# Drawing Inspiration from Biological Optical Systems

**H.D. Wolpert**

**Bio-Optics:** wolpert.bio-optics@dslextreme.com

**Abstract**

**B** io-Mimicking/Bio-Inspiration: How can we ***not*** be inspired by Nature? Life has evolved on earth over the last 3.5 to 4 billion years. Materials formed during this time were not toxic; they were created at low temperatures and low pressures unlike many of the materials developed today. The natural materials formed are self-assembled, multifunctional, nonlinear, complex, adaptive, self-repairing and biodegradable. The designs that failed are fossils. Those that survived are the success stories. Natural materials are mostly formed from organics, inorganic crystals and amorphous phases. The materials make economic sense by optimizing the design of the structures or systems to meet multiple needs. We constantly "see" many similar strategies in approaches, between man and nature, but we seldom look at the details of natures approaches. The power of image processing, in many of natures creatures, is a detail that is often overlooked. Seldon does the engineer interact with the biologist and learn what nature has to teach us. The variety and complexity of biological materials and the optical systems formed should inspire us.

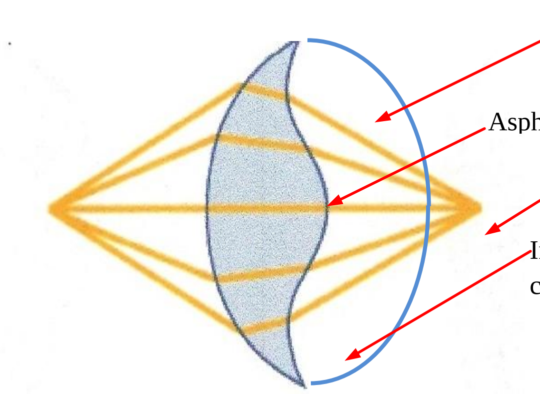
**Key Words:** Bio-Mimicking, Bio-Inspiration, Biological Optical Systems

## 1.0 THE DAWN OF BIOLOGICAL OPTICAL SYSTEMS

The dawn of biological optical systems can said to begin with the trilobite, Figure 1. Eyes of the trilobites were the first to use optics coupled with a sensory perception in nature. Trilobites emerged at the beginning of the Cambrian era some 570 million years ago and became extinct about 250 million years ago. Some of the eyes are characterized by a close packing of biconvex lenses beneath a single or separate corneal layer that covers all the lenses. These lenses are generally hexagonal in shape and range from one to more that 15,000 per eye. The eye lens is rigid without accommodation; instead the lens was formed as a doublet with an aspheric correcting interface. The outer lens was made from calcite orientated along the c- axis with a refractive index of 1.66, Figure 2. Calcite micro-lenses in the brittle star also exhibit this specialization of crystal orientation, without the aid of x-ray diffraction or other techniques [1].

Figure 1 Trilobite Fossil

The intra-lensar bowl has a calculated index of 1.63 speculating that a perfusion of a small amount of soft organic tissue could have easily reduced the refractive index of calcite to the inferred value. The design of the trilobite's eye could qualify for a patent disclosure. Prior art in the patent would mention the Schmidt telescope plate in performing a function similar to that of the wavy interface of the trilobite eye lens. The refracting interface between the two lens elements follows a design worked out by Descartes and Huygens in the mid-seventh century [2].




**Side Bar:** To put the age of Trilobites in perspective: Trilobites appeared 570 Million years ago, died 250 Million years latter. The first dinosaur appeared on earth approximately 230 million years ago and went extinct 165 million years latter. After the dinosaurs disappeared 65 million years ago people appeared on earth [3].

Figure 2 Biconvex Trilobite Lens
(Adopted from: smgon@aloha.net)

Many of the trilobite eyes are turret like, in the shape of truncated cones. The combined visual field of the two eyes covers the animal's entire surroundings. Figure 3 is an example of one such eye.

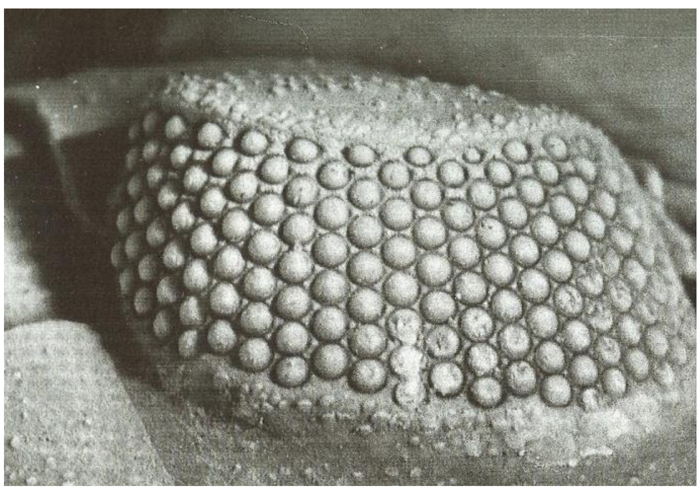


Figure 3 *Reedops* Trilobite Eye [2] (Figure courtesy of Riccardo Levi-Setti and the U. of Chicago Press)

## 2.0 BIOLOGICAL SCANNING OPTICAL SYSTEMS

Scanning optical system designs are not uniquely owned by man. There are several biological designs that are unique and inspire bio-mimicking. The mantis shrimp is one such biological specimen. The two apposition compound eyes are mounted on mobile stalks that are independent of one another as shown in Figure 4. The eye movements involve rapid sequencing or redirection for targeting prey (i.e., saccadic movement) after which they stabilize the image and slowly track the object. During the saccadic movement there is a momentary blindness to allow the animal to change its point of fixation without being dragged back to the starting point by reflexes that normally stabilize the glaze. The whole process of redirecting the gaze, tracking a moving object, in which the two eyes appear to move independently, often up to $70^0$ in an instant, stabilizing the image, and slowly scanning an object are essentially uncorrelated.

