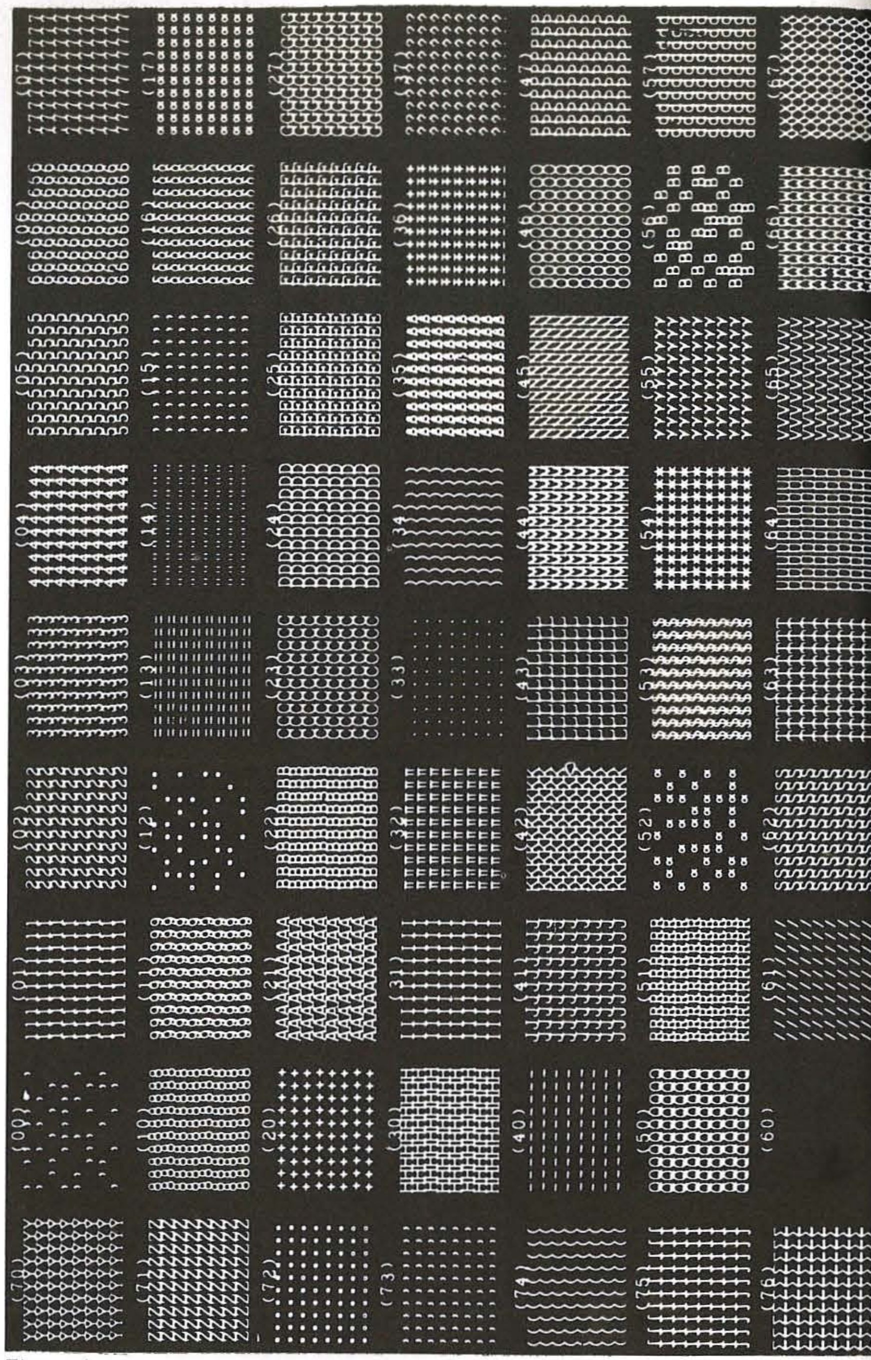

Figure 1

Computer-Produced Grey Scales
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Ken Knowlton and Leon Harmon

