# THE COMPUTER GRAPHICS SCENE IN THE UNITED STATES

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We briefly survey the major thrusts of computer graphics activities, examining trends and topics rather than offering a comprehensive survey of all that is happening. The directions of professional activities, hardware, software, and algorithms are outlined. Within hardware we examine workstations, personal graphics systems, high performance systems, and low level VLSI chips; within software, standards and interactive system design; within algorithms, visible surface rendering and shading, three-dimensional modeling techniques, and animation.

## 1.0 INTRODUCTION

There is a great deal of activity in the field of computer graphics in both universities and the private sector. The intent of this paper is to survey briefly the major thrusts of computer graphics activities, examining trends and selected topics rather than offering a comprehensive survey. To do so would surely require a book in itself!

Computer graphics in the United States appears to be growing in practice, theory, and applications. The increasing number of industry vendors and the concomitant scale of the large annual conferences are surely both indicators. The sales figures for computer graphics equipment are another. The heavy use of computer graphics technology in diverse fields is yet a fourth indicator. A modest amount of federal research money is applied to computer graphics algorithms and software. As hardware costs decrease, universities find that decent graphics displays and workstations are becoming affordable, and consequently more interest is generated among students and even faculty. Students are learning computer graphics not only for its own sake but also as a tool in the study of mathematics, physics, and, of course, engineering. While the number of universities doing (funded) basic research on computer graphics is not large, the work produced is novel and of high quality; in other words, we do not feel stagnant as a discipline but rather are experiencing a period of considerable growth and excitement.

In the remainder of the discussion we will outline current directions of professional activities, hardware, software, and algorithms. Within hardware we examine workstations, personal graphics systems, high performance systems, and low level VLSI chips; within software, standards and interactive system design; within algorithms, visible surface rendering and shading, three-dimensional modeling techniques, and animation.

## 2.0 PROFESSIONAL ACTIVITIES

Computer graphics' considerable growth in the 1980's is reflected in dramatic increases in professional activities. A considerable number of very active graphics associations exist and new publications appear at an increasing pace.

### 2.1 State Of Graphics Associations

SIGGRAPH is the Special Interest Group on Computer Graphics of the Association of Computing Machinery (ACM). It is the largest of the ACM Special Interest Groups with 11,000 members. SIGGRAPH is dedicated to further the theory, design, implementation, and application of computer-generated graphics and interactive techniques.

The main SIGGRAPH activity is its yearly conference. In 1983, the conference was held in Detroit, Michigan, July 25-29. The first two days were dedicated to one and two day courses on twenty-three different topics, ranging from fundamental principles to advanced special seminars. Some of the topics covered were introduction to computer graphics; introduction to raster graphics; introduction to film, television, video, and printing; user interface design; color perception; computer animation; image synthesis; computer aided design; solid modeling; freeform surfaces; robotics; and a number of application topics. About 2300 people attended the courses.

The next three days were devoted to the technical program. Thirty-four high-quality papers were presented in eleven sessions on topics such as image generation, raster algorithms and techniques, solid modeling and shape representation, standards, user interfaces and input techniques, and applications. Panel sessions were held in parallel with the technical paper sessions. The panels were devoted to a number of diverse topics of current concern and interest ranging from computer graphics education to solid modeling, CAD/CAM, and simulation of natural phenomena. Two panels were devoted to trends in computer graphics in Japan. Over 3300 people attended the technical sessions and panels.

The exhibition featured over two hundred vendors who demonstrated the latest in graphics hardware, software, peripherals, and services. The exhibitors also gave presentations on their product and services in the Exhibitor Forum. Over 14,000 people attended the exhibit.

Among the special events were the Film and Video shows and the Art Show. The Film and Video shows featured the latest scientific and artistic computer-generated animation graphics in a state-of-the-art audio/visual environment. The works in the Art Show were selected from over a thousand art works by a jury of well-known computer artists. The Art Show has travelled during this year to museums and galleries in the U.S., Canada, France, Italy, and Japan.

Through a recent change in the SIGGRAPH by-laws, an awards program has been instituted. At SIGGRAPH'83 the first two awards were given. The Steven A. Coons Award has given to Ivan Sutherland for his outstanding creative contributions to computer graphics, and the Achievement Award was given to James Blinn to recognize his significant research accomplishments.