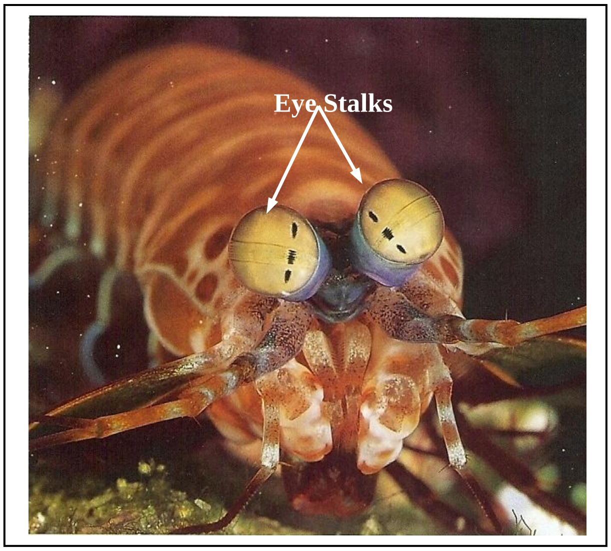



Figure 4  Mantis Shrimp  (Picture courtesy of Roy Caldwell, UC Berkley)

Each eye of the mantis shrimp has three distinct views of the same object in space; imaging in the upper hemisphere, the middle, and lower hemisphere's of each eye. This is evident in Figure 4, where three pseudo pupils in each eye are seen as "dark" spots indicating that they are all aligned to absorb light coming from the same direction. These three overlapping fields could provide a form of monocular range finding, analogous to binocular triangulation in the human eye. A close-up view of a gonodactyloids mantis shrimp is seen in Figure 5. This eye has a band of six ommatidia separating the upper and lower hemispheres of the eye (The squilloid mantis shrimp has only two parallel rows in their mid-bands). Rows one through four of the gonodactyloids shrimp mid-band are for color vision. Each of the four bands has eight different visual pigments giving it a visual range from 400nm to 550nm making it truly multi-spectral. In addition, each of these four rows has three additional layers containing carotenoid compounds to tune and shape the wavelength of light that reaches the visual pigments allowing the wavelength band to be extended to 650nm in almost ten equal spectral intervals [(4)]. With this degree of spectral resolution the ability to distinguish subtle color differences is unique. Rows 5&6 of the central band are used for detection of UV and polarized light. These ommatidia simultaneously measure four linear and two circular polarization components [(5)]. Polarization sensitivity enhances the contrast vision in a liquid environment as any microscopist knows in attempting to image living cells in a liquid.

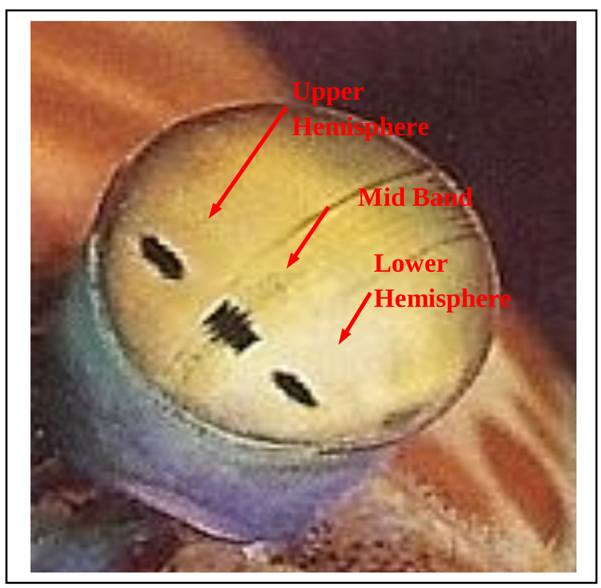



Figure 5 Close-up of Mantis Shrimp Eye (Picture courtesy of Roy Caldwell, UC Berkley)

We haven't talked about the upper and lower hemispheres of the eye. Both only have one type of photo-pigment. The upper hemisphere is sensitive to only short wavelengths the lower to only longer wavelengths. Both hemispheres are apparently used to capture form and motion [(6)]. The two hemispheres of the eye have overlapping fields-of-view by as much as $20^0$ to $30^0$. For these ommatidia of the hemispheres to function effectively, the fields must be stabilized, but not so for the center band, which must be scanned across a region of special interest to gather color and polarization information. This mid-band must be scanned over an angle of about $12^0$ at roughly $40^0$ per second [(1)]. Capable of rotating, the eye, this mid-band, can be orientated to scan across a region at $90^0$ to the long dimension of the band to obtain the best quality information. It was found that the paradoxical situation of stabilization, for the upper and lower hemispheres and scanning of the mid band, is solved by time sharing these functions of the eye.

The linear scanning capability of the mantis shrimp eye is analogous to multi-spectral scanners designed by man. A basic layout of such a multi-spectral scanner is shown in Figure 6. This is shown for an aircraft or spacecraft system viewing the ground.

