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PERCEPTION, PICTURE PROCESSING AND COMPUTERS

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INTRODUCTION

The ability to interpret and respond to the significant content of pictures is shared by a large proportion of the animal kingdom and a small but growing number of machines. The machines (usually digital computers) will classify simple shapes and printed letters and digits represented (by means of a suitable television scanner) as a matrix of 1s and 0s. Animals, and specifically man, will do this and more; that is, not only will a human subject correctly recognise letters written badly but also comment, 'That's a funny way to write a two', or 'It's a good portrait, but the eyes are a little too far apart'. No machine can as yet approach this sort of performance. We may well ask, therefore, what if anything we can learn from a study of 'machine perception' which could conceivably help us to understand human perception. The answer lies in the fact that any realistic account of the mechanism underlying perceptual or any other human skills will be complex. The virtue of a computer lies in its ability to capture in a definite form processes of indefinite complexity and subtlety, and moreover, to permit an *evaluation* of the efficacy of the proposed description by trying it out on the actual task.

This paper will be concerned with a description of a new method of interpreting pictures, now under development. The method arises directly out of earlier attempts (Clowes & Parks 1960, Clowes 1962) to develop letter recognition machines for commercial use. However, it now appears that the approach is capable of a wider interpretation in terms both of psychological observations and recent physiological evidence.

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HIERARCHIES OF DESCRIPTION

Psychologists concerned with analysing complex behaviour often have to select an appropriate level of description. For example, driving a motor car can be characterised in terms such as 'overtaking', 'giving way', 'filtering', or at a more detailed level in terms of 'changing from 2nd to 3rd gear', 'turning the wheel anti-clockwise', 'depressing the clutch pedal' or yet more detailed still in terms of the positions of the limbs as a function of time. Choosing the correct level of description might be vital to the assessment of the relative skills of two drivers, or the design of two different types of car. On the other hand perhaps all these levels of description should be employed simultaneously—if so, how are they related? This question forms the basis of a book *Plans and the structure of behaviour* (Miller, Galanter & Pribram 1960) in which it is shown that the problem arises not only for manual skills, but also in many cognitive processes and especially in language. It is in this latter case that perhaps the clearest expression of a hierarchy of description is evident—phonemes, syllables, words, phrases, clauses, sentences . . .—and it is also the area in which the most progress has been made in answering these questions.

LINGUISTIC GRAMMARS

The problem is to formulate a reasonably precise set of rules by means of which we can take an utterance, e.g., 'the boy kicked the red ball' and, by

S_1	=	NP	+	VP	(1)
S_2	=	NP	+	VP_1	
VP	=	V	+	NP	(2)
VP_1	=	V	+	ANP	(3)
NP	=	T+N			(4)
ANP	=	$T+N_1$			
N_1	=	A+N			(5)
V	=	kicked/rolled/pushed/			(6)
T	=	the/a/every/			
N	=	man/boy/ball/			
A	=	red/young/striped/			

FIG. 1. A set of ordered substitution rules specifying the grammar of a simple sentence.

applying the rules in the prescribed manner, can obtain a description of this utterance at a number of different levels.

Let us confine our attention to three levels: words, phrases, sentences. Fig. 1 shows a set of rules sub-divided into numbered groups (1, 2, 3, . . . , 6).

We can regard each rule as defining a permissible substitution. Thus group 6 rules state that we may replace any of the words red, young, striped (i.e., any adjective) by the symbol A, and similarly for verbs, nouns and articles. So that the sentence

the boy kicked the red ball

becomes by application of group 6

(6) T N V T A N

Group 5 states that a pair of symbols A, N appearing *contiguously and in that order* can be replaced by N_1 so that the string becomes

(5) T N V T N_1

and so by application of successive rules, in descending order of their group number, we obtain

(4) NP V ANP
(3) NP VP_1
(2) NP VP_1
(1) S_2

If we now combine these different strings of symbols into one diagram (Fig. 2) we have a description of the utterance at a number of levels in a fashion which indicates the relation between the levels.

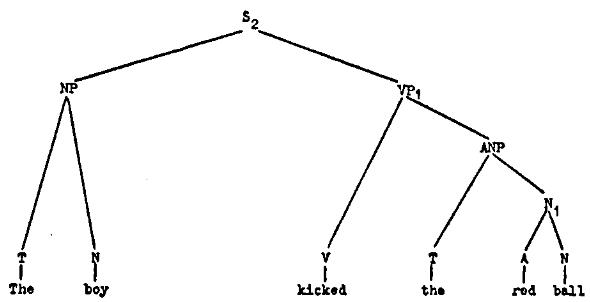

FIG. 2. The structural analysis of a simple sentence as obtained by applying the rules of FIG. 1.

The rules may be used to generate or analyse sentences. A typical generative sequence starting from the schema S_2 would be $S_2 \rightarrow$ NP $VP_1 \rightarrow$ T N $VP_1 \rightarrow$ the N $VP_1 \rightarrow$ the boy $VP_1 \rightarrow$ the boy V ANP $\rightarrow \ldots \rightarrow$ the boy kicked the red ball. The generative path can be diagrammed in tree form as in Fig. 2.

