

# TO ARTIFICIAL 'INTELLIGENCE

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Preface

These are the collected lecture notes of the course, Artificial Intelligence 2, given at the University of Edinburgh in the academic year 1975/76 by the staff of the Department of Artificial Intelligence. Despite its title the course was introductory, requiring no previous knowledge of AI or Computer Science (The "2" is a code meaning "not for first years"). The course attracted students from: psychology; linguistics; philosophy; computer-science; mathematics and many other disciplines. It has now run for two years.

Teaching a new and multi-disciplinary course, like AI, is very hard. Even though we put a lot of work into it, we are still conscious of the need for improvement, especially in the teaching of programming to social science and arts students. By binding our notes into this volume we hope both to promote feedback and perhaps save others some work. The notes have, however, not been edited for a wider audience and still contain parochial references.

Rather than attempt a broad survey of the field we have tried to show how AI programs are built. This was done by taking a series of tasks; proposing and discussing ways of modelling them; then extending and debugging these models. Students eventually tried this for themselves in their projects. A lot of emphasis was placed on the acquisition of skills e.g. programming, writing robot operators; writing a context free grammar; line labelling polyhedral scenes etc. General issues were delayed until the students had acquired some grasp of the subject. Most discussion of these issues took place in class discussions and student presentations and so is not recorded in the notes.

These notes are divided into five sections: Representation of Knowledge; Natural Language; Visual Perception; Learning; and Programming. Page numbers are consecutive within sections and each has an appropriate prefix (e.g. RK39). The lectures were not given in this order. In particular the Representation of Knowledge and Programming lectures were closely integrated. The actual sequence of lectures is given in Appendix 2.

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During the two years the course has been running, a tremendous number of people have had a hand in it. We would like to thank the various: demonstrators; tutors; project supervisors; lecturers and examiners, without whom it would not have been possible. Although it is not possible to mention everyone, we would like to single out: Peter Buneman, the original organiser; Colin McArthur and Rosemary Robinson, who kept LOGO running; Aaron Sloman, our external examiner; and last but certainly not least, the secretaries: Jean, both Margarets, Peggy and Eleanor, who tirelessly produced this huge volume of notes.

Forward and backward deduction

Summary of LOGO Inference Package

Visual Perception

Structural Descriptions

Structural Descriptions

Structural Descriptions

Visual Perception

Interpretation, Semantics and Models

Object identification and the use of stored prototypes

Line Finding

Contribution to a theory of visual perception

Learning

Spinal's Chess-like player and Hill-climbing

Structural Learning and General Concepts

Perceptions

Deduction

Production systems

Schemata

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Instructions: Find the rule by which figure A has been changed to make figure B. Apply the rule to figure C. Select the resulting figure from figures 1 to 5.

Questions to ask yourself

- Can you do it?
- Is intelligence needed?
- Could we explain to someone how to do it?
- Could we write an instruction booklet?
- Would it be intelligent if a machine could do it?
- If it could do some such tasks, but not all?

First Recipe

- Consider the original instructions.
- Focus on the important parts of the instructions.
- Finding rule - positive and?
- Applying rule - probably straightforward.
- Selecting best answer - could involve some judgement.

Finding the Rule

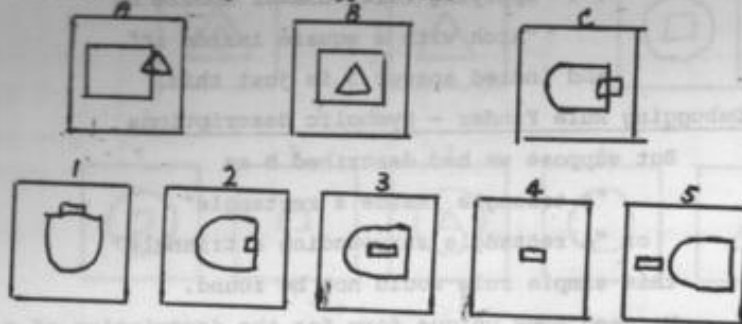
Because the problem is solved "in the head", the rule must apply to some description of A and produce a description of B.

1. Make a description of A.
2. Make a description of B.
3. Compare descriptions to find what must be done to one to produce the other.
4. Use English for descriptions.

### Geometric Analogy Problems

#### Introduction

Pick some task which involves intelligence and try to give a precise recipe for doing task, e.g. analogy tests.



Instructions: "Find the rule by which figure A has been changed to make figure B. Apply the rule to figure C. Select the resulting figure from figures 1 to 5."

#### Questions to ask yourself

- Can you do it?
- Is intelligence needed?
- Could we explain to someone how to do it?
- Could we write an instruction booklet?
- Would it be intelligent if a machine could do it?
- If it could do some such tasks, but not all?

#### First Recipe

Consider the original instructions.

Focus on the imprecise parts of the instructions.

Finding rule - creative act?

Applying rule - probably straightforward.

Selecting best answer - could involve some judgement.

#### Finding the Rule

Because the problem is solved "in the head" the rule must apply to some description of A and produce a description of B.

1. Make a description of A.
2. Make a description of B.
3. Compare descriptions to find what must be done to one to produce the other.
4. Use English for descriptions.

Example 1

A is "A rectangle with a triangle on its perimeter"

B is "A rectangle with a triangle inside it"

Rule is change "on its perimeter" to "inside it"

C is "Arch with a square on its perimeter"

∴ applying rule, answer should be

"Arch with a square inside it"

and indeed answer 3 is just this.

Debugging Rule Finder - Symbolic descriptions

But suppose we had described B as

"A triangle inside a rectangle"

or "A rectangle surrounding a triangle"

this simple rule would not be found.

We need some unique form for the description of a figure.

e.g. [inside triangle rectangle]

Where

1. We drop all superfluous words e.g. "a" and limit ourselves to the objects mentioned (triangle, rectangle) and the relationship between them (inside).
2. We decide always to replace all descriptions using "outside", "surrounding" etc. with the equivalent description using "inside".
3. The objects are put in some fixed (but arbitrary) order. In our case the inside object (triangle) always comes first.

The description [inside triangle rectangle] will be called a symbolic description. The first word (inside) is sometimes called the predicate and the remainder (triangle, rectangle) its arguments. The square brackets are currently just for punctuation. However, when we come to represent these symbolic descriptions in the computer we will see that the brackets are part of the syntax of the data-structure called lists.

Descriptions in example 1 become

A [on triangle rectangle]

B [inside triangle rectangle]

rule change "on" to "inside"

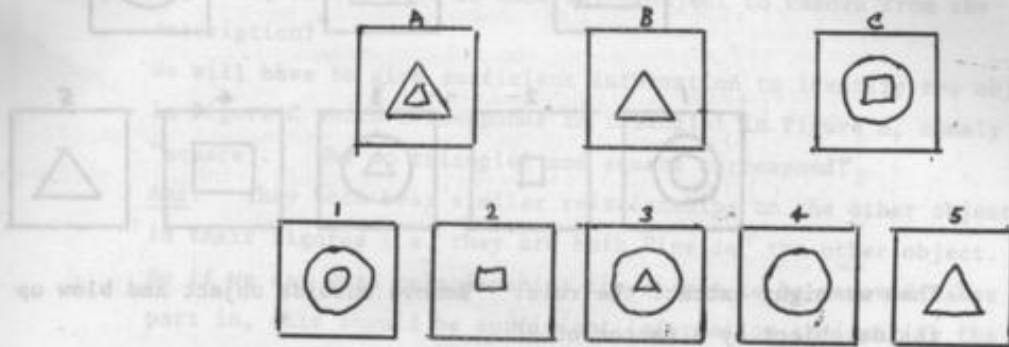
C [on square arch]

New description [inside square arch]

### More Debugging - More complete descriptions

Let us try this on another example:

#### Example 2



Descriptions A [inside triangle1 triangle2]

we must distinguish different objects

B ?

Rule: delete everything?

It would be a good idea to add a list of objects in the figure to our description, or we will not be able to separate answers 2, 4 and 5. It would also be a good idea to allow several relationships in a description.

So our general description becomes:

[objects in the figure] [relationships in the figure]

Try example again

A : [triangle1 triangle2] [inside triangle1 triangle2]

B : [triangle2]

Rule: remove "inside" object and any relationships it is involved in

C : [circle square] [inside square circle]

New description: [circle]

Which answer figure is this a description of?

### Even more Debugging - Similarity descriptions

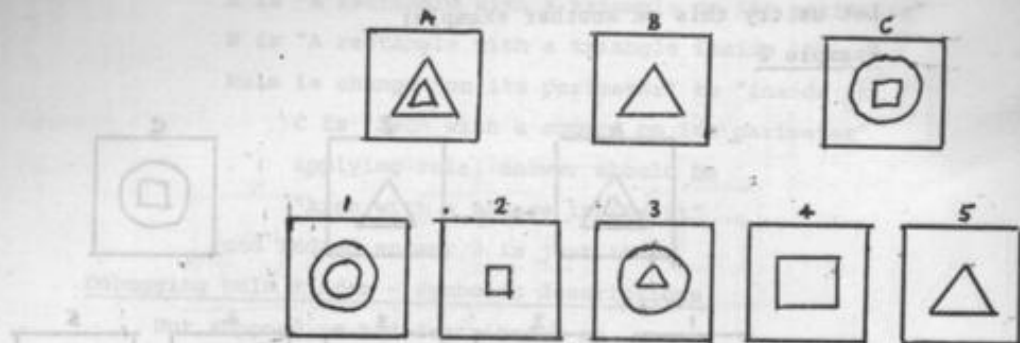
When we gave the triangle in figure B the same name as one of the triangles in figure A we were begging the question. Why are these two triangles matched? Ans. because the similarity between them is most direct.

But suppose that the answer was, as in



was not available but



Example 3

Then we might extract the rule: "Remove outside object and blow up inside object by a factor of 2"

i.e. There are 2 different correspondences between objects in figure A and figure B. From each correspondence we get a different rule, yielding a different answer. We must therefore distinguish objects in figure A from objects in figure B and then make any correspondences explicit.

Thus the descriptions become:

A : [ triangle1 triangle2 ] [ inside triangle1 triangle2 ]

B : [ triangle3 ]

Similarity 1 : [ Sim triangle2 triangle3 direct ] for example 2

Similarity 2 : [ Sim triangle1 triangle3 [scale 2] ] for example 3

means these 2 objects are identical if we apply this transformation to the first.

Making the Rule Precise

Each of the correspondences between objects in Figure A and Figure B gives rise to a different rule.

Can we now be more precise in our definition of a rule?

One thing a rule must do is to say which objects in Figure A correspond to objects in Figure B, and which objects in Figure A are just removed. For instance in our previous example the rules must say:

rule 1. [ Remove triangle1 ] [ Match triangle2 triangle3 ]

rule 2. [ Remove triangle2 ] [ Match triangle1 triangle3 ]

Remove Part

Consider the first rule.

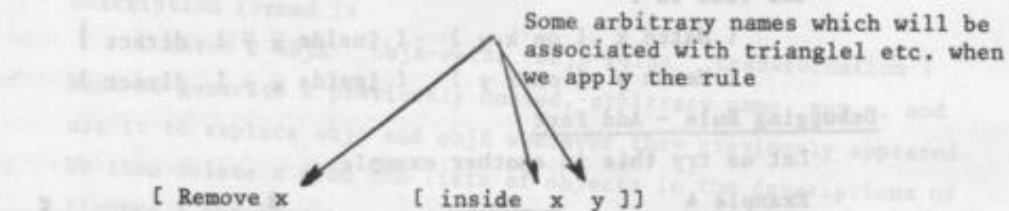
[ Remove triangle1 ] really means, remove "triangle1" from the

list of objects in the description of Figure A and also remove any relationships it is involved in.

But of course triangle1 is not mentioned in the description of Figure C, so how will we know which object to remove from the description?

We will have to give sufficient information to identify the object in Figure C which corresponds to triangle1 in Figure A, namely "square". Why do triangle1 and square correspond?

Ans. they both bear similar relationships to the other objects in their figures i.e. they are both "inside" the other object. So if we say what relationships the object to be removed takes part in, this should be sufficient information to identify the correct object in figure C.



#### Match Part

[ Match triangle2 triangle3 ] means replace triangle2 by triangle3 in the list of objects in the description of Figure A and replace all relations involving triangle2 with the relations involving triangle3.

To make this a rule that can be applied to Figure C we will again have to replace triangle2, triangle3 etc. with some arbitrary name which can be associated with any object.

We will have to add the relations that triangle2 is involved in so that the appropriate association is made.

We will have to add the relations that triangle3 is involved in so that we know what relationships the "new" object is to have.

We will also have to say what transformation must be applied to triangle2 to make it into triangle 3.

So the rule becomes:

```

[ Match y [ inside x y ] nil direct ]
  ^       ^       ^       ^       ^
instruction Joint name relations relations transformations
to "match" of both of y in of y in to be applied
objects Figure A Figure B
  
```

Does this rule totally describe changes?



### Previous Examples Revisited

The rule in example 3 is now

```
[ Remove y [ inside x y ] ]
[ Match x [ inside x y ] nil [ scale 2 ] ]
```

Does the rule totally describe changes?

Let us try to formalize the rule in example 1.

Our descriptions are now:

A : [ triangle1 rectangle1 ] [ on triangle1 rectangle1 ]

B : [ triangle2 rectangle2 ] [ inside triangle2 rectangle2 ]

C : [ square3 arch ] [ on square3 arch ]

Correspondences are :

[ Sim triangle1 triangle2 direct ]

[ Sim rectangle1 rectangle2 direct ]

The rule is :

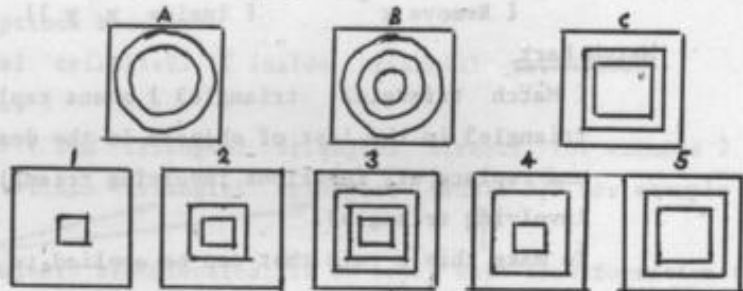
[ Match x [ on x y ] [ inside x y ] direct ]

[ Match y [ on x y ] [ inside x y ] direct ]

### Debugging Rule - Add Part

Let us try this in another example.

#### Example 4



We see that as well as Remove rules we need Addition rules.

[ Add object [ relations it is in involved in in Figure B ] ]

### An English Recipe

Are we now in a position to give a precise recipe for doing geometric analogy problems? Consider the task of finding the rule given the symbolic descriptions of figures A and B and similarities between objects in them.

i.e. given:

a description of figure A in the form

[ objects in figure A ] [ relationships between objects in figure A ]

a description of figure B in the form

[ objects in figure B ] [ relationships between objects in figure B ]

and various similarities in the form

[ Sim objA objB transformation ],

get a symbolic description of a rule which transforms figure A into figure B.

Suppose that there is at most one similarity description for each object in Figures A and B. If not then as in examples 2 and 3 we can form a different rule for each legal combination of similarity descriptions (we might want to make the "most likely" rule first and see if this produces one of the alternative answers). We can now describe how to make the rule description.

Each similarity description, e.g.,

[ Sim objA objB transformation ]

is used in turn to form a "Match" description.

Let objA-relns be those relationships in the description of figure A which involve objA. Similarly for objB-relns. Then the Match description formed is

[ Match objA objA-relns objB-relns transformation ]

Next we generate a previously unused, arbitrary name, say x, and use it to replace objA and objB wherever they previously appeared. We then delete x from the lists of objects in the descriptions of figures A and B.

When this process is finished we look at the lists of objects in the descriptions of figures A and B. For each object, objA, left in the description of A we form a "Remove" description. If objA-reln is defined as before the form of this description is

[ Remove objA objA-reln ]

As before we can replace objA wherever it occurs with some previously unused arbitrary name, say y.

Similarly for each object, objB, left in the description of figure B we form an "Add" description of the form

[ Add objB objB-reln ]

and replace objB with, say, z throughout.

Finally, we put the "Matches", "Removes" and "Adds" together to form the rule.

#### \* Exercise 1.1

Try to write an English recipe for the task of applying the rule description to the description of figure C, to form the description of the answer figure. What are the difficulties?

### Eulogy on Computers

We have made instructions more and more precise - how do we know when to stop? Ans. when we can express instructions in form of a computer program that works.

How close are we to that?

Can we represent description of figures and rules in computer?

Ans. Yes, using list data-structures. We will see how in programming lectures.

Can we automatically form descriptions of figures from, say, input from a T.V. camera?

Ans. Yes - this problem will be addressed in the lectures on visual perception. The impatient can read the recommended paper by Evans (see below)

Can we write a computer program which can carry out the English recipe described in the last section? i.e. form the descriptions of the rule given the descriptions of the figures.

Ans. Yes - using simple list manipulation programs - breaking down - copying and building up lists.

Can we automatically apply rules to description of figures?

Ans. Yes - but rather harder list manipulation involving pattern matching.

### Recommended Reading

T.G.Evans "A Heuristic Program to solve Geometric Analogy Problems". Spring J.S.C.C., April 1964.

These lectures were based on Evans' work but are not an exact description of it.

also section 1.1 of

Minsky, M. and Papert, S. "Artificial Intelligence Progress Report". AI Memo No. 252, MIT. January 1972.

### Exercises

1.2.

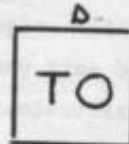


- (a) Give a symbolic description of A, B and C and the similarities between objects in A and B.
- (b) Give a symbolic description of the rule which transforms A to B.
- (c) If this rule were applied to your description of C what would be the resulting description, and what would the answer figure look like?

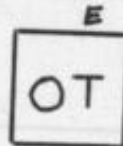
\* 1.3.



- (a) Repeat 2(a), (b) and (c) with the above figure.
- (b) Suppose figure C had been



What goes wrong when we try to apply the description of the rule to the description of D? How might we amend the rule description so that it applies to the description of D and produces a description of E?



[Discussion point - Does the new kind of rule description create problems for the rule-finding and rule-applying recipes?]

\* 1.4.

Discuss briefly the statement

"Since a computer program can now do analogy problems it makes no sense to use them on human intelligence tests."

\* 1.5.

Design a geometric analogy problem which the recipes we have been building could not cope with. Explain why they could not cope. If possible suggest ways of amending the recipes to deal with the new situation.

4th October, 1975.

AB/3.

THE MISSIONARIES AND CANNIBALS PROBLEM(The Problem)

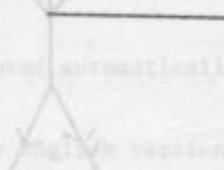
Three missionaries and three cannibals seek to cross a river from the left bank to the right bank. A boat is available which will hold two people and which can be navigated by any combination of missionaries and cannibals involving one or two people. If the missionaries on either bank of the river are outnumbered at any time by cannibals, the cannibals will indulge in their anthropophagic tendencies and do away with the missionaries. When the boat is moored at a bank, it is counted as part of the bank for these purposes.

Find the simplest schedule of crossings that will permit all the missionaries and cannibals to cross the river safely.

W  
C

BOAT

2-2

Solution

1. Initial state: 3 missionaries and 3 cannibals on the left bank, 0 on the right bank.
2. Solution as path of state space exploration.
3. Find solution by exploring tree space.
4. "Depth first search" of state space.
5. Advantages of planning in solving this problem.

Practice Recipe

Can we design a "practice recipe" for finding a solution to this problem? In order to guarantee the procedure about recipe-finding we at making it a computer program from the state space approach. The task initially, to that of writing a computer program that will merely check our solution, and then develop it into a program which finds the solution itself. On the way we will introduce numerous ideas about programming and problem solving.

MISSIONARIES AND CANNIBALS PROBLEM

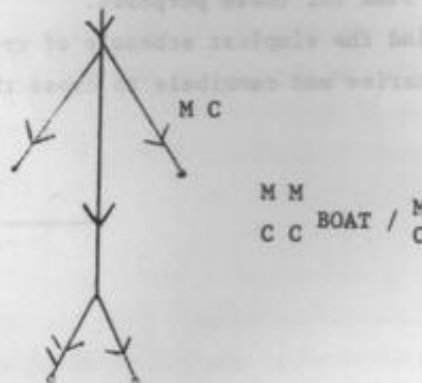
(The Approach)

Introduction

Consider M and C problem presented in handout.

Do it yourself and note the following points:

1. More precise statement of problem in terms of initial and goal states and legal moves.
2. Description of States e.g.  $\begin{matrix} M & M \\ C & C \end{matrix}$  BOAT / M C
3. Descriptions of Moves e.g. move a missionary and a cannibal from left to right.
4. Search Tree, e.g.



5. Solution as path of tree and/or sequence of moves.
6. Find solution by exploring tree.
7. "Depth first search" of real missionary and cannibal.
8. Advantages of planning in advance.

Precise Recipe

Can we design a "precise recipe" for finding a solution to this problem? In order to guarantee the precision of our recipe let us aim at making it a computer program from the start. Let us weaken the task initially, to that of writing a computer program that will merely check our solution, and then develop it into a program which finds the solution itself. On the way we will introduce numerous ideas about programming and problem solving.



What will we need?

1. A formalization of the problem, e.g. in terms of states and moves. How to get from the natural language input to this formalization is an issue we delay tackling until we get to Natural Language part of course.
2. We need to represent "states" inside the computer. We will also need to be able to apply moves to these states to produce new states. It seems natural to represent the states and the objects to be moved as static structures, for instance lists, and represent the move-maker as a procedure to manipulate these lists.

e.g. States represent  $\begin{matrix} M & M & & & & & M \\ C & C & & & & & C \end{matrix} \text{ BOAT} / \text{ as}$

a list called leftbank = [M M C C BOAT]

a list called rightbank = [M C]

Moves represent "move a missionary and a cannibal from left to right" in two parts.

Part 1 as a list of things to be moves, i.e. [M C BOAT] called the "movelist".

Part 2 as a program to transfer these things from one bank to the other, called the Move-left-to-right procedure.

e.g. To Move-left-to-right the movelist

Make new leftbank, old leftbank without the movelist

Make new rightbank, old rightbank with the movelist.

end.

(Note the boat is moved automatically by including it in movelist.)

Solution Checker

If we could turn our English version of the move-left-to-right procedure into a computer program, together with a move-right-to-left procedure, and if we could make leftbank and rightbank take their initial values then we could use the computer to check potential solutions

i.e. we need procedure

To Start-Missionary-and-Cannibal

Make leftbank be [M M M C C C BOAT]

Make rightbank be the empty list

end.

In order to be able to do these things, we are going to learn something about programming which is the subject of the next lecture.

AI2  
1975/76

RK.13

8th October, 1975.  
AB/7.

### The Missionaries and Cannibals Problem

(Building the program)

#### A Solution Checking Program

Armed with our knowledge of programming we can now try to make our recipe for a solution checker more precise.

Leftbank and Rightbank will be variables. Their values at any one time will be the current states of the left and right banks. These variables cannot be local to any of our procedures or their values would be lost when the procedures were exited. Therefore we will not declare them as new and they will become global variables, i.e. always accessible.

The procedures translate fairly directly.

i.e.

```
TO MOVELEFTOR 'MOVELIST
10 MAKE 'LEFTBANK WITHOUT :MOVELIST :LEFTBANK
20 MAKE 'RIGHTBANK WITH :MOVELIST :RIGHTBANK
END
```

similarly

```
TO MOVERTOL 'MOVELIST
10 MAKE 'RIGHTBANK WITHOUT :MOVELIST :RIGHTBANK
20 MAKE 'LEFTBANK WITH :MOVELIST :LEFTBANK
END
```

```
TO STARTMANDC
10 MAKE 'LEFTBANK [M M M C C C BOAT]
20 MAKE 'RIGHTBANK [ ]
END
```

It is necessary to define the subprocedures WITH and WITHOUT. WITH is relatively easy, but WITHOUT is much harder and needs concepts we have not yet introduced, so we delay consideration of it until later in the course.

Let us also define a procedure to tell us the current state. Otherwise we will find it difficult to remember how we are doing.

```
TO PRINTSTATE
10 PRINTLEFTBANK
20 PRINTRIGHTBANK
END
```

TO PRINTLEFTBANK

10 TYPE 'LEFTBANK

20 TYPE SPACE

30 TYPE 'IS

40 TYPE SPACE

50 TYPE :LEFTBANK

60 TYPE NL

TO PRINTRIGHTBANK

10 TYPE 'RIGHTBANK

20 TYPE SPACE

30 TYPE 'IS

40 TYPE SPACE

50 TYPE :RIGHTBANK

60 TYPE NL

END

### Exercises

- 2.1 PRINTLEFTBANK and PRINTRIGHTBANK are very similar. Can you write a procedure with one input which can do the work of both?
- 2.2 These procedures are provided on the library MANDC1 (Do LIB 'MANDC1). Try solving the M & C problem, at the terminal, using them.

### Solution Checking

Using the procedures introduced, we can try solving the problem "by hand", but using the computer to keep track of where we are. We use the procedures STARTMANDC, MOVELTOR, MOVERTOL and PRINTSTATE. For example,

1:STARTMANDC

1:PRINTSTATE

LEFTBANK IS [M M M C C C BOAT] ← starting position

RIGHTBANK IS [ ]

1:MOVELTOR [M C BOAT]

1:PRINTSTATE

LEFTBANK IS [M M C C]

RIGHTBANK IS [M C BOAT]

1:MOVERTOL [M BOAT]

1:PRINTSTATE

RK.15

LEFTBANK IS [M M C C M BOAT]

RIGHTBANK IS [C]

1: MOVELTOR [M C BOAT]

1: PRINTSTATE

LEFTBANK IS [M C M]

RIGHTBANK IS [C M C BOAT]

after these moves, Missionary  
on rightbank gets eaten

1: STARTMANDC

start over again

1: MOVELTOR [C C BOAT]

1: PRINTSTATE

try a different first move

LEFTBANK IS [M M M C]

RIGHTBANK IS [C C BOAT]

#### APPLYMOVE

It seems a bit clumsy to have to specify MOVELTOR or MOVERTOL each time, and also unnecessary. The computer itself ought to be able to figure out which way to move next. How? Suppose, for instance, we are in this situation:

1: PRINTSTATE

LEFTBANK IS [M C BOAT]

RIGHTBANK IS [M C M C]

which way should we move next? Obviously, since the boat is on the LEFTBANK, we have to MOVELTOR.

So if we could get the computer to see which bank the boat is on, then we ought to be able to write a single procedure APPLYMOVE which can decide to MOVELTOR or MOVERTOL as appropriate.

#### Writing APPLYMOVE

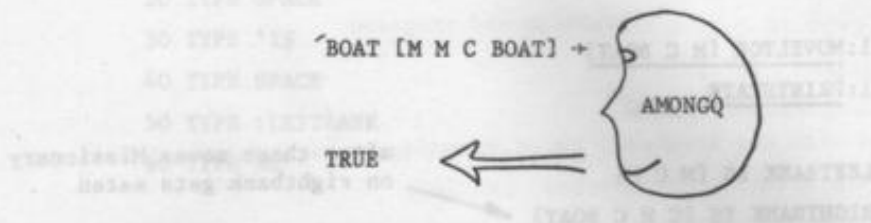
We now try to write the procedure APPLYMOVE. Like MOVELTOR and MOVERTOL it takes a single input, a list of what is to be moved across the river. Let us call it MOVELIST, so we can type in

1: TO APPLYMOVE ^MOVELIST

What do we want APPLYMOVE to do? Well, if the BOAT is at LEFTBANK, we want it to MOVELTOR the MOVELIST and that's all, so we type:

&:10 IF AMONGO ^BOAT :LEFTBANK THEN MOVELTOR :MOVELIST AND STOP

We need a procedure called AMONGQ whose arguments are an item and a list of items, which looks to see whether the item appears in the list. If it does, the procedure returns TRUE; if not, FALSE:



So we have:

```

1:PRINT AMONGQ 'BOAT [M M C BOAT]
TRUE
1:PRINT AMONGQ 'CAT [BOY GIRL CAT DOG]
TRUE
1:PRINT AMONGQ 15 [21 12 212]
FALSE
1:PRINT AMONGQ FIRST [MAN HUMAN CHILD] [CHIMPANZEE MAN ELEPHANT]
TRUE
  
```

In programming lectures we will see how to write AMONGQ

Go back to writing APPLYMOVE

```

&:20 IF AMONGQ 'BOAT :RIGHTBANK THEN MOVERTOL :MOVELIST AND STOP
and that's it:
  
```

&:END

Now, if we SHOW APPLYMOVE, we have

```

TO APPLYMOVE 'MOVELIST
10 IF AMONGQ 'BOAT :LEFTBANK THEN MOVELTOR :MOVELIST AND STOP
20 IF AMONGQ 'BOAT :RIGHTBANK THEN MOVERTOL :MOVELIST AND STOP
END
  
```

That looks O K, so let us try using it in our instructions to the computer:

```

1:STARTMANDC
1:PRINTSTATE
  
```

```

LEFTBANK IS [M M M C C C BOAT]
RIGHTBANK IS [ ]
  
```

```

1:APPLYMOVE [C BOAT]
1:PRINTSTATE
  
```

```

LEFTBANK IS [M M M C C]
RIGHTBANK IS [C BOAT]
  
```

RK.17

1:APPLYMOVE [C BOAT]

1:PRINTSTATE

LEFTBANK IS [M M M C C C BOAT]

RIGHTBANK IS [ ]

1:APPLYMOVE [C C BOAT]

1:PRINTSTATE

LEFTBANK IS [M M M C]

RIGHTBANK IS [C C BOAT]

### Simple interaction

Even with APPLYMOVE we still have to do a lot of unnecessary typing. Why not write a simple program that knows that we want to STARTMANDC and then specify a sequence of moves, with a PRINTSTATE to be done after each? Let's try:

TO MANDC

10 STARTMANDC

20 MAKEMOVES

END

and

TO MAKEMOVES

10 REQUESTAMOVE

20 APPLYMOVE IT

30 MAKEMOVES

END

where we use

TO REQUESTAMOVE

10 PRINTSTATE

20 PRINT [TYPE A MOVELIST]

30 GETLIST

40 IF AMONGQ 'BOAT IT THEN RETURN IT

50 PRINT [YOU FORGOT THE BOAT , DUMMY : TRY AGAIN]

60 REQUESTAMOVE

END

This line reads in a movelist and makes a list out of it

which is then returned



This makes things much easier. For example:

1: MANDC

LEFTBANK IS [M M M C C C BOAT]

RIGHTBANK IS [ ]

[TYPE A MOVELIST]

DATA: C C BOAT

LEFTBANK IS [M M M C]

RIGHTBANK IS [C C BOAT]

[TYPE A MOVELIST]

DATA: C BOAT

LEFTBANK IS [M M M C C BOAT]

RIGHTBANK IS [C]

[TYPE A MOVELIST]

DATA: C C

[YOU FORGOT THE BOAT , DUMMY :TRY AGAIN]

LEFTBANK IS [M M M C C BOAT]

RIGHTBANK IS [C]

[TYPE A MOVELIST]

DATA: C C BOAT

LEFTBANK IS [M M M]

RIGHTBANK IS [C C C BOAT]

#### Towards an M&C solver

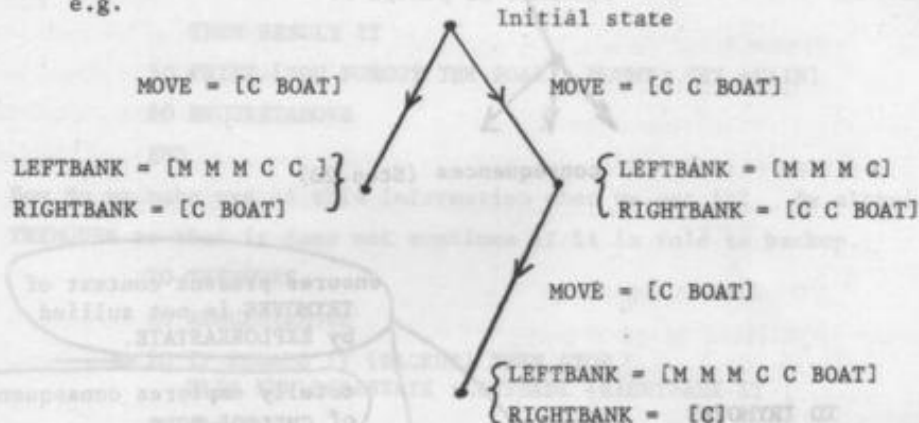
Although so far we have been doing all the problem solving, remember that our goal is to write a LOGO program that can solve the M&C problem by itself. We try gradually working towards such a program.

#### Backup

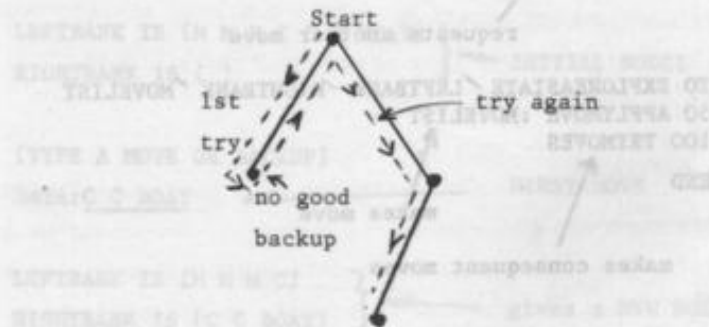
```
We have      TO MAKEMOVES
              10 REQUESTAMOVE
              20 APPLYMOVE IT
              30 MAKEMOVES
              END
```

But what happens if we make a mistake? We have to start again from the beginning. It would be nice to be able to "backup", i.e. to reverse the last move and try again. We recognise that we are really searching a tree

e.g.



Suppose we decide that we are in a blind alley and we want to "backup" and try again?

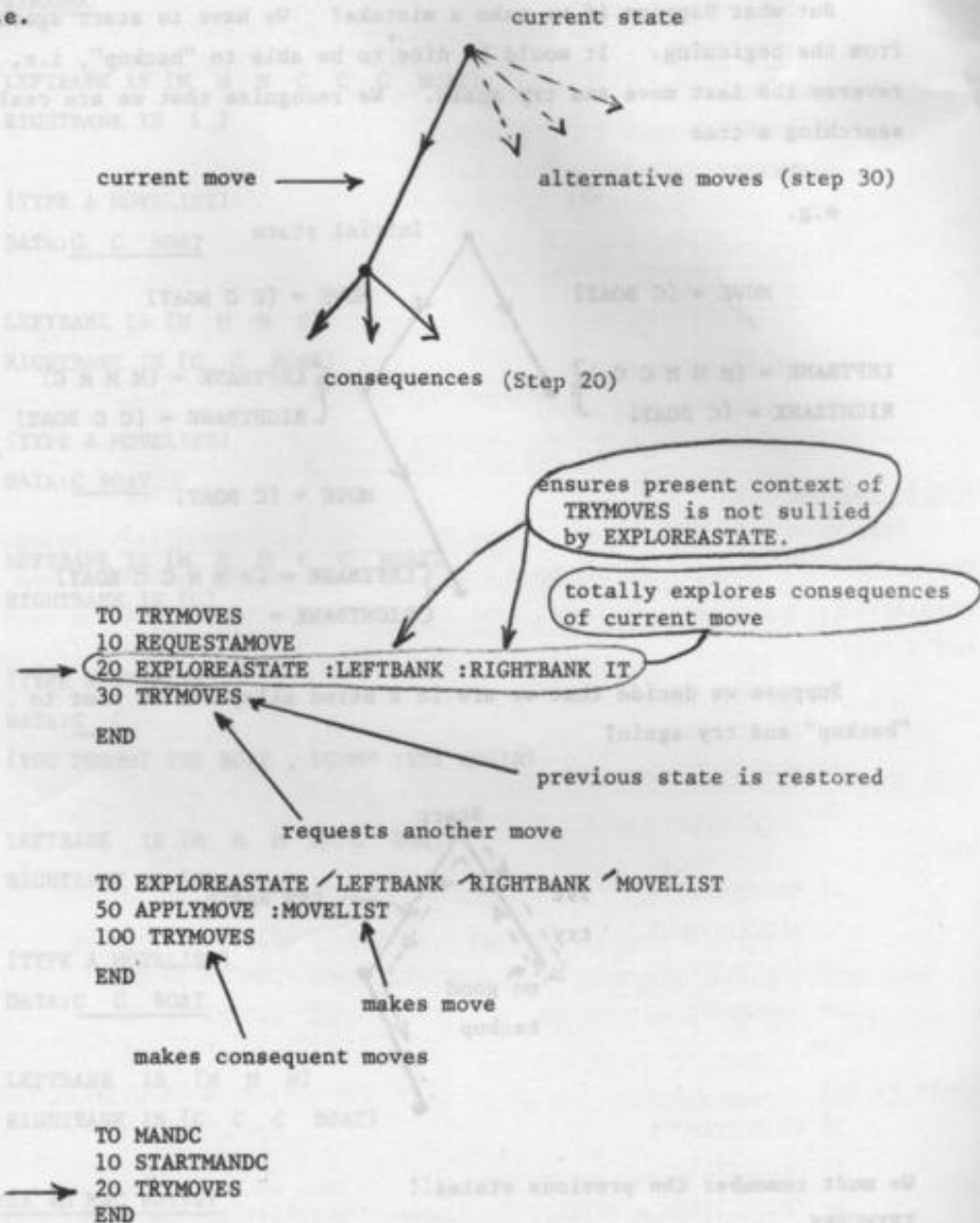


We must remember the previous states!!

#### TRYMOVES

Change MAKEMOVES so that instead of just applying the move at step 20 it also explores all the consequences of applying the move. i.e. it tries further moves. If these consequences are not to our liking we can decide to terminate step 20 and go on with step 30 which tries alternative moves

i.e.



# REQUESTAMOVE

How do we tell the program we have made a mistake and wish to backup? One answer, just say "backup" when it asks for our next move, i.e. after REQUESTAMOVE.

```

      TO REQUESTAMOVE
      10 PRINTSTATE
      → 20 PRINT [TYPE A MOVE OR BACKUP]
      30 GETLIST
      → 40 IF EITHER AMONGQ BOAT IT
           OR EQUALQ IT [BACKUP]
           THEN RESULT IT
      50 PRINT [YOU FORGOT THE BOAT , DUMMY; TRY AGAIN]
      60 REQUESTAMOVE
      END

```

How do we make use of this information when we get it? By altering TRYMOVES so that it does not continue if it is told to backup.

```

      TO TRYMOVES
      10 REQUESTAMOVE
      → 20 IF EQUALQ IT [BACKUP] THEN STOP
           ELSE EXPLOREASTATE :LEFTBANK :RIGHTBANK IT
      30 TRYMOVES
      END

```

Now try on computer.

1:MANDC

```

LEFTBANK IS [M M M C C C BOAT] }
RIGHTBANK IS [ ] } → INITIAL NODE1

```

[TYPE A MOVE OR BACKUP]

DATA:C C BOAT ← FIRST MOVE

```

LEFTBANK IS [M M M C] }
RIGHTBANK IS [C C BOAT] } → gives a NEW NODE2

```

[TYPE A MOVE OR BACKUP]

DATA:C BOAT ← SECOND MOVE from there

```

LEFTBANK IS [M M M C C BOAT] }
RIGHTBANK IS [C] } → gives a NEW NODE3

```

[TYPE A MOVE OR BACKUP]

DATA:M C BOAT ← THIRD MOVE

LEFTBANK IS [M M C]

RIGHTBANK IS [C M C BOAT]

}

← gives a state where  
the Cs eat a M.

[TYPE A MOVE OR BACKUP]

DATA: BACKUP

← so BACKUP

LEFTBANK IS [M M M C C BOAT]

RIGHTBANK IS [C]

}

← to NODE3

[TYPE A MOVE OR BACKUP]

DATA: M BOAT

← and try a different move

LEFTBANK IS [M M C C]

RIGHTBANK IS [C M BOAT]

Checking for solution

In exploring a new state we ought at least to notice when we have solved the problem. This is easily done, by adding a new line (line 80) to EXPLOREASTATE:

TO EXPLOREASTATE LEFTBANK RIGHTBANK MOVELIST

50 APPLYMOVE :MOVELIST

→ 80 IF SUCCEEDEDQ THEN PRINT 'SUCCESS AND QUIT

100 TRYMOVES

END

Here we have assumed the existence of a predicate SUCCEEDEDQ which outputs TRUE when the M&C problem is solved. How could we write such a predicate? One simple way is to notice that there is somebody on the LEFTBANK until the problem is solved, so we could check for that condition:

TO SUCCEEDEDQ

10 RESULT EMPTYQ :LEFTBANK

END

Checking for cannibalism

In a similar way we can arrange for EXPLOREASTATE to check whether the cannibalism condition is violated. Adding an appropriate command to EXPLOREASTATE is straightforward:

```
TO EXPLOREASTATE LEFTBANK RIGHTBANK MOVELIST
```

```
50 APPLYMOVE :MOVELIST
```

```
→ 60 IF MISSIONARIESEATENQ THEN STOP
```

```
80 IF SUCCEEDEDQ THEN PRINT 'SUCCESS AND QUIT
```

```
END
```

But then we have to spell out the predicate MISSIONARIESEATENQ. Well for a start, missionaries get eaten if they get eaten either on the LEFTBANK or on the RIGHTBANK, so if we invent a subsidiary predicate MEATENQ that worries only about one bank at a time then we can write

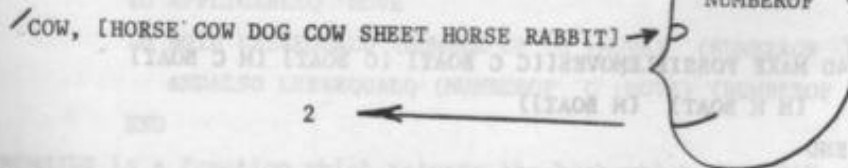
```
TO MISSIONARIESEATENQ
```

```
10 RESULT EITHER MEATENQ :LEFTBANK OR MEATENQ :RIGHTBANK
```

```
END
```

So under what conditions do the missionaries on a bank get eaten? Clearly if there are more cannibals there than missionaries. But this means that we need to be able to count the number of missionaries (or cannibals) on a bank. How do we do this? By our favourite trick of simply supposing a suitable procedure to exist, and then worrying about how to define it later.

So let us assume that we have available a procedure NUMBEROF which takes two arguments, an item and a list of items, and returns the number of times the item occurs in the list:



So NUMBEROF is in several ways analogous to AMONGQ, but whereas AMONGQ merely tells whether or not an item occurs at all, NUMBEROF tells how many times it occurs:

```
1:PRINT NUMBEROF 'COW [HORSE COW DOG COW SHEEP RABBIT]
```

```
2
```

```
1:PRINT NUMBEROF 'M [M C M BOAT]
```

```
2
```

```
1:PRINT NUMBEROF 'M [C C C]
```

```
0
```

So now we can write MEATENQ. The condition that there are more cannibals than missionaries on some BANK becomes just:



```
GRTRQ (NUMBEROF C :BANK) (NUMBEROF M :BANK)
```

But this can't be quite right, since when the number of missionaries is zero it doesn't matter how many cannibals there are. In other words, there have to be some missionaries present if any are to be eaten.

This gives us:

```
TO MEANTENQ 'BANK
10 BOTH GRTRQ (NUMBEROF 'C:BANK) (NUMBEROF 'M:BANK)
   ANDALSO GRTRQ (NUMBEROF 'M:BANK) 0
END
```

Exercise 2.3 Add all the changes made so far to the file MANDC1.

Try running MANDC. You may find it more helpful to make line 60 of EXPLOREASTATE print out an informative message, perhaps:

```
→ 60 IF MISSIONARIESEATENQ THEN PRINT [MISSIONARIES EATEN,
      MOVE REJECTED]
```

#### Generating applicable moves

By now the program is doing all the work except for the actual selection of moves, so the last step is to have it do this as well.

How can it? What basis is there for choosing moves? One way is to simply let it try all the possible moves in turn. This is perfectly reasonable, since there are only five of them. So let us begin by making sure that some list contains all five of these possible moves:

```
TO STARTMANDC
10 MAKE /LEFTBANK [M M M C C C BOAT]
20 MAKE /RIGHTBANK [ ]
→ 40 MAKE POSSIBLEMOVES[[C C BOAT] [C BOAT] [M C BOAT]
   [M M BOAT] [M BOAT]]
END
```

Then in EXPLOREASTATE, we replace the line telling it to TRYMOVES typed in by us, by a line telling it to TRYALL :POSSIBLEMOVES (see line 100 - below). And how should it TRYALL? Simply by trying one at a time:.

```
TO TRYALL :SETOFMOVES
10 IF EMPTYQ :SETOFMOVES THEN STOP
20 EXPLOREASTATE :LEFTBANK :RIGHTBANK FIRST :SETOFMOVES
30 TRYALL BUTFIRST :SETOFMOVES
END
```

We have to change MANDC in the same way:

```

    TO MANDC
    10 STARTMANDC
    → 20 TRYALL :POSSIBLEMOVES
    → 30 PRINT [NO SOLUTION FOUND]
    END

```

(line 30 is justified because if the program does try all possible moves without meeting success, it will indeed have failed.)

There is only one snag left now which is that not all moves are necessarily applicable to a particular state. For example, if we have LEFTBANK IS [M C BOAT] then it is impossible to move two cannibals across! What should we do about this? One possibility would be to modify TRYALL so that it tries only applicable moves, but it seems simpler to add a further test to EXPLOREASTATE, but this time before the move:

```

    TO EXPLOREASTATE 'LEFTBANK 'RIGHTBANK 'MOVELIST
    → 40 IF NOT APPLICABLEQ :MOVELIST THEN STOP
    50 APPLYMOVE :MOVELIST
    60 IF MISSIONARIESEATENQ THEN STOP
    80 IF SUCCEEDEDQ THEN PRINT 'SUCCESS AND QUIT
    → 100 TRYALL :POSSIBLEMOVES

```

What decides whether a move is applicable? Clearly there must be at least as many missionaries on the bank as are specified in the move, and similarly for cannibals:

```

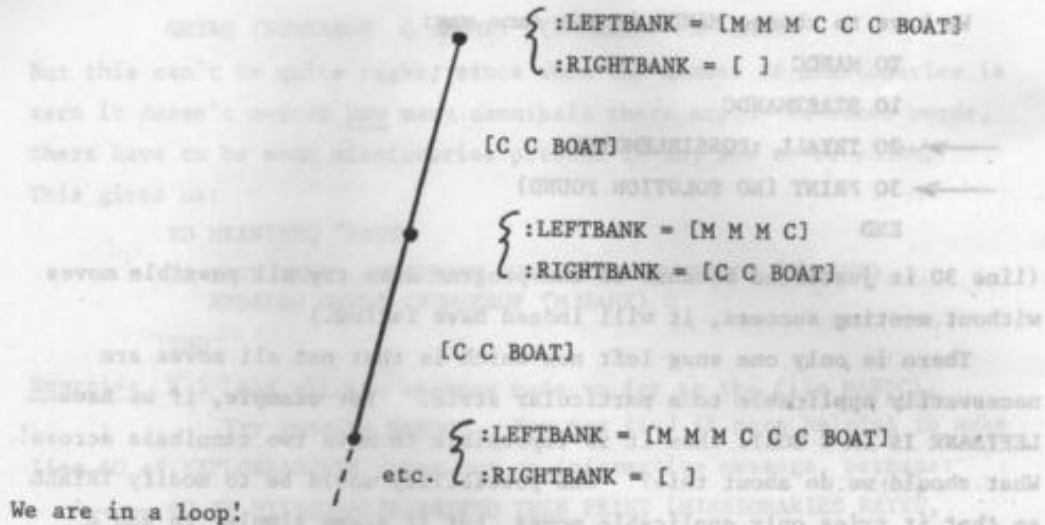
    TO APPLICABLEQ 'MOVE
    10 BOTH LESSEQUALQ (NUMBER OF 'M :MOVE) (NUMBER OF 'M FROMSIDE)
    ANDALSO LESSEQUALQ (NUMBER OF 'C :MOVE) (NUMBER OF 'C FROMSIDE)
    END

```

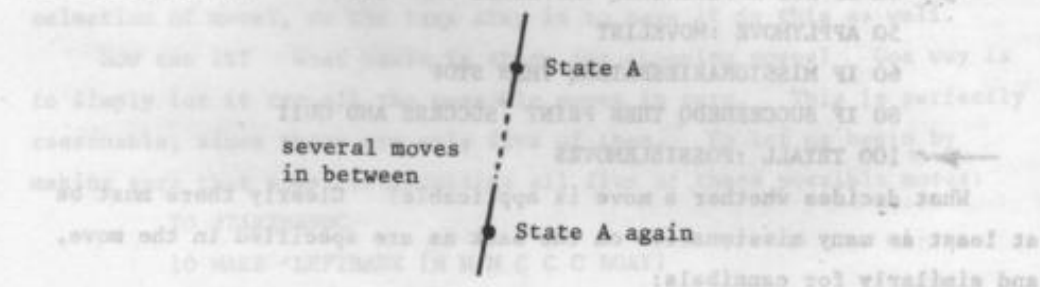
FROMSIDE is a function which returns the bank which the BOAT will be leaving from. Could you write it?

### Looping

Try above procedure out acting as devils advocate



We could avoid this particular loop by ensuring that we do not immediately reverse a step we have just made. Unfortunately there are more subtle loops.



Note that, if we have a solution with repeated states then we can modify it to get a simpler solution without repeated states. Therefore a solution with repeated states is not the simplest solution, which is what is required.

To avoid loops we need to keep track of which states we have seen before and avoid repeatedly exploring them. How shall we do this?

As always, the appropriate changes to EXPLOREASTATE are easy to make. We just need to reject a state if we have seen it before (line 70 - see below), but if on the other hand it is a genuinely new state then we must record the fact that we have seen it (line 90):

```

TO EXPLOREASTATE 'LEFTBANK 'RIGHTBANK 'MOVELIST
40 IF NOT APPLICABLEQ :MOVELIST THEN STOP
50 APPLYMOVE :MOVELIST
60 IF MISSIONARIESEATENQ THEN STOP
70 IF SEENSTATEBEFOREQ THEN STOP
80 IF SUCCEEDEDQ THEN PRINT 'SUCCESS AND QUIT

```

```

→ 90 RECORDNEWSTATE
100 TRYALL :POSSIBLEMOVES
END

```

How are we to remember which states we have seen before? One way would be to keep a list of all the LEFTBANKs and RIGHTBANKs we have seen, and then when we have a possibly new state, check whether we have seen this particular combination before. But that would be a bit complicated, and we can simplify it in two ways:

(a) We don't need to record both the LEFTBANKs and the RIGHTBANKs, since given one we know what the other must be.

e.g. if LEFTBANK is [M C BOAT] then we know that the RIGHTBANK must be [M C M C]

So it would be sufficient to remember just, say, the LEFTBANKs.

