HOW HAS SOFTWARE AFFECTED THE VISUAL ARTS?

WHAT IS THE POTENTIAL FOR SOFTWARE WITHIN THE VISUAL ARTS?

AS A DESIGNER OR ARTIST, WHY WOULD I WANT OR NEED TO WRITE SOFTWARE?

Software influences all aspects of contemporary design and visual culture. Many established artists, such as Gilbert and George, Jeff Koons, and Takashi Murakami, have totally integrated software into their processes. Numerous prominent architects and designers use software extensively and commission custom programs to realize their ideas. The creators of innovative video games and Hollywood animated films also write software to enhance their work.

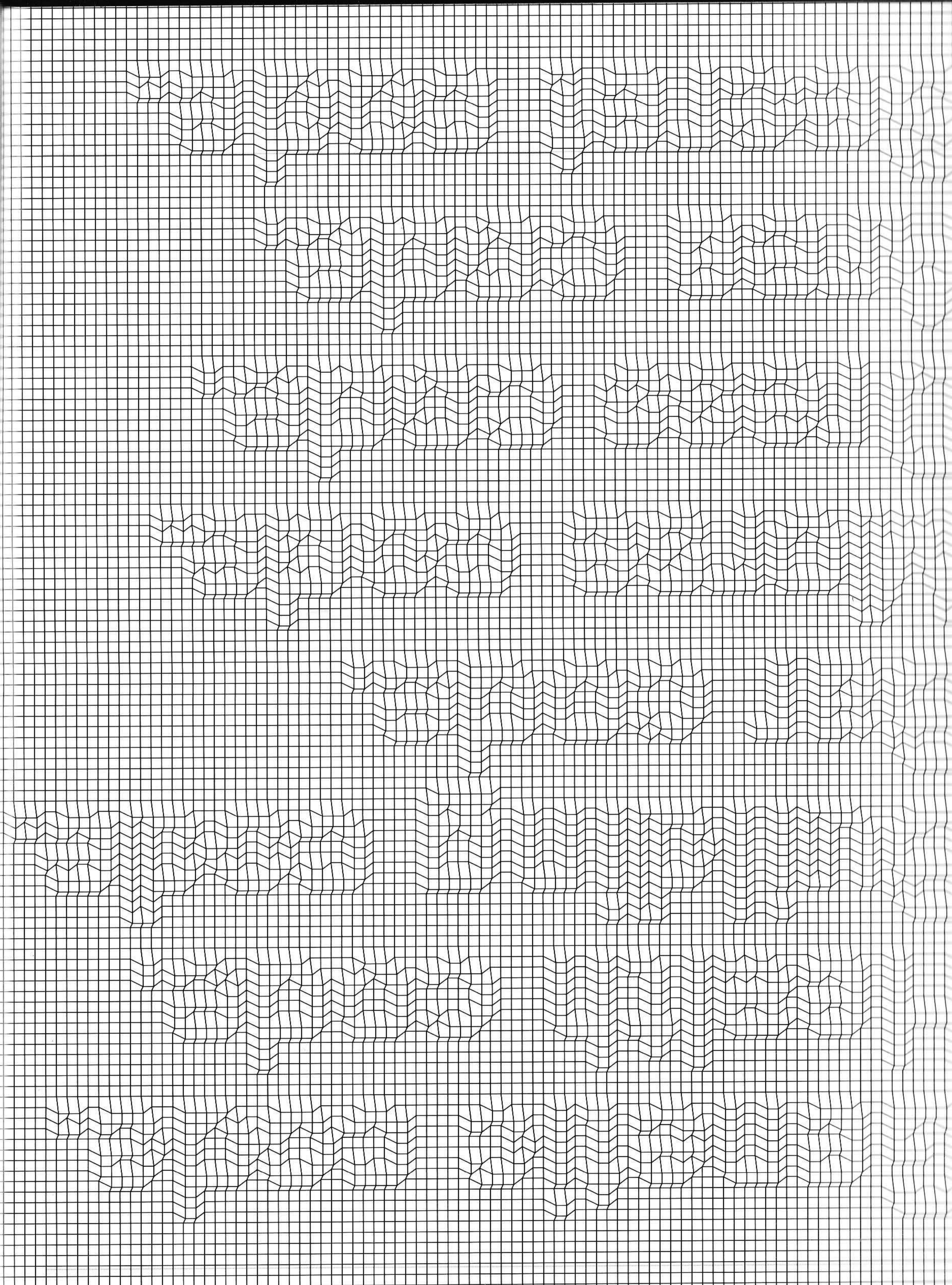
While these exciting developments are taking place at the highest levels of the creative professions, integrating them into design education is a challenge. Even the most motivated student will find the technical boundaries difficult to overcome. As a comprehensive first introduction to software development within the arts, this book seeks to encourage the enthusiasm that the field requires. It will not, however, teach you to program computers. To satisfy that urge, see Processing: A Programming Handbook for Visual Designers and Artists by Casey Reas and Ben Fry.*

* Casey Reas and Ben Fry, Processing: A Programming Handbook for Visual Designers and Artists (Cambridge, MA: MIT Press, 2007).

In Form+Code in Design, Art, and Architecture we define form as visual and spatial structures; code is defined primarily as computer programs, but we extend the definition to include instructions beyond computer code. The book is organized into seven chapters: What is Code?, Form and Computers, Repeat, Transform, Parameterize, Visualize, and Simulate. The first two chapters set the foundation by defining terms and introducing basic concepts. The themed chapters that follow are deeply linked to code. Each begins with an essay to define the territory, continues with images and captions to clarify and explain each theme, and concludes with two illustrated examples of programs. The corresponding source code is available in multiple programming languages and can be downloaded for free from the book's website: http://formandcode.com.

We're tremendously excited about the potential for creating form with code. We hope this book will inspire readers to think further about the relationships between these topics.

The diverse typographic explorations on the title pages of the following chapters began with the same typeface used for this page—Neutral by Kai Bernau. Using Neutral's geometry as a foundation, we developed all of the typefaces by tweaking and writing code using Python, PostScript, and Processing. The title-page typography demonstrates the nature of codification: the embedding of information within a system.



WHAT IS CODE?

Codes typically serve three main purposes. They are used for communication, clarification, or obfuscation.

In Morse code, a word is transformed into short and long pulses so that it can be communicated over a telegraph. The word my is encoded by the sender into "-- -.--"; the resulting sound is then decoded back into my by the receiver.

Genetic information is encoded in sequences of deoxyribonucleic acid (DNA), such as "AAAGTCTGAC," with A standing for adenine, G for guanine, T for thymine, and C for cytosine. The genetic code is a set of rules that use these sequences to build proteins.

The California Health and Safety Code is a set of written laws that codify the rules set forth by the State Legislature. For example, section 12504 states, "Flammable liquid means any liquid whose flashpoint is 100 degrees Fahrenheit, or less."

Ever since the origins of writing, codes have been used to protect messages from unwanted eyes. For example, a code can be as simple as replacing each letter of the English alphabet with a number: A is 1, B is 2, C is 3, etc; with this code, the word secret becomes "19, 5, 3, 18, 5, 20."

The grid on this page began as a simple and evenly spaced pattern. The outline of Neutral was converted to points, and a system was defined in code to map these points on the grid. The point systems are slightly offset from their initial positions to reveal the information.

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-.. . --..-- / - .... . / .-- --- .-. -.. / ... . -.-. .-. . - / -... . -.-. --- -- . ... / .---- ----.
/ ..... / ...-- / .---- ---.. / ..... / ..--- ----- .-.-.-

THE ALGORITHM

There are many types of code. Within the context of this book, we're interested primarily in codes that represent a series of instructions. This type of code—often called an algorithm, procedure, or program—defines a specific process with enough detail to allow the instructions to be followed. While the word algorithm may be unfamiliar to you, its meaning is not. It's just a precise way of explaining how to do something. It is commonly used within the context of computer instructions. While most people wouldn't refer to a pattern for knitting a scarf as an algorithm, it's the same idea.

```
Row 1: (RS) *K2, P2* across
Rows 2, 3, & 4: Repeat Row 1
Row 5: (RS) *K2, P2, C8F* Repeat to last
   4 sts, K2, P2
Row 6: Repeat Row 1
Repeat rows 1-6 for desired length,
   ending with row 4
Bind off in K2, P2 pattern
```

Likewise, directions to get from one place to another, instructions for assembling kit-of-parts furniture, and many other types of guidelines are also algorithms.

```
Hiking Directions to Point Break

From the North:
- Follow the trail from the Nature
  Center
- Turn right at the Water Tower,
  walk until you see the Old Oak Tree
- Follow directions from the Old Oak
  Tree

From the South:
- From the Pinic Grove, follow the
  Botany Trail
- Turn right on the South Meadow Trail
- Turn right on the Meadow Ranch Trail,
  walk until you see the Old Oak Tree
- Follow directions from the Old Oak
  Tree

From the Old Oak Tree:
- Follow the path under the tree
- Turn right onto the Long Hill Trail
- Follow the trail until you reach
  Point Break
```

Algorithms can be defined as having four qualities. These qualities can be easily understood when defined in relation to travel directions.

There are many ways to write an algorithm. In other words, there are always multiple ways to get from point A to point B. Different people will create different sets of directions, but they all get the reader to their intended destination.

An algorithm requires assumptions. Hiking directions assume that you know how to hike, from knowing to wear the right shoes, to understanding how to follow a winding trail, to assuming that you know to bring plenty of water. Without this knowledge, the hiker may end up lost and dehydrated with blistered feet.

An algorithm includes decisions. Directions often include instructions from different starting locations. The person reading the directions will need to choose a starting position.

A complex algorithm should be broken down into modular pieces. Directions are often divided into small units to make them easy to follow. There may be separate directions for coming from the North or South, but at a certain point the directions converge and both groups follow the same instructions.

PostScript

```
gsave
        % move to the center of the page
        306 396 translate
        % repeat from 0 to 360 in increments of 12
        0 12 360 {
                pop
                % draw line from (20,0) to (200,0)
                20 0 moveto 200 0 lineto
                % rotate 12 degrees
                12 rotate
        } for
        stroke
grestore
```

Processing

```
void setup() {
  size(800, 600);
  stroke(255, 204);
  smooth();
  background(0);
}

void draw() {
  float thickness = dist(mouseX, mouseY, pmouseX, pmouseY);
  strokeWeight(thickness);
  line(mouseX, mouseY, pmouseX, pmouseY);
}
```

PostScript, 1982
The PostScript language specializes in defining pages for print output. Although PostScript files can be written in a text editor, they are typically created with a graphical user interface (GUI), which makes it easier to create and edit files but removes the more powerful features.

Processing
Processing is a programming language and environment with a focus on coding form, motion, and interaction. It simplifies and extends the Java language. This Processing program draws a line at the position of the mouse; the line thickness is calculated by the speed of the mouse.

CODE AND COMPUTERS

In computer programming, code (also called source code) is used to control the operations of a computer. It is an algorithm written in a programming language. There are thousands of programming languages, and new ones are developed every year.

Although the words and punctuation used in programming languages look different from written English words, the codes they use are intended to be read and understood by people. Specifically, computer-programming languages are designed for the way people are taught to read and write from a young age, with the precision necessary for instructing a computer. Human languages are verbose, ambiguous, and contain large vocabularies. Code is terse, has strict syntactical rules, and small vocabularies. Constructing an essay and a computer program are, however, both forms of writing, as explained in Processing: A Programming Handbook for Visual Designers and Artists:

> Writing in a human language allows the author to utilize the ambiguity of words and to have great flexibility in constructing phrases. These techniques allow multiple interpretations of a single text and give each author a unique voice. Each computer program also reveals the style of its author, but there is far less room for ambiguity."[1]

In fact, there can only be one interpretation of every piece of code. Unlike people, computers are not able to guess or interpret a meaning if it's not stated exactly. There are rules of grammar in every language, but if I misspell a wurd or two, you will still understand, but the computer won't. Fortunately (or maybe unfortunately), people are highly adaptable, and for many individuals it's easy to learn how to structure code.