SIGGRAPH sponsors many other activities during the year. SIGGRAPH has 17 local chapters in the U.S., Canada, Australia and Europe, which organize regular activities such as lectures and workshops. SIGGRAPH also sponsors workshops on topics of particular interest, and cooperates with graphics societies in the U.S. and other countries. SIGGRAPH publishes a quarterly newsletter, SIGGRAFITTI, and a quarterly report Computer Graphics.

The National Computer Graphics Association (NCGA) is an organization of 6,700 professionals and 50 corporations. NCGA is "dedicated to developing, promoting and improving computer graphics applications in business, industry, government, science and the arts."

One main NCGA activity is its annual conference, which was held this year in Anaheim, California, May 13-17. This conference featured thirty-seven half day tutorials and eighty-six technical sessions. The topics of the tutorials and the technical sessions were applications of computer graphics to areas such as architecture, biomedicine, business, computer-integrated manufacturing, electrical and mechanical CAD/CAM, mapping and cartography, printing and publishing, ship building, and statistics. Other topic areas were graphics hardware and software, microcomputers, human factors, standards, education, legal issues, pattern recognition and image processing, video technology, and art and design.

Over two hundred major computer graphics hardware and software vendors displayed the latest advancements in their products. Exhibitors also gave presentations on their products and services in the Exhibitor Forum.

NCGA cooperated with several organizations to offer special sessions at its May conference and it helps sponsor other conferences and workshops. NCGA has more than 30 state and local chapters that offer regular meetings for its members. NCGA cooperates with the IEEE Computer Society in the publication of IEEE Computer Graphics and Applications, and also publishes a newspaper Computer Graphics Today, and a newsletter Graphics Network News.

SIGCHI, the Special Interest Group on Computer-Human Interaction is concerned with ergonomic aspects of computer graphics, that is how people communicate and interact with computers. SIGCHI is the fastest growing Special Interest Group of the ACM; the membership increased from 580 to 1800 in the past year. SIGCHI publishes a quarterly, called the SIGCHI Bulletin.

In December, 1983 SIGCHI and the Human Factors Society sponsored the second conference on computer-human interaction in Boston, Massachusetts. The conference was attended by 1100 people. The conference offered nine half- and full-day tutorials on various aspects of interaction and interface design. Fifty-six papers were presented on topics such as interface design, command languages, graphics-based interaction, menu and query language design, text editors, intelligent interfaces, cognitive models, programming, physical interfaces, and user documentation. Five panel sessions were also part of the technical program.

There are many other organizations in the U.S. whose interests lie in various aspects of computer graphics, for example, the IEEE Technical Committee on Computer Graphics, the IEEE Technical Committee on Design Automation, and the ACM Special Interest Group on Design Automation (SIGDA). These organizations contribute to give computer graphics practitioners opportunities to exchange ideas and information at regular conferences and workshops.

## 2.2 Publications

Recently, a number of books and journals have become available to the computer graphics community, a situation which has not always been the case. Until Fundamentals of Interactive Computer Graphics [27] appeared, the classic Principals of Interactive Computer Graphics [52] was the only real choice. Now there are several books which cover major portions of the computer graphics world: *Algorithms for Graphics and Image Processing* [55], *Computer Graphics: A Programming Approach* [38], and *Computer Image Generation* [66] to name just a few.

The journal and magazine field is also showing great activity and expansion. The SIGGRAPH Conference Proceedings (which appear as the quarterly *Computer Graphics*) have been and continue to be a major source of the best papers in computer graphics. *IEEE Computer Graphics and Applications* has accelerated to monthly publication and now provides a full color, magazine-style outlet for research and applications in computer graphics. *Computer Graphics World* has also expanded in size and coverage of the field. *Computers and Graphics* recently changed its Editorial Board to bring more European papers into the U.S. *Computer Vision, Graphics, and Image Processing* (formerly *Computer Graphics and Image Processing*) continues to attract and publish high quality research papers. The newest addition to the field is the *ACM Transactions on Graphics* (TOG), publishing journal-quality papers in full color. A number of newspaper-style publications, including *Computer Graphics Today* and the NCGA *Graphics Network News*, also bring information and articles to a broad readership base.

