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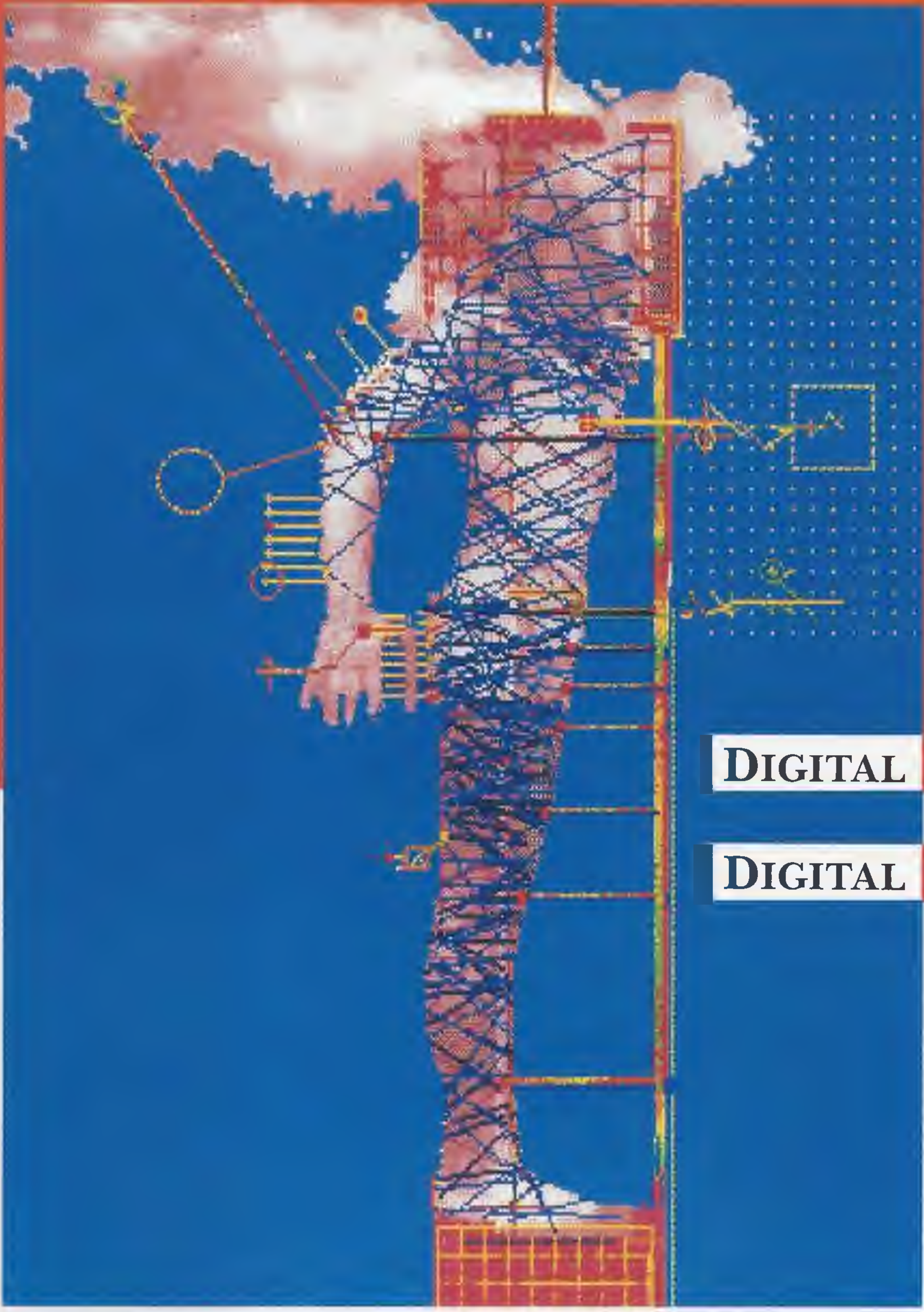

DIGITAL IMAGE
DIGITAL CINEMA

LEONARDO

Supplemental Issue 1990

JOURNAL OF THE INTERNATIONAL SOCIETY FOR THE ARTS, SCIENCES AND TECHNOLOGY

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"Digital Image—Digital Photography", 26 June through 3 September 1990, J. Erik Jonsson Central Library Gallery, Dallas, Texas. Susan Kirchman, Curator

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Cover Artwork: Don P. Miller, computer-manipulated images/Xerox C150 inkjet prints, each 7 × 9.75 in, 1989. Front cover: *Sentinel #1.* Back Cover: *Sentinel #2.* Using an Amiga 1000 computer with Digiview and Deluxe Paint II software, the artist digitized the human form with a video camera linked to the computer and then used a selective process of manipulating those images into an expressive structure that has its ultimate form as an inkjet print.

LEONARDO

Supplemental Issue 1990

JOURNAL OF THE INTERNATIONAL SOCIETY FOR THE ARTS, SCIENCES AND TECHNOLOGY

Welcome

The SIGGRAPH '90 Conference Committee welcomes you to "Digital Image—Digital Cinema", The SIGGRAPH '90 Art Show. The art show committee solicited works that demonstrate both aesthetic quality and a significant use of the computer. In these works either the computer is used in the dynamic generation of the artwork or in the viewers' interaction with the artwork or it contributes to the presentation environment.

The show features paintings, prints, photographs, books, sculptures, environments, interactive installations and videotapes representing a large international community of artists who use the computer in their artistic practice. The jury selected 80 works from among the several thousand submitted. Artists from Austria, Canada, France, Japan, the United Kingdom and the United States are represented in the art show.

Artists, historians, educators, scientists and critics have submitted essays that address the theme "Digital Image—Digital Cinema". These authors present a wide range of views regarding the ways in which the computer extends the practice of art, the study of art or its meaning and context.

The SIGGRAPH '90 Art Show is made possible through the collective effort of artists, authors, jurors, reviewers and a large number of volunteers. The exhibition demonstrates the vitality of this community and a concern for the computer's role in both artistic innovation and conservation. This community is active and searching, as evidenced by its work. Welcome to the 10th Annual SIGGRAPH Art Show.

THOMAS E. LINEHAN
SIGGRAPH '90 Art Show Chair

Das SIGGRAPH '90 Konferenzkomitee heißt Sie herzlich willkommen und dankt Ihnen, daß Sie an der SIGGRAPH '90 Kunstausstellung „Das Digital Bild—Das Digital Cinema", teilnehmen. Das Kunstausstellungskommitee hat sich bemüht, Werke zusammenzubringen, die sich sowohl durch aesthetische Qualitäten auszeichen, als auch durch einen bedeutsamen Einsatz der graphischen Möglischkeiten des Komputers. Die Demonstration der Einsatzmöglichkeiten wird entweder im kreativen Aufbau des Werks gezeigt, oder in der Wechselwirkung zwischen Werk und Zuschauer oder in der Weise in der der Komputer zu der Herstellung des Kunstwerke beiträgt.

Die Ausstellung zeigt Gemälde, Graphiken, Photographien, Bücher, Skulpturen, Environments, interaktive Installationen, und Videos, die eine große internationale Gemeinschaft von Künstlern repräsentiert, die mit dem Komputer arbeiten.

Für die Ausstellung wählte die Jury aus mehreren tausend vorgelegten Werken 80 aus. Künstler aus Australien, Kanada, Frankreich, Japan, Grossbritannien, und den Vereinigten Staaten haben sich an der Ausstellung beteiligt.

Ebenso wurden auch schriftliche Beiträge zum Thema der Ausstellung von Künstlern, Historikern, Paedogogen, Wissenschäftlern und Kritikern vorgelegt. Diese Beiträge zeigen eine breite Fächerung von Vorstellungen bezüglich des Potentials des Komputers für die Erweiterung der künstlerischen Ausdrucksmöglichkeiten, und ebenso für das Studium der Kunst, ihrer Bedeutung und ihres Umfeldes. Die Ausstellung demonstriert die Vitalität dieser Gemeinschaft und ihr Engagement für den Einsatz des Komputers, und für kunstlerische Neuerungen ebenso wie für die Konservierung existierender Werke. Wie die hier vorgelegten Werke zeigen, ist dies eine sehr aktive and erfinderische Gemeinschaft. Noch einmal, seien Sie herzlich willkommen zur zehnten Jahresausstellung der SIGGRAPH.

THOMAS LINEHAN
Leiter, SIGGRAPH '90 Kunstausstellung

皆様，SIGGRAPH '90 アート・ショーへようこそ．今回のアート・ショーは“デジタル・イメージ，デジタル・シネマ”と題し，コンピュータを駆使した高度な技術と高い芸術性を兼ね備えた作品を公募いたしました．創作にあたってコンピュータを使った作品もあれば，コンピュータを使って見ていただく作品もありますし，作品を展示する環境の創設にコンピュータを取り入れた作品もあります．

今回，作品のスタイルは絵画，版画，写真，書籍，彫刻，環境アート，機器，ビデオテープに及び，国際的な規模で作家の方々の交流の場となっております．世界中から寄せられた数千点の中から審査員が厳選に厳選を重ねました結果，オーストリア，カナダ，フランス，日本，イギリス，アメリカからの80点の作品が選ばれました．

作品に加えまして，このカタログには“デジタル・イメージ，デジタル・シネマ”に高い関心をお持ちの方々による論文を収録いたしました．今日コンピュータが広げつつある芸術の領域について，またその中での芸術の概念はどういうものなのかを幅広く論じ，話題を提供してくれます．

開催にあたりましては，作家の皆様，論文執筆者の方々，審査員の方々，とりわけ多数のボランティアの皆様方に御協力をいただきました．美の探求の分野でのコンピュータの役割の追求に意欲を持つ方々が，その意欲をSIGGRAPH '90 アートショーの場で強く世界に表明しておられます．作品はまさにその意欲の表われなのです．では皆さん，第10回SIGGRAPH アート・ショーをご堪能下さい．

トーマス・ラインハン
SIGGRAPH '90 アート・ショー
開催委員長

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EDITORIAL

DIGITAL IMAGE—DIGITAL CINEMA

The theme selected for this supplemental issue of *Leonardo* is, in part, an acknowledgment of the lack of appropriate language to describe the diverse ways the computer is used in artistic practice. This artistic practice is progressively leading us through a continuum of digital variation. Static images, moving images, interactive images—all are being rendered as digital versions of their former selves. The hyphenated theme "Digital Image—Digital Cinema" is meant to suggest this continuum of practice. Many professional artists and filmmakers are pushing aside the traditional boundaries associated with earlier methods and strategies for work.

ACM-SIGGRAPH has sponsored art exhibitions for the past 10 years. These SIGGRAPH art shows have become an important venue for visual artists who are using digital processes in their work. Much of the early defensiveness relating to the computer and art is now fading away. Earlier fears that the computer would mechanize, standardize or trivialize aesthetic values have not proved to be valid. The art community is truly in an exploratory mode with digital processes. The artists selected for the Digital Image—Digital Cinema exhibition have found that digital means extend their artistic reach. The variety and strength of the work in the exhibition demonstrate the power of these digital means and the mastery of the artists who use them.

The authors selected for this catalog chronicle this continuum and variety of artistic practices. The research methods employed by the authors vary from the theoretical to the empirical. The articles examine issues as diverse as the role of digital imagery in art-historical practice (Michael Ester), the degree to which early film theory accounts for current practice in digital cinema (John Berton) and the role that prior knowledge (based on earlier forms) has on our conceptions of the possible in digital imagery (Beverly Jones). Also in this issue Rudolf Arnheim extends his early work in film theory with a new English translation of work originally published in German in 1932. Peter Voci explores the use of the digital image in facial reconstruction for forensic purposes. The strength of the writing and of the artistic practice are to found in their diversity.

Thousands of artists worldwide are exploring digital processes for artistic purposes. The SIGGRAPH '90 Art Show presents the work of many of these professionals who are defining the character and nature of a digital art movement. Artists are testing these new means, digital processes, to see if they can extend their purposes. It is likely not only that such an investigation will uncover new 'means' for traditional 'ends' but also that new artistic ends will become available to the artist.

THOMAS E. LINEHAN

SIGGRAPH '90 Art Show Chair

College Station, Texas

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Language and the Early Cinema

Rudolf Arnheim

Introductory Note

The following short excerpt from *Film* [1] is all but unknown to the readers of the English version of the book as well as to those of the other translations. The edition of 1957, titled *Film As Art* [2], on which all these translations are based, was prepared by the author in the conviction that only the essential sections, dealing with the nature of the visual medium, were still relevant whereas much of what had been observed in the infancy days of the sound film was no longer worth saying. A complete English version of the German original of 1932 had been published in 1933 by Faber and Faber in London in a translation by L. M. Sieveking and Ian F. D. Morrow but has vanished of course long ago even from most libraries. The following few pages, slightly retouched by the author, will give today's readers a taste of the principles that governed discussions of the media in those early days.

Language (1933)

The problem of language is intimately bound up with the question of whether sound film has its own laws and of the relation between sound film and stage.

Speech is a means of communication discovered and used by man: a part of our world as much as men and beasts, houses and trees. And by giving speech the power to describe things, events, reflections, we enable it to bring before our minds completely the whole world of which it is a part. Literature—poetry, narrative, drama in book form—offers us representations of life, made entirely by means of words. We need no sense-impressions of any other kind to supplement such delineations. Hence language is a complete and sufficient material for the art we call literature. Even illustrations to books are generally found to be disturbing. They do not supplement but are at variance with the task of language, which it fulfils alone to our complete satisfaction. Since, however, according to the laws of aesthetics, nothing superfluous may be included in a work of art without detracting from it, language appears to be not merely an adequate but also a very autocratic art medium. Probably where language is used no other means must be employed, so that no lawless jumble, no hybrid form, shall result. Language does do its work unaided because it is capable of doing so.

This would be a very strong argument against the use of the spoken word in sound film. Sound film may be nothing but speech with illustrations; and that must be rejected as bad art. The pictures in silent film gave us an optical image of the world, language gives us a verbal one—if they are coupled, will they not both have the same work to do simultaneously and, therefore, instead of supplementing and uniting each other, hinder one another intolerably? That would certainly be the case if language—besides being an art medium—were not also a part of nature. For while as an art medium it cannot tolerate any rival, as a part of the cosmos it must suffer all the rest of the world beside it. These two functions, moreover, need not even be kept sharply distinct, as is seen from the theatre. A drama is, in most cases, a complete work of art even as a book—thus a purely verbal work of art. Moreover, in this case, language is used merely as the means of expression of people talking, that is, in the same form as it appears in real life. At the same time we do not demand that the language of a drama shall be exactly like that of real life, that is to say that people shall talk on the stage exactly as they would at home. We know, on the contrary, that the drama began very unrealistically; that it arose not as an imitation of our everyday speech but from ceremonial singing, dancing and prayer, and that naturalistic dialogue was only introduced at a comparatively late stage in development. The artist practices his formative work and impresses his style on language just as he does on all other natural objects. Just as the painter does not imitate natural objects but makes them anew with the materials at his command, so the dramatist re-forms the piece of nature which is speech with the art-medium speech which comes from quite a different source.

Although the written drama is a complete verbal work of art, author and audience consent to its being arranged in a sumptuous optical and acoustic setting on the stage. If a chapter of a novel were enacted on the stage with allotment of parts, costumes, sound effects and scenery, we should be shocked. When a play is performed we are not; for, on the one hand, it is repugnant to language as an art medium to be allied with effects of a different kind, but, on the other, it fits in with the rest of visible and audible nature quite peaceably. This curious contradiction can always be felt in theatrical art. The style of theatrical performance oscillates constantly back and forth between one kind of production in which the whole presentation is based on the text of the book—*decor,* action and even the miming of the actors being limited and suppressed as far as possible, in order that the words shall make their effect undisturbed—and the other kind which furnishes a sumptuous flesh-and-blood world, so that speech as a part of nature shall take its proper place with the rest of nature and develop in the most natural manner.

The sound-film situation is very similar, indeed apparently more favorable, for the division is much less clearly marked than in the theatrical world. The verbal part alone of a sound film is quite meaningless and is, indeed, without artistic value. Sound film—at any rate real sound film—is not a verbal work of art supplemented by pictures, but a homogeneous creation of word and picture which cannot

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be split up into parts that have any meaning separately. (This is the reason why so little is to be expected of dramatists and novelists for sound films.) Even the picture part is meaningless alone. Moreover, in general, speech in sound film will be much more effective if used as a part of nature instead of as an art form. Film speech will have to be more lifelike in the same degree as the film picture is more like nature than the stage picture.

It must not give the impression of being something artificial either on account of the polished style and perfection of its phraseology or of fine elocution, if it is not to appear in its surroundings as an isolated foreign substance. Sound film will provide the often casual and scrappy conversation of everyday life, which may even be interrupted by inarticulate sounds and indistinct murmurs—just one sound among many. The attraction of this perfectly natural intimate art of speech has up to the present hardly been exploited at all in sound film. On the contrary, most film actors—partly no doubt because they do not yet feel quite at home with their new craft of speech—talk in an affectedly precise manner that is quite unnecessary and deprives the performance of its best effects.

References

1. Rudolf Arnheim, *Film,* Ian F. D. Morrow and L. M. Sieveking, trans. (London: Faber and Faber, 1933).

2. Rudolf Arnheim, *Film As Art* (London: Faber and Faber, 1957).

Film Theory for the Digital World: Connecting the Masters to the New Digital Cinema

John Andrew Berton, Jr.

ABSTRACT

This article examines the role that theories of photographic cinema play in the criticism of digital cinema. The theories of Georges Melies, Vachel Lindsay, Lev Kuleshov, Andre Bazin and Rudolf Arnheim—critics, theoreticians and filmmakers, the keystones of this work—have proven pertinent to the advancing technology of other cinematic forms. Their ideas have applicability to specific aspects of digital cinema, including the manipulation of illusory space, discrete and explicit control of cinematic elements, the transformation of world spaces into screen space and the role of realistic imagery in determining the content of a cinematic work. Parallels can be drawn between the ideas of these theorists, most of whom wrote during the infancy of photographic cinema, on the developing state of film and that of current digital cinema.

The lack of widely distributed information about what digital cinema is and how it is made has led art theorists to incorrect or ill-informed opinions about the work of digital artists, a medium they did not understand. One approach to any new medium is to apply all the old and well-understood yardsticks of theory and criticism. Although often appropriate, the broad brush of general art theory rarely does justice to the exploration of a specific medium, especially the new and unique medium of digital art. So the question becomes, Where can we begin to apply what we know about art to what we know about digital cinema?

For our purposes in addressing the cinematic aspects of digital art, early theory and criticism of film present interesting parallels and ideas. Much of the essential criticism and theory was written when cinema was new and its boundaries undefined; these attempts to understand an emerging form are conceptually linked to understanding new digital cinema works.

In the early years of cinema, filmmakers found themselves in a creative atmosphere with no clear idea of how to create a work of fine art. The earliest films exposed the technology of motion picture photography rather than artistic creation. Cinematic directors and their audiences found the new visual recording process marvelous and the images in motion so startling that few asked critical questions. The image itself was the key element in the relationship between the image and the viewer. Not until the thrill of novelty had faded did artists and audiences begin to appreciate the abilities of this new medium to carry artistic content.

The parallels between the critical reaction (or lack thereof) to the first cinematic constructions and the first digitally synthesized constructions are clear. Many computer graphics images are also purely demonstrative. Often either they illustrate some mathematical concept that is difficult to model or they simply show the capability of the machine and its software to create complicated models in the first place [1]. As in the early film works, both the creator of the images and the impartial viewer are more interested in process and function than in content and concept. It is from this point that we must step forward to consider how these images, derived purely from a technological process, can transcend that process to carry meaningful artistic and conceptual information.

Comparing Early Film to Digital Cinema

The history of cinematic art is closely linked to that of technology. Periodically, technological changes have forced cinema artists to rethink their creative methods; cinema theorists and critics also have had to adjust their ideas accordingly. The progress of computer technology in the last 30 years has invested technological issues with new critical importance. In the early years of cinema, filmmakers made a critically acceptable transition from technological experimentation to more generalized cinematic approaches such as drama and documentary. Technical achievement was considered a valid part of the creation of fine cinematic art. Now, however, technological experimentation in cinema is often characterized not as a means to a worthy end but as a dazzling, yet contextually empty, approach to image making. Regardless of how much content exists in a high-technology cinema piece, this same criticism is applied. In these cases, the images are so dazzling that critics are blinded to the content and accept or reject the piece out of hand. The innovative character of digital images brings some pieces acclaim, even when they contain little or no conceptual information. By contrast, many works that do contain cinematic substance are rejected on the grounds that high technology is assumed to indicate low content. This is the critical gulf between the traditionally technical and the traditionally artistic. Each school of thought must better understand the other before meaningful criticism of digital cinema can occur. There must be a growing critical concern with how digital images are used creatively, regardless of the extent to which new computing technology is applied to the actual imaging process.

Before an understanding of the computer as an artistic tool is possible, an understanding of the computer as a tool in general must exist. The computer was not designed to create or assist in the creation of art any more than it was designed to facilitate accounting or to organize interesting games. The creators of the tool were more interested in pure technology than was Edison when he invented the motion picture camera. The first computers were mathematical models designed to model more mathematics. That such an

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abstract tool has been bent to use by artists is surprising to some.

The concept of 'tool first; application after' changes the way in which artists approach a tool. Often they must wrest it from the hands of its creators. In this sense the camera, especially the motion picture camera, shares with the computer a distinctive history as an artistic tool. Neither computer nor camera was created with artistic interests in mind, but both were soon directed there despite their practical applications elsewhere. The ability of these tools to create certain types of images drew the initial attention of audiences, forcing the artistic wholeness of the work into the background. While some artists work without particular regard to the day-to-day advance of imaging algorithms and hardware, much of the critically acclaimed computer-assisted artwork is so acclaimed because of its technique rather than its content. At major digital art exhibitions, it is still the most precise modeling of reality that draws the greatest appreciation from audiences. Even the most narrative pieces have drawn attention to themselves on technical grounds.

There are clear parallels between the crowds who applaud bouncing crystal balls and motion blur at computer graphics conferences and the audiences who nearly ran from the theatre at the approach of cinematic trains and villains in the late 1800s. In both cases, it was the startling recreation of unexpected realism that swayed the attention of the viewers. In both, however, some of the artistic expression was lost in the flash of technical achievement. The tool itself receives significant credit for the expressiveness of the image, and the artist is left standing in the shadow of the technology. Misunderstanding of the artist's role has been the root of a certain amount of critical disapproval of technological arts in general. Artists working with these advanced tools must still, unfortunately, prove to their critics that the artist affects the work in profound ways. (For the purposes of this investigation, we will ignore the implications of artificial intelligence and the role of the computer itself as artist, although advances in this area will certainly complicate the criticism of digital cinema in the future.)

The first step in creating a critical base for computer-generated cinema is to step out of the shadow of technological achievement to analyze works in terms of their content and the technique of the artist as opposed to the technical aspects of the tool alone. Throughout the technological changes of the twentieth century, some theories of cinema have endured, finding applicability to a wide range of cinematic approaches. Some of these theories have also specifically discussed how the content of the cinematic work is interpreted and shaped by the photographic technology. These theories in particular are of interest in this discussion.

Vachel Lindsay: The Animation of Cinematic Objects

Vachel Lindsay was a pioneer in the criticism of artistic content in cinema. His 1915 work, *The Art of The Moving Picture,* offers many interesting insights into the emerging cinematic form. Lindsay speaks to the issue of technology and the art of cinema in his discussion of cinema as 'architecture-in-motion'. Lindsay says, "The possible charm in a so-called trick picture is in eliminating the tricks, giving them dignity till they are no longer such, but thoughts in motion and made visible" [2].

Lindsay writes of inanimate objects brought to life by cinema and how these objects can, through their animation, portray emotions that normally are associated with the human counterpart of each object. Although Lindsay points out how the shoes of Cinderella or the throne of a king may carry great content through their cinematic animation or transformation, he adds, "The photoplav imagination which is able to impart vital individuality to furniture will not stop there. Let the buildings emanate conscious life" [3].

Lindsay also offers theories on the way in which inanimate objects may be brought to cinematic life. He argues that the substitution of a human actor may not be the best representation, especially if that substitution is mishandled. "A statue too often takes on life by having the actor abruptly substituted. The actor cannot logically take on more personality than the statue has. He can only give that personality expression in a new channel" [4].

Lindsay's impression of the cinema is that the objects—and by this he means human beings as well—must be given new life by the cinema artist when they are included in the work. He argues that the recording process is not powerful enough to capture the essence of reality. Therefore it is the task of the cinema artist to endow the objects with a life that allows them to rival their real counterparts. Lindsay amplifies his point: "Substitution is not the fairy-story. It is transformation, transfiguration, that is the fairy story, be it a divine or a diabolical change. We might define Fairy Splendor as furniture transfigured, for without transfiguration there is no spiritual motion of any kind" [5]. In other words, it is not that the objects can be manipulated, but rather how that manipulation acts to create life and meaning within the work that counts.

> I have said that it is a quality, not a defect, of the photoplays that while actors tend to become types and hieroglyphics and dolls, on the other hand, dolls and hieroglyphics and mechanisms tend to become human. By an extension of this principle, non-human tones, textures, lines and spaces take on a vitality almost like that of flesh and blood [6].

Lindsay argues, in anticipation of montage theories, that the artist is the key to meaning. Lindsay's elemental ideas can be readily applied to digital cinema. His thoughts on the transformations between actors and objects are precursors to effective criticism of synthetic digital images and synthetic actors in digital cinema. These ideas focus criticism on how the objects are handled by the artist, as opposed to how they are handled by the technology, be it camera or computer. Lindsay's assertion that the artist is the key to content places the semantic burden in the same spot that digital cinema places it. Because there is nothing in digital cinema that is not created by the cinema artist, there can be no other real source of meaning.

Another comment on the cinema by Lindsay has particular application to digital cinema: "The people with the proper training to the higher photoplays in hand are not the veteran managers of the vaudeville circuits, but rather painters, sculptors, and architects" [7]. More so than any other cinematic medium, digital three-dimensional synthetic cinema relies on the skills of the plastic artist to create images, to shape, color and arrange every facet of every object within the screen. The process involves the skills of the painter, the sculptor and the architect. This does not mean that only traditional plastic artists are suited to the creation of digital cinema; it means that the skills of all these artists are a desired component. It also points out that these creative and conceptual skills are more important to the creation of cinematic works than the technical aspects of photography and computer science.

Georges Melies: A Model for New Technical Expression

Although we are now beginning to see some emphasis on content in digital cinema, most digital cinema is still limited to technical exposition, or short dramatic vignettes. In this sense, the state of digital cinema is analogous to the days of film history when the nickelodeon thrived. While Vachel Lindsay was speculating on the future relationships between technique and content, the French director Georges Melies was creating works that exploited technique in a way that created content. Cinema historian Lewis Jacobs credits Melies as the "first to exploit the medium as a means of personal expression. Melies discovered magic in the motion picture camera. He turned its lens away from reality, from mere reporting to fantasy and genuine creation" [8].

In many ways the works of Melies are similar to the kind of work now beginning to appear in digital cinema. Melies used his intuition as a professional magician to create films unique for their time. He exploited the ways in which space and time can be manipulated within the narrow window of cinema. With imagination and cinematographic expertise he created unexpected transformations of shape and character within his works; objects that appeared, disappeared or defied the known laws of nature were popular constructions in Melies's films. More importantly, Melies did not stop with a concentration on technical achievement. While other filmmakers were attempting to figure out exactly how Melies had created his double exposures, fades, dissolves and animations, Melies was busy finding ways to use his technique to carry substantial content. He used original scenarios as well as screenplays adapted from the literature of the day. Melies's scripts called for multiple scenes within a single film, while most of his American contemporaries refused to use more than one camera shot in the interest of proving to their audience that nothing had been 'faked'. Some of these filmmakers implied that Melies was misusing the technology of film, although an equally strong case could be made that they themselves were being misused by the technology.

Even though Melies's work was closely involved with the state of the art, he did not let that aspect of his work rule the overall piece. He used his technique to augment his artistic sense, not to create it. In this regard, Melies's work says much to the digital cinema artist. He showed early film cinematographers that reality was not the only plane on which the camera could be focused, and that the technology of cinema, which could be an end in itself, need not be so limited. Jacob's essay on Melies credits him with freeing cinema from "the slavery of dull imitation" [9]. This is a bondage from which digital cinema is only beginning to escape. The common use in digital cinema of the single shot, demonstrating that nothing has been 'faked', so as to amaze the audience with the later knowledge that the image was 'faked' after all, is an example of how easily digital artists, believing themselves in the vanguard of cinematic creation, can fall into a very old conceptual trap. The films by Melies exemplify for the digital cinema artist how new technology can be used effectively to create interesting works that outlast their technical novelty.

Lev Kuleshov: Montage in Digital Cinema

Of the Soviet theorists, Sergei Eisenstein is perhaps the most well known, but it is the ideas of his mentor, Lev Kuleshov, that seem to bear most keenly on the critical issues of digital cinema. Both digital cinema and Soviet film theory use the definition and exploration of elemental units of technique as the ground for creating cinematic works. The Soviets approached cinema in this fashion because they were filmmakers, as opposed to film viewers, and felt a need for better definition of the elements that contribute to better filmmaking. Lev Kuleshov, V. I. Pudovkin and Sergei Eisenstein were the first filmmakers to theorize seriously about their work. Their quest to understand the basic units of cinema is analogous to the processes that computer programmers and artists use to define and refine software used for digital cinema. Synthetic digital cinema requires that each parameter of motion in the frame, and each constructional component, be reduced to manageable quantifiable elements. Some of these elements have been effectively implemented by the Soviets.

One of the primary elements that Kuleshov identifies as crucial to successful cinema is the simplification of important points. This includes the use of close-ups, the simplification of background elements and the careful selection of shots and the directions of action. In Kuleshov's view, attention to organization within the creative process must occur in order to present viewers with an image they can quickly and efficiently understand. "The material of cinema must be extremely simple and organized. If a film is constructed by montage, then each piece will run for a certain short time. In order that everything filmed be seen, perceived, and understood in a brief given space of time, one must show the content of each piece in extremely concrete and organized ways" [10].

Because of the elemental nature of the cinematic shot, Kuleshov believes that all attention should be paid to the precise organization of each shot and then to the organization of these shots into the montage that forms the completed piece. According to Kuleshov, without this organization the viewer is confused and cannot correctly interpret the work. In this case, a correct interpretation is one that coincides exactly with the interpretation the director of the work intended. Kuleshov also stresses that the use of screen space must be not only organized but also optimized. He advocates that no part of the screen go unused by the cinematographer. Unused screen space allows viewer-controlled interpretations to creep in and diffuse the intended meaning of the shot.

> In cinema you have a given plane, the four-sided screen, which has no depth of light stereoscopically. Therefore, in order to give maximum expressiveness to the symbol, one must exploit the given plane of the screen with optimal economy. In other words, there must not be one piece of superfluous space on the screen, and if you show something which cannot occupy the whole surface, then all excess must be eliminated. Every tiny piece, every quadrate on the screen must not only be put to work, but put to organized work in simple, clear, expressive forms [11].

Kuleshov further argues that viewers will try to make sense of everything they see; therefore, any part of the scene that is not accounted for by the filmmaker they will explain themselves. He claims that cinematic work cannot be effective if this occurs. Kuleshov also calls for the precise organization of the three-dimensional world space lying within the camera's object view. The world space should be as organized as the screen space (although the former is dependent on the latter). These ideas have some surprisingly direct correlations to three-dimensional digital rendering. Kuleshov refers to the structuring of actions within the world space, principally but not exclusively through the motions of actors in the pyramid formed by the camera lens' angle of view and the screen space's plane of action. Throughout his ideas, Kuleshov seems to call for exactly what digital cinema offers: complete control over every structural element in both the world space and screen space of the shot.

In digital cinema, the uncontrolled elements of reality that Kuleshov fears will distract and confuse the viewer do not exist. Although the appropriation of real imagery through digitization is a part of digital cinema's symbolic structure, the possibility of unforeseen symbols is radically diminished. Digital cinema does not present an image to the viewer unless it explicitly creates displayable elements. The digital artist has a great deal of control over the elements that concerned Kuleshov and also enjoys the advantage of building a structure unique to the work. Since each object must be generated individually, the artist is less likely to create and include objects that lack meaning—at least in theory. Ironically, often the opposite is true in practice. Objects created for a synthetic cinema piece generally represent a significant amount of creative effort, at least with today's technology. Thus an artist will often include objects in digital works simply because they are available, whether or not they carry meaning. Like all cinema artists, the digital animator must learn to throw away elements, occasionally, for aesthetic reasons, in spite of the work and technique that went into their creation.

In addition to providing a cinematic medium almost exactly suited to Kuleshov's ideas on organization and composition, digital cinema allows a level of control over world space that challenges some of Kuleshov's theories of montage. Kuleshov claims that montage is the process by which most of the substance and meaning of cinema is created. He likens the creation of cinema to a building process, where each piece of cinematic material is carefully laid into place to create the overall effect. Three key types of montage form Kuleshov's basic structure: exterior montage, created across the frames by editing; vertical montage, created by the interaction of elements such as sound, music and color; and interior or intra-shot montage, which is created within a single frame by composition, acting and synthesization. Although Kuleshov especially decries the application of theatrical acting to cinema, he does admit that the actor can contribute to the montage. "The rhythm and meaning of the montage is not only derived from the interaction and interrelationship of the given segments . . . but the montage also resides within these shots, in the filmed action of the person, for example, in the actor's performance" [12].

More important than Kuleshov's admission that the work of a talented actor can contribute to a cinematic work is the concept that occurrences within the frame of a given shot contribute not just to the shot, but to the montage. This concept is crucial to a discussion of how digital cinema creates meaning for the viewer. The digital cinema artist has complete control of and responsibility for the content of both the screen space and the world space. Anything within the scope of the technology is possible for the artist. A digital artist would not need exterior montage to recreate many of the effects created in Kuleshov's famous experiments of the early 1900s. The potential semantic power that this interior synthesis suggests has led many digital cinema artists to attempt works wholly dependent on interior montage. These pieces are characterized by completely synthetic scenes, ray-traced to perfection, with beautiful moving camera shots past objects that float effortlessly and impossibly through colored lights and immense spaces. Most of these attempts have resulted in beautiful images with little content.

If a work depends solely on any one type of symbol structure, the result is often an exercise or a demonstration, as Kuleshov discovered about his own work when he realized that montage created by editing alone lacked the cinematic power of a montage of montages. When exterior, vertical and interior montages combine in an overall montage, they create a symbol structure that can clearly express complex messages. Kuleshov's emphasis on the elements of cinematic montage can be especially helpful in the criticism of digital works. In digital cinema, not only the exterior montage but also the interior montage is composed of separate elements, organized to create visual and semantic effects. The precise control of these elements in digital cinema allows a great amount of semantic synthesis within the shot. With more control over interior montage than most of their cinematic counterparts, digital artists must not forget that exterior and vertical montage can, and probably should, figure in the creation of any cinematic work.

Andre Bazin: Creating Meaning Beyond Montage

Understanding the semantic content of the image itself, as opposed to that created with montage, has been a cornerstone of modern cinema theory. Although these more recent theories do not negate the montage theories of the Soviets, they do argue that montage is not the sole means of cinematic expression. The proponents of these theories claim that realism plays the largest role in this expression, and that the hand of the artist in cinema is a guiding influence rather than an ultimate arbiter of semantic substance. Of the theorists who speak for realism as the basis for cinematic symbolism, the French critic Andre Bazin speaks more eloquently than most. Bazin agrees with theorists such as Siegfried Kracauer [13] that photographed reality is the key to cinematic semantics, but he goes one step farther in his writings by discussing how the elements of reality work to transcend the formal limitations of cinema. Bazin argues that montage is not the only, or even the best, way cinema artists can express themselves. Cinema artists, according to Bazin, can be most expressive not by aggressively manipulating the medium to direct the attention of the viewer to the symbol, but by letting the symbols flow from the reality of the image. The imprint of the artist is seen in the subtle influences placed upon this image by the techniques of cinematography and editing. Whereas Kuleshov argues that artists must take complete control of their work in order to make an effective presentation, Bazin claims that cinema artists must allow the image of realism to carry the cinematic content [14].

Bazin does not place all of realism's impact on its ability to express space as a visual concept. Certain psychological factors also enter into his theory. A cinematic work based in reality provides viewers with a conceptual base from which they may form interpretations. A real image is filled with keys and clues to symbols and meaning, the same keys and clues viewers use outside the cinema to interpret their environment. From this we can infer that the more real the cinematic images appear, the more information they embody and the more easily they may be interpreted. The more complex the imagery, the more capability the image has to carry meaning and content. We can also infer that images carry even greater semantic weight if they are formed from a reality or segment of reality with which the viewer is familiar.

Photographic reality is far more complex than digital synthesis technology will currently allow. The image of reality is filled with the multiple complexities of nature. The depth of information contained in the color, textures and motion of nature is substantial. It is doubtful that any human construct can rival this complexity. Additionally, the space from which images may be drawn is unlimited. Even on a Hollywood sound stage, there is the opportunity to take the camera out the back door and into another photographable arena. It is true that the gap between the complexity of the photographed image and the synthetic digital image is rapidly narrowing. The digital animator can now create rich world spaces from which compositions may be extracted. Nonetheless, the digital cinema artist does not yet enjoy the luxury of easily accessible databases of infinite complexity.

Because of its current state, digital image synthesis remains an incomplete substitute for natural reality in terms of complexity. Beyond the limits of what has been digitized and constructed within the digital world space there is literally nothing to see. Unlike Kuleshov, Bazin believes that artifacts beyond the frame do affect the symbolism within it. If the world space is incomplete, as is the case in a digital cinema piece, the semantic qualities of the image are also incomplete. This limiting factor does not, however, close the door on the exploration of digital cinema through theories based in realism.

The limit of a given digital world space is not a barrier. It is simply a boundary. The digital world space has the potential to reach the complexity of real world space. Although unachievable in practice, it is a theoretical possibility, and therefore digital works can be addressed by theories based on complex realism. Bazin's ideas, though rooted in realist theory, can apply to digital cinema in myriad ways. Not only do they allow for the sorts of images created by digital synthesis, they provide some direction as to how these images might be used most effectively in a cinematic work.

Bazin anticipates some of the developments in digital cinema in his discussion of the role of technological advances in cinema. In Bazin's estimation, the advance of the technology of cinema is expressed in its ability to represent nature more accurately, not in its ability to represent the technological capability of human beings. This does not deny digital cinema a place in the aesthetics of cinema but rather points out that technical realism in digital cinema should not be an end in itself. Both Melies and Lindsay make similar statements, although they stress the ability of cinema to stretch and reinterpret reality, whereas Bazin is more concerned with cinema's ability to recreate reality accurately with a minimum of reinterpretation. All three believe that technology cannot materially change cinema if it exists only for its own sake.

The modeling of physical reality has been a mainstay of digital imaging, since computers have routinely allowed artists to create near-photographic representations of solid objects. The developing technology of digital rendering allows artists to move in the direction of more complex images, as suggested by the realist ideas of Bazin. Unfortunately, many artists who pursue realism fail to serve any goal beyond demonstration of the imaging technology. The same pieces that fail to meet the criteria of Melies, Lindsay and Kuleshov also fail to meet the criteria of Bazin, even though they would seem to aim in that direction. To meet Bazin's expectations, the digital cinema artist must create a world space using both the imagistic and contextual complexity of reality, embracing the highest possible technology in image generation without allowing the technology itself to rule the work. This an artist can achieve by letting the technology, in this case the computer, control the technical aspects of the image in much the same way that a camera controls the technical aspects of recording reality on film. The computer makes the viewer believe that an object exists, but the artist must make the viewer believe that the object's existence has meaning.

As techniques are developed for the synthesis of complex realistic images, those techniques can be applied to the creation of complex non-real images. If the complexity of the image is taken as an important part of its ability to carry semantic weight, then the complex non-real image has a semantic potential roughly equivalent to that of a real image. This potential for image making creates an image base on which the technology can draw. A similar process can also take place in terms of motion. The motion base is created from an understanding of complex motion, through the development of analytical and algorithmic computer software and interfaces. When these spatial and temporal databases are sufficiently complete, they fall almost entirely into the technical domain of the computer. They free the artist to explore the conceptual aspects that provide the necessary balance between content and technique.

Probably Bazin would not have approved of the techniques of realism employed by digital cinema artists. Nonetheless, his idea of the natural symbolism of cinema as embedded in the complexity of reality points digital cinema not just toward realism but toward an aesthetic based on images that approach the complexity of reality—whether these images are imitative or purely imaginary. Bazin's work is also filled with thought on the selection of reality for cinematic purposes. These ideas are as applicable to synthetic computer-rendered worlds as they are to the real world of live action cinema.

Rudolf Arnheim: The Technological Filter

The selection of reality is also a concept discussed by Rudolf Arnheim in his early studies of photographic and cinematic theory. In his theories, he argues that it is not the artist or the subject that creates the essential symbols of cinema. Rather, he states, it is the way in which objects are interpreted by the camera that defines the object's cinematic existence and its cinematic meaning.

Specifically, Arnheim discusses different cinematic views of a simple cube and different conclusions that can and cannot be drawn about the physical nature of the perceived object based on the object's relation to the camera. In some views, the cube is clearly defined; in other views, the exact shape of the object is less clear, even unclear. By this analogy, Arnheim shows that the camera is an interpreter, not just a recorder. As an interpreter the camera becomes an active element in the creative process, not simply a passive device that records existent phenomena [15].

Arnheim calls the space created in cinema an artificial space. The camera interprets the real space in a way that fundamentally changes it, flattening three-dimensional reality onto a two-dimensional plane. By its inherent selection of a single point of view, it cuts out some segments of reality that would otherwise be visible to a viewer unrestricted by the camera. Digital cinema gives new meaning to Arnheim's ideas on artificial space. In the most simplistic sense, computer graphics recreate space in the same way that photographic cinema does; but on a deeper level, digital cinema can create artificial spaces within spaces. For the first time, cinema tools can actually reshape spaces before the viewing transformation occurs. Conventional cinema transforms space through the process of collecting light on a film plane. In digital cinema, constructs such as texture mapping, image processing and digitization allow artists to create controllable artificial spaces with real substance. If photographic cinema has great artistic potential in part because its representations of reality are filtered, then digital cinema has the same potential because its filtering process is much more complex, and much more controllable.

Given that cinema filters the space in which it operates, it is now important to ascertain how this interpretation can best be employed artistically. In plotting the course of cinematic expression, Arnheim states:

> As distinguished from the tools of the sculptor and the painter, the camera starts to turn and a likeness of the real world results mechanically. There is serious danger that the film maker will rest content with such shapeless reproduction. In order that a film artist may create a work of art it is important that he consciously stress the peculiarities of his medium. This, however, should be done in such a manner that the character of the objects being represented should not thereby be destroyed, but rather strengthened, concentrated, and interpreted [16].

Arnheim argues that the sense of reality should not be lost, but neither should the sense of artificiality be removed, because that artificiality is the essence of artistic expression in cinema. He promotes the concept that the best cinema can be created by concentration on the specific characteristics of the medium. This concept directs the digital artist to create realistic complexity tuned to the unique aspects of digital cinema, which include the ability to create non-real images in non-real spaces, free from physical realities. This appears to argue against realism per se, and possibly for the elimination of editing. Ironically, Arnheim once spoke out against any form of three-dimensional cinema because it would erode the semantic power of editing [17].

Although Arnheim made several statements about the dangers that advancing technology posed to what he considered the essential aspects of cinema, he never expected that technology would grind to a halt, or that significant numbers of cinema artists would remain attached to silent films as the only viable cinematic form. In more recent commentary, he has even pointed to newer abstract forms of cinema as the exceptions to his theories of the middle 1930s. In assessing what additions should be made to his earlier theories, he says, "Nothing of what has happened . . . seems to me new enough in principle to require inclusion in a book which is not a chronicle, but a theory of film, except perhaps the remarkable blossoming of the 'abstract' film, the beginnings of what someday will be the great art of painting in motion" [18]. When Arnheim's ideas are widely applied to digital cinema, this art of 'painting in motion' becomes an unknowing allusion to computer-rendered imagery, a cinematic form where the artist controls each aspect of an image with the facility of a painter wielding a brush.

Summary

The theories and criticisms discussed here are directed toward understanding the basics of cinema. As such, they have application to all forms of imagery in motion, including digital cinema. An examination of these theories reveals ideas with special application to the unique aspects of the digital medium.

Understanding technology means using it as a means to a conceptual end, not as an end in itself. As digital technology extends the image making capability of the artist, we must understand how the conceptual nature of digital cinema also expands. As computers handle more and more technical aspects of artists' work, they mentally liberate artists from much of the tedious work that image making requires, allowing them to focus on concept, content and creative uses of the medium.

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Digital Dilemmas

Timothy Binkley

ABSTRACT

Computer imagery is fraught with divers conundrums and paradoxes associated with the fact that it is both abstract and concrete. It confounds familiar ways of understanding appearance and reality. We can begin to resolve the perplexity by using the idea of recursion to contrast digital imaging with picturing. It is particularly useful to explore the concept of an interface and to study its role in the imaging system. Digital images cannot be understood outside the context of the complete interactive system in which they occur.

We make our instruments, and then they make us, changing our perceptions, our image of ourselves.

—Heinz Pagels [1]

When I saw David Em at a recent SIGGRAPH meeting, I asked him what he had been working on recently. "Digital art", he said, undulating the fingers of his upheld hand in a teasing sinuous wave. He then proceeded to describe his return to making palpably solid sculptures after publication of the acclaimed picture book about his computer art [2]. Em's pun epitomizes the dilemmas we face when trying to understand computerized image-making. A finger is a 'digit', but a number is, too. Although both are discrete items from a collection of similar and related elements, they could not be more different: one is a physical object, the other is a concept. Yet when making computer art, we integrate them by molding intangibles with our hands. Computers somehow bridge the gap between object and concept, challenging venerable categories of thought that have become second nature in our culture.

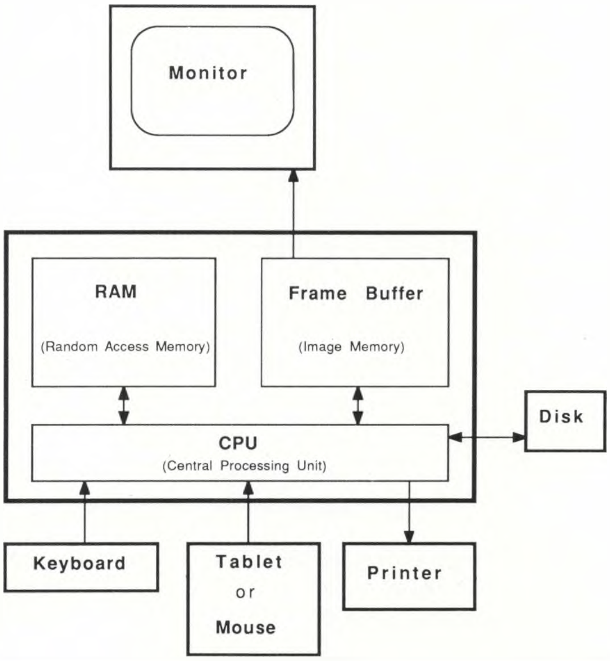
WHERE IS THE DIGITAL IMAGE?

'Digital image' is an oxymoron. An image is an appearance that is inherently visible; a number is an invisible abstraction. If a digital image is something one can see (by experiencing it with one's eyes), one cannot compute it; but if one can apply mathematical operations to it, then it has no intrinsic visual manifestation. In discussions of computer art, such antinomies insistently crop up [3]: we draw a picture without making a mark, wield brushes that have no bristles, mix paints that do not pour, model objects without any matter, illuminate them with dimensionless lights that never burn out . . . and merely by waving a wand create a prodigious menagerie of things. Is there no end to the innumerable inconsistencies? Perhaps we can at least find an emollient to soothe the irritation of 'digital images'.

When such computer cant is bandied about, what does it refer to? Let us consider for a moment a 'Canonical Configuration' for a computer graphics system (Fig. 1). This configuration consists of the common components required for working in one of the currently regnant environments: a paint system, a modelling and animation system, and a page-layout system. These basics are necessary even when writing programs or playing a video game. In such systems, the image typically is stored in a piece of computer hardware called a 'frame buffer', which contains standard random access memory (RAM) chips allocated to 'image memory'. A video monitor is connected to the frame buffer in order to display the picture—or rather the numbers—held inside. Photographing the monitor (Fig. 2) is one of the most frequently used methods of preserving its transient images in a tangible visual format. Another popular way of converting it to 'hard copy' is to print it out (this is how Fig. 1 itself was produced).

Where is the digital image located? Offhand, one would be inclined to say it is on the screen; and indeed that is where one's gaze is concentrated. But is there anything digital about what appears on the cathode ray tube (CRT)? The fact that the screen shows an array of individual dots called 'pixels' might be taken as evidence confirming the digital nature of the picture. The coarse mosaic of most early computer images was once considered a telltale sign of computer involvement, for better or worse. The difficulty with this view is that most CRTs are

Fig. 1. The Canonical Configuration. Virtually all computer graphics systems contain these basic elements. The information constituting an image is stored in the frame buffer as numbers and interfaced to a video monitor where it is displayed as colored pixels of light.



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not digital, but rather analog display devices. The fact that one sees an image composed of dots does not make it digital. Were the pointillists making digital art because they applied paint in individual dabs of color? More important, there might be no visible fragmentation into discrete elements. In the short history of computer graphics, we have seen resolution increase dramatically, to the point where one must scrutinize a screen carefully to see that it is composed of tiny dots. It is conceivable that magnification would be required to descry pixels in the future. Furthermore, usually viewers studying the image (as opposed to the screen) are far enough from the screen that the pixellation is unnoticeable. Straightforward perception of the image might reveal nothing that cries out 'digital' or tells us that it must have been made with a computer. After analysis, one might notice effects that could only be computer generated, but this is not always the case. The inference from screen to frame buffer is tenuous: imagine a ruse in which someone hides a videocassette recorder inside a computer case and boasts of spectacular 'real-time animation' on the monitor.

Suppose instead we identify the digital image with the contents of the frame buffer. This seems to make some sense since that piece of hardware is unique to computers. It is not found in painting, photography or even in (precomputerized) video. The frame buffer is certainly a principal performer in the arena of computer art, but in what sense can the information stored in it be construed as an image? Its contents are just bits and bytes like figures in a spreadsheet, and there is nothing intrinsically visible or image-like about them. There is no way of telling by the numbers whether they are an image: any set of numbers can be run through the frame buffer. A text file may not make an interesting or desired picture, but if properly formatted it can be displayed on the monitor as readily as a picture file.

Another difficulty with the idea that the image is in the buffer is that the same collection of numbers can give rise to quite different images, none of which has any priority as the true appearance. The contents of the buffer could appear equally well as a video image, a photograph of a video image (as in Fig. 2), a lithograph (Fig. 3) or a work in one of a variety of other media. Each of these images may look quite different though derived from the same file of numbers. So if the numbers are the image, which one are they?

It is tempting to think that somehow what makes an image digital are the numbers that underlie it because they ultimately determine the criteria for its appearance and establish its identity. Figures 2 and 3 may look different, but what they *do* look like, as well as the fact that they are both versions of an artwork called *Time*, is determined by their relationship to the buffer. The reason they look different is that they are realized in quite different media, one based on light, the other on pigment. However, our quandary persists even if we examine a single medium. Anyone who has spent much time in a computer art lab knows that the same image on two different monitors may look surprisingly dissimilar due not only to vagaries of ambient lighting and inconsistencies in adjustments of brightness and contrast but also simply because each monitor has unique characteristics (as a result of, for instance, its physical makeup, its age or the use it has been given). The computer simply is not a medium, and it is subverting our customary identification of images with media [4]. In a medium, the image is produced by manipulating visible objects, and image information is inseparable from the physical material storing it. But in computer art—unlike video, painting, photography or sculpture—a frame buffer takes priority over what appears on the monitor and the only way to control the image is through the buffer contents. Media have no trans-media criteria for the identity of an image; computers *do*, whatever that may portend. We save to disk a file of numbers and call them up whenever we want to recreate a given picture. Though the image may be fleeting on the screen, the numbers preserve it. The essence of the buffer lies in its numerical contents, and the physical basis of the medium that stores them is incidental. Whether the computer is a Turing machine chattering through paper tape, a current model based on electrons, or a future one employing light does not affect its ability to manage image memory. What is essential is that the buffer contents are computable and transferrable to an appropriate output device such as a CRT. But this still does not resolve our dilemma about where to find the digital image. Maybe the answer lies in exploring the connection between these two pieces of hardware.

Pictures, Types and Tokens

Could we perhaps view the image on the CRT as a *picture* of the frame buffer? It certainly is a picture with some kind of subordinate relationship to the buffer. But then what exactly is the picture supposed to be a picture of? Since the buffer is full of numbers, I suppose the monitor would display a picture of numbers. But a picture of a number is just the number itself.

Consider the following thought experiment. Suppose I write on a blackboard a proof of the proposition that the square root of 2 is an irrational number [5]. If I take a photograph of the blackboard, it is a picture of what I wrote, but not a picture of the proof. The photograph *is* the proof every bit as much as the chalk marks on the board are, and anyone can check the steps of the argument equally well in either manner of presentation [6]. Wherever the symbol $\sqrt{2}$ appears in the photograph it refers to the same number I wrote on the board and not to a picture of that number. The reason for this is that, strictly speaking, one cannot make a picture of a number. A number is an abstraction with no physical substance that could have a certain physical appearance. This is why the contents of the frame buffer can be moved so freely about the system from buffer to a monitor, disk or printer: because they are abstract concepts they are not uniquely embodied in any particular medium, and hence can readily be stored in any of them.

When I write a number on the board, I make a physical mark, which is sometimes called a *token* of the number. The number itself is a *type*, which some mathematicians think of as an exalted Platonic Idea which resides in an immaterial firmament accessible only to the intellect [7]. If I put another $\sqrt{2}$ in *this* sentence, it is a different token of the same number designated in the preceding paragraph. I can write a number with Arabic or Roman numerals, Babylonian or Mayan; it can appear in stone or in string or in a Jasper Johns painting, and all of these physical manifestations are marks which 'betoken' the ethereal existence of an abstract number. The same is true for letters of the alphabet and any similar abstractions used in mathematics, computer science and other formal disciplines.

The tokens in the photograph are not the same *tokens* as the tokens on the board. One set is made of chalk and the other set, made of photographic emulsion, is a picture of the first set. Nevertheless, a photograph of the chalk tokens on my blackboard constitutes tokens of the same *numbers and symbols* (and hence delineate the same proof). A picture of a token is itself a token, just as a photograph of a photograph is a photograph [8]. What makes something a token of a number is its reference to the number and its ability to function in appropriate sign-manipulation systems that furnish mnemonics to assist concrete beings in the processing of abstract numbers.

I have said before that the buffer contains numbers, but I think it is now clear that only tokens of numbers reside there and not the numbers themselves, which take up no physical residence. One might question whether electric charges in RAM or magnetic fields on a disk are genuine tokens of numbers since people cannot recognize or use them as such. But I believe computers are forcing us to extend the class of tokens to include the ones they use since they can 'recognize' such things as numbers and use them as 'mnemonics' to record quantities and to manipulate them in much the way we do. They are just a lot faster at it. Moreover, computers can readily communicate to us what numbers they are 'thinking' about by converting them into tokens we can use.

Let us now raise again the question about the status of the image on the monitor. Should we view it as a picture of the tokens in the buffer? Has one set of tokens been transcribed into another, as when the buffer contents are transferred to a file on disk? Can pixels simply be tokens of numbers? Probably not. We cannot use them as such and neither can the computer. These dots of color are intended to be processed by the human visual system, which most likely does not sense them as tokens of numbers and then calculate an image from them in the brain. We do not experience pixels as numbers and cannot manipulate them as numbers. The monitor may in some way 're-present' the buffer, but not as numbers. The relation between the numbers in the buffer and the colors on the screen is something else. The concept of picturing has led us on an

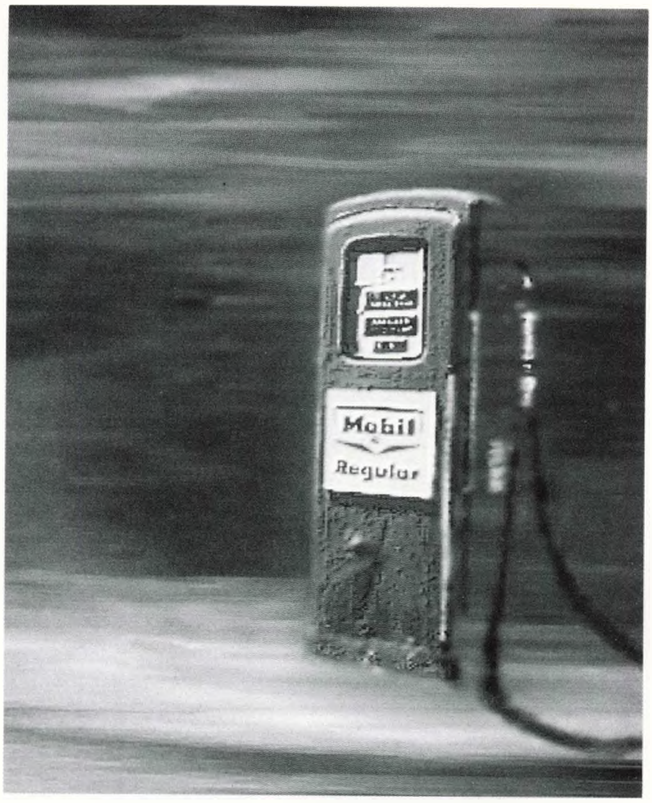

Fig. 2. Louis DiGena, *Time*, photograph of a computer-generated image, 1989. The image was photographed using a film recorder that contained a flat-screen black-and-white video monitor to which a frame buffer was interfaced. Three passes were made for each of the additive color primaries: red, green and blue.

Fig. 3. Louis DiGena, *Time*, limited edition lithograph, 1989. Color separations for the lithograph were generated by a computer and then output to a printer in black and white. Although both Figs 2 and 3 originated in the same file of numbers, they look quite different because they were realized using different interfaces to different media.

excursion through a labyrinth. Perhaps it can lead us out.

A Recursive Picture Paradox

Consider Magritte's *The Human Condition* (Fig. 4). This intriguing painting pictures another painting. It demonstrates something very fundamental about the picturing relation: picturing can be *recursive,* which is just to say that one can apply it to itself to make a picture of a picture [9]. It is enlightening to examine precisely how the nested picturing is accomplished in this painting. One of its intriguing qualities is that Magritte painted his canvas in such a way that the part representing the depicted painting looks like a continuation of the part representing the depicted landscape. He designated where the depicted painting lies not by modifying the appearance of the paint there, but rather by alluding to conventions of painting that define it as a medium, i.e. by exposing some of the 'unpainted' canvas edge and by deftly positioning a painted easel.

The recursiveness of picturing gives rise to a paradox that can be called the Russell Picture Paradox, since it is based on Bertrand Russell's famous paradox about sets [10]. Most of us have seen amusing pictures that carry the whimsy of Magritte's recursion one step further to picture themselves. For me, one of the most memorable examples is a picture I saw in a magazine as a child which prodded me to reflect on dilemmas of self-reference. An arm was upheld above an inviting tropical beach. The hand held a copy of the magazine turned to the page with the picture of the hand holding the magazine . . . This process can be automated in video feedback by pointing the camera at the monitor.

We see then that some pictures picture themselves and some do not. Let us imagine making a picture of all the pictures that do *not* picture themselves. Such a picture will not be easy to make since most pictures fall into the category we are depicting and our image will have to represent a prodigious collection. But this should not deter us; some pictures depict vast panoramas covering thousands of miles of landscape, or the entire earth viewed from space, or even thousands of galaxies festooned across the starry sky. Our troubling picture seems almost humble by comparison; and in any event it is a thought experiment that need not be executed to make its point. Now let us pose the question: Does our picture picture itself? Will this picture of all pictures that are not self-depicting contain an image of itself? Well, if it *does,* then it is self-depicting and should *not* appear as one of its subjects by virtue of the way it has been defined. On the other hand, if it does *not* show up among the pictures it depicts, then it *should* because it is suppose to picture all pictures that do not picture themselves. Either way we have a contradiction.

Interfaces

Whatever relationship obtains between the buffer and the monitor, it is *nonrecursive.* To see why this is so, let us expand our horizons and contemplate a 'Complete Canonical Configuration' (Fig. 5), which includes direct input to the frame buffer as well as outputs to imaging devices that are not connected to the frame buffer. The various graphics peripherals are connected to the computer through what is called an 'interface'. Consider the scanner. Its interface reverses the relationship between the buffer and the monitor. It transforms colors into numbers by creating a set of tokens for them in RAM. At one end, it will accept any input that conforms to its *analog aperture* defined by a set of physical constraints. At the other end, it produces output that conforms to a *digital format* defined by logical constraints. Any colored object can be *digitized* through the scanner interface if it can be placed on the scanning surface, and the resulting digital information comes out formatted in a specified way. In between there is an *analog-to-digital converter,* which performs the metamorphosis necessary to get from one mode to the other.