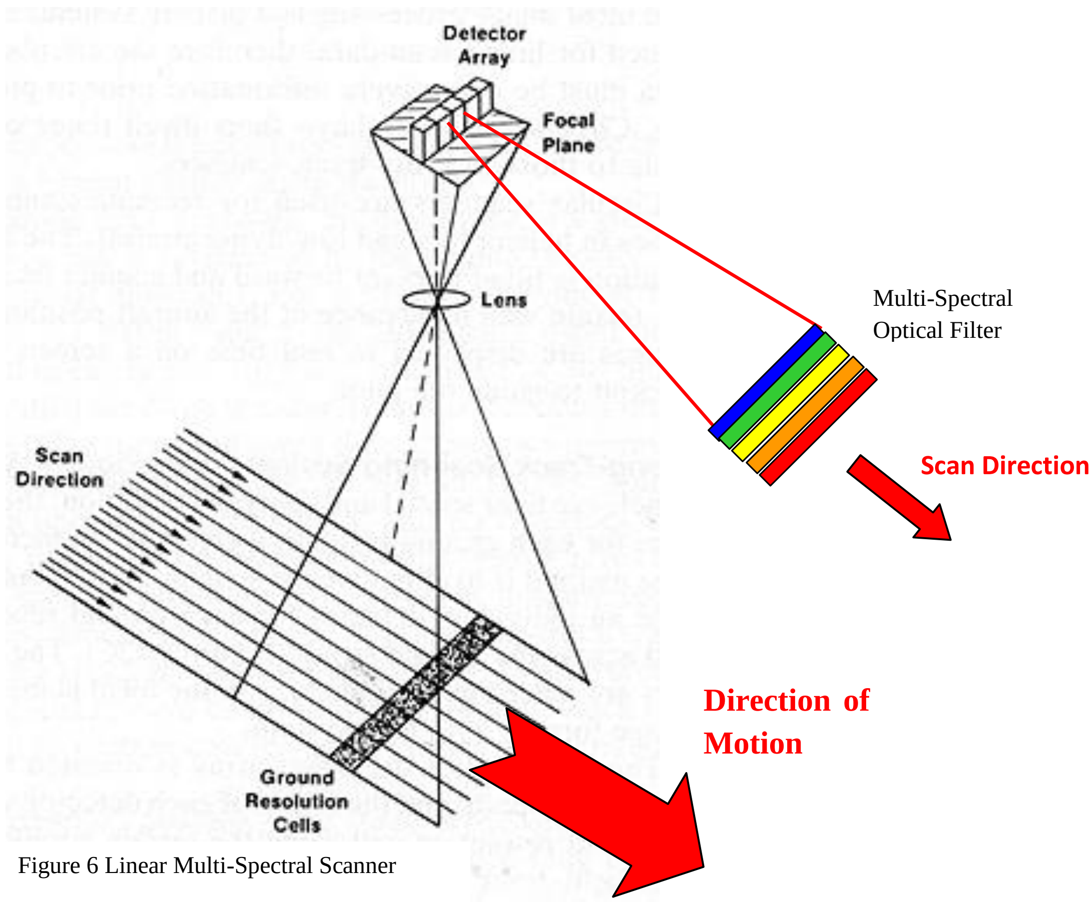
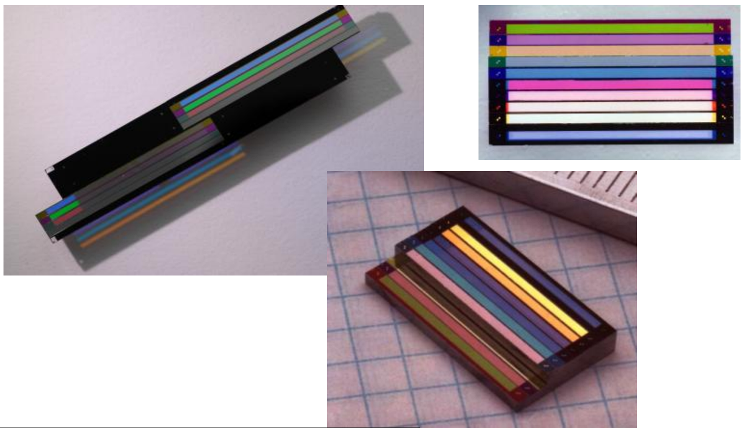



Figure 6 Linear Multi-Spectral Scanner

Scanning in this instance comes about by forward motion of the airplane or the trajectory of a spacecraft carrying the multi-spectral imager. In a ground based system, a scanning mirror, replicating the scanning motion of the mantis shrimp eye, would be required.

The heart of any multi-spectral scanner is the multi-spectral optical filter (*Ommitidia*) and the detector focal plane (*Photoreceptors*) and this is the case for the mantis shrimp. An example of some Landsat multi-spectral filters are shown in Figure 7. Cut into strips and bonded together, the filter assembly is positioned in proximity to a focal plane. The expense of these assemblies results from the accuracy of the various optical filters central wavelengths, the bandwidths, sharpness of the cut-on and cut-off slopes, out-of –band blocking, low scattering characteristics, mechanical tolerences and they are one of a kind, not self assembeled as in the mantis shrimp.

**Linear Multi-Spectral Optical Filters**



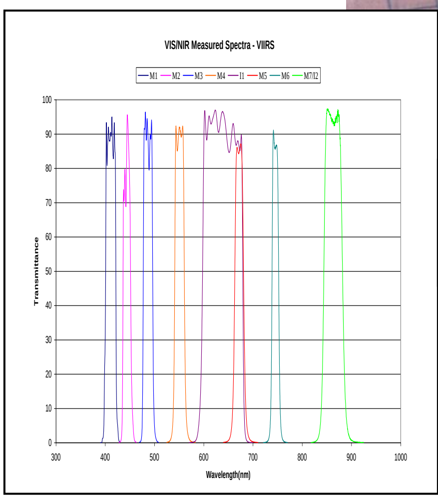



Figure 7 Landsat Type Multi-Spectral Filters (Figures courtesy of Barr Assoc. Westford, MA.

Making the parralism's of existing scanning multi-spectral imaging technology to natures approach is easy but the point may be lost. We constantly "see" many similar strategies in approaches, between man and nature, but we seldom look at the details of natures approaches. Seldon does the engineer interact with the biologist. While Landsat multi-spectral approaches may require sharp cut-on and cut-off optical filters, there are other applictions where subtile color differences, in low color contrast environments or camouflaged situations, may be required. Detection of objects of interest, in this instance, may be better served with more spectral bands that have some overlap to bring out slight color diffferences. Image processing, in many of natures creatures, is often overlooked. We have to be inspired with the image processing that goes on within the Mantis shrimp. They have the upper and lower hemispheres doing motion detection and shape detection requiring stabilization of the eye. The scanned, central band, is detecting color, it can do ranging and detect polarization and each eye can target a different part of its visual field. All of this is done in real time, at low power with a computer (*brain*) that is small in size.

Besides the mantis shrimp there are other creatures that have evolved independent eye movement, that can point each eye in a different direction. In this mannor they can be doing surveillance with one eye and detection of objects of interest with the other eye but in different parts of the object field.

### 2.1 Jumping Spider & Telephoto Optical Systems

Nature has developed, through evolution, other scanning optical sysems worthy of bio-inspiration. Spiders have opted for single eyes rather than compound eyes. Most have eight eyes in all (Some have six) and these are of two kinds: The two large principle eyes, in the jumping spider, point forward, have a rather small field-of-view. The secondary eyes are fixed; they cover more peripheral fields-of-view and act only as motion detectors. If motion is detected in the secondary eyes they direct the attention of the spider to the principal eyes. The two principal eyes have rather narrow fields-of-view. The retina of each eye is long and narrow, around $1^0$ by about $20^0$, orientated and shaped like a boomerang. The retina can move horizontally $10^0$ and torsionally rotate $\pm 25^0$ to get the best aspect to scan over an object of interest and inspect it [7][8].

Another interesting aspect of the jumping spider's principal eyes is that they have a telephoto capability. There is a pit or depression in the center of the principal eye. The concave negative surface at the bottom of this pit functions optically as a negative magnifying lens, increasing the effective focal length of the eye, providing the eye with 50% better acuity. With this telephoto lens the visual acuity of the spider approaches that of man. A similar telephoto pit exists in the eyes of hawks as shown in Figure 8.

