

Animal Eyes

Prof. Ramesh Raskar

November 13, 2008

Lecture 9

This is a guest lecture by Quinn Smithwick based on the book *Animal Eyes*[1]. Section titles roughly match slide titles.

We use \Rightarrow to indicate reference to application in modern technology.

Eye Function

The fundamental purpose of the eye is to compare intensity of light coming from different directions. Hence, two characteristics are of importance:

directional resolution – comes from optics and photoreceptor density

sensitivity – ability to collect light, contrast (dynamic range)

Both are optimized for the environment, task, size, available computational power. For instance, a small fly has a tiny brain and need to navigate. In contrast, a big whale in the depth of oceans needs to collect the little light there is. We can distinguish different kinds of requirements:

- diurnal (day+night) vs. nocturnal
- flat vs. 3-d vision
- prey vs. predator
- slow vs. high speed

Thus, high directional resolution is not always needed or available. On the other hand, sensitivity might not be an issue if in bright light.

We'll see how different animal eyes evolved to match their environment. And remember, animal build the eyes from the stuff they eat. Also, animals don't always depend on light/vision, there are many other senses – often better in the environment.

Rhodopsin

Rhodopsin is the protein in photoreceptor. It's a light sensitive molecule that is actually a combination of *retinal* and *opsin*. Inactivated it's all folded up, but when struck by light

it unfolds and releases the opsin. This triggers a *signal transduction cascade* and electrical impulse in *bipolar cells* (a type of sensory neurons specialized for transmission of special senses). Retinal is also known as *vitamin A*, so it makes sense when mom's tell their children to eat carrots for better sight. Different opsin molecules absorb different wavelengths, leading to color vision using *cones*. Ratios of responses to wavelengths determine the perceived color.

Cryptochromes are special blue light photoreceptors that allow birds to see magnetic fields! Struck by blue light the protein separates. The more magnetic field the longer it stays active, hence it is less sensitive to incoming light. I.e., the more magnetic field present, the darker the vision. This way, birds can orient themselves with the magnetic field. One downside: it's superoxide - very toxic - so it's okay for birds, as they don't live long, but might be unhealthy for humans.

Preferential orientation of rhodopsin leads to polarization sensitive vision. In human eyes, they are stored in disc, no specific orientation, we're equally sensitive to all polarizations. But in some insects, they are aligned in particular direction so they can tell polarization. If we look in the sun, there is polarization band due to scattering. Bees can orient themselves to sun by observing this polarization.

⇒ See also solar compass that used polarizers to figure out where North is (also given as toys on airliner flights).

Parietal Eye

Parietal eye is not really an eye, it only detects light/dark but does not resolve direction. Lizards have light sensors in addition to regular lights. These sensors are used for thermoregulation, circadian rhythms, triggering hormone production, etc., but also general motion detection, e.g. occlusion in sky might indicate predatory bird. As this sensor sees blue/green it can sense time of day (because sky color changes red → blue → red). It might also help navigation.

⇒ Functionally, they are equivalent to street light switch photodetectors (which turn the street lights on at night).

Eye Spot

Eye spot is a single photoreceptor. By adding pigment to shield the photoreceptor from one side, we can sense directionality. The pigment definitely helps, if we're a unicellular euglena with translucent body. This way the euglena can drive itself towards the light. Note that the motion towards the light is spiral: it can only compare light intensity by changing body orientation, can't go in a straight line.

The reason this works is the Lambert's Law: the measured intensity depends on the incident angle of the directional light to the collecting surface.

Starfish and jellies have many eye spots (on each leg) despite having no central nervous

system (“intelligence in the extremities”).

Eye Pit

Depression instead of pigment shield gives greater directionality.

⇒ This is just like IR burglar alarm – if it crosses one beam and not the other then we detect the difference.

We can add more photoreceptors in a pit. That’s how snakes get their IR detection. Interestingly, even though the raw sensed data is like a blob, the brain can do edge detection and robustly tell rabbit from other things.

How does IR sensing compare to other light sensing? It’s more like sensing heat contact (like sensing heat in skin) than a photochemical process (there is no rhodopsin).