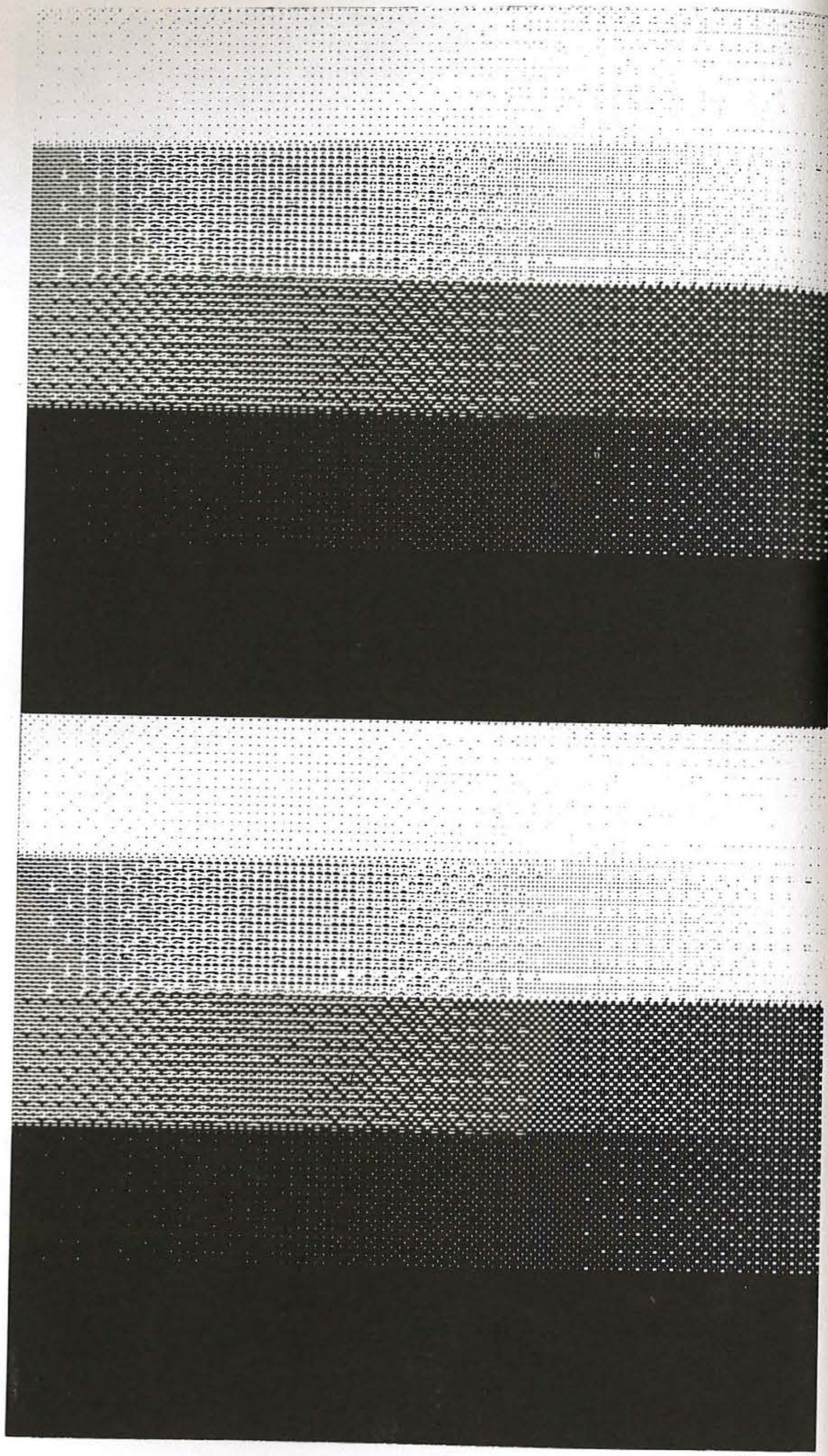

Figure 2

Introduction

- Black-and-white halftone or textured pictures are usually microscopically black or white at a point, owing to the physics, chemistry, or mechanics of the processes by which they are normally made or reproduced. Computer-produced pictures are also black or white at a point, largely because of the film and machinery used. Constraints of speed, resolution, cost and cathode-ray-tube technology have tended to make available mainly binary processes. Hence dots or stencil-extruded characters on microfilm are the most common output format.
- Various techniques have been devised **to obtain multilevel presentations using two-level reproduction apparatus. One of the earliest of these uses the different sizes and shapes of alphanumeric characters to provide different grey levels when viewed distantly. When this technique is combined with overstrikes (super-imposed printing), many** brightness values can be obtained [12].
- A single element—the dot—can be used in clusters defined by software-coded patterns to render halftone pictures, provided that an appropriate black-to-white ratio is obtained for every "unit area" of the picture [5,14]. We define unit area as that subarea of the picture plane within which no picture detail is required and sufficiently small such that, upon viewing, its average brightness is perceived.
- When relatively small numbers of brightness quantizing levels are used, objectionable contours often become apparent. The use of deliberately introduced noise to **break up these contours was pioneered by W. M. Goodall about two decades ago [4]. It was later found that with suitable coding, pseudo-random noise can be used to break up quantizing contours to give results comparable to those obtained with three times as many levels [13].** In effect, deliberately introduced noise causes fragmentation of mono-tone areas locally while preserving the appropriate average grey level over a neighborhood. In this way the few densities available are feather-edged to make density transitions less sharp; this gives the illusion that the picture has a much larger number of quantum steps. When combined with an overstrike range of eight (i.e., allowing a character to be struck up to eight times), this procedure allows a conventional line printer to yield extremely smooth results [11]. Similar techniques have been applied with excellent effort to microfilm printers [14].
- **This paper presents the results of some of our own efforts toward achieving grey values. Using the basic ideas of micro-pattern selection and interpolated noise, these techniques demonstrate several new ways to obtain smooth density scales with straightforward application of** existing hardware and some novel software techniques.
- We limit our investigation to situations in which space is discretely quantized in two dimensions into cells; these are the unit areas mentioned above. We shall refer to the smaller structures filling cells as "elements." These elements in all instances are either dots or characters defined by the machinery used. The grey values that we have employed constitute in most cases a small set, usually eight or sixteen. Of course, here, as in all other procedures where final grey-scale representation is obtained by using clusters of picture elements, **spatial resolution has been traded off for brightness resolution.**
- **The aims of these experiments have been to develop expertise in the computer processing of pictures and to experiment with novel and artistic effects. With such experiments, some intriguing questions about**