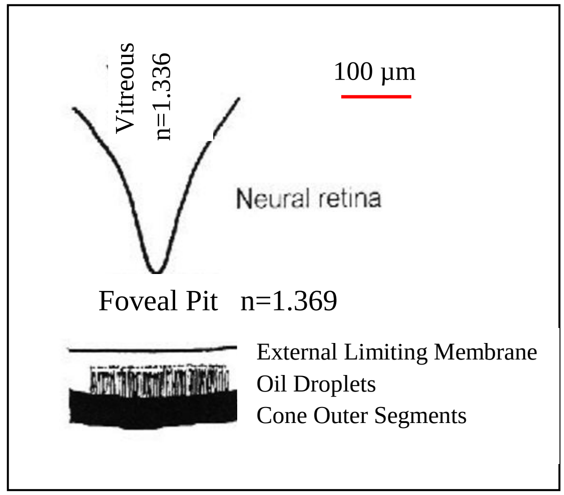



Figure 8 Hawk Telephoto Neural Retina (Figure courtesy of M.L. Land, U. of Sussex, UK)

### 2.2 Other Bio-Optical Scanners

The sea snail *Oxygyrus* is from a group of mollusks that have a peculiarly narrow retina consisting of three receptors wide by about 410 receptors long that covers a field-of-view of about $3^0$ by $180^0$. The one dimensional structure of the retina would make little sense unless it moved in some way and it indeed does. The eyes move sweep through an arc $90^0$ at right angles to the long dimension of the retina, reminiscent of a Nipkow scanner. Two exterior lenses focus light on a smaller interior lens set deep inside the body. The second lens and photoreceptors move constantly across the plane of the exterior lenses like a TV camera. It takes this creature from 1/5 of a second to several seconds to form a complete image. In some ways this is similar to a confocal scanner.

## 3.0 BIOLOGICAL OPTICAL SENSOR FUSING

Some reptiles, bats and moths have the ability to see the green (0.55 µ), red (0.7µ) and some into the near Infrared (IR 0.7 to 2.7µ), others such as the jewel beetle "see" into mid IR (3 to 5 µ) and some such as the rattle snake and green tree python "see" into the long IR (8 to 12 µ). Reptiles have both a "gimbaled" visual detection system (the eye) on a fixed or moving platform.

Bats and some moths, on the other hand, have well developed visual systems and high frequency acoustical sensors. The rattle snake and green tree python "see" in the visible and into the long wavelength infrared. The sensor fusing of these animals, enables them to have extremely low false alarms and low false positives, and should be the envy of any Radar or Infrared engineer and worthy of bio-mimicking.

Figure 9 Big Eared Townsend Bat
( Attribution-Wikipedia)

## 4.0 WARNING SENSORS – THE APPOSITION COMPOUND SENSOR EYE

More than 3/4's of the species in the animal kingdom are equipped with compound eyes. Compound eyes can consist of from a few to thousands of individual lens systems or ommatidia consisting of individual cornea lenses, crystalline cones and photo-detectors.

The dragonfly has approximately 28,000 ommatidia in a single eye and is one of the supreme examples of micro-optics on the wing. The "wrap-around" feature of the dragonfly eye enables it to view approximately 70$^{o}$ horizontally and 90$^{o}$ vertically, up and over the head as well as in the forward direction. Such eye features are useful as warning sensors, collision avoidance, land mark recognition for finding mates and food. In addition, the Instantaneous Field-Of-View (IFOV) of the individual ommatidia can vary in angle and they can overlap to provide depth perception in a single eye.

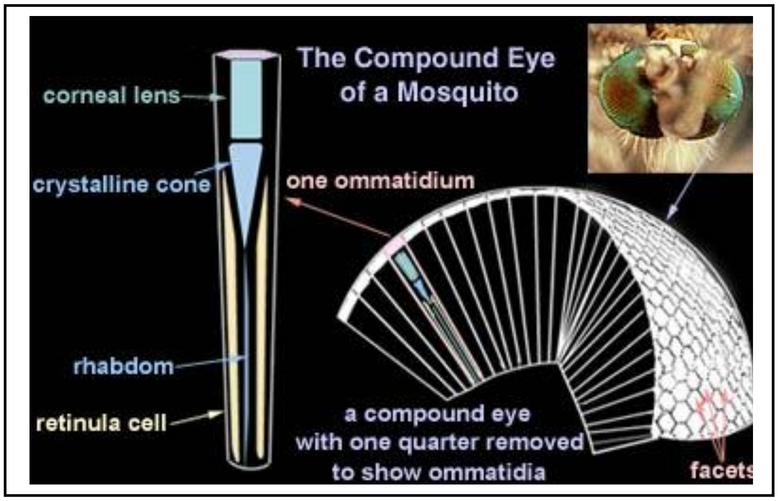



Figure 10 Apposition Compound Eye (Attribution © David Denning BioMEDIA) Assoc.)

A wonderful example of a bio-inspired compound eye, named the "DragonflEye", is composed of multiple small lenslets placed on a spherical dome each imaging to a coherent fiber bundle. The ends of the fiber bundles are in turn reimaged to a common flat focal plane, as shown in Figure 11, courtesy of Dr. Paul Thomas Topaz. The rational for investigating the compound eye has been to develop a wide FOV sensor for collision avoidance, autonomous navigation and missile warning with the potential for parallel high speed parallel processing. Fiber bundles in the prototype are round, leaving dead spaces in the field-of-view (FOV) which could be reduced by imaging to smaller or square fiber bundles. To achieve a wide FOV, the output of the fiber bundle is reimaged to a focal plane with a demagnification of from 2 to 5x.

