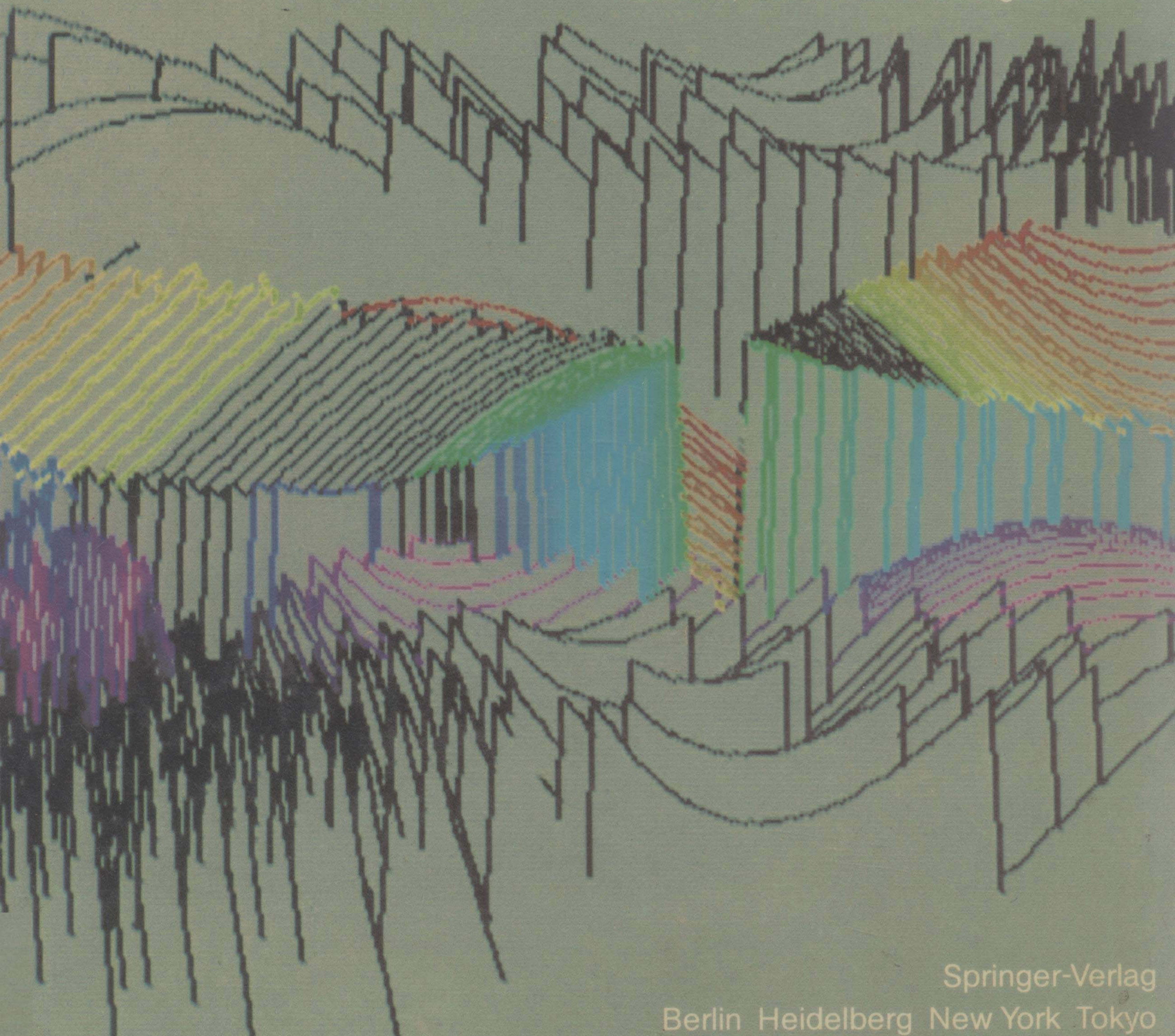
Herbert W. Franke

Computer Graphics – Computer Art

Second, Revised and Enlarged Edition



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With 133 Figures, Some in Color

