JOHN LEWELL

COMPUTER GRAPHICS

A SURVEY OF CURRENT TECHNIQUES AND APPLICATIONS

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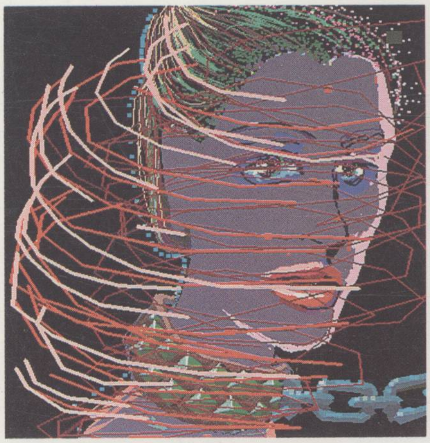
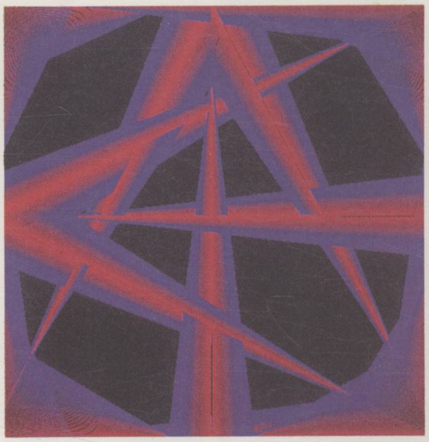
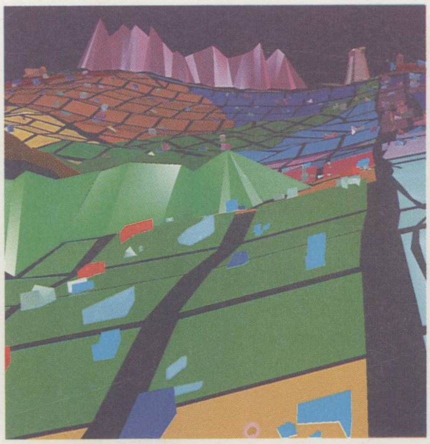
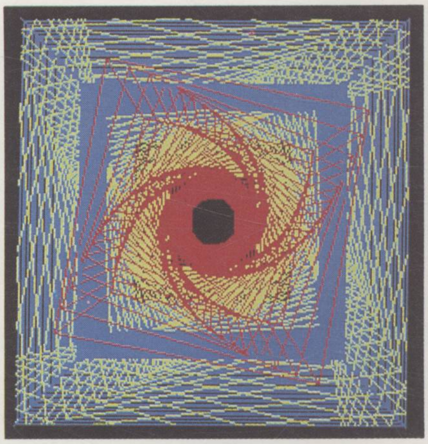








Computer-assisted painting *Electric Lady*, DEI/Mark Lindquist *Digital Effects, Inc., New York, New York*

INTRODUCTION TO COMPUTER GRAPHICS

In the 1980s, on a normal busy day in the working week, you might observe the following activities taking place at various points around the globe. A businessman in Frankfurt, Germany, examines a graph of his company's sales in fifty European cities. An architect in Houston, Texas, takes his client on a conducted tour of a building that does not yet exist. In New York, a choreographer plans a ballet, setting 'dancers' in motion and watching their movements even before anyone has arrived for rehearsals. An electronics engineer in Santa Clara, California, pieces together a complex labyrinth of circuits destined for a new microprocessor. An archaeologist in Oxford, England, deciphers writing on an ancient fragment of stone. And on the other side of the world, in Tokyo, Japan, an automobile engineer tests a new model on a rough surface, even though no prototype of the vehicle has been constructed.

All of this will sound very mysterious until we realize that there is a common factor linking these people and their diverse activities together. Each of them is using a powerful new tool to generate images. They are using a computer. The common factor is *computer graphics*.

Making, storing and manipulating pictures

During this decade, the image-making capability of the computer has reached a level of sophistication that allows people with little or no knowledge of computing to use an electronic system for manipulating pictorial data. At the same time, experts have pushed the techniques of computer imaging to new heights of realism, and manufacturers have introduced improvements to electronic displays that suddenly make the home television set appear to be wholly inadequate in quality, colour and resolution.

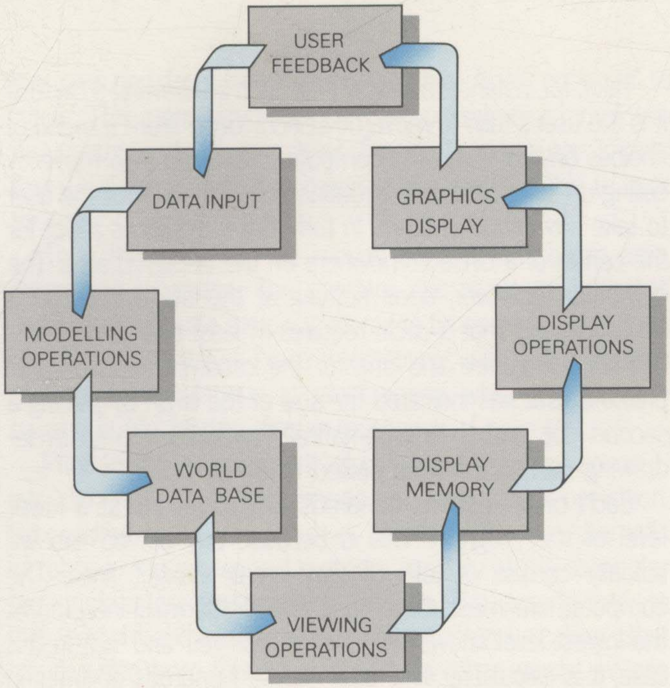
Not since the birth of photography in the nineteenth century has any technological development had such a profound impact on the way we make pictures. For it is with the *making* of pictures – not simply the recording or transmitting of them, as in film or television – that we are chiefly concerned in this book. Making a picture, storing it, and manipulating it on a computer: this is the essence of computer graphics.