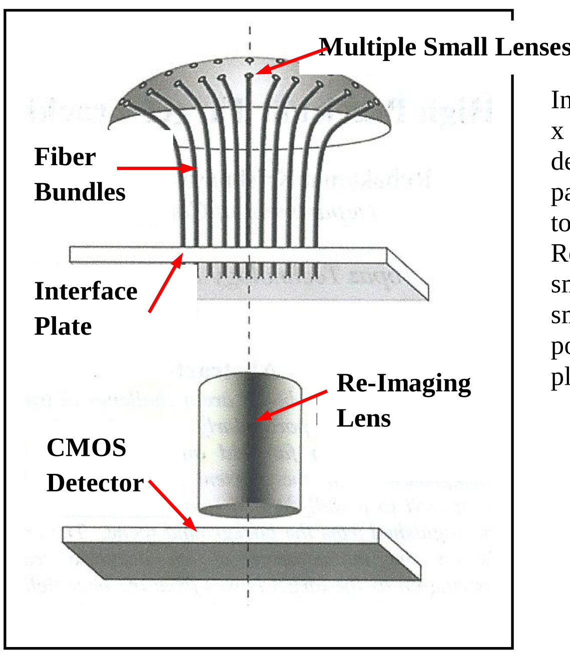



Figure 11 Bio-Inspired DragonflEye - Compound Eye (Ref.10 © May'04 IEEE)

In one prototype configuration developed, the FOV is 150$^{0}$ x 10$^{0}$ using 25 lenslets imaging to a 1024 x 1280 CMOS detector array. For full hemispherical coverage, using parameters in the existing system, would require from 300 to 600 small lenses, a difficult but not impossible task. Replacing the single detector array with multiple and smaller detector arrays and/or employing readouts with a small defined region of interest, higher readouts would possible than could be obtained from a single large focal plane [9].

Apposition and Super-Position compound eyes are shown in Figure 12. In the apposition compound eye 12(a) light shields or pigmented baffles extend between the ommatidia, to restrict light to a single rhabdom or *photoreceptor*. In the Super-Position eye, light is collected from several ommatidia, or not, depending on illumination conditions. Under high illumination (*light adopted*, ***LA*** )light shields extend, 12(b), restricting light to a single rhabdom. Then under low light conditions (*dark adopted*, ***DA****)* 12(b) the pigment baffles retract allowing light from several ommatidia to be focused on one rhabdom gathering all the photons possible but at sacrifice of resolution. These super-position refracting type as shown in Figure 12 or reflecting as shown in Figure 13.The usefulness of this detection feature permits wide dynamic response and the detection under both high light illumination and low light level conditions.

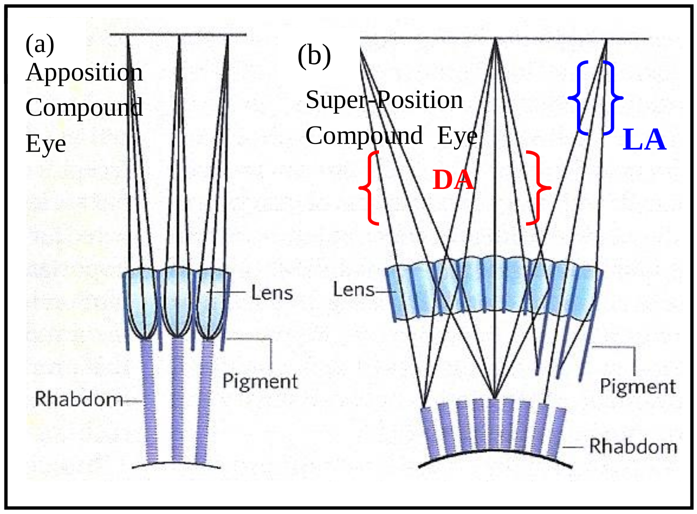



Figure 12 Super-Position Eye (Attribution Nature vol.443, 12 Oct. '06)

## 5.0 USESES OF POLARIZATION IN NATURE

One of the earliest forms of navigation has been attributed to the Vikings around the year 1,000 AD. They are reported to have used "sunstones" or cordierite, a crystal found in pebbles along the coast of Norway. They used the sun and its pattern created in the sunstones for navigation. Navigation by the sun is still used by man, animals and insects. With knowledge of earths' path around the sun and accurate time keeping, man's navigation by the sun has become more accurate from the time of the Vikings. Man can only marginally detect polarized light as discovered by Haidinger in 1846 but most of us cannot sense polarization without some electro-optical or mechanical means. Many insects and animals, however, can detect polarized light with ease and many use this feature for navigation, as discovered in the late 1940's [11].

Without the use of "sunstones" the eyes of some animals and insects allows them to detect polarized skylight, which assists in navigation, helps in clutter rejection, eliminates unwanted specular reflections and enhances detection capabilities under certain illumination conditions. The mantis shrimp, previously discussed, is one such animal that can sense the state of polarization that is used in enhancing the contrast of under water objects. Man uses this feature in microscopy for enhancing the contrast of living cells in a liquid.

Some insects and animals make use of sky polarization for navigation and for other purposes. This includes some fishes, the brittle star, crayfish, cuttlefish, octopi, the African dung beetle, the honey bee, many long distance flying birds, crickets, some butterflies and the black dessert ant. In the latter case the black dessert ant is a solitary daytime feeder. Foraging over 200 meters from its cool under ground nest in the $160^0$ F degree heat of the dessert, it must quickly get back to its under ground home or it will quickly die after finding food. The axis of the eyes of this insect are elevated approximately $53^0$ above the horizon and $90^0$ apart to better analyze polarization of the sky for navigation "home". Navigation "home" is always a straight line vs. the outward foraging path which is very twisted and lengthly. Men who refuse to consult a map or ask directions might take advantage of this feature if they were endowed with this analyzing feature.

## 6.0 BIOLOGICAL REFLECTORS

Some eyes are equipped with reflectors in back of the photoreceptor so that light makes a double pass through the sensor to increase its quantum efficiency or light gathering power. We see this approach applied in silicon detectors where the absorbing layer might be two thin to achieve good "red" response.

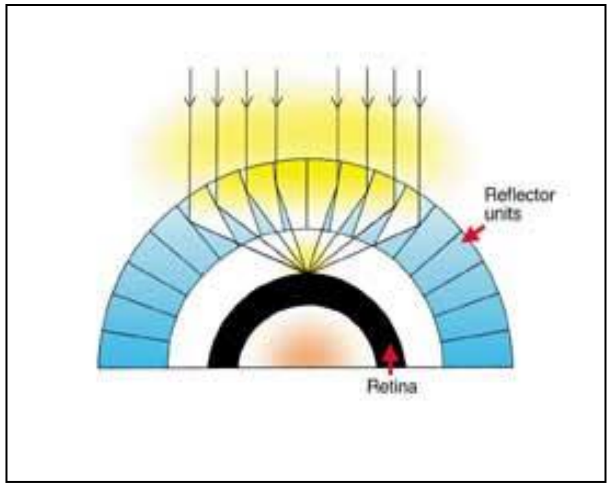



Figure 13 Lobster Eye [12] (Figure courtesy of Simon & Schuster, author M.J. Denton)

Other eyes, such as those in the lobster, are compound eyes. The eye consists of a series of square cross-sectional channels, each lined with a mirror like reflecting wall. The channels are tapered, decreasing in cross-section, so that light is concentrated to the photoreceptors. The configuration has inspired others to consider how such an optical device could be adopted for other uses such as light pipes to concentrate "light" on a detector and increase the field-of-view. This has been used in Infrared radiometers. Used in reverse, the light pipe (*Lobster Eye*) can be used in illumination engineering to flood a large field.

