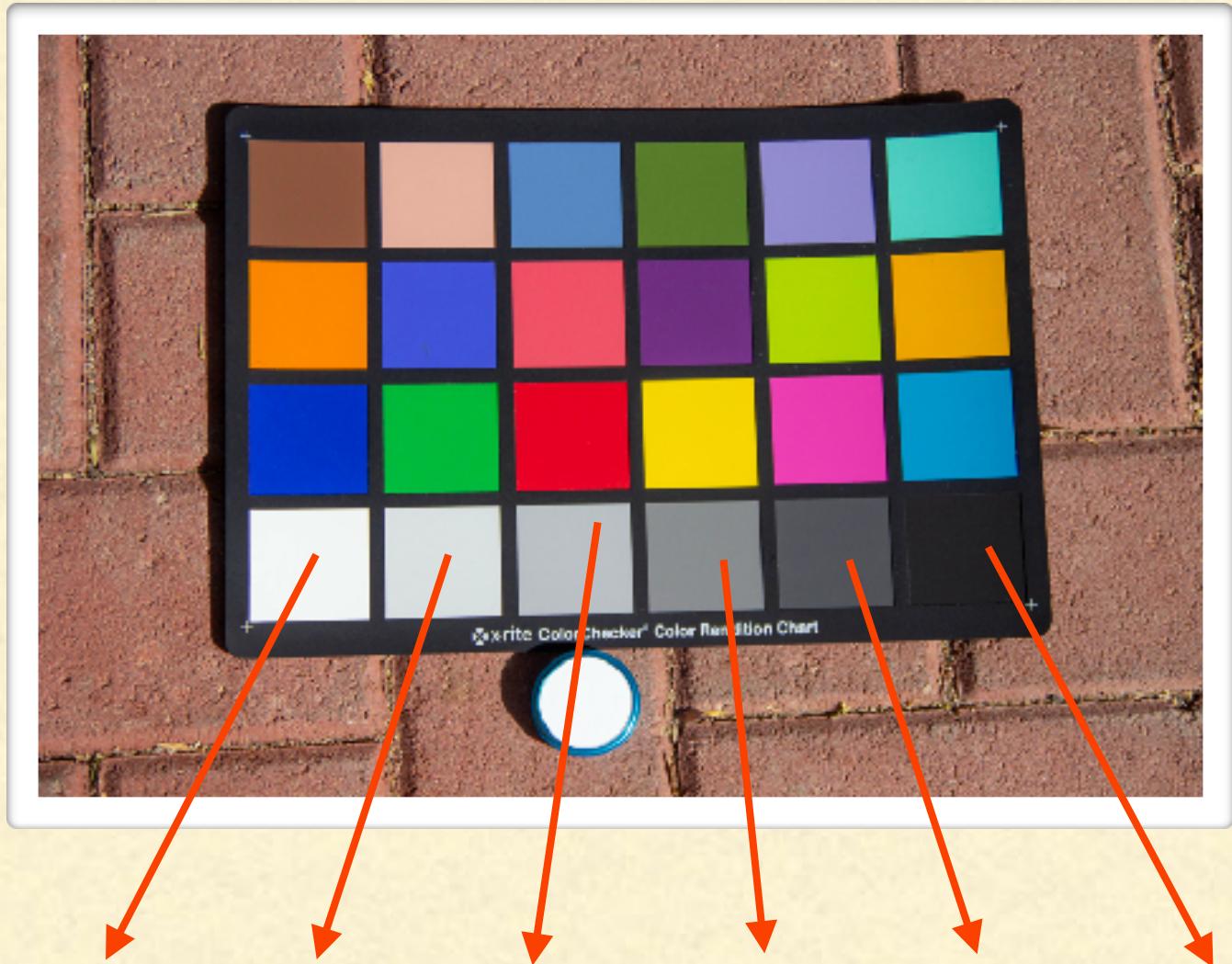
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take a raw photo of a
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How To Check Linearity of an Image