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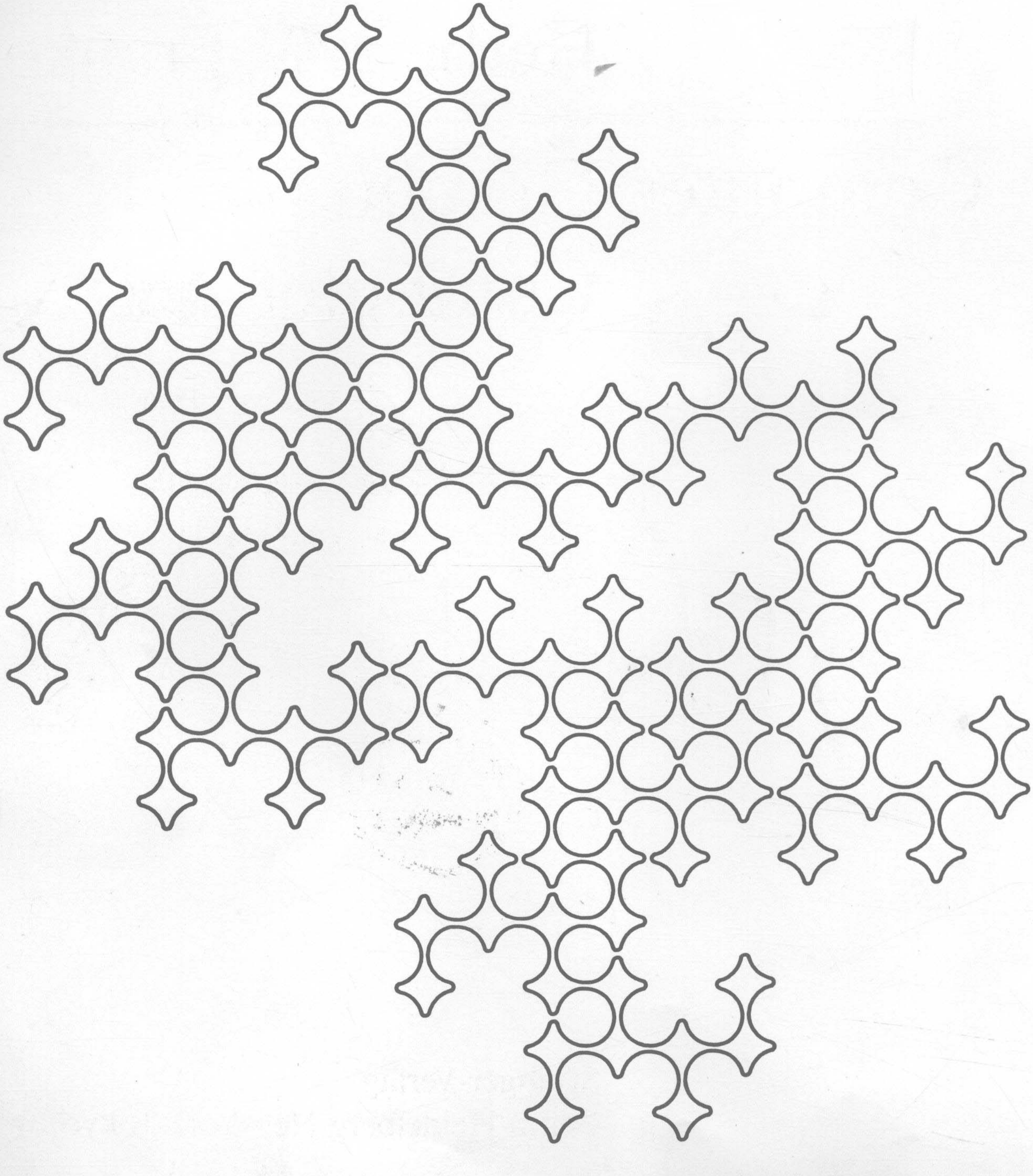
Mathematical Landscape, *perspective presentation of a mathematical function of two variables; system DIBIAS, DFVLR, Oberpfaffenhofen, Herbert W. Franke and Horst Helbig*

Frontispiece:

1 Digital graphic from the series DRAKULA (DRAchenKUrven überLAgert), *1971, by Herbert W. Franke, programmed by Josef Vordermaier, executed with the Siemens System 4004 and a CalComp drum plotter. This drawing is based on a seventh order dragon curve built up from 127 instructions for left and right twists. The elements are taken from a repertoire of curve sections chosen for their superpositioning and connection characteristics. By the choice of different elements, curve sections, and the manner of combination and superimposition, a multiplicity of figuration is achieved*



Preface to the Second Edition

Ten years have passed since the first edition of this book, a time span during which all activities connected with computers have experienced an enormous upswing, due in particular to the advances in the field of semiconductor electronics which facilitated microminiaturization. With the circuit elements becoming smaller and smaller, i.e. the transition to integrated circuits, the price of hardware was reduced to an amazingly low level: this has definitely been an impulse of great importance to the expansion of computer technology, as well as to areas far removed from technology.

The increased execution times and storage capacities achieved by semiconductors were necessary conditions for the breakthrough of computer graphics which has occurred in the meantime. While a decade ago it was still considered to be a special application for computers, today computer graphics can be regarded as being completely integrated into computer science. The output of computational results in graphical form occurs just as often as the numeric representation, but in addition a multitude of further, partly surprising applications has developed. Picture processing has become a widely used method for evaluating the results of scientific photography, in close collaboration with pattern recognition, a structural analysis effected with the aid of numerical methods. CAD (computer-aided design)/CAM (computer-aided manufacturing) are important areas of current research.

Computer-aided process control has surfaced as a new area, the central supervision of technical systems with the aid of screens. Furthermore, various text processing systems are worth mentioning, the characters of which are generated with computer graphical methods, but which also permit supplementation by simple graphic representations.

The transition from mechanical plotters to graphics terminals is a development characteristic of the last few years. They open the way to regional representation, to the unlimited use of color, to dynamic display, and to interactive use. While in former times the use of color was attributed more to a playful need for ornamentation, it is generally accepted today that much better overviews can be achieved by representing particularly complex configurations in color. In some cases, as for instance in process control, one could hardly do without colors. It is scarcely necessary to stress that the availability of colors further assists artistic ambitions.