## 3.0 GRAPHICS SYSTEMS

The general trend of graphics system improvement is continuing with faster generation of more complex objects, higher-resolution displays, and more bit-planes for better color. This development is possible largely by more powerful micro-processors and cheaper memory. Although software development is still lagging behind hardware development, that disparity is diminishing. More and more vendors are offering device independent graphics packages based on the Core or on GKS. Some vendors also offer software or the combination of software and hardware for fast generation of solid objects such as the Lexidata Solidview system. One of the most dominant trends is the development of workstations, which provide integrated software environment with high-bandwidth graphical I/O as the standard user interface.

It is impossible to do justice to all graphics systems developments. We only highlight four important areas. One area is the research on "processor per pixel" display systems, the other three are commercial developments: sophisticated graphics system chips which provide near real-time solid object rendering; workstations, which provide general purpose operating systems, programming languages, and tools for application program development, and whose standard interaction is through graphics; and a high performance system which uses VLSI chips to expand graphics function performance.

## 3.1 Processor-Per-Pixel Display Systems

Pixel-planes [30] is a display system architecture based on a smart image memory. In this system, simple processing circuitry is integrated with each individual pixel in the frame-buffer. The processor chips can (1) identify the pixels that lie inside a polygon, (2) determine the visible pixels in the polygon through a z-buffer scheme, and (3) smoothly render the visible pixels. The input to Pixel-planes is a sequential set of polygons that have been already transformed, clipped and had a lighting model applied. Although experimental at this time, this system can potentially generate objects in time which is linear in the number of polygons and independent of polygon size.

A similar display system architecture, which has rectangular area filling as its primitive operation, has been proposed by Whelan [75].

## 3.2 Micro Technology

The graphics industry, as well as the computer industry, is being influenced by the development in the micro technology area. One example is the recent announcement by Texas Instruments of the Advanced Video Display Processor. This is one VLSI chip that includes circuitry for video refresh, interface to the microprocessor, and control of the image manipulation in the frame-buffer.

Another exciting development is the Weitek Tiling Engine which was displayed at SIGGRAPH '83. The Tiling Engine is an attached processor that can be employed to extend an existing graphics system. The Tiling Engine accepts solid objects represented as polygons, and renders these polygons through a z-buffer algorithm. High-resolution (1280 x 1024) images can be generated in 3-5 seconds, depending on the object complexity. Objects can be Gouraud and Phong shaded. A number of other facilities are available, such as cross sectioning, contouring, patterning, and picking. A preprocessor accepts bi-cubic patches which are tesselated to polygons.

A transformation processor has been added to form the Weitek Solids Modeling Engine. The Solids Modeling Engine can tesselate, transform (including perspective divide), clip, scale, light model (with multiple light sources), and shade 120 patches (tesselated into 6000 polygons) in 3 seconds!

The Solids Modeling Engine can be integrated with a variety of host and graphics terminals, as well as with some workstations.

## 3.3 Workstations

Workstations are built around several principles: (1) each user has a single dedicated CPU, (2) the users are connected through a network, and (3) the user interfaces to the CPU through a high-resolution bitmap display.

The primary applications area for the workstations are not necessarily computer graphics, but they all employ some form of graphics for general interaction, and the workstations support at least some primitive graphics functions. We will briefly review three workstations (or families of workstations) which support a varying degree of graphics functions. As we will see in the next section, a high-performance, three-dimensional graphics system is also designed around the workstation paradigm.

The first family of workstations, the Xerox D-machines, consists of the Dorado (Xerox 1132), the Dolphin (the Xerox 1100), and the Dandelion (The Xerox 1108) which represent a set of extremely powerful workstations, designed primarily for Artificial Intelligence applications. The Dorado, the most powerful of the systems, has the processing power of more than five times that of a Vax 11/780 when running Lisp. (For arithmetic it does not compare as favorably.) The Dandelion runs at about one-third the speed of the Dorado, and the Dolphin at one-tenth the speed. The Dorado can be configured with as much as 8Mbytes of memory; the Dolphin and the Dandelion start at 1.15M and 1.5M bytes of main memory, respectively. The D-Machines have facilities for interfacing to a local communications network.

The D-machines include a high-resolution (1024 x 808 pixels) black-and-white display, and the Dorado can also be equipped with a color display (480 x 640 pixels) with up to 256 colors. The interaction is done through a keyboard and a mouse. The D-machines run Interlisp-D, but Smalltalk and Mesa are also available. Interlisp-D provides simple raster graphics functions: a bit-block operation with texturing, text with multiple fonts, lines, and spline curves. Interlisp-D also provides a display management system which supports multiple windows, menus, and a set of graphics utilities. The graphics functions are integrated into Interlisp-D, which makes it easy to experiment with graphical user interfaces.

