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On the History and Aesthetics of the Digital Image (1999)

[51 – 65

Peter Weibel

I

Probably the most significant event since the very invention of the image are the changes in man's conception of the image that the advent of the digital image is entailing. However trenchant and decisive this may be, the history of the image already prepared the ground for it.

If we assume that the major distinction between the traditional image and the digital one is that the classical form of depiction is analogical—that is, it follows the principles of similarity, congruency and continuity—and that the electronic form of depiction is digital—that is, it uses the smallest, discontinuous, non-homogeneous elements—then we can separate our reflections on this topic from those movements in art which advanced the rupture in the traditional conception of the image. This extends from the insurrection of the abstract at the beginning of this century to kinetic art.

In accepting this distinction (from the concept of "digital art" evolves dialectically the concept of "analog art" which by definition signifies nothing else than classical art), we must overlook certain philosophical incongruencies. So, for instance, the fact that there are of course analogous elements in digital art and digital elements in analog art, since in the last analysis, any continuous analogous process can be reduced to small discontinuous pieces, in the same way a continuous line can be constructed from discontinuous dots. In the latter case, the distance between the adjacent dots is so small that it can no longer be discerned by the human eye. This awakens the illusion of a continuous line when in fact the distance exists numerically and can be represented. Digital art does exactly this: it allows analogous processes in nature to be represented digitally.

By means of dots that correspond to a specific number, the computer is able to generate a line on a connecting monitor. The monitor screen is a sort of number field in which each number which consists either of a digit, digit pair, or a sequence of digits, (e.g. 00101) can be matched with a dot. The representation of numbers is generally performed with two digits (0/1), so-called binary digits, since this is the only way numbers can be represented electrically, that is, by means of electrical impulses for 1and no impulses for 0. Thus we can say that digital representation and binary representation are linked to each other.

The computer then computes the number sequence, that is, the sequence of dots which on the connecting monitor create the impression of a line. This, of course, is only possible when the resolution capacity of the monitor screen is so great that the distances between the dots can be made so small that this distance and the size of the dots can no longer be discerned by the eye, although they actually exist numerically.

For greater clarity, I will retrack some ground and go into further detail. When a monitor screen has only a small resolution capacity, this means that it is a field of numbers comprising only few numbers. So that the small amount of numbers (= dots) can fill the field, they must be large enough since of course it is only possible to fill this field with a smaller number of dots when there are more of them. Eight large dots, however, placed next to each other linearly over the surface of the monitor screen by no means must appear as a line. Rather, one needs a great number of dots in such quantity and so minute that they seem continuous as a line does. A display the size of a normal TV screen with about

600 rows each with 800 dots is a number field consisting of 480,000 dots. It is easy to imagine how small these 480,000 dots have to be to fit in the screen and thus how easily the illusion of a line can be awakened. Since these dots can also have a different color, it is possible not only to produce forms but also color surfaces, so that the colored forms awaken the impression of motion and authenticity when they are changed, or rather, moved 25 times a second. The greater the resolution capacity is, the greater the number of dots or numbers available for depiction is, the greater the representation's authenticity, the better the illusion of realness and the more realistic the depiction actually appears. The efforts to obtain a greater resolution (e.g. 1,000 rows) are born of the wish to achieve greater visual realism.

If one considers that this amount of numbers and dots is not activated by simply tracing the image input with a beam as in television but rather entered into a computer for computation, one can imagine the great number of calculating operations and algorithms (commands defining the steps) needed for creating the line of a human profile on the monitor screen. Here there are no images or a reality to serve as a model but only numbers and calculating operations which through electronic transformations create forms that then appear on the monitor screen as forms. This is called artificial image generation, synthetic imagery, the basis of which is the number. If one considers that numbers not only correspond to the dots but also to their colors and intensity, meaning that the computer monitor must deal with millions of numbers for a simple color image for which the programmer has to come up with an algorithm (a sequence of commands for the calculating steps), one can easily conceive how much calculating work is needed to make just one non-moving digital image. If these images are supposed to move in a natural way too, needing to be changed 25 times per second, the amount of calculating operations becomes excessive, posing great demands on the rapidness and complexity of the computer's calculating power.

If we strain our imagination a bit more, we would expect the line drawn on a tablet with a light pen (joystick) to appear immediately and not only after lengthy calculating operations on the computer monitor screen and the movements on the tablet to be simultaneously followed by the line appearing on the monitor screen. By the same token, one would expect the sounds a pianist produces by hitting the keys to resound right away—and not later. This must take place in "real time"; thus the piano can said to be a "real-time display."

The enormous amount of calculating that the computer must surmount within a second of time can, of course, only be accomplished by supercomputers. For this reason, the motion and forms of figures on the screens of video games are clumsy, the low level of their motion and representation hardly awakening the illusion of realness. The calculation procedures required for higher levels implemented in microchips simply cannot be performed. The same holds true for personal computers.