(b) We still must be careful over what it is about the LEFTBANKs that we remember. Suppose that we have previously seen a LEFTBANK of [M C BOAT], and that it is now [C M BOAT] then they are really the same LEFTBANK even though they are not "equal":

```

1:PRINT EQUALQ [M C BOAT] [C M BOAT]
FALSE

```

What is really important about the LEFTBANK is the number of missionaries and cannibals (and boat) there, not the order in which they appear in the list. This suggests remembering the LEFTBANK as a group of three numbers:

(number-of-boat-on-leftbank, number-of-missionaries-on-leftbank, number-of-cannibals-on-leftbank).

So that, for example,

[M C BOAT] corresponds to [ 1 1 1 ]

one boat

one missionary

one cannibal

Let us define a procedure to construct these triples:

```

TO STATETRIPLE

```

```

10 << NUMBEROF BOAT :LEFTBANK

```

```

NUMBEROF M :LEFTBANK

```

```

NUMBEROF C :LEFTBANK >>

```

```

END

```

funny list brackets <<...>>

allow elements to be results

of procedure calls.

So that we have, for example:

1: PRINT STATE

LEFTBANK IS [M M M]

RIGHTBANK IS [C C C BOAT]

1: PRINT STATETRIPLE

[ 0 3 0 ]

If we have a list STATESEEN which holds all the state triples we have seen, it is easy to write our procedures to examine or update it:

TO SEENSTATEBEFOREQ

10 RESULT AMONGQ STATETRIPLE :STATESEEN

END

TO RECORDNEWSTATE

10 MAKE 'STATESEEN FIRSTPUT STATETRIPLE :STATESEEN

END

And we should remember to start STATESEEN off with the initial LEFTBANK

TO STARTMANDC

10 MAKE 'LEFTBANK [M M M C C C BOAT]

20 MAKE 'RIGHTBANK [ ]

→ 30 MAKE 'STATESEEN [ [ 1 3 3 ] ]

40 MAKE 'POSSIBLEMOVES [[C C BOAT] [C BOAT] [M C BOAT]

[M M BOAT] [M BOAT]]

END

Exercise 2.4 Make these additions and try using them. As before, you will find it more helpful if line 70 of EXPLOREASTATE prints out an appropriate message.

Try it You can get a demonstration of this way of solving the problem from LIB 'MANDC2. The procedure used to print out what is happening is called PEXPLOREASTATE. Have a look at it, and compare it with the version of EXPLOREASTATE given above.

Exercises 2.5 Edit STARTMANDC and change the order of POSSIBLEMOVES. Describe the effect this has.

2.6 The representation of states by LEFTBANK and RIGHTBANK is redundant. Modify the M & C program so that only LEFTBANK is explicitly represented.

\* 2.7 The "STATETRIPLES" we invented to record states already reached, suggest an alternative way of representing states. Modify the M & C program so that it uses this representation.

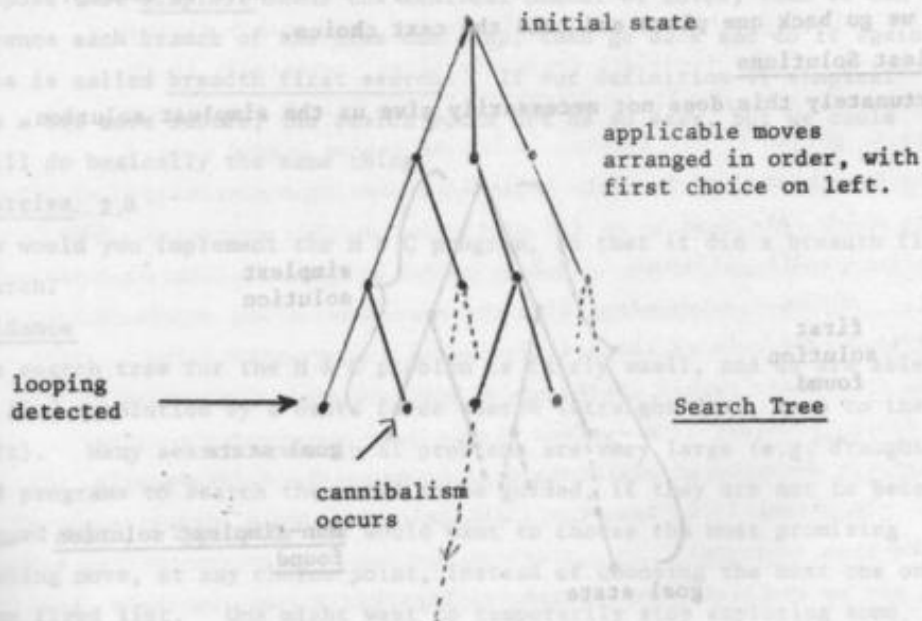


# MISSIONARIES AND CANNIBALS PROBLEM

(Search Techniques)

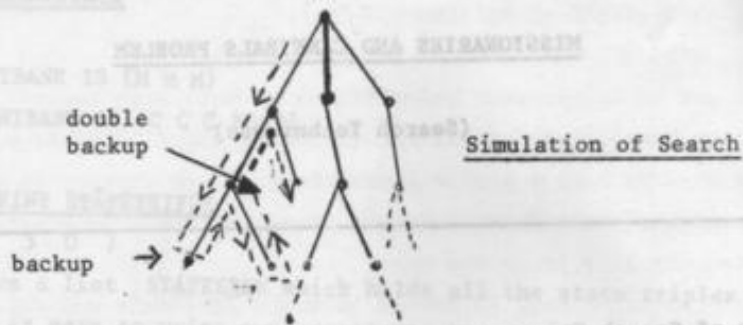
## Analysis of Search Strategy

We can represent all possible sequences of moves in the missionaries and cannibals problem by a tree



We can regard the program as growing some of this tree as it runs, and thus exploring it. In what order does it grow the tree? What was our search strategy?

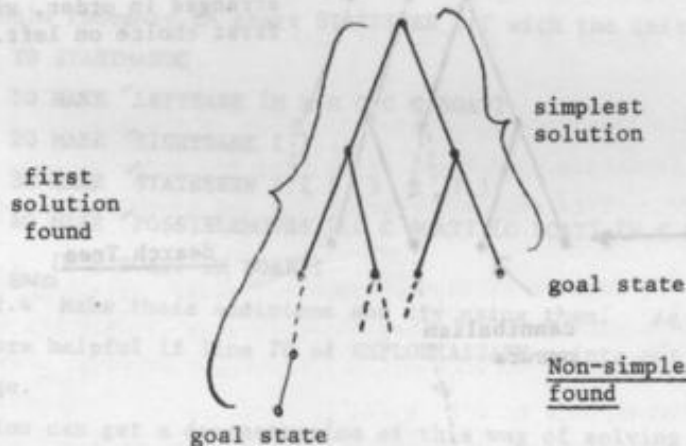




This is called depth first search. That is we keep going down, taking the left-most branch at every choice point, until we have to backup. Then we go back one place and take the next choice.

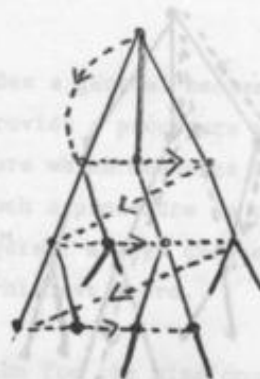
#### Simplest Solutions

Unfortunately this does not necessarily give us the simplest solution.



We may find a complicated solution on the left-hand side, before a simple one on the right-hand side. We could search the whole tree then choose the simplest solution from among all the solutions found. Alternatively we could explore all solutions in parallel so that the first found was bound to be the simplest.

RK.31



Breadth First Search

Suppose that simplest means the smallest number of moves, then we can advance each branch of the tree one step, then go back and do it again. This is called breadth first search. If our definition of simplest was a bit more subtle, the search would not be so easy, but we could still do basically the same thing.

Exercise 2.8

How would you implement the M & C program, so that it did a breadth first search?

Guidance

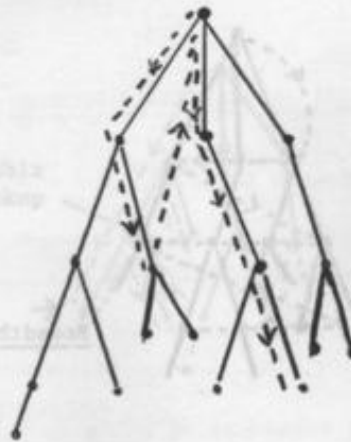
The search tree for the M & C problem is fairly small, and we are able to find a solution by a brute force search (straight down, keep to the left). Many search trees in AI problems are very large (e.g. draughts) and programs to search them need to be guided, if they are not to become bogged down. Typically one would want to choose the most promising looking move, at any choice point, instead of choosing the next one on some fixed list. One might want to temporarily stop exploring some particular state and move on to another, while reserving the right to come back.



the states identified



identical states

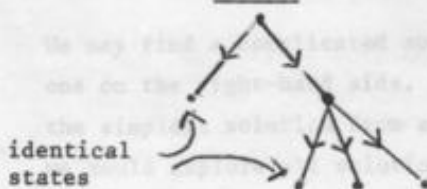


"intelligent" search strategy

### Graph Traverser

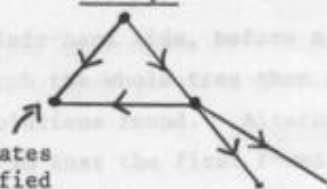
Many AI programs can be regarded as involving some search through a search tree. These trees are typically large (especially if the problem domain is not well understood) and the search through one needs to be guided if the program is not to become bogged down. Attempts have been made to write general purpose tree searching programs which only need to be fed particular details about the state descriptions and legal moves. Having such a program available makes it easier to formalise problems like the missionaries and cannibals. This is important when it comes to designing a program to solve problems from their verbal statement. One such general search program is the Graph Traverser of Doran and Michie (see recommended reading). Their program searches graphs instead of trees. The difference is slight. In a tree if we have two identical states on different branches we record them separately, in a graph we use one node to record them both. When we say we are searching a graph, rather than a tree, we imply that the test for looping is built-in to our program.

A Tree



identical states

A Graph



the states identified

### Evaluation Functions

The Graph Traverser provides a general mechanism for guiding search. The user is expected to provide a procedure which takes a state and calculates a numerical score which measures how close the present state is to the goal state. Such a procedure is called a Heuristic Evaluation Function. The graph traverser always chooses to explore next the unexplored state with the highest score.

#### Exercise 2.9

Write an evaluation function for the missionaries and cannibals problem.

#### Exercise 2.10

The "Eight-Puzzle" is played on the 3 x 3 tray illustrated below:

1	2	3
4		5
6	7	8

Mounted in the tray are eight 1 x 1 square pieces, which are free to slide left, right, up or down into an empty square. The standard position is illustrated in which the centre square is empty and the numbers are arranged in numerical order. The puzzle is played by initializing the pieces in some other order and then trying to get them back into the standard position.

- (a) Explain how a course of play can be represented as a search through a tree or graph.
- (b) How would this representation help you to design a computer program to solve eight-puzzle problems?
- (c) Suppose you were writing such a program. How could you represent in LOGO: states of the tray and moves. Explain in English (or LOGO) how you would apply moves to states to produce new states.

### Recommended Reading

Doran, J. 'An Approach to Problem Solving' Machine Intelligence 1,  
Edinburgh University Press, pp. 105-23.

DRAUGHTSIntroduction

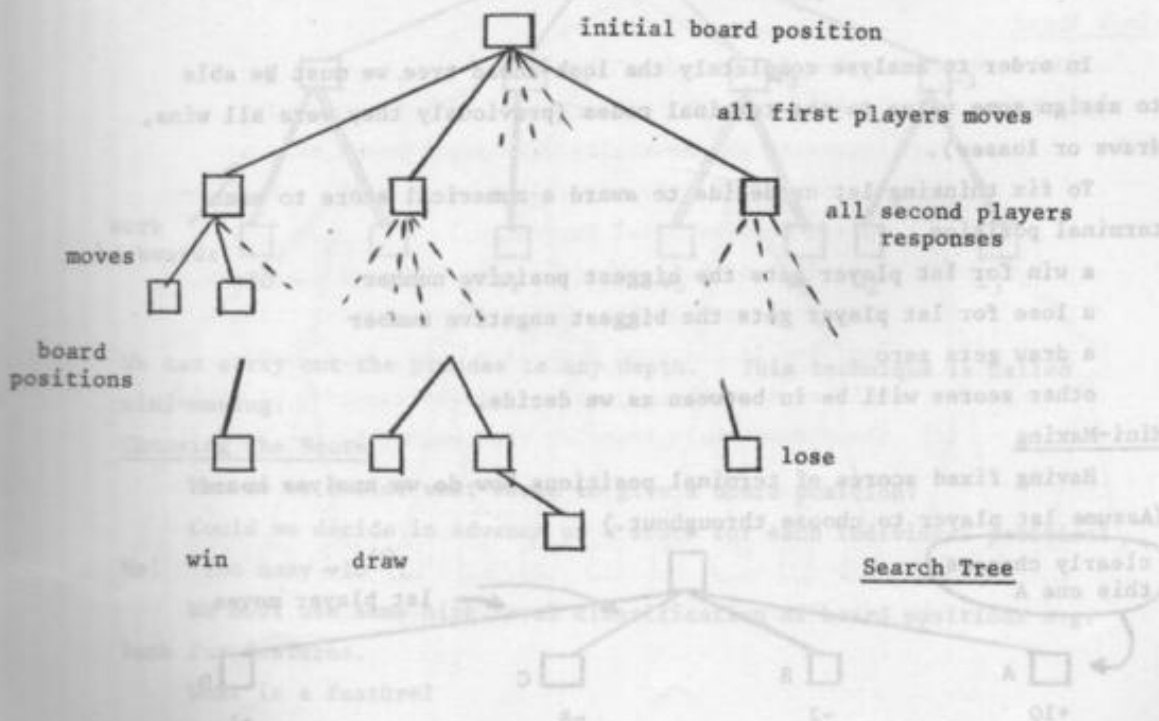
In many ways M & C was a toy problem. For instance the search tree was very small and we did not need to exercise much intelligence in searching it (once we had arrived at the formal representation). We now turn our attention to a problem area, where it is perhaps easier to see how to represent the problem as searching a tree, but where the search raises formidable problems.

The problem area is draughts.

Can we give a precise recipe for playing a good game of draughts?

Complete Analysis (and the search tree)

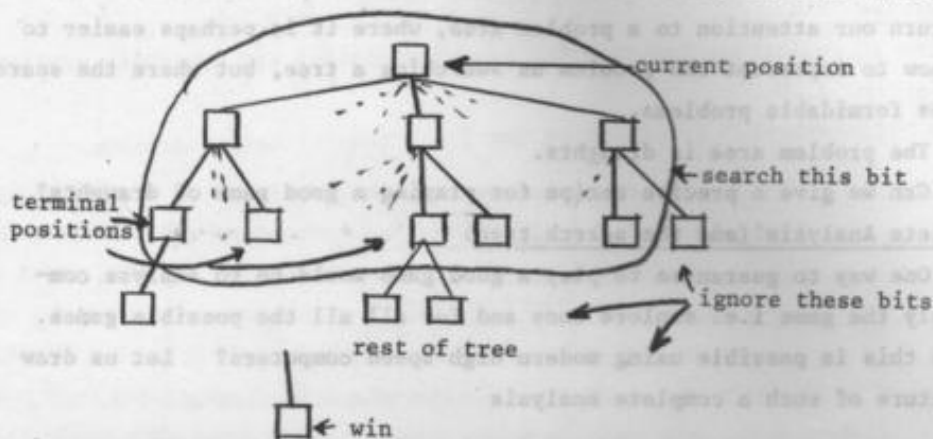
One way to guarantee to play a good game would be to analyse completely the game i.e. explore once and for all all the possible games. Maybe this is possible using modern high speed computers? Let us draw a picture of such a complete analysis



It has been estimated that this tree contains  $10^{40}$  nodes. If we make the (very optimistic) assumption that we can consider 3 nodes per millimicrosecond then it would take  $10^{21}$  centuries to explore the whole tree. Clearly this is out of the question! (Regardless of how we search the tree, depth first, breadth first, etc.)

### Look Ahead

An alternative to searching the whole tree is to search some way ahead, whenever we have a choice, to see which is locally the best choice



In order to analyse completely the look-ahead tree we must be able to assign some value to the terminal nodes (previously they were all wins, draws or losses).

To fix thinking let us decide to award a numerical score to each terminal position

a win for 1st player gets the biggest positive number

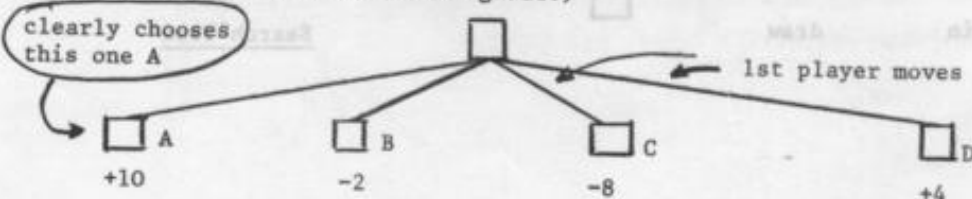
a lose for 1st player gets the biggest negative number

a draw gets zero

other scores will be in between as we decide.

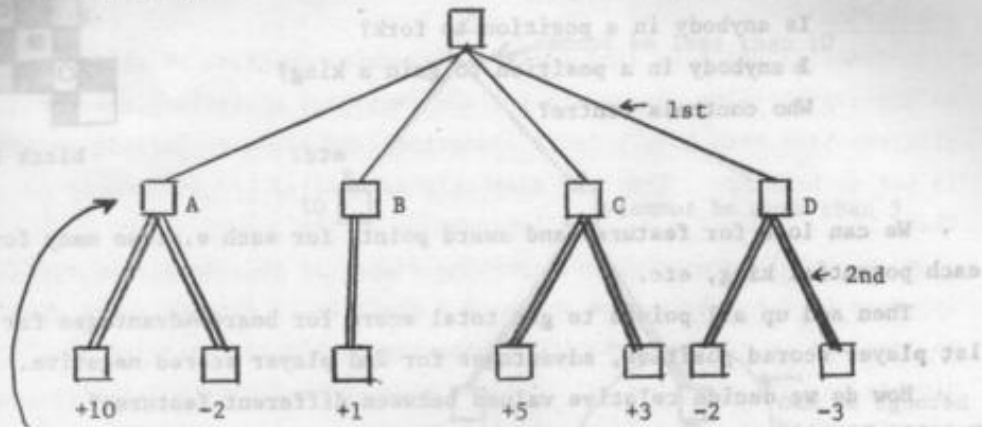
### Mini-Maxing

Having fixed scores of terminal positions how do we analyse board? (Assume 1st player to choose throughout.)





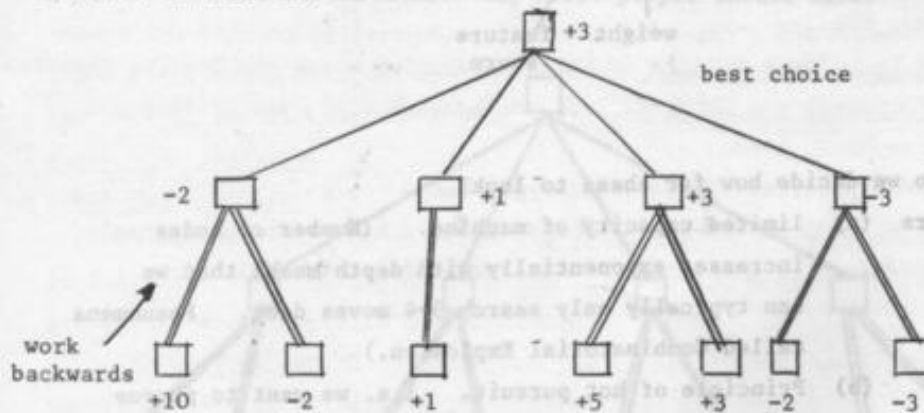
## 2 level lookahead



Is A best move?

No! because 2nd player can be assumed to take -2 branch to maximise his chances, so B for instance, would be better. In fact C is best because 2nd player can take +3 branch at best.

Can we formalise this



We can carry out the process to any depth. This technique is called mini-maxing.

### Choosing the Score

How do we decide what score to give a board position?

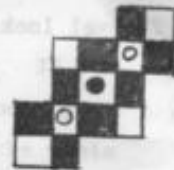
Could we decide in advance on a score for each individual position?

No! Too many  $\sim 10^{40}$ .

We must use some high level classification of board positions e.g. look for features.

What is a feature?

- e.g. Who has the most pieces?  
 Is anybody in a position to fork?  
 Is anybody in a position to gain a king?  
 Who controls centre?



etc.

black fork

We can look for features and award points for each e.g. so many for each potential king, etc.

Then add up all points to get total score for board. Advantages for 1st player scored positive, advantages for 2nd player scored negative.

How do we decide relative values between different features?

Usually by experimentation and practice. Therefore it is useful to be able to adjust relative values easily.

Ans. Score each feature separately, without regard to relative values then weight each score before adding them together

$$\text{i.e. Total Score} = w_1 \times s_1 + \dots + w_n \times s_n$$

weight

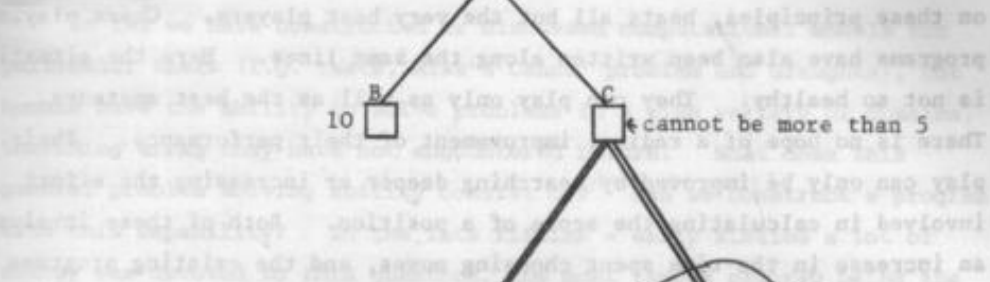
feature  
score

### Look Ahead

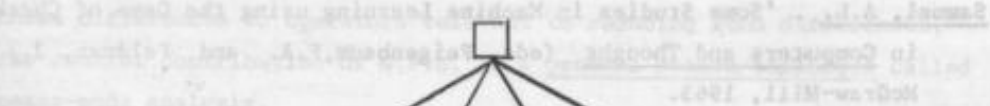
How do we decide how far ahead to look?

- Factors
- (a) limited capacity of machine. (Number of nodes increases exponentially with depth means that we can typically only search 3-4 moves deep. Phenomena called Combinatorial Explosion.)
  - (b) Principle of hot pursuit. i.e. we want to pursue longer those branches that are not stable. For instance if the next move is a jump, keep looking unless we are nearly exceeding the capacity of machine.
  - (c) Close down those branches that cannot be any good

□ ←



This refinement is called  $\alpha$ - $\beta$  search.



### Conclusion

Samuel's checkers (American for draughts) program, which is based on these principles, beats all but the very best players. Chess playing programs have also been written along the same lines. Here the situation is not so healthy. They can play only as well as the best amateurs. There is no hope of a radical improvement of their performance. Their play can only be improved by searching deeper or increasing the effort involved in calculating the score of a position. Both of these involve an increase in the time spent choosing moves, and the existing programs already use all the time allocated to them under tournament rules.

The whole area of chess playing programs is currently undergoing a revolution. New techniques are being explored. For instance, using high level descriptions of board positions to carry out a strategic search, before unpacking this into a more detailed, deep, but narrow search. For a good account of the problems of the old approach and some of the new techniques, see the paper by Berliner.

### Recommended Reading

Samuel, A.L. 'Some Studies in Machine Learning using the Game of Checkers' in Computers and Thought (eds. Feigenbaum, F.A. and Feldman, J.) McGraw-Hill, 1963.

If this area particularly interests you, see

Berliner, H. 'Some Necessary Conditions of a Master Chess Program' Proceedings of the 3rd IJCAI, p.77-85, Stanford, 1973.



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## The General Problem Solver

### Introduction

So far we have constructed or discussed computational models for particular tasks (I.Q. tests, Miss' & Canns' problem and draughts), but humans have the ability to solve problems in a wide variety of domains, including areas they have not encountered before. What does this general problem solving ability consist of? Can we construct a program with this capability? In the late fifties - early sixties a lot of energy was devoted to this question, the most famous program being the "General Problem Solver" (or G.P.S. for short) of Newell, Simon & Shaw.

Naturally it is necessary to explain a particular problem to G.P.S. This is done by giving descriptions of the initial and goal states of the world (called objects) and operators to transform these objects. Thus just as in the Miss' and Canns' problem, G.P.S. has to search for a sequence of operators which transform the initial object into the final object. To help it with this search G.P.S. must also be given a procedure for finding differences between objects and a way of relating these differences to operators relevant to reducing such differences. The central contribution of G.P.S. is a general search technique called means-ends analysis.

### Means-End Analysis

To see what this is consider the problem of getting from my home in Edinburgh to Trafalgar Square, London. G.P.S. would go through a process of reasoning like the following.

"My goal or end is to transform "me at home" into "me in Trafalgar Square". The first task is to compare these two states and find the difference. I find the difference to be one of location. The means I have of reducing differences of location are operators like "walk" or "travel by train". Some operators, like "walk", can be rejected as infeasible, but "travel by train" is feasible, so my next task is to apply this operator to the initial state, "me at home". Unfortunately the operator will not apply immediately because the conditions are not right - I am not at the station. So I set up a new subgoal to transform "me at home" into "me at the station". Again the difference is one of location and again I find the "travel" operators. I can reject "walk" as infeasible (I am lazy) and "go by train" as a potential loop



and select "go by taxi". This cannot be applied because the conditions are wrong - the taxi driver does not know I need him. The difference is one of information, so I look for an operator which can reduce differences of information and find the communication operators like "use the telephone" .....

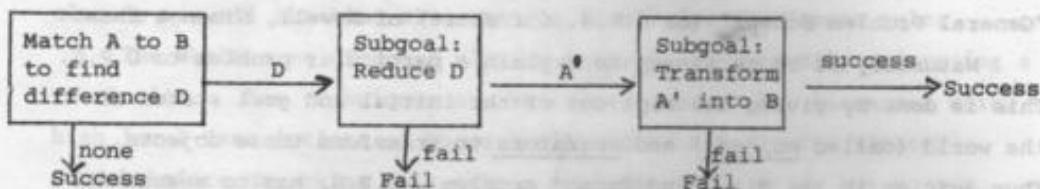
This kind of analysis can be carried on to any required depth and will eventually produce a plan consisting of a sequence of operators.

### Methods

Means-ends analysis is embodied in GPS as a series of procedures called methods. These are usually explained by the following flowcharts.

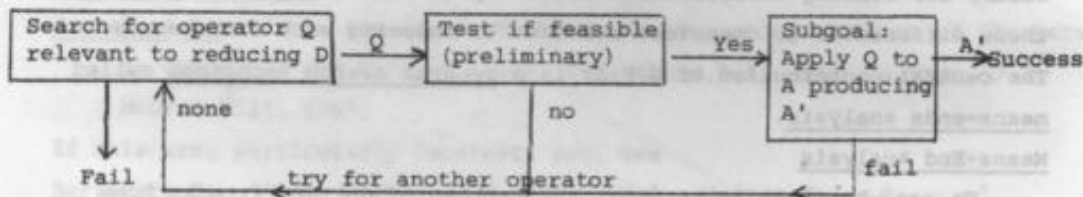
#### Method 1

Goal: Transform object A into object B.



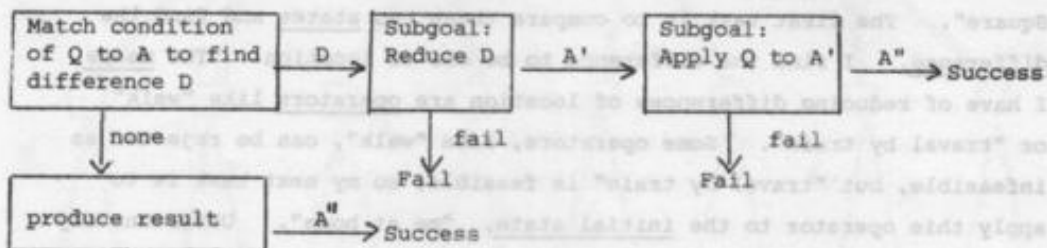
#### Method 2

Goal: Reduce difference D between object A and object B.



#### Method 3

Goal: Apply operator Q to object A.



G.P.S. can achieve goals of three different types:

1. Transforming one object into another.
2. Reducing a difference.
3. Applying an operator.



For each type of goal there is a method. These methods generate subgoals and call the appropriate methods to achieve these subgoals. Thus each method can call itself and the others in a highly recursive way.

Exercise 4.1 Using the above flowcharts, trace the behaviour of G.P.S. on the Trafalgar Square example.

#### Defining the Problem

How can we describe a problem to G.P.S.? We must choose a way of describing states of the world. A good way might be lists of symbolic descriptions like:

[[At me home] [Near me telephone] [Has me £29]]

We must also tell it what operators are available, what preconditions they have and how to apply them to one object to produce another. For instance, we could describe the operator "go by train" as

"provided the object contains [At me station]  
form a new object by deleting [At me station]  
and adding [At me station2]." (in a suitable  
procedural form of course)

Unfortunately this is not all, we must also give G.P.S. a procedure for picking the most significant differences between objects. e.g. location is the most significant difference between the initial state above and [[At me Trafalgar Square]]. Then it must be able to use these differences to extract relevant operators. This is usually done by feeding G.P.S. a difference, operator table.

e.g.

operator difference	walk	train	taxi	phone	table	write
location	X	X	X			
information				X	X	X

A cross in a square indicates that the operator in this column is useful for reducing the difference in this row. These differences must also be ordered by the difficulty of reducing them. The most difficult is always selected as the most significant between objects and there is a check to see that we

never try to reduce a hard difference as a subgoal of an easier one.

G.P.S. also requires us to supply a procedure for testing the feasibility of an operator in some particular situation. For instance, we might reject "walk" if the differences in location is more than a mile, or reject "write a letter", if the demand for information exchange is pressing. This feasibility test is a hack enabling us to include ad-hoc, unsystematized knowledge which supplements the distance, operator table. If we succeeded in systematizing this knowledge we might prefer to include it in the table

e.g.

location difference in miles	walk	taxi	train	plane
0 - 1	X			
1 - 10		X	X	
10 - 100			X	
> 100				X

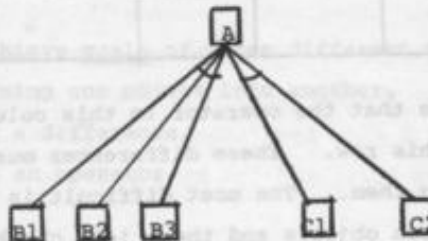
This is rather a lot of information to have to give for a particular problem and the question arises as to whether G.P.S. succeeds as a general problem solver. We will return to this later.

#### The Search

When G.P.S. is set loose on a problem it gets involved in a complicated series of recursive calls to the three methods. It is useful to have a neat way of describing the search behaviour. We present such a way here.

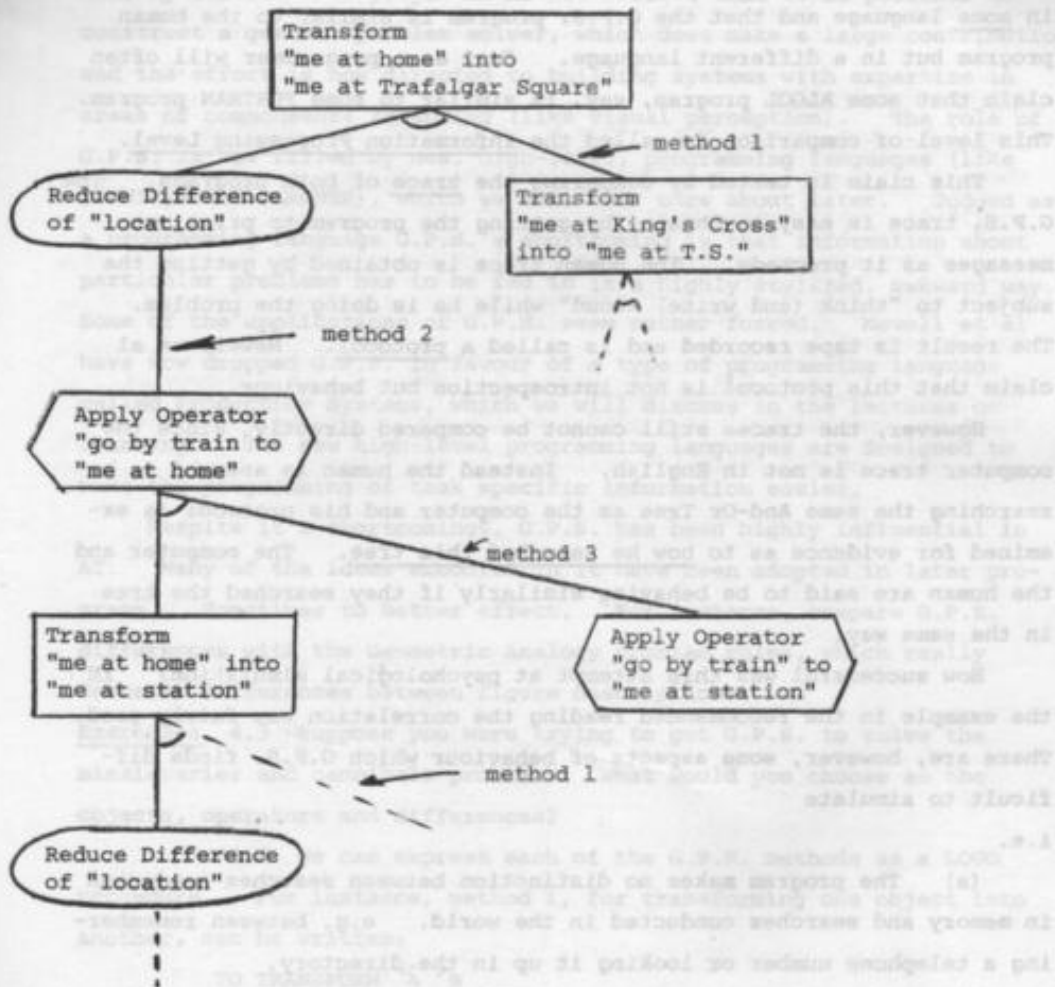
Another description for the G.P.S. search strategy is problem reduction. Problem reduction is the strategy of exchanging your current goal for a series of simpler subgoals and then exchanging these for even simpler subgoals, until all the subgoals are trivial. Problem reduction searches can always be represented as And-Or Search Trees. These are like ordinary search trees except that the subnodes of a particular node can be grouped into And Bundles.

e.g.



The three B's are one And Bundle. The two C's are another. The interpretation is that subgoals B1, B2 and B3 together establish A, and that subgoals C1 and C2 together establish A.

The search for a solution to the "Trafalgar Square" example can be illustrated by the following And-Or Search Tree. This tree is searched in a depth first manner.



**\*Exercise 4.2** Explain how the look-ahead tree used in draughts can be regarded as a type of And-Or Search Tree.

#### Psychological Validity

G.P.S. was claimed to be not only a general problem solver, but also to have psychological validity, i.e., it was supposed to solve problems in a similar way to humans. How could we test this claim? First we have to choose a level to make the comparison. For instance, at a very basic level, that of the excitation of neurones and currents passing

through transistors the human and the computer are obviously behaving differently. On the other hand at the gross level of whether they both solved the problem the similarity can be trivial. Newell & Co's contribution was to define an intermediate level of comparison, that of the programs running in each. Even this is not quite right. It would clearly be silly to claim that people are programmed in LOGO or any other computer language. What Newell does claim is that people are programmed in some language and that the G.P.S. program is similar to the human program but in a different language. Just as a programmer will often claim that some ALGOL program, say, is similar to some FORTRAN program. This level of comparison is called the Information Processing Level.

This claim is tested by comparing the trace of both programs. The G.P.S. trace is easy to obtain, by getting the program to print out messages as it proceeds. The human trace is obtained by getting the subject to "think (and write) aloud" while he is doing the problem. The result is tape recorded and is called a protocol. Newell et al claim that this protocol is not introspection but behaviour.

However, the traces still cannot be compared directly, since the computer trace is not in English. Instead the human is assumed to be searching the same And-Or Tree as the computer and his protocol is examined for evidence as to how he searched this tree. The computer and the human are said to be behaving similarly if they searched the tree in the same way.

How successful was this attempt at psychological simulation? In the example in the recommended reading the correlation was fairly good. There are, however, some aspects of behaviour which G.P.S. finds difficult to simulate  
i.e.

- (a) The program makes no distinction between searches conducted in memory and searches conducted in the world. e.g. between remembering a telephone number or looking it up in the directory.
- (b) The program does not handle meta-remarks (i.e. reflections about the task) like "this is difficult" or "I am lost" etc.
- (c) Subjects sometimes handle similar goals in parallel, which the program could not do. e.g. The subject might consider, and reject, several modes of transport (aircraft, ship, hovercraft), at a stroke, whereas the program would have to consider each possibility individually.
- (d) Subjects sometimes indulge in a more complex kind of back-up than the depth-first search which G.P.S. is capable of. e.g. When planning how to get from King's Cross to Trafalgar Square, realizing you will

not have enough money for a taxi unless you decide to walk from home to Waverley after all.

### Conclusions

As a general problem solver, G.P.S. was not an unqualified success. It's main shortcoming was the tremendous amount of information that had to be input about each particular problem and the small contribution made by G.P.S. Few people in AI now believe that it is possible to construct a general problem solver, which does make a large contribution, and the effort is now directed to building systems with expertise in areas of commonsense reasoning (like visual perception). The role of G.P.S. is now filled by new, high-level, programming languages (like CONNIVER and PLANNER), which we will hear more about later. Judged as a programming language G.P.S.'s shortcoming is that information about particular problems has to be fed in in a highly stylized, awkward way. Some of the applications of G.P.S. seem rather forced. Newell et al have now dropped G.P.S. in favour of a type of programming language called Production Systems, which we will discuss in the lectures on learning. The new high-level programming languages are designed to make the programming of task specific information easier.

Despite it's shortcomings, G.P.S. has been highly influential in AI. Many of the ideas embodied in it have been adopted in later programs. Sometimes to better effect. For instance, compare G.P.S. differences with the Geometric Analogy problem rules, which really describe differences between figure descriptions.

Exercises 4.3 Suppose you were trying to get G.P.S. to solve the missionaries and cannibals problem. What would you choose as the objects, operators and differences?

\*4.4 We can express each of the G.P.S. methods as a LOGO procedure. For instance, method 1, for transforming one object into another, can be written:

```

TO TRANSFORM 'A 'B
  10 NEW [D A1]
  20 MAKE 'D FINDDIFF :A :B
  30 IF EQ :D 'NONE THEN RESULT 'SUCCESS
  40 MAKE 'A1 REDUCEDIFF :D :A
  50 IF EQ :A1 'FAIL THEN RESULT 'FAIL
  60 TRANSFORM :A1 :B
END

```



Express the other two methods as LOGO procedures (Hint: Method 2 is more difficult because of the loop. Make a list of all relevant operators then work down this). Each of the methods call sub-procedures, like FINDDIFF. Write these using CALLUSER, then run your program on the "Trafalgar Square" example.

\*4.5 There is a deep bug in the G.P.S. flowcharts associated with back-up. What is it?

#### Recommended Reading

Newell, A. and Simon, H.A. 'G.P.S., A program that simulates human thought' in Computers and Thought (eds. Feigenbaum, E.A. and Feldman, J.) pp.279-93, 1963. McGraw-Hill.

If you are particularly interested in the computer simulation of human behaviour (i.e. in information processing models) then another good reference is:

Newell, A., Simon, H.A. and Shaw, J.C. 'Elements of a Theory of Human Problem Solving' in Readings in the Psychology of Cognition (eds. Anderson and Austel) - available in the library.



# ROBOT PLAN FORMATION 1

(Background)

## The Problem

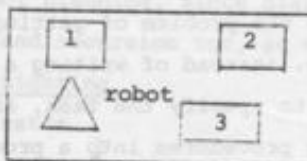
Suppose we had a robot janitor, looking after a suite of rooms. We want to give him a series of tasks to perform each day, then leave him to it. We do not want to have to give him a separate program for every conceivable task. Rather we would like to give him a few basic programs (called operators), and have him put them together into a big program to perform whatever task we give him. The task will usually be explained, by giving a description of the desired state of the rooms.

## Example - Collecting Boxes

Suppose the current state of one of the rooms is

Initial

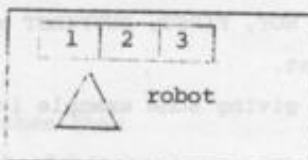
Room A



We might ask that all the boxes be put in the same place, i.e.:

Final

Room A



where the robot has available two operators

- i) he can go from one place to another
- or ii) he can push something from one place to another

He might devise the plan:

1. go to box 2
2. push it to box 1
3. go to box 3
4. push it to box 1

It will be no use him just performing various operations at random, until he chances upon some combination that works. This would take far too long, and might cause irrevocable harm to the rooms. Rather he must form a plan. To form a plan he must perform a G.P.S. like means/ends analysis i.e. Find the difference between his current description of the rooms, and the description of the desired state, then pick an operator relevant to reducing that difference. This implies that he must know something about his basic operators, for instance, under what conditions they can be run, and what their effects are.

#### Automatic Programming

This problem is analogous to the problem of getting computers to write their own procedures. i.e. instead of writing a procedure to do a task, we would like to be able to specify the task, and have a computer program put together its existing procedures into a procedure to achieve this task. This is called Automatic Programming. The operators here will be the procedures that have already been written. The task will be described by making statements about the values various variables, should have, before and after the procedure is run.

#### Example - Reversing a List

Given the procedures EMPTYQ, NOT, FIRST, BUTFIRST and FIRSTPUT, write a procedure to reverse a list.

We might explain the task by giving some example input/output pairs

e.g. input is [A B C D]

output is [D C B A]

or by giving a mathematical definition of REVERSE

e.g. REVERSE of [] is []

otherwise

REVERSE of :LIST is LASTPUT (FIRST :LIST) (REVERSE BUTFIRST :LIST)

We would expect the program to write a procedure like

```

TO REVERSE 'LIST
10 NEW 'ANS
20 MAKE 'ANS []
30 WHILE NOT EMPTYQ :LIST
    THEN FPUT F :LIST :ANS
    AND MAKE 'LIST BF :LIST
40 RESULT :ANS
END

```

### Comparison

Work is going on in both domains, robot planning and automatic programming and there has been useful interaction between the fields. We will be mainly concerned with the former in these lectures. The work on robot planning has tended to concentrate on searching for, so called, simple plans. i.e. a sequence of operators, as in the collecting boxes example. On the other hand, people in automatic programming have been unable to ignore the need for conditionals, loops and recursion, as in our list reversing example. Consequently they have made less progress (this work is still in its infancy), but results in this domain should have repercussions in robot planning, since plans for everyday tasks need conditionals, loops and recursion too, as the following example shows.

### Example - Cigarette Lighting

```

To light-a-cigarette
Put cigarette in your mouth
get a flame
hold flame against end of cigarette
inhale until cigarette lights
end

```

#### To get-a-flame

```

If you have matches then
Take a match out of box
Strike match against box repeatedly, until it lights
else ask someone else for a light
end

```

Each of the lines with "until" in them, imply repeating some action until some predicate is true i.e. looping. Compare the use of WHILE in the list reversing example p RK.50.

### Describing the task

How can we describe the task of "collecting three boxes" to a computer program? Answer - by giving a symbolic description of the initial state of the room, and the final goal.

e.g.

Initial State [AT ROBOT A] [AT BOX1 B] [AT BOX2 C]  
[AT BOX3 D]

Final Goal [AT BOX1 ?X] [AT BOX2 ?X] [AT BOX3 ?X]

A, B, C and D are constants representing places. ?X is a variable which may be assigned a place as its value during the construction of the plan. In what follows it will not always be possible to say, in advance, which variables are to be assigned values (denoted 'X') and which are to be replaced by their values (denoted :X). We will therefore drop the prefixes ' and :, and write ?X instead. When the inference system meets ?X, it will first check to see whether X has been assigned a value. If X has a value, ?X will mean :X, else, if X has no value, ?X will mean 'X. This facility is not implemented in LOGO at present. (Feb. 1976)

When we search for a plan we will need to represent intermediate states. These can also be represented as a set of facts. Note that a fact, like [AT ROBOT A], may be true at one time and false at another. We can deal with this in at least two ways:

(a) We can give each fact an extra argument, stating at what time or in what situation, the fact is true

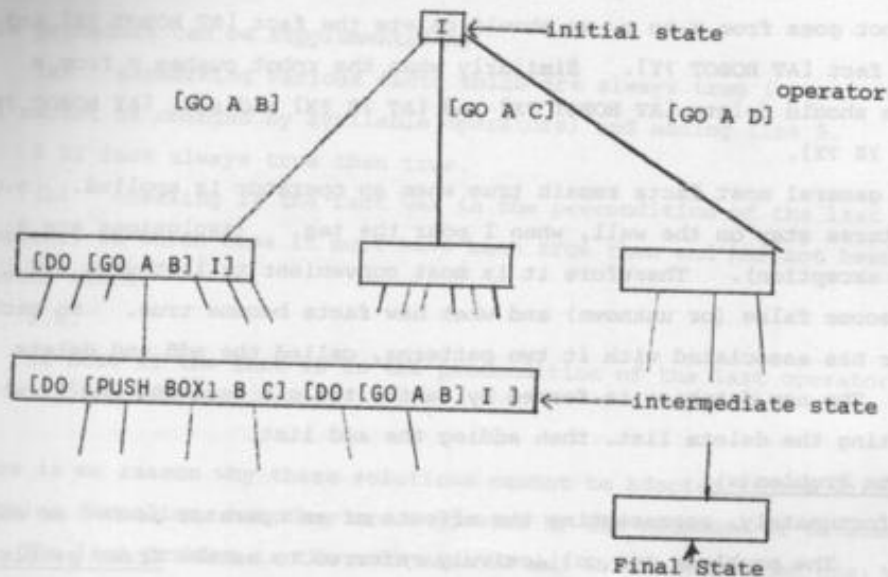
e.g.

```
time ( [AT ROBOT A 1]
      [AT ROBOT C 2]
      [AT ROBOT A INITIALLY]
situation ( [AT ROBOT C [DO [GO A C] INITIALLY]]
            (called the situation calculus)
```

(b) We can have a sequence of databases each one labelled with a particular time or situation.

(a) and (b) are essentially (logically) the same, but (b) is more suggestive when it comes to designing an efficient computer program to do planning, so we will adopt it here.

In fact what we will really need when we are searching for a plan is not a sequence of databases, but a search tree of databases, where the links are operators



Clearly simple times will not do to label these states (why?), we must use situations.

#### Representing the Operators

How can we describe the operators to the computer program? It is easy to represent the two operators "robot go from x to y" and "push z from x to y" as [GO ?X ?Y] and [PUSH ?Z ?X ?Y], but in order to construct sensible plans we must also know.

(a) when the operators can be applied

(b) what effect they have on databases

We deal with (a) first. In our planning model we must say what properties the database must have for an operator to be applicable to it.

For instance, for the robot to go from x to y, he must first be at x.

So we can say that [AT ROBOT ?X] is a precondition of [GO ?X ?Y] i.e.

[AT ROBOT ?X] must be true in a database (s, say) before we can apply [GO ?X ?Y] to produce a new database, [DO [GO ?X ?Y] S]. Similarly the preconditions of [PUSH ?Z ?X ?Y] are [AT ROBOT ?X] and [AT ?Z ?X]. Thus each operator will have associated with it a pattern called its precondition, and this precondition must be true in a database if the operator is to apply to it.

We now turn to (b), representing the effects of the operator. These are represented in our planning model by instructions about how to modify a database when an operator is applied to it. For instance, when robot goes from x to y, we should delete the fact [AT ROBOT ?X] and add the fact [AT ROBOT ?Y]. Similarly when the robot pushes z from x to y, we should delete [AT ROBOT ?X] and [AT ?Z ?X] and add [AT ROBOT ?Y] and [AT ?Z ?Y].

In general most facts remain true when an operator is applied. e.g. the pictures stay on the wall, when I pour the tea. (explosions are a notable exception). Therefore it is most convenient to list what old facts become false (or unknown) and what new facts become true. So each operator has associated with it two patterns, called the add and delete lists. The new database is formed by taking the old database and first subtracting the delete list, then adding the add list.

#### The Frame Problem(s)

Unfortunately, representing the effects of an operator is not as easy as this. The problems are collectively referred to as the frame problem (The name comes from an early proposed solution to them). We discuss these problems in the order of their increasing difficulty.

The first problem we have already dealt with, namely, we overcome the tedium of listing all the facts which remain true, when an operator is applied, by only mentioning (in the delete list) those which become false (or unknown).

The second problem is one of computational efficiency. In a realistic planning situation, any one of the databases will be very large, containing perhaps thousands of facts. The search tree similarly may contain thousands of databases, each of which will be very similar. Storing all these facts in the computer will use up lots of space. Every time a new database is created we will have to spend lots of computer time copying facts into it. The solution is to store only the initial database and the add and delete lists every time an operator is applied. To decide whether a fact is true in a database we apply



the following procedure.

To Isq fact database

10 If the database is the initial one, access as normal.

20 Else if the fact is in the add list of the last operator then true.

30 Else if the fact is in the delete list of the last operator then false.

40 Else call procedure recursively on the previous database.

end

This procedure can be supplemented by

(a) earmarking various facts which are always true (true initially, and cannot be changed by available operators) and adding line 5.

5 If fact always true then true.

(b) checking if the fact was in the precondition of the last operator, in which case it must have been true then and has not been deleted since.

i.e.

35 Else if the fact is in the precondition of the last operator then true.

There is no reason why these solutions cannot be adopted in the situation calculus formalism, but they are suggested by the sequence of databases.

The last problem is the most serious and is still an open one, namely, that the effects of an operator may be more subtle than can be represented by simple add and delete lists. We delay further discussion of it until later.

## ROBOT PLAN FORMATION 2

### (Making Plans)

#### Collecting Boxes Again

We now turn our attention to how to actually make a plan given a description of the task and the operators. We will work through the "collecting three boxes" example in detail.