The list of computer graphics users could be extended indefinitely. Dr Tony Diment, a graphics expert, has said: 'There now seems to be no area of human endeavour that cannot be enhanced by the application of computer graphics.' This is an extravagant claim, but it may not be as wide of the mark as one might at first suppose. While computer graphics is unlikely to enhance the writing of poetry or the composing of music it can certainly be applied to an astonishing range of tasks. Its users already include film makers and television designers, astronomers and biologists, artists and stock-brokers – and these are strange bedfellows indeed. But computer graphics, like the computer itself, is infinitely

▷ **Model of an interactive system**
The user completes the loop in this functional model of an interactive graphics system, indicating commands and reacting to the machine's responses

▽ **State of the art workstation**
The Dicomed Imaginator is a complete graphic design station for generating images intended for high-resolution (up to 8000-line) photographic slides. By moving the hand cursor around the digitizing surface an artist can select drawing functions which are represented as a menu on the screen. Inside the console is the hardware necessary to support several interactive design programs and provide mass storage for the picture data

Dicomed (UK) Limited, Ascot, Berkshire, England



adaptable. Anyone who deals with moving or static images, or who compiles or refers to information that can be given graphic expression, will eventually have access to computer graphics in his (or her) daily work. Even away from the working environment we are already constantly exposed to computer-generated images: in press advertisements and posters, at the cinema, and especially on television.

Yet the new techniques are not familiar to everyone, despite the proliferation of the pictures they generate. In fact, never before have we been able specifically to *generate* images with any degree of sophistication. Pictures are normally drawn or painted, or perhaps constructed, or they are 'taken'. The idea of generating an image carries with it an implication of power – of the ability to make visible what would otherwise remain invisible.

To a great extent this is true. Nothing better demonstrates the power of the computer than operating a three-dimensional, high-resolution graphics display. To be able to 'fly through' a completely modelled DNA molecule, or across an artificial landscape, as real as though it had been filmed by a cameraman, and in each case to be able to control your flightpath as an aircraft pilot does, is an experience guaranteed to renew a sense of wonder.

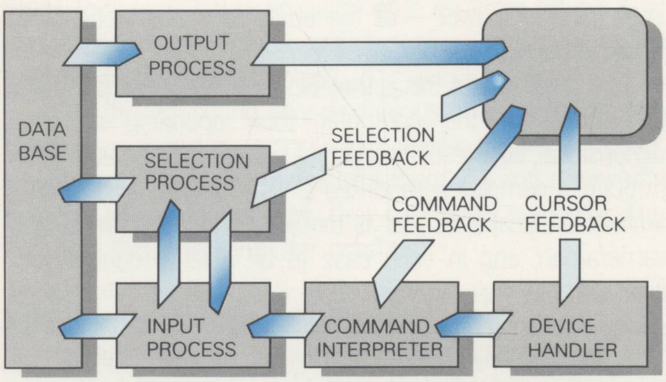
Interactive graphics

The example of flight simulation introduces a concept that is fundamental to computer graphics. The majority of graphics systems are *interactive* in their design. Whether you are simply viewing a picture, or actually constructing a picture element-by-element, the system allows you to interact with it. You make a move – then you wait – then the computer makes a move – and it waits. The process is somewhat like a game of chess, except that it can be played so quickly that the user and the computer often appear to be performing simultaneously.

Suppose, for example, you are looking at an image that has already been made on a graphics system. It is displayed on a *visual display unit* (VDU) and may very well be such a highly realistic three-dimensional image, complete with a light source and shadows, that we can call it an 'object'. By moving a control lever (a *joystick*) you can rotate this object and look at the back of it. When you switch to another mode – 'pan' instead of 'rotate' – you can cause it to move from side to side.

The consequent movement of the object on the VDU will appear to be fluid and continuous, but it is not. If you were to slow down the process in order to examine exactly what is happening you would discover that the computer is carefully noting 'your turn/my turn/your turn ...'. By keeping pressure on the joystick you are sending a whole chain of repeated commands: 'move left, move left ...'. After each one the computer makes its move. In other words, the *analog* (continuous) movement of the control lever is being translated into *digital* (discrete) instructions, many times each second, and after each command the computer performs its task – such as calculating the new position of the object when it is moved a fraction to the left. Then it waits. After all, you might change your mind at any time and decide to move the object to the right.

This interactive process is particularly significant when the user wants to construct an image. By its ability to make millions of calculations in a very short time (and the most powerful computers can make over 100 million in a single second) the computer can act as a servant to the designer.