The dynamics of display which can be achieved on the screen is also of significance for the visual arts. It is a necessary condition for some technical applications, for example when simulating dynamic processes. Although the graphics systems operating in real time were not designed for artistic purposes, they nonetheless open the most exciting aspects to the visual arts. While the static computer picture was still a realization in line with the usual form of representation in the fine arts, computer graphics now becomes the instrument for a form of artistically created graphical sequences, precursors of which, however imperfect, were the kaleidoscope, water fountains illuminated by color, and, subsequently, animated pictures. Just as it is possible to produce sound elements with a musical instrument in any combination and sequence, computer graphics systems allow free graphical play with colors and shapes. In contrast to animated pictures, production in real time is possible, and thus even free improvisation – surely the most stimulating form of artistic activity.

The free and flexible way to use a computer differs widely from its operation in former years – the off-line mode using punched cards and resulting in long waiting periods for the mechanically produced graphics.

Other developments point in the same direction: excellent adaptation of the machine to man, and not vice versa, leads to an increasing use of interactive systems. The classical computer languages then serve, for the most part, only the purpose of preparing for a user-oriented mode of operation, particularly for users without any knowledge of computer science. The program logic is oriented towards a question-answer-dialogue, menus and decisions which lead to further questions and answers until the desired result is obtained.

The method thus applied is that of trial and error, a mode of operation well adjusted to the processes of human thinking and acting. Routine questions are solved internally, without the user noticing it, and omissions or mistakes are indicated on the printer or graphics terminal. In this way – supplemented by suitable hardware – one comes very close to customary artistic activity, for instance painting and drawing, so that the artist can work in a fashion appropriate for enjoying, in addition, considerable advan-

tages, for instance the possibility to change colors, to enlarge segments of pictures, to move elements across the display surface, etc.
It must be stated, however, that the interest of professional artists in the new tools is relatively low; visual art is heading into other directions and, similar to photography in the past, the new medium will probably not be integrated into the conventional art scene, but might serve as a challenge for the creation of a new profession. This trend was aided by the development of some new applications of computer graphics during the last few years which were commercially oriented and were therefore able to attract the interests of computer scientists more than the free artistic activities, but which, on the other hand, are closely connected with the latter and which can profit from its experiences. Four areas are to be distinguished:

1. *Design* – from architecture to patterns for textiles.
2. *Animation* – from movies and advertising to computer games.
3. *Visualization* for instructional purposes.
4. *Experimental aesthetics.*

The work procedures of designers of industrial products – car bodies are a well-known example – as well as those of architects and of civil engineers resemble the technical processes of CAD and CAM with the aesthetic aspect being added as an additional factor. Basically, the same technically proven methods are being used by the designers. The situation looks a little different in the area of textile design. Technical constraints – as, for example, that of repeat and duplicate – play merely a subordinate role, aesthetical criteria demand to be considered first and foremost. Special systems which are also compatible with the automated production in weaving and knitting mills are offered by some companies for these purposes. Besides, textile design is a task which can also be solved with conventional systems, based on software which is not too complicated.
The area of animation has become known particularly because of new methods in producing animated pictures; its use spans the whole range from generating phase pictures to simulated technical objects and landscapes. But one can also consider the area of computer games under the aspect of animation which, in this case, is still achieved by rather simple means, but which, eventually, will most certainly use more sophisticated simulation techniques – another area of application which will be of commercial interest and which holds great promise for the future.
Besides its use in the movie industry, the advertising industry and the area of computer games, a further interesting possibility for using these techniques has developed, and that is simulation for educational purposes, for example for the training of pilots and railway engineers.
The special task of computer graphics in the field of instruction is the visualization of instructional material, as is possible particularly in mathematics, physics, and chemistry, but which will gradually extend to other subject areas. The new method permits the use of pictures as an alternative to formulas – thus making many relationships visually conceivable, with all the advantages of providing a better overview and of making the material easier to retain. In contrast to the usual illustrations, dynamic processes can also be demonstrated by computer graphics methods, not only in a linear sequence, but also with varying parameters which offer the student the possibility of experimenting. Another consequence of these possibilities is the "electronic museum" in which all kinds of processes can be demonstrated by computer simulation.
The fourth kind of application, experimental aesthetics, is related to computer art in two ways. On the one hand, computer graphics has proven to be the medium which provides the science of the fine arts, aesthetics, with the vehicle for experimenting – by making it possible to construct and vary pictures according to certain aesthetic laws and by succeeding in simulating stylistic peculiarities of certain epochs and artists. On the other hand, it becomes more and more apparent that the aesthetically oriented modes of expression, as they are used in conventional textbooks and academies, are of little avail to the artist who works with technical systems, particularly with computers. He needs a rational theory as theoretical basis which uses principles that can be formulated mathematically and which provides a link to science and technology by referring to the reality of the human processes of perception. Thus, computer graphics proves to be the instrument which, at the same time, contributes to its own theoretical underpinning.
It becomes evident from the situation briefly outlined above that

the number of those interested in the possibilities of computer graphics has increased considerably over the last few years. Besides computer scientists themselves, who suddenly find themselves confronted with tasks which are at least partially aesthetically oriented, there are the members of other professions - artists, designers, educators, etc. - who want to inform themselves of the subject matter. Since this book is not only meant for computer scientists, the outline of the new edition will remain unchanged: After a simple description of the means and methods, a historical summary and a discussion of the artistic possibilities facilitated by the computer will follow. These chapters of the book have been thoroughly revised and updated. A section which deals with the above-mentioned new applications of computer graphics means and experiences in the commercial field has been added.

