

SYNTHETIC STEREOGRAMS

Computer Programming for Autostereoscopic Displays

by

Lynn Fulkerson

M.A. San Diego State University (1975)

Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Visual Studies

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
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Abstract

A system for designing achromatic holographic stereograms utilizing computer graphics is explored. This work is placed in both a personal and an historical context. The author's objectives in leaving traditional artistic media to explore the spatial imaging characteristics of holography are described. Selected examples from the history of art, of scientific theories in optics and perception being used by artists to broaden the parameters of visual media, are discussed. Precedents for the application of computer graphics in the development of synthetic holographic stereograms are examined. Particular attention is given to: synthetic images without monocular cues: representation of real space; and the mutual influence between the media of computer graphics and holography. A computer graphics package for generating images for synthetic stereograms is presented. In developing parameters for these graphics programs, the optical properties of holographic stereograms and contemporary theories of stereograms and contemporary theories of stereopsis are applied.

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Chapter One

PREFACE

The characteristics of holography which are crucial for my abstract designs include horizontal parallax, perceptual pattern matching, and real image projections. These optical qualities will be described in detail below. In addition, when holography is combined with computer graphics, the potential for abstract design is theoretically endless: computer graphics extends holography into representation of synthetic images. While investigating computer graphics for holographic stereograms, my main interest at MIT, my concerns continued to be the contemporary representation of abstract space with technology. My investigation clarified the distinction between two-dimensional computer graphics and the new dimension of holographic stereograms. The next chapters will discuss the attributes of computer animation as it evolves into a composite image for the stereogram: the characteristics of motion parallax added to stereo-perspective present a spatial image unique to contemporary technology.

Holographic optics represent the real world with a precision unique to holography. The image represents the object in a point to point correspondence, with the exception of magnification due to wavelength variations. Measurements may be taken from the image of an object on the plane of a hologram. However, the holographic stereogram previously used photographs of a world that included several monocular depth cues. The use of digitized stereo information alters the flexibility of selectively eliminating or including monocular depth cues. Therefore, the metrics of the image from computer graphics for a composite stereogram may be the metrics of the real world. The "real space" characteristic of holographic stereograms motivated the design of this project. Contemporary theories of

stereoscopic perception were used during the calculations of the graphics animation for effectively stimulating fusion. When the object space of the grid in "Hcube" was successfully measured to correlate with the desired dimensions, the object space was defined and controllable.(See 9-5) This thesis explores the program design developed by the author for holographic stereograms.

Chapter Two

INTRODUCTION

Every medium used for visual expression has properties inherent to it, which influence the final image. This chapter will describe the dimensional characteristics in holography that present options to the artist that are not available in abstract painting. The ability of the hologram to represent space without reference to linear perspective was a quality I sought in my paintings, beginning in 1975.

Initially inspired by the work of artist Bruce Nauman to investigate the visual results of layering transparent pigment, I organized a series of paintings that varied the order of three primary colors. The circular format for each painting contained within it a compacted circle grouping; this format was chosen to center the viewer's attention on the resulting subtle color variations. I selected acrylic paint as the medium for this project. Certain attributes of this medium lend themselves well to abstract painting, and to my objectives in particular. Most important, acrylic pigments are easily extended into transparent substance. (Rhoplex AC33 is used to spread the colors to transparency, applied on a waterproofed canvas) The plastic nature of acrylic permits the pigments to hold together during this extending process, where oil paints break down into particles. Secondly, the chemical basis of acrylic paint is a polymer or lightweight plastic and dries quickly. This drying time factor allowed short time periods between layers and meant that succeeding layers of primaries could be superimposed without the pigments mixing together on the canvas. The drying time also meant quick visual results for immediate evaluation. Altering the sequence of the primaries thus changed the neutral tones of the final painting: this phenomenon was central to that project. [Fulkerson 75] In the next series of paintings I explored the kinds of space and volume possible within this

limited format of compacted circles. The circles became spheres and the spaces between the spheres were also modeled into forms. The suggestion of form and space around the plane of the painting was extended to an illusion of vast space when sections of the canvas were left blank. In the paintings that evolved, the blank canvas became both the literal plane of the painting and the illusion of a vast empty space. Within that space the sphere group balanced as objects and as slots that were left blank. The series explored several combinations of the sphere-space groupings, both as symmetrical and asymmetrical designs. (9-1)

In this second series of paintings, I attempted to explore a new realm of spatial representation: the suggestion of space within the abstract design of non-linear shapes (as distinct from the use of linear perspective). Encouraged by positive critical reception to the work to continue the investigation of abstract space, I searched other media for new representational options. In the following years, I investigated several 3-D media for dynamic auto-stereoscopic freedom. [Okoshi 76]

Chapter Three

A PAINTER'S APPROACH TO HOLOGRAPHY

The similarity between my paintings and holography was that both were concerned with representing space without traditional linear perspective. In 1973 I had first noted holograms' ability to present multi-dimensional forms as light focused in space. In 1975, I began exploring the practical problems of developing a holography studio. During this period, I assembled a holography laboratory, and began producing laser illuminated holograms as technical and aesthetic explorations. Supplementing technical readings, I reviewed the state of the art form and attitudes of the art community toward holography.

In September of 1975 I visited New York City and viewed the permanent exhibit at the School of Holography. Earlier that year, the International Center for Photography had exhibited *HOLOGRAPHY '75, THE FIRST DECADE*, a significant display by a major gallery. The reviews for the ICP exhibit discussed the activities of the holography community and some opinions about holography as an image. In December 1975 issue of *Popular Photography* critic Kenneth Poli summarized both the activity and attitudes:

The show's title, *Holography '75, The First Decade*, should have taken the responsibility for content off the shoulders of both the cosponsors. It signaled, after all, only a survey of a short, formative period. ...

In the *New York Times* for Sunday, July 20, Hilton Kramer's column "Art Views" said, "The esthetic naivete of this show must really be seen to be believed. ...

The *New Yorker's* anonymous reviewer wrote, in what could have been an entry in the magazine's own Non-Stop-Sentence Derby, "The show here ...three- dimensional-looking images reminiscent of those

vulgar 42nd Street novelty- store items like the plastic-coated postcards of Christ with a crown of thorns...

Whether or not one shares the views of these two reviewers is beside the point--which both seem to have missed. The point of the show seemed to be that, what started out to be (and still largely remains) a scientific tool, has at least potential as an artistic tool, has at least potential as an artistic medium. On the walls of the ICP were the gleanings of the short childhood of holography. The show was presumably saying that, along with their experiments, testing, and probing with a new scientific tool, the technicians and scientists in holography were also attempting to make images that were fun to look at, not just necessary as working tools. As a bonus, along the way, some artists had also discovered the fascination of the new medium and were trying to learn its grammar -- with varying degrees of success.

Martin Levine, in the suburban Long Island newspaper *Newsday*, called it the "most interesting photo show in the New York area... An exciting and, I suspect, historically important show....What the show does best is simply stir the imagination, and it does that so well that it should give the technique an important boost. By the end of the second decade, holography is clearly going to be a major force in art, science and amusement."

The respected weekly *The Village Voice*, in its art column by David Bourdon, said, "At this early stage, it's hard to tell what, if anything, distinguishes the artists from the scientists... So far the medium is more entertaining than artistically expressive. But, while holography has yet to find its Stieglitz or Steichen, it's plain to see that the medium will continue to lure new and talented devotees."

And John Gruen's "On Art" in *The Soho Weekly News* said, "So enamored are they of the science involved, that the final products look, for the most part, like unimaginative samplers for a new photographic line.... The absence of fertile imagery is the exhibits's fatal flaw, although it must be admitted that even at its most banal, holography is never less than arresting..."

"Standing midway between the still photograph and the movies, holography seems destined to become a major art form. It can only

progress, however, by true artistry--by holographers who will have the vision to transcend the medium's already marvelously transcendent attributes." [Poli 75]

Throughout history many innovations have been received with skepticism. The past also records that many pitfalls were eventually surmounted, and inventions absorbed into standard technique. As a painter attempting to use a new technology for my aesthetic concerns, I drew inspiration from painters in the past who were influenced by concepts in optics and those who used optical devices. [Wheelock 77]

During the Northern Renaissance in the Netherlands, Rembrandt and his pupils derived a better understanding of light and space from the invention of optical instruments. Seventeenth century painting expressed new skills in representation of depth and new concepts in illumination. Theories of perspective were controversial, debating the merits of perception against mathematics as the foundations for representing space. Treatises in optics gave painters a better understanding of light rays. Popular in the Netherlands were convex mirrors, wide angle lenses and the *camera obscura*. The camera obscura, which presented an image focused and projected onto a flat surface, provided the opportunity to study in detail a 2-D translation of 3-D space. (See 9-2) The new ideas influenced individual artists to various degrees. Rembrandt, an established artist, exhibited very subtle changes in representing a given scene within his paintings. He incorporated more dramatic effects in innovative lighting techniques such as illumination sources within the painting scene itself. His pupils, however, were free to overtly challenge the boundaries of perspective and introduced optical distortions into their paintings. Vermeer succeeded in developing the most sophisticated combination of geometric perspective and subtle space manipulation to create a unique style of representing interiors. [Wheelock 77] (9-3)

The primary difficulty of some artists' tendency towards geometricizing perspective theory, however, was that it became more and

more divorced from the practical needs of the artists. Dutch artists were particularly untheoretical. Although their paintings often have moralizing and symbolic overtones, their primary interest was in their visual impressions of the physical world, in representing this world in terms of light and space. In short, their interests were optical. For them the new discoveries about optics and vision were undoubtedly as significant as many of the geometrical theories that surrounded the study of perspective. [Wheelock 77]