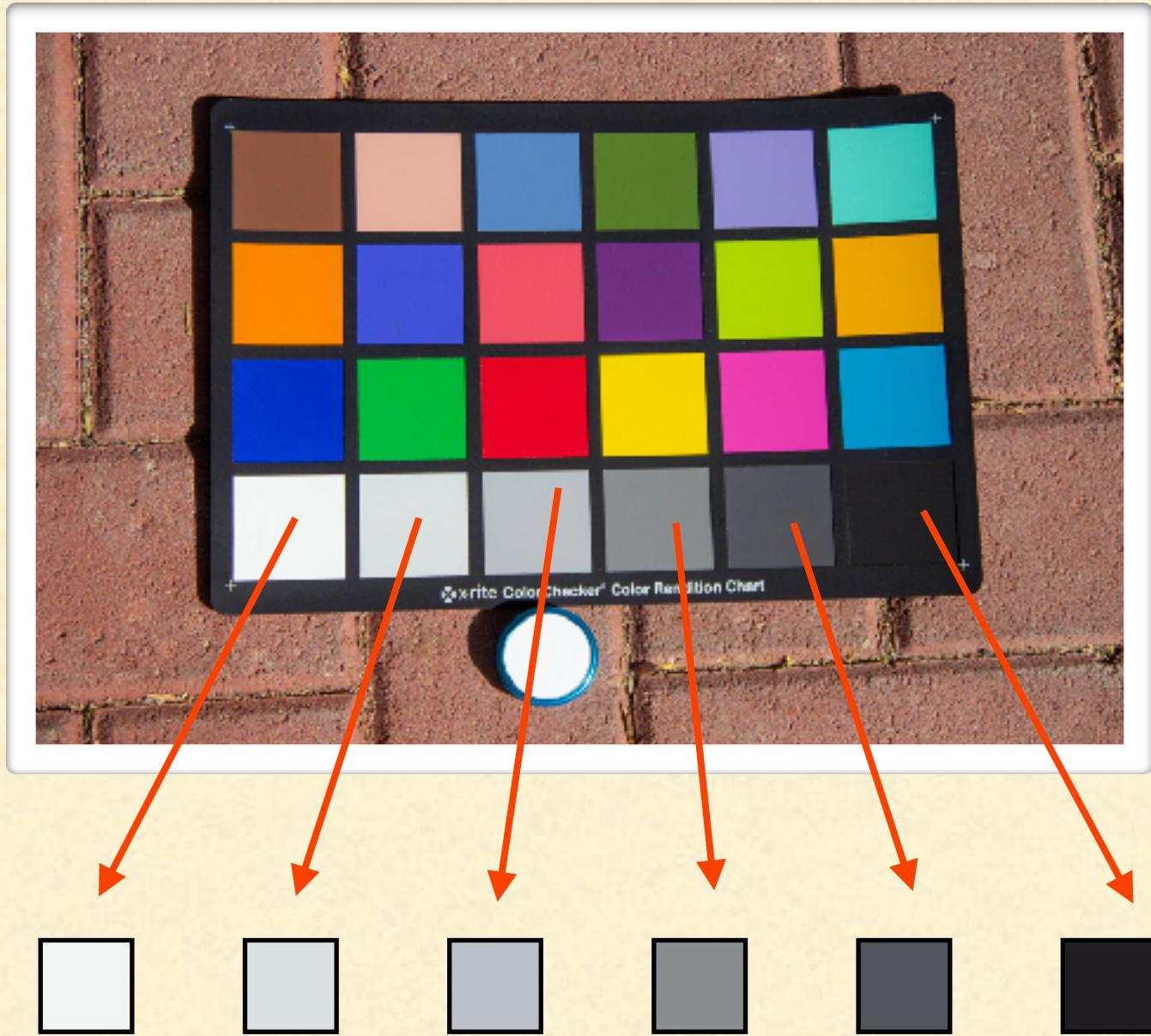
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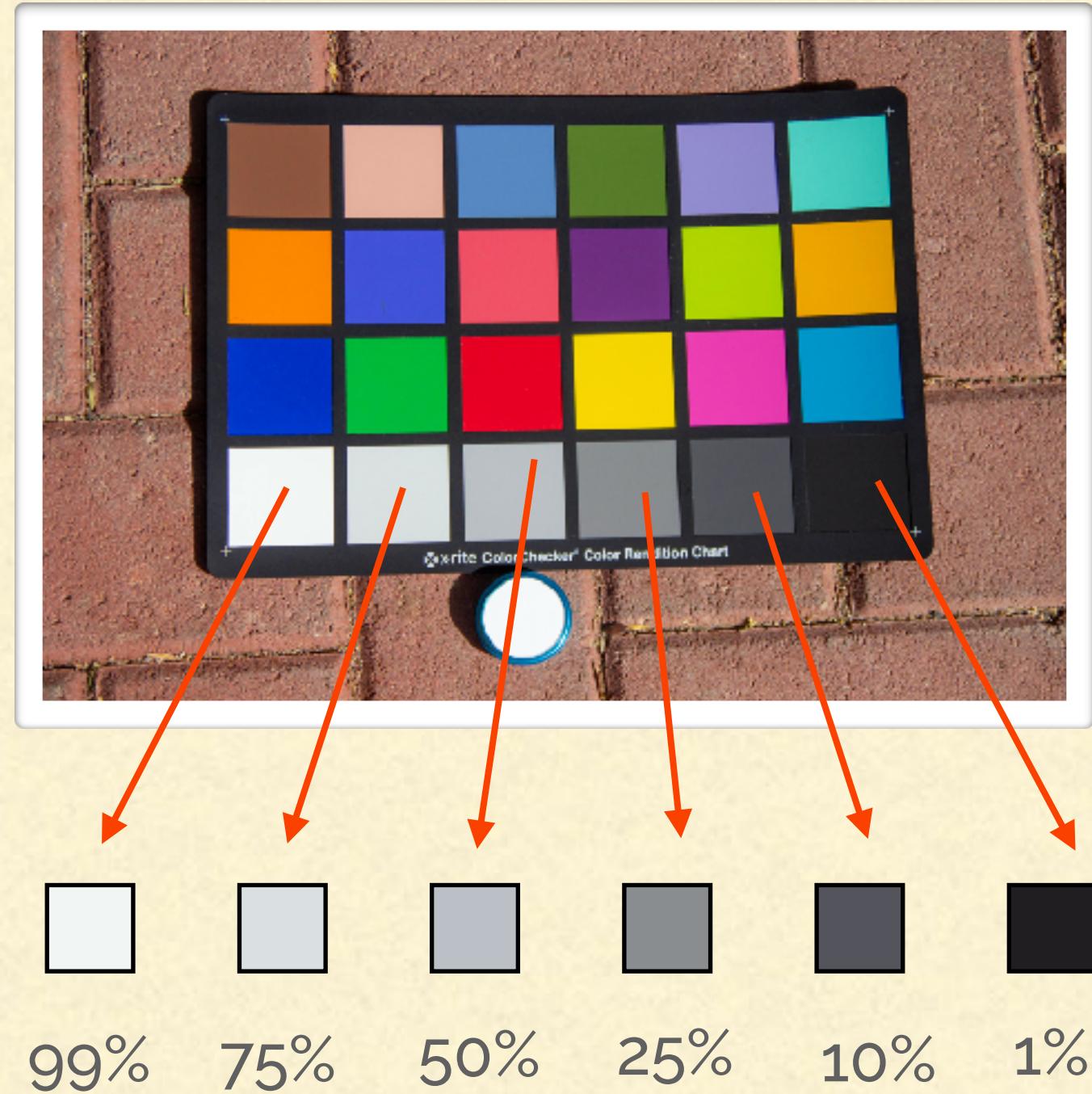
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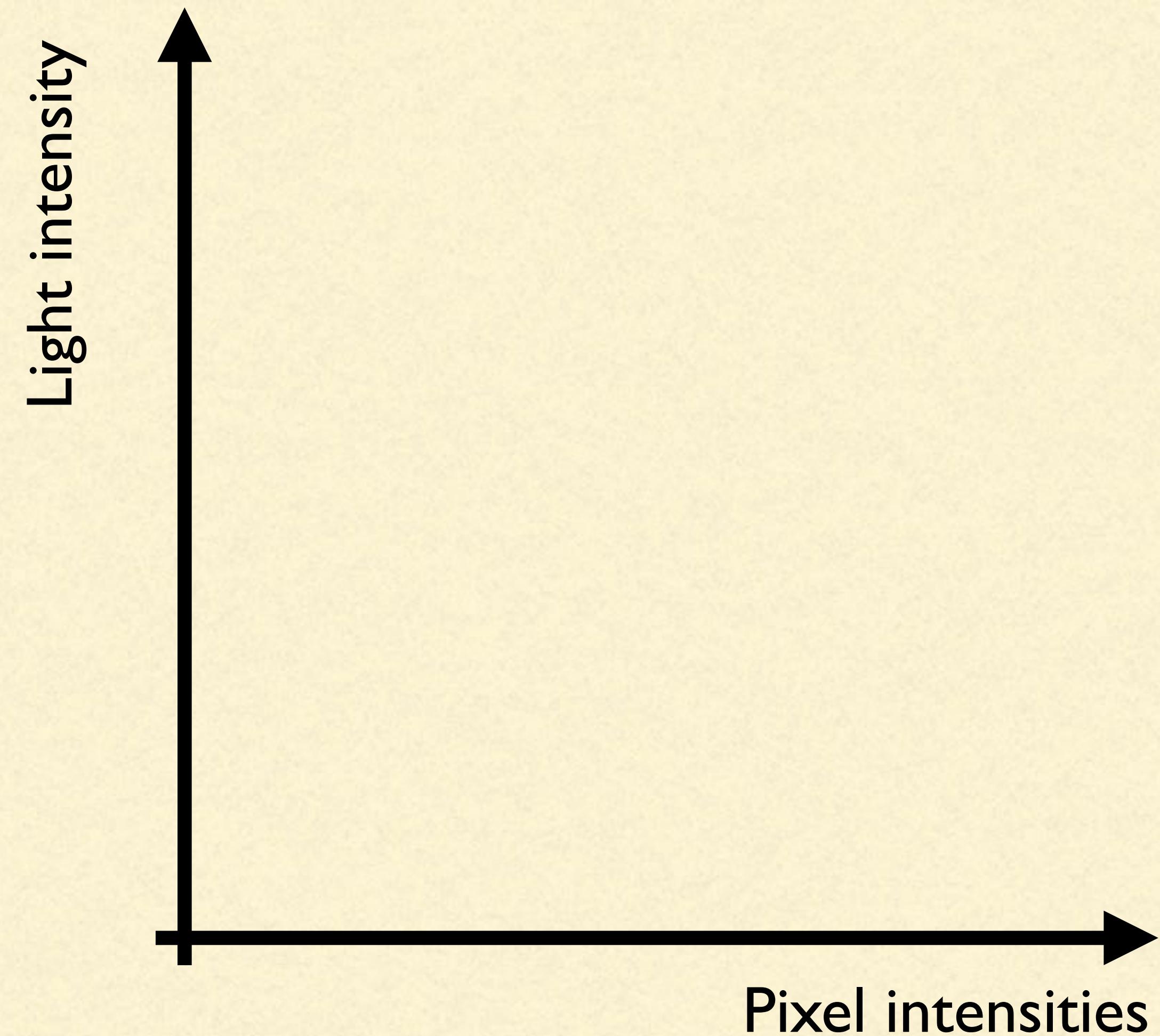
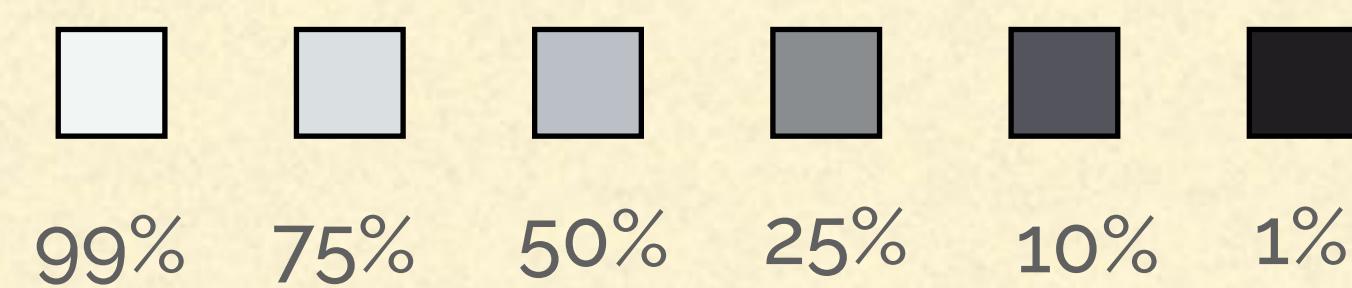
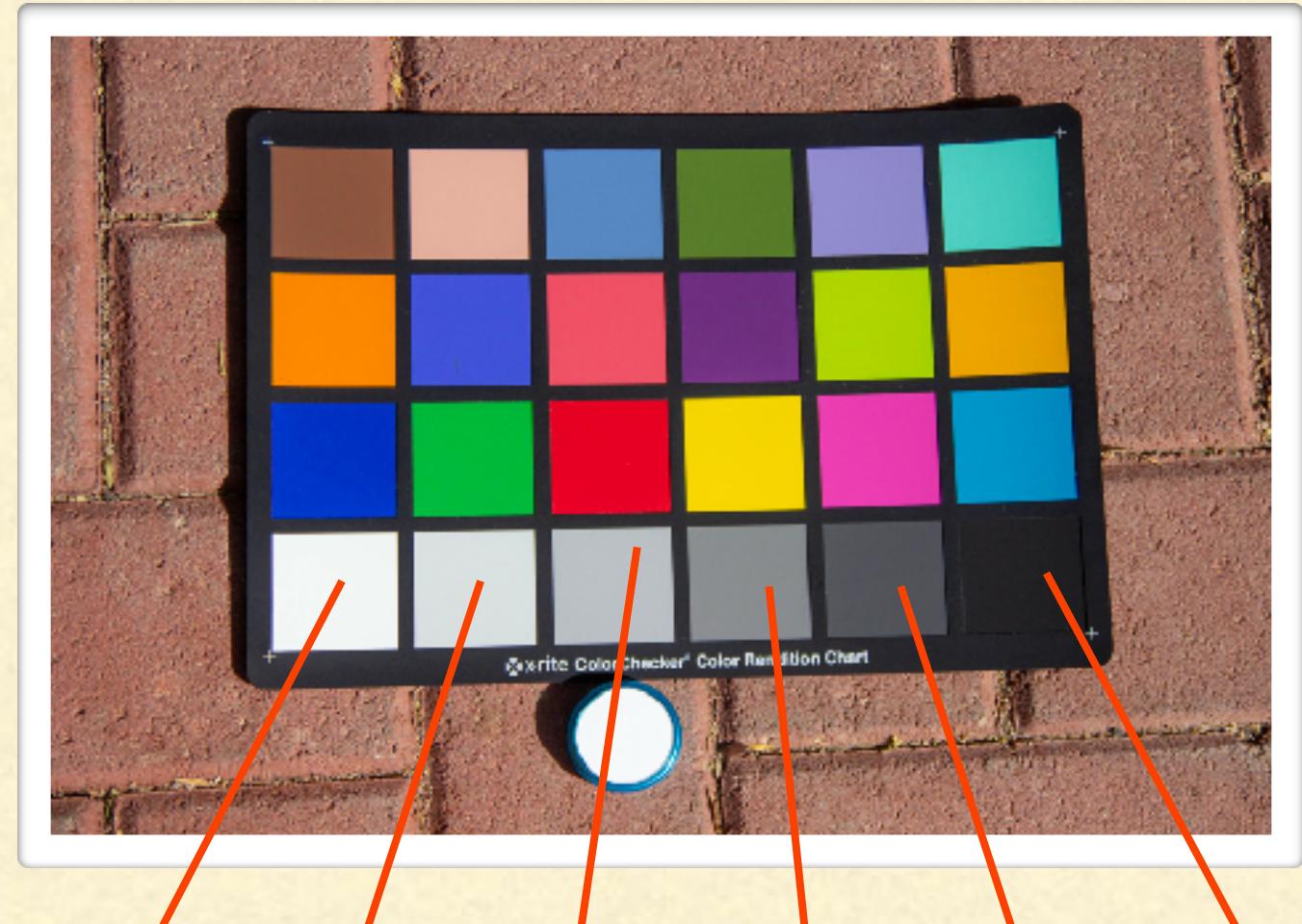
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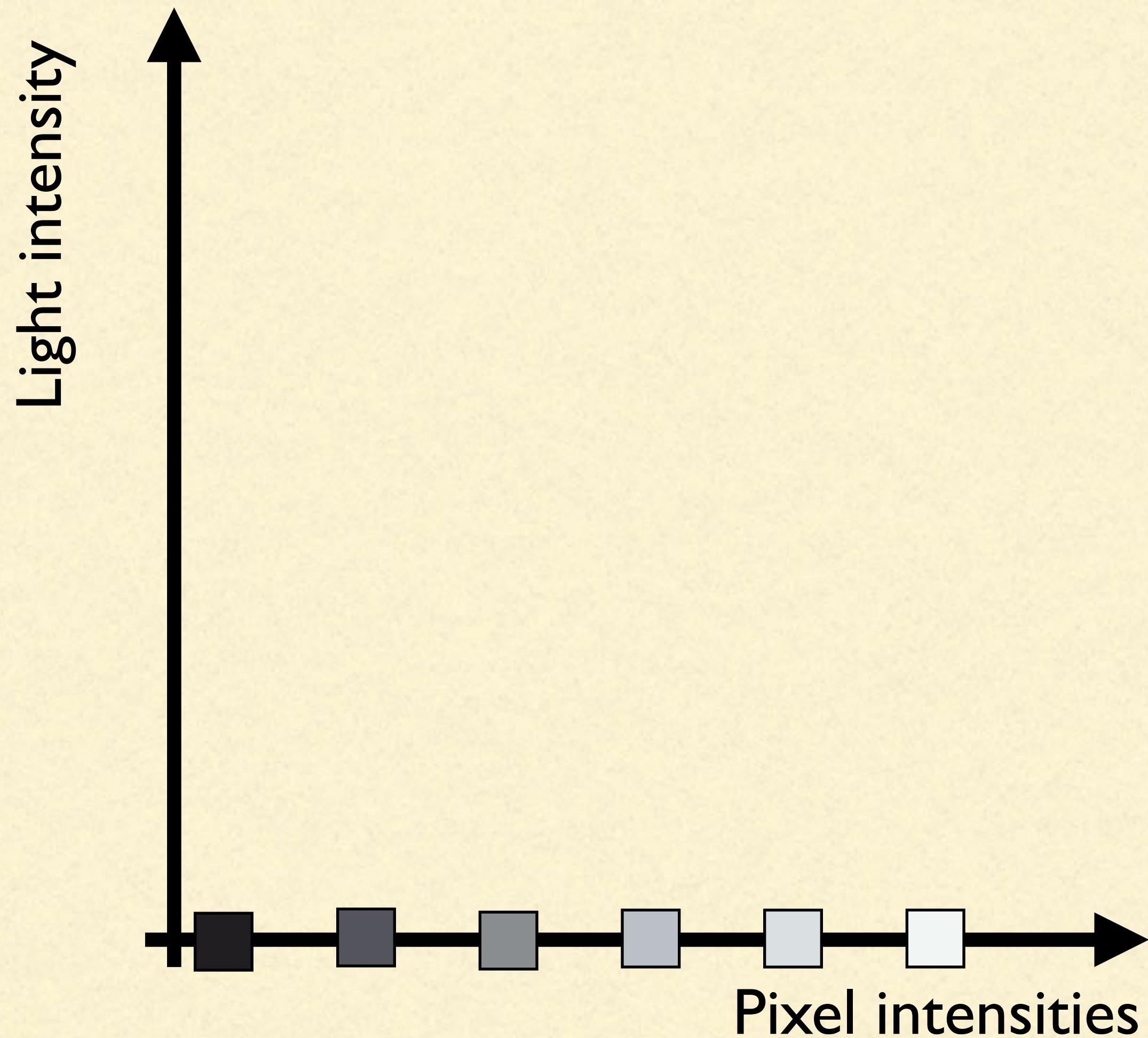
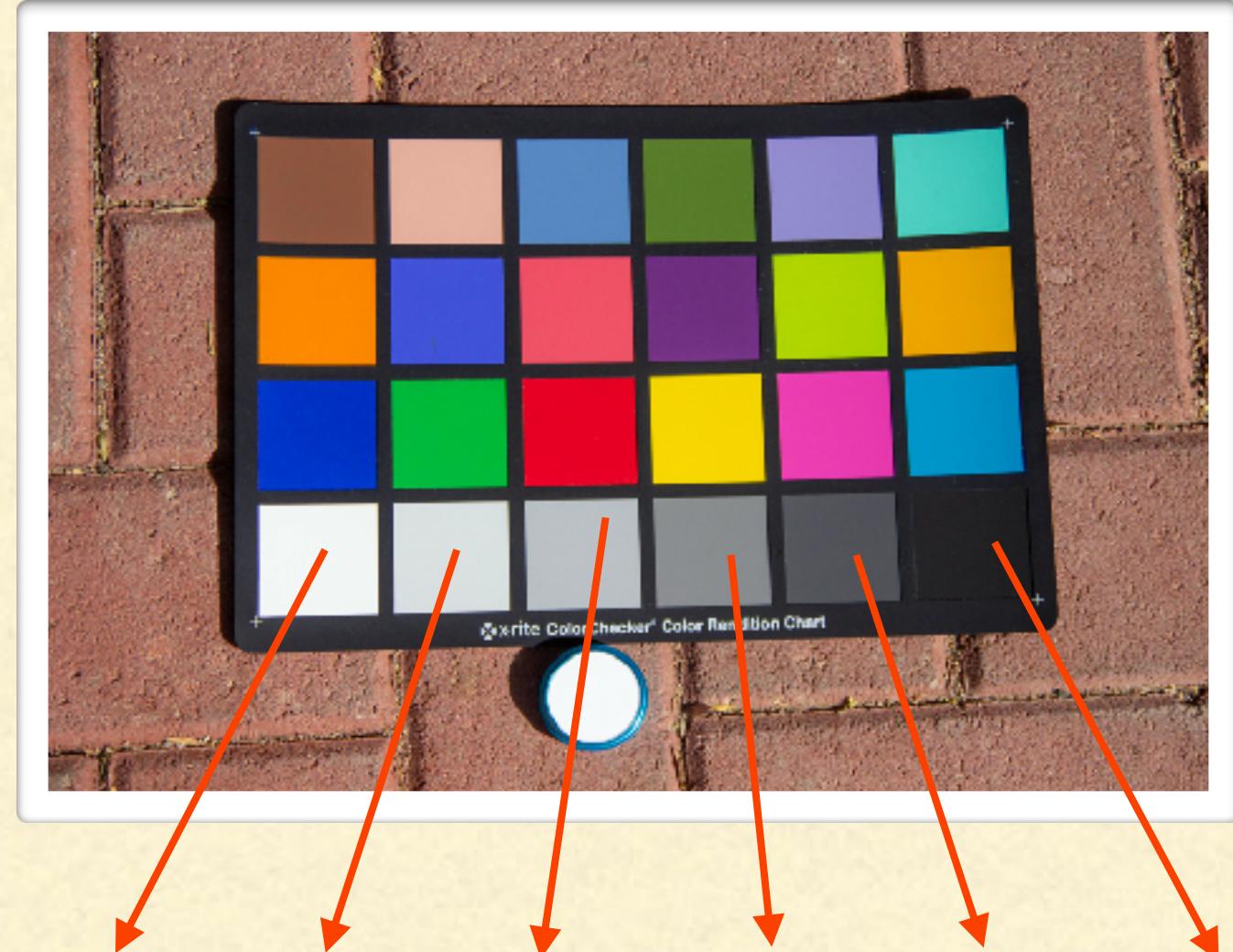
