lecture 25

image displays

- Weber/Fechner/Stevens Laws
- gamma encoding
- gamma correction
- display calibration
- limitations of 'global tone mapping operators' (eye candy)

Review: lectures 22, 23

We have discussed several physical aspects of displays.

- color
    - display can be either a projector or a monitor
    - spectrum of emitted light at each pixel is a weighted sum of RGB spectra
    - trichromacy and metamerism
    - anaglyph: 3D stereo displays

- dynamic range

    - high dynamic range (HDR) scenes and images,
    - tone mapping and low dynamic range (LDR) displays

Today, we will concentrate on the latter.

Review: Perceptual issues in Graphics

In many computer graphics techniques, we can get away with approximations without people noticing.
This allows us to save space and/or time.

Examples:

- level of detail (meshes lecture 11)

- shading (if X is smooth, then we can sample & interpolate)

- environment mapping
  (we are not able to judge the correctness of mirror reflections)

How can one quantify the differences that people can detect ?

Example: Intensity Discrimination

(a general problem in human perception)

- taste:
  - sweetness (# ml of sugar dissolved into water),
  - saltiness, spicyness, etc.

- hearing (dB)
  loudness, frequency

- touch
  - pressure, weight

- vision
  - brightness
  - hue
  - saturation

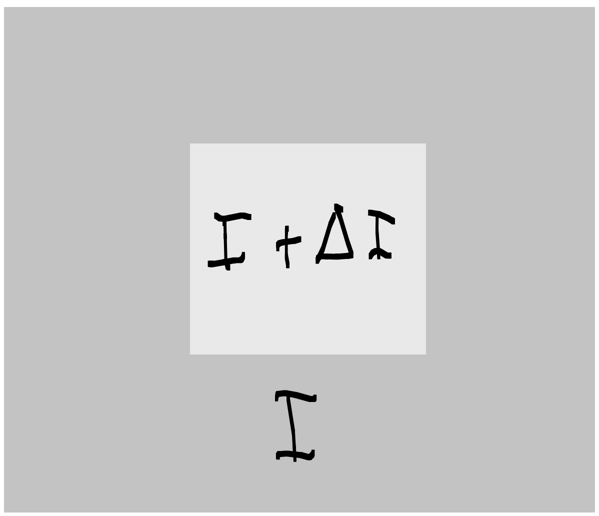
"Just Noticable Difference" (JND)

In the figure below, is the center is slightly brighter or darker than the surround ?

Seems trivial. But when the center intensity is very close to the surround intensity, the center will not be visible.

The question is, how small a difference can you notice?

The answer to this question is called the JND.



Intensity Discrimination

- taste:

  n vs n + Δn grams of sugar per 100 ml

- hearing (dB)

  n vs. n + Δn loudness units (unspecified)

  n vs. n + Δn Hz (cycles per second of tone)

- touch (weight)
  - n vs. n + Δn Newtons

- vision
  - brightness
  - hue
  - saturation

JNDs are typically non-linear functions of the intensity.

- taste
  1 vs. 2 teaspoons sugar in tea more noticable than 11 vs. 12

- hearing
  - loudness is measured in log of amplitude of sound wave
    i.e. decibels (dB) is a log scale

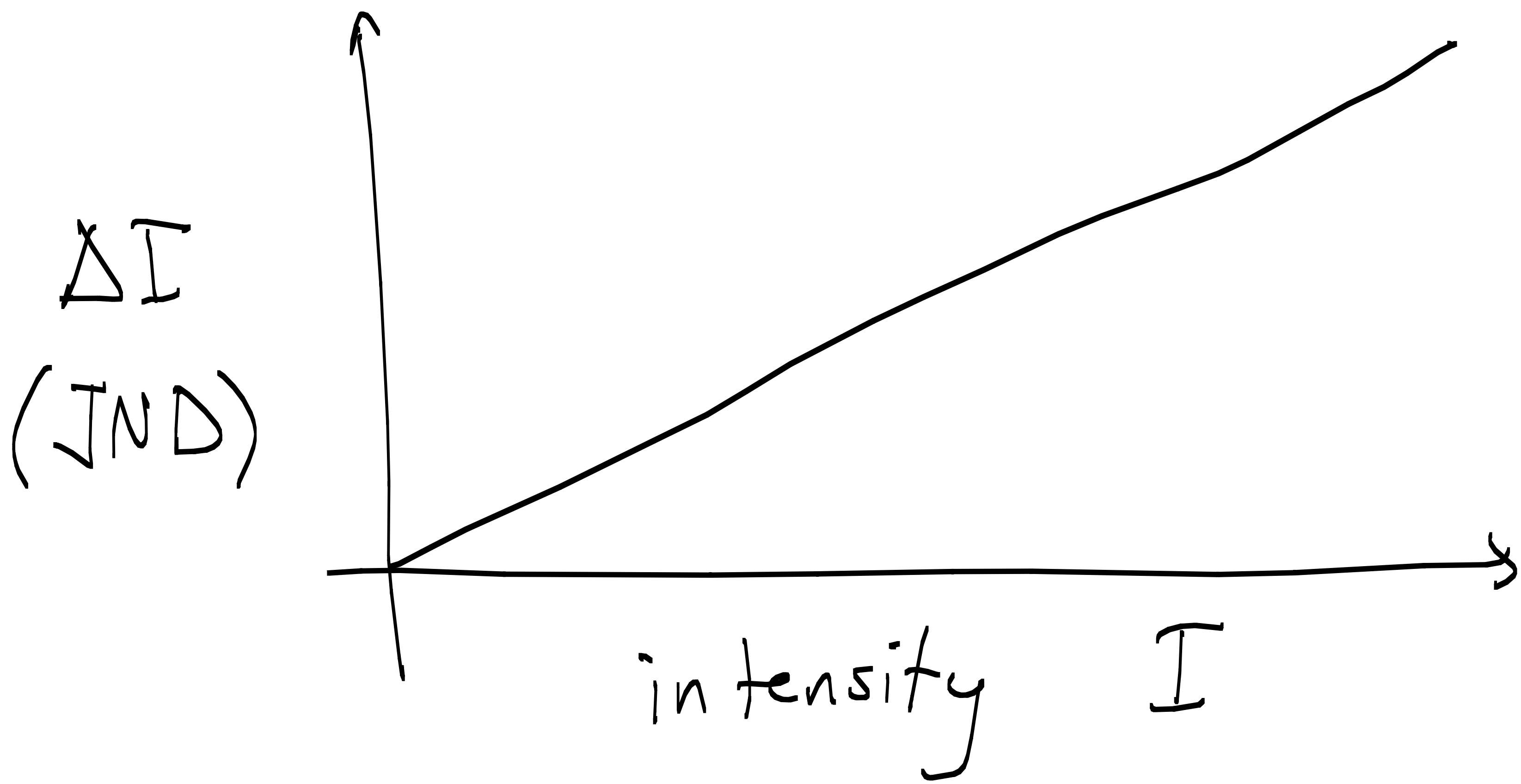
- touch
  - 1 vs. 2 kilograms is more noticeble than 11 vs. 12 kg

- vision
  - brightness ?
  - hue ?
  - saturation ?

Weber's Law

The "just noticeable difference" in intensity is proportional to the intensity.

$$\Delta \text{ intensity} = \text{constant} * \text{intensity}$$



Fechner Law

- connects physical intensity with *perceived intensity*

How do you measure perceived intensity? e.g. next slide

ADDED: Fechner showed that if perceived intensity is proportional to JND (and if Webers Law holds), then perceived intensity grows with log of intensity (Proof omitted). That is:

$$\Delta \text{ perceived intensity} = k \frac{\Delta I}{I}$$

$$\Longrightarrow \text{perceived intensity}(I) = k \ln \frac{I}{I_0}$$

where I_0 is detection level.

Example: intensity of light

Choose N=10 neutral (R = G = B) values of intensity such that they appear uniformly spaced, or equally discriminable.

Such an experiment allows us to connect perceived intensity with physical intensity.

