lecture 24

image capture

- photography: model of image formation
  - image blur
  - camera settings (f-number, shutter speed)
  - exposure
  - camera response
- application: high dynamic range imaging

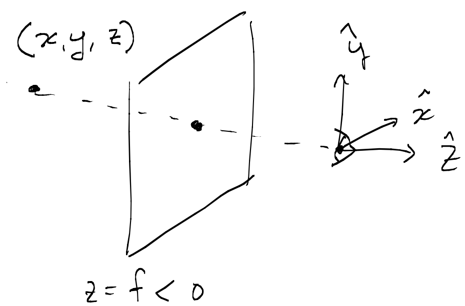
Why learn about photography in this course?

- Many computer graphics methods use existing photographs
  e.g. texture & environment mapping, image matting.
  Understanding them can only help us to better use them.
- Many computer graphics methods attempt to *mimic* real images and their properties. See next slide
- Digital photographs can be manipulated to achieve new types of images e.g. HDR as we'll see later

Geri's Game: Note the background is blurred.

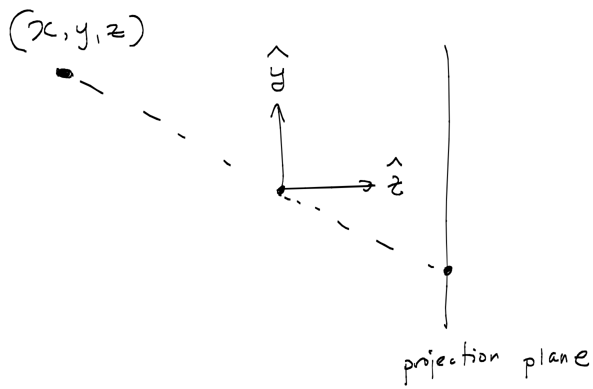
https://www.youtube.com/watch?v=9IYRC7g2ICg

As we have seen, in computer graphics, the projection surface is in front of the viewer.



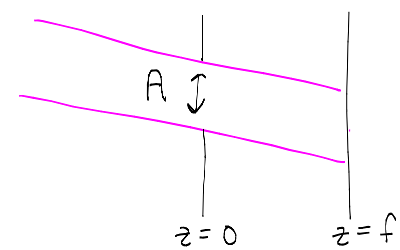
We were thinking of the viewer as looking through a window.

In real cameras and eyes, images are formed behind the center of projection.



Aperture

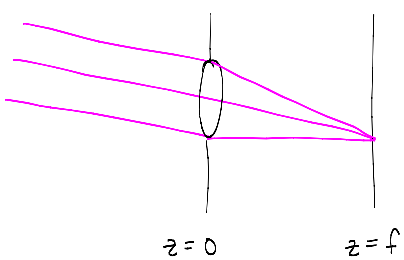
Real cameras (and eyes) have a finite aperture, not a pinhole.
The diameter A of the aperture can be varied to allow more or less light to reach the image plane.



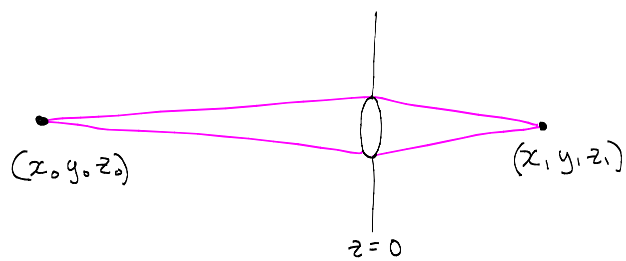
Lens

Cameras (and eyes) also have a lens that focusses the light.

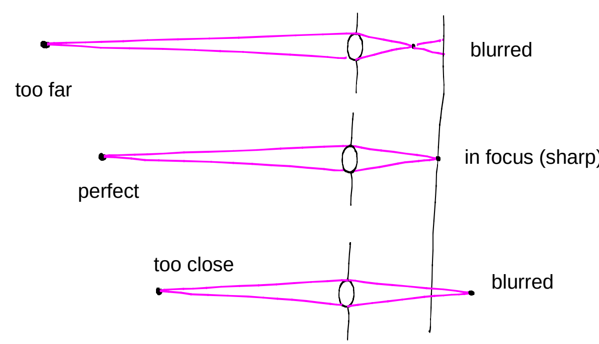
Typically the aperture is in front of the lens, but for simplicity I have just drawn it as below.