In the field of digitally moved images, digital computer animation, there is not only a demand for monitors with greater resolution but also for supercomputers that are increasingly rapid and large, since only these computers are able to perform the enormous amount of calculations required for the forms, colors, and movements created numerically by the computer to appear on the monitor screen or (transmitted by laser) to appear on the film strip with an impression of realness. If one could buy the world's most rapid computer, one would come closer to the goal of generating, metaphorically speaking, colorful moving forms corresponding to natural objects in the real world by means of comprehensive calculating operations across the number field of the monitor screen. This means not only processing huge amounts of data regarding position, intensity, color, etc., of hundreds of thousands of dots within fractions of a second, but also computing the calculating operations needed for their control (=formation) which can only be done numerically as well. Such digitally generated images can, given the optimal resolution and calculating capacity of supercomputers, produce increasingly realistic simulations of 3-D objects and events.

Digital Productions in Los Angeles has the most rapid computer in the world, Cray-1, of which only about 25 exist running 24 hours a day. The digital image is supposed to simulate 3-D objects and events realistically by means of "digital scene simulation," as the company calls this method on the basis of computer-generated moving images. A film-design studio creates reality by computer—this is the ultimate goal of the digital image. Or is it? The contrary, I would say, since it is the essence of the digital image rather to create more than reality by computer, but this more looks more real. The basic principle (in the sense of the idealistic German ontology) of the digital image is precisely to make irreality realistic by computer. We don't need any moving photographs but rather the digital image to move beyond these, transforming the depiction (of reality) into a generation of images (of a new reality).

The digital image unites the possibilities of painting (subjectivity, freedom, irreality) and of photography (objectivity, mechanics, reality). Reproduction and fantasy, the two excluded sisters, are reconciled in the digital image. In the future it may be possible to speak of digital film or digital video, since the digital image can be realized in any medium.

The digital image which allows one to intervene in each section of the picture surface as freely as the artist can in the canvas to form each portion of the picture as I wish does not just emancipate the apparative art from its tortuous and constricting mechanics but also liberates our thinking in images par excellence from its many constraints. Thus the digital image is the first real foreboding of the "liberated image" like the digital sound of "liberated sound," the program of which was set down at the turn of the century. The art of the twentieth century has undertaken the emancipation of the image in two phases: in the first half of the century with Futurism, Cubism, Cubo-futurism, Suprematism, Dadaism, Surrealism, etc.; in the second phase, with Action Painting, Fluxus, Happening, Pop Art, Kinetism, Op-Art, Ambiente, Arte Povera, actions, performances, etc.

Aspects of this emancipation are visible as features of the digital image. I mention only the color forms of the abstract up to the Informel, the machine iconography of Dadaism (from Hausmann to Picabia), synthetic image findings and object transformations of Surrealism (from Dali to Magritte), the interaction and participation present in Happenings, etc. In the visual music films, or videos, abstract color impressions appear once again; also Surrealist collages, since the digital image is a collage expanded in terms of time and the number of spatial layers, as well. This collage is a composition in time and, similar to music, has left the two-dimensionality of the surface for the fourth dimension. The raster technique (Lichtenstein, Warhol, Dieter Rot, Sigmar Polke, etc.) is still another tacit characteristic of the digital image like the participation of the audience in video art (from installations to video games).

Many of the aesthetic aspects of earlier forms of art are directive for digital art which, however, transcends these. The examples one could still name for this are too numerous. The plotted line of some drawings by Matisse up to Warhol have ended in the plotter (a drawing device of the computer). From Pointillism to Divisionism all the way up to the raster technique, there are dot techniques that call painting as an analog art into question. The synaesthetic concepts of the total artwork from the turn of the century already formulated the program of music videos: to make visible what is audible. The actual development of electrical and electronic art began in the mid-sixties, on the one hand in popular music: light shows, slide projections, films, pulsing fluid elements, experiments with the electrical guitar; on the other hand, in the avant-garde: video art which could reach back to the great tradition of the abstract film; neonworks, installations, etc. In the media art of today, one mainly finds mixed forms, in art as well as in popular culture. Lucas' superproductions as well as Laurie Anderson's music videos use film, video techniques, and digital technology to an equal extent. We are standing before the quantum leap: digital image-works are becoming independent of other artistic forms, digital art is becoming autonomous. The most noticeable transformation of the digital image with respect to the phenomenology of its aesthetics and its relation to the classical analogous image (in spite of all genealogy) is best illustrated in the transition of the monitor screen of TV to the computer screen.

To the extent that the picture surface of the TV has become a familiar source of imagery, the computer monitor screen seems alienating and disturbing.

This, because the first, TV, carries on with the passive consumption of conventional picture codes, whereas the computer demands an interaction with new pictorial codes. The transformation of the TV screen into a computer screen through the connecting video display which make a computer out of a static object, also signifies another change: the monitor suddenly assumes new aesthetics of information and communication. If it is the special feature and advantage of digital art that it is ideally suited for digitally depicting analogous processes in nature, if, in other words, a pictorial technique perfectly matches its object as digital scene simulation (the digital realistic simulation of 3-D objects and ever in time) does, then this can only mean that the work itself is digitally organized, that everything analogous is also expressible in digital form. Thus digital art is becoming a more and more adequate expression of our world.