The Apollo DOMAIN system is a high-performance local area network of dedicated processors (the DN660, the DN460, and DN300). The highest performance processor, the DN660, is designed around a proprietary 32 bit bit-slice CPU and a 16 bit bit-slice display processor. The DN660 can be configured with up to 4 Mbytes of main memory and 2 Mbytes of display memory. The DN660 can be equipped with a high-resolution (1024 x 1024 pixels) display with up to 256 colors or a medium resolution display (512 x 512 pixels) with full color capabilities (24 bit planes).

The Apollo systems run a proprietary Unix-like operatiing system, which supports network wide virtual memory management and interprocess communication. FORTRAN-77, PASCAL and C are available. The operating system's display manager provides multiple windows, with independent processes operating in each window. The interactive graphics functions can run either under the display manager or control the entire display screen.

The display processor performs a variety of graphics functions, such as bit-block transfers, raster operations, vector generation, area fills, and tile fills. High-level graphics software is provided by the ACM SIGGRAPH Core package, which is available from all languages. Apollo also provides icon-driven electronic spread sheets, mail, calendar, and document preparation, and a large variety of application software is available from third party vendors in, e.g., finite element analysis, CAD/CAM, and modeling. The Weitek Solids Modelling Engine has been interfaced with an Apollo system to provide real-time raster graphics. Other workstations, such as the Sun workstations, are built around standard microprocessors, operating systems, and network protocols. The Sun workstations are built around a MC68010 with up to 4 Mbytes of main memory, runs full Unix 4.2, and support the Ethernet local area network. The Sun workstations support 220 standard Unix utilities, a multi-window display manager, an implementation of the ACM SIGGRAPH Core graphics package, and high-level third party application programs, to provide a powerful computing environment.

The Sun Workstations employ custom VLSI chips to implement raster operations. The Sun Workstations support high-resolution (1152 x 900 pixels) black-and-white displays, and medium resolution (640 x 480 pixels) color display with 8 bit-planes. The color monitor is used as a peripheral to the mono-chrome workstation, and the system software, such as the window manager, cannot run on the color monitor.

## 3.4 The IRIS System

The IRIS Graphics System [18,19,70] is a peripheral frame-buffer system which has a processing pipeline similar to that of high-performance vector systems, where several graphics operations occur simultaneously in a sequential set of processors. The central part of the graphics processing pipeline, the geometry subsystem, consists of 12 identical VLSI chips [18]. The chips can be programmed to do dot products, clipping, and scaling. Typically, the pipeline is configured such that the first four chips perform matrix multiplication, the next six clipping, and last two scaling to screen coordinates. One significant difference between this processing pipeline and those of high-performance vector systems (other than it generates solids) is that the geometry engines operate on floating point data.

The IRIS system can be configured as a terminal or as a workstation. The terminal consists of a Motorola 68000 and a geometry-chip pipeline. In the terminal version, the graphics application runs on a host and generates display list commands which are interpreted by the MC68000 and the geometry pipeline. The workstation may have a second processor, a Motorola 68010 which functions as the host. The MC68010 runs Bell Laboratories' Unix, and can run as a node in an Ethernet environment. The IRIS software includes a window manager which supports mixed test and 3D graphics. Thus, this graphics workstation has a complete environment of operating system, programming languages, tools for program developments, as well as facilities for high-performance three-dimensional graphics.

## 3.5 Supercomputers

The computing demands of high resolution graphics easily tax the most powerful processors. Anyone who has waited overnight for a visible line or surface rendering can readily attest to this situation. In applications requiring numerous images (commercial animation for example), excessive turnaround time means a real productivity loss and, should the resulting images be unacceptable, an even longer delay. Consequently, at least one major commercial animation firm, Digital Productions, has obtained a CRAY XMP computer solely for the creation of digitally synthesized images. With this supercomputer and a extremely fast input/output processor, Digital Productions is able to achieve near real-time synthesis of complex, three-dimensional, shaded graphics. Other supercomputer applications in graphics are the generation of ray-traced superquadric images by Alan Barr of California Institute of Technology, and complex water, terrain, cloud and molecular models done at Lawrence Livermore National Laboratory by Craig Upson and Nelson Max [50].