The configuration has also been adopted for X-Ray astronomy. Because high energy X-ray photons must be incident at near grazing incidence or their high energy will penetrate into the mirror, a sequence of mirrors, at near grazing incidence, like the lobster eye, was used for the design of the X-ray observatory Chandra [13].

## 7.0 BIOLOGICAL CATADIOPTRIC OPTICAL SYSTEMS

The eye configurations of some animals are catadioptric, meaning they are made up of refracting and reflecting components, like some telescopes. A scallop has approximately 60 one millimeter diameter catadioptric eyes along the top and bottom edges of its shell as shown below in Figure 14(a) (*Note dark dots*). Light enters the eye through

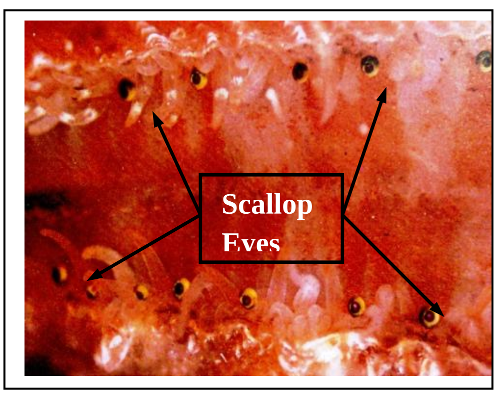



Figure 14(a) Scallop Eyes (Attribution: Facts on File [14]

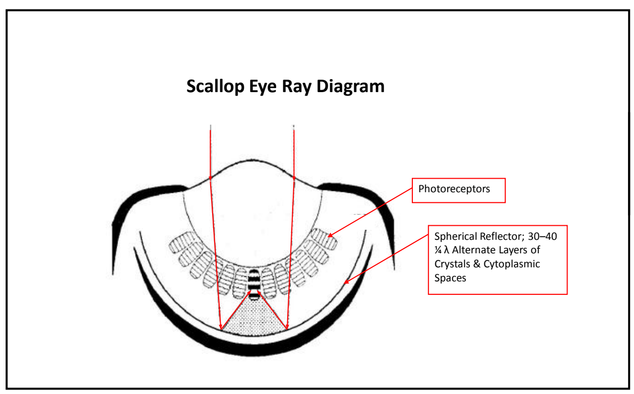



Figure 14(b) Catadioptric Ray Diagram, (Adopted from Foundations of Neurobiology, W.H. Freeman & Co., eye configuration similar to the deep sea squid)

a refracting aspheric lens, correcting for spherical aberration, then is reflected from a spherical mirror to the photoreceptors. Such small well corrected lenses should be the envy of any cell phone company, endoscope manufacturer or spy camera optical system manufacturer. Like the scallop, the deep water squid has a similar optical configuration, Figure 14(b) but this eye is on the opposite side of the size scale. The largest squid known has an eye that is 270 mm diameter.

Commercial multilayer mirrors are made by alternating coats of vacuum deposited materials such as magnesium fluoride and zinc sulfide. Nature does the same thing by self assembling 30 to 40 $1/4\lambda$ alternate layers of guanine (n=1.83) and cytoplasm (n=1.36) achieving nearly 100% reflectivity from approximately 475nm to 580nm. Nature makes its self assembled mirrors without the use of a vacuum system, without optical monitors, without computer control and using naturally available materials at low temperatures.

## 8.0 BIO-INSPIRED/BIO-MIMETIC OPTICAL SYSTEMS

Bio-Inspired optics attempt to replicate the components of animal vision systems. Applications include autonomous warning sensors, collision avoidance detectors, micro air vehicles, small robotic applications, and medical applications.

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> **Side Bar.** DARPA had funded a program called BOSS or the Bio-Optic Synthetic Systems Program. Funding through phase II was carried through until the end of May '08. The program had three thrust areas: (a) Variable focal length lenses using shape changing micro-fluidic lenses and more conventional movable lens systems which included gradient index lenses, inspired by the octopus. The inspiration for this thrust was the human eye that changes shape thereby altering its refractive power. (b) Foveated imaging systems using high dynamic liquid crystal spatial light modulators and (c) photonic sieve diffractive optics, patterned after the brittle star, to replace refractive or reflective optics in imaging systems.

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A bio-mimetic artificial compound eye has attracted a lot of research attention because it can achieve such a wide FOV. It exhibits a huge potential for medical, industrial and military applications. Lenses imaging with FOV's over $90^0$ have been achieved with "fish eye lenses" which are large, heavy and composed of expensive multiple elements requiring precision alignment. The bio-mimetic artificial compound eye achieves all these attributes but with small size and weight. Luke P. Lee, et. al., at the Bimolecular Nanotechnology Center, University of California, Berkley, is working on such a device. A microphotograph of a honeybee apposition compound eye that they are mimicking is shown in Figure 15(a). The make-up of the natural ommatidia (facet lens, crystalline cone and rhabdom – wave guiding to photoreceptors) of this honey bee eye is shown in Figure 15(b). The artificial ommatidia, shown by an electron microphotograph, 15(c), like an insect compound eye, consists of a refractive, polymer micro-lens, light guiding polymer cone and a self aligned waveguide (*fiber optic*) to collect light before detection by a photo-detector, 15 (d). The spherical configuration of the artificial ommatidia is achieved through a polymer replication process. The use of miniaturized arrayed optical components fabricated by using semiconductor planar processing technologies has been proposed to simultaneously mimic the structure functions of an individual ommatidium. The