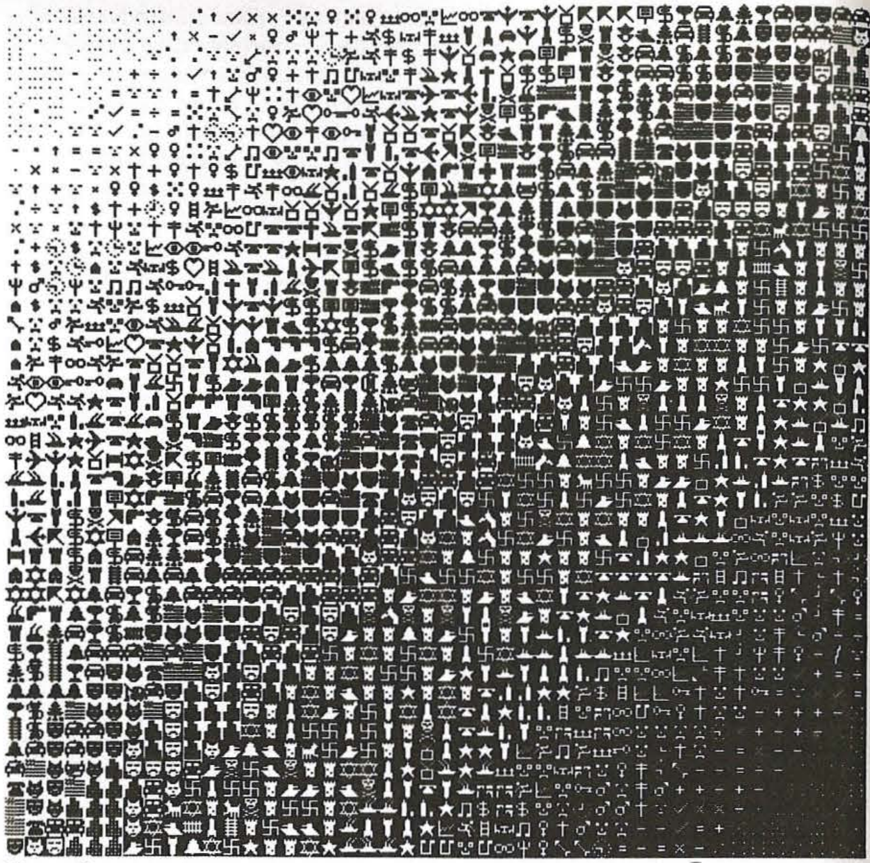

Figure 3a

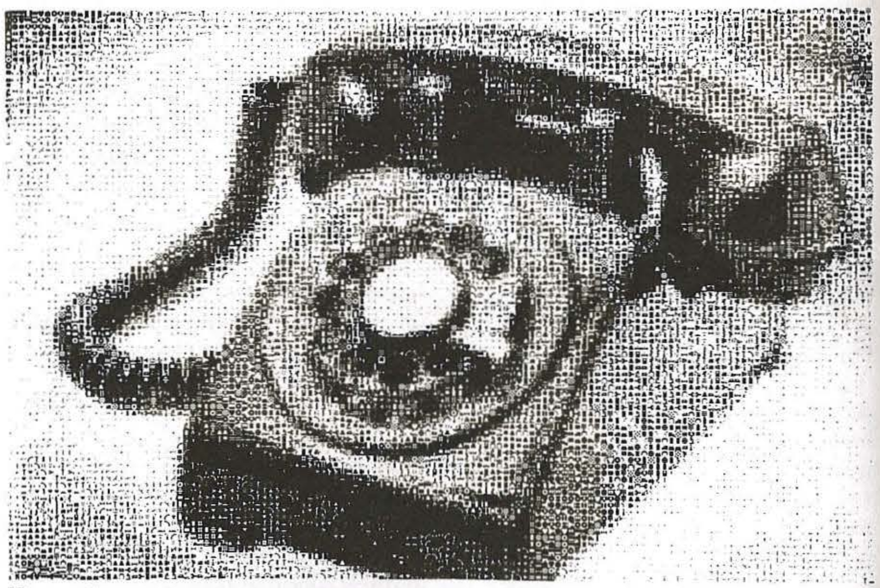

Figure 3b

human visual perception emerge, though no attempts to answer them are reported here.

- The hardware used for all the work described below has been either the Stromberg Datagraphic 4020 or 4060 microfilm printer. The software used was a language for making movies, the BEFLIX system [8] and its variants [9,10].

Textures and Grey Values From Hardware-Defined Elements

- A Charactron tube such as the one used in an S-D 4060 provides a large number of distinguishable elements—the individual characters—which may be used to form pictures or textures. Figure 1 shows many of these characters and demonstrates both the textures (when viewed close up) and the different grey values (when viewed from afar) which may thus be achieved.

The use of a few characters to achieve effectively many grey levels is extended by the technique demonstrated in figure 2 [6]. Here seven different characters (including blank) are used to achieve several dozen levels. The scheme is as follows: A photo or other initial display (in the demonstration, simply a folded grey wedge) is first divided into "supercells" of 4x4 cells each, and a regular 'hoise" pattern is added to the original brightness values, the peak value of the pattern being set equal to one brightness step. (The regular noise pattern is better than random or pseudo-random noise because it avoids the large noticeable clumps which the latter introduces. One pays for this, of course, by the introduction of regular structure.)

- The result of this process is that high contrast detail (i.e., that which is defined by brightness differences of more than one level) is preserved at cell-size resolution, since cells are processed individually except for the small values added before quantization. But areas distinguished from each other by less than a brightness level (but more than one-sixteenth of a level) can also be seen as different because, on the slightly brighter side of a subtle demarcation, one or more cells of a supercell are made to fall above a basic quantization threshold while the corresponding cells on the dimmer side remain below the threshold. In principle, one should therefore expect to be able to detect 96 grey values in figure 2 (six fundamental transitions divided into sixteen steps each); whether this many distinct levels can actually be achieved is a question of hardware and photographic control.
- It should be emphasized that, in the above procedure, cells of a supercell are treated separately—the character printed in each position is determined by the original brightness of that cell, and also by its appropriately shifted threshold. Thus, a thin black line across the picture would blank out only a few cells of each supercell that the line traverses. Likewise, a high-contrast step which cuts across supercells may be perceived with high spatial precision, as are in fact the horizontal divisions between the four parts of figure 2. Furthermore, the numbers added within a supercell are scattered so that the more pronounced the contrast is between two areas, the fewer are the cells over which the eye must ultimately "average" the resulting brightness in order to detect the difference.