It is not clear how influential the camera was in motivating new techniques in nineteenth century painting. It is documented, however, that some Impressionist painters used the camera to record scenes and used those photos as references for their paintings. Degas photographed ballet performances for later painting sessions. The Post-Impressionist who used concepts in optics to formulate his theories of representing color in his painting was Georges Seurat. [Homer 64]

Following the Impressionists' concerns with light as it interacts with various surfaces, Seurat challenged the notion that perceptual impressions were accurate. Seurat studied physicists Rood, Chevreul, and Maxwell to understand the physical aspects of light as well as the way the retina receives visual information. His methods, which he described as "divisionism" were arduous but produced paintings with a vibrance unique to his style. Seurat no longer mixed his colors on a palette, instead based his paintings on the idea that pigment placed in dots of primaries would mix in the retina as secondary colors with more clarity. [Homer 64]

"The actual result, however, did not conform to the theory. Looking at 'Side Show' from a comfortable distance (12-15" for the colorplate, 7-10' for the original), we find that the mixing of colors in the eye remains as clearly visible as the tesserae of a mosaic (compare colorplate 14). Seurat himself must have liked this unexpected effect--had he not, he would have reduced the size of the dots--which gives the canvas the quality of a shimmering, translucent screen. In 'Side Show', the bodies do not have the weight and bulk they had in the 'Bathers;' modeling and foreshortening are reduced to a minimum, and the figures appear mostly in either strict profile or frontal views, as if Seurat had adopted the rules

of ancient Egyptian art Moreover, they are fitted very precisely into a system of vertical and horizontal coordinates that holds them in place and defines the canvas as a self-contained rectilinear field. Only in the work of Vermeer have we encountered a similar "area-consciousness" [Janson 64] (9-4)

In both the Renaissance and Post-Impressionist periods, artists used concepts in optics as references to further their individual visual vocabulary. The artists continued to use the medium of pigments on a flat surface and alluded to space. As we have seen in the cases of Vermeer and Seurat, their investigation of the physical laws and perceptual characteristics of the real world improved their ability to represent space. Contemporary investigations of holography as a new medium require the artist to leave the traditional media altogether and to adopt the optical device itself as the vehicle for visual expression. The basis for this change in procedure is in the medium of holography itself: the optics and perceptual characteristics of holography as a dimensional medium are the only tools capable of expressing dimensional space as focused light.

Chapter Four

STEREO PERCEPTION

When designing holographic stereograms, the most immediate new concern is the physiology of stereo perception. Holography is somewhat distinct from the dimensional qualities in sculpture; the optimum viewing distance in holography necessitates closer examination of the image, and a limited viewing side-to-side motion of approximately twenty degrees. These two characteristics define the physical parameters that become the vehicle of communication between the image and the viewer. An understanding of stereo perception is beneficial in both the design of the computer program and the efficiency of the holographic stereogram.

The investigation of stereoscopic vision began in the 19th century by Sir Charles Wheatstone. In 1832, Wheatstone recognized depth perception as a combination of two visual fields, one from each eye. Therefore, depth was a comparison of two images and the change of viewpoint from one eye to the next. He initially used drawings that incorporated the shift in perspective, but when photography was invented, he utilized the recording ability of the camera, shifting the position of the camera the distance between the eyes. The photographs were then repositioned to be viewed by each eye, in a viewer he invented. The Wheatstone viewer was a right angle mirror device separating the information channeled to each eye. The viewer was placed between the two photos and the observer looked into the viewer so that each eye only viewed one photo, thus reproducing the parallax shift of stereo vision.

¹ Stereo photography was popularized, and viewing devices changed in structure,

¹The Wheatstone viewer did not limit the size of the image and is currently the central theme of an exhibit of large scale Polaroid photos (20"x24", 40"x 80") by contemporary artist Douglas Davis in Soho, NYC.

design and ease of viewing. The photos were placed in front of the eyes, separated by a divider. Lenses were added to aid the convergence and fusion of images by the observer. Stereo cameras flourished which would photograph dual pictures of both contrived and natural scenes. Other stereo devices were invented in attempts to incorporate this third dimension of space into the photographic inventions that soon evolved.

Further development necessitated a better understanding of the characteristics of stereoscopic vision. The physiology of stereo vision, an enquiry as old as Euclid, continues to contribute to the understanding of both vision and the relationship of the eye and the brain. Investigation in robotic vision, which utilizes pattern matching of stereo pairs, has rekindled interest in stereo perception. [Okoshi 76]

Chapter Five

APPLICATION OF STEREOPSIS TO STEREOGRAM

5.1 PATTERN-MATCHING BEHAVIOR

Twentieth century technology contributed to a better understanding of stereo vision, when in 1964 Bela Julesz used computer generated random dot stereo pairs to investigate retinal pattern matching. Julesz tested the ability of the human mind to compare two fields of view devoid of familiarity cues (monocular depth cues). The images he used consisted of dot patterns, computed for random distribution.

A stereo pair of random dots is shown in the figure (9-7). Viewed individually each image appears as a random array of dots, but viewed stereoscopically the area in the center appears as a square that recedes into a second level of depth. The effect is accomplished by slightly shifting the central portion of the image from left to right. The shift is imperceivable with monocular vision but with both eyes, the brain's pattern matching of retinal images compares the dot array of each image and organizes the priorities in depth. (9-8) Several levels of perceived depth may be accomplished with this technique.(9-9) [Julesz 64]

5.2 LOCAL AND GLOBAL STEREOPSIS

This series of experiments introduced new concepts related to stereo vision. In addition to eliminating familiarity cues, Julesz initiated new concepts of stereoacuity. Soon, distinctions of stereo vision subdivided into concepts of local and global stereo vision. Local stereopsis recognizes disparity as a major contribution to depth perception. [Potegal 82] Stereopsis is the perception of depth by shifting images on the retina because of their shift of viewpoint. This is easily

tested. First hold two pine needles at arm's length, one directly behind the other and about one inch apart. If they are within your personal stereoscopic vision, you will easily perceive them as distinctly two pine needles that are aligned one inch apart. However, if they are outside of your ability to fuse them or you move them apart further than one inch, you will perceive them as three pine needles and in a flat array.

Global stereopsis is a characteristic clarified in dot patterns. During the comparison between the two matrices of random dots on the two retinas, the mind is able to distinguish beyond disparity. Within the dot patterns, more than a dot-to-dot correspondence exists. For each dot in one image, there exist several dots in the second image that are a potential match. However, the precision of retinal pattern matching is not confused by the multiple choice of random dots. This suggests that a higher order of perceptual processes is called into play when viewing stereo pairs of random dots. [Potegal 82]

5.3 IMPLICATION FOR COMPUTER GRAPHICS

These precision attributes of stereoacuity suggested that the incremental shifts in computer graphics used for stereograms need to be much smaller than those increments immediately visible with monocular vision. The animation for stereograms increments twenty-one frames within the interocular distance used for stereopairs. This pattern matching approach to the parameters needed to stimulate stereo perception influenced my approach to the necessary calculations for stereograms and resulted in smaller increments.

Chapter Six

STEREOGRAMS A COMBINATION OF HOLOGRAPHIC OPTICS AND STEREOSCOPIC PHOTOGRAPHS

Holographic stereograms are one stage of an evolutionary process. Part of the twentieth century is the technology that resulted from a better understanding of the atom and how it may be manipulated. The many facets of holography would not exist without the invention of a coherent light source in 1961. Laser technology began as a low powered inefficient light source and developed into an industry of countless applications. The phenomena of spatial and temporal coherence make it possible, for the first time, to accurately record the phase shift of a given light. Holography was in fact first called “wavefront reconstruction” which describes the recording and reproduction of the wave formation that is perceived when viewing a hologram. The topic of this chapter is the description of “how” holography happens. The relationship between the coherent light of the laser used to produce a hologram and the incoherent light of the illumination source reconstructing a hologram will be the theoretical foundation for this discussion.

6.1 THE HOLOGRAPHIC PROCESS - A PRIMER

Light Amplification of Stimulated Emissions of Radiation (LASER) produces one of the most elegant results of atomic research. As an atom gains energy, an electron will be stimulated to jump to an outer orbit. When the electron re-establishes itself in its original orbit, the previous energy input is released as a photon. The type of gas used determines the wavelength of the photon. As it travels in the laser tube, and is reflected by mirrors on the ends, it picks up other photons and the wave is

amplified. A prism in the laser cavity refracts the desired wavelength, which is emitted from the tube as the laser beam. When used in holography, that beam is split into two beams; half goes directly to a film plate and half is reflected off the object onto the film plate.

Coherence is a characteristic of laser light that defines the wave as consistent from crest to crest and trough to trough. Laser light is both temporally (as it moves in a given direction) and spatially (from wave to wave as it is grouped) coherent. The section of the wave formation from one crest to the next crest is considered one cycle. If that cycle is interrupted (as in a reflection from an object) at any stage, the wave begins a new cycle and “changes phase.” If the surface of that object also varies in its reflection properties, the intensity of the light is also influenced. The combination of these changes in intensity and phase create a pattern called the “wavefront.”