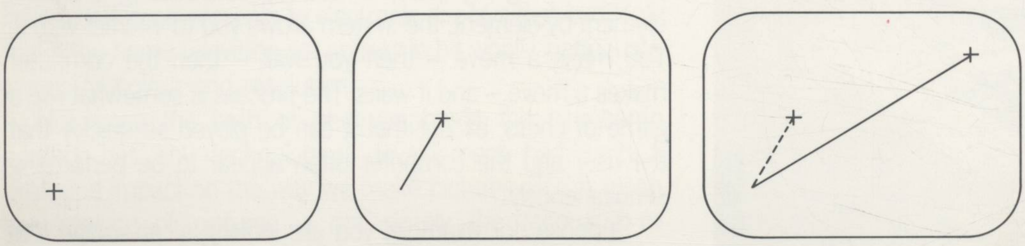


△ **Interactive processing**
Each stage of interactive processing provides feedback to guide the user. For example, moving the screen cursor in response to the user's hand movements is the computer's first task

Take, for instance, a simple task such as drawing a circle. If it is the user's turn to move he selects 'circle' from a *menu* of choices on the VDU. The computer makes its own move by calling up its circle-drawing routines; then it waits for the user to take advantage of them. In turn, the user places a dot for the centre of a circle somewhere on the displayed area. The computer, however, does nothing at this stage because it already knows that a circle requires at least two commands: one for the centre and one for the circumference. It waits until the user has indicated the size of the circle by placing a second dot, and then automatically switches into its circle-drawing routine, which is poised ready for action.

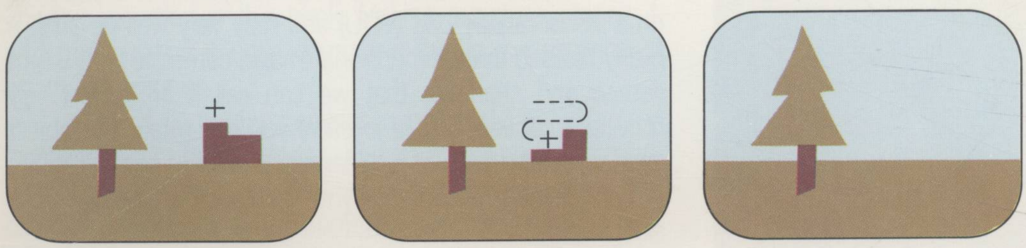
Each circle requires hundreds of calculations at a lower level of the program. This is because any curved line will actually consist of lots of very small straight lines. The computer, we must remember, is a digital machine, and at the lowest level knows only two things: 'yes' and 'no'. In this case, it is calculating 'line' and 'no-line' hundreds of times in order to draw the circle.

A slow machine will take longer to draw a shape than a fast machine, and the user will not get his turn in the interactive game until the whole circle has been drawn. Fortunately, since circle drawing is a relatively simple set of calculations, the shape will appear almost instantaneously. Now the interactive process can continue – and we can begin to see why computer graphics is becoming such an indispensable tool. For not only has the computer drawn a circle, but it *also 'knows' what it has drawn.* In its memory it

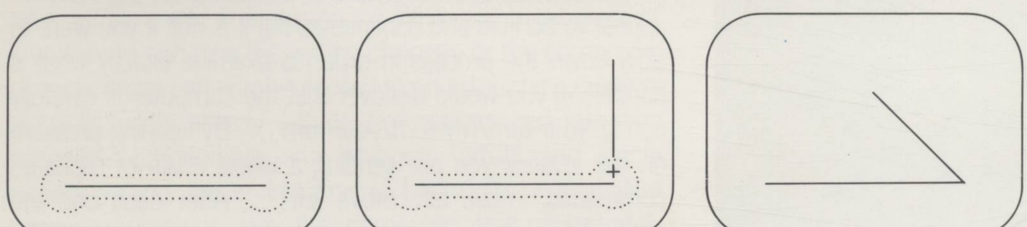


+ = SCREEN CURSOR

◁ **Drawing lines**
In the 'rubberbanding' method of drawing, a line can be anchored at a point and then 'stretched' to any other point



◁ **Erasing**
Removing part of a raster image can be done by selecting the exact background colour and overpainting the object



◁ **Accurate positioning**
If the program provides some accuracy aids, such as a gravity field around each line, an object is quickly built

has switched from one state to another: from 'no circle' to 'circle'. This means that the user can continue to interact with the machine at a higher level. Since the computer 'knows' that it is now displaying a circular shape, it is also able to treat this new object as a whole.

Thus the circle can be moved around the screen area, shrunk or expanded. The operator can move to a 'repeat' mode and replicate the circle as many times as he wishes. All of this process takes place interactively, with the computer making its calculations at great speed while the operator pauses briefly for the display to change.

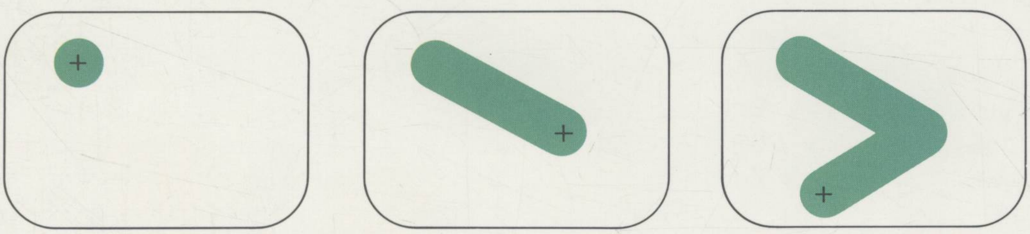
Prior to the development of computer graphics, computing did not have this mode of interactive operation. Processing was carried out in *batches.* But the dramatic increase in the power and memory capacity of the computer has made interactive graphics possible. The experts refer to the 'higher-bandwidth man/machine communication' that has resulted from this development. In other words, we can now talk to the computer more easily and in more detail – using shapes as well as words – and its replies, too, have become more intelligent.