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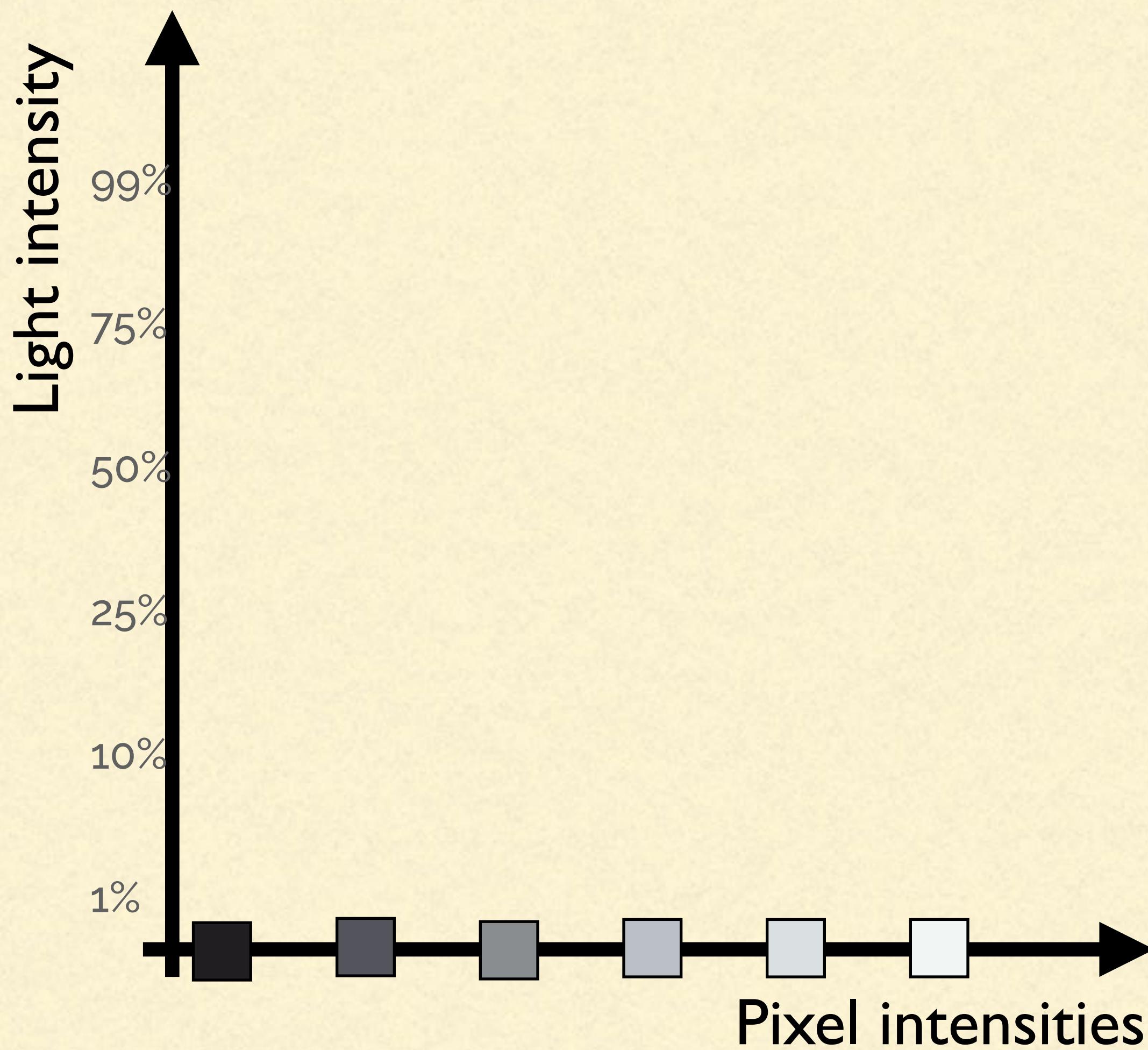
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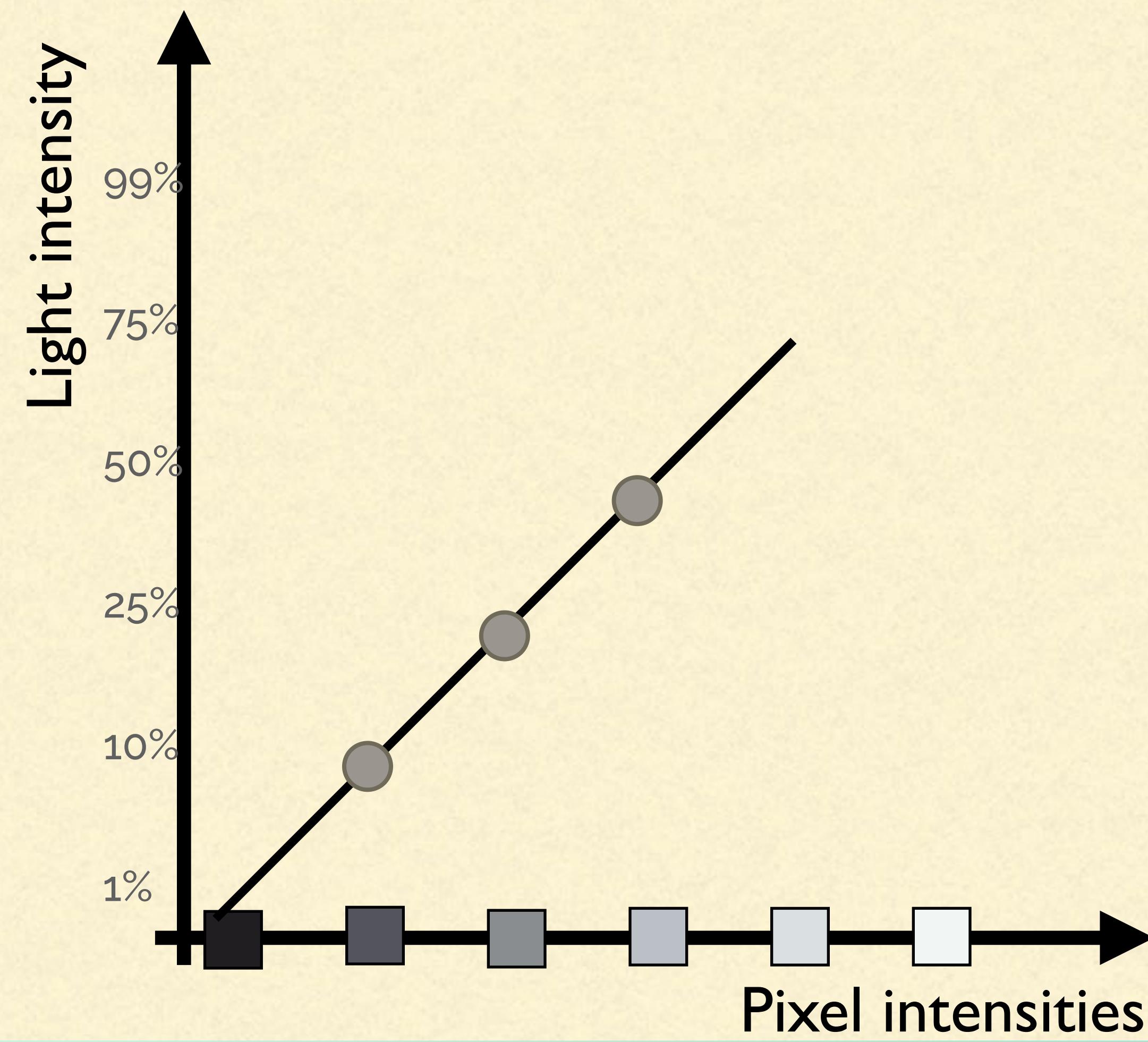
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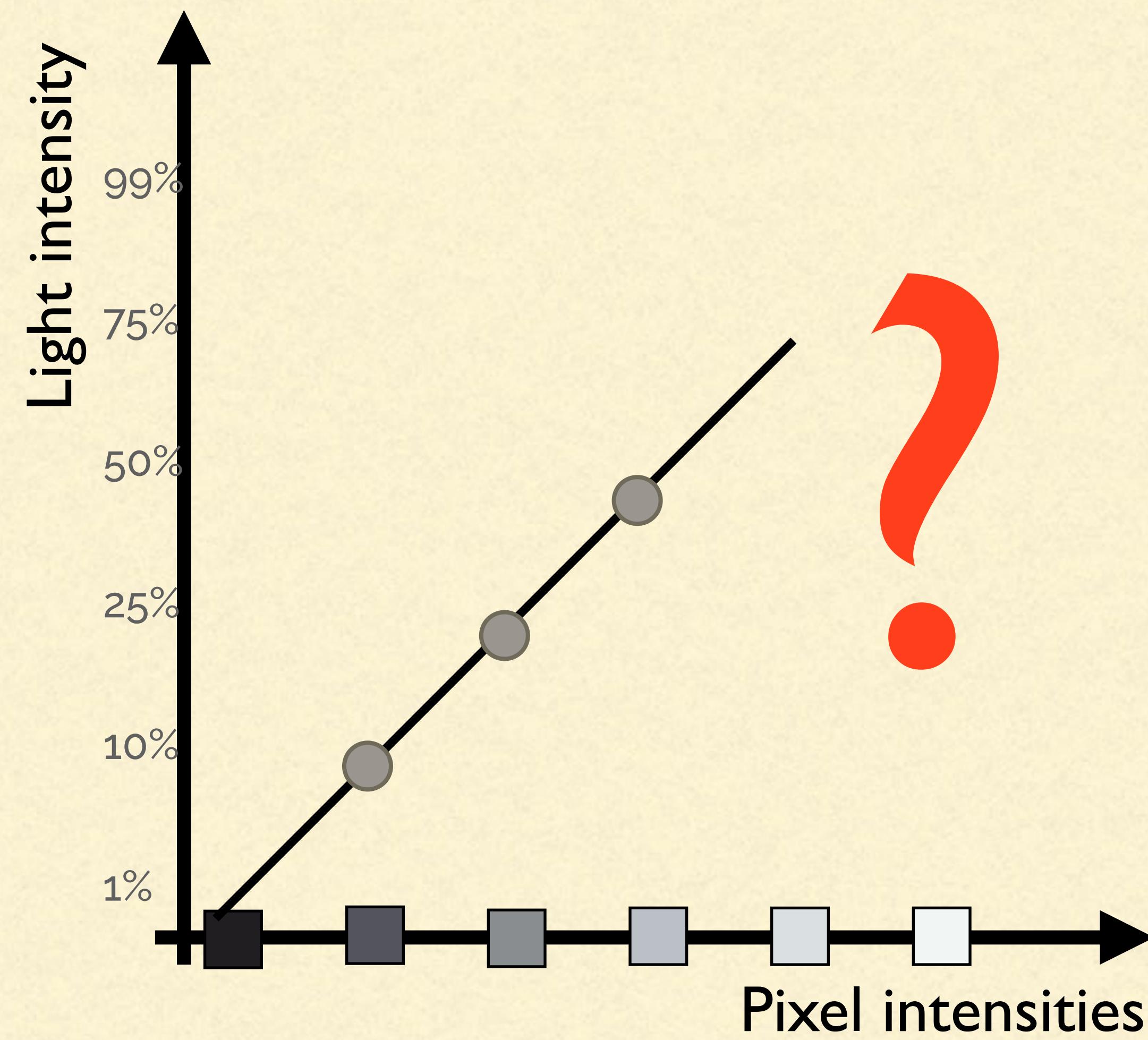
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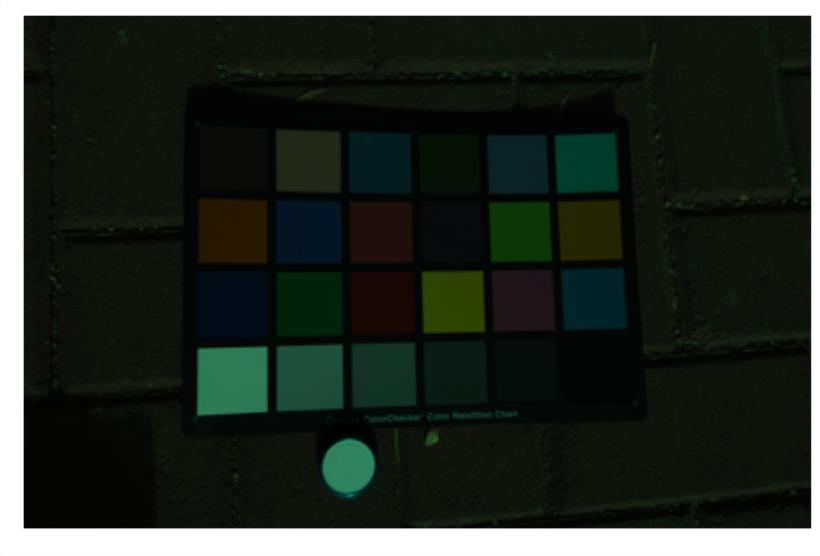
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Linear vs Non-Linear Images

