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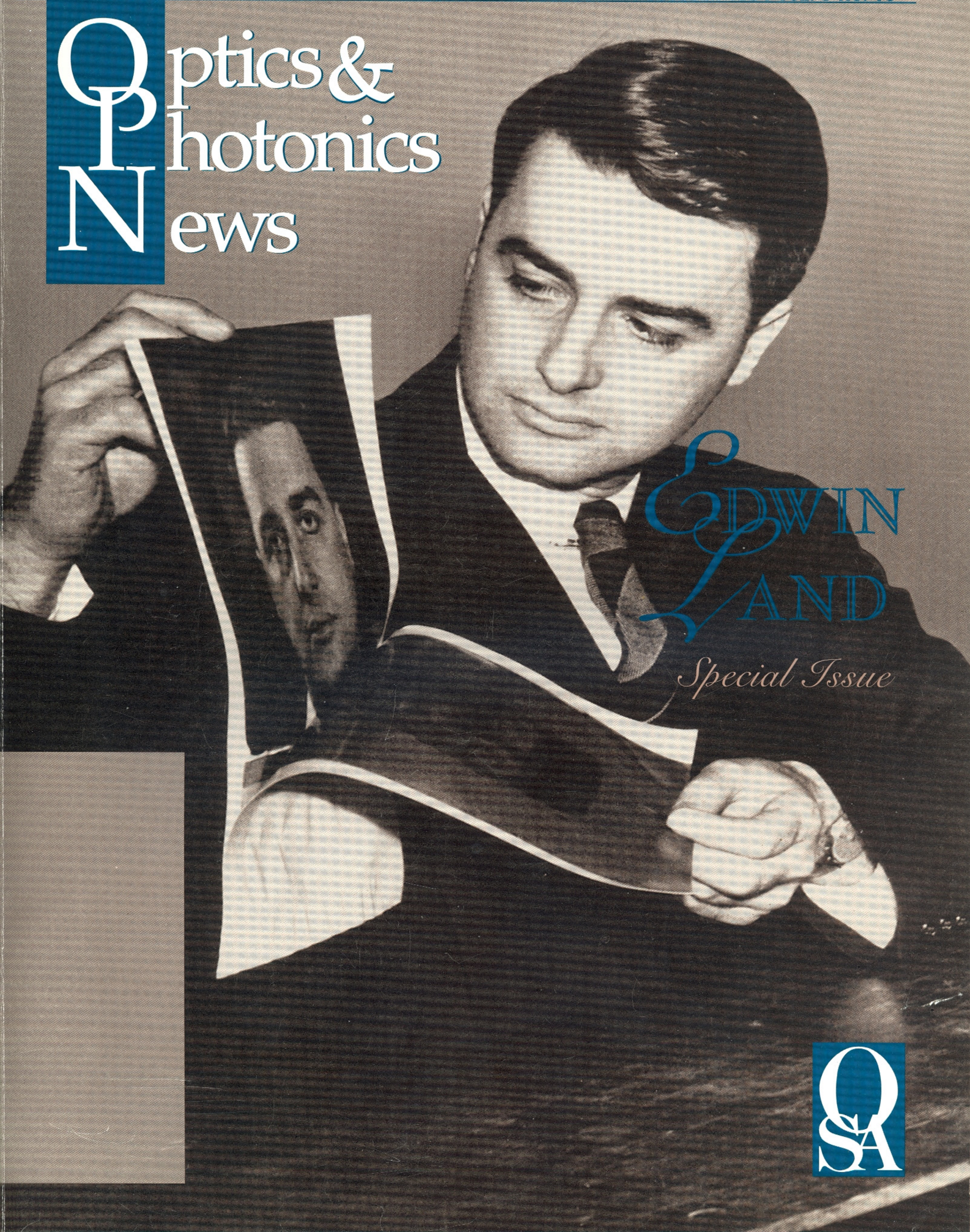

