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Optical Computation with Negative Light Intensity with a Plastic Bacteriorhodopsin Film

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The inability to use light intensity to represent negative values limits the potential of optical computing. The protein bacteriorhodopsin, an optically switchable bistable material, was used to represent an image as a local concentration of one of its two states. Light of one wavelength increased this concentration and represented positive intensity, whereas light of a different wavelength decreased the concentration and represented negative intensity. Optical subtraction was demonstrated by performing the mathematical operation of a difference of Gaussians. The electro-optical characteristics of bacteriorhodopsin films portend a variety of practical applications for this system.

Measurements of light intensity traditionally have allowed the recording of only positive values. Nonetheless, for practically every mathematical operation the representation of negative values is essential. Thus, the use of optical devices in computational schemes and image processing would be enhanced by the ability to directly find decreases in light intensity. For example, every optical device blurs the image of a single point; this spread of intensity limits the ability to resolve two closely spaced points of light. Although it is possible to reconstruct the real image mathematically, the required operations involve both positive and negative values. Here, we report how a bacteriorhodopsin (bR) film can be used to subtract two positive light intensities in order to represent a negative value.

We have prepared plastic bR films with high optical quality (*1*). The purple initial state of bR can be transformed into a relatively stable yellow form called M by absorption of a photon of the appropriate wavelength (*2*). This M state, in turn, can be switched back to the bR state by absorption of a photon of another wavelength. These light-driven state changes are more fully described in terms of the photocycle of bR (Fig. 1).

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The value of a pixel in an image can be represented by the concentration of the bR or M state. Shining yellow light on a pixel would increase the concentration of the M state, whereas shining blue light would increase the concentration of the bR state. If a film is originally prepared with equal concentrations of bR and M, then negative and positive values can be represented as increases in the concentrations of bR or M that correspond to a surplus of blue or yellow light, respectively. We used this characteristic of such a bR film to approximate the operation of a difference of Gaussians (DOG). This operation has historical importance as a method of edge enhancement in image processing (*3*).

Edge enhancement can be formulated as a map of loci where the Laplacian of the convolution of the image with a Gaussian changes sign (*3*). Thus, the edges of an image $I(x,y)$ are defined as the zero-crossing of the operator

$$\nabla^2 G(x,y) * I(x,y) = \nabla^2 \int\int G(x - x', y - y') dx' dy' \quad (1)$$

where

$$G(x,y) = \frac{1}{2\pi\sigma^2} \exp\left[-\left(\frac{x^2 + y^2}{2}\right)\right] \quad (2)$$

Mathematically, however, $\nabla^2\{G * I\} = \{\nabla^2 G\} * I$. Thus, instead of convolving with a Gaussian and then taking the Laplacian, it is possible to convolve with the Laplacian of a Gaussian. Moreover, the Laplacian of the Gaussian can be approximated by a DOG. Explicitly, this DOG can be written as

$$\nabla^2 G(x,y,\sigma) = G(x,y,\sigma_1) - G(x,y,\sigma_2) \quad (3)$$

where σ_1 and σ_2 are the widths of two two-dimensional Gaussians. These widths should have a ratio of 1:1.6 if the DOG is to approximate $\nabla^2 G(x,y,\sigma)$ (*4*). An example of such an approximation for a one-dimen-

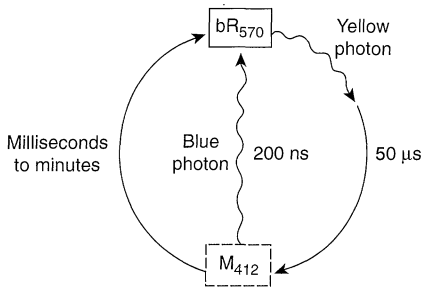

Fig. 1. The photoinduced cycle of bR with the two intermediates of importance for this study. The bR state absorbs a yellow photon within the broad bR absorption with a maximum at 570 nm. This transforms into intermediate states (not shown) and then decays to the relatively stable M state within 50 μs. M is thermally transformed into the initial pigment bR; the lifetime of this transition depends on the sample preparation. The M state can be converted into the bR state within 200 ns by absorption of a blue photon (*2*). Stable, optically uniform films of bR can be produced by embedding bR in a polyvinyl alcohol (PVA) polymer matrix (*1*). These films can withstand normal environmental conditions over many years of operation. To obtain a good-contrast film, we mixed bR with PVA at a 1:5 ratio. The bR suspension had an initial optical density of ~19.2, which resulted in a film with an optical density of ~4. In this film the lifetime of the M state at room temperature was several minutes. This lifetime can be varied from a few milliseconds for wet samples to several hours in samples that are dried at high pH. However, in all of these samples, the yellow and purple light produce a photostationary concentration of bR and M in as fast as tens of microseconds. The absorption bands of M and bR do not overlap, so relatively low power is needed to switch a sample from one pure state to another.

sional DOG is shown in Fig. 2A.