This diagram—a so-called *tree*—indicates not only that the utterance is a sentence, but also what type of sentence it is (S_2 rather than S_1), as well as indicating what features (i.e., phrases like ANP, etc.) it had which caused the *label* S_2 to be applicable. Let me hasten to add at this point that this is not presented as a serious piece of linguistics (there are grounds for believing it to be incorrect in several ways) but merely as an introduction to the notion of a set of rules (the grammar) and a procedure for applying them (a parsing algorithm) by which we can rigorously derive a *structural description* of a complex object like a sentence. A mechanism or mechanisms of this type undoubtedly underlie our ability to understand sentences.

PICTURE PROCESSING

Comparable mechanisms for processing pictures have not appeared to any significant extent either in Artificial Intelligence or in Psychology. Instead the emphasis has been on classifying pictures, i.e., upon the equivalent of deciding the type (S_1 or S_2) of a sentence The possibility that a structural description of a pictorial object is necessary has only recently emerged in Artificial Intelligence (Kirsch 1964). It appears to be crucial to the automation of many picture processing tasks (e.g., interpreting bubble-chamber photographs, recognising fingerprints). That perceptual behaviour involves description as well as classification could be supported by innumerable examples beyond the two already quoted in the introduction to this paper. However, it seems to have received scant attention in recent psychological literature. This may well be because overtly descriptive (rather than classificatory) behaviour has a large verbal element. There is a strong temptation to avoid this 'complication' by designing experiments which merely require simple YES/NO responses and which have, therefore, no significant verbal component.

It follows from the foregoing remarks that our own objective is the development of a formal (i.e., rigorous) theory of picture processing which aims to provide a structural description of pictorial objects as well as a classification of them (wherever appropriate). The particular system I shall describe is by no means the only possible approach, both Ledley (1964) and Narasimhan (1964) have proposed alternatives. I shall illustrate the technique in terms of a limited class of pictures—the handwritten numerals. There are several reasons for choosing this class. (1) They are (hopefully) relatively simple objects; (2) at least two levels of description naturally occur, e.g., the symbol 7 is readily described as 'a horizontal stroke above a diagonal stroke . . .'; (3) psycholinguistic skills, e.g., reading (with which the Unit† is primarily concerned), involve pictorial objects of this type.

A PICTURE GRAMMAR FOR HANDWRITTEN NUMERALS: NOTATION

The substitution rules in the linguistic grammar (Fig. 1) contain on their right-hand side (typically) two elements, e.g., T, N or NP, VP, linked by a relational operator '+' meaning 'followed by'. This operator expresses the notion of contiguity as it arises in a *string* of symbols; contiguity in a

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geometrical sense is the more general relationship 'next to'. Thus a simple pictorial property like 'Edge' (i.e., boundary between black and white regions of the picture) might be defined as 'black area next to white area'. Specifically we might define a North Edge as 'white area *above* black area', which can be expressed in a rigorous (computable) form with the aid of a suitable notation. For example, in a pictorial notation the definition of North Edge for a picture composed only of black or white elements might take the form illustrated in Fig. 3. This asserts that the point arrowed

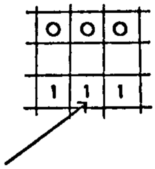

FIG. 3.

will be said to have the property N EDGE if it and the points to the left and the right of it are black (i.e., *True*) and the three points denoted '0' are white (i.e., *False*). If we introduce a Cartesian co-ordinate system we can write this definition as a Boolean expression:

$$\begin{aligned}\text{N EDGE}\,(x, y) = \; & \text{PICTURE}\,(x-1, y)\;\&\;\;\text{PICTURE}\,(x, y)\\ \& \; & \text{PICTURE}\,(x+1, y)\;\&\sim\text{PICTURE}\,(x-1, y+2)\\ \&\sim & \text{PICTURE}\,(x, y+2)\;\&\sim\text{PICTURE}\,(x+1, y+2) \qquad (1)\end{aligned}$$

where (x, y) is the 'arrowed' point, a black point has the value *True* and a white point the value *False*.

The assignment of a label (e.g., N EDGE) to a picture point involves a decision based upon the state of a number of neighbouring points. Fig. 3 is a picture of the decision criterion. The values of only 6 specified points are considered. All other points are ignored, for the purpose of assigning this label to the arrowed point.

IMPLEMENTATION

This notation is used in the picture analysis program with some small differences for reasons of economy and ease of programming. Fig. 4 shows a system of such definitions as they are input to the computer. The first two lines specify various program options relating to print out, etc., and also define the size (48 × 48) of the input picture. The third line is the definition for N EDGE given above (1), but specified in Reverse Polish (i.e., parenthesis free) form.† Repetitions of the label PICTURE have been suppressed and the label N EDGE appears at the end of the definition rather than preceding it. The x, y appearing on both sides of the expressions (1) above have also been omitted, it being understood that this rule is applied to the picture (Fig. 5(a)) for all values of (x, y) so as to derive another picture called (Z) N EDGE (Fig. 5(b)). The axes have been rotated so that x is measured down the

† The Reverse Polish form of the Boolean expression (A & B) v (~ C & D) is A, B, &, C, ~ D, &, v.