The principal advantage a supercomputer offers (beyond sheer computing speed) is the availability of significant simulation systems to model fluid flows, weather patterns, material deformations, and so on. These systems are likely to contribute to future commercial and entertainment animations. There is also an effort underway in the United States to provide supercomputer access to university research [22]. Such an arrangement will benefit computer graphics as well as the obviously compute-bound engineering and scientific simulations at which the effort is aimed.

## 3.6 Personal Graphics

The personal computer market is continually growing in the U.S., and the systems are becoming more sophisticated. High quality computer graphics is now affordable both for individuals and small businesses. Although there are many vendors offering systems for a few thousand dollars, the market is dominated by IBM and Apple Computer. Analysts estimate that over 2 million PCs alone will be sold in the U.S. this year [58]!

IBM offers four systems in the Personal Computer series, the PCjr [42], the PC, the PC portable, and the PC XT [41], ranging in base price (including monitor) from approximately $1100 to $5600. The smallest PC is a large home computer. The larger PCs, particularly when augmented with third party processor chips, monitors, and output devices, can be configured as sophisticated graphics systems.

All four systems are based on Intel 8088 microprocessors and can be augmented with high speed arithmetic units. The PCjr base system has 64K bytes of memory which can be doubled to 128K bytes; the PC XT can be configured with up to 4 megabytes of virtual memory, using a third party vendor coprocessor chip. The user has the choice among several monitors, from his home television to low- and medium-resolution RGB monitors with up to 16 colors. Third party vendors provide color monitors with resolution up to 1024 X 1024 pixels.

All systems have a variety of input devices and printers. In addition, third party vendors are providing color graphics plotters, 35mm slide recorders, single frame video input, and frame grabbers which can receive and display video images in real time.

The Personal Computers provide the user with most common programming languages, for example, FORTRAN, Pascal, C, BASIC, and LISP. A large amount of applications software is available from both IBM and third party vendors. In the graphics area, the PCs provide paint programs and presentation graphics software with spread sheets and charting programs.

A year and a half ago Apple Computer introduced the Lisa [57], and this year the Macintosh [79] entered the market place. Apple Computer has four systems in its Apple 32 SuperMicro family. The lowest priced system is the Macintosh for about $2500. The Lisa 2, Lisa 2/5, and Lisa 2/10 range from about $3500 to $7500.

What distinguishes the Apple 32 family from other personal graphics systems is the human interface: the desktop metaphor, the mouse/icon interaction, and the shared user interface between programs. (This has been imitated by other personal computer vendors.)

All systems in the Apple 32 family are based on the Motorola 68000 microprocessor. The Macintosh has 128K bytes RAM and 96K bytes of ROM, and the Lisas can be equipped with up to 1M bytes of memory. All display monitors are black-and-white and of medium-resolution, and the standard interaction device is a mouse. All systems can also be equipped with printers and an Apple Image writer.

The Macintosh main graphics programs are its MacPaint program for free form presentation graphics and the MacDraw for object-oriented drawing. Available programming languages are Mac BASIC and Mac Pascal. The Lisa2 is a larger version of the MacIntosh with the same software. The Lisa 2/5 and 2/10 run the Lisa Office System desktop environment, which, in addition to word processing applications, provides facilities for free form presentation graphics (LisaDraw), and facilities for business graphics (LisaGraph). Third party vendors provide Unix operating systems for the Lisa 2/5 and 2/10, which provides programming languages such as FORTRAN, COBOL, BASIC, C, and Pascal, and a large set of application programs. A third party vendor also provides a Tektronics 401X graphics protocol for the larger Lisas; this protocol is supported by most mainframe graphics software.

## 4.0 SYSTEM SOFTWARE

By "software" in this section we mean those parts of a system which affect how a programmer "sees" his or her graphic software environment; the issues of graphical algorithms *per se* are examined later. Thus the programmer has two principal fronts to deal with: the access routines to graphical functions and the interface routines to the user. The former is generally regarded as the most developed and consequently several "standards" have been proposed or adopted. The latter is more fluid, and forms the basis for considerable research with interesting and provocative prospects for the future.