How can such operations be optically implemented? The optical system needs to perform two operations: convolution with a Gaussian and subtraction. In our system, a Gaussian distribution of light is achieved by using an out-of-focus image. The subtraction is achieved by using two wavelengths, each with a different Gaussian distribution. Ordinarily, optical systems are fine-tuned to overcome chromatic aberration such that images created by multiple wavelengths are all focused. In contrast, our approach is to take advantage of chromatic aberration such that yellow and blue wavelengths are not focused to the same focal plane and thus create slightly different images on the film. When two such images, yellow and blue, are simultaneously projected on a film of mixed bR and M states, the resulting spatial distribution of concentration reflects the power difference between the two images.

In addition, the lens in an optical system is usually optimized to create a one-to-one correspondence between the point on the object and its image on the film. In out-of-focus optics, this correspondence is relaxed; in other words, the light projected on a specific point in the film contains contributions from the corresponding point in the image and from its surrounding loci. The projected image then becomes a convolution of the original image with the optical system's point-spread function (PSF). To the extent that a single-lens PSF can be approximated by a Gaussian, a single lens can produce a convolution of the image with a Gaussian function. In our optical system with chromatic aberration, the width of the PSF depends not only on the distance from the focal plane, but also on the wavelength of the light. Therefore, given the properties of bR films, two wavelengths with different PSFs (Fig. 2B) can simultaneously convolve an image with two Gaussians.

Imagine that an object is illuminated with two lasers: a blue (442-nm) helium cadmium (He-Cd) laser, which is within the absorption band of M, and an argon ion laser operating at 514 nm, which is within the absorption band of bR that peaks in the yellow. The light reflected by or transmitted through the object at both wavelengths is collected by a lens with high chromatic aberration and projected onto a bR film that is located at a point removed from the focal plane. Because each laser beam contains the image convolved with a different Gaussian, and because the film stores the difference of the two beams, the image imprinted on the film will be the DOG transformation of the original image. A local decrease in bR concentration indicates a surplus of yellow light that represents negative DOG convolution in this region. An increase in bR concentration indicates a net effect of blue light and a positive convolution (Fig. 3A).

We have experimentally demonstrated this effect by using a single lens with chromatic aberration. To estimate the width of the edge, we consider a point of height a above the optical axis (Fig. 3B). The images produced by the green and blue laser beams on the bR film are represented as having different heights, a' and a'', respectively. Whether a' is produced by the green or the blue light depends on where the film is placed relative to the focus of the lens. According to the lens maker's formula (5)

$$1/f = (n - 1)\left(\frac{1}{R} - \frac{1}{R'}\right) \qquad (4)$$

where f is the focal length, n is the refractive index of the lens, and R and R' are the radii of curvature of the lens. We can esti-

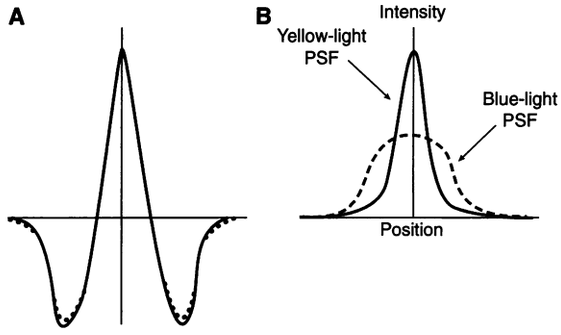

Fig. 2. (**A**) An example of a DOG approximation to the Laplacian of a Gaussian (dotted curve). The best approximation to the Laplacian of a Gaussian ($\nabla^2 G$) using a DOG occurs when σ_1/σ_2 (as defined in Eq. 3) is ~1.6. The one-dimensional DOG, shown as a dotted curve, is similar to the operator $\nabla^2 G$ with the appropriate σ. (**B**) A lens with chromatic aberration produces different PSFs for different wavelengths. In this case, the image of a point created by a blue beam spreads according to the wide Gaussian, and that created by a yellow beam spreads according to the narrow Gaussian. Thus, a point imaged by blue and yellow light creates two blurred images with different widths.