FIG. 4. A partial 'picture grammar' for handwritten numerals. Each group of rules is preceded by the control instruction + CODE NNL + 02BY02.

```
+LINEYYX+48BY48
+CODENNL+02BY02
ZPICTURE.(00,00) NOT     .(00,01) NOT     AND     .(00,02) NOT     AND     .(02,00) AND     .(02,01) AND     .(02,02) AND
Z(02,01)ZN   EDGEX048,48
ZPICTURE.(00,00) NOT     .(00,01) NOT     AND     .(00,02) NOT     AND     .(02,00) AND     .(02,01) AND     .(02,02) AND
Z(02,01)Z    BLOBX000,72
ZPICTURE.(00,00).(01,00) AND     .(02,00) AND     .(00,02) NOT     AND     .(02,02) NOT     AND     .(01,02) NOT     AND
O(01,00)ZE   EDGEX024,00
ZPICTURE.(00,00).(01,00) AND     .(02,00) AND     .(00,02) NOT     AND     .(02,02) NOT     AND     .(01,02) NOT     AND
O(01,00)Z    BLOBX000,72
ZPICTURE.(00,00).(00,01) AND     .(00,02) AND     .(02,00) NOT     AND     .(02,01) NOT     AND     .(02,02) NOT     AND
Z(00,01)ZS   EDGEX024,48
ZPICTURE.(00,00).(00,01) AND     .(00,02) AND     .(02,00) NOT     AND     .(02,01) NOT     AND     .(02,02) NOT     AND
Z(00,01)Z    BLOBX000,72
ZPICTURE.(00,00) NOT     .(01,00) NOT     AND     .(02,00) NOT     AND     .(00,02) AND     .(01,02) AND     .(02,02) AND
Z(01,02)ZW   EDGEX048,00
ZPICTURE.(00,00) NOT     .(01,00) NOT     AND     .(02,00) NOT     AND     .(00,02) AND     .(01,02) AND     .(02,02) AND
Z(01,02)Z    BLOBX000,72
ZPICTURE.(00,02).(01,01) AND     .(02,00) AND     .(02,03) NOT     AND     .(03,02) NOT     AND     .(04,01) NOT     AND
Z(01,01)ZSE  EDGEX024,24
ZPICTURE.(00,02).(01,01) AND     .(02,00) AND     .(02,03) NOT     AND     .(03,02) NOT     AND     .(04,01) NOT     AND
Z(01,01)Z    BLOBX000,72
ZPICTURE.(00,02).(01,03) AND     .(02,04) AND     .(02,01) NOT     AND     .(03,02) NOT     AND     .(04,03) NOT     AND
Z(01,03)ZSW  EDGEX024,72
ZPICTURE.(00,02).(01,03) AND     .(02,04) AND     .(02,01) NOT     AND     .(03,02) NOT     AND     .(04,03) NOT     AND
Z(01,03)Z    BLOBX000,72
ZPICTURE.(00,03) NOT     .(01,02) NOT     AND     .(02,01) NOT     AND     .(04,02) AND     .(03,03) AND     .(02,04) AND
Z(03,03)ZNW  EDGEX048,24
ZPICTURE.(00,03) NOT     .(01,02) NOT     AND     .(02,01) NOT     AND     .(04,02) AND     .(03,03) AND     .(02,04) AND
Z(03,03)Z    BLOBX000,72
ZPICTURE.(00,01) NOT     .(01,02) NOT     AND     .(02,03) NOT     AND     .(02,00) AND     .(03,01) AND     .(04,02) AND
Z(03,01)ZNE  EDGEX048,72
ZPICTURE.(00,01) NOT     .(01,02) NOT     AND     .(02,03) NOT     AND     .(02,00) AND     .(03,01) AND     .(04,02) AND
Z(03,01)Z    BLOBX000,72
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FIG. 4. *(continued)*

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.CODENNL.02BY02
ZW  EDGE.(02,01)ZE  EDGE.(02,01).(02,02) OR      AND     Z   BLOB.(01,00) NOT     AND     .(01,03) NOT     AND     .(00,01
 NOT      AND     .(00,02) NOT      AND     2(02,01)ZN   ENDX048,60
ZN  EDGE.(01,02)ZS  EDGE.(01,02).(02,02) OR      AND     Z   BLOB.(01,00) NOT     AND     .(02,00) NOT     AND     .(00,01
 NOT      AND     .(03,01) NOT      AND     2(01,02)ZW   ENDX048,12
ZN  EDGE.(01,00)ZS  EDGE.(01,00).(02,00) OR      AND     Z   BLOB.(00,01) NOT     AND     .(01,02) NOT     AND     .(02,02

 NOT      AND     .(03,01) NOT      AND     2(01,00)ZE   ENDX048,00
ZW  EDGE.(00,01)ZE  EDGE.(00,01).(00,02) OR      AND     Z   BLOB.(01,00) NOT     AND     .(02,01) NOT     AND     .(02,02
 NOT      AND     .(01,03) NOT      AND     2(00,01)ZS   ENDX048,48
ZNW EDGE.(00,02)ZSE EDGE.(00,02).(01,03) OR      AND     Z   BLOB.(00,00) NOT     AND     .(01,01) NOT     AND     .(02,02
 NOT      AND     .(03,03) NOT      AND     2(00,02)ZSW  ENDX048,72
ZNE EDGE.(02,03)ZSW EDGE.(02,03).(03,02) OR      AND     Z   BLOB.(03,00) NOT     AND     .(02,01) NOT     AND     .(01,02
 NOT      AND     .(00,03) NOT      AND     2(02,03)ZNW  ENDX048,36
ZNW EDGE.(02,00)ZSE EDGE.(02,00).(03,01) OR      AND     Z   BLOB.(00,00) NOT     AND     .(01,01) NOT     AND     .(02,02
 NOT      AND     .(03,03) NOT      AND     2(02,00)ZNE  ENDX048,84
ZNE EDGE.(00,01)ZSW EDGE.(00,01).(01,00) OR      AND     Z   BLOB.(03,00) NOT     AND     .(02,01) NOT     AND     .(01,02
 NOT      AND     .(01,02) NOT      AND     2(00,01)ZSE  ENDX048,24
ZN  EDGE.(00,00)ZS  EDGE.(00,00).(01,00) OR      AND    Z00 LINEX060,00
ZNW EDGE.(00,00)ZSE EDGE.(00,00).(01,01) OR      AND    Z45 LINEX060,36
ZW  EDGE.(00,00)ZE  EDGE.(00,00).(00,01) OR      AND    Z90 LINEX060,24
ZNE EDGE.(00,01)ZSW EDGE.(00,01).(01,00) OR      AND    Z135LINEX060,12
ZE  EDGE.(00,00).(01,00) AND    .(02,00) AND    2(01,00)ZE   EDGEX036,00
ZS  EDGE.(00,00).(00,01) AND    .(00,02) AND    2(00,01)ZS   EDGEX036,24
ZW  EDGE.(00,00).(01,00) AND    .(02,00) AND    2(01,00)ZW   EDGEX036,48
ZN  EDGE.(00,00).(00,01) AND    .(00,02) AND    2(00,01)ZN   EDGEX036,72
ZSE EDGE.(00,02).(01,01) AND    .(02,00) AND    2(01,01)ZSE  EDGEX036,12
ZSW EDGE.(00,00).(01,01) AND    .(02,02) AND    2(01,01)ZSW  EDGEX036,36
ZNW EDGE.(00,02).(01,01) AND    .(02,00) AND    2(01,01)ZNW  EDGEX036,60
ZNE EDGE.(00,00).(01,01) AND    .(02,02) AND    2(01,01)ZNE  EDGEX036,84
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FIG. 4. *(continued)*

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*CODENNL*028Y02
Z90 LINE.(00,00).(01,00) OR     ZNW  END.(00,00)ZN    END.(00,00) OR     ZNE  END.(00,00) OR      AND     ZN  LIMBX072,00
Z00 LINE.(00,00).(00,01) OR     ZNE  END.(00,01)ZE    END.(00,01) OR     ZSE  END.(00,01) OR      AND     2(00,01)ZE  LIM
X072,12
Z90 LINE.(00,00).(01,00) OR     ZSE  END.(01,00)ZS    END.(01,00) OR     ZSW  END.(01,00) OR      AND     2(01,00)ZS  LIM
X072,24
Z00 LINE.(00,00).(00,01) OR     ZSW  END.(00,00)ZW    END.(00,00) OR     ZNW  END.(00,00) OR      AND     ZW  LIMBX072,36
Z00 LINE.(00,01)Z45 LINE.(00,00).(01,00) OR      AND      Z135LINE.(00,02).(01,02) OR      AND     2(00,01)ZN  CURVX072,48
Z90 LINE.(01,01)Z135LINE.(00,00).(00,01) OR      AND      Z45 LINE.(02,00).(02,01) OR      AND     2(01,01)ZE  CURVX072,60
Z00 LINE.(01,01)Z135LINE.(00,00).(01,00) OR      AND      Z45 LINE.(00,02).(01,02) OR      AND     2(01,01)ZS  CURVX072,72
Z90 LINE.(01,00)Z45 LINE.(00,00).(00,01) OR      AND      Z135LINE.(02,00).(02,01) OR      AND     2(01,00)ZW  CURVX072,84
ZN  EDGE.(00,00)ZS  EDGE.(00,00).(01,00) OR      AND      Z00 LINEX060,00
ZNW EDGE.(00,00)ZSE EDGE.(00,00).(01,01) OR      AND      Z45 LINEX060,72
ZW  EDGE.(00,00)ZE  EDGE.(00,00).(00,01) OR      AND      Z90 LINEX060,48
ZNE EDGE.(00,01)ZSW EDGE.(00,01).(01,00) OR      AND      Z135LINEX060,24
Z00 LINE.(00,00).(00,01).(00,02) AND     AND    2(00,01)Z00 LINEX060,00
Z45 LINE.(02,00).(01,01).(00,02) AND     AND    2(01,01)Z45 LINEX060,72
Z90 LINE.(00,00).(01,00).(02,00) AND     AND    2(01,00)Z90 LINEX060,48
Z135LINE.(00,00).(01,01).(02,02) AND     AND    2(01,01)Z135LINEX060,24

*CODENNL*02BY02
.(00,00)ZZERO    X180,00