Non-interactive graphics

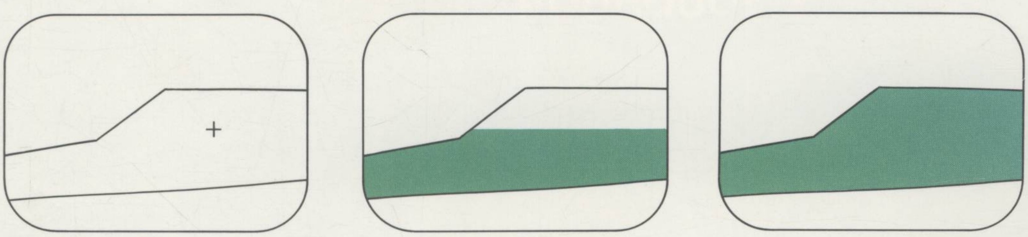
Not all of computer graphics is interactive. Non-interactive, or *passive*, computer graphics can be equally useful, depending on the application. In many instances, a picture can be made on an interactive system and then turned into passive computer graphics for viewing. The pictures in this book are a good example. They have been 'frozen' on to paper, where they permit only passive viewing by the reader. However, many of them still exist as electronic data. If you had the appropriate display system you could manipulate the image of, say, the fighter plane, rotating it on the VDU and perhaps zooming in to examine the detail of a wing section.

Since computer graphics is not restricted to the electronic medium it frequently takes on a non-interactive role. Whenever the electronic image is placed on paper or film for convenient viewing or projection it becomes non-interactive. Even on conventional video, frames follow each other in a sequential *linear* mode. Interactive systems always require a computer to calculate the display. If there are many different options, the data must be selected in a *non-linear* fashion. Non-linearity is the chief characteristic of the new technology, and it is lost when pictures are frozen into the older and more conventional media.

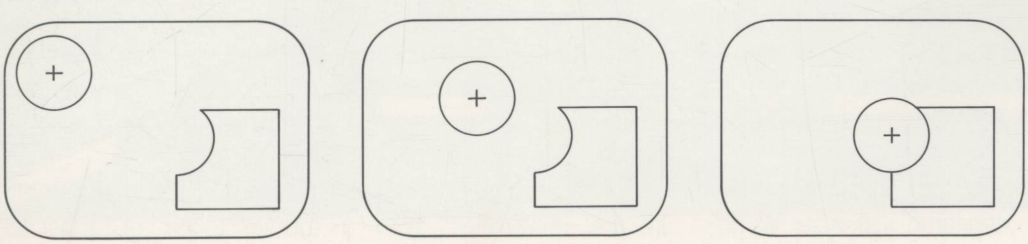
One advantage of non-interactive graphics is that all the processing power of the computer can be devoted towards providing the highest picture quality. By calculating one line at a time, a *film recorder* will produce an image with a higher *resolution* (finer-grained detail) than can be obtained on an electronic display. Likewise, *plotters* and *printers*, which draw the images on paper, can show detail that would not be readable on the screen. In architecture and engineering, the portability and convenience of non-interactive graphics are essential, while back at the computer all the interactive techniques can still be employed to create the images.



◁ **Painting with a 'brush'**
The user selects a brush (a small matrix of pixels of a particular size and shape) for freehand sketching



◁ **Colour-fill**
Here, a 'seed' pixel is put within a bounded area and that area gradually fills with the chosen colour



◁ **Positioning shapes**
In some systems, shapes may be 'dragged' around the screen area until the composition is correct

The role of computer graphics

Users of computer graphics can be divided into two groups: those whose primary concern is with the image itself (such as graphic designers, film makers or illustrators); and those for whom the image is merely a carrier of information (scientists, engineers or business graphics users). This is a most important distinction to make. The majority of computer graphics applications have been adopted by the second group of users. For the scientist or engineer the picture is not an end in itself, but a means to an end.

A physicist, for example, may very well be studying subatomic reactions. When he creates a simulation of these reactions on a computer his chief concern is that the system accurately simulates his concept of the reaction. If he has a graphics display to help with the task he is using it as an *interface* (mediating device) between himself and the *application data base* of the computer (the store of data relating to the task in hand). The graphics system is merely the 'front end' of the whole computer system. It provides a way of communicating with the machine.

Similarly, the businessman who wants to see an analysis of his company's performance will expect the computer to provide him with the latest figures in a convenient and easily-readable format. Again computer graphics can be a means to an end. The alternative would be a list of figures that would require long and careful scrutiny before market trends could be spotted. With graphics, the information is presented to be seen at a glance. A market trend is immediately recognizable when figures have been translated into a graphic format.

Computer graphics for such purposes has enjoyed remarkable success during the past few years. One reason for this success can be found in the development of computing as a whole. Computers quickly became such powerful processors of data that the sheer quantity of their output was fast outstripping our own human capacity to deal with it. When a machine makes millions of calculations every second it sends back answers that are often as complex as the questions being fed to it. Thus the design of a graphic interface was prompted by necessity, and eventually became a branch of computing in its own right.