These components comprise an *interface template* that defines the structure of the conversion process. Each interface has a unique template that delineates its analog aperture and digital format and also describes an algorithm (a set of step-by-step instructions) for traveling between their respective substance and form. The video camera interface will not work with the video monitor any more than it will work with the tablet or the plotter. Unlike the bi-directional communication within a computer that takes place between the central processing unit (CPU) and RAM, an interface template defines a one-way conduit for going either in or out. The computer usually needs to do some processing to move data from the digital format of one template to that of another. If the user draws on the tablet or digitizes a picture with the scanner, the input is not automatically produced in a format appropriate for display on the plotter or in the buffer. The interface template is usually 'hard wired' into a piece of hardware that contains the analog/digital converter, although like any formal structure it could be implemented through software as well. Absent appropriate hardware, a stalwart soul could even try to figure out an apt conversion and then sit down at the keyboard to type in the numbers after taking measurements of the object to be digitized.

It is possible to define and manipulate digital formats that are not tied to any particular interface. This is typically what happens in a so-called 'object-oriented application'. Object structures that have no hardware realization are formally defined by software. A three-dimensional (3-D) modeling and animation package will usually define digital formats for an *object space* in which three-dimensional objects are created and animated using two-dimensional tools for input and display, such as the tablet and the monitor. The digital formats of the interfaces used to depict this world reside in what is called an *image space,* and the computer performs transformations from one to the other to display completely digital 3-D objects [11]. One major difference between the two is that image space always has a pre-defined finite resolution, while object space has a potentially infinite one: its resolution can be varied by adjusting the scale at which objects are mapped to images. This accounts for the vast range of 'hyper-zooms' that have become a popular special effect seen on television and are an essential tool for examining certain new mathematical creations, such as the Mandelbrot set [12]. An object space 'free-floats' in RAM since its digital format is not interfaced to any particular peripheral. It is suitably transformed into digital formats as needed to affect and observe its contents.

Because numbers can both describe abstract properties and be exemplified in real objects, it is possible to make interfaces that communicate between the recondite computational world inside a computer and the concrete perceptual world outside. This transformation correlates heterogeneous domains. Unlike picturing, interfacing establishes a correspondence between two incompatible formats. It is a heteromorphic mapping, or *heteromorphism*. This is why the interface function is not recursive. Once the continuous analog scanner signal has been converted into discrete numbers, it cannot be done again by redirecting the output. Numbers do not convert into numbers through that interface; it only converts electronic scanner signals conforming to the appropriate analog aperture into numbers conforming to the specified digital format. To digitize something is to turn it into digits; that can be done only once. The process, of course, can be repeated but not recursed. The interface functions as an ontological gateway that transfigures its entrants into creatures of an entirely different order. Robust conscripts turn into disembodied concepts when they pass this portal and there is no turning back.

Picturing involves a *homo*morphic conversion (homomorphism) since it turns one picturable thing into another picturable thing. This is responsible for the transparency that makes a picture like a window and enabled Magritte to represent different objects with the same patch of paint simply by virtue of where he placed the frame. The resultant recursive potential gives rise to the Russell Picture Paradox. An interface, however, is not like a window one can peer through to examine what lies beyond. Because they are *hetero*morphic (hence non-recursive), interface conversions possess an opacity that immunizes them against the paradox. There are at least two reasons why this is fortunate. First, if the conversion process of digitizing input were so threatened, we could not be sure it would produce computable results. Second, the input and output of the system would possess potentially problematic limitations preventing certain things from being abstracted or concretized through the interfaces. The coherence of interface templates would not be assured and our system might be subject to feedback distortions or faced with the task of sorting out the layers of an infinite regress. As it is, anything describable with numbers (whether picturable or not) is digitizable and realizable, albeit maybe not with ease. This comprehensiveness undergirds the touted quest for absolute realism in computer graphics, which some of its proponents claim will be achieved by the third millennium.

If the video camera and the video monitor share both a digital format and the frame buffer that houses this format (as they do in some systems), we can turn the camera on the monitor to simulate video feedback. However, because the computer can perform sundry transformations on the contents of the buffer, the system is not compelled to enter a feedback loop. In most cases, the computer must execute a special procedure to connect disparate digital formats in order to create any feedback in the first place. The potentially vicious cycle has been broken, interrupted by heteromorphisms that suspend among them a veritable universe of computable creatures constrained by mathematical and not physical parameters. This object space offers the computer artist an option unavailable to Magritte. Imagined objects can be modeled inside their imagined reality by redirecting the viewer's attention from the image space to the object space. It is almost like reaching through the picture frame to encounter depicted worlds directly. The perceptual opacity of an interface does not deter it from functioning as a transport. The hand manipulates not only a stylus but also an imaginary object as a computer conveys the movements from one to the other. The identical textures of the painting and the landscape in *The Human Condition* underscore the inability of painters to do this: the canvas is an impenetrable barrier where reality is splayed from either side against the resistant physicality of the medium. Using the computer becomes a two-way interactive experience based on a variety of input and

Fig. 4. Rene Magritte (1898–1967), *La condition humaine* (The Human Condition), oil on canvas, 1.0 × .81 × .016 in, 1933. (Courtesy of National Gallery of Art, Washington, DC. Gift of the Collectors Committee. Copyright © 1990 C. Herscovici/ARS, N.Y. Reprinted by permission.) This painting demonstrates the recursive nature of picturing since it contains a picture of a painting. The painted surface looks essentially the same whether it represents the landscape or the painting of the landscape.

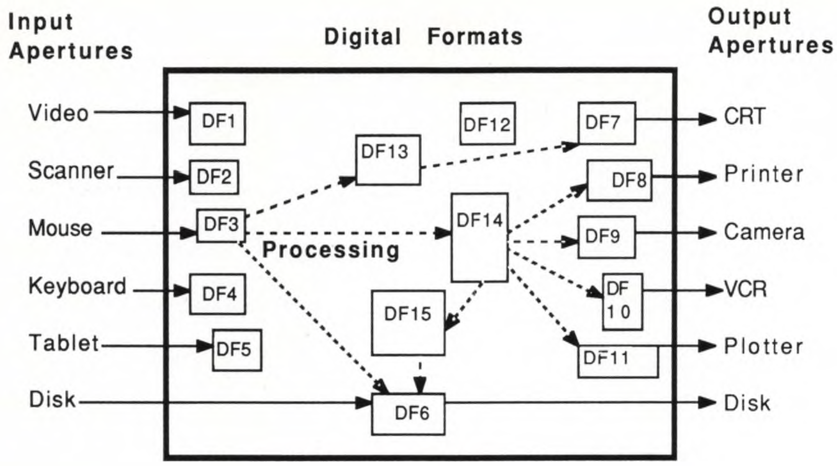

Fig. 5. The Complete Canonical Configuration. Interfaces for a variety of peripherals convert between analog apertures and digital formats. Some digital formats reside solely inside the computer, unconnected to peripherals by interfaces. The frame buffer is just one among many possible digital formats and the CRT one of many possible output devices.

output interfaces to a world where objects are digits and actions are formal procedures. This 'virtual reality', populated by agency as well as presence, is the foundation of interactivity.

The Reality of Interactivity

A digitizer devours anything describable. It has an omnivorous appetite excluding no property or process that can be delineated in numbers and symbols. Its indiscriminate embrace is all-encompassing. The abstract dominion of numbers becomes a surrogate reality that is difficult to distinguish from the real one because any perceivable difference can itself be incorporated through an appropriate interface conversion. The content of a description need not differ from what is described in any way describable. The 'reality' counterpoised to a computer simulation of it is ultimately mute, unknowable, like Kant's 'thing in itself' (the *Ding an sich*) [13]. There is no way to quantify the difference between quantities and unquantifiables. "The Tao that can be said is not the eternal Tao" [14]. Consummate reality may be elusive, but anything that can be digitized can be simulated. Even physical impossibilities are not excluded: multiple objects in the same place at the same time are fine, provided they do not abrogate the rule of logical consistency.

An interactive computer graphics system contains concretizing interfaces, which implement and display descriptions, as well as abstracting interfaces, which concoct them. Describing is like measuring but also like imagining; it can be used to say what something is like or what it might be like. But this distinction is weakening. Because computers actively process information they receive, the descriptive act can be turned automatically toward a generative one. The 'what' and 'how' of virtual creation are intimately linked through the formal mathematical structures that define them both. A computer artwork might exist equally well as either a set of procedures or a list of properties, neither of which need be its unique determinant. The contrary of Wittgenstein's admonition "Whereof one cannot speak thereof one must remain silent" [15] is "Think it, have it". Articulating the properties of an object is enough to conjure up its reciprocal presence, and describing an action becomes tantamount to being able to execute it.

What gives virtual reality its realism is, in part, the expansiveness of its scope, which is related to the universality of mathematics [16]. But an even more important factor is our immersion in it, our ability to interact with an alter ego. Interfaces form bridges between the real and the virtual and back again. We cross them to inhabit a strange place that is both concrete and abstract. A human hand grasping a real sensor holds, at the same time, a virtual paint brush or the controls of a virtual space vehicle. Since a hand can be described with numbers as readily as any denizen of virtual reality, we too can 'live' in these synthetic universes. We visit a territory we can probe, inquiring about and interacting with its residents to bring to life with equal ease bizarre fantasies as well as sedate realities.

Responsiveness has been one of the most eminent criteria for ascertaining the reality of something. We negotiate our quotidian world ostensively: approaching an object, we point to it, touch it, and say "this thing here". This is something that cannot be done with pictures or fictions. Although the picture of the picture in Magritte's painting can be pointed to, it cannot be bumped into and tipped over. Yet that is just the sort of thing one might do in one of the virtual environments being researched at such places as VPL and the (U.S.) National Aeronautics and Space Administration (NASA), which immerse the participant in imaginary surroundings using helmets, headphones, EyePhones and DataGloves that create a replete sensory envelope [17]. But anyone using a modeling and animation system to produce a cinematic experience works in a similar virtual studio. Even the simplest simulator, such as a paint system, thrusts one into a virtual world where one interacts with virtual objects. In using these systems, we are interacting with numbers and algorithms; however, because of the ontological shift in interface conversions, we do not experience them as numbers but instead as objects possessing a puckish presence that rivals real ones. Moving a hand will change the numbers and will also change the shapes and colors on the screen so that phenomenologically the interlocutors are objects and images rather than abstractions. That is why simulators can be so effective in preparing people to handle multiple contingencies and in helping them to develop a wide variety of skills, from repairing equipment to apprehending evildoers to flying airplanes. Trainees can be put into any situation a computer can describe by placing them in an appropriate simulator, thereby enabling them to accumulate valuable experience quickly and safely.

Heteromorphisms joining us to a virtual partner make interactivity possible. An interfaced computer system escapes being slaved to the mindless mockery of media, since it can engage the user in a lively retort cycle of responsive behavior. This is one of the most unique contributions of computers to culture. Because interactivity has long been a bastion to our sense of reality, the interactive system raises to new heights the age-old quandary about what reality really is. Computer graphics systems confront us with a web of interrelated paradoxes that challenge the hallowed dichotomies by which our culture has understood reality. Threatened are some of the most fundamental distinctions: real/imaginary, concept/percept, descriptive/generative, physical/mental. Heinz Pagels has claimed that "the radical distinction between mind and nature will disappear with the development of the new sciences of complexity and the categories of thought that development entails" [18]. The computer transcends our current efforts to categorize it.

We cannot begin to unravel these puzzles without looking at the entire system: individual components are meaningless unless they work together. Instead of isolating our attention on the 'digital image', it is imperative to examine how its complete environment functions. Many of our traditional concepts were based on the essential passivity of information that was inseparable from the media in which it was stored. Now information is separable and interactive. This may mean that, in the future, images will be treated more like abstract types than cantankerous characters or precious objects. The computer ultimately challenges many of the neat distinctions we have accrued over the course of centuries of living without these paradoxically intelligent machines. Now that they are a presence in our culture, we will need to change the way we think and live. The human condition does not stagnate.

References and Notes

1. Heinz Pagels, *The Dreams of Reason: The Computer and the Rise of the Sciences of Complexity* (New York: Simon & Schuster, 1988) p. 316.

2. David A. Ross and David Em, *The Art of David Em: One Hundred Computer Paintings* (New York: Abrams, 1988).

3. For example, Donna Cox, "The Tao of Postmodernism: Computer Art, Scientific Visualization and Other Paradoxes", *Leonardo* Supplemental Issue, *Computer Art in Context: SIGGRAPH '89 Art Show Catalog* (1989) pp. 7–12.

4. See my articles "The Computer Is Not A Medium", *Philosophic Exchange* (Fall/Winter 1988–89); and "The Wizard of Ethereal Pictures and Virtual Places", *Leonardo* Supplemental Issue, *Computer Art In Context: SIGGRAPH '89 Art Show Catalog* (1989) pp. 13–20.

5. I.e. that it cannot be expressed in the form *a/b*, where *a* and *b* are integers and *b* is not 0. Pythagoras is attributed with having discovered the first such proof.

6. Similarly, when the character of Alan Turing slips into mathematical reverie in the middle of the play *Breaking the Code* by Moelwyn Merchant, he is not doing some kind of second-rate literary mathematics. His arguments can be subjected to the same scrutiny as if they were presented in the journal *Mind*.

7. For a recent expression of this popular view, see Roger Penrose, *The Emperor's New Mind* (Oxford: Oxford University Press, 1989).

8. Although there is a difference. A picture of a token is a token of the *same* number as the one represented by the token pictured. But a picture of a picture is *not* usually a picture of the same things; maybe it *cannot* depict the same things. The photographs of Sherry Levine pose an apropos quandary.

9. Nelson Goodman claims that 'picture of' is a non-relational description, so that when we call something a 'picture of Pickwick', we are merely describing features of the picture and not a relationship it has to something else, namely Pickwick. See his *Languages of Art* (Indianapolis, IN: Hackett, 1976). Goodman's analysis is, at least in part, an effort to account for pictures of imaginary things. I am presupposing in what follows that this explanation will not suffice for at least some cases of 'picturing'. It seems to me useful to treat picturing as a relational function in attempting to explain pictures of pictures, especially when they occur in a feedback loop as they do in video. Maybe we will just have to live with the idea that we can make pictures of imaginary things. It seems to happen all the time when a computer is used to model and animate objects.

10. See Bertrand Russell, *The Principles of Mathematics* (Cambridge, U.K.: Cambridge Univ. Press, 1903).

11. The distinction between object space and image space is a standard one in technical discussions of graphics software. See James Foley and Andries Van Dam, *Fundamentals of Interactive Computer Graphics* (Reading, MA: Addison-Wesley, 1982).

12. The Mandelbrot set, a geometrical object defined in the complex plane, has received a great deal of attention recently from artists as well as scientists. It is usually displayed through a sequence of images depicting its self-similar shapes over an extensive range of scales. See, for example, H. -O. Peitgen and P. H. Richter, *The Beauty of Fractals* (New York: Springer-Verlag, 1986).

13. See Immanuel Kant, *Critique of Pure Reason (Kritik der Reinen Vernunft)* (Riga: Hartknoch, 1781).

14. The first statement in the *Tao Te Ching* by Lao Tzu.

15. Ludwig Wittgenstein, *Tractatus Logico-Philosophicus* (London: Routledge & Kegan Paul, 1961).

16. Alvy Ray Smith is reported to have said "Reality is merely a conventional measure of complexity. If we can simulate reality then we're getting images of a sufficiently pleasing complexity." Quoted in Fred Ritchin, "Photography's New Bag of Tricks", *New York Times Magazine* (4 November 1984) p. 55. See also Timothy Druckery, "L'Amour Faux", *Digital Photography*, catalog for the show organized by SF Camerawork (San Francisco: SF Camerawork, 1988).

17. This research is beginning to bear fruit in the form of relatively inexpensive and accessible systems, including a glove peripheral for Nintendo machines. It is understandably receiving much attention in the popular press. See, for example, Steve Ditlea, "Inside Artificial Reality", *PC/Computing* (November 1989). Myron Krueger was an early pioneer in developing this technology and understanding its potential. See M. Krueger, *Artificial Reality* (Reading, MA: Addison-Wesley, 1983).

18. Pagels [1] p. 15.

Computer Graphics: Effects of Origins

Beverly J. Jones

ABSTRACT

New forms of art and technology are frequently cast in the mode of old forms, just as other aspects of material and symbolic culture have been. Only when these new forms become available to the larger population can they affect cultural patterns of maintenance and change. The author traces the evolution from alphanumeric hardcopy, static and dynamic screen images, through objects and events that are not screen-based, to dynamic, interactive, multisensory output. The effects of origins and prior practices in both technology and art on form, content, material, technique, meaning and purpose of computer graphics are explored. Speculation regarding possible and probable futures are raised.

New developments in any particular field only become part of the general culture when they enter the experience of people who are not specialists in that area.

—Waddington

Computer graphics, as defined by Franke and Beyer [1], has been in existence a relatively short time. Changes in the form of this medium, from static alphanumeric hardcopy to dynamic interactive multisensory output, have been dramatic and rapid. These changes are not simply technical effects. They contribute to maintenance and change of culturally conditioned conceptual patterns in the larger cultural historical context. By reviewing specific works and what appear to be underlying conditions and assumptions that shaped these works, I hope to establish the relation of specific image, object, event or environment to conceptual frames. These frames exist within art and technology and are present in other forms of symbolic and material culture.

Examples from other media illustrate cultural tendencies to cast developing forms of material and symbolic culture in previous modes. The stone columns of ancient Egyptian architecture were based on earlier bound papyrus columns. Early oil paintings were similar in technique to egg tempera paintings and did not take advantage of oil's mixing properties, slower drying and resultant appearance of softer edges. Early mass-produced furniture imitated handcrafted furniture in form and applied ornamentation. The motorized McCormick reaper had a cast-iron bull's head on the front. Many other such examples exist.

Electronic and photonic art forms have been and will continue to be influenced by their origins and practices. Two earlier papers examine computer graphics as a reflection of culturally embedded aesthetic theories based on varying views of reality [2] and developing technologies of communication as reflecting cultural maintenance and change [3]. In this paper the origins and practices of computer graphics from 1945 to the present are examined to reveal cultural patterns embedded in their material and symbolic form. Reflecting origins and prior practices, these embedded patterns may have existed in art, technology or other aspects of material and symbolic culture. It is a premise of this paper that old cultural patterns do not die. They may fade or become more evident; that is, they may be deemphasized or emphasized. Only as part of the general 'nonexpert' culture can such patterns contribute significantly to maintenance and/or change [4].

An analogy may be drawn between early views of potential uses for electricity and those of potential uses for the computer. Electricity had been considered theoretically interesting but of little or no practical value. The potential for widespread and multiple uses of microcomputers by the general public was suggested as late as 1978 at the Second West Coast Computer Faire. Several engineers and programmers were amused, because of the impossibility of there being "that many programmers". This perspective is analogous to early market predictions of the Mercedes Benz Corporation, which limited the number of potential automobile sales to the very low number of trained chauffeurs then available.

These examples express the tendency to set limits of 'the possible' based on previous experience, knowledge and conceptual frames. An increasing number of contemporary theorists are stressing the importance of origins and practices in unmasking assumptions within current forms and practices [5]. Those who originate and use new forms of art and technology embed their assumptions in the new symbolic and material forms. As time passes the original users develop familiarity and facility. New users bring additional assumptions and considerations of form, content, material, technique, meaning and purpose. However, some traces of the origins and practices remain in these forms, which consequently contribute to both cultural maintenance and change. Cultural patterns are affected in proportion to the spread in the use of these forms.

Selected examples of earlier and contemporary computer-related images, objects, events and environments are examined to show reliance on previous forms and to present evolving possibilities in harmony with larger cultural and historical patterns. A tension has existed in the development of computer graphics between the scientific and artistic views of imagery and their evaluation. Origins and evolving practices are seen both to support and to diminish this tension. These practices increasingly penetrate the population at large. An examination of the fluctuating borders between computer graphics theory and practice in scientific/technological use, in artistic use and in 'everyday' use reveals differing patterns of cultural authorization. These patterns may be said to support cultural maintenance if, for example, the same authorizing assumptions are present

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across uses. Conversely, if sufficient new and different authorizing assumptions are present, they may support cultural change.

Conceptual Background

C. P. Snow, in *The Two Cultures and the Scientific Revolution,* discussed the growing lack of understanding between the artificially divided intellectual spheres of the arts and humanities and of the sciences. Several papers examine the potential of the computer as information processor to join divided intellectual spheres [6–8]. Computer scientists and technologists may assist individuals in the arts and humanities to understand potential uses for computers. Theorists from the arts and humanities may examine implicit assumptions in the form, function and content of developing technologies. Perhaps more important, theorists in the arts and humanities may assist scientists, engineers and technicians in directing the development of new technologies toward cultural goals before technological ones. This would entail emphasizing potential effects on the quality of human life, especially in aesthetics and ethics. These transdisciplinary objectives have been proposed for educators as well. Disciplinary divisions within the institutions of education present obstacles to planning cultural goals before technological developments [9] and encourage the prevalent reactive planning mode. Active planning requires participation of many individuals with varying perspectives and prior experiences in order to set cultural goals on which to base future technological development. This is in harmony with the position of Weizenbaum [10], who emphasizes the importance of human choice in directing the consequences of technological innovation. Rather than directing the consequences, however, I propose selecting them. In part, problems arise when we attempt to implement this mode of thinking, because educational institutions remain rooted in origins and prior practices. Among these origins and practices are the separation of intellectual disciplines, and of theory from practice within disciplines, the decontextualization of knowledge from lived experience, and heavy reliance on a model of nineteenth-century scientific knowledge as a value-free framework in which to place and communicate all knowledge.

Institutional enculturation within restricted disciplinary frameworks results in very different concepts of the 'limits of the possible' and the 'dimensions of the desirable' held by individuals trained in the arts and humanities from those trained in the sciences. Although most institutionalized education remains inside disciplinary boundaries, the most innovative research in many disciplines has become transdisciplinary. It is evidenced by hyphenated disciplinary names in the sciences, by cross listings of the same event in performance and gallery advertisements in the arts, and by artistic and technical scientific work sharing media such as computer graphics, holography and other photonic applications. Computer uses such as computer graphics have been adopted across disciplinary boundaries and are present in multiple disciplines. The development of the MIT Media Lab is based on the integration of three formerly separated media industries; Negroponte's design for the MIT lab's logo displayed the intersection of three areas, broadcast and motion picture industry, print and publishing industry, and the computer industry [11]. The integration of formerly separate areas in multimedia photo-optic telecommunications continues this trend [12]. The development of computer graphics clearly reflects trends diminishing the rigidity of boundaries among disciplines and applications. Contemporary work in disciplines formerly untouched by computer graphics now reveal convergence that may lead to reevaluation of structures within institutional education. Areas in which alphanumeric symbolic textual representations constituted primary analytic tools now utilize visual spatial representations. No single academic area such as computer science or graphic art 'owns' computer graphics. Rather, individuals in pure and applied science, cognitive and social science, the arts, humanities and professions use it with varying assumptions and purposes. Areas of scientific and technological inquiry such as artificial intelligence, pattern recognition, human/computer vision systems, human/computer interfaces such as iconic screen interfaces, visual programming, and scientific visualization all utilize computer graphics. Education and communication use graphics and multimedia in a hypermedia environment. Entertainment and advertising use computer graphics for special effects, camera control, storyboard construction and other applications. In short, computer graphics has escaped narrow specialization and may contribute significantly to cultural maintenance or change.

Early misunderstandings and difficulties of collaboration between computer graphic pioneers from art and computer science may be seen as resulting, in part, from different educational enculturation. Effects of these origins and practices remain, but a gradual improvement has been achieved. Individual computer graphic pioneers are merging education in art and computer science in themselves or forming a partnership with others who have complementary skills. Teams from multiple disciplines are working in academic institutions developing scientific visualization and cognitive and perceptual research; in government research for defense and other practical applications; and in advertising and entertainment. Nonspecialists use home computers for business, education and entertainment, many with iconic graphic interfaces.

These instances of transdisciplinary, multidisciplinary and cross-disciplinary research and practice are becoming more prevalent. However, educational and other cultural institutions still support separate disciplines. Until they are altered, separateness of values, attitudes and beliefs of individuals enculturated within the distinct academic disciplines will perpetuate the status quo. Recent theoretical work in cognitive science and computer science, as well as that in contemporary theory in the arts, humanities and social sciences, provides theoretical rationales for cultural change.

Background: Computer Graphics History

The Early Years and Beyond

In the 1940s analogue computers were used to generate the earliest computer graphics and display them on oscilloscopes [13]. Ben F. Lapofsky and Herbert W. Franke were among the pioneers creating these images. Franke's graphics were phase forms, presented as events rather than as static imagery. Lapofsky's *Oscillon No. 4* was included in the first edition of Franke's book, *Computer Graphics—Computer Art.* His work continues to explore similar forms. An early version of a plotting device was the Henry drawing computer, a modified analog computer designed by D. P. Henry that produced drawings by a combination of pen movements and table movements.

It was not until the 1960s that digital imagery replaced the prevailing analog imagery. Examples of digitally computed imagery included alphanumeric hardcopy from teletypes, line printers and flat-bed plotters. At nearly the same time, linear, drawn hardcopy of geometric forms was produced as geometric calculations such as Lissajous figures and vector graphics. Because early computers had low capacity of speed and memory, these calculations were generated in a painfully slow display, then recorded by photographing the screen or drawn by plotters.

Usually these images were done by engineers and technicians employed by government, industry or large research institutions. The design of hardware and software reflected practical purposes, as did most of the images done in these settings. Not all images served technological research or practical purposes; some were done in 'spare time' by engineers and technicians. For example, an image called *Stained Glass Windows,* a graphic designed in the Army Ballistics Research Laboratory, reflects a desire by individuals not trained in art to produce aesthetic imagery. It received second prize in the Computer and Automation Computer Imagery Contest in 1963. Although color was not introduced for images created for practical purposes, it sometimes occurred in images created for visual aesthetic purposes. John C. Mott-Smitt produced an early scientific visualization of subatomic particles in a force field. He also varied this same program for visual aesthetic purposes; he introduced color by utilizing color filters and creating multiple exposures from his visual display screen. Nake introduced color in the plotter-drawn images of matrix multiplication. He assigned various numbers to colors and supplied the plotter with colored drawing pens.

An example of the more prevalent practical imagery done at this time is William Fetter's seven-system man. This program created the image of a man with seven movable components using data representing a fiftieth-percentile pilot of the U.S. Air Force. Its purpose was to assist in the design of an ergonomically efficient cockpit. Fetter and his technical group also attempted a computer-graphic landing simulation for the air force. These graphics are transparent wire-frame constructions; that is, they used no hidden-line algorithms.

Perhaps the most effective and most cited computer-graphic imagery of the early period is that of the Computer Technique Group of Japan. By combining photographic and geometric data, this group produced graphics that may be read as political commentary, *Kennedy in a Dog* and *Marilyn Monroe in a Net.* These transformations and their two-dimensional interpolations such as *Running Cola Becomes Africa* may be considered classics of this early period. The group also produced one of the first interactive environmental pieces, called *Automatic Painting Machine No. 1.* It consisted of a painting mechanism, control unit, paper-tape reader and a happening zone. Four types of input were used to control this device: manual, paper-tape program, light-sensor input from happening zone and sound-sensor input from this zone. The machine produced painted canvases up to 2 by 1.5 meters; the painting instrument consisted of four color sprays operated by compressed air through electromagnetic valves. All the individuals comprising the Computer Technique Group were engineers and programmers; none were professional artists.

Nicholas Negroponte and the architectural machine group Seek produced experimental computer-controlled environments at MIT.

For example, they created an experimental computer-controlled habitat for gerbils in 1970. Another example of interactive environmental pieces is Bonacic's computer-controlled sculpture featured in *Leonardo* in 1974. This sculpture received environmental input from sensors.

Individuals with art backgrounds who were active in early computer graphics and continue their work include Charles Csuri, G. Nees, Robert Mallary and Duane Palyka. Csuri's static graphic, *Sine Curve Man,* and his transformations on film, *Hummingbirds* and *Aging,* were done with assistance from computer programmers. In 1970 he published "Interactive Sound and Visual Systems" based on his work at Ohio State University. Palyka's alphanumeric printer output for designing two-dimensional artworks was based on variables in the programming; these works were included in the first computer-art exhibit, "Cybernetic Serendipity". Many computer graphic artists later used this technique. Nees and Mallary created sculptures with computer-aided design and computer-controlled manufacturing techniques. In an essay, "Art, Cybernetics and the Supermarket", Moles noted the potential of introducing a variable into computer programs that control machine tools for industry, causing every item that emerged from an assembly line to vary slightly. The variability would probably be cosmetic in nature, not essentially altering the product's purpose or functional form. It could consequently be regarded as an example of marginal differentiation.

At the Second West Coast Computer Faire held in 1978, several projections were made. It was proposed that small computer systems similar to the larger systems used by Mallary for sculptures, by Laurie for weavings and by others for prints be used by individuals to create unique furniture, fabrics and prints suited to their special requirements. Applications programs with many optional branches could assist in the design process. The completed design in the form of digital data could be used to direct mechanical production of the objects. In short, computer-aided manufacturing could be customized rather than characterized by exact repetition and centralized assembly-line mass production. It was also proposed that small microprocessors be used for games and appliances. However, these applications would remain in the style of mass production, allowing the consumer little control except by veto of non-purchase. In contrast, small computer systems with suitable applications software could allow individuals to design and control essential aspects of environment. This was presented as emphasizing an appropriate role of human choice in directing the uses of technology.

These projections present a view of electronic manufacturing that is parallel to the much earlier views of Borsodi on mechanical mass production. He noted the potential for individual control of mechanical manufacture of clothing and household textile products, based on the advent of the home sewing machine. This view suffers from an optimism born of ignorance of the constraints of cultural maintenance and change, particularly the social and economic context of origins and practices. This view also ignores important differentiations between conceptual possibility and feasibility. Relationships between these are based on complex interactions of social, economic, educational and historical factors; that is, origins and prior practices must be considered. Interestingly, computers have been used to customize the tailoring of suits in West Germany and of bikinis in southern California. Measurements of the individual are taken by laser-based optical scan in the West German instance; digital photos and keyboard entry of measurements are used in southern California. Although these products are customized to a client's body, individual conceptual design differences are not employed—that is, earlier concepts of the designer and tailor as experts remain.

During the early years of computing, other individuals and teams produced work that presaged later and current technologic/scientific and artistic work. For example, working at Bell Labs in 1966, Knowlton and Harmon produced gray-scale images from drawings, photographs and real objects by using data from a photodensitometer. This instrument presents the scanned image so prevalent in contemporary work. Later work on picture processing has been done at the Jet Propulsion Lab in Pasadena [14]. Also working at Bell Labs in 1964, E. Zajak depicted a satellite orbiting in space. In 1967, also at Bell Labs, A. Michael Noll produced a film that depicts a four-dimensional object rolling through our three-dimensional world. These examples prefigure the work of scientific visualization, in which things that have never been seen and may never be seen are presented as graphic imagery to stimulate conceptual thinking. This imagery augments thought formerly supported by alphanumeric and primitive graphic symbols [15]. Noll also produced a set of Mondrian simulations, which he presented to a group of subjects, asking, Which is the Mondrian? and Which do you prefer? [16]. This early attempt at analysis and simulation of visual forms led to generative aesthetics. Even earlier (1957), R. A. Kirsch et al. reported experiments in processing pictorial information using a digital computer [17]. The work of Noll and Kirsch presages more complex picture processing, pattern recognition and the links between computer graphics, artificial intelligence and remote sensing. The evolution of this early work can be traced in Rosenfeld's compilations [18].

The middle period of computer graphics is one of continued tension between technological/scientific and artistic realms. This tension reveals itself in choices of images, intentions and, increasingly, in conceptions of 'how the world is and ought to be'. During the middle years cost and scale of technology also became an important variable. Scientists and technologists continue to develop the most sophisticated and expensive technology. Few artists have access to this equipment. They rely on cheaper scaled-down versions of early technology; those artists who do gain access to the technical labs but lack training in science and technology encounter conceptual, technical, environmental and organizational difficulties. David Em's accounts of working in the Jet Propulsion Lab in Pasadena document these difficulties from an artist's perspective [19]. The involvement of artists with computers during the middle years is well documented in Leavitt's *Artist and Computer* and in periodicals such as *Leonardo* and *Art Forum*. ACM and IEEE publications document the development of technological and scientific imagery.

The primary form of computer imagery in the early years was the two-dimensional screen or plotter graphic. Three-dimensional screen imagery consisted of transparent wire-frame images. With increases in memory space and speed, and the construction of hidden line algorithms, illusory three-dimensional images began to appear on computer screens. In the mid and late 1970s further increases in speed and memory led to raster graphics and then to displays of three-dimensional colored, shaded and textured images on computer screens. Optical effects such as reflection and transparency became technically possible. Examples of these effects were developed at technological research sites such as the University of Utah. Duane Palyka worked at this site. Leavitt presents images of Palyka using some of the earliest paint programs and a digitizing tablet developed at the University of Utah. His work with this hardware and software represented a sharp departure from stereotypical geometric computer imagery. Because his imagery simulated and explored earlier artistic media, Palyka could use it to present concepts from within the mind of the artist, much as if he were drawing or painting them. He worked with Ivan Sutherland's first interactive drawing system, Sketchpad. Other interesting developments at this site include Sutherland's device that directed the display directly into the visual system of the person wearing the device, who could see a three-dimensional wire frame world suspended in space around her or him [20]. This development was an initial step toward virtual environments. Later, a report on GROPE-1 by Batter and Brooks, working at another site, illustrated the development of another step toward virtual environments, tactile and kinesthetic illusion [21]. This work and that of Fetter presage the virtual environments that currently exist for defense simulations. One task that had been set for the University of Utah research group by their government funding source was not met: the generation of dynamic three-dimensional screen graphics displayed in real time. Even though the images presented color, light and shade, reflections, transparencies and opaqueness, their display took a long time to generate on the screen. The task of generating real-time graphics required a conceptual shift rather than purely technological improvement.

Graphics done by computer scientists, engineers and technicians continued to be practical and increasingly to be rooted in assumptions of objective realism. Their creators believed they could create an adequate simulation of visual and physical aspects of the world grounded in mathematical formulae and algorithmic expression. (In this, they entered the realm of visually simulating three-dimensional reality on a two-dimensional surface, the same problem that had occupied Roman artists practicing illusionism and Renaissance artists who revived visual perspective.) Scientific visualization involves expression both of physical laws and of visual/optical laws. Both artists and scientists abstract natural laws from the 'real' world to express it mathematically and to present it visually.

With the development of ray-tracing techniques, particle systems, and other techniques for depicting the three-dimensional world and dynamic systems within it, technical imagery outstripped the planar illusionism previously practiced by artists. With greater precision in reality simulation through computer graphics came the realization that the images formed were too perfect, or hyperreal. These hyperreal images failed to create the visual effect of the real world, because they did not include imperfections and irregularities characteristic of natural phenomena. Consequently, they looked 'too plastic'. They revealed the abstract nature of physical law—its abstraction and noncorrespondence to the vision of lived experience. Attempts to remedy the problem of hyperreality included applying variations in textural-pattern maps to the surface of illusory three-dimensional computed objects. Degraded versions of the hardware and the software developed during this stage are now available for use by artists. An interesting result has been work based on aesthetic modernism, which concentrates on composition with elements and principles of design but also treats the two-dimensional surface as three-dimensional. The work of M. Pruitt is characterized by this combination [22].

While computer scientists and technicians were pushing back the technical limits of computer graphics, many artists explored characteristics of earlier computer-graphic imagery. Following the first major international exhibition of computer art in London in 1968, more artists began to take an interest in the computer as an artistic medium. By the late 1970s, computers were more available to artists, although the latest and most expensive models remained in the laboratories of industry, government and research institutions. Computing power remained a scarce resource. Many artists began using the computer as a designing or executing device. A common practice, utilized by Barbadillo, Sykora, Giorgioni, Marcus and Leavitt, among others, involved generating multiple designs from a single program, choosing one and executing it in a traditional art medium. Palyka and Molnar had used this technique earlier. Most of the resulting work was visually similar to modernist art.

Modernist schools of criticism—formalism and empiricism—analyze composition in terms of elements and principles of design. Both schools of criticism can be viewed as reductive; that is, they ignore historical, social or representational references within an artwork. They decontextualize a set of abstract references, elements and principles of design in order to describe and analyze the work. The empiricist school of criticism attempts to make aesthetic and artistic critical analysis in a scientific manner. It describes artworks by reducing them to their elements, analyzes by relations among these elements, and interprets and judges based on these descriptions and formal analysis. Its method is similar to the scientific method of observation, analysis, proposal and testing of hypotheses. Both formalist and empiricist criticism claim to be universally applicable to art, whatever its context, and value-free. Consequently, this style of art, whether associated with computer graphics or not, may be said to confirm cultural assumptions similar to those of scientific research and practices of scientific visualization using computers.

Other artists were interested in taking advantage of computer control of external devices for creating artifacts or for creating interactive, responsive sculptures or environments, some of which cross disciplines within the arts as well as across the arts and sciences to incorporate sound and human movement received from sensors and keyboards. Ihnatowicz and Cohen join art and artificial intelligence in their sculpture and drawing. Their works attempt to assimilate scientific, psychological and philosophical discourse. Ihnatowicz's sculpture *Senster* presents motions that may be interpreted as emotional behaviors such as distress and fear in reaction to large crowds and noisy environments. Jasia Reichardt commented, "It is as if behavior were more important than appearance in making us feel that something is alive," and "Confronted by this artificial device, it is clear that people have no difficulty in organizing their psychological responses as if The Senster were alive—an animal or another human being" [23].

Cohen has constructed a series of computer programs that direct the activities of a drawing turtle. He attempts to describe the process by which human beings read symbols and images. His programs imitate experts who know aspects of picture making, such as shading, spatial distribution and determination of inside and outside of forms. He regards the computer as an intelligent assistant, analogous to a human assistant to an artist such as Rubens. This work recalls the Turing Test. Can we mistake the drawn expression of a machine for that of a human artist? These artworks reveal their relations to movements in the art world such as happenings and participatory theatre. In them, the division between artist, participant and artwork diminishes in importance.

Cohen's work extends early attempts to produce computer simulation of the style of artists such as Klee, Hartung and Mondrian. Cohen also attempted stylistic simulations of Bach's musical style. Kirsch and Kirsch have continued this type of analysis and simulation in a symbiotic expression of human skills and machine capabilities. In this wife-husband team, the wife is an art historian and the husband a programmer who did early research in pattern recognition. They combine an art historian's understanding of style and a programmer's technical skills to define that tentative style in the parameters of a computer program. The computer produces multiple images based upon their analyses; they test the 'goodness of fit' of these images to the art historian's sense of style and revise the program accordingly. These activities are a symbiotic interplay between human/human and human/machine [24]. Trying to determine what is viewed as an aesthetic object, others have attempted to define and program parameters of aesthetic value. The algorithmic aesthetics studies of Stiny and Gips are an example of this [25].

Gradually computing power has become accessible: hardware and software developed in the laboratories of government, industry and research institutions are available for mini- and microcomputers and economically feasible for small institutions and individuals. Based on more complex hardware and software, these are labeled 'degraded forms', simpler and more economical; among them are draw-and-paint programs, similar to those developed at the University of Utah, and scanned imagery, such as that developed at Bell Labs. Discussions on the appropriate form for computer graphics as art have followed these developments. Are there forms unique to computer graphics? Should computer graphics be used as an adjunct to other media, to emulate other media, or should it be used as a unique medium in itself? Does the work of art reside in the concept, in the computer program, in the process of performing or running this program, or in some phase of the output? If the program contains randomization, stochasticism, variables derived from environmental sensors or other interactive data, how does this affect its status as art? What of its status as original or reproduction? These are among the many questions that computer artists began to raise and have not yet fully addressed. An examination of aesthetic theories embedded in scientific/technical and artistic computer-graphic imagery, theory and practice, begins to reveal the extent of embedded cultural origins and practices in this medium. Embedded assumptions from science, technology, and the context in which these forms were originated also influence computer graphics. Form, content, meaning and purpose of contemporary computer graphics show these origins and practices.

Recent and Contemporary Computer Graphics

Artistic Uses

An examination of the computer graphics selected by recent SIGGRAPH jurors displays the continued split between the scientific/technical and the artistic. Artistic uses of computer graphics imitate the appearance, message and techniques of other contemporary art forms. For example, note the artistic theoretical emphasis on pastiche and text reflected in the supplemental issue of *Leonardo* titled *Computer Art in Context* [26]. In the face of emphasis on context by some contemporary art theorists, most artistic uses of the computer remain separate from practical, scientific or technical uses. Theorists such as Sekula in photography, Rossler in video and this author in computer graphics have urged simultaneous consideration of the multiple uses of computer graphics—artistic, technical, scientific, commercial and practical—within a single social and historical context influenced by overlapping origins and practices. It is in this vein that computer graphics for advertising, entertainment and other practical purposes may be examined.

Context of Daily Life

Contemporary uses of computer graphics retain traces of their origins and earlier practices. Although Licklider and Taylor insisted on the potentially widespread effects of computers [27], others viewed the computer world as an island economy. Now daily life is affected by computing. Even Licklider may have been surprised at the ubiquity of computer graphics. Practical and professional communities of advertising, entertainment, publishing, telecommunications, business, finance, education and medicine have joined the academic, scientific and artistic communities in using this medium.

Viewing the realm of everyday life as separate from the theory and practice of intellectual disciplines—or decontextualizing knowledge—often precludes an examination of practical uses. The origins and early practices of computer graphics shape the form and content of video games, technical effects in movies and advertisements, use of home computers for educational programming, desktop publishing and other practical applications. These relatively recent phenomena bring computer graphics from the lab to the home, business and community. The work of John O'Niell offers an interesting example of the interaction of theory and practice from the art world with the origins and practices of early technical/scientific graphics. Most video games clearly show their origins in military simulation. John O'Niell retired from the official art world (the institutional art world that sees art as separate from daily life, or decontextualized; this modernist view of art has interesting parallels to the modernist separation of scientific theory from practical effects) because he believed that art was important not in itself but only as it affected people. He believed that it had to reach people in a medium they could relate to, in a language they could understand and at a price they could afford. He believed that "material is 'art' if it can excite and stimulate observers or users to a new perception, or throw them out of an established mode of perception" [28]. He began to work in visual board games, then in video games. He produced the graphics for Atari's game *ET*. Working under the signature of Admacadiam, he produced a series of games. His *Flytes of Fancie* are game simulations of aspects of living (dreaming, loving, traveling and so on), expressed in graphics and sound. Intended as fantasy entertainment at one level, at more complex levels they may move the player toward new or renewed levels of awareness. They manifest contemporary art theory that regards art and life as integrally related and opposes modernist decontextualization of art. O'Niell's work forms an interesting parallel to a more recent publication by Berman. Berman's work reflects a trend in the history of science similar to that in contemporary art theory that stresses the contextual and value-laden aspects of theory and practice. In evaluating computer technology in terms of human value, Berman states,

> The thing to ask of any new philosophical statement, any extension of computer hardware into schools, universities, or therapists' offices, and of any new toys such as Pac-Man or Apple II is only this, Does it take me into the things I fear most and wish to avoid, or does it make it easy for me to hide, to run away from them? Does it enable me to shut out my environment, ignore politics, remain unaware of my dream life, my sexuality, and my relations with other people, or does it shove these into my face and teach me how to live with them and through them? If the answer is the latter, then I suggest to you that we are on the right track. If the former then it is my guess, as Merleau-Ponty says, that we are sinking into a sleep from which, in the name of enlightenment itself, there will be no easy awakening [29].

The form of O'Niell's game has not become popular, however, in any way comparable to military or sports simulations or to adventure games. An extensive study of the creators, participants, and form and content of video games may shed light on how the origins and practices of early computer graphics relate to current design of video games. The addiction to video games treated by such organizations as Vidanon may connect with Berman's questions about encountering and jousting with personal reality or escaping it through one addiction or another.

Image-processed digital photography occurs in mass media publishing, television news, and as photographic evidence in court cases; its use has raised legal and ethical questions. Computer-generated characters, sets, and environments for television and the motion picture industry are being explored. *Tron* was the first movie to include a large segment of computer-generated imagery. Particle systems for simulating fire and explosions and fractals for mountains and planet surfaces have been used. *The Last Star Fighter* used live actors intercut with computer-graphic imagery. Early technical attempts to simulate human motion and human facial expression were quite disappointing. Using the fifty-first percentile to find an average human form and motion is time consuming [30]; the resulting images are boring because the movements are smooth and lack variety. Unique and dramatic variety in human motion have traditionally held the attention of the entertainment industry. Consider for example, John Wayne's walk and Marilyn Monroe's.

By 'faking it', by adding visual, dramatic and artistic content to the calculated content, David Zeltzer created several moments of computer-generated animation of a human skeleton [31]. Later at the same lab (Cranston-Csuri at Ohio State) a computer-generated animation, *Snootley and Muttley*, by Susan Van Baerle and Douglas Kingsbury, brought drama and story to computer animation of nonhuman three-dimensional cartoon characters.

In 1985 *Tony de Peltrie,* a film of a computer-generated three-dimensional human cartoon character who expressed emotion through facial and bodily motion, was presented at SIGGRAPH by Lachapelle, Bergeron, Robidoux and Langlois from the Centre de Calcul of the University of Montreal [32]. However, the expenses of resources and time make widespread use of computers to generate usual film content impractical at present. The 7-min-50-sec film *Tony de Peltrie* does not present the illusion of human drama but a caricature of it. It cost $1.5 million and took 3 years to produce. A more recent example of computer-generated special effects in the film *Abyss* is the pseudopod, a tentacle of water that takes on the facial features of film characters in an effort to communicate with them. To create the pseudopod took 6 months; this included creating multiple tapes and sending them to the director, Jim Cameron, receiving his instructions, comments and changes by fax and sending him a new tape the same day or the next day. The supervisor of computer graphics, Jay Riddle, and designers Lincoln Hu, Mark Dippe, Scott Anderson, John Knoll and Steve Williams created the effect at ILM (Industrial Light & Magic, a division of LucasFilm). Riddle states,

> He [Jim Cameron] was able to essentially direct the action of the pseudopod rather than just hand us a set of storyboards and tell us to come back to him with something in six months. It also made for a quick turnaround process, which was very important to us if we were going to prove that computer graphics could be commercially viable [33].

This same production that used sophisticated hardware and software to produce the pseudopod used low-end computers, Macintosh II, to augment the traditional film production processes. For example, storyboards drawn by an artist were scanned, manipulated and printed using the Mac. Images were resized and enhanced to select the best camera angle. A low-end software package, Super3D, was used to build computer models from drawings for set designs and props. The models could be rotated to show how they would look in perspective when they were built and "flown on and off the screen" via computerized animation so the director could approve or modify designs. The *Abyss* creative team also employed the first real-time camera simulator developed by David A. Smith (author of the Macintosh game *Colony*), to guide the filming of the underwater base. This enabled the design team to 'walk' around a wire-frame image of the underwater base displayed on the monitor. It allowed them to preview, albeit in simple detail, how the set would look before the studio spent tens of thousands of dollars building it. It also showed the best camera angles from which to shoot the film. Smith built the simulator on the Mac by encoding blueprints of the base in the three-dimensional authoring system he used to create *Colony.*

Computer graphics in advertising and entertainment rely heavily on the appeal of technical special effects made possible by earlier scientific/technical developments. In *American Cinematographer,* Lee cites Platerick, president of Computer Opticals, as stating, "Dialogue is dialogue. Sex is sex. What the audience wants is special effects." In the same article she quotes Tony Valdez describing typical graphics techniques. For the future, he predicts that "a moviegoer will walk into a screenless theatre, put on a headset and become part of the visual experience—possibly adding his own interpretations" [34]. Interestingly enough, such screenless environments exist not in theatres but in virtual environments created in defense labs for practical defense simulations, as earlier computer graphics were. These environments are also being 'played with' in artistic ways by individuals in the labs. They present remarkable visual and tactile realities [35]. Each user is clothed in a suit that transmits computer-generated visual and tactile data. Through input devices users may create and share new elements in their virtual reality. An interviewer talking with Jaron Lanier expressed concern for the addictive properties of the experience by analogy to earlier reality-transcending experiments with psychedelic drugs. Several statements by Lanier reflect art as reality shaping or transcending. Many of his views on virtual environments are similar to those expressed earlier by O'Neill about his games. Virtual reality uses computerized goggles, gloves and body suits to synthesize shared reality, which surrounds the participant; it appears to remain stable and to present different views as the participant moves head and body, as a normal room would. The gloves allow participants to feel the synthesized reality. Unlike in the real world, however, participants may design and take the form of another animate or inanimate object. Participants dressed in virtual-reality gear may see one another in the designed forms and interact with one another. As Lanier describes the potential of his virtual reality device—the "Home Reality Engine"—users can create and share a virtual world of their own design. The creation and sharing of tools, environments, creatures and experiences complete with sight, sound and touch are technically possible. Of its transcendent nature Lanier states,

> Idealistically, I might hope that Virtual Reality will provide an experience of comfort with multiple realities for a lot of people in western civilization, an experience which is otherwise rejected.... It will bring back a sense of the shared mystical altered sense of reality that is so important in basically every other civilization and culture prior to big patriarchal power.... If the technology. . . . has a tendency to increase human communication, human sharing, then I think it's a good one overall,... the television is bad but the telephone is good. . . . I do hope that Virtual Reality will provide more meeting between people. It has a tendency to bring up empathy and reduce violence [36].

This view assumes that the participatory and creative potential of this technology will be emphasized. Valdez predicts a less active moviegoer. Two science fiction works written many years apart have discussed similar technologies: Aldous Huxley's *Brave New World* in which people went to the Feelies, a multisensory movie environment, and William Gibson's *Count Zero* and *Mona Lisa Overdrive,* in which people plugged into a simulated stimulus deck, a multisensory simulator more like a television with a headset, providing private rather than shared experience. Both of these technologies were created by experts, not by participants; based on existing technologies, these marked the limits of the possible. Television is not necessarily a technology of centralized control and expert production. That is, however, the primary way in which it has been implemented. These examples raise questions about the potential implementation of virtual reality for advertising, entertainment, education and business, as well as questions about relationships between possible and the probable form, content and implementation of a new form.

Lanier expanded his beliefs regarding the transcendent character of this technology:

> Virtual Reality starts out as a medium just like television or computers or

written language, but once it gets to be used to a certain degree, it ceases to be a medium and simply becomes another reality that we can inhabit. When it crosses over that boundary it becomes another reality. I think of it as acting like a sponge where it absorbs human activity from the physical reality plane into the Virtual Reality planes. To the degree that that happens there is a very beneficial asymmetry that comes into play. When Virtual Reality sponges up good energy from the physical plane, then what you get in Virtual Reality is beautiful Art, beautiful dance, beautiful creativity, beautiful dreams to share, beautiful adventures. When Virtual Reality soaks up bad energy from the physical plane, what we get is some decrease, however small in violence and hurt on the physical plane in exchange for events on the Virtual plane which while they might be uglier, are of no consequence whatsoever because they are virtual [37].

In some ways similar to Aristotle's theory of catharsis as related to drama, Lanier's theory appears unsupported by research on effects of violence in television. In discussing the most vivid experience of virtual reality, Lanier states that it is the experience of leaving it:

> Because after having been in the reality that is manmade, with all the limitations and relative lack of mystery in that, to behold nature is directly beholding Aphrodite; it's directly beholding a beauty that's intense in a way that just could never have been perceived before we had something to compare physical reality to [38].

Lanier believes that humanly created artifacts pale beside the reality they imitate. Berman argues that the same effect occurs at the theoretical, professional and practical levels of computer usage: "a formal, disembodied and abstract reality is informing the mode of perception and cognition held by those engaged in that activity" [39]. The tendency toward abstracted experience and away from richly lived experience permeates technological encounters. This abstracted experience may heighten some sensations and sedate others and for this reason may be examined as a potential addiction. I believe the concern for addiction to virtual reality might be viewed in light of addiction to television, video games and home computers. As symptoms of larger societal problems, they figure in a plethora of literature, including Schaef's *When Society Becomes an Addict* [40]. Embedment of abstracted forms of reality based on origins and prior practices appears strong. Reality transcendence may also be seen as a form of reality emphasizing selected components. Consequently, whether the form, content and use are based in prior practice or theories of reality construction or in theories of reality transcendence, they are impoverished in light of natural, lived experience. This condition applies quite well to two examples, video games and virtual reality, and causes me to temper the visionary prediction of conceptual possibilities with probabilities based on origins and practices. As these current and developing uses of computer graphics evolve, what is going on in the academic and technical world of computer graphics?

Contemporary Technical and Scientific Research

Contemporary research continues to be viewed as separate from daily life, although its economic and conceptual ties to industry, government and research institutions remain. More research appears transdisciplinary, however. Researchers in cognitive science are part of a recognized multidisciplinary complex that relies on neurophysiologists, psychologists, anthropologists and sociologists to inform computer scientists interested in artificial intelligence and human/computer interaction. They all use computer graphics to a greater extent than could have been previously imagined.

Some of the research questions concern the role that imagery plays in cognition [41], how graphic interfaces, graphic- and object-oriented and iconic programming languages [42] and pictorial information retrieval figure in computer science [43]. Others investigate how we understand, simulate and best utilize the varying characteristics of human and machine vision [44], the visual and conceptual relationships between animation, simulation and visualization [45], and the value of graphic representations of mathematical, scientific and logical conceptual constructs as opposed to alphanumeric representations [46].

Conclusions

Cultural valuing patterns embedded in early computer usage include validation of alphanumeric representation over graphic, tactile or kinesthetic representation. Separation of disciplines and decontextualization of knowledge are still institutionally maintained but are changing in the practices of theory and research.

Culturally accepted concepts embedded in technical/scientific imagery remain in hardware and software used later for artistic and entertainment purposes, among them techniques for the display of three-dimensional visual form. When scientists take these techniques to their logical limits in the technical/scientific realm, they find that they need to borrow the concepts and methods of artistic practice in order to create graphic images that look more real than images based solely on algorithms. Scientists label this practice with terms such as 'faking it', revealing continued ambivalence about the relative value of visual reality (as presented by artists to make it 'look real') compared to scientific reality (based on physical laws, optics, etc.). The legitimation of the scientific as a value-free representation of reality provides a basis for its own deconstruction. This occurs when viewed through the eyes of artists from the same culture as the scientist, engineer or technician but with a different educational enculturation. This also occurs if we examine this reality through historical imagery or cross-cultural imagery and through what has been written or recorded about these images. That is, the relative status of scientific reality is revealed.

Simultaneous examination of scientific/technological and artistic uses of computers reveals aspects that show they share authorizing assumptions. This may be compared to the use of spatio-graphic juxtaposition of texts by Genet and Hegel by Derrida in his work *Glas* [47]. Although Genet and Hegel may appear as opposites, they may also be seen to share assumptions of materiality of language and authorization of gender politics. Science and art may be shown to share embedded patterns. Scientific realism assumes that immutable natural laws may be represented symbolically as one-to-one correspondence with reality, expressed, for example, in the illusion of three-dimensional space on a two-dimensional surface in art and in illusory three-dimensional computer graphics. Abstraction of concepts or theories about natural law may also be represented as scientific visualization—for example, in a construct such as a model of the functional architecture of the visual cortex [48]. Through this abstracted representation, its reductionist nature emphasizes some aspects and deemphasizes others. There is a correspondence to abstraction in the visual arts. In these representations, aspects of form and/or meaning are emphasized or deemphasized. Even the methods employed in modernist criticism show correspondence to the scientific method. Consequently, both scientific and artistic sources rely on culturally embedded patterns of reality represented by varying degrees of abstraction in symbolic and material culture. Their shared assumptions about the value of abstract representations of reality have contributed to the practice of decontextualization, to cultural maintenance of that larger embedded pattern.

In *Arts and Ideas* [49], Fleming has labeled the twentieth century a century of relativity. In mathematics, Gödel showed the contextual nature of mathematical proofs. Einstein's theory of relativity, Heisenberg's uncertainty principle, and quantum theory brought relativity and contextuality to the physical sciences. Contemporary theorists in cognitive psychology, anthropology and philosophy also call our attention to the relative nature of human knowledge and values. Many stress individual, cultural and historical differences rather than panhuman universals. Attention to detail and context are in conflict with the valuing of abstraction and decontextualization. Consequently this may contribute to cultural change. Artists, scientists or technicians may accept these trends, reject them or operate in a culture influenced by them without awareness of their influence. In any case, their work reflects this influence. As these aspects permeate the larger culture and the experience of nonspecialists, cultural change may occur.

In examining possible and the probable trends in computer graphics, cultural maintenance and change must be considered. The gradual shift from decontextualization inherited from the past to our contemporary emphasis on context is reflected in historical and contemporary computer-graphics imagery and purposes. Divisions of knowledge, separation of the practical from the theoretical and other assumptions about knowledge formerly taken for granted have been challenged in this century. As this shift continues into the next century, it may generate new concepts of what knowledge involves. These concepts may be based not only on alphanumeric print media but on experience and expression through data obtained and expressed in graphics, sound, touch and movement.

Telecommunications using photonic transmission, fiber optics, promises delivery of multiple services and multimedia to the home over one vehicle. This may include telephone, fax, television, computer data, database queries and telemetry. The development of technology, theory and practical applications join to amplify some conceptual structures and decrease emphasis on others. As these changes occur we need increasingly to provide citizens a broad education that includes technology and its relation to human values. Technological development brings unexpected results. In constructing scenarios for the future, writers may be optimistically visionary, pessimistically visionary or unable to envision future effects. In any case, the visions remain rooted in their experience and understanding of the status quo. From this stance, will the future resemble the pessimism of Huxley's *Brave New World* or Gibson's cyber-punk science fiction? Or will it bring a new positive reality rooted in the present but not yet imagined? Will it extend the present with unexpected cultural constructs emphasized and deemphasized? These views exhibit limits of the possible and the relationship of new technology to origins and prior practices. In the two fictional cases we see the delivery of canned realities made in centralized settings by experts, for delivery in public and private settings. In Gibson's reality only the experts can experience the true euphoria of completely disembodied experience. It consists of death in the natural world and living on in a humanly constructed cyberspace. These two authors' science-fiction accounts reflect experience with movies in theatres and television as alienated private viewing: separate from 'real life', with no effects accruing to lived experience. Their views contrast as markedly from Lanier's vision for virtual reality as early visionary predictions for television contrast with its current uses. Lanier proposes the creation and sharing of virtual realities by individuals for purposes of transcendence. Both science-fiction accounts see virtual realities as constructed by experts in centralized production settings for purposes of sensual stimulation with no acknowledgment of causal or logical connection to the practical world. They are decontextualized fictive experiences. Contemporary psychological research regarding effects of violence in television on attitudes and actions conflicts with this view. In light of this discussion, I leave the reader to consider the relationship of possible and probable uses of computer graphic applications, including virtual reality, in terms of origins and practices.

References and Notes

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Digital Image—Digital Photography

Susan Kirchman

The SIGGRAPH 1990 Art Show Committee decided to sponsor an exhibition of works that concentrate on the interaction of photographic imagery and computer technology [1]. This exhibition came about because of one interesting aspect of computer-mediated artworks that has been developing over the last several years. As the curator of this exhibition, I chose to put together a group of works that investigate not only the technical combination of these media but also the conceptual basis for choosing such tools of investigation, collaboration and production.

The integration of the traditional photographic image with computer technology seems, at first, to be antithetical. The veracity of the photographic image is undermined immediately and completely by our awareness of the computer's capability to fictionalize seamlessly even the most official documentary photographic data. In some cases the computer is utilized to call this very issue into question, as in the work of Esther Parada. Her piece *Define/Defy the Frame* (Fig. 1) consists of a fold-around portfolio which opens to reveal an accordion-pleated poster. In a statement integrated into the piece, Parada writes: "The intent of *Define/Defy the Frame* is to encourage an expansion of the viewer's perspective beyond the parameters of attention established by the U.S. government, and reported—whether in meticulous detail or skimpy sound byte—by the media" [2]. She refers to her work as the ongoing process of challenging received information. Enlarged pixels obliterate color photographs of a Salvadoran mother with silhouettes of soldiers, many soldiers. Parada absconds with the media images and points out the fiction in some, drawing our attention to what they tell us . . . and to what they don't.

In the work of some of the other artists in this exhibition, photographic material is used because it is simply the most direct reference to the social, cultural or political framework that the artist wishes to invoke as context for his or her ideas. Artists such as Paul Berger utilize the photographic image for its contextual references. "To appropriate coded messages from the information environment, to recombine them with overlaid significations suggests that this culture is laden with tremendously potential raw material. Paul Berger has, since the late 1970s, explored this type of information, refunctioning data and recontextualizing its effects" [3]. In the lushly colored large inkjet prints by Berger (Fig. 2), the television weatherperson proclaims his/her forecasts for our futures, and perhaps the future of humankind. By appropriating that familiar and generic personality, Berger has fused into the work a reference that we all know, one to which we pay attention.

In some works exhibited in the art show, it is insignificant who made the original photograph that is portrayed in the work; in others it may be conceptually important that the artist did *not* make the original photograph. It is the postmodern version of photographic material that most of these artists integrate into their statements. MANUAL (the col-

Fig. 1. Esther Parada, *Define/Defy the Frame* (detail), Macintosh II computer using Digital Darkroom and Quark Xpress software, plus a 35-mm slide manipulated on a Canon Color Laser Copier 500, 1990.

Fig. 2. Paul Berger, *World2AA* from the *CARDS* series, inkjet print produced using IBM PC with Targa 16, and TIPS and RIO software, 24 × 30 in, 1989.

Susan Kirchman (educator, artist), Visualization Laboratory, Texas A & M University, College Station, TX 77843-3137, U.S.A.