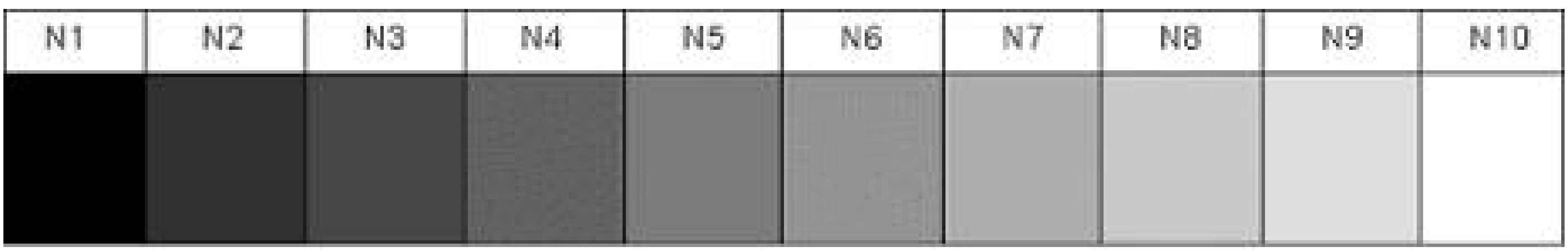
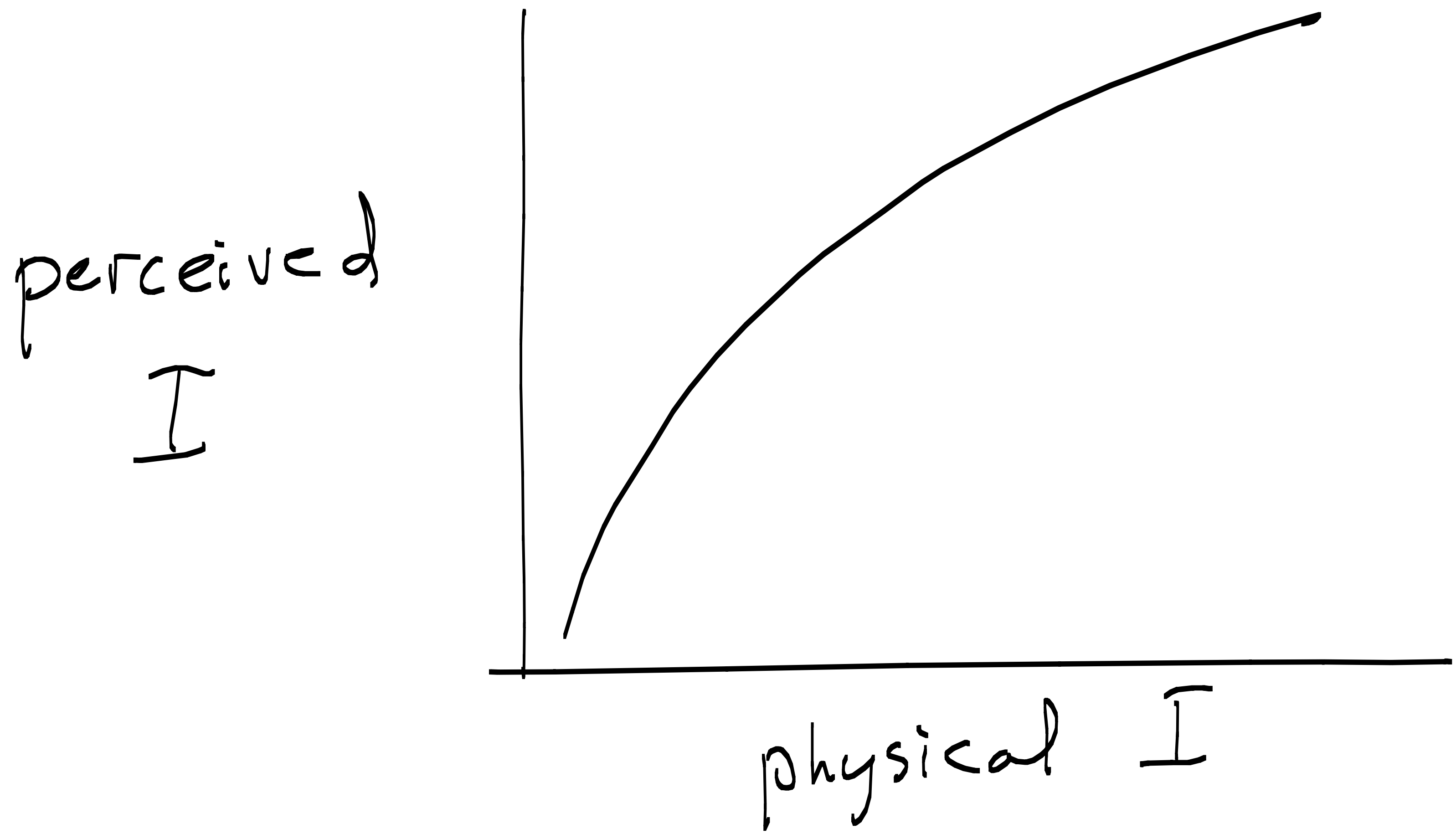


Figure 1

From Fechner's law, we would expect perceived intensity to grow with log of physical intensity.



Steven's Law

perceived I = (physical I)$^{\gamma}$

$$\text{perceived } I = (\text{physical } I)^{\gamma}$$

To Honor Fechner and Repeal His Law

A power function, not a log function, describes the operating characteristic of a sensory system.

S. S. Stevens

One hundred years ago G. T. Fechner (*1*) published the fruits and findings of a ten-year labor—an event that we celebrate as the nascence of the discipline called psychophysics. In the century since the *Elemente der Psychophysik* first made its stir, the simple but controversial logarithmic law that goes by Fechner's name has invaded almost all the textbooks that mention human reactions to stimuli. It is fitting and proper, therefore, that we should gather

understanding on how they should build it; my psychophysical edifice will stand because the workers will never agree on how to tear it down."

These words were published 17 years after the appearance of the *Elemente*. By that time Fechner had had full opportunity to correct his magnum error, for at least two different arguments had by then been made in favor of what has more recently appeared to be the correct relation between the

cause new techniques have made it plain that on some two dozen sensory continua the subjective magnitude grows as a power function of the stimulus magnitude (*6*).

It is understandable that Fechner should fight stubbornly throughout his later decades to salvage his intellectual investment in the thesis that a measure of the uncertainty or variability in a sensory discrimination can be used as a unit for the scaling of the psychological continuum. He had sensed the essence of this possibility as he lay abed on that famous morning of 22 October 1850, and he had put the idea promptly and tenaciously to work. But why should such an unlikely notion have persisted for so long in other circles, and why should it have blossomed out in such noted and provocative guises as those devised by Thurstone and his school? I have puzzled so often about the ability of this fancy to persist and grow famous that I have accumulated a list of possible reasons for it. I will run quickly through a

appeared in Science 1961

http://sonify.psych.gatech.edu/~walkerb/classes/perception/readings/Stevens1961.pdf

One standard model for vision is that perceived intensity ("brightness") is related to physical intensity by approximately a power law. This is consistent with Steven's Law.

http://en.wikipedia.org/wiki/Lab_color_space

$$\text{perceived } I \approx (\text{physical } I)^{1/3}$$

We are more sensitive to changes in physical intensity at small values of intensity. i.e. the JND's are smaller at small intensity values. (True for Weber/Fechner too.)