The Initial state is

[AT ROBOT A] [AT BOX1 B] [AT BOX2 C] [AT BOX3 D]

call this state  $S_1$

The Final state must satisfy the pattern

[AT BOX1 ?X] [AT BOX2 ?X] [AT BOX3 ?X]

The operators are described in the following table

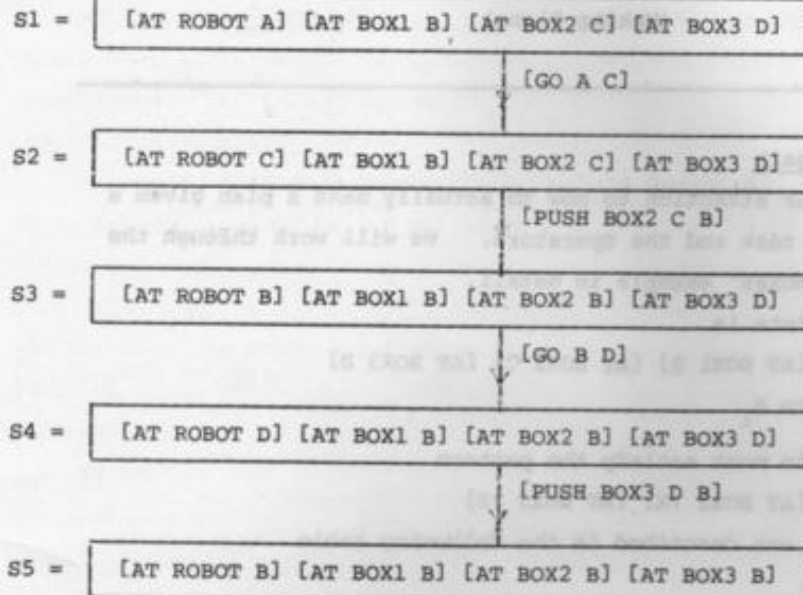
Operator Table

Operator	Preconditions	Delete List	Add List
[GO ?X ?Y]	[AT ROBOT ?X]	[AT ROBOT ?X]	[AT ROBOT ?Y]
[PUSH ?Z ?X ?Y]	[AT ?Z ?X]	[AT ROBOT ?X]	[AT ROBOT ?Y]
	[AT ROBOT ?X]	[AT ?Z ?X]	[AT ?Z ?Y]

The plan we will build up is:

[GO A C] [PUSH BOX2 C B] [GO B D] [PUSH BOX3 D B]

As we build this plan up, we will need to refer to the intermediate states, so it will be helpful to define them now. They are defined by the following diagram.

Planned State SequenceThe Plan

At each stage of building the plan we consider the current state and plan, and the goals we have still to achieve. Initially we are in state  $S_1$  with the goal [AT BOX1 ?X] [AT BOX2 ?X] [AT BOX3 ?X] and no plan. Our first step is to see whether we can satisfy this goal in the current state. We can satisfy [AT BOX1 ?X] by assigning B to ?X. This leaves us with the goal [AT BOX2 B] [AT BOX3 B] which is not satisfied in  $S_1$ , and becomes our first difference. We concentrate on trying to achieve one of the facts, say the first [AT BOX2 B], and look for a means of reducing the difference. A means would be any operator, that contains in its add list, a pattern which matches [AT BOX2 B]. The only such operator is [PUSH ?Z ?X ?Y], which contains [AT ?Z ?Y]. We assign BOX2 to ?Z and B to ?Y, and decide to try to apply [PUSH BOX2 ?X B]. But for an operator to be applicable to a state, its preconditions must be satisfied, so we must check [AT BOX2 ?X] [AT ROBOT ?X] in  $S_1$ . We can satisfy [AT BOX2 ?X] if we assign C to ?X, but then [AT ROBOT C] is not true and becomes our second difference. Again we look for an operator with a matching pattern in its add list, and first find [GO ?X ?Y] with pattern [AT ROBOT ?Y]. We match C to Y, and try to apply [GO ?X C]. The preconditions of the operator are satisfied in  $S_1$ , if we assign A to

X. Now the preconditions of [GO A C] are satisfied and we apply it to create state  $S_2$ . Similarly the preconditions of [PUSH BOX2 C B] are satisfied so we apply it to create state  $S_3$ .

We are now left with the task of achieving [AT BOX3 B], in the current state  $S_3$ . This is done in a very similar way to the achievement of [AT BOX2 B].

We can sum up the above argument by listing the stages of development of the plan together with a note about the reason for the change.

#### Development of Plan

##### Current Plan

[PUSH BOX2 ?X B]

[PUSH BOX2 C B]

[GO ?X C] [PUSH BOX2 C B]

[GO A C] [PUSH BOX2 C B]

##### Reason for Change

to achieve [AT BOX2 B]

to make precondition match  
[AT BOX2 C]

to achieve [AT ROBOT C]

to make precondition match  
[AT ROBOT A]

These 2 operators can now be applied to  $S_1$  to produce  $S_3$  and the first goal is achieved.  $S_3$  is now used for checking preconditions.

[GO A C] [PUSH BOX2 C B]  
[PUSH BOX3 ?X B]

to achieve [AT BOX3 B]

[GO A C] [PUSH BOX2 C B]  
[PUSH BOX3 D B]

to make precondition match  
[AT BOX3 D]

[GO A C] [PUSH BOX2 C B]  
[GO ?X D] [PUSH BOX3 D B]

to achieve [AT ROBOT D]

[GO A C] [PUSH BOX2 C B]

to make precondition match

[GO B D] [PUSH BOX3 D B]

[AT ROBOT B]

The remaining 2 operators can now be applied to produce  $S_5$  and the second goal is achieved.

#### Search

The process of making a plan described above really involves search. At any stage there may be several preconditions or goals (e.g. [AT ?Z ?X] and [AT ROBOT ?X]) remaining to be satisfied and we must attempt them in some order. There may also be several operators applicable (e.g. GO and PUSH), and these must be attempted in some order. In each case we have chosen to use the order in which they appear in our operator table.

This order was carefully chosen. We never had to remake a choice. We could have got stuck in all the normal ways. We might have got in a

loop. We might have got into a situation where no operator was applicable. We might have produced a non-optimal plan. We could recover from these situations by remaking one of our choices.

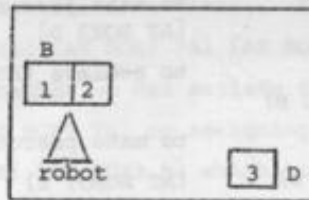
Note that the search space was not as big as it would have been if we had just tried putting together operators in random order. For instance every attempted plan must include the PUSH operator. The search tree is made smaller by the use of G.P.S. like means/ends analysis.

#### \*Exercise 5.1

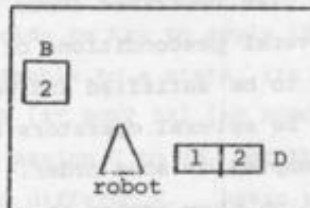
Think of a non-optimal plan for the collecting three boxes example. At what points must we exercise different choices to get this plan rather than the previous one?

#### Protection

Note that all the conjuncts of the final goal must be simultaneously true at the end and all the preconditions of an operator must be true just before the operator is applied. Unfortunately, a goal, once achieved, can be deleted later by the effect of a subsequent operator. In our example [AT BOX1 B] was true initially, but it could have been inadvertently deleted, during the course of achieving [AT BOX2 B] or [AT BOX3 B]. e.g. Suppose we have reached the state



The robot must go to D to collect Box3. Suppose it (stupidly) tried to get there by applying, [PUSH BOX1 B D]. The resulting situation would be



[AT BOX1 B] would be deleted - a retrograde step.

How can we prevent this happening? We could insist that PUSH be not used to achieve goals like [AT ROBOT D]. Unfortunately there are situations in which we prefer PUSH to GO, e.g., Achieve [AT ROBOT D] [AT BOX1 D]. In any case this is an example of a wider problem - how not to destroy an achieved goal during the achievement of a subsequent one. People sometimes have trouble with this, e.g. "How can you take your car to the garage, then come home but leave it there?".

Another solution is to protect achieved goals and preconditions, until they are no longer needed, i.e., mark them in some way and arrange that any operator, which tries to delete a marked fact, is not incorporated in the plan. Thus once we had achieved [AT CAR GARAGE], no operator which deleted this would be considered, and we would have to go home by bus. Of course when we have achieved [SERVICED CAR], this mark would be removed.

#### Stacking Boxes

We now further debug our plan formation recipe, by considering a new example. We will consider a robot with a single ability, he can stack and unstack boxes. We will express this by a single operator [MOVE ?X ?Y ?Z], which means "move box X from place Y to place Z". A place can be another box or the floor. In our very simple world all boxes are assumed to be the same size, so in order for the operator to be applicable, place Z must be "clear" - that is, if it is a box there must be no other boxes on it. To simplify matters further, we will assume that there is always room on the floor, by asserting that the floor is always "clear". To make box X easier to manipulate we will further insist that it must be "clear" before it can be moved.

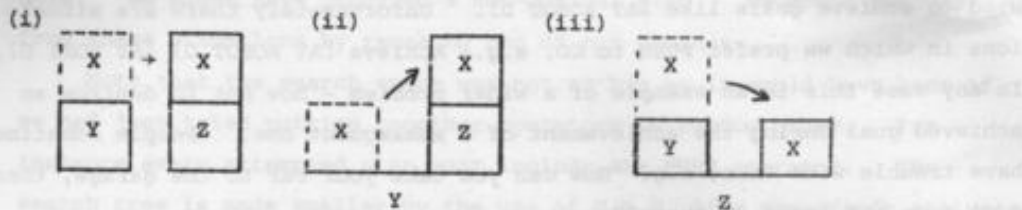
We can sum all this up by the following table and diagrams.

Operator Table

Operator	Preconditions	Delete List	Add List
[MOVE ?X ?Y ?Z]	[DIFF ?X ?Z]	[ON ?X ?Y]	[ON ?X ?Z]
	[DIFF ?Y ?Z]	[CLEAR ?Z]	[CLEAR ?Y]
	[ON ?X ?Y]		[CLEAR FLOOR]
	[CLEAR ?X]		
	[CLEAR ?Z]		



There are three cases to consider.

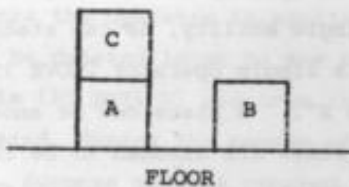


Note [CLEAR FLOOR] is needed in the Add List because it is inadvertently deleted in case (iii). This begins to show the inadequacy of add and delete lists for dealing with the effects of operators.

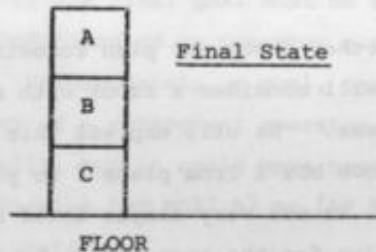
### A Three Box Problem

Consider the problem defined by the following diagram.

Initial State,  $S_1$



Final State



We can describe the initial state by

[ON C A] [ON A FLOOR] [ON B FLOOR]  
[CLEAR C] [CLEAR B] [CLEAR FLOOR]  
[DIFF A B] [DIFF B C] etc.

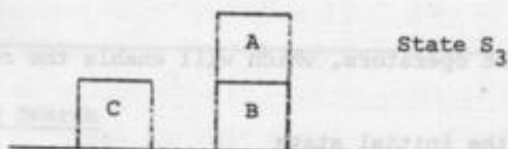
We can describe the final goal by

[ON A B] [ON B C]

Suppose we decide to work on [ON A B] first. We pick the only relevant application of an operator [MOVE A ?Y B]. We can satisfy all but one of the preconditions of this by choosing Y to be FLOOR. We are left with the precondition [CLEAR A]. The only relevant operator application for reducing this is [MOVE ?X A ?Z], and the preconditions of this are all satisfied if we let X be C and Z be FLOOR, so the plan is now

[MOVE C A FLOOR] [MOVE A FLOOR B]

This partial plan can now be executed and achieves [ON A B]. It creates the state



So we protect [ON A B] and proceed with proving [ON B C]. The only relevant operator application is [MOVE B FLOOR C]. Unfortunately a precondition of this is [CLEAR B] and the achievement of this would undo [ON A B], which is protected.

This difficulty arises because we tried to achieve the 2 goals independently with 2 plans, and then put these plans one after the other i.e.

[MOVE C A FLOOR] [MOVE A FLOOR B]  
followed by [MOVE B FLOOR C]

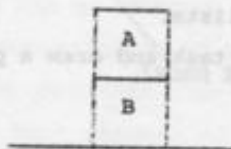
In fact the 2 goals interact and their plans have to be intermingled in order to achieve both goals at the same time. (Trying the plans in reverse order results in a similar difficulty). So we try inserting the new operator [MOVE B FLOOR C] in different places in the previous plan. It turns out that the sequence

[MOVE C A FLOOR] [MOVE B FLOOR C] [MOVE A FLOOR B]  
works.

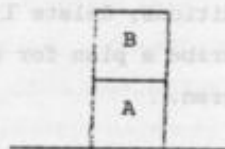
### Exercise 5.2

Consider the problem defined by the following diagram.

Initial  
State



Final  
State



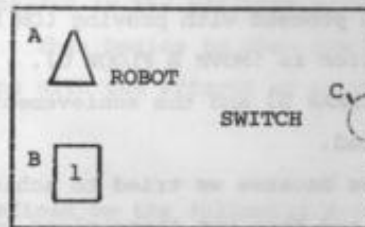
- Give a description of the initial state
- Give a description of the final goal
- Give a plan using the MOVE operator
- Draw a diagram of the planned state sequence
- Show how your plan could have been discovered by a planning

program, by listing the stages of its development, giving reasons for each change.

### Exercise 5.3

Design a set of robot operators, which will enable the robot to turn a light switch on.

i.e. Starting from the initial state



achieve the goal [STATUS SWITCH ON]

Describe the initial state with the facts:

[AT ROBOT A] [AT BOX1 B] [AT SWITCH C]

[STATUS SWITCH OFF] [ON ROBOT FLOOR] [TYPE BOX1 BOX]

Give the robot the 2 operators GO and PUSH described earlier. In addition, give him an operator [TURNON ?X], which is applicable provided that X, the switch, is initially off, the robot is standing on a box and the box, robot and switch are at the same place. This operator changes the status of the switch from off to on. To get on the box the robot will need an additional operator [CLIMBON ?X], which is applicable provided X is a box, the robot is initially on the floor and both are at the same place. You will need to alter PUSH so that it can only push boxes, and both GO and PUSH to make sure the robot is on the floor before they are applied.

a) Describe the four operators by drawing an Operator Table giving their preconditions, delete lists and add lists.

b) Describe a plan for achieving the task and draw a planned state sequence diagram.

### ROBOT PLAN FORMATION 3

(Assorted issues)

#### Controlling Search

During the process of making a plan we have to exercise various choices.

i.e. we have to choose

- a) Which unachieved goal or precondition (hereafter, collectively called subgoals) to work on next.
- b) Which fact from the database to try to match the subgoal against.
- c) Which relevant operator to try to apply.

Making these choices badly can cause us to:

- a) go into a loop
- b) work on a branch containing an unachievable subgoal.
- c) Find a non-optimal plan.

It is obviously of crucial importance to make these choices sensibly.

The following diagram illustrates a stage of the development of the plan to collect three boxes.

#### Current Database

[AT ROBOT A] [AT BOX1 B] [AT BOX2 C] [AT BOX3 D]

#### Current Subgoals

[AT BOX2 ?X] [AT ROBOT ?X]/[AT BOX1 B] [AT BOX2 B] [AT BOX3 B]

#### Current Plan

[PUSH BOX2 ?X B]

The top line is a description of the current (and initial) state. The second line lists the various goals and preconditions which have yet to be satisfied. The 3 goals on the right of the stroke are the original 3 goals. The underlined goal has already been satisfied. We are working on the next one, [AT BOX2 B]. The bottom line lists the partial plan, containing one operator [PUSH BOX2 ?X B]. The operator is point-

ing, with a single headed arrow, at the goal it is meant to achieve. It is pointing with a double headed arrow, at its preconditions.

To continue with building up the plan we must choose one of these preconditions to work on next. If we choose to work on [AT ROBOT ?X] next, something silly happens. [AT ROBOT ?X] is matched against [AT ROBOT A] i.e. A is assigned to X. We next try to satisfy [AT BOX2 A]. Even if we are very sensible (or lucky) with the remaining choices, we are now bound to get a non-optimal plan. e.g. [GO ROBOT C] [PUSH BOX2 C A] [PUSH BOX2 A B] ... etc. What kind of control mechanism would choose to work on [AT BOX2 ?X] first?

The area is still controversial, but one method is to arrange the subgoals into a hierarchy, according to how difficult they are to satisfy, and always work on the hardest subgoal first (c.f. G.P.S. ordering of differences and difficulty of goals). According to this method [AT BOX2 ?X] is tackled before [AT ROBOT ?X] because it is more difficult to get a box to a place than the robot to a place. At the top of the hierarchy are the subgoals which are impossible to change, unless they are already true, i.e., those like [TYPE ?X BOX] and [AT SWITCH ?X], which no available operator can effect.

A hierarchy for the "switch on the light" example is given below

top	[TYPE ?X ?Y]
	[AT SWITCH ?X]
	[STATUS ?X ON]
	[ON ROBOT ?X]
	[AT BOX ?X]
bottom	[AT ROBOT ?X]

At present, these hierarchies have to be provided by the human programmer for each new domain. Work is proceeding on the problem of having the planning program work them out for itself, by examining the operators which achieve each subgoal.

If we correctly choose [AT BOX2 ?X] and satisfy it by assigning C to X, we must then work on [AT ROBOT C]. Since this fact is not in the database, we must find a relevant operator to apply. Both GO and PUSH have patterns in their add lists of the form [AT ROBOT ?Y], so both are relevant. We can choose either but would clearly prefer GO. Choosing PUSH would lead to a non-optimal plan.



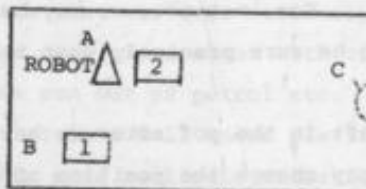
How can we express or characterize our preference, in order to get a general solution to the problem? Notice that if one choice of operator works, we do not need to try another. This is different from the situation with subgoals, where all subgoals need to be satisfied for a successful conclusion. So the sensible choice is to choose the easiest operator first. The easiest operator means the one with the easiest preconditions. We can see that GO is easier than PUSH, since the preconditions of GO are a subset of those of PUSH.

#### Macro Operators

It is possible for our robot to indulge in an elementary form of learning, by remembering the plans he constructs. In effect a plan, properly remembered becomes a new ability, i.e., a new operator (sometimes called a macro operator). Properly remembered here means, of course, not only remembering the sequence of operators which constitute the plan, but also working out under what conditions the plan can be applied and what its effects are, i.e., we need to know the preconditions, add list and delete list of the new operator. These can all be worked out (at the cost of some book-keeping) by studying the derivation of the plan. The preconditions of the new operator are just the subgoals which were not achieved by an operator, but by direct reference to the initial state. The add and delete lists can be worked out by comparing the initial and final state.

To be useful these macro-operators must be generalized, before they are stored as new operators. For instance, if we were remembering the plan to switch on the light we would not want to insist that it be BOX1 we climb onto - any box would do. Similarly the precise places involved are not of interest. In practice the operators are generalized before the precondition and, add and delete lists are worked out, but the same principles apply.

Even with generalization the macro operators are still susceptible to slight changes in the initial situation. Suppose that the initial state of the switch on light example were:





We would like the robot to be able to adapt the plan

[GO ?P1 ?P2] [PUSH ?B ?P2 ?P3] [CLIMBON ?B] [TURNON ?S]

and only use the last 3 operators. Otherwise it might pick up BOX1 and take that to the switch. Therefore the plan is stored in a triangular table, with the preconditions and effects of each operator stored separately. This is explained in the reference. The details are not important. Using this the robot is able to execute subplans of the plan. He is also able to recover to a certain extent when the plan goes wrong during execution. (See last section on executing plans).

Great care must be exercised over the formation of macro operators. Properly used the robot can be taught how to achieve a complex task that it previously found too difficult. Suppose that the search tree of a task is so large that the robot cannot find a plan in a reasonable length of time (an all too frequent occurrence). By giving it a judicious training sequence of simpler tasks, the robot can be made to learn just those macro-operators he needs to solve the original task. Let loose on it again he quickly finds a short plan consisting of these macro-operators. However, if we allow the robot to form macro-operators for every task he performs, he quickly becomes bogged down with hundreds of operators with long preconditions and add and delete lists. The search trees of all tasks become too large for him to find any plans. Getting the robot to decide for himself what is worth keeping, and what is not, is a long way off.

#### Exercise 5.4

From a macro operator called [COLLECT ?B ?P1 ?P2 ?P3] for collecting 2 boxes. Look at the operator table for GO and PUSH to decide what the preconditions, add list and delete list of the new operator, COLLECT, should be.

#### The Frame Problem re-visited

We now return to the most serious aspect of the Frame problem - that the effects of an operator may be more subtle than can be represented by simple add and delete lists. For instance, we may have to refer to the previous state before we can be sure precisely what to add or delete e.g.

- (i) How much tea is left in the pot after we have poured one cup?
- (ii) pushing one box, may change the position of another if they are joined by a rod or rope or one is on top of another.

We can think up situations in which the contents of the add and delete lists depends on an arbitrary amount of deduction. If this deduction is too computationally expensive to perform, e.g. an explosion, or if we have imperfect information about the previous state, then we may be unable to predict the effect of an operator. We may resort to:

- (a) predicting nothing
- (b) predicting the "most likely" event and being prepared to be contradicted
- (c) adding or deleting laws instead of facts
- (d) performing the operation and observing the result.

Can you think of circumstances under which you would resort to each of the above possibilities? Can you think of any other possibilities?

The plan formation program we discussed in these lectures modelled the effects of operators using the add and delete lists. So it was not able to handle these more subtle effects. What modifications to it are required, and whether these modifications would enable us to preserve our solutions to the other aspects of the frame problem is an open question.

Executing Plans (and the Qualification Problem)

If the plans our robot janitor is to make are ever to be put to use, there must be a procedure associated with each operator, which will actually perform the operation, e.g., really make the robot go from a to b. Such a procedure is called the operators action routine. We must be careful to distinguish the operator from the action routine. The operator, with its preconditions, and add and delete lists, is only a model of the action routine, just as our databases are models of states of the real world.

Because our planning program is only a model, it is liable to go wrong due to unforeseen difficulties. For instance, we may make a plan to go to America, by driving to the airport by car, catching the 3.00 p.m. plane etc., only to find that the car runs out of petrol halfway or the airplanes crew are on strike. This problem is called the Qualification Problem. Again the problem has been foolishly named after a possible solution, though not one that was ever seriously proposed. The solution is that one could hedge ones plans about with various qualifications, about what to do if you ran out of petrol etc. This may be possible for simple worlds, but it is a well known platitude that one "can't think of everything" for more realistic situations. Note also that we would need plans with conditionals to handle qualifications.

The solution to this problem would seem to be, that one would want to write qualifications into the plan to deal with the most likely difficulties, but that, more importantly, the action routines must have the capacity to fail and pass control back to the planning program, together with a message about what went wrong. Unfortunately, how to provide a measure of what is "most likely" and, how to decide what has "gone wrong" with a plan, are not well understood at the moment.

#### Coda

Several A.I. groups have written robot plan formation programs. The best known program is probably S.T.R.I.P.S. - the Stanford Research Institute Problem-Solver. This program is used by SHAKEY, the Stanford Research Institute robot, to form plans for the tasks he is given. You can read more about the program, and possible extensions of it, in the

#### Reference

Fikes, R.E., Hart, P.E. and Nilsson, N.J. "Some New Directions in Robot Problem Solving", in Machine Intelligence 7, eds. Meltzer, B., and Michie, D., p405-430 E.U.P. 1972.

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## Natural Language - 1: Sentence Generation

### 1. Introduction

Reasons for studying computer processing of natural language

- (1) understanding language;
- (2) understanding intelligence (language as the window into the mind);
- (3) natural language would be a very desirable way to communicate with computers and would 'democratise' computer use;
- (4) it is interesting.

How we understand and respond to sentences is very mysterious, and introspection is little help.

Computer studies of language involve linguistics (generative grammar), logic (logical languages as a possible unambiguous standard way of expressing meaning of natural languages) and computer science (compiling techniques and data representation).

### 2. The insult program

TO ELEMENT 'N 'L RESULT

1Ø IF :N=1 THEN RETURN FIRST :L

2Ø ELEMENT (:N-1) (BUTFIRST :L)

END

nth element of L

TO CHOOSEANY 'L

1Ø NEW 'R

2Ø MAKE 'R (RANDOM ((COUNT :L)-1))+1

3Ø RESULT ELEMENT :R :L

END

Chooses a random element of L

TO DOANY 'L

1Ø APPLY CHOOSEANY !L

END

Executes a random element of L, a list of command names

TO OUT 'X

1Ø TYPE SPACE AND TYPE :X

END

Prints its argument preceded by a space

TO SUGGEST1

1Ø OUT 'GET AND OUT 'LOST

END

TO SUGGEST2

1Ø OUT 'GO AND OUT 'JUMP AND OUT 'IN AND OUT 'THE AND OUT 'LAKE

END

TO/

```

TO SUGGEST
  1Ø DOANY [SUGGEST1 SUGGEST2]
END

TO MISNAME1
  1Ø OUT 'ROTTEN AND OUT 'SWINE
END

TO MISNAME 2
  1Ø OUT 'FILTHY AND OUT 'BEAST
END

TO MISNAME
  1Ø DOANY [MISNAME1 MISNAME2]
END

TO INSULT
  1Ø SUGGEST AND OUT 'YOU AND MISNAME
  2Ø PRINT NL
END

```

### 3. The insult grammar

```

insult -> suggest 'you misname
suggest -> 'get 'lost
suggest -> 'go 'jump in 'the 'lake
misname -> 'rotten 'swine
misname -> 'filthy 'beast

```

A context-free grammar is a set of production rules, made from non-terminal symbols (naming phrases) and terminal symbols (quoted words).

Each production rule consists of a non-terminal (on the left) and a list of terminals and/or non-terminals (on the right).

There is a starting symbol (here it is insult).

You can think of the grammar in two ways

#### (i) An inductive definition

```

'filthy 'beast is a misname
'rotten 'swine is a misname
'go 'jump 'in 'the 'lake is a suggest
'get 'lost is a suggest

```

A suggest followed by 'you followed by a misname is an insult.

#### (ii) As a recipe for generating sentences

To generate an insult generate a suggest then 'you then a misname

To generate a suggest generate 'get then 'lost

or To generate a suggest generate 'go then 'jump then 'in then 'the  
then 'lake

To generate a misname, etc.

### Exercise/



Exercise 1.3 Write a grammar to produce at least 100 insults in any language you choose, (try to manage with less than 100 production rules).

4. Number grammar

```
ump -> 'one
ump -> 'two
. . . . .
ump -> 'nine
umpteent -> 'ten
umpteent -> 'eleven
. . . . .
umpteent -> 'nineteen
umpty -> 'twenty
. . . . .
umpty -> 'ninety
upto99 -> ump
upto99 -> umpteent
upto99 -> umpty
upto99 -> umpty ump
umphum -> ump 'hundred
upto999 -> upto99
upto999 -> umphum
upto999 -> umphum 'and upto99
```

(\* means a hard exercise, \*\* means a mini-project)

Exercise 1.4a Continue by defining upto9999999.

Exercise 1.4b Do it in French or German or Gaelic or whatever.

Exercise 1.4c Program the random generation for upto999 (you can pretend 3 to 8 don't exist to avoid tedium).

\*Exercise 1.4d Write a program to take a number expressed as a list of digits and print its name.

\*\*Exercise 1.4e Adapt 1.4d to write a teaching program which generates lists of digits at random, generates the English and French (or language X) name simultaneously prints one, asks the user for the other and tells him if he is right.

\*Exercise 1.4f We could represent the grammar by

```
to grammar
1/8 [[ump quote one][ump quote two]...[ump quote nine]
    [umpteent quote ten]....
    [umpty quote twenty] ..
    [upto99 ump][upto99 umpteent][upto99 umpty ump]
    ....
end
```

Write/

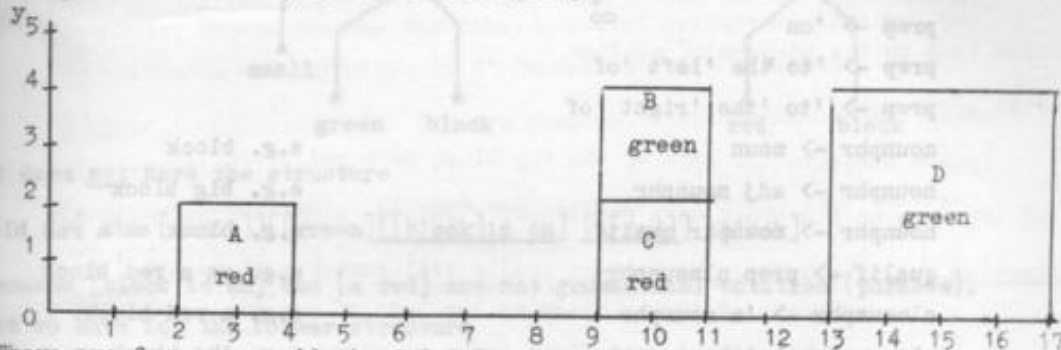


Write a function to generate random number names from this representation of the grammar instead of the representation by individual functions we used before.

## Natural Language - 2: Generating Blocks World Sentences

### 1. Blocks World

A world rather simpler and less disturbing than our own, although perhaps a trifle dull, is the Blocks World.



There are four square blocks A,B,C,D  
of fixed size 2 units for A,B,C and 4 units for D  
of fixed colour red or green  
of variable position (x,y) denoting mid-point of base.

e.g. A has  $x=3$ ,  $y=0$

B has  $x=10$ ,  $y=2$

There are relations between any blocks a and b

a is to the left of b if  $x_a + \frac{1}{2} \text{size}_a + \frac{1}{2} \text{size}_b < x_b$

a is to the right of b if b is to the left of a

a is on b if  $y_a = y_b + \text{size}_b$

and a is not to the left of b

and a is not to the right of b.

Exercise 2.1 Define above similarly. (But what exactly does above mean  
in English? Does it mean anything  
exactly?)

### 2. Sentences about blocks world

Assertions There is a green block to the left of the big block.

The small green block is on a red block.

The block to the left of the small green block is to  
the right of the big green block.

Questions Is a small block to the left of a green block?

Is a block to the right of a red block a green block?

The following grammar will generate these and similar sentences:

noun/

noun -> 'block	
adj -> 'big	
adj -> 'small	
adj -> 'red	
adj -> 'green	
prep -> 'on	
prep -> 'to 'the 'left 'of	
prep -> 'to 'the 'right 'of	
nounphr -> noun	e.g. block
nounphr -> adj nounphr	e.g. big block
nounphr -> nounphr qualif	e.g. block on a red block
qualif -> prep clnounphr	e.g. on a red block
clnounphr -> 'a nounphr	e.g. a red block
clnounphr -> 'the nounphr	e.g. the block on a green block
assertion -> 'there 'is 'a nounphr	e.g. there is a green block
assertion -> clnounphr 'is qualif	e.g. a red block is on a red block
question -> 'is clnounphr qualif	e.g. is a red block on a red block
sentence -> assertion	
sentence -> question	

(clnounphr means closed noun phrase, no more adjectives can be prefixed)

Exercise 2.2a Use a penny to hand simulate RANDOM and generate three sentences at random.

Exercise 2.2b Try to find some stupid sentences generated by this grammar (not just lies, stupid sentences).

\*Exercise 2.2c Add rules to generate each of the following kinds of sentences:  
What is on the small red block?

The big block is green.

A block between the small red block and the big block is green.

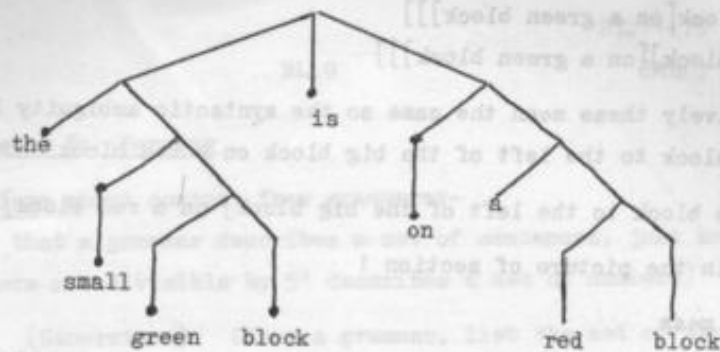
\*Exercise 2.2d Make up a grammar for recipes in cookery books (add a pound of sugar, mix in a spoonful of flour, bake slowly). If you try cooking your random recipes you will discover that semantics without semantics is nothing but a pain in the gut.

### 3. Structure of sentences

A sentence like 'the small green block is on a red block' has a syntactic structure: here is a way of showing it

[ [ the [[small][green][block]] ] is [[on][a[[red][block]]]] ]

or as a tree



It does not have the structure

[ [ the [small]] [[green] [block is on] [a red]] ] block ]

because [block is on] and [a red] are not grammatical entities (phrases). But we have for the former structure

[block] - noun

[green block] - nounphr

[small green block] - nounphr

[the small green block] - clnounphr

[block] - noun

[red block] - nounphr

[a red block] - clnounphr

[on] - prep

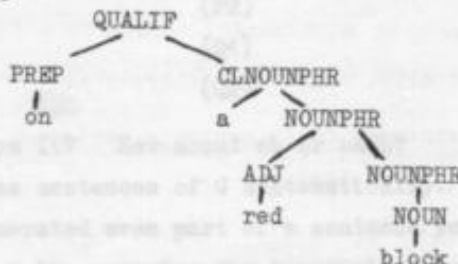
[on a red block] - qualif

[the small green block is on a red block] - assertion

We could easily make the generating program type out an indication of the structure by making each procedure like nounphr print out its own name before it starts, so that we get

QUALIF PREP on CLNOUNPHR a NOUNPHR ADJ red NOUNPHR NOUN block

or pictorially as a tree



#### 4. Ambiguity

The phrase 'red block on a green block' could have the structure (omitting some brackets)

[red/

[red[block[on a green block]]]  
or [[red block][on a green block]]

Intuitively these mean the same so the syntactic ambiguity is harmless.  
But 'green block to the left of the big block on a red block' could mean

[[green block to the left of the big block] on a red block]

which is B in the picture of section 1

or it could mean

[green block[to the left of the big block on a red block]]

and there is no big block on a red block. This is semantic ambiguity.

**Exercise 2.3** Check that the grammar really will generate these two readings of 'green block to the left of the big block on a red block' and draw their trees as above.

Natural Language - 3: Parsing

## 1. Some problems about context free grammars:-

(remember that a grammar describes a set of sentences, just as 'the even numbers not divisible by 5' describes a set of numbers)

Problem 1 (Generation) Given a grammar, list the set of sentences it describes.

Problem 2 (Parsing) Given a sentence and a grammar test whether the sentence is one of those described by the grammar.

Problem 3 (Induction) Given a set of sentences make up a grammar which describes them.

Problem 4 (Equivalence) Given two grammars do they describe the same set of sentences.

What do you think is the order of difficulty of these?

The parsing problem is the one which interests us next. For example, does the grammar of the last lecture produce these sentences?

- (a) There is a small block on a red block
- (b) Is a red block on a red block on a red block?
- (c) A green block is there on the red block

More important, what structure if any does it attribute to them? Is this structure unique?

2. An example to help us understand the parsing problem

Here is an easy grammar G, starting symbol P (using lower case instead of ')

$P \rightarrow a P Q$  (P1)

$P \rightarrow a Q$  (P2)

$Q \rightarrow c Q$  (Q1)

$Q \rightarrow b$  (Q2)

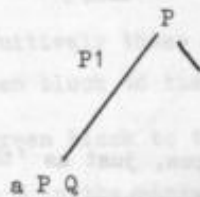
Does cca come from it? How about ab or aacb?

Try generating the sentences of G systematically.

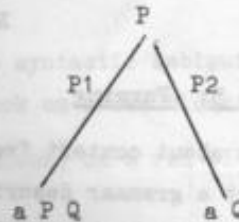
When you have generated even part of a sentence you can see whether it could be cca by comparing the terminal symbols (a,b,c) at the front.

P/





No good

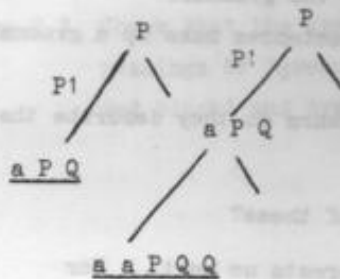


No good No good

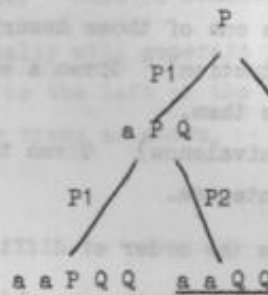
So oca does not come from the grammar G.

How about ab?

P



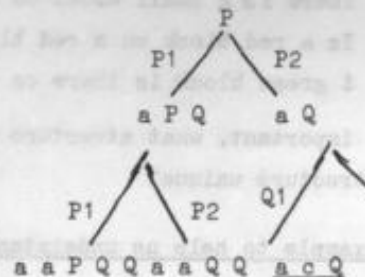
No good



No good No good



No good No good



No good No good No good

Continue this systematically. Can you generate ab?

Exercise 3.1 Try to systematically generate sentences from the above grammar to get aacbb.

### 3. A parsing program for this grammar

Our convention will be that each phrase has a parsing procedure which is given a string to parse and returns the remainder of that string after removing the phrase it is looking for; but if it fails to find it then it returns 'FAIL'. We will write a collection of procedures for the grammar just given.

TAKEOFF/

TAKEOFF just tries to remove a given word from a string of words. P tries P1 and if that doesn't work P2. Similarly Q tries Q1 and if that doesn't work Q2. P1 takes off 'A, if the result is O.K. it removes a P, and if still O.K. it removes a Q.

```

to takeoff 'word' :string
  if emptyq :string then result 'FAIL
  if not (:word=f :string) then result 'FAIL
  result bf :string
end

```

e.g. takeoff 'A[A B C] = [B C]  
 takeoff 'D[A B C] = 'FAIL

```

to OK 'x
  not (x='FAIL)
end

```

```

to P 'string
  new 'stringrem (remove a P from front or fail)
  make 'stringrem P1 :string (remainder string)
  make 'stringrem P2 :string (remove a P1)
  if OK :stringrem then result :stringrem
  make 'stringrem P2 :string (otherwise remove a P2)
  if OK :stringrem then result :stringrem
  result 'FAIL (P2 didn't work either)
end

```

```

to Q 'string
  as P but using Q1 and Q2
end

```

Examples Q[C B A A] -> [A A], Q[A B] -> 'FAIL, P[A B C A] -> [C A]

```

to P1 'string
  make 'string takeoff 'A :string (remove 'A P Q)
  if not OK :string then result 'FAIL (takeoff 'A if possible)
  make 'string P :string (FAIL if couldn't take off 'A)
  if not OK :string then result 'FAIL (FAIL if couldn't take off P)
  make 'string Q :string
  result :string (result is remainder or FAIL)
end

```

```

to P2 'string
  make 'string takeoff 'A :string (remove 'A Q)
  if not OK :string then result 'FAIL
  make 'string Q :string
  result :string
end

```

to Q1 'string

...

end

to Q2 'string

...

end

**Exercise 3.2** Write out some of the procedures needed to parse numbers with the number grammar given previously (not for all the productions, just enough to get the idea). Try your procedures on the machine if you have time.

4. A more general parsing program

The program which we gave in section 3 has three disadvantages

- (1) (practical) it is rather long, each production needing a substantial procedure
- (2) (theoretical) it will sometimes fail to find a parse when one exists.

To understand (2) consider the grammar, starting with R,

$R \rightarrow a Q d$

$Q \rightarrow b$

$Q \rightarrow b c$

Trying this on [a b c] using a program like that of section 3 we get function calls:-

```

R[a b d]                                -> []
  R1[a b d]                             -> []
    Q[b d]                               -> [d]
      Q1[b d]                            -> [d]

```

But on [a b c d]

```

R[a b c d]                             -> FAIL
  R1[a b c d]                           -> FAIL
    Q[b c d]                             -> [c d]
      Q1[b c d]                          -> [c d]

```

whereas  $Q2[b c d] \rightarrow [d]$  which eventually makes P succeed.

- (3) (theoretical) it goes into an infinite recursion if given productions of the form  $P \rightarrow P \dots$ . But this is not fatal because it is always possible to rewrite a grammar so as to avoid such productions.

Disadvantage (2) suggests that we define a function  $P'$  which takes a string as argument and produces a set of strings as result (the empty set now corresponds to FAIL).

Disadvantage (1) suggests that we go further in search of brevity and define a function  $P''$  which takes a set of strings as argument and produces a set of strings as result. To be clearer suppose P is a symbol in the grammar.

Let  $\bar{P}$  be a set of strings - all strings generable from P.

Let  $P'_s$  where s is a string be the set of all strings t such that  $s=pt$  for some string p in  $\bar{P}$ .

Let/

Let  $P^*S$  where  $S$  is a set of strings be the set of all strings  $t$  such that  $s=pt$  for some string  $s$  in  $S$  and some string  $p$  in  $P$ .

We will now write a program for the grammar of section 3 with a function  $P^*$  for each symbol  $P$  (we just call it  $P$ , not  $P^*$ , in LOGO). We have corresponding functions, from sets of strings to sets of strings, for each production. For terminal symbols we define a special function takeoff which takes a word and a set of strings to a set of strings.

For each production we simply do the functions corresponding to its components in sequence. For each non-terminal symbol we do the function for each of its productions and join up the result. We start the whole process on a set whose only element is the given string and expect as result a set whose only element is the empty string (i.e. nothing remains when a  $P$  is removed from the front.) We represent both strings and sets by lists (confusing, but that is all LOGO offers).

Here is the program, followed by some examples (we call the functions  $PP$  and  $QQ$  because  $P$  is already used for  $PRINT$ )

```

to takeoff 'word 'strings
  1 $\emptyset$  new 'string
  2 $\emptyset$  if emptyq :strings then result []
  3 $\emptyset$  make 'string f :strings and make 'strings bf :strings
  4 $\emptyset$  if emptyq :string then result takeoff :word :strings
  5 $\emptyset$  if :word=f :string then result fput (bf :string) (takeoff :word :
    strings)
  6 $\emptyset$  result takeoff :word :strings
end

to PP 'strings
  1 $\emptyset$  if emptyq :strings then result []
  2 $\emptyset$  result join P1 :strings P2 :strings
end

to QQ 'strings
  1 $\emptyset$  if emptyq :strings then result []
  2 $\emptyset$  result join Q1 :strings Q2 :strings
end

to/

```

```

to P1 'strings
  1Ø result QQ PP takeoff 'a :strings
end
to P2 'strings
  1Ø result QQ takeoff 'a +strings
end
to Q1 'strings
  1Ø result QQ takeoff 'c :strings
end
to Q2 'strings
  1Ø result takeoff 'b :strings
end
to parse 'string
  1Ø new 'strings
  2Ø make 'strings PP << :string >>
  3Ø if (count :strings)= Ø then result 'nogood
  4Ø if (count :strings)> 1 then result fput 'ambiguous :strings
  5Ø if not emptyq f :strings then result fput 'toolong f :strings
  6Ø result 'good
end

```

Example

```

takeoff 'a [[a b c]] -> [[b c]]
takeoff 'a [[d c]] -> []
takeoff 'a [[a b c][a d e][d c]] -> [[b c][d e]]
P2[[a b d][a a t b e]] -> [[d]]
P1[[a b d][a a t b e]] -> [[e]]
PP[[a b d][a a t b e]] -> [[d][e]]

```

Example

```

[one] is up <[one]>=1
[twenty] is up <[twenty]>=20
[twenty one] is up <[twenty one]>=21

```

Notice that we use the syntax symbols, up etc. as variables in the equations standing for any string of that syntactic class. If a production involved more than one occurrence, e.g.  $P \rightarrow a P a P$ , we would have to use subscripts, e.g.  $\langle (P) \rightarrow \dots \langle (P) \dots \rangle \rangle$ .

That



Natural Language - 4: Translation

We have written random generator programs for insults and for sentences about blocks, also a parser for a b c sentences. The parser just said whether a string of words belonged to the grammar; can we go further and produce a 'meaning' for a sentence? (What is a meaning? Good question.) Let us try, as a very simple example, to get the actual number from a number name. We will use ' $\langle(\dots)\rangle$ ' for 'the meaning of ...', and we will express the way in which the meaning of a string depends on the meanings of its components by writing equations, one alongside each production.

Number grammar with meanings

ump  $\rightarrow$  'one'  $\langle(\text{ump})\rangle = 1$

ump  $\rightarrow$  'two'  $\langle(\text{ump})\rangle = 2$

.....

umteen  $\rightarrow$  'ten'  $\langle(\text{umteen})\rangle = 10$

.....

umpty  $\rightarrow$  'twenty'  $\langle(\text{umpty})\rangle = 20$

.....

upto99  $\rightarrow$  ump  $\langle(\text{upto99})\rangle = \langle(\text{ump})\rangle$

upto99  $\rightarrow$  umteen  $\langle(\text{upto99})\rangle = \langle(\text{umteen})\rangle$

upto99  $\rightarrow$  umpty  $\langle(\text{upto99})\rangle = \langle(\text{umpty})\rangle$

upto99  $\rightarrow$  umpty ump  $\langle(\text{upto99})\rangle = \langle(\text{umpty})\rangle + \langle(\text{ump})\rangle$

umphun  $\rightarrow$  ump 'hundred'  $\langle(\text{umphun})\rangle = \langle(\text{ump})\rangle * 100$

upto999  $\rightarrow$  upto99  $\langle(\text{upto999})\rangle = \langle(\text{upto99})\rangle$

upto999  $\rightarrow$  umphun  $\langle(\text{upto999})\rangle = \langle(\text{umphun})\rangle$

upto999  $\rightarrow$  umphun 'and upto99'  $\langle(\text{upto999})\rangle = \langle(\text{umphun})\rangle + \langle(\text{upto99})\rangle$

Example

[one] is ump  $\langle([one])\rangle = 1$

[twenty] is umpty  $\langle([twenty])\rangle = 20$

[twenty one] is upto99  $\langle([twenty one])\rangle = \langle([twenty])\rangle + \langle([one])\rangle = 20 + 1 = 21$

Notice that we use the syntax symbols, ump etc. as variable names in the equations standing for any string of that syntactic class. If a production involved more than one occurrence, e.g.  $P \rightarrow a Q b Q$ , we would have to use subscripts, e.g.  $\langle(P)\rangle = \dots \langle(Q_1)\rangle \dots \langle(Q_2)\rangle \dots$

This/

This way of specifying meaning goes rather naturally with the notion of context free grammar. Such grammars and our meaning equations are restrictive but, as you will see, we can extend their usefulness still using the same basic ideas.

### 3. A translation program

To program a translator instead of a parser, we need to have functions which build not just readable strings but also meanings. In general a string of words will produce a string of meanings, rather than just one meaning. We can think of the translation process as taking words off the front of the word string and putting meanings on the back of the meaning string. Thus an (intermediate) stage of the translation consists of a string of meanings (its left) and a string of words (its right).

Consider the stage produced in translating 'two hundred and twenty seven', with the rules used to obtain them.

Rule	Left (meaning string)	Right (word string)
	[]	[two hundred and twenty seven]
rule/2	[2]	[hundred and twenty seven]
rule/3/1	[200]	[and twenty seven]
	[200]	[twenty seven]
rule/3/2	[200 20]	[seven]
rule/7	[200 20 7]	[]
rule/20/4	[200 27]	[]
rule/27/5	[227]	[]

We finish with a unit string of meanings on the left and an empty string of words on the right.

We want to use the same technique as our second parsing program, adapted by using states instead of just strings of words. In our translation functions will all take a pair of states as argument and produce a pair of states as result. They are

meaning word  $\rightarrow$  meaning

takes an individual word to its meaning or NUMBER if it has none.

meaning string word string  $\rightarrow$  state

takes a state represented by a list of the two.

begin word state  $\rightarrow$  ?

produces true if the right of the state begins with the word, false otherwise.

A.I.2.  
1975/76

NL.18

3.12.75  
RMB/4

## 2. A translation program

To program a translator instead of a parser, we need to have functions which handle not just remainder strings but also meanings. In general a string of words will produce a string of meanings, rather than just one meaning. We can think of the translation process as taking words off the front of the word string and putting meanings on the back of the meaning string. Thus an (intermediate) state of the translation consists of a string of meanings (its left) and a string of words (its right).

Consider the states produced in translating 'two hundred and twenty seven', with the rules used to obtain them.

Rule	Left (meaning string)	Right (word string)
	[ ]	[two hundred and twenty seven]...
ump/2	[2]	[hundred and twenty seven]
umphun/1	[200]	[and twenty seven]
	[200]	[twenty seven]
umpty/1	[200 20]	[seven]
ump/7	[200 20 7]	[ ]
upto99/4	[200 27]	[ ]
upto999/3	[227]	[ ]

We finish with a unit string of meanings on the left and an empty string of words on the right.

We want to use the same technique as our second parsing program, adapted by using states instead of just strings of words. So our translation functions will all take a set of states as argument and produce a set of states as result. They are

meaningof word -> meaning

takes an individual word to its meaning or NOMEANING if it has none.

mkstate meaning-string word-string -> state

makes a state represented by a list of the two.

begins word state -> T

produces true if the right of the state begins with the word, false otherwise.

newstate word state1 -> state2

only used if state1 begins with the word.

Removes this word from the right and puts its meaning (if any) on the back of the left.

takeoff word state-set1 -> state-set2

for each state in state-set1 which begins with the word, remove the word from the right and get a new state with the meaning of the word on the back of the left.

example: if meaningof 'two = 2

takeoff 'two mkstate[1] [two three four]

-> [[1 2] [three four]]

We need some way of associating some semantics with each production. Consider

upto99 -> umpty ump      <(upto99)> = <(umpty)> + <(ump)>

After we have used this production and called the umpty and ump functions we should have a set of states each of whose left is [... x y] where x is the meaning of the umpty part and y is the meaning of the ump part. We need to add these two together to produce a state with x+y on the end instead. A general function dosesemantic will do all this for any semantic operation, not just addition.

nargs function-name -> N      Number of arguments (1 or 2)

dosesemantic1 function-name state -> state-set

function-name names an arbitrary semantic function.

This is applied to the last element of the left of the state and the result replaces it (or if nargs gives 2 to the last two elements and the result replaces them). A set consisting of just this state is produced, unless the result of applying the given function was FAIL when the empty set is produced (production was semantically inapplicable).

example: dosesemantic1 'sum mkstate [1 2 3] [four five]

-> [[1 5] [four five]]

dosesemantic function-name state-set1 -> state-set2

does dosesemantic1 to each state of state-set1 and collects together all the results.

