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From the Editor

Here's the "summer" issue of The Biological Physicist, highlighting two biological physics journals – one is a print journal, and the other lives online. Also check out a new funding program from HFSP. And turn to page 2 to learn what freshman physics can tell you about the evolution of your own eyes!

Our next issue will appear at the end of August, featuring more lab profiles. If you have an idea for a lab or department profile, or want to write an essay about a topic of current interest in biological physics, send me an email! We are still at the beginning of Volume 2 of The Biological Physicist, and have many virtual pages to fill over the coming year. I look forward to your input!

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Essay

Evolution of the Eye: Lessons from Freshman Physics and Richard Dawkins

by Sonya Bahar

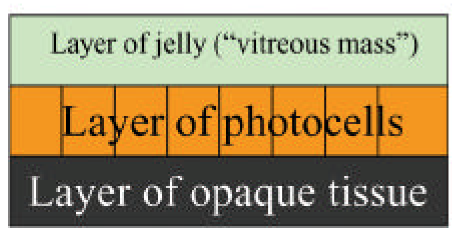
How can you read this page? How can you see to avoid bumping into your department chairman in the hallway? *How did the eye evolve?*

The question of eye evolution has long puzzled biologists (not to mention "creationists", who often use the supposed complexity of the eye as an argument against evolutionary theory). The complexity of the eye was baffling to even Charles Darwin himself, who wrote that "[t]o suppose that the eye, with all its inimitable contrivances for adjusting the focus to different distances, for admitting different amounts of light, and for the correction of spherical and chromatic aberration, could have been formed by natural selection, seems, I freely confess, absurd in the highest possible degree." [1]

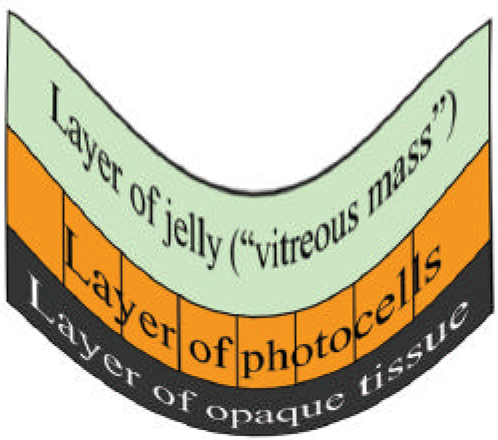
But it is not absurd. It is simply a question of natural selection acting on freshman physics. Once you start with a light-sensitive cell, the rest is almost easy! Light-sensitive cells abound in nature, though the particular pigments they use, and the relation between photosensitivity and neural firing, is not completely understood in all cases. For example, the crayfish has two light-sensitive neurons in its rear end (actually in its 6th abdominal ganglion) [2,3]. These neurons fire slowly (at around 5-7 Hz) in the dark, and speed up to around 30 Hz when subjected to bright light. (The light sensitivity in the crayfish photoreceptors is thought to enhance the animal's sensitivity to hydrodynamic motion, and to be related to a predator escape response [4].) There are even light-sensitive cells in butterfly genitals, male and female, though what they are used for only the butterflies themselves seem to know [5].

So if you have a light-sensitive cell, how do you get from that to an eye without divine intervention? One photocell by itself can sense the presence or absence of light, nothing more. But if the cell is attached on one side, apical or basal, to a "dark screen" of opaque tissue, it can detect, albeit in a rudimentary way, the direction of the incident light. As Richard Dawkins writes in his beautiful book *Climbing Mount Improbable*, "An animal with only one photocell in its head can steer towards, or away from, light, provided the photocell is backed by a screen. A simple recipe for doing this is to swing the head like a pendulum from side to side; if the light intensity on the two sides is unbalanced, change direction until it is balanced. There are some maggots that follow this recipe for steering directly away from light." [1]

Suppose you have a few light-sensitive cells, backed by opaque tissue-screens, lined up, like this:



(Note that we have laid a hypothetical layer of a jelly-like vitreous mass on top of the photocells. For now, one can consider this a protective, but translucent, tissue layer, insulating the delicate photocells from the eternal environment. It can play a much more significant role than that, however, as we will see below.) Suppose this line of light-sensitive cells curves into a concave “cup” shape with the photosensitive regions of the cells on the inside of the cup, like this:



Different photocells now point in different directions, and directional sensitivity is greatly enhanced. The proto-eye can now sense, in a crude fashion, the angle of incident light.