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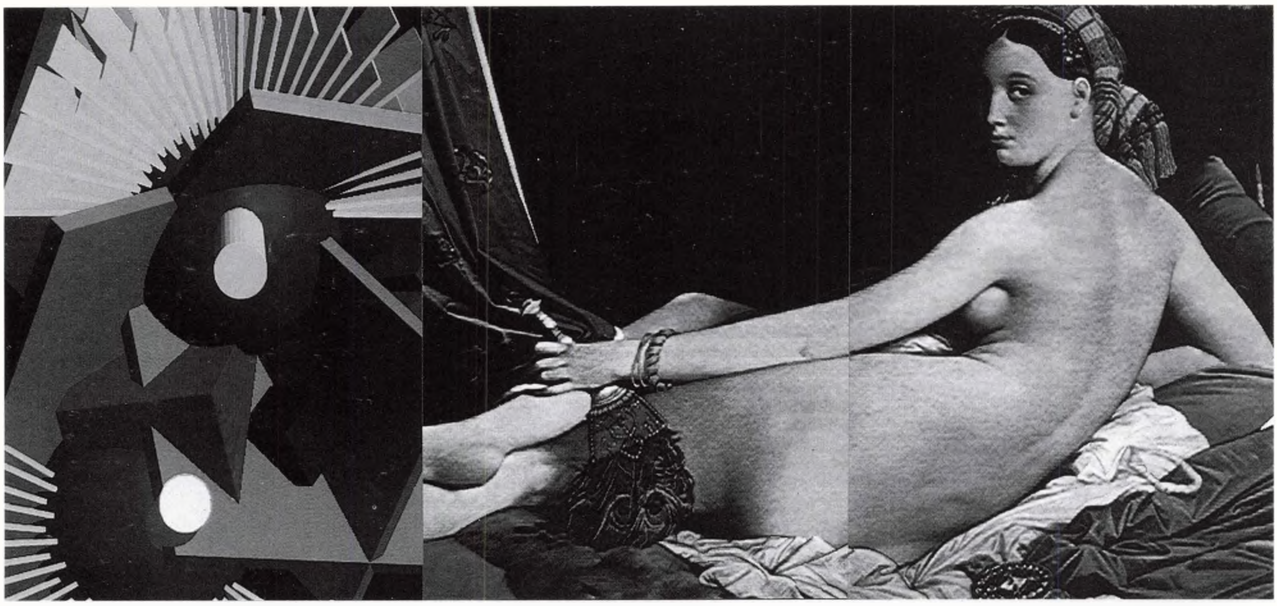

Fig. 3. MANUAL (Ed Hill and Suzanne Bloom), *Perfect World*, Ektacolor triptych produced using IBM PC with Targa 16 and TIPS software, 96 × 30 in, 1990.

laborative team of Suzanne Bloom and Ed Hill) appropriates images from the public domain, usually advertising. "The image appropriations are more embezzlements than simple thefts. They seize not just images but systems of belief, and subject them to doubt: traditions of art, their use by advertising, the codes of television . . . these currencies are assailed in these works" [4]. Working collaboratively for about 16 years, MANUAL finds that the computer allows for interactivity between the artists and the machine during the evolution of the idea/image (Fig. 3).

This exhibition attempts to go beyond the technological, beyond the formal, and into the ideas that are instigated by these works. "Artists have contact by brain with all parts of the world in today's computer mediated culture. And to simply say that 'the art work speaks for itself' is to ignore the whole from which the work evolves" [5]. The computer's role in the generation of this artwork is varied. At the most basic level the computer functions as the perfect collage tool, ascribing a visual parity to images from disparate sources, putting them into visual context with each other. However, at another level it is capable of transcending the role of 'tool' to become a creative partner, a conceptual collaborator, interactively lending its unique contribution to the final work.

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Digital Image—Digital Cinema: The Work of Art in the Age of Post-Mechanical Reproduction

Roger F. Malina

ABSTRACT

Computers are transforming existing art forms and allowing new kinds of art forms to be developed. Because the computer is primarily a machine for processing information, not a machine for making objects, it provides a malleable medium that provides the artist with a large variety of tools for manipulating sense data. The work that contains the result of the artist's creativity is the software and the data, not any particular image or output produced using that software. The ultimate goal of artmaking using computers, in this light, is not to create art objects but to create dynamic art subjects, to produce families of aesthetically interesting outputs, or art performances, which are as different from each other as possible within the constraints of the software. This situates computer art within the larger context of the study and development of artificial life. To create significant artworks of this type, it will be necessary to improve the computer's capacity to be an autonomous artmaking subject; this will require the extension of the computer's senses, the expansion of its capabilities, and means for the computer to provide sensory inputs to the human nervous system and to other computers.

Digital computers are the most plastic medium ever to come under the hand of the artist. Yet computer art is often viewed by art theorists as unsuitable for significant artistic expression. In many scientific and commercial applications the immutability of digitally stored information or software is of course a desirable attribute; computer viruses that alter stored information are viewed as pests, not as agents for creative change. The perception of the inflexibility of computer art systems, and their unsuitability as tools for artistic expression, is perhaps reinforced by the widespread use of pre-packaged software, such as computer graphics 'paintbox' systems, and by the fact that most computer artists do not develop their own software.

Most digital data is in fact inherently malleable and changeable. The computer is foremost a machine for creating interactions, for symbol manipulation and for processing information or sense data; it is not primarily a machine for making objects or fixed representations. Digital information is inherently plastic because the way that it is stored allows it to be easily changed, and the computer provides many tools for making such changes. The unique computer tools available to the artist, such as those of image processing, visualization, simulation and network communication are tools for *changing, moving* and *transforming,* not for *fixing,* digital information. These processes are carried out by the computer under rules potentially controlled by the artist.

There is a second well-understood feature about computer art. In traditional plastic art forms, the artwork is embedded in the material itself and is directly accessible to the human senses. In computer arts the artwork itself, embedded in digital data and software, is not directly accessible to the human senses. The computer artwork must be projected or transformed into a form apprehensible by the human senses. The choice of output device, whether cathode ray tube or film or sound, is in itself an artistic choice that can be exercised. In a trivial sense this is also true of photography and film, since the artwork cannot be seen until projected onto a reflective screen; however, the range of choices of output modes for a film negative is very narrow. This aspect of computer art connects it to the time-based and performing arts, where the creative work is in the score or text [1].

These two facts—that digital, stored data and software are inherently malleable and that the software is the art—have a number of consequences that change the nature of the work of art in the age of post-mechanical reproduction.

The Impact of Computers on Pre-Existing Art Forms

We can notice two kinds of effects of the new computer technologies on artmaking. First, new kinds of art forms are enabled by the unique capabilities of the computer. I have argued in a previous article that the only significant kind of computer art, within the context of the history of art, will be the type that could not have been made *without* the computer [2].

Second, the introduction of the computer is affecting artmaking in pre-existing or traditional art forms. Just as the introduction of the technology of photography had multiple and profound effects on painting, so the computer is affecting pre-existing art forms. The computer is leading to change both in static art forms, such as painting, photography, sculpture, poetry and literature, and in time-based art forms, such as kinetic art, film, video, music, dance and theater.

The effect of the use of computers on pre-existing art forms is two-fold. First, computers are being used as labor-saving devices or cost-saving devices to achieve existing artistic goals of artists using pre-existing art forms. This is already evident in music where computer-driven sound synthesizers, samplers and sound mixers are now being widely used by contemporary composers to generate and manipulate sounds of traditional instruments. Second, the computer can be used as a 'sketch pad' for trying many variations of a composition or visual design very quickly. The artist then implements the final design in a traditional medium; for example, artist John Pearson executes charcoal drawings or paints canvases after exploring the design using a computer and selecting a computer-generated design as a

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starting point [3]. Computer graphics systems are now being widely used to generate simulated landscapes and scenes that are then displayed as photographs and judged as conventional photographic art.

Computers have been adopted with remarkable speed, within one generation of their widespread availability, by artists working in traditional art forms. Computer artists using computer graphics images are already creating work that either is indistinguishable from that made using painting techniques or is equally successful artistically and aesthetically. Similarly, computer animation films are now competitive with films made by traditional film animation techniques; the recent winning of an Academy of Motion Picture Arts and Sciences Award by a computer animation short is an example. Although these kinds of artworks are still often classified, exhibited and juried as computer artworks, it would be more appropriate to include them within more traditional art venues.

Widespread use of computers is also redefining and re-directing artmaking in pre-existing art media. For instance, computer techniques are introducing new visual vocabularies into painting. A trivial example is the fact that false color imaging, a common method of visual display for scientific data, has affected the visual vocabulary of some painters. Other examples are images created using fractal mathematics. In music, sampled sound has made available new kinds of sounds; for example, computers have been using sampled human voices to create songs that could not in fact be physically performed by live singers.

Film and television productions are beginning to exploit techniques such as the mixing of synthetic and real actors, the use of computer-generated scenery, and simultaneous display of multiple scenes on a split screen or in multiple windows. Digital television sets now available permit simultaneous viewing of two television stations on one television screen. We can anticipate new kinds of film scripts that exploit this capability by simultaneously presenting several linked film sequences. These kinds of technological developments represent the evolution of film technologies that has continued unabated since the introduction of cinema as an art form [4]. In dance, choreographers and artists such as John Sanborn [5] are developing new choreographic vocabularies that exploit editing techniques available in digital image processing (e.g. multiplication of images, reversal and inversion, scale changes, color manipulation). These new dance forms, marriages of video and traditional dance, could never be performed live but represent true extensions of dance as an art form.

One of the problems facing the artist using computers in pre-existing or traditional art forms is that the computer was not developed with the specific needs of artists in mind. The computer keyboard, mouse, digitizing tablet are all inferior tools for drawing compared to a piece of charcoal. The musician who is able to use two hands, two feet, breath and body motions, sometimes simultaneously, to control traditional musical instruments can be severely constrained if the only interface to the computer is a keyboard. State-of-the-art computer graphics systems still are not as flexible as a paintbrush and paints for producing realistic landscapes, and music-computer interfaces offer less control than a sliding trombone or violin bow. Development of computer-human interface technology is an area of key importance for computer artists.

One result of the lack of artists' involvement in directing the technological development of the computer is that the impact of the computer on existing art forms, although significant, has been short of revolutionary. Award-winning computer animation films have done little to advance the art of animation beyond the achievements of the 1920s and 1930s. The creators of abstract film and abstract art explored in detail most of the artistic issues being studied, at great expense, by many computer artists using expensive computer graphics. Surrealistic and photo-realist painters have already achieved the artistic goals being addressed by software simulating realistic landscapes and scenes. It is inappropriate to use the computer to address artistic issues that are better addressed using other technologies, except as training exercises for students.

New Art Forms Enabled by the Computer

Several lines of analysis are needed to elaborate the new kinds of art forms that are enabled by the computer. The first involves understanding the specific capabilities of the computer and creating art forms that exploit these. This approach, experimental and empirical, is being followed by many computer artists. As argued by John Berton [6] the concept 'tool first, application after' changes the way artists approach a tool. Berton argues that the motion picture camera shares with the computer a similar history of assimilation into artistic practice. Many computer artists not interested in learning to program the computer live within the constraints of software developed for other purposes, just as a painter is happy to leave the chemical formulation of paints to the paint manufacturer. These artists are assuming that the computer is a mature artistic technology. There are risks in this approach. Neither the steam engine nor the spreadsheet is a particularly useful tool for artmaking. Many artists creating kinetic artworks and applying new technology to art during the 1960s and 1970s failed to transcend the capabilities of the technology. The proponents of the empirical approach argue that until the artist has access to the technology, its potential for artmaking cannot be fully understood. A larger context for this argument is that, since contemporary culture is being driven by contemporary science and technology, one of the roles of the artist is as 'colonizer' of the technology for artistic ends. Some technologies, and some capabilities of computers, will not however prove hospitable hosts to the artist. I do not believe, for example, that copying machines or facsimile machines will prove to have significant, long-lasting value as art media.

If the computer is to be used as a starting point for artistic practice, it is wise to understand the change of world-view or paradigm that will ensue. The computer is of course not aesthetically neutral, since it enables certain kinds of artmaking in preference to others. Historians of science have documented in detail the impact of specific technologies on human affairs. The role of the technology of perspective in restructuring how humans viewed the world around them and their place in it has been extensively explored. As many have argued, the systems of perspective buttressed, if not gave birth to, the Renaissance belief that the individual was the center of his or her universe [7].

A recent study by Coleman argues that the technology of lens instruments—compound lens microscopes and telescopes—led to important epistemological effects, i.e. it reinforced the concept of the centrality of the observer and the precept that visual observation (of natural phenomena and/or controlled experiments) was essential to scientific inquiry. These ideas underlay the philosophical ideas of the seventeenth-century Rationalist philosophers such as Descartes, Spinoza and Leibnitz.

There is a growing literature discussing the way the computer is becoming a new metaphor for explanations of physical and human phenomena. Sally Prior [8] has discussed the feminist analysis that questions the way in which the development of the computer is driven in the male-dominated computer industry; the dominance of war games in the computer-game industry is an obvious observation. Current metaphors based on the computer tend to connect to earlier metaphors of mind/body duality, rather than to emphasize the more holistic—and equally appropriate—metaphors of general systems theory.

Roy Ascott has discussed extensively how the use of computers and telematics system may change art practice. As he points out:

> There is no doubt though that telematic networks and computer systems, used merely as tools of production, will certainly and very effectively promote sterility and alienation in the culture . . . The principles of Socrates—critical reflection, personal development and sustained inquiry—must not be undermined in this new technological environment by the principles of Cato, which estimated everything by what it produced.

He cites for instance that

> the primary effect of creative interaction within computer networks is to render obsolete the distinction in absolute terms between the artist and viewer as producer and consumer, respectively [9].

Such an impact is of course incompatible with the whole foundation of the current commercial art market. This theoretical context of art made using the computer was well understood by the early pioneers of computer art. As early as 1968, Marc Adrian noted, "If in today's dealing in computer graphics the 'artist' is asked to sign a limited edition, then surely that is a concession to worn out conventions from which we will surely depart before too long" [10]. Yet a review of most of the art in computer art shows and computer graphics shows indicated that this 'convention' is still in force.

The Computer as a Technology Responding to an Existing Discursive Practice

An alternative analysis views the computer as a solution to pre-existing artistic ideas that could not be fully realized using prior technologies. The archeological method of French philosopher Michel Foucault, for instance, views the history of new technologies as beginning with the development of discursive desire and social imperatives. The development of a specific technology is then a response to this desire. One of Foucault's concerns was a critique of traditional historical ideas about inventions and beginnings:

> Archeology is not in search of inventions; and it remains unmoved at the moment (a very moving one, I admit) when for the first time someone was sure of some truth; it does not try to restore the light of those joyful mornings. But neither is it concerned with the average phenomena of opinion, with the dull grey of what everyone at a particular period might repeat. What it seeks . . . is not to draw up a list of founding saints; it is to uncover the regularity of a discursive practice [11].

Following Foucault, we need to shift from the context of current computer artmaking to the context of a larger regular discursive practice for which the computer is the desired object. One break in the discursive language of art occurred with the Constructivists early in this century. In 1966, Marshall McLuhan looking back at that period made the assessment, "The achievement of Constructivism was the abandonment of pictorial illusion in favor of multi-faceted and multi-dimensional art and can be seen as the rediscovery, after centuries of visual space and three dimensional pictorial space, of the whole human sensorium" [12]. The beginnings of practical technologies that allow the whole human sensorium to be addressed are now evident in multimedia and hypermedia workstations, virtual reality systems and technologies that allow direct connections to the human nervous system [13]. Included in this discursive practice are the longstanding artistic goals to create synaesthetic art forms that connect visual and sound art forms. There have been repeated experiments during the past 100 years to create various kinds of light organs, which can now be seen as precursors to multi-media computer works.

Within and preceding the Constructivist agenda is the long-standing search for prescriptive approaches to artmaking, a discourse that ranges from the Pythagorean school in early Greece to ongoing attempts to connect art and mathematics. These connections between art and mathematics are in a real sense fully realizable through the use of the computer. One example is the current applications of fractal mathematics for image making; there are numerous artists who have sought to create artworks that in some sense are examples of visual and experimental mathematics [14]. Max Bill made the following statement that makes this direction visible:

> I am of the opinion that it is possible to develop an art which is fundamentally based on a mathematical approach . . . The primordial element of all visual art is geometry, the correlation of the divisions on a plane or in space . . . The mathematical approach in contemporary art is not mathematics in itself and hardly makes any use of what is known as exact mathematics. It is primarily a use of processes of logical thought towards the plastic of rhythms and relationships [15].

In recent years there have been a number of fertile areas of research, including the algorithmic aesthetics of, for example, James Gips and George Stiny, the generative aesthetics of Mihai Nadin or of Herbert Franke, and the current work in shape grammars by Ray Lauzzana and by Russell and Joan Kirsch. These research directions can be viewed as contained in a larger discursive practice that seeks to develop artificial intelligence, more recently extended to the general study and development of artificial life (the synthesis and simulation of living systems). The scientific study of artificial life has recently been the topic of two workshops at the Santa Fe Institute of New Mexico [16]; these workshops have made explicit the importance of this new science to the art of the future.

Christopher Langton defines 'Artificial Life' as

> the study of man-made systems that exhibit behaviors characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis of living organisms by attempting to synthesize life-like behaviors within computers and other artificial media. By extending the empirical foundation upon which biology is based beyond the

> carbon-chain life that has evolved on earth, artificial life can contribute to theoretical biology by locating life-as-we-know-it within the larger picture of life-as-it-could-be [17].

This agenda, locating art-as-we-know-it within the larger picture of art-as-it-could-be, is of course the agenda of the art 'avant-garde' in every period; the computer artist, working the agenda of the new field of artificial life, is defining the new art avant-garde (as the term has been applied in this century).

We can then identify one of the specific goals of the computer artist as that of developing an artistic or creative Other, an artistic Other that in turn elicits an aesthetic experience in the artist; the computer artist of the future will seek ways to break the perceived alienation of the individual in contemporary society and to create new connections to society and the surrounding world. The computer is a technology that responds to this need and to the discursive practice arising from it. Quoting Foucault again,

> I understand by the term 'apparatus' a sort of—shall we say—formation which has as its major function at a given historical moment of responding to an urgent need. The apparatus thus has a dominant strategic function . . . The apparatus is thus always inscribed in a play of power, but is always linked to certain coordinates of knowledge which issue from it but, to an equal degree, condition it. This is what the apparatus consists in: strategies of relations of forces supporting, and supported by, types of knowledge [18].

TECHNOLOGY

There are a number of attributes that could allow the computer to become a *creative art-making machine* rather than merely a significant artmaking tool. These attributes include the ability to have an in-built learning capability; the ability to connect to other computers or to people over short and large distances using various types of telecommunications technologies; the ability to collect information from the environment and to issue information through several sensory modes, many of them not directly available to the existing human senses; the ability to be used in real-time interactive display with humans or other devices; and the ability to create synaesthetic works.

These attributes can in turn be viewed as the areas of key technological development that will allow the computer, as a component of an artificial life form, to carry out its own evolution and, through this intermediary, the evolution of the human organism. The technologies can be grouped into three areas, according to purpose. The first purpose is its use to extend or expand our information collecting systems; that is, our senses. Thus telescopes and microscopes and other light-collecting technologies extend the capability of our eyes to scales that our eyes cannot by themselves reach. These technologies also extend our visual range to include wavelengths of light to which our eyes are not sensitive. The telephone and other sound-collecting technologies allow us to extend the geographic and wavelength range of our hearing; the development of computer networks has been in response to this need to extend the sensory apparatus. An important impact of the extension of the computer through computer networks is to give credence to the concept of 'mind at large'. As argued by Gregory Bateson, the human plus the computer plus the environment can be viewed as constituting a thinking system, which today can be considered planetary in dimension. The current awareness of global environmental issues is one consequence of this perspective. Telecommunications artists, such as Eric Gidney, Carl Loeffler and Roy Ascott, then seek to create new kinds of artworks appropriate to this extended human organism.

Visualization tools—that is, computer-graphics tools—make up one of the most developed areas of computer technologies and are the fundamental technology usable to convert this expanded sensorium to a form that the human being can access. Virtual reality systems represent a major advance in providing new visualization environments. The development of new ways of connecting the environment directly to the human nervous system, bypassing the existing human senses, is one of the most important long-range agendas in this field; examples of artists working in this area are Stellarc, who has been working with a large variety of biomedical technologies, and composer David Rosenboom, who has been developing a direct musical interface to the composer's brain.

The second kind of purpose for technology is to amplify innate capabilities and functions. Thus storage devices, from books to photography to computer disks, allow us to increase both the size of our memory and the timescales over which information is collected. Machines extend the range and power of our limbs and our capability for locomotion and mechanical action. The development of robotic technologies and cybernetics is important for achieving future artistic goals; when viewed as an artistic Other, the computer needs to become mobile. Computer artists are working in a number of areas for this agenda. Australian dancer and computer scientist Don Herbison-Evans has for a number of years been developing basic software for computer choreology. Artist Margo Apostolos has been working with advanced robots in performance and artistic contexts. Workers in artificial life such as Randall Beer have been developing artificial insects, such as miniature robots capable of maneuvering around computer circuit boards to carry out circuit repairs. Artist Vernon Reed has been for some years creating cybernetic jewelry that can be viewed as a pre-cursor to cybernetic art insects.

The third kind of purpose for technology is to create artifacts—that is, to change our environment by creating objects, events or processes that in turn affect us. The technologies of art are used to create artifacts that affect our emotions and how we understand the world around us. The ability of computers to create interactions between the artist and the artwork situates the new artworks in a non-traditional format. Such formats would include the interactive environments of Myron Krueger, the interactive novels of Judy Malloy, and the global performance and interactive works such as *La Plissure du Texte* that were set up by Roy Ascott. It is very unlikely that the context of the commercial art market place, the gallery or the museum will be appropriate venues for this kind of art. These institutions derive from the needs of a prior, and exhausted, discursive practice. The computer artist is, by necessity, creating new exhibiting and displaying contexts and institutions appropriate to the new discursive practice. Paul Brown notes, "It is my opinion that practitioners should not waste their time trying to convince the arts mainstream of the value of their work. Our involvement in SIGGRAPH (1990 will mark the 10th anniversary of the SIGGRAPH Art Show), Ars Electronica, FISEA and other events constitutes the evolution of an international and interdisciplinary *Salon des Refuses*" [19].

The educational structure also needs to be responsive to the needs of the new discursive practice. A number of attempts have been made to outline these new educational approaches, including Roy Ascott's call for a new Art Academy and Jurgen Claus's vision of an Electronic Bauhaus. Manfred Eisenbeis' New Art School in Cologne and the UNESCO programs to define new supporting structures for the arts in an electronic culture are promising signs that these institutions are indeed taking shape [20].

Post-Mechanical Reproduction

The remaining question is that of *reproduction*. There are a large number of technological inventions that have allowed the production of mechanical copies from an original. The goal of mechanical reproduction is to produce copies that are indistinguishable from the original in as many ways as possible. In the case of many technologies, the goal of mechanical reproduction was embedded in a larger goal of representation. Thus Louis Daguerre stated, "In conclusion the *Daguerreotype* is not merely an instrument which serves to draw Nature; on the contrary it is a chemical and physical process which gives her the power to reproduce herself" [21]. The printing press, photography, xerography, telefacsimile, television, video, all allow the making of mechanical copies.

A different kind of reproduction is made possible by software—this is what I will call post-mechanical reproduction (although a more descriptive term such as 'generative reproduction' is needed). The goal of post-mechanical reproduction is to make copies that are as different as possible from each other, but constrained by a set of initial rules. The prototypical type of post-mechanical reproduction is of course sexual and biological reproduction.

As noted by Marc Adrian, the reproductive capability of computers to produce copies of work is very different from that of photography. "The social consequences of the computer used in an artistic context lie rather in the fact that with each basic program, if it contains more than a minimum of aleatoric moments, a practically inexhaustible number of dissimilar realisations is possible" [22].

The computer is not just a useful tool for mechanical reproduction; rather it is the first tool available to the artist that is ideally suited for post-mechanical, or generative, reproduction. Artist Roman Verostko, in a recent *Leonardo* article, makes a compelling case that the art software should be viewed as genotype. He states

> This new artistic process, while hardly the same, is remarkably analogous to the biological process of epigenesis. The software . . . may be viewed as a genotype, because it is a code for how to make work. The software can make a family of works, each work being unique (one of a kind, yet familiar). The potential for crossing families of different artists opens the possibility of hybridization of form and eventually of a genealogy of form [23].

I believe that this argument is compelling and that we are seeing the birth of a new aesthetics appropriate to the new art forms. This aesthetic theory will require not only that we evaluate individual artworks, but also that we assess the art subject's ability to produce families of aesthetically interesting outputs, whether objects, events or processes, which are as different as possible from each other within the constraints of the software created by the artists. Not only is the software the art, but the behavior of that software constitutes the work of art in the age of post-mechanical reproduction.

Afterthoughts

It is necessary to review the larger context and the desirability of creating artificial life forms. Paul Brown states:

> A tightly coupled man-machine symbiosis should lead to a close creative collaboration between man and machine. Eventually it's likely that we will see pure machine art—the product of what is essentially an alien intelligence—for the first time in human history. The potentials offered by interaction with these artificial and, once they pursue an independent evolutionary path, alien intelligences, will open up exciting new potentials for the creative artist [24].

As elaborated by Frank Dietrich,

> Previously, we had created art objects in which, by reflecting on them, we found echoes of ourselves. Now we are creating another subject, the Other that is not a mechanical contraption, such as in kinetic art, but a dynamic, autonomous entity capable of producing and understanding symbols—a machine capable of communication. This Other is really another subject which we cannot presume to be similar to us even though it can simulate a similarity that can make it indistinguishable from us. This Other manifests itself in a material physicality that is not our flesh, and it possesses a mind that is not our mind [25].

One vision of this future is provided by cyberpunk author William Gibson in his descriptions of worlds connected by computer networks and populated by bionic humans and artificial intelligences. Gibson is reported to have been surprised by those who found his vision not uncomfortable: "It never occurred to me that it would be possible for anyone to read these books and ignore the levels of irony" [26].

To quote Paul Brown, discussing the problems facing our planet,

> Donald Michie has suggested that these problems are too complex for humans to understand and solve, and that our only hope is to develop artificial intelligence systems that can grasp the totality of the problem and so suggest viable paths of action. A dilemma here is that in order to create that technology, we need a level of industrialization that will, in the short term, increase pollution; by committing ourselves to this particular solution we also guarantee its need [27].

It is surely one of the roles of the artist to question not only the discursive practice leading to the need for the computer, but also the epistemological consequences of accepting the technology. There is need to make evident the nature of the underlying discursive practice, determine its desirability, and ensure that appropriate technologies are used. As noted by Sally Prior, in her presentation in Adelaide, we need to understand whether the discursive practice also leads to a technology for artificial compassion.

Acknowledgments

This paper is based on a talk given during the Adelaide Festival at the Center for Experimental Art, March 1990. The talk was given at a panel session organized by Virginia Barratt of the Australian Network for Art and Technology. The panel was titled "The Work of Art in the Age of Post-Mechanical Reproduction". Barratt chose this title not only in ironic reference to the phrase coined by Walter Benjamin, but as a satirical comment on the other panels at the festival—panels that dealt at great length with currently fashionable French philosophers. The other panelists were Sally Prior and Paul Brown. This final version of this paper is strongly influenced by their presentations at the panel.

References and Notes

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2. Roger F. Malina, "Computer Art in the Context of the Journal *Leonardo*", *Leonardo* Supplemental Issue *Computer Art in Context* (1989) p. 67.

3. John Pearson, "The Computer: Liberator or Jailer of the Creative Spirit", *Leonardo* Supplemental Issue *Electronic Art* (1988) p. 73.

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the Digital World: Connecting the Masters to the New Digital Cinema", in this issue.

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18. Foucault [11] p. 195.

19. Paul Brown, "Beyond Art", paper presented to the panel The Work of Art in the Age of Post-Mechanical Reproduction, Adelaide, Australia, March 1990.

20. Eisenbeis [5] p. 13.

21. Louis Daguerre (c. 1939) as quoted in Helmut and Alison Gernsheim, L. J. M. Daguerre, *The History of the Diorama and The Daguerrotype* (New York: Dover, 1968) p. 81.

22. Franke [1] p. 119.

23 Roman Verostko, "Epigenetic Painting: Software as Genotype", *Leonardo* **23**, No. 1 (1990) p. 17.

24. Brown [19] p. 6.

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26. Brown [19] p. 1.

Not-Art Digital Images: An Artist's Perspective

Peter Voci

ABSTRACT

Working with the New York State Police and the Nassau County Medical Examiners Office, a forensic anthropologist, a forensic medical photographer and an imaging systems artist attempted to reconstruct a face from the skull of a young woman. Facial feature components selected from police identification kits were digitized and manipulated to match control points and overlaid onto a digitized version of the skull. In this way a series of images was created that were called 'not-art' even though an artistic aspect was present.

An Unidentified Woman

In the summer of 1989, a motorist stopped his car along the side of the Meadowbrook Parkway on Long Island, New York, to relieve himself. As he went into the wooded area he discovered the remains of a young woman. The New York State Police were called in and an investigation began. An apparent drug overdose victim without identification, she was assumed to have been left at this site by her friends, the last people who saw her alive. The Nassau County Medical Examiners Office determined that she had been dead for some time before being found. Her body was in an advanced stage of decomposition, making the task of identification difficult. She did not correspond to any known missing person. The traces of drugs that were found in sample body tissue seemed to rule out any foul play. Fingerprints were obtained by a hydration process used by the forensic staff, but no matching prints were on record. Dental records might have been used to make a positive identification if someone similar to her had been reported missing, but since that was not the case it was impossible to know which dentist to consult. (Such a search would theoretically be possible if all dental X rays ever taken were digitized and stored, later to be recalled by a pattern recognition program. Such a system, although practical, does not currently exist.)

A forensic sculptor may be called in to try to define facial structure on an existing skull. Cork tabs of various thicknesses (determined according to tissue depths at particular facial locations) are glued to the skull; a modeling compound is then used to fill the gaps between the tabs, and a smooth top coat is added to complete the reconstruction. This technique, however, has a low success rate when used in the identification process. The sculptor starts with average tissue depths obtained from medical reference guides that record ranges in studied corpses. Since even slight changes alter the overall final composition, much guesswork is automatically included in this procedure. One needs only to recall the changes evident in a person one has not seen in 10 years, especially if a dramatic weight change or disease has occurred. The adult skull may have changed little, while the outward appearance has undergone a dramatic transformation. Moreover, forensic sculpture entails the subjective component of the sculptor as an artist, which may result in stylization of the resultant image.

The Imaging Project Develops

Walter Poppe, a forensic medical photographer and a graduate student in my computer graphic class at the New York Institute of Technology, was instrumental in bringing together a research group that included himself, Spencer Turkel, the forensic anthropologist working on the case, and myself, an imaging systems artist. We met initially to discuss the possibility of using a digital imaging system to identify this woman from the remains. My task was to develop the approach and construct an image that the police would use in asking the public for its help. (This is not unlike what a sketch artist would provide from information supplied by eyewitnesses.) We were working with the same information that was given to a forensic sculptor, but in a different medium. We wondered, of course, just how sound the results would be. We would never find out unless we carried out the project.

Television commercials advertise computer imaging systems that make cosmetic surgery seem simple and easy. There are certainly legitimate prosthetic surgeons and reconstruction specialists using imaging technology in the medical profession, and their research efforts are bringing shattered lives back together again. Law enforcement agencies too use digital imaging technology to assist in the search for missing persons and fugitives. We realized that much research was still needed to make accurate conclusions, since we were just beginning to see the possibilities. Because we had many questions, we felt a slight apprehension, similar to that of a painter facing a blank canvas. Somehow this is a personal acknowledgment of the official start of a work.

The Procedure

Our approach was straightforward: we concentrated on building the facial tissue and components part by part on the skull, which acted as the visual armature for this additive technique. We set out to duplicate what the forensic sculptor does; however, our method would allow us to have a constant reference to the underlying structure because of the display characteristics of the medium. Besides the fact that we were working with transparent layers, another important difference with employing computer graphics was that we had

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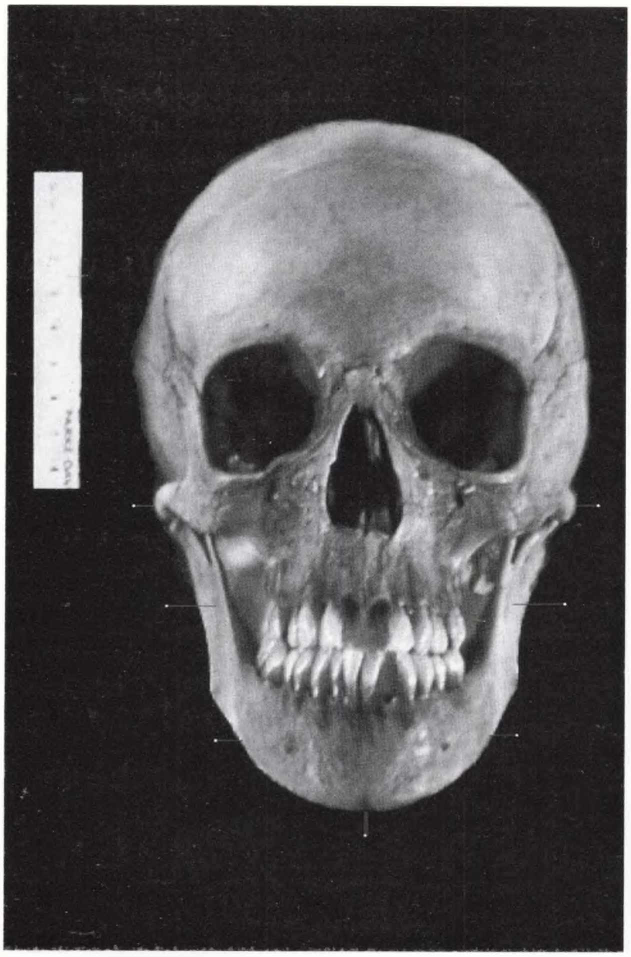

Fig. 1. Frontal digitized skull with the tissue depth reference points and facial outline. Copyright 1989 Peter Voci. Reproduced by permission.

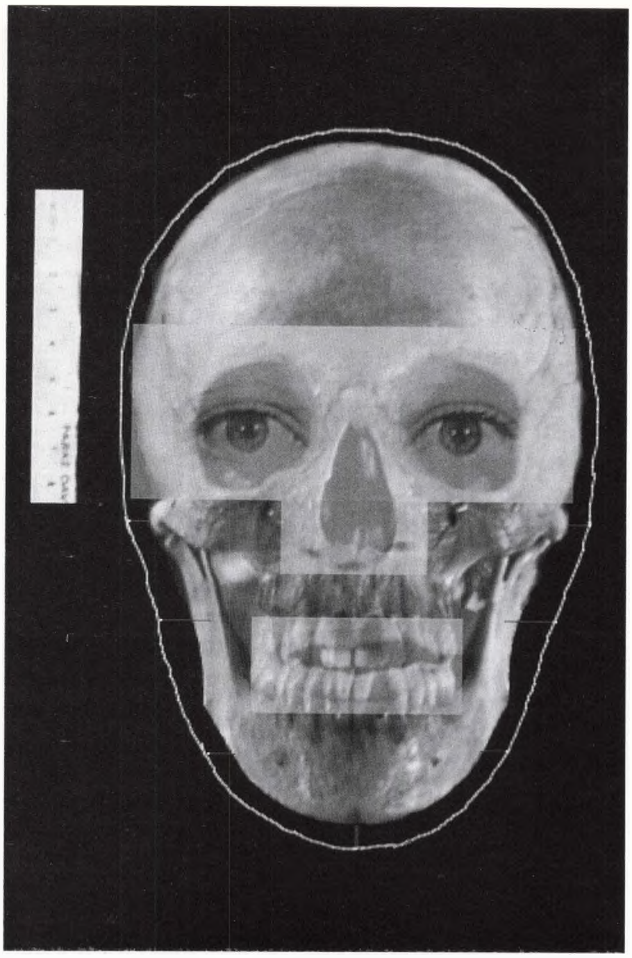

Fig. 2. A partial superimposition of the facial features, in scale, to match control points. Copyright 1989 Peter Voci. Reproduced by permission.

greater global manipulation control of an interactive nature.

The first step was to digitize the skull in a frontal elevation, then to determine the best tissue depth measurement points (Fig. 1). The information in *The Human Skeleton in Forensic Medicine* by Krogman and Iscan [1] gave us the basic facial outline. Additional reference points allowed us to place markers on the image of the skull to facilitate the subsequent layering of the eyes, nose and lips. These components were digitized from the identification kits that were supplied by the police department. To match the individual facial features to the reference points on the skull, image processing software was used. For example, we located and marked the reference points for the eyes. There was no exact match in size or distance apart in the kit, so we used the closest match, but then we reshaped, resized and overlaid the restructured parts in proper placement. The results of these techniques were as close as we could come to a visual description of a specific facial arrangement. The same steps were used to place the other facial components, and before long the whole became greater than the sum of its parts (Fig. 2). An unusual point was reached in this process. There on the screen was a synthesized portrait that had evolved with a cohesion of form that forced us to stop and analyze what seemed to have developed almost automatically. What had been expected to look similar to a police artist's sketch took on a distinctly unique appearance. This was the not-art image crafted to a likeness of a living personage based on skeletal remains.

To complete the image, a skin patch was digitized and recopied to create the opaque facial surface (Fig. 3). Hair was added and color glazes were included throughout in order to better model the image, which took on a portraiture quality. Instead of a black-and-white sketch, we had a color portrait (Fig. 4.).

We Had Our Doubts

With the image completed, we had more questions than when we started. What if different facial features were chosen and fitted to the same skull? Would the results differ to such a degree that the whole project was merely an exercise in randomness? After all, one can simply change one's facial expression and almost change into another character. Use of a computer may have complicated things in a way—it may have allowed us to forget about the subjective burden placed on the forensic sculptor. The computer, like the camera, somehow implants an unmeasured amount of the objective by the very nature of the built-in methodical descriptions that these devices provide.

We also needed to examine the human factors. Was the given forensic information accurate to begin with? Would the image, if distributed, and if it gave a misleading impression, hinder rather than help the prospect of discovering the identity of this person? The general public, after all, would be asked to recognize a particular face. This image, as a portrait, was not as vague as police sketches, which in fact allow greater latitude by providing fewer visual cues. In addition, if we told the public that a computer had been used in the creation of this image, its credibility might be too firmly fixed, because of the tendency to believe in technological method. If a figurative pencil drawing is shown to someone, a typical question may be, Who is this supposed to be? However, if a photograph of the same subject is shown, the question is then much more direct: Who is this? The photograph and the subject become one and the same on an emotional level.

We needed to devise a test to prove that this technique was worth further commitment. One suggestion was to work from an X ray of the skull of a living person without ever seeing the face during the reconstruction experiment. Only after an image was finished would we compare the result to a photograph of the model. This test would of course have to be repeated a number of times with different models to confirm previous results. Another avenue to explore was that of three-dimensional computer graphics. The Smithsonian Institution in Washington, D.C., has a collection of plaster death masks along with a collection of matching skulls. If a three-dimensional database were created of the measurements of each mask and matching skull, we could extract the differences between them. With a large enough number of models, perhaps a face-generating program could be developed to display a facial match for any new digitized skull. An automated process such as this might help in a wide variety of cases where the leads are few.

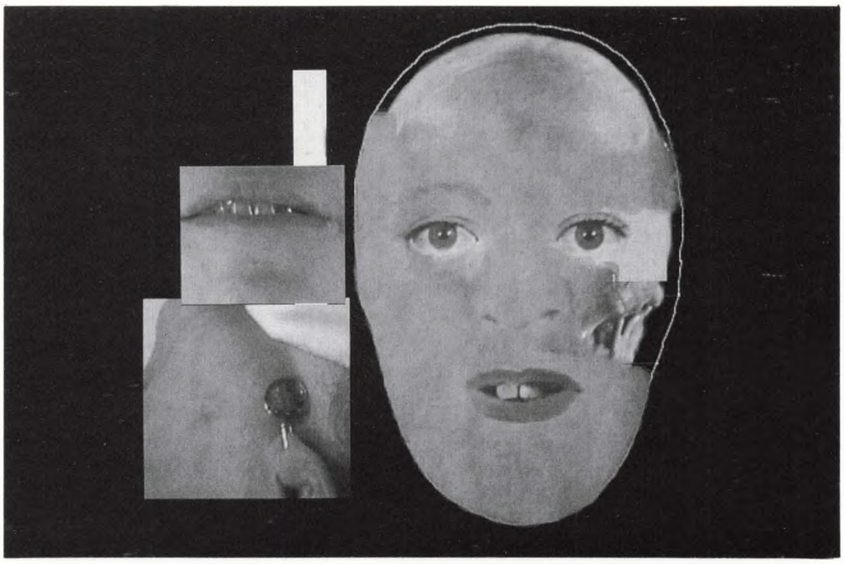

Fig. 3. Digitized skin patch references, with recopying in progress, to create the opaque facial surface. Copyright 1989 Peter Voci. Reproduced by permission.

Fig. 4. The image as a portrait.

Art and Craft

Throughout each step of this project, it was necessary for us to be particularly aware of the distinction between art and craft. Although artistic skills were employed in the development of these images, there was an unexpressed understanding from the start to adhere to a rigorous 'not-art' approach. Purely aesthetic concerns had to be suppressed. The antithesis of design seemed to be required, since each facial component had only one possible location on the array of reference points.

Naturally we wondered just how scientific our methods were. Even though our target image appeared to be remote and almost transparent, paradoxically it was relatively close to the structure of the skull itself. This was similar to the pure contour drawing exercise introduced by Kimon Nicolaides in *The Natural Way to Draw* [2] and reinforced by Betty Edwards in *Drawing on the Right Side of the Brain* [3]. Here one tries to capture the image of a model without looking at the sketch pad until the drawing is completed. One would not always expect an accurate rendering as the result of this method. In fact, the drawing may say more about the person who made it than about the subject.

It is an accomplishment just to render a model accurately, even with continuous study; it is certainly a much greater challenge to construct an accurate facial rendering from only the skeletal structure. Here the artist cannot express his or her own experiences but must work within the parameters of the craftsperson as imaging specialist. Future identification work, whether based on digital information, optical methods or even some genetic data, may develop to a point where conclusions can be arrived at with a high degree of probability. Practical applications would soon follow.

One of Us

As questions kept arising, we documented our work with a series of notes, slides and thermal prints. Investigators from the New York State Police Department visited my laboratory to view the superimposition process and see the final image. The investigators asked whether the image could be altered in several ways. Their information and reference materials from the discovery site required subtle but important changes. Using digital technology allows modifications without much difficulty in most cases. Some of the suggested modifications included altering the hairline as well as the hair style and color. We also made a version of the image showing this person in poor health as a result of drug-taking.

As we continued to redefine the image, we felt hopeful of a good result. At one point an investigator on another case thought he recognized the image as that of a certain missing person with a conviction record. After a fingerprint check, however, it was determined that she was not the dead woman.

This woman is, unfortunately, still unidentified. She may of course be identified in the future. If and when that comes about, perhaps we will know how valid our efforts have been. Until that time, we will look at this image as an icon, a not-art digital image that symbolically might represent any one of us.

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Temporal Coherence with Digital Color

Brian Evans

ABSTRACT

To structure time with abstract visual materials requires a visual grammar of line, shape and color. Color is especially problematic, difficult to measure in all but the simplest applications; the literature of color theory and harmony is often confusing. To devise a syntax for structuring time with color, one can turn to the concepts of tension-release, of neutral, balanced and weighted color domains and of discrete computer raster images; they help to create and measure time-based color compositions. In parametrically defined color palettes, *Color Study #7* (a computer-generated animated film) demonstrates the application of these ideas to a simple and effective compositional approach. Codifying this now common filmmaking practice, the author hopes to encourage others interested in aesthetically strengthened visual presentation to explore and develop time-based visual grammars.

Music composition usually structures materials in time-based relationships, through historically established grammars or, over the last century, often through grammars invented by the composer. These grammars allow control of the materials so that a composed piece will make formal sense in time. They offer a meaningful framework upon which a composer's particular musical vision can be built.

As in music, the fundamental dimension of animation is time. The problems for the animator are the same ones a music composer faces—temporal coherence. But in using abstract visual materials, there is no centuries-old tradition the artist can turn to for guidance. Abstract visual composition ('composition' used here with respect to time rather than space) has two aspects that need to be considered, the graphic forms or shapes, and color.

A large body of theoretical work exists for static imagery. Extracting basic principles from the time-based art forms (theatre, poetry, music, dance, etc.) and applying them, along with fundamental ideas of color theory and graphic design, provides a starting point for a grammar and eventually a language of abstract visual composition.

Even in static imagery, use of color has proven to be an especially thorny issue and hence artists often make decisions based on personal whim. Some are so intimidated that they avoid the issue altogether, using only grayscale or restricting their output to black pen plotters. The literature on color theory is often contradictory or confusing, caught up in heady geometric descriptions and vague terminology. With the addition of the time dimension, aesthetic control of color appears to be futile. However, some basic principles about color relationships and interactions, combined with a common thread found in the temporal arts, suggest a possible direction.

Music theory and analysis are based on measurement of the sonic dimensions, such as pitch, rhythm and timbre. Our Western musical practice deals with organized collections of these dimensions as discrete events. This has simplified the invention or codification of musical syntax. In measurements of color relationships, such codification has been problematic. To allow easy measurement of color relationships, works on color theory and harmony have been forced to use simple geometric shapes [1].

With computer graphics, this situation has changed. We now have the capability of measuring color relationships with great precision because of the discrete nature of raster images. This simplification of color measurement allows us to apply theories of color harmony with precision and to explore their use in time. The computer then affords the animator powerful tools for composing pieces with structural integrity in temporal color relationships.

TENSION-RELEASE

Most time-based art forms (Western art forms in particular) have in common the idea of *tension-release*. A sense of motion in time occurs through the creation of tension and its resolution. Narrative forms such as theatre or literature ordinarily create conflict that builds to a climax and resolves itself in the denouement. Simple poetry accomplishes this motion through establishment of a rhyme scheme, repetition or a patterning of imagery that sets up expectations and moves tension to resolution as the expectations are met. In music a common approach is to move from dissonant to consonant pitch relationships.

There are myriad subtle ways in which this dynamic manifests itself in all the temporal arts, but the underlying principle of tension-release is what actually moves us through time. Can we establish this same relationship when using color in time?

The Neutral Color Domain

We must first find a color domain that can be defined as relaxed or resolved. The most obvious solution here is the grayscale, or the absence of color—a *neutral* domain. There is no percept of tension with color if there is no color. Starting with this premise we can build a hierarchy of color relationships and construct a simple, but effective, color grammar.

The Balanced Color Domain

In the nineteenth century Chevreul defined the phenomena of successive contrast and simultaneous contrast for subtractive color [2]. These phenomena allow us a perceptual basis for the idea of a neutral or gray color domain as being relaxed. In the case of successive contrast, staring at one of a pair of complementary colors will cause its complement to appear when one's attention is moved to a neutral ground. For example, staring at red and then focusing on a

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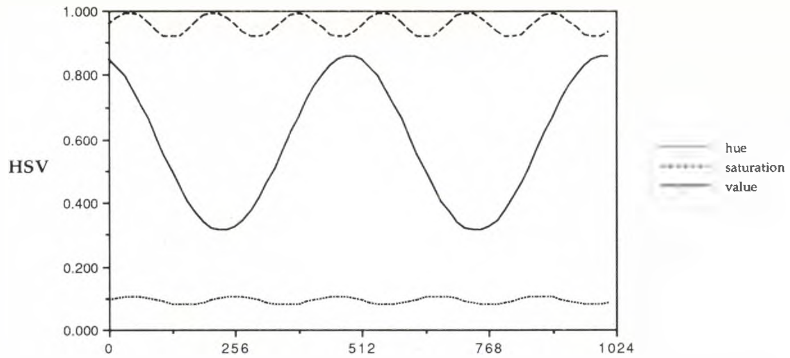

Fig. 1. Frame 1800 from the color palette of *hsv* space shows color map entries 0–1,023.

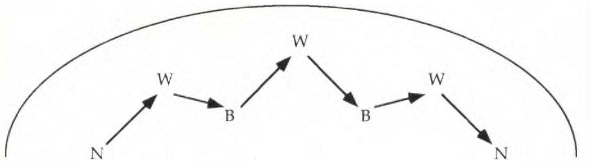

Fig. 2. Color domain arch form shows neutral (N), balanced (B) and weighted (W) functions.

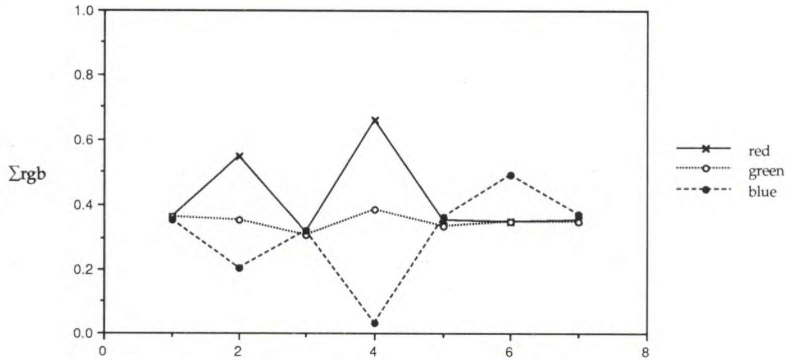

Fig. 3. *rgb* summations for keyframe color maps of *Color Study #7*.

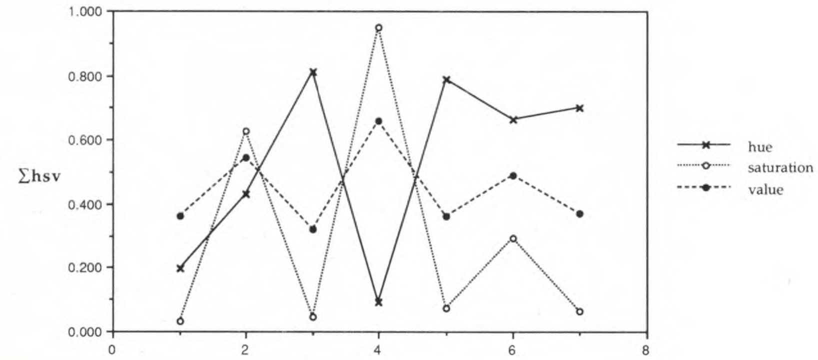

Fig. 4. *hsv* summations for keyframe color maps of *Color Study #7*.

neutral gray background will cause green to appear. Fatigue in the cones of the eye, caused by the imbalanced color domain of red alone, has caused a tension in the color percept.

In the case of simultaneous contrast, also based on the principle of color complements, prolonged observation of a color will cause its complement to appear in neighboring regions. For example, a light gray square surrounded by red will appear green. Here a lateral inhibition in the retina causes the complementary impression. Again we have a tension in the color percept.

These ideas indicate that the eye is always striving to balance the color environment, to create the relaxed state that exists when it is viewing an unperturbed gray. Expressing a similar premise nearly two centuries ago, Goethe stated in his treatise on color,

> The whole ingredients of the chromatic scale, seen in juxtaposition, produce an harmonious impression on the eye. . . . When the eye sees a colour, it is immediately excited, and it is its nature, spontaneously and of necessity, at once to produce another, which with the original colour comprehends the whole chromatic scale. A single colour excites, by a specific sensation, the tendency to universality.
>
> To experience this completeness, to satisfy itself, the eye seeks for a colourless space next [to] every hue in order to produce the complemental hue upon it.
>
> If again, the entire scale is presented to the eye externally, the impression is gladdening, since the result of its own operation is presented to it in reality. We turn our attention therefore, in the first place to this harmonious juxtaposition [3].

More recently Rudolf Arnheim sums up what many color theorists discuss in their attempts to define and codify color harmony.

> These three fundamental primaries [he is speaking of the subtractive primaries—red, yellow and blue] behave like the three legs of a stool. All three are needed to create complete support and balance. When only two are given they demand the third. The tension aroused by incompleteness of the triplet subsides as soon as the gap is filled.
>
> This particular structural combination of mutual exclusion and attraction is the basis for all color organization—much as the particular structure of the diatonic scale is the basis of traditional Western music [4].

From all this we can define the second level in our hierarchy as a *balanced* color domain. A color domain is in balance if the sum of the colors in an image will neutralize each other so as to equal gray.

The Weighted Color Domain

The remaining color juxtaposition is the domain where one hue is dominant. This *weighted* color domain will be the most dynamic, the most unsettled and, in an abstract sense, the most dissonant. To say a color domain is dissonant or inharmonious is not to say it is bad. As a matter of fact, in music the most beautiful and interesting sounds may be those with kinetic energy, those that create tension. The same is true for visual imagery. (In music, harmony deals with all pitch relationships, not just those that are consonant; unfortunately, when color harmony is discussed a qualitative aspect usually is attached to the label. This paper considers color harmony to include the set of all color relationships, in the hope of finding some guiding principles for structuring those relationships as they unfold in time.)

Similar to the consonance-dissonance

structure in music is the three-level hierarchy of color relationships that we have now defined. We can apply these to abstract visual composition: tension moves to resolution from weighted to balanced to neutral color domains.

Color Measure

What is of importance in applying these ideas of color theory is not the specific colors used but rather the relationships of the colors. A simple way to measure color relationships of a raster image to determine the quality and syntactic function of its color domain is to make separate summations of all red, green and blue (*r*, *g* and *b*) intensities in the image and to normalize them between 0.0 and 1.0 [5]. The simple formulae are

$$r_{sum} = \left(\sum_{i=0}^{n-1} r_i \right) / \text{MAX}$$

$$g_{sum} = \left(\sum_{i=0}^{n-1} g_i \right) / \text{MAX}$$

$$b_{sum} = \left(\sum_{i=0}^{n-1} b_i \right) / \text{MAX}$$

with *n* being the total number of pixels in the image and MAX being the maximum possible summation intensity for each color. Assuming 8 bits for each color, MAX = $2^8 n$. The summation triplet for red, green and blue values is denoted Σrgb. A totally white image, for example, would have a summation of

$$\Sigma rgb = (r_{sum}, g_{sum}, b_{sum}) = (1.0, 1.0, 1.0)$$

The quality or syntactic function of the color domain described by Σrgb is easily determined. If the components are equal, the image is either neutral or balanced. If the image is seen to be all in the grayscale it is neutral; otherwise it is a balanced color domain. If the components are not equal, the image is weighted.

Using simple transformations we can also create an *hsv* summation triplet for the image [6]. The hue (*h*) will tell the favored hue in a weighted color domain (0–1 in circular fashion, with red = 0, green = 0.333, blue = 0.666 and red = 1.0). The value (*v*) tells the maximum intensity of the image (0–1), and the saturation (*s*) tells us how balanced (*s* = 0) or weighted (*s* = 1) the color domain is. If for example

$$\Sigma hsv = (0.666, 0.295, 0.492)$$

the summation triplet indicates a color domain with a weighting in blue. The saturation level is low, which would indicate a gray-blue weighting, a low-saturate blue. With an intensity value near 0.492, we can also expect the image to be relatively bright.

It is important to reiterate that the summation triplets Σrgb and Σhsv tell us little about the actual color values in the image but give more general information about the color domain of the image. To understand this clearly, we can pick for analysis two color keyframes from the animation *Color Study #7* (see Color Plates 1a and 2a).

Color Plate 1a is frame 2400 from the study. It is an example of a balanced color domain. The *rgb* and *hsv* summations for the images are

$$\Sigma rgb = (0.355, 0.335, 0.362)$$

$$\Sigma hsv = (0.790, 0.0746, 0.362)$$

We can tell from both triplets that the image is balanced. The *rgb* components are nearly equal, and the saturation level is near zero. If there is a weighting at all, it is in the violet range, but the overall effect should be minimal as the *rgb* summation intensities balance one another.

To further illustrate this balance, we can redistribute the pixels from frame 2400 in random order within the raster. If the image is truly balanced, the overall impression when seen from a slight distance should now be gray. The pixels should mix together like the dots of a Seurat painting. This image can be seen in Color Plate 1b. It has a neutral quality with perhaps a slight tinge of violet as indicated in Σhsv.

Color Plate 2a, frame 3000 from the study, has the following summation triplets:

$$\Sigma rgb = (0.347, 0.348, 0.492)$$

$$\Sigma hsv = (0.665, 0.295, 0.492)$$

Here we have a domain weighted in blue with low saturation. Redistributing the pixels gives us an image with a definite blue weighting, but not highly saturate, as seen in Color Plate 2b.

Parametrically Defined Color Palettes

Now that we have defined a basic color syntax, how can it be compositionally applied? An early problem encountered is how to move from one color domain to another. One solution is to use color maps for key images and to interpolate from one keyframe map to the other.

In its simplest form this solution is not satisfactory, as interpolating through the *rgb* values from one map to the next can often wash out all detail in an image. For example, in Table 1, linear interpolation from a start color to an end color has a pure gray as the midpoint color. Setting up keyframe color palettes to avoid these relationships would require heavy constraints and make the task overly difficult and needlessly limiting.

A simple and effective method is to define the keyframe color maps parametrically and then to interpolate through the parameters rather than through the actual color values. The ICARE color map editor designed by graphic artist Donna Cox will allow this parametric definition [7]. With ICARE, the *rgb* entries in a color map are derived from periodic functions. Parameters of amplitude, frequency, phase and offset are plugged into a sine function that calculates the *rgb* array elements for the color map. In *Color Study #7* this approach was applied to an *hsv* rather that an *rgb* color space and then transformed into the *rgb* map entries.

Table 2 shows the parameters defining the color palette for frame 1800 (Color Plate 3) of the study.

Figure 1 shows graphically the *hsv* components for each entry of the 1,024-

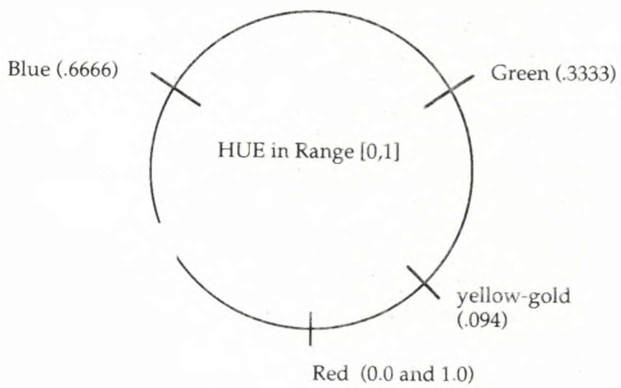

Fig. 5. Hue values normalized to the range of 0–1 as used in Σhsv color domain components.

element color map used with the image. The hue component is of very low amplitude centered around yellow-gold. The color is highly saturate, with little visible gradation as defined by a high offset for the saturation value with a low amplitude. The value component shows a high amplitude, which should manifest as apparent gradations of lightness and darkness that give the appearance of pseudo-3-dimensionality to the raster image.

By selecting keyframe color maps, defined parametrically, we can interpolate through the parameters to create in-between palettes, with a separate color palette for each image in the animation. Since we have the ability to measure the color domain with respect to neutral, balanced or weighted function, it is now possible to create a weighted color domain and interpolate to a balanced or neutral domain. The reverse is of course also true. We can now structure time with color!

A Compositional Approach

Color Study #7 illustrates one method of applying these ideas to temporal color composition. An analysis of the compositional approach used with respect to the evolving color relationships in the study reveals an underlying arch form (Fig. 2). The arch form is a common musical architecture in which the focus or perhaps climax of the piece occurs in the middle. The closing half works its way to the end as a loosely mirrored unraveling of the first half.

We accomplish this analysis of the study by dividing its 3,600 frames into six equal sections of 600 frames each, using seven keyframe color palettes. A storyboard of the entire composition can be seen in Color Plate 4 with the animation progressing from upper left to lower right. The study begins and ends in a neutral color domain. The peak of the study is at frame 1800 (see Plate 3) which has the maximum hue weighting of any image in the composition.

Figure 3 illustrates the movement of the color by examining Σrgb components for each keyframe palette. Balanced or neutral domains will have equal Σrgb values. Looking at the components for keyframes 1 and 7, along with the corresponding images (first and last images in the storyboard, Color Plate 4), we can see that they are neutral. Keyframe 2 is a weighted color domain with an orange tendency. Σrgb for keyframe 3 returns us to a balanced domain (corresponding approximately with row 2, image 2 of Plate 4) and then the study progresses to the climax point at keyframe 4 with a yellow-gold weighting (Plate 3). Again we return to the balanced domain we analyzed earlier (Plates 1a and 1b), and then on to another weighted relationship, also analyzed earlier (Plates 2a and 2b). The blue weighting resolves itself to the neutral keyframe 7 palette, ending the composition (corresponding with the image in the lower right of Color Plate 4).

In Fig. 4 we can also follow the arch form, using Σhsv components. The actual image intensity, or value (v), peaks at the midpoint, keyframe 4. The saturation summations agree with the Σrgb components: low saturation values indicate neutral or balanced domains. The hue component indicates overall hue weighting for saturated domains; keyframe 4 shows a hue value of 0.094 or yellow-gold (see Fig. 5). Actual Σrgb and Σhsv components for the keyframe palettes can be seen in Tables 3 and 4.

Unresolved Issues

Color is only one aspect of a visual composition, and color domains are one small part of a complete color grammar. Although we have established a syntax for moving through color relationships we have not dealt with the connotative aspects of particular hues—what might be considered the semantic side of a color grammar.