Before a piece of code can be run on a computer, it must be converted from a human-readable format to a computer-executable format; these are sometimes called machine code, binaries, or executables.

This conversion transforms the code into software. It can now run (or execute) on a computer. Machine-based code is usually represented as a series of 1s and 0s:

```
0001 0001 0000 1001 0000 0001 0000
1110 0000 1001 1100 1101 0000 0101
0000 0000 1100 1001 0100 1000 0110
0101 0110 1100 0110 1100 0110 1111
0010 0001 0010 0100
```

While this series of 1s and 0s looks different from source code, it's a literal translation of the human-readable code. This translation is required for the computer to be able to follow the instructions. We think you'll agree that understanding what these sequences of 1s and 0s mean is more difficult than reading the source code. This format instructs the computer's operations at the lowest level. Each bit (1 or 0) is grouped into bytes (a sequence of eight bits) that define how the computer makes calculations and moves data into and out of the processor.

[1] Casey Reas and Ben Fry, Processing: A Programming Handbook for Visual Designers and Artists (Cambridge, MA: MIT Press, 2007), 17.

Spacewar!, 1962
This early video game simulates a space battle between two ships. Each ship can rotate left and right, thrust, and fire.

A star in the center of the screen pulls each ship into its gravitational field. Here, it's seen running on a DEC PDP-1 computer.

THINKING IN CODE

Software is a tool for the mind. While the industrial revolution produced tools to augment the body, such as the steam engine and the automobile, the information revolution is producing tools to extend the intellect. The software resources and techniques at our disposal allow us to access and process enormous quantities of information. For example, the science of genomics (the study of the genome) and the collaborative scholarship of Wikipedia were not possible without the aid of software. But using software is not only about increasing our ability to work with large volumes of information; it also encourages new and different ways of thinking.

The term procedural literacy has been used to define this potential. Michael Mateas, an associate professor in the computer science program at the University of California, Santa Cruz, describes procedural literacy as "the ability to read and write processes, to engage procedural representation and aesthetics."[2] One component of procedural literacy is the idea that programming is not strictly a technical task; it's an act of communication and a symbolic way of representing the world. A procedural representation is not static. It's a system of rules that define a space of possible forms or actions. Video game designer Ian Bogost defines this elegantly in his book Persuasive Games: The Expressive Power of Videogames:

> To write procedurally, one authors code that enforces rules to generate some kind of representation, rather than authoring the representation itself. Procedural systems generate behaviors based on rule-based models; they are machines capable of producing many outcomes, each conforming to the same overall guidelines.[3]

A video game like Spacewar! is a good example of a procedural representation. Playing the game requires understanding the spatial and kinetic relationships between two opposing spaceships. Each player controls a ship by rotating left and right and by thrusting the rocket with the goal of shooting down the other ship. To write the game, a procedurally literate individual had to break the behaviors into modules with enough detail so that they could be programmed. The primary complexity involved in creating the game is not technical; it's about choreographing all of the components into a coherent and enjoyable experience. Procedural literacy is a general way of thinking that cuts across all programming languages and even applies to thinking outside the domain of writing source code.

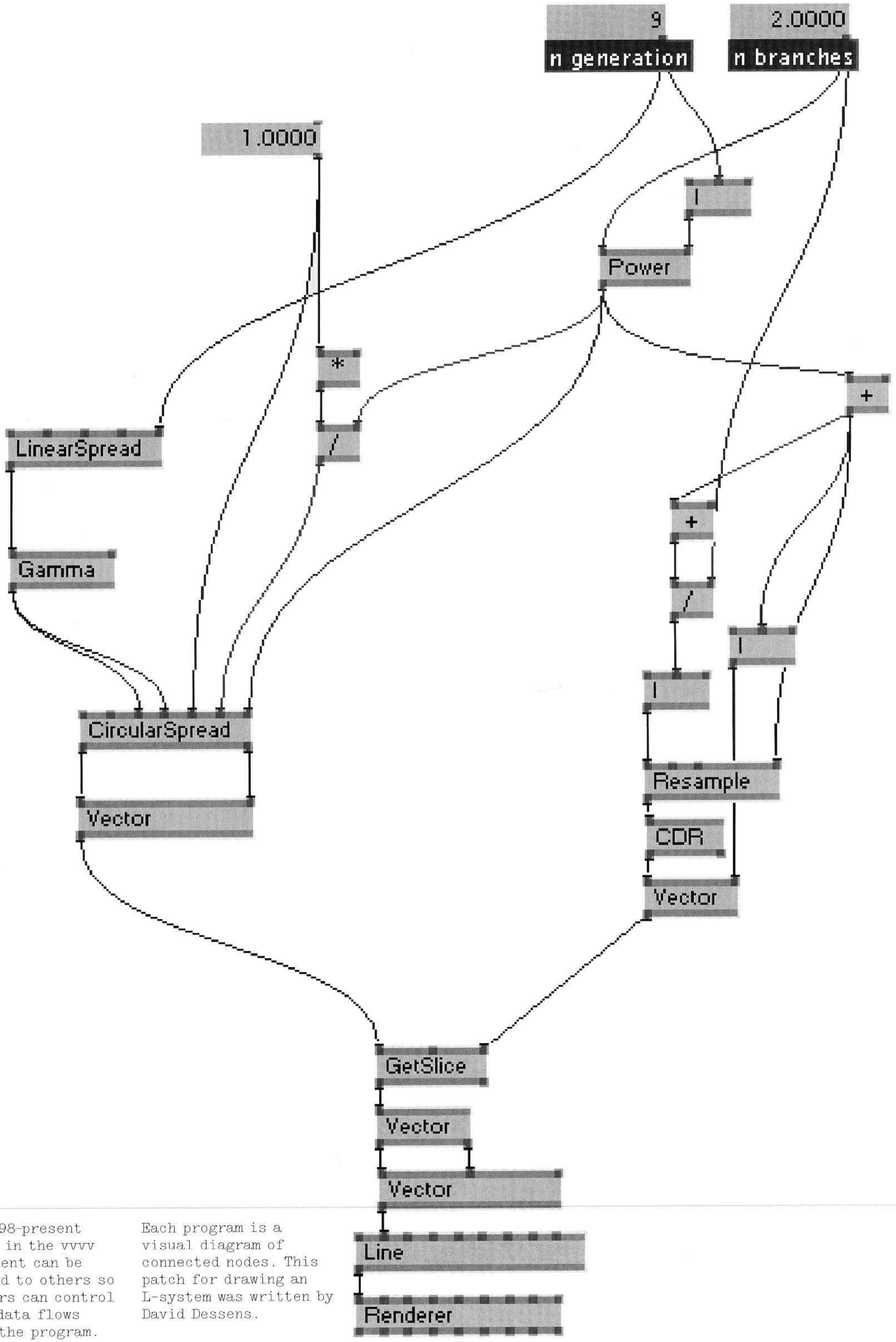
Each programming language is a different kind of material to work and think with. Just as a carpenter knows the unique properties of various woods, including oak, balsa, and pine, a person knowledgeable about software knows the unique aspects of different programming languages. A carpenter building a table will select the wood based on factors such as cost, durability, and aesthetics. A programmer selects a programming language based on the estimated budget, operating system, and aesthetics.[4] The syntax (or grammar) of each programming language structures what is possible within that language. Different programming languages encourage programmers to think about their work through the affordances (or action possibilities) and constraints of that language.

The way that a programming language encourages a certain mode of thinking can be demonstrated by comparing two very different languages: BASIC and LOGO. In each of these programming environments, drawing a triangle requires a different approach and understanding of space. BASIC relies on an established coordinate system and requires the knowledge of coordinates; lines are drawn by connecting one coordinate

[2] Michael Mateas, "Procedural Literacy: Educating the New Media Practitioner," Beyond Fun, ed. Drew Davidson (Pittsburgh, PA: ETC Press, 2008), 67.

[3] Ian Bogost, Persuasive Games: The Expressive Power of Videogames (Cambridge, MA: MIT Press, 2007), 4.

[4] There are many reasons why one programming language may be preferred over another. For example, some languages allow code to be written faster, but this is usually at the expense of how fast the code is capable of running. Some languages are more obscure than others, therefore reducing the chances that another programmer knows of the language.



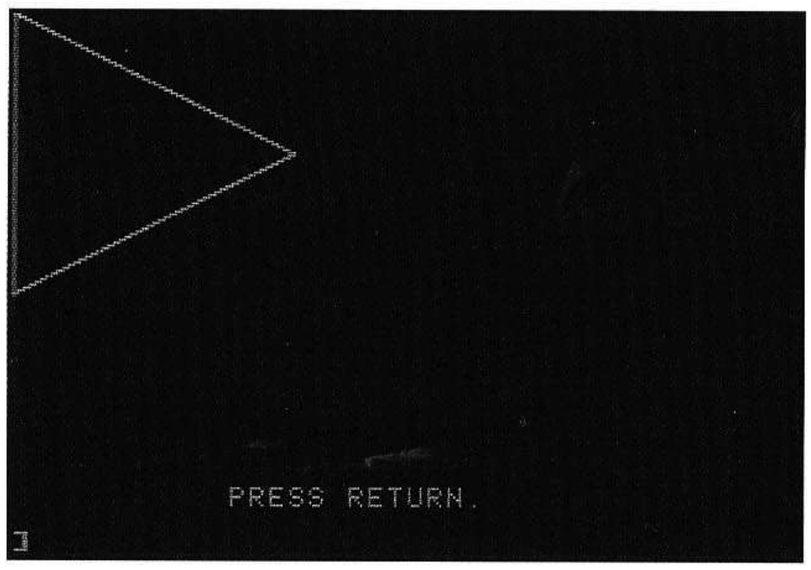
vvvv, 1998-present
Each box in the vvvv environment can be connected to others so that users can control the way data flows through the program.

Each program is a visual diagram of connected nodes. This patch for drawing an L-system was written by David Dessens.

[5] The BASIC language was designed in 1964 to teach non-technical university students how to program. Variations of it were used to teach many children and hobbyists how to program in the early era of personal computing.

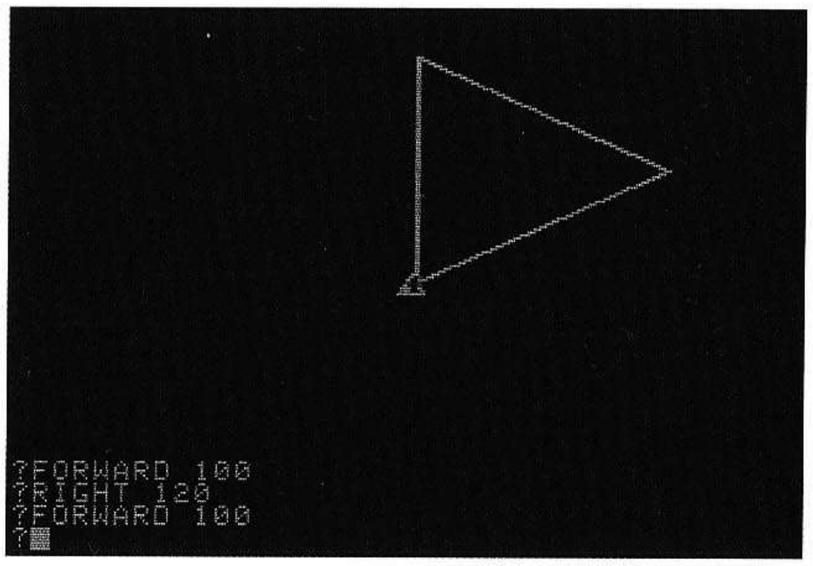
[6] In LOGO, first developed in 1967, drawings are made by moving a triangular turtle around on screen. Early versions of the language moved a robotic turtle around the room.

to another.[5] In contrast, LOGO is a language developed for young children who have not yet studied geometry; it allows the user to code a shape with only an understanding of angles and the difference between left and right. In this program, the child draws lines by directing the path of a turtle on screen. The child imagines that he or she is the turtle and moves forward, turns to the right, moves forward, turns to the right again, and then moves forward to complete the triangle.[6] Although both languages allow the same shapes to be drawn, BASIC promotes objectivity, while LOGO fosters exploration. Additionally, LOGO encourages the programmer to run the code mentally, which is a useful skill for developing procedural literacy.