For color-based science, we can only use linear images!

	PROS	CONS
RAW (LINEAR) IMAGE		
JPG (NON-LINEAR) IMAGE		

Linear vs Non-Linear Images

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	PROS	CONS
RAW (LINEAR) IMAGE	<ul style="list-style-type: none">• Scientifically usable	
JPG (NON-LINEAR) IMAGE		

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	PROS	CONS
RAW (LINEAR) IMAGE 	<ul style="list-style-type: none">Scientifically usable	<ul style="list-style-type: none">Colors in the camera's unique color space
JPG (NON-LINEAR) IMAGE 		

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	PROS	CONS
RAW (LINEAR) IMAGE 	<ul style="list-style-type: none">Scientifically usable	<ul style="list-style-type: none">Colors in the camera's unique color spaceDark, low-contrast
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JPG (NON-LINEAR) IMAGE	<ul style="list-style-type: none">Colors in a standard color space	

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JPG (NON-LINEAR) IMAGE	<ul style="list-style-type: none">Colors in a standard color spaceBright, vivid colors, high contrast	

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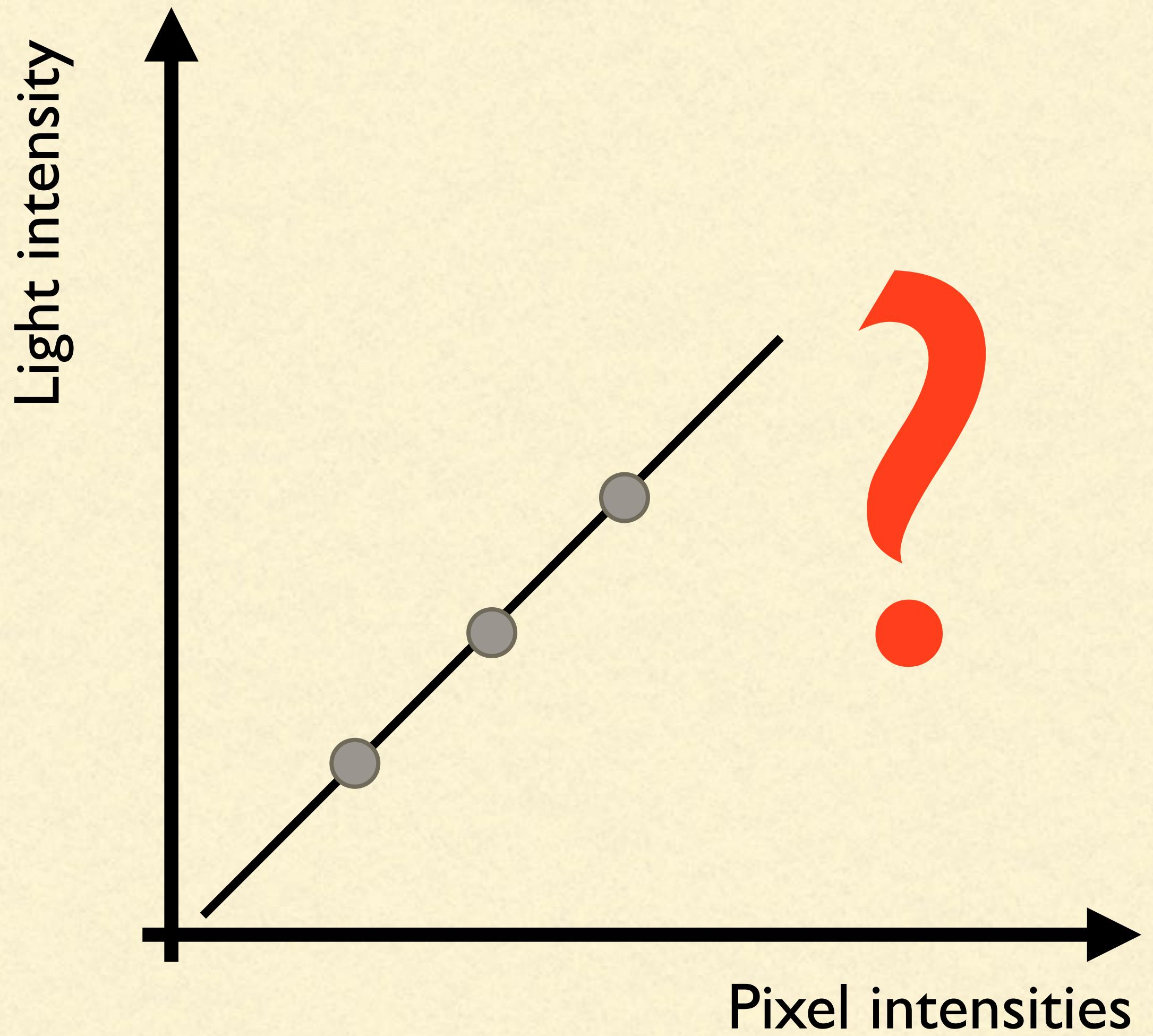
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JPG (NON-LINEAR) IMAGE	<ul style="list-style-type: none">Colors in a standard color spaceBright, vivid colors, high contrastCan be readily displayedVisually pleasingNo calibration needed, ready to shareSmall file size 	<ul style="list-style-type: none">Scientifically meaningless

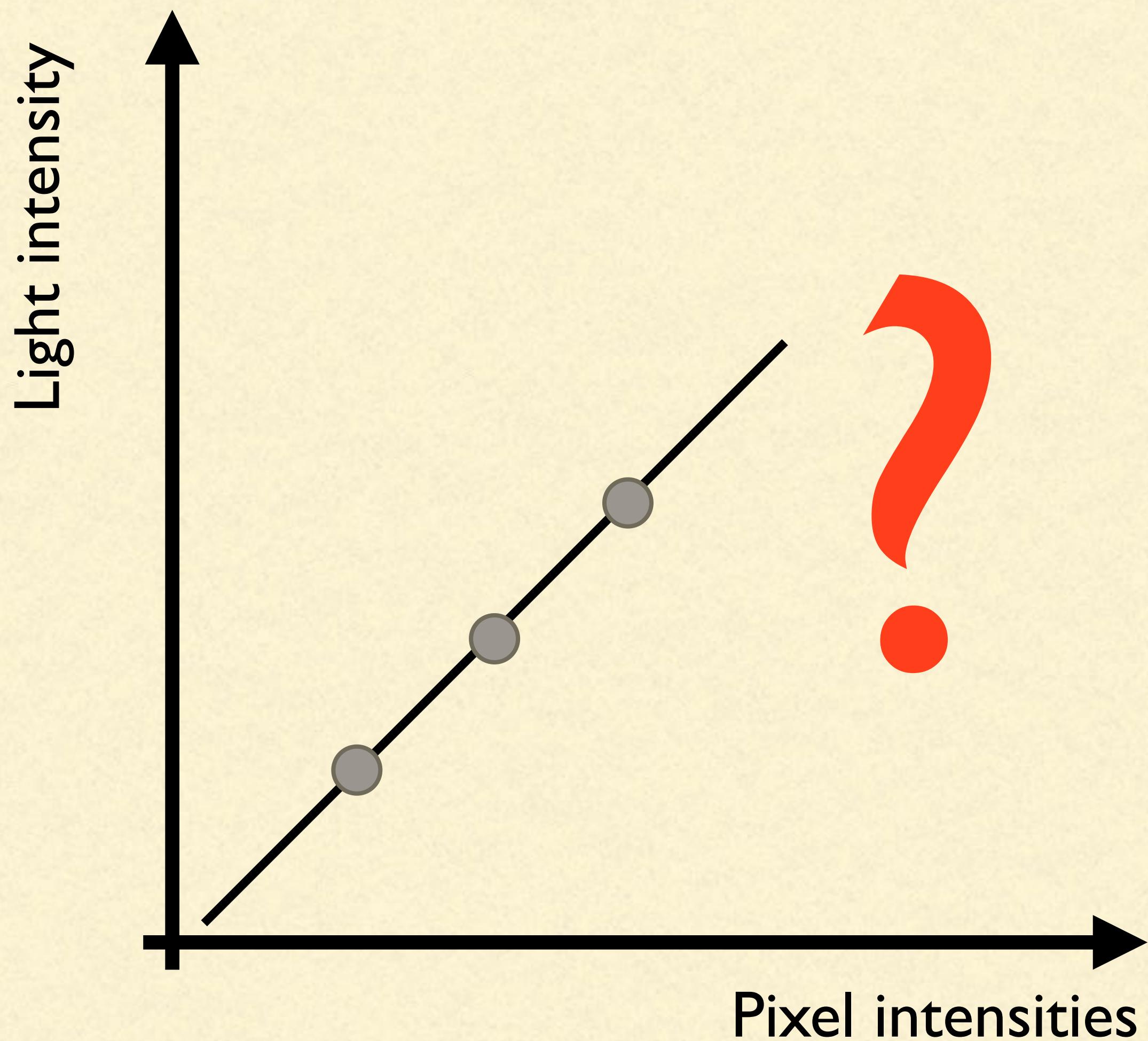
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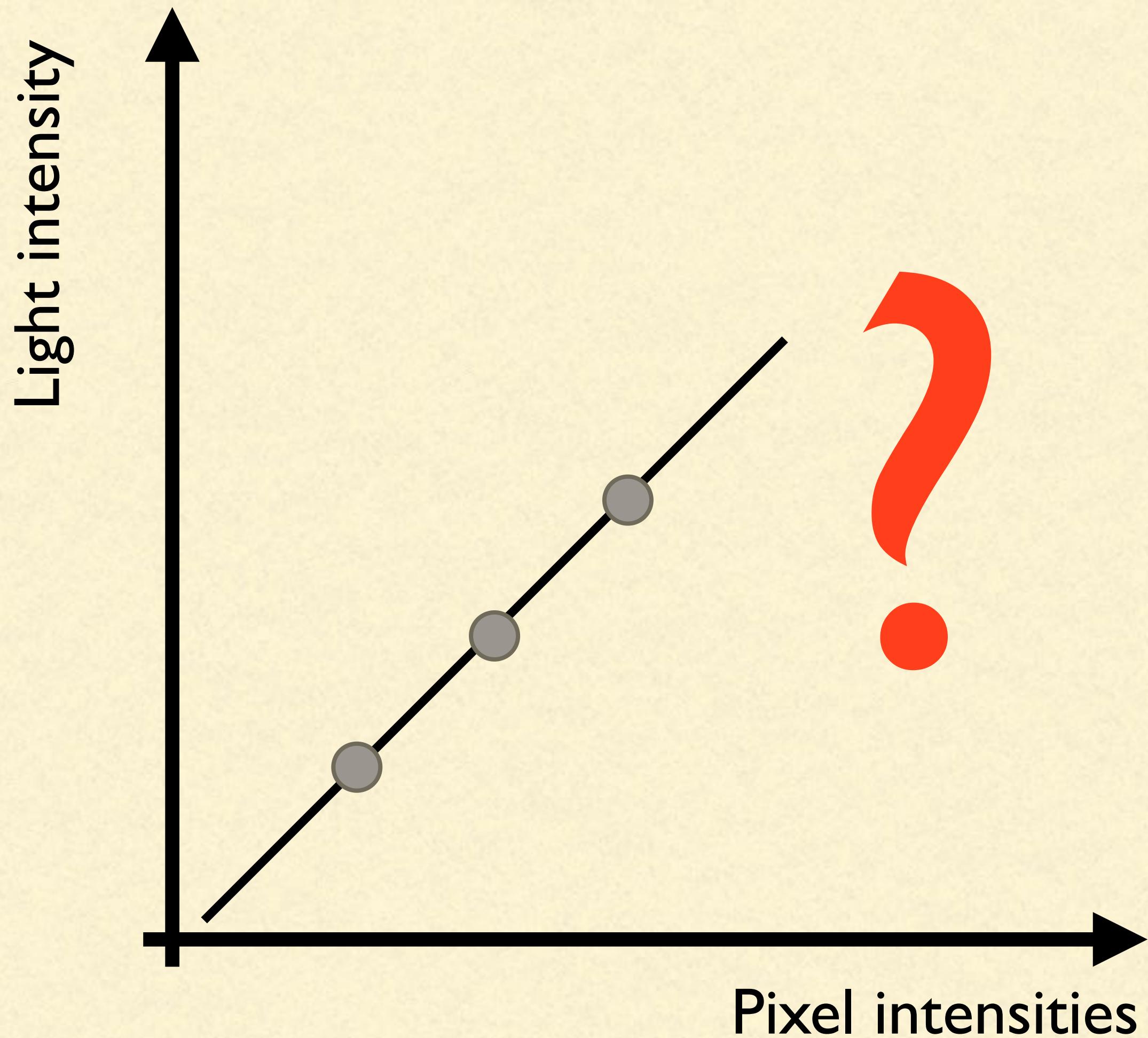
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- ▶ If the response is linear:

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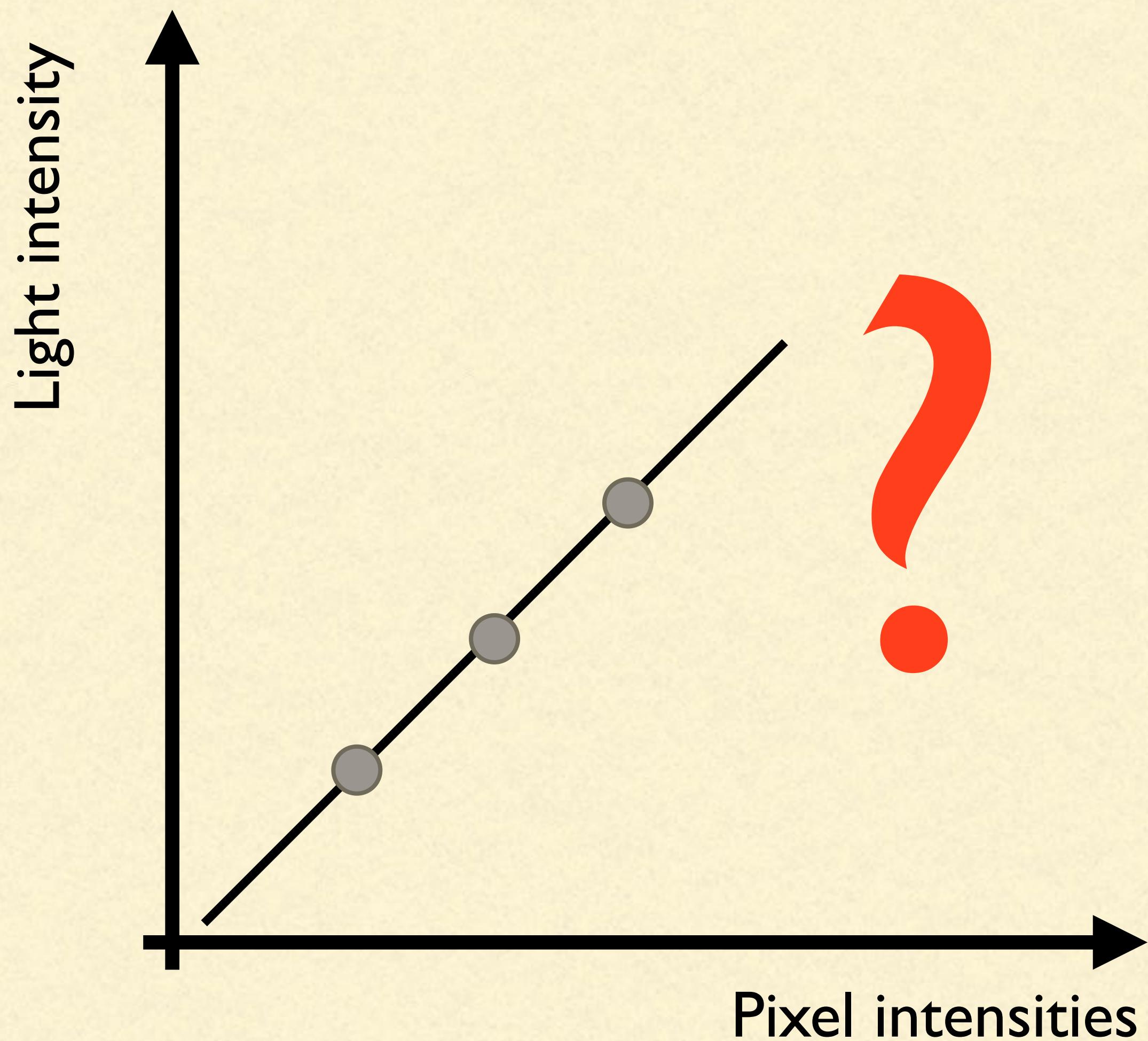
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- ▶ If the response is linear:
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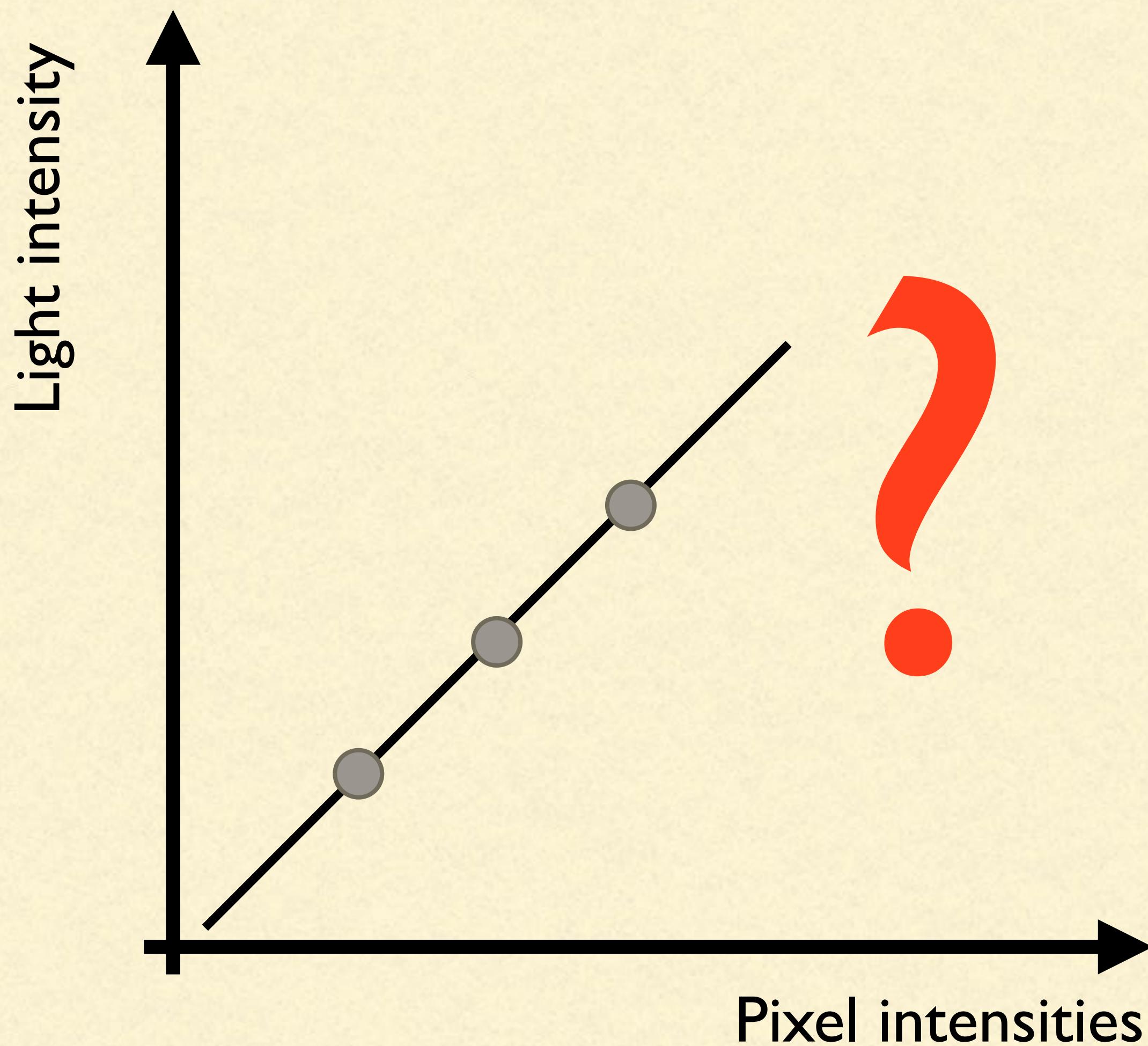
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target under sunlight

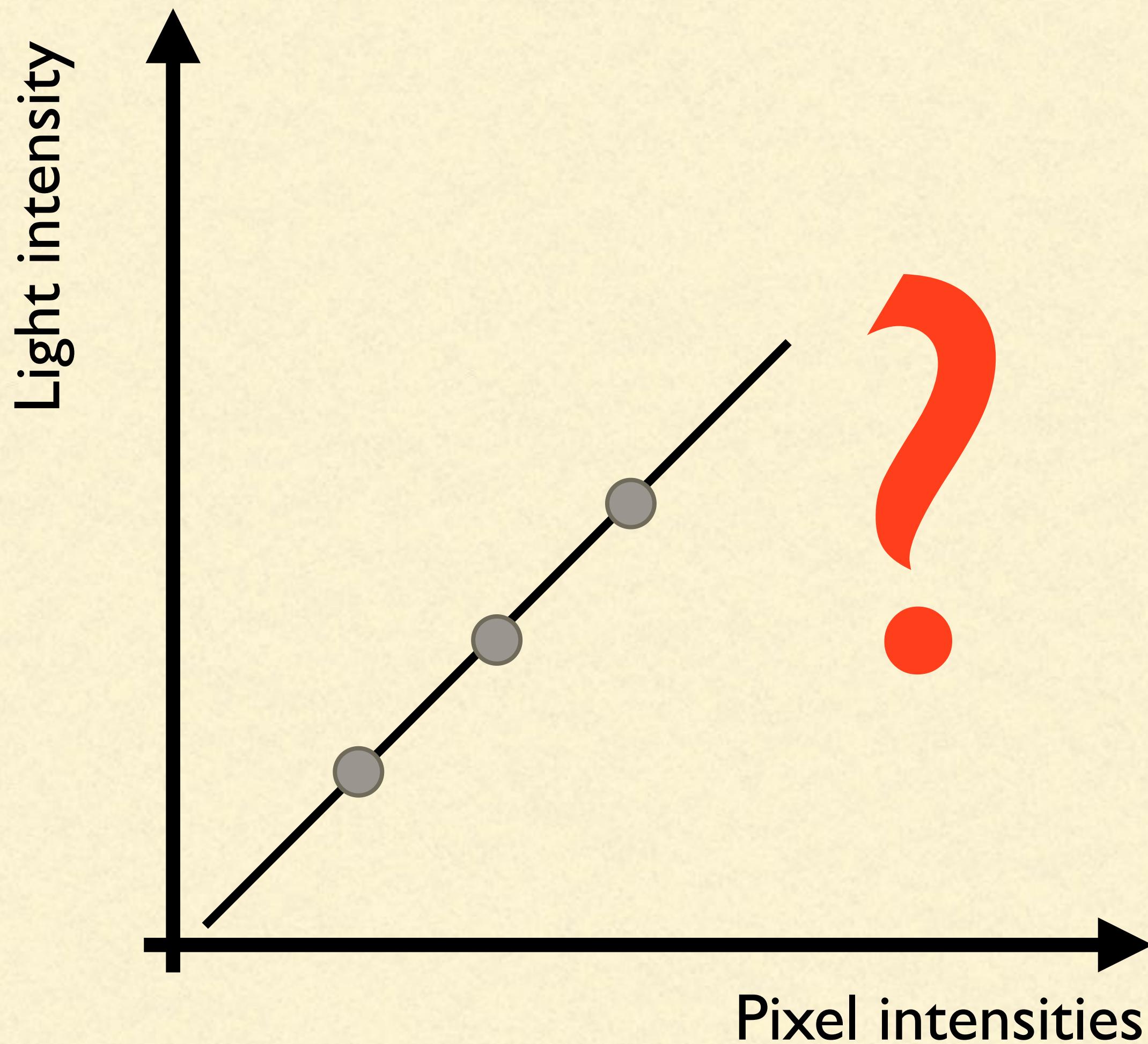
How To Check Linearity of an Image



- ▶ If the response is linear: 
- ▶ We can use this camera for science
- ▶ If the response is not linear:

To check linearity,
take a raw photo of a
high-quality color
target under sunlight

How To Check Linearity of an Image

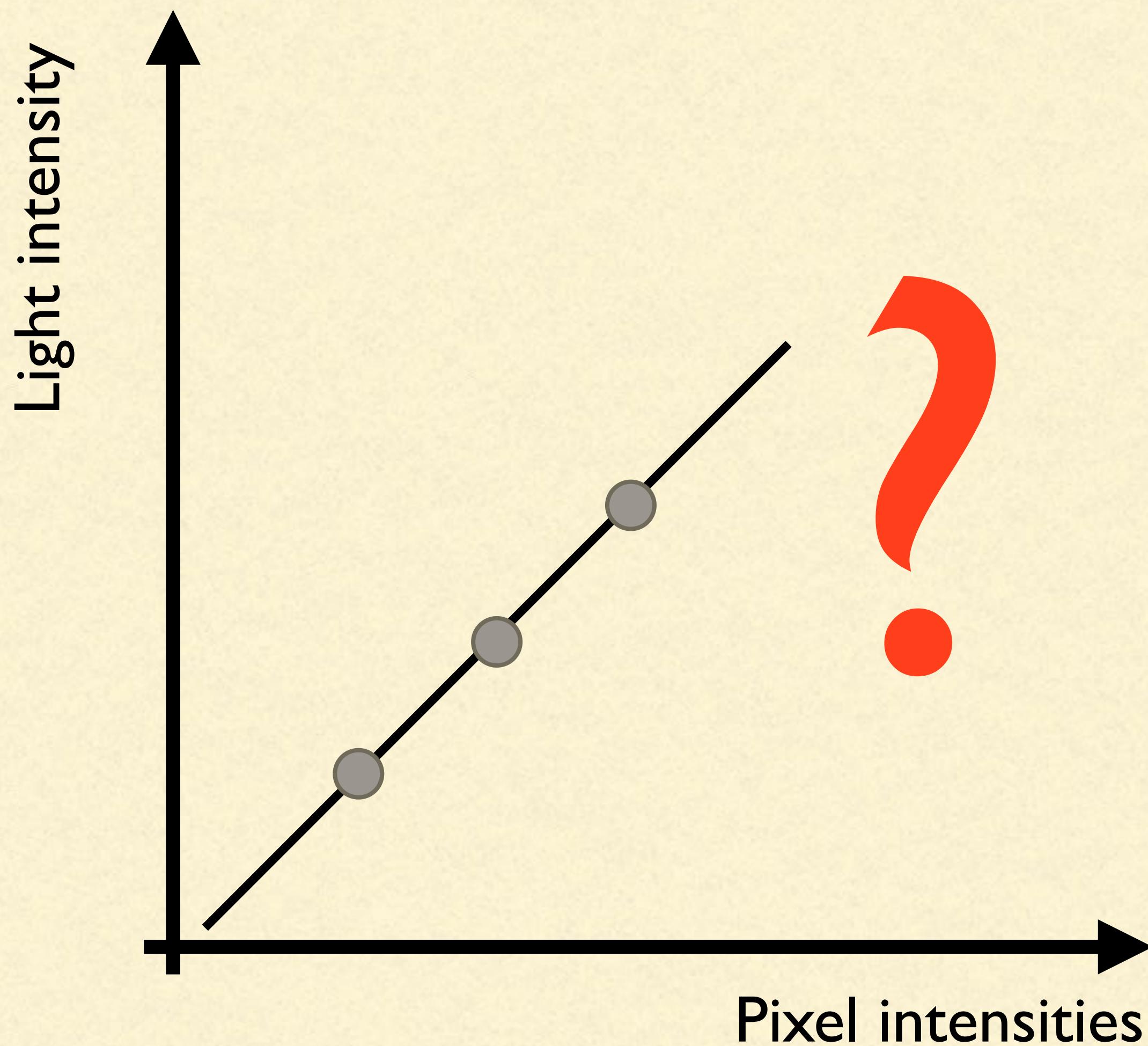


- ▶ If the response is linear: 
- ▶ We can use this camera for science
- ▶ If the response is not linear:
- ▶ We can linearize the response (but that can create more problems than it solves)



To check linearity,
take a raw photo of a
high-quality color
target under sunlight

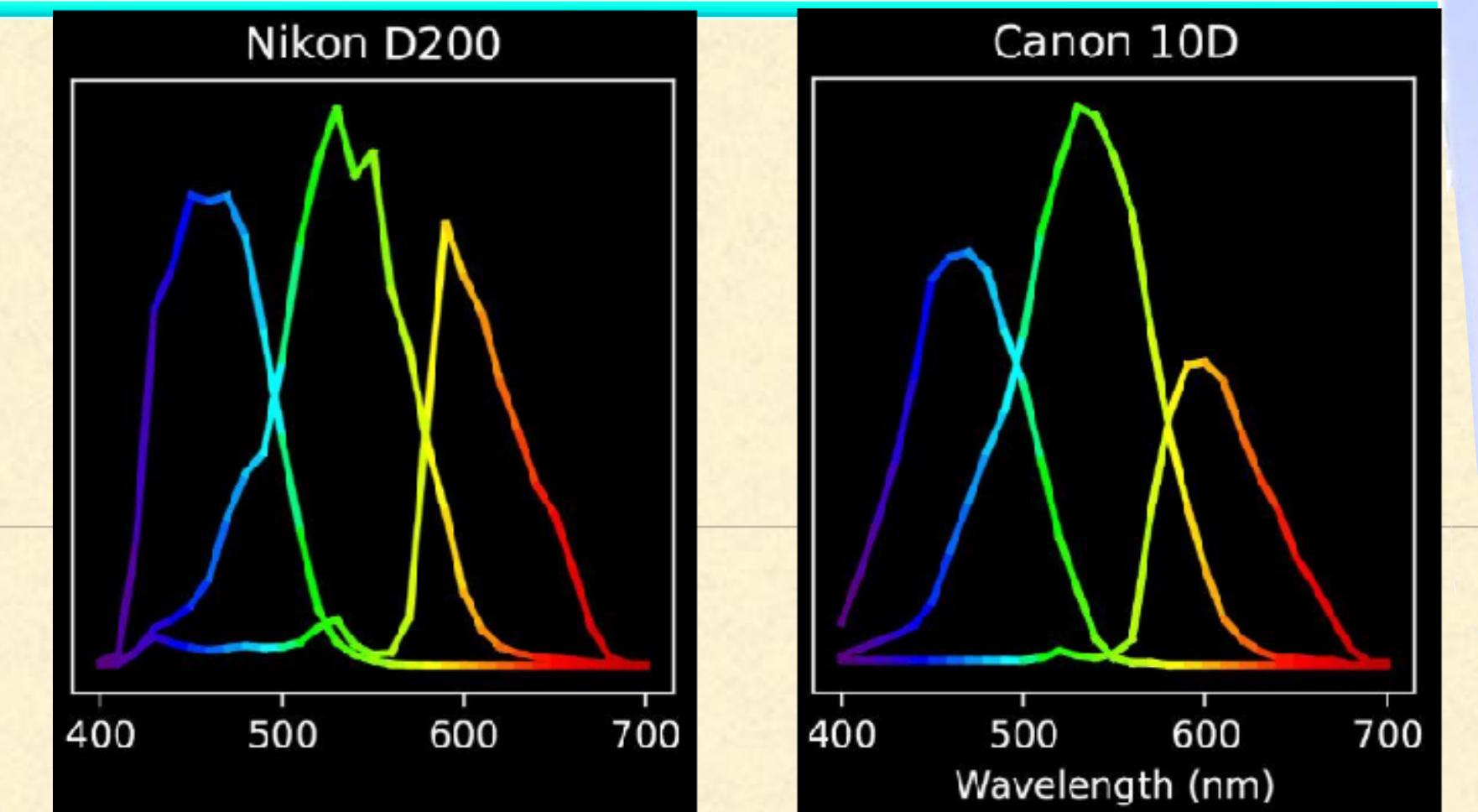
How To Check Linearity of an Image



- ▶ If the response is linear: 
- ▶ We can use this camera for science
- ▶ If the response is not linear:
- ▶ We can linearize the response (but that can create more problems than it solves)
- ▶ We can use another camera :-)

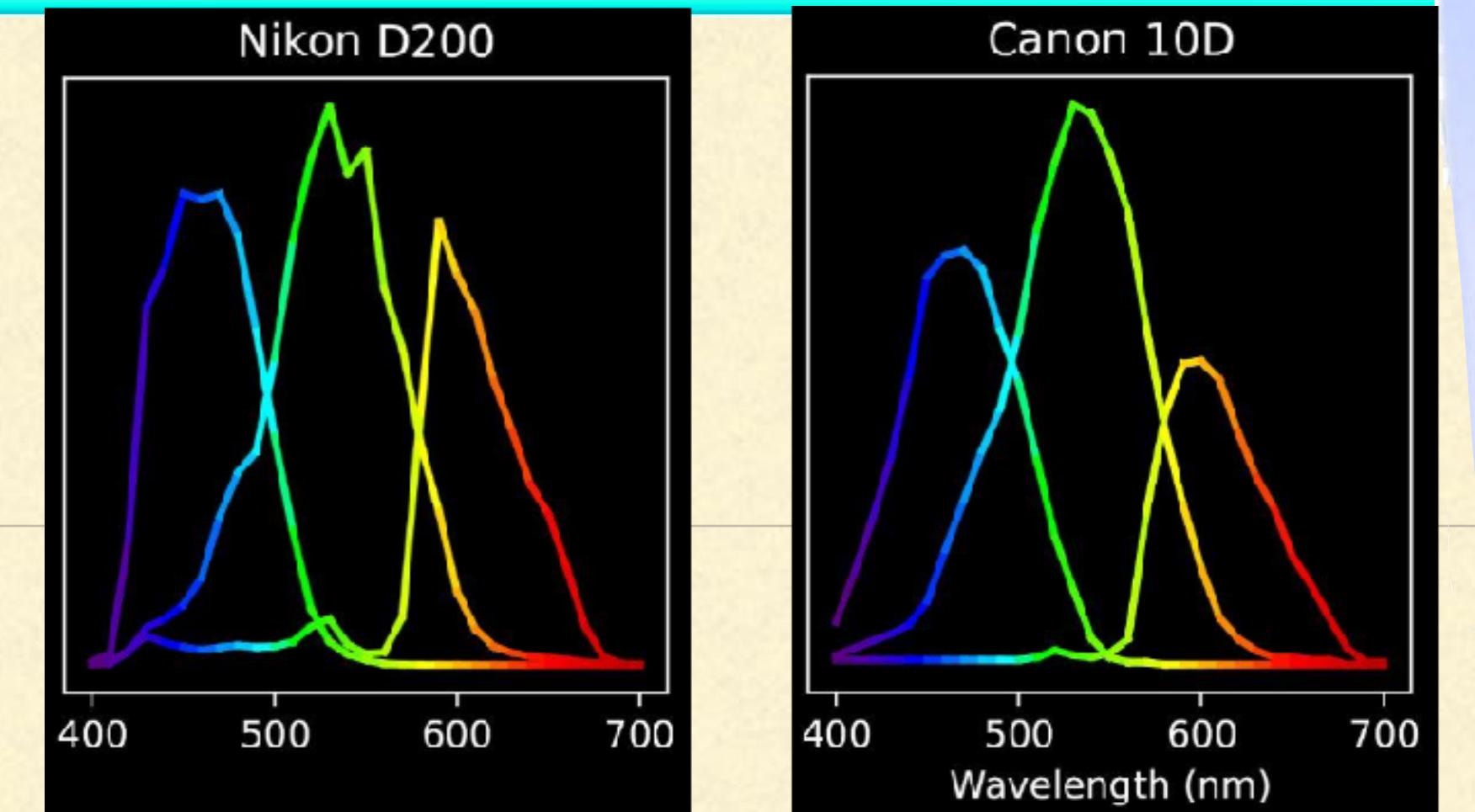


RAW Image Manipulation



We can only use RAW images for color-based science, and they need some processing.