A brief history

Digital computers made their first appearance in the 1940s. The IBM Mark I computer was a massive electromechanical device, weighing 5 tons and occupying a whole room. It contained over 3300 relays – mechanical parts that registered 'on' or 'off' states – and over 800 km (500 miles) of wiring. Yet the Mark I could perform only relatively simple arithmetic, such as multiplying two 23-digit numbers, a task that took six seconds to complete.

Vacuum-tube computers, with electronic *flip-flop* (on-or-off) circuits replacing the relays, appeared just after World War II. The ENIAC (Electronic Numerical Integrator And Calculator) was the first of these, built for the US Army in 1946. Since the circuits were now all-electronic, the speed of computation showed a dramatic increase. With machines built in the early 1950s, 10-digit numbers could be multiplied in 1/2000 second. The vacuum-tube machine is now generally acknowledged as the first viable computer; it was marketed for business and scientific applications, despite its limited memory capacity and still – by today's standards – relatively low speed. Such a machine was the UNIVAC I, and it represents the 'first generation' of computers.

The second generation brought computing to the forefront of technology. Transistors replaced vacuum tubes, bringing still greater speed, and, above all, reliability. The size of computers shrank dramatically, since a transistor was only 1/200th the size of a vacuum tube. It also gave off only a fraction of the heat, and transistors could thus be packed together in a very small space. Software advances were made, and with these new techniques the number of potential computer users was greatly expanded.

Towards the end of the second generation, interactive computer graphics made its first appearance. At the Massachusetts Institute of Technology, a brilliant young student was working on his PhD thesis. It proved to be the seminal work in computer graphics, and it did more than any other single piece of research to launch the computer graphics industry.

The student was Ivan Sutherland, who is now one of the partners in the Evans & Sutherland Corporation, many of whose graphics displays were used in producing the illustrations that are shown in this book. Sutherland introduced the concept of using a keyboard and a hand-held *light pen* for selecting, pointing and drawing – in conjunction with an image displayed on a VDU. He built computer images by a method of replicating standard picture components, adding together points to make lines, and lines to make shapes. These, and many other techniques that Sutherland pioneered, are still in use today.

Most significantly, the data structure built by Sutherland on the TX-2 computer was very different from anything that had been done before. It was based on the *topology* of the object being represented, that is, it accurately described the relationships between the various component parts. Prior to this, computer representations of an object had merely been representations of the picture – not of the object itself. To an engineer, for example, the usefulness of the earlier method was extremely limited. With Sutherland's system, which he called Sketchpad, a clear distinction was drawn between the model that was represented in the data structure and the picture that you saw on the screen.

Sketchpad, introduced in 1963, caused great excitement in the universities. With a further touch of brilliance, Sutherland made a documentary film about his new system, and a print of it was sent to every computer centre in the United States. Being primarily a visual subject, computer graphics was most vividly explained by means of a visual medium. The film showed a number of techniques, many of which have since become familiar to millions of users.

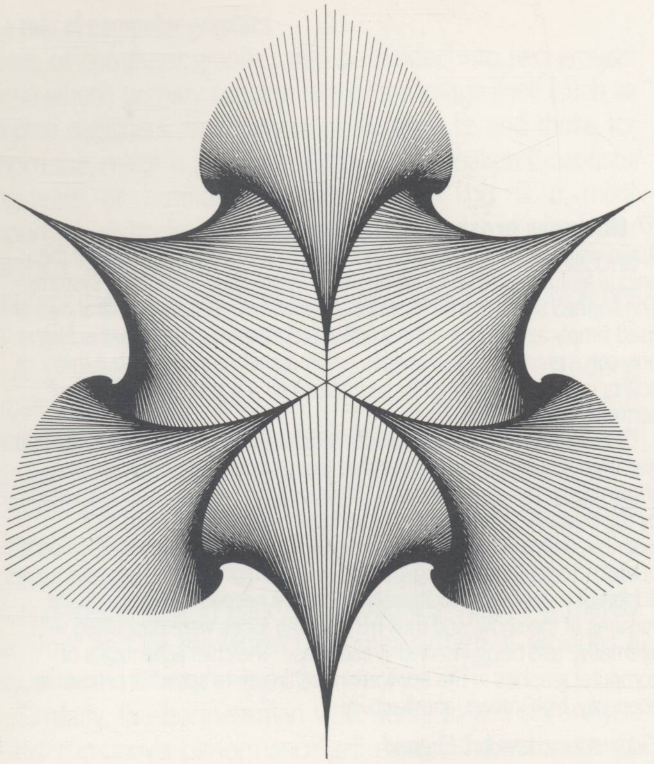
One such technique Sutherland called '*rubberbanding*'. He used a light pen to fix a point on the screen and then, by moving the pen, stretched a line from it to another part of the picture area, eventually anchoring it in position. But most exciting of all was the demonstration that the computer could work out which of the lines defined the front surface of an object, while eliminating any other lines that would be temporarily hidden from view. The hidden lines remained in the data structure, stored in the computer memory, and would reappear when the object was rotated on the display.

The limitations of Sketchpad were in the computer rather than the concept. The second-generation machine could not contribute any 'richness' to the image. Only one graphics command existed: the facility to place a dot on the screen at a particular location. Collections of dots would make a line, but that would produce only a skeleton of an image.