⇒ Could we use animal eyes directly in technology (rather than building cameras)? There are at least two challenges: eyes are active metabolically, and they give off a lot of information that needs to be processed quickly, but maybe one day...

Compound vs. Simple Eyes

Compound eyes are composed of many tubes, or *ommatidia*. These pigmented tubes provide very narrow field of view. Many photoreceptors (retina) share a single pit. The aperture is small for directionality, but is limited by diffraction.

⇒ This is similar to gamma/x-ray Soller collimators. (Which we use because we can’t bend these wavelengths.) These waste a lot of energy but we get some imaging.

Pin-hole Eye

⇒ This is analog to the pin-hole camera.

It uses pin-hole optics to form directional images. But pin-hole aperture leads to dim images, is open to environment, and faces diffraction problems. To protect the chamber, we can fill the chamber with transparent goo/jelly (humor) and cover the aperture with transparent layer (cornea). Note, there is only slight difference between the humor (1.34) and the water (1.33) so there is no actual refraction.

Spherical Lens

The protein *crystallin* concentrates to form simple lens. The diffractive index $n = 1.4 > n_{water} = 1.33$. This allows larger aperture, more light, sharper images. However, the lens needs small focal length (limited by the size of the eye), so requires small radius of curvature leading to spherical lens.

A spherical lens combined with a spherical sensor lead to spherical and chromatic aberrations. However, because the lens is radially symmetric and retina is curved, any asymmetric aberrations (astigmatism, coma) are absent or negligible. One benefit of spherical lenses (combined with spherical sensors) is that focus length is independent of direction.

One problem with spherical lenses is in-lens focusing (the rays cross inside the lens). How can we prevent this? We could use a pupil, but that restricts directionality. Or...

GRIN Lens

...use a gradient index (GRIN) lens. Change index of refraction radially (due to concentration of crystallin) from 1.38 (in periphery) to 1.52 (in the core). Now the light rays bend continuously within lens, providing spherical-aberration-free images. We get shorter focal length without in-lens focusing, which leads to greater light gathering power.

⇒ GRIN in modern technology allows fewer elements to correct aberrations leading to more compact/lightweight designs. Layered lenses: make a GRIN sheet, stamp it to bend it. In photocopiers: there is no circular lens – there’s a GRIN rod, it acts as an optical relay transferring the image from the paper to the drum.

Chromatic Aberration

Different wavelengths bend at different angles leading to different focus lengths. Remember diffraction grating is the opposite of prisms/lenses: ”blue barely bends, red rotates radically” (true in gratings, opposite in prisms).

⇒ In cameras, we can use gratings combined with lenses to cancel out chromatic aberrations, for instance diffractive-optic lens from Nikon (D-O lens).

In animal eyes, put different photoreceptors at different depths (e.g., spider) but retina is very thin, so the possible variation is limited.

⇒ Technological equivalent is Foveon S3 sensor stack.

Alternatively, vary the refractive index of the lens (GRIN-like) so there are multiple foci. The red from inner radii focuses at same plane as the blue from outer radii (e.g. cats).

Focusing

One focal length is not going to work at all distances. Bigger eyes collect more light (aperture) and also more angular resolution for given receptor size, but result in shallower depth of focus.

Fish and cephalopods move the lens relative to the retina to change focus (using muscles).

⇒ New technology explores mechanics-free focusing – apply current to change the shape or refractive index.

Visual Streaks and Fovea

Ganglion cells receive the electrical signals from many photoreceptors and send them to the brain via the optic nerve. Creatures that live in 3-d worlds (birds, flying insects, fish...) have the ganglion cells evenly distributed. For surface animals, the ganglion cells are concentrated with higher density in a "visual streak". This leads to high resolution vision and greater processing allocation in the horizontal plane (e.g., horses, surface feeding fish, rabbits, seabirds, dogs).

Other animals have area centralis (fovea) – single or multiple regions with high ganglion cell density in a small visual field – that is combined with moving the eyes around. This scanning and fixation allows to perceive high resolution in large fields of view.