Grey Values and Textures From Software-Defined Elements

- In the above examples the various grey-scale manipulations depend principally on available hardware elements (dots or characters) arranged in rather simple, regular ways in cells. This section includes examples where more elaborate software manipulations are employed to obtain a richer variety

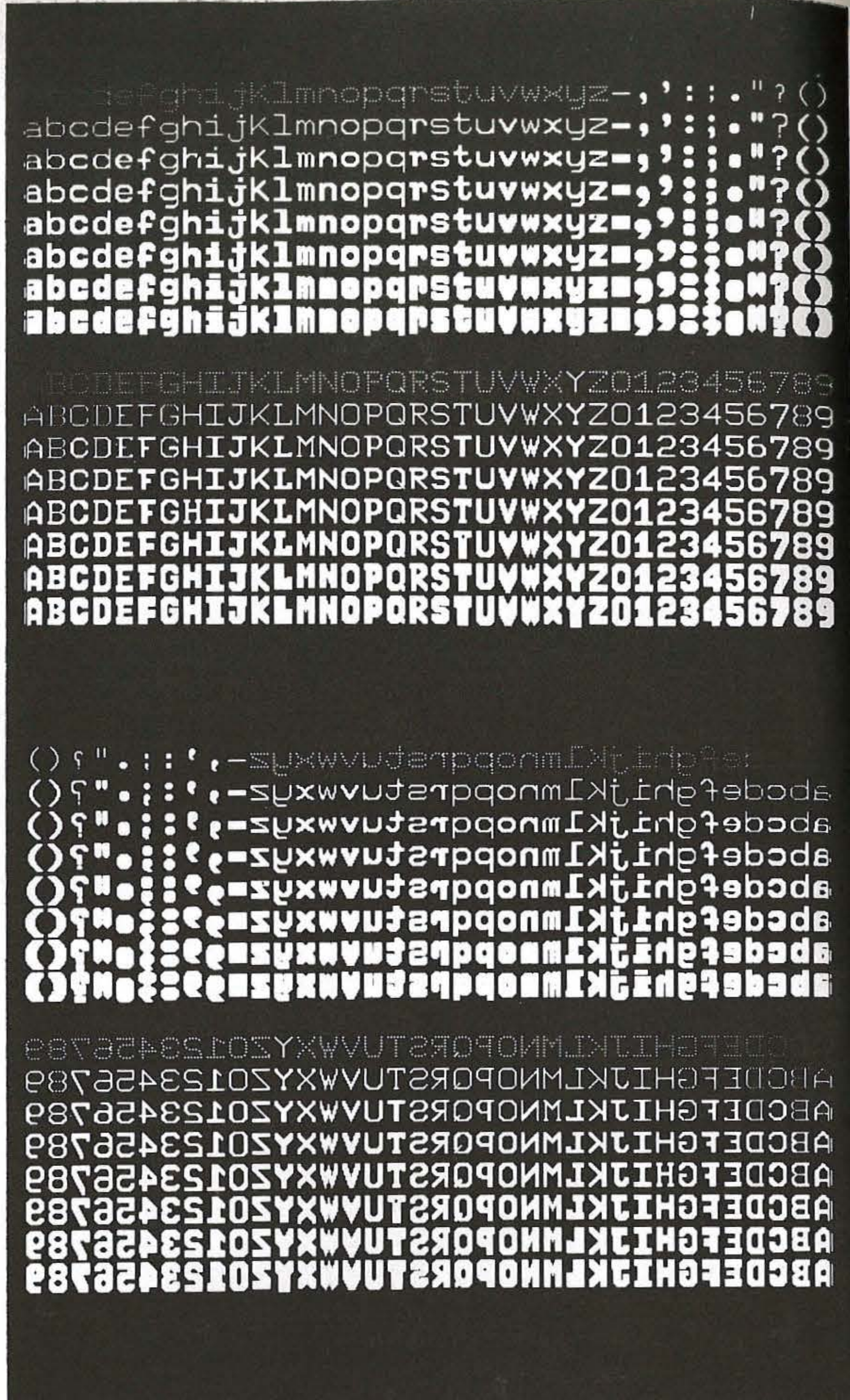

Figure 5a

of outputs. By exploiting the flexibility of programmed picture transformations, one can obtain results that are not so constrained by hardware limitations as are the earlier examples we considered. Not only is there an increase in the variety of the available character set, but new operations are made possible such as orientation change and complementation. With easily programmed manipulations like reflections and changes in connectivity, novel perceptual and artistic effects can be achieved. The following examples illustrate some of the variety obtained in grey-scale manipulations by using software-defined elements. •

• **Figure 3a shows how a sixteen-level grey scale can be synthesized with appropriate numbers of dots used to form recognizable micro-patterns in minute (11 x 11 dot) matrices. Figure 3b came from a photo which, after processing to obtain such a grey scale, is represented by 11,616 (132 x 88) cells. The computer, after noting the required level for each cell, selected one pattern at random from the available patterns for that level (up to fourteen for some levels, as few as five for others) and drew it. For visual interest, a pattern was sometimes reflected or rotated 90° as determined by probabilities specified for that pattern [5]. In figure 3b the micro-patterns are formed by 15 x 15 dot matrices.**

In each of these pictures, rather surprisingly complicated "Gestalt" images are obtained from small amounts of information. The 11 x 11 matrix has only a few times more resolution than is commonly accorded alphanumeric characters. Yet in figure 3a much more complex images can be plainly perceived.

