1. Visual perception

Reading

Optional:

Glassner, *Principles of Digital Image Synthesis*, sections 1.1-1.6.

Brian Wandell. *Foundations of Vision*. Sinauer Associates, Sunderland, MA, 1995.

Research papers:

Spencer, Shirley, Zimmerman, and Greenberg. Physically-based glare effects for digital images. SIGGRAPH 95.

Ferwerda, Pattanik, Shirley, and Greenberg. A model of visual adaptation for realistic image synthesis. SIGGRAPH 96.

Outline

1. Image formation
2. Structure of the eye
3. Photoreptors
4. Visual phenomena

Forming an image

First, we need some sort of sensor to receive and record light.

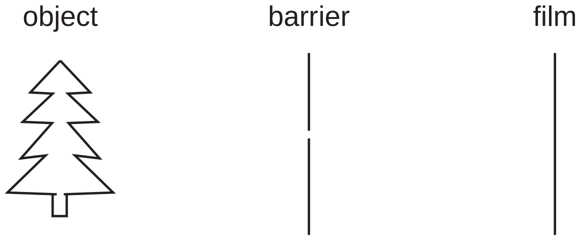
Is this all we need?

Do we get a useful image?

Restricting the light

To get rid of the blurriness, we could use a barrier to select out some of the light rays and block the rest.

This is called a **pinhole camera**.



Advantages:

- easy to simulate
- everything is in focus

Disadvantages:

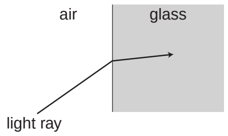
- needs a bright scene (or long exposure)
- everything is in focus

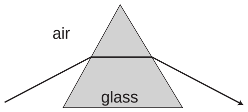
Collecting the light

Instead of throwing away all but a single ray, let's try to collect a bunch of rays and concentrate them at a single point on the sensor.

To do this, we need to be able to change the path of a light ray.

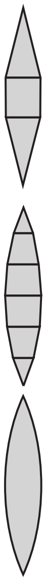
Fortunately, we have **refraction**. Light passing from one medium into a denser one will bend towards the **normal** of the interface.





Stacking prisms

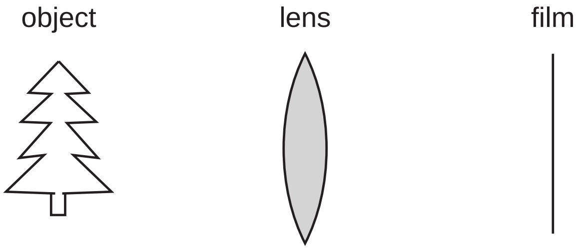
We can use variously shaped prisms to take light rays of various angles and bend them to pass through a single point.



As we use more and more prisms, the shape approaches a curve, and we get a **lens**.

Forming an image with a lens

We can now replace the pinhole barrier with a lens, and we still get an image.



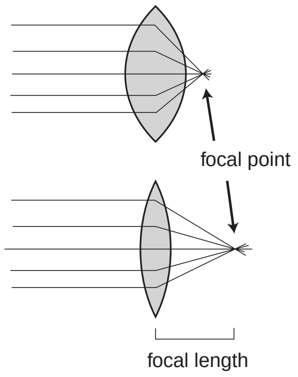
Now there is a specific distance at which objects are "in focus".

By changing the shape of the lens, we change how it bends the light.

Optics

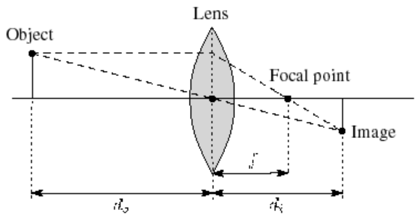
To quantify lens properties, we'll need some terms from *optics* (the study of sight and the behavior of light):

- **Focal point** - the point where parallel rays converge when passing through a lens.
- **Focal length** - the distance from the lens to the focal point.
- **Diopter** - the reciprocal of the focal length, measured in meters.
  - Example: A lens with a "power" of 10D has a focal length of ________.