In holography, the wavefront coming from an object then interferes with the original coherent wavefront of the laser beam at the film plate. The interaction between the two wavefronts results in an increase in intensity (or constructive interference) at points when the waves are in phase. If the object wavefront is out of phase with the laser coherent wave a decrease of intensity occurs (destructive interference). This interference pattern is recorded on the film. After processing, the film, now a hologram, is placed in the exact position of its recording and re-illuminated by the laser beam. The laser’s coherent light is then diffracted by the particles in the hologram’s emulsion and thereby recreating the original object wave front, and the object wavefront is transmitted from the hologram and perceived by the viewer. Due to the density of the silver halide in the film emulsion, (3000 lines/mm), the amount of information transmitted contains a change in perspective within the distance between the eyes. In a laser illuminated hologram, the viewpoint parallax is in both the horizontal and vertical directions.

The characteristic of holography that has made possible both image plane holograms and also incoherent light illumination of holograms, is the reconstruction of the real image and subsequent recording of that image. The real image is a point by point reconstruction of the object focused in the space on the side of the viewer. Therefore, if a film is placed into the plane of the real image, the image may be recorded and reconstructed on the plane of the hologram. Image parallax and real image projection are two characteristics that are unique to holography as a medium.

The above process is described on various levels throughout the available literature concerning holography. The author recommends "*Principles of Holography*" by Howard Smith of Eastman Kodak [Smith 75] which describes the concepts governing holography. Written as a physics discussion, it has the unique characteristic of including definitions of the terms used and consistent use of those terms throughout. It reaches a larger audience than most discussions of the physics of holography by also including prose equivalents of the math equations. His presentation is therefore a thorough description and a basic foundation for the further study of the holography that has evolved since Smith's book was published in 1975.

6.2 COMBINING HOLOGRAPHIC OPTICS WITH PHOTOGRAPHY

The twenty-five years of holography's history has been an exploration of applications for holography's inherent physical characteristics. This exploration has included attempts at making holography part of the broadening field of visual media. Viewing a hologram in a non-industrial environment has been a goal of the field of display holography. The transition from laser illumination to widely available white light sources for reconstructing the image, has meant years of researching the response of diffraction gratings to various frequencies of light.

Recent advances in the quality of mass production has popularized holography as a viable technique for optically conveying visual information to the observer. The research in holographic stereograms at MIT's Spatial Imaging Group, centers around the advantages of combining the image capabilities of computer graphics with the dimensional characteristic of holography. This project focuses on the aesthetic value of abstract space representation within the scope of computer generated holographic stereograms.

The development of holographic stereograms in particular and what events influenced its progress are difficult to substantiate. However, there is a sequence of events that combine stereopsis and holography which begin with computer generated three-dimensional movies. In 1965, A. Michael Noll wrote in *Computers and Automation* about "Stereographic Projections by Digital Computers;" [Noll 70] in the same year, in the journal, he also published an article on "Computer-Generated Three-Dimensional Movies" [Noll 70] in which he investigates the advantage of stereo pairs for display of random objects with no monocular depth cues. His objects consisted of random dots that were connected by lines within a designated cube.

In January of 1968 *Applied Physics Letters* included an article on "Holographic Stereograms From Sequential Component Photographs" by J.T. McCrickerd and Nicholas George. The method describes using a sequence of photos, taken on a straight line, of an object illuminated in incoherent light. The second step holographically records the sequence, each frame through an aperture, as a horizontal array of slit holograms. When illuminated with coherent light, the object is stereoscopically viewed through the slit array, each slit presenting a different perspective of the object. Then in 1970 Noll teamed with D.H.Berry, and M.C. King, to publish "A New Approach to Computer-Generated Holography" in *Applied Optics*. Noll again used random vector graphics to produce a hologram of a

sequence of computer generated images. The series is a rotation around the y axis of vector graphics within a cube of 3-D space. Holographically recorded and stereoptically viewed, Noll hologram illustrate the advantage of combining media to present a new autostereoscopic device.

Previously the computer had been used to calculate the wavefront emerging from an imaginary object. This method usually consumed well over a day of computer time. Adding stereoscopic sequences into holography reduces computer time and presents a realistic three-dimensional image. Several advantages of holographic stereograms include; no dead spots, pseudoscopic images, or flickering, which often accompany other auto-stereoscopic viewing devices. Noll also suggests an additional step to produce a rainbow hologram of the computer images. White light holograms prior to the Benton rainbow hologram were viewed in a narrow bandwidth and were very dim. The increase in brightness of the full spectrum of white light transmission holography allowed Noll to view his computer generated hologram in ambient light. Very bright holographic reproduction of computer graphics meant holographic stereograms would continue to be an important part of 3-D information storage. Monochromatic viewing of rainbow holograms later would be improved by superimposing the spectral colors into an achromatic holographic stereogram. [Benton 80]

Chapter Seven

ACHROMATIC HOLOGRAPHIC STEREOGRAMS

Stereograms have the potential for a wide range of content. Photographs destined for holography could be of real world scenes and from the CRT, which could be digital video or computer raster graphics. The achromatization of the image rendered a greater solidity and brightness. The ability to combine raster computer graphics to the dimensional characteristics of holography, (the ease of white light viewing with brighter, more efficient achromatic holographic techniques; and the potential for design within the abstract space of holography) justified the investigation described in this project.

The achromatic holographic stereogram is a technique that combines the optics of holography with stereoscopic perception. Autostereoscopic freedom is gained by multiple photographs superimposed within the horizontal optical viewing angle of the hologram. Achromatic color is obtained by overlapping the multiple frequencies available in diffraction of the white light illumination. A detailed discussion of the achromatic stereogram is available in Benton's patent "Holographic Products and Processes" #4,445,749. May 1984. The physical characteristics of the achromatic stereogram suit the desired qualities for the designs that motivated this investigation.

The achromatic holographic stereogram combines photographs of computer graphics from a high-resolution CRT. The computer image is a single frame of a composite animation. The specific movement of the animation in stereo-perspective and horizontal motion are included in the chapter on the computer graphics design. In Benton's achromatic stereogram technique the camera movement is parallel with

the image on the CRT. A linear shooting arrangement reduces keystone distortion by keeping the image parallel to the lens of the camera to the film. A Dunn Camera was used for the recording of the monochromatic computer images onto 35mm film.

The film is then used in the holographic process by projecting each frame on a diffusion screen as the object wave. In order to accommodate stereopsis, the stereo-perspective movement of the image must be placed in the y direction on the diffusion screen (9-10). This positioning anticipates the two-step process and pseudoscopic projection of the real image in the second step. The apparent distance of the image on the CRT from the camera is equal to the distance between the diffusion screen and the holographic plate. The angle of the reference beam is arbitrary. The lens on the reference beam for this project was a collimating lens with a mask to restrict excess light from around the slit on the H1 plate. The patent suggests a cylindrical lens that would concentrate a linear reference beam and reduce exposure time. Exposure time is calculated according to the ratio between the object beam and reference beam, and according to the sensitivity of the film. The object beam or diffusion screen is a flat surface with the computer image focused on the side facing the holographic film. The angle of film holder and mask to the diffusion screen is the "achromatic angle;" the effects of this angle will be discussed later. [Benton 84]

A mask is used to delineate the section of the H1 hologram to receive each consecutive frame of the animation. The mask contains an elongated narrow slit. The slit is long enough to allow a useful vertical viewing zone for spectral overlap in the final hologram. (9-11)

The width of the slit (Δx) is influenced by the distance (D) from the hologram to the diffusion screen and the distance (d) between the hologram and the observer.

The relation is:

$$\Delta x < 3D/(D+d)$$

The range of Δx is usually between one and three millimeters. The upper limit is chosen to keep the hologram width smaller than the pupil diameter. If this upper limit is exceeded, the discontinuities in the image become noticeable as the hologram is scanned visually. Decreasing the size of the strips frequently causes diffraction noise off the edges of the slit and decreases the resolution of the reconstruction. [Noll 70]

The second step of the achromatic hologram reconstructs the slit array with the conjugate of the reference beam, and the real image projection is recorded by a second holographic film. During the second step in *rainbow* holography the vertical parallax is limited by spreading the reconstruction beam into a horizontal slit. This results in a very bright final hologram. In holographic stereograms all the object points focus on a single plane, thus reducing color blur. Therefore, the conjugate beam may be spread with an open aperture collimating lens. The conjugate reconstruction produces the achromatic angle between the H1 plate and the H2 final hologram. (9-12) [Benton 84]

Viewing the H2 final hologram with a conjugate of the second-step reference beam will produce a slit array at the distance and angle of the construction set-up. If the reconstruction beam is the same wavelength as the laser that produced the hologram, the slit array will reconstruct in the exact position of the H1. However, if the reconstruction of the H2 is with a multiple wavelength light source each wavelength will reconstruct an individual slit array. The specifications for the achromatic angle are calculated so the three reconstructed arrays will overlap. It is the overlap that achromatizes the image for the viewer. The vertical viewing angle widens as a by-product of the achromatic angle. Each slit array position and vertical

placement is influenced by the wavelength of its reconstruction. The magnification and demagnification of the reconstructed images on each side of the conjugate image supports the advantage of using 5145A as the center wavelength (found in Argon lasers). The vertical viewport for an achromatic stereogram may be as much as 30 degrees if the H1 hologram is up to 42cm high. This overlap of the multi-wavelength also allows for color mixing possibilities. (see 9-13 to 9-18) [Benton 84]

Chapter Eight

COMPUTER GRAPHICS FOR SYNTHETIC STEREOGRAMS

The unique considerations of the programmer designing holographic stereograms include concerns about the objects themselves, how they are illuminated, and stereopsis within the animation. The object subroutines result as a combination of the practical need to shorten the rendering time for each frame of the animation and a paint systems approach to solids modeling.