.(00,00)ZONE     X180,09
Z45 LINE.(02,01)ZS  LINE.(00,00).(01,00) OR      AND     ZN  CURV.(00,01)ZE' CURV.(01(02) OR      AND     ZE  LIMB.(03,01
.(03,02) OR      AND     2(02,01)ZTWO     X180,18
.(00,00)ZTHREE   X180,27
.(00,00)ZFOUR    X180,36
.(00,00)ZFIVE    X180,45
.(00,00)ZSIX     X180,54
.(00,00)ZSEVEN   X180,63
.(00,00)ZEIGHT   X180,72
.(00,00)ZNINE    X180,81
```

```
A LOST 2       -012345678911234567892123456789312345678941234567895123456789612345678971234567898123456789912345-
                ZPICTURE
        000 000-                                                                                                         -00 000
        001 001-                                                                                                         -01 001
        002 002-                                                                                                         -02 002
        003 003-                                                                                                         -03 003
        004 004-                                                                                                         -04 004
        005 005-                    456701                                                                               -05 005
        006 006-                   34567012                                                                              -06 006
        007 007-                 12345670123                                                                             -07 007
        008 008-                012345670123                                                                             -08 008
        009 009-               701234    123                                                                             -09 009
        010 010-              670123     123                                                                             -10 010
        011 011-              67012      123                                                                             -11 011
        012 012-              6701      0123                                                                             -12 012
        013 013-              6701      0123                                                                             -13 013
        014 014-              670     67012                                                                              -14 014
        015 015-              670   4567012                                                                              -15 015
        016 016-                    456701                                                                               -16 016
        017 017-                 12345670                                                                                -17 017
        018 018-                 123456                                                                                  -18 018
        019 019-               7012345                                                                                   -19 019
        020 020-               70123                                                                                     -20 020
        021 021-               7012                                                                                      -21 021
        022 022-              67012                                                                                      -22 022
        023 023-              6701                                                                                       -23 023
        024 024-              6701                                                                                       -24 024
        025 025-             56701234                                                                                    -25 025
        026 026-             567012345                                                                                   -26 026
        027 027-            4567012345                                                                                   -27 027
        028 028-            45670123456                                                                                  -28 028
        029 029-            45670123 567012                                                                              -29 029
        030 030-            456701234567 12                                                                              -30 030
        031 031-             56701  456701                                                                               -31 031
        032 032-             567     5670                                                                                -32 032
        033 033-                      6                                                                                  -33 033
        034 034-                                                                                                         -34 034
        035 035-                                                                                                         -35 035
        036 036-                                                                                                         -36 036
        037 037-                                                                                                         -37 037
        038 038-                                                                                                         -38 038
        039 039-                                                                                                         -39 039
        040 040-                                                                                                         -40 040
        041 041-                                                                                                         -41 041
        042 042-                                                                                                         -42 042
        043 043-                                                                                                         -43 043
        044 044-                                                                                                         -44 044
        045 045-                                                                                                         -45 045
        046 046-                                                                                                         -46 046
        047 047-                                                                                                         -47 047
A LOST 2       -012345678911234567892123456789312345678941234567895123456789612345678971234567898123456789912345-
```