Optics, cont'd

By tracing rays through a lens, we can generally tell where an object point will be focused to an image point:

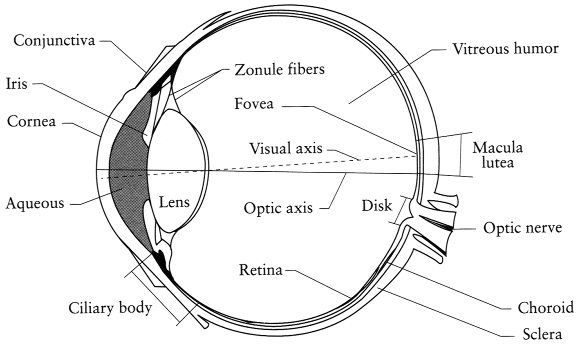


This construction leads to the Gaussian lens formula:

$$\frac{1}{d_o}+\frac{1}{d_i}=\frac{1}{f}$$

Q: Given these three parameters, how does the human eye keep the world in focus?

Structure of the eye

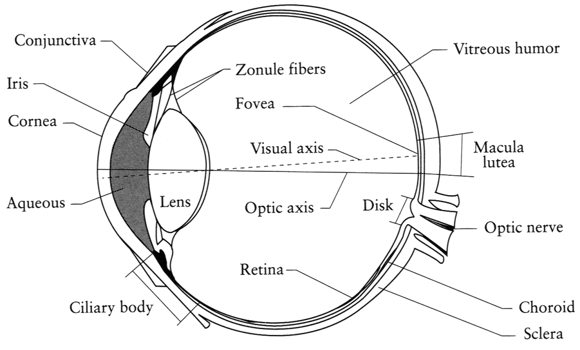


Physiology of the human eye (Glassner, 1.1)

The most important structural elements of the eye are:

- **Cornea** - a clear coating over the front of the eye:
  - Protects eye against physical damage.
  - Provides initial focusing (40D).
- **Iris** - Colored annulus with radial muscles.
- **Pupil** - The hole whose size is controlled by the iris.

Structure of the eye, cont.

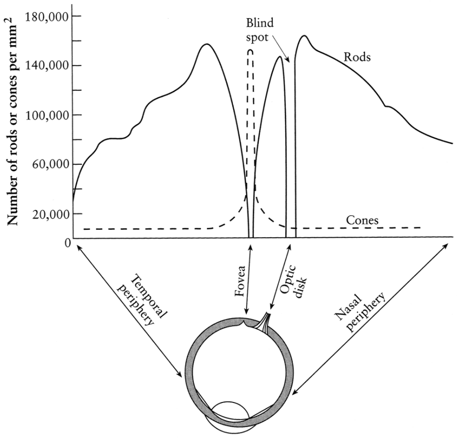


Physiology of the human eye (Glassner, 1.1)

- **Crystalline lens** - controls the focal distance:
  - Power ranges from 10 to 30D in a child.
  - Power and range reduces with age.
- **Ciliary body** - The muscles that compress the sides of the lens, controlling its power.

  Q: As an object moves closer, do the ciliary muscles contract or relax to keep the object in focus?

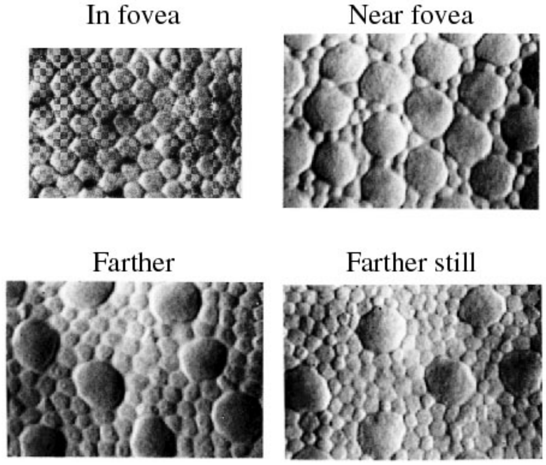
Retina



Density of photoreceptors on the retina (Glassner, 1.4)

- **Retina** - a layer of photosensitive cells covering 200° on the back of the eye.
  - **Cones** - responsible for color perception.
  - **Rods** - Limited to intensity (but 10x more sensitive).
- **Fovea** - Small region (1 or 2°) at the center of the visual axis containing the highest density of cones (and no rods).