Here then are the general procedures for writing translator programs.

```

to mkstate 'left 'right
  1Ø result << :left :right >>
end

to begins 'word 'state
  1Ø new 'right
  2Ø make 'right f bf :state
  3Ø if emptyq :right then result false
  4Ø if :word=f :right then result true
  5Ø result false
end

to newstate 'word 'state
  1Ø new 'left 'right 'meaning
  2Ø make 'left f :state and make 'right f bf :state
  3Ø make 'meaning meaningof :word
  4Ø if :meaning='nomeaning then/mkstate :left (bf :right) result
  5Ø result mkstate (lastput :meaning :left) (bf :right)
end

to takeoff 'word 'states
  1Ø new 'state
  2Ø if emptyq :states then result []
  3Ø m 'state f :states and m 'states bf :states
  4Ø if begins :word :state then result fput (newstate :word :state) (
    takeoff :word :states)
  5Ø result (takeoff :word :states)
end

to dosesemantic! 'fn 'state
  1Ø new 'left 'right 'fnresult
  2Ø make 'left f :state and make 'right f bf :state
  3Ø if 1=nargs :fn then m 'fnresult apply :fn (last :left)
  35 if 1=nargs :fn then m 'left bl :left
  4Ø if 2=nargs :fn then m 'fnresult apply :fn (last bl :left) (last :
    left)
  45 if 2=nargs :fn then m 'left bl bl :left
  5Ø if :fnresult='fail then result []
  6Ø result << mkstate (lastput :fnresult :left) :right >>
end

to dosesemantic 'fn 'states
  1Ø new 'state
  2Ø if emptyq :states then result []
  3Ø result join (dosesemantic! :fn f :states) (dosesemantic :fn bf :states)
end

```

A.I.2.  
1975/76

NL.21

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RMB/4

### 3. Using the translation program on number names

To use the procedures defined above to translate a particular grammar with particular meaning specification, we need to write some more procedures corresponding to the rules of that grammar. Below are the procedures for the number name grammar up to 99. The final procedure test1 tries upto99 on a given string of words, putting a full stop at the end and ensuring that only final states which have devoured all the string upto the stop are printed. (The basic procedures are in my file NLTRANS and the ones below are in NLNUMTRANS.)

Exercise 4.1 Try to work out on paper in outline the computation produced by test1 [twenty two]. What procedures are called with what arguments? (Don't do all the details.)

Exercise 4.2 Write the extra procedures needed to do up to 99.

#### Number name translation procedures

to meaningof 'word

1~~0~~ if :word='one then result 1

2~~0~~ if :word='two then result 2

3~~0~~ if :word='twenty then result 2~~0~~

9~~0~~ result 'nomeaning

end

to nargs 'fn

1~~0~~ if :fn='sum then result 2

2~~0~~ if :fn='times1~~0~~ then result 1

3~~0~~ break

end

to ump 'states

1~~0~~ join ump1 :states ump2 :states

end

to ump1 'states

1~~0~~ takeoff 'one :states

end

to ump2 'states

1~~0~~ takeoff 'two :states

end

to/



```

to umpteen 'states
  !p umpteen! :states
end

to umpteen! 'states
  !p takeoff 'ten :states
end

to umpty 'states
  !p umpty! :states
end

to umpty! 'states
  !p takeoff 'twenty :states
end

to upto99 'states
  !p join join join upto99! :states upto992 :states upto993 :states
    upto994 :states
end

to upto99! 'states
  !p ump :states
end

to upto992 'states
  !p umpteen :states
end

to upto993 'states
  !p umpty :states
end

to upto994 'states
  !p dosemantic 'sum ump umpty :states
end

to test! 'wordstring
  !p p takeoff 'stop upto99 << mkstate [] (lput 'stop :wordstring) >>
end

```

Natural Language - 5: Conversations about blocks1. Simple approach: phrases translate to sets

Let us try to use our translation program on simple sentences about the blocks world, the sentences generated by the grammar we gave earlier. It is reasonable to take the phrases to have the following meaning:-

noun	}	
simplenounphr		- a set of blocks
nounphr		
elnounphr		
adj	}	- a property of blocks
qualif		
prep		- a relation between blocks
assertion	}	
question		- no meaning, just a printing effect
sentence		

How should we represent these meanings in our program? The most straightforward way is:-

set of blocks	- set of blocks
property of blocks	- set of blocks with that property
relation between blocks	- set of pairs of blocks in that relation

where as usual we use LOGO lists for sets, and we use words to name blocks.

For example	block	- [A B C D]
	red	- [A C]
	small	- [A B C]
	small red block	- [A]
	left	- [[A C][B D][C D]]
	left of red block	- [A]
	big block left of red block	- []

We can manufacture these meanings with three main semantic functions:-

DOPROP :XS :YS - list of all elements occurring in both the lists  
XS and YS (intersection)

DOREL :XYS :YS - YYS is a list of pairs. The result is the list  
of first elements of those pairs whose second  
element is in YS.

For example, block

small

red

big

is represented by the matrix

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

FALSE  
TRUE

THEN RESULT :FIRSTSOFBF -  
HEN RESULT :FIRSTSOFBF

```

TO DOPROP 'XS 'YS
  1/ IF EMPTYQ :XS THEN RESULT []
  2/ IF MEMBERQ F :XS :YS THEN RESULT FPUT (F :XS) (DOPROP BF :XS :YS)
  3/ RESULT DOPROP BF :XS :YS
END

TO DOPROPREV 'XS 'YS
  1/ DOPROP :YS :XS
END

TO UNIQUE 'XS
  1/ IF (COUNT :XS) = 1 THEN RESULT :XS
  2/ IF (COUNT :XS) = 1 THEN RESULT 'FAIL
  3/ P 'AMBIGUOUS AND QUIT
END

TO TESTEMPTY 'XS
  1/ IF EMPTYQ :XS THEN 'CORRECT ELSE 'LIAR
END
ETC.

TO NOUN 'STATES
  1/ TAKEOFF 'BLOCK :STATES
END

TO ADJ 'STATES
  1/ JOIN JOIN JOIN TAKEOFF 'BIG :STATES TAKEOFF 'SMALL :STATES TAKEOFF
    'RED :STATES TAKEOFF 'GREEN :STATES
END

TO PREP 'STATES
  1/ JOIN JOIN PREP1 :STATES PREP2 :STATES PREP3 :STATES
END

TO PREP1 'STATES
  1/ TAKEOFF 'ON :STATES
END

TO PREP2 'STATES
  1/ TAKEOFF 'OF TAKEOFF 'LEFT TAKEOFF 'THE TAKEOFF 'TO :STATES
END

TO PREP3 'STATES
  1/ TAKEOFF 'OF TAKEOFF 'RIGHT TAKEOFF 'THE TAKEOFF 'TO :STATES
END

TO SIMPNOUNPHR 'STATES
  1/ JOIN SIMPNOUNPHR1 :STATES SIMPNOUNPHR2 :STATES
END

TO SIMPNOUNPHR1 'STATES
  1/ NOUN :STATES
END

TO SIMPNOUNPHR2 'STATES
  1/ DOSEMANIC 'DOPROP SIMPNOUNPHR ADJ :STATES
END

TO NOUNPHR 'STATES
  1/ JOIN NOUNPHR1 :STATES NOUNPHR2 :STATES
END

TO NOUNPHR1 'STATES
  1/ DOSEMANIC 'DOPROPREV QUALIF SIMPNOUNPHR :STATES
END

```

```

TO NOUNPHR2 'STATES
  1/ SIMP NOUNPHR :STATES
END

TO QUALIF 'STATES
  1/ DOSEMANTIC 'DOREL CLNOUNPHR PREP :STATES
END

TO CLNOUNPHR 'STATES
  1/ JOIN CLNOUNPHR1 :STATES CLNOUNPHR2 :STATES
END

TO CLNOUNPHR1 'STATES
  1/ NOUNPHR TAKEOFF 'A :STATES
END

TO CLNOUNPHR2 'STATES
  1/ DOSEMANTIC 'UNIQUE NOUNPHR TAKEOFF 'THE :STATES
END

TO ASSERTION 'STATES
  1/ JOIN ASSERTION1 :STATES ASSERTION2 :STATES
END

TO ASSERTION1 'STATES
  1/ DOSEMANTIC 'TESTEMPTY NOUNPHR TAKEOFF 'A TAKEOFF 'IS TAKEOFF 'THERE
    :STATES
END

TO ASSERTION2 'STATES
  1/ DOSEMANTIC 'TESTNONEINBOTH QUALIF TAKEOFF 'IS CLNOUNPHR :STATES
END

TO QUESTION 'STATES
  1/ DOSEMANTIC 'ANSWEREMPTY QUALIF CLNOUNPHR TAKEOFF 'IS :STATES
END

TO SENTENCE 'STATES
  1/ JOIN ASSERTION :STATES QUESTION :STATES
END

```

To use this translator we need a main function which makes a set containing just one state from a given list of words, applies a given phrase function to this set of states, then prints the meaning part of each resulting state (there should only be one unless the phrase is ambiguous)

```

TO DO 'PHRASE 'WS
  1/ APPLY :PHRASE << << [] :WS >> >>
  2/ MAPLIST IT [PRINT F EACH]
END

```

For example we should get

```

DO 'NOUNPHR [SMALL RED BLOCK]
[A C] (result)
DO 'SENTENCE [THERE IS A BIG BLOCK ON A BLOCK]
LIAR (printed by assertion!)
NONE (result)

```

Natural Language - 5 contd.

2. A more flexible approach: translation to functions

The program in the last section is rather inflexible. Suppose we want to change the world by moving, or painting, some block. We have to adjust the meanings of all the words affected: 'on', 'left', 'right', 'red', 'green'. So a conversation with commands like [Put the red block on the big block] would be hard to implement. We can get over this by having a separate world model and computing the meanings of words like 'on' when we encounter them, using this model. The model can be changed; it can also be displayed to give non-verbal output.

The world model can be just a list of pairs, each a block name and a block description as follows: colour, dimension, x-coordinate, y-coordinate. For the world we had before:-

```
[[A [RED 2 2 0]]
 [B [GREEN 2 5 2]]
 [C [RED 2 5 0]]
 [D [GREEN 4 11 0]]]
```

We can write basic functions colof, dimof, xof, yof which take the name of a block and give its colour, dimension, x-coordinate and y-coordinate in the current world.

Now we can program a meaning function for each word in a natural way. Let us use the name  $\phi_{xyz}$  for the meaning function associated with the word 'xyz'.

```
 $\phi_{block}$           -> list of blocks (i.e. their names)
 $\phi_{red\ block}$      -> truthvalue
 $\phi_{on\ block\ block}$  -> truthvalue
and so on
```

```
to makeworld
   $\phi_m$  'world' [[A [RED 2 2 0]] [B [GREEN 2 5 2]]
               [C [RED 2 5 0]] [D [GREEN 4 11 0]]]
end

to lookup 'x' 'yys'
   $\phi$  if .yys=[] then type :x and p 'notfound and quit
   $\phi$  if :x=f' :yys then result f bf f :yys
   $\phi$  lookup :x (bf :yys)
end (finds the y corresponding to x in the list of x-y-pairs yys)

to colof 'b          to xof 'b
   $\phi$  f lookup :b :world   $\phi$  f bf bf lookup :b :world
end                    end

to/
```



```

to dimof 'b          to yof 'b
  10 f bf lookup :b :world  10 f bf bf bf lookup :b :world
end                  end

```

(Note colof 'b, xof :b etc. now depend on the state of the world. We lazily made this a global variable instead of passing it to each function as a parameter.)

```

to oblock
  10 maplist :world 'f
end

to obig 'b          to ored :b
  10 (dimof :b)>2    10 (colof :b)='red
end                  end

to osmall 'b        to ogreen :b
  10 (dimof :b)<3    10 (colof :b)='green
end                  end

to oon 'b1 'b2
  10 if not((yof :b1)=(yof :b2):(dimof :b2) then result false
  20 if either(oleft :b1 :b2)(oright :b1 :b2) then result false
  30 result true
end

to oleft 'b1 'b2
  10 (xof :b1)+(dimof :b1) <= (xof :b2)
end

to oright 'b1 'b2
  10 left .b2 :b1
end

to meaningof 'w
  10 if :w='block then result 'oblock
  20 if :w='big then result 'obig
  etc.
end

```

Now we have to rewrite DOPROP and DOREL to cope with a function name as first argument instead of a list. But wait, how do we handle qualif?

qualif->prep clnounphr

Its meaning is a property of blocks but we cannot easily produce a LOGO function to represent this property. We will just have to use a list as we did before, so DOPROP must accept lists as well as function names.

```

doprop(function-name or set-of-blocks) set-of-blocks->set-of-blocks
dorel function-name set-of-blocks->set-of-blocks

```

```

to doprop 'prop 'ys
  10 if listp :prop then result olddoprop :prop 'ys
  20 if apply :prop (f :ys) then result fput (f :ys) (doprop :prop (bf :ys))
  30 doprop :prop (bf :ys)
end (subset of ys which have property)
    (olddoprop is doprop of last section)

to/

```

```

to dorel 'rel 'ys
  if filter block :rel :ys
end
to filter 'xs 'rel 'ys
  join(filter!(f :xs) :rel :ys) (filter (bf :xs) :rel :ys)
end (finds all x in xs which are related to some y in ys)
to filter! 'x 'rel 'ys
  if empty? :ys then result []
  if apply :rel :x (f :ys) then result <<x>>
  filter! :x :rel (bf :ys)
end (<<x>> if x related to some y in ys, else emptylist)

```

With these redefinitions our program should work as before but more flexibly since its behaviour depends on the current value of the variable WORLD.

## Natural Language - 6: A la recherche du temps perdu

### 1. History and time contexts

So far all our sentences about blocks have referred to a single state of the world, the present one. Let us try to extend our system to discuss the past, giving the blocks world a history. This brings up the important idea of interpreting a phrase in a context, in our case a time context. Other contexts would be place ('come here') or speaker ('I killed Cook Robin').

Let us simply take 'Monday' 'Tuesday ... as the times, and define the blocks history as a set of day-world pairs. If we use the notation  $X \rightarrow Y$  to abbreviate  $[X Y]$  for readability we have as a possible history

```

[MONDAY->[A->[RED 2 2 0]  B->[GREEN 2 5 2]
          C->[RED 2 5 0]  D->[GREEN 4 11 0]]
[TUESDAY->[A->[RED 2 5 4]  B->[GREEN 2 5 2]
           C->[RED 2 5 0]  D->[GREEN 4 11 0]]
[WEDNESDAY->[etc.

```

(Nothing much happened between Monday and Tuesday except that the red block to the left of a red block was put on the small green block.)

We also need to know what day it is today, say THURSDAY.

So global variables HISTORY and TODAY describe our model (they can be set up by a procedure MAKEHISTORY corresponding to our previous MAKEWORLD).

If we want to know what the world was like on Monday  
 LOOKUP 'MONDAY' :HISTORY will tell us, and  
 LOOKUP 'TODAY' :HISTORY gives us the news.

What sort of sentences should we have? How about:-

The block which was to the left of a red block on Monday is on a block.

On Wednesday the block which was to the left of the block which was on a big block on Monday on Tuesday was to the right of the block which was on a red block on Thursday.

Has the big block been on a small block?

The point is that we can't evaluate

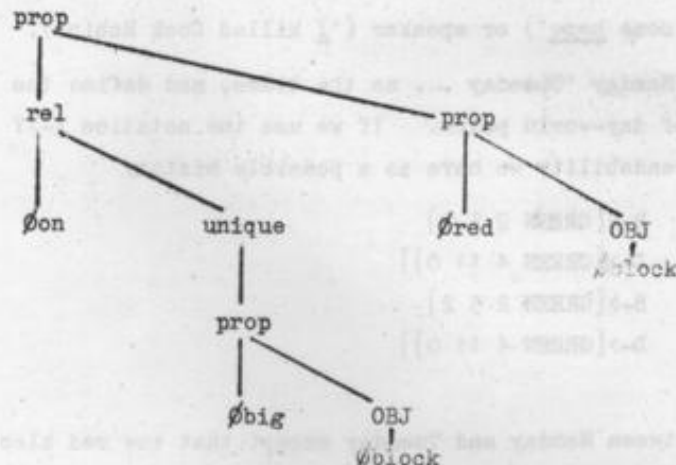
on a big block

to find which blocks it describes until we know which day we are talking about. So when we translate such a phrase we cannot pass on a list of blocks as the result, as we did previously.

So/

So let us pass back a description, which can be evaluated for a given day when we have read enough to know what day it is. This description can be a list of lists of lists ... , that is a tree structure, using markers OBJ (object), PROP (property), REL (relation), UNIQUE (to handle 'the'). The tips of the tree can be the names of semantic functions ØBLOCK, ØRED, etc.

The phrase [RED BLOCK ON A BIG BLOCK] would give the tree



This would be represented by lists thus

[PROP [REL ØON [UNIQUE [PROP ØBIG [OBJ ØBLOCK]]]] [PROP ØRED [OBJ ØBLOCK]]]

We could also allow such descriptions to have as components lists of blocks, which we have already evaluated.

Such trees are easily constructed by functions makeobject etc; thus

```

to mkobj :x
  Ø <<'obj :x>>
end
to mkprop :pr :x>>
  Ø <<'prop :pr :x>>
end

```

similarly for mkrel and mkunique.

Now we need a function to evaluate descriptions for a given day and produce a list of blocks. It can use our previous functions DOPROP, DOREL and UNIQUE, thus

```

to eval 'descrip 'day
  new 'world
  m 'world lookup :day :history
  if wordq :descrip then result :descrip (e.g. Øbig)
  if 'obj=f :descrip then result apply second :descrip
  if 'prop=f :descrip then result doprop
    (eval second :descrip :day)
    (eval third :descrip :day)
  if 'rel=f :descrip then result dorel
    (eval second :descrip :day)
    (eval third :descrip :day)
  if/

```

```

if 'unique=f :descrip then result unique
                                (eval second :descrip :day)

result :descrip                  (i.e. set of blocks, already evaluated)
and

(Note second  $\equiv$  f bf, third  $\equiv$  f bf bf)

```

Now doprop anddorel which make reference to :world will have the right world to work in, since it is set up as a local variable and made to be the world for the day supplied. Eval just calls itself recursively to evaluate subtrees (think of it as solving subproblems of evaluation).

## 2. Semantics for blocks with tense

Here then is the semantic specification for blocks with reference to past time. The new productions are marked with an asterisk. Coding the specification as LOGO procedures is tedious but straightforward. Notice that a production which does not know what day it is makes a description; one which is given a day evaluates descriptions.

```

simpnounphr -> noun                mkobj<(noun)>
simpnounphr -> adj simpnounphr     mkprop<(adj)>
nounphr -> simpnounphr qualif      mkprop<(qualif)><(simpnounphr)>
nounphr -> simpnounphr             <(simpnounphr)>
*nounphr -> simpnounphr tqualif     mkprop<(tqualif) <(simpnounphr)>
qualif -> prep clnounphr           mkrel<(prep)><(clnounphr)>
*tqualif -> 'which 'was qualif 'on  eval<(qualif)><(day)>
      'day
clnounphr -> 'a nounphr             <(nounphr)>
clnounphr -> 'the nounphr           mkunique<(nounphr)>
assertion -> 'there 'is 'a nounphr not emptyq(eval<(nounphr)> today)
*assertion -> 'on day 'there 'was  not emptyq(eval<(nounphr)><(day)>)
      'a nounphr
question -> 'is clnounphr qualif   exercise
*question -> 'has clnounphr 'been  exercise
      qualif
sentence -> assertion              if <(assertion)> then p 'correct else p 'liar
sentence -> question               if <(question)> then p 'yes else p 'no
*sentence -> 'today 'is day        m 'today<...>

```

## Exercises

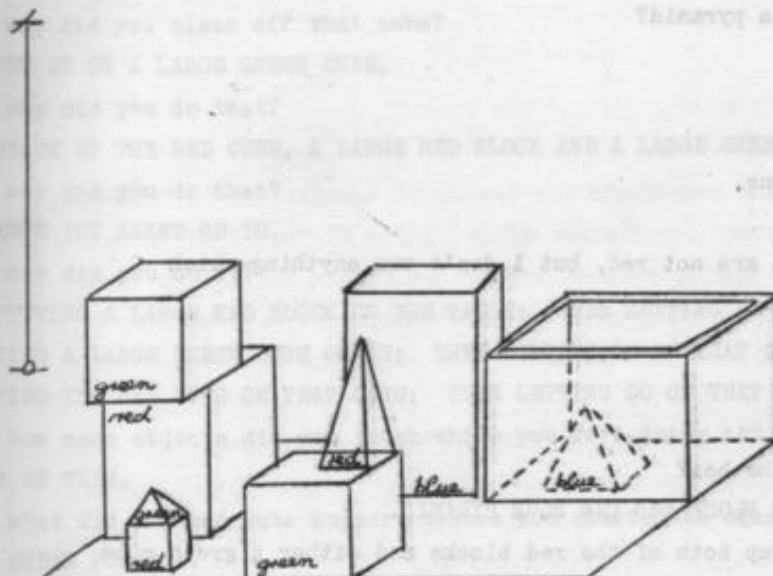
1. Fill in the semantics of questions.
2. Hand simulate in outline the action of the eval procedure on the description tree given above and day MONDAY, using the history given at the beginning.
3. Write LOGO procedures for the new productions, using those for the 'More flexible program' of section 5.2 as prototypes.



Natural Language - 7: Winograd's conversational program

- References Winograd, T. (1973) 'A procedural model of language understanding' in Schank and Colby: Computer Models of Thought and Language. Freeman, San Francisco.
- Winograd, T. (1972) 'Understanding Natural Language'. Edinburgh University Press. (A full account if you want more detail.)

1. Sample dialogue



1. pick up a big red block.
- OK.
2. grasp the pyramid.
- I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.
3. find a block which is taller than the one you are holding and put it into the box.
- BT"IT," I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.
- OK.
4. what does the box contain?
- THE BLUE PYRAMID AND THE BLUE BLOCK.
5. what is the pyramid supported by?
- THE BOX.
6. how many blocks are not in the box?
- FOUR OF THEM.
- 7./



7. is at least one of them narrower than the one which i told you to pick up?

YES, THE RED CUBE.

8. is it supported?

YES, BY THE TABLE.

9. can the table pick up blocks?

NO.

10. can a pyramid be supported by a block?

YES

11. can a pyramid support a pyramid?

I DON'T KNOW.

12. stack up two pyramids.

I CAN'T.

13. the blue pyramid is mine.

I UNDERSTAND.

14. i own all blocks which are not red, but i don't own anything which supports a pyramid.

I UNDERSTAND.

15. do i own the box?

NO.

16. do i own anything in the box?

YES, TWO THINGS: THE BLUE BLOCK AND THE BLUE PYRAMID.

17. will you please stack up both of the red blocks and either a green cube or a pyramid?

OK.

18. which cube is sitting on the table?

THE LARGE GREEN ONE WHICH SUPPORTS THE RED PYRAMID.

19. is there a large block behind a pyramid?

YES, THREE OF THEM: A LARGE RED ONE, A LARGE GREEN CUBE AND THE BLUE ONE.

20. put a small one onto the green cube which supports a pyramid.

OK.

21. put the littlest pyramid on top of it.

OK.

22. how many things are on top of green cubes?

I'M NOT SURE WHAT YOU MEAN BY "ON TOP OF" IN THE PHRASE "ON TOP OF GREEN CUBES"

DO YOU MEAN:

1 - DIRECTLY ON THE SURFACE

2 - ANYWHERE ON TOP OF?

23. had you touched any pyramid before you put the green one on the little cube?

YES/

YES, THE GREEN ONE.

24. when did you pick it up?

WHILE I WAS STACKING UP THE RED CUBE, A LARGE RED BLOCK AND A LARGE GREEN CUBE.

25. why?

TO GET RID OF IT.

26. why did you do that?

TO CLEAR OFF THE RED CUBE.

27. why did you clear off that cube?

TO PUT IT ON A LARGE GREEN CUBE.

28. why did you do that?

TO STACK UP THE RED CUBE, A LARGE RED BLOCK AND A LARGE GREEN CUBE.

29. why did you do that?

BECAUSE YOU ASKED ME TO.

30. how did you do it?

BY PUTTING A LARGE RED BLOCK ON THE TABLE; THEN LETTING GO OF IT; THEN PUTTING A LARGE GREEN CUBE ON IT; THEN LETTING GO OF THAT CUBE; THEN PUTTING THE RED CUBE ON THAT CUBE; THEN LETTING GO OF THAT CUBE.

31. how many objects did you touch while you were doing it?

FOUR OF THEM.

32. what did the red cube support before you started to clear it off?

THE GREEN PYRAMID.

33. there were five blocks to the left of the box then.

NO, ONLY FOUR OF THEM: THE RED CUBE, TWO LARGE GREEN CUBES AND A LARGE RED BLOCK.

34. put the blue pyramid on the block in the box.

OK.

35. is there anything which is bigger than every pyramid but is not as wide as the thing that supports it?

YES, THE BLUE BLOCK.

36. does a steeple

SORRY, I DON'T KNOW THE WORD "STEEPLE".

37. a "steeple" is a stack which contains two green cubes and a pyramid.

I UNDERSTAND.

38. are there any steeples now?

NO.

39. build one.

OK.

40. call the biggest block "superblock".

O.K.

41./

41. have you picked up superblock since we began?  
YES.

42. why did you drop it?  
BY "IT", I ASSUME YOU MEAN THE SUPERBLOCK.

I CAN'T EXPLAIN A NON-EXISTENT EVENT.

43. is there anything to the right of the red pyramid?

YES, FOUR THINGS: THE BOX, THE RED CUBE, THE BLUE PYRAMID AND THE BLOCK  
NAMED SUPERBLOCK.

44. thank you.

YOU'RE WELCOME!

## 2. Semantics - some remarks

a. Our LOGO program computes a set (list) of blocks when it is unsure which one is meant e.g. [green block] gives list-[B D]. Winograd in his Planner system chooses one of the blocks and uses a 'back track' facility in Planner to go back and repeat with the next block. We can't do this in LOGO, but computing the list seems about as good.

b. Winograd actually creates some Planner program and then runs it. We just run existing program. His Planner program looks rather like sentences in logic. For example:

a red cube which supports a pyramid

```
(GOAL (IS ?X1 BLOCK))
(GOAL (COLOR-OF ?X1 RED))
(GOAL (EQUIDIMENSIONAL ?X1))
(GOAL (IS ?X2 PYRAMID))
(GOAL (SUPPORT ?X1 ?X2))
```

This is more sophisticated than our description trees in the final LOGO program.

c. Even the dictionary of word meanings has the names of procedures in it. (Similarly in our LOGO program MEANINGOF 'ON is a procedure name 'DON)

d. Notice the complexity of a word like 'the'. Sentence 2 'Grasp the pyramid' is ambiguous, but 'Grasp the red pyramid' is O.K. since the model world only has one red pyramid. In sentence 5 'What is the pyramid supported by?' there is no ambiguity, since a particular pyramid has just been mentioned; here the ambiguity is resolved by syntactic context not by reference to the model. Our LOGO program could not do this unless we made procedures like NOUNPHR store the meaning and the corresponding input string or tree.

3. Syntax - some remarks

- a. Notice the complexity of the syntax Winograd can handle compared with our little LOGO one. Ours with only a few kinds of phrases was still a bit hard to keep in one's head. If we simply invented 199 more kinds of phrases we would get in a muddle.
- b. To avoid a very big context free grammar with lots of arbitrary names of phrase classes Winograd uses 'Systemic Grammar', due to Halliday (he doesn't regard the choice as crucial, just helpful). There are just four basic kind of phrase

Clause	'Is it red?', 'it is on the table', 'on which he sat'
Noun group	'A big man', 'the man in a hurry', 'cars'
Preposition group	'On top of the table', 'with', 'in the iron mask'
Verb group	'lives', 'will have been living', 'to be kissed'

But each of these is subdivided (into subspecies and subspecies as a biologist would say). The subdivisions are characterised by features, DETERMINED, MASCULINE, SINGULAR, ANIMATE, TRANSITIVE, INTERROGATIVE, etc. So instead of a class

MASC SING CL NOUN PHRASE (!!!)

we might have NOUN GROUP with features MASCULINE, SINGULAR, CLOSED. This makes it easy to ensure that subject and verb agree in number without writing separate procedure rules for each case (in French they must also agree in gender). We can also ensure more easily that verbs like 'loves' get ANIMATE subjects. Notice, too, that one would expect the semantics of 'loves' to be different according to whether the object is animate or not. 'John loves Mary' implies that John is in love, but 'John loves ice-cream', doesn't.

The subdivisions of CLAUSE are very complicated (see extract from Winograd's book 'Understanding Natural Language' ps. 48,49). Even this does not exhaust the matter because we can also make distinctions based on transitivity/intransitivity.

- c. Winograd writes his parser in a special language PROGRAMMAR. This is not all that different from LOGO but is specially designed for parsing. For example we do not need to mention the string S all the time. For example the grammar

S/

S -> NP VP

NP -> DETERMINER NOUN

VP -> VERB/TRANSITIVE NP

VP -> VERB/INTRANSITIVE

corresponds to the PROGRAMMAR program

(PDEFINE SENTENCE

(( (PARSE NP) NIL FAIL)

(( (PARSE VP) FAIL FAIL RETURN)))

(PDEFINE NP

(( (PARSE DETERMINER) NIL FAIL)

(( (PARSE NOUN) RETURN FAIL)))

(PDEFINE VP

(( (PARSE VERB) NIL FAIL)

(( (ISQ H TRANSITIVE) NIL INTRANS)

(( (PARSE NP) RETURN NIL)

INTRANS

(( (ISQ H INTRANSITIVE) RETURN FAIL)

In the second line above (PARSE NP) has two 'directions' NIL and FAIL after it. It uses the first if it succeeds, the second if it doesn't. (PARSE VP) has a third direction RETURN, which is used if it succeeds and there is not more string left.

NIL means go onto next instruction.

FAIL means output a fail and restore string to the previous one (like CHECK).

RETURN outputs a result, after attaching the new node to the parse tree (rather like TRY).



Question answering and inference - 1: The inference system1. Introduction

We wrote a LOGO program to accept sentences about the blocks world and make some primitive responses to them. But the model to which the sentences referred was put in as a collection of lists described in LOGO. It was not the result of our conversation. This might be a fair representation of a system which answers questions about a scene it sees through a TV camera or even about some specific body of data like airline timetables. But often we derive our knowledge from sentences: 'Read this passage and answer the questions below' as the school books say. So we need to represent an incomplete model in a way that is easy to add to or change. The list representation was specific (it knew just where everything was), not too easy to change and needed special LOGO code for concepts like ON. An alternative to lists+procedures is facts+inference rules.

2. Memory

The program must store some information about the blocks world, for instance "The block is red". We adopt the same method as we used in the geometric analogy problems and the making of structural descriptions, and for the same reasons i.e. we use symbolic descriptions.

We could choose say [RED BLOCK] or [COLOUR BLOCK RED]. The latter will be most versatile, for instance if we wanted to answer the question "What is the colour of the block?".

Typically we will want to store a large collection of such facts inside the computer. As a first approximation we can imagine a list of them, e.g.

```
[[COLOUR BLOCK RED] [BELONGS BLOCK ME] [BIG BLOCK]
```

```
[ON BLOCK1 BLOCK] ..... ]
```

Such a collection of facts is usually called a database.

Retrieval

How would the program use this database to answer the question "Is the block coloured red?". First it would have to analyse the sentence and build up the description [COLOUR BLOCK RED]. Then it would call:

AMONGQ/



AMONGQ [COLOUR BLOCK RED] :DATABASE

and print "yes" or "no" as the result of this call was "true" or "false" (should it be "no" or "do not know"?).

The problem of building up descriptions from the English input has been the subject of our natural language lectures.

### 3. Organising the Database

Unfortunately the number of facts that have to be stored in most non-trivial domains, is very large. Searching down a long list as AMONGQ does take a long time. It is rather as if one was searching for a book in the library by looking at every book. Our solution to this problem is similar to the library's - we index the database. Various indexing systems are used to organise databases. We have made a system available in LOGO (available through BORROWFILE or LIBRARY as 'ECMI/1' INFERENCE). You can add a fact to the database with the command ASSERT

e.g. ASSERT [COLOUR BLOCK RED]

ASSERT [BIG BLOCK]

To decide whether a fact is present we have provided the test function ISQ,

i.e. ISQ [COLOUR BLOCK RED]

corresponds to

AMONGQ [COLOUR BLOCK RED] :DATABASE

### 4. Blocks World

Let us fill the database with some facts about a little world consisting of two blocks, both red, one big and one light (weight). We must choose proper names for the blocks, say block1 and block2. The procedure SETUPWORLD will set this up for us.

TO SETUPWORLD

10 CLEARDATABASE

20 ASSERT [COLOUR BLOCK1 RED]

30 ASSERT [COLOUR BLOCK2 RED]

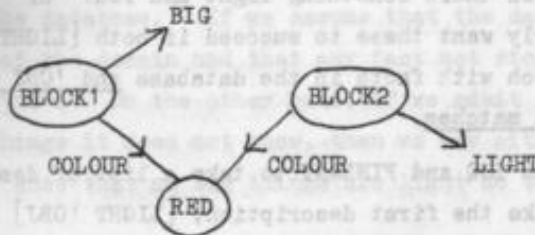
40 ASSERT [BIG BLOCK1]

50 ASSERT [LIGHT BLOCK2]

END

## 5. Semantic Networks

These sequences of assertions are a little difficult to read so just as in the structural description problem we can represent them as a network (these networks are variously called semantic networks, relational nets or graphs in the literature).



## 6. "Wh" Questions

Suppose we ask the question "What colour is BLOCK1?". What do we want the program to do? The program should look for a fact of the form: [COLOUR BLOCK ??] in the database, where ?? is any argument whatever, and returns as its result whatever ?? turns out to be (in this case RED).

We have already met something in LOGO which plays a similar role to ??, namely a LOGO variable e.g. 'COL. We will use the same notation here and write [COLOUR BLOCK 'COL]. Originally COL will be unassigned, but during the course of answering the question it will be assigned a VALUE, in this case RED. So we need a procedure say FINDANY, which takes [COL] and [COLOUR BLOCK1 'COL] as arguments and returns RED as result.

e.g. 1: PRINT FINDANY [COL] [COLOUR BLOCK1 'COL]

RED

This procedure will have to compare [COLOUR BLOCK1 'COL] against facts in the database looking for one which matches. e.g. [COLOUR BLOCK1 RED]. Matching [COLOUR BLOCK1 'COL] against a fact consists of checking that the first and second items of the fact are COLOUR and BLOCK respectively and then assigning the third item to 'COL (i.e. MAKE 'COL 'RED). FINDANY will then return a list containing just :COL as its result.

Similarly "What is coloured red?" could be translated into

FINDANY ['OBJ] [COLOUR 'OBJ RED]

Not just "Wh" questions (Which ...?, What ...?, Who ...?, How ...?, etc.) need to use variables. We might ask "Is anything red?". This naturally translates into

ISQ/

ISQ [COLOUR 'OBJ RED]

which should return true if any fact in the database matches [COLOUR 'OBJ RED] (assigning the appropriate item to 'OBJ in the process).

## 7. Conjunctions

Suppose we ask "Is there something light and red?" or "What is light and red?". We clearly want these to succeed if both [LIGHT 'OBJ] and [COLOUR 'OBJ RED] match with facts in the database and 'OBJ is assigned the same item in both matches.

We will want both ISQ and FINDANY to take a list of descriptions as input. They will take the first description, [LIGHT 'OBJ] and compare it with facts from the database, until they find one that matches (e.g. [LIGHT BLOCK2]) OBJ will be assigned the value BLOCK2. It will not do to continue the process by looking for something to match with [COLOUR 'OBJ RED], because OBJ may be assigned some other value than BLOCK2. Rather the database must now be searched for something to match with [COLOUR BLOCK2 RED], i.e. having found a value for OBJ, we replace all remaining occurrences of X by this value. We signify this to the procedures ISQ and FINDANY by putting a quote in front of any OBJ which is to be assigned a value, and a colon in front of any OBJ which is to be replaced by its value, i.e. we write

ISQ [[LIGHT 'OBJ][COLOUR :OBJ RED]]  
FINDANY [OBJ] [[LIGHT 'OBJ] [COLOUR :OBJ RED]]

To sum up

'OBJECT means OBJECT is a variable which is to be assigned a value in the match, called an unbound variable.

:OBJECT means OBJECT is a variable which is to be replaced by the value of 'OBJECT, called a bound variable.

OBJECT means OBJECT is a constant that stands for itself, like RED, BLOCK2 or COLOUR.

## 9. Failure

If ISQ and FINDANY are working properly they should fail to find an object which is both big and light.

i.e. ISQ [[BIG 'OBJECT] [LIGHT :OBJECT]]  
should return FALSE. (FINDANY returns [ ])

If/

If we had written:

```
ISQ [[BIG 'OBJECT] [LIGHT 'OBJECT]]
```

then ISQ would have returned TRUE by assigning first BLOCK1 to OBJECT then BLOCK2 to OBJECT.

What we do with this output of FALSE when we get it depends on our conventions about the database. If we assume that the database has complete knowledge of the domain and that any fact not stored is false, then we will print "no". On the other hand, if we admit the possibility that there may be things it does not know, then we may either print "I do not know" or try to show that no big things are light so that we can print "no".

Either of these conventions can be useful in different circumstances. We should always be clear which we intend.

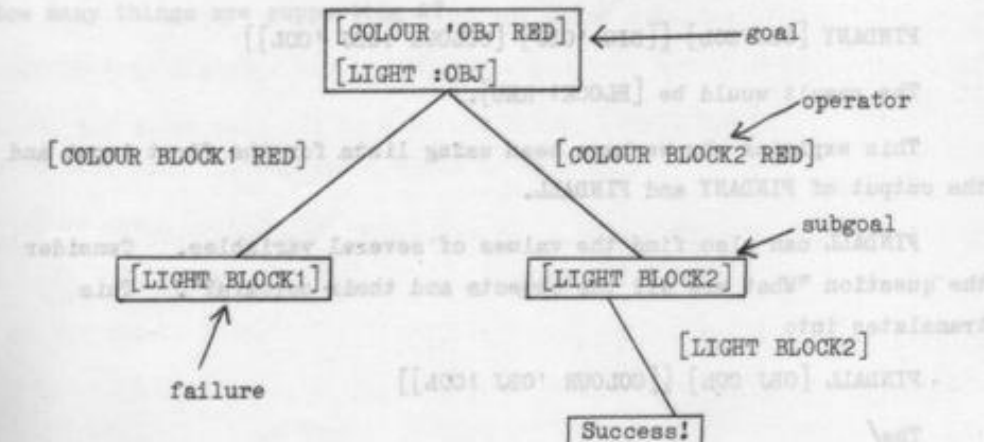
#### 9. Search

Suppose we had asked "Is anything red and light?"

i.e. ISQ [[COLOUR 'OBJ RED] [LIGHT :X]]

There is a good chance that the initial comparison of [COLOUR 'OBJ RED] with facts in the database would have assigned BLOCK1 to 'OBJ. Since [LIGHT BLOCK1] is not in the database, ISQ would have returned false unless it was able to "back up", undo its assignment of BLOCK1 to 'OBJ and assign BLOCK2 instead. Thus ISQ and FINDANY must be prepared to search for assignments to the variables which simultaneously satisfy all the descriptions. With a lot of conjunctions and a lot of variables in the input, ISQ and FINDANY may have to do a lot of searching before they succeed (or fail). We can represent these searches by a search tree.

e.g.



The nodes of the tree are goals or descriptions to be matched. The arcs or operators are facts from the database.

#### 10. FINDALL

There may be several alternative assignments which lead to success. Both ISQ and FINDANY are satisfied with the first successful assignment they find, but there are occasions when we are interested in all the successful assignments. For instance, suppose we ask "Which things are red?". We would expect the answer "BLOCK1 and BLOCK2". A procedure FINDALL is provided in LOGO. Its syntax is similar to FINDANY except that it returns a list of all successful assignments.

e.g. FINDALL [THING][COLOUR 'THING RED]

returns [[BLOCK1] [BLOCK2]]

N.B. not [BLOCK1 BLOCK2] for a reason which will soon be clear.

#### 11. Many Variables

Some questions may involve using several variables. For instance suppose we ask "What colour is the big object?". We would probably translate this into

FINDANY [COL] [[BIG 'OBJ] [COLOUR :OBJ 'COL]]

which would return [RED].

In the process BLOCK1 would be assigned to OBJ and RED to COL.

Only the value of COL is returned as the result of FINDANY, because [COL] was given as its first input. If we wanted the value of OBJ as well, for instance in answer to the question "What is the big object and what colour is it?", we would write

FINDANY [OBJ COL] [[BIG 'OBJ] [COLOUR :OBJ 'COL]]

The result would be [BLOCK1 RED].

This explains why we have been using lists for the first input and the output of FINDANY and FINDALL.

FINDALL can also find the values of several variables. Consider the question "What are all the objects and their colours?". This translates into

FINDALL [OBJ COL] [[COLOUR 'OBJ 'COL]]

The/



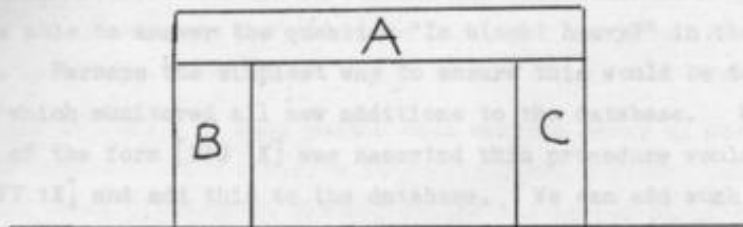
The result of which is

[[[BLOCK1 RED] [BLOCK2 RED]]

which explains why the result of FINDALL is a list of lists.

Exercise 1.1 Write FINDANY in terms of ISQ. (i.e. assume ISQ is provided, but FINDANY is not.)

Exercise 1.2



Represent the above picture as a procedure which makes a series of assertions in a database.

e.g. TO ARCH1  
 10 CLEARDATABASE  
 20 ASSERT [ONEPARTIS GROUP A]  
 etc.

Exercise 1.3 Translate the following questions into procedure calls which could access the database set up by ARCH1.

Is A lying?

What is lying?

What is to the left of C?

What is to the right of B?

What things are supporting A?

What is the arch constructed from?

What are the supports of the arch?

How many things are supporting A?



A.I.2.  
1975/76

QAI.8

4.2.76.  
RMB/AB/2

Question answering and inference - 2: Forward and backward deduction

1. Deduction

So far the knowledge in our database has been simple facts or assertions. Not all knowledge is of this type. Some knowledge is in the form of laws like "All big things are heavy" (people often use very rough generalisations). With this law and the fact that block1 is big we should be able to answer the question "Is block1 heavy?" in the affirmative. Perhaps the simplest way to ensure this would be to have a procedure which monitored all new additions to the database. Whenever a fact of the form [BIG 'X'] was asserted this procedure would deduce [HEAVY :X] and add this to the database. We can add such a procedure to our world model using the procedure ASSERT. Let us edit the procedure SETUPWORLD and add line

```
15 ASSERT [IMPLIES [BIG 'X] [HEAVY :X]]
```

You should read this law "The fact that X is big implies the fact that X is heavy". The first description [BIG 'X'] is called the antecedent and the second [HEAVY :X] is called the consequent. The procedure works by matching the antecedent against all incoming assertions. If a match succeeds the procedure asserts the consequent, replacing any variables with their assigned values. Such a procedure is sometimes called an "Antecedent Theorem", an "If asserted method" or a "Demon" and the kind of deduction it does is variously called "Forwards deduction", "Forwards chaining", "Bottom up reasoning" or "Hypotheses driven deduction".

We should be sure to add such "demons" before asserting any facts, because it will only deduce consequences of facts asserted after it itself has been asserted. Thus when line 40, which is

```
40 ASSERT [BIG BLOCK1]
```

is executed, our demon will set to work and ASSERT [HEAVY BLOCK1]. (If line 40 were line 13, our demon would do nothing.)

Now if we ask

```
ISQ [HEAVY BLOCK1]
```

we will get the result TRUE.

2./

## 2. Problems with Forwards Deduction

Unfortunately it is not always convenient to draw all possible conclusions from the things we assert. Typically an already large database will become cluttered with facts we may never need to know. Imagine, for instance, what would happen to our database if every time we asserted [HUMAN X], we deduced [HAS X HEART], [HAS X HEAD], [HAS X HAIR], [HAS X LUNG] etc. Any new assertion would lead to an explosion of deductions, the database would become so full that we would find it increasingly hard to retrieve facts.

The situation is worse because some demons lead to a call of themselves. Consider "Every human has a human mother". If we asserted [HUMAN JANE1] we would deduce and assert [MOTHER JANE2 MUM1] and [HUMAN MUM1] where MUM1 was a new constant. This would lead to a new deduction [HUMAN MUM2] and so ad infinitum. Clearly some laws need to be kept for use only when needed.

## 3. Functions

In the previous example we cheated a bit. Each application of the law "Every human has a human mother", introduces a new constant, (e.g. MUM1, MUM2, .... etc.). But we have not yet discussed a mechanism for introducing new constants. We now correct this omission.

A first approximation might be to include a new constant in the statement of the laws

e.g. [IMPLIES [HUMAN 'X] [HUMAN MUM]]  
[IMPLIES [HUMAN 'X] [MOTHER :X MUM]]

This would work for the first application of the law to say [HUMAN JANE] producing [HUMAN MUM] and [MOTHER JANE MUM], but the second application (to [HUMAN MUM]) would produce [HUMAN MUM] and [MOTHER MUM MUM] which would be silly. Clearly the new constant should depend on the particular value of X at the time the law is called. The device we introduce to deal with this problem is to represent the new constant by something like an explicit LOGO procedure call using the function name MUMOF and taking :X as argument. So MUM1 will be represented by

[MUMOF JANE]

and MUM2 by

[MUMOF [MUMOF JANE]]

The/

The law "Every human has a human mother" can now be represented as  
 [IMPLIES [HUMAN 'X] [HUMAN [MUMOF :X]]]

together with

[IMPLIES [HUMAN 'X] [MOTHER [MUMOF :X]]]

Exercise Represent the law "Every human has a head".

#### 4. Backwards Deduction

What we need is a law which will only be invoked when it is needed to answer some question.

e.g. when we ask ISQ [HEAVY BLOCK1] it changes the question to  
 ISQ [BIG BLOCK1] which returns true. But [HEAVY BLOCK1] is  
never asserted.

In LOGO we store such a law by typing

ASSERT [TOINFER [HEAVY 'X] [BIG :X]]

Read this law "To infer that X is heavy, deduce that X is big".

ISQ [HEAVY BLOCK1] first checks to see if [HEAVY BLOCK1] is in the database. If not it then checks in a database of laws to see if any are relevant. This means matching the consequent of the law against the current goal (e.g. [HEAVY 'X] against [HEAVY BLOCK1]). Then the current goal is replaced by the antecedent of the law (with any assigned variables replaced by their values), e.g. ISQ [HEAVY BLOCK1] is replaced by ISQ [BIG BLOCK1].

Such laws are variously called "Consequent theorems" or "If needed methods", and the kind of deductions they do are called "Backwards deduction", "Backwards chaining", "Top down reasoning" or "goal directed deduction".

We will want to allow the antecedent of our "TOINFER" laws to consist of several descriptions

e.g. [TOINFER [METAL 'X] [HEAVY :X] [COLOUR :X GREY]]

This will cause no problems since ISQ etc. can handle conjunctions of goals.

#### 5. Search Again

Just as it was possible to make the wrong assignments to variables and have to back up, it is possible to apply the wrong law and have to back up. Suppose we edit SETUPWORLD to have two TOINFER laws corresponding to

"All metal things are heavy"

"All big things are heavy"

i.e.

TO SETUPWORLD

10 CLEARDATABASE

13 ASSERT [TOINFER [HEAVY 'THING] [BIG :THING]]

15 ASSERT [TOINFER [HEAVY 'THING] [METAL :THING]]

20 ASSERT [COLOUR BLOCK1 RED]

30 ASSERT [COLOUR BLOCK2 RED]

40 ASSERT [BIG BLOCK1]

50 ASSERT [LIGHT BLOCK2]

END

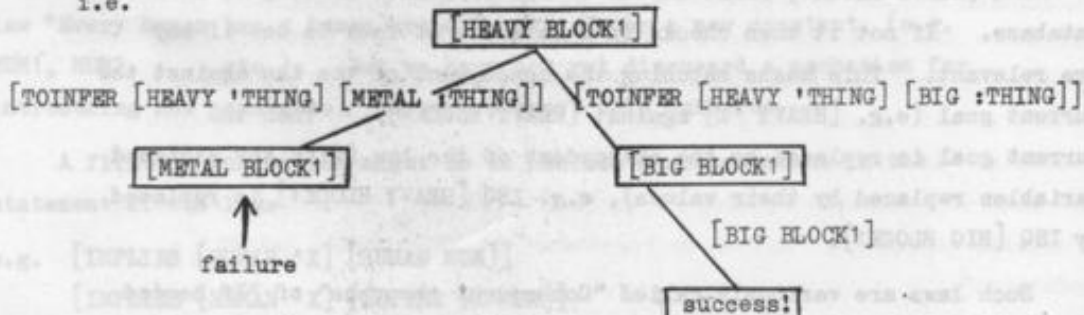
If we ask

ISQ [HEAVY BLOCK1]

in our current INFERENCE system the first law "all metal things are heavy" will be used first and it will call ISQ [METAL BLOCK1]. This will fail, so if the original goal is not to fail, ISQ must be prepared to back up and try the second law.

We can represent the search by a tree

i.e.



The arcs can now represent laws or facts from the database.

Even these TOINFER laws do not prevent explosions. For instance, suppose we added the law:

[TOINFER [ON 'X 'X] [ON :X 'Y] [ON :Y :Z]]

corresponding to that if one block is on top of another and a third is on top of that, then the top block is on top of the bottom block.

Suppose we now ask

ISQ [ON BLOCK1 BLOCK2]

Since this is not in the database the law will be invoked and

ISQ/

ISQ [[ON BLOCK1 'Y'] [ON :Y BLOCK2]]

will be called.

This will call

ISQ [[ON BLOCK1 'Y1'] [ON :Y1 'Y'] [ON :Y BLOCK2]]

and so, ad infinitum.

## 6. Predicate Calculus

Those of you familiar with predicate calculus will find all this rather familiar. In fact this is a procedural version of a subset of predicate calculus. For that reason you will sometimes see programs like this referred to as "Inference systems" or "Theorem provers".

## 7. Logical Arguments

We can get the program to perform most of the logical deductions that you find in the literature. For instance consider

All Humans are Fallible

Turing is human

Socrates is human

Socrates is Greek

Who is a fallible Greek?

translate this into

ASSERT [TOINFER [FALLIBLE 'X'] [HUMAN :X]]

ASSERT [HUMAN TURING]

ASSERT [HUMAN SOCRATES]

ASSERT [GREEK SOCRATES]

FINDANY [X] [[FALLIBLE 'X'] [GREEK :X]]

to get [SOCRATES].

## Exercises

You try this with:

2.1 All men are mortal

Socrates is a man

Is Socrates mortal?

## Ontology

We have met a very limited class of entities in this simple descriptive language, i.e. just:

Physical/





Physical objects like block<sup>1</sup>, block<sup>2</sup>

Properties like red

Relations between them like colour, big

Assertions like [COLOUR BLOCK<sup>1</sup> RED]

Laws like [IMPLIES [BIG 'X] [HEAVY :X]]

To conduct reasonable conversation we will have to represent:  
places; times; events; actions; substances, etc.

- 2.2 (a) Using the LOGO inference system translate each of the following sentences into a procedure call corresponding to its meaning:

The Pope is good

John Wayne is good

John Wayne is courageous

Anyone who is good and courageous is a hero

Who is a hero?

- (b) Suppose the translations of the sentences above the line were used to set up a database and the translation of the sentence below the line were used to interrogate that database. Draw the search tree of that interrogation.