For any point (x0, y0, z0), there is a corresponding point (x1, y1, z1), called the conjugate point. All the rays that leave (x0, y0, z0) and pass through the lens will converge on (x1, y1, z1).



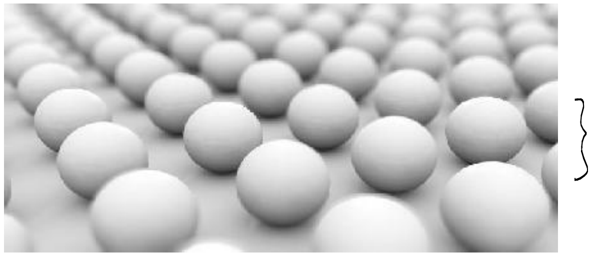
For a fixed distance between the lens and sensor plane, some scene points will be in focus and some will be blurred.
(I will spare you the mathematical formulas.)



Depth of Field

"Depth of field" is the range of depths that are ~ in focus.

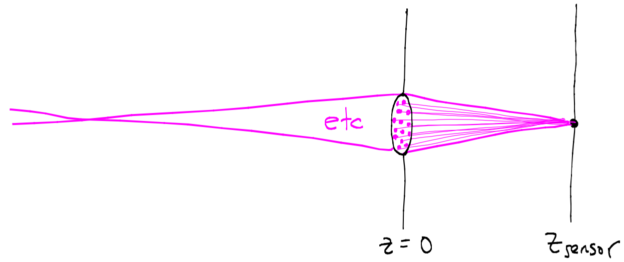
[Definition: the blur width is less than the distance between pixels.]



How to render image blur ? (sketch only)

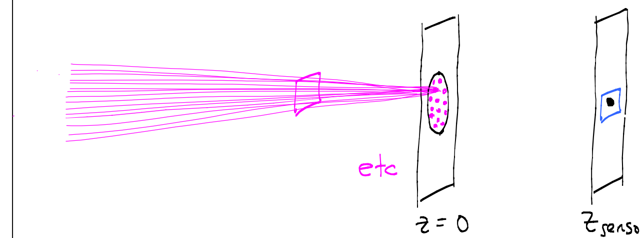
http://http.developer.nvidia.com/GPUGems/gpugems_ch23.html

Method 1: Ray tracing (Cook et al. 1984)
For each point *on the image plane*, trace a set of rays back through the lens into the scene (using formulas I omitted). Compute the average of RGB values of this set of rays.



Method 2: "Accumulation buffer" (Haeberli and Akeley 1990)

Render the scene in the standard OpenGL way from each camera position within the aperture (one image shown below). Each of these images needs to be scaled and translated on the image plane. (Again, I will spare you the math.)
Then, sum up all the images.



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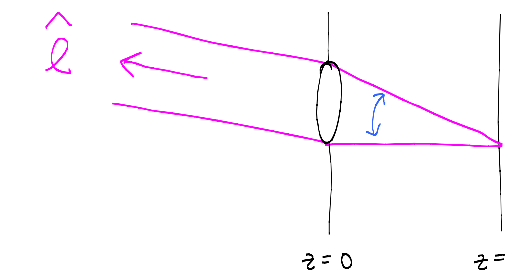
Camera Settings

The total light reaching each point on the image plane depends on the intensity of the incoming light, and on the angle of the cone of rays which depends on the aperture.
There is also a proportionality factor -- not shown.