Edwin Land

Special Issue

The following article appeared in 1994 after Edwin Land passed away. It was a part of a Special Edition of Optics and Photonics News, edited by Richard Weeks, entitled *Edwin Land: An Artist who Chose Science and Technology for his Medium.*

Land's Chemical, Physical, and Psychophysical Images

By **MARY A. AND JOHN J. MCCANN**

No man in history can surpass Edwin Land as the Maker of Imaging Systems. During his entire life Land was fascinated with the "interaction of light and matter." The constant theme throughout his 535 patents is *new ways to make images*. That theme holds equally well for all three major areas of Land's research-polarizers, photography, and human color vision-and even *in* the areas *of* public service for the United States.

Land didn't invent just one new instant imaging system; he invented and patented for Polaroid a litany of new systems that were chemically and physically very different from each other. In addition he was Special Advisor to the President for Foreign Intelligence under Eisenhower, Kennedy, Johnson, Nixon, Ford, and Carter. His committee led the progression from aerial reconnaissance using high resolution photography, to early and advanced CCD systems. These programs started *in* World War II and continued through the U2 missions that led to electronic imaging used in satellite imagery. This work was the foundation of today's commercial electronic imaging.

We joined Polaroid Research labs in 1960 fresh from college. We were both fascinated by how exciting research could be and, as did many people in Polaroid labs, worked all day and half the night because it was so much fun. By recalling some of the photographic systems either in place or under development, we hope to convey the excitement of the Polaroid labs under Land's direction. These projects were all stimulated by Land's unique mind and personality. He had a true passion for research. He didn't play golf or go to sports events: His idea of fun was to be in his lab. His favorite story was his latest experiment.

NEW KINDS OF IMAGES

Land left Harvard as a freshman to make an inexpensive sheet polarizer to solve the serious problems of glare from automobile headlights. **In** New York City he "read every book on polarized light in the New York Public Library," and worked to make a polarizer (orienting microcrystals of Herapathite) in a laboratory at Columbia University. He returned to Harvard and was given his own lab. **In** 1932, while still an undergraduate, he described his synthetic sheet polarizers at a colloquium of the Physics Department. His first molecular polarizers were made of polyvinyl alcohol stained with iodine. Although not an imaging system per se, these polarizers were critical building blocks for the future.

Images in Vectorial Inequality

Land described Vectographs®, his first imaging system, in the *Journal of the Optical Society of America* in 1940.' It was a single-sheet stereo image, viewed with polarizing glasses. It used a left and right-eye stereo images made by dye-transfer onto the Vectograph sheet. This sheet consists of an isotropic base, with stretched polyvinyl alcohol sheets laminated on opposite sides of the base with their stretch directions perpendicular. Iodine ink is imbibed into exposed and developed photoresist, where it is taken up in accordance with the thickness of the photoresist, then the ink is transferred to the PYA, forming polarizers that vary in density in an imagewise fashion. The two polarizing images can then be viewed with polarizers with perpendicular left- and right-eye orientations. The most dramatic application of the Vectograph was in three-dimensional representation; it became a valuable tool for aerial reconnaissance during World War II and was used to map all of Normandy Beach before the allied invasion.

Instant Images in Silver (sepia)

Land described one-step photography in the *Journal of the Optical Society of America* in 1947.[2] He used a silver halide emulsion donor sheet to give adequate sensitivity to light, and the camera to both expose the emulsion and process the film. The developer was (and still is) contained in a pod that was broken when the donor and receiver sheets were pulled through a set of rollers. The exposed silver halide grains develop and their silver remains in the negative. The unexposed grains dissolve and the silver is complexed and transferred to a positive receiving sheet. There, catalyzed by metallic sulfide nuclei in the sheet, the complex is reduced to form metallic silver. The first images were sepia in tone. Land told the story3that Kenneth Mees of Kodak predicted that Land would kill himself in trying to make a process neutral in tone--a good warning, but one that did not discourage Land.