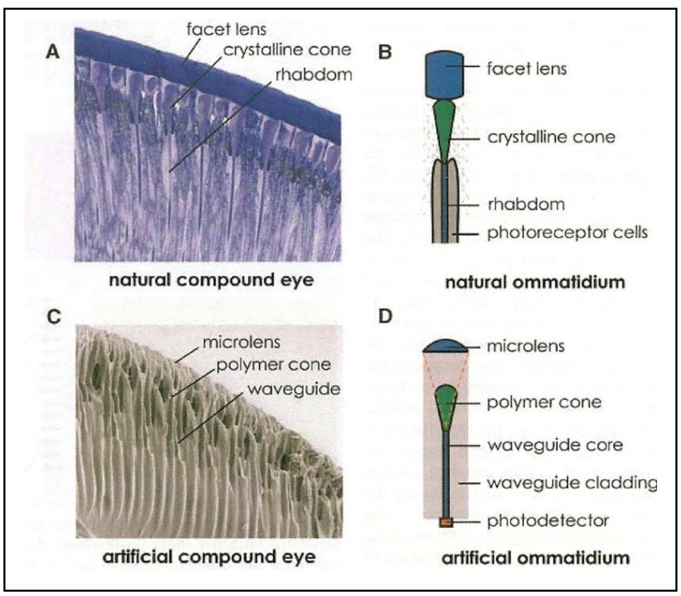


Figure 15 Bio-Mimetic Artificial Compound Eye [15] (From "Biologically inspired Artificial Compound Eyes", reprinted by permission from AAAS)

formation of polymer waveguides, self aligned with the micro-lenses, is realized by a self writing process in a photo-sensitive polymer resin [15]. This artificial eye like its biological counter part focuses onto a concave surface which is not compatible to the planar processing of CMOS focal planes. The imaging system developed by the Fraunhofer Institute group, described in the following, overcomes the requirement for a curved focal plane but it has other drawbacks.

A high compact imaging system with a variable field of view without any moving parts has been demonstrated by researchers at the Fraunhofer Institute for Applied Optics and Precision Engineering, Jena Germany. This camera combines an ultra thin artificial apposition compound eye with a variable focal length liquid lens. The change of optical power of the liquid lens when a voltage is applied changes the magnification of the micro lens array imaging system.

A Micro-Lens Array (MLA) with apertures is positioned on the front side of a thin glass substrate. A CMOS detector array with a pitch smaller than that of the MLA is located in the focal plane of the micro-lenses on the back side of the substrate- polymer sandwich. The pitch difference of the lenses and photoreceptors enables diverging field's-of-view for each of the photo-detectors, mimicking an apposition compound eye. By applying a voltage across the liquid lens the power of the lens is altered resulting in a change in the magnification of the imaging system. In the configuration shown, combining the variable focal length liquid lens with an with an artificial compound eye imaging system, the requirement for the displacement of two variable lens groups, which is required in a conventional zoom lens system is removed [16]. An advantage of the configuration is that it enables the use of a conventional CMOS silicon focal plane, processed on planar rigid silicon substrate using current standard lithographic processing techniques. The processing approach is not; however, without the disadvantage of a poor photo-detector fill factor and low sensitivity.

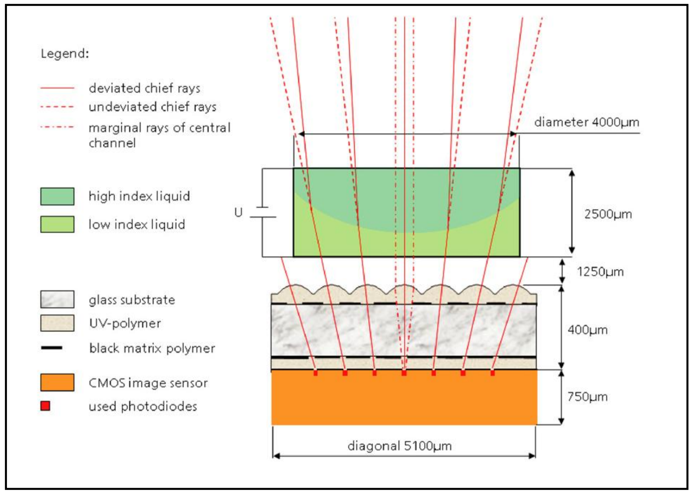


Figure 16 Schematic Drawing of Artificial Compound Eye (Figure courtesy of BioIns Biomim 3(2008))

Artificial compound eyes of the future may not have to attempt to interface with a flat focal plane. Researchers at Stanford University have been developing a monolithic but flexible silicon focal plane that can conform to non-planar contours. In their sensor, each pixel exists on its own small silicon island connected to its four neighbors by thin silicon springs allowing the overall focal plane surface to deform as it were a stretchable rubber sheet. A prototype device 1x1cm2 with 105x105 islands was deformed from silicon 30 µm thick and it was formed into a hemispherical dome with a radius of 1 cm [17]. Using this strategy, researchers at the University of Illinois at Urbana-Champaign, IL and Northwestern University, Evanston IL have succeeded in developing a working camera having 16x16 pixels on a curved focal surface. This technology being developed will be suitable to either concave or convex surfaces enabling wide field-of-view and low aberration compact bio-inspired imaging cameras [18].

## 9.0 HUMAN EYE IMPLANTS INSPIRED FROM NATURE

For the betterment of man kind perhaps one of the most inspirational bio-mimicking programs are those that enable blind people to “see” with retinal implants. The start of this movement might be said to have begun with mimicking of the human retina by Carver Mead at California Institute of Technology. The biologically inspired analog VLSI system designed and tested brought together a theoretical understanding of the human eye, how it functions and processes information on a silicon chip. Using this knowledge, implants in the human eye now make it possible for blind people to gain some sight, even though it might be shadows and course by sighted standards.

Retinal implants that enable this vision are of two kinds; sub-retinal and epi-retinal. **Sub-retinal implants** are inserted in an area where there is a loss of rods and cones. Micro-photodiodes replace the damaged photoreceptor cells. An interface is made with the remaining neural network which is still capable of processing electrical signals generated by the implanted photo-cells. With this type of implant no external electronic camera or processing equipment is required and eye movements, not head movements, are all that are required to locate an object of interest. To power the implant a solar cell is mounted on the implant, illuminated by an IR photo-diode mounted external to the eye on a pair of glasses.