BASIC

```
10 HGR : HCOLOR = 3
20 HPLOT 0, 0 TO 100, 50 TO 0, 100 TO 0, 0
30 END
```



LOGO

```
FORWARD 100
RIGHT 120
FORWARD 100
RIGHT 120
FORWARD 100
```

Visual programming languages (also called graphical programming languages) provide an alternative way of thinking with code. Writing a program with a visual programming language is similar to making a diagram instead of writing a text. Three of the most popular visual programming languages within the arts—Max, Pure Data, and vvvv—were influenced by the way sounds are constructed using patch cables attached to analog synthesizers. Virtual cables, represented as lines on screen, are used to connect programming modules together to define the software. Visual programming languages make it easy to generate and filter images and sounds, but they are often too cumbersome for writing long, complicated programs. For example, the Max program is written in the text programming language C++, not a visual programming language.

PROPOSAL FOR WALL DRAWING, INFORMATION SHOW

Within four adjacent squares,

each 4' by 4',

four draftsmen will be employed

at $4.00/hour

for four hours a day

and for four days to draw straight lines

4 inches long

using four different colored pencils;

9H black, red, yellow and blue.

Each draftsmen will use the same color throughout

the four day period,

working on a different square each day.

Proposal for a Wall Drawing, Information Show,
by Sol LeWitt, 1970
The instructions for LeWitt's drawings are executed by a skilled draftsperson who interprets the instructions during the drawing process.

CODE AND THE ARTS

ENIAC computers. ENTAC cost almost $500,000 and weighed over thirty tons. This U. S. Army photo shows two of the computer's programmers.

Beginning in the 1940s, code was developed to assist with work in the fields of science and engineering. Seymour Papert, a pioneer in researching computers and creativity, explains the situation at the time:

> The world was at war. Complex calculations had to be done under time pressures not normally felt by mathematicians: numerical calculations related to the design and use of weapons; logical manipulations to break ever more complex codes before information became old news....It's unlikely that they gave even a passing thought to making computers user-friendly to people with softer styles than theirs.[7]

The decisions made about computers and programming languages since that time have, along with other factors, hindered the synthesis of software and the arts. It's an unfortunate fact that many languages used within the arts were not originally designed for those areas. The software desires of designers, architects, and artists are often different from those of scientists, mathematicians, and engineers. The technical skill required to create visual form with the most dominant languages, such as C++ and Java, often takes years to acquire.

An alternative way of considering code is revealed through the work of artists who in the 1950s and 1960s began to experiment with software and themes related to software, such as dematerialization and system aesthetics. These explorations were first presented to the general public in the exhibition Cybernetic Serendipity, held at the Institute of Contemporary Arts in London in 1968; as well as in the shows Software—Information Technology: Its New Meaning for Art, held at the Jewish Museum in New York in 1970; and Information, held at the Museum of Modern Art (MoMA) in 1970. The curator of the Software exhibit, Jack Burnham, described the works on view as "art that is transactional in that they deal with underlying structures of communication and energy exchange."[8] Among the works on view, Hans Haacke's ambitious Visitor's Profile sought to reveal the elite social status of the museum's patrons as a form of critique of the art world. Using a computer interface, it tabulated personal information solicited from visitors. Les Levine exhibited Systems Burn-off X Residual Software, a collection of photographs discussed within the context of software. Levine claimed that images are hardware, and that information about the images is software. He wrote the provocative statement, "All activities which have no connection with object or material mass are the result of software."[9] Similar to Levine's piece, many of the works featured in the Information exhibition at MoMA were characterized as "conceptual art."

At the same time, artists and musicians—including Mel Bochner, John Cage, Allan Kaprow, Sol LeWitt, Yoko Ono, and La Monte Young—created a different type of conceptual and process-based art by writing instructions and creating diagrams as a form of art. For example, instead of physically making the drawings, LeWitt encoded his ideas as instructions that were used to produce drawings. He wrote a series of rules to define the task of a draftsperson, but the rules are open for interpretation; therefore many different results are possible. Ono's artworks, such as Cloud Piece, are instructions for life; each short text asks the reader to perform actions like laughing, drawing, sitting, or flying. Like programmers, these creators all wrote instructions for actions. Through their use of English as the programming language, they introduced ambiguity, interpretation, and even contradiction.

Simultaneous with these conceptually focused explorations, engineers were creating programming systems for the creation of visual images. In 1963 at Bell Laboratories, Kenneth C. Knowlton wrote BEFLIX, a specialized program for constructing animation, which he used

[7] Seymour Papert, The Children's Machine: Rethinking School in the Age of the Computer (New York: Basic Books, 1994), 157.

[8] Jack Burnham, Software—Information Technology: Its New Meaning for Art (New York: The Jewish Museum, 1970), 10.

[9] The New Media Reader (Cambridge, MA: MIT Press, 2003), 255.

CLOUD PIECE
Imagine the clouds dripping. Dig a hole in your garden to put them in.

1963 Spring

Cloud Piece, by Yoko Ono, 1963
Ono's artwork is the instructions. The reader imagines or performs the actions.

BASIC

```
10 DEFINT A-Z' DRAW100SQ
20 CLS
30 MOVE$="!AX"
40 DRW$="!AY"
50 OPEN "COM1:1200,0,7,1" AS #1
60 PRINT #1, "!AE";
70 FOR ROW=0 TO 90 STEP 10
80   FOR CLM=0 TO 90 STEP 10
90       GOSUB 310
100      PRINT #1, MOVE$+STR$(ROW)+STR$(CLM)
110      GOSUB 310
120      PRINT #1, DRW$+STR$(ROW+10)+STR$(CLM)
130      GOSUB 310
140      PRINT #1, DRW$+STR$(ROW+10)+STR$(CLM+10)
150      GOSUB 310
160      PRINT #1, DRW$+STR$(ROW)+STR$(CLM+10)
170      GOSUB 310
180      PRINT #1, DRW$+STR$(ROW)+STR$(CLM)+";"
190 NEXT CLM
200 NEXT ROW
210 PRINT
220 GOTO 70
230 '
240 '
250 '
260 '
270 'XON/XOFF subroutine
```

Hypertalk

```
on mouseUp
  put "100,100" into pos
  repeat with x = 1 to the number of card buttons
    set the location of card button x to pos
    add 15 to item 1 of pos
  end repeat
end mouseUp
```

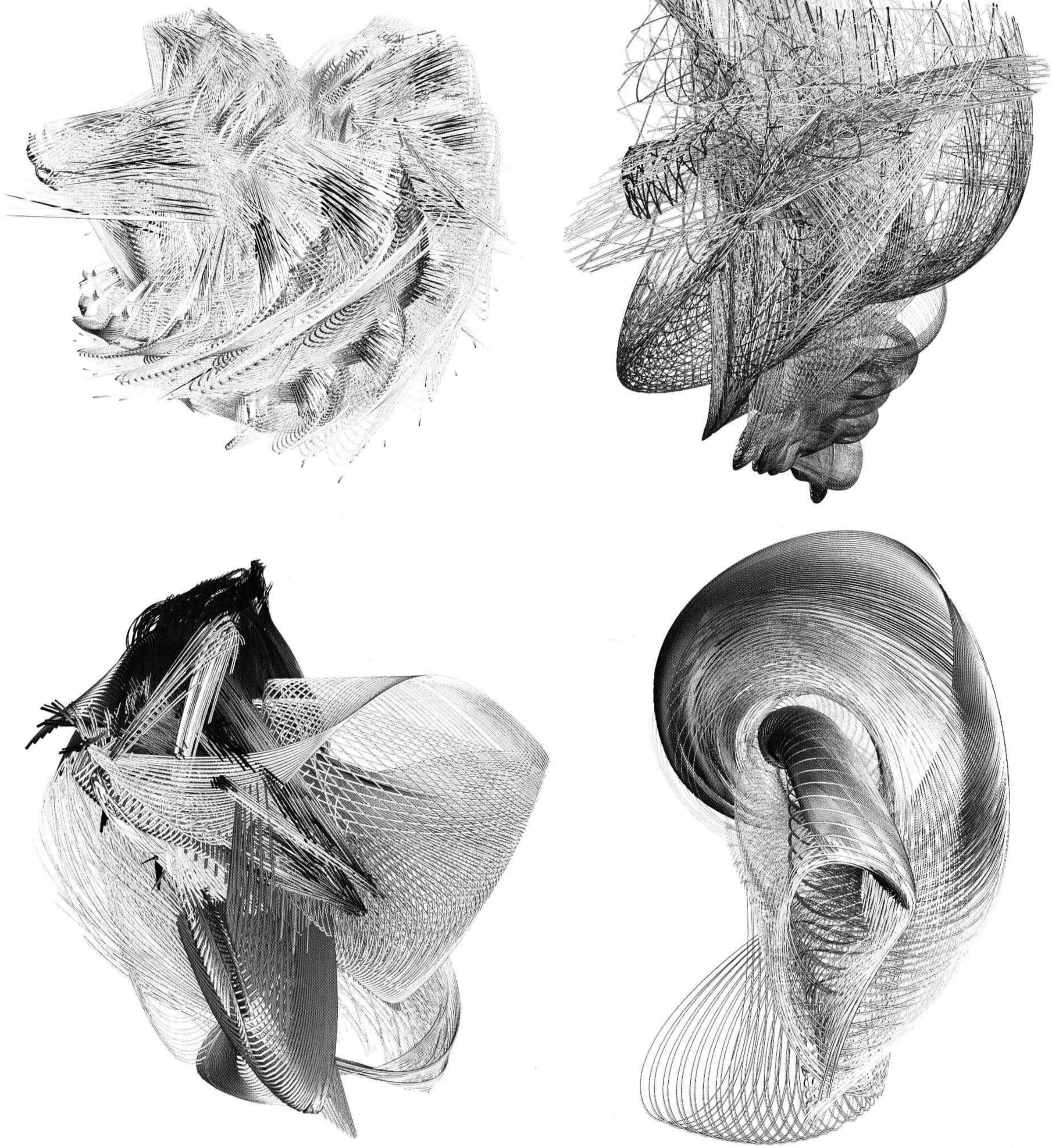
BASIC, 1964
This program draws a grid of 100 squares. It demonstrates how the BASIC language can be used to control a mechanical drawing arm known as a plotter.

HyperTalk, 1987
The HyperTalk language was written to be easy for beginners. It is more similar to English than most other programming languages.

to create early computer films in collaboration with artists Stan VanDerBeek and Lillian F. Schwartz. The computer-generated film, Permutations, was created in 1966 by John Whitney Sr. using GRAF, a programming library developed by Dr. Jack Citron of IBM. Both BEFLIX and GRAF were built on top of the language Fortran. From these and other early explorations, the development of programming languages written expressly for the arts has continued to gain momentum, building toward the current frenzy of activity.

In the 1980s, the proliferation of the personal computer allowed programming to reach a wider audience, which in turn led to the development of HyperTalk, a programming language for Apple's unique HyperCard application (an early hypermedia system). The related Lingo language was developed for the first release of Adobe Director in 1988 (formerly Macromedia Director, and before that MacroMind Director). Lingo was the first programming language used by many designers and artists in the era leading up to the development of the World Wide Web in the early 1990s. The early days of the web fostered intense graphic programming exploration, primarily channeled through the ActionScript language. The rise of programming literacy within the arts and architecture communities has led to the current proliferation of programming options; many are featured within this book.

The influence of code is not limited to the screen and projected image. It is also felt in physical space. Code is used to control elements of products, architecture, and installations. It is used to create files that are output as prints and made physical through computer-controlled machines that cut and assemble materials, including wood, metal, and plastic. Code is rapidly moving outside the boundaries of the screen and is starting to control more aspects of the physical world. There are examples of this in the Producing Form section of "Form and Computers" (p. 37), as well as throughout this book.