- 2.3 If X is a parent of Y and Z is a sister of X then Z is an aunt of Y.

If X is a parent of Y and X is an aunt of Z then Y is a cousin of Z.

A mother or a father is a parent

Mary is the mother of John

Fred is the father of Jane

Mary is the sister of Fred

Daisy is the wife of Fred

Who is the cousin of Jane?

Draw the search tree of the above.

- 2.4 What additional laws do you need to answer "Who is the aunt of John?"

2.5



Using the LOGO INFERENCE system:

(a)/



- (a) Give a partial symbolic description of the above drawing of a face sufficient to answer "yes" to the following questions, by direct database lookup:

Is the mouth in the lower portion of the face?

Is the left eye in the upper portion of the face?

Is the nose in the centre of the face?

- (b) In addition represent the laws that:

Anything in the centre of the face is also in the middle portion.

Anything in the middle portion of something is always above anything in the lower portion.

Anything in the upper portion of something is always above anything in the middle portion.

- (c) Represent the question:

Is the nose above the mouth?

Draw the complete search tree of its interrogation of the database.

- (d) In addition represent the law:

To infer that x is above y show that x is above z and z is above y. and the question:

Is the mouth above the nose?

Draw some of the search tree of this interrogation. What problem arises? How might it be overcome?

Does your solution involve changing the LOGO INFERENCE system?

#### Recommended Reading

Raphael, B. 'A Computer Program which "Understands"'. AFIPS Conference Proceedings Vol. 26, Part 1, 1964, pp. 577-99.

Sussman, G.J., Winograd, T., Charniak, E. "Micro Planner Reference Manual". MIT AI Memo 203A, 1972. (Read lightly, not attempting to learn Microplanner.)

Question answering and inference - 2: AppendixSummary of the LOGO INFERENCE package1. Access

The inference system consists of a number of procedures available as a file in NEWLOGO. It provides facilities for making a database, retrieving from it and doing forward and backward inference.

2. Patterns

A pattern is a list of pattern elements or patterns.

A pattern element is either

- (1) A constant, i.e. a word or number
- (2) A quoted variable, i.e. a quote followed by a variable name
- (3) A colon variable, i.e. a colon followed by a variable name.

Examples of patterns:- [LIKES JOE FOOD]  
 [LIKES JOE 'XX]  
 [NEAR 'XX :CURRENT]  
 [LIKES JOE [DAUGHTEROF :XX]]  
 [[LIKES JOE 'XX] [AVAILABLE :XX]]

A pattern is simple if its first is a pattern element, otherwise it is compound. Compound patterns are understood as conjunctions.

Example: all but the last pattern above are simple.

3. Procedures

Notation: Pat-pattern, T-truthvalue, L-list, Ll-list of lists,  
 Vl-list of variables.

CLEARDATABASE

- Clears the database.

ASSERT simple-pat

- Adds pattern to database,  
 any colon variables take  
 their current values.

Example - ASSERT [COLOUR RED :OBJ]

ISQ Pat -> T

- Tests whether pattern  
 matches one in database.

A quoted variable is  
 assigned a value by the  
 matching if possible. Colon  
 variables take their current  
 values/

values whether assigned by MAKE or by matching. New values are available after ISQ is finished. For a compound pattern each component is matched in succession, depth first.

Example - ISQ [[BIG 'XX] [BAD :XX]]

FINDANY V1 Pat -> L

- The pattern is matched against the database; result is the list of subsequent values of the variables named in V1.

Example - FINDANY [XX] [BIG 'XX]

FINDALL V1 Pat -> L1

- Like FINDANY, but finds all possible ways of matching the pattern with the database; result is the list of all possible lists of subsequent values of the variables named in V1.

#### 4. Rules

ASSERT can also be used with a rule as argument.

Rules use antecedents and consequents, which are simple patterns.

There are two kinds of rules:-

[IMPLIES antecedent consequent]

- subsequently, when any pattern which matches the antecedent is asserted the consequent is also asserted (with the then current values of the variables, including assignments to variable while matching the antecedent).

Example - ASSERT [IMPLIES [STUDENT 'X] [INDUSTRIOUS :X]]

[TOINFER consequent antecedent1 antecedent2 ...]

- whenever the system tries to match some pattern of the same form as the consequent it can instead try to match the pattern(s) defined by the antecedent(s) (all of them conjunctively).

Example/

Example - ASSERT [TOINFER [MAN 'X] [MALE :X] [HUMAN :X]]

- Restrictions
1. No colon variables in the consequent of a TOINFER rule.
  2. Variables occurring in the rules must not clash with any variables that appear in non-rule patterns. Adopt a convention like X,Y,Z only for rule-variables.

#### 5. Negation

In a compound pattern any component after the first may be negated by [NOT [...]].

Example ISQ [[RED 'X] [NOT [SMALL :X]]].

#### 6. Using the system

- (a) Access the system from NEWLOGO\* by  
LIBRARY 'ECMIØ1 'INFERENCE  
or BORROWFILE 'ECMIØ1 'INFERENCE (like GETFILE)
- (b) Do CLEARDATABASE to initialise the system first of all.
- (c) If variable THINKALOUD is TRUE (default value) the system prints a commentary on its search. Make false to prevent this.
- (d) Like other variables, variables in patterns are best declared NEW in procedures which use them.
- (e) The system is extremely sensitive to the order in which it tries TOINFER-rules. Rules asserted first are tried last, so assert the simplest rules last. Search is depth first, so beware of infinite recursion.

---

\* To get NEWLOGO in EMAS initially  
command: APPENDLIB (ECMIØ5. NEWLOGLB)  
command: COPYLOGO (to make your AI2LOGO files available)  
Thereafter call it with command: NEWLOGO.

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SW/1

STRUCTURAL DESCRIPTIONS

TASK: How could we get a sensible description of figure A?

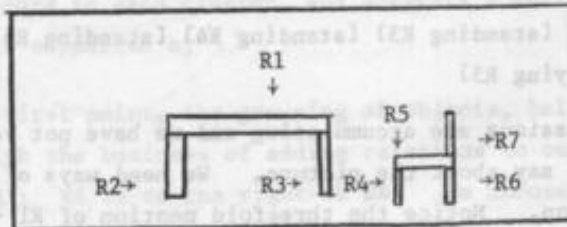


Figure A

We would prefer "a chair near a table" to

"5 vertical rectangles and 2 horizontal rectangles".

Let us look again at the process of achieving a symbolic description of a picture we went through in the analogy lectures.

a) We need to achieve uniformity of predicates.

If several descriptions are possible, e.g.

"a triangle inside a square"

"a square surrounding a triangle"

we arbitrarily chose a predicate, say, "inside" and then stick to it, to enable rigorous comparison between descriptions.

b) To avoid ambiguity, we express the elements involved in the relationship in a fixed order. [inside triangle square] must be distinguished systematically from [inside square triangle].

c) We ignore superfluous words such as "with", "a", "it".

d) In cases where we have two objects of the same shape, we distinguish them in the obvious way:-

triangle1 , triangle2

e) We list the objects in the figure, explicitly, and our descriptions take the form

<set of objects in figure> <set of relationships in figure>

Now consider our task figure

For convenience we abbreviate "rectangle" to "R".

The set of objects in the figure is [R1 R2 R3 R4 R5 R6 R7].

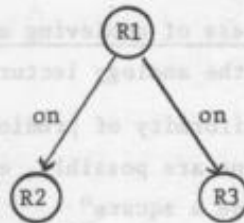
We could describe the spatial relationship between R1 and R2 using "above", "below", "under" or "on". "On" includes the idea of touching and suits our purposes best. Thus:-

[on R1 R2] [on R1 R3] [on R5 R4] [on R5 R6] [on R7 R5]

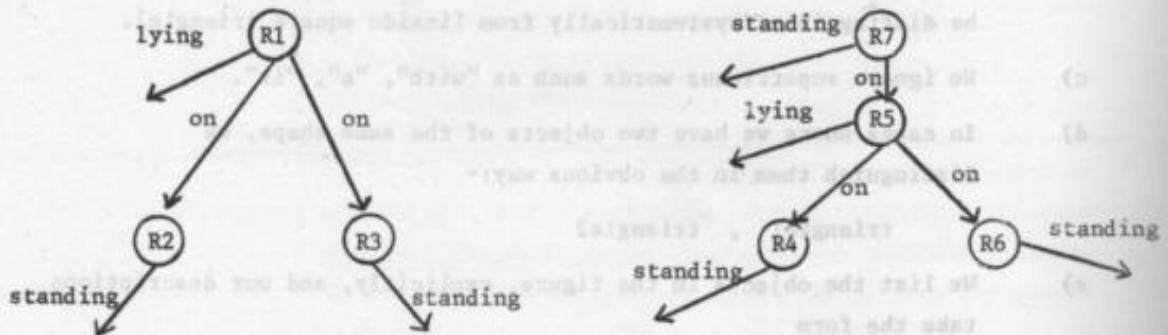
We capture the different orientations thus:-

[standing R2] [standing R3] [standing R4] [standing R6] [standing R7]  
[lying R1] [lying R5]

Rather a lot of expressions are accumulating and we have not yet expressed half the things we need to say about the picture. We need ways of making it easier to see what is going on. Notice the threefold mention of R1 - three facts about R1 have been asserted. We have a way of grouping references to the same object by creating a node to represent the object and using directed arrows to represent the relationships it has with other objects.



The third fact about R1 [lying R1] tells us about a property of R1 rather than how it is related to other objects. We treat properties as one-place relationships, in that the descriptions of the property is attached to an arc hanging from the node





There are two interesting consequences of this representation.

1. The objects from two clusters by virtue of their relations. Viz:-

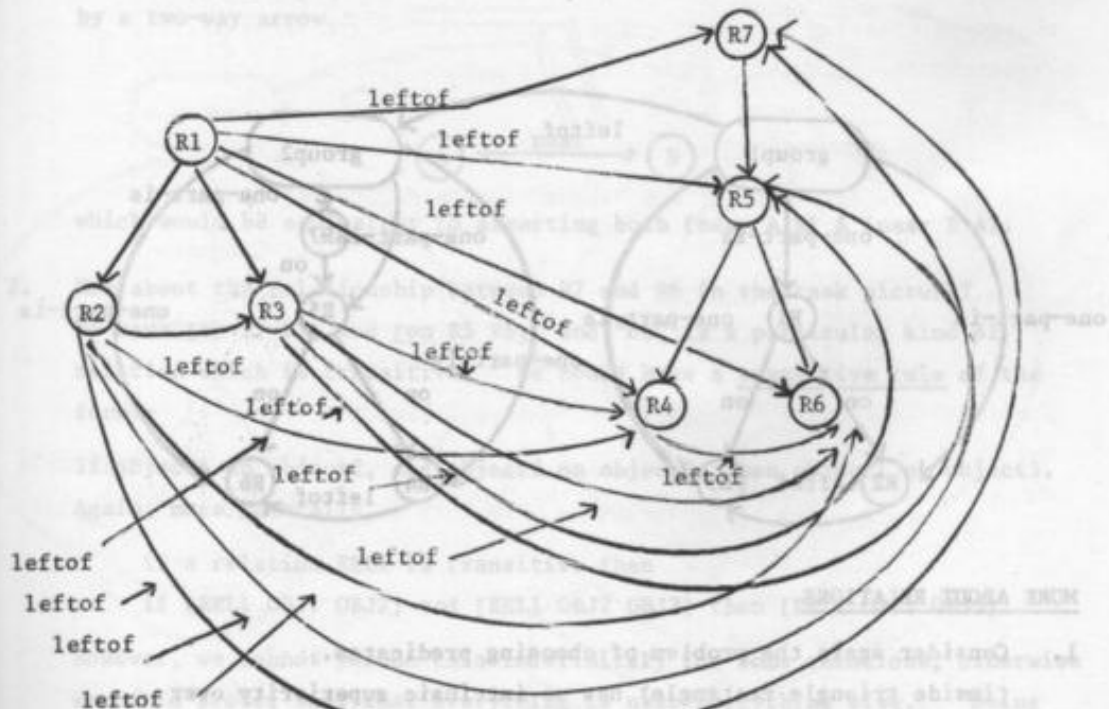
group 1 [R1 R2 R3]

group 2 [R4 R5 R6 R7]

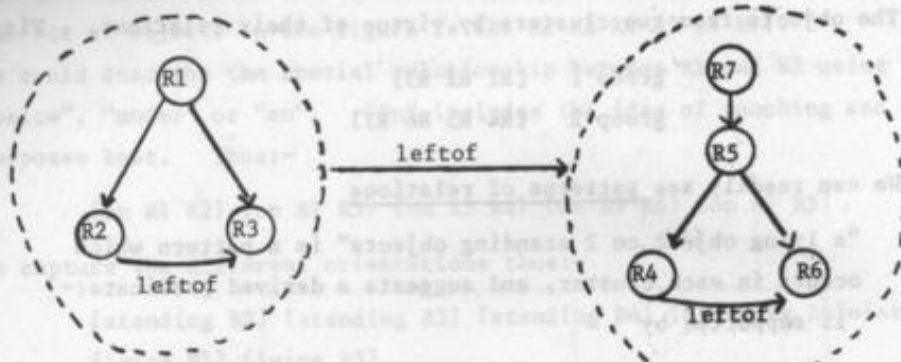
2. We can readily see patterns of relations

"a lying object on 2 standing objects" is a pattern which occurs in each cluster, and suggests a derived predicate:-  
"is supported by"

How does the first point, the grouping of objects, help us in our task? Let us proceed with the business of adding relations to our network e.g. R2 is to the left of R3; R6 is to the right of R4. We choose, arbitrarily, "leftof" as the canonical predicate and insert.



Much more convenient to group relations



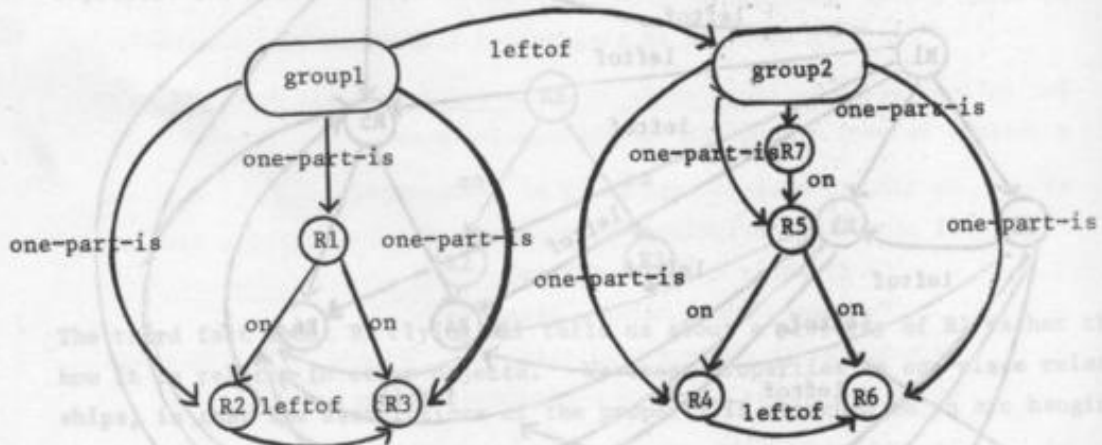
[leftof group1 group 2] [leftof R2 R3] [leftof R4 R6]

But we need a way to refer to



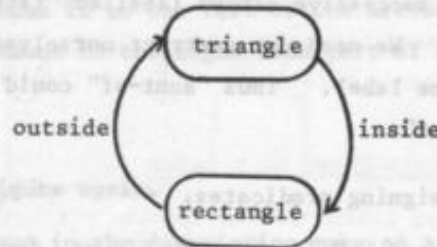
and what do we mean by this

dotted circle anyway? We make explicit the relationship "one-part-is"



#### MORE ABOUT RELATIONS

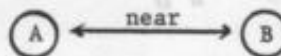
1. Consider again the problem of choosing predicates.  
[inside triangle rectangle] has no intrinsic superiority over [outside rectangle triangle]. We could introduce explicitly the fact that the two are equivalent by using two arrows each time the relationship occurred in the network:-



Alternatively, and more economically, we can provide this information once and for all in the form of a rule about inverses.

Inverse rule: if obj1 inside obj2 then obj2 outside obj1. More generally, if one relation REL1 is the inverse of another relation REL2 then if [REL1 OBJ1 OBJ2] then [REL2 OBJ2 OBJ1].

Some relations like next to or near are symmetrical and can be represented by a two-way arrow



which would be equivalent to asserting both [near A B] & [near B A].

2. How about the relationship between R7 and R6 in the task picture?  
We have [on R7 R5] and [on R5 R6], and "on" is a particular kind of relation which is transitive. We could have a transitive rule of the form:-

If object1 on object2, and object2 on object3, then object1 on object3.  
Again, more generally,

if a relation REL1 is transitive then  
if [REL1 OBJ1 OBJ2] and [REL1 OBJ2 OBJ3] then [REL1 OBJ1 OBJ3].

However, we cannot pursue this indefinitely for some relations, otherwise we could prove, say, that everything is near everything else. "Being near to" seems to include the idea of "distance away from" relative to some activity i.e. near enough to be affected by.

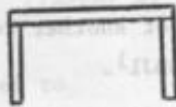
3. In network terms, we have traversed two directed arrows in order to get [on R7 R6]; in both cases, the directed arrow had the label "on".

In the same way, two successive arrows labelled "father-of" could give us "grandfather-of". We need not restrict ourselves to successive arrows having the same label. Thus "aunt-of" could be "mother-of" followed by "sister-of".

4. Problems arise in assigning predicates.

a) Recall "is-supported-by" in the task figure, derived from

grouping "one lying rectangle on two standing rectangles".

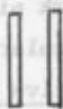


But what about

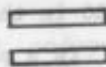


?

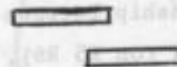
b) Consider "leftof" and "above" in the following:-



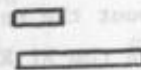
leftof



above

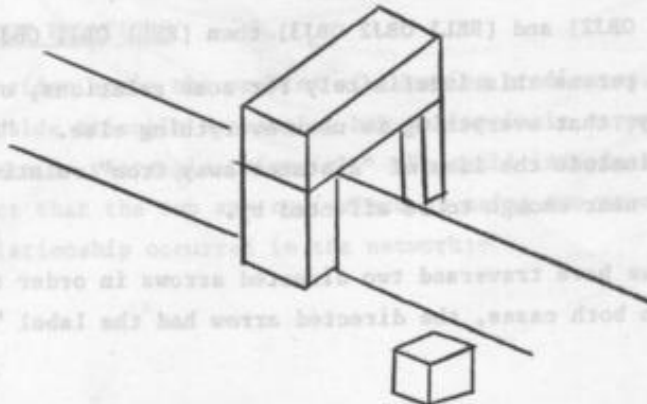


above & leftof



?

c) The cube is rightof the arch in the picture, but in the real world scene which this represents, the cube is on the leftof the archway.



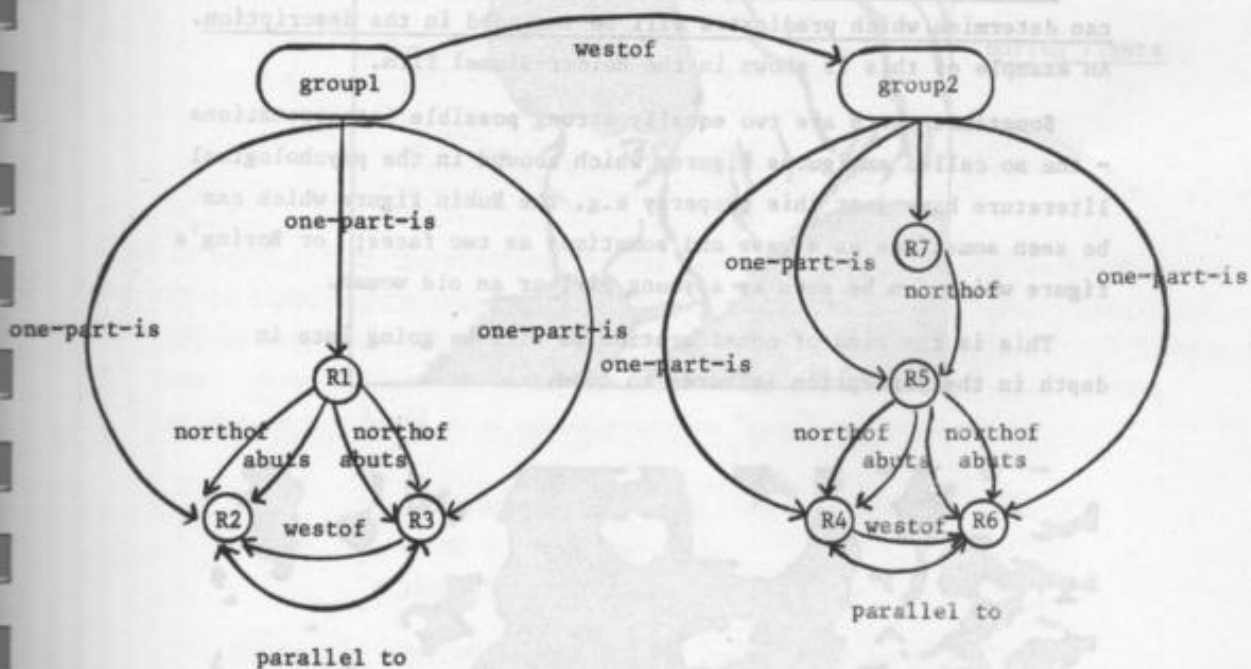
This is a matter of frame of reference in terms of which the relations are defined. The cube is to the left of the archway as seen from the point of view of someone in the right-hand part of our picture.

#### POINT OF VIEW

Consider the task figure again.

All the relations used in the description make an assumption about the figure VIZ that we are looking at a side view of some scene and that for example points in the top part of the picture correspond to higher points in the scene than do those in the lower part of the picture.

Now let us assume that the picture represents an aerial view of some scene. What happens to our description?



Notice (a) We have some symmetric relations } and the same general  
                   some transitive relations } rules already developed  
                   some inverse relations } for these will hold.

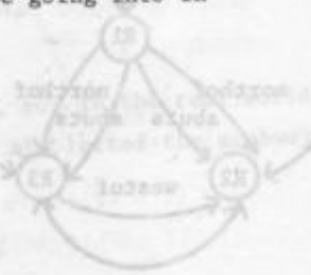
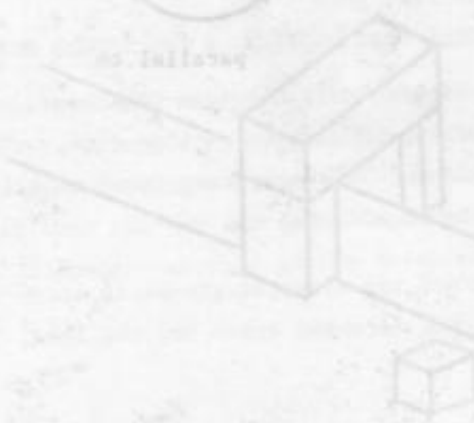
(b) A crucially important set of remarks

How difficult was it for you to see the picture as an aerial view? The familiar arrangement of parts triggers concepts we already have i.e. evokes the labels "table" and "chair" for group1 and group2 respectively; i.e. imposes the viewpoint. We see the 3 rectangles R1, R2 and R3 as a table. Parts take their names from the wholes they are seen to belong to, e.g. R1 becomes "table-top". No such ready interpretation emerges for an aerial view.

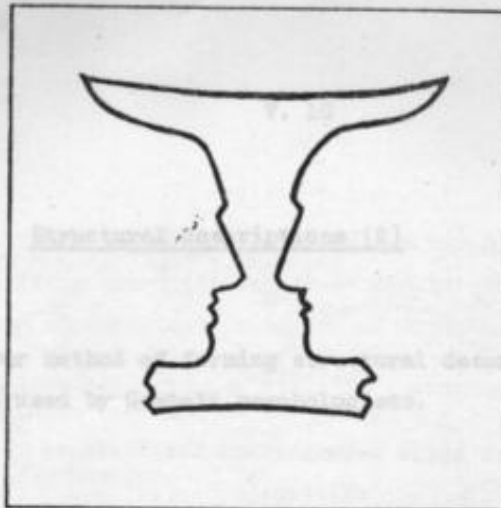
We find that a global decision such as viewpoint assignment can determine which predicates will be included in the description.  
 An example of this is shown in the Heider-Simmel film.

Sometimes there are two equally strong possible interpretations - the so called ambiguous figures which abound in the psychological literature have just this property e.g. the Rubin figure which can be seen sometimes as a vase and sometimes as two faces; or Boring's figure which can be seen as a young girl or an old woman.

This is the kind of consideration we will be going into in depth in the perception lectures to come.







Rubin figure



Boring figure

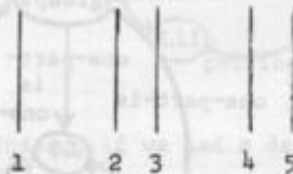


## Structural descriptions (2)

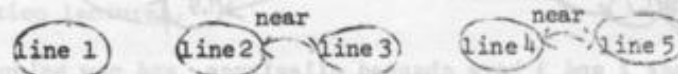
We try out our method of forming structural descriptions on some standard displays used by Gestalt psychologists.

### 1. Grouping

Example a. Consider this display of 5 vertical lines.



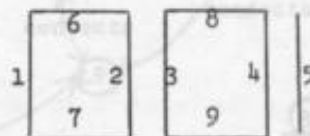
Our description might look like this:-



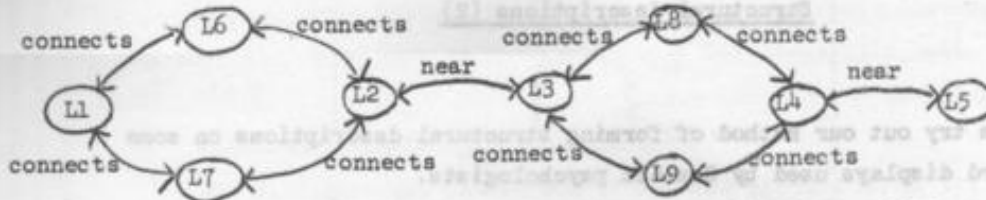
We could put in "parallel-to". But since each line is parallel to every other line, such a tag would only load up our description without providing any evidence for grouping. Similarly properties like "vertical" and "straight" would occur attached to every node and would not affect our bias to form groups on the basis of a shared relation "near" as follows:-

- group 1 : line 2 and line 3 (abbreviate L2 & L3)
- group 2 : L4 and L5
- group 3 : L1

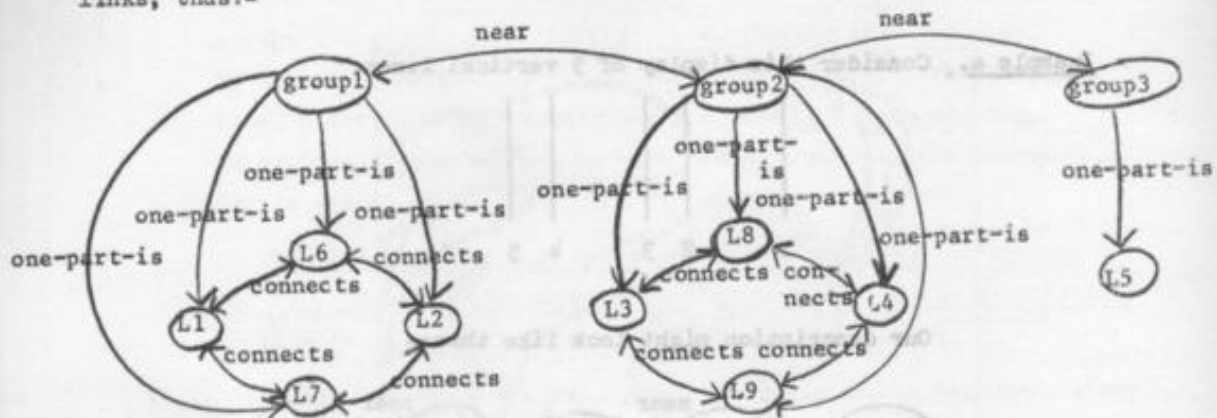
Example b. Now we add 4 lines to our display to get:-



The new feature is that certain lines are connected.



Again three groups fall out quite naturally on the basis of closed rings of links, thus:-



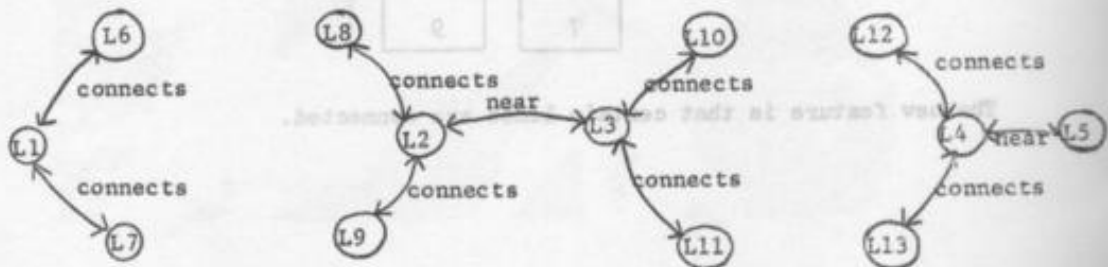
Notice how lines 2 and 3 have changed allegiance, and now belong to different groups. The nodes in groups 1 & 2 formed closed rings. To keep the skeleton of our description clear, we will not follow through the details of adding features like "parallel-to" and "at-right-angles-to", necessary to provide the basis for identifying groups 1 and 2 as rectangles.

Instead we look at

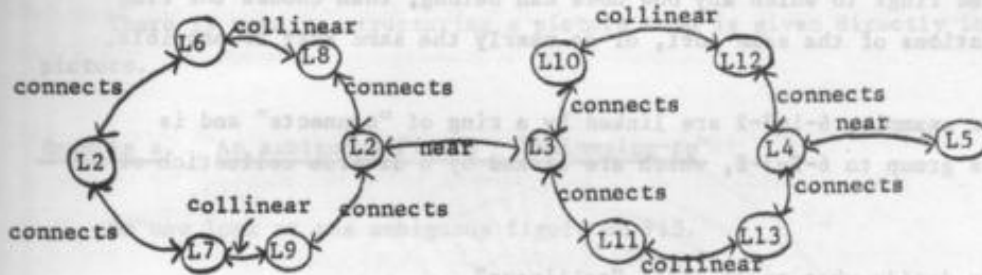
Example c.

	6	8	10	12	
1		2	3	4	5
	7	9	11	13	

This yields the following:-



At first blush, we might seem to be back to situation (a) with the same three groups. However by noticing the collinearity of the hanging lines 6 & 8, 7 & 9, 10 & 12, 11 & 13, we form a conceptual "closure" of the shape thus:-

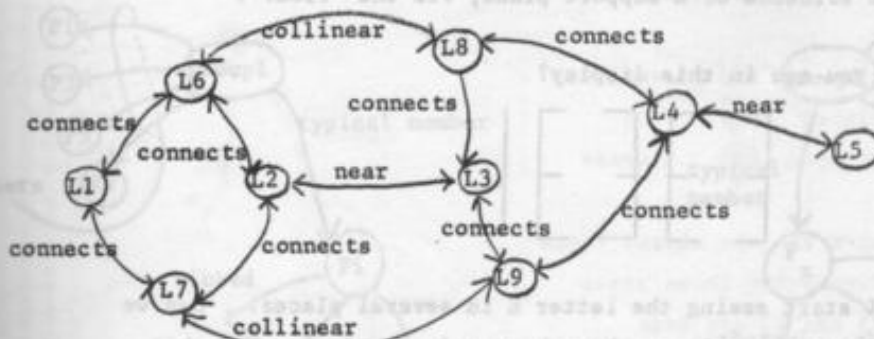


Now we are in situation (b). Indeed, if we had a description of the rectangles in (b) stored away, we could imagine that finding the hook "┌" (L6-L1-L7) could invoke the stored description or model of a rectangle i.e. trigger the expectation of a rectangle, and lead to an active search for the rest of the rectangle. More of this in the perception lectures.

Notice, however, that there is a bug in our recipe.

Since we have granted our system the ability to notice collinearity in situation (c), we should have noticed the collinear lines in situation (b). And when we allow this, we find that because this relation involves only some nodes, it seriously affects our grouping.

The description of situation (b) should have been



Now we can no longer claim that two groups fall out naturally. There is more than one way of extracting groups from this network. We need to have a way of ordering our grouping criteria. For example, if there are two possible closed rings to which any one node can belong, then choose the ring formed by relations of the same sort, or as nearly the same sort as possible.

So in our example, 6-1-7-2 are linked by a ring of "connects" and is preferred as a group to 6-2-3-8, which are linked by a diverse collection of relations.

Now we have to decide what to do about "collinear".

One of the reasons for grouping is to form entities which at a higher level can themselves behave as primitive elements in a relation

e.g. group1 near group2

However we would still want to retain the ability to relate part of one group to either the whole of another group, or to part of another group.

e.g. Consider again the task figure in the previous handout. (P V.1) We observe that the bottom lines of the two rectangles forming the "chair" are collinear, and that the same goes for the bottom lines of the rectangles forming the "table". Furthermore all these lines are collinear i.e. part of part of the "chair" group is collinear with part of part of the "table" group, and we can, and probably do, use this evidence of a support plane, viz the "floor".

Example d. What do you see in this display?



At this point, I start seeing the letter E in several places. Can we get this description with the rules we have been using so far? Try this example yourselves.

Suggestion.



Suggestion. There is a much deeper bug in our method, which was hinted at by the remark on P12 which referred to the possibility that hooks of the form "[ " might invoke the STORED DESCRIPTION or MODEL of a rectangle.

There is more to structuring a picture than is given directly in the picture.

Example e. An ambiguous figure - "belonging-to"

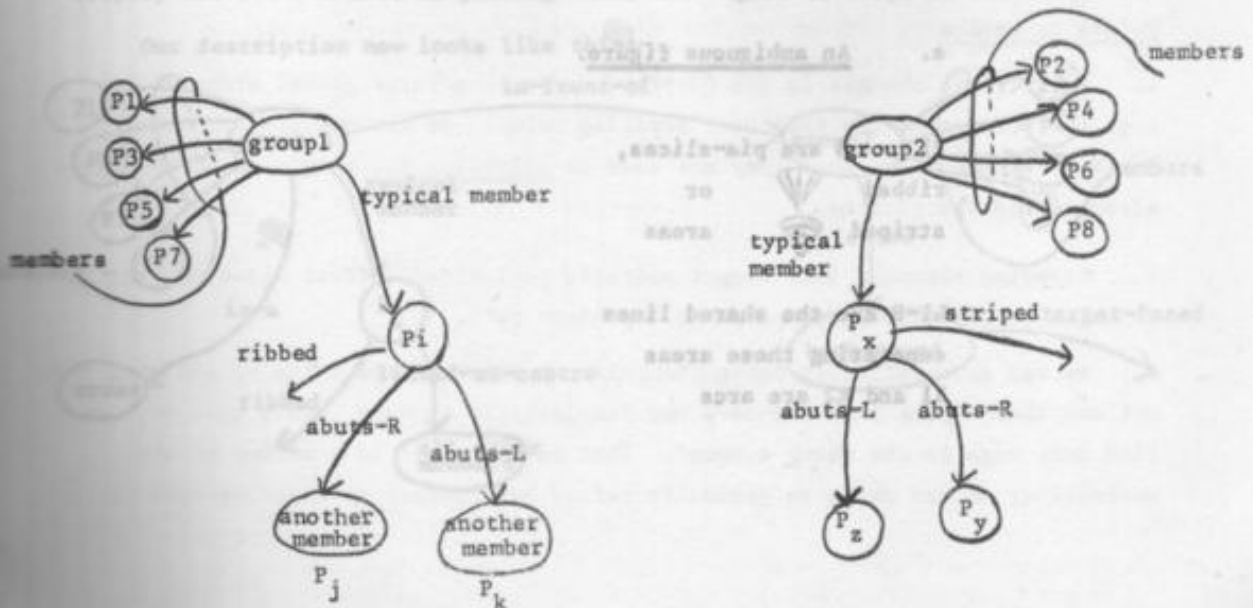
We now look at the ambiguous figure on P15.

This can be seen either as a cross of 4 ribbed pie slices on a background disc of concentric circles, a target; or as a cross of striped pie slices on a background disc of radiating spikes. In the former case, the arcs are seen as the visible parts of complete circles; in the latter they are seen as true arcs.

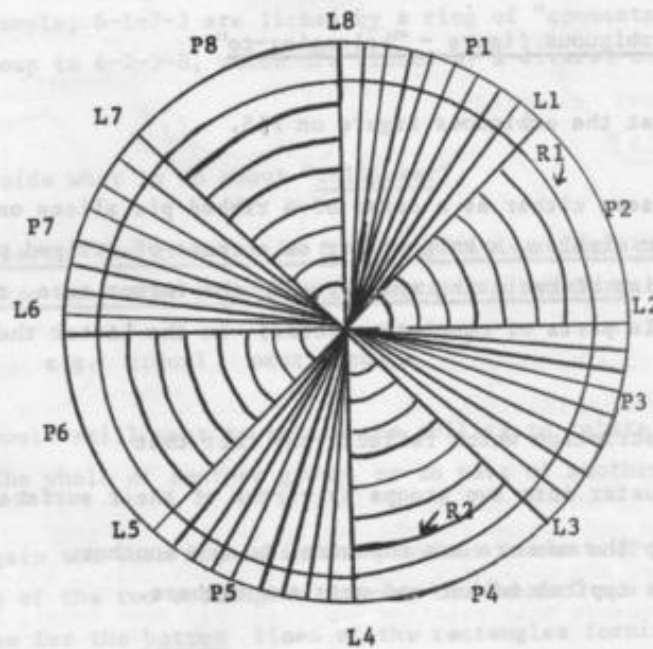
We form a description which reflects the fact that

1. The areas cluster into two groups by virtue of their surface markings.
2. In each group the members are identical to one another.


We describe a typical member and note the members.







e. An ambiguous figure.

P1 - 8 are pie-slices,  
ribbed  or  
striped  areas

L1-8 are the shared lines  
separating these areas  
R1 and R2 are arcs

But what are we to do with lines 1-8?

Consider L1 and the areas directly separated by it VIZ P1 or P2. We could see L1 as belonging either to P1, or to P2, or to both. Let us follow through the consequences of each choice.

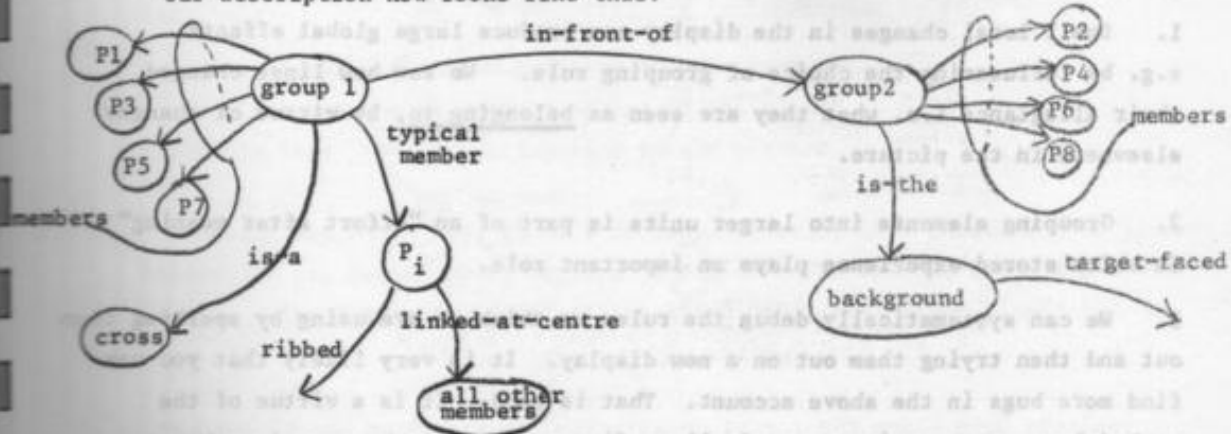
(1) Suppose we choose to assign L2 as the boundary of P1. This leads us to expect L8 to form the other boundary of P1 which then achieves the status of a closed figure.

RULE: Try to group lines into closed figure.  
Thus, P2 and P8 become background. If P1 is to remain a typical member of our group 1, then we are led to postulate boundaries for all the other members of the group in the same way; the group now consists of 4 pie slices joined at the centre. Group 2 consists of 4 bits of background and we are likely to see them as one area patchily occluded by the cross of closed figures by noticing that the arcs in these areas form matching sets of T-junctions with the figure boundaries:-



Again we form "conceptual" closures as we did in the earlier rectangle display and see the arcs as passing under the figure to complete the circles.

Our description now looks like this:-



- (2) Suppose we choose to assign L1 to P2.

Applying our closure rule, we get L2 belonging to P2 as well, to form a closed figure. The consequence of this spreads through the display, this time turning all group 2 areas into closed figures joined at the centre to form a cross. Now we hallucinate radial spikes behind the figure. The description follows the previous pattern.

- (3) If we try to assign L1 to both P1 and P2, we run into difficulties. What is involved is conceptually splitting each line, and inhibiting the T-junction effect, in order to see a flat surface of alternately ribbed and striped figures. We just don't seem to do this very readily.

More examples of how context influences the structural descriptions being constructed are given in the figures on P V.19.

#### In Summary

We have explored, in a tentative way, some of the methods we as human observers use to group lines into shapes into coherent structures. Grouping imposes an organisation on the figure, structures it into a meaningful whole.

#### Points to notice

1. Small local changes in the display can produce large global effects e.g. by influencing the choice of grouping rule. We saw how lines changed their allegiance i.e. what they are seen as belonging to, by virtue of changes elsewhere in the picture.
2. Grouping elements into larger units is part of an "effort after meaning" in which stored experience plays an important role.
3. We can systematically debug the rules we think we are using by spelling them out and then trying them out on a new display. It is very likely that you can find more bugs in the above account. That is good. It is a virtue of the methodology we are using to gradually refine our recipes by exposing them to



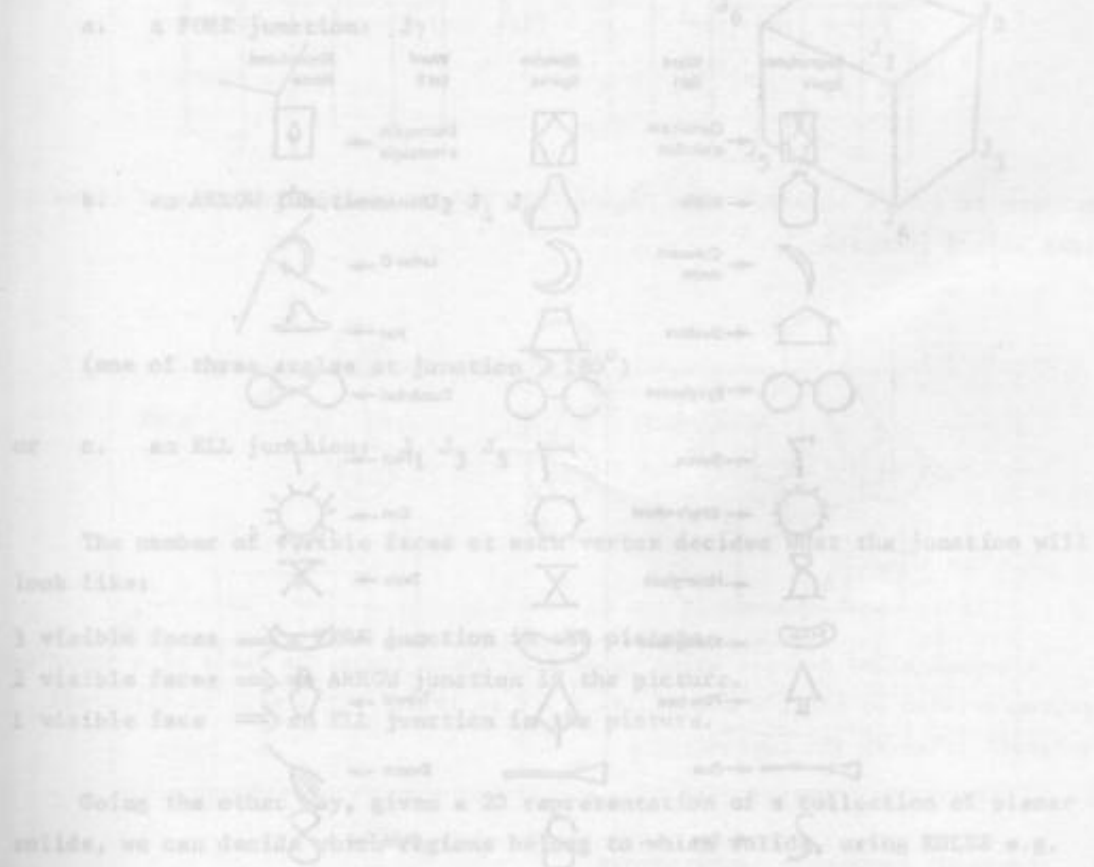
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STRUCTURAL DESCRIPTION 3

new cases. The best way to find bugs which elude the kind of hand-testing we have been doing is to program up the rules and run the program on a set of examples.

Choosing good examples is an important part of the story.

We take this up next time.



The number of visible faces at each vertex is what the junction will look like:

1 visible face — 1 visible face — 1 visible face

2 visible faces — 2 visible faces — 2 visible faces

3 visible faces — 3 visible faces — 3 visible faces

4 visible faces — 4 visible faces — 4 visible faces

5 visible faces — 5 visible faces — 5 visible faces

6 visible faces — 6 visible faces — 6 visible faces

7 visible faces — 7 visible faces — 7 visible faces

8 visible faces — 8 visible faces — 8 visible faces

9 visible faces — 9 visible faces — 9 visible faces

10 visible faces — 10 visible faces — 10 visible faces

11 visible faces — 11 visible faces — 11 visible faces

12 visible faces — 12 visible faces — 12 visible faces

13 visible faces — 13 visible faces — 13 visible faces

14 visible faces — 14 visible faces — 14 visible faces

15 visible faces — 15 visible faces — 15 visible faces

16 visible faces — 16 visible faces — 16 visible faces

17 visible faces — 17 visible faces — 17 visible faces

18 visible faces — 18 visible faces — 18 visible faces

19 visible faces — 19 visible faces — 19 visible faces

20 visible faces — 20 visible faces — 20 visible faces

21 visible faces — 21 visible faces — 21 visible faces

22 visible faces — 22 visible faces — 22 visible faces

23 visible faces — 23 visible faces — 23 visible faces

24 visible faces — 24 visible faces — 24 visible faces

25 visible faces — 25 visible faces — 25 visible faces

26 visible faces — 26 visible faces — 26 visible faces

27 visible faces — 27 visible faces — 27 visible faces

28 visible faces — 28 visible faces — 28 visible faces

29 visible faces — 29 visible faces — 29 visible faces

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36 visible faces — 36 visible faces — 36 visible faces

37 visible faces — 37 visible faces — 37 visible faces

38 visible faces — 38 visible faces — 38 visible faces

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40 visible faces — 40 visible faces — 40 visible faces

41 visible faces — 41 visible faces — 41 visible faces

42 visible faces — 42 visible faces — 42 visible faces

43 visible faces — 43 visible faces — 43 visible faces

44 visible faces — 44 visible faces — 44 visible faces

45 visible faces — 45 visible faces — 45 visible faces

46 visible faces — 46 visible faces — 46 visible faces

47 visible faces — 47 visible faces — 47 visible faces

48 visible faces — 48 visible faces — 48 visible faces

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74 visible faces — 74 visible faces — 74 visible faces

75 visible faces — 75 visible faces — 75 visible faces

76 visible faces — 76 visible faces — 76 visible faces

77 visible faces — 77 visible faces — 77 visible faces

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84 visible faces — 84 visible faces — 84 visible faces

85 visible faces — 85 visible faces — 85 visible faces

86 visible faces — 86 visible faces — 86 visible faces

87 visible faces — 87 visible faces — 87 visible faces

88 visible faces — 88 visible faces — 88 visible faces

89 visible faces — 89 visible faces — 89 visible faces

90 visible faces — 90 visible faces — 90 visible faces

91 visible faces — 91 visible faces — 91 visible faces

92 visible faces — 92 visible faces — 92 visible faces

93 visible faces — 93 visible faces — 93 visible faces

94 visible faces — 94 visible faces — 94 visible faces

95 visible faces — 95 visible faces — 95 visible faces

96 visible faces — 96 visible faces — 96 visible faces

97 visible faces — 97 visible faces — 97 visible faces

98 visible faces — 98 visible faces — 98 visible faces

99 visible faces — 99 visible faces — 99 visible faces

100 visible faces — 100 visible faces — 100 visible faces

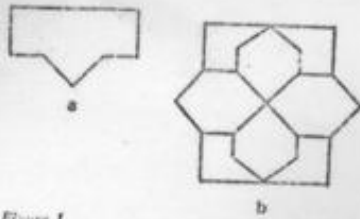


Figure 1

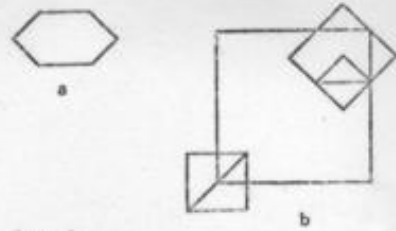


Figure 2

TASK: Try and find Fig (a) in Fig (b) in each case.

(After K. Gottschaldt (1926); in Experiments in Visual Perception.  
Ed M.D. Vernon. Penguin)

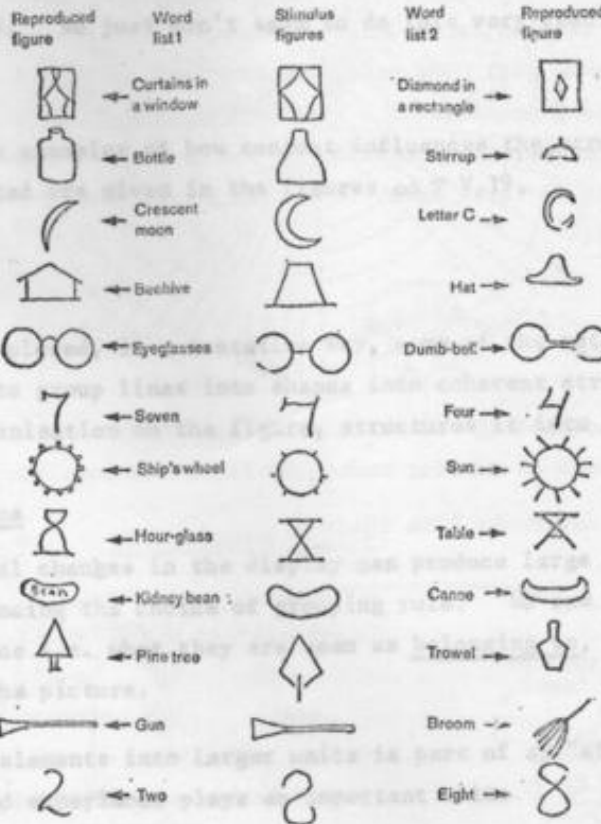


Fig. 6. Ambiguous figures. (After L. Carmichael *et al.* in *Journ. of Experimental Psychology*, vol. 15, p. 80)

Subjects were shown the series of stimulus figures shown in the central column, each of which could represent two things. As each figure was shown, names from list 1 were read out to one group; alternative names for each figure from list 2 were read out to another group. The two groups were then asked to draw what they had seen as accurately as possible.