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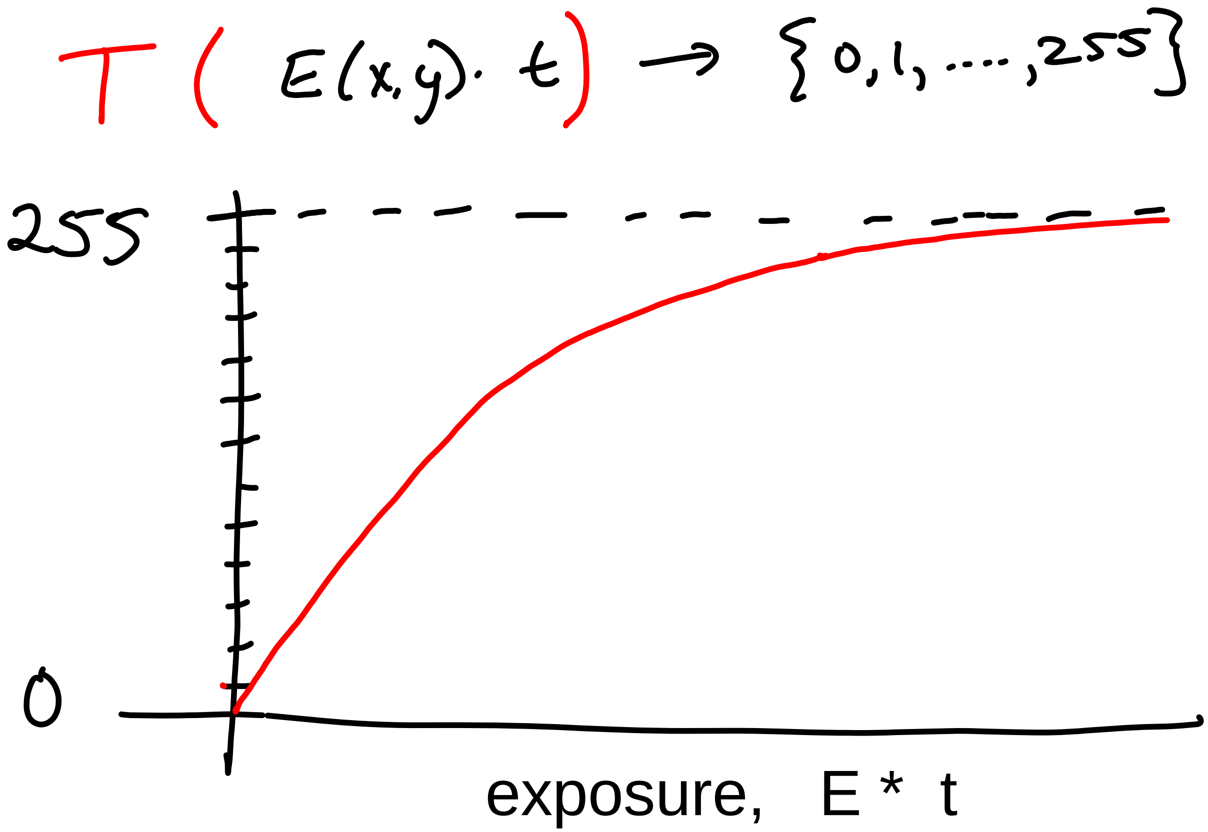
Recall last lecture:
Camera Response & "compressive non-linearity"



This compressive non-linearity *is consistent with* the laws of Weber/ Fechner/Stevens. The encoding of physical intensity is more precise at small intensities than at large intensities.

Gamma Encoding (power law)

Film cameras:

Until 2005, most cameras used film. The film response function was a compressive non-linearity, namely the opacity of the film varied as a *power law* with the exposure. The exponent was typically called γ but we will say $1/\gamma$ to be consistent with how we use γ later.

Digital cameras (two step encoding):

First, encode with linear response, 12 bits per RGB channel (RAW).

Second, convert from RAW to JPEG or TIFF, 8 bits per RGB value. JPEG and TIFF use a compresive non-linearity, namely a *power law* with an exponent $1/\gamma = 1 / 2.2$. We refer to it as "gamma encoding".

http://www.cambridgeincolour.com/tutorials/gamma-correction.htm

What does gamma encoding achieve?

Consider a scene such that part of it is in shadow and part is in direct sunlight, such as the one below. If you were in the *real scene* (which has very high dynamic range i.e. HDR), you would be able to discriminate small intensity differences within the shadow region (because of Weber/Fechner/Stevens laws).

The image below shows a log mapping of the HDR intensities. It enables us to discriminate the intensities in the darker parts of the scene.

Recall this example from last lecture:

The image was obtained by computing a HDR image from a set of JPGs, and then re-mapping the intensities using a compressive non-linearity (log).

The displayed image on the previous slide does not reproduce the original dynamic range in the scene. Why not? Because we are using a low dynamic range display to show this image!

So what are the intensities actually being displayed here ?
I will get to that in the rest of the lecture.

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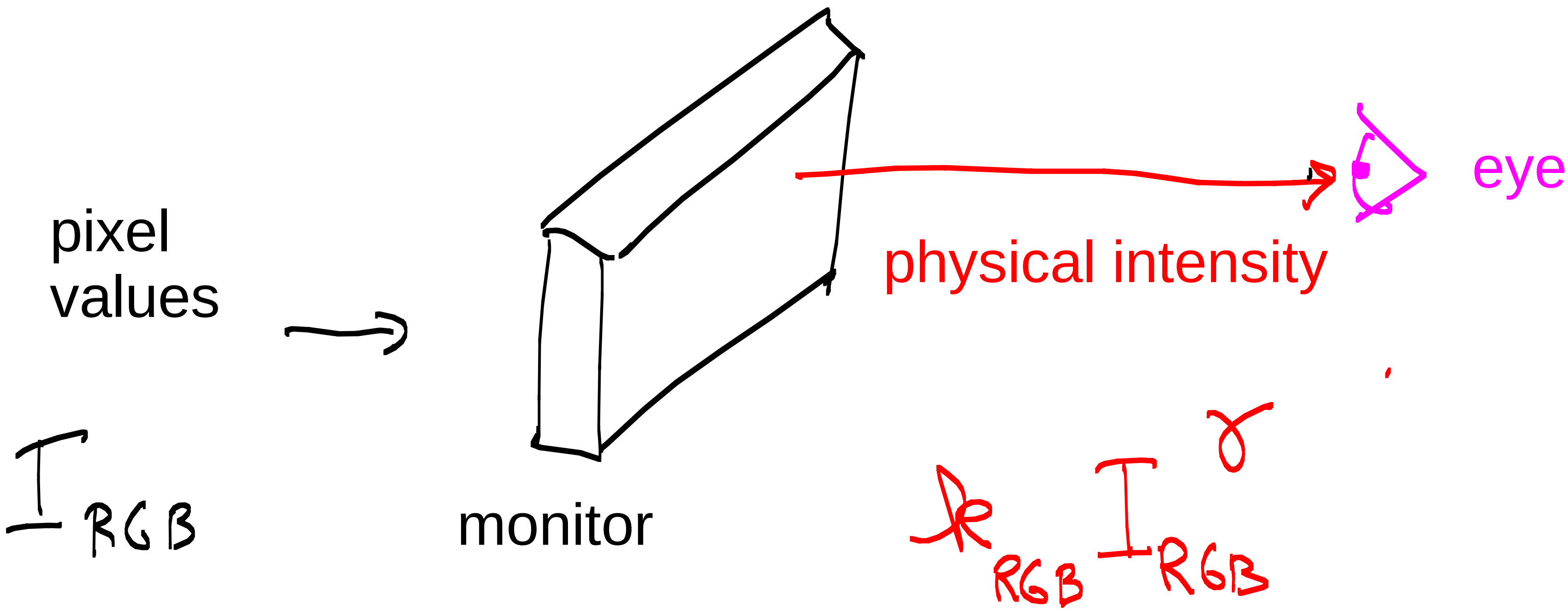
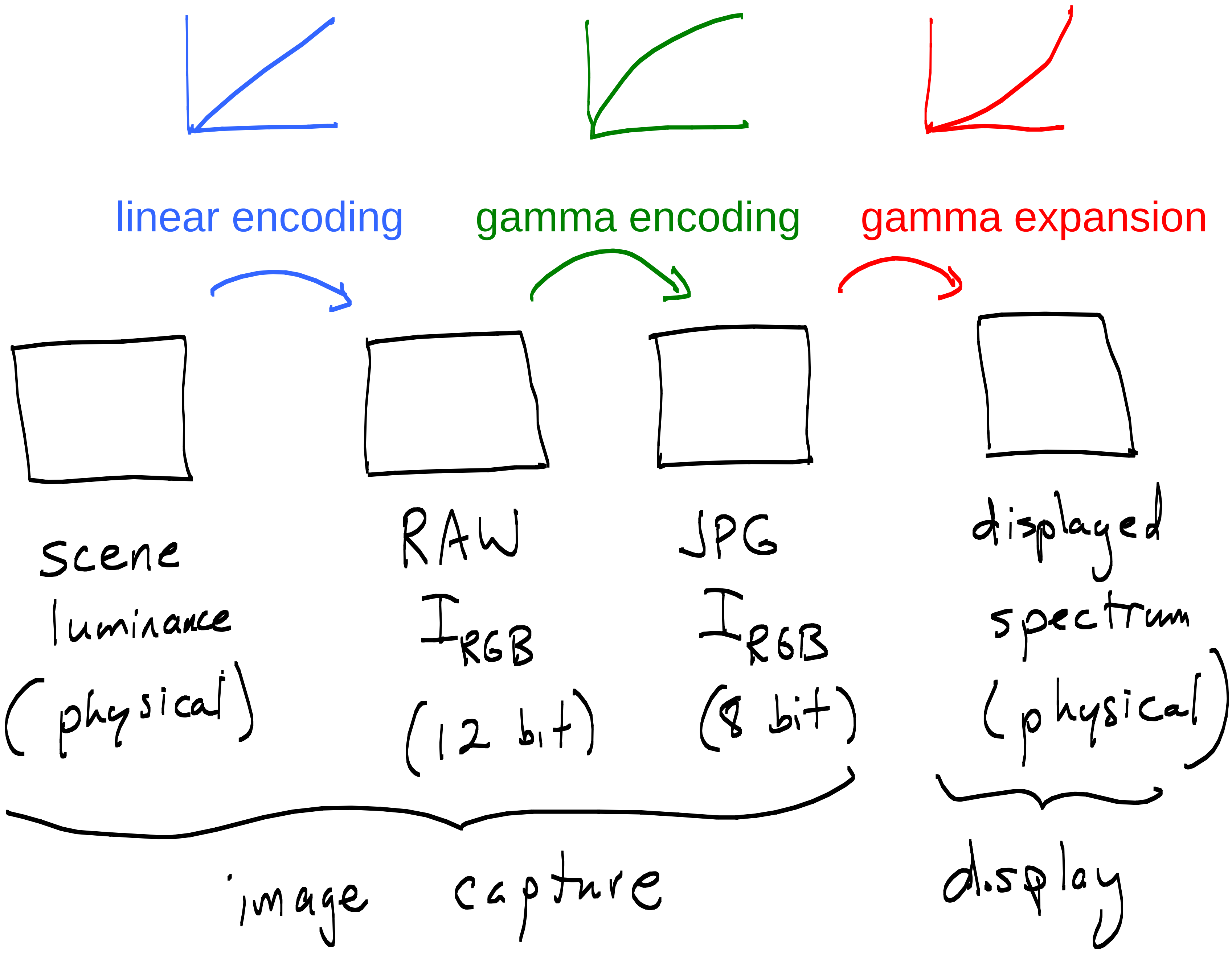
Gamma expansion (display)