Other issues remain: questions of shape and form; the distribution of different hues and values over the image; questions of temporal design; and the evolution of abstract shapes in time. A complete time-based visual grammar has many facets, all of which must eventually be considered in abstract visual composition. These questions are, of course, more than can be covered in a short paper, but they suggest many directions for further study.

The imagery for *Color Study* #7 is a visualization of a simple mathematical process. Each frame is a two-dimensional grid of 10-bit numbers, which are assigned color from a 1,024-element color map. Although the procedure for creating the animation frames is beyond the scope of this paper, it uses a simple design principle that is worth noting. The piece is set up with a start frame and an end frame defined. All frames in between are calculated as interpolations revealing a single gestural phrase. A simple motion of relaxation-tension-release is created by moving from and to points of dynamic symmetry [8], from one point of visual balance in spatial composition to another.

As temporal color relationships are of primary importance in the study, elements of motion and shape were minimized, using either simple shapes or a single gesture. Theories of tension-release in pure design already exist and provide a good point of departure for further work in the non-color design aspects of a time-based visual grammar [9]. Combined with this color research, they begin to establish a language for abstract visual composition.

Final Remarks

Color Study #7 illustrates rigorous control of color relationships over time. It shows that it is possible to create coherent compositions with a formal foundation similar to that found in traditional Western music practice.

The idea of a neutral-weighted dynamic with respect to color is not a new one. Hence this work serves not so much as theoretical invention but rather as codification of a practice in filmmaking that dates back at least 50 years. In 1939, MGM's *The Wizard of Oz* was divided into three sections. The opening and closing, set in the stability of 'home', were in neutral black and white. The action of the story in the land of Oz was in color.

Today's music videos make extensive use of the interplay of neutral (black and white) and weighted domains. An hour's worth of viewing demonstrates that, though filmmakers may not follow a rigorous theory, they instinctively understand the kinetic potential of structuring time with color.

The work discussed here is but a start toward a design language for abstract visual composition. Over the last century experimental animation has made only a small mark on the artistic landscape [10]. Many of the problems these filmmakers faced have been alleviated with the advent of computer technology. Obstacles of expense, equipment access and time expenditure all have

Table 1. Start, midpoint and endpoint of the color map, which defines color as 1 byte (0–255) each of red, green and blue.

	start	mid	end
red	160	120	80
green	200	120	40
blue	20	120	220

Table 2. Sine function parameters of frame 1800, color map (*hsv* space).

		hue	saturation	value
amplitude	[0–1]	0.012	0.039	0.273
frequency		5.0	6.0	2.0
offset	[0–1]	0.094	0.953	0.586
phase	(radians)	0.0	0.0	1.885

Table 3. Σ*rgb* components for keyframe palette color domains.

keyframes	red	green	blue
1	0.361	0.363	0.352
2	0.547	0.352	0.204
3	0.318	0.306	0.320
4	0.659	0.386	0.034
5	0.355	0.335	0.362
6	0.347	0.348	0.492
7	0.354	0.349	0.373

Table 4. Σ*hsv* components for keyframe palette color domains.

keyframes	hue	saturation	value
1	0.197	0.030	0.363
2	0.072	0.627	0.547
3	0.810	0.044	0.320
4	0.094	0.948	0.659
5	0.790	0.075	0.362
6	0.665	0.295	0.492
7	0.701	0.064	0.373

been minimized. As interest in technology for technology's sake wanes (as the technology becomes more readily available), the focus will return to its creative use. The body of work and theory will grow.

In abstract animation, the need for a working vocabulary and grammar is paramount. There is of course no one solution for each aesthetic problem to be encountered. It is doubtful that artists will even agree on what the problems are. This research offers one approach to the problem of color.

Although this paper has focused on the technical elements of a process, it must be remembered that the details of craft are important to the artist but should be invisible and seamless to the audience. As in analyzing a music composition, we can graph, chart and quantify the elements of a piece and lose sight of the work as a piece of music. We are, after all, dealing with art. While we accept the discipline and responsibility of the craft, we must be cautious of overintellectualizing what we do, and of leaving the work cold and sterile.

Finding that balance is a challenge all artists face. John Whitney says, "Art, unlike science, is proven by art alone" [11]. As we each find our own way, and as we discover and share new techniques, the work eventually will speak for itself, with time as the final arbiter.

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10. Russett and Starr [9].

11. Whitney [9].

Acknowledgments

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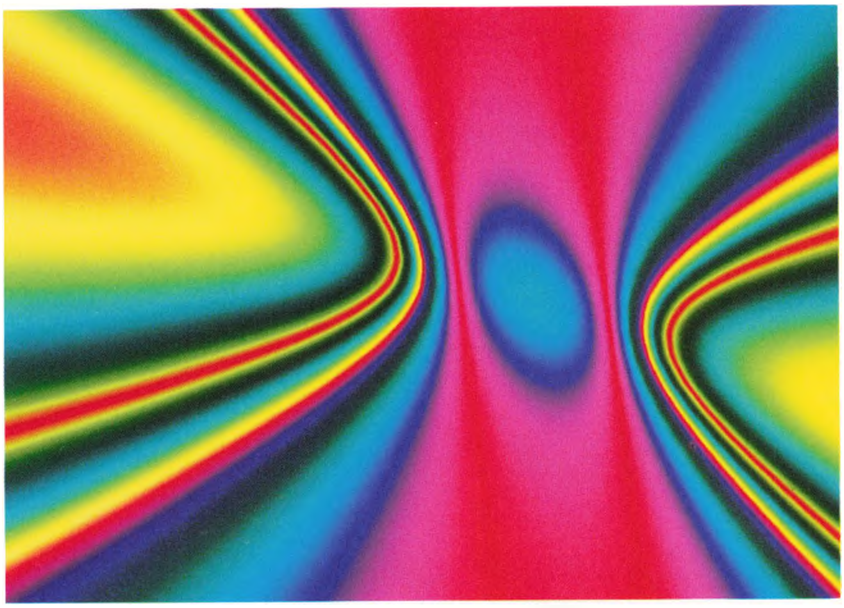
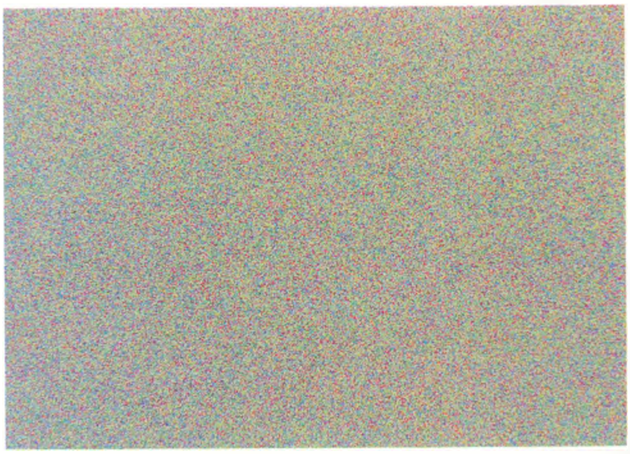
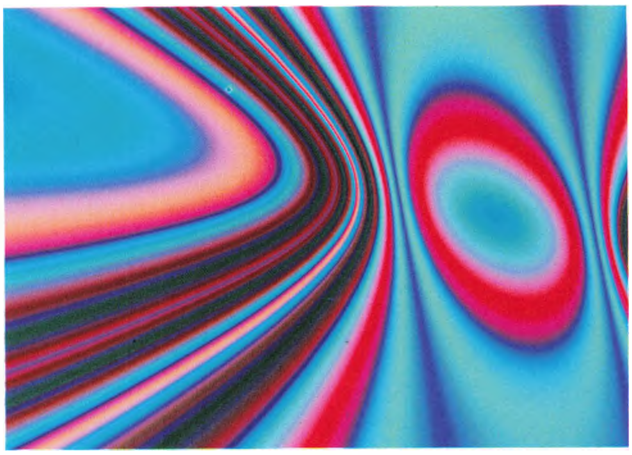


Color Plate 1a. (left) Frame 2400 of *Color Study #7* (keyframe color palette 5), an example of a balanced color domain in which *rgb* summation intensities balance one another.

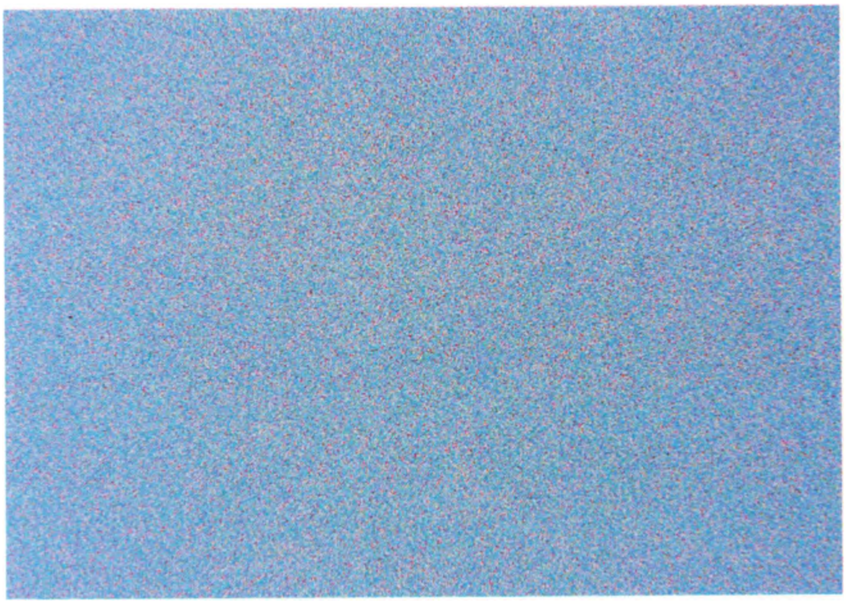


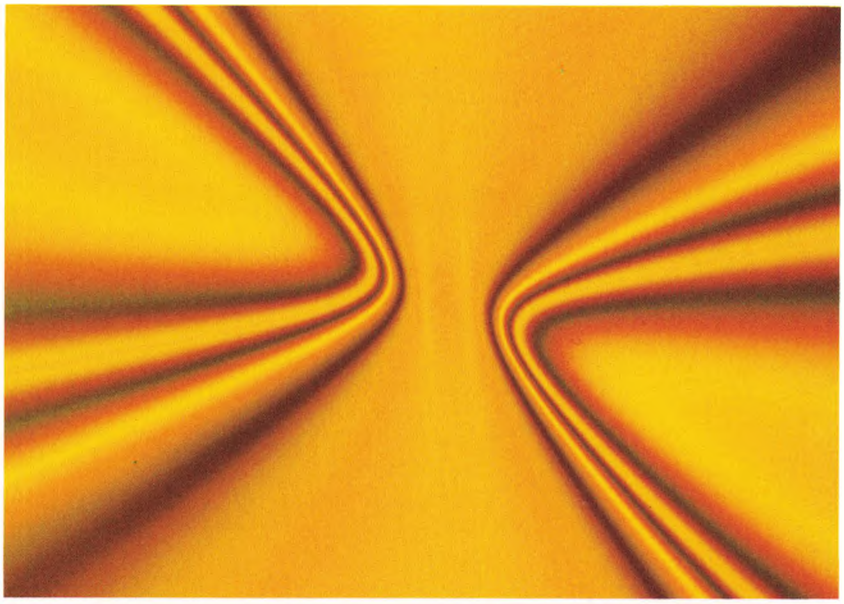
Color Plate 1b. (left) Random redistribution of pixels in frame 2400 (see Color Plate 1a), demonstrating a neutral quality due to the balanced color components.

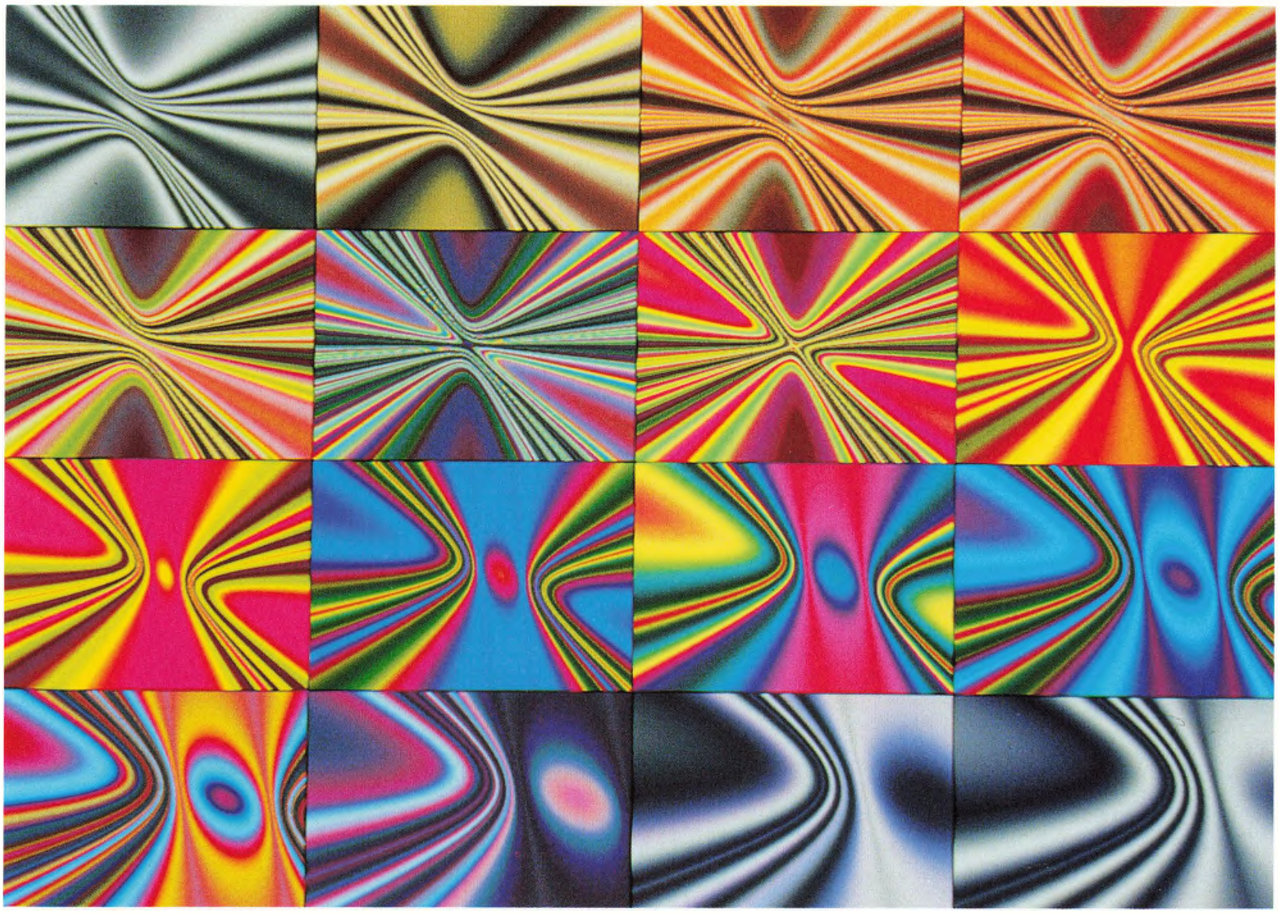


Color Plate 2b. (right) Random redistribution of pixels in frame 3000 (see Color Plate 2a), demonstrating a weighting in low-saturate blue.

Color Plate 2a. (right) Frame 3000 of *Color Study #7* (keyframe color palette 6), a domain weighted in blue with low saturation.







Color Plate 3. (top) Frame 1800 of *Color Study #7* (keyframe color palette 4), climax of the composition, with a high-saturate yellow-gold weighting.

Color Plate 4. (bottom) Representative frames from the entire composition of *Color Study #7*, beginning, at the upper left, in the neutral color domain, passing through a colored domain (orange), then a balanced domain (row 2, image 2) and to the peak with maximum weighting (yellow-gold); the study resolves at the lower right in the neutral domain after passing through another weighted domain (blue).

Image Quality and Viewer Perception

Michael Ester

ABSTRACT

Improving the quality of digital images can have great impact on information storage and transfer, pushing the feasibility of image databases well beyond existing practical limits. How good do images have to be? Among the considerations for selecting image quality is the extent to which viewers can discriminate among variations in quality. What differences in resolution and dynamic range (bit-depth) can they see? Groups of art historians were asked to rate a series of displayed test images; the results show how participants' responses compared with the actual range of image quality. Practical implications of viewers' perceptions are discussed.

Of the many academic and commercial fields that depend on collections of visual materials, the art community is surely an obvious and significant constituency. Museums, universities, study centers and individual scholars maintain large holdings of reproductions of works of art—thousands and hundreds of thousands of images. These collections serve a variety of research, educational and managerial needs and encompass an assortment of printed and photographic media (slides, transparencies, prints, etc.). Visual archives are not only an important resource; they constitute major capital investments and operating commitments in cost, staff time and facilities.

The prospect of combining text databases on works of art with electronic images is by no means a new idea. For more than a decade, art-related projects have linked textual descriptions to images stored on videodisc [1]. Large-scale projects using digital imagery are more recent [2], with an increasing number of applications exploring this technology. Conferences of national and international associations, such as the Museum Computer Network, Museum Documentation Association, and Visual Resources Association, now regularly include sessions on image applications.

If the art world has been quick to approach systems for integrating catalog information and images, there has, however, been little general inquiry into the articulation between computer imagery and art historical practice. How do art historians use reproductions? How should art historians' activities define and give shape to the way users interact with systems? What standards of image quality are appropriate to the field and for what purposes?

The Art History Information Program of the J. Paul Getty Trust initiated a study to look at both image quality and functional characteristics of image use. It created a context of day-long meetings in which art historians could learn about and see key features of image technology, and where they in turn could offer their experience in two key areas: their assessment of differences in image quality, and their views of and practices in using existing photographic materials. This paper reports on one part of these sessions—the visual responses of the participants and their ability to discriminate among images of different quality.

Nine meetings were held at Getty offices in Santa Monica, California, and at the National Gallery of Art in Washington, D.C. Groups were kept small, ranging between seven and 10 attendees drawn from the United States and Europe. Although the general term 'art historian' is used in this paper, the participants came from a variety of art professions, encompassing curators, academic researchers, catalogers of works of art, and the senior staff of art institutions. As is typical of the art community, many individuals divide their time among several of these activities. Technical specialists and administrators also attended the sessions but do not figure in the study results.

Selection of Image Quality

Anyone who works with digital imagery is aware of the relationship between image quality and storage. Increasing image resolution and dynamic range to improve quality creates a geometric expansion of information per image. Storage can easily run to several megabytes or more per image. Image databases—where there is convergence of large numbers of images, concern with fidelity to a source, and real-time access—present an extreme situation. If, from the standpoint of modern image-processing capabilities, image databases are a relatively tame application of computer graphics, the sheer scale of data for image databases can pose daunting technical requirements for image capture, storage, transfer and processing. This is despite major advances in lossless and 'lossy' image compression (i.e. in which information can be reconstructed or not, respectively).

The selection of image quality has received little attention beyond a literal approach that fixes image dimensions at the display size of a screen. The use of electronic images has scarcely transcended the thinking appropriate to conventional reproduction media. To some extent this is understandable in light of the technology in use: analog images residing on videodisc provide little latitude for choice; what is shown on the screen is normally the visual entirety of the stored electronic image. It is more surprising that many users of completely digital systems have *also* equated the image with the screen, even though with this technology image information is independent of display and can be reduced and modified dynamically to suit a variety of presentations. Although a detailed framework for selecting image quality is beyond the scope of this paper, it is useful to examine a few general considerations as a context for visual discrimination.

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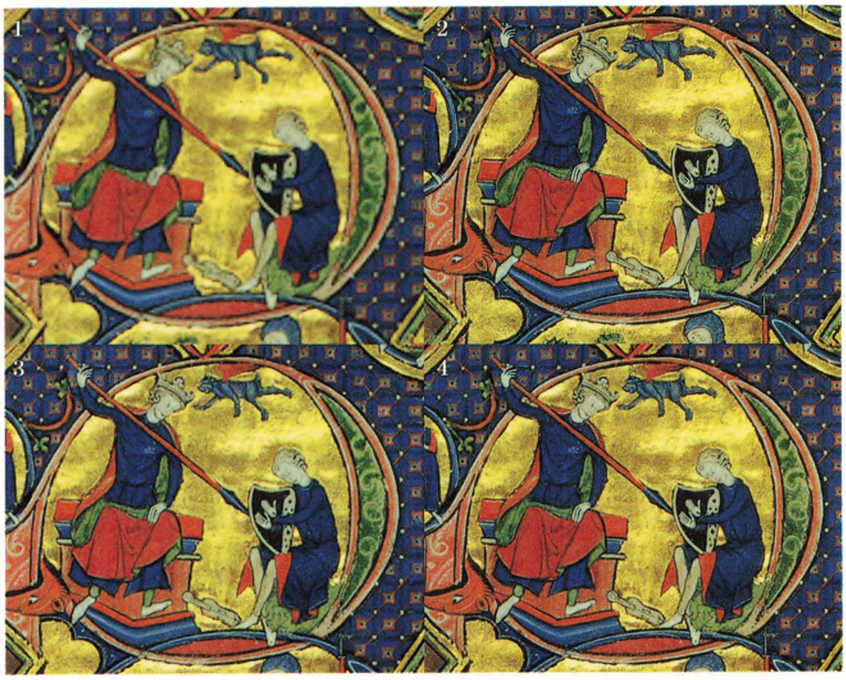

Color Plate 1. Color example of a composite frame. Artwork: Artist unknown, *Psalter with Canticles* (called *The Paris Psalter*), *folio 28 v*, illuminated manuscript (c. 1250–1260). (Source reproduction courtesy of the J. Paul Getty Museum)

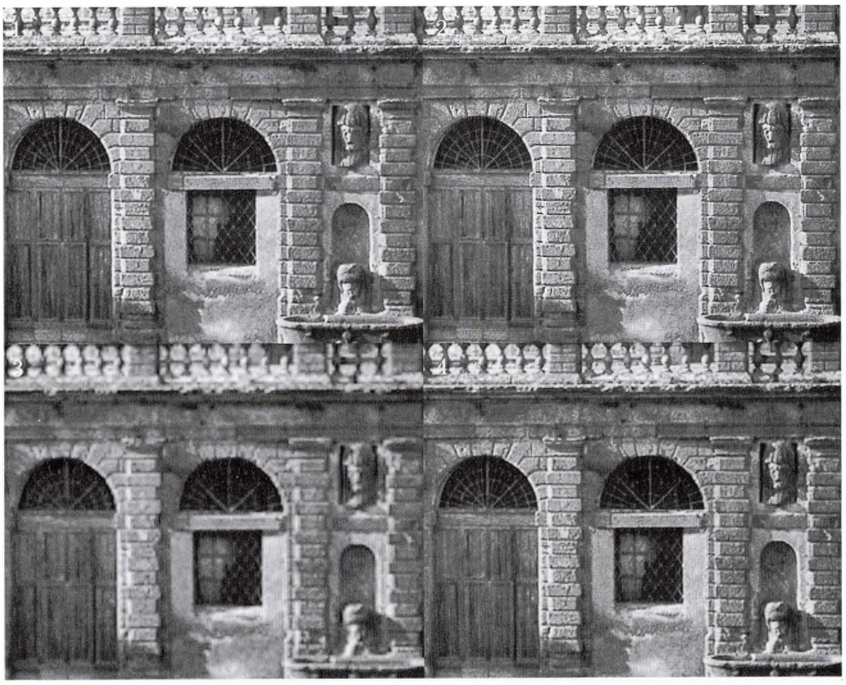

Fig. 1. Grayscale example of a composite frame. Artwork: Giacomo Barozzi Vignola and Antonio da Sangallo the younger, Palazzo Farnese facade, Caprarola (Lazio), Italy. (Source reproduction courtesy of the Getty Center for the History of Art and the Humanities)

A seemingly obvious point is that no single level of image resolution and dynamic range will be right for every application. Variety still characterizes current photographic media: different film stocks and formats each have their place depending on the intended purpose, photographic conditions and cost of the photograph. Likewise, no one would seriously contend that original photography is always the best choice: xerox facsimiles and printed reproductions are used routinely to good effect by art historians. However, an additional difference with digital imagery is that de facto standards of conventional media do not yet exist. Instead of a few comfortable choices, selection of image quality is open to a continuum of possibilities.

The motivation for selecting image quality that most frequently occupies developers is meeting the needs of immediate applications within the constraints of today's technology. *Delivery-quality* images—images intended for working applications—must conform to feasible technical and functional environments, including the user's computer platform and available communications and distribution channels. Contrasts between large and small collections, stand-alone versus broadly deployed image systems, and varying levels of technical sophistication offer wide latitude for choosing image quality.

Perceived quality, in the context of image delivery, is a question of users' satisfaction within specific applications. Do images convey the information that users expect to see? What will they tolerate to achieve access to images? Perceived quality is situation dependent: an image level considered acceptable for recognizing a work of art may be objectionable for other purposes. There is also a strong element of efficiency in evaluating delivery-quality images—a good image is one that conveys a maximum perception of quality for the amount of stored data.

If balancing today's application requirements and technical constraints represents one perspective on image quality, another equally important viewpoint goes beyond the short-term interests of users and developers. What can be termed *archival quality* places a premium on safeguarding the long-term value of images and the investment in image acquisition.

Capturing large numbers of images is the most expensive and time-consuming aspect of an image database project

[3]. Significantly, the largest expense is not likely to be the actual step of scanning. Instead, study of large-scale microfilm campaigns [4] indicates that the greatest costs are for the cataloging of materials, followed closely by a succession of labor-intensive manual procedures: locating, reviewing and assembling source material; preparing and tracking it; and controlling its quality. The creation of each photographic frame is a modest part of the cost [5]. Examination of costs for videodisc projects results in similar conclusions [6]. More difficult to quantify are these projects' disruptions of personnel, facilities and circulation of materials over extended periods. Given these demands, few organizations will rescan major repositories more than once a generation.

Although no strategy can protect against eventual obsolescence, standards for scanning a collection should ensure the images' greatest longevity. Several factors determine whether the quality of original capture is critical:

Quality of the source. The quality of image capture can be no better than the source image of a scan; the source imposes the upper limit on possible image quality. Different source media set varying scanning requirements.

Quantity of the source. Smaller collections encourage more expedient decisions about image quality by minimizing the penalty of rescanning.

Archival value. Is the material of transitory value or less significant as subsequent reproductions become available? Investment in image quality is appropriate to the extent that visual information has long-term interest and source reproduction is intended for multiple uses.

Long-term use. What are the intended applications within the expected life of an image? What levels of detail are needed? Will images be projected or printed? Will users only browse images? Even in a situation that does not involve constant demand, occasional access may be critical to an organization or an individual user when the need arises.

Technology and cost. Higher-quality images generally cost more and demand systems of greater technical sophistication. Moreover, evolving technology can affect the adequacy of long-term decisions; projections that appear acceptable today may seem woefully short-sighted within a few years. Given the required labor resources, the net expense of future scanning or re-

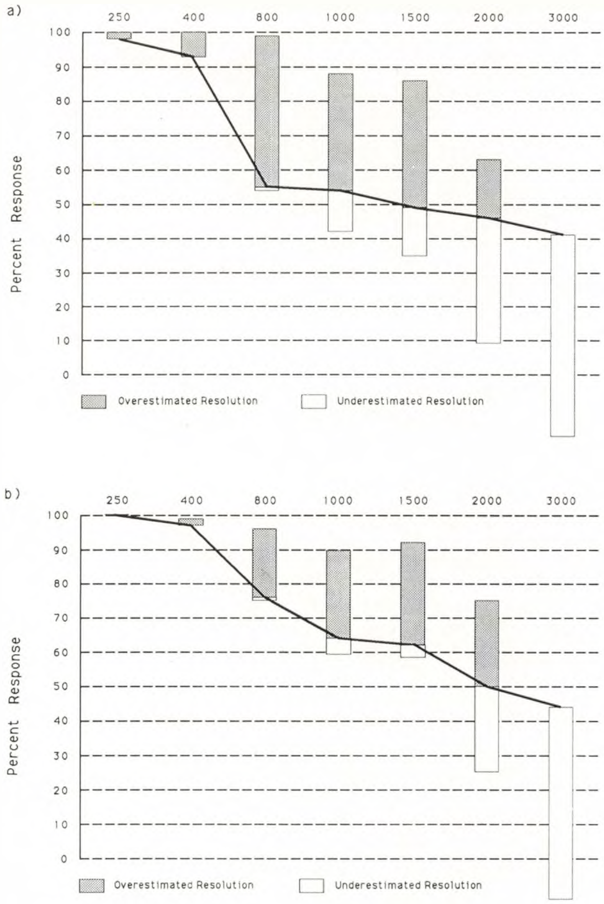

Fig. 2. Participants' responses to resolution values for (a) color and (b) grayscale images.

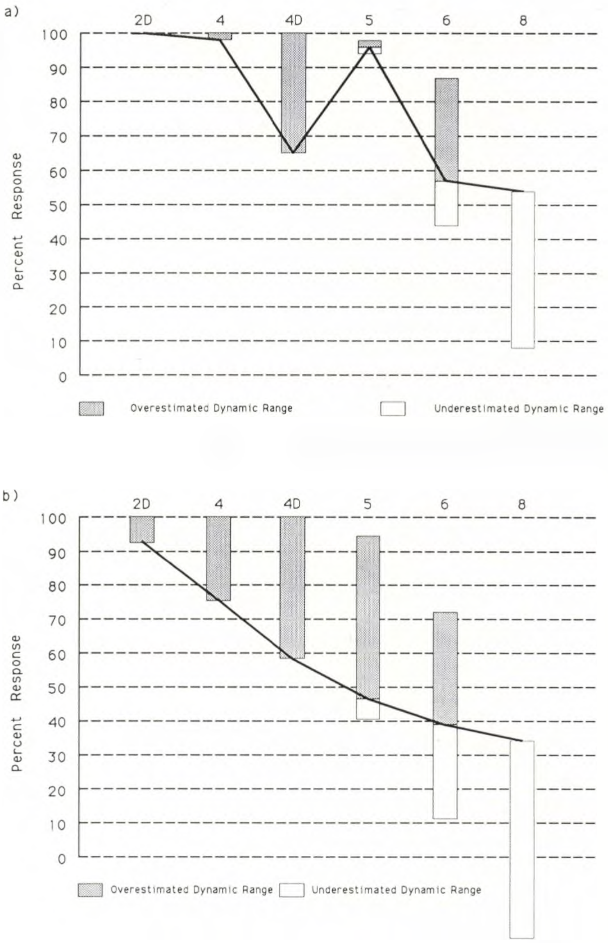

Fig. 3. Participants' responses to dynamic-range values for (a) color and (b) grayscale images.

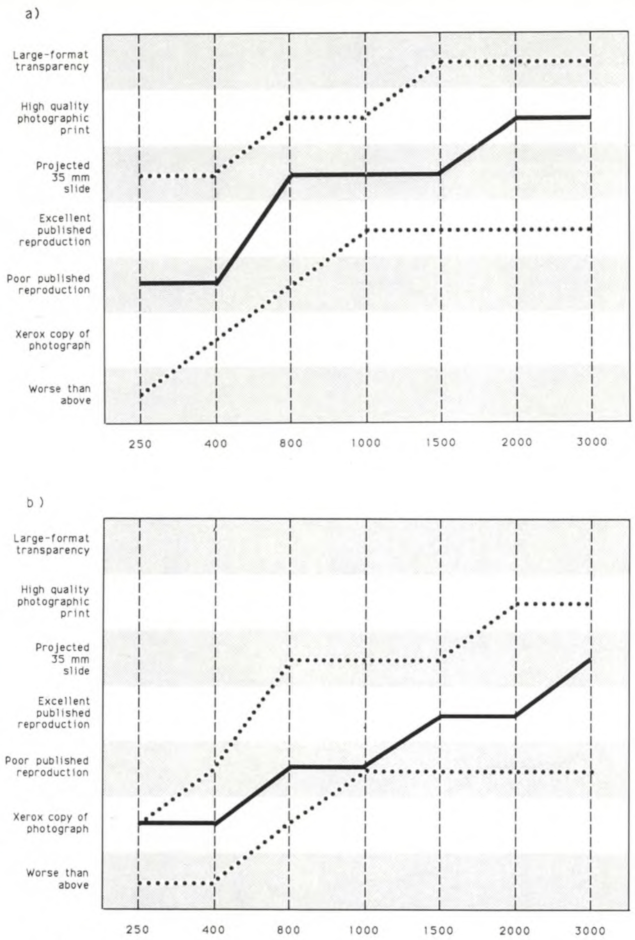

Fig. 4. Media comparison for resolution values of (a) color and (b) grayscale images.

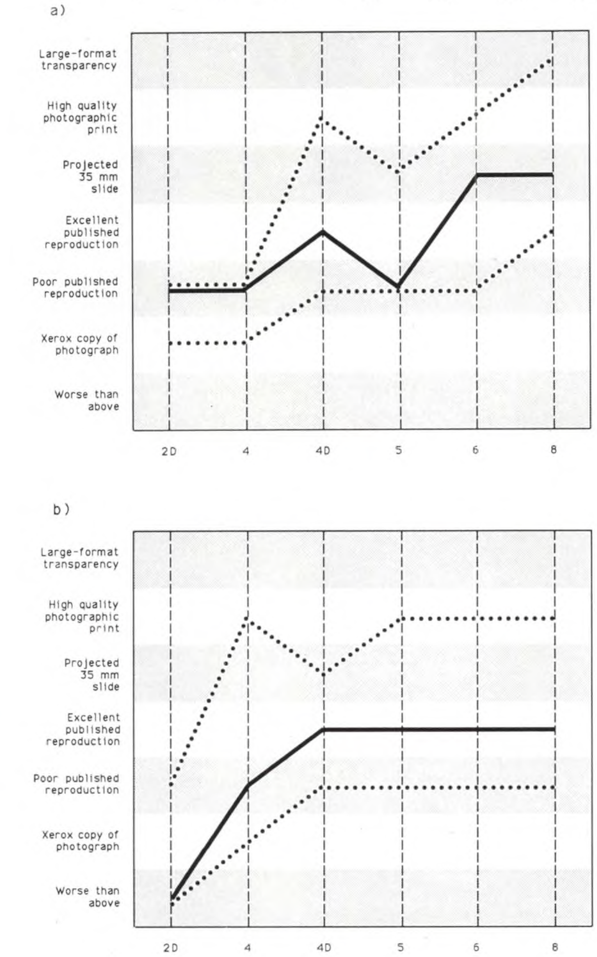

Fig. 5. Media comparison for dynamic-range values of (a) color and (b) grayscale images.

scanning may rise irrespective of technical improvements.

Viewer perception. Central to the subject of this paper, the ability of a viewer to discriminate among images of different quality is also a key ingredient in this mix. For archival quality, attention should be on the upper end of the spectrum—can viewers perceive the next increment of image quality, and if so, what is the visual margin of the improvement?

Initially, it may seem that delivery quality and archival quality represent two alternative perspectives about how source reproductions should be stored in electronic form. And this section points out that decisions in each case are guided by different issues. But to miss the potential interaction between delivery quality and archival quality is to lose a valuable opportunity to reconcile the two sets of interests. Delivery-quality images are a natural derivative of archival-quality images. It is always possible to degrade higher-quality images, and even to support several quality levels of an image at the same time [7]. Similarly, archival-quality images can be reduced and converted from one medium to another—for instance, from digital images stored on magnetic disk to analog images stored on videodisc. What cannot be achieved is the reverse process: low resolution and dynamic range cannot be elevated to a higher-quality image, methods of image enhancement notwithstanding.

Different operating contexts make delivery quality and archival quality complementary in practice as well as in principle. Delivery-quality images are presumed to operate at real time, or near real time. There is no particular reason why archival-quality images must conform to this constraint or even be on line. There are many long-term storage media today that can practically and economically store large quantities of archival-quality images if the requirement for immediate access is relaxed. Archival quality images can remain the electronic source, which users repeatedly mine to take advantage of technical change.

From this perspective of different image qualities to serve delivery and archival needs, what differences can viewers see? The next sections report on the ability of participants in the rating sessions to discriminate among variations in resolution and dynamic range.

Image-Rating Sessions

To rate images in this study, participants were divided into groups in front of two monitors; the same succession of composite frames was shown on both monitors. Composite frames consisted of a screen display divided into image quadrants; each quadrant presented a different treatment of the same pictured content (see below). Quadrants within a composite frame varied either by resolution or by dynamic range.

Participants were provided rating sheets with four numbered quadrants drawn at the top of each page; a separate rating sheet was used for each frame. Participants were requested to examine the quadrants and put them in relative order of quality, marking the order in the appropriate quadrant on the rating sheet. Relative order did not require viewers to retain an absolute standard from frame to frame; comparisons and judgments could be based entirely on the content of each screen. The rating sheet also listed familiar photographic media at the bottom of the page. Participants were asked to compare each quadrant to this media list and indicate the observed similarity between the two. Twelve composite frames were shown during each session: eight images comparing resolution values and four images comparing variations in dynamic range. One-half of the frames displayed grayscale images; the other half were in color. Initially, viewers were allowed to compare quadrants until they signaled they were done; at first, this took about 2 to 3 minutes per frame. Once participants indicated they were familiar with the procedure, images were left on the screen for 2 minutes at a time.

Composite Frames for Resolution

In this paper, resolution will be expressed in pixels, as the linear dimension of a digital image. An image cited as a 1,000 image, for example, corresponds to an image 1,000 pixels on each side, or a 1,000-pixel-by-1,000-pixel surface. The resolution test values selected for rating were: 250, 400, 800, 1,000, 1,500, 2,000 and 3,000. To give a sense of range, 400-resolution images are comparable to NTSC TV broadcast quality; 1,500 images approach high-definition television (HDTV) quality. The relative information content of the resolution values can be derived from the image area, or the product of the linear dimensions. A 2,000-resolution image, for example, contains (2,000 × 2,000 =) 4 million pixels, or four times as much information as a 1,000 image. Similarly, a 250 image has about 6% of the information in a 1,000 image.

To create composite frames for evaluating resolution, full-sized images were degraded (sampled) to the linear specifications described above. Next, a detail with the pixel dimensions of a quadrant was extracted from the highest-resolution image for a frame. For remaining quadrants, the same picture detail was captured from lower-resolution images and resized (expanded) to fill the quadrant area. The allocation of different resolution details to quadrant positions (upper left, upper right, lower left and lower right) was varied from frame to frame to avoid obvious predictability. Printed examples from the digital sources, Color Plate 1 and Fig. 1, give an approximate idea of composite frames seen by the participants.

Composite Frames for Dynamic Range

Dynamic range quality was stated in terms of the bit-depth allotted to image pixels. For grayscale images, bit-depth values constituted the entire information range; for color images, bit-depth values corresponded to the content for each of the red, green and blue (RGB) components of a pixel. The specific test values selected were 4, 5, 6 and 8.

In addition, 2-bit and 4-bit examples of dithered images were included in the tests. Techniques used for *dithering* generally trade off spatial resolution to enhance dynamic range and smooth the effects of reduced grayscale or color space to make images look better. Dithered images provide no improvement in information over unprocessed images of the same bit-depth. Where fidelity to a source is an issue, justification of the changes to 'improve' the image is problematic. In basic terms, the method developed for this study compares an image of reduced bit-depth to the original image and minimizes the differences. Processing was interpretable against the source and appeared visually effective.

To construct composite frames for testing dynamic range, a quadrant-sized section was prepared from an image at full bit-depth (8 bits for grayscale and 24 bits for color). The section was then reduced to the desired bit levels for adjoining quadrants. As with the test frames for resolution, positioning of different quality treatments of dynamic range was varied from frame to frame.

The procedures used in this study involved inevitable compromise between an attempt to control the variability of participants' responses and the practical considerations of the rating context. Initially, it seemed desirable to use the same work of art and subject content for all composite frames. During preliminary trials, however, display of a constant source image produced strong complaints—viewers found that repeated exposure to the same image quickly proved tiresome and dulled their sensitivity to visual differences. Some eight different works of art were shown during the rating sessions.

Discretion was possible in avoiding obvious biases in perception of image quality. It is known that subject matter with little detail and smooth surfaces can understate perceived differences in resolution [8]. Accordingly, composite frames testing resolution leaned toward more complex and 'busier' source images. The reverse approach was used for composite frames testing dynamic range.

To some extent the rating context is also likely to overaccentuate image quality as it would appear in most practical situations. The close juxtaposition of visual differences draws attention to quality distinctions that might otherwise go unnoticed. This relation applies especially to the composite frames used for resolution, where lower-resolution examples were expanded to fit the quadrants of a frame. While correctly presenting the relative content between different resolutions, enlarging poorer-resolution details magnified their flaws. Deficiencies of low resolution would be less apparent at a smaller display size.

Rating Results

Fifty-six participants completed the rating sessions. Collectively they viewed 672 composite frames and rated the images in 2,608 frame quadrants (with 80 missing observations). There were 1,712 observations for resolution and 896 observations for dynamic range; one-half of the images were in grayscale and the rest were in color. From the rating sheets completed by art historians, information was compiled by the different test values for resolution and dynamic range. The quadrants in each composite frame contained an actual order of relative quality determined by the test values represented. Participants could rate a quadrant in this usual order, or they could assign an order corresponding to another test value. For each test value, a count was made of the different test values attributed by participants. The rating data were put into tables showing the percentage of different observed resolution and dynamic range responses for each actual test value.

Resolution

Summary graphs for resolution are shown in Fig. 2a for color and in Fig. 2b for grayscale. The connected center line in each graph indicates the percentage of correct assignments for resolution values—that is, when a participant identified a quadrant with its actual order of relative quality. The columns above and below the center line represent the percentage of viewers' errors. The distance above the center line indicates the percentage of times participants overestimated images, rating them of higher quality than they were; the distance below the center line represents the percentage of times participants underestimated images, rating them of lower quality than they were. The reader should note that there are constraints on the two extremes: 250-resolution images could not be underestimated; 3,000-resolution images could not be overestimated.

One immediate observation that the two graphs suggest is that art historians were much more forgiving for color images than for grayscale images. They rated black-and-white images more accurately than color images and had less of a tendency, for black and white, to assign higher resolution values to poorer-resolution images. However, this difference eroded as resolution increased and correct discrimination decreased; ratings for black and white and for color were very close for 2,000- and 3,000-resolution images. This difference between color and grayscale was consistent with many comments that arose during the meetings. There are several reasons why art historians work predominantly with grayscale photographs, but one frequently mentioned is that color tends to seduce the eye with a spurious sense of fidelity; color reproductions look more true to the original even though they may depart significantly from it. Art historians find grayscale less distracting in this respect, and many believe that grayscale images foster greater concentration on the content and detail of the work depicted.

Starting with Fig. 2a for color, virtually all of the 250-resolution images were correctly identified, and there was only a small percentage of errors for 400-resolution images. There was a distinct break at 800, where accuracy dropped, with nearly all the error occurring in overestimation of this resolution. Discrimination decreased gradually for successive resolution values. Once again for 1,000 and 1,500 images, most of the error was distributed toward the overestimation side of the graph. Yet underestimation of images did begin to grow, becoming particularly striking between 1,500 and 2,000, where the percentages for overestimation and underestimation appeared to flip. At the upper extreme, 3,000-resolution images were underestimated more than half the time.

The results for grayscale (Fig. 2b) were reasonably similar to those for color, although the trends were less pronounced. The percentage of correct ratings descended more slowly for grayscale until the 2,000- and 3,000-resolution images. Also, compared with Fig. 2a, the decline from 400 to 800 in Fig. 2b was less steep and became a gradual descent from 400 to 1,000.

Figures 2a and 2b give a useful collective look at the range of resolution values. However, they do not tell the full story of how under- and overestimation were distributed—it is impossible to say, for example, how the overestimation of 1,000-resolution images in Fig. 2a was distributed among higher-resolution images. For this information, it is necessary to look at the ratings for individual resolutions. Graphs of successive resolution values illustrate the trends described above: initially, they spread to the right as resolutions are overestimated and then to the left as resolutions are underestimated (see Figs A1 and A2 in the Appendix, showing individual resolution test values for both color and grayscale).

How should one interpret the rating results for resolution in terms of making practical decisions? Because viewers can readily single out the poorer quality of 250- and 400-resolution images, should they not be used for image systems? Though participants' responses suggest that these resolutions may be unappealing choices for archival quality, the same levels have good uses in applications. The ideal application of low resolution is in contexts where the user can trade image quality for greater functionality—browsing, or moving and viewing several images at once, for example. At certain stages of image use and examination, access and mode of use can effectively offset an image's perceived lower quality.

For applications placing greater premium on the fidelity and study quality of images, the 800-resolution image for color should mark a clear improvement in perceived quality. The 1,000-resolution level is a better dividing line for both grayscale and color; it generally received higher ratings than its true quality. The other notable break point occurred between 1,500- and 2,000-resolution images. The 1,500 value marked the highest resolution that still had the leverage of overestimation. Delivery of working images should stress the greatest perceived quality for the storage and transfer overhead; 1,500 is the high end where this advantage remains intact. But if the objective is to pick a capture resolution where discrimination notably breaks down, the other side of this pair, the 2,000-resolution images, seems a good candidate. Further support of 2,000 as an appealing choice for archival capture is the fact that viewers rated the 3,000-resolution image (for both color and grayscale) at 2,000 nearly as often as they rated it correctly.

Dynamic Range

Figures 3a and 3b show the results from viewers' responses to dynamic range tests. As in Fig. 2, the center lines indicate the percentage of participants' responses that correctly assigned quadrants to bit-depth test values; the column distances above and below the center lines represent the percentage of responses that overestimated and underestimated bit-depth, respectively. The bit-depth legend at the top of the graphs refers to the entire bits-per-pixel for grayscale and the bits-per-RGB component for color (a test value of 8 for color produces a 24-bit pixel). The letter D on the bit-depth legend denotes dithered images. Graphs for individual dynamic range test values are found in the Appendix, Figs A3 and A4.

The differences between the two graphs in Fig. 3 are striking. For grayscale, the ability of participants to distinguish among the undithered test values shows a definite decline. Only one-third of the participants correctly identified full 8-bit quadrants. This result is in distinct contrast to the same values for color: 4- and 5-bit color images appeared readily discernable, with no marked drop in discrimination until the 6- and 8-bit test values. Even then, the decline was less extreme for color.

Since the graphs for resolution (see Fig. 2) show that viewers perceived variations in grayscale quality more acutely than variations in color, it is interesting to suppose that resolution may be perceptually more important for grayscale images and that dynamic range may be more significant for color. There is support for this idea in studies of human vision, which suggest that the eye has less spatial sensitivity to color (chromaticity) than to brightness (luminance) [9]. Likewise, block compression schemes that operate in YUV (luminance, hue, and saturation) rather than RGB color space exploit this same relationship.

Dithering of images after reducing dynamic range to 4 bits improved participants' ratings of these examples compared with the unprocessed, 4-bit images. Viewers overestimated dithered image quality more for grayscale than for color examples: they rated dithered grayscale quadrants as comparable to 8-bit quadrants 25% of the time, as against 12% for color (see Appendix). Dithering does not appear to have helped much with a 2-bit dynamic range; participants readily distinguished these images from those with other test values; in the case of color, there were no exceptions.

An important motivation for our assessing dynamic range was the prospect of identifying intermediate bit-depths that rated strongly and thus might offer savings in image storage. Less direct advantage is achieved by reducing dynamic range than by reducing resolution. Resolution is a product of the image's dimensions, while dynamic range is a linear increase based on the number of bits per pixel. For instance, a reduction in grayscale from 8 to 6 bits causes only a 25% saving in image size. The loss of dynamic range occurs at a power of 2: in this example, the values a pixel could assume drop from 256 to 64. (For color, a comparable reduction would occur in each of the RGB components.)

Given these trade-offs, none of the values for color below 8 bits look very attractive, either because they do not produce much in the way of savings (i.e. 6 bits) or because they were not favorably compared by viewers. The one exception is the 4-bit dithered (4D) image, which may offer considerable promise, depending on processing. Otherwise for color images, at least in this comparative context, it would appear preferable to achieve desired storage reductions through reduction in resolution rather than in dynamic range. Grayscale images offer greater opportunity for dynamic range reduction. The 4D and especially the 5-bit test values received good ratings and could be used, in situations where economy is critical to an application, to bring about significant saving in storage.

Media Comparison

As participants rated quadrants on resolution and dynamic range, they also compared each quadrant to a list of reproduction media (see Figs 4 and 5) and indicated the media entry that most closely matched image quality. However, before we look at the results of the media comparisons, some cautionary remarks are in order.

Since they involved less control over the standards participants used to evaluate images, the media comparisons were the 'softest' data collected during the rating sessions. Although the list of media implied a strict hierarchy of quality, establishing the order and differences between media actually involved considerable personal latitude—differences between poor and excellent published images and between xerox quality and poor publication, for example. Likewise, some art historians find photographic prints preferable to transparencies, and high-quality publications preferable to slides. More problematic, however, was the fact that rating of quadrants by media assumed that participants could establish their own distinguishing criteria for associating images with one or another media category and could consistently apply this scheme across a succession of test images. It is unreasonable to think that such a standard was consciously devised and unlikely that an absolute scale was carried through the entire rating session.

A few other points are worth noting. The participants themselves were not altogether confident that their visual experience with photographic material would translate to displayed images: for most of them, viewing images (especially high-quality images) on a screen was a new experience with an unfamiliar technology. Considerable bias was also encountered. Several art historians associated digital imagery with microfilm or home television (i.e. with images they could not handle directly). On both counts, conservative ratings were anticipated, although the results did not provide obvious support for this expectation.

Figure 4 shows the media comparison for the different resolution test values; Fig. 4a shows the results for color images and 4b the results for grayscale. Since there was no presumed correct answer against which to compare viewer responses, the solid line indicates the reproduction medium where the median of viewer responses occurred. The dashed lines bracket media selections that included two-thirds of the responses for a resolution value.

The media comparisons, like the results for resolution, suggest that color inherently raised the perceived image quality; ratings were uniformly higher in Fig. 4a than in Fig. 4b. The range of values for grayscale images stayed at least a medium below those for color, and the slope for grayscale was also more gradual and continuous over the media scale. Some other trends observed earlier were also evidenced in the media comparison data. The 250- and 400-resolution images fared poorly compared with images with other test values although even here the color distinction noticeably boosted perceived quality (e.g. *poor published* versus *xerox* quality for grayscale images). The jump between 400 and 800 was likewise apparent, as was a transition between 1,500 and 2,000. The grayscale results showed similar characteristics although the effect was more muted.

How literally should one interpret the results? Are color 2,000- and 3,000-resolution images as good as photographic prints? Are 1,500 images equivalent to excellent graytone publications and color slides? The cautionary remarks stated above are relevant here. But more concretely, note that for resolution values on the graphs the spread of the distributions (two-thirds of the responses) was quite large, often spanning three or four media on the vertical axis.

A reasonable, if more conservative, position would be to suppose that the third below the median is fairly safe ground as a statement of how participants evaluated displayed images. This would suggest, for instance, that viewers considered 2,000 grayscale images somewhere between *poor published* and *excellent published* images and would place 1,000 color images between *excellent published* images and *35-mm slides.* Following this line of thinking also establishes discontinuities of perception;

for instance, 250 and 400 do not overlap in this range with higher resolution color images; images of 800 resolution and below do not share lower thirds with 1,500 and above in grayscale.

For the media comparisons of the dynamic range test images, Figs 5a and 5b follow the same format as the previous two graphs; they also merit the same reservations about interpretation of the results. Many of the features evident in these two graphs have been discussed previously, including the lower threshold of discrimination for grayscale, the higher ratings associated with color imagery and the effectiveness of dithering for enhancing the perceived quality of 4-bit images (shown as 4D on the graphs). The 2-bit dithered (2D) images for grayscale were judged to be very poor, while the color version was rated more highly than might have been expected from the dynamic range results in Fig. 3a.

The media comparisons for 8-bit color and grayscale were puzzling initially: the respective median ratings of *35-mm slide* and *excellent published* reproduction were a category lower than the highest media scores for resolution data (Fig. 4). The reason for this difference is a function of rating procedures rather than users' perceptions. In composite frames for resolution, resolution was allowed to vary while dynamic range was held constant at a full 8 bits. In composite frames for dynamic range, bit-depth was altered for different quadrants while resolution was held constant within frames and was kept within a 1,500 range between frames. This arrangement was fine for the relative comparison of dynamic range test values. However, for comparison with the absolute scale of media categories, it meant that participants did not see the highest resolution qualities in this context.

Rating Photographic Prints

As part of the presentation on electronic image technology, participants were shown an array of electronic reproductions ranging from fax media to photographic prints. Among the last of these were four 8-×-10-in color prints of *The Drawing Lesson* by Jan Steen. The four prints were derived in different ways:

1. printed from the 4-×-5-in transparency supplied by the J. Paul Getty Museum;
2. printed from a 4-×-5-in duplicate transparency of (1), above;
3. printed from a transparency generated by a digital source (a stored image of approximately 1,500-pixel resolution and full color bit-depth was output to a filmwriter);
4. printed from a 35-mm slide supplied by the J. Paul Getty Museum.

Table 1. Participants' responses to prints from different photographic sources (percentages are shown for each rating order).

Source	Rating Order 1	2	3	4
Original Transparency	66	24	3	0
Digital Image	22	76	6	0
Duplicate Transparency	2	0	69	29
35mm Slide	10	0	22	71

Positive film was delivered to a photographic service, which produced inter-negatives and created the four-color prints.

In early sessions, the four prints were set out on a table and viewers were asked as a group to assign them to the respective sources. Midway through the series of meetings, this exercise was moved from the general demonstration and incorporated into the formal rating part of the program. The rationale behind this change was that allowing art historians to examine photographic prints would provide an opportunity to obtain responses to a familiar medium.

The prints were arranged and labeled as four quadrants, analogous to the composite frame format employed for displayed images; the same rating sheet was used. Because rating began late in the sessions, the results offer responses from only 36 participants, or 144 rating scores for the prints. Each column in Table 1 shows a rating order and the percentage that the different print sources received. Rows in the table are arranged so that the highest values for the columns appear in the diagonal.

Participants selected the print from the original transparency as the best of the four photographs, with the digital source a distant second. The digital source dominated second place; nearly all the remaining responses for the original transparency placed it second. The original transparency and the digital source occurred in only 9% of the responses for third and fourth place. The print from the duplicate transparency took third place, with the 35-mm slide accounting for the next-highest percentage in this column. Participants rated the print from the 35-mm slide in fourth place.

Somewhat surprising is that the digital source, even without using the highest resolutions, compared favorably to all sources but the original transparency. The original transparency could be expected to capture the top rating, not only because the source medium was of high quality but also because the digital source and the duplicate transparency were one generation removed from it. Although we would be overinterpreting this limited data to presume that digital sources of this order rival the best photographic reproductions, the results do lend credence to the medium as a vehicle to study quality material.

How difficult or easy was discrimination among the prints? Participants from all the groups stated that they would be comfortable using any of the prints for study purposes. For most participants, rating the prints meant identifying the best quality among a set of satisfactory study examples. Participants indicated that the print from the 35-mm slide presented the most obvious differences and that ordering the other three prints was much more difficult. From such comments during the sessions, we expected closer ratings among the latter three sources than actually materialized. Either the participants did not take into account their unconscious visual skills, or they were discussing functional differences rather than strict issues of quality.

Conclusion

This paper began with the question, How good do images have to be? It was suggested that decisions about resolution and dynamic range are inseparable from the intended use of an image. Just as different conventional reproduction media and film formats are appropriate in different situations, so too should it be expected that multiple levels of quality will find a place within the electronic medium. Two motivations for selecting image quality were discussed. Delivery quality places the premium on satisfying the needs and constraints of specific applications. Archival quality lays emphasis on the investment for initial image capture and the long-term value of images. Looked at as alternatives, these contrasting perspectives exist in obvious tension. Both sets of interests can be addressed without inherent contradiction, however, provided that archival quality determines the quality of scanning and that archival images become the reservoir of quality that is reduced and modified to suit the requirements of delivery quality.

For this study, groups of art historians were asked to view images of works of art that presented different combinations of resolution and dynamic range; they were likewise asked to compare digital images to other familiar reproduction media. Following are some of the general points that emerged from the study:

- Grayscale and color images elicited contrasting profiles of participant response. There is sufficient variation to suggest that parameters of image quality for grayscale and color should be distinct.
- Viewers were more demanding for grayscale resolution than for color resolution: discrimination remained higher for grayscale images over most resolution values. At the upper end of the resolution scale, ratings became very similar as discrimination declined for both grayscale and color.
- Color images showed breaks in perception at the low and high ends of resolution. Overestimation of resolution was concentrated in the 800 through 1,500 range.
- Results from dynamic-range comparisons indicated that viewers were much more sensitive to changes in bit-depth for color than for grayscale. There was a steady drop in participants' abilities to distinguish successive grayscale values. Discrimination between bit-depth values for color images remained relatively high.
- Comparison of images with known reproduction media closely followed the trends observed for resolution and dynamic range. Despite reservations the art historians voiced about electronic images, they gave high ratings to images in several resolution and dynamic-range categories.

This paper also outlined some of the factors that shape archival and delivery quality, such as the users' environment, the nature of the application, the size of a collection, the quality of the source, the archival value of images and the state of technology. Viewer discrimination also should figure as an essential ingredient in selecting image quality. If viewers are unable to distinguish better-quality images from poorer-quality ones, then additional image data and storage are superfluous. At the same time, selecting an extremely low level of quality risks severe restriction in the ways images can be used and premature obsolescence of the image collection. Appreciating what a viewer can see provides an opportunity to exploit trends and discontinuities of perception both to capture images and to put them in the hands of users.

Acknowledgments

I am grateful to several individuals and organizations for their help with this study. Marilyn Schmitt and Susan Siegfried helped compile source reproductions and review the rating sessions and this text. The J. Paul Getty Museum and the Center for the History of Art and the Humanities kindly furnished the photographic materials used for test images. Pixar, Inc. provided systems and staff involvement. Bill Woodard and Brian Sullivan provided technical support and Woodard compiled the ratings results. Raul Guerrero handled repeated shipping and reinstallation of equipment; Kris From prepared the graphs. The National Gallery lent their facilities and services for the meetings held in Washington, D.C. I am grateful to Henry Millon for his advice and to Frances Biral, who saw to the myriad arrangements and assignments that arose. My special appreciation goes to the art historians who participated in the study.

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1. For examples, see J. Cash, "Spinning Toward the Future", *Museum News* **63**, No. 6, 19–22 (August 1985); L. Corti, D. Wilde, U. Parrini, and M. Schmitt, eds., *SN/G: Report on Data Processing Projects in Art*, 2 vols. (Pisa: Scuola Normale Superiore; Los Angeles: The Getty Art History Information Program, 1988).

2. Musee d'Orsay, *The Orsay Museum Audiovisual* (information brochure).

3. For the purposes of this study, photographic reproductions, rather than original works of art, were the presumed source for scanning. The direct capture of objects introduces considerable technical complexity, including many new decisions, such as the photographic conditions and lighting, that are nontechnical and relate to content.

4. P. A. McClung, "Costs Associated with Preservation Microfilming: Results of the Research Libraries Group Study", *Library Resources and Technical Services*, (October/December 1986) pp. 363–374.

5. Although McClung's study focused on microfilming entire books, she cites the cost and time for individual frames, as is the norm for visual archives, where each image is a separate entity.

6. Cash [1].

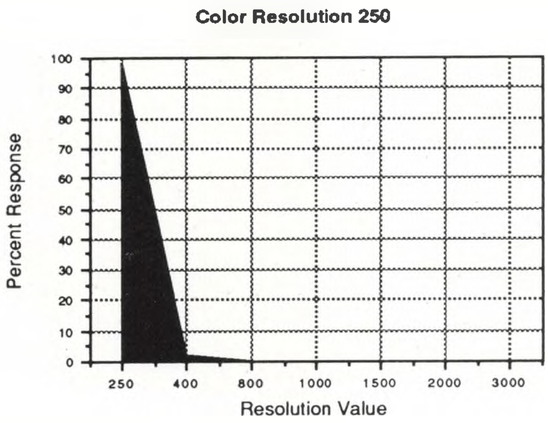
7. Incremental improvement of image quality through progressive transmission is one approach under review by the CCITT and ISO Joint Photographic Experts Group for transmitting images. Progressive transmission sends a succession of encoded layers that incrementally improve quality levels.

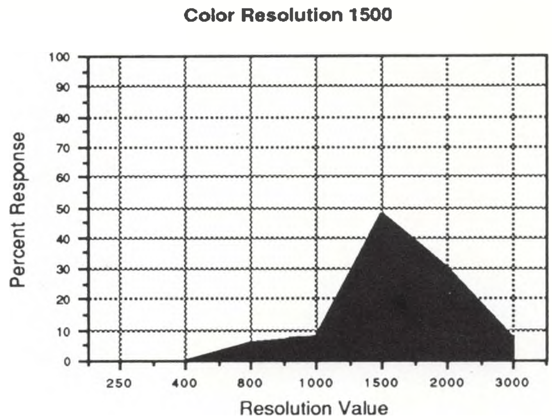
8. See the classic study by T. S. Huang, "PCM Picture Transmission", *IEEE Spectrum* **2** (December 1965) pp. 57–63.