The algorithms for illumination of each primitive in my stereograms reflected my personal approach to three-dimensional shapes. By correlating the pixel to a pencil point, the three-dimensional form of the shapes is produced by highlights and shadows. A circle is looped, redrawing at the circle's center but reducing the radius and tone to evolve into a sphere; a rectangle becomes a box, and an ellipse becomes an oval. A cylinder was a line looped with the one end forming an ellipse and the other end containing a flat ellipse shape. The direction of the illumination source for each primitive was controlled by the direction of the center motion as it loops through the cycle. The input for the direction is the x,y coordinates within the outside parameters of the shape. (see appendix A).

Accommodating stereopsis in the animation program necessitated special consideration in placement of the shapes within the format of the object space. Both the animation characteristics of perspective rotation and horizontal movement were calculated. These pixel increments designated the starting points for each shape and its incrementation per frame, during the horizontal animation. The increments were added to the center x of each primitive. Centralizing the information in the program

structure allowed variations to the animation with minor changes by the user. Basic trigonometric calculations would be done and added to the increments when it was necessary to change either the perspective rotation or horizontal movement. The following algorithms are a description of the unique considerations in image perspective when the programs is animated for a composite stereogram.

8.1 COMPUTER PROGRAMS FOR HOLOGRAPHIC STEREOGRAMS

The calculations for image rotation necessary to accomodate stereo perception use perspective projection. Traditional perspective has been adapted to computer graphics for two main reasons: most accept it as an accurate representation of reality; and with computer data storage it is easily adapted to animation. One goal of realism is that of showing three-dimensional spatial relationships on a two-dimensional surface. Computer display devices have been two-dimensional. Therefore, three-dimensional objects must be projected into two-dimensions, with considerable loss of information which can sometimes create ambiguities in the image; there are numerous examples of the effective optical illusions created by limited depth cues. The traditional solution to the problem of clarifying the image is to add more monocular depth cues. And, the graphics programmer can always rely on the mind's compensation to fill in the gaps. Thus, for practical reasons, planar geometric projection has been the basis for representing spatial relationships. However, computer images for auto-stereoscopic devices must consider additional perspectives for multiple viewpoints. [Foley 82]

Planar geometric projections are described by the relation of the center of projection to the projection plane. The center of projection is the line drawn from the viewer/camera lens to a point along the projection line. In perspective projection the distance from the plane of projection to the center of projection is finite.

Parallel projection describes the distance of the center of projection from the projection plane as infinite. [Foley 82] This project makes use of the concept of stereo-perspective which combines the projection from two points in the object space and relates both points to two viewpoints from the eyes, then compares the difference in the angles created by the relationships. [Marr 82] In this scheme the center of projection is the distance from one eye to two points in the object space. The projection plane is the screen. The stereo-perspective is then taken from both points in the object space and projected to the second eye. The relationship between the two projections becomes the guideline for the parallax shift within the animation. These calculations are inserted into the program and result in a relationship of all points in the image to each successive frame in the animation.

8.2 COMPUTER HARDWARE AND SOFTWARE

The Perkin Elmer 3230 used for this project controlled a Ramtek frame buffer used for the graphics display. Software on the Perkin Elmer is the MagicSix operating system developed by the Architecture Machine Group at MIT.

8.3 ALGORITHMS

The graphics package developed by the author for this project was a paint system for three-dimensional primitives and three-dimensional animations. The animation parameters were discussed in the above section on stereo-vision. The primitives used for the elements of these animations were designed for utility and for the time constraints of the animation. The primitives include: a sphere, an oval, a cylinder, a series of converging slats, and a box.

Among the primitives, a sphere is traditionally the most difficult shape to represent on a two-dimensional plane. Also, the sphere is an element in my earlier work as a

painter and sphere groups have continued to be a dominant theme in my holograms. The program that draws the sphere is a looping circle that reduces in radius and tone:

```
x,y = position of the first circle
N = number of loops and radius of first circle
dds = increment used to reduce the radius for each loop
dx,dy = calculates the x,y positions of the
        illumination source
color = color + 1, linear shadowing
ram$filled_circle = a predefined function.

Shade_loop:  do i = 1 to N;
              x = x+dx;
              y = y+dy;
              radius = radius-dds;
              color = color + 1;
              call ram$filled_circle;
            end;
```

The primitive in this graphics package which forms a rounded oval is designed with the same looping function as the sphere but uses a pre-defined subroutine for the solid ellipse. The illumination source is calculated and added to the x,y positions of the ellipse. The amount that the focus deviates from center is controlled by a function xss. The xss function is continued through the shadowing loop.

A third primitive, a cylinder, was selected in order to include a vertical shape within the three-dimensional graphics package. The cylinder was designed to be variable in length and width. To be consistent with the 3-D package, its shadow needed to change viewpoints and initially be from the right. The desired shadowing necessitated a linear pixel looping:

```
x1,y1 = top left edge
```

```

x2,y1 = top right edge
x1,y2 = bottom left edge
    A = center of ellipse curve
    a = x1 + A, B = A/2
    color = color + 1, linear shadowing
ellipse equation = B* $\sqrt{1-(x-a)*(x-a)/(A*A)}$ +b;
ram$line = a pre-defined subroutine that draws
a vertical line.
ellipse = paints an ellipse on the top end
of the cylinder.

Cylinder loop: do while (x<x2);
                x = x+1
                y2 = (ellipse equation)
                color = color + 1;
                call ram$line (x,y1,x,y2,color);
            end;
            call ellipse;

```

The most versatile of the primitives designed for this project but used only in the interactive program and not the holographic stereograms is a subroutine named "box". It is a looped rectangle. It can be extended to the size of the screen and used as a background frame to hold several other shapes and the floor design. Or it can be used as a small structure within the overall picture. Its viewpoint may be varied to facilitate the desired viewpoint of the overall picture and the depth, size and rectilinear dimensions of the box may be determined by the user.

To unify the overall space in the image, one of the primitives in the graphics package is a series of converging slats. This routine uses a pre-defined polygon function. The program draws a series of polygons that appear to converge to an arbitrary vanishing point. In addition to computing a linear illumination model, as

in the sphere, oval, and cylinder, this subroutine computes the foreshortening as it changes from viewpoint to viewpoint.

```
x,y[1,2,3,4] = polygon edges
    swidth = width of the front edge of each polygon
    ewidth = width of the back edge of each polygon
    height = viewing angle
    ds = increment between front edges
    de = increment between back edges
    sstart = the beginning of the array of polygons
    ssend = the end of the array of polygons
    width = ssend - sstart;
    estart = middle - (width/2) * (ewidth/swidth);
    poly = function to draw a polygon

do ix = sstart to ssend by ds;
    x[1] = ix;
    y[1] = sy;
    x[2] = ex;
    y[2] = ey;
    x[3] = ex + ewidth;
    x[3] = ey;
    x[4] = ix + swidth;
    x[4] = sy;

    call poly(x,y);
end;
```

8.4 GRAPHICS PACKAGE

Programs for holographic stereograms are a composite of primitives as subroutines within a picture format and then as a whole. The image was animated in the

horizontal direction. The animation program follows the calculations discussed earlier as parameters for stereo-projection. To facilitate easy user interface, all the calculations for the entire picture are stored in the section heading the program.

Programs were designed to experiment with the interactions between computer programs and the holographic stereogram. The original goal of controlling space in the final hologram was maintained during the design of the holograms and their programs. The last hologram/program, "God's Eye", was designed using the knowledge gained by the previous programs but designed as an image with aesthetic concerns, a universal idea conveyed with elementary terms.

The animation program for the holographic stereogram is designed around parameters for stereo-perspective and horizontal parallax only (HPO). To facilitate these characteristics the image starts on the left one-quarter of the screen and moves across the screen to the right one-quarter of the screen. During this horizontal movement the image/object also translates about a central plane to include proper shift for stereo vision. The starting position of the image corresponds to the number of frames in the animation and the angle of view from the observer. The calculations for the two movements must be combined into a single increment per frame, designated as $dx_{1,2,3,4}$, in the program "Hcube", discussed in detail below. The movement of the image across the screen also includes a calculation corresponding to the relationship between the observer and the illumination source designated as $dx_{a,b,c,d}$. The scaling of the grid and the size ratios of the spheres correspond to the perspective projection of the stereo calculations. The code in the program **Hcube** that designates these functions is located in the section heading the program.

Grid:

cx_1, cx_2, cx_3, cx_4 = starting position of each grid, positions
correspond to parallax shift per level of depth

cy1, cy2, cy3, cy4 = 240, there is no movement in the y direction.

ss1, ss2, ss3, ss4 = the scale of each grid per level of depth.

Spheres:

cx1, cx2, cx3, cx4 = starting position of each level of spheres.

cya, cya3, cya2, cya1 = 240, there is no movement in the y direction.

dx1, dx2, dx3, dx4 = the increments of the light source
as the viewpoint changes.

dya, dyb, dyc, dyd = the change in the highlight on the object as
it is placed further back in the depth projection

Increments per frame:

dx1, dx2, dx3, dx4 = the increments to be added to the x center of the
object in the image according to its intended depth
and parallax shift.