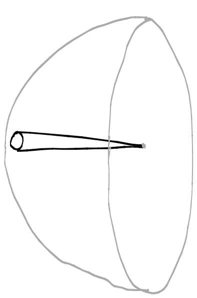
$$E(x,y) = L(\vec{l}) \text{ * angleOfConeOfRays(x)}$$



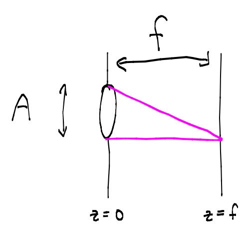
"Solid Angle" is a 2D angle. It is defined to be the area of a unit hemisphere (radius 1) covered by the angle.

Angle has units radians (or degrees).
Solid angle has units "steradians".

e.g. You can talk about the solid angle of the sun or moon.



Angular width of the lens as seen from the sensor is $\frac{A}{f}$.
The units are radians.

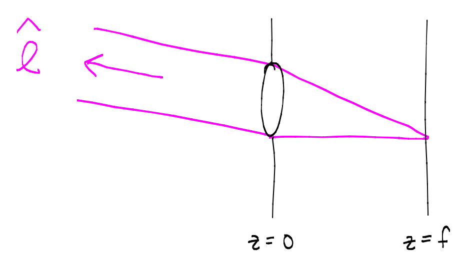


The solid angleOfConeOfRays is proportional to $\left(\frac{A}{f}\right)^2$

(This is a familiar effect: the area of a 2D shape grows like the square of the diameter.)

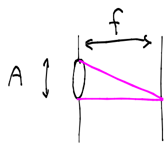
The total light reaching each point on the image plane (per unit time) is thus as follows, where L(l) is the intensity of the light in direction l.
Here we ignore color spectrum but in fact E( ) also depends on wavelength of light (see color lecture).

$$E(x,y) = L(\vec{l})\left(\frac{A}{f}\right)^2$$



F-number (definition) = f / A

Since f / A (or its inverse) is fundamental to determining how much light reaches the image plane, this quantity is given a name.



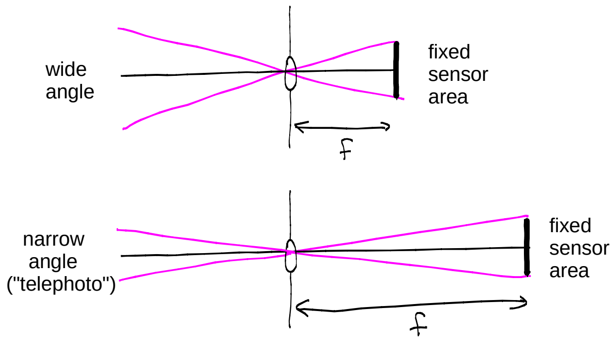
On typical cameras, the user can vary f-number:

$$1.4,\ 2,\ 2.8,\ 4,\ 5.6,\ 8,\ 11$$

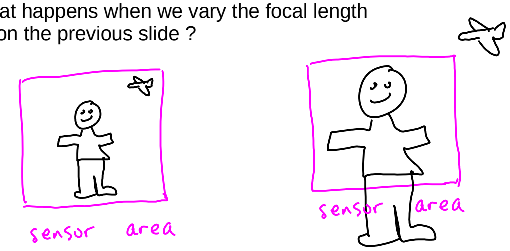
$$\approx \sqrt{2},\ \sqrt{4},\ \sqrt{8},\ \sqrt{16},\ \sqrt{32},\ \sqrt{64},\ \sqrt{128}$$

The mechanism for doing this is usually to vary the aperture.

It is also possible to fix the aperture and vary the focal length.

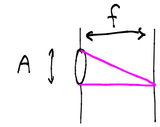


What happens when we vary the focal length as on the previous slide ?



small f (wide angle)

large f (telephoto)



The image is darker for the larger focal length f. Why? Because the angle of the lens is smaller when viewed from a point on the sensor.

Shutter speed 1/t (t = time of exposure)

Image intensity also depends on t.

Typical t

$$\ldots, \frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \frac{1}{16}, \frac{1}{32}, \frac{1}{64}, \frac{1}{128}, \frac{1}{256}, \frac{1}{512}, \ldots$$

Typical shutter speed $\frac{1}{t}$ (on camera dial)

$$\ldots, 2, 4, 8, 15, 30, 60, 125, 250, 500, \ldots$$

Application: Motion Blur (Cook 1984)

Exercise: very subtle rendering effect here. Can you see it?