II

Computer graphics can be said to have formally begun with the work of Ivan E. Sutherland in 1963.[1] Sutherland is a disciple of the pioneers of information and image processing machines at MIT, Claude Shannon, Marvin Minsky, and Steven A. Coons. Sutherland works now at the University of Utah, Salt Lake City, a center of computer animation and digital images in the United States. In his now classic thesis, he showed how a computer could be employed for interactive design of line drawings using a simple cathode-ray tube display and a few auxiliary input controls. Others had already connected CRTs to computers in the early fifties to generate simple output displays. But it was not until Sutherland developed his system for man-machine interactive future generation that people became aware of the potential offered by computer graphics.

The realization of this potential, however, was slow to develop. Three major barriers were encountered. The first was the then high cost of computing. It was quickly discovered that computer graphics, especially if it was to be interactive, imposed inordinate demands on computers in terms of both processing requirements and memory size. During the sixties, the cost of meeting these demands could be justified only for research purposes in a few universities and some large industrial research laboratories.

The second barrier was a lack of understanding of the intricacies of the picture-generating software that would be needed for an effective computer graphics system. It was soon learned that one had to develop a data structure that in some sense would mirror the often barely realized but visually obvious relationships inherent in a two-dimensional picture. (In fact, the origin of much of today's data management theory can be traced to early work in computer graphics.) Algorithms for hidden-line removal, shading, and scan conversion were needed and generally proved far more complex than was first anticipated. Even as ostensibly simple a task as drawing a straight line segment or arc of a circle on a digitally oriented display turned out to require algorithms which were by no means trivial.

Fortunately, as it has many other technological innovations, time favored computer graphics. The cost of computer equipment kept dropping year after year, while that of labor kept increasing. Operating systems were improved, and our ability to cope with complex software became more sophisticated. Impressive progress was made in the development of algorithms for generating pictures, especially those intended to represent views of three-dimensional objects. The progress, though slow, has been sufficient that now, at the beginning of the eighties, computer graphics is finally becoming accepted as an effective, powerful, and economically sound tool of the engineer, scientist, designer, manager, illustrator, and artist

Computer graphics entails both hardware and software technology. As with conventional numerical computing, we may have both batch and interactive modes. In the batch (or "passive") mode, the speed with which pictures are generated is of secondary importance, and they may appear on a digitally controlled pen plotter, or a CRT. For the interactive (or "active") mode, the time of picture generation is critical, and the display must appear on a CRT, or a plasma panel.

In the early days of computer graphics, primary attention had to be given to the hardware. This is much less true today, since excellent high-performance hardware has become available from many manufacturers. Instead, the emphasis has now shifted to the algorithms for generating the various kinds of pictures that are desired (line drawings, grayscale shaded pictures, color pictures, perspective projections of three-dimensional objects, etc.) and to the software for conveniently programming (i.e. "drawing") the pictures.

Graphics Systems

Timothy Johnson's paper[2] may be considered an extension of Sutherland's work from two to three dimensions. In a simple, straightforward manner, it guides the reader through the techniques needed to design 3-D, planar-faced solids using the orthographic and perspective 2-D projections familiar to every engineer and designer. Homogeneous coordinates are introduced to permit 3-D translation, rotation, and scaling to be accomplished with a single matrix multiplication. Johnson adopted this technique from Roberts' work[3] relating to this description of 3-D solids. The paper addresses many of the subtle problems encountered in trying to design a 3-D plane. In a real sense, this paper is as much the forerunner of 3-D graphics as Sutherland's first paper is the forerunner of computer graphics in general.

Already in Sutherland's paper, the need is pointed out for structuring the image-defining data in a way that will facilitate the various manipulations one needs to perform on the data in an interactive computer environment. In succeeding years, this realization was strongly reinforced as more researchers took up the challenge offered by computer graphics. Data transformations known to be conceptually simple could become horrendously costly in computer time without careful attention to data structure. Indirectly, in the process of studying how to do graphics with a computer, much insight was gained in how we humans perceive 2-D and 3-D structures and subconsciously draw on much "world knowledge" available to us. The development of effective data structures was recognized as one of the key challenges facing computer graphics; and much attention was devoted to it.

Graphics Facilities

Interactive computer graphics—the word "interactive" is almost always assumed when one refers to computer graphics—requires the availability of a display medium in which a picture can appear within a fraction of a second after all the necessary data for it have been generated by the computer.

The "third-generation" graphics terminals, rather than relying on software to perform the transformations of scaling, translating, and rotating, are equipped with special high-speed hardware which is used to perform these transformations "on the fly"—that is, in a continuous manner as the image-describing data list is converted by the display processor to electrical analog signals which cause the desired deflections of the CRT beam. As a result, the transformations are accomplished essentially without any loss of time. Previous graphics terminals permitted the display of "moving" images by having the display processor transform (scale, translate, and rotate) slightly the images from one display frame to the next. This worked well for simple images (generated by small image lists). For larger images, even the most powerful computers proved unable to compute the required transformations fast enough to permit refreshing the image at the required 30 frames per second. The unpleasant flicker of the image was the inevitable result. Also, recognizing the importance of fast transformation for 3-D graphics, Hagan and his associates[4] extended the hardware transformation capability at once to three dimensions. The ready facility for modeling 3-D objects *in motion* represented an important advance in the field. In more recent years, high-speed digital transformation has replaced the analog circuitry. However, the general design concepts described in this paper still govern the architecture of high-performance graphics terminals.