## 4.1 Standards

The discussion of graphic standards, more than any other topic within computer graphics, seems to evoke emotional responses from otherwise rational people. It is not our intent nor desire to enter into the fray in this paper. Let us simply offer the observation that the volatility of the issue is evidence that computer graphics practitioners in the United States care about standards, which is certainly better than the opposite. GKS [69] is clearly making a impact on software from United States vendors, though many others have already made a commitment to provide and support systems based on the ACM SIGGRAPH Core standards proposal. The lack of three-dimensional primitives in GKS is an important issue. The more powerful workstation concepts and the accepted language bindings are favorable features of GKS. For further discussions of the issues surrounding all the standards (GKS and NAPLPS) and proposed standards (CORE and PHIGS) see a recent issue of Computer Graphics World [15,32,71,83].

## 4.2 Interactive System Design

With the advent of more sophisticated graphics, more challenging applications, lower cost devices and computers, and a wider user base, the issues of interactive system design and user interfaces are becoming extremely important. Recent developments in the 1980's are pointing the way to serious models of interactive systems which avoid the ad hoc nature of many previous system designs. The basic idea is to provide a "User Interface Management System" (UIMS) that completely separates the user inputs and graphical responses from the application modules [44,72,82]. The model is similar to the one adopted for database design which isolates data from the program by a specific well-defined interface.

Those who have engineered large interactive programs will appreciate that the interactive interface is a significant portion of the system code and the part most difficult to write with the programming languages in common use, since all existing languages have been designed with rather sequential and non-graphical input and output structures. Various methods for improving this situation have been proposed: at one end by specifying a "grammar" for the interactive dialogue [53] and perhaps redefining current programming languages [54], and at the other end looking toward interactive design of the system itself [14,34,36,64]. To some extent the latter view is infiltrating user consciousness though the presence of "window management" capabilities on the bitmapped displays found on personal computers and workstations.

# 5.0 ALGORITHMS

Graphical display algorithms have an obvious fascination because of the visual aesthetics produced by well-rendered synthetic images. Computer synthesized, modified, enhanced, or manipulated images are becoming commonplace in entertainment, commercial advertising, scientific displays, and even personal computers. Recent research appears to be focusing on two predominant visible surface rendering techniques: ray tracing and z-buffering, with considerable effort being devoted to highly realistic light and shading models. Methods for improving image quality through anti-aliasing raster images are still being studied [11,77], and the task of anti-aliasing temporal effects in complex animation sequences is receiving considerable attention.

The most popular visible surface display technique demonstrated at SIGGRAPH'83 was clearly that of ray-tracing (for example, [63,76]). This algorithm offers such display realism that most other approaches cannot compete in visual effects. Ray-tracing permits simulation of multiple light sources, shadows, transparency, reflection, refraction, and textures. The algorithms work with any object representation which permits the determination of the intersection between a ray and the object. The only negative features of ray-tracers to date is the relatively difficult task of anti-aliasing, the generation of hard-edge shadows, and the high cost of producing each image. The first problem is being solved by selectively producing the picture at higher resolution where there is more detail (rather than simply supersampling everywhere); the second problem appears to be the subject of very recent work to appear in the SIGGRAPH'84 proceedings; and the final problem may eventually succumb to clever software [2,35] or to special-purpose hardware graphics processors. As described below, many new and interesting object representations have become feasible due to the flexibility in display offered by the ray-tracing technique: among them are algebraic surfaces, superquadrics, and other parametrically defined surfaces.

The other technique receiving considerable attention, especially from hardware designers, is the z-buffer technique. The primary advantage of the z-buffer method is that the input polygons need not be sorted prior to scan conversion into the frame buffer. Since there is no direct polygon sort, there is no need to store the polygon display list in the display memory allowing the image to be built up incrementally as the polygons are available. Modifications to the simple z-buffer technique are being tried in order to provide features not normally available with z-buffers, notably true transparency and "soft" shadows [67]. The illusion of transparency is typically obtained through partial (patterned) scan conversion of polygons, allowing the more distant polygons to partially show through (as is done on the Lexidata Solidview system and the Weitek Tiling Engine).

Shading and texturing methods continue to strive for better illusion of reality and are starting to achieve beautiful results. The earlier research on clouds [10] and natural surfaces [21] has led to a simpler look-up table approach for an automobile "showroom" display system [74]. Fractal techniques have been used to generate textures [8]. The New York Institute of Technology has also reported its method for efficiently generating textures without generating distracting aliasing effects using multiple resolution, pre-filtered texture images [81].