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SW/3STRUCTURAL DESCRIPTION 31. 2D drawings of planar solids: first visit.

The three faces of a cube meet at a trihedral vertex. In a 2D drawing of a cube, the three edges forming such a vertex are represented by the junction of lines, forming either:-

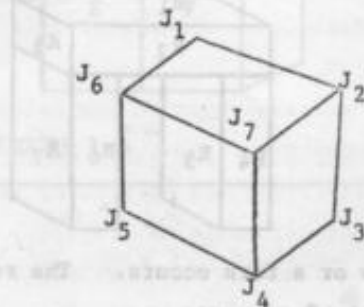
a. a FORK junction:  $J_7$ b. an ARROW junction:  $J_2 J_4 J_6$ (one of three angles at junction  $> 180^\circ$ )or c. an ELL junction:  $J_1 J_3 J_5$ 

The number of visible faces at each vertex decides what the junction will look like:

3 visible faces  $\Rightarrow$  a FORK junction in the picture.2 visible faces  $\Rightarrow$  an ARROW junction in the picture.1 visible face  $\Rightarrow$  an ELL junction in the picture.

Going the other way, given a 2D representation of a collection of planar solids, we can decide which regions belong to which solids, using RULES e.g.

a. The FORK rule links all three regions surrounding a junction.

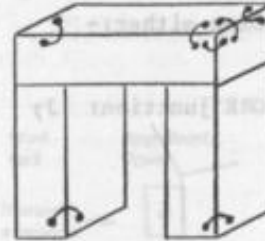
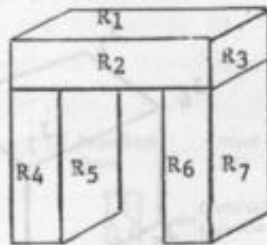




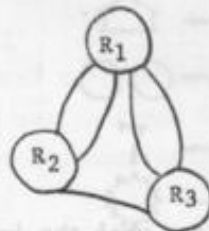
- b. The ARROW rule links two of the regions contributing to the junction.



For example:-



an arrow or a fork occurs. The regions can be grouped on the basis of these links into 3 groups:-



A



B

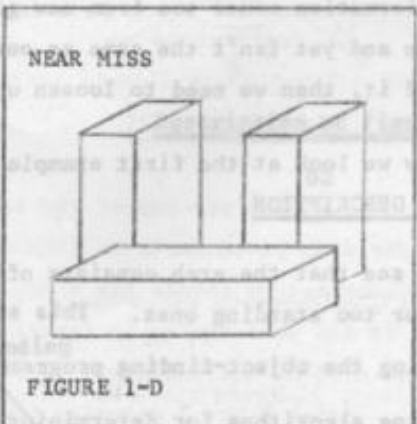
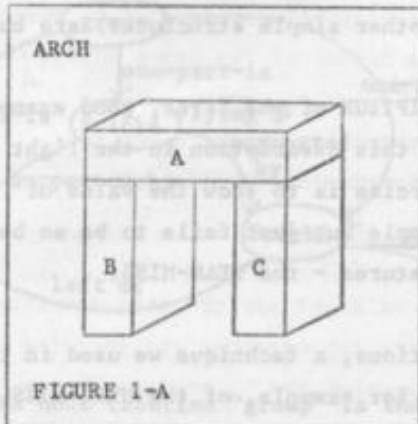


C

A segmentation process using rules like these forms the basis of a computer program written by Adolpho Guzman at M.I.T in 1968. This will be discussed in detail later in the course.

## 2. LEARNING STRUCTURAL DESCRIPTIONS

We explore the problem of learning, using and extending the ideas of building and manipulating descriptions, which we have developed so far. We will follow through a process of description refinement in response to a judiciously selected training sequence. This is a simple minded version of a well know program written by Pat Winston at M.I.T. and figure 1 A-D shows the sequence of exhibits he used to "teach" the concept of an ARCH.



## 1. Preliminary account

The world consists of children's building blocks, brick-shaped or wedge-shaped, out of which the arches (and other simple structures) are built.

The idea is to set up an INITIAL DESCRIPTION of the first, good example of the concept, and then to gradually debug this description in the light of subsequent exhibits. The point of the exercise is to show the value of exhibiting something which is nearly an example but just fails to be so because of the presence or absence of only a few features - the NEAR-MISS.

The process rests on comparing descriptions, a technique we used in the analogy problems. We build a description, for example, of the NEAR MISS, and compare it to the one we already have of a good example. The difference between the two tells us precisely why this new thing didn't make it - it highlights which of the features in our first (model) description, are just not allowed to be missing. We enrich our description by adding this information about mandatory features of the concept.

Information comes too from new good examples - if this new thing is still a goodie and yet isn't the same as our standard good example with which we have compared it, then we need to loosen up our description to cover this new case.

## 2. Now we look at the first example (figure 1A) and build up our INITIAL DESCRIPTION

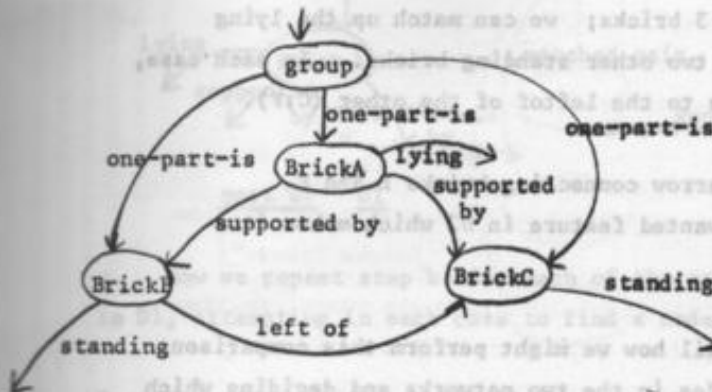
We see that the arch consists of 3 bricks, one lying on and supported by the other two standing ones. This step is achieved in Winston's program by

1. using the object-finding program of Guzman mentioned on PV.21 above.
2. using algorithms for determining relations like LEFTOF, ABOVE, SUPPORT, IN-FRONTOF.

## 3. LEARNING STRUCTURAL DESCRIPTIONS

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Our initial description would look like this:-



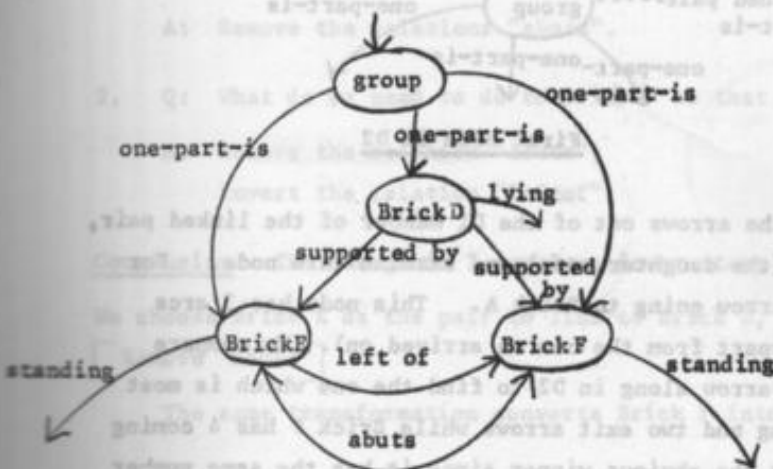
Description of figure 1A

D1

Note: The node labelled "group" is the distinguished entry node into the description.

We set this description up as our MARK1 model of the concept of an arch.

3. Next we build up a description of the second figure.



Description of figure 1B

D2

4. Now comes/

#### 4. Now comes the task of comparing descriptions.

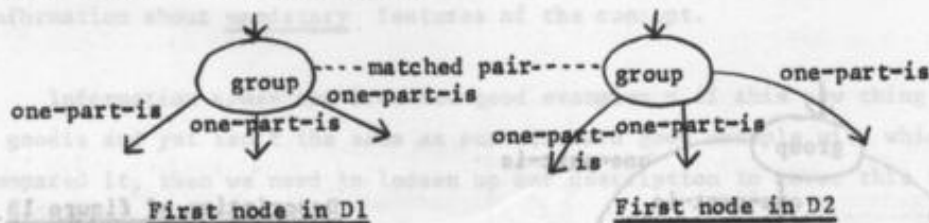
In each case we have a group of 3 bricks; we can match up the lying bricks (A:D) as each is supported by two other standing bricks. In each case, one of these standing bricks (B:E) is to the left of the other (C:F).

BUT There is an extra "abuts" arrow connecting bricks E and F.

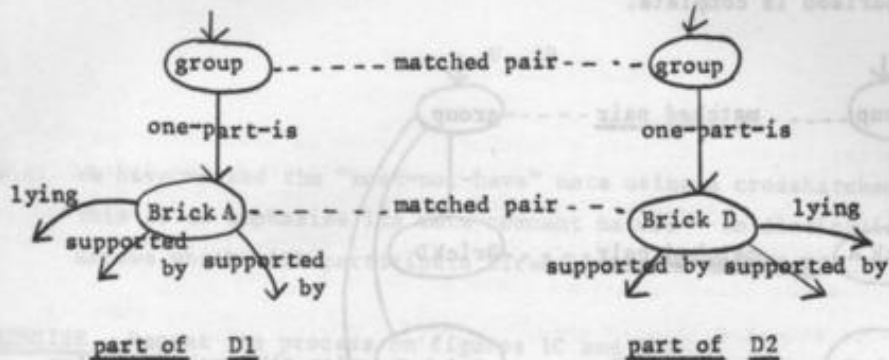
We conclude that this is the unwanted feature in D2 which makes it a non-example.

Let us spell out in greater detail how we might perform this comparison. The process involves matching the nodes in the two networks and deciding which nodes to pair up. We note that any node or arrow may be present in one description and not in the other.

- a. We start at the entry nodes. In each case we find a node with 3 arrows leaving it. Furthermore the arrows have the same labels. We decide to pair up these nodes as a matched pair.



- b. We then follow any one of the arrows out of the D1 member of the linked pair, locate the node it connects to (the daughter node) and examine this node. For example, suppose we choose the arrow going to Brick A. This node has 3 arcs leaving it and none coming in (apart from the one we arrived on). We compare this with each of the nodes one arrow along in D2 to find the one which is most similar. Brick E has 3 entering and two exit arrows while Brick F has 4 coming in and one leaving. Brick D is the obvious winner since it has the same number of arrows as our criteria node, and moreover these have labels which match up exactly with those of the criteria nodes, so we link these nodes as follows:-



c. Now we repeat step b. for each of the other daughter nodes of "group" in D1, attempting in each case to find a node in D2 which best matches it.

For Brick B, the comparison looks like this:-

<u>incoming arrows</u>	<u>outgoing arrows:</u>
Brick B supported by	standing; leftof
Brick E supported by; abuts	standing; leftof
Brick F supported by; leftof; abuts	standing

1. Q: What do we need to do to Brick E so that it will exactly match Brick B?

A: Remove the relations "abuts".

2. Q: What do we need to do to Brick F so that it will exactly match Brick B?

A: Remove the relation "abuts";  
Invert the relation "leftof".

Conclusion: The change in 1 involves fewer steps than does the change in 2.

We choose Brick E as the pair to link to Brick B, under the transformation

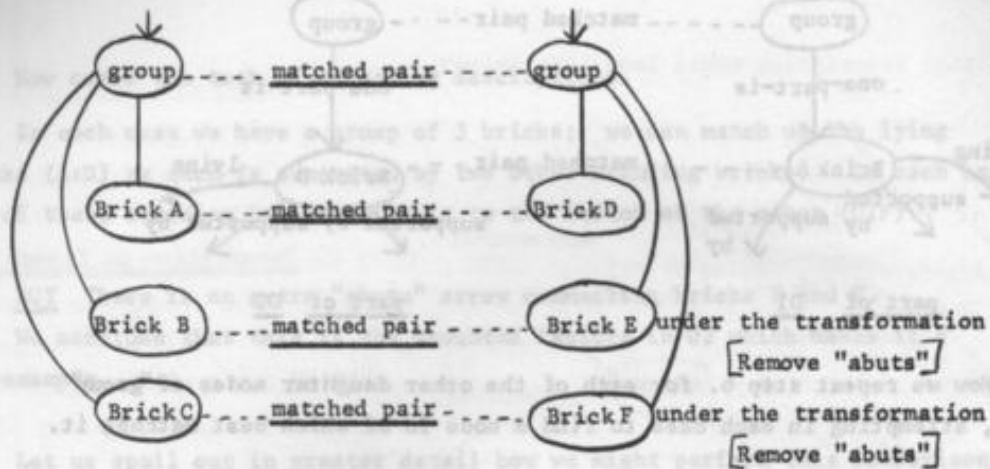
[Remove "abuts"]

The same transformation converts Brick F into an exact match of Brick C.

So/

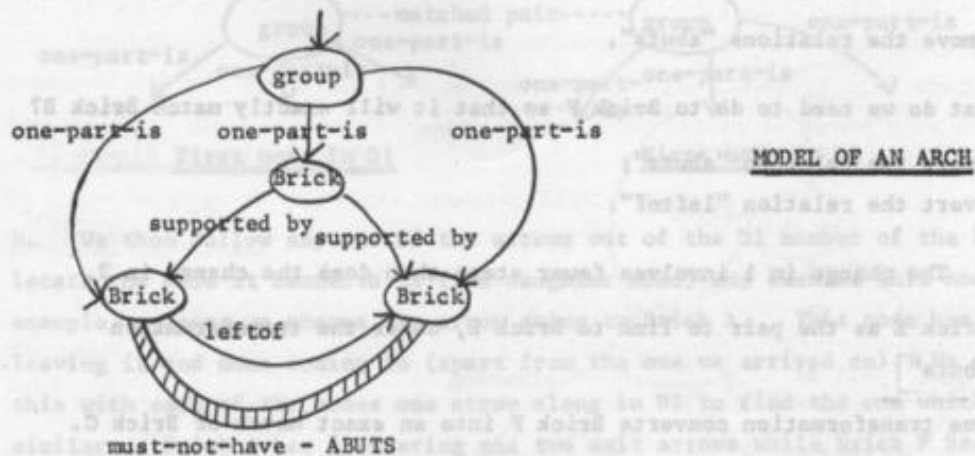


So now our comparison is complete.



5. Now we have located the bug in figure 1B, and can describe it in terms of the transformation we had to make in order to get a match. Another way of saying this, is that Remove "abuts" describes the mismatch. The way to ensure that we get a match in the first place is not to allow an "abuts" relation.

We capture the information gained from analysing this bug by recording on our model a "must-not-have" note.



Note:/

## VISUAL V. 28

We are interested in studying machine vision for several reasons:-  
 Note: We have marked the "must-not-have" note using a crosshatched link.  
 This is to emphasise its meta-comment nature - to distinguish it from  
 arrows which will participate directly in the matching.

EXERCISE Repeat the process on figures 1C and 1D.  
 Omit the detail in steps 4a-c.

(1) Form descriptions of the figure

(2) Find the mismatch by inspection

(3) Update the model appropriately

## II. Understanding line drawings

- line drawings as input using digitizers, e.g. Texmate cartoons.
- low level symbolic description of line drawings as input
- typically drawings representing scenes from blocks world.

### General Remarks

Much of the work has involved a simplified world of objects with flat surfaces. We know the world does not consist of only such objects; however, this simplification has been a very productive one, leading to the development of a series of programs, each built as a result of the experience gained from, and attempting to repair the limitations of, the previous ones and all contributing to an A.I. theory of perception.

It is convenient to start with a consideration of line drawings representing scenes of planar objects. We will come back to the problem of real world input later.

### VISUAL PERCEPTION

We are interested in studying machine vision for several reasons:-

1. To increase understanding of human perception
2. To increase understanding of intelligence - perception is a rich area in which to study knowledge-based reasoning.
3. Many connections with other branches of A.I. e.g. perceptual strategies in game playing.
4. Application possibilities, e.g. the designing of industrial robots.

#### Kinds of Tasks

- I Robot perception of real world scenes of simple objects.
  - recognition of objects as a task in itself  
e.g. first set of Freddy programs recognised spectacles, cups.
  - as part of performing actions on such objects.  
e.g. assembly tasks, as in current Freddy project; pushing boxes around, as at S.R.I.; copying structures from a collection of spare parts, as at M.I.T.
- II Understanding line drawings
  - line drawings as input using digitiser, e.g. Peanuts cartoons.
  - low level symbolic description of line drawings as input
  - typically drawings representing scenes from blocks world.

#### General Remarks

Much of the work has involved a simplified world of objects with flat surfaces. We know the world does not consist of only such objects; however, this simplification has been a very productive one, leading to the development of a series of programs, each built as a result of the experience gained from, and attempting to repair the limitations of, the previous ones and all contributing to an A.I. theory of perception.

It is convenient to start with a consideration of line drawings representing scenes of planar objects. We will come back to the problem of real world input later.

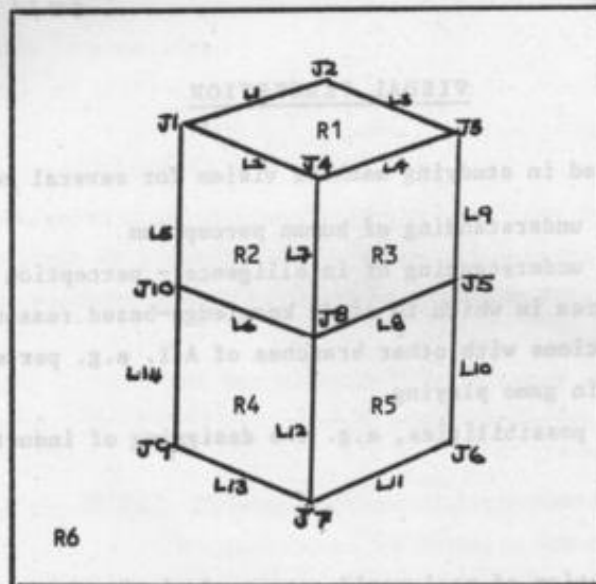


Fig. 1a

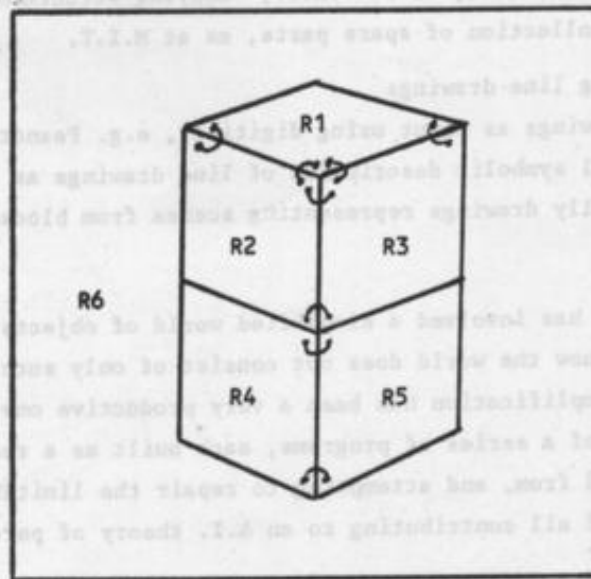


Fig. 1b

```
linklist: [ [R1 R2][R2 R3][R3 R1][R1 R2][R4 R5][R4 R5][R3 R2][R3 R1] ]
```

### INTERPRETATION OF LINE DRAWINGS

We take up the story begun on pp. V.20 and 21, where we introduced some of the ideas incorporated in Adlopho GUZMAN's program, SEE.

#### Points to recall

- (a) The task under consideration is the SEGMENTATION task.

When we as observers look at a line drawing, say fig. 1a, we see one cube lying on another. We allocate the regions to one or other of the cubes present. How do we do this? What information would we need to provide a program in order that it could perform this task?

- (b) We follow Guzman's program and tackle the problem in two steps:-

- (i) Collect local evidence for linking regions.
- (ii) Weigh this evidence and accumulate groups of regions.

- (c) What kind of local evidence can we use?

We exploit the fact that some places in the picture contain more information than others VIZ. the points at which several lines meet i.e. the VERTICES or picture JUNCTIONS. As usual, we need some vocabulary for describing these picture fragments in order to be able to talk about and use them. To the set of junctions already mentioned - the FORK, the ARROW and the ELL - we add two more, as shown in fig. 2, VIZ. the TEE junction and the PSI junction.

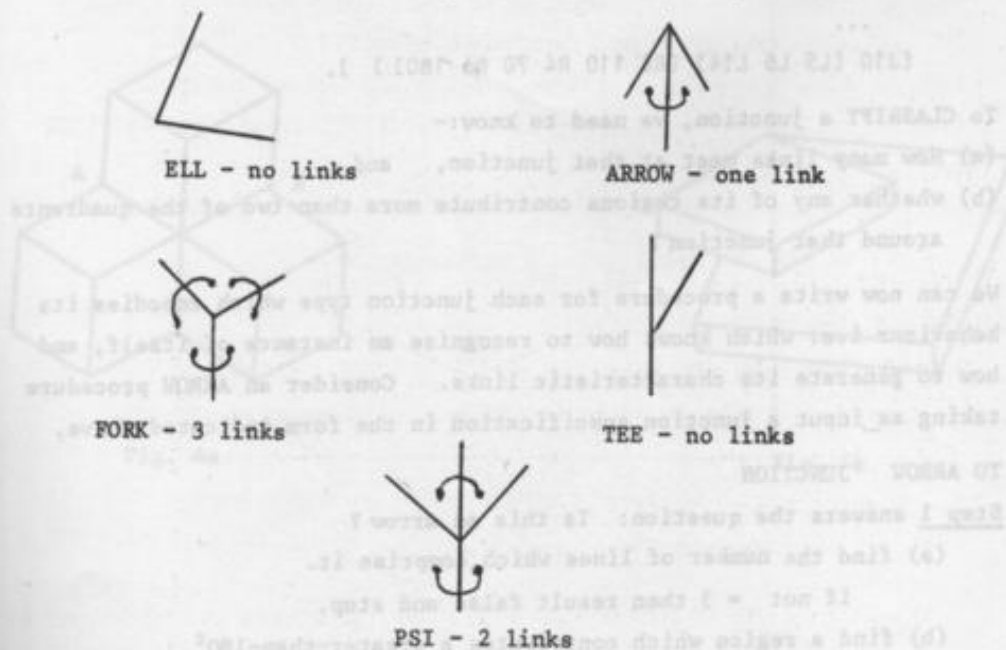


Fig. 2: JUNCTION TYPES and the links they generate.

### Linkage generation

Fig. 2 displays the links generated by these junction types.

- (a) We have already considered the FORK rule (p. V.20), which links all three regions comprising the junction; and the ARROW rule (p. V.21), which links the pair of regions which flank the shaft of the arrow.
- (b) An ELL junction contributes no links.
- (c) The links generated by a PSI junction reflect its origin; that is to say, it is really an ARROW sitting on a FORK.
- (d) A TEE provides powerful evidence for not linking the regions on opposite sides of its crossbar.  
e.g. in fig. 3, the circled TEE junction is evidence that R1 and R4 belong to different objects.

### Programming Suggestions

Suppose we input the picture description as a list of junctions where each junction is specified by its name; the list of lines which form it; and the list of regions which meet at this point, given as the region name alternating with the size of the angle it contributes to the junction.

For fig. 1a, such a junctionlist would take the form:-

```
[ [J1 [L1 L2 L5] [R1 40 R2 70 R6 250] ]
  [J2 [L1 L3] ...
  ...
  [J10 [L5 L6 L14] [R2 110 R4 70 R6 180] ] ].
```

To CLASSIFY a junction, we need to know:-

- (a) How many lines meet at that junction, and
- (b) whether any of its regions contribute more than two of the quadrants around that junction?

We can now write a procedure for each junction type which embodies its behaviour i.e. which knows how to recognise an instance of itself, and how to generate its characteristic links. Consider an ARROW procedure taking as input a junction specification in the form indicated above.

TO ARROW 'JUNCTION

Step 1 answers the question: Is this an arrow?

- (a) find the number of lines which comprise it.  
if not = 3 then result false and stop.
- (b) find a region which contributes a greater-than-180°



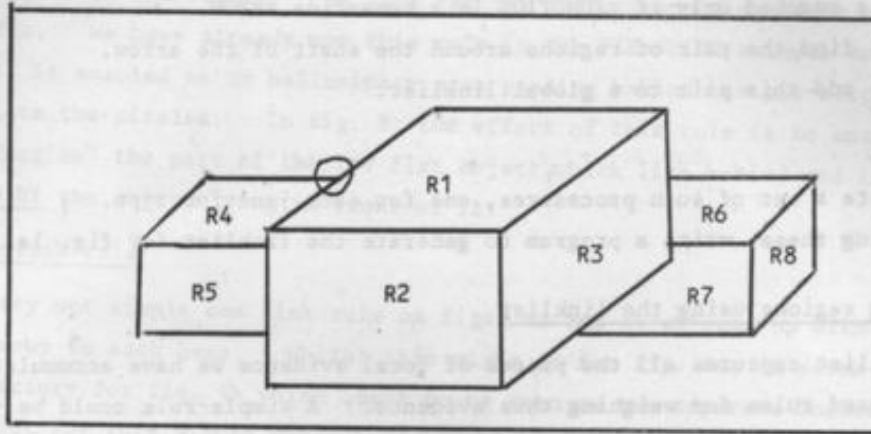


Fig. 3

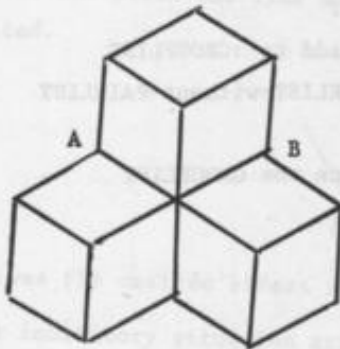


Fig. 4a

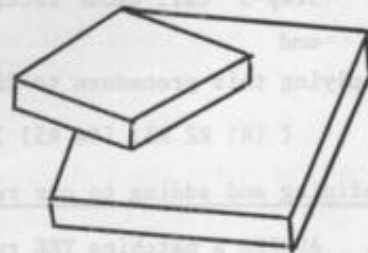


Fig. 4b

angle to the junction.

if none, then result false and stop.

Step 2 is reached only if :JUNCTION is a bona-fide ARROW.

(c) find the pair of regions around the shaft of the arrow.

(d) add this pair to a global linklist.

### EXERCISE

(a) Write a set of such procedures, one for each junction type.

(b) Using these, write a program to generate the linklist for fig. 1a.

### Grouping regions using the linklist

The linklist captures all the pieces of local evidence we have accumulated. We now need rules for weighing this evidence. A simple rule could be:-

One-link rule: Group all regions which are linked to one another by at least one link.

Given a linklist such as that shown in fig. 1b, and a global slot for accumulating all groups of connected regions, initially empty, which we call GROUPLIST, we can write a procedure for grouping regions containing the following steps:-

TO GROUP 'LINKLIST

Step 1 if :LINKLIST empty then stop

Step 2 choose a pair from :LINKLIST and set this up as a group

Step 3 find all pairs containing at least one element in common with this group and form into PAIRLIST

Step 4 form the union of all such pairs and add to :GROUPLIST

Step 5 call GROUP recursively with input LINKLIST-without-PAIRLIST

end

Applying this procedure to fig. 1b, we would produce the GROUPLIST

[ [R1 R2 R3] [R4 R5] ]      ? What about R6

### Refining and adding to our rules

#### 1. ADDING a matching TEE rule

We need such a rule to segment fig. 3 on p. V.33



Matching TEE rule

This rule applies when we have a pair of TEE junctions whose shafts are collinear, as in the figure. We link regions on corresponding sides of the shafts. We have already met this rule in the PIE-SLICE example on p. V.16; it enabled us to hallucinate arcs passing behind the pie-slice to complete the circles. In fig. 3, the effect of this rule is to enable us to "imagine" the part of the low flat object which lies behind and is OCCLUDED BY the object lying in front of it.

## 2. Two-link rule

When we try our simple one link rule on figs. 4a and 4b we come up with a single group in each case. Whilst this might do for fig. 4a, it seems unsatisfactory for fig. 4b which ought to be seen as two separate bodies. One way out for this figure would be to require at least 2 links between regions before admitting them into the same group.

## 3. Inhibiting link-formation

While this rule would produce a more reasonable solution for fig. 4b, it would not help in fig. 5. It is true that this could represent a single body with the top brick glued on to the bottom one; however, it would be nice if our program could separate these two. We can achieve this by introducing the idea of inhibiting link formation in certain contexts. That is to say, if we allow the context of a junction to influence the information it yields. Thus, if the arm of a fork ends in the barb of an arrow, do not place the link across that arm. i.e. the dotted link is inhibited.



This gives the desired effect in fig. 5.

Another inhibitory situation arises when one of the regions contributing to a junction is known to be background. In this case we do not place links between this and other regions.

e.g. at B in fig. 5, we would only place one link;

at A and B in fig. 4a, we would also only place one link.

Further examples require the addition of more inhibiting rules.

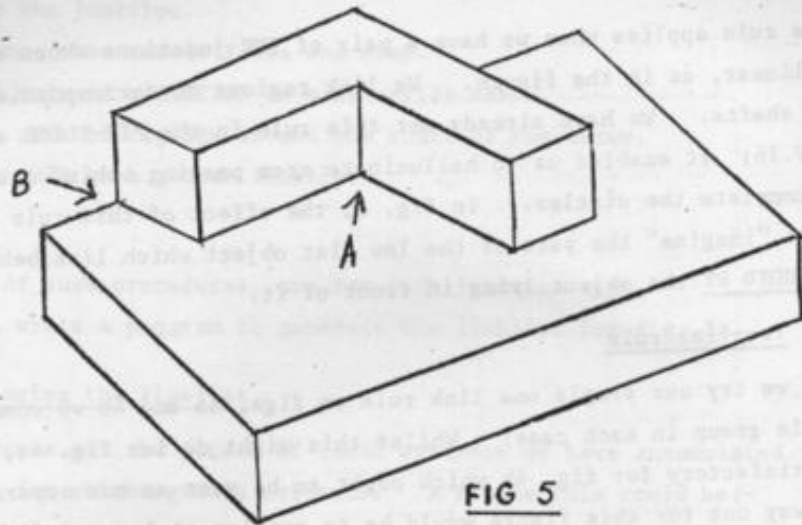


FIG 5

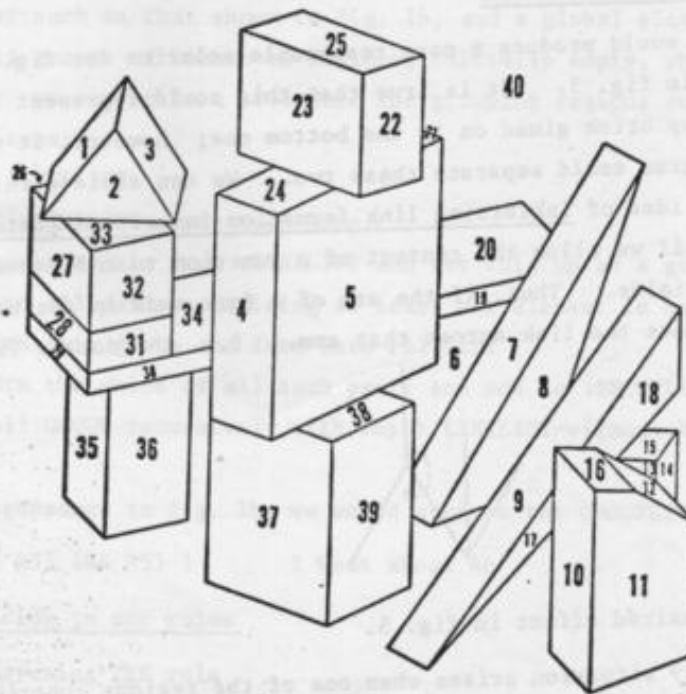


FIGURE 'MOMO'

(BODY 1. IS :3:2:1)	(BODY 7. IS :25:23:22)
(BODY 2. IS :32:33:27:26)	(BODY 8. IS :14:13:15)
(BODY 3. IS :28:31)	(BODY 9. IS :10:16:11:12)
(BODY 4. IS :19:20:34:30:29)	(BODY 10. IS :18:9:17)
(BODY 5. IS :36:35)	(BODY 11. IS :7:8)
(BODY 6. IS :24:5:21:4)	(BODY 12. IS :38:37:39)

FIG 6

### Summary of GUZMAN's program in its final form

"In the first pass, the program gathers evidence through the vertex-inspired links that are not inhibited by adjacent vertices. In the second pass, these links cause binding together wherever two regions or sets of previously bound regions are connected by two or more links. It is a somewhat complex but reasonably talented program which usually returns the most likely partition of a scene into bodies."

(E.g. fig. 6)

This summary is taken from "The MIT Robot", P.H. Winston (1972) in Machine Intelligence 7, Edinburgh University Press.

### PROBLEMS

The program comes to grief on fig. 7 and fig. 8. Try these.

In fig. 7, we notice that the program cannot SEE holes.

In fig. 8, it cheerfully accepts the impossible DEVIL'S PITCHFORK as one body.

An analysis of these deficiencies provides the basis for the next group of scene analysis programs.



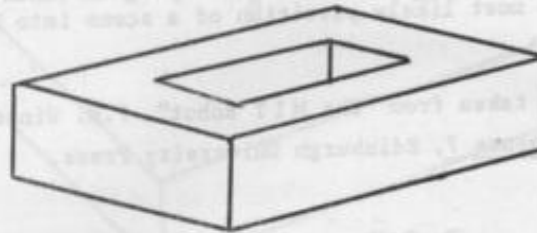


FIG. 5

Fig. 7

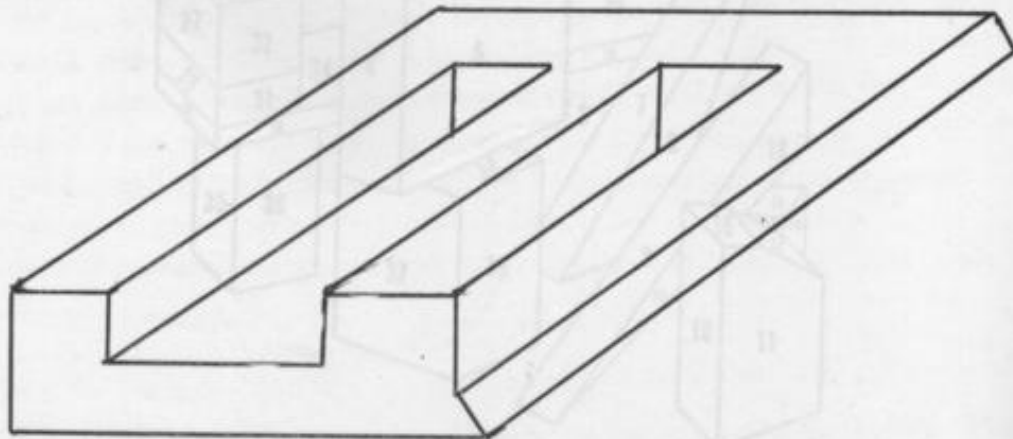


Fig. 8

(CODE 1. 12 13:1:1)	(CODE 7. 12 13:1:1)
(CODE 2. 12 13:1:1)	(CODE 8. 12 13:1:1)
(CODE 3. 12 13:1:1)	(CODE 9. 12 13:1:1)
(CODE 4. 12 13:1:1)	(CODE 10. 12 13:1:1)
(CODE 5. 12 13:1:1)	(CODE 11. 12 13:1:1)
(CODE 6. 12 13:1:1)	(CODE 12. 12 13:1:1)



### INTERPRETATION, SEMANTICS AND MODELS

Consider again the configuration in fig. 5 (p. V.36), which led us to postulate our first inhibitory rule. The source of the link that caused the trouble was the FORK at A and the difference between this fork and the forks in the previous figures is that it occurs at a concavity in the object, whereas previous forks were at convex corners.

Another way of saying this:-

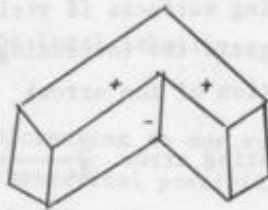
Whether or not a linkgenerating rule works, depends on the 3D situation represented by the 2D drawing.

That is to say, we need to attend to the 3D feature to which the 2D fragment corresponds. When we see fig. 1a (p. V.30) as one cube on another, we are using the following mapping rules from the picture domain into the scene domain.

lines in the picture correspond to edges of solid objects;  
regions in the picture correspond to surfaces meeting at these edges;  
 and junctions in the picture correspond to corners, where 2 or more edges meet, i.e. where several surfaces meet.

#### The CLOWES-HUFFMAN linelabelling technique

As pointed out on p. V.20, when we look at a corner of a convex object end on, so that all 3 surfaces which meet at that corner are visible, we depict that corner as a fork in our line drawing. Our fork rule which links all 3 regions does so correctly. If we rotate the object (or walk round it) until just beyond the point where one of the surfaces disappears from view, a drawing from this point of view will show our same corner as an arrow. Again the 2 surfaces which remain visible are just the ones which the arrow rule links. But we would like to be able to handle concave objects as well. If we look at the concave edge of an L-shaped solid (labelled "-" in the figure),



we see that the corner at which it meets 2 convex edges (labelled "+") is depicted as an ARROW. If we rotate this solid (anti-clockwise, say)

until the (left hand) surface disappears, that corner is now represented by an ELL.



One arm of this ELL corresponds to the convex edge at which the remaining 2 visible surfaces meet. But now one of these surfaces disappears under the other arm of the ELL; this latter line depicts the edge of the occluding surface A. We call such an edge an OCCLUDING edge, and label it with an "-". The labelling convention requires the occluding surface to be on the right when facing the direction of the arrow.

So our occluding surface is partly hiding one of the original 3 surfaces we could see, and totally hiding another. Notice that all three surfaces we have been talking about belong to the same body. In scenes containing several polyhedra, a so-called occluding edge can partially or completely hide surfaces of bodies other than the one it belongs to. The external edges of all bodies occlude the background.

#### There are 4 possible interpretations of a line

1. The line represents an edge, both of whose contributing surfaces, A and B, are visible.

(a) convex, labelled "+"  $\frac{A}{B} \quad +$

(b) concave, labelled "-"  $\frac{A}{B} \quad -$

2. Only one of the contributing surfaces is visible; the arrowhead labels an edge that belongs to the (occluding) surface on the right (as you move in the direction of the arrow)

(c) occluding: in-pointing arrow  $\frac{C}{B} \quad \rightarrow$

(d) occluding: out-pointing arrow  $\leftarrow \frac{A}{C}$

(C is further away and passes under A or B)

### Pictorial Inference

Now label fig. 8 (p. V.38). You will notice that different ends of lines A, B and C have different labels on them. We have contravened a basic rule of polyhedral scene interpretation, VIZ.

A given line (in the picture domain) must have the same meaning (in the scene domain) all along its length.

Using this single COHERENCE rule the line labelling method (published independently by Clowes 1971 and Huffman 1971) correctly detects impossible objects like this devil's pitchfork.

What is the effect of adding all this information?

Since there are 4 possible interpretations of a single line, there are  $4^2$  possibilities for an ELL and  $4^3$  possibilities for each ARROW and each FORK. If we were to embark upon the task of automatically producing all possible labellings of a given picture, say, a simple cube, by systematically considering the possible labellings of each junction, the space of possibilities we would be searching over would be very large. We appear to have created a combinatorial explosion. The striking fact is that very few of these are physically possible. These can be visualised using the following reasoning:-

The 3 planes which meet at a corner divide the space around that corner into 8 octants - some of these octants are filled with solid material and some are empty.

one octant filled implies all convex edges contributing to corner  
three octants filled implies 2 convex and one concave edge  
five octants filled implies 2 concave and one convex edge  
seven octants filled implies 3 concave edges.

Any corner can be viewed from each unoccupied octant around it and  
ALL VIEWS FROM A GIVEN OCTANT GIVE THE SAME CONFIGURATION.

Fig. 9 (p. V.42/43) shows the possible views for each corner type.

This figure summarises the legal labellings which have a meaning in the real world.

We have added semantic information to our system, but instead of searching over the whole space of theoretical possibilities, we need to search only over this restricted range of possible corner models.

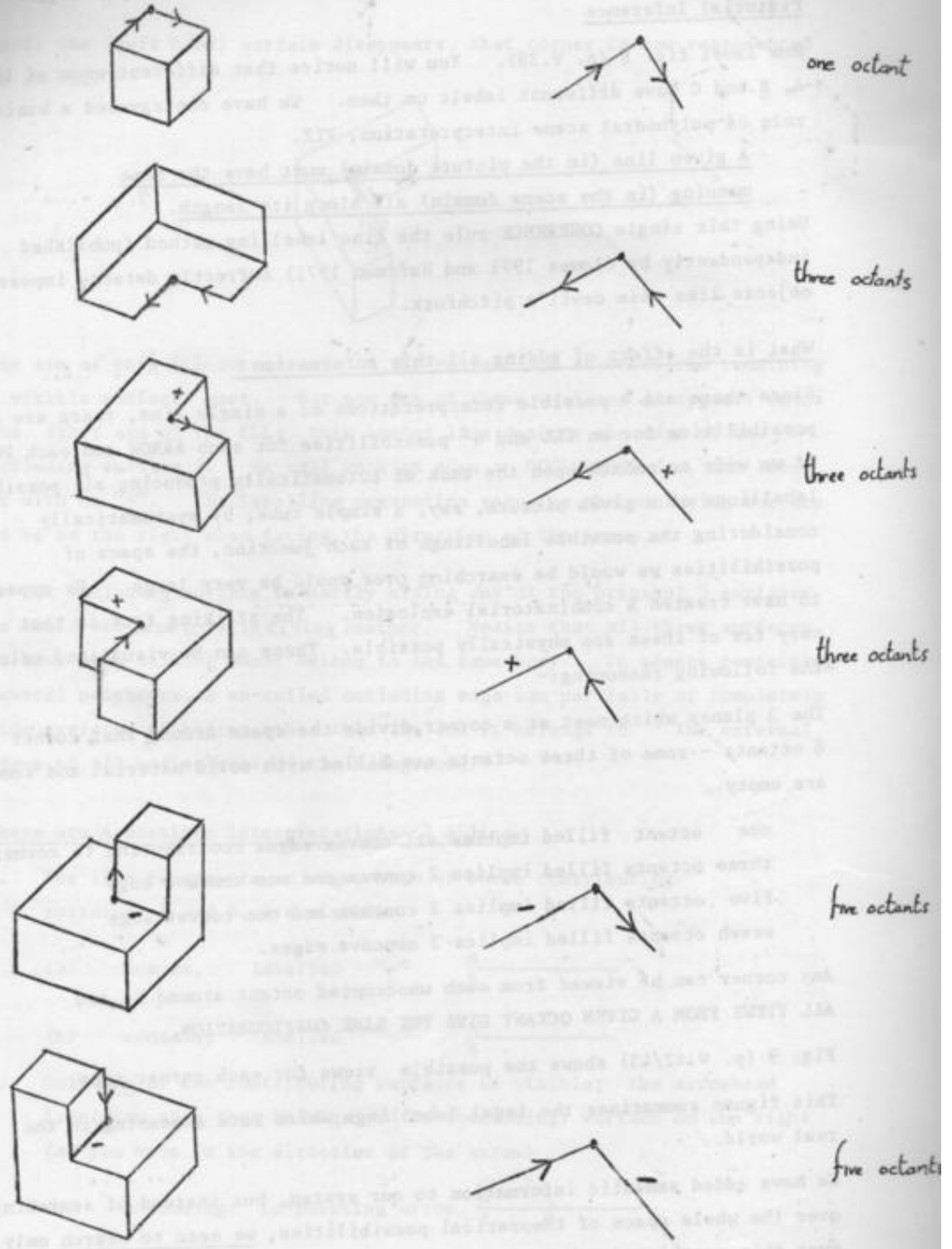
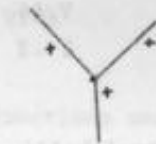
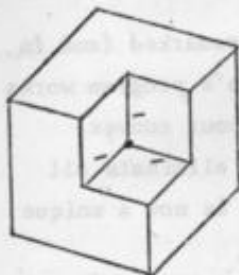
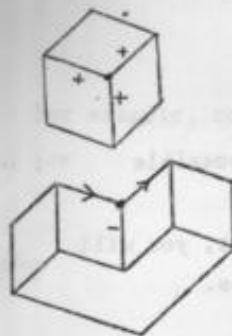


FIG. 9

Legal labellings of an ELL junction



one octant

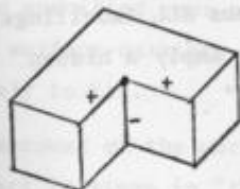


three octants



seven octants

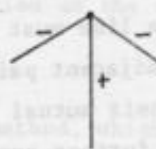
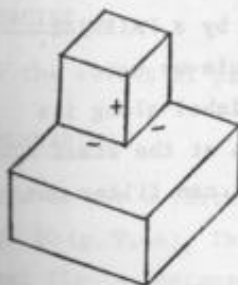
FIG 9 (contd)

Legal labellings of a FORK junction

one octant



three octants



five octants

FIG 9 (contd)

Legal labellings of an ARROW junction

EXERCISE

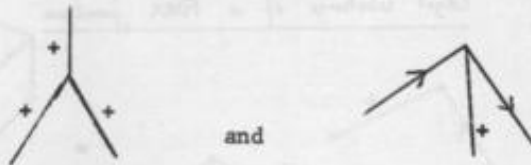
Use the table of possible line-labellings to generate all possible labellings of a cube.

Notice that since the last choice has to mesh with the first, you will produce a graph, best represented on line drawings of a cube.

Another look at GUZMAN'S program

Now we can look back at the linkgenerating rules. We remarked (and in this, we use the analysis of Mackworth 1974) that Guzman's program works as well as it does because of the implicit assumption about convex bodies. Consider the legal labellings table again and eliminate all those possibilities which involve concave edges - there is now a unique labelling for each junction.

In the case of FORKS and ARROWS, if we disallow all lines labelled concave, we are left with the unique labellings



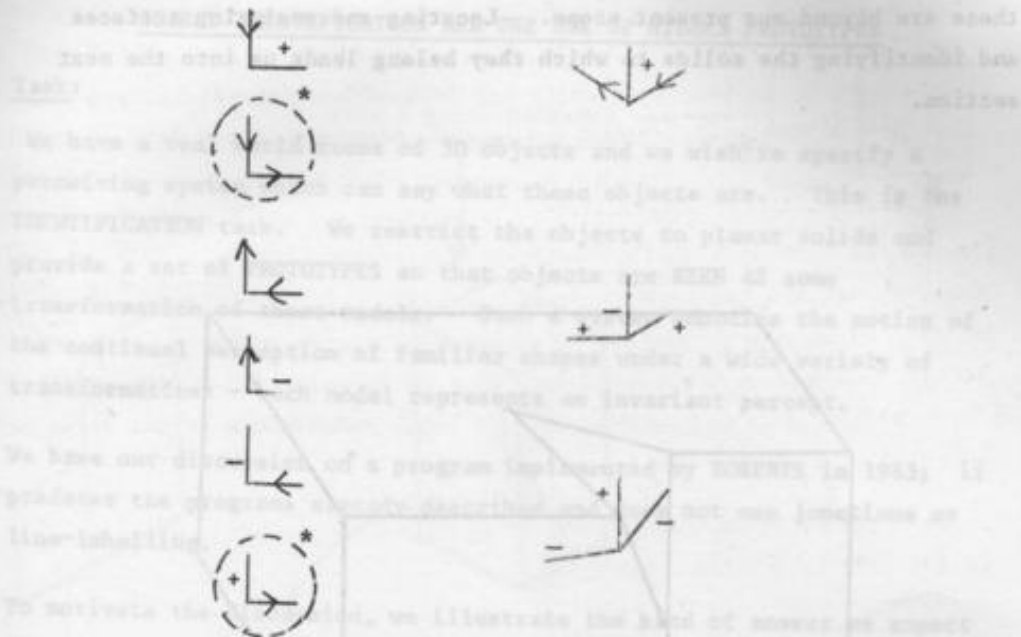
If we look at fig. 9 (p. V.42/43) showing how the various ELL labellings arise, we see that all but the first imply a hidden concave edge.

Progressive constraint satisfaction - the WALTZ effect

A dramatic reduction of the search space can be achieved by a PAIRWISE ELIMINATION OF POSSIBILITIES. This involves the same rule we have already used, VIZ that a single line must have the same label along its entire length. By comparing adjacent pairs of junctions at the start of the search and satisfying their mutual constraints, we can filter out many of the possibilities from further consideration.



For example, consider 2 adjacent junctions one ELL and one ARROW



Whichever of the 3 legal labellings of the ARROW we choose, we will never have a match with the 2 starred possibilities of the ELL junction. So under these particular circumstances, these latter two need never be considered again. By repeating this process of pairwise constraint satisfaction on each adjacent pair and by allowing the consequences of each elimination to percolate through the whole figure, a remarkable reduction in the search space is achieved. To use an analogy, the more specified your piece of jigsaw puzzle is i.e. noting its colour and surface markings as well as its contour, the fewer places it is likely to fit.

An account of the work of WALTZ who first noticed and exploited this effect is given in "the MIT Robot" (reference p. V.37).

#### EXERCISE

Try the effect of pairwise elimination on the cube example used previously.

#### COPLANARITY

There is yet a further bug in our method, which shows up when we use it on fig. 10 (p. V.46). This is satisfactorily labelled, i.e. accepted as a legal figure, because the method cannot distinguish between different degrees of convexity or concavity and makes no requirement about surface

coherence. More recent programs have been generated by this bug but these are beyond our present scope. Locating and analysing surfaces and identifying the solids to which they belong leads us into the next section.

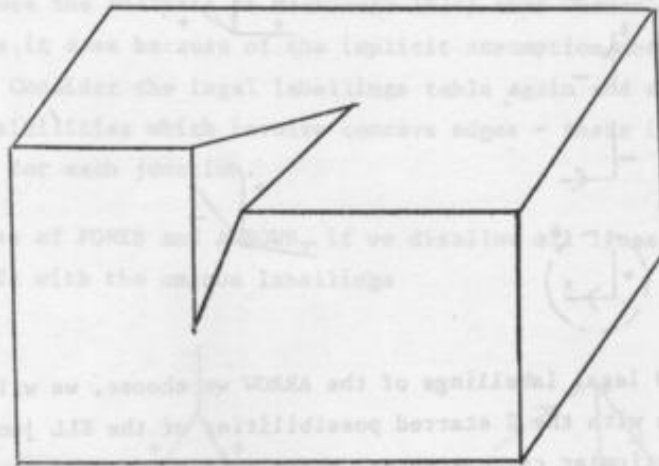


Fig. 10.