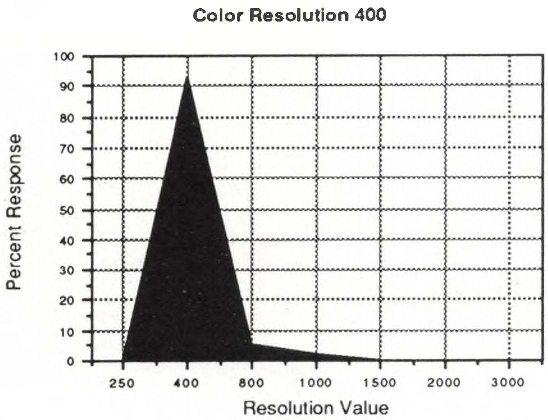
9. Gerald H. Jacobs, *Comparative Color Vision* (New York: Academic Press, 1981) Chap. 6.

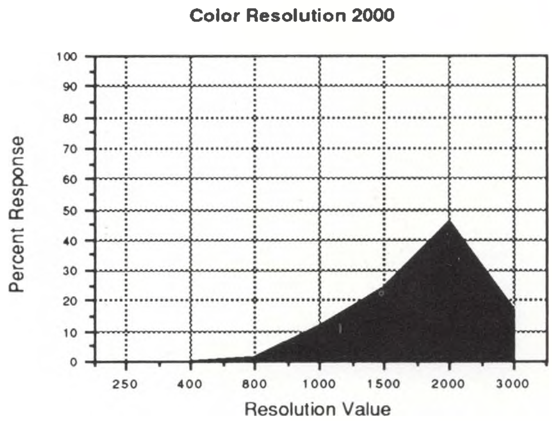
Appendix

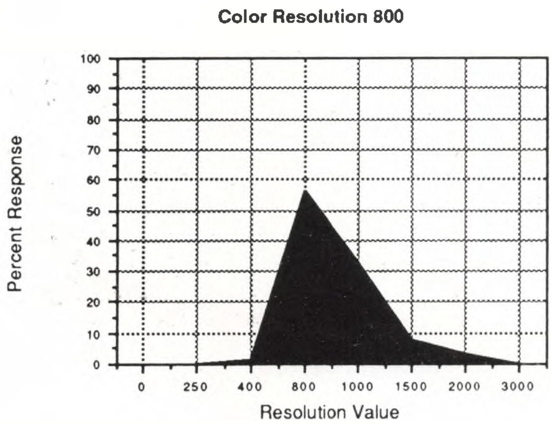
(see following pages)

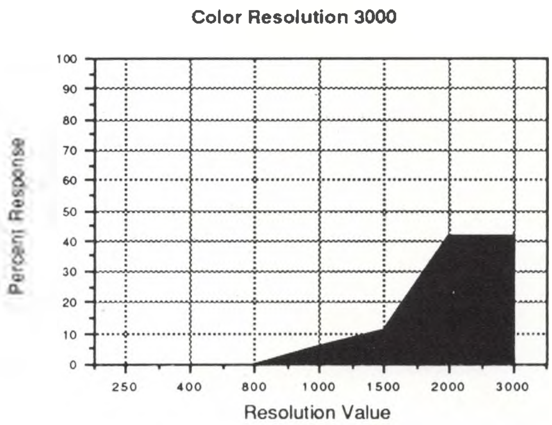












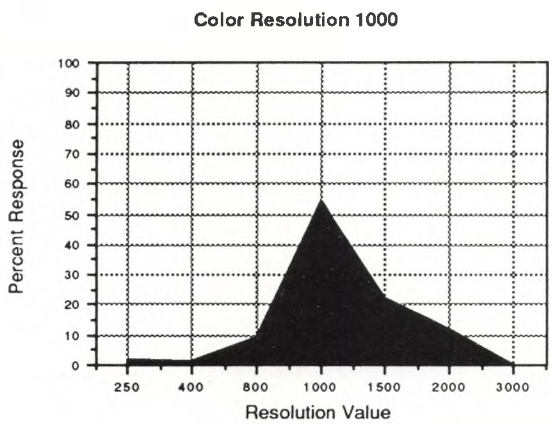


Fig. A1. Graphs for individual resolution test values, color.

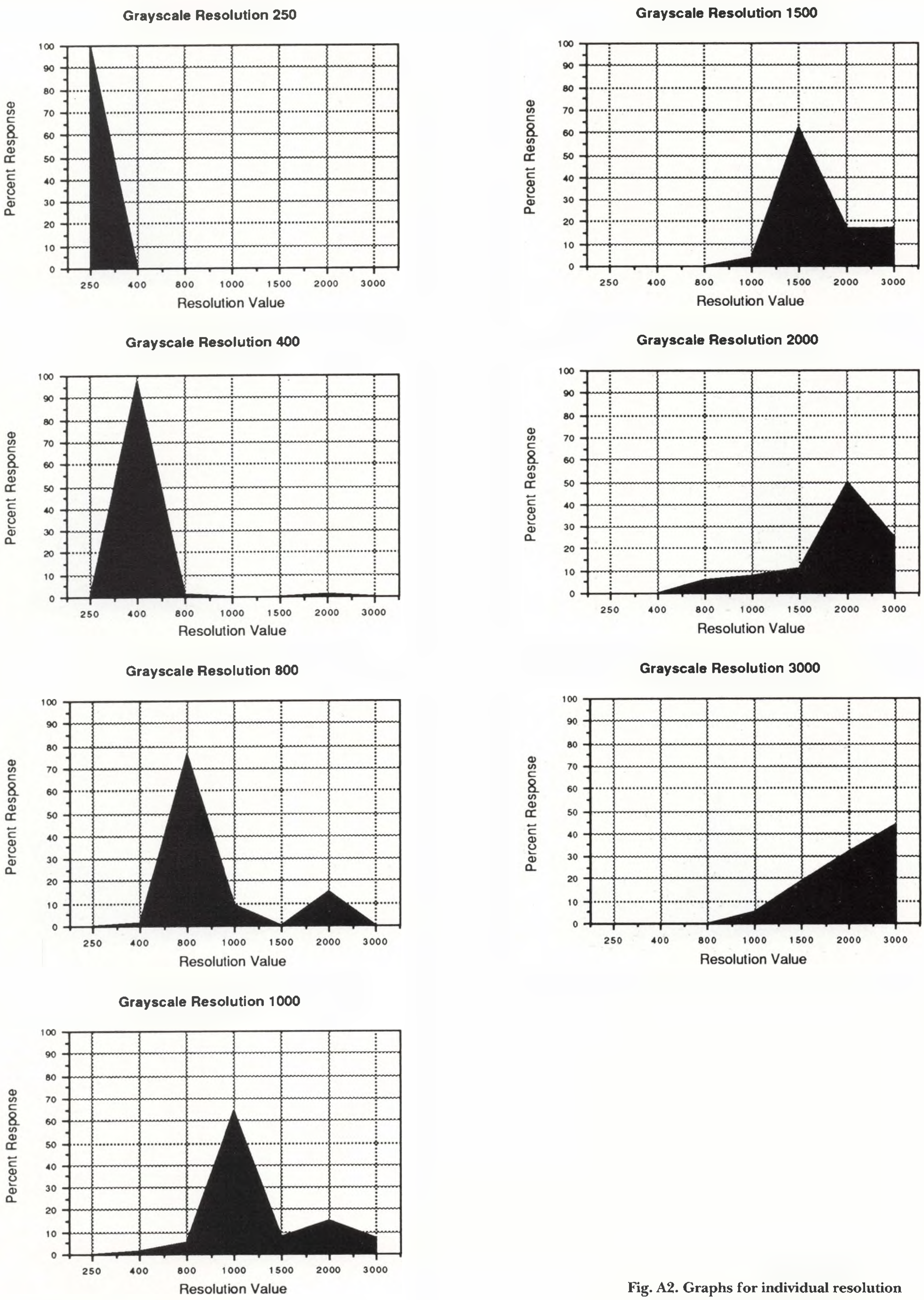


Fig. A2. Graphs for individual resolution test values, grayscale.

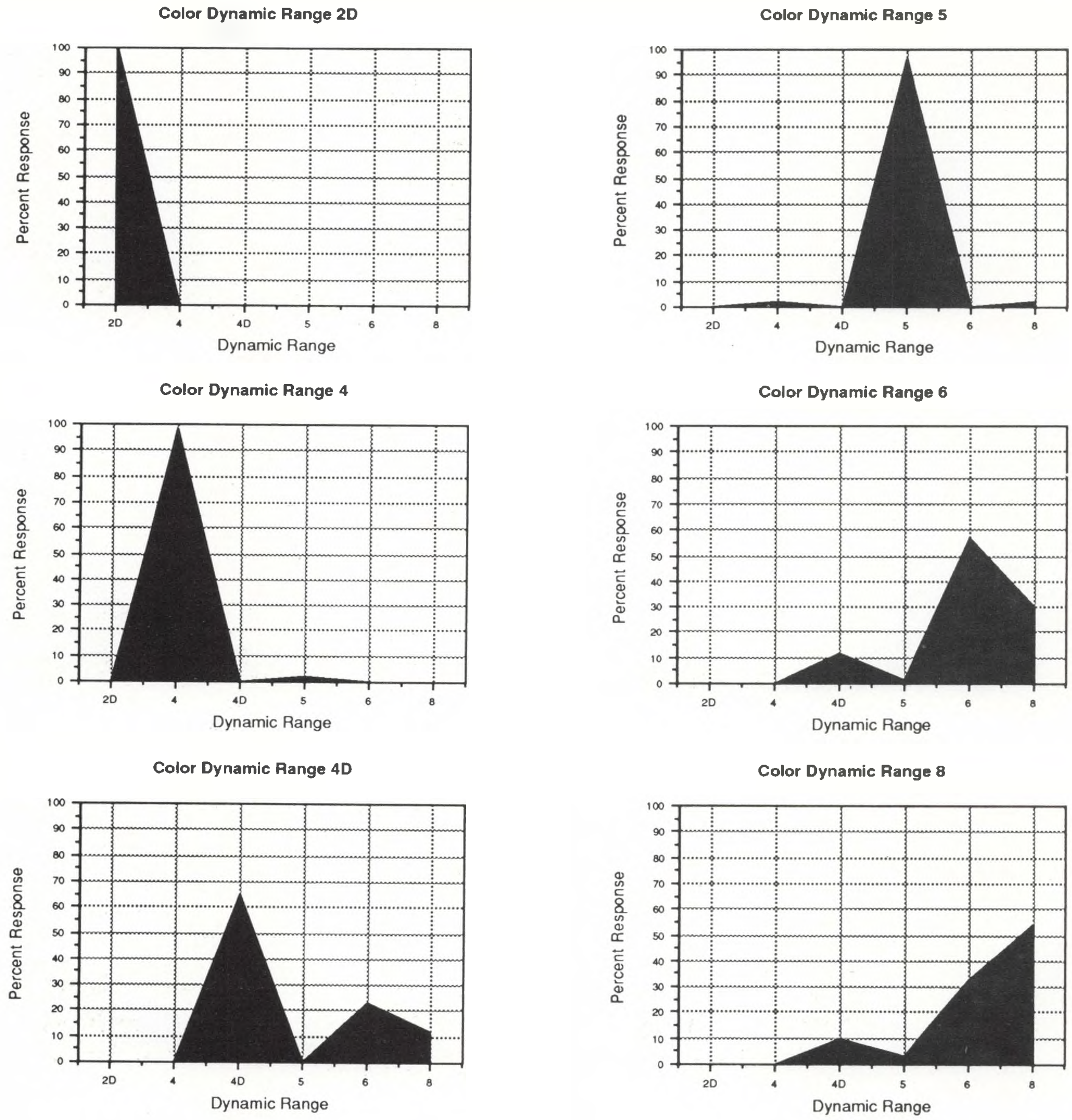


Fig. A3. Graphs for individual dynamic range test values, color.

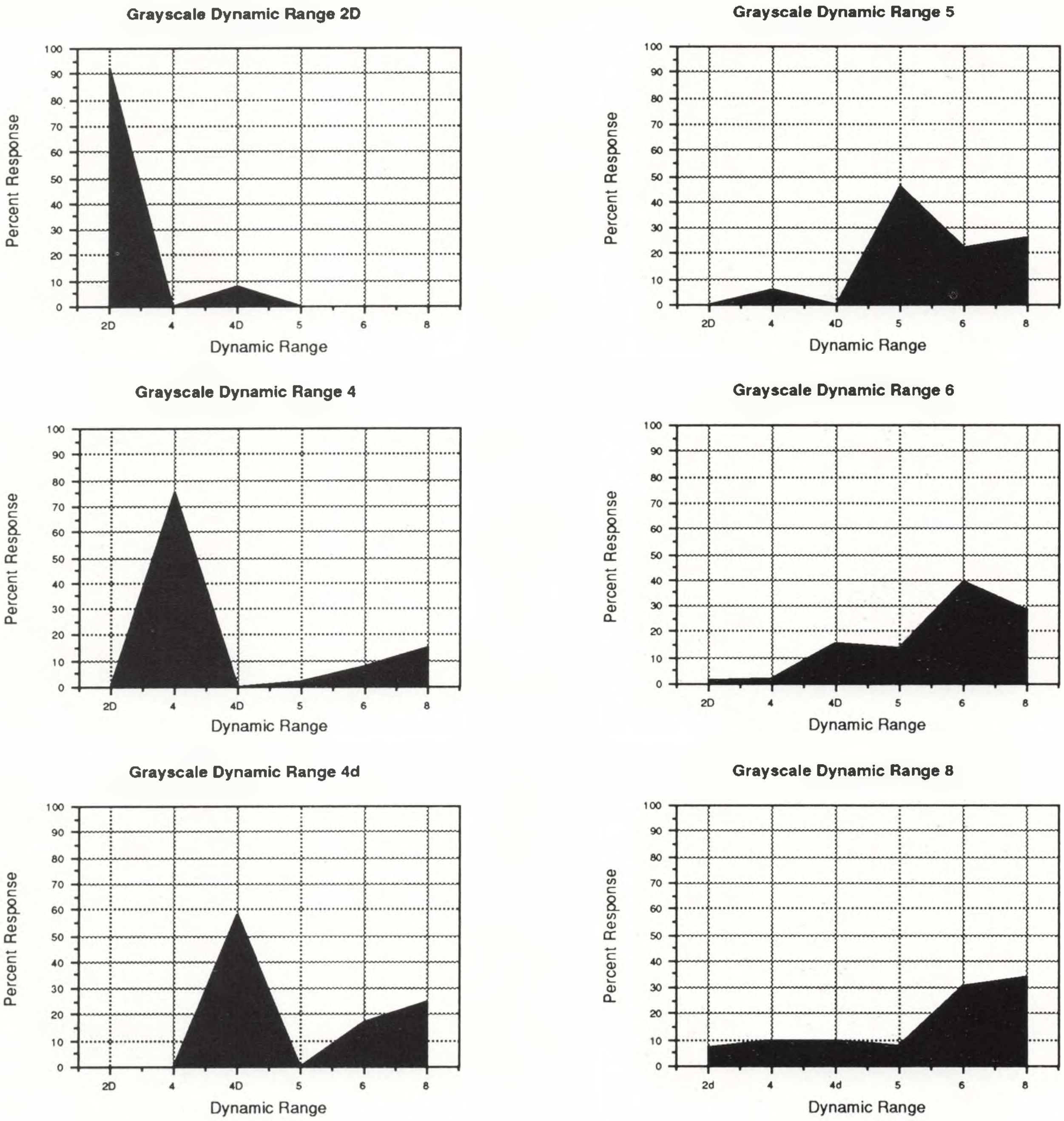


Fig. A4. Graphs for individual dynamic range test values, grayscale.

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Computer Graphics as Allegorical Knowledge: Electronic Imagery in the Sciences

Richard Wright

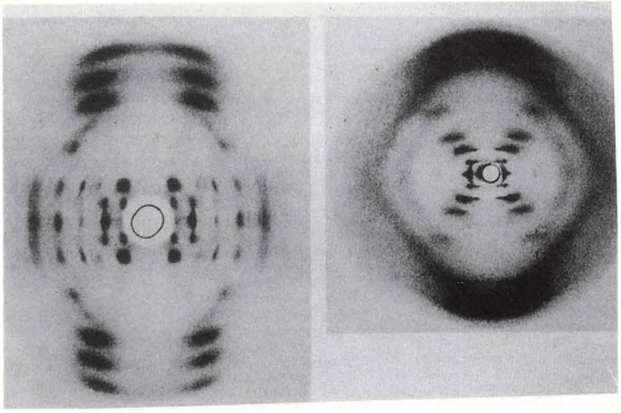
ABSTRACT

This informal paper studies the effects of the recent introduction of computer-generated imagery on the practice of science and its function in understanding the world. It intends to introduce the subject of computerised visualisation for scientific purposes into a wider debate, to show the diversity of issues involved—scientific, cultural and philosophical—and to build a context in which they can be critiqued. The author seeks to show the variety of scientific imaging and its influences on scientific knowledge; as both experiments and results are increasingly expressed in terms of imagery, the image assumes an integrity of its own and the object to which it refers becomes obscured. This leads to a shift of focus away from abstract theory as the embodiment of knowledge to the ascension of an allegorical image-based science with computer graphics as its natural language.

In 1987 the Panel on Graphics, Image Processing and Workstations of the U.S. National Science Foundation published its report on Visualisation in Scientific Computing (ViSC), which recommended that all scientists and engineers should be provided with their own computer-graphics workstations as well as access to advanced computer visualisation facilities [1]. Thus has the agenda now been set for the majority of scientific work to be conducted through the medium of computing in general and computer graphics in particular. Although the impact of such technology on the practice of science is not in question, its implications for the nature of scientific knowledge itself have received little attention.

The orthodox position on scientific use of computer graphics views it as an almost prescientific tool for the analysis of empirical or other data—a preliminary and informal stage at which the scientist can gain signposts for further promising investigation by more traditional and rigorous means. But in fact the whole context of scientific work is changing. Scientists now place more emphasis on being able to 'see' what they are doing. They desire to change the level of abstraction at which they are working from one of purely conceptual and ideal objects to their realisation in dynamic simulations and visual feedback [2]. And this in turn shifts their commitment away from abstract theory and numbers in scientific investigation to a concentration on its visual forms, using intuitive perceptual qualities as a basis for evaluation, verification and understanding. The ViSC panelists refer to this process as merely "putting the neurological machinery of the visual cortex to work", but the mechanical and utilitarian terms in which this view is expressed should not hide the fact that the cognitive role of imagery in the minds of scientists goes much deeper. Scientists have always mentally 'visualised' problems, but now the imagery is externalised, objectified, and constitutes understanding itself rather than making theory more accessible.

Fig. 1. **DNA X-ray diffraction photograph, from J. Darius, "A Concise History of Scientific Photography", in *Beyond Vision* (Oxford University Press, 1984). Reprinted by permission. R. G. Gosling and M. H. F. Wilkins, 1950 (left), R. E. Franklin, 1952 (right). The picture on the right was finally decoded after careful measurement by Crick and Watson as indicating an intertwined double helix structure, after Franklin herself had apparently lost interest in the helix hypothesis.**



Many characteristics of computer graphics conspire to make scientific imagery in itself a constituent of knowledge apart from its value in crystallising concepts. These characteristics include the continuous surface of many computer images that lack discrete pictorial elements with fixed diagrammatic references, the inscrutable algorithmic processes by which formulae and data are transformed into visible output, and the multitudinous array of visualisation techniques and parameters possible, often of equal intrinsic validity.

In the study of complex phenomena many problems can be answered only by direct simulation or collections of data far beyond the scale of human assimilation. These activities can often be expressed only in terms of imagery. Furthermore, in the inexact sciences that attempt to model highly contingent events, a form of 'pure' simulation is emerging that seeks only to reproduce the behaviour of phenomena without any pretence to a theoretical understanding. In these cases the generation of visualisation imagery could assume the status of a common epistemological currency—the creation of a visual knowledge.

Visualisation in Scientific Method

The drive towards a totality of understanding or 'finality' in scientific research has resulted in the desire to acquire immense amounts of information about a phenomenon to

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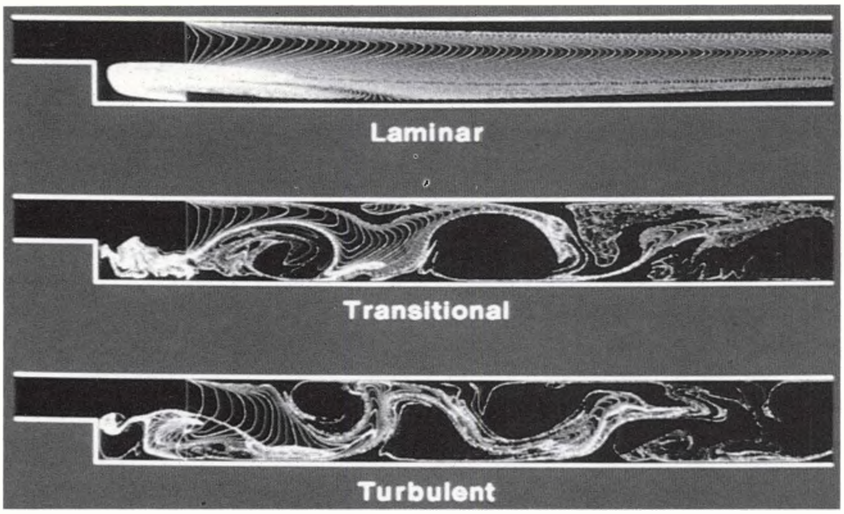


Fig. 2. Real-Time Bubble Injection. J. B. Salem (Thinking Machines Corp.), J. A. Sethian (Univ. of California, Berkeley) and A. F. Ghoneim (MIT), digital image, 1988. (Photo: J. Salem) Copyright 1988 Thinking Machines Corp. Reprinted by permission.

ensure certitude and has led to what has become known as the 'firehose of data' effect. For years satellites and radio telescopes have continuously transmitted to laboratorie‹ on earth signals that scientists simply do not have the facilities to examine efficiently and must 'warehouse' until techniques become available. Added to these data are new channels of information provided by geophysical instrumentation, medical scanners and the results of supercomputer simulations, the resolutions of which also constantly increase. The sensitivity of events in complex natural systems to nebulous external influences, as well as the possibility that the most innocuous observation might make some essential contribution, has brought scientists to the classical dilemma of empirical research.

Mechanical instruments were first used at the stage of experimental testing, to allow empirical data to be unambiguously apprehended and measured. Controlled laboratory conditions were required to purge perception of human error and allow factual observation to flow into the scientific consciousness unimpeded. But in order to compare experimental results with statements of theory it was still necessary to express them in similar terms. Much effort was made in the first decades of the century by the logical positivists to develop a 'language of observation', a language of neutral terms into which both theory and fact could be translated in order to evaluate their 'correspondence'. It was this final project that proved vulnerable to the criticisms of conventionalist epistemologists like Thomas Kuhn [3]. There is no way to decide on a completely objective standard of reference; the terms in which experience is ordered and recorded cannot be theory-neutral. Although logical positivism as a philosophy has passed into history, its ghost lingers on in the form of a dogged adherence to the notion of scientific activity as a formal matter of deducing mathematically defined relationships from the observable quantities that present themselves, while paying lip service to something vaguely called 'scientific creativity' to account for the innovations and deviances that do not fit this pattern.

Scientific insight does not flow uninhibitedly merely from the diligent recording of observations. Furthermore, the assimilation of these facts for the deduction of hypotheses is practical only on a small scale, for reducible, mechanical or localised phenomena. Outside these narrow boundaries scientists have the choice either to find methods to automate the analytical process or to supplement the limitations of empirical research with more efficient theory generation. The possibilities offered by computers and graphics make both these approaches feasible.

Contemporary research into the psychology of perception strongly suggests that the ability to see forms is the result of a learning process, based on the exposure of the developing infant to the visual characteristics of its surroundings [4]. This means that the power of perception, though repeatedly tested against everyday situations for accuracy, is dependent on the contingency of the experiences of each individual subject. The existence of simple optical illusions indicates that these learnt responses to stimuli are vulnerable to errors in unfamiliar circumstances. It has also come to light that even the low-level orientation-detecting cells of the visual cortex are not entirely innate but need to be fully exercised if they are to develop correctly; otherwise, basic perceptual abilities will be impaired [5]. In principle, therefore, we cannot with any certainty trace the results of the process of visual perception to the object that caused them: we cannot be sure of what we see. Although this fact seems to militate against the use of visualisation techniques as an analytical aid, it is also the main reason that visual perception is so powerful as a tool. The extreme situations that produce optical illusions do not occur in most applications of computer graphics. The study of graphical depictions usually involves a simple visual monitoring or feedback of computational processing. But the ability to perceive tenuous relationships between subtle fluctuations in data derives from the flexibility and sensitivity of vision that is the flip side of its ambiguity. This unpredictability permits 'creativity' in knowledge generation and allows alternative and potentially more valuable hypotheses to come to the surface for consideration [6].

If empirical research is to remain practical in an age of increasing data bandwidths, more powerful methods of analysis must be developed, particularly visualisation techniques. But these retinal methods of intuitive research harbour no pretensions to the aloof objectivity of an observation language. Computer graphics, with its variety of technical contingencies and perceptual subjectivity, is anything but a neutral analytical tool, but this is precisely its strength—and the weakness of traditional analysis, now reduced to post-rationalising the visualisation process. Mathematical rigourists can remain skeptical of the value of this retinal dissection and maintain that 'pictures don't prove anything', for what reason could there be to investigate one feature of our data over any other just because it looks more interesting? But this is the situation that we now must recognise: to trust our eyes and accept that we can no longer thoroughly analyse empirical data down to the last mote, if we wish to extract useful information.

Nor can we investigate complex systems by drastically simplifying them into manageable sets of equations. Phenomena do not have to be reduced to fundamental laws in order to be understood, but need to be shown as they work themselves out in practice [7]. When these patterns of behaviour are expressed visually they can be comprehended by intuition in their full complexity.

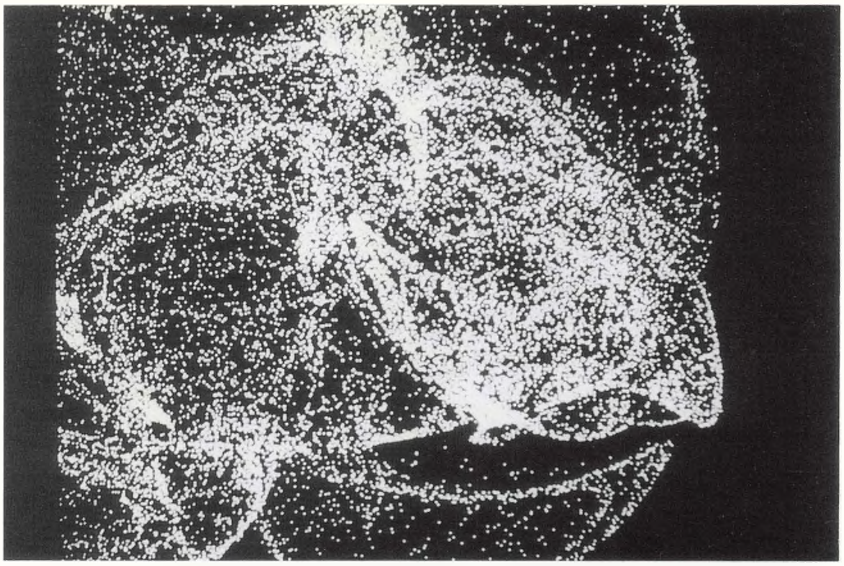


Fig. 3. Malcolm Kesson, strange attractor, digital image, 1989. Reproduced by kind permission of the artist. All rights reserved.

Computer imaging strategies have now become not only the means by which knowledge is derived, but also the way it is presented and communicated—in effect, the way knowledge is constituted in the mind of the scientist. The goal of much current research in computer graphics is to increase the efficiency of disseminating research results in forms of imagery. In electronic scientific journals, papers are published as electronic mail accompanied by digital graphics and animated sequences as well as interactive graphics [8]. This enables readers and reviewers to study experimental evidence in much the same form that the author experienced it. Once again the abstract theoretical substrata of natural laws are displaced from the focus of attention and we become more aware of science as a consensual process, accepting the experimental techniques that best satisfy the pragmatic results we desire. Mathematical algorithms can generate effects that agree with observations, but an abstract unifying concept to explain *why* they work is slipping ever further over the epistemological horizon, leaving us gazing wistfully at its afterimage on our VDU (visual display unit) screens.

The visual properties of numerical imagery have to be accepted as sufficient to demonstrate an 'unseen' natural force at work, or at least as a preliminary indicator of such. This view implies that the visualisation of phenomena can be identified with the phenomena themselves. Such is the case where computer models have been used as substitutes for experimental testing, especially in areas that touch political and ethical problems such as building atomic weapons or testing medicines and cosmetics on live animal subjects. In instances where graphics are used to visualise something without direct reference to the external world—such as an abstract system of pure mathematics (which formally any algorithm could be)—imagery may assume the status of a 'real' object. Without anything to compare it against, it seems that this must be what a particular mathematical object actually 'looks like'.

Now that mathematical as well as other scientific objects can exist on the retinal as well as theoretical level, we might enquire what effect computer graphics has in realising scientific research as imagery—in the form of electronic visualisations rather than the ruler and compass of yesterday—how computer graphics affects our perception of these objects and our reaction to them.

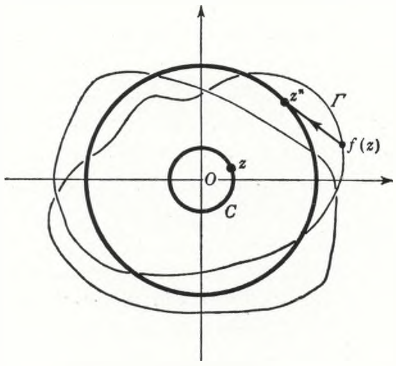


Fig. 4. Fundamental Theorem of Algebra. Topological proof that "in the field of complex numbers every polynomial equation has a root". The complex numbers here are 'visualised' as points in a plane to aid conceptualisation. Source: R. Courant and H. Robbins, *What Is Mathematics?* (Oxford Univ. Press, 1941) p. 270. Reprinted by permission.

THE IMAGE AS OBJECT

The Phenomenology of the Electronic Image

Much scientific visualisation does not involve computer graphics [9]. In fundamental physics the bubble chamber is used to record the paths of subatomic particles resulting from particle accelerator experiments. X-ray diffraction patterns are widely used in the fields of atomic radii, crystallography and molecular biology. But if we compare examples of these with recent electronic visualisations of the dynamics of turbulence or archaeological reconstructions we see clear differences in the quality, the phenomenology, of two types of imagery (Figs 1 and 2).

The surface of an electronic image is 'photographic' in quality. It is composed of smooth tones and graduations rather than keenly delineated shapes and edges; it is unstable and fluid rather than linear and graphic. The pictorial elements that make up these images are not sharply differentiated. They are often difficult to measure and resist strict zones of demarcation [10]. As a result, each element of the image may not correspond straightforwardly to some property of the phenomenon it is supposed to visualise. Such images are not diagrammatic in function; since they generally lack lines and shapes that might represent forces or components, their shifting and floating surfaces cannot easily be split up and labelled. Many pictures are 'holistic' in character: the points that make up a Heron map depend on the mapping function as a whole and not on any particular coefficient or term (Fig. 3). We cannot isolate a group of pixels and analyse what they represent in any useful way. Such an image is to be perceived for subtle visual relationships between areas, qualitative properties for which the human eye has retained its superiority over measuring

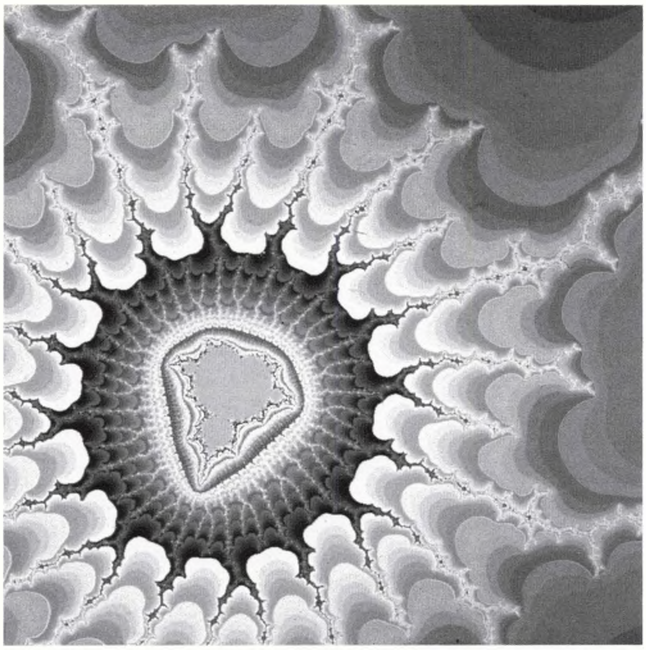


Fig. 5. Richard Wright, Mandelbrot set, digital image, 1987.

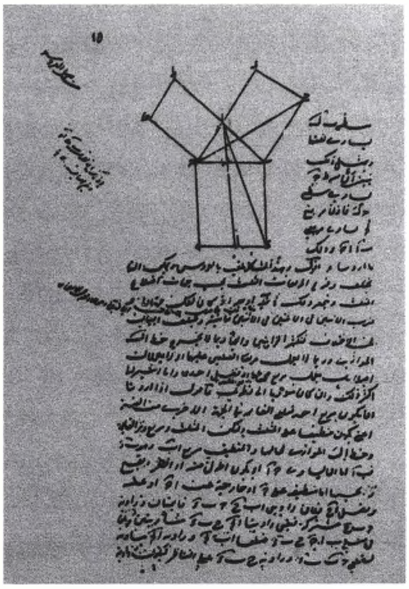


Fig. 6. Pythagoras Theorem. Arabic proof from Euclid's Elements.

devices [11]. This is of course why visualisation has become so important, because scientists need to be able to detect very subtle relationships in phenomena that are not reducible in any obvious way to simpler formats.

The information in a computer image is much richer than that in a diagram, because the form of the information is different. It has latent content, several alternative interpretations being possible [12]. A lexicon for reading synthetic imagery is not always conveniently available, because the properties of the function the image represents are not always known beforehand. New scientific imagery needs to be analysed like artistic imagery, semantically rather than lexicologically. Its surface is composed of continuous signifiers as in a conventional photograph or film, not a series of discrete signs and symbols each with their associated meaning as in a graph or plan (Fig. 4). Computer-generated graphics are not expressions of abstract theoretical explanations but rather visual analogues of events. In them, we have an effect of the 'video culture' in its most potent form: scientific knowledge shifting from a *linguistic* base to an *image* base, replacing the positivism of the sign with the semantics of the object.

Electronic imagery is by definition created by no manual or tangible process. On examining a synthetic image we see that it is too delicate, too precise to have been executed by the human hand (Fig. 5). It does not look 'mechanistic' either, and lacks the regularity or symmetry that we associate with graphs and chart plotting. In fact the image shows no evidence of craftsmanship, no brush marks, perhaps no straight lines. This leads to an associated phenomenological effect of synthetic imagery—that *it has not been made,* that somehow it has occurred naturally, like the swirling patterns of oil in a puddle. It is as if it has been *invoked* by human agency but not *created* by it. And this effect need not be entirely a perceptual effect, for such is the sophistication of modern digital processing and image generation that it is most unlikely that viewers can grasp the method whereby numerical data and formal relationships have been transformed into the tableau that confronts them. And even if they did have greater knowledge of the process, or only a general one, the gap between conceptual understanding of the means of production and the perception or visual understanding of the picture on the VDU is so great as to render the one seemingly irrelevant to the other. Some graphics generated by functions with chaotic dynamics are mathematically as well as phenomenologically indeterminable, constantly changing and resisting any attempt to resolve their pattern of growth.

Graphics users find themselves increasingly distanced from the products of their labours. Even for computer programmers there quickly comes a moment when they no longer retain precise understanding of their own algorithm, and indeed this is where part of the excitement of programming comes from—the feeling that the algorithm has taken on a 'life of its own'. Usually this perception does not impair an individual's effectiveness; programmers do not need to get to the bottom of every function they use, nor do users need to be able to fathom the deepest complexities of the packages they work with. But the level of comprehension of the process of image generation always affects its perception. The result is a dislocation from the final output. When staring at the visual subtleties of a numerical image, its creators simply do not know how it got there. This *deterministic alienation* reinforces the visual autonomy of computer imagery. Our inability to empathise with the logical complexities of the machine encourages the emergence of a *digital mythology* to compensate and account for the more dimly apprehended events seen on the screen. It most often manifests itself as a tendency to anthropomorphise, historicise and romanticise every aspect of the machine (as in anecdotal accounts of programs that work only for their creators and no one else).

The authority associated with antique geometric diagrams was based on the fact that they were built up line by line from relationships between the simplest conceivable pictorial elements. Visualisation graphics are derived from mathematical relationships implicit in procedures rather than from explicit geometrical ones. Rather than directly corresponding with the workings of natural forces and of dynamical mathematical functions, intuitive pictorial relationships only allude to or imply them. The resulting absence of the purely referential function in the image distinguishes it from the function of the diagram or graph (Figs 6 and

7). As well as providing a powerful and flexible context for the visualisation process, this dislocation of the image from its referent reinforces its perception as an object in its own right, independent of the data it refers to or even the process that generated it but can usually no longer be inferred from it. It presents itself as a new source of knowledge.

Representation and Visualisation

The phenomenology of electronic imagery, or the way it is perceived, prompts a reassessment of its function as a transmitter of information. But other developments in the role of scientific imagery in the formation of knowledge also require a greater distinction between the terms *representation* and *visualisation.*

The object of visualisation lies implicit or latent in digital memory, waiting to be algorithmically unfurled. The image is constructed by formal rules from this symbolic structure, and its specific realisation depends on the researcher's particular line of interest and the properties of the database under investigation [13]. Because no unique representational scheme is employed, these images are commonly referred to as visualisations—our ability to create that which is visible.

Computer images exist informally in an intuitive space with other visual objects, but they derive from a formal space in the computer's memory. But substituting the term *visualise* for *represent* we create a context in which the image can exist as an independent visual object in its own space and at the same time retain a formal relation with the virtual logical space inside the computer.

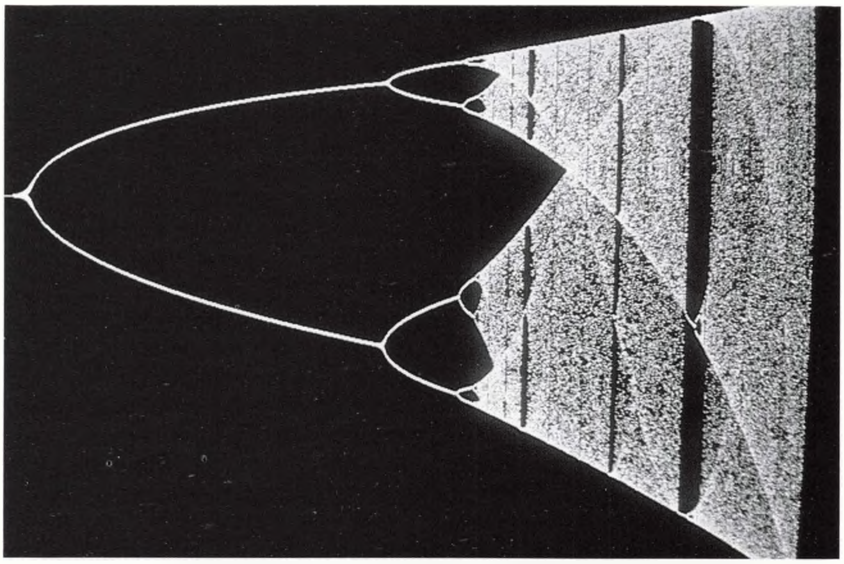
A *representation* re-presents an object in another form or substance such that its essential features remain or directly translate into that new form. *Visualisation* is a specifically selective representation of data in order to produce the desired knowledge. It models certain variables and ignores others, uses certain types of geometry or scalings or filters to make some aspects more apparent and perceptible. Although all modelling involves a simplification of reality, what we have here is a series of functional analogies rather than an abstraction of essential features; knowledge is contingent on visualisation techniques and retinal apprehension. A rendering algorithm has the power to externalise in quite arbitrary forms, from plotting quantities as colour fields to interpolating three-dimensional surfaces ready to be illuminated and viewed. Realistic image synthesis should not be the default option for visualisation; it is sometimes disadvantageous for scientific graphics. The properties that we visualise often have nothing to do with the properties of three-dimensional surfaces; this would create a conflict between the aims of visual realism and epistemological realism. Smoothly shaded geometries casting multiple shadows and reflections can easily confound the observer's understanding and at the same time increase the psychological effects of deterministic alienation by its intimidating photorealism (Fig. 8).

Most urgently researched are methods powerful enough to 'steer' the computation of an object, change the parameters of mathematical functions, select channels of data and alter the rules governing the generation of imagery. A simulation can be adjusted to produce the most satisfactory results, and its effects can be evaluated immediately. Work can begin in the exploration of this function space. In all cases this representation has no truth value; models and rendering techniques as chosen to give the most useful results as efficiently as possible, and many formal mathematical techniques can be applied without strict regard for their appropriateness to a particular real-world situation. It is precisely this flexibility that makes visualisation analytically valuable in the struggle to come to terms with the complex phenomena that science is now tackling. This is the epistemological promise of visualisation. Freed of its representational ties, it usurps the authority of measurement and quantity with the humility of resemblance and visual fluidity.

It is more accurate to think of the abstract data that form the basis of the visualisation scenario as a raw unformed state rather than as the complete embodiment of the images that arise from them. Perhaps data could be completely random and still render a meaningful form, as in synthetic texture generation. These functions generate a new sensory object, an image existent only in this tangible state. The computer still provides a means of contact between different visualisations drawn from the same source, but these data offer no more than a *mediatory fabric* from which to extrapolate its diverse materialisations. In fact the database can be said to remain undefined as an accessible object until a process to externalise it has been applied. Then it is *realised,* made real before our eyes. Visualisation provides accessibility to abstruse logical structures and a means of forming an intuitive conception of the subject.

Computational scientists do not use one single format for viewing their results. They habitually apply a range of techniques to attack the problem from a variety of directions. In the sprawling field of molecular graphics, each visualisation of chemical compounds concentrates on a particular property [14]. Molecules are represented using a whole vocabulary of spheres, rods, spi-

Fig. 7. Richard Wright, Verhulst bifurcation, digital image, 1989. The familiar version of the diagram plotted after the 'transients' have died away—the initial unruly path of the attractor before its periodicity settles down and is easier to observe.



rals, iso-surfaces and colour fields that describes their shape, structural features, electrical potential and molecular dynamics.

Just as a child learns of the qualities of a string of beads by picking them up, turning them over and examining them from different angles, so the best way to form an understanding of a multi-dimensional structure is to explore as many of its aspects as possible. We do not understand a cube if we only view it head on [15]. This approach assumes that each presentation of the object has equal value, even though it may ignore some factors, and that no universal view can encompass all the others [16]. Some images visualise other images. The Mandelbrot set provides a guide to the parameters of the Julia sets, telling us what boundaries to expect, like a visual taxonomy of mappings [17]. The results of simulation imagery are often further processed and visualised, such as by taking animations of vibrating molecules and plotting various paths separately to show how the energy is distributed between chemical bonds [18]. As each visualisation is perceptually different, so no particular visualisation of the 'object', data, function, and so forth is intrinsically more valid, closer to the 'true nature' of the object than any other. We can never really say what the object is; we see only apparitions of it. If the only way we can gain understanding of our experiment is through visualisation techniques, then the visualisations define that object, and the object 'in itself' disappears for good.

A visualisation program is many faceted. Referring to each facet as a manifestation of the same object does not unify them but causes the object to evaporate. Raw numerical data are meaningless to human sensibilities and therefore can no longer count as an observable entity. This awareness that the fundamental object we visualise can become obscured by repeated renditions and resurrected as intuitive imagery is reflected in its unreachable or inexplicable structure or dynamics. We often gain knowledge of natural phenomena by constructing analogous algorithms to model these situations by working in parallel with their observed functioning. Visualisation is one further level above this process, providing access to abstract systems through visual metaphors.

We will now briefly broaden the discussion to include this epistemological context in which computer graphics makes its contribution.

Allegorical Knowledge

Model or Simulation

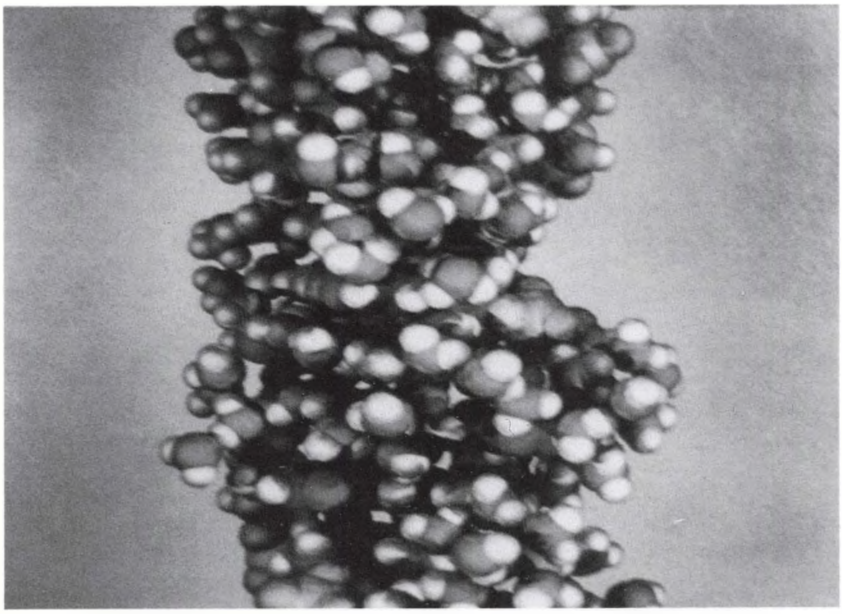
Cellular automata are mathematical objects that serve as models for a wide variety of natural processes (Fig. 9). Monitoring helps pick out characteristics of their intricate structure for further investigation by more rigorous means [19]. But some of their most significant properties derive from the fact that the fixed deterministic rules that control them do not preclude behaviour or states that are unpredictable, given their initial starting conditions. We cannot verify these rules except by explicitly generating them, by a 'try it and see' approach. Once these automata have begun to grow there is no way of telling whether or when they will stop, attain a regular pattern of growth or just carry on indefinitely in chaotic fashion.

These automata are called 'computationally irreducible'. This means that an automaton is one of a class of processes that are equivalent in formal terms to the operation of a digital computer—they exhibit behaviour capable of processing information in a 'universal' way. The initial conditions of the automaton are similar to the data we give to a program, and the evolution and finishing conditions (if it ever comes to a halt) are like the solution or result. Because of this, any way of predicting the result from the starting conditions alone would be equivalent to creating a new faster computer. Because we believe that the current functional definition of a general-purpose computer is composed of the barest minimum of possible operations, no such short-cuts can exist. It is thought that many natural systems also exhibit this property of being universal information· processors. This situation means that many systems cannot be reduced to the abstract laws and formulas we are familiar with, and that we can investigate their properties only by directly simulating them.

Many phenomena such as biological, physical and social structures are so complex that scientists have effectively given up trying to abstract general 'models' from them. They often resort to simulation techniques to get results. Scientists have always attempted to understand the world, but the form of this understanding differs from age to age. To understand a phenomenon in terms of its simulation is generally not to understand its underlying principles. A certain phenomenon may have different 'explanations', just as the workings of the mind can be simulated in different ways. In this case knowledge of something is analogous or allegorical knowledge—not final, unique or certain, but conventional.

In the disciplines of the so-called inexact sciences—psychological, social,

Fig. 8. William L. Luken, z-DNA (animation), digital image, 1987. Ray-tracing was used for this animation to render shadows cast by multiple light sources and interreflections between molecules. Unfortunately this also greatly increased the difficulty in trying to make out which is which. Source: IBM Corporation, Kingston, NY.



economic—the systems under investigation are so complex and so contingent on external factors that simulations developed to cope with these problems frequently have little theoretical justification. The mathematical description of cost analysis, for example, bears little relationship to a theoretical model of the dynamics of the situation and appears to be merely a string of arbitrary coefficients. The final form of these equations are determined from a vast amount of statistical information of past costing performances; the computer adjusts the coefficients until they fit the data. This computational technique is known as *calibration* [20]. The model must be recalibrated to fit each particular application. In this kind of activity no theoretical understanding is either pertinent or forthcoming. Not even a basic mathematical description is seen as useful, but under commercial pressures scientists have found this approach to be the most successful.

The use of computers to solve chess problems by exhaustively searching a large number of combinations of moves many turns ahead is commonly regarded as a clumsy, brute-force and merely transitional technique. But it is enthusiastically applied in crypto-analysis and molecular research [21]. In the latter discipline, the design of a new drug involves theoretical guidance from molecular chemistry in order to cut down the number of alternatives to be tested, but the onus is still on the power of the computer to perform countless checks in a trial-and-error search for the most effective solution.

In this kind of research, as opposed to reductionist analysis, the images and interactive spaces of simulations are understood more and more on the same level at which the simulated phenomenon is experienced. The gap between our conceptualisation of the sensory world and our sensory experience itself disappears, resulting in less tendency to subordinate one to the other. This epistemological background informs our use of computer graphics in the sciences.

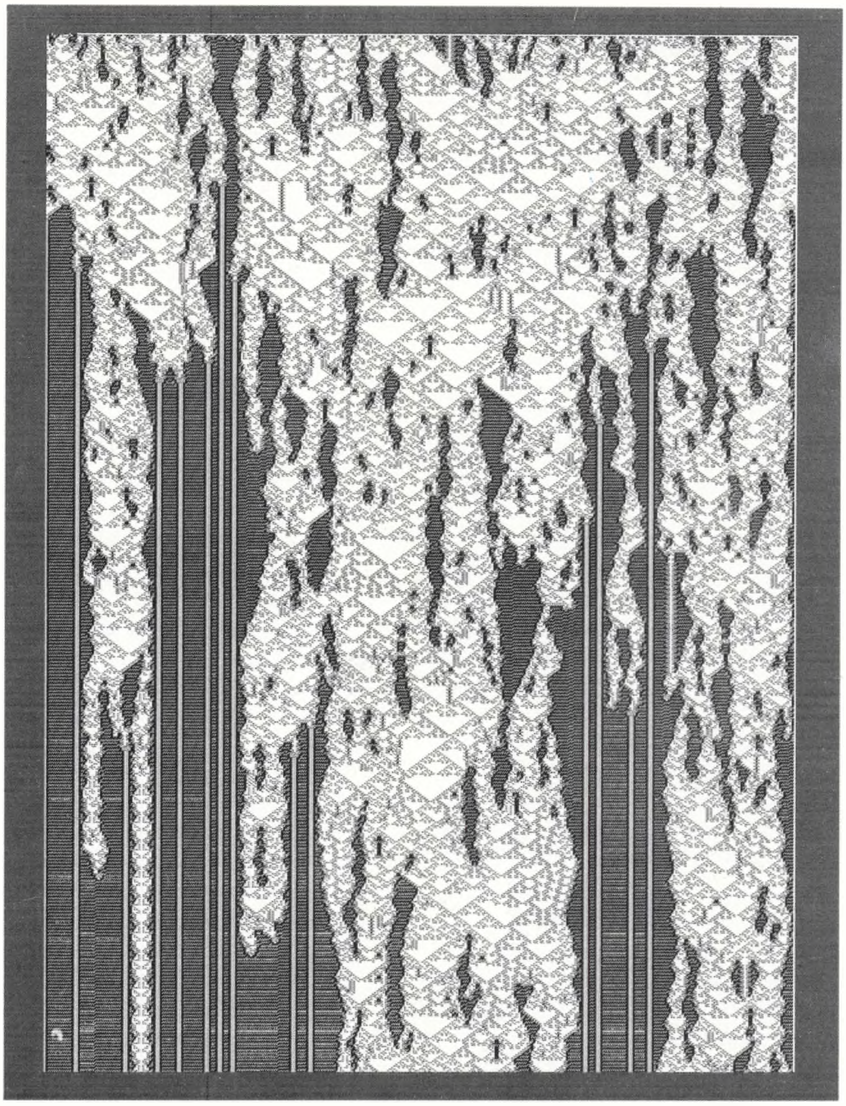


Fig. 9. Aurelio Campa, cellular automaton, digital image, 1989. Reprinted by kind permission on the artist.

Can Computer Graphics Be Science?

The many different solutions to simulation problems are reflected in the diversity and flexibility of visualisation tools to realise the results [22]. To maintain this adaptability and efficiency, the justification and assessment of new research in computer graphics now invariably exemplifies the pragmatic rather than the methodical approach. This computationally intensive but commercially profitable discipline demands always faster, more flexible, more efficient algorithms. A multiplicity of solutions is offered. Jean-François Lyotard refers to this characteristic of 'postmodern' science as the pursuit of *performativity* [23], the pressure in a free-market economy to maximise the input/output ratio of production and to promote a new breed of technoscience. In this new commercial context, research is purposefully directed towards solving practical problems and providing profitably useful results rather than pursuing the nineteenth-century ideals of truth, justice or human emancipation. Science need not gain pure knowledge at all, in the sense of a conceptual understanding, if this has no useful bearing on the task at hand: science has only to *perform*. A copy of any conference proceedings shows that computer graphics is a science of this type.

The ViSC report devotes a significant amount of time to equating the health of computer graphics research with the scientific base of industrial enterprise: "Support for visualisation is the most effective way to leverage this investment in national competitiveness" [24]. It regards computer imagery as an essential feature in exploiting the commercial benefits of advanced computing in technological development and practices.

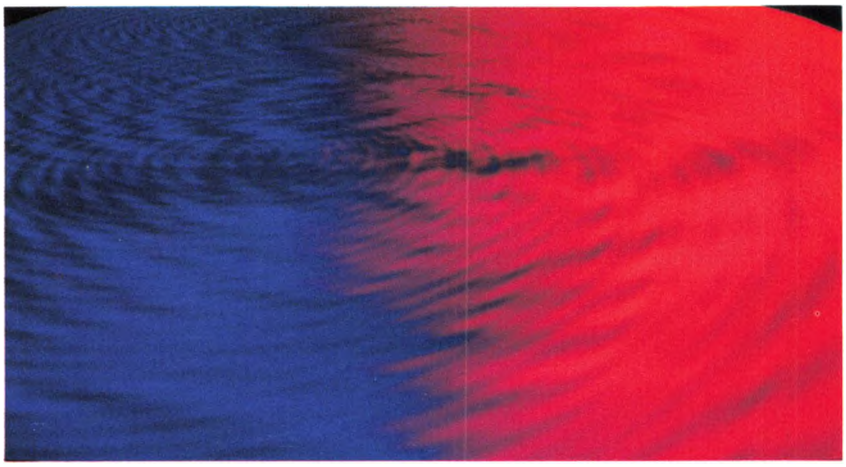
Applications of computer graphics motivated by performativity can have particular influence on its role in scientific research and knowledge production. There is a danger that once programming solutions to visualisation problems have been satisfactorily implemented, they may become entrenched in methodological frameworks difficult to escape from, static interpretations restricting the innovations necessary for the unbounded growth of knowledge [25]. There may be a new temptation to identify the image with a referent, justified perhaps by a perceived ability of the computer to search a space of solutions for exactly the 'right' one. The desire for the standardisation of visualisation techniques could degenerate into a step in this direction, taken to gain a misplaced scientific respectability. If powerful interactive techniques are developed, this danger is lessened by making each package more sensitive to the needs of each project and each researcher. Likewise, the commercial demands of performativity might break up any tendency to stick with adequate models without a continual search for new and potentially more profitable alternatives.

Computer graphics has been criticized for portraying itself as a science—it is not clear how it increases our knowledge or improves our understanding of the world. It continues to epitomise performativity by spending scientific research on increasing efficiency with less memory, smaller and cheaper machines, and faster execution times. Its concerns are to optimise the effectiveness of other sciences, to communicate information more clearly by taking full advantage of the perceptual discrimination of the human visual system. It is a science of analogy rather than representation, of solution rather than explanation. With the help of the computer, scientists have been able to build working symbolic models of natural phenomena. But the relationship between theory and experience has become more problematic. The desire of realism to objectify and explain experience leads to the feeling that a theoretical model has captured some 'essence' of the thing so described and is in that way even superior to it, just as for the Platonists the appearance of things was but a poor reflection of the ideal world of absolute form from which they drew their substance [26]. A computer simulation produces a different kind of understanding. Its graphical output generates an object that is on the same level of experience as the natural world of the subject. This output gives it a literalness as an object in its own right. Computer graphics can seem very realistic (or correct), but it is an alternative reality rather than a duplicate one (Fig. 10) [27]. It is more like a picture of our striving to grasp the world than an explicit modelling of it. It presents a reality in terms of a visual flux, defined by a plurality of means.

Many novel scientific ideas in this century have filtered down into the public's imagination in the form of sensational claims to Eastern cosmology, Buddhist metaphysics and exotic philosophies. Postmodern science seems to have become more evocative and meaningful, not because its outlook is closer to some mystic ideology, but because it has become more formal and is therefore open to more diverse interpretations [28]. Its conventionalist character is exposed, and it is able to allow its propositions to flow freely between varied and conflicting spheres of interest. Science has become less meaningful, less tightly bound to an unchanging external world in the metaphysical sense. In order to understand a complicated phenomenon we need to apply a different model to each of its aspects and to give credence to none above the rest. The question is whether the reaction to this new contingent nature of science will be a nihilistic resignation to ultimate meaninglessness or a pluralistic embracement of the endless flux of creative thought.

Graphics makes scientific research more accessible, giving it a fluid and nontotalitarian expression. This pluralistic approach should supplant performativity by giving new informal and intuitive meaning to science, at the visual level of perception and the imagistic level of conception.

Fig. 10. Hugh Mallinder, vortex, digital image, 1987. Reprinted by kind permission of the artist.



Some Conclusions and Some Emerging Issues

What some scientists would like to have, it seems, is a new 'language of observation', a tidy standardised system of smoothly translating data into pictures and a handbook for their infallible yet somehow also creative interpretation. But unfortunately, as I have tried to show, visual objects exist in their own space and have dynamics we must respect. An article entitled something like "How to Make Sure You Get the Correct Results from Your Pictures" has not, to this author's knowledge, been written, and there are several reasons why it is unlikely, except in very specific areas.

Apart from the inherent ambiguity of perception, an attempt to develop a standardised lexicon to read scientific imagery would seem to be neither practical nor desirable. The sheer diversity of visualisation strategies within even a single discipline would be enough to render interpretive categorisation intractable, apart from the fact that we do not understand many aspects of perception. Computationally derived knowledge tends to be allegorical. Each phenomenon is simulated in its own terms, or behaviorally, and with respect to the final function we wish it to perform. (There are some fairly basic precautions that we can take when tuning visualisations, such as the problem Greenberg mentions of making sure that tonal graduations are perceived as equidistant to match the numerical differentials of the data [29].) To try to fix the interpretation of imagery on higher levels would defeat the whole object of visualisation. If visualisation could be formalised, it could be computerised; we could then automate the whole process from data to algorithm to theory generation and go home. We have no reason to suppose that this is feasible: the impact of robot vision in this area is still an open question. If knowledge production were mechanised, visualisation would lose much of its meaning. The debate would move onto levels not addressable here.

Many of the problems of using imagery in science stem from what some conceive to be incompatibility between visual perception and scientific method. Some also see an incompatibility between orthodox scientific method and what scientists actually do anyway. Scientists desire the certainty of formal deduction and also the impetus of inspired insight. For these people who want to eat their cake and have it, the resort to blatantly intuitive techniques of research may prove intolerable. Much play could be made of recent advancements in the philosophy of science that assert that the ideal of methodological rigour is an abstraction never to be found in the real world beyond the arid confines of the university textbook [30]. Some current thinking even contends that a formal rational approach to science restricts the free growth of knowledge by making it difficult to justify new conceptualisations [31]. Unfortunately, once again this paper is unable to give full justice to these developments except to note that their analogy can be found in the ascension of the doctrine of performativity over the pursuit of truth in scientific praxis described in the last section.

Simplified then, the methodology of scientific visualisation is not strictly in agreement with the doctrine of rationality but is only slightly less so than empirical science in practice. Nonetheless, it has shown itself capable of extending the bounds of knowledge by the explicit use of retinal means. This is something computational scientists should not have to apologise for. Analysts need not feel guilty about having to interrogate output using the more informational methods that are appropriate to the nature of imagery. As the burden of knowledge moves from abstract theory to the simulations and patterns of behaviour visually apprehended, we will find ourselves drawn more irresistibly to the flickering images on our VDUs. People want to look at pictures. We cannot escape the fact that in this age we engage reality on visual and not literary terms. People demand the often-neglected value of meaning in science that computer imagery allows them to appropriate. The special sensory nature of electronic images will continue to cause problems in relating the conceptual to the logical to the visual, but the result should be the realisation of science as an activity that engages all of our vast mental and perceptual faculties and that ungrudgingly respects each contribution they can make.