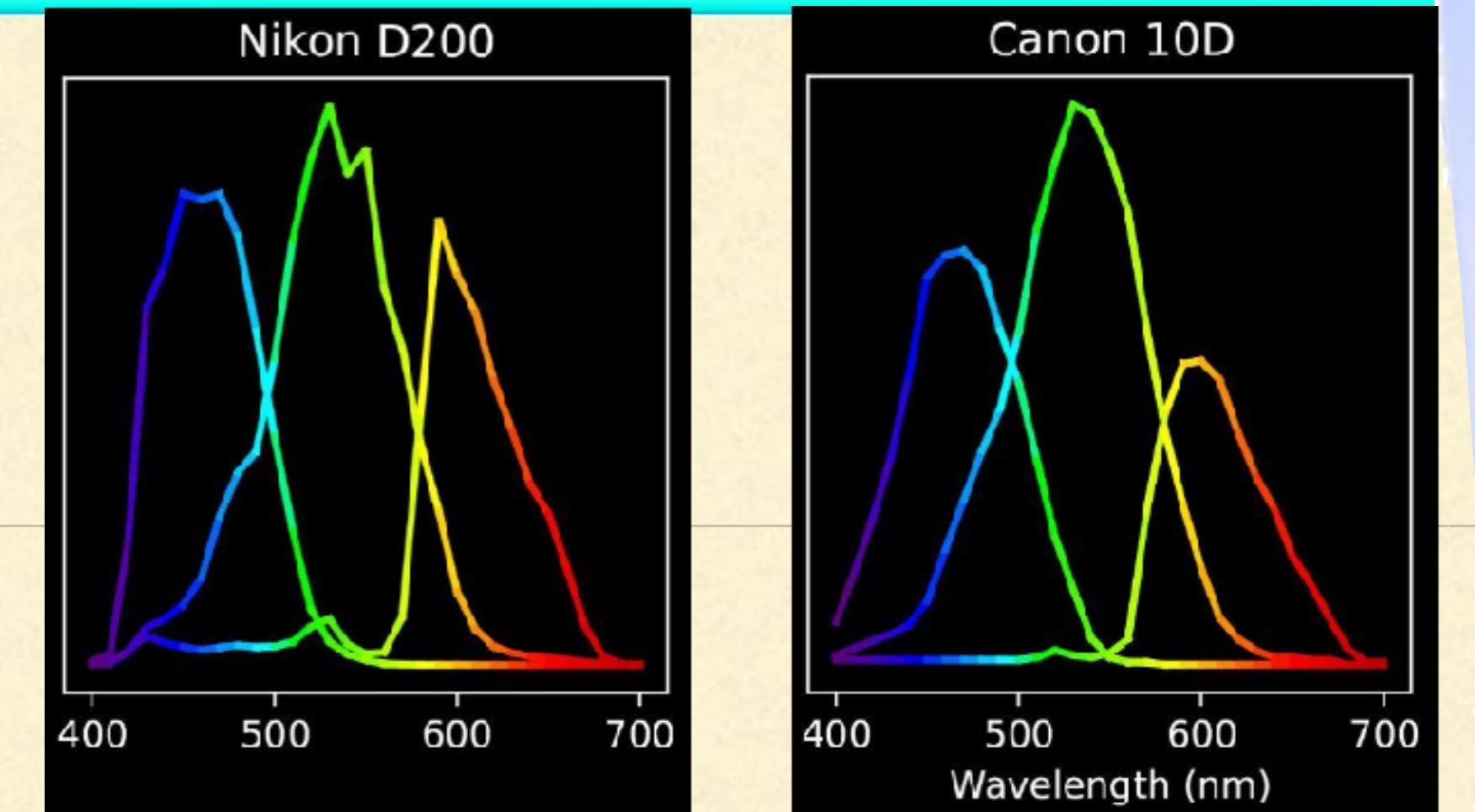
RAW Image Manipulation



- ▶ Each camera captures colors differently !

We can only use RAW images for color-based science, and they need some processing.

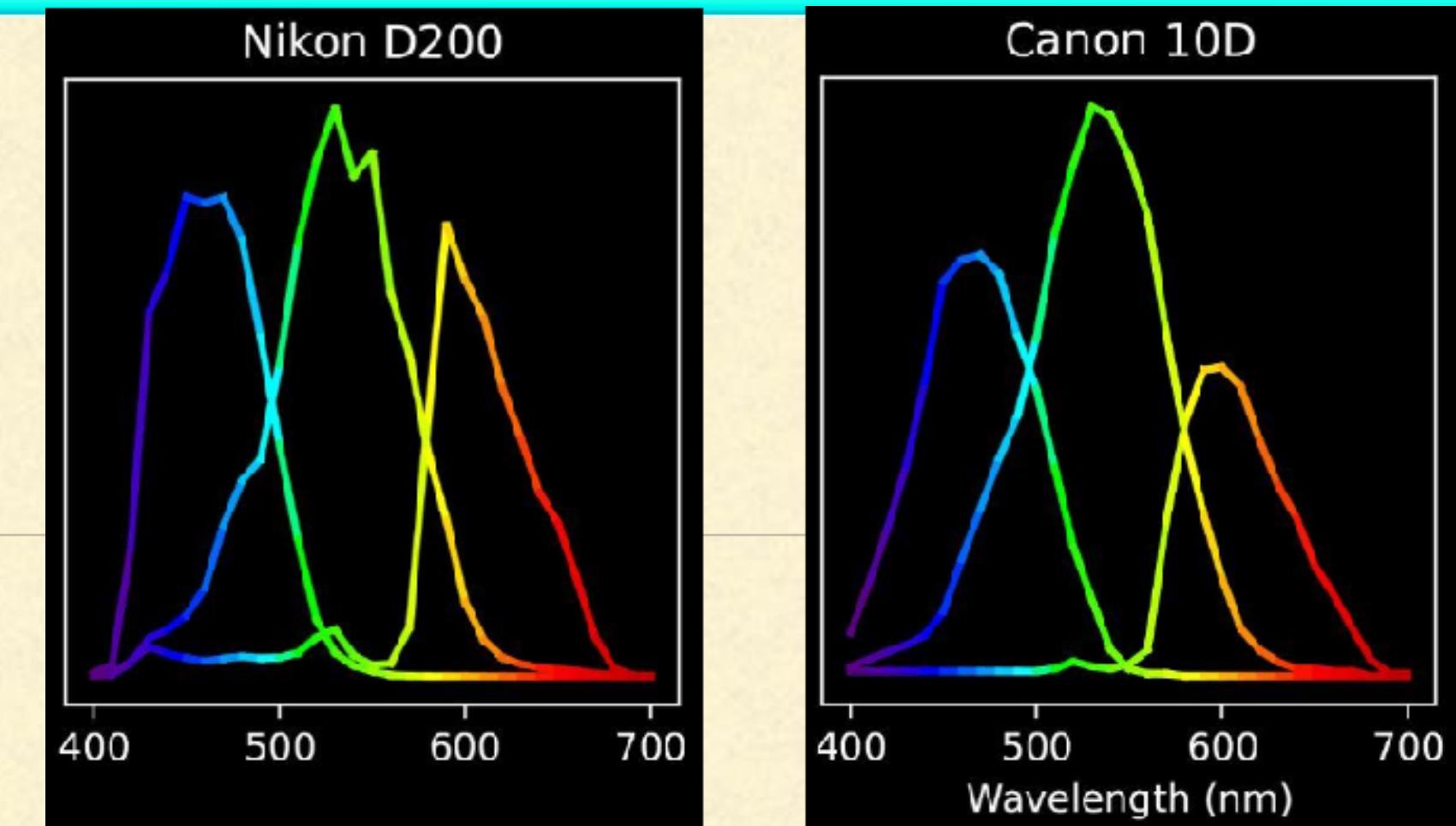
RAW Image Manipulation



We can only use RAW images for color-based science, and they need some processing.

- ▶ Each camera captures colors differently !
- ▶ RAW images cannot immediately be displayed, used, or directly compared to images from other cameras.

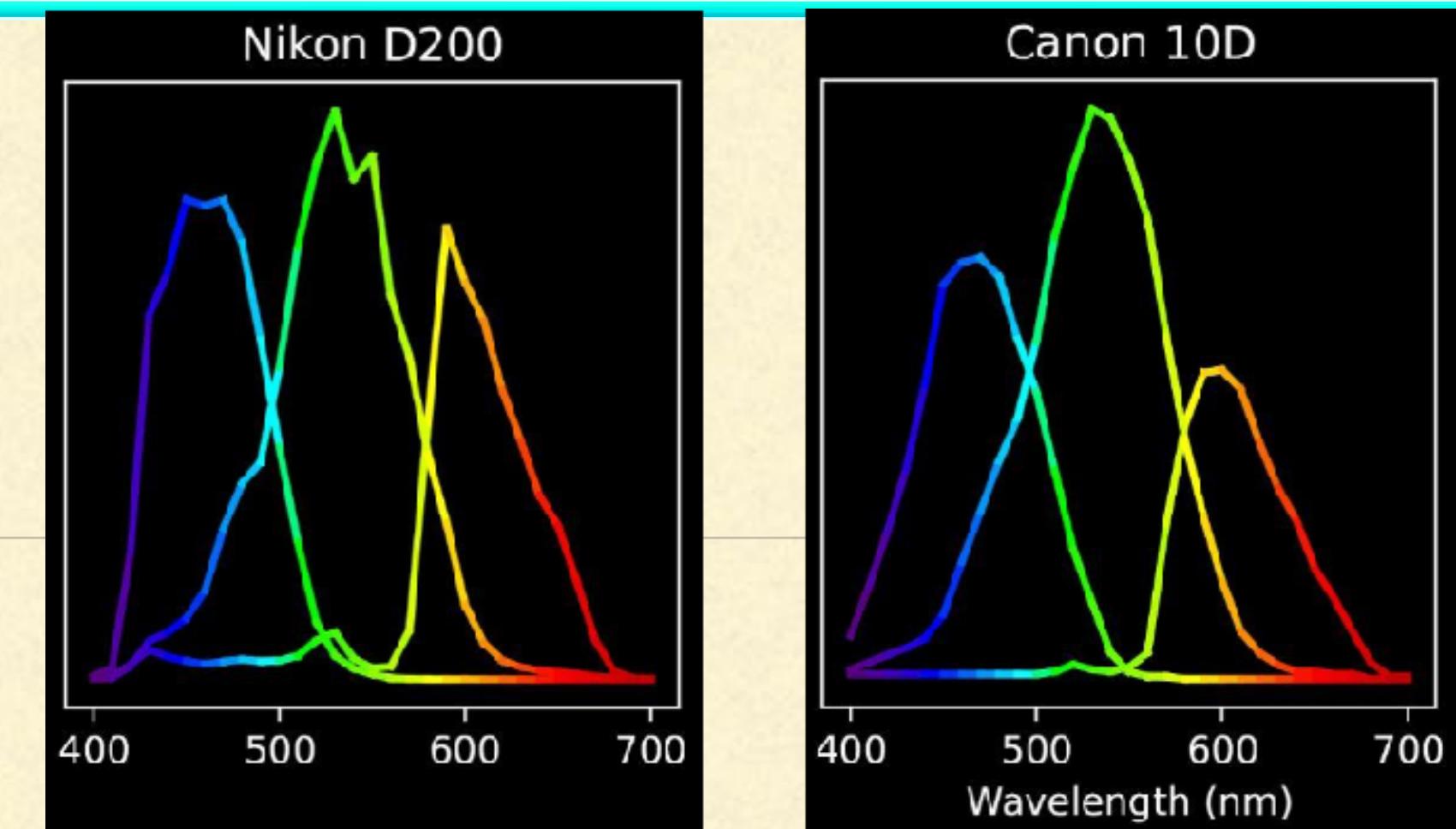
RAW Image Manipulation



We can only use RAW images for color-based science, and they need some processing.