These symbols and the calculations for their movements during the animation remain constant throughout the programs for the holographic stereograms. The changes in the starting positions and placement of the primaries in the image for the hologram God's Eye were added to the above calculations and is designed for aesthetic reasons. The calculations that are included for horizontal movement in the image and the calculations for the perspective rotation of the object are established for holographic stereograms in "Hcube". The additional hologram of God's Eye designs an aesthetic image around the physical parameters of stereoscopic vision characteristic of holographic stereograms.

(the following section is a discussion of the images that resulted from the above programs. These images are a sequence that investigate the unique quality in the representation of space in holographic stereograms.)

Chapter Nine

SPATIAL IMAGING - ITS VISUAL IMPACT

The above programs actually became holographic stereograms. During the process, decisions were made concerning the image content. Thought behind those images were motivated by various factors. It seems fitting to mention how the process itself influenced the stereogram image design. "Hcube" (9-5) included an exploration of "real space", and a three-dimensional "design space". The accent the spatial imaging quality, I designed layers of spheres that looked so cluttered on the two-dimensional CRT the observer is unable to distinguish the individual layers. However, when the image becomes a hologram, the layers and asymmetrical design becomes distinct.

Designing a hologram around the parameters of the holographic stereogram process followed in Hcube, in addition to "real space" aesthetic concerns was the motivation for the design "God's Eye." (9-6) Conceptually, it began by combining traditional ideas with contemporary technology. God's Eye is a Navaho icon usually woven from sticks and yarn. New shapes were added to fit the holographic stereogram sequence. An icon from Islamic art, and my paintings, was placed on the rear surface. The space within the stereogram was unified with a series of converging slats on the floor plan. An arrangement of spheres was designed to carry the observer from the front plan to the back surface.

As a new visual medium, holography must be considered as an image. Holography as light focused in space, as it is perceived, is an product of an image maker. The content of holography then becomes a tool for visual language. Decisions that are made about the content of a hologram are expression of the statement by the image

maker. As holography attempts to join the other media within the visual world, holographic image makers must face the challenge of defining what holography, as a media, may contribute as a unique tool for visual language. Artistic statements have expanded beyond traditional aesthetics to include all facets of the human experience. The broadening of the possibilities for content means a greater task for a new media to enter the available means of expression. This thesis is my attempt to substantiate certain characteristics of holography as uniquely suited for my images. One painter's approach to holography.

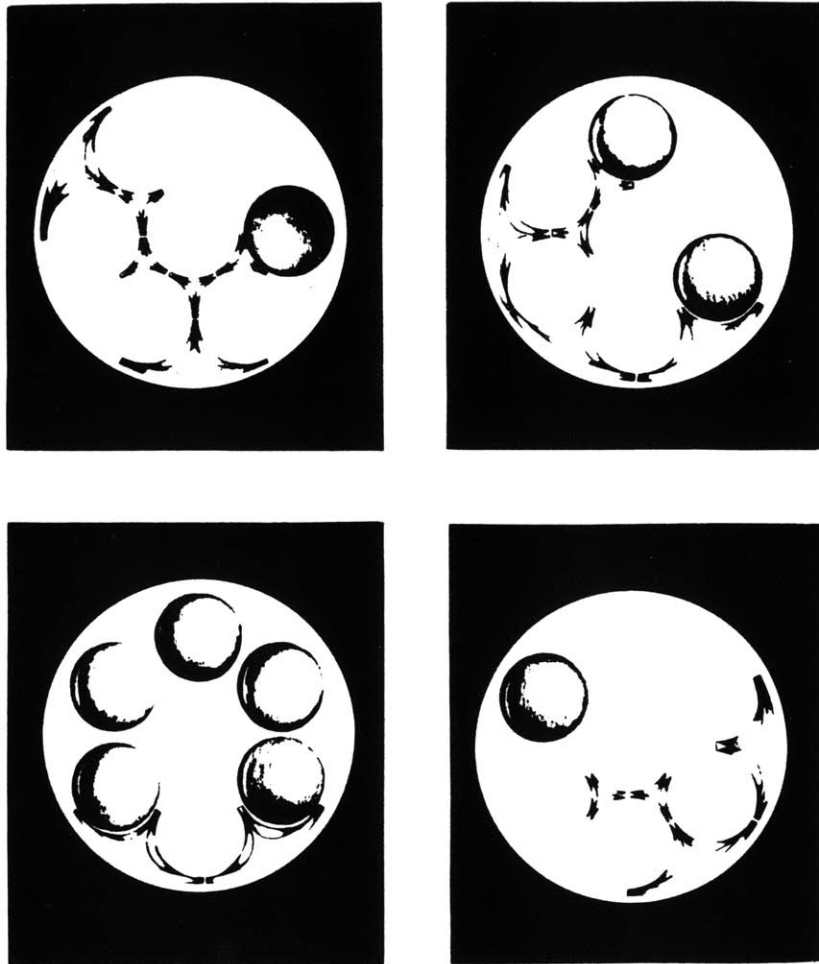


Figure 9-1: Drawings.