Instant Images in Silver (black & white)

The change from sepia-toned to black and white images in a commercial product was accomplished within two years. In the new film, the deposited image silver was restricted to the interstices of a matrix of colloidal silica; it formed aggregates having electrical continuity over large areas, and produced neutral images over the entire density range of the image. Land was fond of saying that the silver in this black and white film was "a new kind of matter." He described in some detail the form of this new imaging material.' Thirty years later, many of the original experimental images were examined by electron microscopy,' and his predictions of the form and size of the silver particles proved quite accurate.

Instant Images in Transferred Dye

Land and Howard Rogers developed Rogers' idea of imaging dye chromophores attached to AgX developer groups. Polacolor® uses red-, green-, and blue-sensitive emulsions to control dye developers of the complementary color. The dye developers react with exposed silver halide and are immobilized, whereas in unexposed areas, the dyes were free to migrate to the receiving sheet. Dye developers were the first major invention necessary for these films; but just a few months before the introduction of the film, the entire structure of the receiving sheet was changed. The polymer chemists were challenged to provide an acidic polymer layer that was incorporated beneath the receiving layer to reduce the pH of the receiving sheet after development. The inclusion of this layer eliminated the need for any post-development washing.

SX-70 System-Integral Images

Perhaps the most exciting time at Polaroid was during the development and introduction of The SX-70 System®. This system incorporated a new camera and new film; both required a number of innovations, and both were the first that Polaroid manufactured for sale in its own factories. The negative and receiving sheet were permanently bound together, and the negative was exposed through the clear receiving sheet. Since the negative and receiver were immediately ejected from the camera, the negative had to be protected from light until development was complete. One of the major inventions of the system were the opacifying dyes that were incorporated in the viscous reagent. These dyes were indicator dyes, having high extinctions at high pH, and turning colorless as the pH dropped after neutralization by the polymeric acid layer. The reagent also contained titanium dioxide that became the white background for the image that was formed on the clear receiving sheet.

Images in Covering Power of Silver

Polavision® is an additive color transparency system. The image is formed in silver and is exposed and projected through a base of red, green, and blue stripes (1,500per inch). Mass production of the reseau base necessitated the invention of the way to make the stripes. Lenticules were first made on the back of the film base, used in a multi-step process to form the stripes with dyed gelatin resists, and then removed.

All of the silver present in the negative is retained in the final image. The system was designed to produce a negative of silver with minimal covering power. It produced a positive of silver with very high covering power in an immediately adjacent receiving layer. In photographs of white objects, light is transmitted through all three stripes to expose the silver halide; the exposed grains develop to silver of low covering power, allowing light through all three stripes, and displaying white. Photographs of black objects have silver of high covering power behind each stripe, allowing no light through. Red objects are seen as red because there is high covering power silver behind the green and blue stripes and much lower covering power silver behind the red stripe.

Images in Psychophysics

Imagine Land's excitement when, in the course of repeating James Clerk Maxwell's first demonstration of color photography for the Royal Institution, he realized that the imaging system in humans was profoundly different from any of the innumerable imaging systems he had created. He knew the literature of imaging; he knew the literature of human color vision. He was totally unprepared for the depth of the disparity between them. Land was quick to realize that the human visual system was fundamentally a field phenomenon, not a point phenomenon as all of his previous imaging systems.

And Many More

In addition to these imaging systems, Land was a supporter and colleague of Howie Rogers and his 146 patents, Lucretia Weed and transparency systems, Dexter Cooper and Red and White television, Steve Benton and White Light holography, Vivian Walworth and regular arrays of silver halide grains, and many, many more. There were dozens of studies going on in the lab all the time. A description of early projects that we shared with him will convey a sense of Land's creativity or willingness to look at a phenomenon in a new way.