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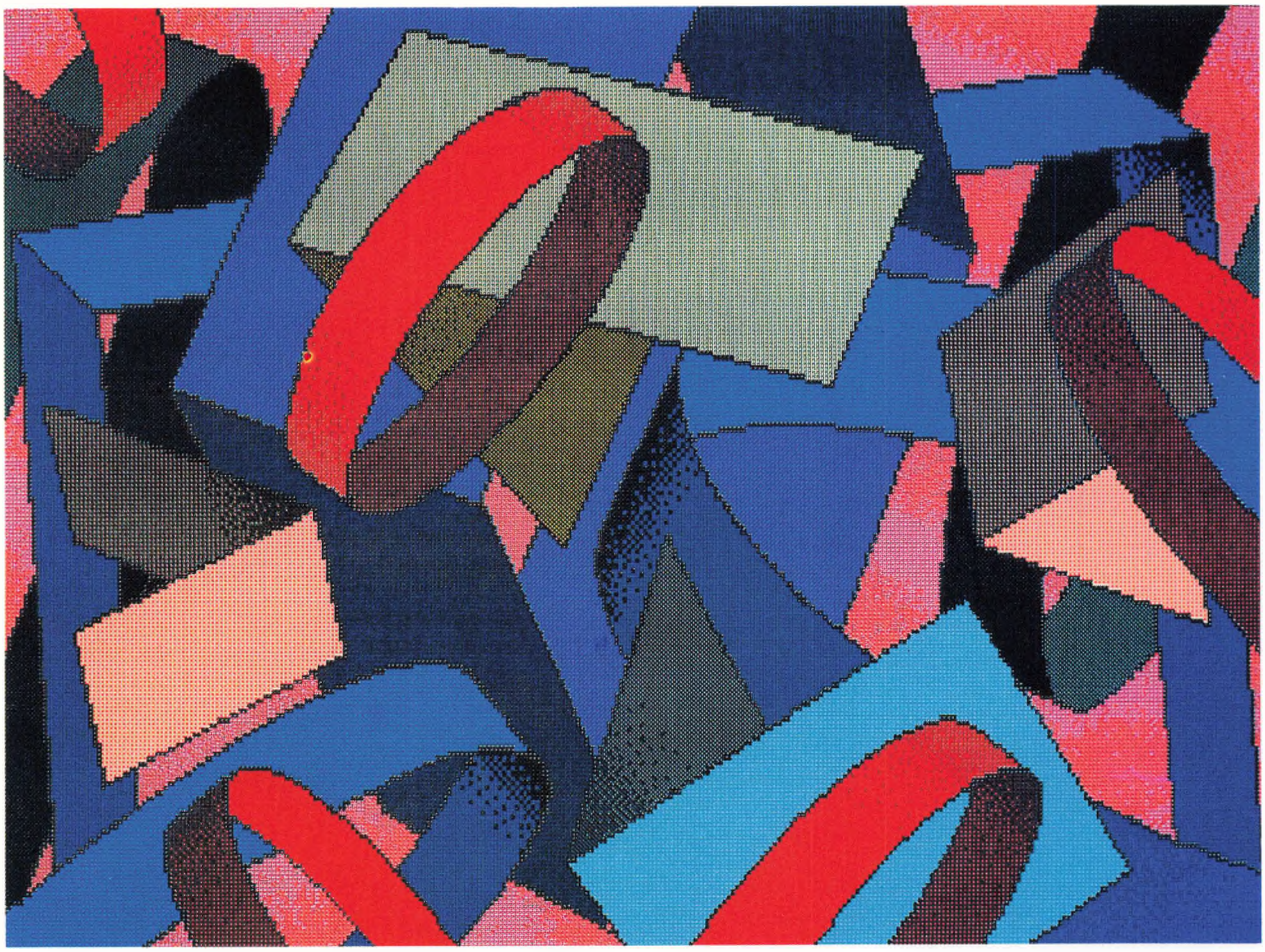
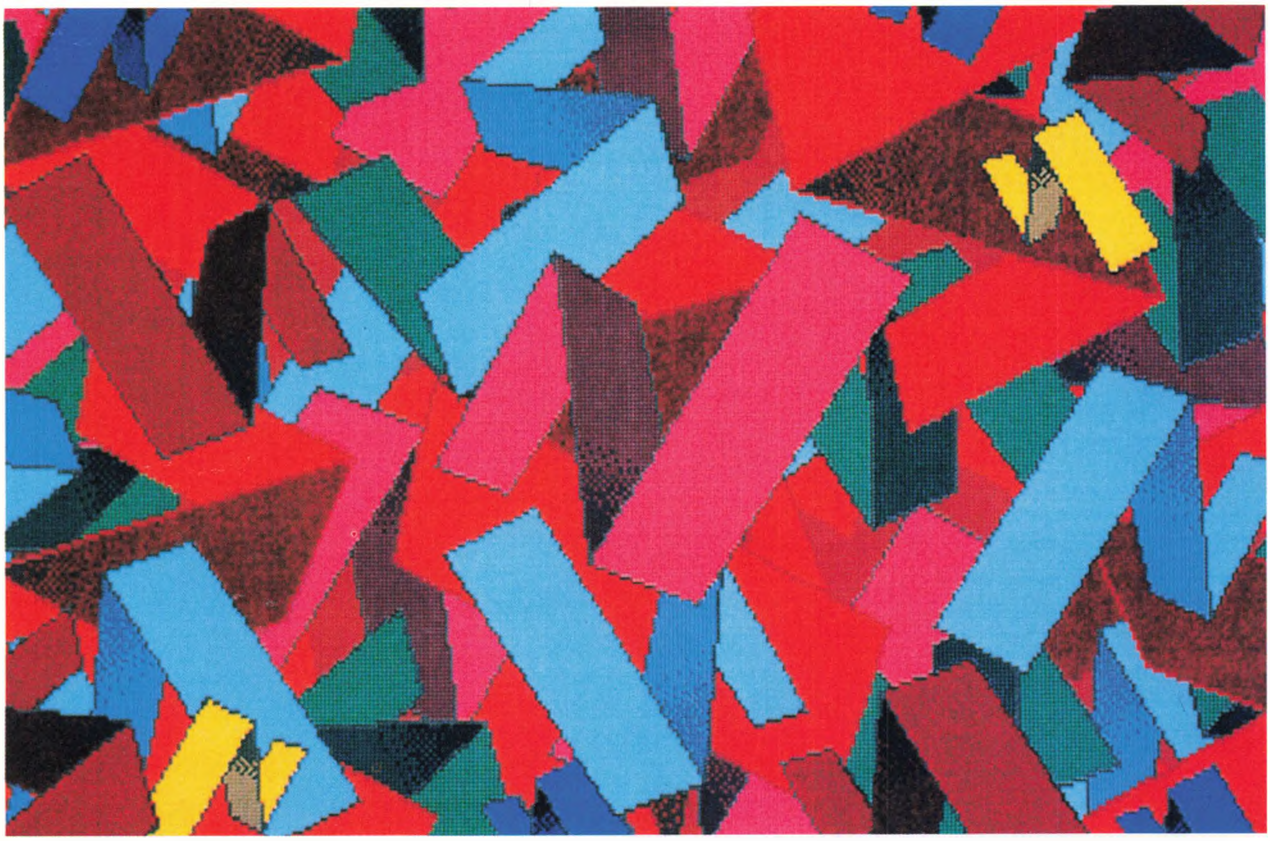
Color Plates



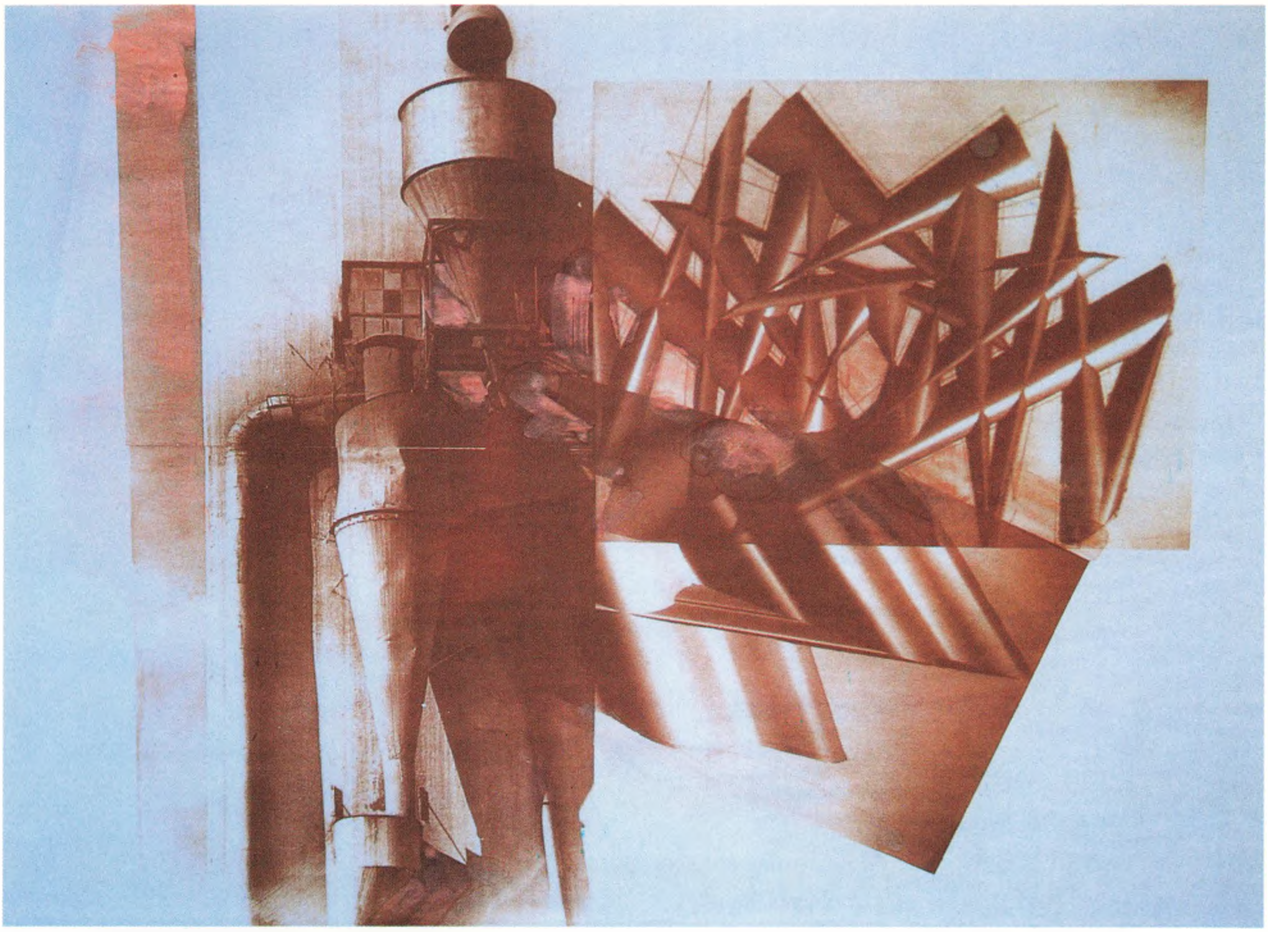


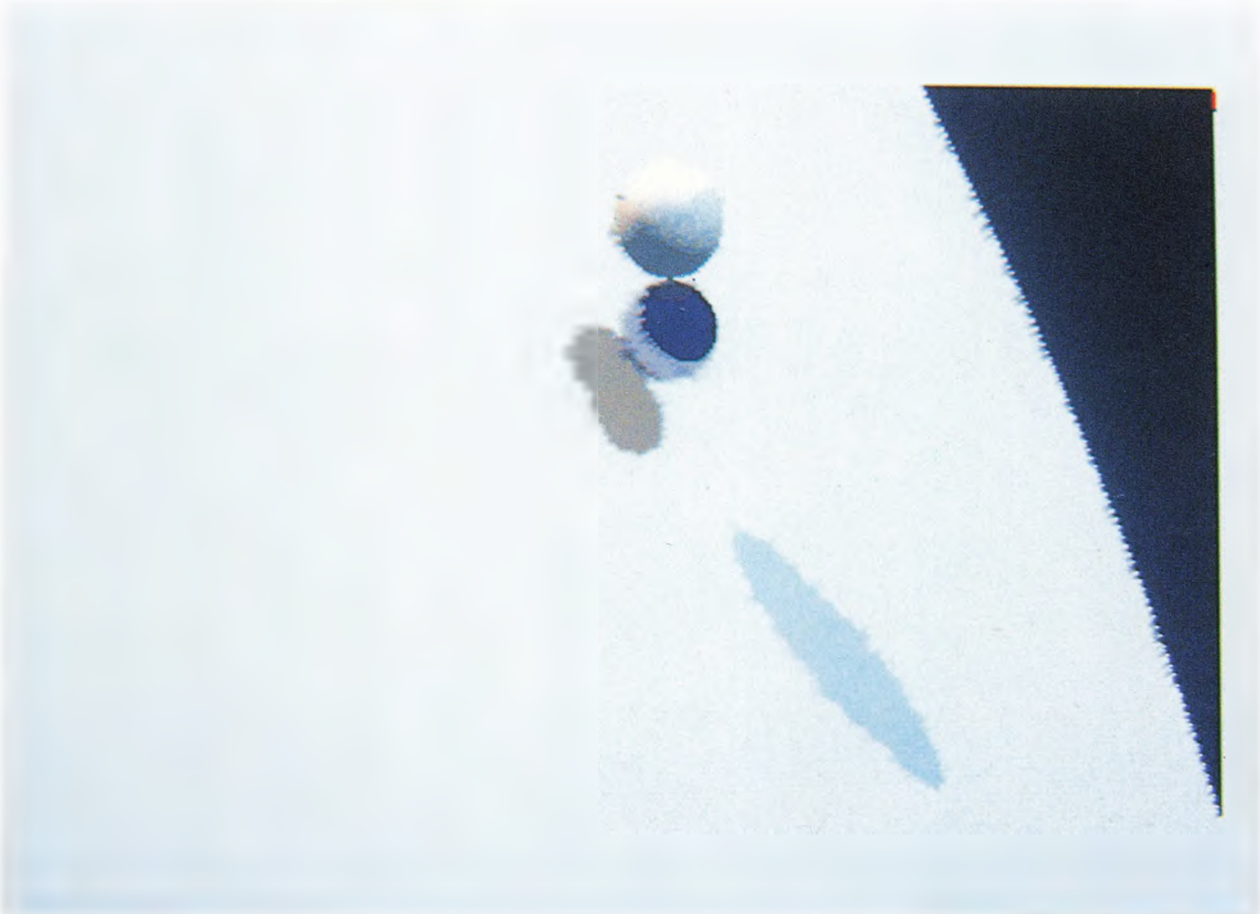
No. 1. (top left) George S. Roland, *Fifth*, inkjet print, 10.5 × 7.5 in, n.d.

No. 2. (bottom left) George S. Roland, *Orangez*, inkjet print, 10.5 × 7.5 in, n.d.

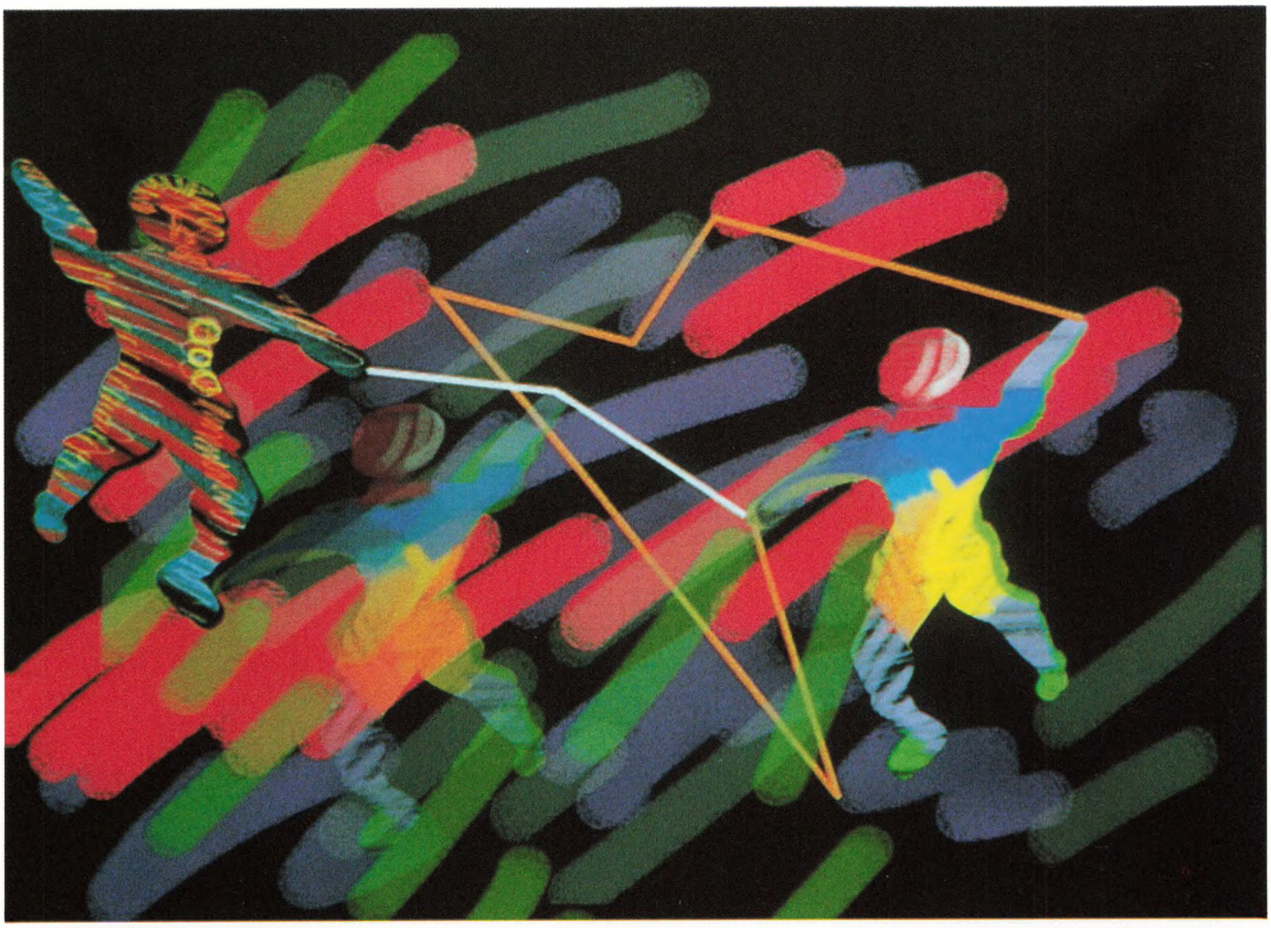
No. 3. (facing page, top right) Craig A. Johnson, *Ohio Fieldwarp*, sepia print, oil paint, 28 × 40 × 1.5 in, 1989.

No. 4. (facing page, bottom right) Anne Russell, Untitled, C-print of raster image. 20 × 16 in, 1987.





No. 5. Barbara Nessim, *Under Wraps*, computer-generated stereo slides, 18 × 14.5 in, 1989.

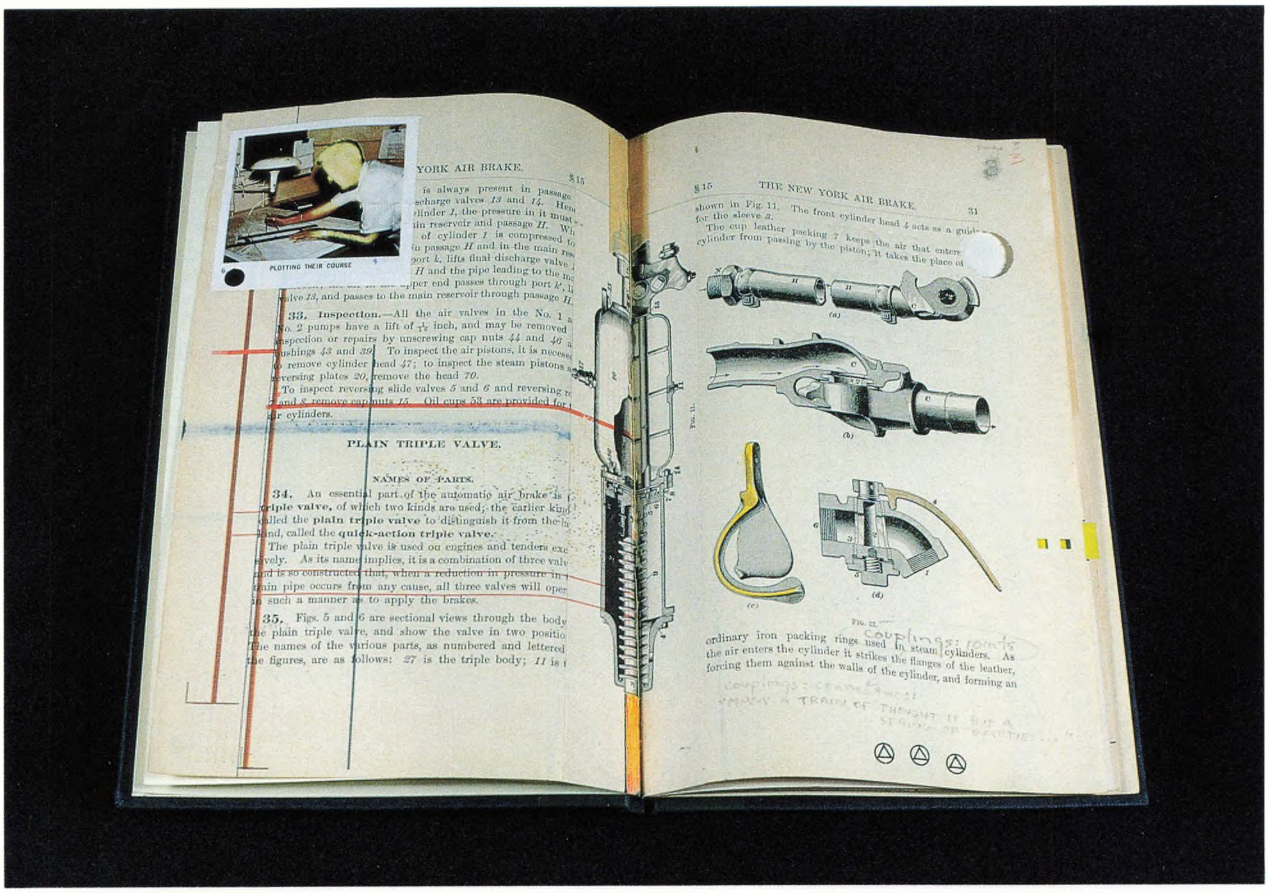


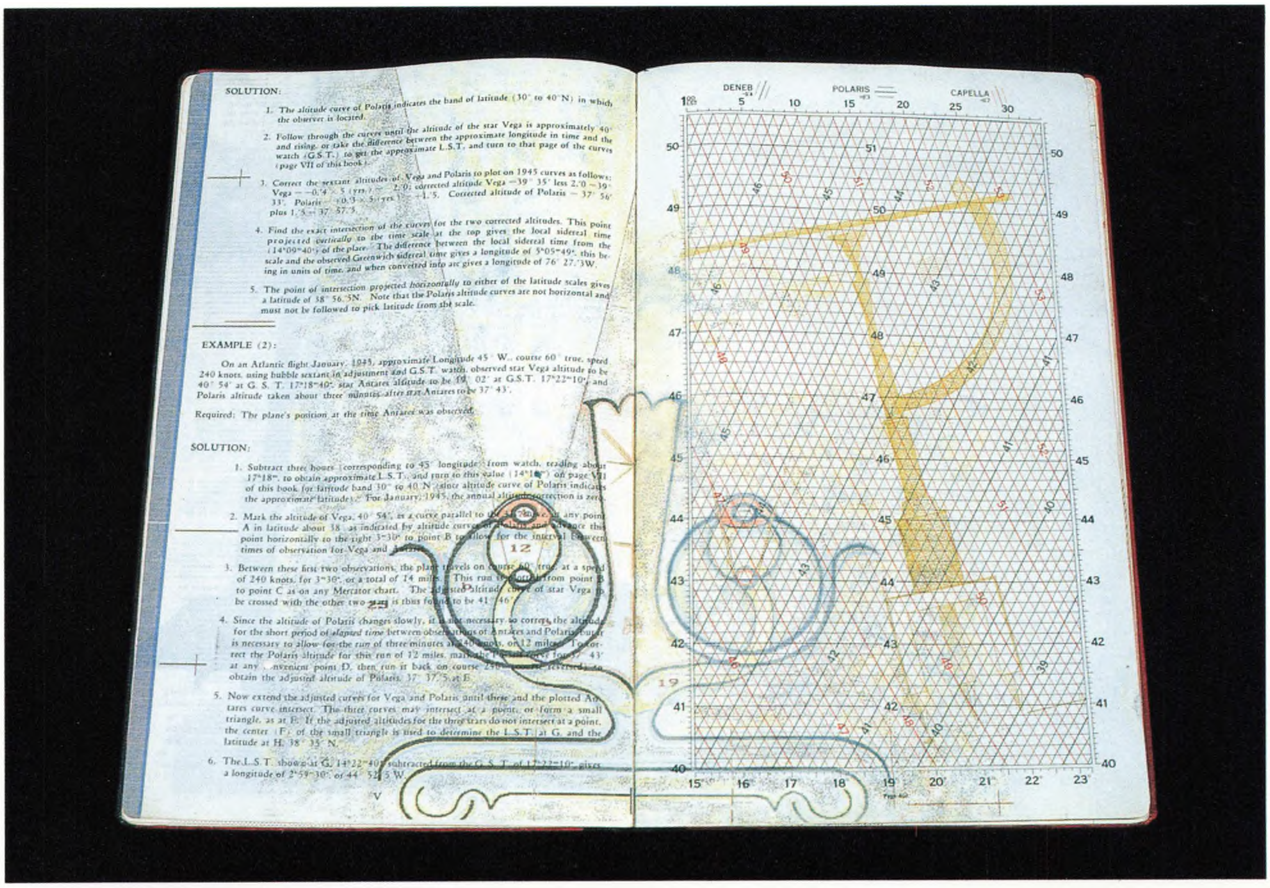
No. 6. Micha Riss, *Fight*, slides, 3-D stereoptics, 1990.

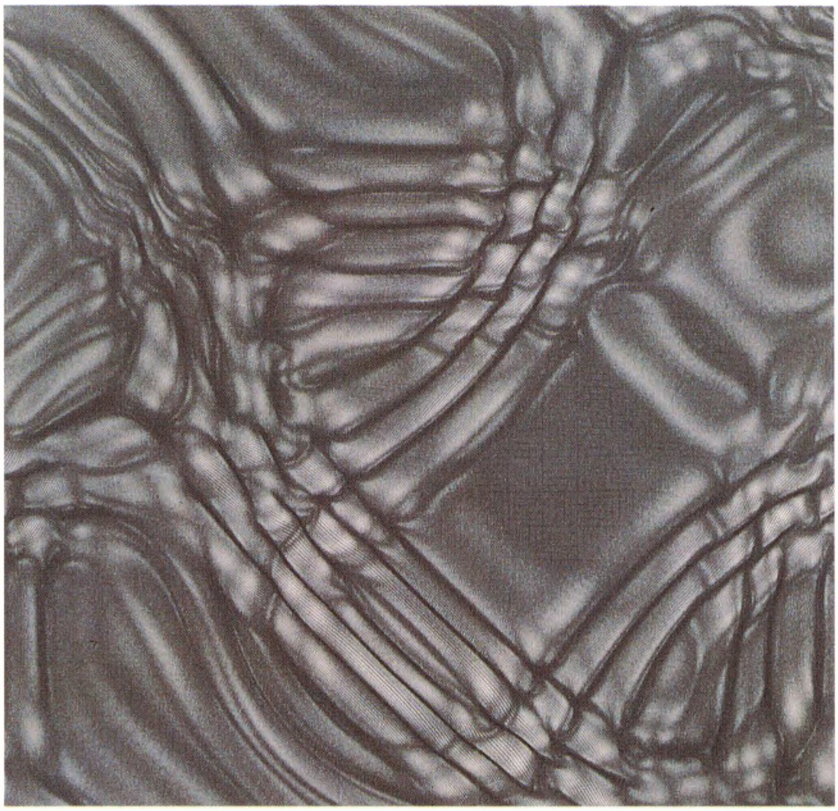
No. 7. (above) Mark Wilson, *4 A 90*, acrylic on canvas, 72 × 72 in, 1990.

No. 8. (top right) Lane Hall, *Decaying Infrastructure*, book format, computer printing and collage, 6 × 12 × 0.5 in, 1989.

No. 9. (bottom right) Lane Hall, *Traveller*, book format, multiple print techniques: computer, lithography, woodcut, etching, 14 × 17 × 0.5 in, 1989.

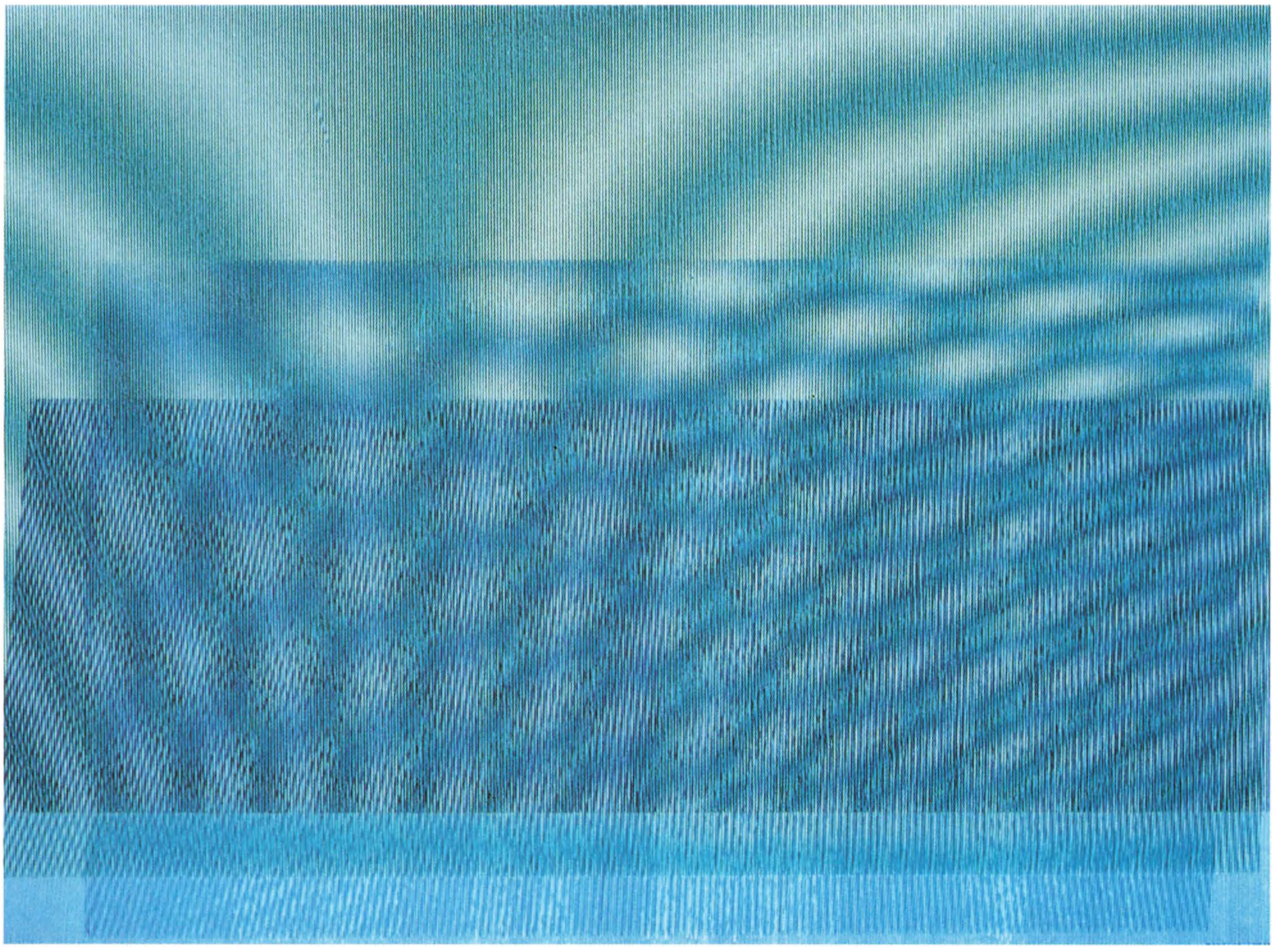

PLOTTING THEIR COURSE
YORK AIR BRAKE.
THE NEW YORK AIR BRAKE.
PLAIN TRIPLE VALVE.
NAMES OF PARTS.

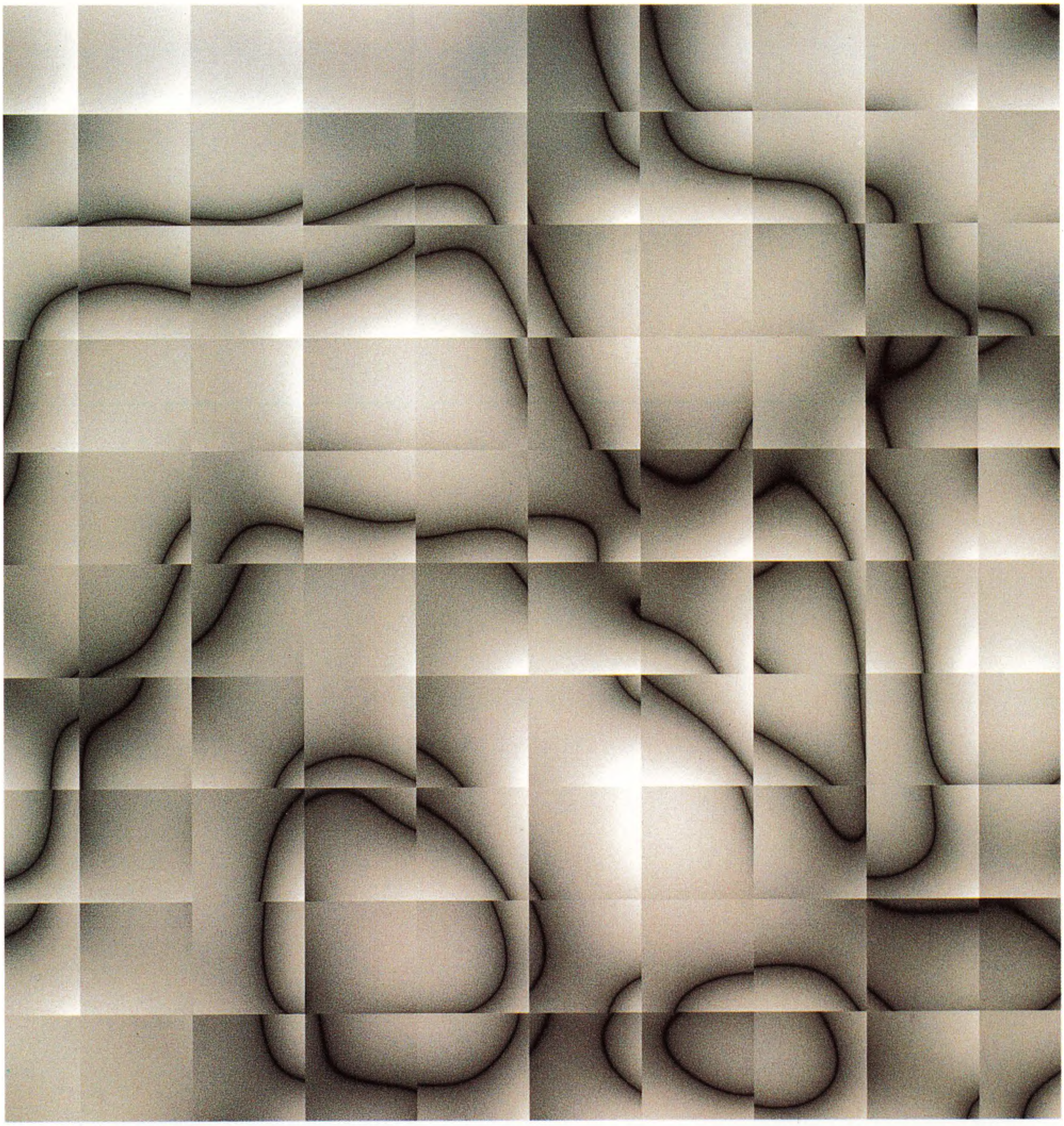

SOLUTION:
EXAMPLE (2):
SOLUTION:
DENEB
POLARIS
CAPELLA



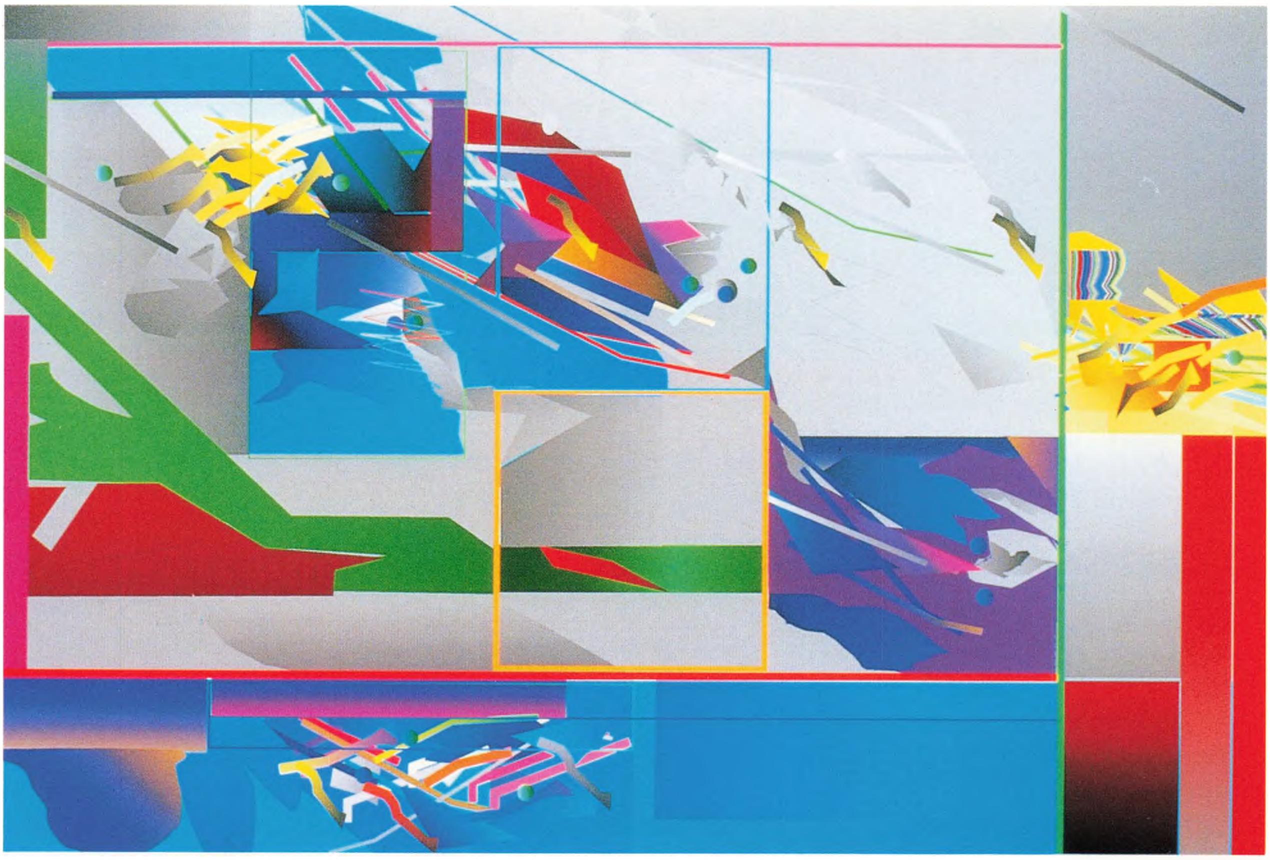
No. 10. (left) Jean-Pierre Hebert, *Laque Noire,* ink on paper, 19 × 19 in, 1989.

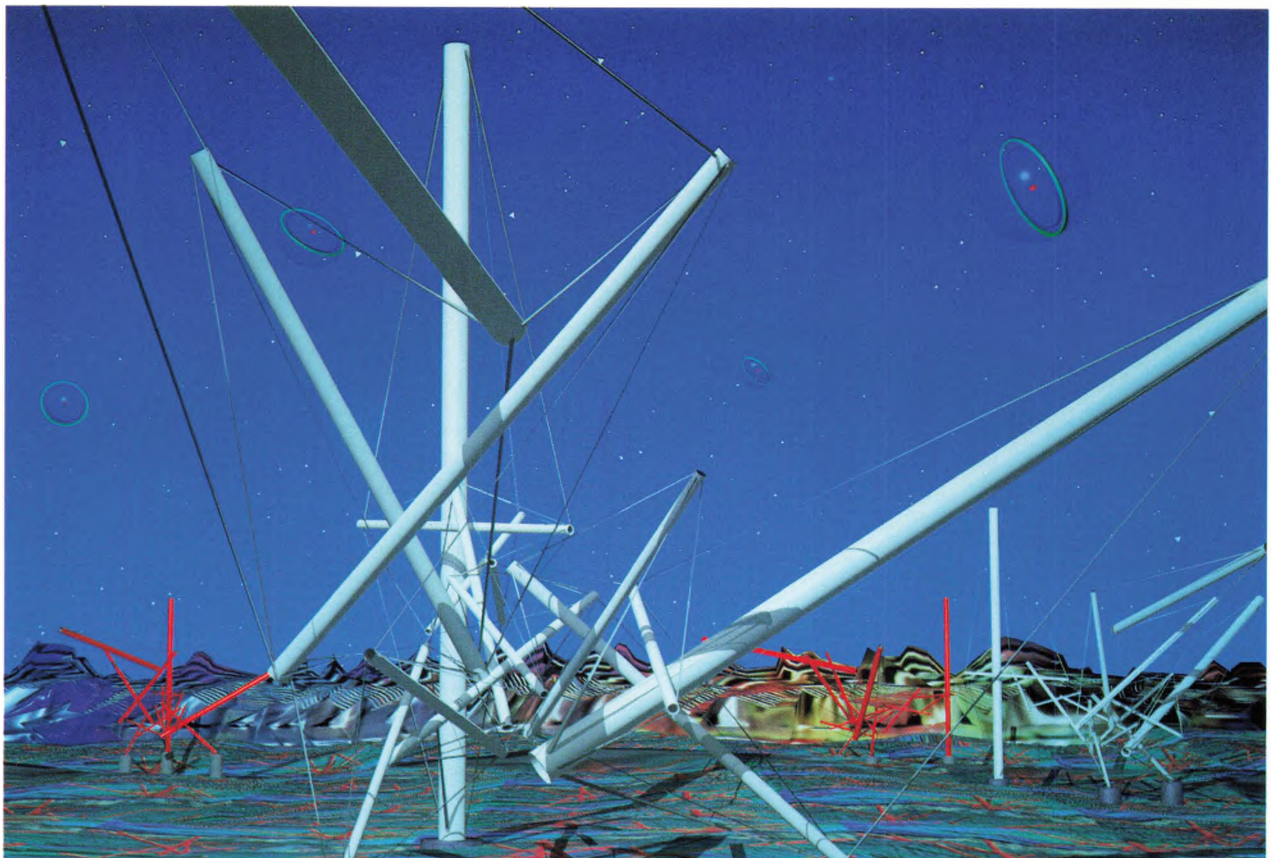
No. 11. (below) Eudice Feder, *Swarm,* plotter drawing, ballpoint, felt tip, ink, 30 × 25 in, 1988.





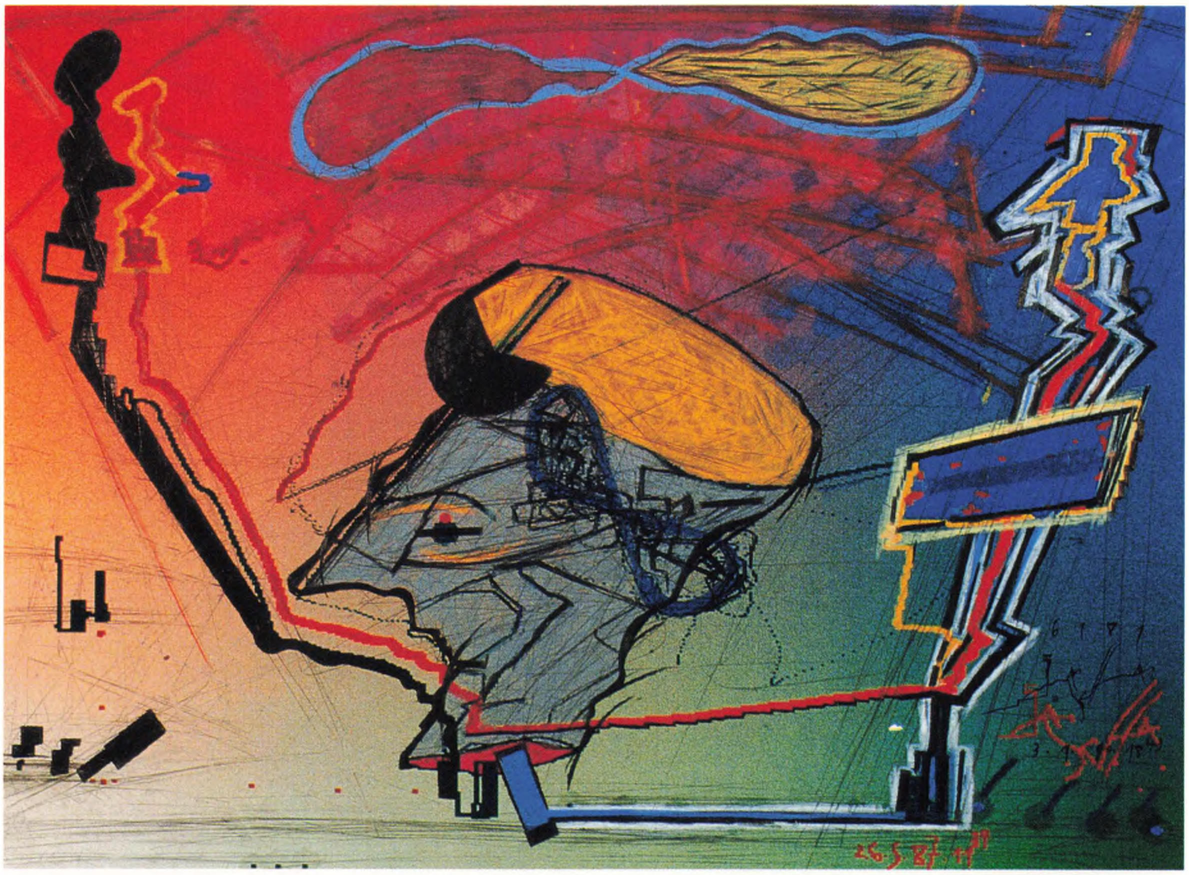
No. 12. Bruce Lindbloom, *Symbiosis*, photographic print, 20 × 20 in, 1989.





No. 13. (top) Kazuya Sakai, *Sky 15C*, print, 22 × 30 in, 1989.

No. 14. (bottom) Kenneth Snelson, *Forest Devils' Moon Night*, one C-print and one stereo pair, 40 × 30 in, 1989.

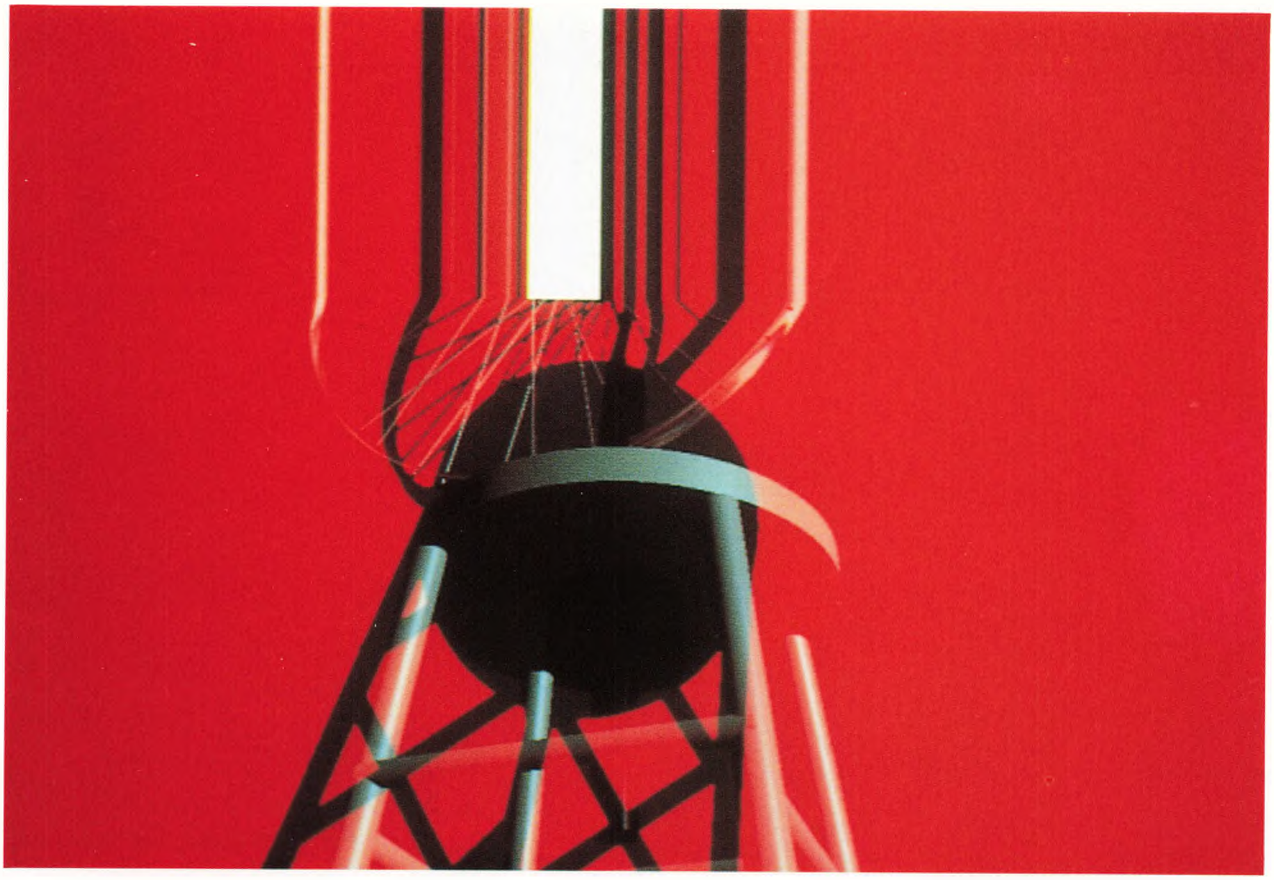


No. 15. (top) Johann Jascha, *Franz*, mixed media, 30 × 20 in, 1990.

No. 16. (bottom) Copper Giloth, *Religion*, collage, 40 × 30 in, 1990.

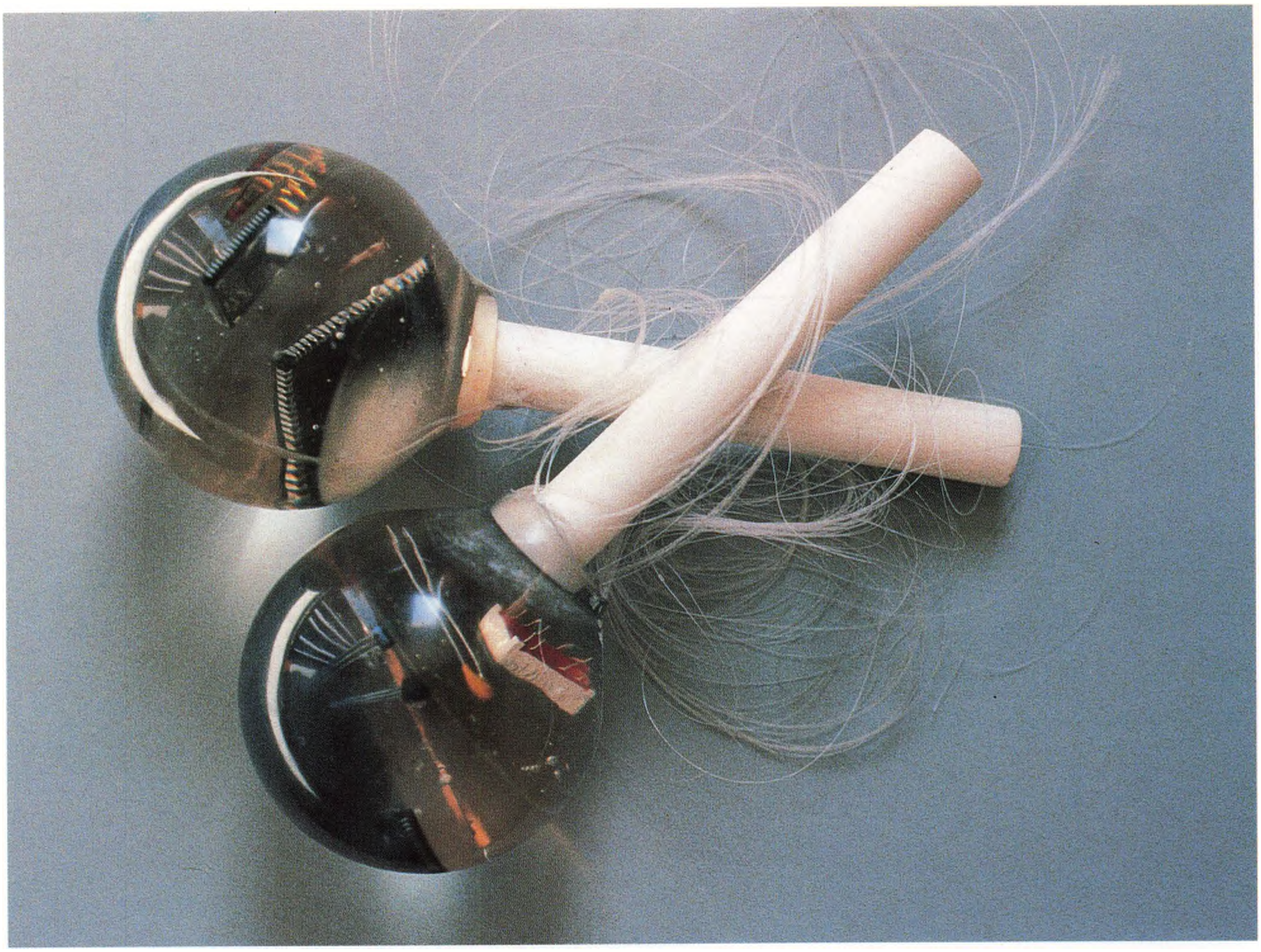
No. 17. (left) Robert Martin, *Bermuda Triangle*, computer image on duratran with fluorescent lights, 25 × 20 × 6 in, 1988.

No. 18. (below) Brad Gianulis, *Salamander Coffee Table*, photograph, 1989. Collaborator: Bill Gain.

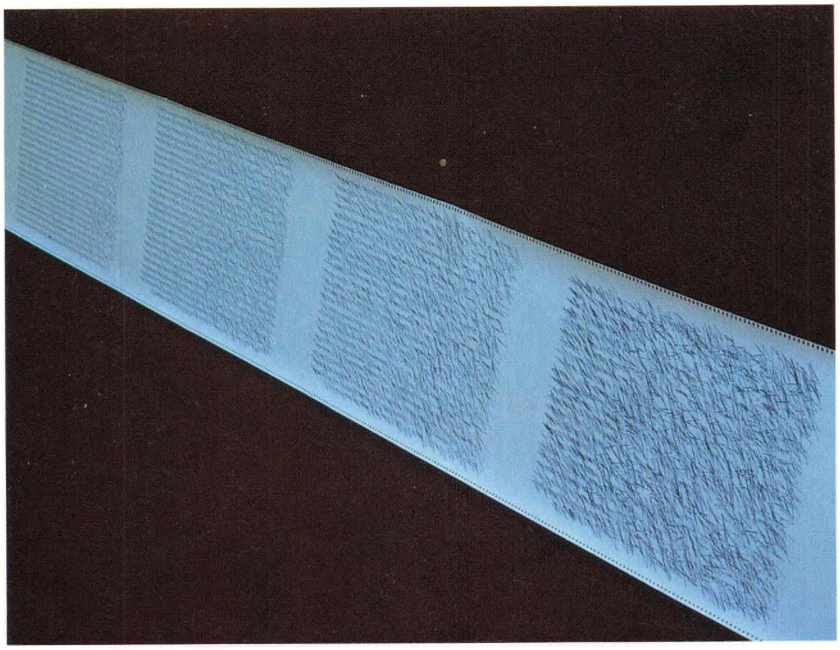


No. 19. (above) Uri Dothan, *Abstract Matters*, computer art/photography, 20 × 16 cm, 1989.

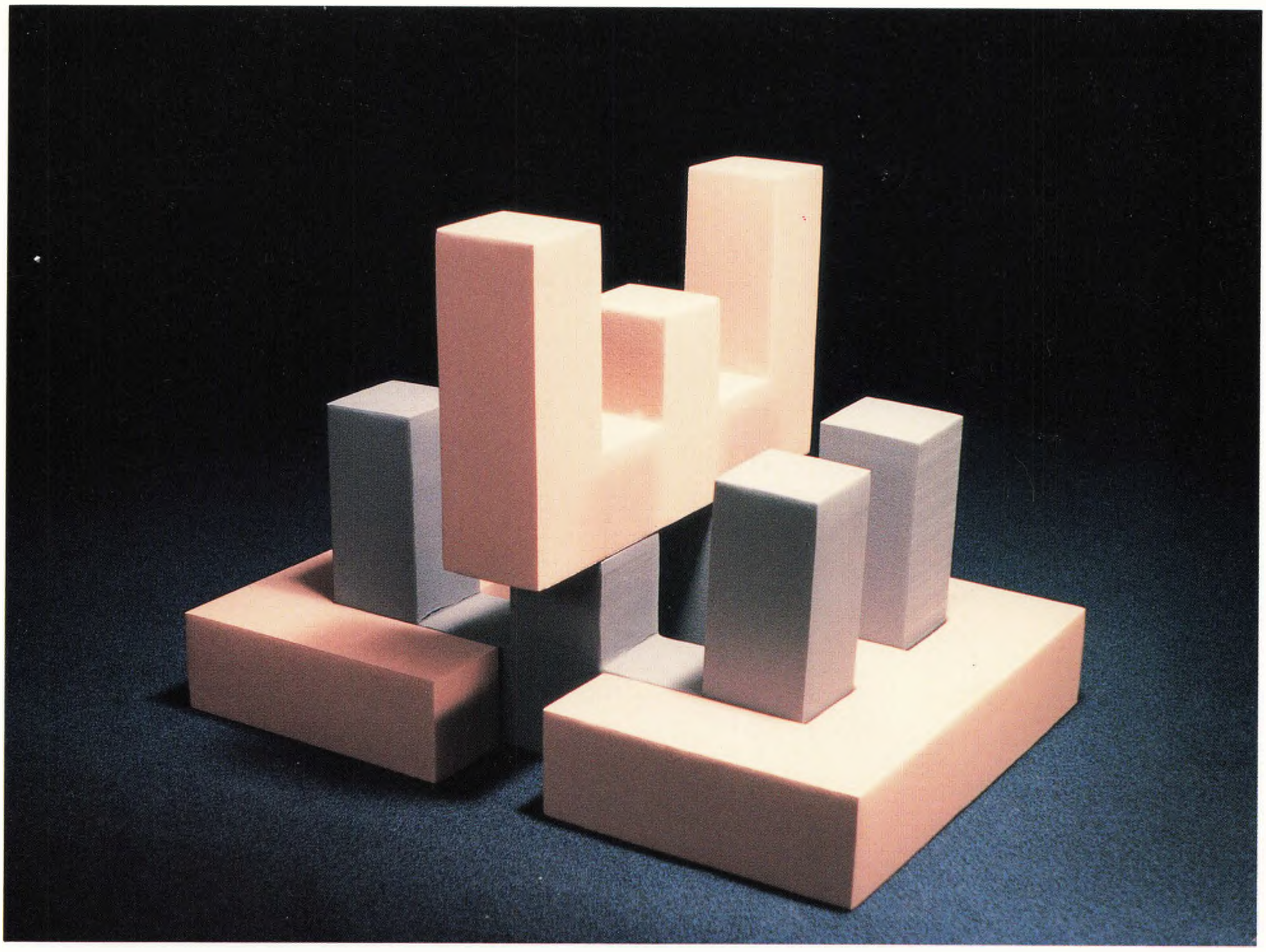
No. 20. (right) Shinya Yusa, *Synergetic Globes*, lighting display unit, 780 × 1000 × 780 cm, 1990.



No. 21. (above) Kathleen LaSalle, *Sand Rattles*, sculpture: computer chips, electronic components, fiber optics, PVC and acrylic resin, 14 × 7 × 3.5 in, 1990. Collaborator: Kevin Casey Simon.