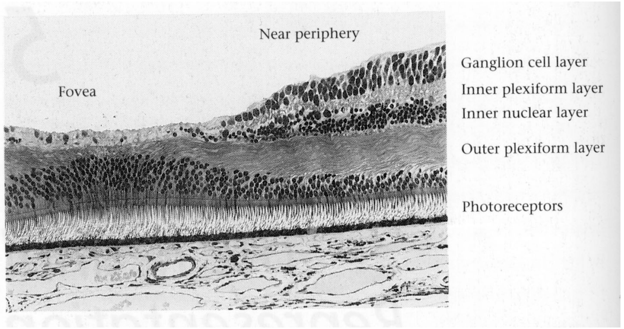
The human retina



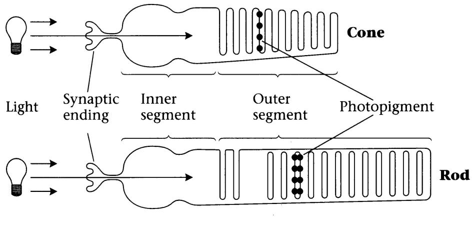
Photomicrographs at incresasing distances from the fovea. The large cells are cones; the small ones are rods. (Glassner , 1.5 and Wandell, 3.4).

Photomicrographs at increasing distances from the fovea. The large cells are cones; the small ones are rods.

The human retina, cont'd



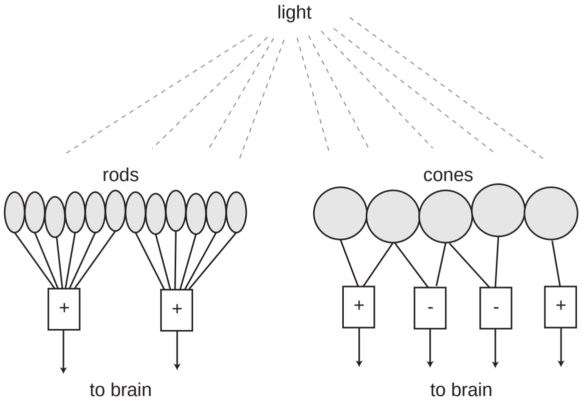
Photomicrograph of a cross-section of the retina near the fovea (Wandell, 5.1).



Light gathering by rods and cones (Wandell, 3.2)

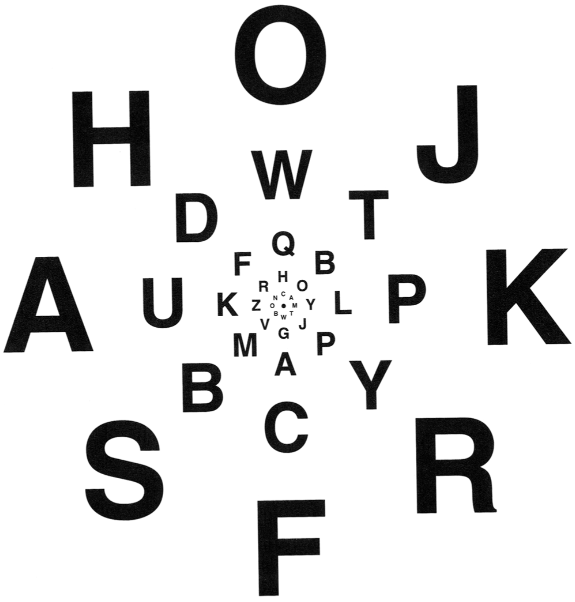
Neuronal connections

Even though the retina is very densely covered with photoreceptors, we have much more acuity in the fovea than in the periphery.



In the periphery, the outputs of the photoreceptors are averaged together before being sent to the brain, decreasing the spatial resolution. As many as 1000 rods may converge to a single neuron.

Demonstrations of visual acuity



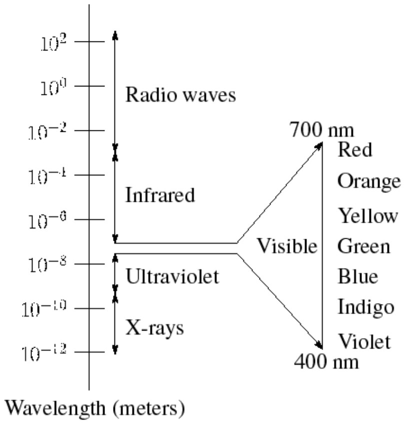
With one eye shut, at the right distance, all of these letters should appear equally legible (Glassner, 1.7).