A NEGATIVE TRANSFER SYSTEM

A curious phenomenon seen in laboratory test exposures was that very low levels of exposure led to transferred density darker than with no exposure at all-a *small density reversal.* Investigations of this minimal effect led to a new class of *negative system reagents* that transferred a positive image at high exposures and a negative image at lower exposure. What mechanism could invert the shape of the response curve?

Normal Polaroid black and white diffusion transfer images are positives. Silver halide grains in high exposure areas are developed in place, and there is little or no silver available for transfer to the receiver, making white in the print. In areas of low exposure, the unexposed silver halide grains dissolve and the silver transfers to the receiver, making black in the print.

The negative system reagent uses chemical antifoggants that coat the grains and make their surface insoluble. While normal unexposed grains would dissolve and transfer, these do not. However, with small amounts of exposure, these coated grains exhibit significant silver transfer. It was not at all obvious how this could happen at the level of the grains. Land predicted that somehow the insoluble coated grain could be unlocked by development at a single site so that the silver halide inside the grain could be dissolved and transferred to the receiver. In essence, the grain dissolved inside out. He predicted that since both dissolution and development are energetic processes, a violent reaction ought to occur at a single site on the surface of the grain.

This was the hypothesis, but how do you find the experimental test? Mary's assignment was to make infrared movies of the development of grains that had been given low exposures of white light.

The microscopic movie images are shown in Figure 1. The top image shows the grain at the onset of development. Each frame is 1 second later. The movie confirms the hypothesis that the silver that transfers is coming out of the grain as gas comes out of a rocket. The high concentration of antifoggant on the surface of the grain inhibited development except at the bottom of the grain, (see frame 2). As the silver came out of the grain, a small amount developed to form slender silver threads, but the majority complexed and transferred. The development and dissolution happen with such force that the grain moved five microns in the frame through its gelatin medium. This movie showed that the grains did not explode, but the silver halide dissolved from the inside of the grain. This pattern happened very often: A curious observation caught by a prepared mind, an intense review of the literature, an experiment that sharpened the hypothesis, and a dramatic new result.

RETINEX

Land's interest in color vision had developed along with his early interest in polarizers. His first published paper[7] on retinally and cortically fused colors predated by six months his first synthetic polarizer paper.

There are three different strains of thinking in color theory: The first is a descendent of Thomas Young's proposition that there are three kinds of receptors in the retina. Color appearance is a function of quanta catch at a pixel. The second is that color needs corrections for local effects. Von Kries' notions of adaptation and Hering's ideas of opponency and R. Hunt's model are good examples of using the quanta at a point and adding additional coefficients. The third approach was started by Land. He noted experimentally that the correction factors need to be as large as the entire range of input-white and black, red and green, and blue from the identical quanta catch. Because Land had made so many different pixel-based imaging systems, both chemical and electronic, he could not imagine a coefficient-based mechanism that could generate correction as large as input. Instead, his innumerable experiments led him to the idea that human vision was field based. Retinexes generate images by the intercomparisons of each type of receptor before the interaction with other types.

Adaptation-What Adaptation?

Land believed it was important to thoroughly understand the literature both by reading and repeating important experiments. He repeated James Clerk Maxwell's first color projection experiment. It used three black-and-white transparencies each taken and projected with a red, green, or blue color filter. Land loved to experiment. He would study the effect of more "red light" or less "blue light." What happened with different contrast film? He often said, "Science is the technique of keeping yourself from kidding yourself." To believe any hypothesis, Land needed the feeling of certainty that only comes from series of probing experiments.