Most monitors and projectors emit an RGB intensity (to be more precise, they emit RGB spectra) at each pixel that is power function of the pixel RGB value, namely they raise the value to an exponent γ. Often γ = 2.2 but for older CRT's γ = 2.5.

http://www.cambridgeincolour.com/tutorials/gamma-correction.htm

The gamma expansion cancels the gamma compression, if one is indeed exactly the inverse of the other. (In practice, the two models are only approximately gamma power laws, so they don't exactly cancel).



Gamma correction

What happens when we display an image rendered with OpenGL ?

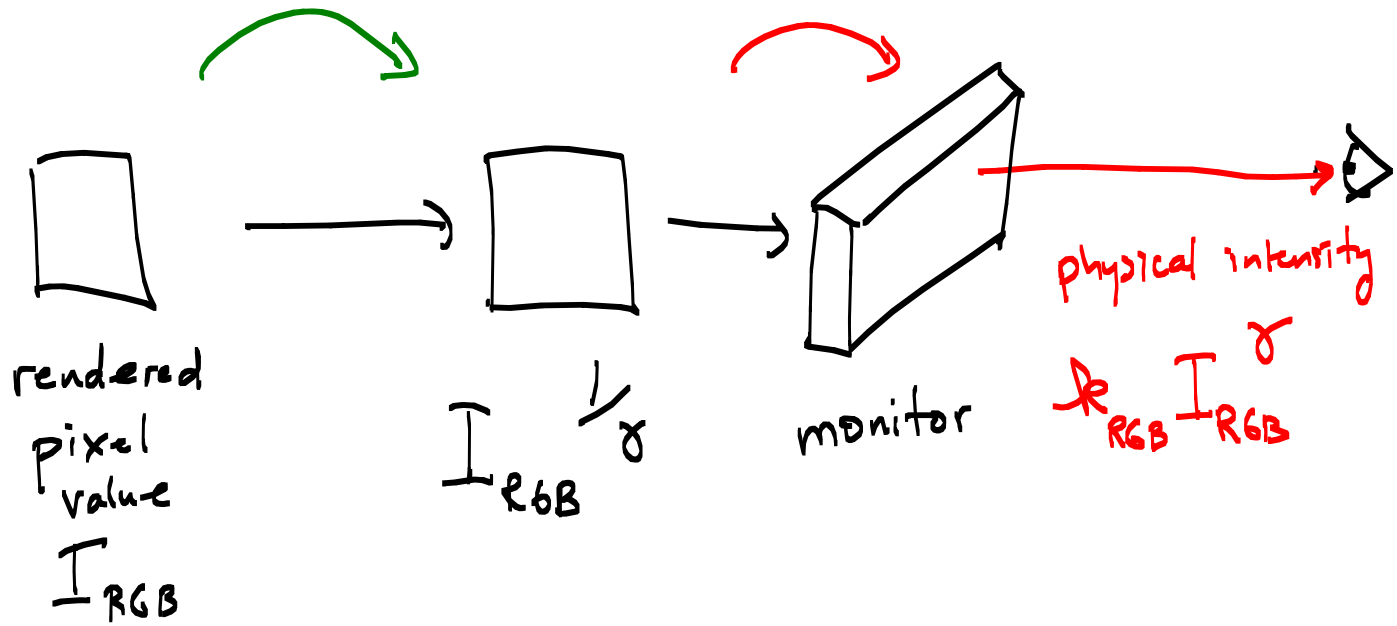
The monitor's built-in gamma expansion now creates a problem since there is no need for it !

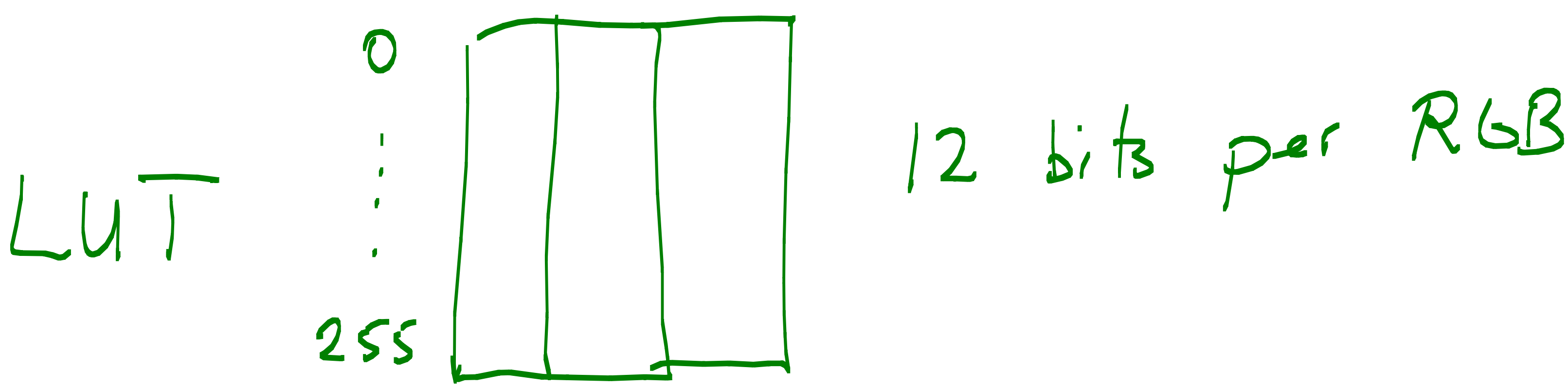
To guard against the gamma expansion for rendered images, we must apply a compressive non-linearity to the rendered RGB values before they are sent to the monitor. That will cancel out monitor's gamma expansion.

This is called "gamma correction", since now we are cancelling out the monitor's gamma.