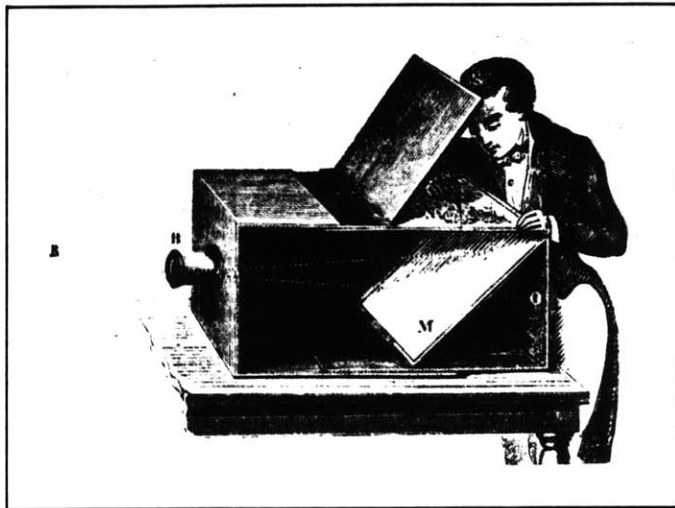


Figure 9-2: Camera Obscura



Figure 9-3: Vermeer

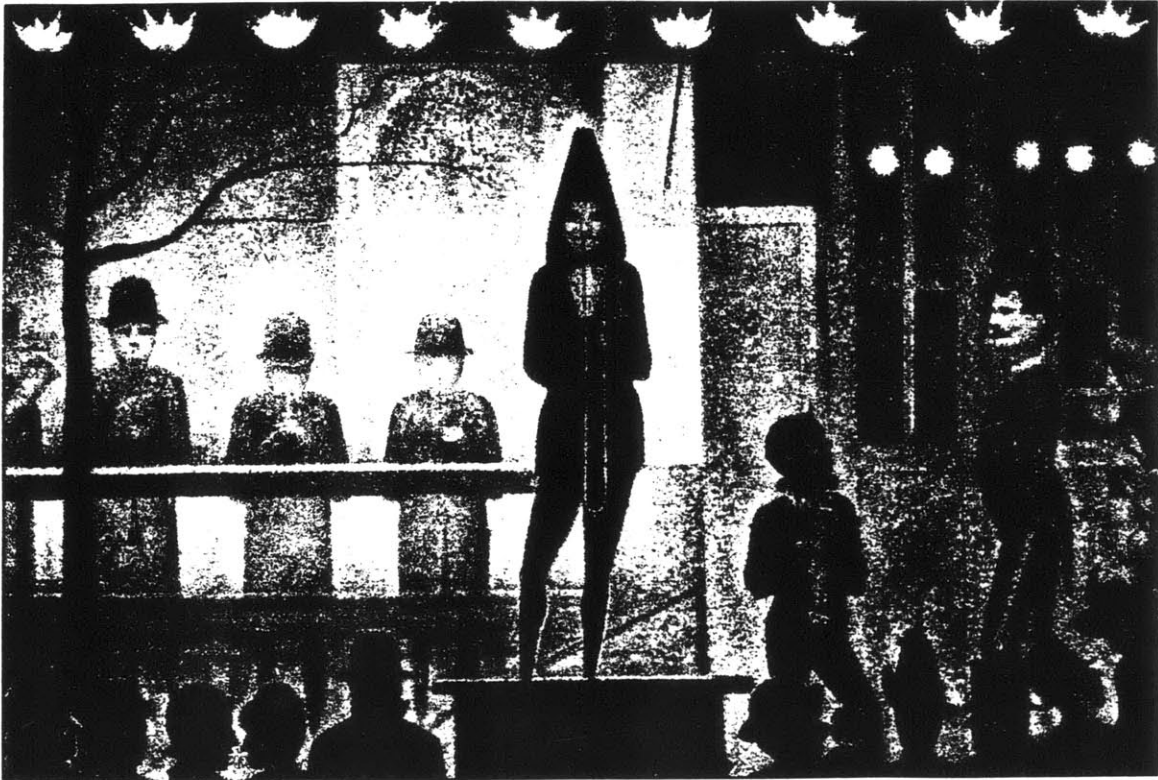


Figure 9-4:Seurat's Divisionism

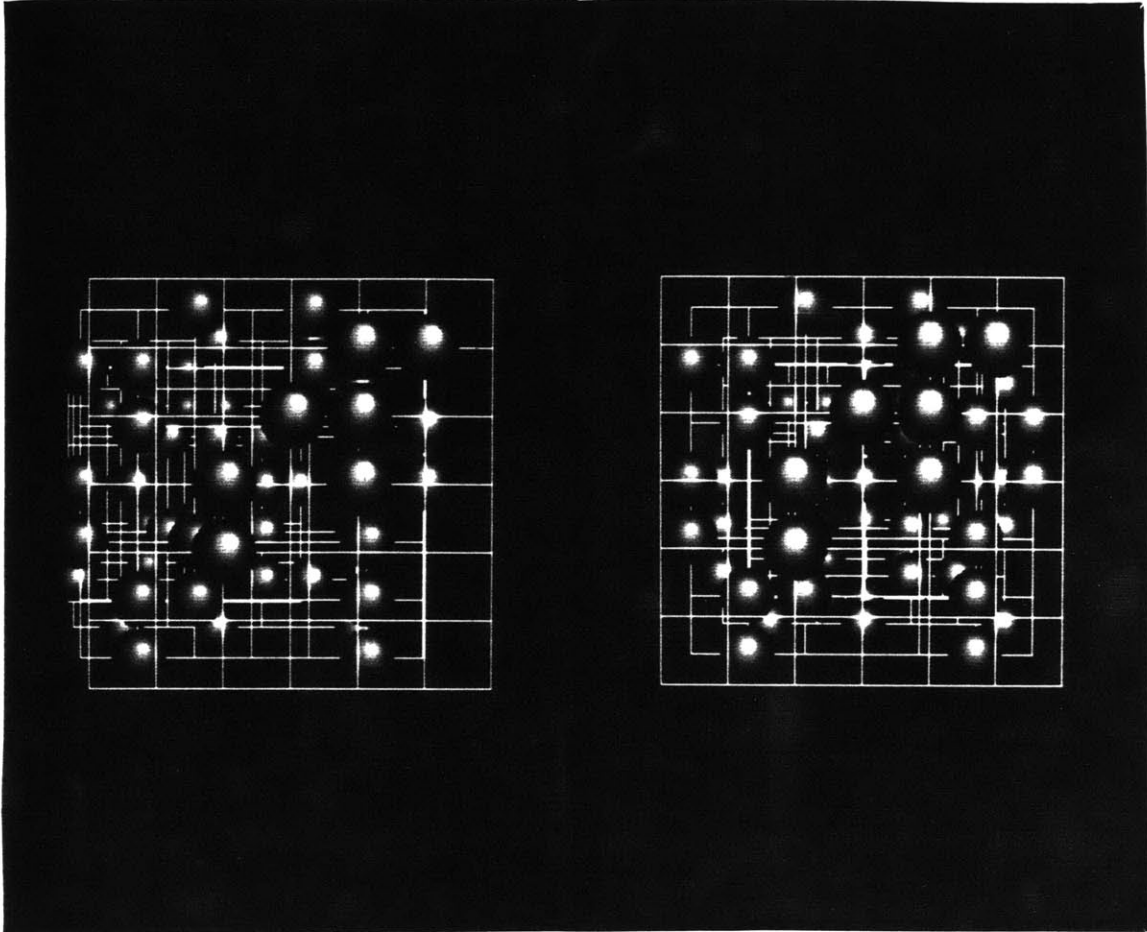


Figure 9-5:HCube

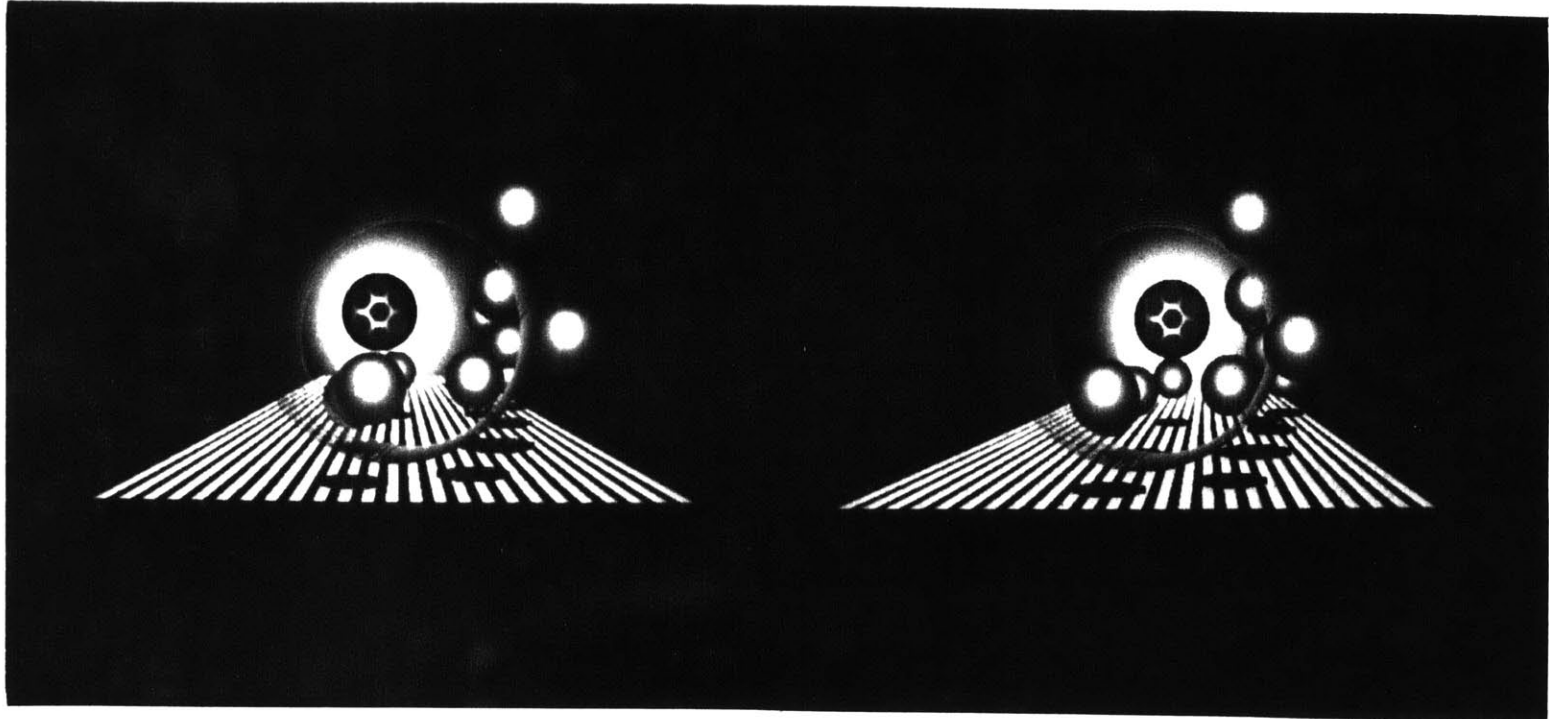


Figure 9-6: God's Eye

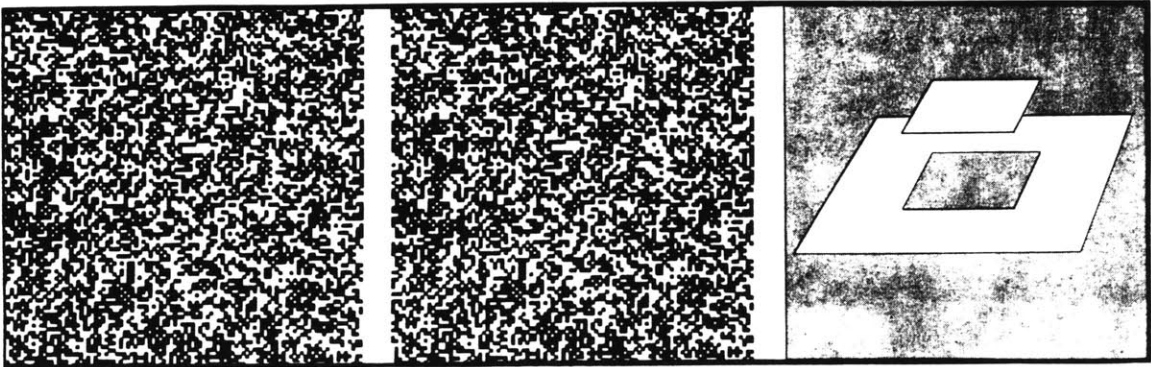


Figure 9-7: Stereopair of random dots