In recent years there has been an increasing interest in raster displays over vector displays. Raster CRT displays offer the potential advantages of permitting the use of inexpensive black-and-white or color commercial television monitors, of simplifying the refresh problem, and permitting selective erasure. Their main disadvantage is the need for a relatively costly refresh memory, although with the cost of computer memory dropping steadily in recent years, this disadvantage is becoming progressively less important. A second disadvantage is that line-drawing data is normally *specified* in vector form, that is, as a sequence of line segments defined in a display file in terms of the coordinates of the lines' endpoints. To display a line drawing on a raster display requires an operation known as scan conversion, in which the original line-segment-defining data is converted to appropriately positioned dots in the bit patterns of sequential scan lines.

Scan conversion is important not only for CRT raster display, but also, of course, for the various raster-scan hardcopy devices such as electrostatic plotters and line printers.

Although line printers were never intended to serve as graphical output devices, their ready availability makes them appealing for both line-drawing and halftone graphics.

Computer Graphic Terminals

It is generally accepted that a computer graphic terminal is defined as one which contains means for graphic output (particularly in the form of a cathode-ray tube display) and means for graphic input (particularly in the form of a hand-operated electronic device for the input of pictorial information and for user interaction with the display). There are innumerable additional features normally associated with such terminals, the most common one being the inclusion of a conventional keyboard, often augmented by a set of special "function buttons," in the user's console. The more sophisticated terminal systems may also include means for quickly generating hard copies of displayed pictures, means for optically scanning hard-copy input drawings, and conventional printers of various types.

Although computer-driven CRT displays were used, particularly for debugging purposes, in some of the earliest digital computer systems, widespread interest in graphic consoles is relatively recent and is due to the great emphasis presently placed on improving man-machine communication. It is clear that the present state of the art in graphic terminals has been reached as a result of

1) efforts to satisfy requirements for military terminal systems to allow machine operations to quickly comprehend and respond to real-time tactical situations.
2) recent improvements in display hardware (e.g. digital-to-analog and analog-to-digital converters, vector and character generators, etc.).
3) the development of real-time computer systems which can efficiently handle large numbers of interrupts from peripheral devices.

Algorithms for Line and Curve Generation

A subject of considerable importance to both designers and users of computer graphics systems is the development of efficient algorithms for generating lines and curves. Since a refresh vector

display image must be redrawn at least 30 times per second, the amount of picture data that can be displayed depends critically on the speed with which the data can be generated. Much effort has gone into the development of fast hardware algorithms for generating vectors, characters, circles, and free-form curves. The problem is equally important when display output is to appear in hard copy on a digitally controlled pen plotter or a raster-line plotter.

The paper by Bresenham[5] is generally recognized as the first in which the generation of a digital line segment was methodically examined. The paper addresses the problem of finding the best digital approximation to a line segment specified by the coordinates of its endpoints. In a sense, it describes a "software vector generator" for a digital plotter.

A digital plotter consists of a pen that can be controlled to move stepwise in a unit distance forward or backward in the *x* direction, a unit distance (forward or backward) in the *y* direction, or any combination of both simultaneously. In effect, the pen is constrained to move from one node of an implicitly defined square mesh to one of the neighboring modes. It is thus not possible to draw a true straight line segment at any arbitrary angle. Instead every "straight" line segment—and, in fact, every curve—must be approximated by a chain of tiny, fixed-length line segments. The result is what is called a *digital straight line*. Exactly the same effect is obtained if a line or curve is to be drawn with an electrostatic plotter (or simply with a line printer). However, in this case the curve is approximated by a chain of dots (characters, in the case of the line printer) located at the mesh nodes, rather than by tiny line segments connecting mesh nodes.

The problem of finding the "best" such digital approximation to a curve has interested a number of investigators. Some have concentrated on algorithms for which the approximation deviates a minimum from the true curve; others have shown a willingness to accept greater deviation in exchange for more rapid (or simpler) computation.

Efficient algorithms for generating good-quality digital approximations for a large class of mathematically defined curves, for the generation of digital "circles" and "free form" curves, were developed in the seventies.

Graphics Languages

The usefulness of a computer graphics system is strongly dependent on the effectiveness of the language available for creating the required abstract geometric structures and for displaying them on a CRT or plotter. Languages for computer graphics—just like computer languages in general—can be grouped into

1) low-level, assembly-type languages
2) high-level, procedure-oriented languages
3) high-level, process-oriented (application-oriented) languages.

During the early and middle sixties, researchers developed a variety of graphics systems in striving to facilitate the application of computer graphics in a broad range of problems. In general, the early attempts at designing graphics languages emphasized the generation of line-drawing output and were confined to the use of graphical primitives in what were essentially assembly-type languages.

Generation of Halftone Images

Almost all the early work in computer graphics was concerned with vector-type graphics—that is, output was displayed on a CRT whose beam was made to trace out the actual lines of the generated line drawing. This was fully satisfactory for all forms of engineering drawings and most architectural drawings. However, it did not readily lend itself to generating halftone images that could be used for displaying an object in terms of shaded or textured surfaces. Interest in generating halftone images finally developed in the late sixties. One of the first dealing with this topic was Bouknight[6] from the University of Illinois at Urbana. The algorithm he describes can be regarded as an extension of the Warnock[7] algorithm over which it achieved a considerable speed improvement by scanning the image in raster fashion. It thus not only generated a halftone picture but simultaneously was able to remove hidden surfaces. Its use, however, was limited to planar-faced objects.