⇒ This resembles the NASA/JPL multiresolution foveal camera – a dynamically reconfigurable vision system, with pixels as basic resolution elements.

Prof. Raskar observes that another way to achieve similar result is to keep sensor resolution constant but use the lens to distribute the angular resolution over the sensor. Then the image is warped, and needs to be processed, but we effectively get more sensors looking at the directions of interest.

Multiple Lenses

Pontella has three lenses to focus the light. The first lens is aspherical to avoid spherical aberration. Using multiple lenses, each lens needs to bend the light less, leading to lower aberration at the end.

⇒ Multi-element lenses by Canon or Nikon. Why do we have so many lenses in cameras? A single spherical GRIN lens would solve the problem, but won't work on planar sensor and still has chromatic aberration. Single-n lenses are cheaper than GRIN and work fine with a flat sensor (which is also cheaper to manufacture on a silicon wafer). Also note that in traditional film photography, we had to do all the correction in optics, as there was no software to dewarp the image.

Remember, when refocusing, we need to adjust all elements of the system.

Cornea

In water, the cornea has little focusing power (index of refraction $n \approx 1.4$), but in air, a lot of bending happens on the cornea. The focusing power can be divided between cornea and the lens in ratio 1:2. That's why it's so difficult for to focus in water. Flat goggles help as they introduce a layer of air before the cornea.

Aspherical corneas reduce spherical aberrations. Although off-axis aberrations may be greater, we still can get higher resolution in the fovea.

Accommodation

Fish move the lens relative to the retina. But mammals, birds and reptiles can deform the lens: changing the radius of the curvature changes the focal length. Interestingly, lens are naturally balls that are stretched into ellipses. So focusing the eye to a shorter focal length actually relaxes the muscles.

⇒ Fluid/liquid lens from a-star or Varioptic can change shape. Prof. Raskar hints another company LensVector has new technique that changes the refractive index of LCDs electronically.

Iris/Pupil

Prof. Raskar notes: at any stage of technology, many of these animal designs are not practical, but over time, we can get inspired to create materials that can work like this, or go back biology to exploit biological principles – completely change the wiring. "All of the ideas are out there, they will completely change the game in a few years."

Quinn notes: it took nature half a million years to change eye from pit-balls to lenses...

Light collection increases with aperture size, but spherical and other aberrations increase with aperture. Pupil in vertebrates varies to obtain the best compromise between sensitivity and resolution.

Arythmic animals (day+night) must protect the photoreceptors. Fish don't have eyelids, and need to swim away to protect eyes.

Circular pupils cannot restrict below a certain limit due to muscles. In contrast, slit pupils can close smaller and perhaps faster (e.g., octopus, snake, horse, cat, etc.). Cats have two moving circular openings, allowing huge dynamic range. In contrast, humans can only restrict the light 1:2.

Note, if we used multi-focus lenses (like cats) then circular iris would block the blue ray focus (coming from peripheral rays), but slit preserves all. Note, often we don't need all of the colors, as long as at least one color stays in sharp focus.

⇒ we have irises in our cameras. To photograph nuclear bomb explosions, Edgerton used two polarizer plates to quickly control intensity of incoming light.

Nocturnal Animals

Nocturnal (also deep-sea) animals have large pupils to collect as much light as possible. In this case, resolution is not as important as sensitivity.

In fact, at such low levels of intensity, we start observing statistical nature of light. The noise level at the amount of light we get determines the effective resolution. This leads to lower contrast. Because in low light we just can't get enough contrast+resolution, there is no point trying to increase the resolution. Instead, just get all the light you can. Hence,

we get large pupil aperture, large eyes, large lenses (which reduces visual acuity), and lots of rods (typically color-blind).

Reflective Eyes

Tapetum lucidum behind retina reflects the focused light from the lens back again through the retina for a chance to be captured again (for increased sensitivity), e.g. in cat eyes.

What if we get too much light from the double pass? Sharks actually have pigment to cover the reflective coating – so that light only passes the retina once – to protect the retina.