Figure 4 is another photograph similarly spatially quantized, this time on a single frame of 35mm film by means of a high resolution version of BEFLIX capable of drawing black-and-white dot pictures up to **1024 x 1366 dots in size [9]. The very different appearance of this picture from figures 3a or 3b results from the nature of the 12 x 12 micro-patterns—they are small maze-like units, whose lines are two slots wide, designed to match up with their neighbors so as to form large combinatoric structures. This picture consists of 112 x 45 cells quantized into thirty grey levels.**

• **A final example is presented in figure 5—a "picture story" which is a legible text when viewed from nearby and a high-quality photograph when seen from far away. This is similar to the text-picture produced by M. R. Schroeder**

[14], but where that process used overprinting to obtain grey scale, this process uses dot occupancy and character shift, as follows:
The elements were taken from the seven-font grey-scale alphabet shown in its entirety in figure 5a. Here each letter is defined by dot occupancy in an 11 x 19 matrix, numbers for the seven levels having been set arbitrarily at 32, 50, 69, 89, 110, 132, and 155 dots. The text for this picture was prepared carefully to be exactly 64 lines of 73 characters each, not counting spaces (achieved by judiciously inserting or deleting commas, etc.) Then appropriate forms of the designated letters were positioned with an average horizontal spacing of three units and a vertical spacing of two (giving therefore a 14 x 21 unit area). Spacing between words was achieved by squeezing together the end letters of words as follows: single-letter words—no repositioning; two-letter words—each letter moved one unit toward the other; three-letter words—each letter moved two units; four-letter words—end letters moved in two, next-to-end letters in one.

- With only seven levels, straightforward quantizing leads to the unnatural steps and plateaus previously discussed. The effect of smoother-than-seven level quantization of figure 5b was achieved by a technique for graduated transition between levels similar to that illustrated in figure 2.