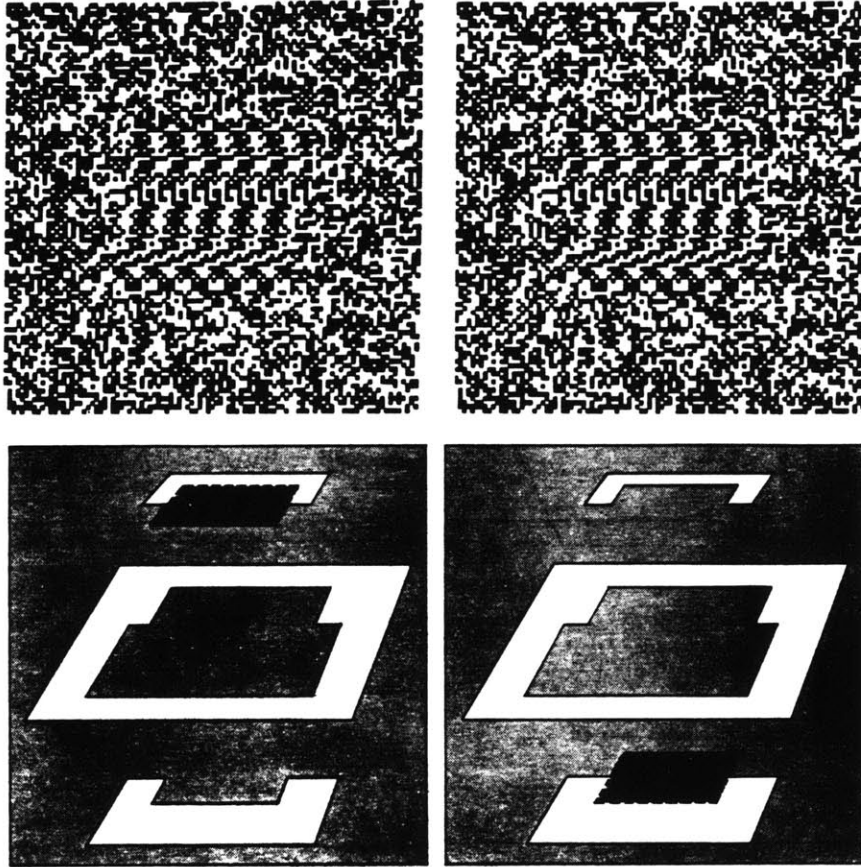


Figure 9-8: Pattern Matching of Retinal Images

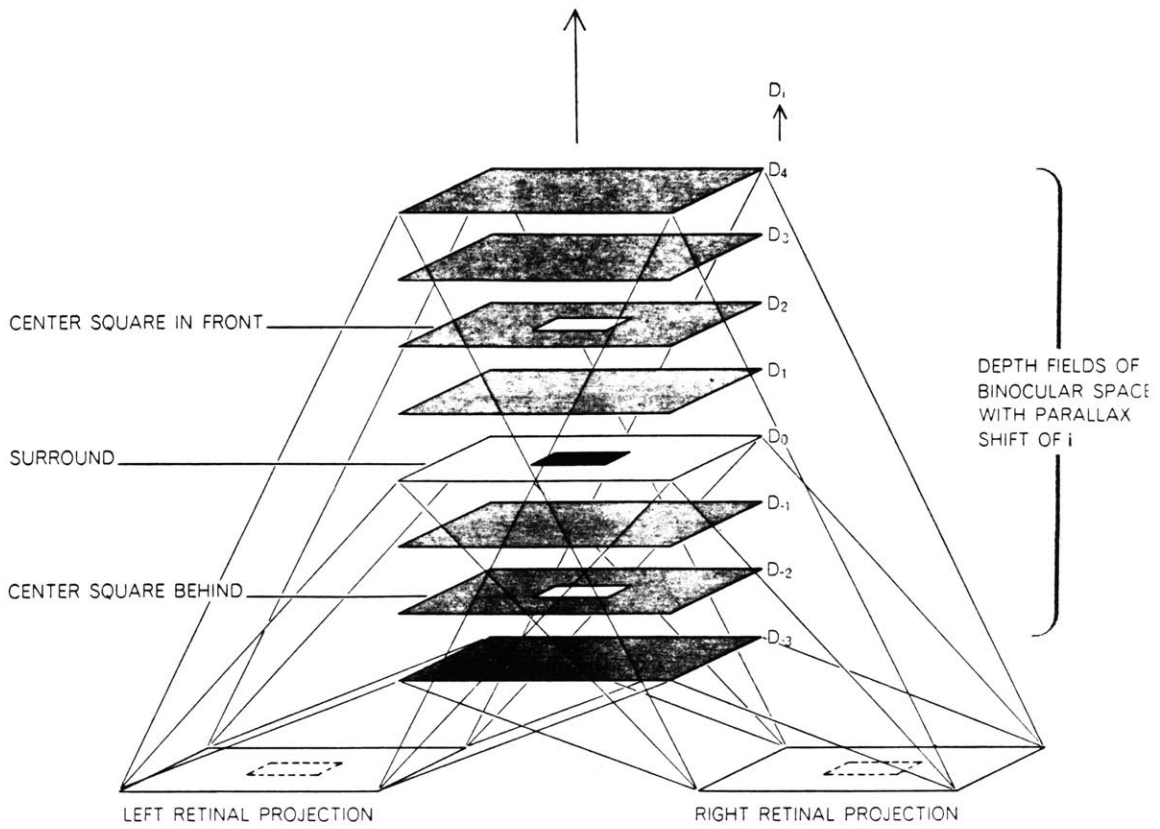


Figure 9-9: Depth Levels

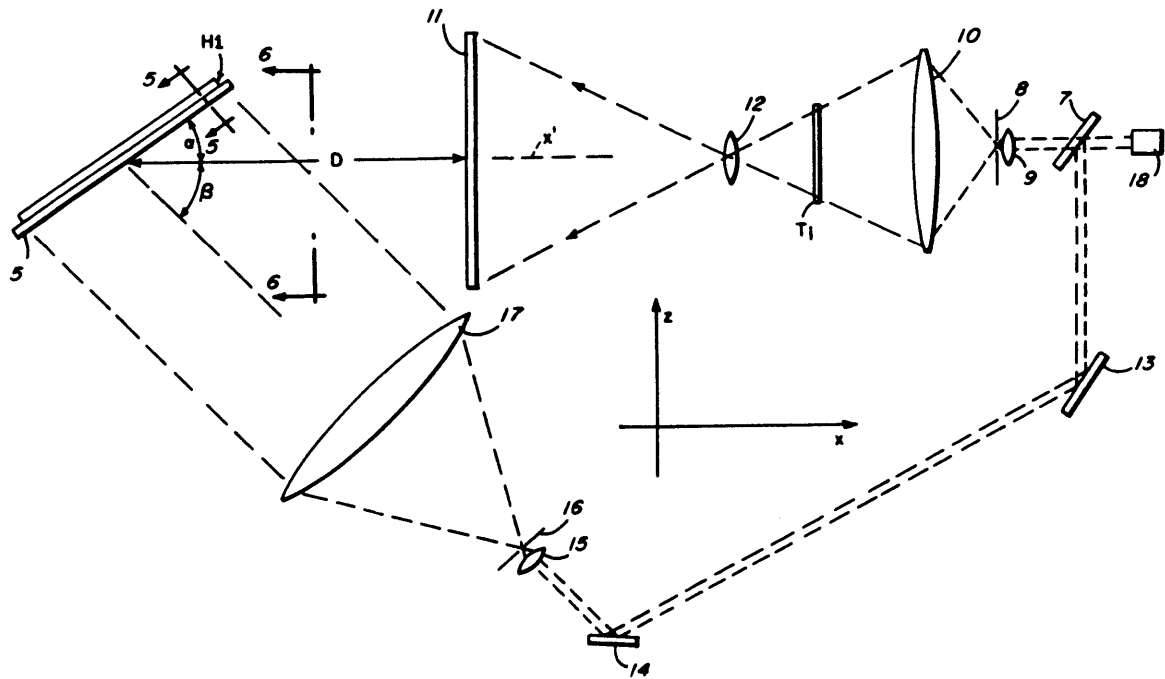


Figure 9-10: Benton's patent Figure 4

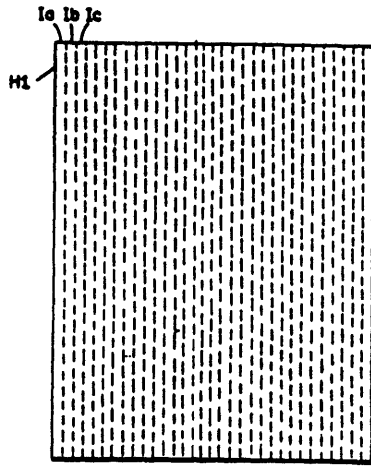
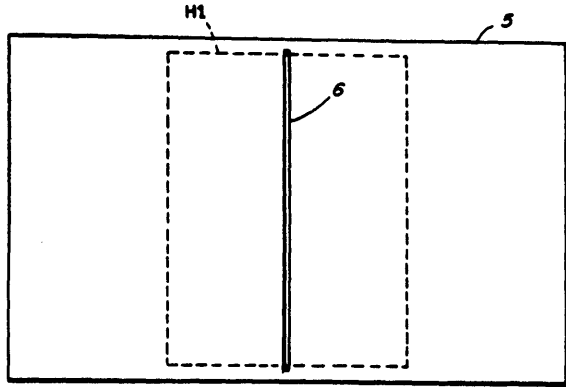
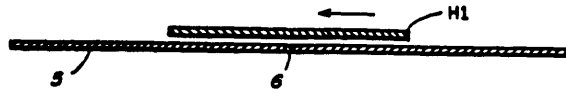