A major advance in the rendering of halftone images was made by Gouraud.[8] Gouraud approximated curved surfaces by means of small polygons so that discontinuities in shading at the boundaries would be eliminated. He was able to generate pictures of curved surfaces having remarkably smooth textures. The application of Watkins' algorithm readily permitted the elimination of hidden surfaces.

Catmull[9] of the New York Institute of Technology found a method for producing shaded images of curved surfaces based on the use of curved (bicubic) patches rather than polygons. The patches are as small as a raster element. Pictures of unusual realism were obtained, including pictures of "transparent" objects. The work in many ways represents the achievement of truly quality textured pictures.

A careful study of the problem of computing the intensity for each pixel of a shaded raster-display picture was made by Blinn[10] of the University of Utah.

Computer Animation

Interest in the use of computers to generate motion pictures developed almost immediately with the advent of computer graphics. As early as 1964, Knowlton[11] published a paper describing the computer production of animated movies. This was rapidly followed by a virtual explosion of activity in this field. Initial efforts were concerned primarily with simulated motion of fairly simple objects. The images were line drawings, and the objects were limited to polygons or 2-D projections of polyhedra. In all but the most trivial cases, no provision for hidden-line elimination was included.

A major advance in computer animation occurred with the publication of Ronald M. Baecker's 1969 paper which is based on his doctorate thesis for his PhD at the Department of Electrical Engineering at MIT. Baecker carefully examines the requirements for an interactive computer animation system, and then, in a step-by-step manner, traces through the various tasks necessary to obtain a computer-generated movie. The paper provides an excellent introduction into all aspects of computer animation and should be regarded as "must" reading for anyone interested in this field.

Animation is the graphic art which occurs in time. Whereas a static image may convey complex information through a single picture, animation conveys equivalently complex information through a sequence of images seen in time. It is characteristic of this medium, as opposed to static imagery, that the actual graphical information at any given instant is relatively slight. The source of information for the viewer of animation is implicit in picture change; change in relative position, shape, and dynamics. Therefore, a computer is ideally suited to making animation "possible" through the fluid refinement of these changes.

McLaren's description of animation:
Animation is not the art of *drawings*-that-move but the art of *movements*-that-are-drawn.
What happens *between* each frame is more important than what exists *on* each frame.
Animation is therefore the art of manipulating the invisible interstices that lie between the frames. The interstices are the bones, flesh and blood of the movie; what is on each frame, merely the clothing.

Although the computer's entrance into animation has been a recent one (1964), the growth of interest and activity has been phenomenal. Experience to date strongly suggests that the following statements are true:

1) The animated display is a natural medium for the recording and analysis of computer output from simulations and data reduction, and for the modeling, presentation, and elucidation of phenomena of physics, biology, and engineering.[12–14] Depiction through animation is particularly appropriate where simultaneous actions in some system must be represented. If the animation is the pictorial simulation of a complex, mathematically expressed physical theory, then the film can only be made with the aid of a computer.

2) The computer is an *artistic and animation medium* a powerful aid in the creation of beautiful visual phenomena, and not merely a tool for the drafting of regular or repetitive pictures.[15–18]

Three aspects of the role of direct graphical interaction in computer graphics are particularly relevant to computer animation:

1) The availability of immediate visual feedback of all results, final or intermediate;

2) The ability to factor picture construction into stages, and to view the results after each stage; and,

3) The ability to sketch pictures directly into the computer.

The power of immediate visual feedback in animation is striking. The computer calculates, from its representation of a dynamic sequence, the individual frames of the corresponding "movie." Like a video tape recorder, it plays it back for direct evaluation. A small change may be made, the sequence recalculated, and the result viewed again. The cycle of designation of commands and sketching by the animator, followed by calculation and playback by the computer, is repeated until a suitable result is achieved. The time to go once around the feedback loop is reduced to a few seconds or minutes. In most traditional and computer animation environments, the time is a few hours or days. The difference is significant for now the animator can see and not merely imagine the result of varying in movement and the rhythm of a dynamic display. Thus he will be led to perfect that aspect of animation that is its core: control of the changing spatial and temporal relationships of graphic information.

Interactive computer-mediated animation is the process of constructing animated visual displays using a system containing, in one form or another, at least the following eight components:

Hardware:

1) A general-purpose digital computer.

2) A hierarchy of auxiliary storage. This is listed separately to emphasize the magnitude of storage required for the data structures from which an animation sequence is derived and for the visual images of which it is composed.

3) An input device such as a light pen, tablet plus stylus, or wand, which allows direct drawing to the computer in at least two spatial dimensions. The operating environment must, upon user demand, provide at least brief intervals during which the sketch may be made in real time. The animator must then be able to draw a picture without any interruption. Furthermore, the computer must record the "essential temporal information" from the act of sketching. Sampling the state of the stylus 24 times per second often suffices for our purposes.

4) An output device, such as a standard computer display scope or a suitably modified TV monitor, which allows the direct viewing of animated displays at a rate such as 24 frames per second. This is essential to enable the interactive editing of animation subsequences. The final

transmission of a "movie" to the medium of photographic film or videotape can but need not use the same mechanisms.