- ▶ Each camera captures colors differently !
- ▶ RAW images cannot immediately be displayed, used, or directly compared to images from other cameras.
- ▶ Effort is needed to convert RAW images to an image format we can manipulate (e.g., tiff), then to a standard color space (e.g., sRGB).

RAW Image Manipulation



We can only use RAW images for color-based science, and they need some processing.

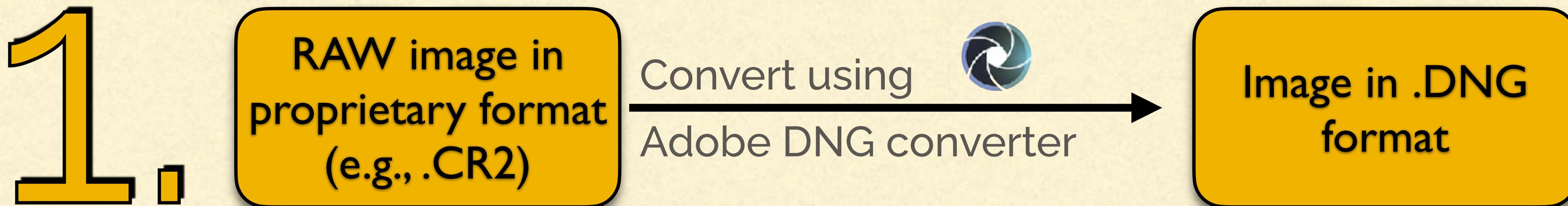
- ▶ Each camera captures colors differently !
- ▶ RAW images cannot immediately be displayed, used, or directly compared to images from other cameras.
- ▶ Effort is needed to convert RAW images to an image format we can manipulate (e.g., tiff), then to a standard color space (e.g., sRGB).
- ▶ Processing RAW images needs an understanding of image formation and some programming skills.

RAW Image Manipulation Workflow

1.



RAW Image Manipulation Workflow



RAW Image Manipulation Workflow

1.

RAW image in
proprietary format
(e.g., .CR2)

Convert using
Adobe DNG converter

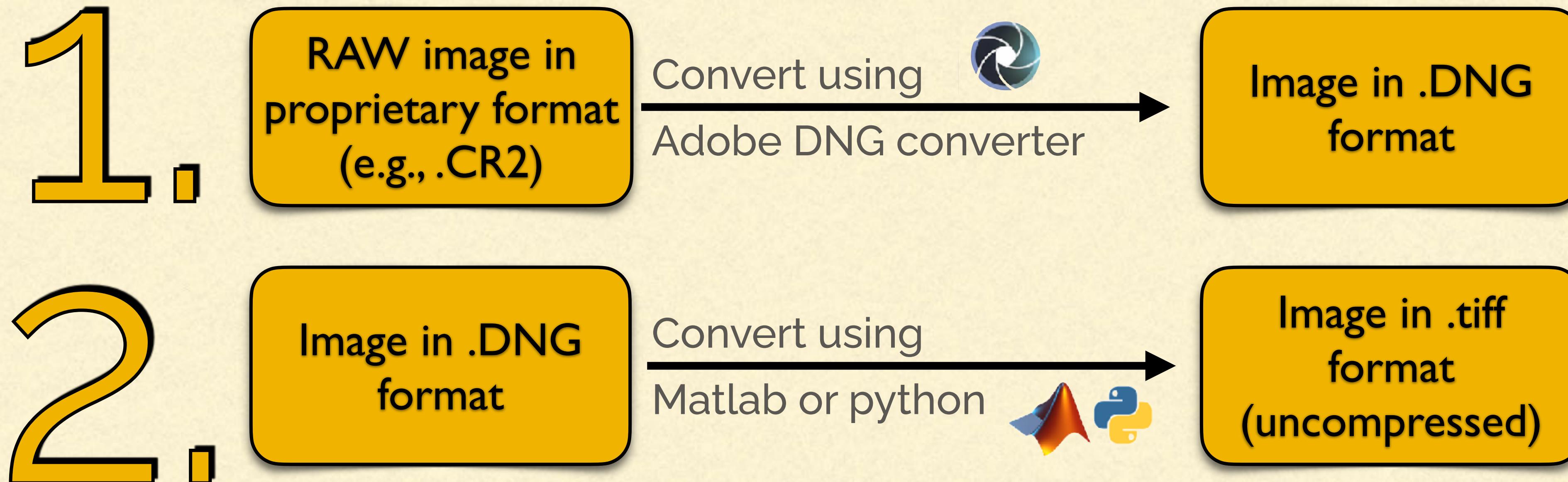


Image in .DNG
format

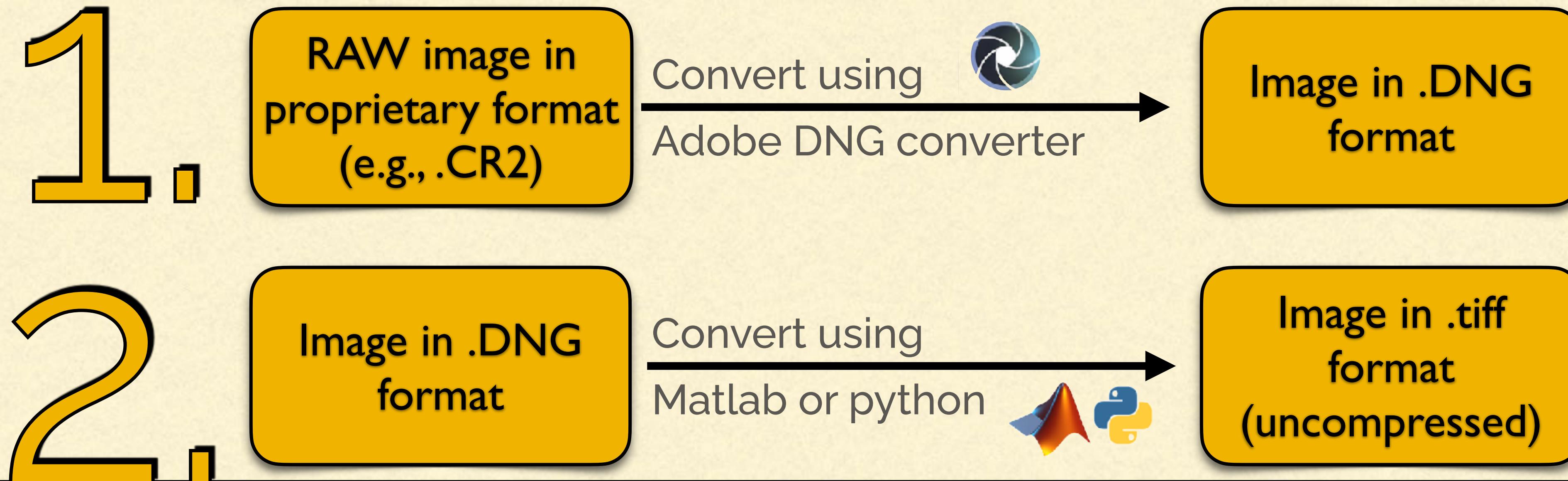
2.



RAW Image Manipulation Workflow



RAW Image Manipulation Workflow



(Optional: If you don't have enough compute power)

RAW Image Manipulation Workflow

1.

RAW image in
proprietary format
(e.g., .CR2)

Convert using
Adobe DNG converter



Image in .DNG
format

2.

Image in .DNG
format

Convert using
Matlab or python

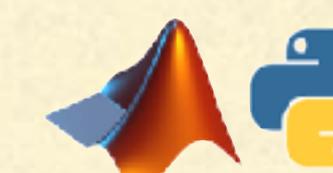


Image in .tiff
format
(uncompressed)

3.

(Optional: If you don't have enough compute power)



RAW Image Manipulation Workflow

1.

RAW image in
proprietary format
(e.g., .CR2)

Convert using
Adobe DNG converter



Image in .DNG
format

2.

Image in .DNG
format

Convert using
Matlab or python

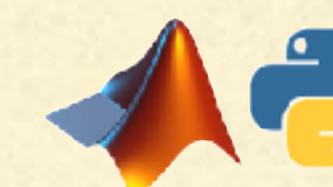


Image in .tiff
format
(uncompressed)

(Optional: If you don't have enough compute power)

3.

Image in .tiff
format
(uncompressed)

Resize using
Matlab or python

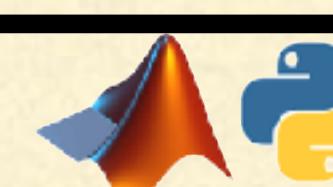
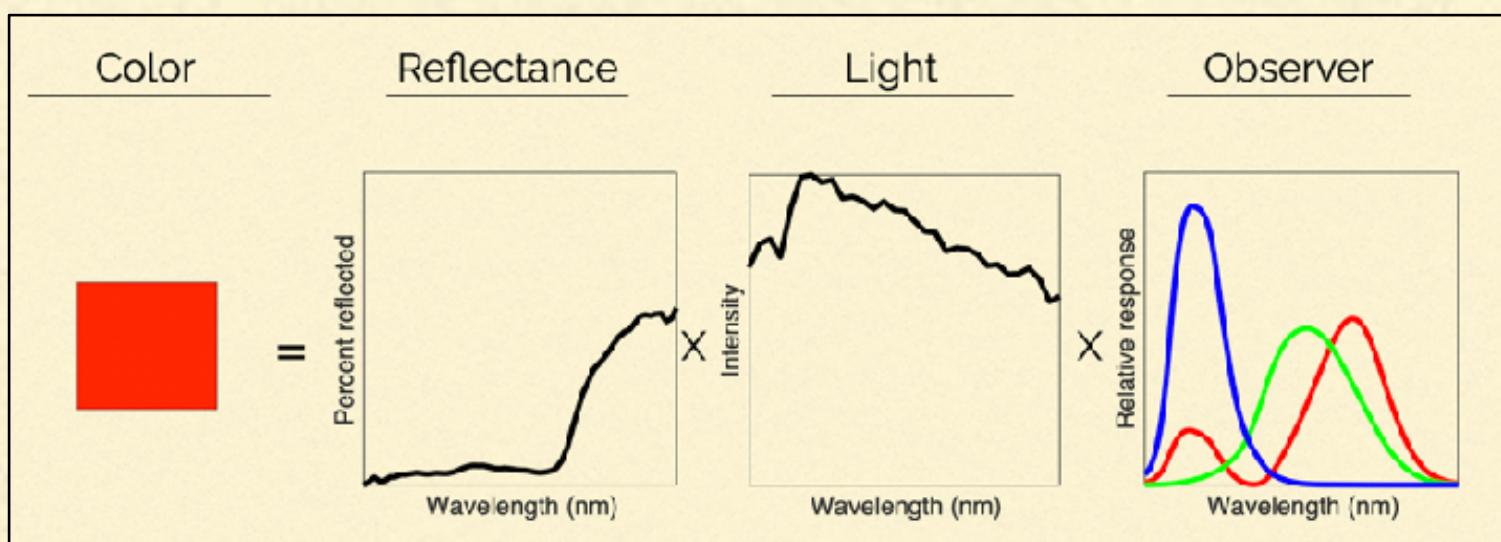
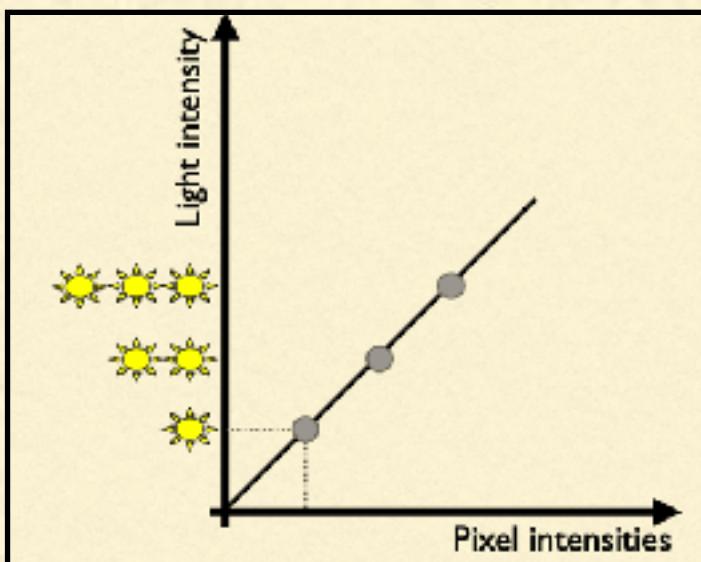


Image in .png
format (losslessly
compressed)

LAB: RAW Image Manipulation & Basic Image Formation



1. Raw image → linear .tiff → linear .png
2. Check linearity of your image
3. Simulate image formation