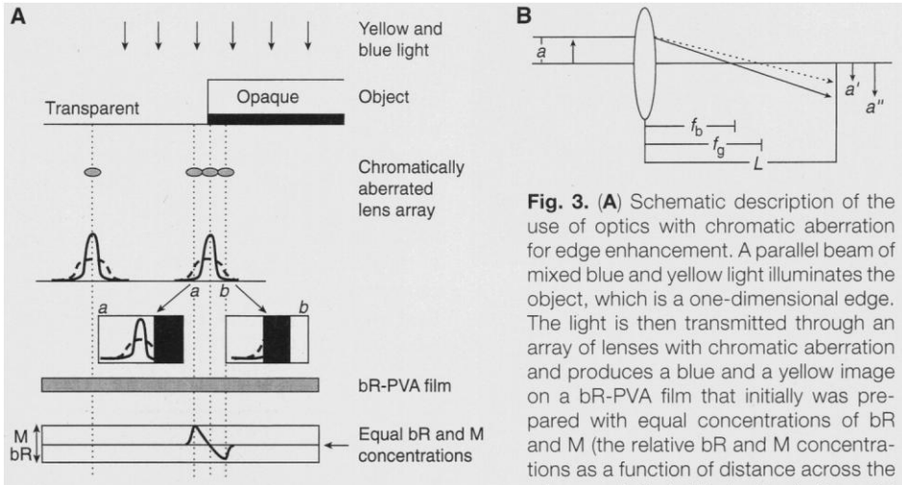

Fig. 3. (**A**) Schematic description of the use of optics with chromatic aberration for edge enhancement. A parallel beam of mixed blue and yellow light illuminates the object, which is a one-dimensional edge. The light is then transmitted through an array of lenses with chromatic aberration and produces a blue and a yellow image on a bR-PVA film that initially was prepared with equal concentrations of bR and M (the relative bR and M concentrations as a function of distance across the edge are plotted at the bottom). At a point within the opaque region of the edge, there is no change in the bR and M concentrations because this region did not receive any light. A point under the transparent region of the edge also shows no difference because this region of the object, which receives yellow illumination with a broad PSF and blue illumination with a narrower PSF, is exposed to equal total powers in the yellow and blue wavelengths. The same is found for a lens in the array that is directly under the edge. However, to the left of the edge (point marked a) only a small part of the two PSFs is obscured. Thus, for the yellow light, which has a narrower PSF, only the extreme tail of this PSF is obscured. In contrast, for the blue light a larger portion of the PSF remains concealed; thus, more yellow than blue light shines on point a, and the M concentration increases. At point b, to the right of the edge, only the tails of the two PSFs are exposed. However, the blue light has a wider PSF and therefore contains more power in the tail. Thus, at this point more blue light shines on the film, and consequently the bR concentration increases. (**B**) The width of the edge produced by a single lens with chromatic aberration can be evaluated using the lens maker's formula. An object of height a is imaged by a lens. The object is imaged onto a screen at a distance L from the lens. Because the foci f_b of the blue light (solid line) and f_g of the green light (dashed line) are in the same plane, the green image has a height a' and the blue image has a height a'' for this position of the screen.

mate the edge width (w)

$$\Delta w = a' - a'' = aL\Delta n\left(\frac{1}{R} - \frac{1}{R'}\right) \quad (5)$$

where $\Delta n = n_b - n_g$ (the refractive index at the blue and green wavelengths), a is the height of the object, and L is the distance of the bR-PVA film from the lens.

For our experimental system, an edge 1 mm wide is produced by an object 1 cm above the optical axis at a distance of 20 cm from the lens. These values were achieved by illuminating an object (Fig. 4A) with a single lens made of heavy flint (Virgo Optics, Port Richey, Florida) having a large chromatic aberration (Δn = 0.025). The

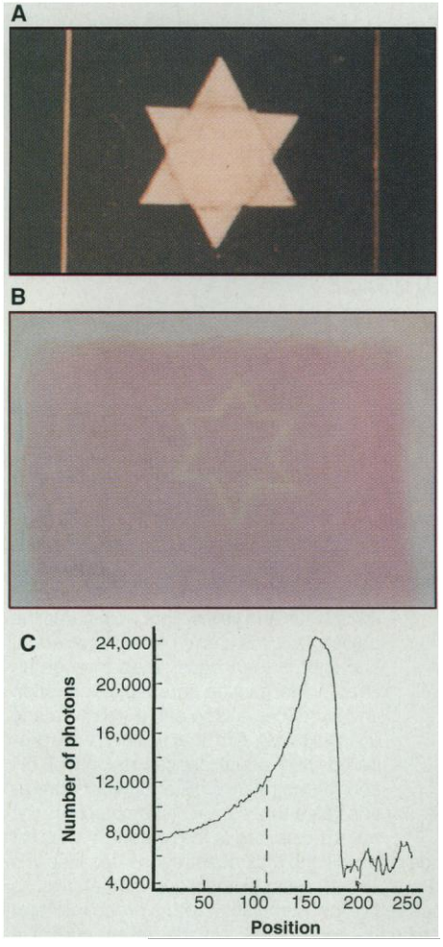

Fig. 4. Real-time edge detection with a bR film. (**A** and **B**) The object is the pink star shown in (A), and its edge-enhanced image is shown in (B). In this experiment, a heavy flint lens was used with a radius of curvature of $R = -R'$ = 10 cm and refractive indices n(434 nm) = 1.675 and n(589 nm) = 1.650. (**C**) A cross section of the detected edge, showing the number of photons detected by a CCD camera as a function of position along the bR-PVA film. The edge width was approximated by counting the pixels that showed a significant signal and multiplying by the pixel width.