But, this concave eye-cup cannot form an image. If an object is placed directly in front of the cup, light rays from every part of the object will impinge on all the photocells in the cup, forming an infinity of images. To get a single image, one must consider the principle of the pinhole camera. If the cup becomes deeper and deeper, its edges closing to a narrow aperture, like this:

then a single (inverted), image will be projected onto the photocells lining the surface of the cup.

Let’s pause for a moment, though, to consider how we “get” from a single photocell, backed by opaque tissue, to this cartoon model of a pinhole-camera eye. In order to understand this, it is critical to understand a basic principle of natural selection. A frequent claim made by creationists is that they eye could not have arisen by natural selection “because what good is half an eye?” This argument misses a critical point. In fact, a little photosensitivity *is* better than none. An animal with a photosensitive cell in its head, or anywhere else on its body, has can sense more of its environment, and thus has better skills for coping with life, than an animal without such a cell. So it has a selective advantage. By the same token, an animal with a concave cup of photosensitive cells can do a little better still, since it can not only perceive light but also the direction from which the light is coming – potentially a big advantage for sensing the location of predators or prey. So, even though this hypothetical animal still cannot form an image, it can navigate its environment better than an animal without such technology. If you want to think of this as half an eye, or 7% of an eye, or whatever, that’s fine. In this sense, part of an eye *is* better than none.

Now let’s return to the pinhole camera eye. This setup can form an image, but we are still a long way from Rembrandt! The pinhole eye still has problems. First of all, a very small pinhole can act as a diffraction grating, blurring the image. Secondly, a pinhole eye doesn’t let in very much light, so image formation becomes problematic in low-light conditions. These problems can be solved by returning, again, to undergraduate physics. Replacing the pinhole camera eye with a lens eye solves both these problems. First, lenses exploit the refractive properties of light to focus light on a point. A lens would also solve the “diffraction grating” effect of a small pinhole, since it would let in much more light. But how do we make the transition from a pinhole eye to a lens eye?

Importantly for the evolutionary argument, a lens does not have to be carefully ground in order to significantly improve image quality. Even a semi-transparent lens with irregular curvature will bring some improvement. Richard Dawkins shows a beautiful example of this in Figure 5.12 of “Climbing Mount Improbable”. He conducted a simple experiment in which he hung a plastic bag full of water in front of a pinhole camera. Even this lousy lens give a much sharper image than the pinhole alone. Open up the pinhole to let in more light, and make the curvature of the lens smoother, and the image is improved again. As before, each little improvement gives an advantage to the animal who possesses it. As Dawkins puts it, “None of these splodges of jelly would move Mr Zeiss or Mr Nikon to write home. Nevertheless, any lump of jelly that has a little convex curvature would mark significant improvements over an open pinhole.” [1]

But biologically how would a curved, transparent lens arise? We have already imagined that on top of the photocells is another layer – a gel-like, translucent tissue. Small distortions in the volume and curvature of this tissue could easily give rise to a crudely lens-like structure:

Dan-Erik Nilsson and Susanne Pelger [6] conducted a simulation in which they varied different parameters in just such a three-layer construction, changing only one parameter in each step, and then only by a small amount. They considered parameters such as concavity of the entire system, (picture their construction bending into a cup-like shape with the layer of opaque tissue on the outside), convexivity of the vitreous mass, thickness and refractive index of the vitreous mass. They showed that a continuous series of transitions can lead from the three-layer construction to a fish-like eye in 364,000 generations or, they estimated, half a million years. (Of course, if any of my readers are “young earth creationists” who believe the earth to be only 4000 years old….well, that’s an argument for another essay.) Nilsson and Pelger published their simulations in a landmark paper entitled “A pessimistic estimate of the time required for an eye to evolve” [6].

Of course, there is a long way between computer simulations and real eyes. There are a number of other adjustments that make animal eyes particularly useful – muscular control which allows for changing aperture size (look at the your cat’s pupils in the dark and then when she is sitting on a windowsill in bright light!), muscular control over the shape of the lens, allowing the eye to focus on objects at various distances. And we have not even touched on the many different types of eyes that appear to have evolved separately in vastly different types of animals (vertebrate lens eyes vs. insect compound eyes, for example), let alone the neural processing of visual information. But the simple arguments by Dawkins, Nilsson and Pelger suggest that the evolutionary process through which vision developed is, in principle, fully decodable. The process can be deciphered using the tools of biological physics, neuroscience, freshman physics, and the principle of natural selection.

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