1975/76

SW / 6

# OBJECT IDENTIFICATION AND THE USE OF STORED PROTOTYPES

## Task:

We have a real world scene of 3D objects and we wish to specify a perceiving system which can say what these objects are. This is the IDENTIFICATION task. We restrict the objects to planar solids and provide a set of PROTOTYPES so that objects are SEEN AS some transformation of these models. Such a system embodies the notion of the continual perception of familiar shapes under a wide variety of transformations - each model represents an invariant percept.

We base our discussion on a program implemented by ROBERTS in 1963; it predates the programs already described and does not use junctions or line-labelling.

To motivate the discussion, we illustrate the kind of answer we expect our system to produce. In the first example, shown in fig. 1 (below), the 2 x 1 cuboid is SEEN AS A CUBE expanded along the Y-axis.

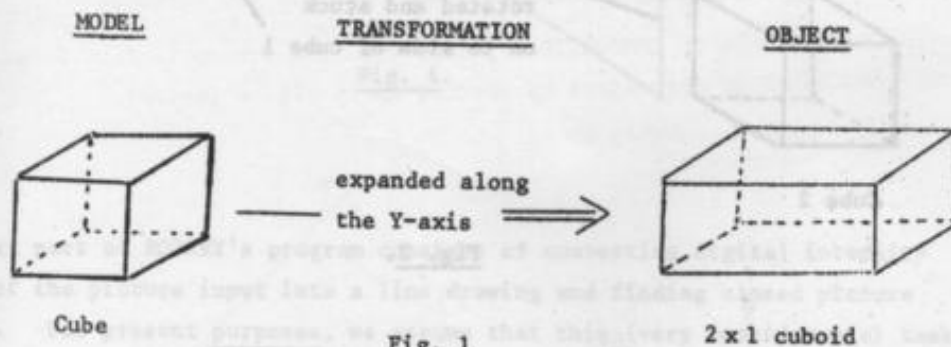
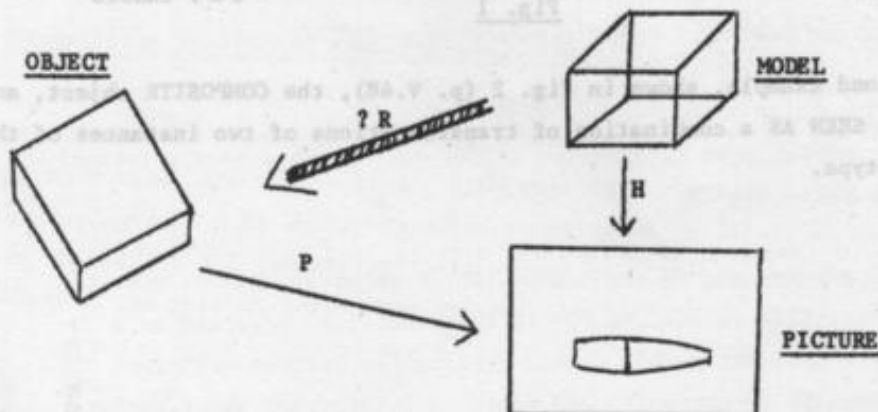
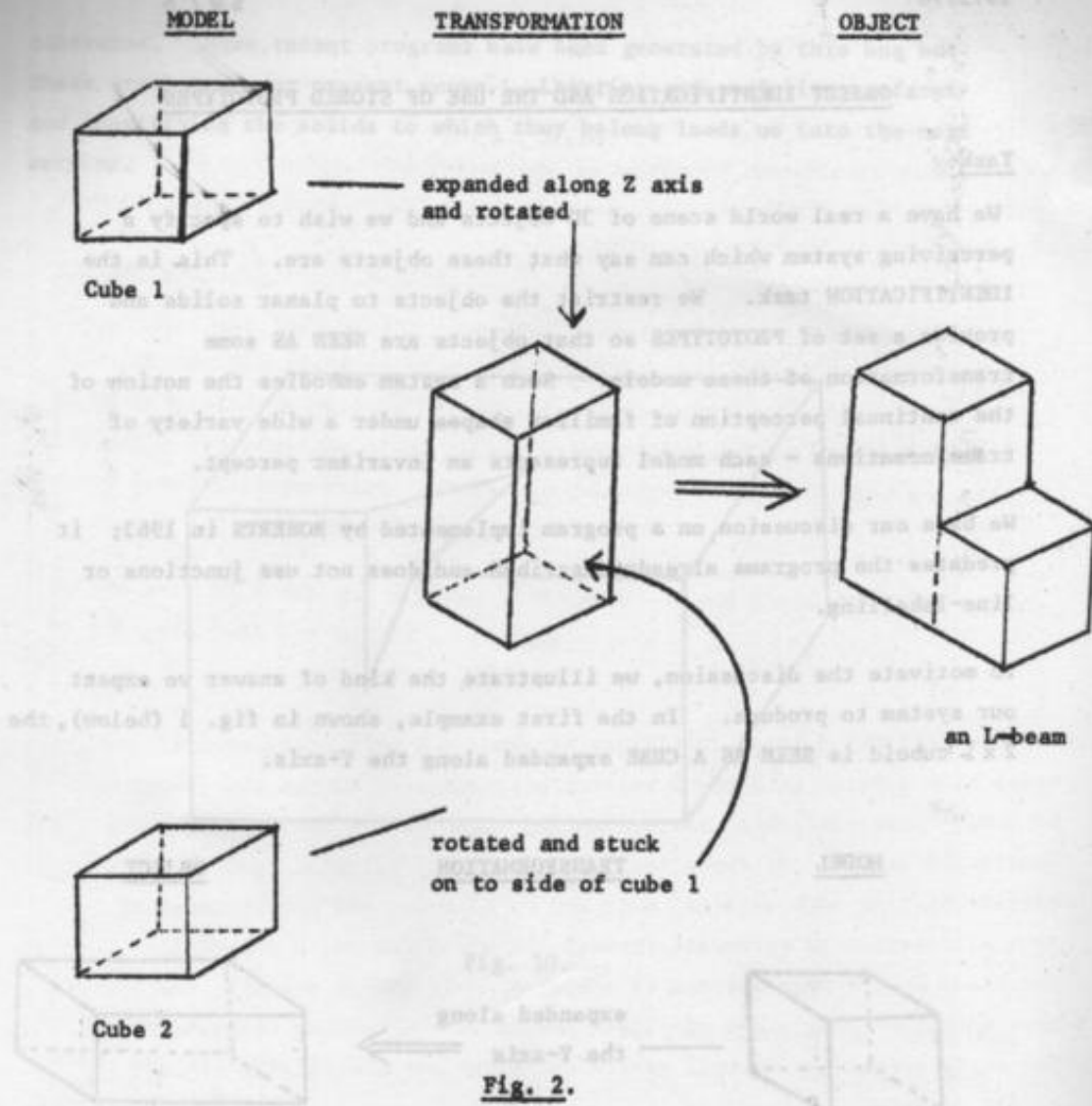


Fig. 1

In the second example, shown in fig. 2 (p. V.48), the COMPOSITE object, an L-beam, is SEEN AS a combination of transformations of two instances of the CUBE prototype.



### METHOD

In order to find the relation  $R$  (see fig. 3 (p. V.48)) between the MODEL and the OBJECT, we take an indirect route via a TV camera picture of the unknown object. We set up the more tractable task of finding a PICTURE description with which to compare our stored MODEL description and so derive the relation  $H$ . Then we can use  $R = H \times P^{-1}$  (the inverse transformation) to solve our problem.

### Picture description

Taking a picture of the object corresponds to projecting 3D points in the object through a focal point on to a 2D picture plane (see fig. 4 below). For a given camera and picture size, this transformation is known.

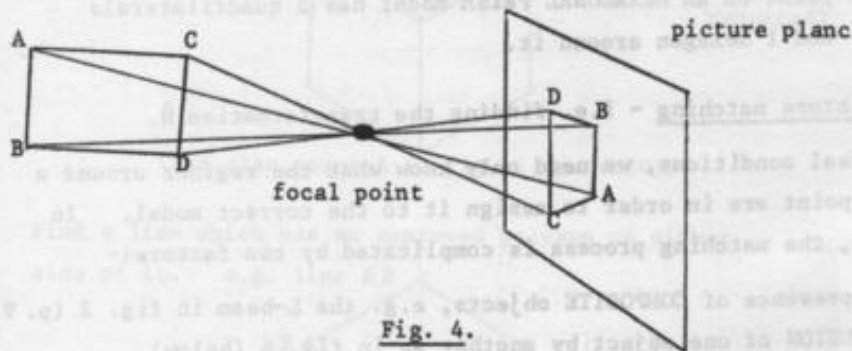


Fig. 4.

The first part of ROBERT's program consists of converting digital intensity values of the picture input into a line drawing and finding closed picture regions. For present purposes, we assume that this (very considerable) task has been completed. The resultant PICTURE DESCRIPTION consists of:-

- (i) set of lines represented by their endpoint coordinates, and
- (ii) a set of regions bounded by these lines.

### Model description

We use three prototypes as shown in fig. 5 (p. V.50). A MODEL DESCRIPTION consists of:-

- (i) a set of point coordinates representing the corners of the model, and
- (ii) a list of the polygons surrounding each point.

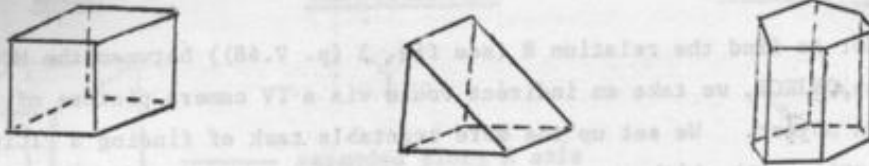


Fig. 5.

Given the three models shown, the set of APPROVED polygons is restricted to convex polygons of sides 3, 4 or 6.

Each point on a CUBE model has 3 quadrilaterals around it.

Each point on a WEDGE model has 2 quadrilaterals and 1 triangle around it.

Each point on an HEXAGONAL PRISM model has 2 quadrilaterals and 1 hexagon around it.

Model-picture matching - i.e. finding the transformation  $H$ .

Under ideal conditions, we need only know what the regions around a picture point are in order to assign it to the correct model. In practice, the matching process is complicated by two factors:-

- (a) The presence of COMPOSITE objects, e.g. the L-beam in fig. 2 (p. V. 48)
- (b) OCCLUSION of one object by another as in fig. 6 (below).

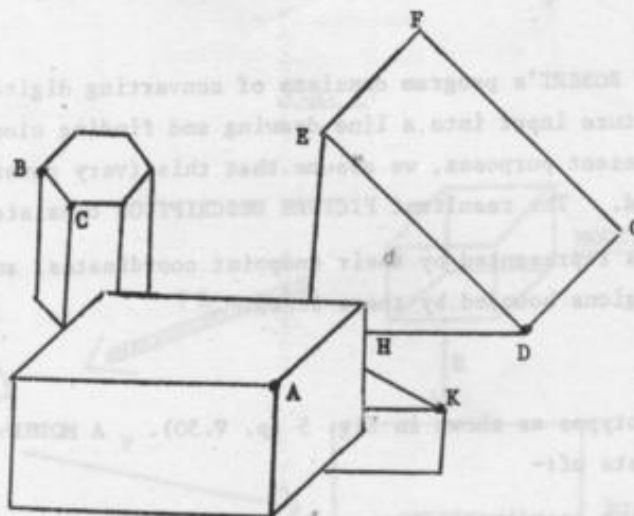


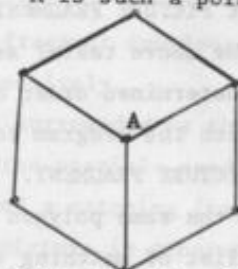
Fig. 6



This means that regions in the picture may not belong to the set of APPROVED POLYGONS. Our task is to find the largest picture fragment which will home in on the right model most rapidly, where "right" means contains a matching model fragment. Roberts provides an ordered sequence of 4 tests, allowing successively greater departure from the ideal - i.e. from a picture of non-composite, non-occluded object.

We illustrate by considering a picture of a simple cube, and the collection of objects depicted in fig. 6 (p. V.50).

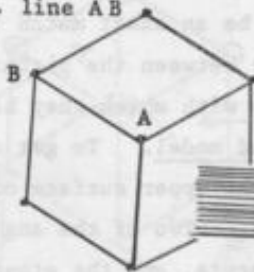
- Test 1 Find a picture point which is completely surrounded by approved polygons. A is such a point



(7 picture points required)

(See also point A in fig. 6 (p. V.50))

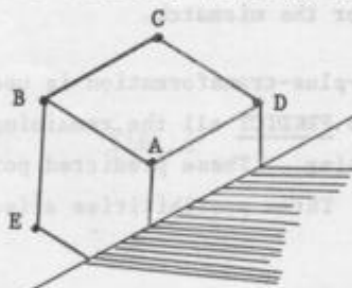
- Test 2 Find a line which has an approved polygon on either side of it. e.g. line AB



(6 picture points required)

(See also line BC in fig. 6 (p. V.50))

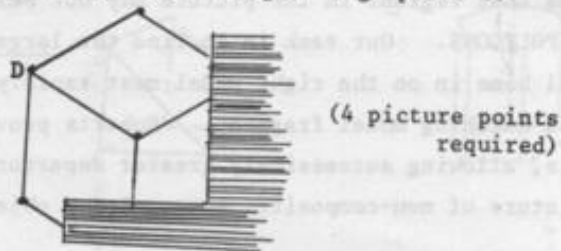
- Test 3 Try for an approved polygon with a line coming from one of its vertices : ABCD, with line BE.



(5 picture points required)

(See also DEFG, with line DH, in fig. 6 (p. V.50))

Test 4 Find a point from which 3 lines emerge. e.g. point D.



(See also point E in fig. 6 (p. V.50)).

#### Selecting a model

The next step is to use the best PICTURE FRAGMENT (this will be the largest fragment which passes the above tests) as the basis for model selection. Roberts uses a predetermined order of models i.e. CUBE - WEDGE - HEXAGONAL PRISM over which the program searches for a MODEL FRAGMENT to correspond to the PICTURE FRAGMENT. That is to say, it looks for a MODEL point surrounded by the same polygon structure as the selected PICTURE point and constructs a list of matching (i.e. topologically equivalent) MODEL-PICTURE points pairs.

If the object were identical in shape, size and orientation to the standard prototype, there would be an exact match (taking into account the loss of the third dimension) between the picture points projected by that object and the model points with which they have been paired.

A MISMATCH reflects a transformed model. To get an intuitive feel for what this could mean, consider the upper surface of a cube as it is tilted backwards away from the vertical. Two of the angles, starting off as  $90^\circ$ , would become increasingly more acute, and the other two more obtuse. The degree of acuteness (obtuseness) reflects the degree of tilt.

ROBERT's program uses standard matrix manipulation to calculate the combination of transformations (rotation/translation/perspective/expansion-along-an-axis) to account for the mismatch.

Finally, the selected model-plus-transformation is used to generate the rest of the picture, i.e. to PREDICT all the remaining picture points not so far involved in the matching. These predicted points are compared with the actual picture points. Three possibilities arise:-

- (a) A fit means we have found the correct model and the transformation H.
- (b) If some of the model generated-points fall outside the external boundary of the picture, this means we have the wrong model and we try another.
- (c) If all the generated points fall inside the boundary but do not account for all the picture lines, this indicates that we are dealing with a picture of a composite object. We need to decompose the object into subparts which can be seen as transformed models.

#### Decomposition

Consider the L-beam in fig. 2 and reproduced below in fig. 7.

Finding a "good" picture fragment involves trying the four tests outlined above successively.

There is no picture point surrounded by three approved polygons (Test 1). Applying Test 2 yields three possible candidates. Line 1, flanked by regions A and B, would find a matching fragment in the CUBE model, but when the rest of the picture is generated by this model, some points fall outside the picture boundary.

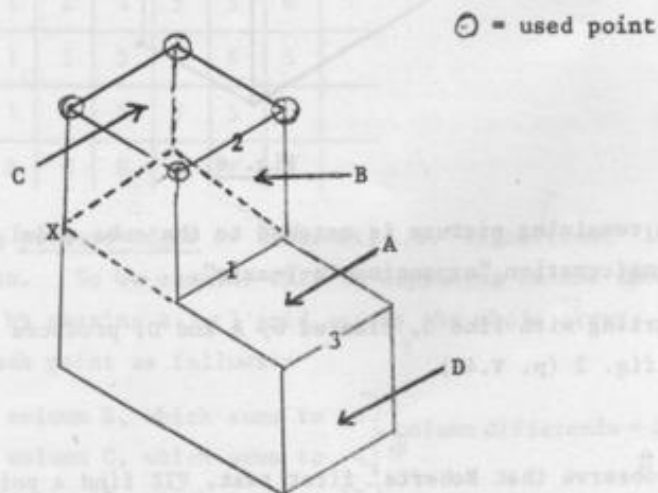


Fig. 7.

Line 2, flanked by polygons B and C, is more promising; the points predicted by the CUBE model which it matches would fall within the external boundary of the picture. Roberts decomposes the picture using the following steps:-

1. All model lines and points are added to the picture if not already there (dotted lines in fig. 7 (p. V.53)).
2. If a model point falls on a picture line, insert the point (X in fig. 7 (p. V.53)).
3. Each visible model point in the picture which does not connect to any non-model line is marked "used" (© in fig. 7 (p. V.53)).
4. Delete all used points and their attached lines and polygons

Carrying out these steps on fig. 7 leaves us with fig. 8.

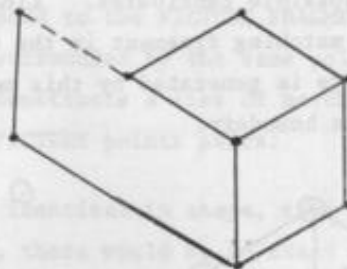


Fig. 8.

The remaining picture is matched to the cube model under the transformation "expansion-in-Y-axis".

Starting with line 3, flanked by A and D, produces the result shown in fig. 2 (p. V.48).

#### NOTES

1. We observe that Roberts' first test, VIZ find a point surrounded by three approved polygons, corresponds to Guzman's FORK heuristic; and his second test, VIZ. find a line flanked by accepted polygons is just our old friend the ARROW rule.
2. Roberts' system incorporates a two-way addressing process whereby stimulus cues ("good" picture fragments) address or invoke internal models, which in turn suggest (predict) where the rest of the picture will be.
3. Combining the ideas of Roberts with those of Guzman, Clowes & Huffman, we see the possibility of a hierarchy of semantic models.

Points 2 and 3 will be taken up again in a later lecture.

LINE FINDING

Many A.I. systems developed to analyse real-world scenes have involved producing a line drawing as a definitive stage in the processing of the scene. Fig. 1 (p. V.56) shows typical stages in the process of transforming a TV camera picture into a description of the scene. We give a simple-minded version of the second stage of this process VIZ the detection of discontinuities in the intensity array, using a local gradient operator and thresholding - and then discuss difficulties which arise and proposals for overcoming these problems.

Gradient operator

A TV picture of a 3D scene records the light intensity or brightness level (a product of illumination and reflectance of the surface). The brightness intensity at each small area of the resultant picture is converted via an analogue-to-digital convertor into an integer to produce an array of numbers - the "digitised image". A small portion of such an array (under near ideal conditions) might look like this:-

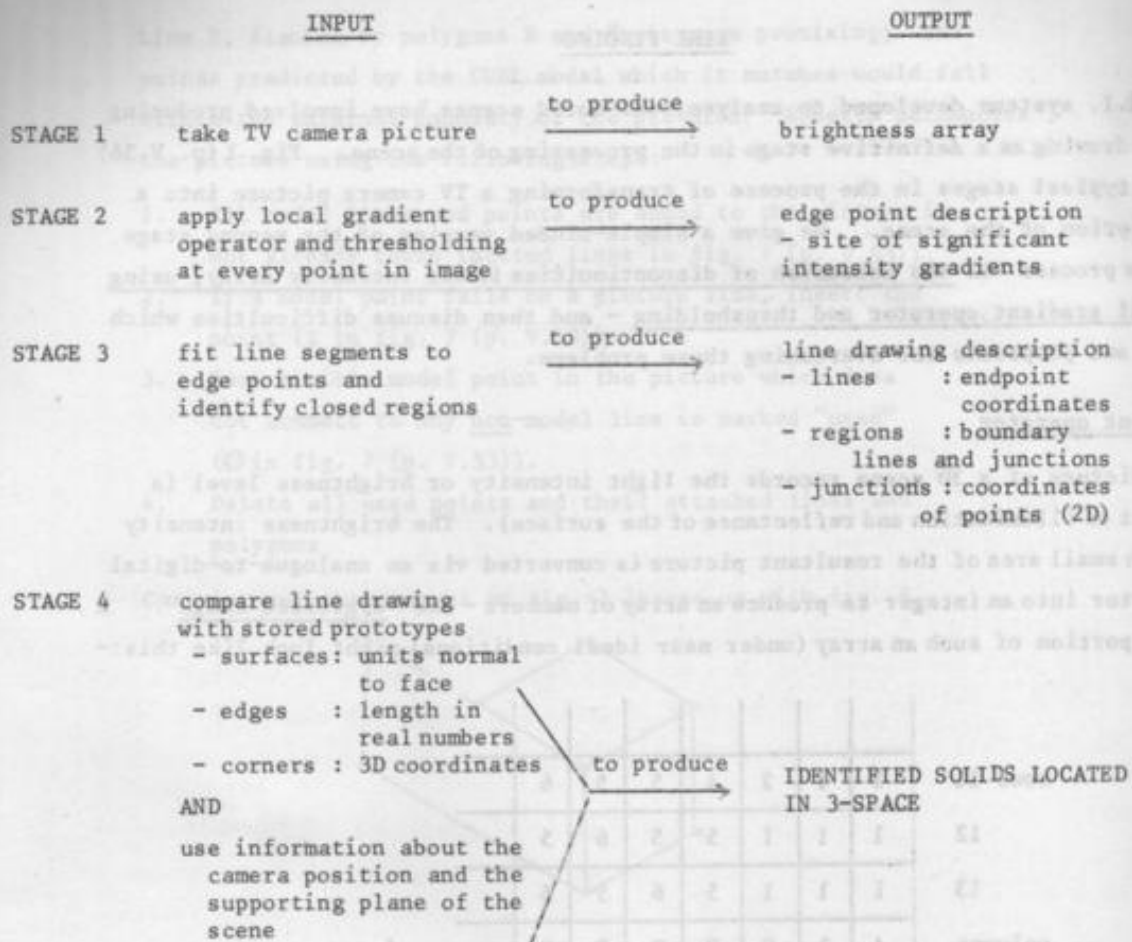
rows 11	1	1	2	4	5	5	6
12	1	1	1	5	5	6	5
13	1	1	1	5	6	5	5
columns	A	B	C	D	E	F	G

We are interested in finding picture edges of interest, i.e. "significant" local changes in picture brightness. So we examine what is happening in the immediate neighbourhood of each point by passing a 3x3 grid across the whole array, and computing the gradient at each point as follows:-

Point D12 is flanked by column E, which sums to 16 } column difference = 12  
 and column C, which sums to 4 }  
 and by row 13, which sums to 12 } row difference = 1  
 and row 11, which sums to 11 }

Clearly there is a lot happening in the row direction and not very much change in the column direction. In contrast,

Point B12 yields a column difference of 1  
 and a row difference of 1



**Fig. 1 Showing stages in scene analysis**

(derived from Falk (1972)).



We can compute the gradient as

$$(i) \text{ the amount of difference} = \sqrt{\text{column difference}^2 + \text{row difference}^2}$$

$$(ii) \text{ the direction of difference (as its tangent)} = \frac{\text{column difference}}{\text{row difference}}$$

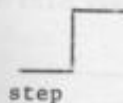
NOTE that the edge should be perpendicular to the gradient. Repeating the process for each picture point, we get an array of gradients. Since we are not interested in small differences, we eliminate these by applying a threshold, leaving only the edge points of interest.

#### Fitting line segments

Under ideal conditions, the edge points found in stage 2 should line up nicely. Unfortunately difficulties arise with actual pictures of real world scenes due to mutual illumination, scattering effects at edges, smudges, shadows, object deformities such as surface chips, surface markings and a whole battery of instrument defects. Background noise is high; variations within a picture region can be larger than the step across to the next region. This gives rise to spurious points which are above the threshold and if we increase the threshold we risk losing significant points. In general it is difficult to find a good compromise! Consequently a line finder which tries to piece together edge points by tracking at  $90^\circ$  to the gradient direction at each point, i.e. by "following its nose" in the direction of a putative edge can be misled by wrong local data into going off in the wrong direction: and hampered by missing edge points.

To overcome these difficulties, several approaches have been used, which include ideas of the following sort:-

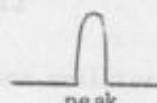
- (1) Brightness contrast across edges falls into 3 categories:-



step



roof

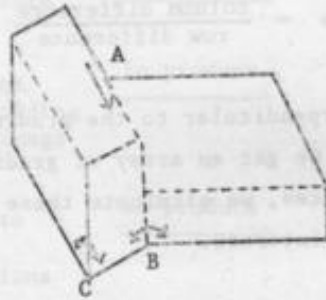


peak

So use a set of different gradient operators to facilitate detection of particular edge types (Binford-Horn).

- (2) Look at edge points more globally to find sets of collinear points (O'Gorman-Clowes).

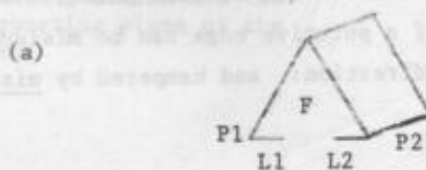
- (3) Find external boundary lines first, since these are more easily found, and use typical configurations in the contour to guide search (Shirai).



e.g. concavities are good places to start. They could conceal a T-junction, e.g. at A, so look for one by looking along the extension of one arm of the concavity; find the 3rd line at a junction, e.g. B, C, by doing a circular scan; in either case try to find a line parallel to a contour line.

- (4) Don't try too hard for a complete line drawing at preprocessing stage and leave it to high level programs to complete the picture by adding lines. e.g. Falk provides 3 procedures to do this job, VIZ:-

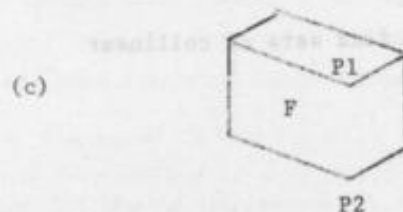
- (i) JOIN which can complete the face F in (a) by joining the 2 hanging collinear lines L1 and L2



- (ii) ADDCORNER which extends dangling lines L1 and L2 in (b) to complete the corner and so complete the face F.



- (iii) ADDLINE which looks for evidence that a complete line has been missed and adds a line between P1 and P2 in (c) to split F into two



NOTE: The improvements in line-finding listed above involve using global properties, using progressively more context, using partial results to suggest the possible position and orientation of lines still to be found.

e.g. collinearity of edge points (2 above)

collinear lines already found (4a)

parallelism (3)

known junction types (3, 4b and c)

i.e. A KNOWLEDGE OF WHAT IS BEING LOOKED FOR IS DEPLOYED TO PROVIDE GOAL-DIRECTED SEARCH.

#### ALTERNATIVES TO LINE FINDING

1. Instead of looking for discontinuities in the intensity array to find lines in the picture, we can look for REGIONS of similar intensity  
e.g. The programs used in the Edinburgh robot project to recognise spectacles, cups, etc., mentioned on p. V.29, used REGION FINDING.
2. We can use range-finders to locate surfaces of objects in the scene  
e.g. (i) the LINE-STRIPING technique in the current FREDDY project  
(ii) the use of a laser beam at Stanford, and by vision workers in Japan.

#### COMMENTS

The assumption that producing a line drawing is a necessary stage in the analysis of a scene is open to question. It would seem more profitable to regard line drawings as an expression of - i.e. as generatable from - an internal description which is itself a 3D description. This is not to say that the reverse process can't occur - it obviously can. When in fact a line drawing as such is input, e.g. as a diagram - or a PEANUTS cartoon - it can be readily seen as representing a 3D scene, as indeed is a drawing composed of dots. In a technical drawing, e.g. a circuit diagram, the conventions in terms of which the elements of the drawing map into concepts in the domain

e.g.  means resistor

must be explicitly acquired before the observer can make sense of the drawing.

Strip cartoon devotees gradually acquire a great mass of conventions:-

e.g. in a PEANUTS cartoon, "distance" means "distance from action", and there are 3 positions of importance in the picture:-

middle ground - where the centre of the action takes place

background - for observer status

(iii) foreground - for emphasis.

See Minsky and Papert (A.I. Memo 252) for a discussion of how children reveal their internal representations in their drawings.

CONTRIBUTION TO A THEORY OF VISUAL PERCEPTION

We now draw together themes from previous lectures.

The formation and use of symbolic descriptions

In our consideration of grouping processes, we built up the notion of a hierarchical description and suggested a role for an intermediate description (page V.12)

"if we had a description of a rectangle stored away, we could imagine that finding the hook "[" could invoke this description".

We postulated (page V.8) that it was easier to see the picture under consideration as a side-view (of a chair and table) rather than as an aerial view, by noting that

"the familiar arrangement of parts triggers concepts that we already have" and that "parts take their names from the wholes they are seen to belong to".

We saw (page V.17) how lines can change their allegiance i.e. what they are seen as belonging to, by virtue of changes elsewhere in the picture. Small local changes in the display produced large global effects. Grouping elements into larger units was part of an "effort after meaning" in which stored experience plays an important role (page V.17).

In the 4th, 5th and 6th lectures, we considered programs (Guzman, Clowes-Huffman, Roberts) for analysing line drawings. These programs deploy a vocabulary of descriptions to refer to significant parts of the picture e.g. arrow, fork junctions, and a repertoire of procedures (rules) for manipulating these descriptions. Guzman showed how junctions provided pieces of evidence for linking the regions of which they were part, into whole bodies (page V.32) and how the effect of any one bit of local evidence could be modified by the context in which the junctions occurred, i.e. the presence of a particular neighbouring junction could inhibit link formation (page V.35).

Both the Clowes-Huffman line-labelling approach and Roberts' program introduce the notion of models. In the former, each of Guzman's picture parts has a set of possible models, e.g. there are 4 possible edge models for each line in the picture (page V.40). Edges meeting at a point constitute corner models and the number of physically possible corner models for each junction type was seen to be surprisingly small (pages V.42,43). Since in a complete line drawing, each line connects two junctions, applying a coherence rule that a single line must have the same edge model along its entire length captures the fact that the assignment of a meaning to each junction must take place within the context of its immediate neighbours. Interpretation of a picture is then equivalent to searching over the set of possible corner models for each junction in the picture, applying this rule.

In this line-labelling scheme, concave objects are handled in the same way as are convex objects. Roberts' system adopts an alternative possible mechanism, in which concave objects are seen as decomposable into a small set of prototype convex models. Finding the right model involves the topological matching of the polygon structure around picture points with the polygon structure around model points. It is point-dominated and no intermediate models e.g. edges or surfaces, are used. Again the search for a solution takes the form of a search over possible models. A more powerful, suggestive way of describing the seeing process is as a two-way addressing system whereby stimulus cues ("good" picture fragments) address (or invoke) internal models (or schemata) and these models, once invoked, suggest (or predict) what and where the rest of the picture might be.

We need both the stimulus patterns and bottom-up analysis of the Behaviourists; and the candidate models (or WHOLES) and top-down hypothesis-generation of the Gestaltists. By adopting this middle-ground position, we can account for such features of the human perceptual system as for example its constructive gap-filling nature - for models allow us to hallucinate the missing bits; and the role of mental set in perception in determining which models are to be considered. In the figure on page V.62 we show a selection of examples to illustrate this two-way process.

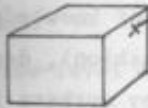
#### Knowledge-driven analysis

Notice (page V.52) that when we had collected our model-picture point pairs, we did not expect an exact match. Instead, we expected to be able to account for the mismatch by one of a given number of transformations, i.e. to interpret or make sense of the mismatch between the incoming perceptual pattern and the stored concept. A crucial element of stored conceptual structures must consist of knowledge of how to handle such mismatches.

In our discussion of the low-level process of line-finding, we showed (page V.59) how a knowledge of what is being looked for can be deployed to provide a goal-directed search. The analysis is conducted in terms of assumptions (hypotheses, prejudices) about what is significant (relevant) and what is noise to be ignored. Notice (page V.57) that surface markings are listed among the difficulties to be overcome. An alternative possibility would be to exploit their presence, which is exactly what the perception psychologist Gibson does in his demonstration of how surface texture can provide depth information, - as the surface recedes, the markings get closer together. Shadows were regarded as a nuisance by the early vision programs, until Waltz showed how to use the evidence they provide to cut down the number of possible interpretations of a picture, as shown in the M.I.T. film EYE OF THE ROBOT. Shadows tell us what the scene looks like from the viewpoint of the light source.



V.62



This acute angle is SEEN AS a right angle. Our cube schema has "right-angled" as part of its description. Recognition involves projecting a right angle on to the acute angle



Our schemata includes the rule:

Things further away appear smaller:  
To get the correct size, enlarge correspondingly.

Converging lines mean "receding into the distance". So we project a larger man on to the stimulus of the same size.



image 12. Judds.  
image 13. Kohnen.



"We may regard pictures as lying in a kind of continuum. At one end there will be drawings, realistic paintings and photographs that are representational. .... At the other, the fantasy end, will be inkblots or pictures in the fire or in clouds .....

For most people plate V will be at the fantasy end, meaning as little or as much as an inkblot .....

People appropriately trained in interpretation of radiographs will recognise it as a radiograph of part of a human head ... "

from 'Anatomy of Judgement'  
M.L.J. Abercrombie.

Figure 1



Developing vision systems capable of representing different varieties of knowledge, and allowing these to interact in different ways (in a heterarchical fashion), depending on on-going partial results, is the challenge currently being tackled by workers in A.I. vision projects e.g. the FORTRAN CODING SHEET project at Essex University; the "SPOTTY PICTURES" project and the "PUPPET" project, both at Sussex University. This work is very much influenced by the seminal paper "A framework for representing knowledge" by Marvin Minsky.

### Action perception

The view of the perceptual process as a constructive, interpretative activity in which we see the current situation in terms of what we know, is captivated by Clowes' slogan

"We can not SEE. We can only SEE-AS".

Work in this department on Action Perception has involved an extension of these ideas to a richer domain which includes moving objects. This can produce a dramatic increase in the range of concepts which enter into the interpretative process. Thus moving objects become participants in event-sequences or actions, in terms of which they acquire roles such as agent or patient. We become concerned with what caused the perceived movement and with the attribution of motives to the participants. The Belgian Psychologist Michotte used simple 2-D "meaningless" shapes such as squares, circles and triangles moving in relation to one another over a screen; subjects viewing such displays receive impressions of one object chasing another, pushing one another, fleeing from another, and so on. Except for isolated instances, these effects were independent of the particular shape used. These observations form an ideal basis for our task of modelling the perception of moving objects on a computer.

In the classical LAUNCHING experiment, the subject fixates a stationary red square (B) in centre of a white screen, while from a point 40 mm left of centre, a black square (A) travels towards B and stops when it reaches it; B then moves off to the right. Observers see object A bump into object B and give it a push.

What we require in order to produce an "explanation" of, or to give an account of, the impressions reported by Michotte's subjects is, in the first instance, the development of a vocabulary of symbols appropriate to various levels of interpretation of the kinetic displays.

### Examples

- low-level descriptions of position : bar (position  $p_1$  (time  $t_1$ ))  
bar (position  $p_2$  (time  $t_2$ ))  
low-level description of change of position : A moves  
intermediate description  
in relation to another object : A approaches B rapidly  
in relation to a previous movement : A moves to-and-fro  
high-level description of causal sequence : A bumps into B and  
pushes it forward
- Depending on the reference point chosen, the description of the movement of an object, e.g. A moves, can become:

A approaches B  
or A moves across screen  
or A withdraws from B

An important issue is how to represent moving objects in the computer in such a way as to facilitate the generation of descriptions of their movements. We input the process continuum as successive time slices, or conceptual snapshots, depicted as a frame sequence rather like a strip cartoon. It is as though the observer takes successive samplings of the movement processes and forms descriptions of each, so that the difference-descriptions between successive frames express the changes which have occurred during a particular time-interval. (cf. use of difference-descriptions by EVANS in his ANALOGY program, and by WINSTON in his LEARNING STRUCTURAL DESCRIPTIONS program).

The experiments are input to the program in the form of low-level symbolic descriptions of a sequence of snapshots of moving objects. The program is required to build up a description of what is happening in the form of event-sequences to check relevant constraints, and so decide which of the act types it knows about corresponds to the input sequence.

There will in general be more than one way of pairing picture regions in successive frames and we need a way of choosing which of the possible pairings corresponds to an ENDURING OBJECT IN MOTION. For example, in figure 2

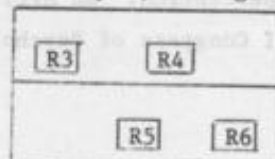


Figure 2

which region should we combine with R5; R3 or R4 to which it is nearer? If we choose R4 we are left with the pair R3.R6; but (R3.R5; R4.R6) is better in that it gives a combined pairing which involves the least overall change in position.

In Weir (1976)\* we detail the steps involved in forming descriptions from the experimental data: e.g. we show how the factors influencing the choice of a reference point radically affect the intermediate descriptions generated. Since these latter form the components of ACTION SCHEMATA, this in turn influences which particular action schema will be evoked. Fig. 3 gives a representation of some of the features of a PUSHING or LAUNCHING schema. Any component could evoke this schema. Typically, an instance of [x collides with y] would be responsible for an active search for the "withdrawal" of the patient y. "Suggestions" link similar schemata and facilitate rapid access.

Anyone who wishes to pursue further the view of perception outlined above might like to read the D.A.I. Research Report No. 15 "Using LOGO to catalyse communication in an autistic child" by Sylvia Weir and Ricky Emanuel.

\* "From object perception to person perception: An Artificial Intelligence view".

Proceedings of XXIst International Congress of Psychology, Paris, July, 1976.

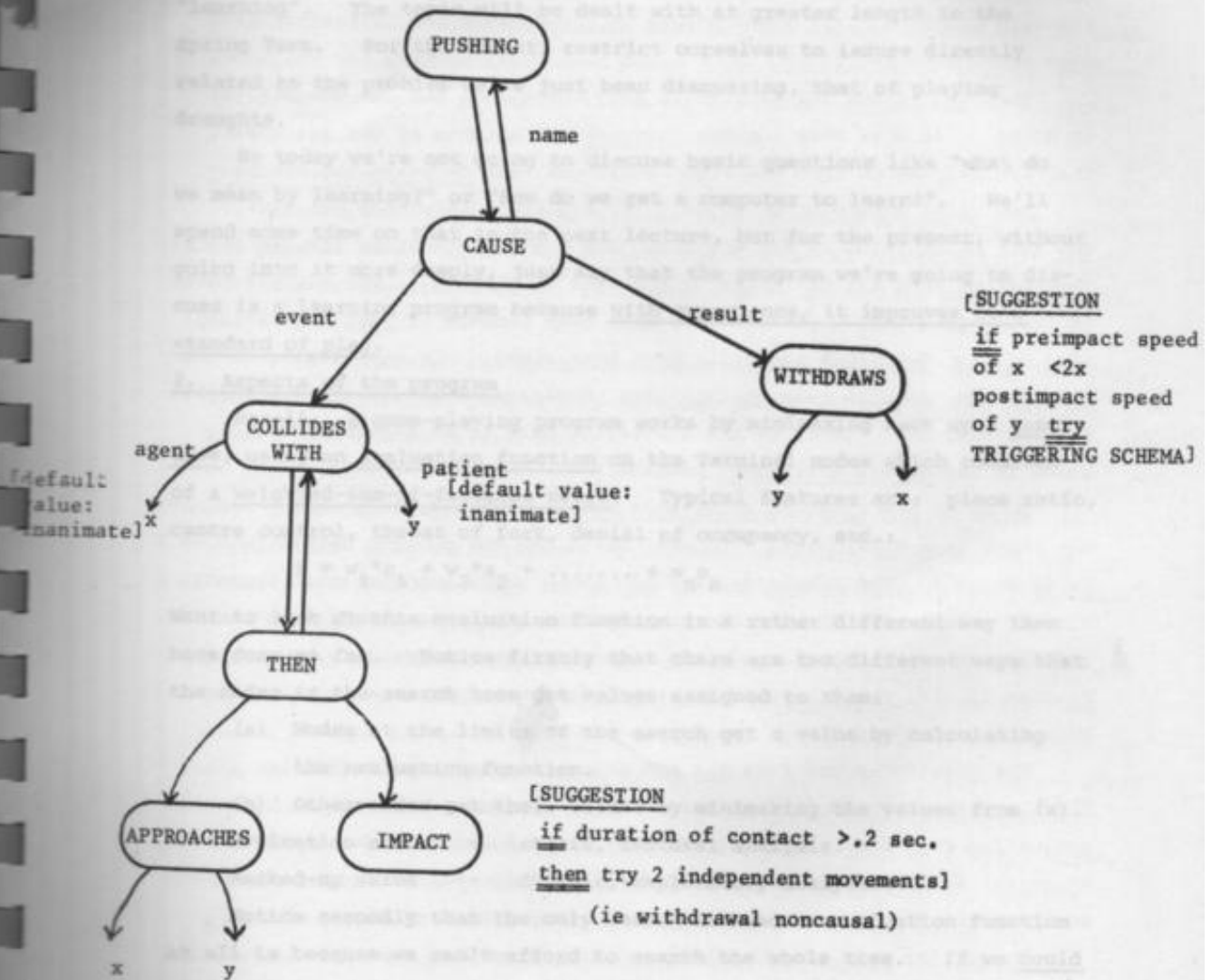


Figure 3. Pushing Schema.

## Learning - 1: Samuel's Checkers-player and Hill-climbing

### 1. Introduction

This is the first of two preliminary lectures on the subject of "learning". The topic will be dealt with at greater length in the Spring Term. For the moment, restrict ourselves to issues directly related to the problem we've just been discussing, that of playing draughts.

So today we're not going to discuss basic questions like "what do we mean by learning?" or "How do we get a computer to learn?". We'll spend some time on that in the next lecture, but for the present, without going into it more deeply, just say that the program we're going to discuss is a learning program because with experience, it improves its standard of play.

### 2. Aspects of the program

Recall: a game-playing program works by minimaxing back up a game tree, using an evaluation function on the Terminal nodes which consists of a weighted-sum-of-features score. Typical features are: piece ratio, centre control, threat of fork, denial of occupancy, etc.:

$$S = w_1 * s_1 + w_2 * s_2 + \dots + w_n * s_n$$

Want to look at this evaluation function in a rather different way than have done so far. Notice firstly that there are two different ways that the nodes in the search tree get values assigned to them:

(a) Nodes at the limits of the search get a value by calculating the evaluation function.

(b) Other nodes get their values by minimaxing the values from (a).

Evaluation score - static, featural analysis.

Backed-up value - dynamic, exploratory analysis.

Notice secondly that the only reason we need an evaluation function at all is because we can't afford to search the whole tree. If we could search the whole thing, we would be able to assign nodes their true value of +1 (win), 0 (draw), or -1 (lose). But in fact we have to terminate the search somewhere, and at these points we have to make do with an approximation to the true value.

In other words, the evaluation score is a second-rate substitute for a full exploratory search. It is intended to tell us approximately what we would find, if we were able to carry out the full search that in fact we can't.



### 3. Generalisation learning

The question now is this: in the "weighted sum of features score", where do the weights come from? What should they be? And the proposed answer is that the program should learn the appropriate weights by experience - it should continually be adjusting its weights to improve its standard of play. (It also chooses an appropriate set of features - more on this below.)

The idea is for the program to play for a bit, and see how well it is doing. It must then somehow increase the weights of the features that are helping to make the right decisions, and decrease the others.

How often should it do this? If it does it only once per game, the rate of learning is far too slow, and one is extracting far too little information from all the activity involved in playing. For example, even if the program lost a game, it may have been because of just one mistake: most of its decisions may still have been right. Or conversely, if the program won, does it mean that all its decisions were equally responsible for the success? (What we are discussing here is an aspect of what is known as the credit assignment problem.)

So we do the updating after each move. This is sufficiently frequent, but there is a difficulty. On what basis can the program decide "how well it is doing"? The simple description given above supposes that there is a trainer standing by to tell the program "Yes, that was a good move" or "No, you did the wrong thing". In the absence of such a trainer, how can the program itself, which is already making the best decisions it can, also know how good these decisions are?

The solution comes from the two points we discussed in Section (2). There are two ways of finding the value of a board position, (a) by static evaluation function, (b) by dynamic search. Since it looks further ahead, score (b) is less dependent on the details of the evaluation function, and so it can be used as a criterion for the correctness of score (a).

To say the same thing a different way: remember that (a) is regarded as a prediction of (b), so that it can serve as a substitute for it. The better the evaluation function, the better that prediction. If the evaluation function were perfect, the two scores would be in agreement throughout the game. So all we have to do to see how good the evaluation function is, is to see how closely it corresponds to the backed-up score.

So for boards encountered during actual play, compute

$$\Delta = (\text{backed-up score of board resulting from chosen move}) - (\text{evaluation score for current board})$$



If  $\Delta$  is +ve, then the evaluation score made an under-estimate, so the +ve terms in the polynomial should have more weight, and the -ve terms less weight. If  $\Delta$  is -ve, the score was an over-estimate or even led to the wrong choice of move, so the weights should be altered conversely.

In fact, the program keeps a cumulative average record of the "correlation" between the sign of each term and the sign of  $\Delta$ , and this is used to adjust the weights after each move. The correlation of a given feature tells us how good a predictor it is, so the better it is, the more weight it's given.

#### Term selection

The evaluation polynomial involves only 16 out of a possible 38 features. The program keeps track of which term has the lowest "correlation", and if any term is lowest too often, it is replaced by a new term which initially has zero weight.

With experience this program becomes highly competent, a "better-than-average" player with good middle- and end-game play, though the openings remain weak and unconventional.

#### 4. Hill climbing

Occasionally during learning, the program is temporarily unable to improve its play any further. It is then necessary to give it a big "kick", by setting to zero the weight of the leading term in the polynomial.

Why does this happen?

Samuel is essentially using the technique of hill climbing to optimise the program's performance. This technique is appropriate when for some reason you are unable to analyse the task in such a way as to deduce the best weights (e.g. in draughts, nobody knows how to do this). Instead you start from where the program is and make a long series of small improvements.

Compare this with trying to reach the top of a hill on a foggy night, without a map. The general idea is to "keep going upwards". One can

- (a) find the line of steepest slope and take a step along it;
- (b) try steps in different directions, and choose the best;
- etc.

This method suffers from various problems. The one that concerns us here is the problem of secondary peaks (or local maxima). You may have reached a peak, but is it the highest one? One solution is to try making random leaps. To do better, you have to know more about the structure of the problem. (Another difficulty is that of encountering a "mesa", a large area where there is no change whichever way you move, and therefore no clue to the correct direction.)

Hill climbing is a technique widely used and studied even outside of AI.

#### REFERENCES

- A.L. Samuel (1959), Some studies in machine learning using the game of checkers. IBM Journal of Research and Development, 3, 211-229. Reprinted in Computers and Thought (eds. E.A. Feigenbaum and J. Feldman), pp. 71-105.
- A.L. Samuel (1967), Some studies in machine learning using the game of checkers. II - Recent progress. IBM Journal of Research and Development, 11, 601-617.
- In his 1959 paper, in addition to the "generalised learning" discussed here, Samuel describes a form of "rote learning" in which selected board positions encountered during play are remembered, and used to increase the effective depth of search, thereby improving the program's play. See pp. 79-83 in Computers and Thought.

## Learning - 2: Structural Learning and General Comments

### 1. Digression: "concept identification" experiments

We take a quick look at a chapter of Experimental Psychology in order to provide ourselves with certain terminology and ideas. In a "concept identification" experiment, the subject is presented with a set of objects varying in some systematic way, e.g. cards with shapes varying in outline, number, size, colour, etc. A "concept" is a subset of the objects specified by a simple rule. Different kinds of rules define different kinds of concepts:

conjunctive - e.g. red and square

disjunctive - e.g. red or square

equivalence - e.g. both red and square, or neither.

For a given concept, certain attributes are relevant. E.g. for "red and square", colour and shape are relevant attributes, the rest are irrelevant.

Subject is shown examples one at a time, and told whether or not they are instances of the concept the experimenter has in mind. The subject's task is to guess the rule.

A strategy commonly used for learning conjunctive concepts is "conservative focussing". Here the subject remembers the first positive instance, and then gradually strips away its irrelevant attributes. We can see that if a new example differs from the first in several attributes but is still a positive instance, then those attributes must all be irrelevant. Whereas if the new example differs in just one attribute and is a non-instance (a "near-miss"), then that attribute must be relevant. This should all sound vaguely familiar.

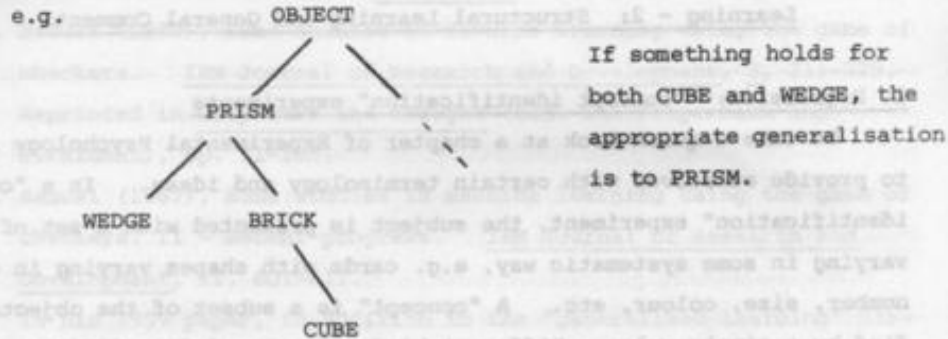
The field was opened up by a book by Bruner, Goodnow & Austin in 1956. Since then more than 1200 similar experiments have been published.

### 2. Winston's program revisited

(a) Consider the process of building a model from a sequence of positive instances and "near-misses", e.g. HOUSE (see Figure 1). The formation of the MUST-BE and MUST-NOT-BE links is the detection of the relevant attributes.

(b) When having to relax a requirement, Winston's program makes an appropriate generalisation by finding the first superordinate entity that includes both cases. For example, in case I - C of learning ARCH (see handout SW/3), it finds that both a BRICK and a WEDGE are acceptable as

cross-members, so generalises them to PRISM.



(c) Previously learned concepts can be used in new ones.

e.g. ARCH as a component of ARCADE (see Figure 2).

Such a concept is necessarily hierarchical: ARCADE could not be learned without first learning ARCH - it would become hopelessly complicated.

(d) These iterative structures like ARCADE and COLUMN are handled in the same way as simple structures. The networks have a TYPICAL-MEMBER link, and a NUMBER-OF-MEMBERS which can be "appropriately generalised" to be an INTEGER (implicitly,  $> 2$ ). See Figure 3.

### Discussion

Note the central importance of near misses for the learning. Successful learning is dependent on being given a good training sequence. Viewing learning as the building of an internal description gives us a rational basis for discussing "good teaching".