Summary

- There are many ways to achieve results which subjectively approximate continuous-tone photographs using binary output. In each case the processed picture must be viewed from far enough away for the eye to achieve sufficient spatial integration. Interesting and artistic effects often result when the familiar dots of halftone screening are replaced by deliberately more complete patterns or structures. A tabulation of computer-generated or processed pictures of this paper appears in Table I, together with the significant parameters that pertain to each.
- Intriguing questions still remain—how we perceive what we perceive is not clear. In figure 3b, for example, the dial holes are perceived as quite round at a distance. When these details are examined closely, however, they "disappear" or lose their character or identity almost mysteriously. Either of two (or perhaps both) possible mechanisms may be involved—low-pass filtering of spatial frequencies (sizes of details), or interpretation in accordance with prior experience. According to the first explanation, it would seem that at moderate distances the visual system filters out the fine details that are irrelevant for its purposes, whereas with close viewing, those details (which now subtend larger visual angles) somehow overwhelm this filtering capability (that is, high-contrast details of optimum size cannot be sufficiently ignored in order to recognize larger structure subtly presented).
- The second explanation for these phenomena is that we may recognize the overall object or setting and then process smaller structure largely in terms of our expectations—for example, we may first recognize the object as a telephone (figure 3b) and then "see the finger holes as

Table I
Summary of computer-generated or computer-processed pictures described in this paper.

All examples were produced by Stromberg Datagraphics microfilm printers.

Figure	No. of Characters*	Cell Size	Raster Size	Levels of grey scale
1	59	1 x 1	126 x 92	59
2	6	1 x 1	252 x 184	96
3a	1	11 x 11	504 x 504	16
3b	1	15 x 15	504 x 504	16
4	11	12 x 12	1024 x 1366	30
5b	1	14 x 21	1024 x 1366	7

*not including blank

round because of past experiences with actual telephones.

- One of the earliest to point out the power of the eye to "see" more than it ought was Selfridge [15, figure 8]. More formal essays to explore recognition of low-information spatially quantized patterns [2,3] also indicate that much lies in the eye of the beholder. Extensive discussion of similar considerations can be found in a recent monograph by Julesz [7]. This intriguing topic requires extensive investigation in order to achieve satisfactory elucidation. Given the presently strong and growing emphasis on graphical and pictorial displays, our technology could benefit considerably from that understanding.
- We acknowledge with appreciation the helpful critical comments on an early draft by M. E. Harmon, A. B. Lesk, and A. Rosenfelt.

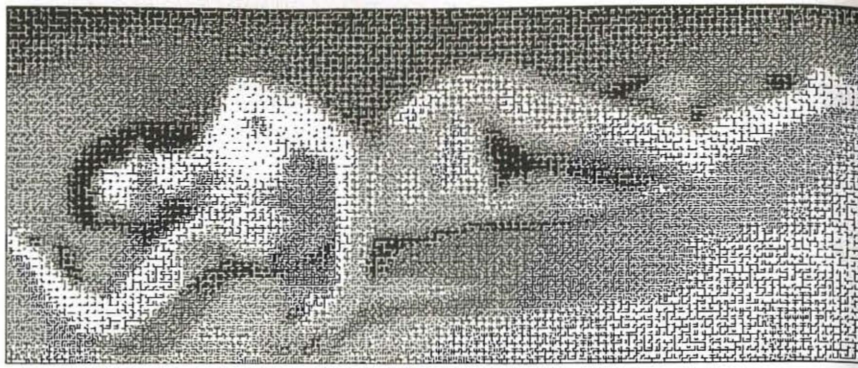

Figure 4

Figures

Figure 1
Some characters producible on S-D 4060, octal codes by which they are referenced, and textures which each produces when used to fill an area. These characters are used by the TARPS language in which four codes are used to designate 50/50 probabilistic selection between certain characters and blanks. (As with all succeeding illustrations, except figure 3b, the output is produced on a single frame of 35mm film.)

Figure 2
A folded grey wedge processed by the technique described in the text and ultimately produced by the characters blank, apostrophe, quote marks, =, $\pm$, Σ, and B.

Figure 3a
A sixteen-level grey scale consisting of appropriately designed and classified miniature patterns. Each pattern defined by dot occupancy in an 11 x 11 raster.

Figure 3b
A photograph flying-spot scanned, divided spatially into 11,616 (132 x 88) squares, quantized in grey scale to sixteen levels, then rendered in terms of the small patterns of figure 3a by using a 15 x 15 matrix. In any given level, random selection was made from the appropriate set of patterns. Entire picture was originally produced on six frames of 35mm microfilm. (Copyright 1969 by the American Association for the Advancement of Science.)