In spite of the considerable progress which computer graphics has experienced within the last ten years, it should not by any means be considered as having reached the stage of full maturity - thus, the last part which is devoted to future prospects remains indispensable. The short time span during which computer graphics has been researched and applied has certainly not been sufficient to let it mature into a great, well-recognized art form. But undoubtedly we are dealing with a part of that "gentle" technology demanded by so many which enriches man's life on a cognitive and creative level without causing any harm.

I would like to thank Dr. Imai-A. Roehreke and *Digital Equipment*, Munich, for assisting me in the design of computer graphics and for providing the possibility of using a *Professional 350*. I would further like to thank Mr. Horst Helbig, DFVLR, Oberpfaffenhofen, Prof. Dr. Georg Nees, Siemens, Erlangen, and Johann Weiss, Technical University, Vienna, for revising the manuscript, and also Prof. Dr. Otto E. Laske, Newcombe, Needham (Massachusetts), for his support in compiling the section on computer music. Further more I am indebted to Prof. Dr. Günther F. Schrack, Vancouver, for his valuable advice, and in particular to his wife Antje, for translating the new parts of this book into English. The first edition was translated by Gustav Metzger. Last but not less heartily I would like to thank Dr. Friedbert Stohner for his careful work on the German and English editions and for his pleasent co-operation during the preparation of this book.

I am also obliged to all friends, colleagues and companies who made their graphics available for illustrating this book.

HWF

Preface to the First Edition

The works from computers nowadays covered by the term computer art are in my opinion among the most remarkable products of our time:

- not because they surpass, or even approach, the beauty of traditional forms of art, but because they place established ideas of beauty and art in question;
- not because they are intrinsically satisfactory or even finished, but because their very unfinished form indicates the great potential for future development;
- not because they resolve problems, but because they raise and expose them.

Mass-produced electronic digital computers have existed for around twenty years, and the term computer art has been in current use for about five years. Compared with the latest stylish movements – such as Op and Pop – that is a long time, but in relation to technical developments it is a very short one. Computer art, however, is dependent on the computers – it cannot achieve more than these will permit: it expresses the progress taking place in computer science. If one accepts the predictions of the experts, then the most interesting developments are yet to come, especially in the field of programming, i.e. software. As long as this growth continues computer art too has the potential to perfect its methods and thrust toward new domains. The goals toward which it is advancing are still obscure, yet the almost palpable indications of that future appear fantastic. Computer art can place the whole field of aesthetics as well as artistic practice onto new foundations – an idea that will be substantiated later in this book.

Ever since the emergence of computer art, all kinds of arguments have been used to deny a connection between computer and art; this too will be discussed. In this book the terms computer art and computer artist will be used in a descriptive sense; recognition as an art form remains a matter for individual judgment.

When I first decided to present a comprehensive survey of the new phenomenon of computer art, I felt that, for once, it would be possible to trace the development of an art form from its earliest beginnings, and that it would be easy to incorporate a complete documentation of its classical phase, in its historical context. This advantage has now disappeared, not only because of the phenomenal increase in activities, but also because it is only now being realized that computer art was practiced in many places well before it attracted international attention. Nonetheless, an attempt will be made to present a survey of initiatives and methods – but on no account can this be complete.

The demarcations of the subject present yet a further difficulty. Many of the works to be discussed have their origin in scientific and technical tasks; in the USA any kind of pictorial output of computer results is designated as computer graphics. Some of these results have a considerable aesthetic interest, and others require only a slight modification to remove them from the realm of science and technology and place them for consideration in the sphere of art. Works by W. A. Fetter, which are among the first computer drawings and which emerged from a strictly technical problem – the most efficient design of an aeroplane cockpit – have received art awards; computer graphics made for scientific and technical purposes cannot therefore be entirely excluded from the field of computer art.

A further question relates to the instruments. Although the first aesthetic graphics produced with the aid of large data processing installations came as a surprise to many, they did in fact have precursors. In particular, the analogue computer had already been employed for free artistic expression. And even before this, attempts had been made to create graphic images by means of optical and mechanical implements; these images too could be seen as aspects of analogue calculation. In accordance with the usage of the first large computer art exhibition – *Cybernetic Serendipity,* London 1968, organized by Jasia Reichardt on a suggestion by Max Bense – a work of computer art will be understood here as being any aesthetic formation which has arisen on the basis of the logical or numerical transposition of given data with the aid of electronic mechanisms.

Computer art already embraces many forms of traditional art – there are computer-generated graphics, sculptures, films, choreography, poems, music. All these developments stand in close relationship; only music has followed its own development, based on the intentions of electronic music. Since a bulky literature is already in existence, computer music will be considered in this book only in so far as it is related to other activities in computer art.