1-mW argon ion and He-Cd laser beams were expanded to illuminate the entire object (~1 cm^2) simultaneously and were combined with a beam splitter to produce overlapping fields of illumination. A shutter was used to achieve variable time exposure ranging from 0.25 to 4.0 s. The longer exposure time allowed us to store a sharp picture of the edges using 35-mm Kodacolor film, ASA 400 (Fig. 4B). When the illumination is turned off, the bR film thermally returns to its original state. Alternatively, the film can be photochemically refreshed within 200 ns with a flash of light having the appropriate mix of wavelengths.

Within the limitations of our single-lens experimental arrangement, edges with high signal-to-noise (S/N) ratios of ~5.86 were achieved (Fig. 4C). We estimated this S/N ratio by imaging the detected edge with a charge-coupled device (CCD; model 512, Photometrics, Tucson, Arizona). The apparent S/N ratio of the system is limited by scattering from the object's borders and from edge smearing caused by nonuniform characteristics of the film. The S/N ratio can be significantly improved by increasing the laser intensities. The edge width is approximated by counting the number of 20-μm by 20-μm pixels that the edge spanned on the CCD chip. For the object shown in Fig. 4, this number was 70 pixels, corresponding to an edge 1.4 mm wide (Fig. 4C). This value would improve with better optics and processing conditions, taking maximal advantage of the demonstrated optical resolution of these films, which is <0.2 μm (6). In addition, the sensitivity at which our device maps the edges is affected by the initial ratio of bR to M. Thus, it is feasible to control this ratio by a feedback loop, thus dynamically altering the sensitivity of the film to edges with different contrast. In other words, the nature of the film could be used to control whether dominant edges or all edges are detected.

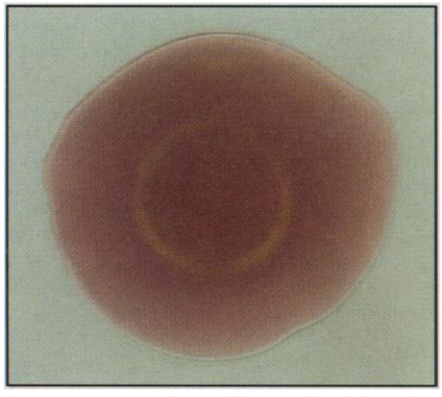

Fig. 5. An edge-enhanced image of a circle under white light illumination. The edge is the transition from an enhanced external purple bR strip to an enhanced internal yellow strip.

Lasers, with their highly defined wavelengths, are useful to observe the effects of such narrow-band illumination during this exploratory phase of the investigation. However, the use of lasers has two major disadvantages: the experimental setup is complex and expensive, and it is difficult to obtain lasers that produce light in the bands overlapping the bR and M absorptions. The absorption peak of bR is 570 nm, whereas the commonly available argon ion laser has its longest wavelength emission at 514 nm. Similarly, the absorption peak of M is 412 nm, whereas the He-Cd laser has an emission at 442 nm. The He-Cd laser emission overlaps both the bR and M absorption bands and is therefore not as effective as the argon ion laser in switching molecules. Thus, from the initial mixed state the He-Cd laser is not able to create an enhanced bR concentration near the edge. This can readily be seen in the edges recorded on the bR film with these lasers; the edge is not bounded by enhanced bR and M concentrations but rather is seen as simply a region of higher M states. This problem can be overcome, and the experimental arrangement can be simplified, by using a mercury-lamp white light source. With such a source, the simultaneous effects of both wavelengths are fully apparent (Fig. 5) where the edge is clearly defined by the transition from a strip of enhanced bR concentration to a strip of enhanced M concentration.

A main concern with optical computing is its eventual integration with electronic computers. One of the great advantages of the bR system is its electro-optical properties. The photoinduced transitions from the bR to the M state and from the M to the bR state are accompanied by charge movements of opposite polarity that are readily detectable (7). Therefore, the optical recording of positive (excitatory) and negative (inhibitory) light intensities directly correlates with the associated electrical signals. Thus, our scheme for recording negative light intensity may have the potential for practical application.

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