FIG. 5(*a*). The picture to be analysed. The origin of coordinates is the cell immediately beneath the Z of Z PICTURE. The picture is defined to be only 48 × 48 elements hence in the direction (down the page) we can only print lines 0 to 47. Each 'black' element is represented internally as a binary digit. For display purposes, however, the 'black' elements are numbered (on a scale of 8) in the horizontal direction.

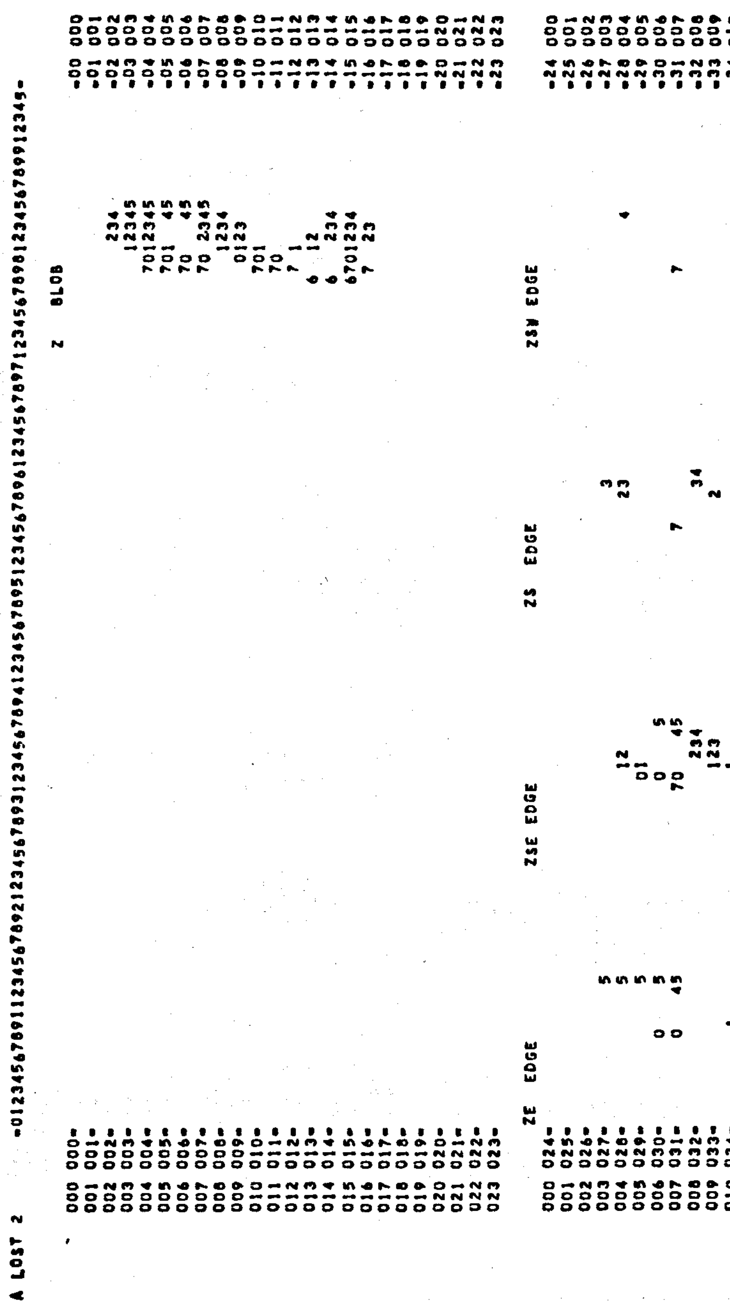

FIG. 5(*b*). The outcome of the first group of rules when applied to Fig. 5(*a*). Note that the 'origin cell' of the array ZN EDGE is at the absolute location $x=48$, $y=48$ as stated in the picture grammar.

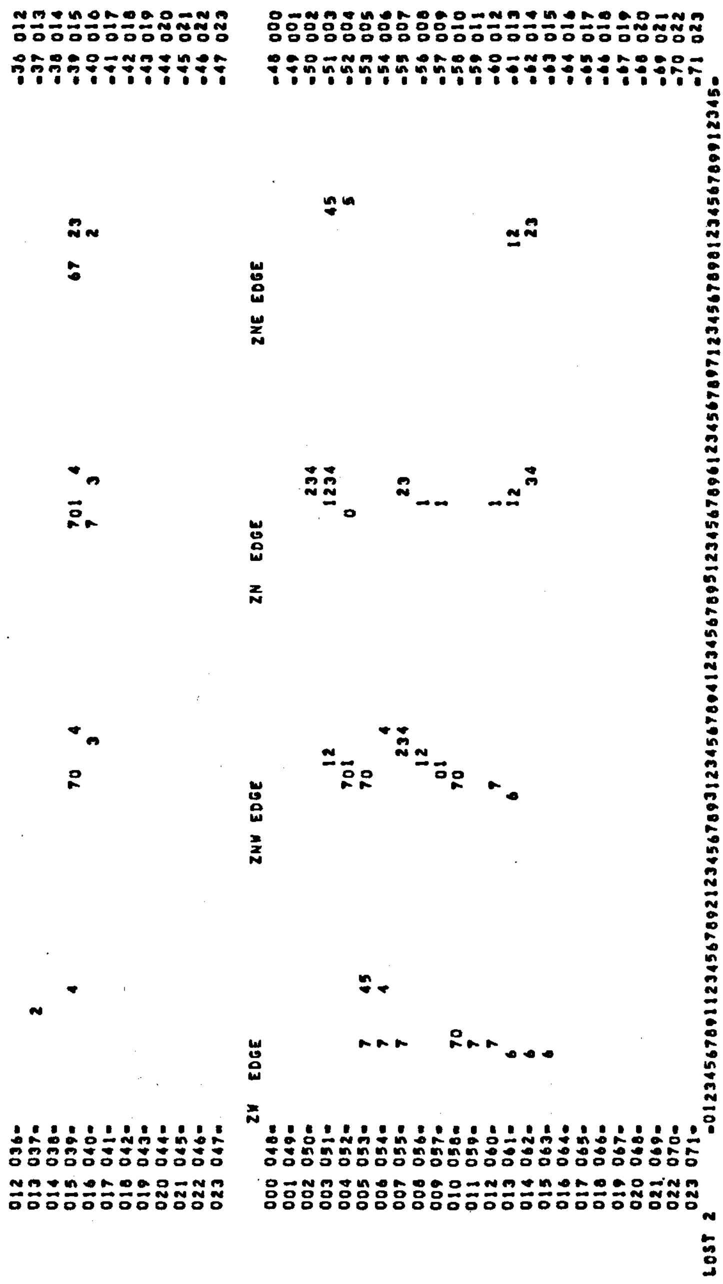

FIG. 5(b). (continued)

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A LOST 2       =0123456789112345678921234567893123456789412345678951234567896123456789712345678981234567899123456=

                ZE  EDGE    ZSE EDGE    ZS  EDGE    ZSW EDGE    ZW  EDGE    ZNW EDGE    ZN  EDGE    ZNE EDGE
        000 036=                                                                                               =36 000
        001 037=                                                                             5                 =37 001
        002 038=      6         0                                               0                              =38 002
        003 039=      6         0 2                                3             1                             =39 003
        004 040=                 12                                             01                             =40 004
        005 041=                                                   3                                           =41 005
        006 042=                                                                                               =42 006
        007 043=                            4                      3                                           =43 007
        008 044=                                                                                               =44 008
        009 045=                                                                                               =45 009
        010 046=                                                                                               =46 010
        011 047=                                                                                               =47 011

                ZE   END    ZW   END    ZSE  END    ZNW  END    ZS   END    ZN   END    ZSW  END    ZNE  END
        000 048=                                                                                               =48 000
        001 049=                                                                                               =49 001
        002 050=                                                                                               =50 002
        003 051=                                                   3                                           =51 003
        004 052=                                                                                               =52 004
        005 053=                                                                                               =53 005
        006 054=                                                                                               =54 006
        007 055=      6                                                                                        =55 007
        008 056=                                                                                               =56 008
        009 057=                                                                                               =57 009
        010 058=                                                                                               =58 010
        011 059=                                                                                               =59 011