Strand Tower,
by Testa & Weiser,
Architects, 2006
Strand Tower precursors were generated using a purpose-built software (Weaver) and coded through an iterative templating process. Specific fiber behaviors or traits such as fraying, bundling, knitting, and bias patterning are coded into the design. Fiber agency and affiliation is more informal and multidimensional than conventional woven patterns.

WHY CODE?

The use of software in the arts can be separated into two categories: production and conception. In the first category, the computer is used to produce a preconceived form; in the second, the computer participates in the development of the form. Within the context of this book, we're primarily interested in the latter. (It is important to note that this distinction does not imply a value judgment but does impact the types of forms that are created.)

Using the computer to reduce the amount of time needed to create a complex, repetitive composition was often the motivation for the early adoption of software and its integration into the creative process. This was especially important in the field of animation, where subtle changes had to be repeated thousands of times to create the illusion of motion; however, this alluring technical benefit has had a profound effect. If initial production takes one-tenth the time that it would take to execute the work by hand, then the artist can create ten versions in the same amount of time. This way, many versions can be created and the best chosen. Efficiency facilitates the creative process by enabling more time for exploration as less time is needed for the final production. Eventually the computer came to be understood as more than just a production tool. People started to see it as, in the words of computer graphics pioneer A. Michael Noll, "an intellectual and active creative partner that, when fully exploited, could be used to produce wholly new art forms and possibly new aesthetic experiences."[10]

Often, to realize a new or unique vision requires that artists and designers exceed the limitations of existing tools. Proprietary software products are general tools designed for the production of specific types of forms. If you are already using software for your work, why constrain yourself to the expectations of a software company or another programmer? To go beyond these limitations, it is necessary to customize existing applications through programming or to write your own software.

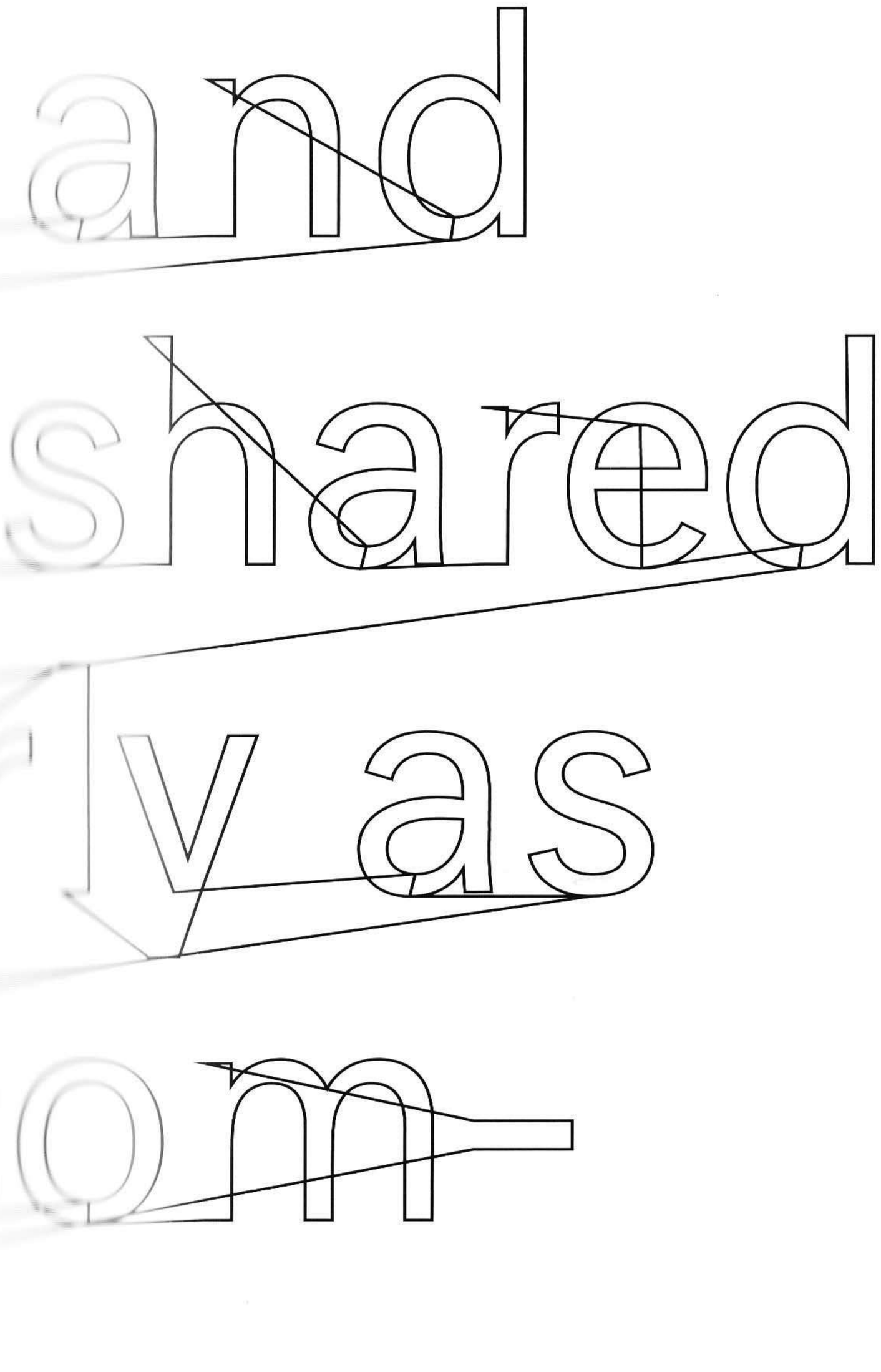
Each existing form of media—whether drawing, printing, or television—is capable of assuming new qualities of expression. For example, video games demonstrate many of the distinct characteristics of software. If you've ever succumbed to the pleasures of a great game (we know some of you have; if you haven't, then what are you waiting for?), you already know that the emotions experienced while playing are different than those felt while watching a film or looking at a drawing. Games can be physically engrossing and socially engaging, and they can sustain intense fascination over a period of months.

In reference to the emerging media of his time, theorist Marshall McLuhan wrote, "Today we're beginning to realize that the new media aren't just mechanical gimmicks for creating worlds of illusion, but new languages with new and unique powers of expression."[11] Writing code is one gateway for realizing these new forms. Learning to program and to engage the computer more directly with code opens the possibility of not only creating tools, but also systems, environments, and entirely new modes of expression. It is here that the computer ceases to be a tool and instead becomes a medium. We hope the following chapters will provide evidence for you to draw your own conclusions about the potential of software in the visual arts.

[10] Jasia Reichardt, Cybernetics, Art, and Ideas (New York: New York Graphic Society, 1971), 143.

[11] Edmund Snow Carpenter and Marshall McLuhan, Explorations in Communication: An Anthology (Boston, MA: Beacon Press, 1960), 2.

Computers form have a history near old as the puter itself



Even before the advent of the modern personal computer in the late 1970s, "computing machines" were used by designers in the aerospace and automotive industries to perform complex calculations, and by scientists to develop intricate simulations of the physical world. The advantages initially offered by computers came in the form of efficiency and precision. Exploring new possibilities was not a priority; more importantly, they were used to perform calculations in a fraction of the time. The efficiency offered by the computer extended to the production of technical blueprints and allowed complex geometric drawings to be created far more quickly than with conventional techniques. Today, computers are still used as accurate drafting machines, but new ways of using them have opened new territories.

These letters convey the way computers interpret and display typography as a series of points, lines, and curves. For example, Adobe's PostScript language renders typography with three commands: moveTo, lineTo, and curveTo. To create this typeface, the moveTo command was removed, rendering the letters as a continuous line.

DRAWING WITH COMPUTERS

In 1963, Ivan Sutherland pioneered the graphical user interface (GUI) with his Sketchpad; this initiated a paradigm shift in how people interacted with computers. Sketchpad's interface consisted of a set of switches and dials, a display, and a light pen—a device used to draw directly on the screen. By pressing switches on a control panel while drawing, the user was able to instruct the computer to interpret the movement of the pen in different ways. Each time the pen touched the screen, a new line was added between the last point and the new one. In this way, the user could draw simple polygons. Another switch was for drawing circles, and another for arcs, etc.; this allowed for fairly sophisticated drawing. Sketchpad gave designers a way to directly manipulate objects on screen without having to first write a numerical, code-based representation of those objects. After the objects were made, they could be duplicated, moved, scaled, and rotated to create new compositions.

Sketchpad was much more than a crude analog of paper and pen; it was a fundamentally new way to design. When drawing in Sketchpad, the designer could make use of constraints in order to form new relationships between elements and to force them to behave in specific ways, for example: snapping the end points of line segments to other end points or lines, keeping lines parallel, or forcing them to have the same length. The user could also create more sophisticated constraints, for example: a constraint could be designed to simulate the load-bearing properties of a bridge.

With the first computer-aided design (CAD) systems, Sutherland's innovations left the lab and entered industry. The software used within the fields of engineering and architecture lacked many of his innovations and served as little more than an analog for pen and paper. They allowed designers to draw using mathematical lines and curves rather than T-squares, drawing boards, and pencils. These "high-powered drafting machines" were hailed for their efficiency, speed, and productivity.[1] Drawings that would have taken days could now be done in hours.

Even in this capacity, drawings made on the computer were considered a poor substitute for hand-drawn sketches and diagrams. Some people felt that the drawings produced by CAD machines were cold and overly technical, preferring the "slightly wobbly line work and imprecise endings of hand-drawn lines."[2] There were other obstacles to integrating CAD systems into industry. Some felt that they presented a new temptation—to never stop editing a drawing or set of plans; others believed that there were too many assumptions in the software that restricted the design possibilities.[3] As a result of these and other problems, computers were considered insufficient for the conceptual stage of design and were often used only at the end of the creative process. The advantages focused primarily on saving the designer's time and increasing productivity.

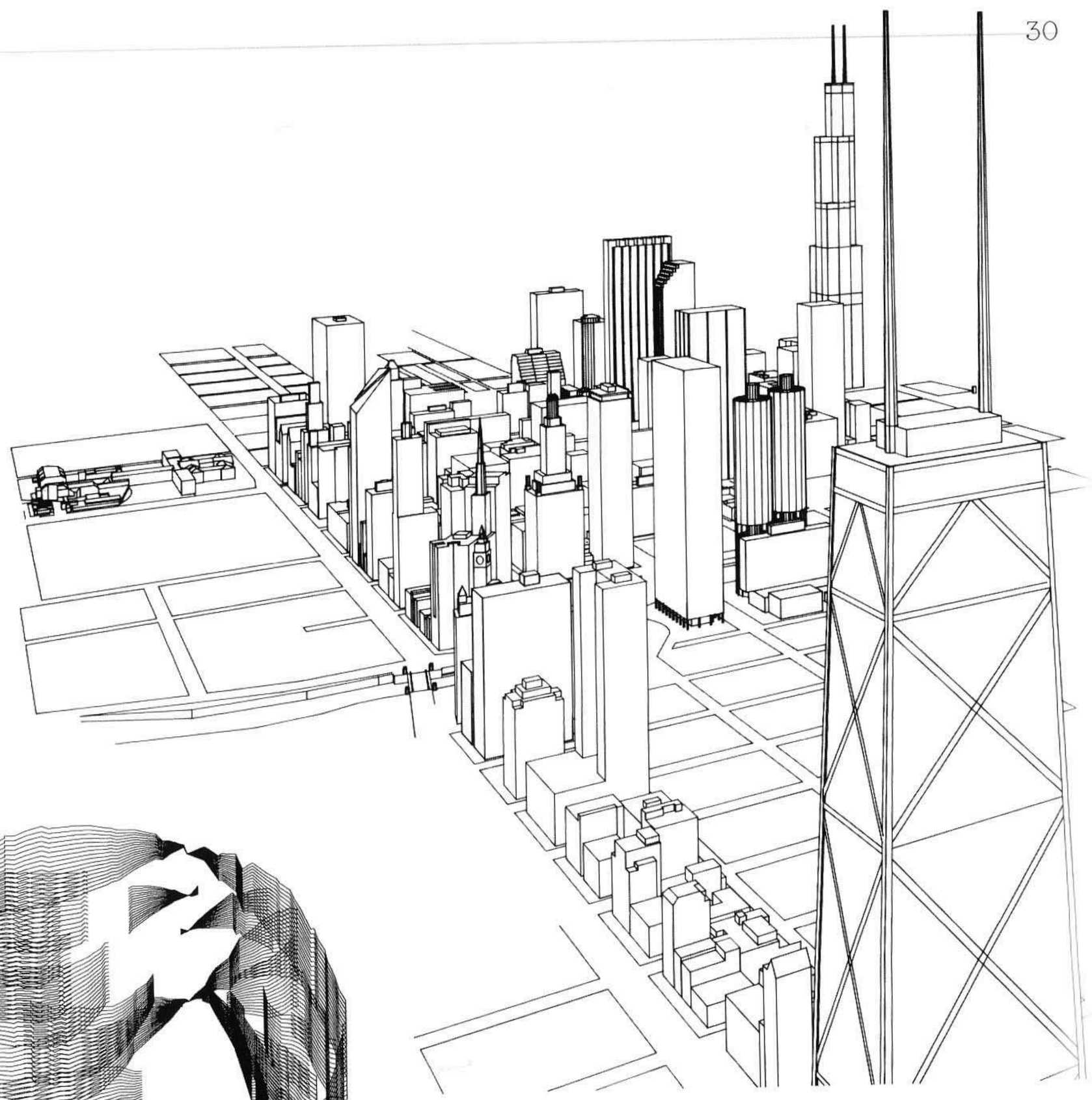
Within the design industry, however, the field that has been most profoundly transformed by the use of computers is graphic design. The proliferation of the personal computer—and, later on, the laser printer—laid the foundation for desktop publishing. Apple's LaserWriter could reproduce typography and images at much higher resolutions than previous home and small-business printing technologies. Perhaps more importantly, the LaserWriter included PostScript, which made it possible to use a wide array of fonts in the design, because they were now treated as software as opposed to physical metal type or transferrable lettering. This opened the door for designers to create and distribute their own typefaces and to have more control over the final typesetting. These technologies enabled vibrant activity and widespread innovation within the field of visual design in the 1980s and 1990s, ranging from the fonts of