Access to computer art is hindered by a difficulty unknown in other art forms: its practice requires a certain elementary mathematical and technical knowledge. A similar difficulty arises for a comprehensive presentation such as is attempted here: in order to acquire a true understanding, a brief consideration of the functions and working methods of computer installations is unavoidable. Since this leads to a deeper insight into the historical development of computer art as well as its underlying theory, this preparatory section takes up the first part of the book. It also appeared desirable to demonstrate certain methods by examples, which also had to be referred to in the historical part. The result is a certain overlapping, but this does have the advantage of further clarifying the interconnections between the technical and the creative aspects.

As the most convincing evidence for the state of computer graphics is the exemplary image, an effort was made to present an illustrated survey of the manifold possibilities of computer-generated pictorial imagery. Following the addition of many new works, the pictorial part of the book became far larger than had been originally planned; thanks are due to the publishers for the wide scope of the illustrations. I am especially indebted to Dr. Frieder Nake, presently in Vancouver[1], and to Mr. Peter Henne, Bad Godesberg[2], who have taken the trouble to read the manuscript, and who have made valuable suggestions regarding corrections and supplementation of the text. I am also obliged to the firm of Siemens AG, Munich, for enabling me to carry out computer graphic experiments with their data processing installation, the Siemens System 4004: I thank all collaborators from their Bereich Datenverarbeitung for their friendly support of my work. Finally, I am grateful to all those who have supplied pictures, and who have helped with information - especially the members of the Computer Arts Society, London.

HWF

[1] Now (1984) Professor at the University of Bremen
[2] Now (1984) GMD, Birlinghoven

Contents

Installations and Methods

1 The Computer and Aesthetic Processes

In creating a work of art it is vital to design an arrangement from elements, such as forms, words, and sounds. And these elements have above all to conform to one condition: they must be perceivable. The elements are the smallest perceivable units - *Apperzepteme,* in the terminology of Max Bense. Since only vision and hearing have the capacity of taking in such complex structures as aesthetic objects, our concern is with visually or aurally perceivable units.

Two phases are to be distinguished in the production of a work of art:
1. The preparation of elements *(Apperzepteme).*
2. The conception of the arrangement.

These two phases are different in principle. The making of the sign carriers is a physical procedure. In order to mechanize it, physical machines are needed; examples are drawing machines, typewriters or musical instruments. In contrast, the conception of an arrangement is not a physical but an informational process; and it is only through cybernetics, and particularly through information theory, that this can be clearly elucidated. It follows then that the second, essential phase of the artistic process cannot be accomplished with energetic, physical-technical machines; it has become amenable to mechanization only since effective information-processing machines have appeared - the computers. That is the fundamental novelty of the situation produced by the irruption of the computer into the sphere of the arts; for the first time it has become possible to insert a mechanical aid into the creative phase of artistic production.

2 The Analogue Computer

The analogue computer does not have the widespread uses of the more recent digital computer, but it is actually better suited for a variety of functions, and it is likely to remain what it has always been in the past - a major instrument of computing. So-called hybrid computers - combined systems of analogue and digital computers are available for special purposes.

The orders which are grasped by the analogue computer are relations that can be represented with the aid of parallel (synchronously) working calculating registers, namely by electrical quantities, like voltages, which vary with respect to time. Special wiring permits, for example, the addition and subtraction of voltages and their multiplication by constant factors. In technical applications one seeks to imitate, by means of these voltages, the quantities which are to be computed. They function as models of the computing values, they are analogous to them - hence the term analogue computer. In computer technology one tries, through the use of voltages, to produce organizations that are of aesthetic interest. The advantage of analogue computing is that functions can be represented as a whole, and do not have to be dissected into number and dot sequences as with the digital computer.

3 The Digital Computer

The digital computer, too, encodes the quantities with which it calculates by means of electric currents and voltages, not, however, as functions of time, but as single impulses. There are only two signs:

- *no impulse* means 0;
- *impulse* means 1.

Any desired number can be expressed using this numerical system, the binary system. The table below shows the binary coding (second column) of the ten decimal numbers (first column). The interpretation of the binary numbers is indicated following the equality sign.

0 . . .	0 =	0.2^0
1 . . .	1 =	1.2^0
2 . . .	10 =	$1.2^1+0.2^0$
3 . . .	11 =	$1.2^1+1.2^0$
4 . . .	100 =	$1.2^2+0.2^1+0.2^0$
5 . . .	101 =	$1.2^2+0.2^1+1.2^0$
6 . . .	110 =	$1.2^2+1.2^1+0.2^0$
7 . . .	111 =	$1.2^2+1.2^1+1.2^0$
8 . . .	1000 =	$1.2^3+0.2^2+0.2^1+0.2^0$
9 . . .	1001 =	$1.2^3+0.2^2+0.2^1+1.2^0$