It is widely appreciated that anti-aliasing methods are essential for quality image generation. Last year, however, three groups reported on techniques for temporal anti-aliasing, or incorporating motion blur into animated images. One approach uses a generalized camera model to selectively blur object images [59], another uses smeared spheres or polygons with a pixel-by-pixel visibility assessment [45], while a third uses tiny stochastically moved "particles" to leave smooth tracks in the image [60]. Korein and Badler showed how their method can be used to blur the images of a fast moving articulated human figure model, while Reeves demonstrated his system with the "Genesis" sequence from the movie "Star Trek II: The Wrath of Khan."

## 5.1 Three-Dimensional Modeling Techniques

The design and display of three-dimensional objects has promoted the use of various solid object models. "Wire-frame" drawing and drafting systems are still around, of course, but with the tendency to integrate the design stage with the engineering analysis and even manufacturing processes, powerful object representations are proving useful. A solid shaded rendering has much visual satisfaction, but in recent systems, such as GMSOLID [12] and PADL [13], mass properties, machining, and material strength are also important [61]. Among systems oriented to the design of mechanical parts, boundary representations (such as polyhedral networks) and constructive solid geometry (CSG) predominate. Other solid representations include cuberille or voxel spaces (frequently encountered in medical applications [40]), and oct-tree encodings [51]. Curved surface patch systems are used not only for their overt surface design capabilities, but also for assessing more subtle characteristics of "smoothness" and for creating more natural compound shapes [24]. Procedurally or parametrically defined objects are the subject of considerable study, especially for their facility to model classes of complex, natural appearing objects. We will briefly examine each of these methods.

One consequence of the growth of solid modeling schemes based on polyhedral networks is the emergence of various fast display devices capable of accepting polygons directly and creating, usually by a z-buffer method, a visible surface rendering. The first commercial system of this sort was probably the Lexidata Solidview system; more recent systems include the Raster Technologies 1/25S and the Weitek Tiling Engine. By preprocessing polygons in a solid, unchanging model, considerable display time may be saved. Acceptable real-time performance with a substantial polygonal database has been demonstrated on an Adage Ikonas microcoded display processor [29]. CAD/CAM applications seem to tolerate short (1-20 second) delays in delivering complex shaded images. An important constraint, however, is that the database must be polygonal, not simple wire-frame. The problems of converting such a database into a polyhedral one are formidable [49], and often the results require human assistance to resolve ambiguities.

Another consequence of polyhedral solid modeling systems is that model creation becomes a bottleneck. Databases may contain objects of two or three thousand polygons, and hundreds of thousands may be needed for detailed models. Interactive systems incorporating a generous menu of polygon model generating tools are in use [16]. Numerous object design and digitization techniques exist, but the newer ones appear to utilize some novel technologies, for example, computerized-axial tomography (borrowed from the medical domain [40]), laser or structured light rangefinding [1,78], photogrammetry [26], and direct spatial digitization (using devices such as the Polhemus 6-axis system or the Science Accessories 3D Sonic Pen). Gossard at MIT has proposed a constraint-based system to describe the relationships between parts [33].

The constructive solid modelers depend upon the basic set operations of intersection, union, and difference to create complex models from simple transformed instances of a few basic primitives: cubes, cones, cylinders, spheres, curved surface patches, solids of revolution, and so on. The principal advantages to a CSG model are the ease of computing mass properties and its sympathy to the ray-tracing method of graphics display. The primary difficulty with CSG representations appears to be object definition: the method of construction of an object is not necessarily unique, and interactive, real-time visualization of the modeling task is difficult.

Other solid modeling schemes with great promise are cuberille or voxel spaces [40] and oct-trees [51]. Here data is rather easily and directly obtained from suitable scanning instruments (X-ray or sometimes ultrasound), and computer graphics techniques are used to section, enhance, and display the resulting three-dimensional images. Work is progressing on clinical use of the voxel technique in diagnosis and surgical planning. In an oct-tree encoding, space is recursively subdivided into cells which are contained within the object of interest. The finer the decomposition, the more accurate the display. Phoenix Data Systems implements, in hardware, oct-tree encodings for real-time shaded renderings.