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At the end of a long evening of experimenting with "Maxwell's" three projectors, a colleague had shut off the blue projector and. had put the green filter away, leaving an image of red and white light. The colleague remarked that the color was still there. Land replied, "Oh yes, that's color adaptation." Everyone went home. About 2 a.m., Land sat up in bed saying "Color adaptation, what color adaptation"? He got out of bed, went back to the laboratory and started three decades of experiments on complex images. Land knew the color literature better than almost any color specialist. He intensely read the papers and repeated the experiments. He had assimilated the color adaptation ideas handed down from Helmholtz, von Kries, Hecht, and Wald. He searched for evidence of color adaptation as the explanation for what he saw and he never found any. Instead, he set about creating a better understanding of how we see real world complex images. The experiments on Red and White, Mondrians, Retinex, and neurophysiology of V4 are all in the scientific literature. With a quick mind that playfully questioned everything, particularly his own hypotheses, Land had a passion for experiments. He literally could not sleep when he found an experiment that was "trying to tell him something."

Colors from Red & White

By 1961, when John joined the lab, Land and colleagues had a remarkable collection of Red and White images: beautiful still lifes, portraits, outdoor scenes, and a recreation of Velazquez' "The Toilet of Venus." Numerous images were probes as to the mechanism driving the Red and White phenomena. One showed that superimposing two red records, thus doubling the contrast of the red record, had little effect on the color of the red and white image. As a counterpoint, a red positive projected in red with a red negative projected in white produced very little color variation. Land spent many hours probing and reprobing the colors produced with two-color projections. He often shared laboratory experiments in college lectures. A whole generation of scientists recall with great excitement an undergraduate experience of hearing Land talk about his color experiments. Land's business success attracted the press, who thoroughly annoyed the "color establishment" of the 1950s. They banded together to criticize his enthusiastic introductory paragraphs much more than his unique experiments.[8]

Color-A Field Phenomenon As summarized in Land's 1967 Ives Medal Address, he did new experiments that were restatements of the color appearance principles derived from the Red and White. It presented three new experiments:

The Black and White Mondrian- With non-uniform illumination, a black paper and a white paper in the same display sent the same radiance to the eye. The receptors in the retina generated the sensation white and the sensation black from identical quanta catches in the same field of view.

The Color Mondrian was illuminated with three broadband red, green, and blue variable intensity projectors. The triplet of radiances from a gray area was noted. The illumination was then changed so that the gray triplet came from a red paper. If color is responsive to quanta catch, the domain of colorimetry, the red paper should look gray. The red paper looked red!

Retinex Machine- The third demonstration was an electronic device that processed image information as we thought the Retinex would. First, the notion of using arrays of intensities as the input to models was new at that time. Second, this was the first synthetic retina in which the output was a function of the intensity of all points in the field of view-a spatially driven imagery (Fig. 2).

Everything worked the way it was supposed to. Ironically, it shouldn't have. Careful evaluation of the calculation showed that the circuit should oscillate. Further study showed that the driver for the output display box had a diode that acted as a rectifier. This led to the concept of "reset" shown in the Ratio-Product-Reset model for vision in the Ives Medal Address.[9]

The idea that any remote area of an image influenced all other parts of the image is an important concept. Land, the inventor of hundreds of imaging mechanisms, the corporate head who developed so many imaging systems, was profoundly excited about why human vision was different from Vectographic, photographic, and the then top-secret electronic imaging sponsored by research in foreign intelligence. All commercial and military imagers were responsive to quanta caught at a pixel. Vision is responsive to spatial relationships-the field.

LAND'S LOVE OF THE EXPERIMENT

Our descriptions of negative transfers and Retinexes are just two examples of Land's persistent application of the scientific method to innumerable disciplines. His insatiable love of experiment made Land's laboratory a very exciting place. Land believed in the scientific method; indeed, he reveled in it.

In an address to the Cosmos Club,[10] Land said, "I found myself describing the wonders of the scientific experience. I told of the ways one yearns for a deep insight in some domain; of the strange intuitive program of collecting observations; of the mystery of formation of hypothesis within one; of the competence of the mind-body system to select the crucial experiment; of the excitement of the interaction between experiment and hypothesis; of the sense of relief and even of nobility when the hypothesis was proven true and the stage was set for the next hypotheses. I remarked on the sense of awe that one could be the instrument of this process."