Gamma correction is done using a lookup table (LUT) on the graphics card.

gamma **correction** gamma expansion





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Display Calibration 1 (with photometer)

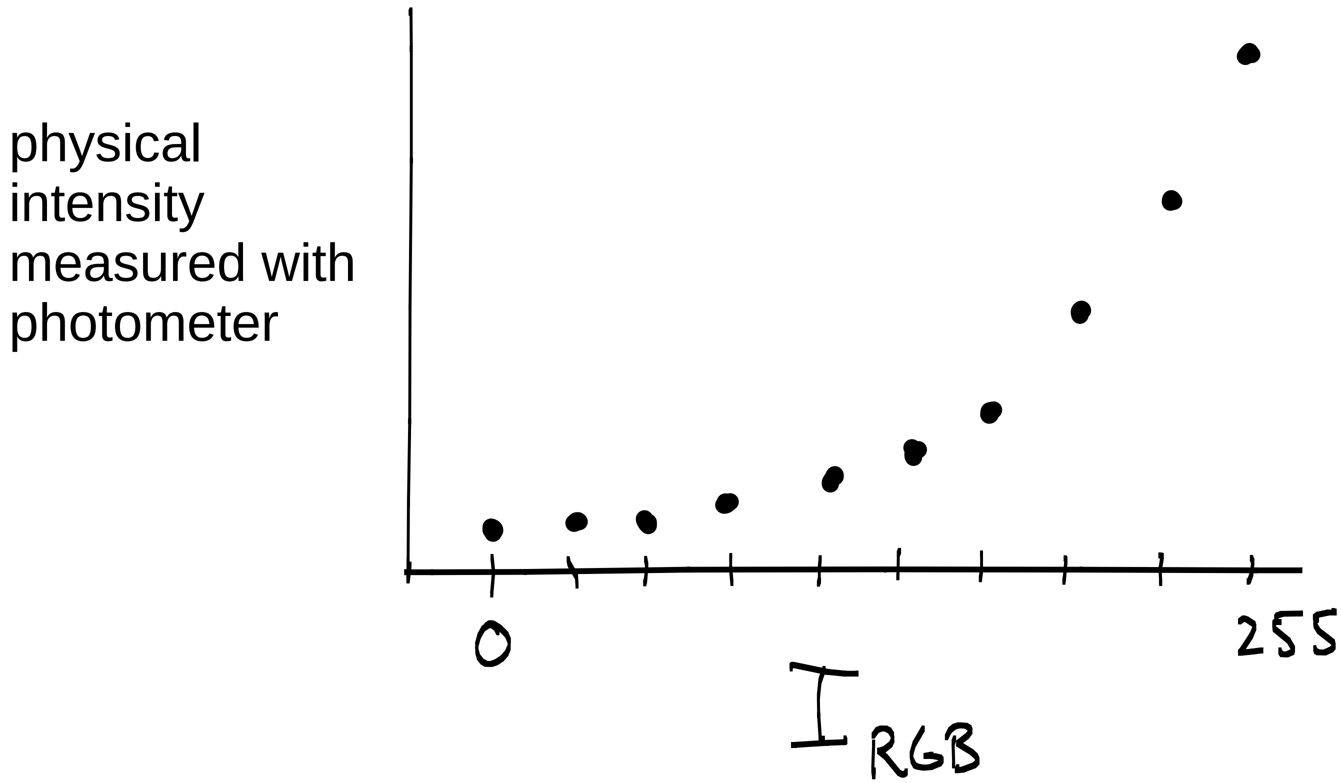
These power laws are very nice, but they are just models. Real *affordable commercial* displays are not required to satisfy the model, and so they typically don't.

Suppose you would like your monitor (or projector) to produce linear intensities, that is, you would like the physical light intensity that is emitted to be roughly proportional to the image RGB values. To do this, we need to measure the monitor's gamma (or approximate gamma) and correct for it.

Monitor "calibration" refers measurement of the curve.

Case 1: Suppose you have a light measurement instrument that can measure the intensity of emitted light very accurately. This instrument is called a "photometer".

Set the color LUT to be linear, and then measure the intensities of uniform intensity (RGB) patches.



We can fit a curve (e.g. approximately a gamma power law) to the measured intensities.   e.g. the fitted curve could be a piecewise linear approximation to the above points.

We can do gamma correction by setting the values in the LUT to be the inverse of this fitted curve.

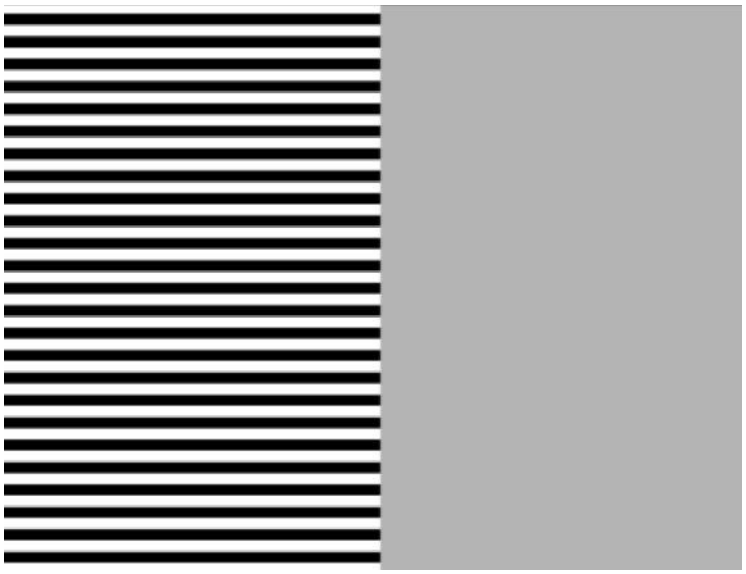
Display Calibration 2 (without photometer)

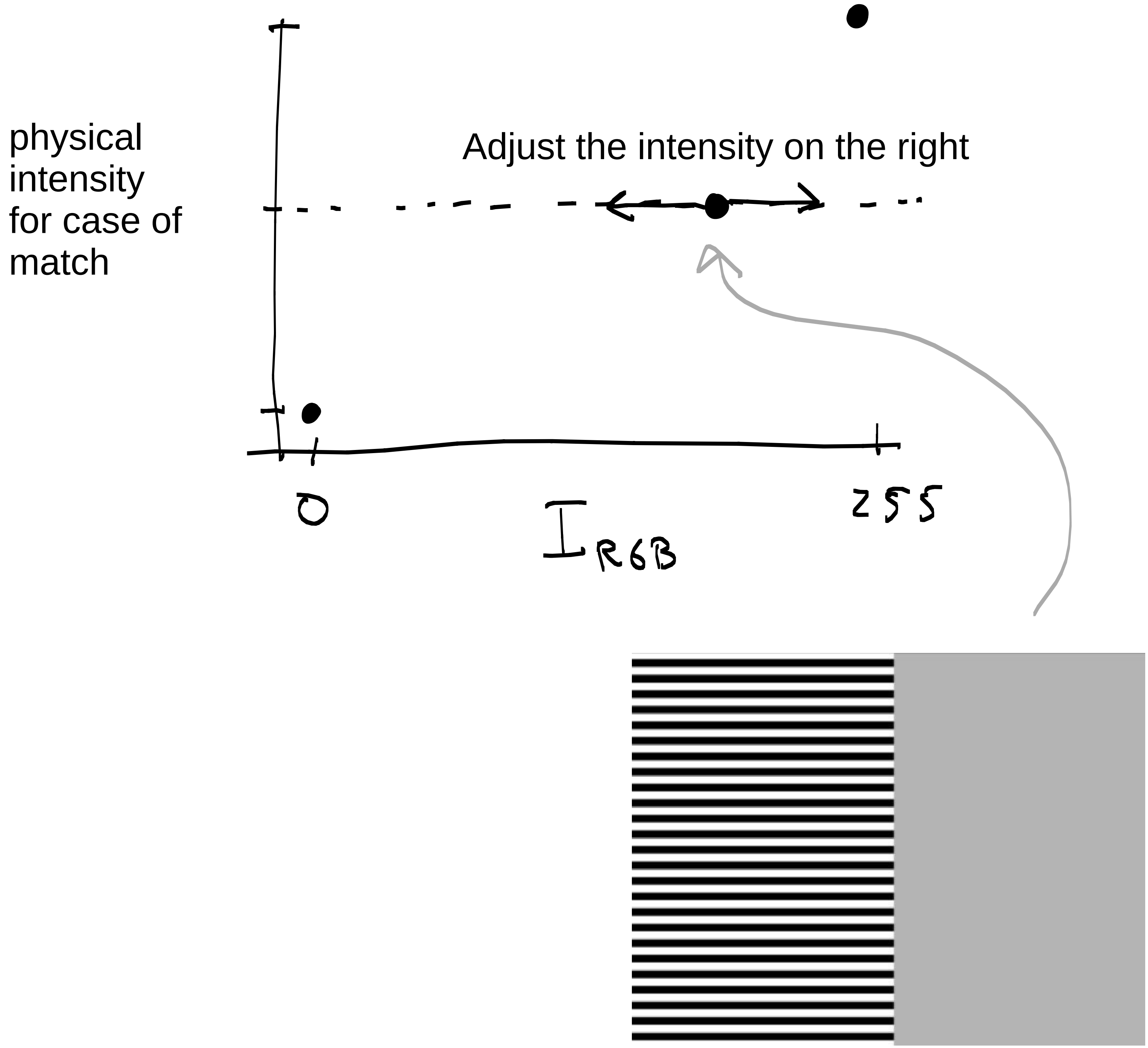
Display a pattern such as below.
The left side shows two alternating intensities (0, 255, 0, 255, ...)
The right side shows a single intensity.