Figure 9-11: Benton's patent Figure 5-7

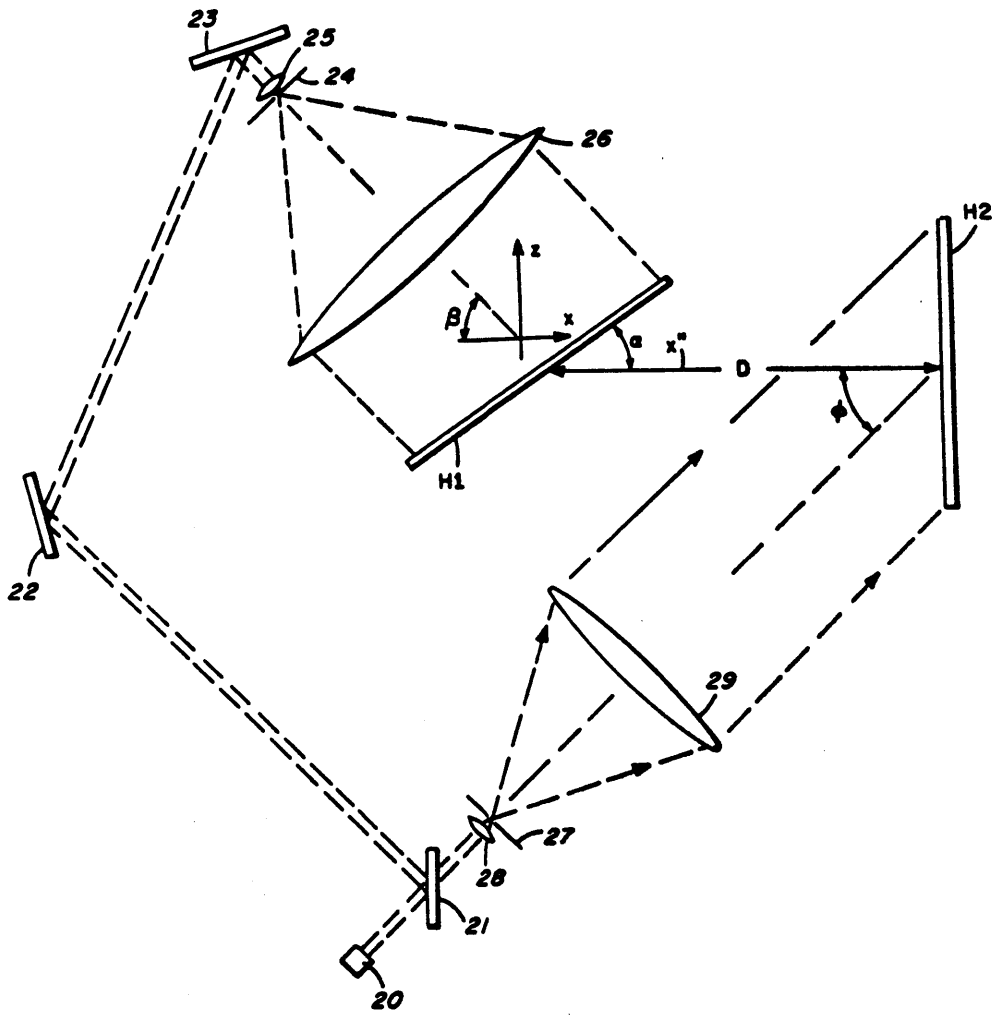


Figure 9-12: Benton's patent Figure 8

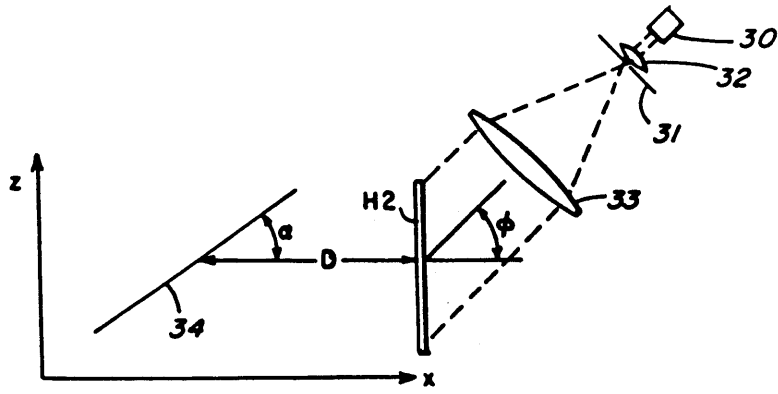


Figure 9-13: Benton's patent Figure 9

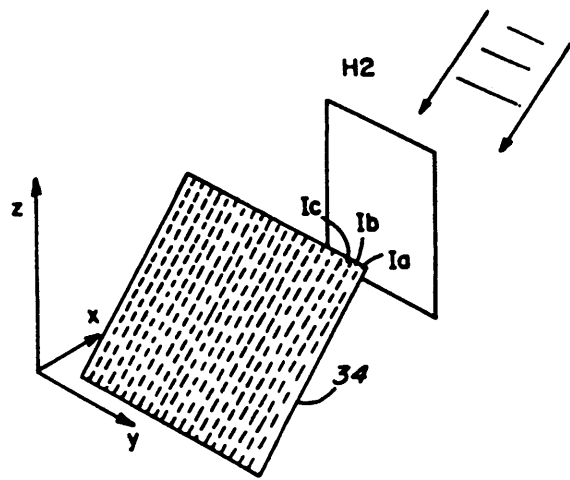


Figure 9-14: Benton's patent Figure 10

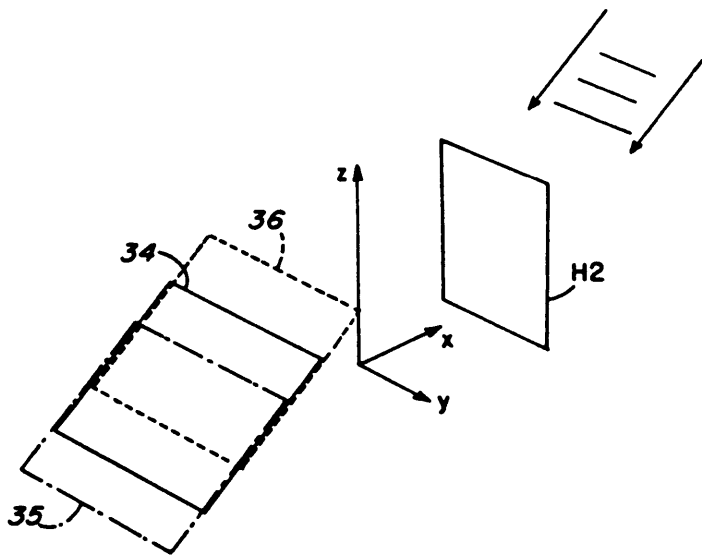


Figure 9-15: Benton's patent Figure 11

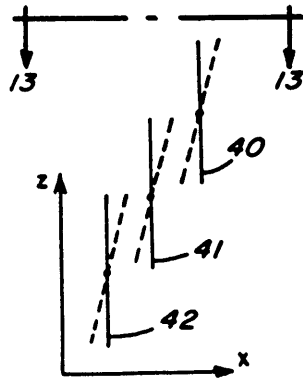


Figure 9-16: Benton's patent Figure 12

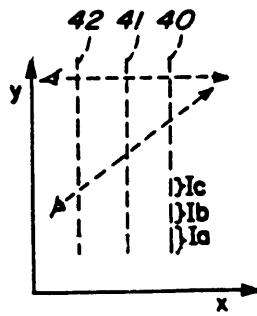


Figure 9-17: Benton's patent Figure 13

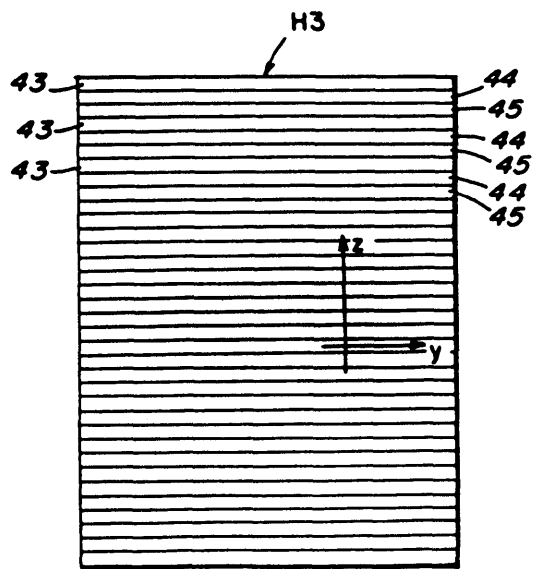


Figure 9-18: Benton's patent Figure 14

Acknowledgements

I'd like to thank everyone who helped me out. You know who you are.

Appendix A

```
sphere:proc(ARGcxh,ARGcyh, radius1,radius2,ARGcolor_h,dx,dy,N);
dcl (ARGcxh,ARGcyh, radius1,radius2,ARGcolor_h);
dcl N fix;
dcl (dx,dy) flt;
dcl (ddx,ddy,ds,dds) flt;
dcl math$sqrt entry (float) returns (float);
dcl (a,b,c) float;
dcl (xa,ya,cxa,cya,radius_a,color_a) flt;
dcl (cx,cy,radius,color) fix;
dcl i fix;
dcl loadcm entry options (variable);
dcl ram$filled_circle entry (fix,fix,fix,fix);
dcl ram$clear entry (fix);
dcl ss fix;
dcl zap entry;

xa = ARGcxh; ya = ARGcyh; radius_a = radius1; color_a = ARGcolor_h;

ddx = float (radius1) * dx; ddx = ddx/float(N);
ddy = float (radius1) * dy; ddy = ddy/float(N);
ds = radius1 - radius 2;
dds = ds/float(N);

dcl ioa entry options(variable);
call ioa ("ddx ^f, ddy ^f, dds ^f, ddx,ddy,dds);

Shade_loop: do i = 1 to N;
    xa = xa + ddx;
    ya = ya - ddy;
    radius_a = radius_a - dds;
    color_a = color_a + 1;
    cx = xa; cy = ya; radius = radius_a; color = color_a;
    call ram$filled_circle (cx,cy,radius,color);
end;
end;
end; /* sphere */
```

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Wash.DC.