Software:

5) A "language" for the construction and manipulation of static pictures.

6) A "language" for the representation and specification of picture change and the dynamics of picture change. We shall introduce in this paper methods of specifying dynamics not possible with traditional animation media and not yet attempted in the brief history of computer animation.

7) A set of programs that transforms the specifications of picture structure and picture dynamics into a sequence of visual images.

8) A set of programs that stores into and retrieves from auxiliary memory this sequence of visual images, and facilitates both its real-time playback for immediate viewing and its transmission to and from permanent recording media.

With the development of raster graphics in the early seventies, efforts were soon made to generate moving raster images. The work of Wylie, et. al. (1967), Gouraud (1971), Warnock (1969), and Watkins (1970) provided an excellent background for the human-face animation developed by Parke[19] of the University of Utah, Computer Division (1972).

Parke's paper describes the representation, animation, and data collection techniques that have been used to produce "realistic" computer-generated halftone animated sequences of a human face changing expression. It was determined that approximating the surface of a face with a polygonal skin containing approximately 250 polygons defined by about 400 vertices is sufficient to achieve a realistic face. Animation was accomplished using a cosine interpolation scheme to fill in the intermediate frames between expressions. This approach is good enough to produce realistic facial motion. The three-dimensional data used to describe the expressions of the face were obtained photogrammetrically using pairs of photographs.

The human face is a challenge for computer animation for at least two reasons. First the face is not a rigid structure but is a complex flexible surface. How is the motion of such a surface specified? Secondly faces are very familiar to us; we have a well-developed sense of what expressions and motions are natural for a face. We notice small deviations from our concept of how a face should appear.

Activities in computer animation have become so vast and widespread that it is impossible even to summarize them. A large collection of computer-generated films—some of outstanding quality—exists, and representative samples can usually be seen at the various annual computer conferences. Of particular interest to a reader seeking insight into this early stage should be the works of Whitney (1968), Max (1975), Csuri (1975), and others still to be named.

The refinement of computer animation systems to permit persons with minimal computer know-how to generate animated films is described in the paper by Hackathorn[20] of the Computer Graphics Research Group at the Ohio State University under the direction of Charles Csuri. A powerful, full-color 3-D animation system is described. The system utilizes a sophisticated animation language. The entire system was implemented on a relatively modest-size minicomputer.

An animation software system has been developed at the Computer Graphics Research Group which allows a person with no computer background to develop an animation idea into a finished color video product which may be seen and recorded in real time. The animation may include complex polyhedra forming words, sentences, plants, animals, and other creatures. The animation system called Anima 11, has as its three basic parts: a data generation routine used to make colored, three-dimensional objects; an animation language with a simple script-like syntax used to describe parallel motion

and display transformations in a flexible, scheduled environment; and the Myers algorithm used in the visible surface and raster scan calculations for the color display.

The development of computer-generated, solid-object animation is changing the way an animator approaches the documentation of an idea. Conversational animation involves drawing and redrawing planar images on each frame throughout the entire sequence. Image creation and image animation are very often the same process. But in a 3-D computer animation environment, the user first builds a colored object, then animates it and these processes are separate. The approach of 3-D color animation is similar to that found in other disciplines such as cinematography, theatre, and choreography.

In the mid-seventies a trend begun in which computer animation began moving away from the domain of the computer engineer and entering that of the professional filmmaker, a sign that the field has truly matured. By the second half of the seventies, extensive use of computer animation was being made to create educational and entertainment films of commercial quality for both the movie and television industries.

Digital Images and the Computer Community

The use of computers is proliferating in the arts of film and video. Computers are used for all aspects of the production process. In the form of microprocessors they are internal to virtually every device, and in the area of machine control, computers are fundamental to every procedure. Computers are integral to the very language and notation of these kinetic art forms which deal with the concepts of light, color, and motion in time and space.

The advent of computer graphics in popular culture, such as special effects for film and commercial advertising, has resulted in the emergence of facilities where artists have helped to direct the focus of research and exploration in image generation and synthesis. Their input has also affected the development of hardware and software systems.

Concurrently, the tremendous effect of personal computers and video game technology on the creative process and art is just beginning to be ascertained and acknowledged. While practitioners of more traditional art forms such as painting, sculpture, and printmaking are now questioning the validity of the computer in their media, film and video artists have always struggled with such concepts as the human-machine interface and the collaboration of the artist/technologist. These artists' achievements, and the resounding acceptance of their art form in major museums and art institutions around the world (as evidenced by this festival), have served to free these artists from questioning the validity of technological art.

It is therefore not surprising that these artists are responsible for some of the most remarkable achievements in the field of computer art. They are artists who have embraced computers as tools of artistic expression to either modify imagery or create entirely new visual realities.

The digital image, computer animation, and graphics are the most significant technological advances in the moving image since the very invention of film. At present advances in computer animation (cartoon trick films produced by computers) are being made in universities, industry, and art. A particularly interesting aspect of this development are the cross-connections between these three areas which are representative of individual work as well as of the whole state of the art.

Researchers are leaving the university for industry, artists are moving into the university and commercial areas, engineers are switching over to art. In the process, encounters occur between the three, involving joint work.