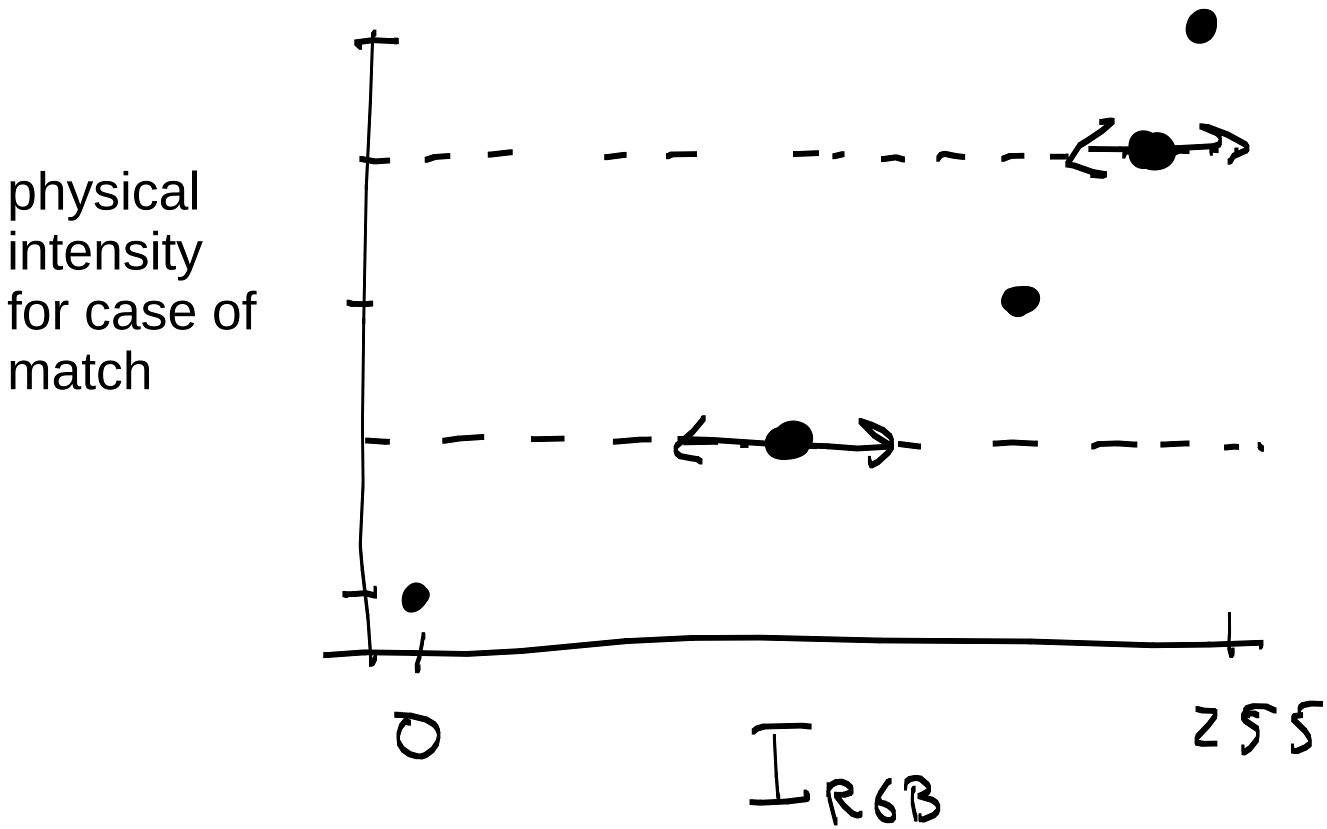
Move way back from the display so that the individual lines cannot be seen i.e. they blur together.

Adjust the intensity on the right until its intensity appears the same as the (blurred single) intensity on the left.

Each line on the left should be a single row in the image. It has been expanded to thick lines for illustration purposes only.

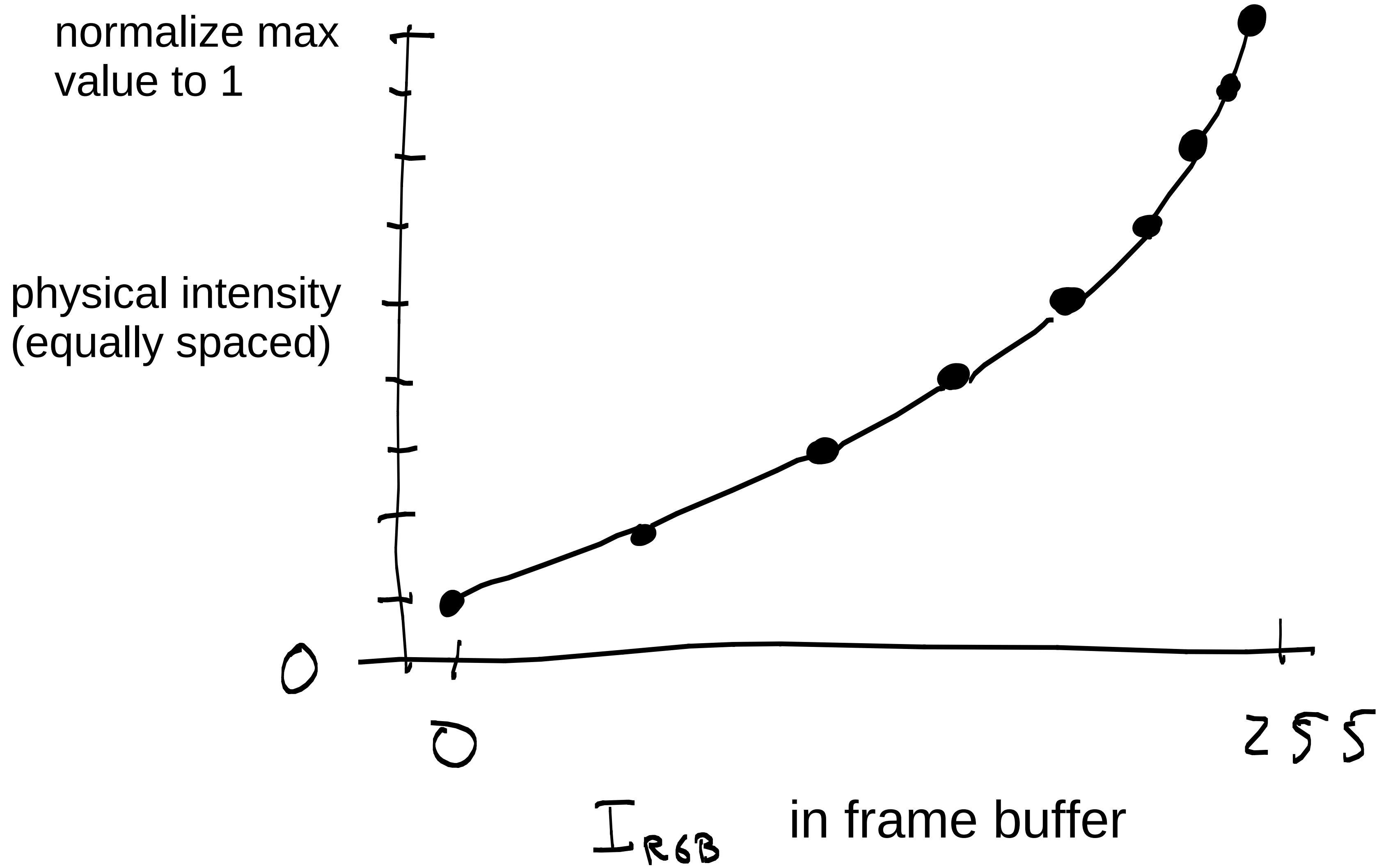



physical
intensity
for case of
match
Adjust the intensity on the right
0
255
I_{RGB}



Repeat the interpolation between new values. Same as on previous slide but now the grid on the left consists of two new I_RGB values.

Each new point on the curve gives an I_RGB value that produces a physical intensity halfway between two other intensities.