▽ **Business presentation graphics**
Audio visual users have been among the first to take advantage of the unique features offered by computer graphics slide-production systems. The finished slides can be included in synchronized audio visual shows or used simply as 'speaker support' visuals during live presentations. Not only can a great variety of images be produced very quickly, but their quality or 'finish' cannot easily be imitated by a graphic artist using conventional materials.

Shown here is a typical example of a business presentation graphic. It was one of hundreds of images that were made for an internationally-shown audio visual presentation. While only six basic images were made by the designer, many variations on them were also required. For example, animated effects were quickly achieved by zooming in on parts of each image, thus making a whole sequence of slides which gave an illusion of movement. Additionally, the client needed foreign-language versions of the show, and thus many of the slides were duplicated with alternative text being inserted in each case. The chief advantages of computer graphics in this application are therefore speed of production, economy, high impact, and flexibility

Eidographics, London, England



△ **Early computer graphics**
During the 1960s the computer plotter was perfected, with the result that a whole new industry began to flourish. Computers demonstrated their power as drawing accessories, useful to artists and engineers alike. This plotter-drawn picture, called *Crest*, is reminiscent of Spirograph images, but is far more precise and complex. It was among the entrants in a competition held in 1968 by CalComp, a leading plotter manufacturer of that era and now a fully diversified graphics equipment manufacturer

CalComp (California Computer Products, Inc.), Anaheim, California

In the development of non-interactive graphics, which preceded Sutherland's work, the problem of image richness had prompted the invention of other *peripheral* (auxiliary) *devices*. Foremost among these was the computer plotter. This is a drawing device that connects endpoints of lines by moving a pen from one *coordinate point* (known position) to another. Both coordinate points are held in the computer memory and the plotter obediently performs the task of drawing the image. In this instance an electronic screen for viewing the picture may be completely optional. Here the *display surface* is paper rather than a cathode-ray tube. Highly complex and rich drawings could be generated by using a computer plotter, as the illustration of an early plot, taken from a CalComp competition (above), demonstrates.

Around 1965, in computing technology, solid-state integrated circuits, the forerunners of today's 'chips', began to replace circuitry composed of individual components. Further miniaturization took place with this third generation of machines, and more peripheral devices were introduced. In order to 'talk' to the computer, researchers found that they needed other graphical input devices that would simulate the more conventional techniques of drawing a picture. The *data tablet and stylus* were introduced, eventually becoming a standard means of data entry.

Somewhat like a drawing board in appearance, the data tablet has a sensitive surface and can register any coordinate point when the stylus is pressed on to it. A *screen cursor* – a small cross – indicates the point on the VDU. This development provided a far more accurate method of entering coordinate data than using a light pen directly on the screen. The resolution of the tablet in terms of the number of points it could indicate was far greater than the resolution of the electronic display. Again, the distinction that had been made between the object in the computer's memory and the image of it on the screen enabled devices such as the data tablet to be of real usefulness to a designer.

With the fourth generation of computers, dating from the early 1970s, computer technology moved into the modern era. Computers could now be connected together to form networks. In graphics, this meant that a single host computer could support a number of design *workstations*. Minicomputers, such as the Digital Equipment Corporation's PDP-11 series, became ideal for the new graphics applications. They offered high speed at an economical price, and thus more computer time could be devoted to graphics research within the budget of a university. Microprocessors – each one a computer on a chip – enabled small personal machines to be manufactured at rock-bottom cost. An Apple II, at the end of the 1970s, was more powerful than the 5-ton IBM machine that heralded the Computer Age.

The growth of graphics

The watershed year for computer graphics was 1980. Until then it had remained largely the domain of scientists, mathematicians, engineers and computer-science experts. But in 1980 the market for computer graphics products began to take off. Graphics systems found their way into broadcast television; into animation studios; and into a variety of businesses that previously had little or no acquaintance with the medium. Yet it was still early days for the new technology. One sure indication of this could be seen in the fact that no art school in the world had yet equipped its facilities with a computer graphics system. Two more years were to pass before this finally happened.

The spectacular growth of computer graphics is recorded in some of the statistics given by the industry. For instance, at the end of 1979 IBM launched its 3279 colour terminal. Within nine months it had received more than 10,000 orders for the system, two-thirds of which were destined for first-time users of computer graphics. In the following year, the total value of all the services, systems and hardware associated with computer graphics topped the billion-dollar mark for the first time. When we remember that barely two decades had passed since Ivan Sutherland gave the industry its initial impetus, we can appreciate the social and economic impact of the new imaging technology.