The following universities are leading in the theoretical research basic for both hardware and software in computer culture and technology as well as in the practical implementation of this: New York Institute of Technology, the Harvard Computation Laboratory of Harvard University, Carnegie-Mellon University, the University of Utah in Salt Lake City, the Massachusetts Institute of Technology, the Berkeley Computer Graphics Lab of the Computer Science Division, the Xerox Palo Alto Research Center, the University of Illinois in Chicago, the California Institute of Technology, etc.

Influential in computer industry are not only military institutions such as NASA, which receive exorbitant sums and have thus been able to make great advances in computer animation, but also film and commercial firms such as George Lucas Ltd., Robert Abel Associates, Cranston-Csuri, Digital Effects, Digital Production. These firms produce special effects with computer graphics for movies and commercials, etc. Also firms such as Atari, Apple, etc., which manufacture personal computers and video games, as well as Bell Telephone Laboratories, IBM, etc., deserve mention when one speaks of the computer communication revolution. Third, there exists a group of artists who in part depend on institutions and industry for support. Before I proceed to describe some of the most important examples of the cooperation between computers and art, I would first like to deal with some of the cross-connections existing between research, industry, and art which are typical of the advent of computer culture. Additional useful information on this topic can also be found in the notes. Tom A. DeFanti is professor at the Department of Electrical Engineering and Computer Science of the University of Illinois in Chicago. He is a computer specialist and computer artist and is presently serving as chair of the SIGGRAPH group. Together with Dan Sandin, Bob Snyder, and Jane Veeder (on whom Gene Youngblood has written an article, so that it isn't necessary to go into detail here) and others, he belongs to the Chicago Circle of Computer Art. His computer graphics language ZGRASS, designed for real-time interaction, has been used by both Jane Veeder and Larry Cuba (Santa Cruz).

Dan Sandin's Digital Image Processor as well as Woody Vasulka's Digital Image Articulator are among the best tools for the further processing of images. Ed Emshwiller can be named along with Veeder and Cuba as one of the leading computer artists. His famous production "Sunstone" (1979)—3 minutes produced in 3 months at the New York Institute of Technology, directed by Alexander Schure—was programmed by Lance Williams and Alvy Ray Smith who works today for Lucas Film. Frederic I. Parke (see his article on the computer animation of faces, 1972) did his doctoral work at the University of Utah. He now works as professor of computer science at the New York Institute of Technology and runs its Computer Graphics Laboratory where Paul S. Heckbert also works on the subject of "Beam Tracing Polygonal Objects."

George Lucas Film Ltd. in San Rafael, California, appears to be the major center of advanced computer graphics, digital image synthesis, and computer animation. Ed Catmull, who was formerly at the University of Utah and has written important articles on computer graphics, also works for Lucas Film. There, he is developing "an analytical visible surface algorithm for independent pixel processing" which is so important for Pixar. Loren Carpenter, whose film "Vol Libre" (2 min.), a computer-simulated trip through a mountain landscape, is a classic of visual work, is now working at Lucas Film on the development of algorithms for hidden surfaces (the A-Buffer, An Antialiased Hidden Surface Method). Adam Levinthal is working at Lucas Film on a "Chap—a SMID Processor"; Rob Cook is concentrating on "distributed ray tracing," one of the newest techniques with which realistic images can be generated on the basis of reflections and shadows. Curtis Abbott, also at Lucas Film, is working with digital sound. Others working at Lucas Film are Rodney Stock, Thomas Porter, Tom Smith, and William Reeves. Stock is the Graphics Engineering Manager and together with the above-named, participated in the project "Pixar." Apart from his film productions (e.g. "Star Wars"), George Lucas' major concern is developing a special technique for digital filmprinting and for the synthetic generation of images for film, which allow an interactive playing with the monitor producing the imagery that I want to see, such as pictures from the air. These pictures obey my input and control mechanisms (e.g. a flight around a rock in a canyon).

Stock used to work as graphics designer at Adage Inc., which developed a graphics terminal (Stock did the vector generation). He went on to work for Evans & Sutherland Corporation, where he did hardware for flight simulation and contributed to the development of hardware for the Ampex Video Art Paint System. As you see, also the pioneer of computer graphics, I. E. Sutherland of the University of Utah (see his work from 1963) runs his own computer firm where also Robert Schumacker, Michael Cosman, and, of course, David Evans work. Like Atari, Real Time Design in Chicago, etc., it develops interactive computer graphics systems. James T. Kajiya did his doctoral work at the University of Utah, then worked for Evans & Sutherland Computer Corporation, and today is professor at the California Institute of Technology.

In the late seventies, important articles on computer graphics were written by James F. Blinn who is also a graduate of the University of Utah and is now working at the Jet Propulsion Laboratory of the California Institute of Technology which has produced computer-generated animations for NASA and the famous TV series "Cosmos." Thomas Spencer and Richard R. Riesenfeld are also from the University of Utah. Riesenfeld has written important articles and is head of the Computer Science and Computer-Aided Geometric Design Group. The University of Utah, the New York Institute of Technology, and Lucas Film Ltd. seem to be the strongholds in the development of the digital image and interactive computer graphics systems.