Amphibious Eyes

Eyes that work in both air and water need to deal with the change in refractive index. The diving duck pushes the lens through the pupil to form a bulge with a very small radius of curvature.

⇒ This gives an idea for new technology: push material through a hole to shape it.

Surface feeding fish use a two curvature lens like bifocal lenses.

Reflective Eyes

Tapetum lucidum in cat or dog eyes is only used for double-pass light gathering. In contrast, here a parabolic mirror is used for focusing. The physics behind the reflection is thin-film interference.

⇒ Compare to a satellite dish or radio-telescope.

A parabola is great for focusing, but works bad for off-axis. A spherical lens works great for off-axis, but causes aberrations.

⇒ In telescopes we use spherical mirror + corrective plate for the second bounce.

Animals have spherical mirrors with correction lenses too, e.g.. scallop.

Compound Eyes

In a fly eye, each tube (ommatidium) gets a lens, and one or more photoreceptors. The brain combines the image to look like a single eye (not millions of eyes). The lens is not really focusing; it's more like light fiber that gets light from some direction. Therefore, the image resolution is really bad, just 1 deg. (like your thumb at the distance of your arm). The fundamental limitation is that diffraction (of the small aperture) limits field of each ommatidium to min 1 deg.

The class noted that there is no backtracking in evolution, once you go down the path of the compound eye, you are stuck bad resolution!

⇒ CCD/CMOS sensor chips have a micro-lens over each photo-element. This 2-micron wide lens on each pixel gathers the light that would otherwise hit the electronics in the element. In the Columbia CAVE lab, camera arrays on bendable sheets have been explored. Although plenoptic cameras also use lenslets array, there is a main lens + a lenslet, so it's more of a hybrid design.

⇒ The Multi-lens Array System by Sony and UAHuntsville has 271 elements, offering gigapixel resolution, imaging $10km^2$ area from an altitude of $7.5km$ resolution better than $50cm$ per pixel. However, Prof. Raskar notes the fundamental limit on angular resolution: the aperture has to be wide enough to avoid diffraction (“the aperture defines your angular resolution”). For 50Gpix resolution you'd need a 1 meter wide aperture.

Superposition Eyes

So far we had apposition: different eyes look at different angular zones. In superposition eyes, rays from different ommatidia hit the same receptor. Such eyes are more sensitive than apposition compound eyes, but require special optics (GRIN lenses, mirrors, etc.) to focus rays from different lenses to a single point on the receptor. Examples include moth and lobster.

⇒ GRIN rod fiber collimators; wide-field X-ray imaging / Lexid X-ray imaging; solar collectors.

Multiple Eyes

Unlike in compound eyes, multiple simple eyes are independent. Spiders have 8 simple eyes: 4 narrow FoV tracking, 4 wide FoV motion. Interestingly, in spider eyes, the retina moves not the lens! In brittle starfish, the whole body is one big compound lens.

Movement

Animals use body motion to increase field of view, to judge distance, and also to stabilize the image. For instance, if you see a spider wiggling, wiggle with it so that it'll underestimate the distance and hit the ground. Class notes chickens move their heads moving back and forth (because their eyes are looking to the sides). Humans have 6 different muscles controlling eyes (rotation is also controlled). Octopus always aligns its eyes horizontally.

⇒ We use line scanning to increase the field of view in many applications: satellite imaging, photo-finish.

Quinn mentions there's a sea animal that can only see a line, but does not need to move – it's just waiting for plankton to float by towards the surface.

Human Future Evolution

What if we colonize Mars? What if many generations later we have colonists that have never been to Earth? Mars is a different environment, how will our eyes adapt and evolve? How is Mars it different? More red, thinner atmosphere... Some magazine cover shown humans with green slit pupil on human colonists.

References

- [1] Michael F. Land, Dan-Eric Nilsson *Animal Eyes* Oxford University Press, 2001

MIT OpenCourseWare
<http://ocw.mit.edu>

MAS.531 / MAS.131 Computational Camera and Photography
Fall 2009

For information about citing these materials or our Terms of Use, visit: <http://ocw.mit.edu/terms>.