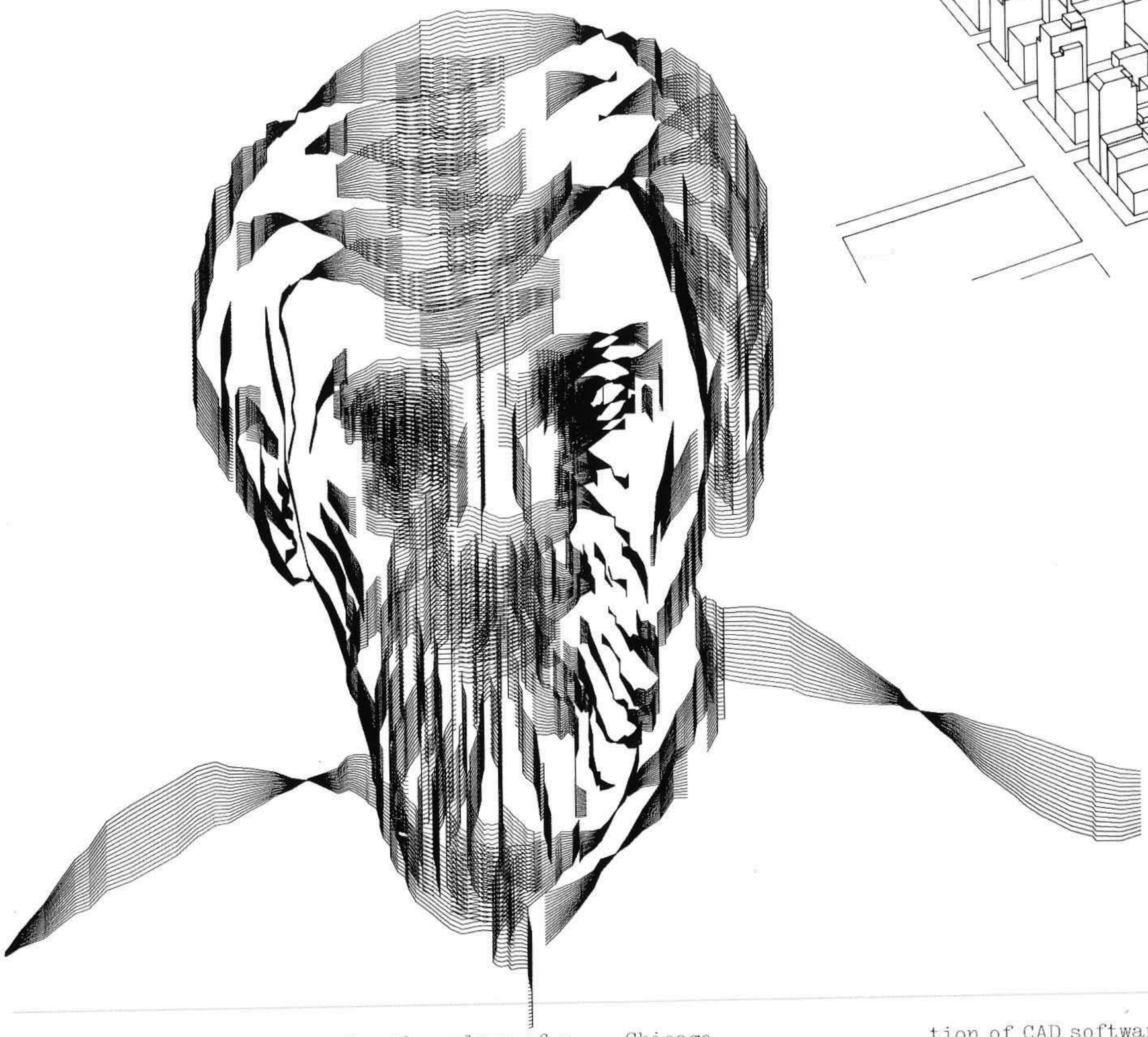
[1] Frank Hoffmann, Cybernetic Serendipity: The Computer and the Arts (New York: Praeger, 1968), 67.

[2] William John Mitchell and Malcolm McCullough, Digital Design Media: A Handbook for Architects and Design Professionals (New York: John Wiley & Sons Inc., 1991), 129.

[3] Christopher Woodward and Jaki Howes, Computing in Architectural Practice (London: Spon Press, 1998), 92.

Sketchpad,
Ivan Sutherland, 1963
With Sketchpad, users drew directly on the screen using a light pen. The behavior of the pen was controlled by a group of switches, buttons, and knobs. This image shows Sutherland using his software on a TX-2 computer.





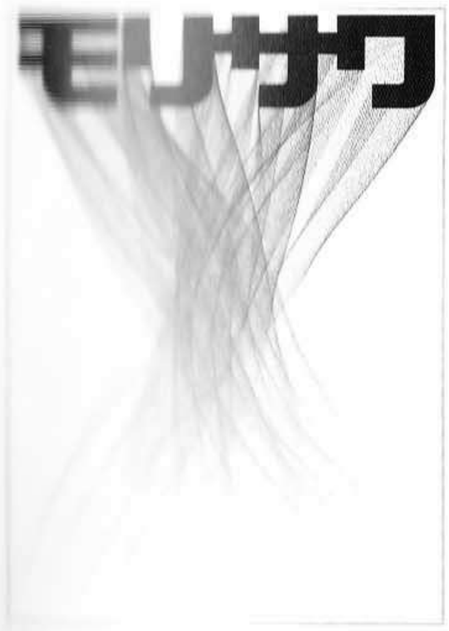
Sine Curve Man,
by Charles A. Csuri,
1967
The geometry for this plotter drawing was created by distorting an image of a face using the values of a sine wave. Like much of Csuri's work, code was manipulated to create an abstraction of the human form.

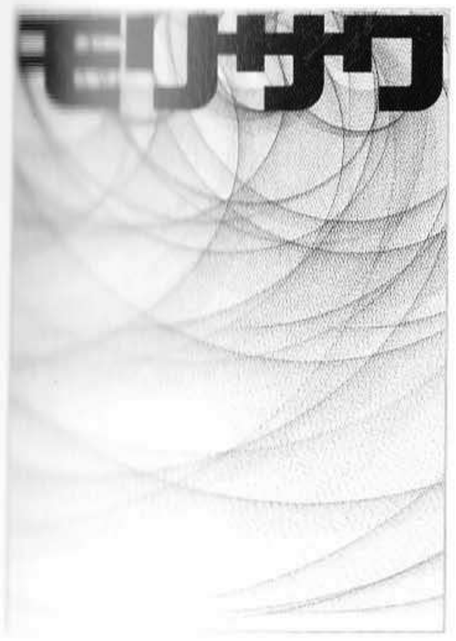
Chicago,
by Skidmore, Owings & Merrill (SOM), 1980
With the rise in computing power and the increasing sophistication of CAD software, it became possible to model entire cities. SOM created a wireframe model of downtown Chicago to give viewers a feel for the city's form and massing of buildings.

Emigre and FUSE, to the radical work of April Greiman, David Carson, and many others.

With PostScript solidifying its place as the de facto standard, Adobe introduced Illustrator as its new visual development tool. With Illustrator, anyone could draw and lay out text and graphics without having to know the intricacies of the PostScript language. Eventually Illustrator, along with Adobe's Photoshop and InDesign applications, became nearly ubiquitous among graphic designers. Interestingly, all three of these applications have introduced scripting languages in recent years that allow users to extend the tools by writing code.

Following the birth of the Internet and other networking technologies, the computer increasingly became a tool for collaboration. Global computer networks called into question the need for centralized offices, in favor of an organization consisting of individuals spread around the globe. This has had a massive impact on the open-source software movement, where large and sophisticated applications are often built by a loose collection of individuals united by a shared interest. These new ways of working also had an impact on the way forms were created. In a distributed environment, different individuals work simultaneously on different parts of the same piece, seeing the whole only after the parts are stitched back together.





Having begun to represent objects and, with the aid of Sketchpad, relationships and behaviors, the real potential for the role of computers in design started to assert itself. If computers could be used to model what we know, then perhaps we could also use them to simulate what we don't know. French architect and philosopher Bernard Cache summed up the history of CAD systems by saying they "have certainly increased the productivity of the idea, but fundamentally they offer no advances over the work done by hand. Now, we can envisage second-generation systems in which objects are no longer designed but calculated."[4]

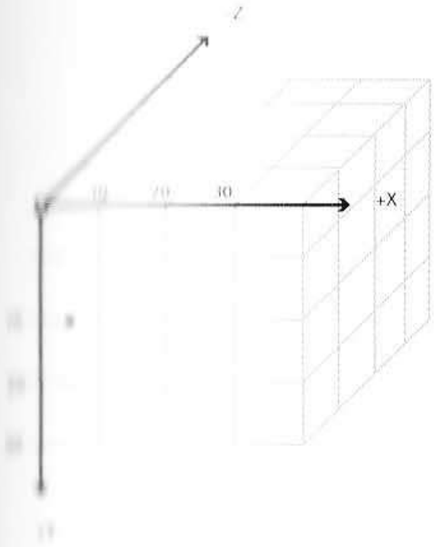
[4] Bernard Cache, Earth Moves: The Furnishing of Territories (Writing Architecture) (Cambridge, MA: MIT Press, 1995), 88.

Morisawa Posters, by John Maeda, 1996
Rather than rely on existing software tools, Maeda wrote his own code to manipulate typographic form. This allowed him to explore a unique graphic language for the ten posters he created for Morisawa. Each poster performs an algorithm to transform the logo of the company.

Electronic Abstraction 6, by Ben F. Laposky, 1952 Laposky used an oscilloscope—a technical device for viewing changes in voltage—to produce his abstract images. Starting in the early 1950s, he refined a process of modulating electronic waveforms to produce stunning and diverse images.