Computer commercials or High Tech commercials are commercials that are actually produced with computers or have a neon-like computer look. Such high technology commercials and special effects for movies are produced by firms such as Robert Abel Associates in Hollywood, or Digital Effects Inc. in New York, or Cranston Csuri Productions in Columbus, Ohio, or the Entertainment Effects Group of Douglas Trumball, Adrian Malone Production or Digital Productions, both in Los Angeles. Judson Rosebush who has written much on this topic is the founder and president of Digital Effects Inc. Jeffrey Kleiser and Donald Leich work there in the computer animation division. Donald L. Stredney and Wayne Carlson are computer animators at Cranston-Csuri. Charles A. Csuri not only produced a famous computer film in 1967, but also wrote important articles on computer animation during the seventies. Robert Abel studied under John Whitney Sr., the pioneer of the digital image and computer film and visual music at the University of California, Los Angeles. His best co-worker is Bill Kovacs. Pat O'Neill, the famous avant-garde filmmaker on the west coast in the sixties, has worked sporadically for Robert Abel as well as for Larry Cuba, in addition to his production of abstract psychedelic films in the seventies.

High Tech Videos for the general public, such as rock videos, are made by Todd Rundgreen ("Utopia Video," "Woodstock in New York")—see his project "Will Powers," produced in 1983 with Lynn Goldsmith for Island Rec.—or Michael Nesmith, Bill Etra (DIGITAL IMAGE), Steve Rutt (LASER TV), etc. Artistic laser TV, laser disc programs, satellite TV projects are produced by Mobile Image (Kit Galloway / Sherry Rabinowitz).

The most interesting example of the interrelationships between art and High Tech business is Digital Productions in Los Angeles, which was founded by John Whitney Jr., the son and former co-worker of John Whitney Sr., the artistic pioneer of computer film, and Gary Demos.

Two further co-workers under 60 are Craig Upson, who worked together with the computer pioneer Nelson Max on developing cloud movements in computer animation, and Sherry McKenna who worked with Robert Abel on his famous "7-Up Bubble Commercial." Gary Demos, 32, worked as assistant for Whitney Sr., who produced his first computer film "Catalog" in 1962. Larry Cuba contributed to the programming of "Arabesque" (1975), 6 min.

The technique was developed by Information International Inc. (Triple) in 1974, the forerunner of

Digital Productions. Digital Productions specializes in digital scene simulation, that is, computer-generated images that realistically simulate 3-D objects and events. With the help of the supercomputer Cray-1 and other now techniques, Gary Demos developed the sophisticated software program at Digital Productions.

John Whitney, Jr., 37, the son of John Whitney Sr., produced "Terminal Self" in 1971. In this project he departed from the geometrically rigid computer films and achieved a spatial effect with figurative means. He has also sporadically worked together with the concept artist Michael Asher in a film by the latter. Whitney Jr. has worked together with his father since he was 15, produced his own abstract film, and designed a number of computer systems such as the Hybrid Optical Printer. In 1973 he was nominated for an Oscar for his contribution to "Westworld." Presently, the firm is working on a 20–30 minute long digital scene simulation for the movie "The Last Starfighter." Also in preparation are digital scene simulations for the film "2010," the follow-up of "2001." What is sensational about digital scene simulation is that it aims at creating computer scenes that are indistinguishable from nature as well as realistic scenes nonexistent in nature. For this purpose, the firm owns the world's most rapid supercomputer Cray-1 (costs 12 million dollars), a number of VAX and IBM small computers, 4 machines for transforming video into 35 min film, 2 film scanners, 3 Evans & Sutherland image systems, and 3 IMI motion systems for attuning the interactions with the objects. This is ushering in the future of electronic film: a movie simulated 100% with scenes that are still photographically so realistic that the audience is not able to distinguish real live action from simulated action. Digital scene simulation is the future of the digital image, of digital art. The example of Digital Productions and the relationship of father to son shows how a formerly marginalized form of art such as the abstract graphic film can become the centerpoint of a new industry. Also, it becomes clear that the experience and efforts over many years in avant-garde film, in particular, in abstract film (from V. Eggeling and C. Fischinger in the twenties to the Whitney brothers, James and John, in the forties) pointed to the future and laid the foundations for a technological revolution of industry. From abstract film to simulation computer film, a new form of film is evolving, a new form of vision and unlimited manipulation of visual data. Since the computer-generated imagery can be stored on both video and film and also be mixed with real scenes, computer animation incorporates the future; the future can be named digital image.

Digital Video

A preliminary stage of this development is the integration of video and computer technology: the digital video. This amalgam is inherent to video itself. In film the picture frame remains untouched; only from the collision of two frames, from the interval of two frames was it possible to construct meaning, motion, action. By contrast, in video it is possible through computer technology to manipulate each single pixel's color and form by means of a computer. The access to each of the 1,000 pixels of 1,000 video lines by means of the computer, and the possibility of changing each single pixel as one pleases, allow for individual, subjective manipulation of the image as in painting and an authentic representation as in photography. After fire and electricity, the digital image stands for the third promethe-ic instrument of artistic representation, that is, simulation. The highly advanced technology of the digital image, its potential for simulation through computer technology, give the individual unlimited access, unlimited possibilities to construct a new visual culture, a new democratic Renaissance.

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