Blind spot demonstration (Glassner, 1.8)

The radiant energy spectrum

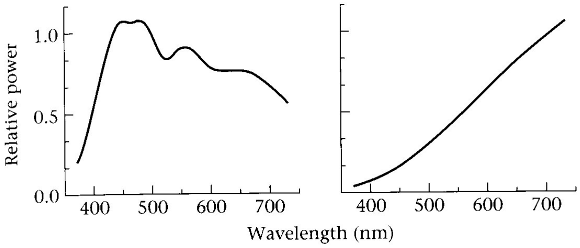
We can think of light as waves, instead of rays.

Wave theory allows a nice arrangement of electromagnetic radiation (EMR) according to wavelength:



Emission spectra

A light source can be characterized by an emission spectrum:



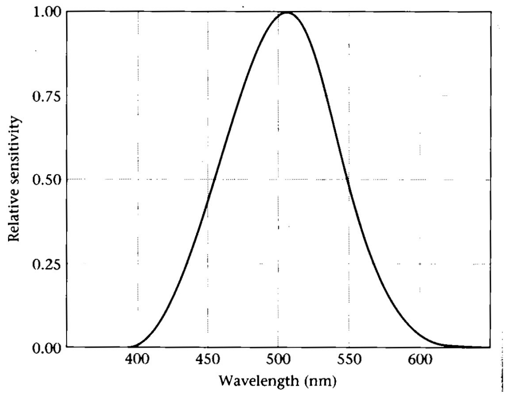
Emission spectra for daylight and a tungsten lightbulb (Wandell, 4.4)

The spectrum describes the energy at each wavelength.

Photopigments

Photopigments are the chemicals in the rods and cones that react to light. Can respond to a single photon!

Rods contain **rhodopsin**, which has peak sensitivity at about 500nm.

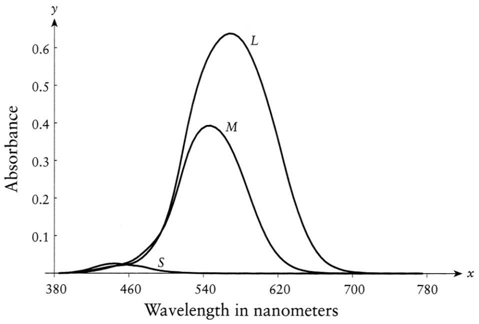


Rod sensitivity (Wandell ,4.6)

Rods are active under low light levels, I.e., they are responsible for **scotopic** vision.

Photopigments, cont'd

Cones come in three varieties: L, M, and S.

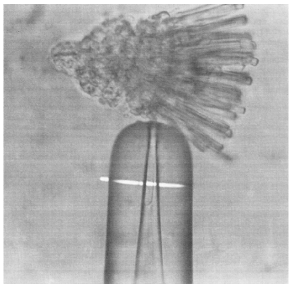


Cone photopigment absorption (Glassner, 1.1)

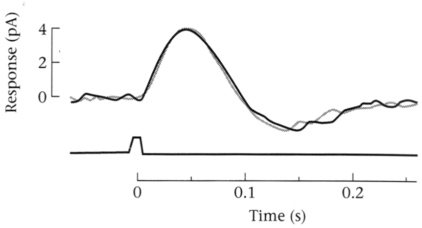
Cones are active under high light levels, I.e., they are responsible for **photopic** vision.

Univariance

Principle of univariance: For any single photoreceptor, no information is transmitted describing the wavelength of the photon.



Measuring cone photocurrent (Wandell, 4.15)



Photocurrents measured for two light stimuli: 550nm (solid) and 659 nm (gray). The brightnesses of the stimuli are different, but the shape of the response is the same. (Wandell 4.17)

Flicker

The photoreceptive cells provide a time-averaged response:

more photons ➠ more response

Above a **critical flicker frequency (CFF)**, flashes of light will fuse into a single image.