                Z00 LINE    Z135LINE    Z90 LINE    Z45 LINE
        000 060=                                                                                               =60 000
        001 061=     5            2                     0                                                      =61 001
        002 062=                              6        70                                                      =62 002
        003 063=     5                     3  6          12                                                    =63 003
        004 064=                                        01                                                     =64 004
        005 065=                           34                                                                  =65 005
        006 066=                                                                                               =66 006
        007 067=      6          1                                                                             =67 007
        008 068=                                                                                               =68 008
        009 069=                                                                                               =69 009
        010 070=                                                                                               =70 010
        011 071=                                                                                               =71 011
A LOST 2       =0123456789112345678921234567893123456789412345678951234567896123456789712345678981234567899123456=
```

FIG. 5(*c*). The outcome of the second group of rules applied to the contents of Fig. 5(*b*).

```
A LOST 2        -012345678911234567892123456789312345678941234567895123456789612345678971234567898123456789912345-

                  Z00 LINE                 Z135LINE                Z90 LINE                Z45 LINE
            000 060-                                                                                          -60 000
            001 061-                                                                       2                  -61 001
            002 062-                                                                       2                  -62 002
            003 063-                                                                                          -63 003
            004 064-                                                                                          -64 004
            005 065-                                                                                          -65 005

                  ZN  LIMB    ZE  LIMB    ZS  LIMB    ZW  LIMB    ZN  CURV    ZE  CURV    ZS  CURV    ZW  CURV
            000 072-                                              2                                       -72 000
            001 073-                      1                                   7                           -73 001
            002 074-                                                                                      -74 002
            003 075-          7                                                                           -75 003
            004 076-                                                                                      -76 004
            005 077-                                                                                      -77 005
A LOST 2        -012345678911234567892123456789312345678941234567895123456789612345678971234567898123456789912345-
```

FIG. 5(*d*). The outcome of the third group of rules applied to the contents of Fig. 5(*c*).