Computing involves control elements constructed in such a manner that they can carry out addition, subtraction, multiplication and division in the binary system. The following rules apply:

$$0+0=0$$
$$0+1=1$$
$$1+0=1$$
$$1+1=10$$

In this way one can add digit to digit, as in the addition of decimal places:

$$\begin{array}{r} 101101 \\ 110111 \\ \hline 1100100 \end{array}$$

In order to multiply, one has only to remember:

$$0\times 0=0$$
$$0\times 1=0$$
$$1\times 0=0$$
$$1\times 1=1$$

Here one can again apply the well-known calculation scheme of the multiplication of decimal numbers:

$$\begin{array}{l} \underline{101001\times 11100} \\ 101001 \\ \;\;101001 \\ \;\;\;\;101001 \\ \;\;\;\;\;\;000000 \\ \;\;\;\;\;\;\;\;000000 \\ \hline 10001111100 \end{array}$$

According to the theory, not merely arithmetical but also logical relationships can be represented by the 0, 1 code. Similarly, addition and multiplication, the logical relationships *and* as well as *or* can be achieved with wiring. A simple change from 0 to 1, such as can be produced via a change-over switch, corresponds in formal logic to the *not*-relation. Since according to this science, each logical relation can be broken down into these three elementary relationships, it follows that the most complex logical dependence is open to imitation by means of switching elements. The rendering of the desired aesthetic order in the form of logical relations is therefore an important task of the artist practicing computer graphics. Mathematical relations are treated as special cases of logical relations.
In principle, work with the digital computer is carried out along these lines:

1. *Programming,* production of an interconnected scheme which corresponds to the desired calculation.
2. *Input,* feeding in those values that are to be manipulated.
3. *Data Processing,* performing the logical-mathematical operations.
4. *Output,* directing the results into a converter device, which sets them out in a form comprehensible to human beings.

It is one of the principal advantages of the large digital computer that the production of the necessary connections, as instructed by the program, does not involve a permanent change of the switch network, but a kind of temporary reorganization. In practice, this is achieved by the opening and closing via current impulses of specific switches, and thereby also certain circuits. Thus, nothing is changed in the disposition of the machinery (hardware, as opposed to software – data, programs, etc.). Again, the instructions for the opening and closing of the circuits can be given with a binary code, like this:

0 . . . close the switch.
1 . . . open the switch.

This enables the same data carriers, the memory – a pile of punched cards or magnetic tape for instance – to be used for programs and for calculating data.

4 Structure of the Computer

A digital computer is made up of certain building elements, of which the most important are the control unit, the register, and the working store or memory. Attached to these are the external devices: input and output units, various external stores, and in certain circumstances even mini- or satellite computers.

- The control unit brings about the running of the program.
- The calculating register carries out the operation.
- The working store holds the working data and the programs.
- The input unit deals with the acceptance of the programs and the calculating data.
- The output unit delivers the results.
- The external stores hold data for eventual use.
- The satellite computers execute calculations which should not be loaded onto the central processor.

Microcomputers

Microcomputers, composed of a few small modules, are gradually assuming more and more tasks which just a few years ago were reserved for computers of the classical type, which were much more expensive and required a lot of space. It is an essential characteristic of microcomputers that the arithmetic logic unit and the central processing unit are located on a single chip as a single integrated circuit. Typical for its organization is the so-called bus, a set of parallel wires with the aid of which the information - data and instructions - is exchanged between the connected modules. The programs are stored in ROMs (read only memory) which have a storing capacity of several thousand bits. The freely addressable RAMs (random access memory) serve the purpose of general data storage. It is to be noted that the latter, as opposed to the read only memories, lose the information once the device is turned off.
In a microprocessor data are processed word by word, i.e. in groups of bits; most frequently the words are 8 or 16 bits long, but 2, 4, and 12 bit words are also used. They are transferred in the bus, word by word, in parallel, i.e. simultaneously.
All the usual devices attached to a mainframe computer can be connected to the microcomputer; the result of connecting several microprocessors is inexpensive systems of remarkable effectiveness. The microcomputer is the basis of the home computer or personal computer which permits data processing to permeate all spheres of life. It will result in strong impulses for graphical systems to be used widely.

5 Hardware

To be able to use a computer for a specific purpose, it is sufficient to have a rough idea about the way it works, about its structure. This material aspect of computer technology, the hardware, will be the subject of this chapter.

Memory

What takes place inside a computer is not really of concern for the user. There is no need to have a detailed knowledge of the computing processes, their organization or their temporal flow, etc.; indeed, with large digital computers this would hardly be possible. The computer is a "black box" in terms of cybernetics, that is to say, one is interested only in the incoming and outgoing data - known in professional language as input and output. The computer graphic artist, too, requires only a slight knowledge of the construction of the machine - there is certainly no need for him to be either a technician or a mathematician. What concern him are the previously discussed programs, which relate to the incoming data, as well as the circumstances and possibilities of the output that are to be discussed later on.
The results of the numerical and logical operations of a computer appear at first in the form of binary characters, coded as current impulses. Where outputs are to be reintroduced into the computer, it pays not to translate them immediately into a form understandable to humans, but to hold them as 0, 1 impulses, which can be reintroduced into the machine in that form. This is the purpose of the various kinds of external memories that are also available for computer graphic applications. Among the most frequently used external memories are:

Punched Cards. Cards of thin cardboard, 8.2 cm wide and 18.7 cm long, having twelve lines and eighty columns. Punched tape and punched cards are used equally as means of input of data to the computer.