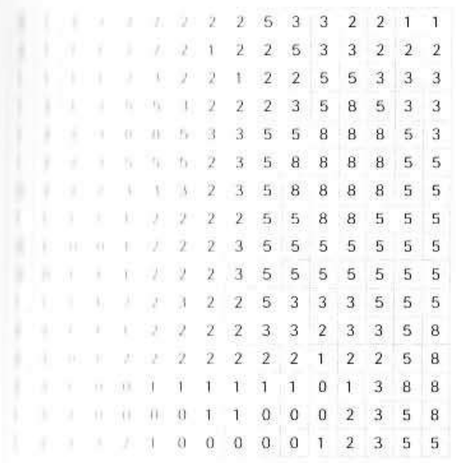
CONTROLLING FORM

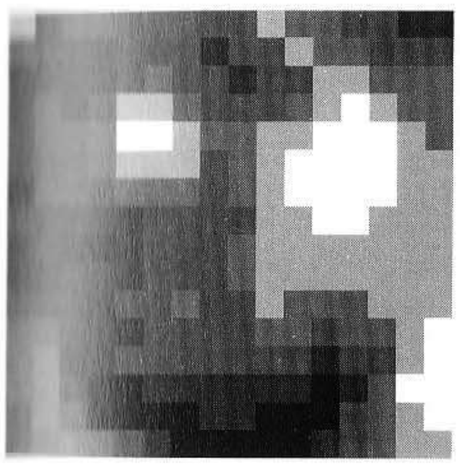
Understanding the ways that code is used in the production and creation of form requires a general knowledge of how form is manipulated by the computer. Outside the computer, form itself is physical and intuitive—it is the curve of a line on a page, the texture of paint, or the slope of a hillside. To manipulate form in the world, we don't need to understand the mathematics behind how things are put together, and we can specify where things are in relative terms, like "over there" or "next to me." If a piece of clay is close enough to touch, then it can be directly molded and shaped. In contrast, computers rely on the ability to specify everything in numerical terms.



COORDINATES

The computer needs to know the position of every mark it draws, either on the screen or with a printer. To do this, we typically use Cartesian coordinates. If you imagine laying a large piece of graph paper over the screen, an x-axis runs from left to right, and a y-axis goes from top to bottom. These axes allow us to specify a precise position on the grid using a pair of numbers, normally the x-value followed by the y-value. For example, a point at (5, 10) is 5 lines from the left edge of the screen, and 10 lines down from the top.





SHAPE

Placing a piece of graph paper on the screen is more than just a metaphor. The screen is, in fact, composed of a grid of points called pixels. One way to draw a form on-screen is to lay the grid of pixels over an image of the form and measure the color value at each pixel in the grid. This method of representing an image makes what is called a raster image.

A raster image, which is sometimes referred to as a bitmap, is a complete description of what is shown on-screen at a given resolution. Resolution refers to how many points make up an image for a given physical size. If an image has a resolution of 800 × 600 pixels, there is a total of 480,000 pixels in the image, therefore requiring 480,000 numbers, with each one representing the color of one pixel. Resolution can be thought of as an image composed of tiles. There are two ways to make a tiled image look better: make the tiles smaller or move farther away from the image. On a computer, the two are related. Since the screen has a set size, lowering the resolution is like increasing the size of the tiles; alternately, you can keep the screen resolution constant and make the image smaller on-screen.

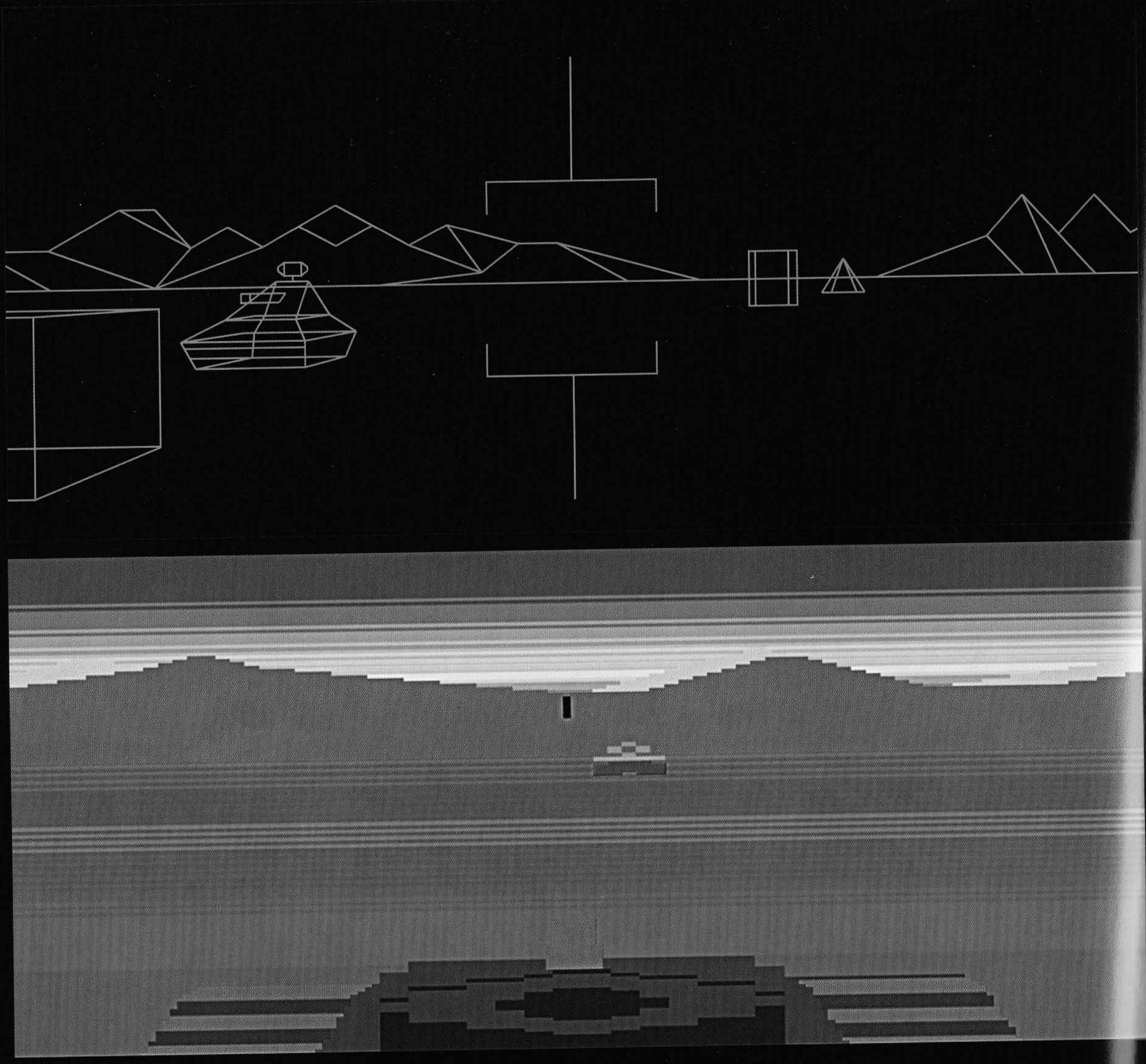
As explained earlier, an image's form, color, and shape must be converted to numbers in order for it to be useable on a computer. As a result, these qualities often lose the continuity that we have become accustomed to in the world. Every image on the computer has a resolution, or a width-by-height measurement, in pixels, but how many pixels are enough? The ever-increasing number of megapixels available in digital cameras and the popularity of high-definition television (HDTV) suggest that there are never enough.

A megapixel is one million pixels. It refers to the total number of pixels in an image. In other words, the width of the image in pixels is multiplied by the height of the image in pixels so that an image measuring 2,048 by 1,536 is said to have 3.1 megapixels (2,048 × 1,536 = 3,145,728). Our eyes see a continuous analog stream of colors. The best we can do to represent that digitally is to increase the resolution to fool the eye into thinking that the image is continuous. But the fact remains that this is just a simulation, and it requires a lot of processing and memory to store enough information for the illusion to hold.

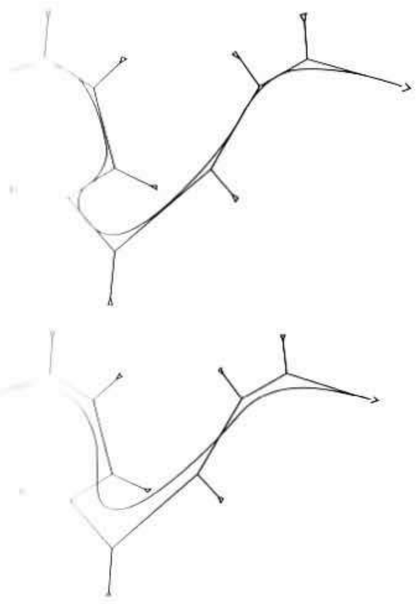
Raster graphics are an ideal way to store and manipulate photographic imagery, but they suffer from the confines of the resolution at which they are created. If we scale a bitmap image up to make it larger, the blocks of color must also be enlarged. This makes raster graphics a less than ideal way

Coordinates
Most computer graphics use a square grid with a horizontal x-axis and a vertical y-axis. An additional x-axis is used to draw 3-D forms.

Raster
A raster is a grid of pixels. The color of each pixel is controlled to create an image.

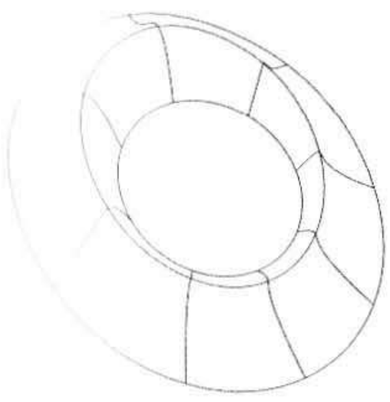


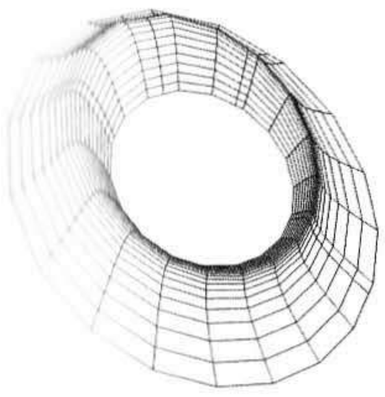
BattleZone,
Atari, 1980 and 1983
The graphics in the arcade version of BattleZone were drawn with vector lines on an oscilloscope. The Atari 2600 home version of BattleZone used raster graphics, because it was displayed on a television set. It was more colorful, but the graphics were lower in resolution.



to store drafting or drawing information that often needs to be moved, scale, rotated, and reworked. For this, there are vector graphics.

Vectors graphics use the same Cartesian grid as bitmaps, but instead of storing the value for every pixel in the image, they store a list of equations that define the image. This is ideal for drafting and precision drawing, where any shape available to geometry—lines, circles, rectangles, and curves—can be combined to create a composition. Because the forms are described using geometric equations, they can be scaled and transformed easily and without losing detail. The scalable nature of vector graphics makes them an essential element in the production of printed matter. A printer may have a resolution many times greater than that of a monitor, and without vector graphics it would be very difficult to create smooth lines and crisp type. Furthermore, fabrication technologies, such as laser cutting and computer numerical controlled (CNC) milling rely on the detail and precision offered by vectors.





Objects in three-dimensional modeling software, such as Rhinoceros and Autodesk Maya, are commonly represented using vectors. In addition to the two-dimensional curves, points, and lines we are familiar with, these applications allow designers to create a number of different objects, such as meshes, NURBS (Non-Uniform Rational B-Splines), and subdivision surfaces.

COLOR

Unlike paint, color on-screen is additive, meaning that the more colors you add together, the closer you get to white. Additive color systems use the primary colors red, green, and blue to create the colors we see on-screen. The common 24-bit color depth allows each base color to be assigned a value from 0 to 255, giving a total of 16,777,216 possible colors—that's more than can be distinguished by the naked eye. For example, pure yellow has a red value of 255, a green value of 255, and a blue value of 0. Light brown has a red value of 140, a green value of 98, and a blue value of 0. Changing this blue value to 255 produces an electric purple.