CFF for humans is about 60 Hz. (For a bee it's about 300 Hz.)

Q: Do all parts of the visual field have the same CFF?

Perceptual light intensity

The human eye is highly adaptive to allow us a wide range of flexibility.

One consequence is that we perceive light intensity as we do sound, I.e., on a *relative* or *logarithmic* scale.

Example: The perceived difference between 0.20 and 0.22 is the same as between 0.80 and _______.

Ideally, to display *n+1* equally-spaced intensity levels

$$\frac{I_1}{I_0}=\frac{I_2}{I_1}=\cdots=\frac{I_n}{I_{n-1}}$$

Example: Suppose $I_0=1/8$ and $n = 3$. What are the four intensity levels to be displayed?

Adaptation

Adaptive processes can adjust the base activity ("bias") and scale the response ("gain").

Through **adaptation**, the eye can handle a large range of illumination:

Background	**Luminance (cd/m^2)**
Moonless overcast night	0.00003
Moonless clear night	0.03
Twilight	3
Overcast day	300
Day with sunlit clouds	30,000

Lightness contrast and constancy

The apparent brightness of a region depends largely on the surrounding region.

The **lightness contrast** phenomenon makes a constant colored region seem lighter or darker depending on the surround:

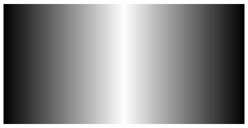
The **lightness constancy** phenomenon makes a surface look the same under widely varying lighting conditions.

Mach bands

Mach bands were first dicussed by Ernst Mach, and Austrian physicist.

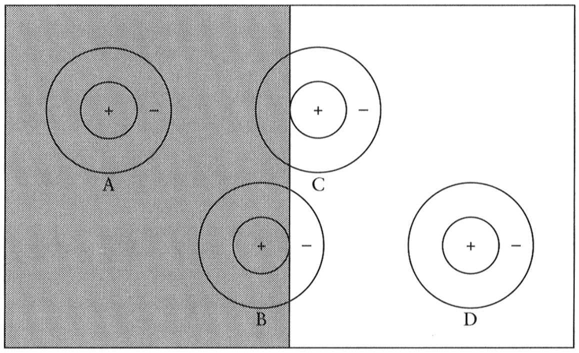
Appear when there are rapid variations in intensity, especially at C^0 intensity discontinuities:

And at C^1 intensity discontinuities:



Mach bands, cont.

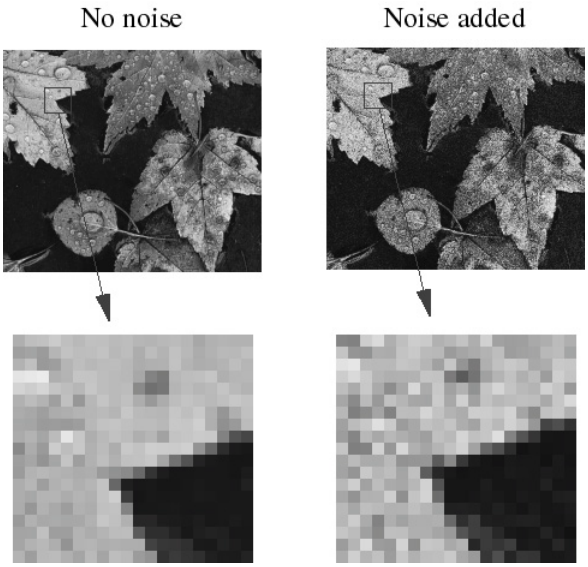
Possible cause: lateral inhibition of nearby cells.



Lateral inhibition effect (Glassner, 1.25)

Q: Why is this summation pattern useful?

Noise



Noise can be thought of as randomness added to the signal.

The eye is relatively insensitive to noise.

Summary

Here’s what you should take home from this lecture:

- All the **boldfaced terms**.
- How a camera forms an image.
- The basic structures of the eye and how they work.
- How light intensity is perceived on a logarithmic scale and is a function of wavelength.
- The phenomena of adaptation and lightness contrast.
- The eye’s relative sensitivity to intensity discontinuities, but insensitivity to noise.