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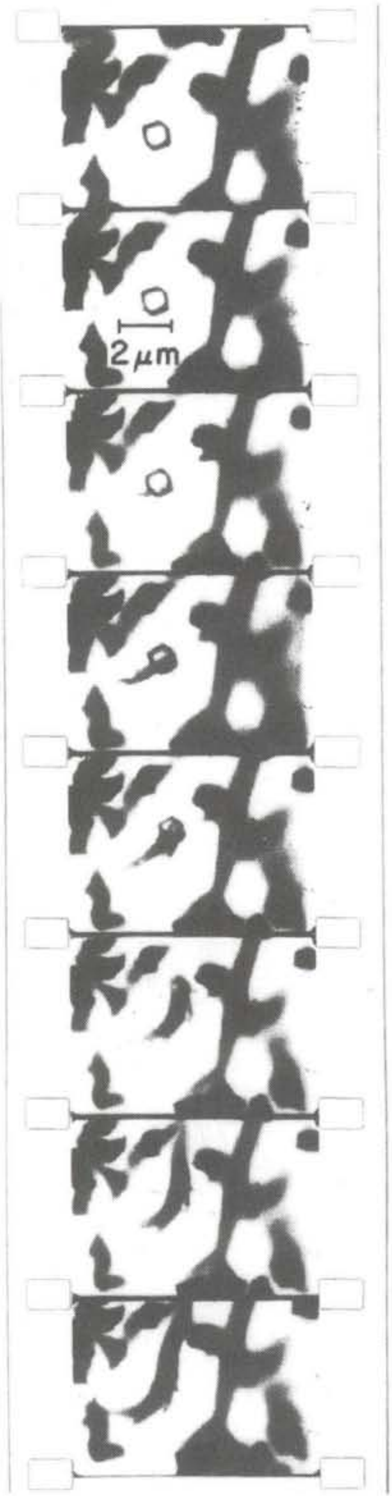

Figure 1. Selected frames of infrared movie of silver halide grains developing with the negative reagent system. The predicted violent reaction moved the grain 5 microns in the emulsion.

Edwin Land and Howard Rogers

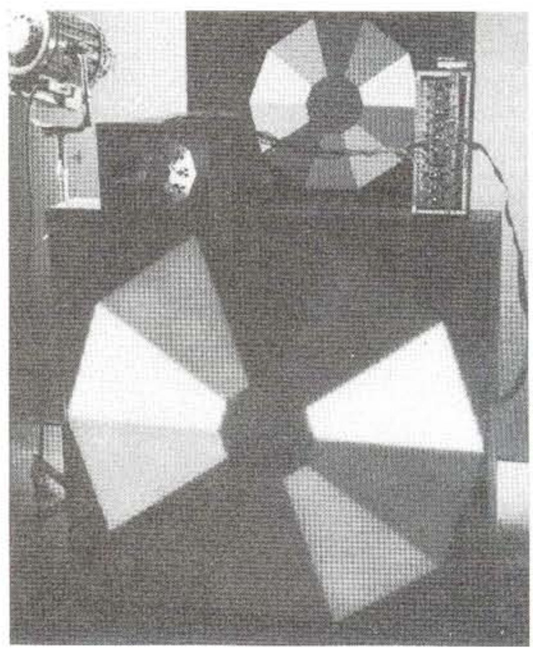

Figure 2. A retinex machine and its display. The spotlight (far left) illuminates a radial arrongement of 10 white, gray, and black popers. The camera (center left, sitting on top of the display device) forms an inverted image of the display. The photocells in the image plane provide the input to the calculation circuit (center right) that compares each pixel with all of the pixels in the image and sends the output to the disploy. This was the first spatially driven electronic imoger. Its output wos lightness-a calculated sensation, not a quanta count.