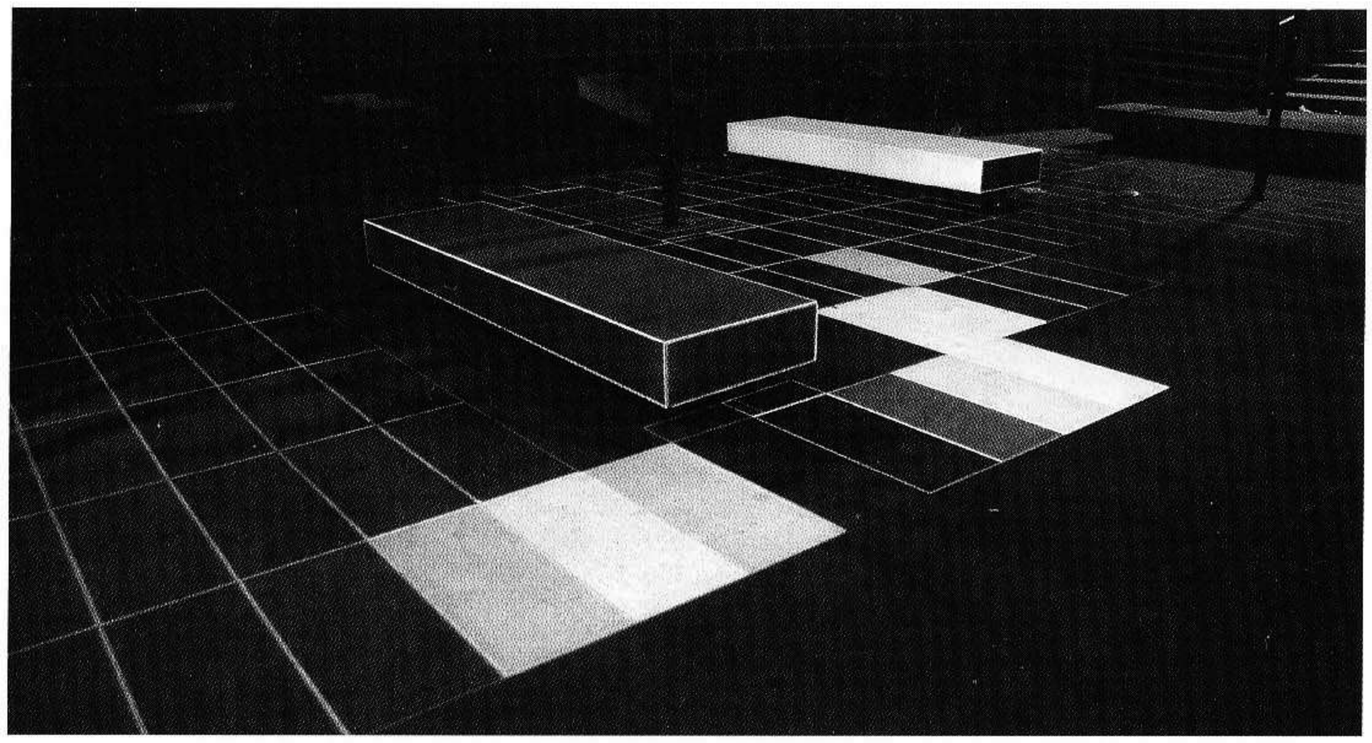
REALISM

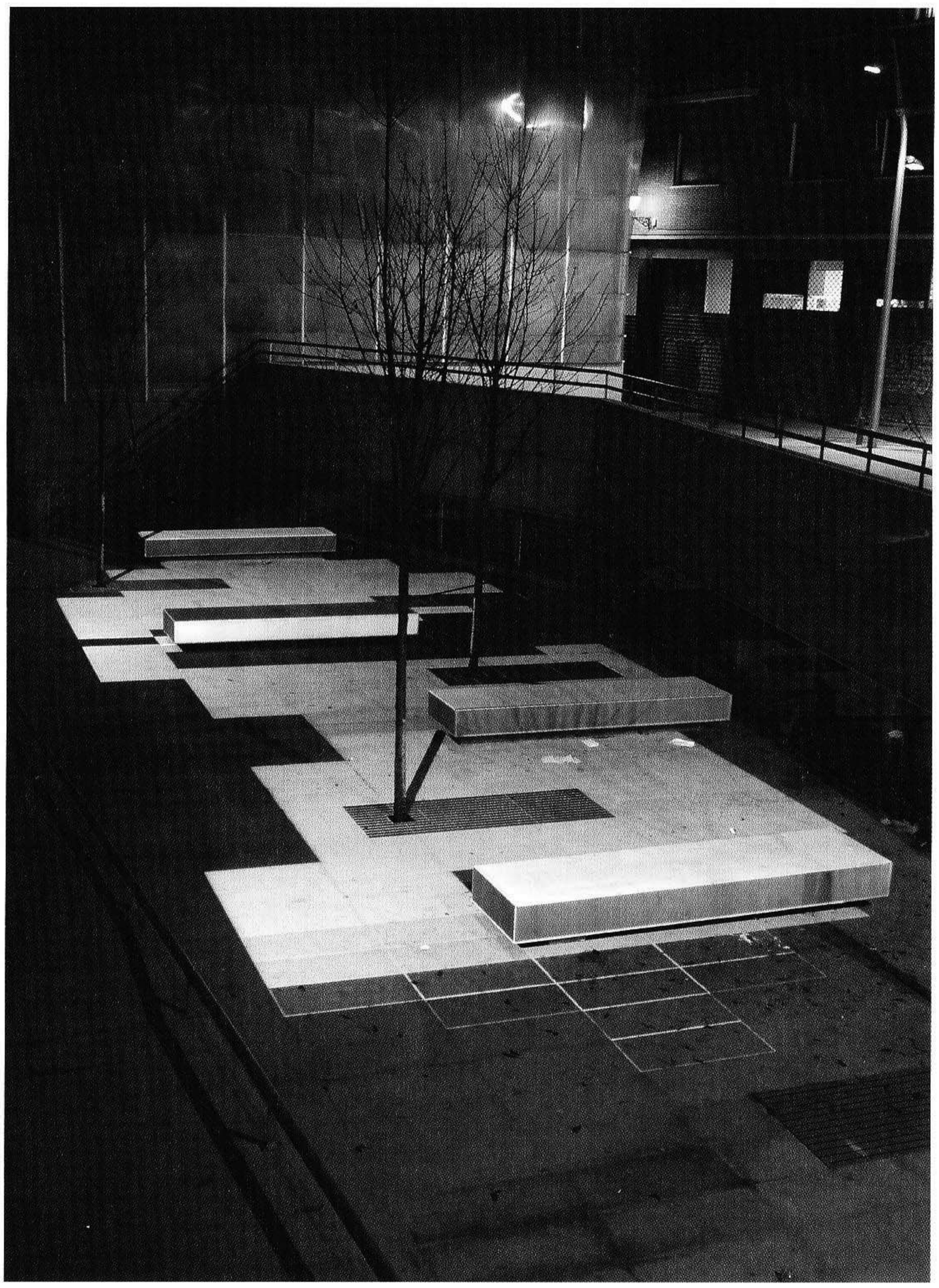
Like the history of European painting until the end of the nineteenth century, the history of computer graphics has prioritized a realistic depiction of the natural world. The bridge between the crude wireframe engineering models produced in the 1960s and the naturalistic form, lighting, and textures of today's rendering tools has spanned over thirty years of focused research. (This transition can be traced, in part, using the dates of the work included in this book.) One of the first effects mastered was the illusion of a third dimension rendered on a flat screen. After that came the hidden-surface algorithm for hiding the lines at the back of a model and making it appear solid rather than composed of wire. Similar to how shading in a pencil drawing helps produce depth and continuity, shading algorithms were developed to create the appearance of smooth surfaces from the hard edges of flat polygon models. Over time, new and better techniques were developed to accurately depict textures and, more importantly, light reflecting off surfaces. Beyond these algorithms, a mathematical model of a camera is at the core of most rendered software images. The parameters of these models imitate those of real lenses, such as focal length, field of view, and aperture. When the image is rendered, the calculated lens optics determines how near or distant the objects appear and distorts the geometry to create perspective. The development of ever-more-realistic rendering techniques continues, but in recent years there's been a renewed interest in non-photorealistic rendering. These techniques make geometric models look as if they were painted or built from clay.

Splines
A spline is a type of curve with a shape defined by the position of control vertices. Splines have a dimension of continuity that affects how close the curve fits to each vertex.

Advanced Geometry
Surfaces can be mathematically defined in a number of different ways. A triangle mesh is a set of connected triangles; NURBS are smooth surfaces created with splines; and subdivision surfaces use recursion to make a fine mesh to represent curvature.

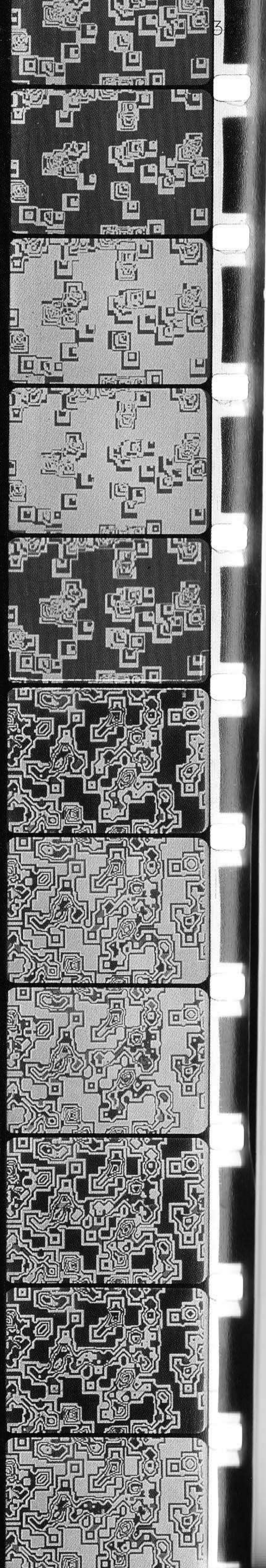
Toward realism
The history of algorithms in computer graphics follows a path toward realism, from coarse outlines to smooth, solid surfaces.





Entramado,
by Pablo Valbuena, 2008
Valbuena combines virtual 3-D models with precisely placed projectors to augment physical space with a closely choreographed sequence of light, which appears to follow and modify the space itself.

Pixillation,
by Lillian Schwartz, 1970
Schwartz worked with Ken Knowlton at Bell Labs to produce the computer-generated sequences of this abstract film.

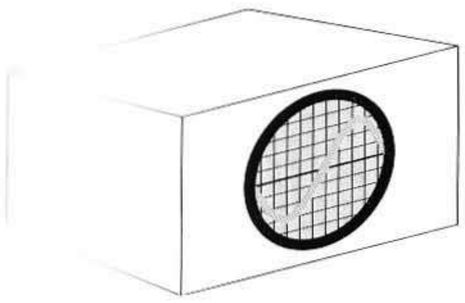


PRODUCING FORM

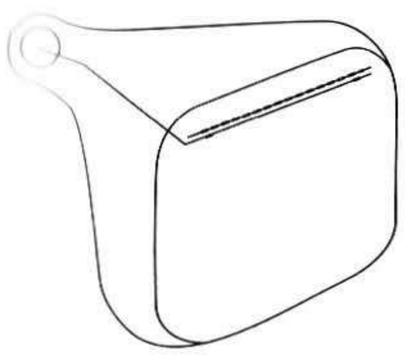
An important aspect of the relationship between form and code is how the abstract, immaterial, and imperceptible world of code comes into contact with our senses. Understanding how color is represented is a part of this relationship, but there are other processes by which the numerical representation of form can be transformed into something that we can perceive, such as light, pigment, or material structure.