**Epi-retinal implants** are required when the retina up to the Ganglion cells are not functioning this includes the photoreceptors, horizontal cells, bipolar cells and the amacrine cells, Figure 17. This is caused by retinal pigmentosa or macular degeneration. An external electronic camera mounted on a pair of eye glasses, shown in Figure18, generates signals containing image information that is sent via an infrared
laser to the photodiode array on the implant. This same laser is also used to generate power to run the implant. The processing chip takes signals sent from the CCD camera and generates electrical impulses that are sent to the electrode array that comes in contact with the ganglion cells. These electrical impulses, then travel via the ganglion cell axons to the optic nerve and then to the brain to be interpreted as an image. To view an object of interest the whole head, not just the eyes, must be rotated to point to the object of interest. To overcome this disadvantage of having to point the head, not just to rotate the eyes to point to an object of interest, work is proceeding to put a camera inside the eye just behind he pupil [19]. This DOE collaborative artificial retina projects goal started with an implant that had 16 electrodes. A 60 electrode model is now in clinical trials and a third model is under development that has 200 electrodes, it will be smaller, draw less power and more importantly be flexible enough to conform to the shape of the inner eye. This flexibility is not lost on researchers that are developing small cameras with simpler optics that require a curved focal plane.

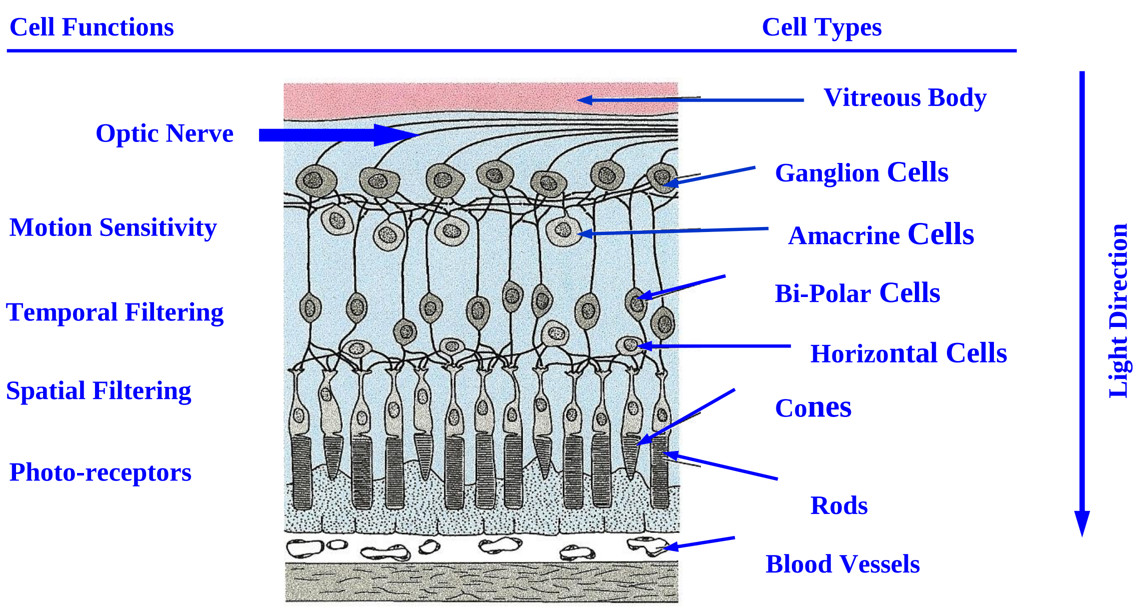


Figure 17 Major Divisions of the Human Retina

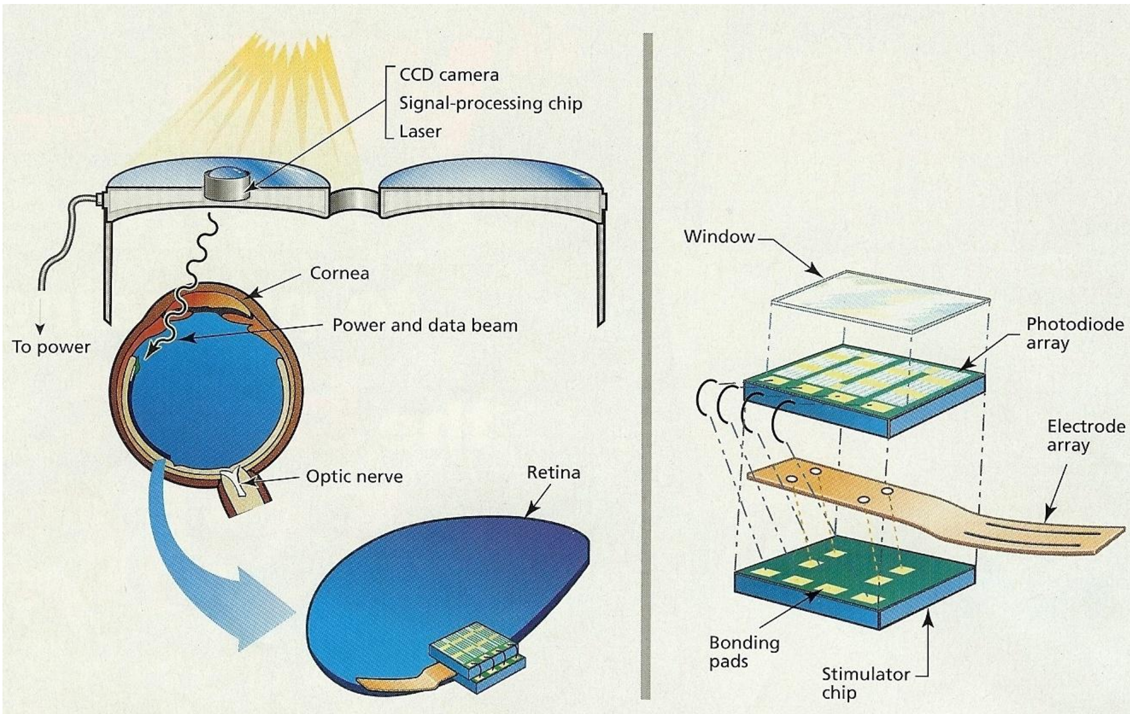


Figure 18a External Glasses to Generate Signals for Implants          Figure 18b Epi-Retinal Implant

Figures 18a & b courtesy of IEEE Spectrum [19]

## 10.0 SUMMARY

Life has evolved on earth over the last 3.5 to 4 billion years. The challenge to all of us is how to preserve bio-diversity so we have a chance to study, research, and learn from nature. It is difficult not to draw parallelisms to materials used in today's products and let it go at that but understanding how nature approaches fabrication and integration is far more difficult but the rewards can be astonishing. The materials used are not toxic and they are created at low temperatures and pressures giving them a lot of advantageous in today's energy environment. The variety and complexity of biological materials and the optical systems formed should be an inspiration to all of us.

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