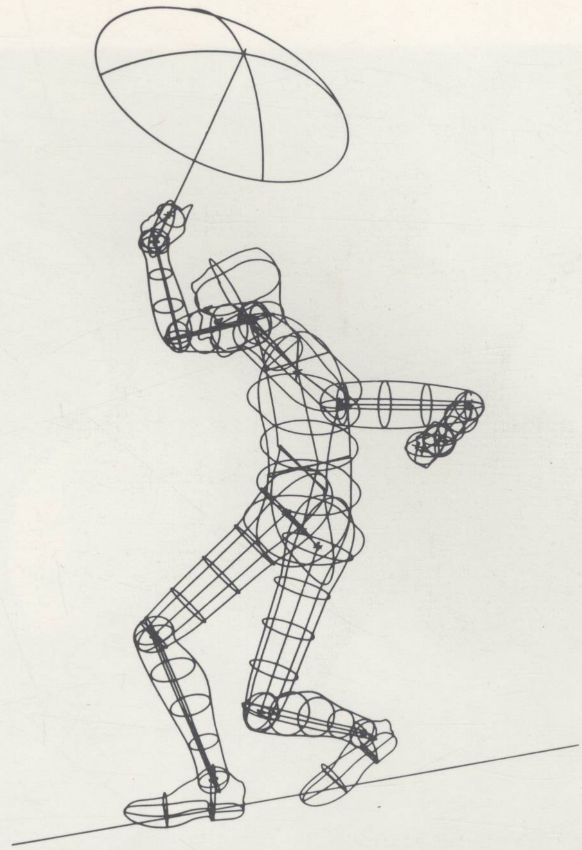
Again, the exponential growth was reflected in figures for conference attendance. The Association for Computing Machinery (ACM) is the official American organization that promotes, and to some extent regulates, the computer industry. When computer graphics first appeared, the ACM established what it called a Special Interest Group on Graphics. This sounded like a small and select body of experts, and it was. In 1976, the group – known by its acronym SIGGRAPH – allowed exhibitors to take part in its annual conference for the first time. Ten corporations displayed their equipment and services. Yet, only four years later, at Seattle, 98 corporations took part in the event, and nearly 7000 visitors attended the exhibition.

Nor did the growth of graphics taper off at this point. In fact, quite the opposite occurred. A breakaway group from SIGGRAPH was formed: called the National Computer Graphics Association (NCGA). It held its own annual conference and exhibition in the United States, and it placed a greater emphasis on the commercial and industrial applications of computer graphics. By 1983, NCGA was attracting over 35,000 visitors from all over the world. Yet SIGGRAPH's annual meeting remained the major academic forum, running no less than 14 simultaneous courses and (incidentally) receiving just as high an attendance as the 'upstart' NCGA. Certainly, the title 'Special Interest Group' had become something of a misnomer. To paraphrase Winston Churchill: 'Some group! Some special interest!'

Research and development

Bringing computer graphics to its launching pad of the 1980s required a substantial investment in research and development. This was underwritten largely by the aerospace, automobile, and defence industries. The bulk of the work was carried out at corporations and universities in the United States and, to a lesser extent, in Britain. Among the corporations who saw the potential at an early stage – at around the time of Sutherland's seminal work – were Boeing, Lockheed and General Motors.

General Motors was the first user of an elaborate graphics system developed by IBM specifically for automobile design. It was called DAC-1 (design augmented by computer). Installed under a cloak of secrecy, the system was eventually made public at the 1964 Fall Joint Computer Conference. The DAC-1 was the first of many purpose-built computer-aided design (CAD) systems that would be used for designing motor cars by the end of the 1960s. The design of cars, planes, and other highly-engineered products provided the necessary stimulus to the development of more versatile



△ **Design evaluation**
CYBERMAN is a three-dimensional wireframe manikin, invented by Chrysler Corporation and used for evaluating layouts of interior components in, for example, the driving compartments of vehicles