LIGHT

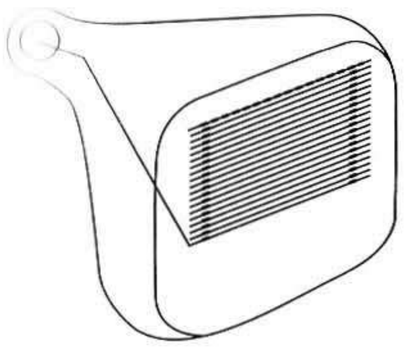
Long before the ubiquity of full-color displays, the oscilloscope served as the primary device for real-time visual output from the computer. Despite its low-quality monochrome image, systems like Sketchpad and early video games made excellent use of this device.



The full-color cathode ray tube (CRT) in the form of the television was targeted as the primary display device for early home video game systems, such as ColecoVision and the Atari 2600. The CRT consists of an electron gun and fluorescent screen enclosed in a vacuum tube. The gun fires electrons at the screen in a left-to-right, top-to-bottom pattern. When the electrons strike the screen, the fluorescent material glows. As a result of this process, the images on CRT screens have a very distinctive appearance.



The invention of the framebuffer was crucial to the widespread use of the full-color CRT, and to computer graphics as a whole, opening the door for digital painting programs, photo manipulation, and texturing. First developed at Xerox Palo Alto Research Center (now called PARC Inc.) in 1972, the framebuffer stored the entire contents of the screen in memory. Prior to this, only vector graphics could be drawn on-screen, because it was impossible to manage the amount of memory necessary to work with rasterized images.



Increasingly, the most common computer displays in use today are liquid crystal displays (LCD). LCDs have numerous advantages over the CRT. They use less power and are smaller, which makes them ideal for mobile computing. They can also update their image faster to provide a more vivid experience. Because LCDs can be made in a range of sizes, from the handheld to a large television, they can be used to create both intimate and public experiences. In addition, they can be modified to make touch screens and to provide physical feedback.

Modern digital projectors allow content to be seen by a large group of people at once. Beyond this basic use, projectors offer a way to immerse the viewer in imagery, augment a physical space, or create nonstandard display shapes such as circles. The front-projection setup, where the image is projected onto the front side of a screen, is the most common. A rear-projection setup, with the image projected onto the back of a semitransparent screen, is a good way to allow viewers to approach the image without worrying about casting shadows or otherwise interfering with the image.

Appearing in everything from key chains to coffee makers to animated billboards; light-emitting diodes (LEDs) are a staple of contemporary everyday life. An LED is an electronic component that creates light when a current is applied to it. Compared to traditional means of generating light, LEDs are far more energy efficient and last longer. In the context of form making, they are interesting for their highly variable appearance and small size. It is possible to create displays of nearly any size or shape by piecing a large number of LEDs together. In this way, each LED can act as a pixel in a raster display. These custom displays are then controlled using hardware and software that make them behave like traditional screens.

Oscilloscope
Oscilloscopes use voltages to control the movement of an electron beam. The movement from left to right is sometimes fixed to a clock, while the movement up and down is controlled by an electrical signal. This setup makes it easy to visualize regular signals like sine waves.

Cathode ray tube (CRT)
Electrons are fired through a vacuum tube at a phosphorescent screen, causing it to glow on impact. In raster displays, the beam moves from left to right, top to bottom.

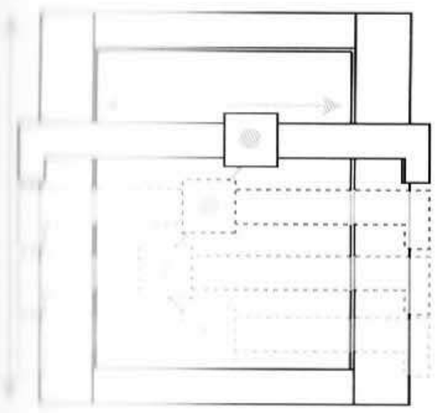
Volume,
by United Visual Artists, 2006
This light and sound sculpture is composed of a series of custom-designed LED columns that respond to the motion of viewers.

Hylozoic Grove,
by Philip Beesley, 2008
Beesley used a laser cutter to create two different types of form for this sculpture. The structure and mechanisms were cut from rigid plastics; while light, flexible plastics were used to create the delicate featherlike elements.

PRINTING

In the early days of computer graphics, images were printed on paper using a plotter in order to make the details, which appeared vague on the extremely limited displays, appear clear. A plotter is a machine that moves a pen over a drawing surface. The pen is given commands to control the direction and speed of movement, making it possible to vary the quality of the lines. By changing the material of the drawing surface or swapping the pen for a pencil, brush, or other drawing instrument, many interesting results have been created.

In the mid-1980s, the first laser printers designed for home use began to appear. Laser printers use a combination of electric charge and focused light to fuse toner to paper. This technique allows them to print 300 dots per inch (dpi), which is considerably higher than the 72 dpi available with the common dot matrix printer.



Though laser printers excel at printing on paper, the invention of the inkjet printer expanded the range of possible mediums and inks available. The basic spray-nozzle design of the inkjet is so flexible that it is now possible to print on diverse types of paper, plastic, and fabric. Even entire circuit boards can be "printed" using conductive ink.

FABRICATION

Fabrication is a catchall term used to describe a host of new technologies that are capable of producing physical objects out of digital representations. In a far more drastic way than printers and screens, various fabrication techniques are used for vastly different purposes and require new ways of thinking about code, space, and structure. The most common and straightforward fabrication tool is the laser cutter, which is mechanically similar to a plotter, except that a laser, rather than a pen, is positioned on an arm that can move in two dimensions. The computer moves the laser along the x- and y-axis of the bed to cut the material. Often, laser cutters have restrictions on the size, thickness, and type of material that can be cut. In addition to movement in two directions, the power of the laser cutter can be adjusted to etch metal and create intricate burn patterns on wood. Though laser cutters are limited to working in two dimensions, many architects, designers, and sculptors have found inventive ways to cut sections (similar to topographic maps) that are then reassembled to create intricate 3-D objects.

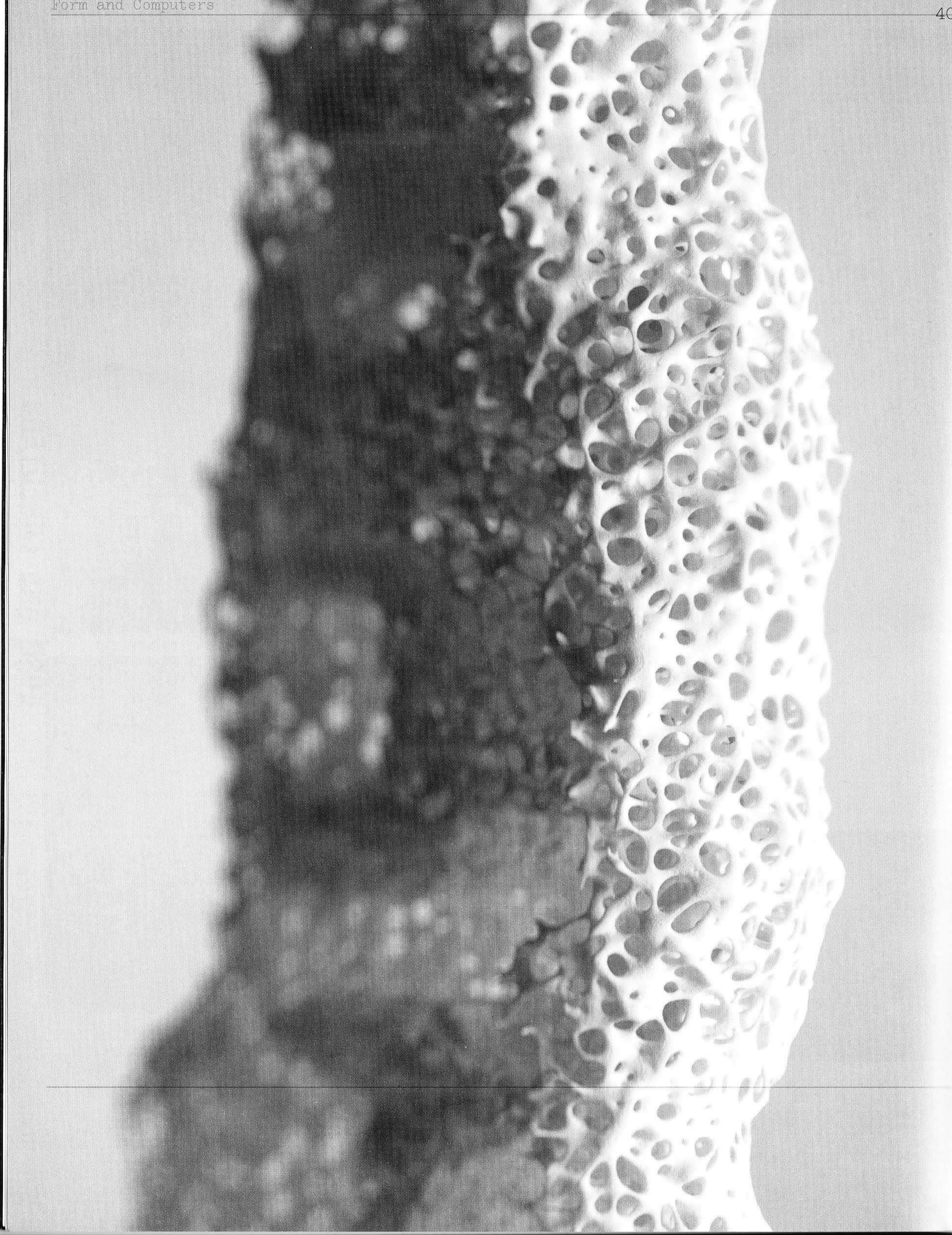
CNC milling, Selective Laser Sintering (SLS), stereolithography, and 3-D printing are just a few of the ways to create fully three-dimensional objects; that is, objects whose representations on the computer screen include information for x, y, and z axes, which are used to control the output device. A CNC-milling machine is similar to a plotter or laser cutter, but with the added flexibility of a continuous up-and-down motion. For example, a router bit is moved over a block of material, and as the bit moves, it cuts away a small amount of material, leaving behind a sculpted surface. In a three-axis machine, the router bit can only move directly up-and-down, making it difficult to sculpt objects from all sides. Some machines mount the block of material on a lathe, which rotates the surface facing the bit in order to provide additional flexibility.

CNC milling is a subtractive process; that is, material is cut away from a larger block in order to create the object. In contrast, SLS, 3-D printing, and stereolithography are additive processes that build up the final object by adding or fusing material together. Additive techniques have the distinct advantage of being able to create hollow spaces, undercuts, and overhangs, which are difficult to do using a three-axis CNC machine.

In a 3-D printer, a model is created by layering and fusing successive cross sections of material. Layers of powdered material, such as plaster, resin, or even cornstarch or sugars, are deposited and then selectively fused together by

...work by moving ...implement, ...by a pen or ...ver a surface to ...its horizontal and vertical positions with two motors. A similar mechanism is used in laser cutters and CNC-milling machines.

Cirrus 2008, by Zaha Hadid Architects, 2008
This sculptural seat, built by Associated Fabrication, is made of milled sheets of Formica and medium density fiberboard.



"printing" an adhesive from an ink-jet-like printer head. After the model is complete, it is excavated from the excess powder, which is then recycled for the next model. Stereolithography and SLS both employ variations of this additive technique. In stereolithography, thin layers of a photopolymer resin are deposited and then cured with an ultraviolet laser to harden the areas where it is focused. Once all of the layers are complete, the remaining liquid is drained and the model undergoes additional curing in ultraviolet light. SLS combines ideas from both 3-D printing and stereolithography. Thin layers of powder are deposited and then fused together using a laser to build the model layer by layer. A distinct advantage of SLS is the wide variety of materials that can be used, including nylon, ceramics, plastic, and metals, making it possible to quickly create prototypes of working machine parts.

structurel,
ie(n)+D, 2008
(n)+D imagine pos-
future worlds and
of living. This SLS
printed model
is described by its creators as, "The cells were no longer enclosures to protect from the outside...[but]'habitable networks, woven space,' an exfoliation of constantly reconfigured habitable organisms."