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Exposure

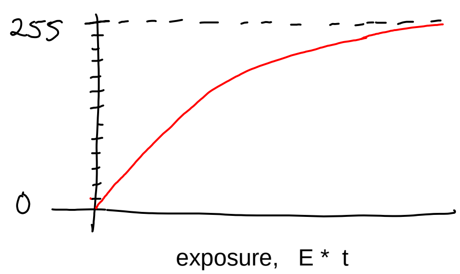
$$\underbrace{E(x,y)\, t}_{\text{Exposure}} = L(\vec{l}) \left(\frac{A}{f}\right)^2 t$$

decrease A & increase t $\Rightarrow$ $E(x,y)\cdot t$ fixed

increase f & increase t $\Rightarrow$ $E(x,y)\cdot t$ fixed (but size changes)

Camera Response

$$T\left(E(x,y)\cdot t \right) \rightarrow \{0, 1, \ldots, 255\}$$



How does this relate to last lecture ?

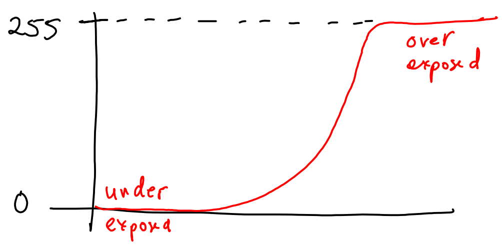
The model for image RGB from last lecture was:

$$I_{RGB}(x,y) = \sum_{\lambda} C_{RGB}(\lambda)\, E(x,y,\lambda)$$

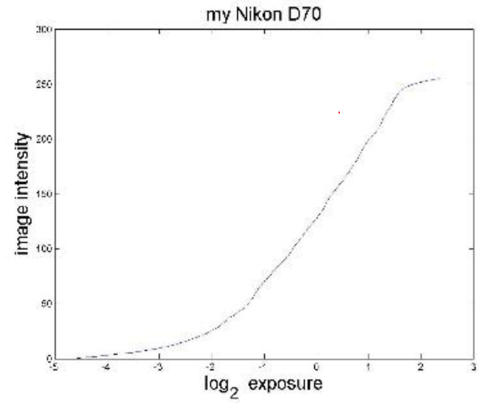
In fact, a typical camera response mapping is

$$I_{RGB}(x,y) = T\left(\sum_{\lambda} C_{RGB}(\lambda)\, E(x,y,\lambda) \cdot t \right)$$

As we will see a few slides from now, it is useful to re-draw camera response curve as a function of log exposure.



log exposure = log E + log t



In few slides, I will say how to compute this curve.

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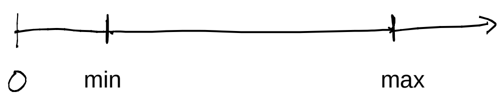
Dynamic range

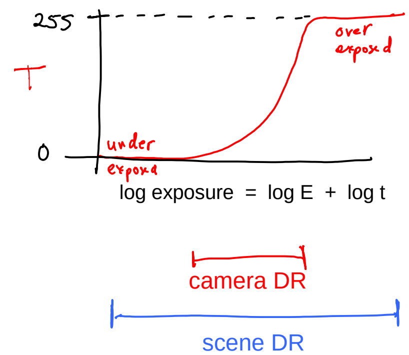


'Dynamic range' of a signal is the *ratio* of the maximum value to the minimum value.

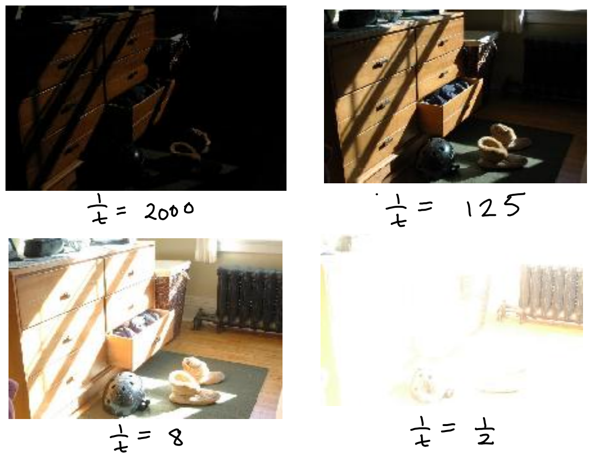
If we look at log(signal), then dynamic range is a difference, max - min.