Curved surface systems also find applications in medical planning [73], as well as in the more obvious mechanical, vehicle, and product design areas [24]. Besides the further mathematical investigation of curve types (such as the new Beta-splines [7]), the practical problems of modeling with splines is receiving significant attention [56]. One of the foremost efforts is the research at the University of Utah to define and implement effective set operations on B-spline patches [20].

One of the recent developments in modeling is the use of deformable superquadric solids [6]. These solids are based on a simple mathematical surface which can be parametrically varied over a wide range of shapes, including prisms, cylinders, spheres, disks, and plates. Barr shows that the parametrization may be changed by a number of deformation transformations to create twisted surfaces, spirals, cones, curved tubes, and so on. Renderings are created by ray tracing. Other research into parametrically or procedurally defined objects, including those defined by algebraic surfaces has been reported [9,37,39,43].

Indirectly related to the parametric object representation are the fractal geometry schemes for generating natural-looking images of "self-similar" objects, for example, mountains, landscapes, coastlines, and clouds. A rather lively debate on the definition and "proper" implementation of fractals has ensued [8,28,48].

Other, non-fractal, methods of building object models with several levels of detail (selected according to the size of its image on the display screen) have been proposed [17,65], but automatic generation of such hierarchies requires further research.

## 5.2 Animation

Given the high quality of images that can be produced, animating them is the logical next step. At one end of the spectrum of possibilities is the fullscale, real-time flight simulator capable of displaying multiple projected images of thousands of shaded polygons at high resolution [66]. At the other end are personal computers and video games which rely upon tight assembly coding, double buffering, and bitmap raster operations for animated images. In between are numerous possibilities: nearly real-time image synthesis from the CRAY XMP at Digital Productions, workhorse VAX computers at New York Institute of Technology, Cranston-Csuri Productions, Lucasfilm, CalTech, and so on. Commercial and entertainment applications motivate and support the production of significant amounts of computer animation. Computer graphics animations, especially of three-dimensional structures technically difficult to model any other way, are becoming a staple of "hi-tech" movies, for example "Tron," "Star Trek II: The Wrath of Khan," "Return of the Jedi," and most recently "The Last Starfighter."

With all this animation activity, it is perhaps surprising that not all animation problems have been solved. Key position and key frame techniques remain staples in animation systems [80], as do the use of spline curves to describe motion paths and movement dynamics [4,47,68]. The two most significant problems remaining are the effective animation of jointed animal- or human-like figures and the interactive design of the animation score itself.

The first problem is being attacked most notably at the New York Institute of Technology, at Ohio State University, and at the University of Pennsylvania. At NYIT, the approach is primarily through careful key position control, and a dramatically effective result was produced as part of a Twyla Tharp dance called "The Catherine Wheel." Various (unpublished) extensions to the key position technique are used to post-process key position motions to model the effects of mechanical vibration or gravity. Some short portions of the film in progress, "The Works," illustrate the technique.

At Ohio State University, Zeltzer is modeling articulated human figures and making them move according to flexible motor control programs constructed for each limb or body unit [84]. Zeltzer's figure (with a skeleton body designed by Don Stredney) has been shown walking and jumping, both of which are difficult motions to specify solely from key positions.

At the University of Pennsylvania, Badler is developing a system for the simulation of people at work in a zero-gravity space environment [3]. This effort is incorporating ideas borrowed from robotics, such as limb reach [46], and is moving toward processing more language-like descriptions of tasks. The graphical simulation of robotic systems is already well-established [23].

The difficulty in specifying animation ("the director's problem") has led to a number of solutions: batch processing of animation commands (used at MAGI), writing special-purpose programs, using powerful animation languages [62], constructing animation sequences with an interactive system [25], and using physical interactive devices [31,47]. Control of a complex articulated figure is still not easily accomplished. One possibility being investigated by Badler is the use of a Polhemus six degree-of-freedom digitizer to provide direct kinesthetic control over the position and orientation of an object or part of a human figure, much in the style of the classic work by Baecker on animation controlled by human dynamics [5]. More knowledgable animation control systems based on artificial intelligence techniques and natural languages are surely forthcoming [84].

## 6.0 SUMMARY

We have tried to show the breadth and directions of computer graphics in the United States. One need only look at prestigious journals and popular magazines, movies and commercials, computer stores and video arcades, to see computer generated graphs, images, pictures, or animations. The decreasing costs of computing and display equipment have certainly accelerated the technology transfer of computer graphics into our daily lives.

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