```
A LOST 2        -012345678911234567892123456789312345678941234567895123456789612345678971234567898123456789912345-

                  ZZERO    ZONE     ZTWO     ZTHREE   ZFOUR    ZFIVE    ZSIX     ZSEVEN   ZEIGHT   ZNINE
            000 180-                                                                                      -80 000
            001 181-                3                                                                     -81 001
            002 182-                                                                                      -82 002
A LOST 2        -012345678911234567892123456789312345678941234567895123456789612345678971234567898123456789912345-
```

FIG. 5(*e*). 'Recognition' as obtained by applying the fourth group of rules to the contents of Fig. 5(*d*). Note that the array size is now 3×3 elements. In principle more than one figure could have been presented in the initial Z PICTURE. Their relative position and identity would have been reflected in this display.

page and y across it, following the numbering appearing in the picture frame. Following the label (Z) N EDGE a further pair of coordinates (048, 48) specify the location in computer memory at which the resultant picture (Z) N EDGE is to be stored. The first group of definitions in the grammar expresses eight EDGE definitions corresponding to eight points of the compass, and a further definition (Z) BLOB which merely collects together the results of all the EDGE definitions in a single picture called (Z) BLOB. The next set of rules in the grammar contains concatenations of EDGES to define LINES having four orientations 00, 45, 90, 135 and line ENDS with eight orientations. These in turn are concatenated to form CURVES (combinations of appropriately oriented lines), LIMBS (combinations of lines and ends) and LINES (combinations of lines). Each set of rules in the picture grammar is separated by a line beginning +CODE. . . .

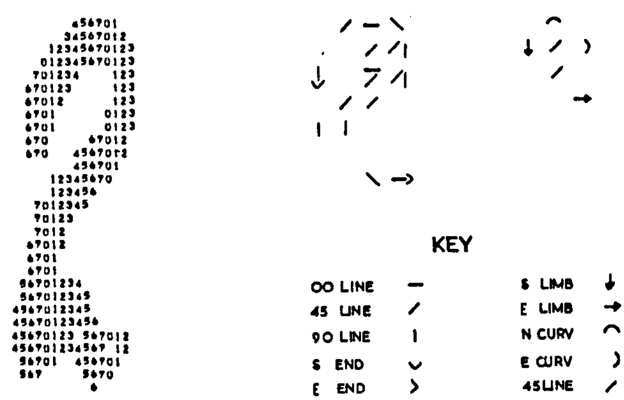
The action of the program is to apply each set of rules to the outcome of the previous set starting with a picture stored in computer memory (cf. the linguistic grammar). The performance of the program is monitored by having it print out those portions of its memory which currently contain a picture after each set of rules has been applied. The area of memory is—in effect—a matrix of 192×96 elements. At any one stage only a portion of this is in use, the portions being allocated by the coordinates associated with picture name given in the grammar, i.e., Z (N) EDGE (048, 48) is stored starting from location 48 (down), 48 (across). Thus the output for the first set of rules is as shown in Fig. 5(*b*).

The size of the initial picture (Z) PICTURE is 48×48 cells, the EDGE versions are, however, reduced in size to occupy only 24×24 cells. The necessity for this reduction in size is intimately connected with the form of picture grammar we have chosen to implement. A feature of the linguistic grammar was that substitutions were always defined for pairs of *adjacent symbols*, nowhere do we find a rule which calls for the replacement of symbols widely separated in the string being analysed. In spite of this immediate constituent or phrase structure restriction it is still possible to reflect with a single label (S) the structure of an extended utterance, because as we proceed with the analysis the string automatically shrinks by the very nature of the substitution operation. In the geometrical analysis we perform on a picture, the same immediate constituent limitation is imposed. If, however, we are able to label an extended property of a picture, e.g., a long line, with 'next to' concatenations, we need to draw together these local properties—hence this reduction in the size of the EDGE versions of the picture.

We can summarise the outcome of this 'parsing' process in a different form by collecting together the contents of several pictures, e.g., ENDS and LINES (Fig. 5(*c*)), and combining them into a single picture with a suitable pictorial convention to indicate the type of picture from which the entry originates (Fig. 6(*b*)). The results of the next level of description (Fig. 5(*d*)) containing CURVES, LIMBS and LINES can similarly be displayed pictorially (Fig. 6(*c*)).

They show that the program has adequately labelled the main features of this '2' and for the purposes of recognition we can define each numeral as being some combination of features. For a '2' this definition will involve a curve, a diagonal and a horizontal; and the last group of rules (Fig. 4) contains such a definition. Comparable definitions for the other numerals can be written.

Definitions of this type do not, strictly speaking, constitute a part of the grammar, and it is with the adequacy of the grammar that we are, at this point, concerned. Fig. 6(*c*) shows that certain regions of the '2', e.g., the intersection of the diagonal and the horizontal, are unlabelled. This arises from the adoption of 'lines' as syntactic categories: we are now studying a grammar having the same form but concerned exclusively with EDGES.