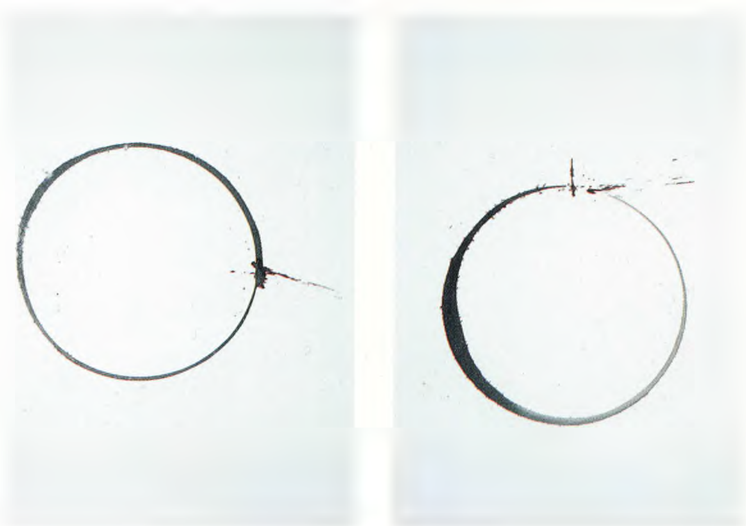


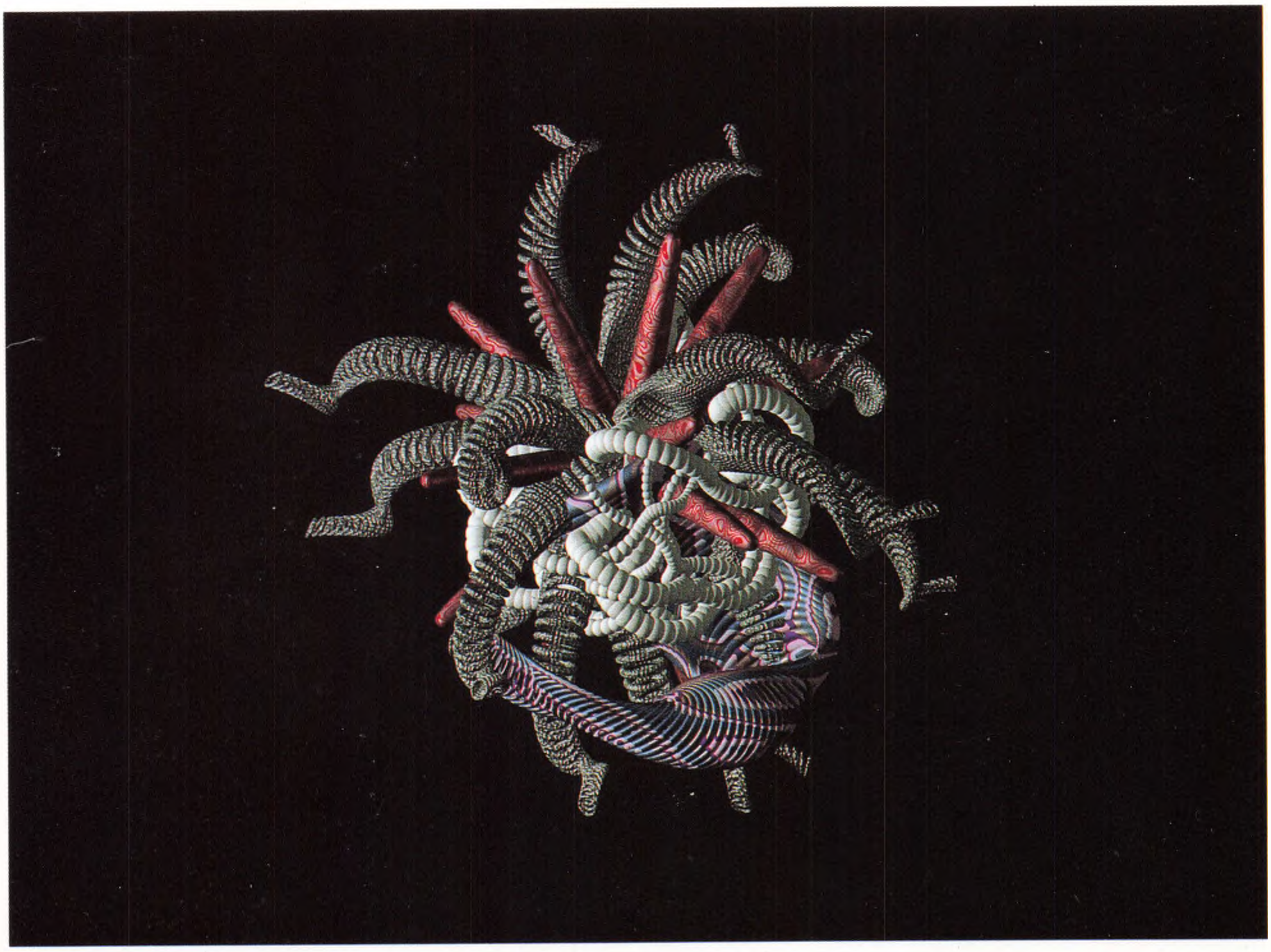
No. 22. (left) Vera Molnar, *Letters of My Mother*, ink on paper (computer output), 175 × 12 in, 1988.



No. 23. (above) Charles Chiles, *Five Ease*, sculpture, 8 × 8 × 6 ft, 1989.

Nos. 24, 25. (below) Kamran Moojedi, *The Circle*, prints, 22.5 × 30 in, 1989.



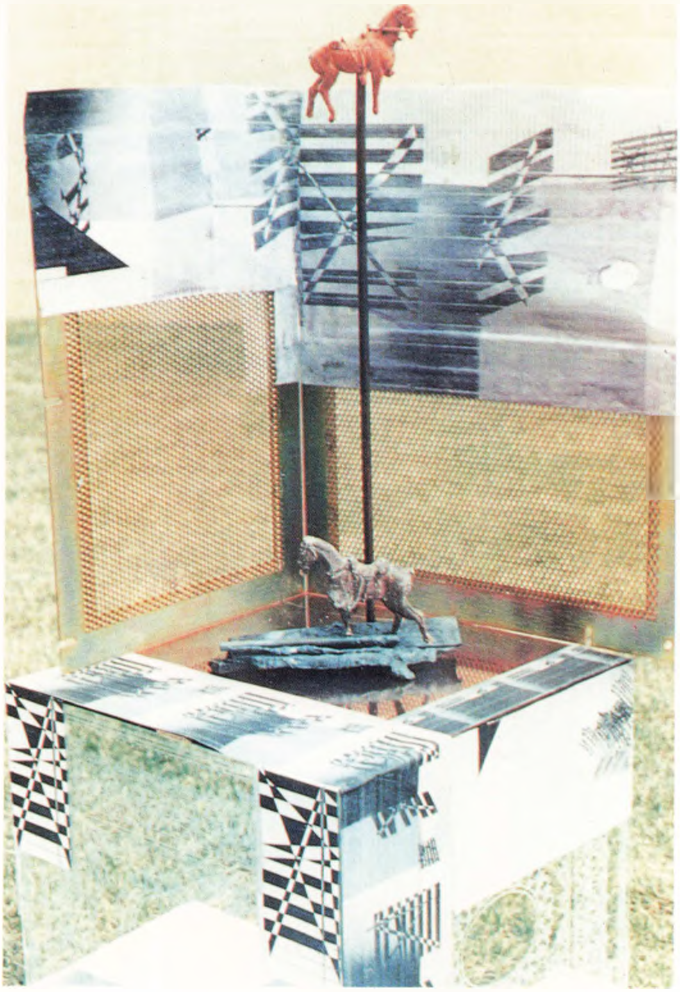


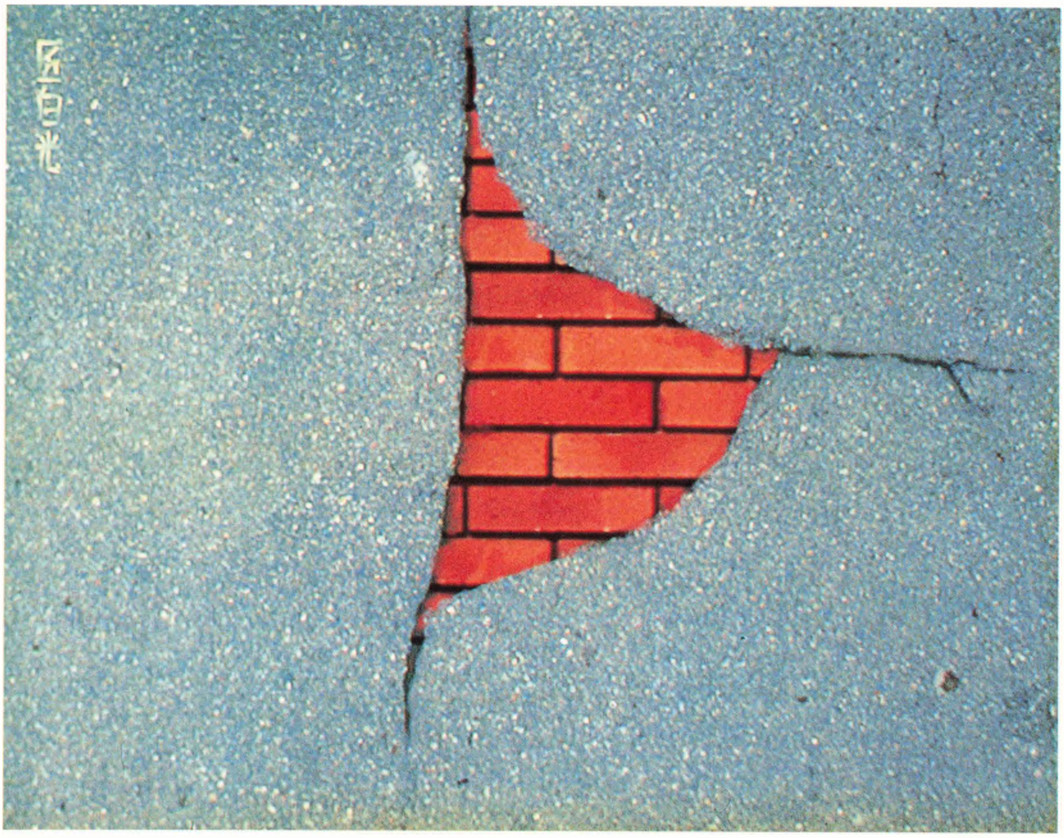
No. 26. (top left) Midori Kitagawa De Leon, *Beyond the Time*, photograph, 13 × 11 in, 1989.

No. 27. (bottom left) William Latham (artist), Peter Quarendow and Stephen Todd (software), *Computer Plant Form 3*, cibachrome print, 40 × 40 × 2 in, 1989.

No. 28. (top right) A. Z. Ursyn, *Hero Horse*, 3-D computer sculpture, 30 × 27 × 20 in, 1989.

No. 29. (bottom right) Alvy Ray Smith, *Photo Finish at the Brickyard*, photograph, 6.5 × 5 in, 1990.

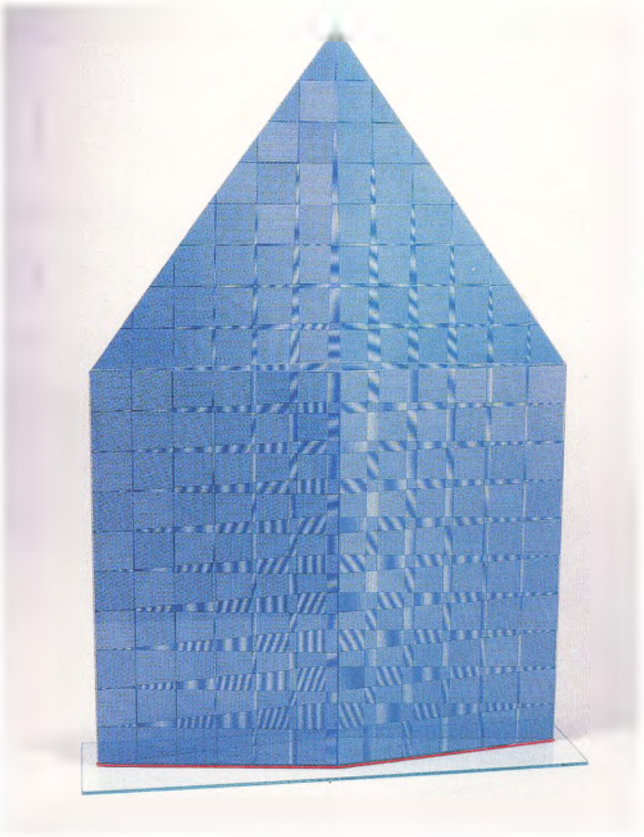


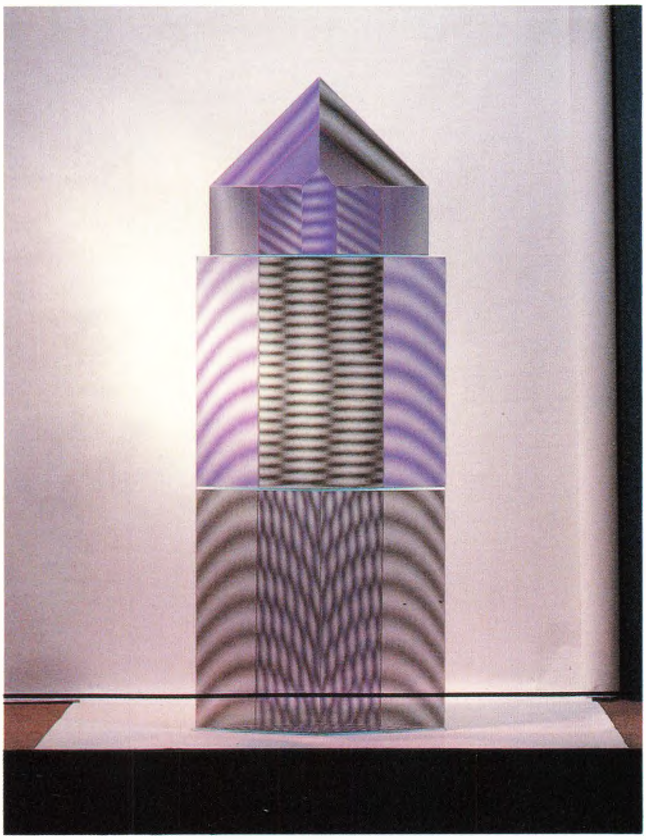


No. 30. (top) Erol Otus, *Unloading*, print, 24 × 20 in, 1989.

No. 31. (bottom) Thomas Plazibat, *Face*, print, 48 × 48 in, 1989.

No. 32. Charles B. Murphy, *Spaceman*, C-print, 10 × 12 × 2 in, 1989.



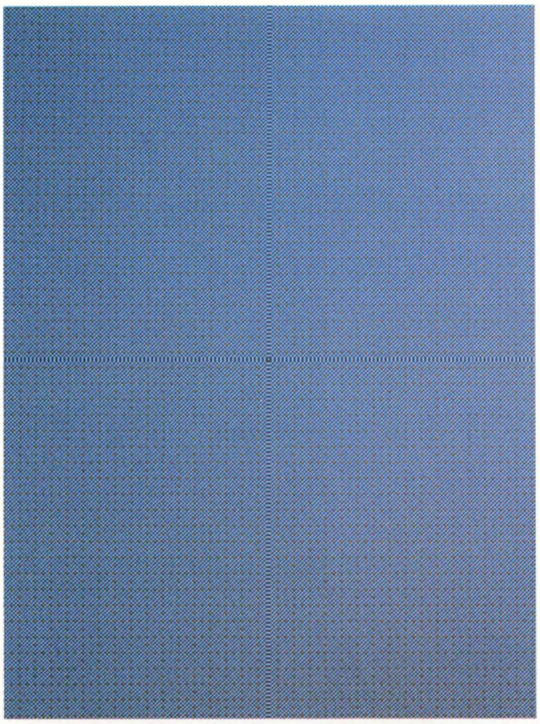


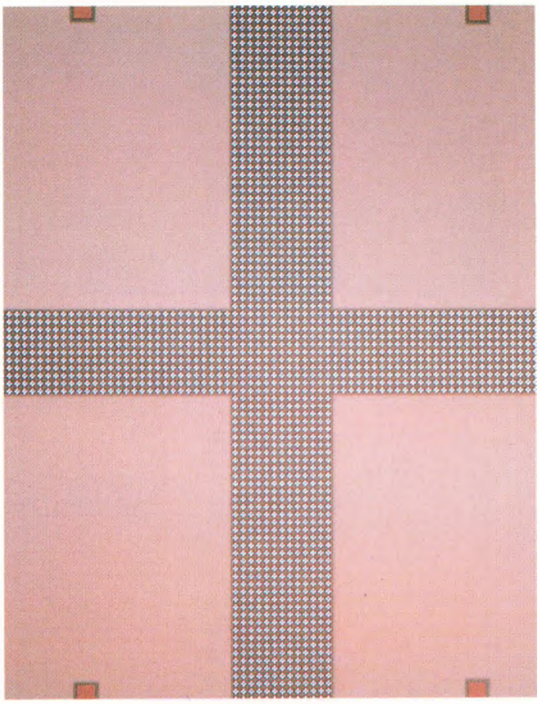
No. 33. (top left) Sydney Cash, *House #2*, plate glass, silkscreened, constructed form, 28 × 36 × 5 in, 1990.

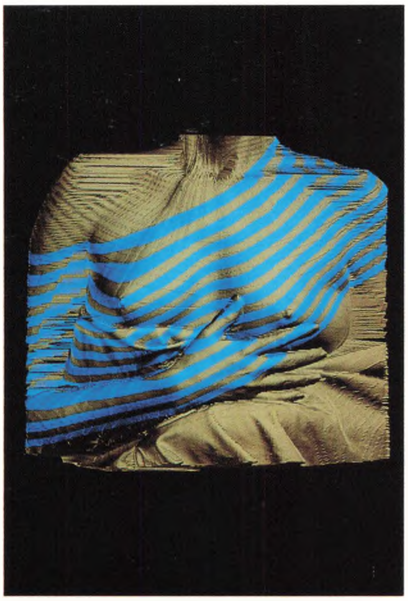
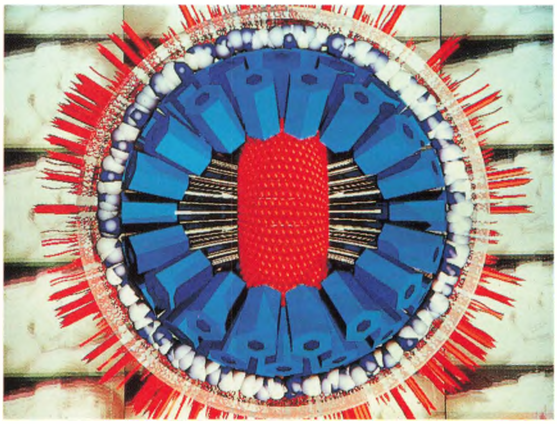
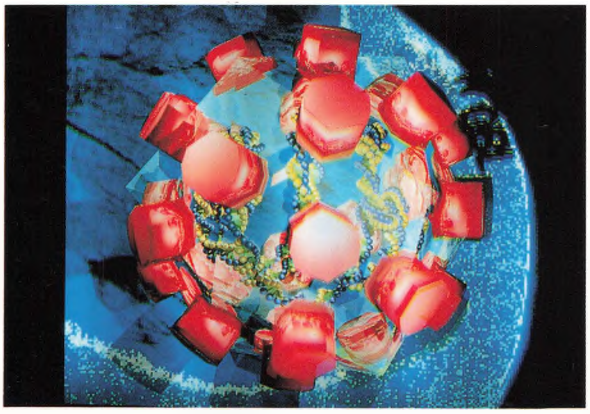
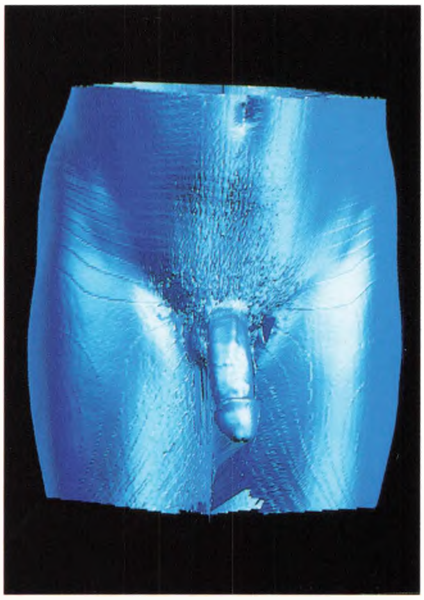
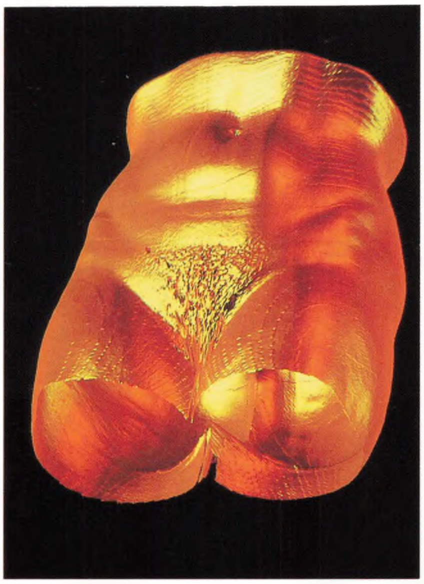
No. 34. (bottom left) Sydney Cash, *House of Virtue*, plate glass, silkscreened, constructed form, 24 × 64 × 9 in, 1990.

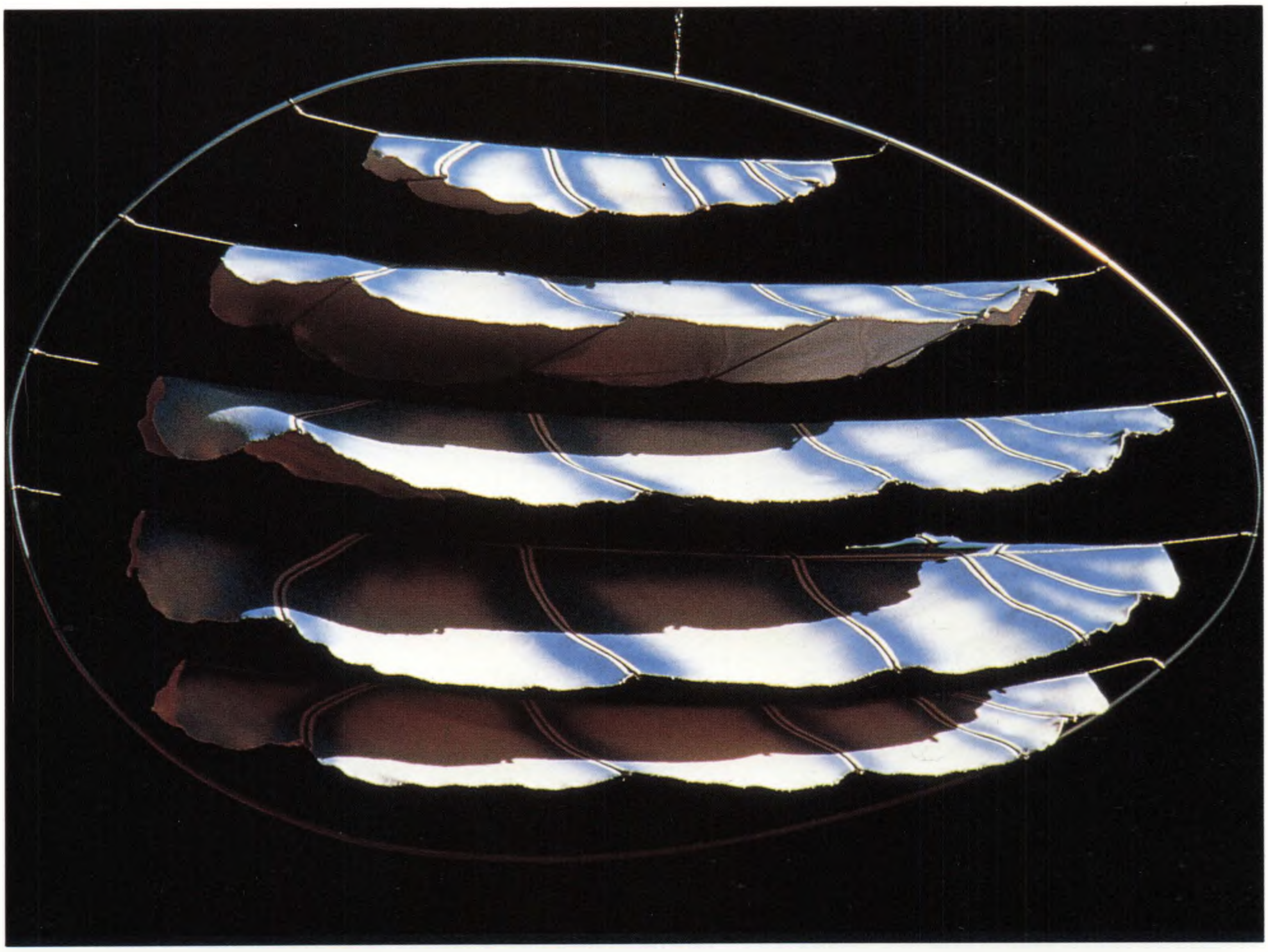
No. 35. (top right) Kent Rollins, *Cyrene*, IRIS print on litho paper, 30 × 40 in, n.d.

No. 36. (bottom right) Kent Rollins, Untitled, IRIS print on litho paper, 30 × 30 in, n.d.



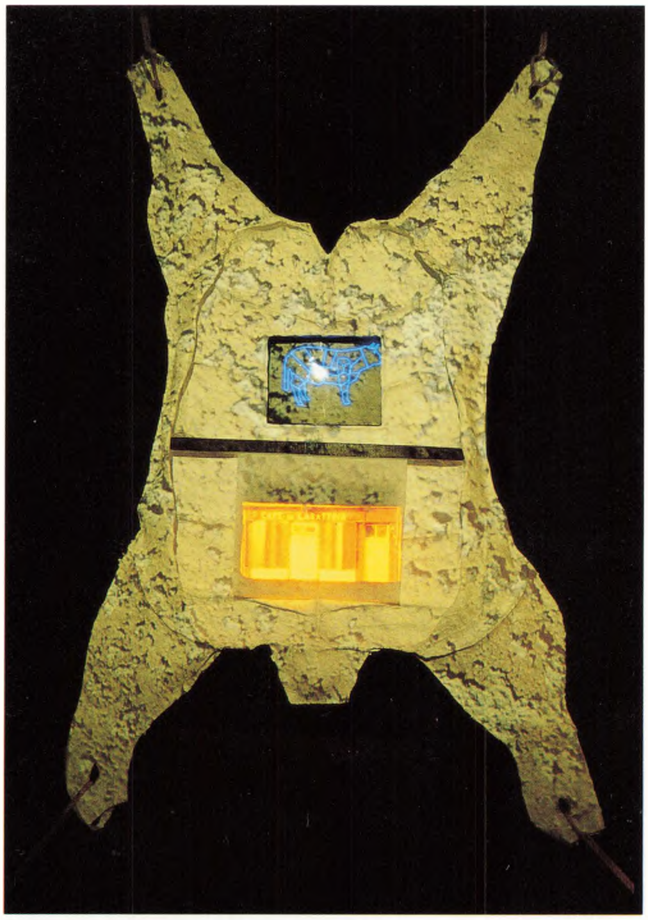


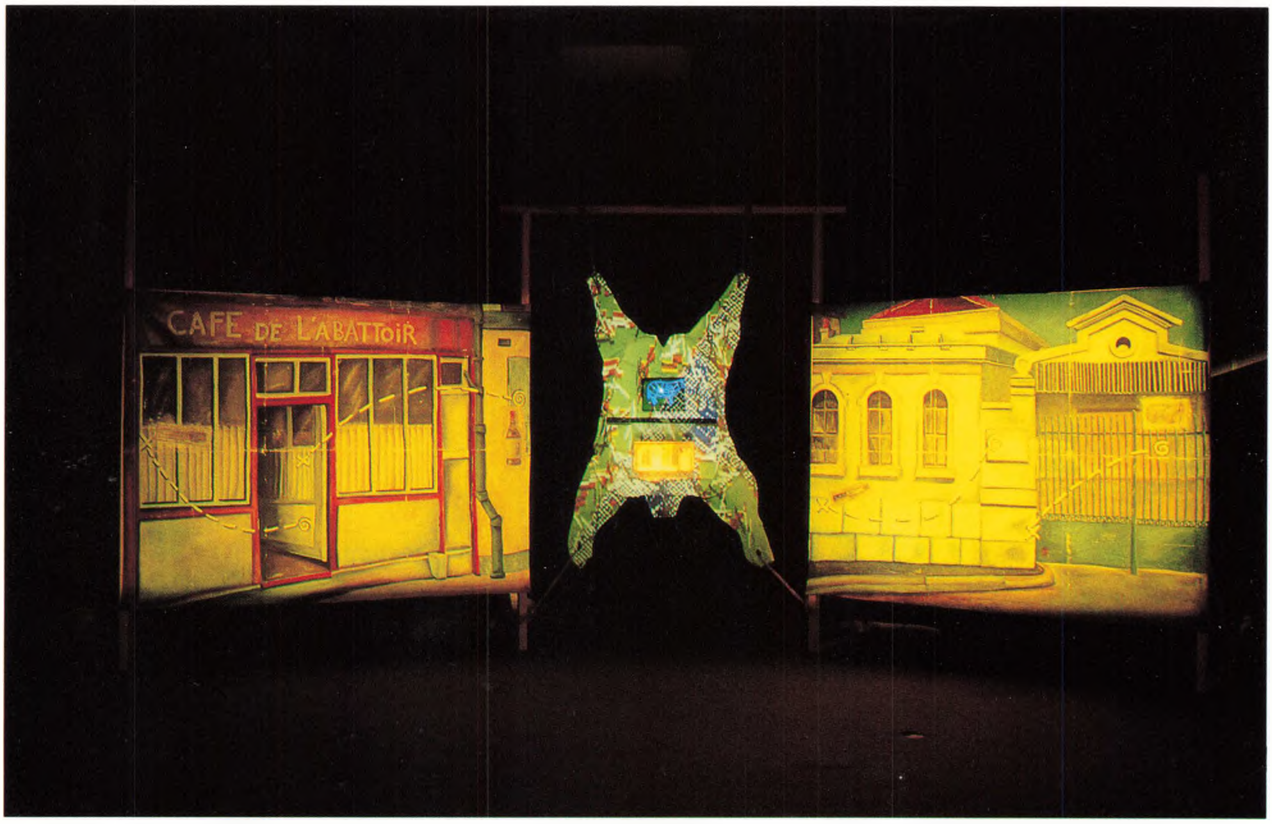






No. 43. (above) Susan Hamilton, *Scarab*, sculpture: canvas, cable, stainless steel, 50 × 29 × 19 in, 1989. Collaborator: Bruce Hamilton.

Nos. 37–42. (left) (ART)^n Laboratory (Randy Johnson, Stephen Meyers, Ellen Sandor, Dan Sandin, Tom DeFanti, Donna Cox, Bernard Rolzmann, Patricia Spear, Paul Neumann, Maggie Rawlings [Illinois Institute of Technology]), *Robert Mapplethorpe/The Nineties,* barrier-strip autostereograms in sculpture, 30 × 100 × 80 in, 1990.



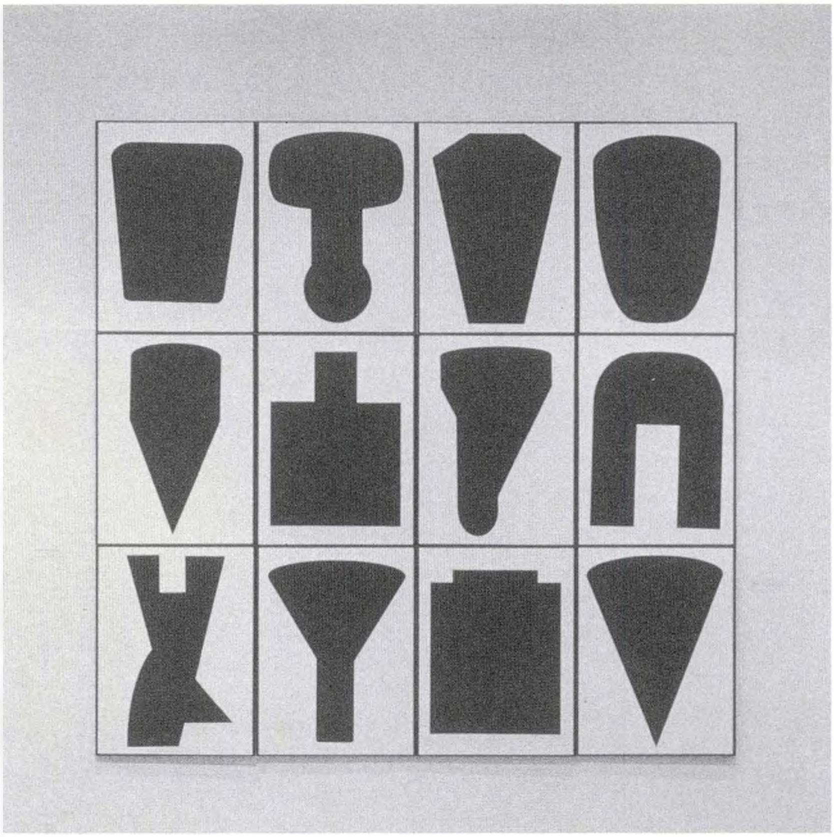

CAFE DE L'ABATTOIR

No. 46. Robert Hamilton, Jr., *Exhibition Experiment #5*, inkjet print, 6 × 4.5 ft, 1989.

Nos. 44, 45. (opposite) Joseph Lefevre, *Le Cafe de L'Abattoir*, large slide projector installation, 550 × 200 × 150 cm, 1989.

No. 47. (above) Jennifer Steinkamp, *Grace*, installation, 5 × 6 × 4 ft, 1989.

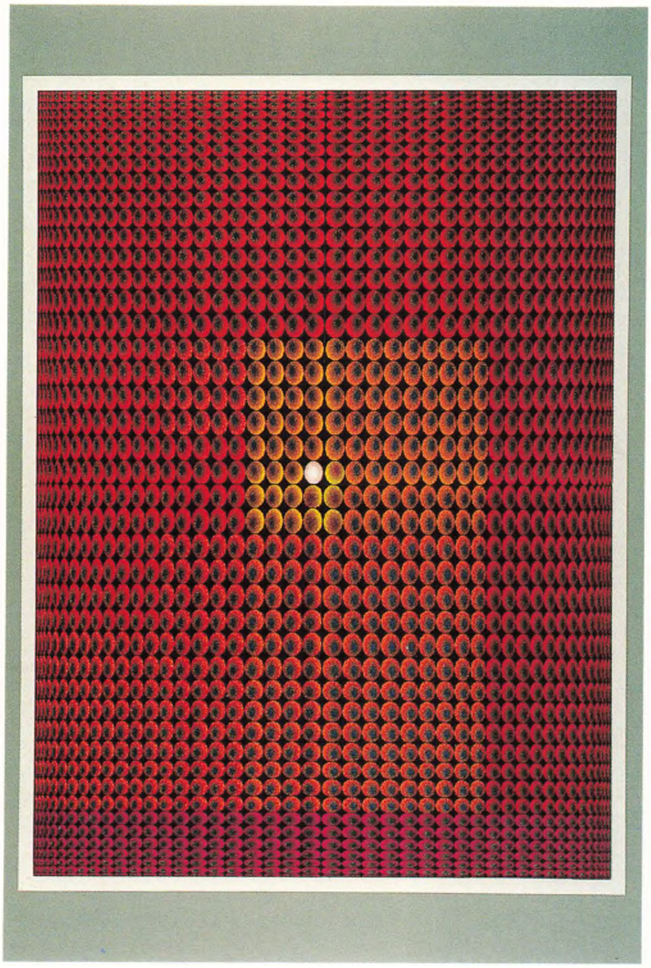
No. 48. (right) Peter Feldstein, *Computer-Generated Photo*, prints, 10 × 10 ft, n.d.



No. 49. Semannia Luk Cheung, *Delicraft Curio*, 3-D computer graphics, 1990. Collaborator: William Wright.

No. 50. (left) Acha Debela, *A Song for Africa*, photograph, 20 × 30 in, 1990.

No. 51. (below) Helen M. Klein, *Darryla*, paper, ink, watercolors, 20 × 49.5 × 2 cm, 1990.



No. 52. (above) James Watkins, *Hidden Symmetry Series (Variation #13)*, thermal print, 18 × 24 in, 1989.

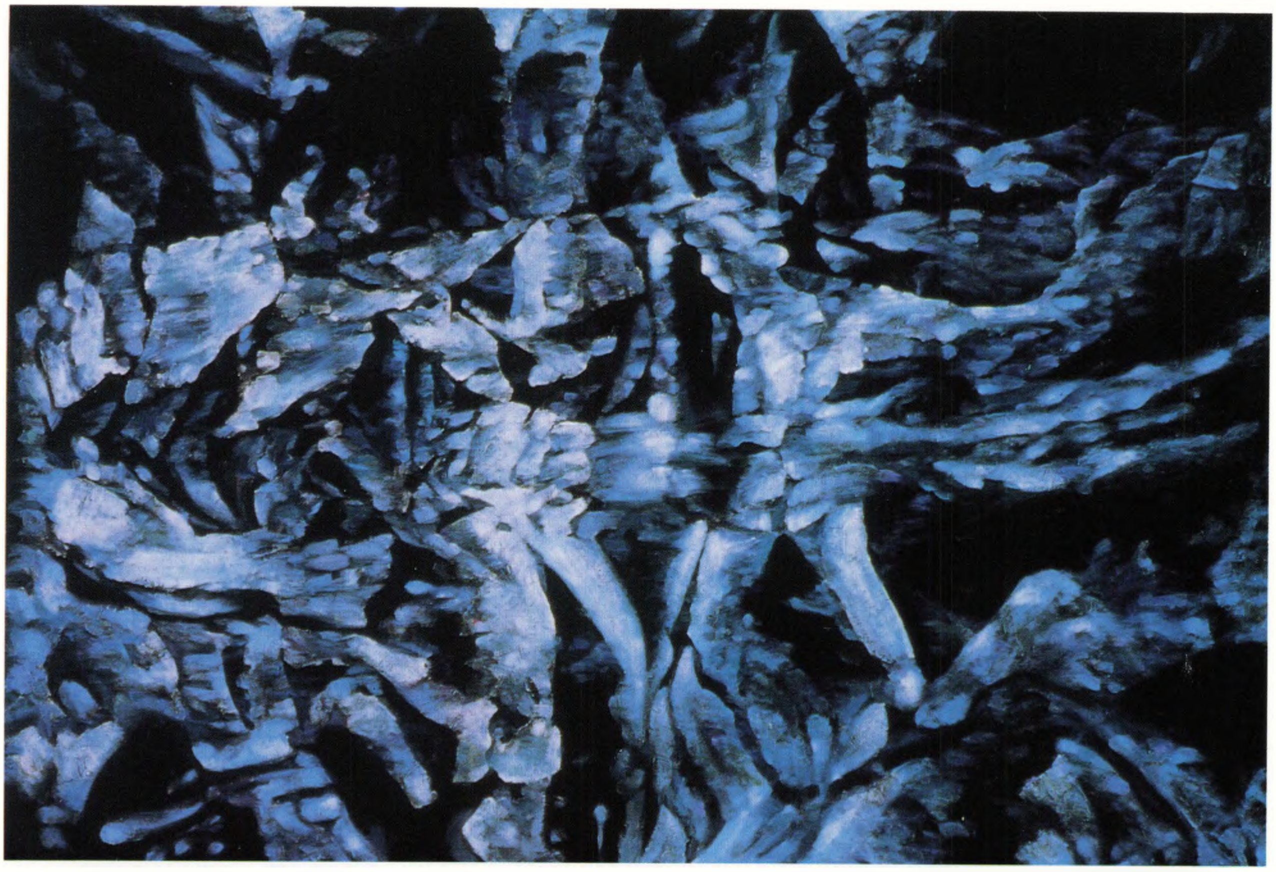
No. 53. (right) Cyber Dada (Troy Innocent, Dale Nason), *Cyber Dada Manifesto*, cibachrome print, 350 × 600 mm, 1989.

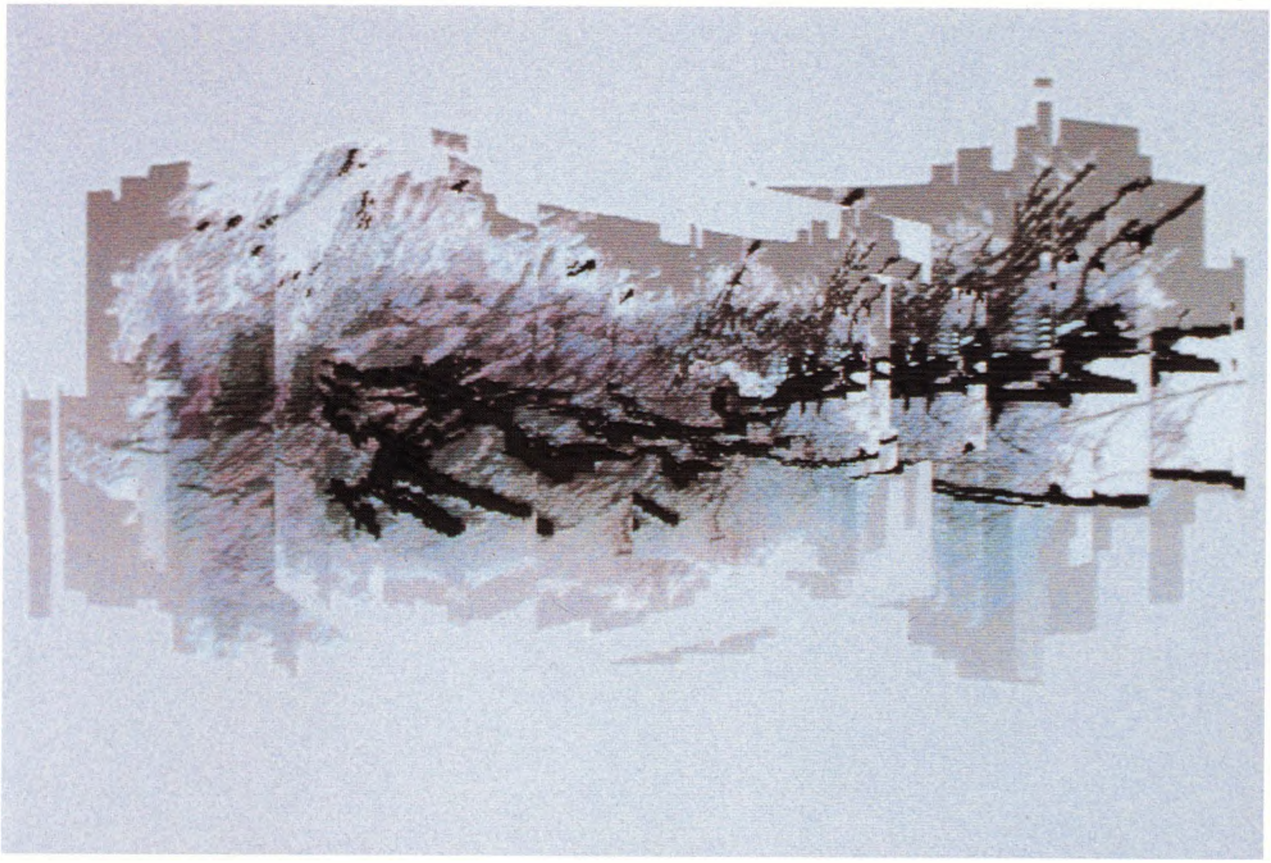
No. 54. (left) Simon Penny, *Ceci n'est pas un oiseau*, installation, n.d.

No. 55. (below) Lily Diaz, *Portrait of Ellie*, three-dimensional display—"Hypergram", 10 × 8 × 7 in, 1989.

No. 56. (top right) Rodney E. J. Chang, *Paint Out No. 19 Revolution*, oil on canvas (painting), 108 × 54 in, 1989.

No. 57. (bottom right) Cynthia King-Judge, *Mare*, inkjet print on handmade paper, 30 × 20 in, 1990.






H
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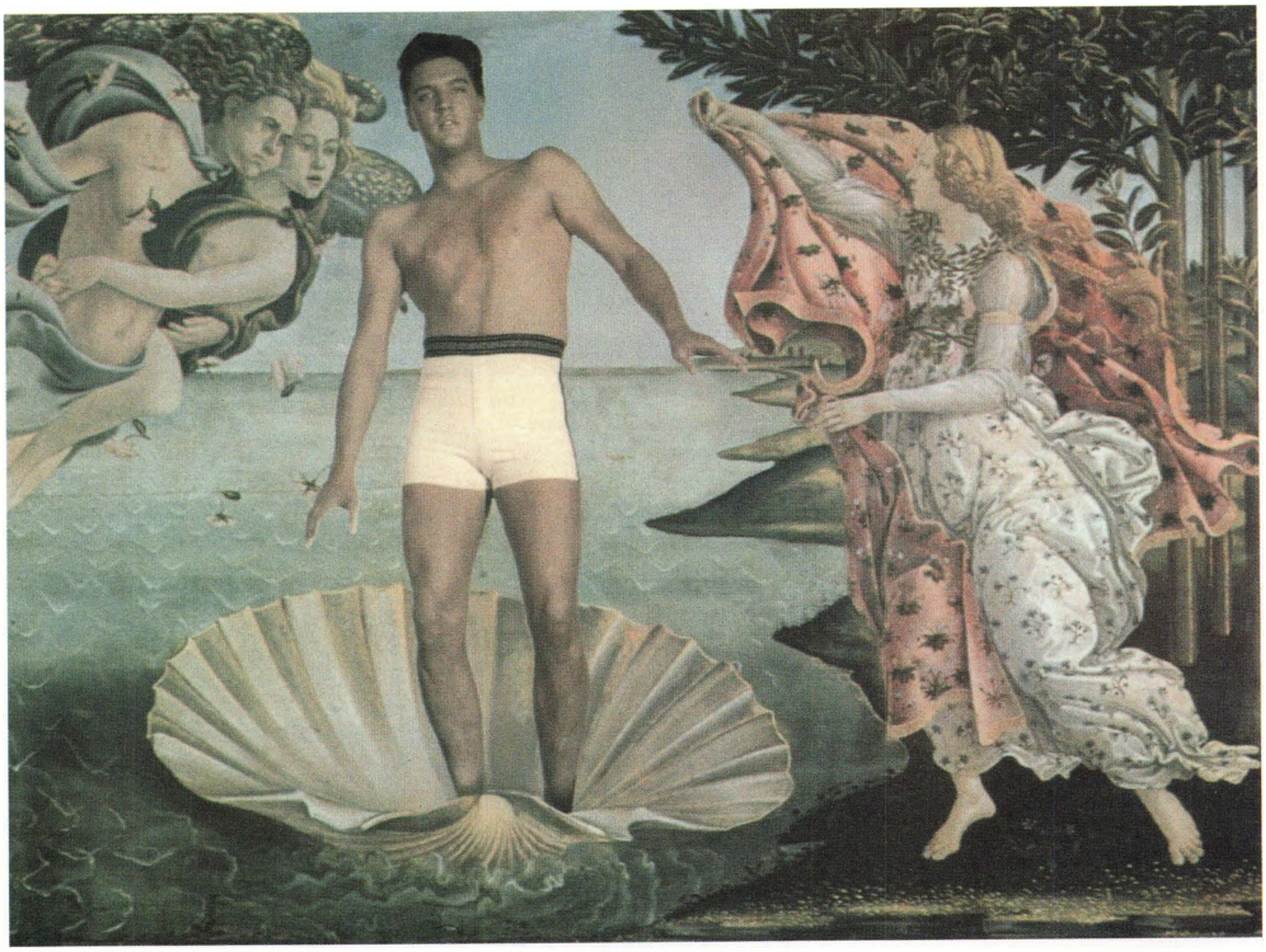
No. 58. (top left) Yuriko Amemiya, *The Balance*, print, 1986.

No. 59. (bottom left) Chantal Zakari, *#1A*, photograph, 14 × 11 in, 1989.

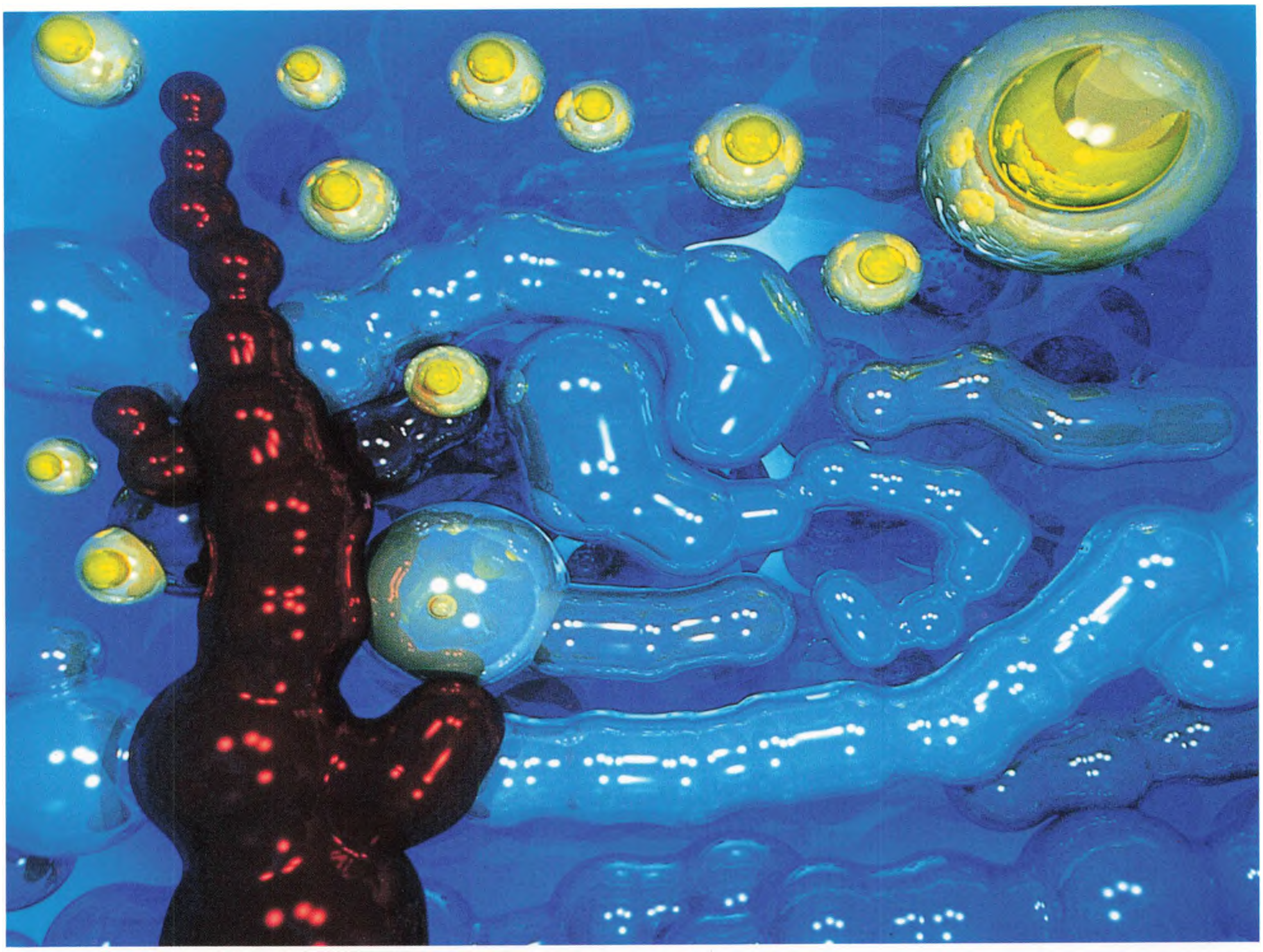
No. 60. (right) Ryoichiro Debuci, *Vision d'une Schizophrene #2*, print, n.d.

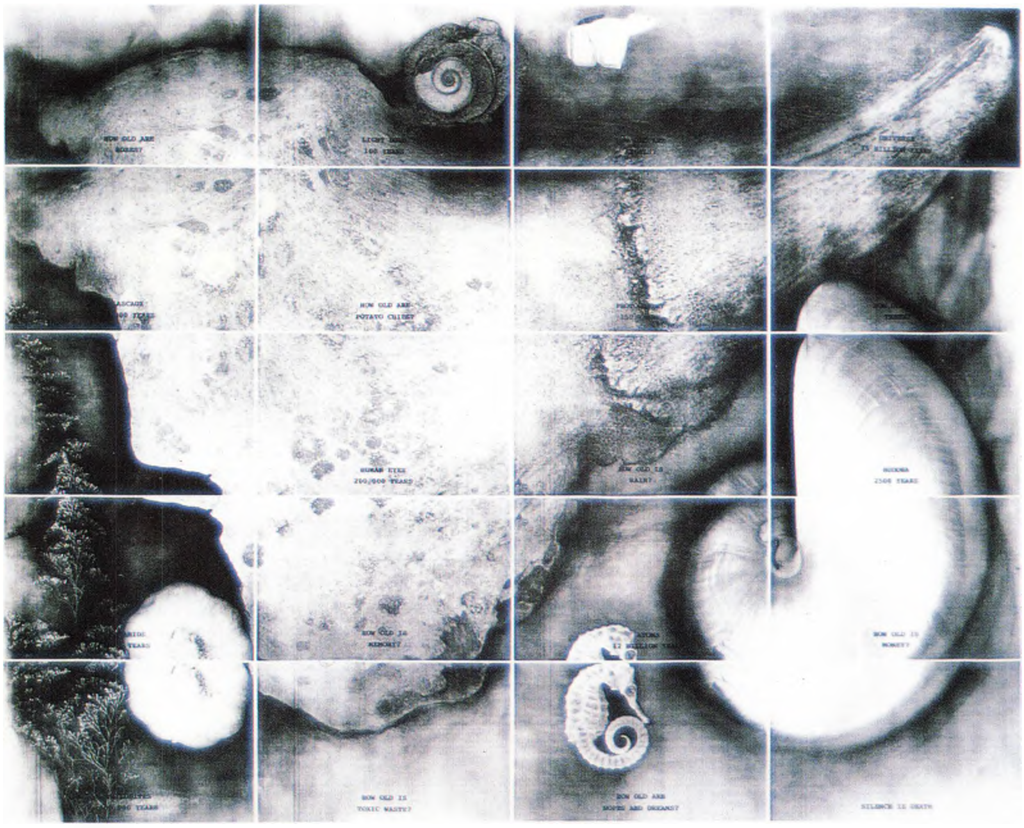


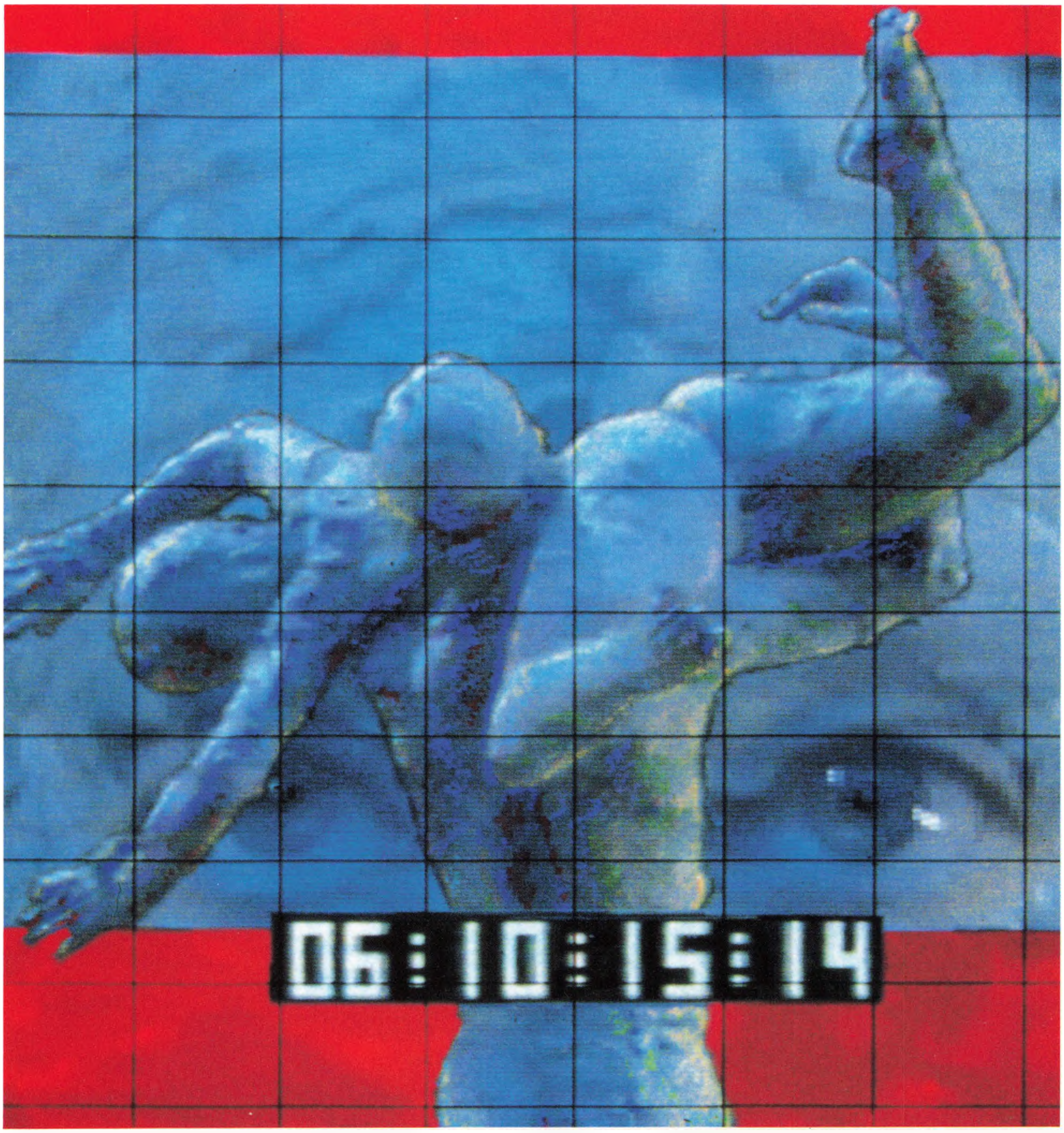
No. 61. Richard W. Maile, *The Birth of Elvis*, photograph, 16 × 20 in, 1990.

No. 62. (above) Carol Flax, *JF 60 (With My Mother's Eyes)*, inkjet print, 40 × 30 in, 1988.

No. 63. (right) Patricia Hoffman, *Making Cheesecake*, iron-on transfers from laser prints, cotton cloth, plaster bandages, 20 × 35 × 5 in, 1989.



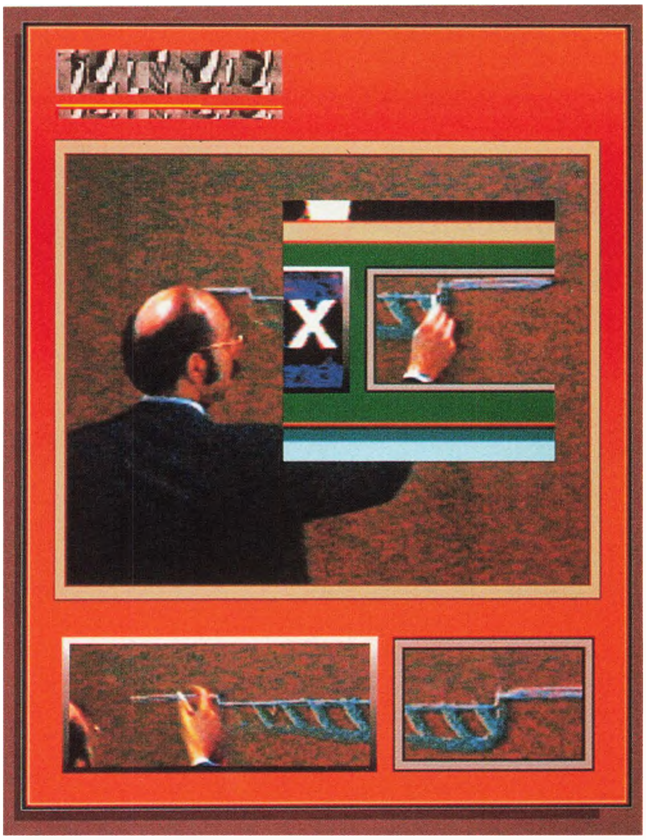

HUMAN EYES
200,000 YEARS
HOW OLD IS
RAIN?
HOW OLD IS
MEMORY?
HOW OLD IS
MONEY?
HOW OLD IS
TOXIC WASTE?
HOW OLD ARE
HOPES AND DREAMS?
SILENCE IS DEATH

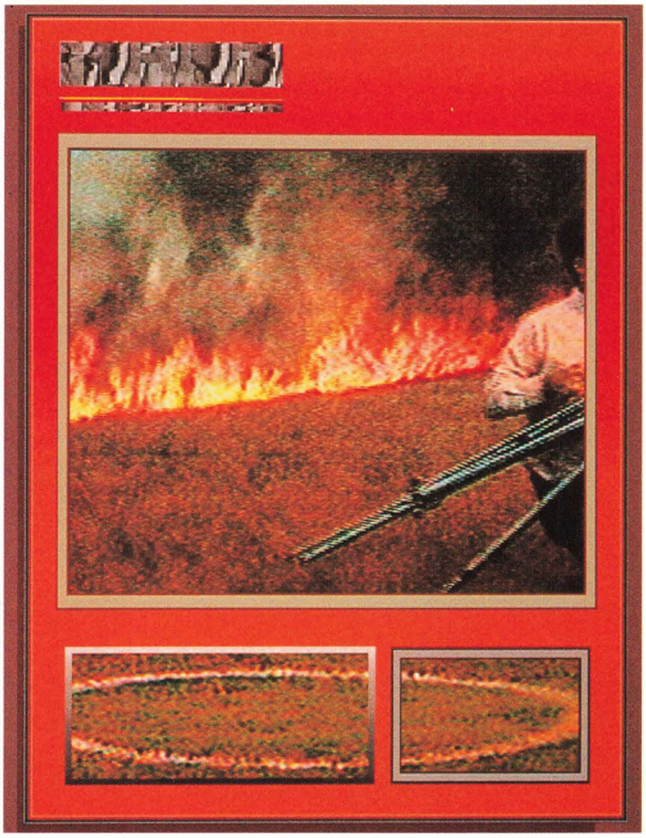


No. 64. (top left) David E. Breen, *Second Night*, photograph, 18 × 12 in, 1990.