Figure 4
Another processed photograph; it consists of 112 x 45 cells. Micro-patterns in this case were small (12 x 12) maze elements arranged so as to join up from cell to cell, producing large, combinatoric forms.

Figure 5a
A seven-font alphabet of thin-to-thick letters used for "picture stories" like figure 5b. Each character is defined by an appropriate number of dots in an 11 x 19 matrix; average numbers of dots for the seven levels are 32, 50, 69, 89, 110, 132, and 155 dots.

Figure 5b
A photograph quantized and rendered by means of the grey-scale alphabet of figure 5a. The smoother-than-seven-level effect was achieved by starting with a 25-level quantization and adding two to even-numbered columns, and one to even-numbered rows, and then requantizing by uniformly mapping four levels into one. (Text is abridged form of the U. N. Declaration of Human Rights; original photograph by Richard Swanson of Black Star.)

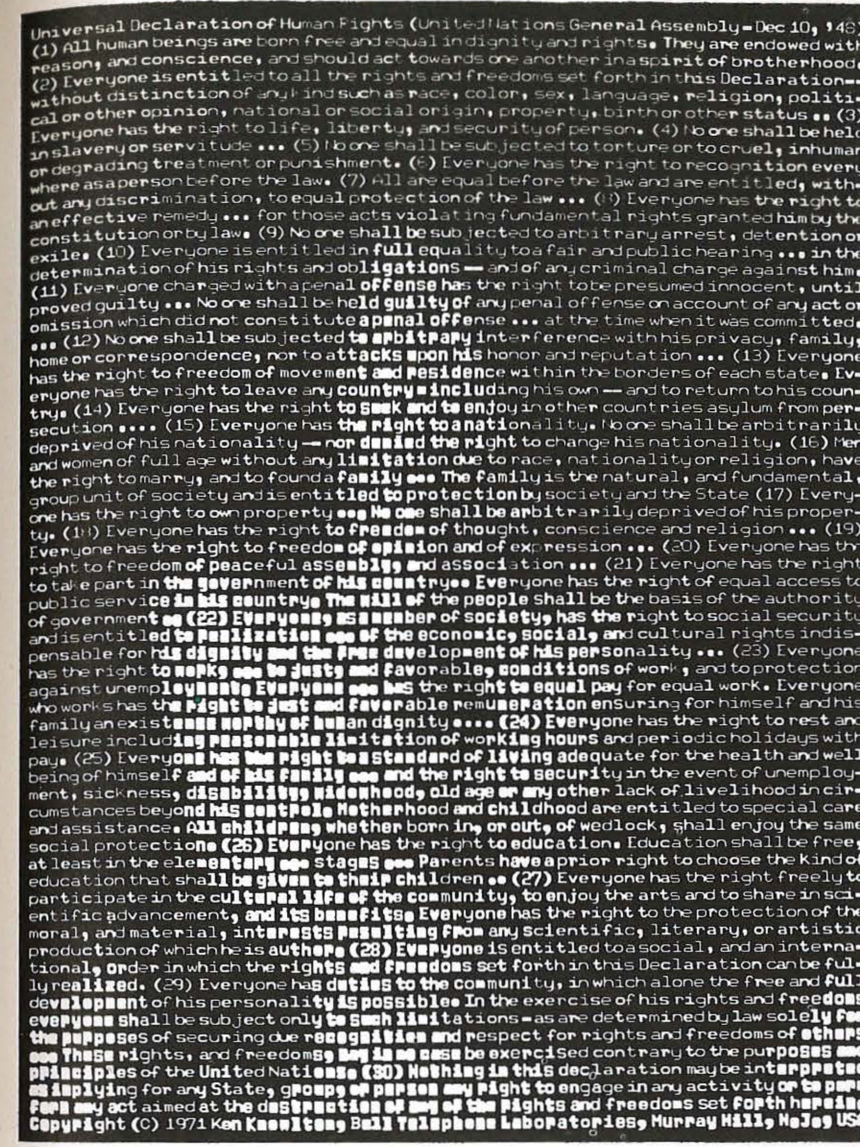

Figure 5b

Notes

1
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2
In principle, one could determine 59 levels by actual measurement. They would not, however, be uniformly spaced nor would their order in brightness be reliably reproducible owing to slight changes in performance of the hardware.

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