Punched Tape. Punched tape is used containing five to eight tracks.

Punched cards and punched tape are mechanical stores. The storing is effected by the punching of holes. The absence of a hole on the prepared store places signifies 0, a hole signifies 1. Reading is carried out by running the cards or tapes beneath metal brushes, electrical contact being produced through the holes. At each hole, i.e. at each contact, there occurs a current impulse that indicates a 1. Mechanical, photoelectrical or dielectrical scanning is also possible.
The use of mechanical means of storage has decreased considerably in the last few years. Compared to storage media using magnetic means, they are awkward to handle, and they do not allow interactive operation.

Magnetic Tape. A plastic tape with a layer of iron or chrome oxide on one side, having four, six or eight information tracks plus an additional track for control purposes. The coding of the binary numbers results from the magnetizing direction. Magnetic drums, magnetic plates and magnetic cards work in essentially the same way.

Disk Drives. Disk drives also operate on the principle of recording on a magnetic medium. They consist of stacks of up to 12 metal disks with 2000 tracks each and are coated by ferric oxide. They have the advantage, as compared to magnetic tapes, that any disk location can be accessed much more quickly, since the read/write head can be positioned over any selected spot of the disk surface and does not have to follow the tracks. The Winchester drive, a compact version of the hard disk drive in a completely closed housing, is becoming more and more popular.

Floppy Disks. Handy floppy disks which also operate on a magnetic basis have become customary particularly for storage purposes in microcomputers. They correspond in shape and size to 45 rpm records.

Holographic Memories. Because of its physical qualities, light would be extremely suitable for storage of data – a storage density of approximately one million bits per square millimeter could be achieved on a flat medium, as for instance on a photographic plate, thus surpassing the density of magnetic surfaces by two orders of magnitude. This would allow the information to be recorded digitally in a raster, the presence of a mark representing the binary number 1 and its absence the binary number 0. In order to avoid errors caused by dust particles, scratches, etc., such a picture, correspondingly reduced in size, would have to be recorded as a hologram. This can be retransformed by means of the usual holographic procedures into the original picture which is then read by a photocell to reconstruct the information. So far, this procedure has not been implemented for widespread use, since it has not met the expectations of its designers.

Bubble Memories. The storage medium for a bubble memory is a magnetic single crystal layer which, e.g. consists of ytterbium-iron-garnet. The direction of magnetization is aligned vertically to the layer. Regions of some thousandths of a millimeter in diameter serve as storage cells. They are stable, repulse each other, and can be shifted like bubbles floating on a layer of liquid. This facilitates the organization of storage space. The storage density is approximately 3000 bits per square millimeter, the access time about 100 microseconds. Some experts envision the robust and comparatively cheap bubble memory to be the random access memory of the future.

Input Devices

Keyboard. The keyboard, a device similar to the typewriter or teletype, usually supplemented by a set of auxiliary keys, is the most widely used means of input. The input device codes the characters selected by the keys into binary numbers. The off-line operation used exclusively in the past effected the transfer to a recording medium – such as punched cards, paper tape, or magnetic tape – within the same device; in on-line operation which is the usual mode of operation nowadays, the characters are transmitted directly to the computer as electronic binary signals.
The alphanumeric and special characters which are represented by the keys can be used in their primarily assigned value, but their function can be reassigned to other purposes by auxiliary keys, such as SHIFT or ESCAPE, for example to move a cursor

in different directions on the screen or to erase parts of a current text line.

In addition to the different types of alphanumeric keys described above, function keys are available which can be assigned any input functions, for example the choice of colors.

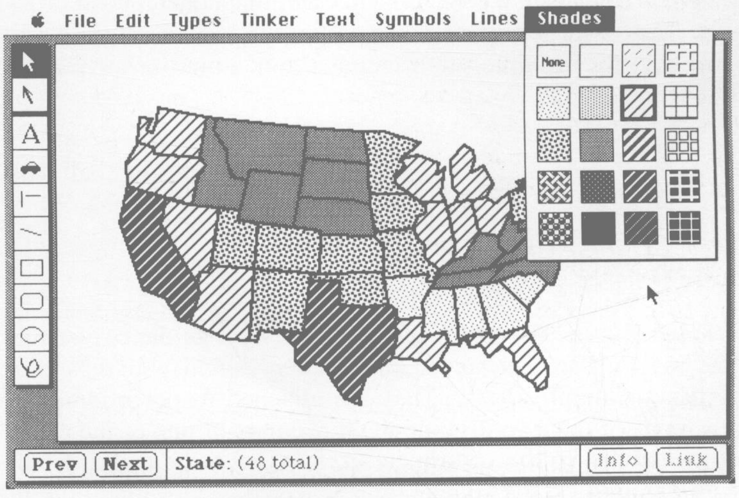
Digitizing Table. The digitizing table or tablet is a very versatile input device well adapted to human actions. It is used as a writing or drawing board; styli or cross hairs which are moved across the drawing surface are employed for the input action. Most devices allow point-by-point input as well as the input of line segment sequences.