(*a*) (*b*) (*c*)

FIG. 6. A pictorial 'summary' of the results of the analysis. (*a*) The input picture Z PICTURE. (*b*) The contents of Fig. 5(*c*) super imposed and coded according to the convention given in the KEY. (*c*) The contents of Fig. 5(*d*) similarly encoded.

RELATION TO PHYSIOLOGY

It is possible to compare the organisation of this system with the organisation of the visual system, as revealed by microelectrode studies in the cat (Hubel & Wiesel 1962, 1965) and the frog (Lettvin, Maturana, McCulloch & Pitts 1959). Briefly the following points emerge:

(1) Cells in the visual cortex only respond to local properties of the visual scene, e.g., edges, line segments. This mirrors the immediate constituent constraint imposed for economic reasons in the picture grammar.

(2) The visual scene is portrayed many times over in the cortex in terms of the different picture properties, each portrayal being 'laid-out' two-dimensionally and 'in register' with all other portrayals. This corresponds to the sets of arrays which are also preserved 'in register', in the computer.

(3) In addition to cells portraying the local properties of corresponding regions of the retinal image, there are also cells (so-called 'complex' cells—

Hubel & Wiesel 1962) which indicate whether a particular local property occurs anywhere over a small area of the retinal image. Such cells are precisely what one would expect to find mediating the 'reduction' of scale (and resolution) injected into the picture grammar.

The detailed nature of the correspondence means that we can usefully consider the possible significance of discrepancies. For example, there are grounds for believing that the picture grammar is premature in beginning with EDGE definitions. In the visual system a considerable amount of processing—so called 'lateral inhibition'—precedes EDGE operations and is performed in the retina. Conversely we may ask of the physiologists what might correspond to certain features of our picture grammar which are designed to provide size invariance. This type of detailed cross-fertilisation is in many ways quite novel, at least with this subject matter.

The notation can also be used to express physiological results, e.g., the properties of a receptive field unit.

RELATION TO PSYCHOLOGY

Ultimately, the psychological relevance of this form of picture analysis will be in its ability to derive structural descriptions of pictorial objects which reflect our intuitions of their shape. To a limited extent the labelling already demonstrated achieves this: it will be more convincing, however, if we can, for example, show that the same grammar assigns adequate descriptions to objects which are generically different, e.g., fingerprints, chromosomes. It can already be shown, however, that by virtue of the way in which it computes picture labels, the system has some interesting weaknesses. Given a numerical value for the notion of local property, e.g., that no definition can refer to array elements separated by more than 10 units, the system is unable to judge the positions of an object relative to some frame, to better than 10 per cent (i.e., 1/10). This limitation appears in many forms of sensory judgment (Miller 1956). Again the system is unable to 'pick out' (i.e., uniquely label) one member of a large matrix of similar objects, e.g., a matrix of A's. This is a familiar experience. We overcome the limitation by 'tracing' or counting along a line with finger or pencil point. Significantly this use of a *pointer* changes the structure of the picture in a way which would also greatly help the computer system.

CONCLUSION

We can now return to a general remark made in the introduction. The essential characteristic of the system we have described is the volume of operations it involves. To calculate by hand the structural analysis illustrated earlier would occupy perhaps 2-3 hours for each numeral and would inevitably contain many mistakes. The validation of a picture grammar in terms of a whole alphabet and subsequently for other classes of picture would, therefore, be unthinkable except by computer. In that we already sense directions in which our approach requires further complications due to over-simplifications like assuming pictures to be only black or white, the claim that psychological theories are necessarily complex, and *require a computer to test them,* will need no further elaboration. In one way it is unfortunate that Artificial Intelligence has been so called, since it suggests that it is concerned with problems quite different from those traditionally studied by the biologist. In fact, however, both disciplines are concerned with the study of very complex systems and collaboration is becoming increasingly fruitful.

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