No. 65. (bottom left) Sheila Pinkel, Untitled, digitized laser-scanned duplicating machine image, 60 × 48 in, 1989.

No. 66. (above) Gregory P. Garvey, *Terrain:06:10:15:14*, print, 8 × 6 ft, 1989. Collaborators: Terese Freedman, Jim Coleman.



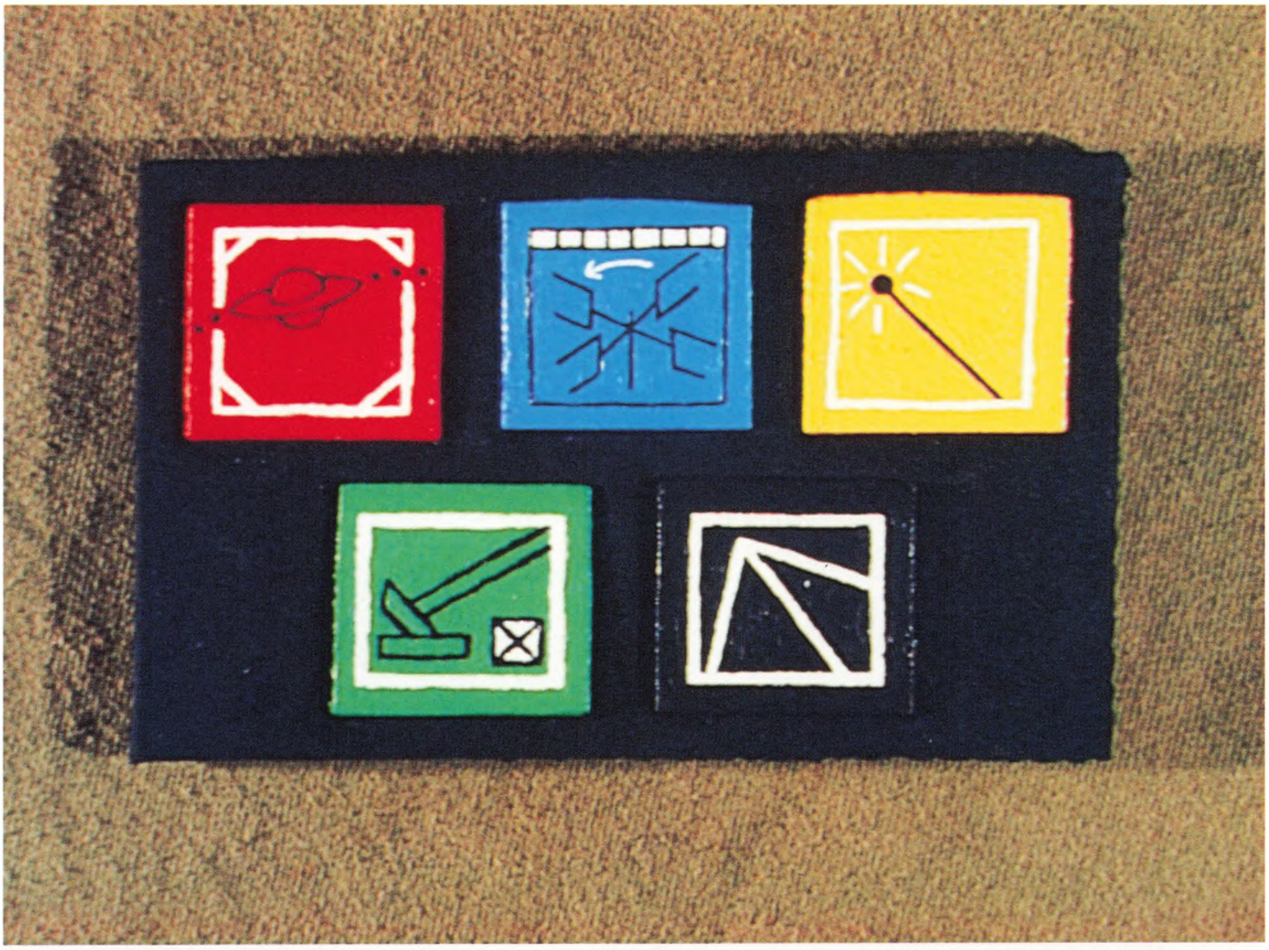


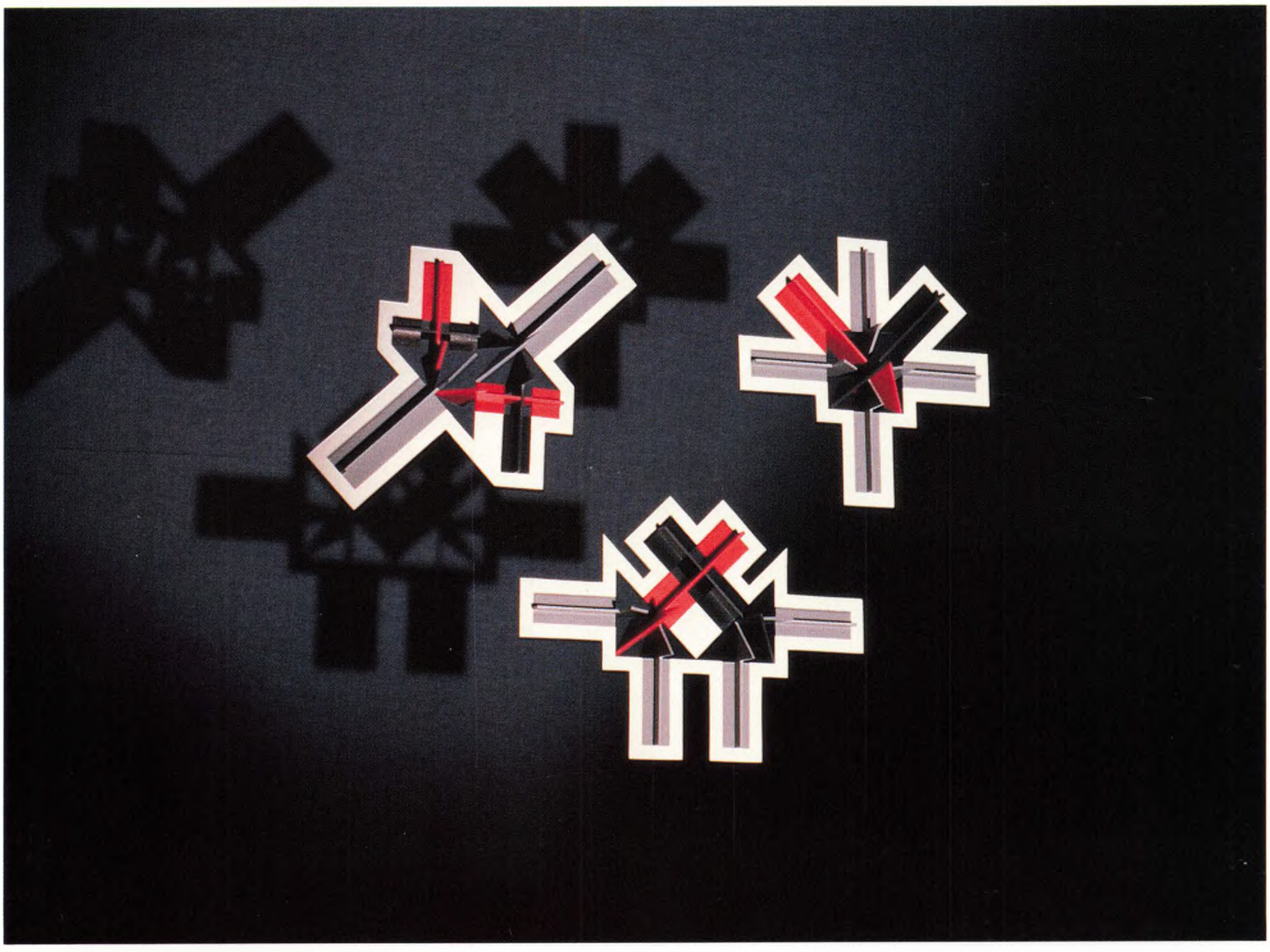
No. 67. (top) Paul Berger, *Mathguy*, inkjet print, 24 × 30 in, 1989.

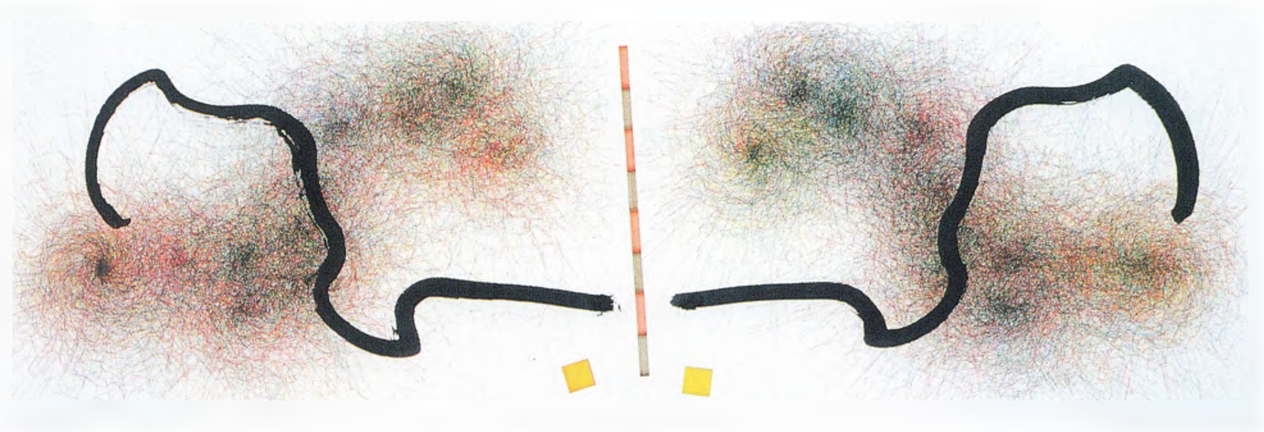
No. 68. (bottom) Paul Berger, *Firerim*, inkjet print, 24 × 30 in, 1989.

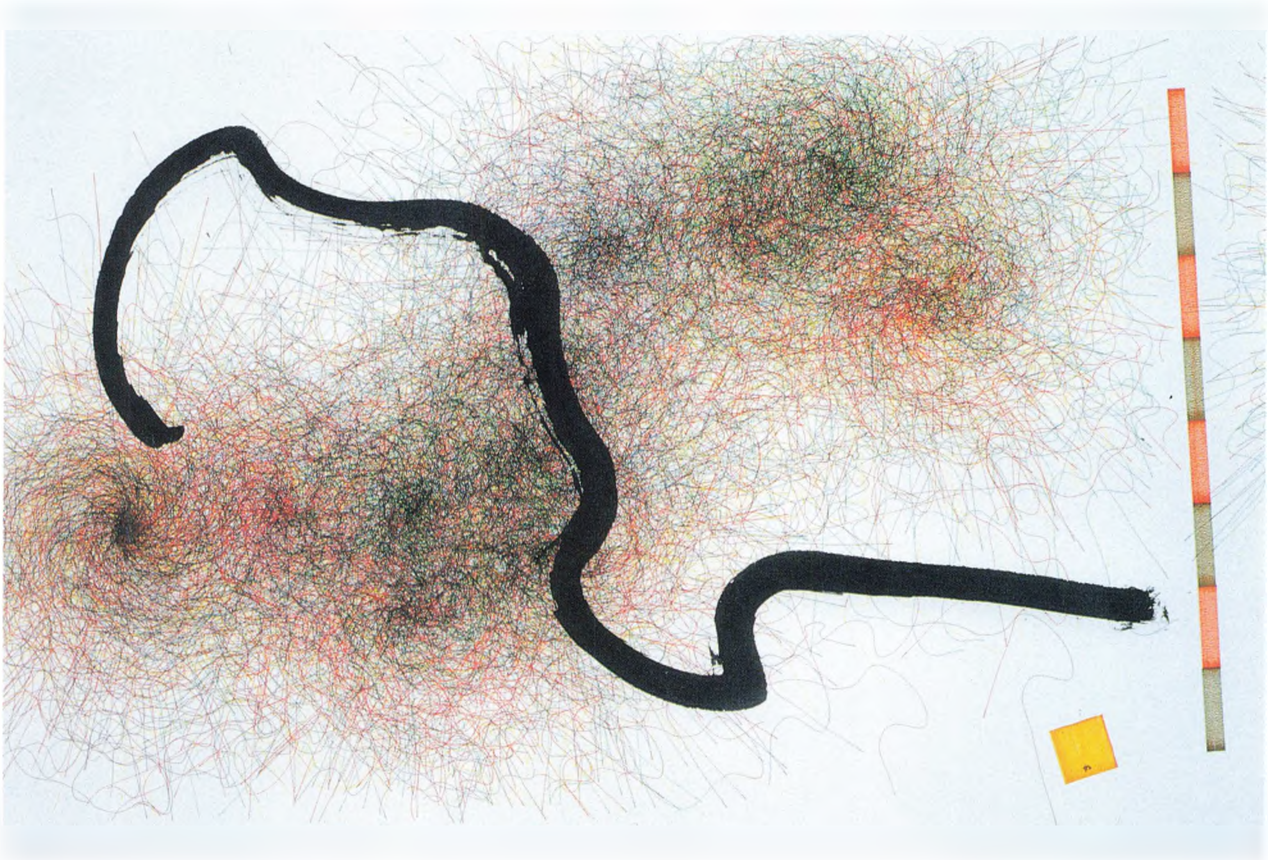
No. 69. (top right) Mark Bajuk, *Pocket Visualization*, acrylic on wood with magnets, suede case with zipper and metal plate, 6 × 4 × 0.75 in, 1990. Collaborator: Mysoon Rizk.

No. 70. (bottom right) Charles Chiles, *Air-Ohs*, mobile, 30 × 30 × 12 in, 1989.





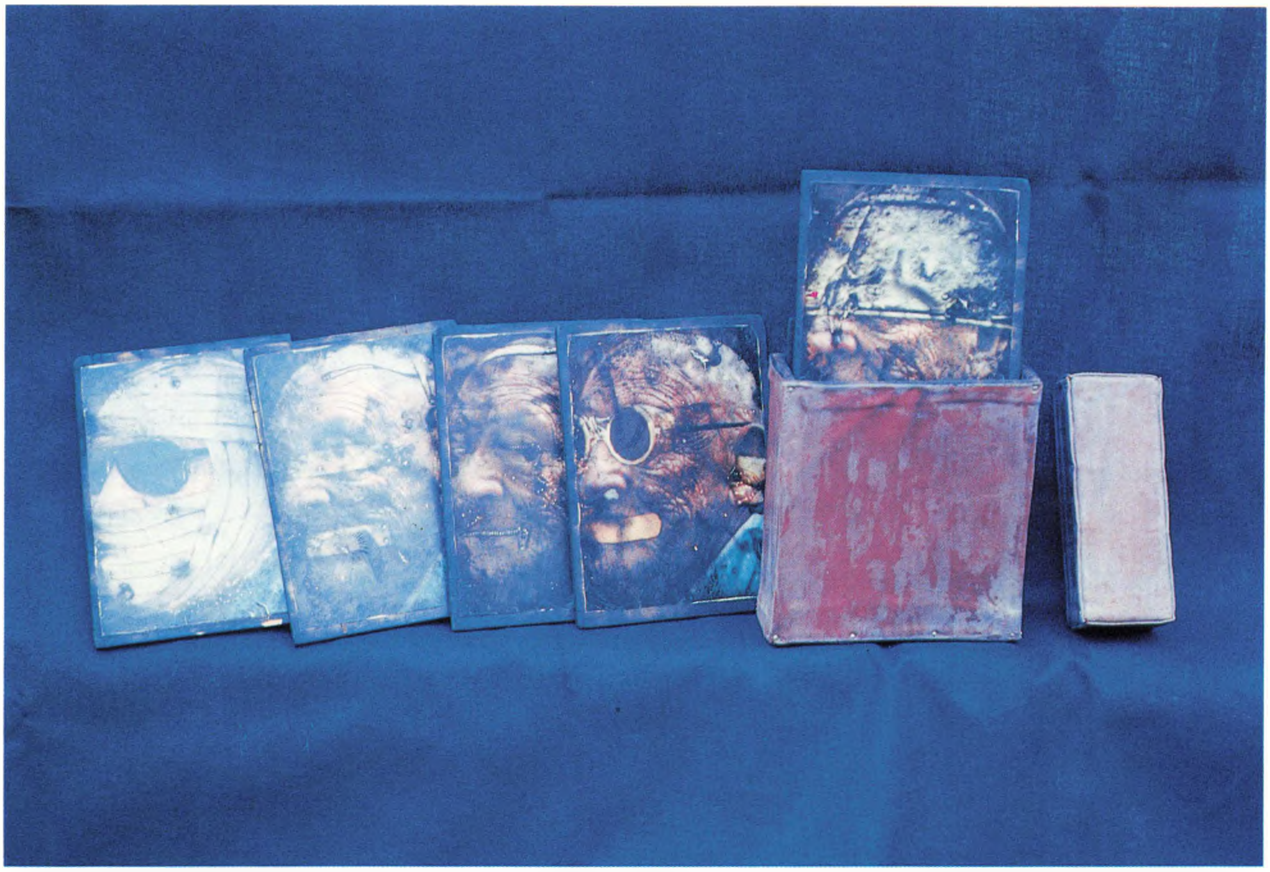


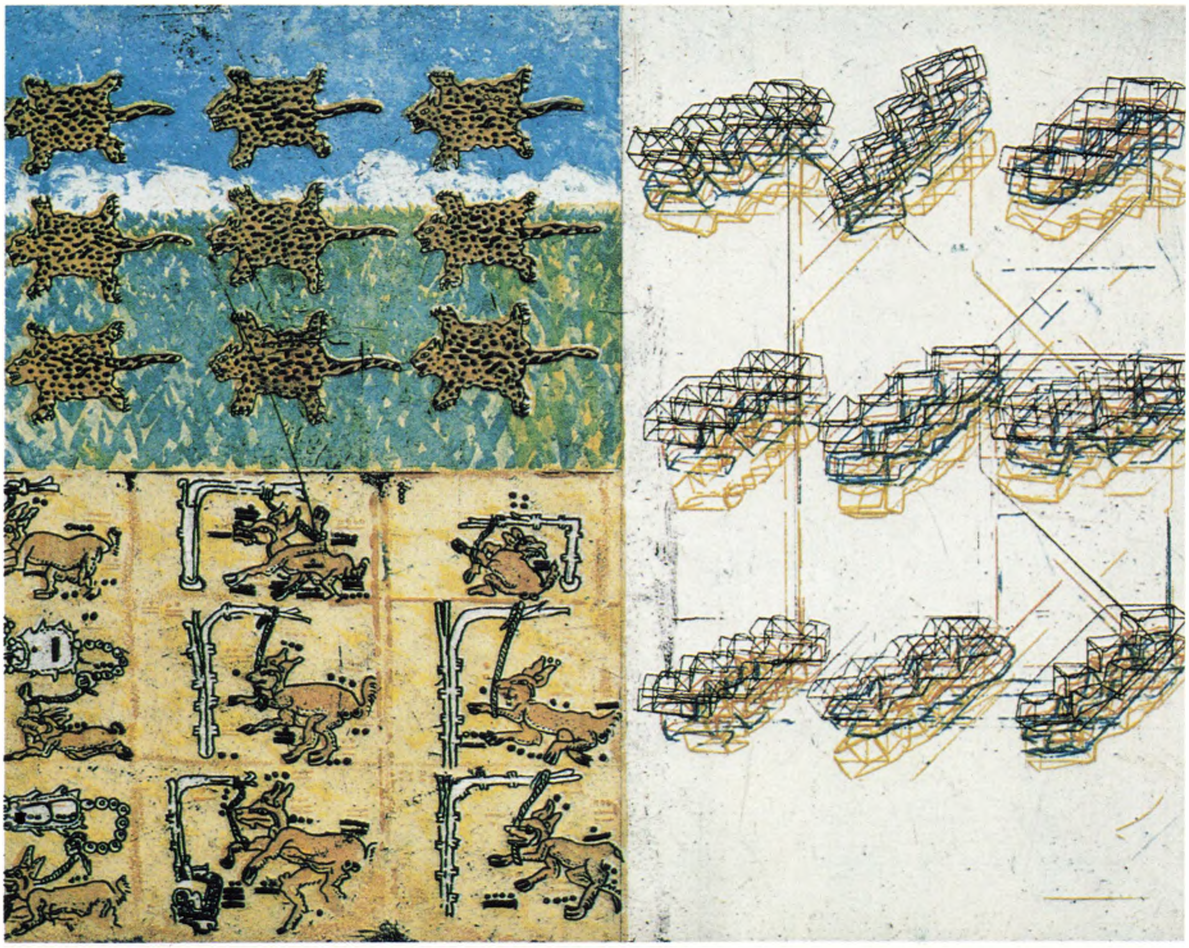


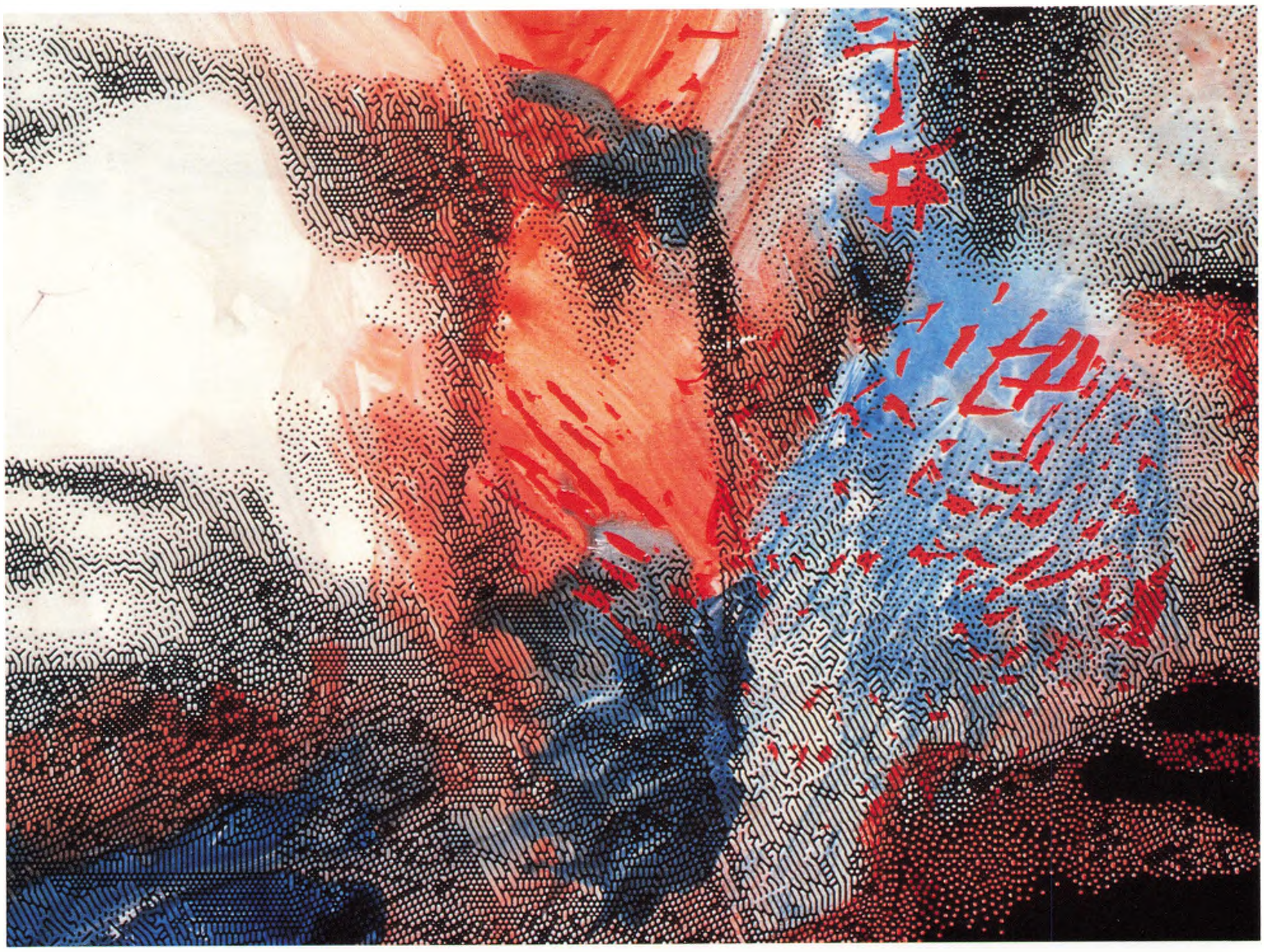
Nos. 71, 72. (above) Roman Verostko, *Lung Shan II*, rag paper, permanent ink, 72 × 24 in, 1989.

No. 73. (top right) Michael Kerbow, *A Pack of Martyrs*, wood, leather, photographs, nails, 6 × 8 × 2.25 in (closed case), 1989.

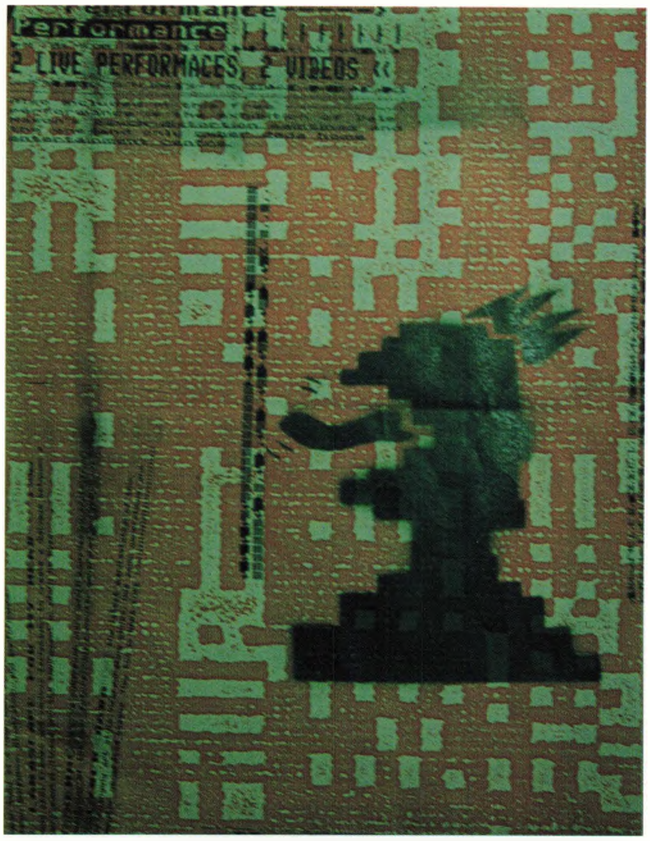
No. 74. (bottom right) Isaac Victor Kerlow, *Freedom and Imprisonment*, etching, 32.5 × 25 in, 1986.





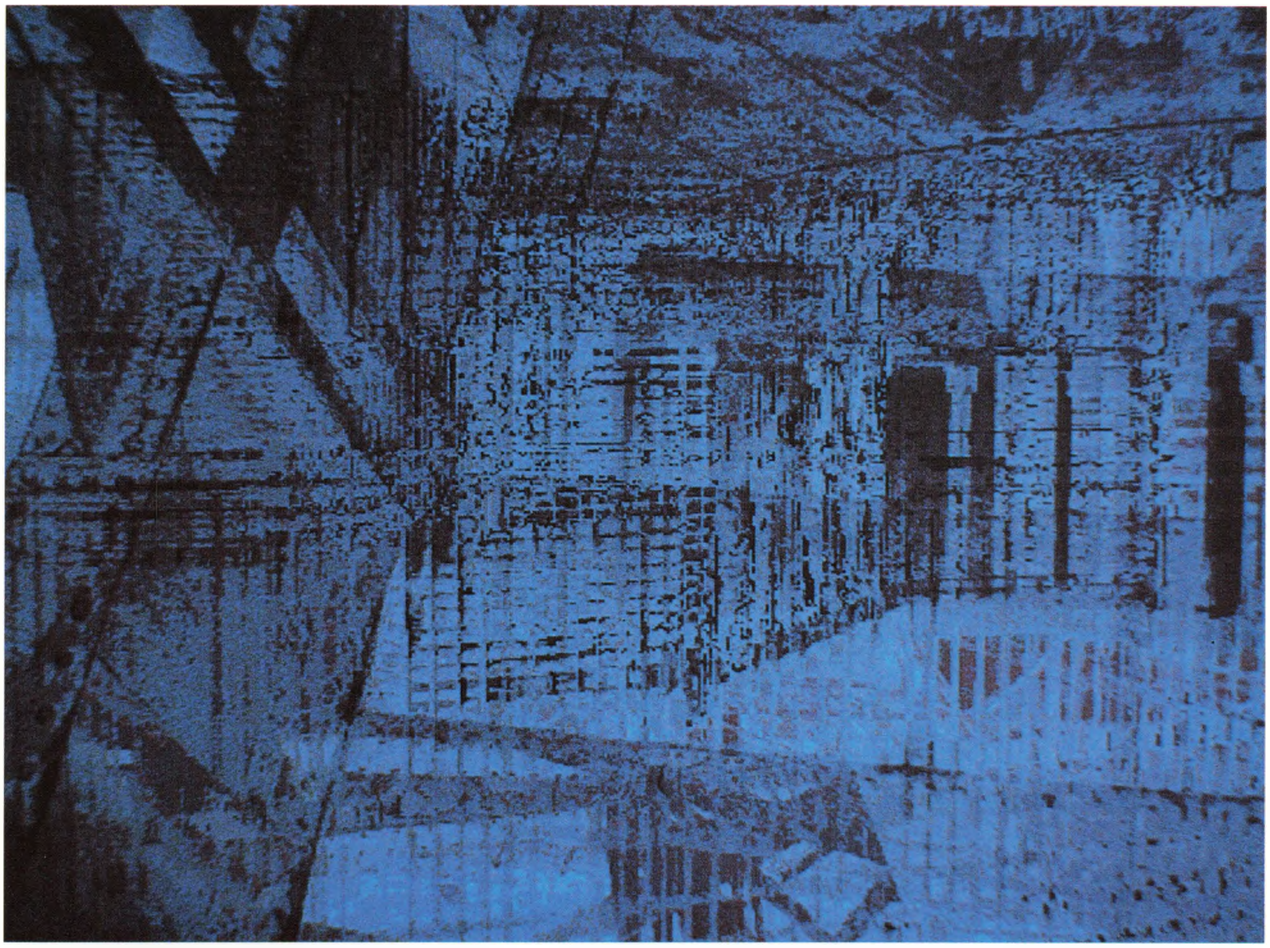


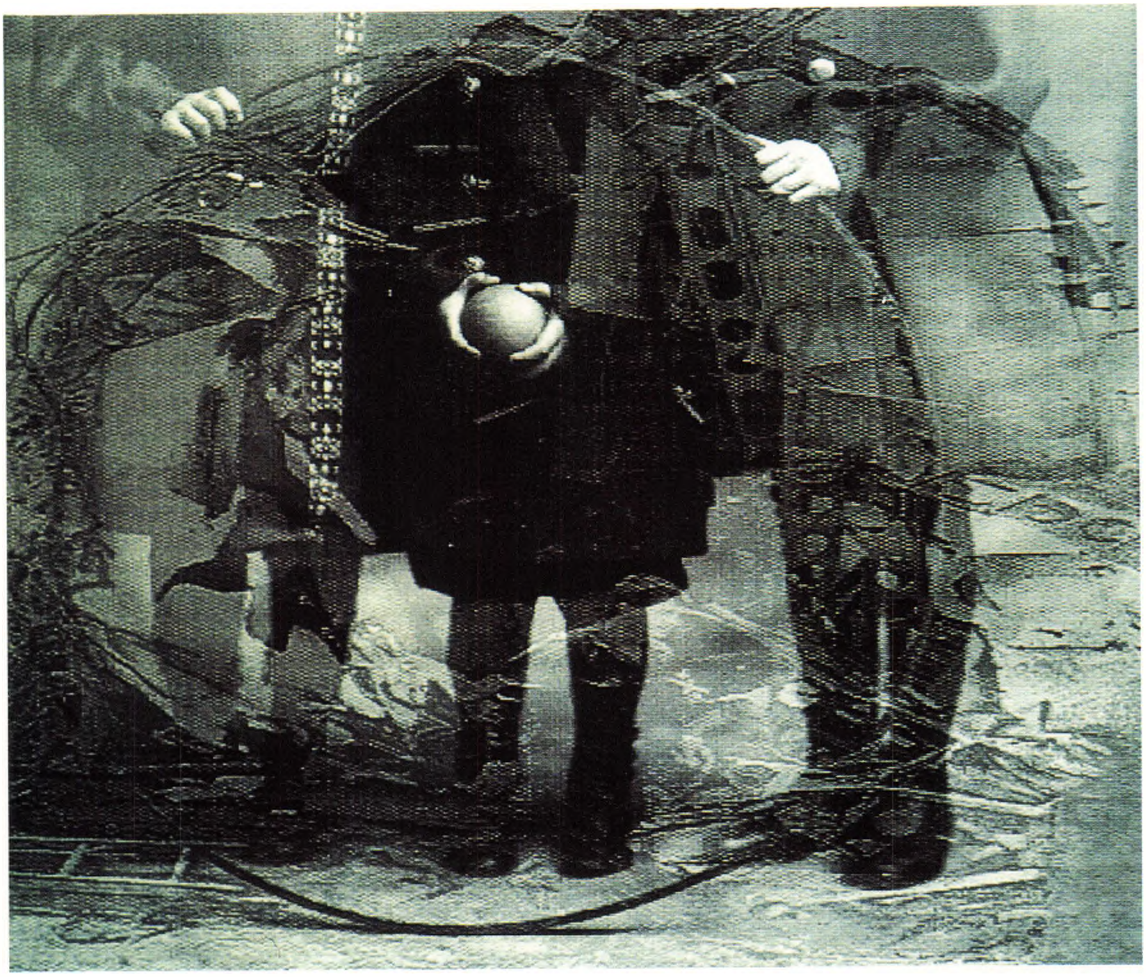
No. 75. Pat Lawler, *The Wall Pieces*, film, acrylic paint, 14 × 11 in, 1989.



No. 76. (right) Dale Nason, *Cyber Dada Performance Poster*, computer printout and photocopy on A3-size paper, 297 × 420 mm, 1989. Collaborator: Troy Innocent.

No. 77. (below) Heidi Tikka, *City Dreams*, cibachrome, 20 × 16 in, 1989.



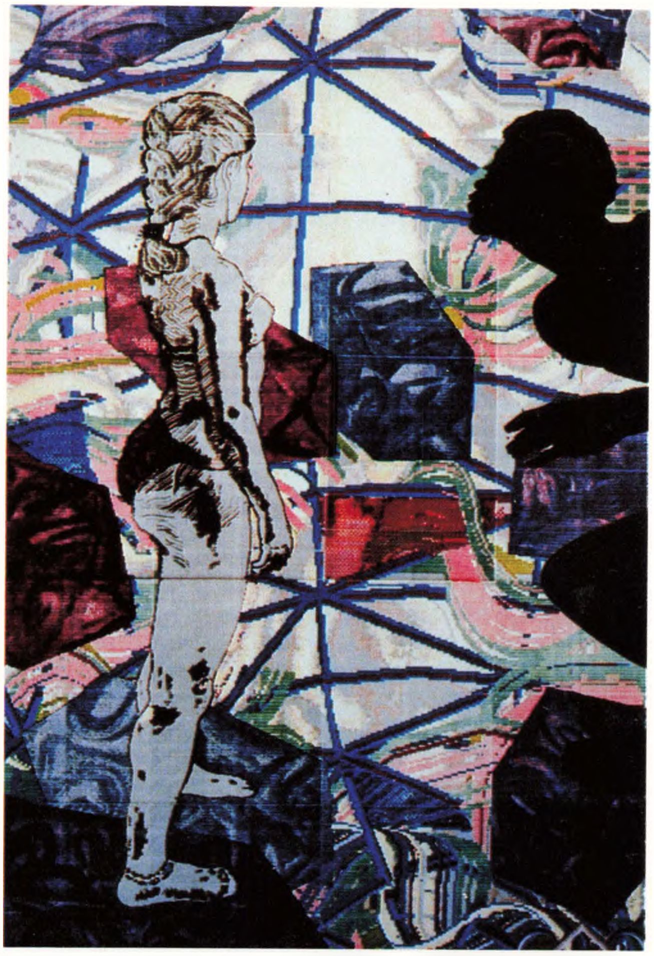


No. 78. (top left) Eva K. Sutton, Untitled, photograph on photo-linen, 2 ft × 4 ft × 4 in, 1990.

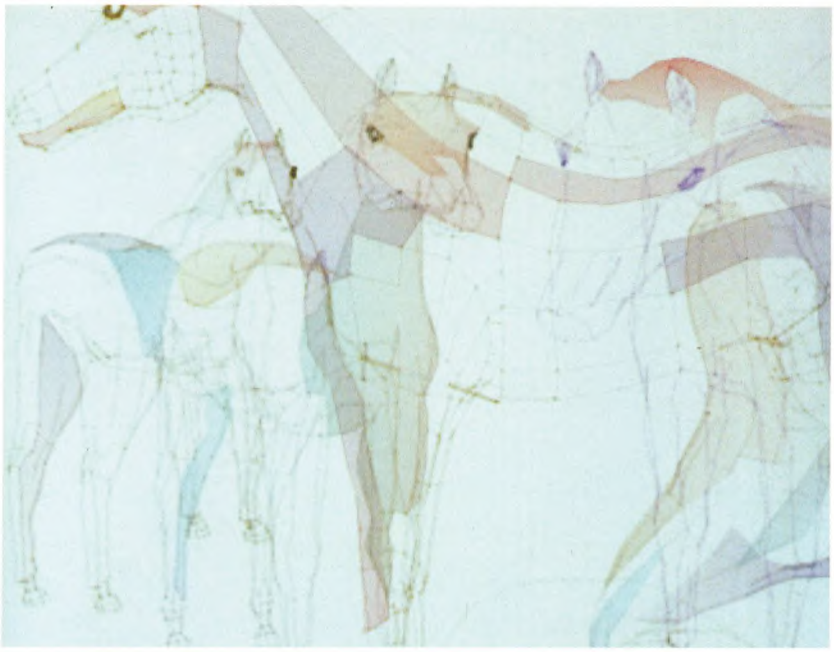
No. 79. (bottom left) Roger Dade, *Carpet Box*, photograph, 7 ft 7 in × 4 ft 7 in × 3 in, 1989.

No. 80. (right) David Glynn, *Tara y Cosimo*, thermal transfer print, 32 × 62 × 0.75 in, 1990.

No. 81. (below) John S. Banks, *Sunwall*, IRIS print, 20 × 24 in, 1990.

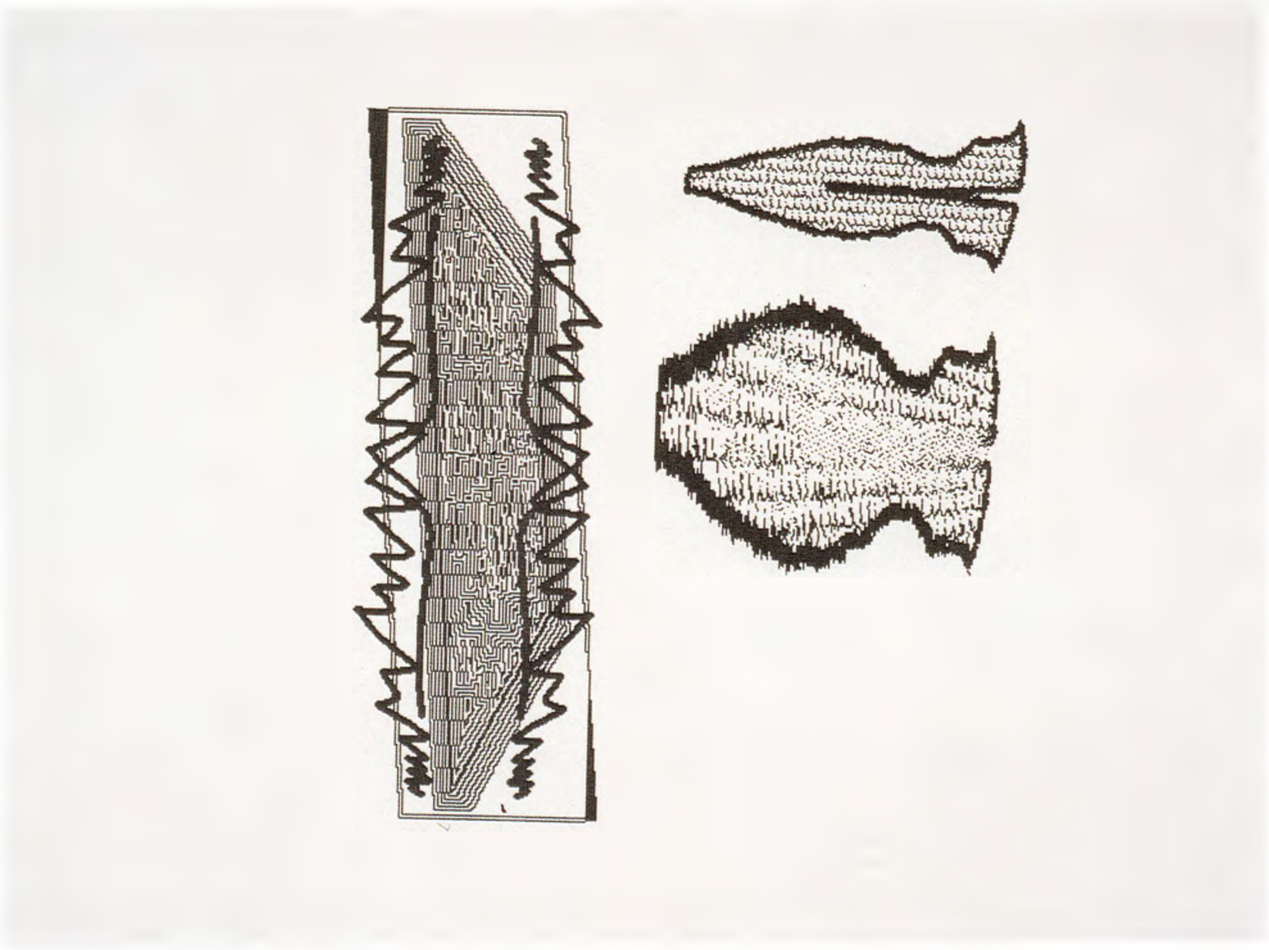


No. 82. Sandro Corsi, *Night Flow,* laser printouts, pushpins, wood, 10 ft × 8 ft × 5 in, 1989.

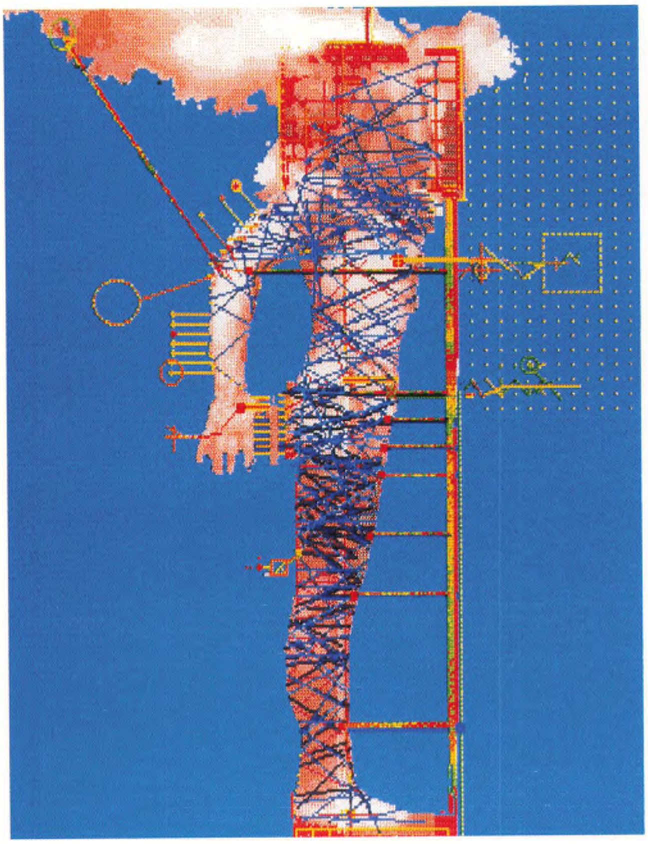


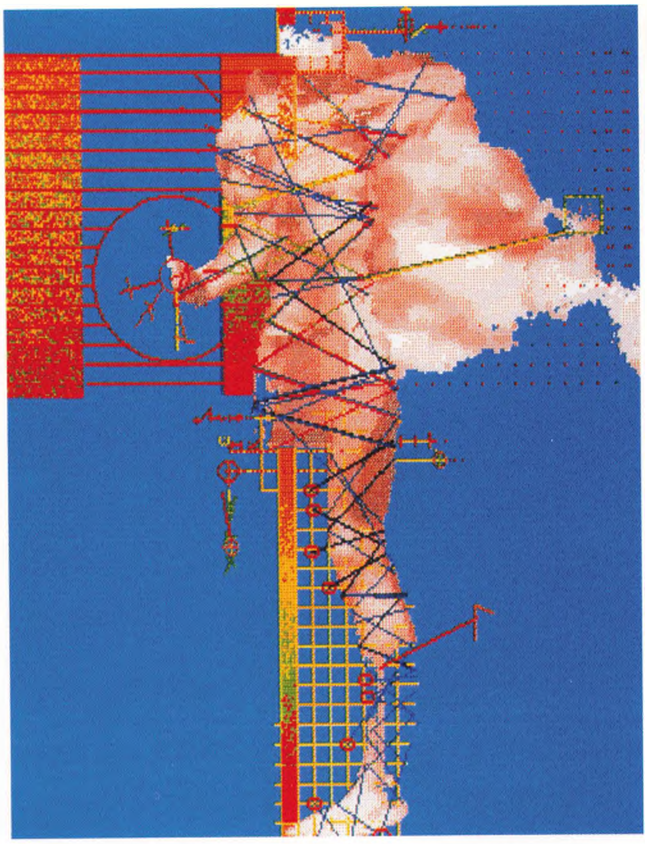
No. 83. (above) Karen Hillier, *You*, 2-D paint environment/film recorded image/cibachrome print, 20 × 16 in, 1990.

No. 84. (left) Andrea Losch, *Horse Study*, photograph, 20 × 16 in, 1990.



Nos. 85, 86, 87. Kathleen Kirka, *Wait/Weight (Triptych)*, laser print, 5 × 5 in, 1990.

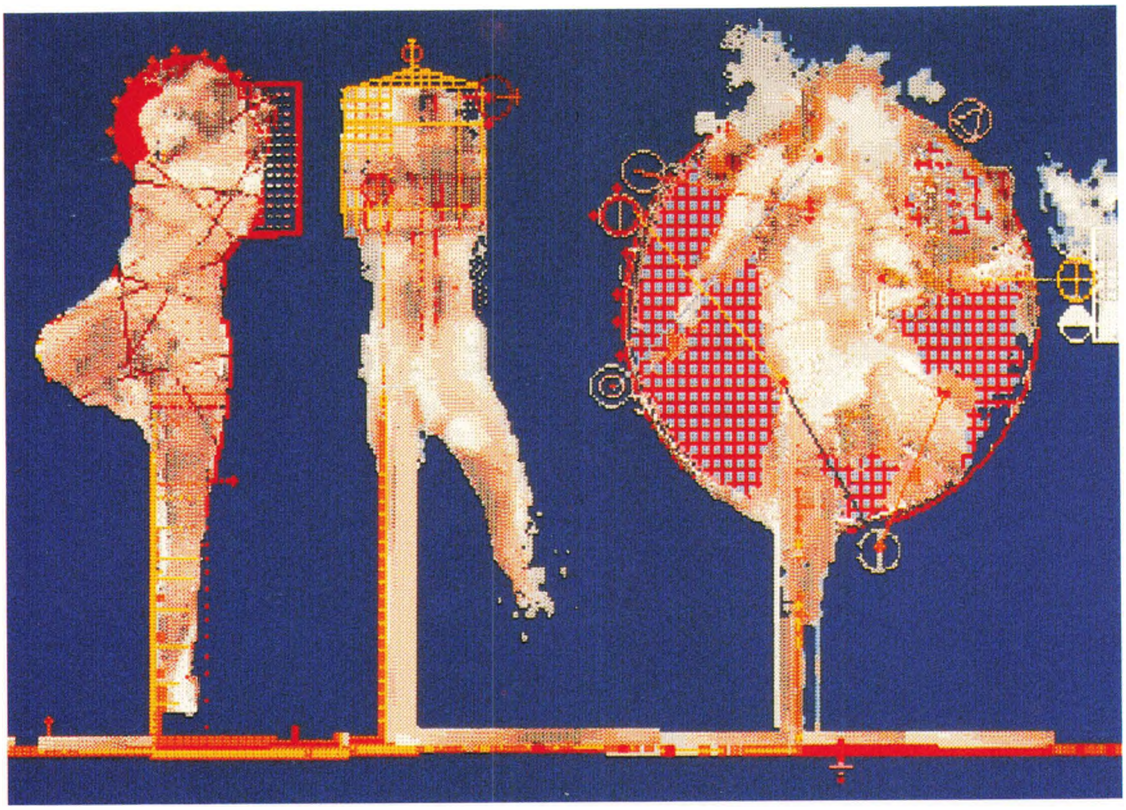




No. 88. (top left) Don P. Miller, *Sentinel #1*, computer-manipulated image/Xerox C150 inkjet print, 7 × 9.75 in, 1989.

No. 89. (top right) Don P. Miller, *Sentinel #2*, computer-manipulated image/Xerox C150 inkjet print, 7 × 9.75 in, 1989.

No. 90. (below) Don P. Miller, *Mutation—Cir*, computer-manipulated image/Xerox C150 inkjet print, 11 × 8 in, 1989.



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Japan

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Pocket Visualization, No. 69
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Champaign, IL 61820
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Banks, John S.
Sunwall, No. 81
401 E. Illinois #531
Chicago, IL 60611
U.S.A.

Berger, Paul
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Firerim, No. 68
6712 Division N.W.
Seattle, WA 98117
U.S.A.

Breen, David E.
Second Night, No. 64
Rensselaer Design Research Center; RPI
Troy, NY 12180-3590
U.S.A.

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House #2, No. 33
House of Virtue, No. 34
151 Reservoir Rd.
Marlboro, NY 12542
U.S.A.

Chang, Rodney E. J.
Paint Out No. 19 Revolution, No. 56
2119 N. King St. #206
Honolulu, HI 96819
U.S.A.

Cheung, Semannia Luk
Delicraft Curio, No. 49
479 Wellington St. W.
Toronto, M5V 1E7
Canada

Chiles, Charles
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Air-Ohs, No. 70
3743 Lajoya
Dallas, TX 75220
U.S.A.

Corsi, Sandro
Night Flow, No. 82
Dept. of Art
University of Wisconsin, Oshkosh
Oshkosh, WI 54901
U.S.A.

Cyber Dada
Cyber Dada Manifesto, No. 53
10 McCubbin Terrace
East Doncaster
Melbourne, 3109
Australia

Dade, Roger
Carpet Box, No. 79
Fern Barrow
Wallisdown,
Poole, BH12 5HH
United Kingdom

Debela, Acha
A Song for Africa, No. 50
170 E. Clearview Ave. #B
Worthington, OH 43085
U.S.A.

Debuci, Ryoichiro
Vision d'une Schizophrene #2, No. 60
Court-Setagaya 101, 1-15-11
Mishyuku, Setagaya-ku, Tokyo, 154
Japan

De Leon, Midori Kitagawa
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Diaz, Lily
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Dothan, Uri
Abstract Matters, No. 19
36 Gramercy Park East #105
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Durlach, David
Untitled (not shown), iron powder in a magnetic field, 1.5 × 1.25 × 15 in, 1988.
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Somerville, MA 02143
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Swarm, No. 11
13122 Rangoon
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U.S.A.

Feldstein, Peter
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133 Augusta, Box 252
Oxford, IA 52322
U.S.A.

Flax, Carol
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437 7th Pl.
Manhattan Beach, CA 90266
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Garvey, Gregory P.
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The Bernoulli Itinerary (not shown), video installation—3 channels, 10 × 3.5 × 6 in, 1990.
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New York, NY 10009
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Decaying Infrastructure, No. 8
Traveller, No. 9
909 Jennifer St.
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Exhibition Experiment #5, No. 46
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U.S.A.

Hamilton, Susan
Scarab, No. 43
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Hebert, Jean-Pierre
Laque Noire, No. 10
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Heeger, David
Movement Without Motion (not shown). video/painting installation.
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Palo Alto, CA 94301
U.S.A.

Hillier, Karen
You, No. 83
712 Eagle Pass
Bryan, TX 77802
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Making Cheesecake, No. 63
124 W. 60th St. #14E
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Engerthstr. 195
A-1020 Vienna
Austria

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2048 Fulton Ave.
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Wait/Weight (Triptych), Nos. 85–87
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Chicago, IL 60609
U.S.A.

Klein, Helen M.
Darryla, No. 51
Eugene, OR 97403
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Krueger, Myron W.
Step Lightly (not shown), interactive computer video, ongoing.
55 Edith Rd.
Vernon, CT 06066
U.S.A.

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Arlington, MA 02174
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Sakakibara, Motonori
One Day of Cassy (not shown), print, 23.5 × 23.5 cm, 1989.
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Japan

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Photo Finish at the Brickyard, No. 29
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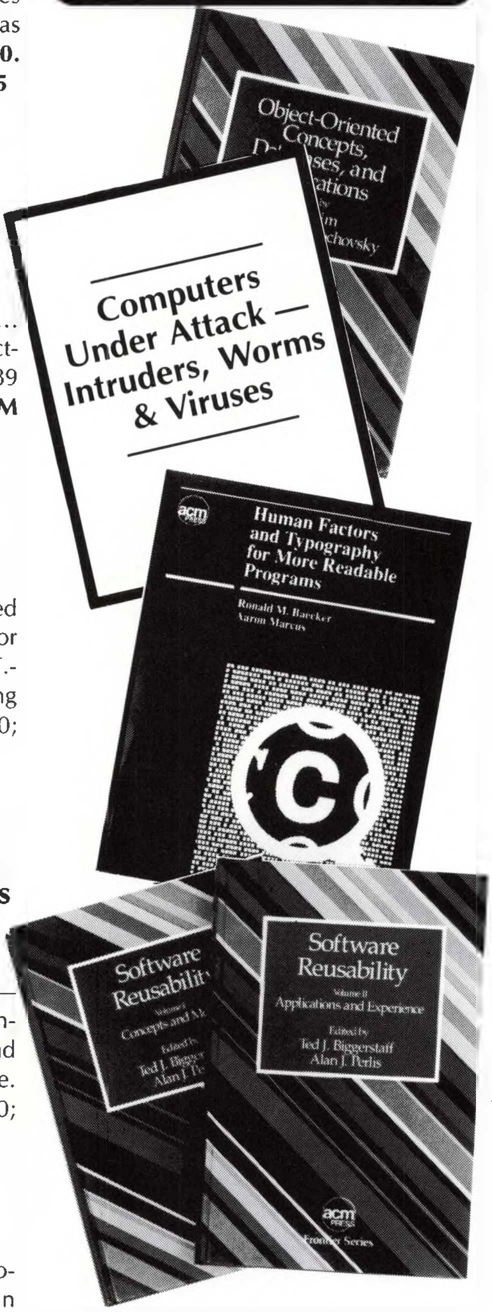

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3. Four full-time years of experience (attach a brief statement).

I attest the above is correct ____
Signature

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☐ **$21.00 Student Member Applicants**
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Faculty Member's Signature ____

Expected Graduation Date: ____/____ (MM YY)

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SIG Membership

Non-ACM Members Only

☐ **SIG Membership only. (Non-ACM Members only).**
Membership in special interest group(s) of your choice includes a newsletter subscription. SIG non-ACM members are not eligible for ACM SIG member rates or ACM membership privileges. *See "SIG Member (non-ACM) Rates" on reverse.*

Mailing List

Optional

ACM occasionally makes its membership list available to companies and societies for computer-related mailings. If you wish to restrict the use of your name for these purposes, please check one of the following:

☐ ACM announcements only.
☐ ACM and sister society announcements only.

For Office Use: Recruit/Promotion Code

Purposes of ACM

Signature Required

To advance the sciences and arts of information processing; to promote the free interchange of information about the sciences and arts of information processing both among specialists and among the public; and to develop and maintain the integrity and competence of individuals engaged in the practice of information processing.

I hereby affirm that I subscribe to the purposes of ACM and understand that my membership is not transferable.

Signature ____ ***Date*** ____

Note: Membership dues include $30.00 ($20.00 for students) toward a subscription to *Communications of the ACM.*

Effective 7/90

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Definitions:

Air Options: Available to overseas members. Circle desired rate(s) and add to publication subscription and/or SIG membership rate(s).

Partial Air Service-Air freight to Amsterdam and Dutch surface mail. Available only to Europe, India, Africa, and Mideast.

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Membership includes a subscription to *CACM*						
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Computing Surveys (quarterly)	103	14.00	9.00	+.15.00	30.00	= $
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PUBLICATION SUBTOTAL $ ________

**Expected Publication Date January, 1991*

Special Interest Groups (SIGs)

Note: SIG members who are not ACM members do not receive a subscription to *Communications of the ACM.*

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Air Options: Available to overseas members. Circle desired rate(s) and add to publication subscription and/or SIG membership rate(s).

Partial Air Service-Air freight to Amsterdam and Dutch surface mail. Available only to Europe, India, Africa, and Mideast.

Full Air Service-Air service from U.S. Available to all overseas locations including Hawaii.

Circle appropriate rate(s) and indicate subtotal. SIG Membership includes a Newsletter subscription.

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	Code #	ACM Members Voting/ Associate	ACM Members Student	SIG Mbrs Non-ACM Mbr. Rates	Partial	Full Air	Total
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SIGADA (ADA)	037	15.00	10.00	37.00	+ 22.00	44.00	= $
SIGAPL (APL)	032	15.00	7.50	40.00	+ 8.00	20.00	= $
SIGARCH (Computer Architecture)	002	20.00	10.00	45.00	+ 17.00	47.00	= $
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SIG SUBTOTAL $ ________

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ISAST

The International Society for the Arts, Sciences and Technology is a non-profit organization founded in 1981. The Society, through its projects and services, seeks to encourage the interaction of art, science and technology.

Publication of Educational and Scholarly Materials

Leonardo is the Society's official journal, published quarterly.

The Society's *Bulletin* provides a survey of services and resources. An annual Directory of Members and Resources is also published.

The Society publishes two electronic bulletin boards. FINEART Forum is a biweekly newsletter. F.A.S.T. is a worldwide directory of resources and opportunities accessible over MCI and ACEN on the WELL.

The Society publishes *Space Art News,* a quarterly newsletter covering the cultural dimensions of space exploration.

Awards and Other Assistance

The Society awards medals and prizes to honor those encouraging the synthesis of the contemporary arts, science and technology.

Frank J. Malina–*Leonardo* Prize

1985 Gyorgy Kepes
1986 Nicolas Schöffer
1987 Max Bill
1988 Takis

Coler-Maxwell Medal for Excellence

1987 Rudolf Arnheim, Otto Piene
1988 Charles Ames, Frieda Stahl
1989 Donna Cox, Janet Saad-Cook

New Horizons Award for Innovation

1986 Evelyn Edelson-Rosenberg
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Sponsorship of Competitions

ISAST is co-sponsoring Project 2001 for a monument to celebrate the start of the third millennium.

ISAST is collaborating with the Fulbright Commission for a Fellowship in Electronic Art/Light Transmission.

ISAST is co-sponsoring the Soviet-American Kinetic Art Exhibition 1990–92.

Collaboration with other Organizations and Individuals

The Society publishes Special Issues and Supplements:

Special Issue 16–3, 1983 Psychology and the Arts
Special Issue 18–4, 1985 Jacob Bronowski: A Retrospective
Special Issue 20–2, 1987 Visual Art, Sound, Music and Technology
Special Issue 20–4, 1987 Art of the Future—The Future of Art
Special Issue 22–1, 1989 Art and the New Biology
Special Issue 22–3/4, 1989 Holography as an Art Medium
Supplemental Issue, 1988 Electronic Art
Supplemental Issue, 1989 SIGGRAPH '89 Art Show Catalog

ISAST Projects

Dialogue Working Group, Space Art Working Group, Speakers Network

ISAST is a member of the Art, Science and Technology Network and the U.S. National Association of Artists' Organizations.

Associate Membership in ISAST

Associate membership in ISAST is open to professionals in the arts, sciences and technology. To apply for associate membership send curriculum vitae to: ISAST, 8000 Westpark Drive, Suite 400, McLean, VA 22102, U.S.A.

Membership benefits include: reduced-rate subscription to *Leonardo* and other ISAST publications; participation in competitions sponsored by ISAST; reduced-rate advertising in *Leonardo;* activity reports published in the ISAST Bulletin; and access to the Society's electronic bulletin boards to report news and opportunities.

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