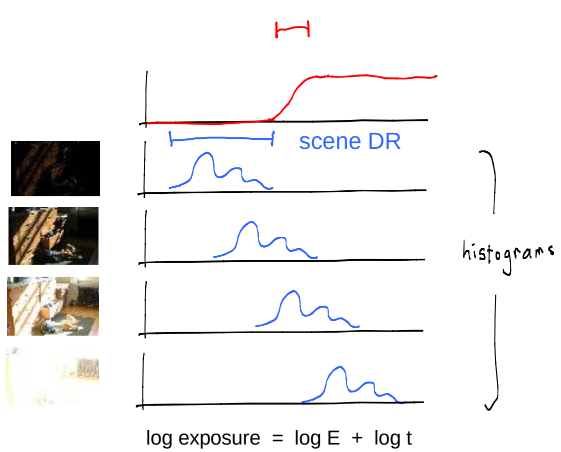
Note that the dynamic range of an exposure image, E(x,y) * t, doesn't depend on the exposure time t.

A typical scene has a dynamic range of luminances that is much greater than the dynamic range of exposures you can capture with a single image in your camera.



Example (scene dynamic range over 4000)





How to compute camera response curve T( ) ?
(Sketch only [Debevec and Malik 1997])

- Take multiple exposures by varying shutter speed (as we did two slides back)
- Perform a "least squares" fit to a model of T( ). (This requires making a few reasonable assumptions about the model e.g. monotonically increasing, smooth, goes from 0 to 255. Details omitted.)
- Option: compute separate models for RGB

Computing a high dynamic range (HDR) image

Given T( ) for a camera, and given a set of new images $I_t(x,y)$ obtained for several shutter speeds, 1/t,

$$\hat{E}_t(x,y) = T^{-1}(\,I_t(x,y)\,) \;/\; t$$

Use the estimate $\hat{E}_t(x,y)$ for which

$0 \ll I_t(x,y) \ll 255$

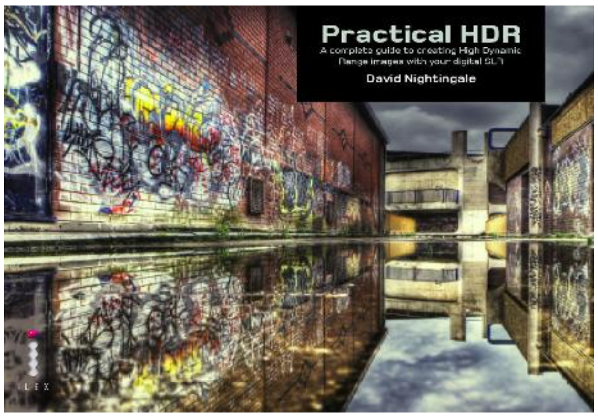
where the T ( ) curve is most reliable.

How to view a HDR image on a low dynamic range (LDR) display ?
This is the problem of "tone mapping". The simplest method is to compute log E(x,y) and scale values to [0, 255]. For example,

Tone mapping is a classical problem in painting/drawing.
How to depict a HDR scene on a LDR display/canvas/print ?

Typical dynamic range of paint/print is only about 30:1.

HDR has always been an issue in classical photography
e.g. Ansel Adams, techniques for "burning and dodging" prints.



HDR images can now be made with consumer level software.

BTW, another image capture problem:
Panoramas / image stitching

- available in consumer level cameras
- based on homographies (2D -> 2D maps)
- traditionally part of computer vision curriculum, but many of the key contributions are by graphics people and are used in graphics

Announcement

- A4 posted (worth 6%), due in two weeks