A matrix of fine wires arranged crosswise is located below the input surface of the tablet. Impulses are transferred according to the same principle used in transformers. The detector loop located in the stylus or in the cross-hair device generates an electromagnetic field which is coupled into the wires. Other models operate according to a different physical principle, but the recording of the grid points basically remains the same. The resolution is usually in the range of a tenth of a millimeter, but can be increased up to 0.02 millimeters for high precision devices.

Digitizing tables can be used for the direct transfer of drawings into the computer memory, for instance by following the contours of a drawing. For artistic purposes, even freehand drawings can be input; depending on the available software, the stored graphical data can be processed further. The point-by-point input offers a mode of operation which is also of interest for artistic use, for instance by indicating merely the vertices of a polygon or of a more complex graphical object which the program then joins by line segments. The digitizing tablet can also be used for coloring or erasing, for example by identifying a given polygon by means of the stylus or the cursor and by initiating the intended operation by depressing a function key. Input procedures of this kind can be simplified if necessary; for instance, the program can include a procedure which renders the exact localization of the points, a tedious task, superfluous – it is sufficient to indicate any point in the vicinity, the program will then automatically substitute the closest point or the closest line segment for the input location.

Another possibility is the use of digitizing tablets in conjunction with menus. These are added to drawings or used as overlay templates; to make his decisions, the user merely needs to place his stylus on a specific area near the graphical representation.

Light Pen. The light pen which is employed just as frequently as input device is used in a similar fashion as the digitizing tablet. Basically it is a photocell with an optical aperture of almost pointlike size. If it is placed on the screen of a vector-refresh or raster terminal (cf. paragraphs on output devices), the optical sensor absorbs the light signal generated by the electron beam which causes it to interrupt the computer. This allows a specific circuit to determine which point was indicated by the light pen, and it is thus possible, similar to the use of the stylus or the cursor of the digitizing tablet, to mark points on the screen or to generate line segments. This permits the direct input of drawings, but the input can also occur by means of menus which are output on the screen for this purpose. If they are used for the representation of graphical data in interactive operation, it is of advantage to work with two output terminals, or else part of the screen can be reserved for the menu and the other part for a working surface. Sometimes the drawing on the screen is overlaid by the menu.



2 Shades menu; Filevision, *Telos Software, USA*

Joystick. The joystick is well known as an input device for computer games, but it can also be used for various other purposes, not the least of which is freeform artistic graphics. It is usually installed in a small box from which a lever protrudes, movable in all directions. Attached are two potentiometers which deliver two voltage values representing coordinate values. The voltages are converted into digital numbers which are stored. In principle, it is possible to refer the numbers to any two given variables, for example direction and speed of a simulated projectile. Usually, however, they are interpreted as point coordinates on the screen. With the aid of this device, it is again possible to mark points or to input sequences of line segments.

Tracking Ball. The tracking ball basically works according to the same principle. As implied by the term, it is a sphere which has been installed in a table such that only a small portion protrudes. It can be turned freely by hand. As with the joystick, it is a device which allows the simultaneous determination of two values. Due to the freedom of movement of the ball - rotation around any axis - it is employed in 3D-graphics, especially when tumbling perspective representations of three-dimensional objects on the screen; the movement on the screen is synchronized with that of the ball. But again, it is possible to coordinate the range of other, not necessarily geometric values with the two values of the tracking ball, for example the brightness and saturation of a color table.

Mouse. The mouse is a special version of the tracking ball with the ball located at the bottom of a freely movable housing. When guiding the mouse over the table top, the ball rotates and registers the coordinates of the positions and tracks.

Thumb Wheels. The setting of coordinates, the guidance of a cursor etc. can also be achieved in a simpler fashion, with the aid of a pair of thumb wheels. They are attached to potentiometers, each one of them controlling the movement of one of the directions parallel to the coordinate axes. As with the tracking ball and the joystick, the voltage range covered is converted into an interval of digital numbers, for instance from 0 to 127. The correspondence is arbitrary - each thumb wheel can be used individually to control any variable.

Optical Scanners. A series of devices allows the automatic transfer and digitization of pictures. The best-known example for such devices operating as scanners is the television camera. But there are also special devices in which a photocell moves line by line across a projected picture, across a flat picture, or a picture mounted on a cylinder. With the aid of filters with which the three primary colours are scanned separately, it is possible to input colors. The optically sensed information is transformed into digital data and stored for subsequent processing. Scanners are employed in particular for picture processing and pattern recognition which will be dealt with later, but they also, for artistic purposes, supply the artist with the means for graphical abstraction.

Sensors. In addition to the usual means of computer input devices described above, further devices can be employed depending on special requirements - basically all devices which allow any physical quantities to be transformed into electrical impulses. These instruments are called sensors, and among others, are used as aids in controlling systems such as production lines. Under special circumstances, they can become important instruments for the artist, for instance when coordinating the composition of animated pictures with music. It is possible with the aid of volume and frequency filters to select certain signals from the sounds, which eventually control the picture-generating processes. Although techniques of this kind can be implemented by relatively simple means, they have rarely been applied.

Output Devices

Intermediate results occurring with more complicated calculations do not have to be translated into human language. The computer frequently uses an external store for dumping without the user being aware of the fact; nor is this information required. Generally the installation handles such organizational tasks in an automatic manner.

The final results, however, must be submitted to a translation