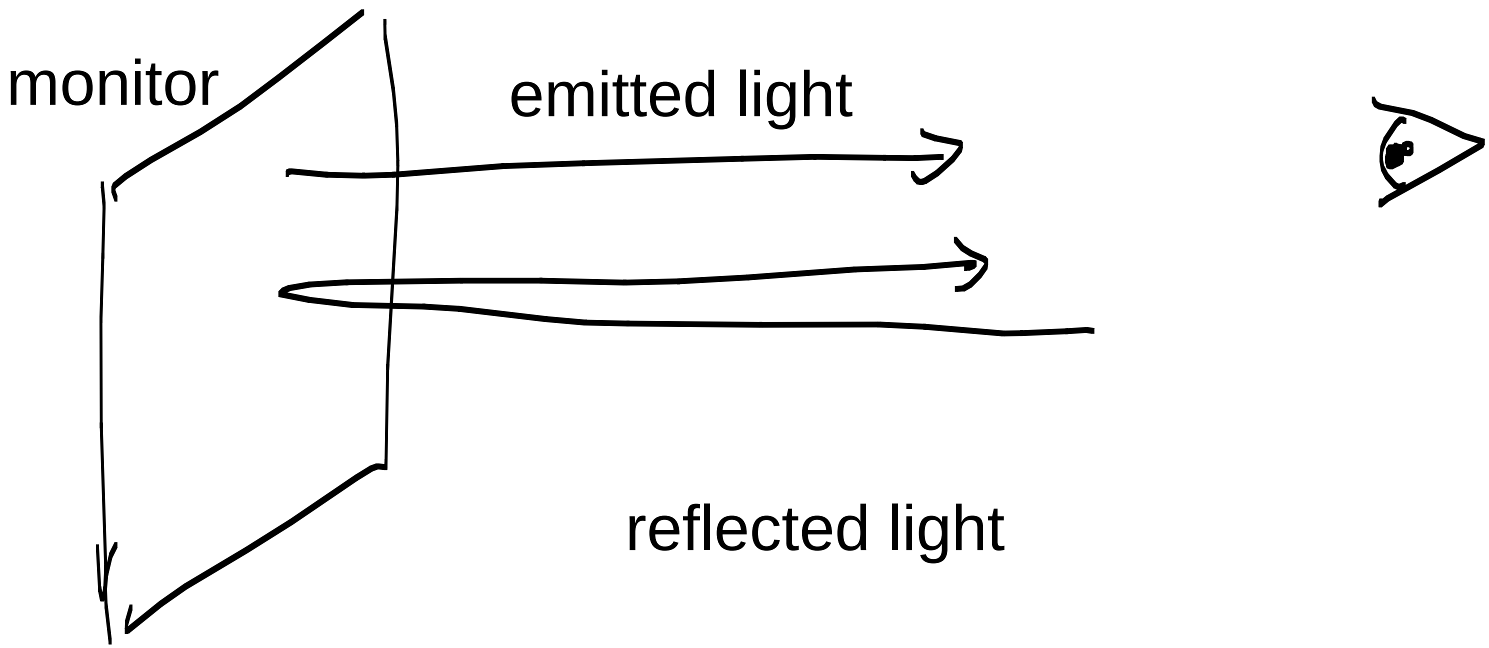
This gives us the end-to-end mapping of the display (RGB value to emitted intensity).

As in the case where had a photometer, put the inverse of this mapping into the LUT. This linearizes the end-to-end mapping.

All of our problems solved?   Unfortunately not.

Real displays still have limited dynamic range.   Why?

One fundamental problem is that "black" is not black, since there is typically ambient light in the scene that reflects off the display and effectively adds light to the points that are supposed to be black.



This reflected light can be accounted for in the calibration, but it still reduces the dynamic range.

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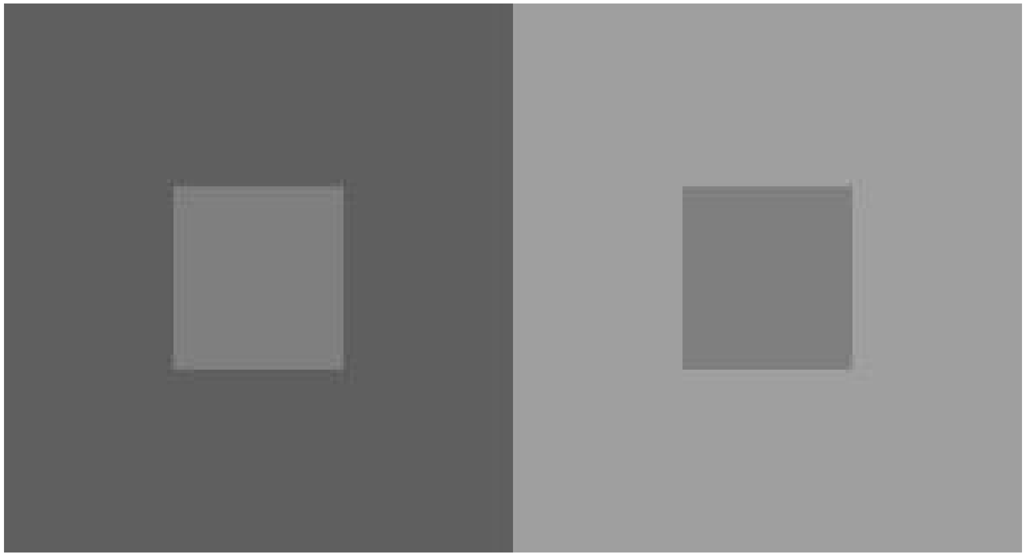
Display technologies require that the mapping from digital RGB to emitted physical intensity is the same for all pixels.

However, in human vision, perceived intensity can depend on spatial context.



"Global" tone mapping operators (such as log & gamma) use the same mapping for all pixels.

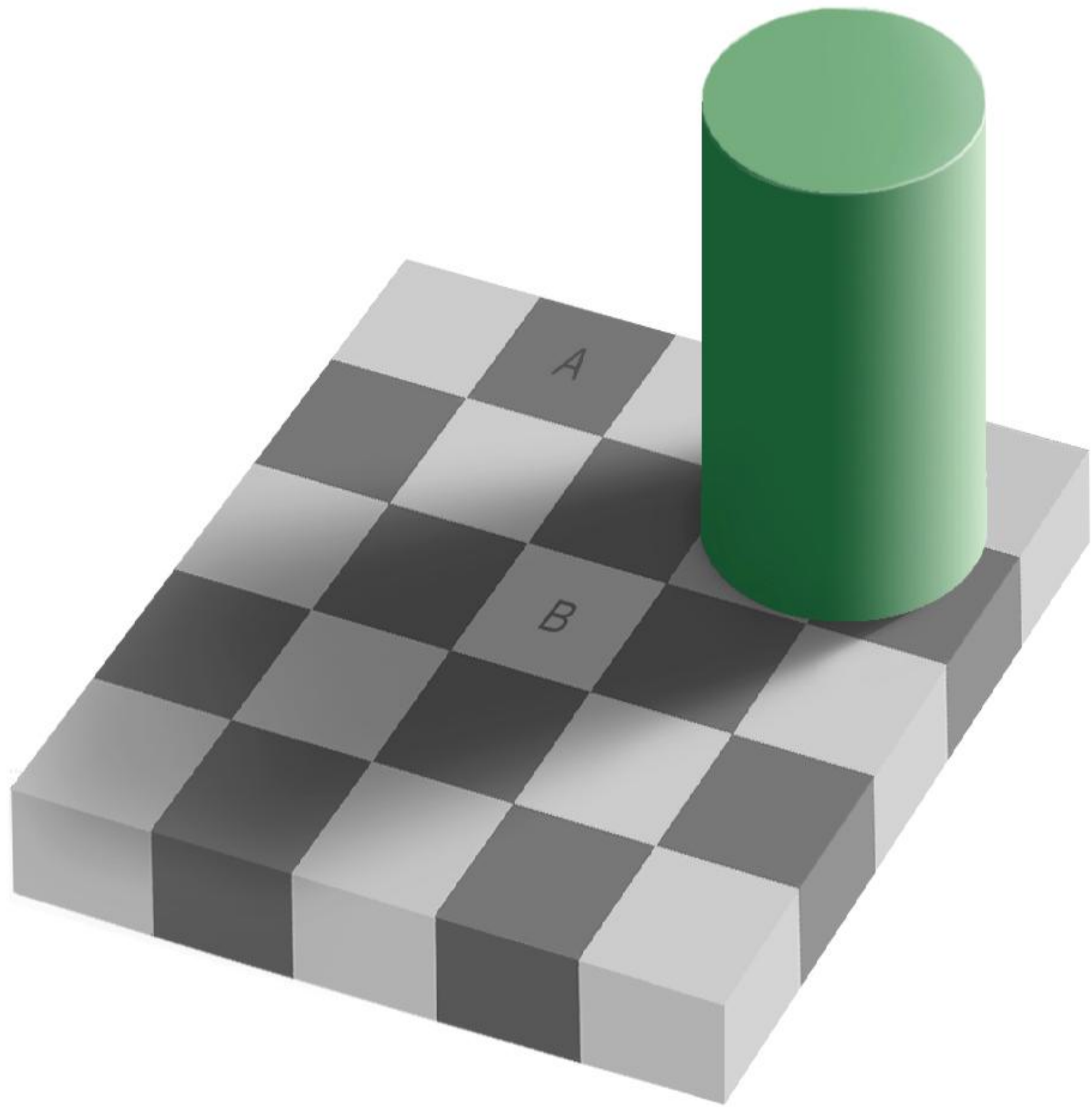
Many "local" tone mapping operators (HDR -> LDR) also have been proposed that are based on such spatial dependencies.   The goal is to increase the *perceived* dynamic range of the displayed image.