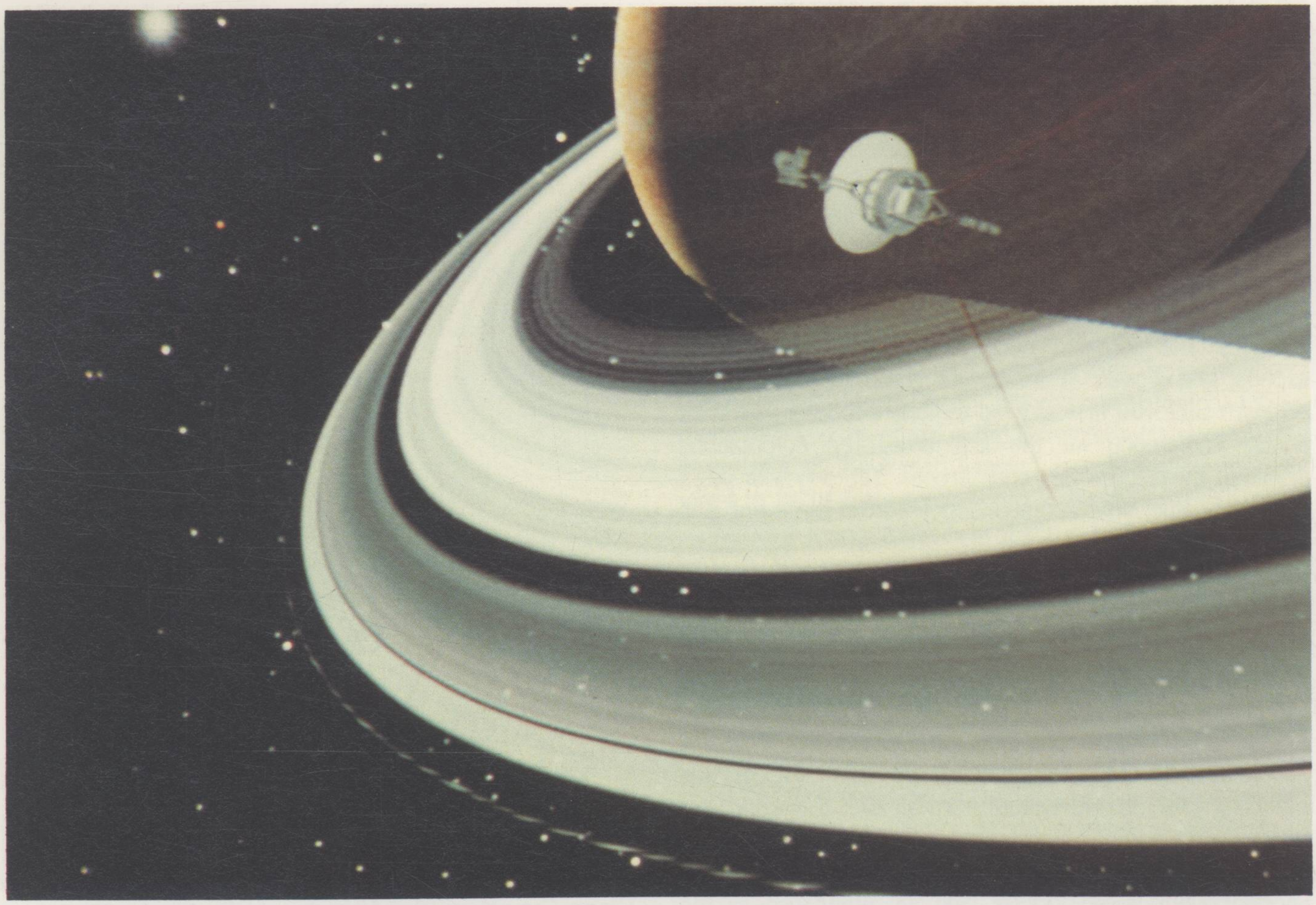
Chrysler Corporation, Detroit, Michigan

CAD equipment that could be used by thousands of different manufacturers.

One of the most successful projects was an early system developed by Itek Laboratories for lens design work. The geometric calculations necessary to lens design are so complex that computer-aided design seemed to be the natural route to follow. The Itek researchers were right. Their system was later bought and marketed commercially by Control Data Corporation, again making the new techniques available to a broader range of users.

It was perhaps surprising that the first major research centre for computer graphics – as opposed to the more general field of computer-aided design – was destined to be established at a small university in the middle of the western United States. The University of Utah enjoyed a golden period of intensive academic research, yielding one breakthrough after another as students and teachers worked together on the problems posed by graphic representation with a computer. It was one of those rare occasions when a unique combination of personalities and circumstances produced a remarkable result.

While teaching at Berkeley, in Northern California, Professor David Evans had seen the film made by Ivan Sutherland



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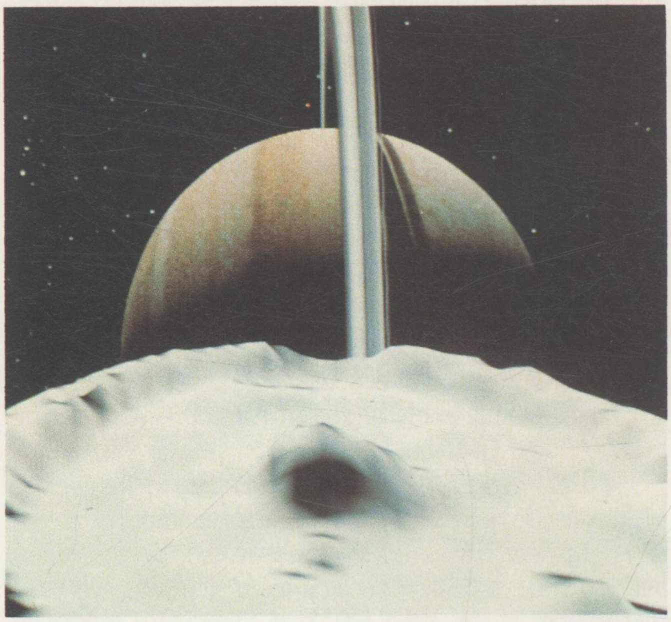
on Sketchpad. 'I was excited by it,' he said, 'but I didn't immediately do anything about it.' Shortly afterwards Professor Evans accepted a post at the University of Utah where he had the task of directing the department of computer science. Constrained by the relatively small budget of the university (Utah, for all its beauty, is not a wealthy state), Evans was forced to concentrate the resources of his department on one carefully-chosen area of research. He opted for graphics.

Computer graphics was an unusual and challenging field of research for the students at Utah. It involved working on subjects whose scope extended far beyond the traditional confines of computing. For instance, it included the laws of perspective, the composition of light and the science of colour. Even geometry could now be reinstated into the mainstream of academic research, some 350 years after René Descartes had reduced it to algebra.

In 1972 at Utah, students worked around the clock, discovering how to describe the shapes and appearances of objects to the computer. One of them was Ed Catmull, who now heads the graphics research team at Lucasfilm. Reflecting on his days in Utah, he said: 'There was very little equipment. But *magic* happened at that time. A lot of good ideas just kept rolling forth.' Catmull's own research was



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△ ▷ **Space simulations**
Realistic simulations of space vehicles flying past planetary bodies have become familiar to millions of people through television. Conceived originally as public relations films for NASA (National Aeronautics and Space Administration), these simulations by Dr James Blinn are scientifically impeccable. Even the stars are in their correct positions