It is important to keep in mind that visual system's ultimate purpose is not to perceive brightness.

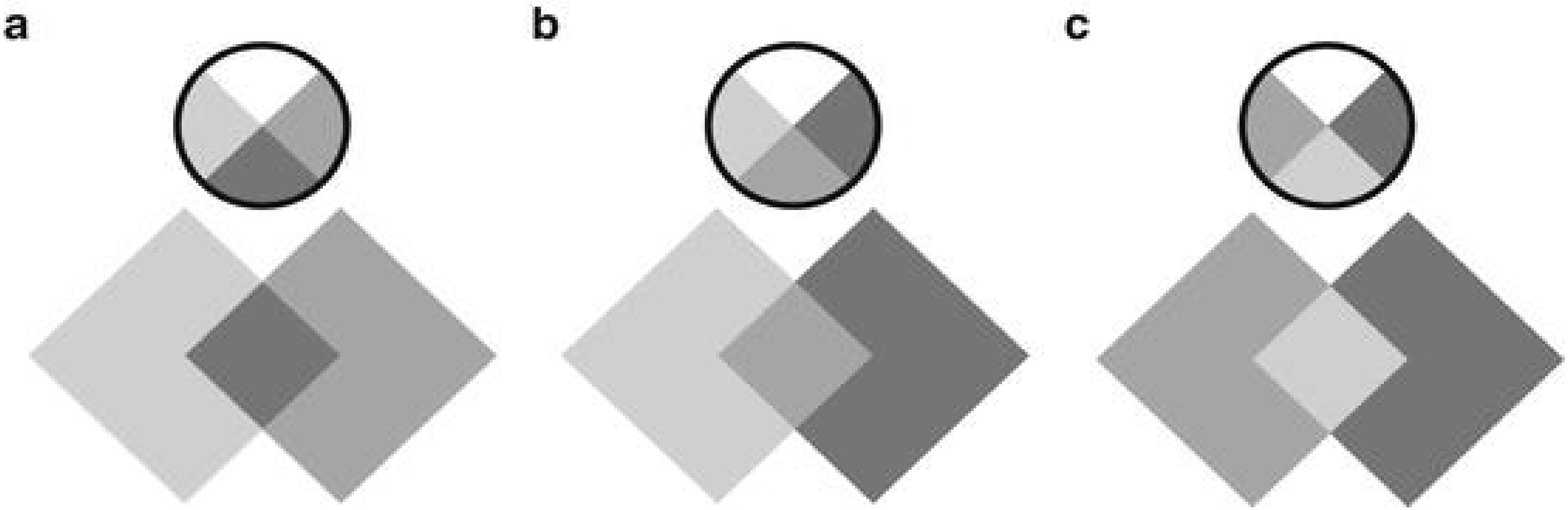
Rather, it is to perceive surfaces (materials and shapes) and 3D spatial relationships, and to recognize objects and events.

Sometimes our perception of brightness is deeply intermingled with out perception of other scene properties (materials, shapes, opacities).

Lets look at a few examples.

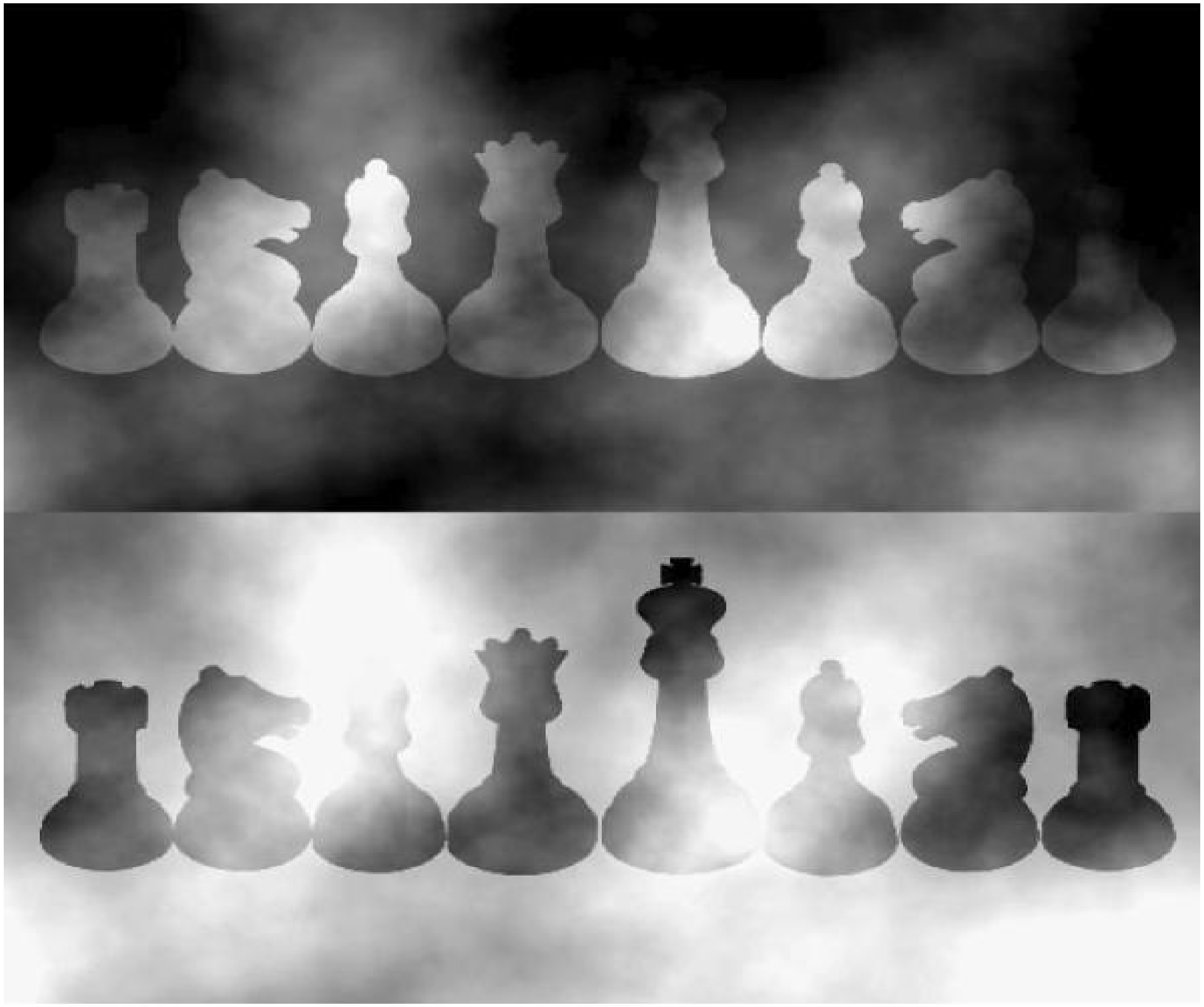


Similar example to last lecture (Adelson's shadow illusion).



Perception of surface color (and opacity) depends on perceived spatial arrangement.

http://link.springer.com/referenceworkentry/10.1007%2F978-0-387-31439-6_559



http://www.nature.com/nature/journal/v434/n7029/full/nature03271.html

In fact, the RGB of each upper chess piece is the same as the corresponding lower one.

It is difficult to come up with a tone mapping operator that would account for the perceived brightnesses in this image.

Announcements

- A4 is due a week from tomorrow.

- Next lecture is the last one. I will go over Exercises 20, 21, 23. (Perhaps Exercises 24, 25 too, but I still need to make some.)

- Course Evaluations (please, at least 50% of you fill them out)