But does this go beyond what Bruner, Goodnow & Austin (1956) did? Compare this view with Bruner's own work on education (The Process of Learning, (1960); Toward a Theory of Instruction, 1966).

Limitation comes from the fact that the technique is essentially "conservative focussing", so it is restricted to learning conjunctive concepts.

e.g. Could it learn the concept "two bricks in the same orientation"

(either both lying or both standing)? What about the concept

"cat"? Or "abuts"? Or "near to"?

### 3. Discrimination nets

Consider the ANIMAL program you played with at the beginning of term:

THINK OF AN ANIMAL

IS IT A MOUSE? :no

OH DEAR, I DID NOT GET THAT ONE

WHAT ANIMAL WERE YOU THINKING OF? : pterodactyl

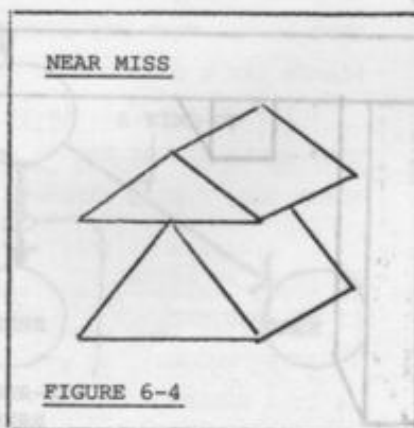
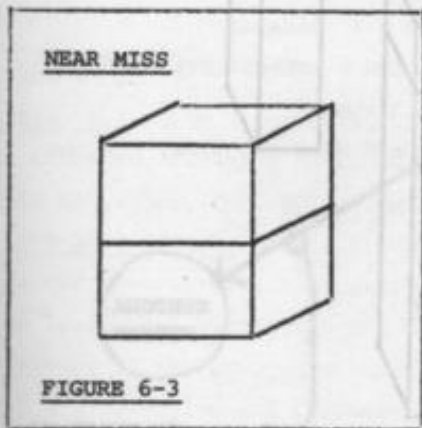
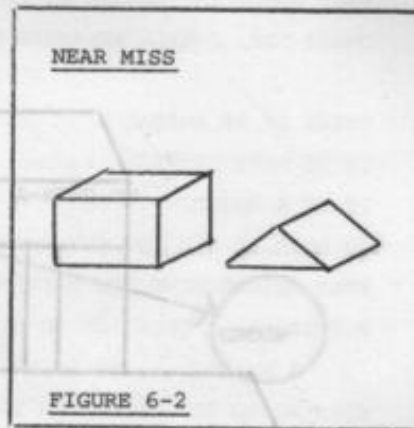
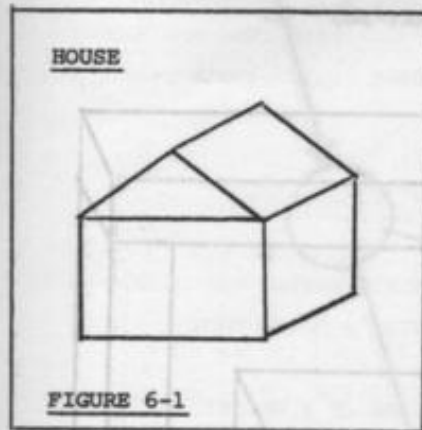


FIGURE 1: HOUSE

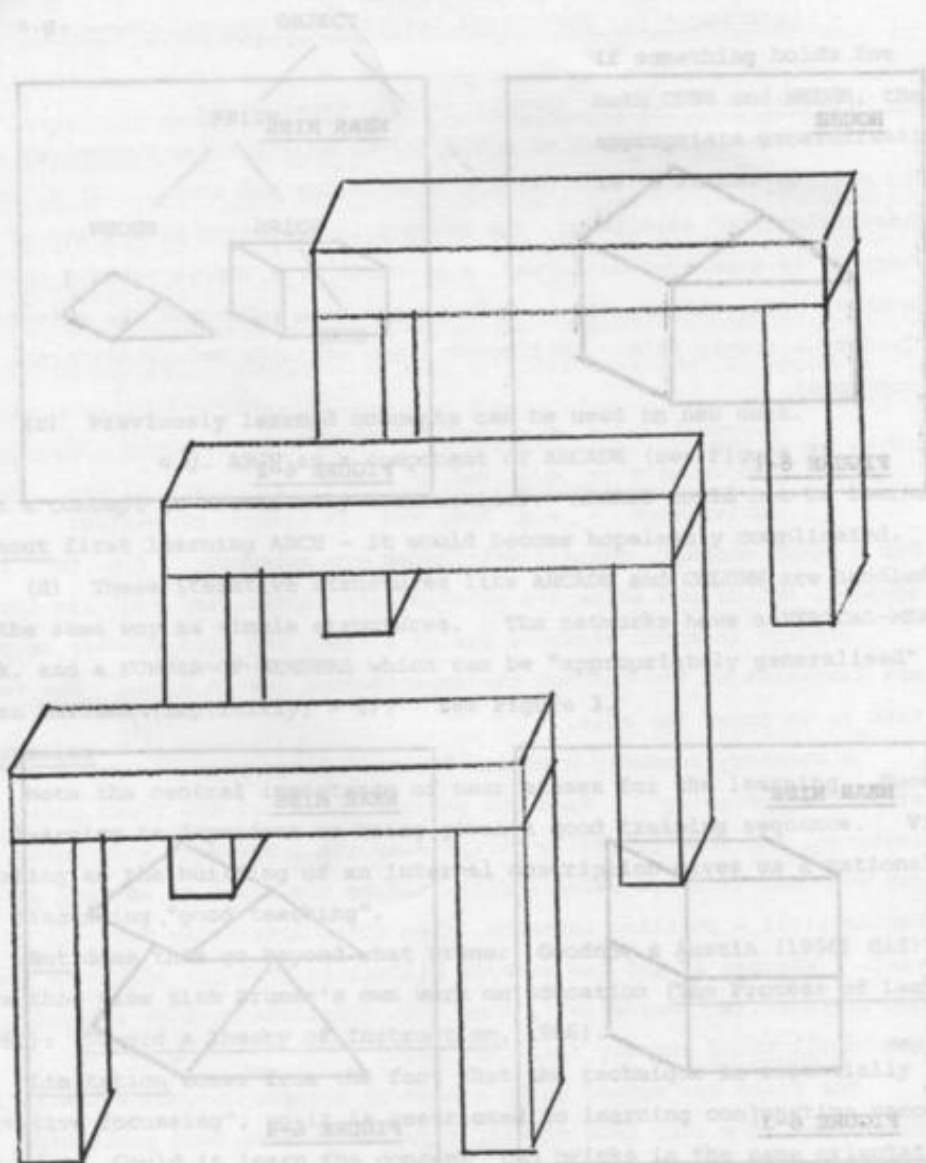


FIGURE 2: ARCADE

3. Discrimination rate

Consider the ANIMAL program you played with at the beginning of term:

THINK OF AN ANIMAL

IS IT A MONKEY?

OF COURSE, I DID NOT GET THAT ONE

WHAT ANIMAL WERE YOU THINKING OF?



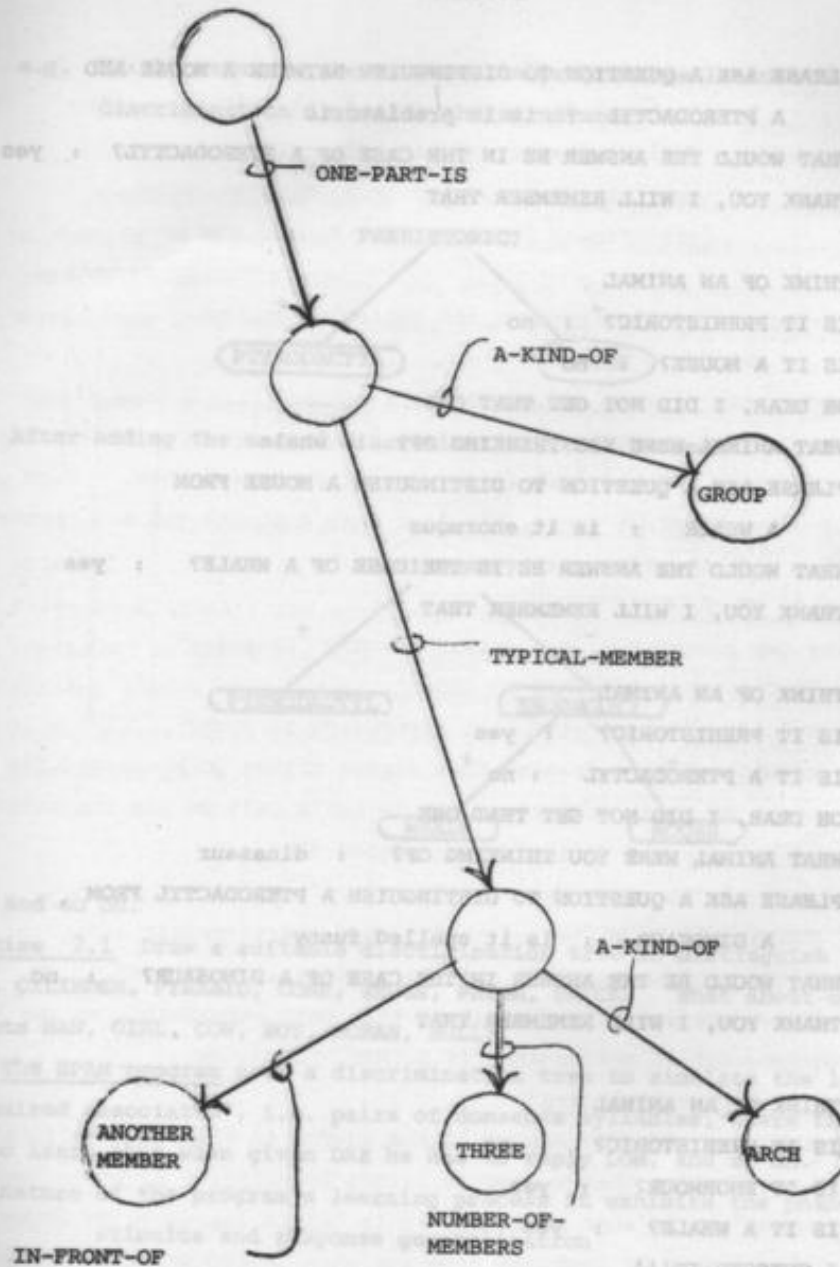


FIGURE 3: ARCADE

L.10

PLEASE ASK A QUESTION TO DISTINGUISH BETWEEN A MOUSE AND

A PTERODACTYL : is it prehistoric

WHAT WOULD THE ANSWER BE IN THE CASE OF A PTERODACTYL? : yes

THANK YOU, I WILL REMEMBER THAT

THINK OF AN ANIMAL

IS IT PREHISTORIC? : no

IS IT A MOUSE? : no

OH DEAR, I DID NOT GET THAT ONE

WHAT ANIMAL WERE YOU THINKING OF? : whale

PLEASE ASK A QUESTION TO DISTINGUISH A MOUSE FROM

A WHALE : is it enormous

WHAT WOULD THE ANSWER BE IN THE CASE OF A WHALE? : yes

THANK YOU, I WILL REMEMBER THAT

THINK OF AN ANIMAL

IS IT PREHISTORIC? : yes

IS IT A PTERODACTYL : no

OH DEAR, I DID NOT GET THAT ONE

WHAT ANIMAL WERE YOU THINKING OF? : dinosaur

PLEASE ASK A QUESTION TO DISTINGUISH A PTERODACTYL FROM

A DINOSAUR : is it spelled funny

WHAT WOULD BE THE ANSWER IN THE CASE OF A DINOSAUR? : no

THANK YOU, I WILL REMEMBER THAT

THINK OF AN ANIMAL

IS IT PREHISTORIC? : no

IS IT ENORMOUS? : yes

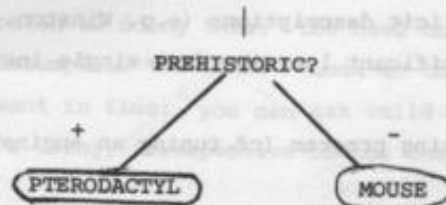
IS IT A WHALE? : yes

I GUESSED IT!!!

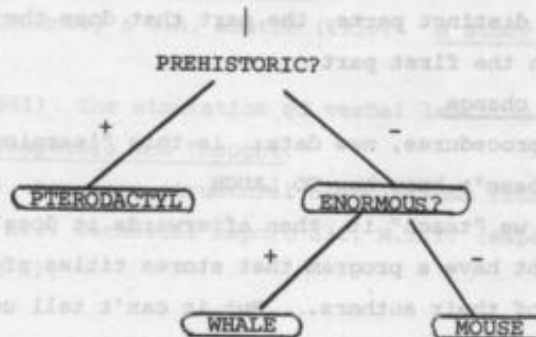
How does the program recognise an animal by testing for suitable features in a sensible way? By making use of a (binary) discrimination tree: a tree in which the terminal nodes are names of animals, and each non-terminal node has

- (a) a test
- (b) a pointer to its YES-node
- (c) a pointer to its NO-node.

e.g. in the sequence above, when the program has learned the first discrimination it builds the structure.



After adding the second discrimination, this becomes



And so on.

**Exercise 2.1** Draw a suitable discrimination tree to distinguish the objects CUBE, CYLINDER, PYRAMID, CONE, WEDGE, PRISM, BRICK? What about one for the objects MAN, GIRL, COW, BOY, WOMAN, BULL?

The EPAM program uses a discrimination tree to simulate the learning of "paired associates", i.e. pairs of nonsense syllables, where the subject has to learn that when given DAX he has to reply LOM, and so on. By the very nature of the program's learning process it exhibits the phenomena of stimulus and response generalisation, retroactive interference, and forgetting as a failure of accessing (rather than storage).

Thus provides a non-probabilistic model of paired-associate learning. Compared to Winston's program, EPAM is cruder but it does its learning more gradually.

#### 4. General comments on learning

##### Paradigms and contrasts

##### (1) Statistical vs structural learning.

e.g. height of man vs number of hands.

Statistical: summarise wide experience in numbers  
 implicit descriptions (e.g. Samuel's program)  
 Structural: reflect characteristics of individual cases  
 explicit descriptions (e.g. Winston, EPAM)  
 significant learning from single instances

- (2) Improving an existing program (cf. tuning an engine)

vs

writing a new program (cf. building a bridge)

In the case of improving an existing program, we already have a program that does the job, and the task is to make it perform better. Such programs usually have two distinct parts, the part that does the job and another part that fiddles with the first part.

#### Trivial kinds of change

- (1) Adding new procedures, new data: is this "learning"?

e.g. LOGO doesn't know how TO LAUGH

But if we "teach" it, then afterwards it does?

e.g. We might have a program that stores titles of books and the names of their authors. But it can't tell us who the author of Waverley is until it has learned it?

- (2) The issue of "store vs recompute"

Essentially a matter of trading off space against time:  
 should the program remember all the results it produces?

If we are selective enough in what gets remembered, we may get an improvement of performance (e.g. MEMO functions).

#### No attempt to define "learning"

- (1) Learning as a possible aspect of the answer in the "what is intelligence?" game. A feeling that a program is not intelligent if it is "merely programmed" to do some task, but it is "if it learns to do it by itself".

- (2) The slipperiness of learning programs when looked at hard. A program that learns to do task T can usually be thought of as simply doing a related task T'.

e.g. Samuel's program learns to play better checkers, or it optimises its performance.

(cf. "the computer just does what its programmer tells it to").

- (3) Informal, everyday use of learning as an "explanation" - as an alternative to "mechanism"?

e.g. How does one ride a bicycle - you can't be told how to do it, you have to "learn by experience".

e.g. From c.1920-1950, Experimental Psychology (especially in the U.S.) was dominated by the "behaviourist" view which saw learning as the problem of psychology.

The objection to doing this: the need to have a sufficient mechanism to accomplish the task. Look at the device/organism at a particular moment in time: you can ask valid questions about the mechanisms it's using, irrespective of how they were acquired.

(BUT ALSO: a deeper sense in which this formulation may be valid?)

#### References

- J.S. Bruner, J.J. Goodnow, & G.A. Austin (1956). A Study of Thinking. Wiley.
- E.A. Feigenbaum (1961). The simulation of verbal learning behaviour, reprinted in Computers and Thought.
- P.H. Winston (1970). Learning structural descriptions from examples. Ph.D. thesis, A.I. Technical Report 231, M.I.T. (especially Chapters 5 and 6).

### Learning - 3: Perceptrons

#### 1. Background

One of the many striking facts about the human brain is that it contains more than  $10^{10}$  neurons, each of which is a sophisticated little computing device in its own right. In the search for the "mechanisms of intelligence", many people have tried to confront this fact, and to ask what kind of organisational principle could enable this vast mass of information-processing units to exhibit intelligent behaviour. This approach is usually loosely called "neural net" studies (at least by workers in Artificial Intelligence).

Underlying much of this research is the widespread notion "... of the brain itself as a rather loosely organised, randomly interconnected network of relatively simple devices". Several key ideas that arose during the 1940's and 50's had an important influence on this line of thought, for instance:

- . the basic idea that lots (but lots!) of simple elements suitably put together can yield interesting, complex behaviour;
- . the theoretical demonstration in the mid-1940's that networks of simple neuron-like elements can be constructed to compute any logical function;
- . results that were starting to appear from neurophysiological studies of the way that information is processed in the visual systems of various animals;
- . proposals from the newly-emerging field of Artificial Intelligence as to how pattern recognition can be done by using a large number of independent little decision-making units, working simultaneously, "organised" in a rather unstructured way.

So far in this course we have examined ways of generating intelligent behaviour by imposing an organisation on a sequential process - that is what programming is all about. By contrast, the emphasis in the neural net studies is largely on self-organising systems. The extreme case is the idea of a system with initially random connections that get selectively strengthened or weakened by learning.



At one time these ideas were very popular, and much research - both experimental and mathematical - was done on devices of this kind. Sometimes over-ambitious claims were made, for example that such devices would be able to play master chess by learning to "recognise" good board situations. Nowadays it is felt (at least by workers in Artificial Intelligence) that this approach has severe limitations. There is a need for greater structure, for an appropriate match between the mechanism and the task to be done.

One class of device to emerge from this work has a particularly interesting history, and we look at it more closely.

## 2. Perceptrons

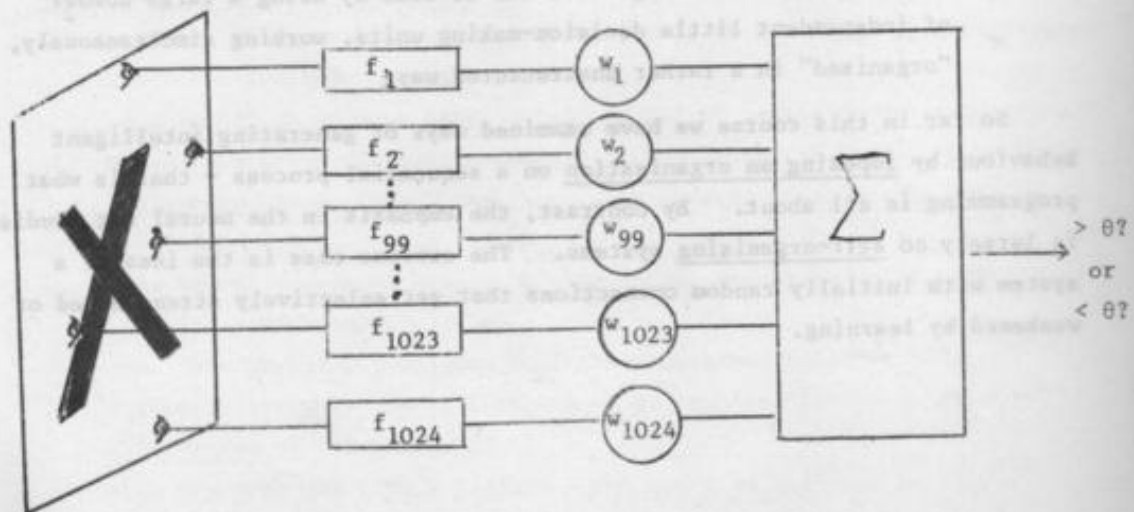
The idea is to have a machine that recognises a class of objects by a simple combining of the evidence obtained from lots of small experiments performed independently. Thus the perceptron provides a paradigm for the intuitive notion of simple decision - making carried out by a richly parallel mechanism.

Presented with an object  $X$ , a perceptron computes the values of various features  $f_i(X)$ , then combines them in a weighted vote:

$$\sum w_i f_i = w_1 f_1 + w_2 f_2 + w_3 f_3 + \dots + w_n f_n$$

This value is compared to a threshold  $\theta$ . If  $\sum w_i f_i > \theta$ , we say the perceptron responds positively. We want it to respond positively if  $X$  is an object of a certain type, and negatively if not.

Eg.    if  $X$  is-a-circle;  
          if  $X$  is-a-convex-figure;  
          if  $X$  is-a-single-connected-figure.



We can imagine some figure projected onto a 2-dimensional "retina" which is "looked at" by a large number of little "demons" each computing one of the  $f_i$ . The outputs of these demons are then multiplied by their respective weights and added together.

How can this device be used to classify objects? Consider two examples:

Example 1. Take the simple case where we want the perceptron to recognise just one particular figure, at a fixed place on the retina. Perhaps a block capital letter X, as shown in the diagram on the previous page.

Let each  $f_i$  look at just one small spot on the retina. For each  $f_i$  that is looking at a spot that should be black if the object is in fact the one we are interested in, suppose it produces output = 0 if its spot is black, and output = -1 if its spot is white. For each  $f_i$  looking at a spot that should be white for the correct object, suppose it produces output = 0 if the spot is white and -1 if it is black.

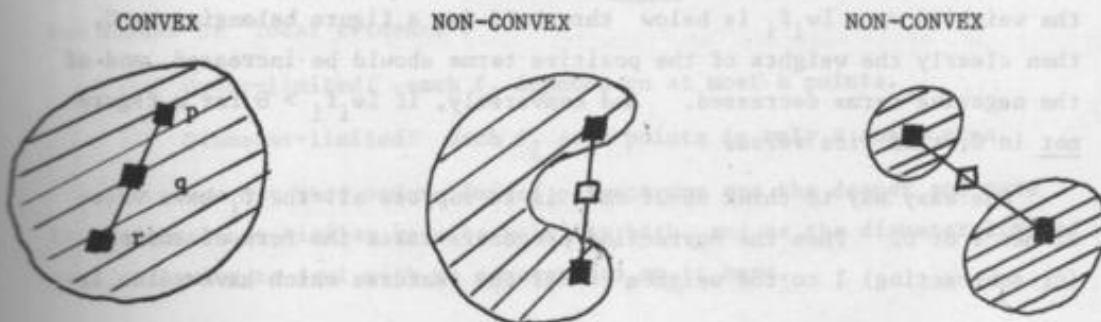
Now consider the perceptron with all weights = 1 and a threshold of -1

$$(\sum_i f_i) > -1$$

If we show this perceptron our desired object, then all the  $f_i$  will have value zero, the whole sum will be zero, and therefore the inequality will be true. But if the object differs in any way from the intended one, then at least one of the  $f_i$  will have value -1, so the whole sum will be  $\leq -1$ , and the inequality will be broken.

So this simple perceptron discriminates between our desired figure and all others.

Example 2. Consider next a case where we want to recognise not just a single object, but a broad class of objects. Suppose we want it to recognise whether the black area forms a single, convex object.



One way of testing for convexity - or even for defining it! - is to consider collections of three collinear points,  $p, q, r$ . In a convex figure, if two points  $p$  and  $r$  are black, then all points  $q$  on the line between them must also be black. In a non-convex figure, however, there will always be some black points  $p$  and  $r$  which have a white point  $q$  between them.

Suppose each  $f_i$  looks at three collinear spots. If the two outer spots are black and the middle one is white, let the  $f_i$  produce output = -1. Otherwise the output = 0.

Suppose now there are enough  $f_i$ 's to "cover" the whole retina, in some sense. Again consider the inequality

$$(\sum_i f_i) > -1.$$

The argument proceeds as before. If the object is convex, then all the  $f_i$  will be zero and the inequality will hold true. But if the figure is non-convex, at least one of the  $f_i$  will have value -1, and the inequality will be broken.

So this perceptron discriminates between convex and non-convex objects.

### 3. Learning in perceptrons

Not surprisingly, given the neural-net background to the perceptron research, much of the interest with perceptrons lies in the question of whether a perceptron can learn to recognise objects. As with Samuel's draughts program, learning is a matter of finding an appropriate set of weights,  $w_i$ . To get the perceptron to learn to recognise a class  $C$ , we present it with a sequence of examples, some in  $C$  and some not. Each time, depending on right or wrong, we take appropriate reinforcing or correcting action.

We can make an intuitive argument for the form the correction should take, analogous to the argument made in discussing Samuel's program. If the weighted vote  $\sum w_i f_i$  is below threshold for a figure belonging to  $C$ , then clearly the weights of the positive terms should be increased, and of the negative terms decreased. And conversely, if  $\sum w_i f_i > \theta$  for a figure not in  $C$ , then vice versa.

One easy way to think about this is to suppose all the  $f_i$  have value either 1 or 0. Then the correction procedure takes the form of adding (or subtracting) 1 to the weights of all the features which have value 1.



But the trouble is that B, which is connected, looks locally just like A or D, which are disconnected.

[But it is quite easy to write programs for a serial machine, e.g. in LOGO, to determine whether a figure is connected, and they use very little storage].

Various other interesting figures can't be recognised:

- e.g. objects that contain other objects;
- e.g. rectangle embedded in context;
- etc.

## 5. Discussion

There is a general moral to be drawn from the analysis. There is no point in discussing elaborate schemes for "teaching" a machine to do something it inherently cannot be made to do. Most of the early proposed schemes lacked careful analysis of

- their inherent limitations
- the rates of learning
- the sizes of the weights  $w_i$ .

Consider for example, the inability of the diameter-limited perceptron to recognise the scene consisting of a single dot.

Notice, however, that Minsky & Papert's analysis applies only to the very simplest kind of perceptron, called "single layered". Real perceptron enthusiasts play with far more complicated varieties, called "multi-layered", and "cross-coupled". etc. It is not at all clear whether limitations analogous to those of Minsky & Papert apply to these more complex perceptrons. (If you are interested, see the careful review of the Perceptron book by Block).

## References

- M. Minsky and S. Papert (1969) Perceptrons: An Introduction to Computational Geometry. M.I.T. Press.
- H.D. Block (1970) A review of "Perceptrons: ....."  
Information and Control, 17, 501-522.



Learning - 4: Induction

1. Induction

Inductive tasks require detection of a pattern, or regularity, in the information presented, such as spotting a trend, seeing similarities, finding odd-man-out, etc.

Examples

- A. Geometric analogy tasks. These were discussed extensively at the beginning of the course - see handout AB/1.
- B. Letter analogies. Fill in the blanks:  
IJ JI PO OP ED --
- C. Letter grouping. Pick out the one that doesn't belong:  
AABC ACAD ACFH AACG
- D. Number groups. State what is common:  
35 110 75
- E. Number relations. Pick the one that doesn't belong:  
2 6 3 9 4 12 6 15
- F. Number series. State the rule:  
15 18 21 24 27 30
- G. Number correction. State the one in error:  
1 2 3 4 5 7
- H. Seeing trends. What is the trend?:  
ANGER BACTERIA CAMEL DEAD EXCITE
- I. Word groups. What is common?:  
MAIM TEST GANG LABEL
- J. Word relations. Fill in the blanks:  
REAL SEAL MEAT NEAT BORE ----



K. Series completion. Your task is to write the correct letter in the blank:

- (i) C D C D C D C
- (ii) A A A B B B C C C D D D
- (iii) A T B A T A A T B A T A
- (iv) A B M C D M E F M G H M M
- (v) D E F G E F G H F G H I I
- (vi) Q X A P X B Q X A A
- (vii) A D U A C U A E U A B U A F U A A
- (viii) M A B M B C M C D M D
- (ix) U R T U S T U T T U U
- (x) A B Y A B X A B W A B B
- (xi) R S C D S T D E T U E F F
- (xii) N P A O Q A P R A Q S A S
- (xiii) W X A X Y B Y Z C Z A D A B B
- (xiv) J K Q R K L R S L M S T T
- (xv) P O N O N M N M L M L K K

Compared to more "deductive" problems, these tasks have a certain "openness". Finding the solution is a genuine "creative act" and involves going beyond the evidence given (cf. a scientific theory). The answer is not in the sequence itself: the problem solver himself has to bring something to the task.

What defines a right answer? Mathematically speaking, there are indefinitely many sequences that begin 1 2 3 4 ...

## 2. Letter sequences

See problem type K in the examples above. Notice how the problems vary in difficulty (e.g. as measured by time taken to solve, or the number of people failing). Some seem especially difficult: (v), (vii), (ix), (xv), ... (Why?). By and large, different people tend to agree about which ones are easier and which ones are harder. (Why?).

Notice how it is important to find the periodicity of the sequence. People usually start by doing this.

Simon and Kotovsky (1973) created a descriptive language for this class of sequences. All that is needed is:

- idea of a repeating pattern, in square brackets [ ]
- idea of pointers into the alphabet
- operations of NEXT and BACKWARD NEXT on the pointers

E.g. (iv): A B M C D M E F M G H M ...

is:  $x \leftarrow A/ALPH$ , [x nx x nx M]

(ix): U R T U S T U T T U ...

is:  $x \leftarrow R/ALPH$ , [U x nx T]

(xv): is:  $x \leftarrow y \leftarrow P/ALPH$ , [x bx x bx x by x+y]

S. & K. find that the harder problems have more complex descriptions. In particular, the sequences that require two pointers impose a bigger memory load and are almost always harder than the one-pointer sequences (Why?).

(A more detailed analysis, based on thinking-aloud protocols and eye-movements is given in Kotovsky and Simon (1973)).

### 3. Induction program

S. & K. wrote various versions of a program to derive the pattern description from the given sequences. This led to the idea of a "natural" ordering of the difficulty of the problems, since a "stronger" version of the program (i.e. one which solved more problems than a "weaker" one) tended to solve all the problems the weaker one did. Indeed, it would be hard to write a program that solved the harder problems and failed on the easier ones.

We look at a "rational reconstruction" of S. & K.'s program, presented by Newell (1973). The idea is to start with a broad class of hypotheses (e.g. "all sequences of period 3") and then make successive refinements by repeated comparison with the given sequence.

The trick is to allow for a large number of possibilities by using variables ( $\alpha \beta \gamma$ ), but then deducing what the variables must be in order to generate the sequence correctly. In comparing the pattern against the sequence, there are six different situations that can occur, each of which leads to an appropriate action:

Case 1: Pattern has a variable  $\alpha$ , sequence has a letter which is pointed to by some pointer x.

Action: replace  $\alpha$  by "x".

- Case 2: Pattern has a variable  $\alpha$ , sequences has a letter which is "next" after some pointer  $x$ .  
Action: Replace  $\alpha$  by "nx x".
- Case 3: Pattern has a variable  $\alpha$ , sequence has a letter  $L$ .  
Action: Replace  $\alpha$  by new pointer "y", and add "y-L/ALPH".
- Case 4: Pattern has a pointer  $x$ , sequence has the letter pointed to by  $x$ .  
Action: That's fine, do nothing.
- Case 5: Pattern has a pointer  $x$ , sequence has the letter next after  $x$ .  
Action: Replace "x" by "nx x".
- Case 6: Otherwise fail.

Let us see how this works out on problem (viii).

i.e. given: M A B M B C M C D M ...

- (1) Guess  $\{\alpha \beta \lambda\}$ , i.e. a sequence of period 3. (See exercise below).

Generate:  $\alpha...$  compared to: M ...

Case 3:  $\alpha$  must be pointer  $x$ , initialised to M.

- (2) Now have:  $x=M/ALPH$ ,  $\{x \beta \gamma\}$

Generate: M  $\beta$ ... compared to: M A ...

Case 3:  $\beta$  must be pointer  $y$ , initialised to A.

- (3) Now have:  $x=M/ALPH$ ,  $y=A/ALPH$ ,  $\{x y \gamma\}$

Generate: M A  $\gamma$ ... compared to: M A B...

Case 2:  $\gamma$  must be "ny y".

- (4) Now have:  $x=M/ALPH$ ,  $y=A/ALPH$ ,  $\{x y ny y\}$

Generate: M A B M B C M C D ...

OK: we're there!

Unlike the S. & R. program, this one does not begin by finding the periodicity of the sequence. But it has no need to, since the hypotheses that it has period one ( $\{\alpha\}$ ) or two ( $\{\alpha \beta\}$ ) quickly come to grief.

Exercise. Show this.

#### 4. Discussion

By working with symbolic descriptions of sequences instead of with the sequences themselves, we have managed to cast the induction problem into the same form as earlier problems we have looked at. As in the

Missionaries & Cannibals problem, for example, we have:

- . an initial state, e.g.  $\{\alpha \beta \gamma\}$ ,
- . which has to be transformed into a goal state,  
i.e. a fully-specified pattern which generates the given sequence,
- . by means of a series of operators, e.g. replace " $\alpha$ " by " $n\alpha x$ ".

Notice that in this case, for each kind of difference between the pattern and the given sequence there is a single kind of change to be made to the pattern, so we never have to undo a decision we made earlier. This means that we can use the powerful matching technique instead of the comparatively weaker tree-search.

The traditional distinction between "deduction" and "induction" leads to a certain mystique attached to the latter. I hope to have dispelled some of this by showing how an "inductive" problem can be solved by the same means as were used for "deductive" problems,

- i.e. (a) use of symbolic descriptions, and  
(b) application of operators to reduce the difference between the current state and the goal state.

Some interesting questions have to do with the hypotheses, e.g., where do they come from? Consider:

(a) O T T F F S S E N.?

(b) S M T W T F S.?

(c) B C D G J O P Q R S T.?

A E F H I K L M N O P Q R S T U V W  
6 3

#### References

- A. Newell (1973) Artificial Intelligence and the Concept of Mind.  
In R.C. Schank and K.M. Colby (eds): Computer Models of Thought and Language. W.H. Freeman, pp. 1-60.
- H.A. Simon and K. Kotovsky (1963) Human acquisition of concepts for sequential patterns. Psychological Review, 70, pp. 534-546.
- K. Kotovsky and H.A. Simon (1973) Empirical tests of a theory of human acquisition of concepts for sequential patterns. Cognitive Psychology, 4, pp. 399-424.

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### Learning - 5: Production systems

#### 1. Need for a constrained language

In the programs we have looked at so far, the "learning" has consisted of the building up of some data structure distinct from the learning program itself:

- e.g. . Winston's descriptive networks
- . EPAM discrimination tree
- . Samuel's weighted evaluation score
- . Simon & Kotovsky letter sequence pattern

However, in order to get a wider range and greater flexibility of learning, and to write programs that acquire the ability to do something they couldn't do before, it will clearly be necessary to have programs that modify and add to their existing program. For example, we might want to write a robot program which, the first few times it is asked to assemble a toy car, does so slowly and painfully from first principles; but after a while, we would want it to have acquired a new procedure for that particular task.

Unfortunately, LOGO and other "ordinary" programming languages are not really suitable for this kind of automatic manipulation. The difficulty is rather like trying to understand someone else's LOGO program, where all the procedures are called just P1, P2, P3, etc., and the arguments and variables are all called X, Y, Z! In order to modify someone else's program, you have to

- know the significance of each of the procedures, arguments, variables, etc.
- understand the purpose of each line in a procedure
- know enough about the context to be able to make the modification without introducing new bugs
- be able to use the EDITor effectively to change the old procedure or define a new one.



Needless to say, it is very hard to automate this process. What we do instead is to simplify and restrict the programming language drastically, and to write programs in this more primitive language in a systematic way. We will suggest a way of doing this by considering how to write LOGO programs that have the desired properties.

## 2. Production systems

First suggestion. Suppose we write our program in the form:

TO MYPROGRAM

1 IF <condition 1> THEN <do action 1> AND GO 1

2 IF <condition 2> THEN <do action 2> AND GO 1

3 IF <condition 3> THEN <do action 3> AND GO 1

:

999 IF <condition 999> THEN <do action 999> AND GO 1

END

Notice that this is a special kind of program. Its execution takes place in a sequence of cycles. During each cycle, just one line gets fully obeyed. LOGO looks at the lines 1,2,3,... in turn, and finds which one has a true <condition>. The <action> on that line is obeyed, and then LOGO jumps back to line 1 and the next cycle begins.

This kind of program has some of the properties we want, for we are now stating explicitly what the conditions are for each possible action to occur. However, this is not yet enough, because we have said nothing about what the conditions and actions are allowed to be. And if we allow arbitrary LOGO code to be written there, then all the old problems come back. So:

Second suggestion. Suppose that we have a WORKING MEMORY, called WM, that is used to hold all the changing information in the system. In other words, there are to be no other variables, lists, etc. to hold data other than those in WM. By analogy with the INFERENCE system (see handout RMB/2), we can think of WM as a database, and we are saying that all data must be stored in the database.

We are now in a position to place interesting restrictions on the conditions and actions. We will say:

- (a) All <conditions> consist of a pattern match against the information in WM, rather like the ISQ pattern match in the INFERENCE system. Call this operation MATCHES. Note that this is the only way of



retrieving information from WM: we allow no FIRSTs, BUTFIRSTs, etc.

- (b) All <actions> consist of an addition to, or modification of, the information in WM, analogous to ASSERT.

Then our program will look like:

TO MYPROGRAM

1 IF MATCHES <pattern 1> THEN <WM-action 1> AND GO 1

2 IF MATCHES <pattern 2> THEN <WM-action 2> AND GO 1

3 IF MATCHES <pattern 3> THEN <WM-action 3> AND GO 1

:

999 IF MATCHES <pattern 999> THEN <WM-action 999> AND GO 1

END

This kind of program is usually written in the following notation:

Rule 1 : <pattern 1>  $\Rightarrow$  <WM-action 1>

Rule 2 : <pattern 2>  $\Rightarrow$  <WM-action 2>

Rule 3 : <pattern 3>  $\Rightarrow$  <WM-action 3>

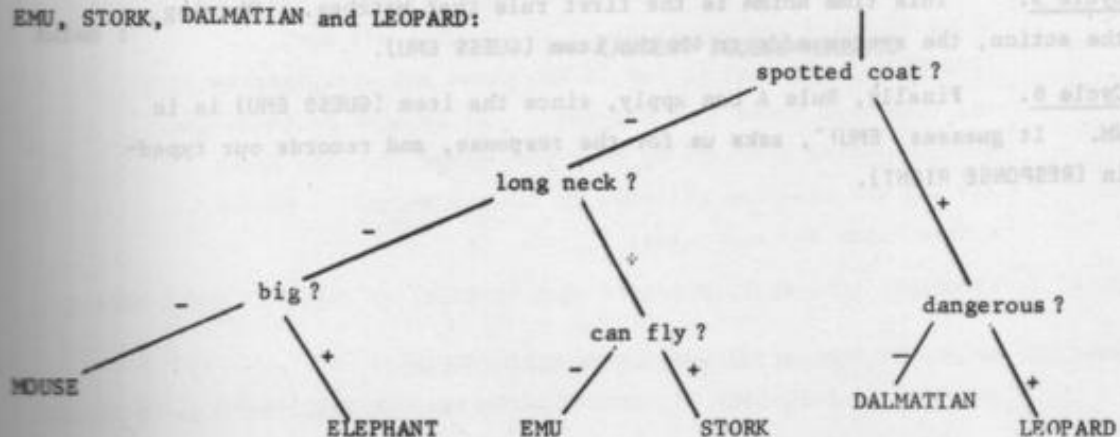
:

Rule 999 : <pattern 999>  $\Rightarrow$  <WM-action 999>

This is called a production system. The individual rules are called productions or production rules.

### 3. An example: ANIMAL program revisited

Remember the ANIMAL program, which guesses what animal you are thinking of by asking a series of questions about its properties? The diagram below shows the state of the program after it has learned about MOUSE, ELEPHANT, EMU, STORK, DALMATIAN and LEOPARD:



On page L.30 is a production system to find which of these animals you have in mind. The notation is similar to that used for the INFERENCE system. The easiest way to understand how the system works is to watch it stepping through an example. Suppose we think of EMU, and suppose that the WM is initially empty.

Cycle 1. The patterns of neither Rule A nor Rule B match the WM, nor do Anim1, Ques1, or Anim2. But the pattern of Ques2 does match (since there is no item [ASKED SPOTTED-COAT] in WM), so the system obeys the actions of Ques2:

- (a) It asks: SPOTTED-COAT ?
- (b) It puts into WM the item [ASKED SPOTTED-COAT]
- (c) It attends to the answer: we type in [ANSWER NO], which gets automatically ASSERTed.

Cycle 2. This time Ques2 does not match, since there now is an item [ASKED SPOTTED-COAT] in the WM. The first rule to match is Ques4, so as in Cycle 1:

- (a) It asks: LONG NECK ?
- (b) It puts into WM the item [ASKED LONG-NECK]
- (c) It attends to, and ASSERTs, our answer: [ANSWER YES].

Cycle 3. This time Rule B matches, since the items [ANSWER YES] and [ASKED LONG-NECK] are both in WM. So, taking the actions of Rule B, the system deletes the item [ANSWER YES], and adds the item [PROPERTY LONG-NECK].

Cycle 4. Ques3 is the first rule which matches. As before, it asks about "CAN-FLY", and gets our [ANSWER NO].

Cycle 5. This time Anim4 is the first rule that matches. Obeying the action, the system adds to WM the item [GUESS EMU].

Cycle 6. Finally, Rule A can apply, since the item [GUESS EMU] is in WM. It guesses "EMU!", asks us for the response, and records our typed-in [RESPONSE RIGHT].

Rule A: [GUESS 'ANIMAL][NOT [RESPONSE 'RIGHTORWRONG]]  
 => [SAY :ANIMAL][ATTEND-TO RESPONSE]

Rule B: [ANSWER YES][ASKED 'PROP]  
 => [DELETE [ANSWER YES]] [ASSERT [PROPERTY :PROP]]

Anim1: [PROPERTY SPOTTED-COAT][PROPERTY DANGEROUS]  
 => [ASSERT [GUESS LEOPARD]]

Ques1: [PROPERTY SPOTTED-COAT][NOT [ASKED DANGEROUS]]  
 => [SAY DANGEROUS ?][ASSERT [ASKED DANGEROUS]][ATTEND-TO ANSWER]

Anim2: [PROPERTY SPOTTED-COAT] => [ASSERT [GUESS DALMATIAN]]

Ques2: [NOT [ASKED SPOTTED-COAT]]  
 => [SAY SPOTTED-COAT ?][ASSERT [ASKED SPOTTED-COAT]][ATTEND-TO ANSWER]

Anim3: [PROPERTY LONG-NECK][PROPERTY CAN-FLY] => [ASSERT [GUESS STORK]]

Ques3: [PROPERTY LONG-NECK][NOT [ASKED CAN-FLY]]  
 => [SAY CAN-FLY ?][ASSERT [ASKED CAN-FLY]][ATTEND-TO ANSWER]

Anim4: [PROPERTY LONG-NECK] => [ASSERT [GUESS EMU]]

Ques4: [NOT [ASKED LONG-NECK]]  
 => [SAY LONG-NECK ?][ASSERT [ASKED LONG-NECK]][ATTEND-TO ANSWER]

Anim5: [PROPERTY BIG] => [ASSERT [GUESS ELEPHANT]]

Ques5: [NOT [ASKED BIG]]  
 => [SAY BIG ?][ASSERT [ASKED BIG]][ATTEND-TO ANSWER]

Anim6: => [ASSERT [GUESS MOUSE]]

#### 4. Properties of production systems

- (1) Notice how the "facts" that have been learned are of the same kind as the original "program" - Rule A, Rule B, and perhaps Anim6. Rule Anim3, for example, is just as much part of the present program as is Rule A, and it is treated in the same way.
- (2) Notice how "modular" the production system is. Each rule states a self-contained part of the knowledge embedded in the total system. Rule Anim3, for example, states that if the animal is known to have a long neck and be able to fly, then STORK should be guessed. Similarly, Ques1 states that if the animal is known to have a spotted coat, but it is not yet known whether it is dangerous, then that should be the next thing to be found out. If we look at the corresponding nodes in the tree, we can see how "reasonable" these rules are.
- (3) Largely because of this modularity, the production system is highly amenable to automatic learning - which is why we were interested in it in the first place.

To see how this automatic learning might happen, again it is best to follow an example. Suppose that we think of OSTRICH instead of EMU. The answers to all the questions will be the same, so the system will still guess "EMU!", but this time we tell it: [RESPONSE WRONG]. What needs to happen?

- (a) Clearly the system must ask us for a distinguishing property of the new animal, i.e. it does an [ATTEND-TO DISTINGUISHING-PROPERTY], and we tell it: [DISTINGUISHING-PROPERTY HEAD-IN-SAND].
- (b) The system now has in hand all the information it needs in order to build the new rules. If it takes all the [PROPERTY ...]s that it has in WM, these are what specify the incorrect guess that was made. If it adds to these the distinguishing property we have just given it, then those are all the features relevant to the new animal. So the system forms two new rules:

ANIM3.5: [PROPERTY LONG-NECK][PROPERTY HEAD-IN-SAND] => [ASSERT [GUESS OSTRICH]]

QUES3.5: [PROPERTY LONG-NECK][NOT [ASKED HEAD-IN-SAND]]  
=> [SAY HEAD-IN-SAND ?][ASSERT [ASKED HEAD-IN-SAND]][ATTEND-TO ANSWER]

and puts them just before the rule responsible for the wrong guess, i.e. between Ques3 and Anim4.

Actually to implement these steps as part of the original production system requires only a few extra rules, and one then has a fully-fledged system capable of learning about new animals. For details of how this is done, see the paper by Waterman.

In fact, production systems of this kind were originally developed for the purpose of modelling human problem-solving behaviour. We will have some more to say about this next time.

#### Reference

- D. A. Waterman (1975) Adaptive production systems. Proceedings of the Fourth IJCAI, pp. 296-303.

Learning - 6: Schemata

1. Production systems as psychological models

- (a) In origin, production systems (PSs) of the kind we looked at last time were developed by Newell & Simon for representing human problem solving behaviour. The data typically consist of thinking-aloud protocols on tasks such as chess and symbolic logic - much the same sort of material as GPS was applied to. PSs turn out to provide a convenient and appropriate form to express the models of problem solving.
- (b) A typical later application of Newell & Simon's ideas is illustrated by the videotape: the use of PSs to investigate cognitive development in children. This work capitalises on the suitability of the PSs for modelling learning, and the ease of adding new rules.
- (c) As a psychological model, the "WM" (see last handout) can be more-or-less identified with the psychologist's "Short Term Memory", and the PS itself with "Long Term Memory", i.e. our knowledge, abilities and memories.
- (d) Parallel evocation. Although we described PSs last time as a serial process, in terms of a special kind of LOGO program which tests the rules one by one until it finds one whose "<condition>" is satisfied, there is a psychologically more interesting way of regarding them. By analogy with the Perceptron, we can think of each rule as a little "demon", each on the look out for its own <condition>. As with the Perceptron, all the demons are active at once. The first one whose <condition> is satisfied yells loudly, and the system obeys the corresponding <action>.
- (e) Thus we get the prototype for the idea of a system working on a recognise-act cycle. More on this below. We can think of the Perceptron-like aspects of the system as "recognising" what to do next, while the LOGO-like aspects actually perform the "acts".



## 2. Schemata

The idea of a schema as a representation of skill and knowledge: information about something and about how to do things with it. Derives from:

- (a) Work of Bartlett (1932: Remembering). Schema as the essence of a story: outline features remembered, plus any unusual characteristics - but distorted in a normalising direction.
- (b) Piaget. Two aspects of adaptation:
  - (i) Assimilation - incorporation of new experience into existing structure.
  - (ii) Accommodation - modification of existing structure (or building of new structure).
 e.g. children's fantasy-play vs imitation.
- (c) Wertheimer (1945, 1959: Productive Thinking). Role of naive, everyday schemata in understanding formal material, such as geometry or algebra. Hence an emphasis on difference between "rote learning" and "real understanding".

Then in AI:

- (d) J.D. Becker: a concrete suggestion for learning and use of simple schemata, but not a working program.

Schema is:

$$\underbrace{[k_1 + k_2 + k_3]}_{\text{event}} \Rightarrow \underbrace{k_4}_{\text{event}}$$

i.e. "if  $k_1$ , then if  $k_2$  and  $k_3$ , then  $k_4$ ". There are weights attached to indicate the confidence of the schema (i.e. the probability of the regularity holding) and the criteriality of each of its components.

The schema can be used, e.g. to achieve  $k_4$ , given  $k_1$ .

- (e) Minsky: "frames" - already discussed, particularly in Vision. High-level guidelines, but no program.

3. What does this buy?

- (a) Can represent knowledge ranging from general to specific. Lots of specialised schemata in an area where you are "expert".
- (b) Place to attach items of information where they are likely to be found when needed.
- (c) Provides the all-important context for perception triggered by a feature.
- (d) Model of cognitive skills: what you can do, as well as what you know.
- (e) (Again:) Idea of a cognitive system functioning on a "recognise-act" cycle. "Recognition" means the evocation of a schema, "act" means its use. The "act" part in humans is serial, quite slow, and depends heavily on symbolic description. The "recognise" part seems parallel and rapid, and is poorly understood.

4. Discussion

- (a) Statistical and structural learning: the need for both, e.g. to learn significantly from a single example and also to continue improving during extended practice.
- (b) Deeper sense of "learning by experience". Our abilities are structured in terms of things that are "familiar" to us, and the actions they lead to. Thus our past experience, captured in schemata, serves to guide our present behaviour.

References

- J.D. Becker (1973): A model for the encoding of experiential information. In Schank & Colby (Eds.), Computer Models of Thought and Language, pp. 396-434.
- H. Ginsburg & S. Oppen (1969): Piaget's Theory of Intellectual Development: An Introduction. Prentice-Hall.
- A. Newell & H.A. Simon (1972) Human Problem Solving. Prentice-Hall.

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How to use the Computer

Experienced users need only read sections 1,5,6,8,10 and 12.

1. Administrative

The computer terminals are situated on level 2 at the East end of the Appleton Tower. They are available on weekdays during term time, from 9.a.m. to 1.p.m. and from 3.p.m. to 9.p.m.

During those hours a demonstrator will be available, whom you can see if you need any help. For certain hours during the week the demonstrator will be someone from the A.I. department and will be familiar with the LOGO programming language. At other times the demonstrator will be from the Computer Science department, and though he will be knowledgeable about EMAS he may not be especially familiar with LOGO. Thus you may find it helpful to spend your 3 hours at the terminal at a time when an AI demonstrator is present. These times will be :

2. The terminal itself

The terminal itself is a kind of electric typewriter made by Olivetti. The main part of the keyboard is laid out like an ordinary typewriter. Notice the "shift" key at the left side of the keyboard, which you must use to type some of the special characters,

e.g. SHIFT and 2 results in "

SHIFT and 7 results in '

Notice also that there is a complete row of numerals across the top of the keyboard. Be careful to distinguish between the letter 'oh' and the digit 'zero', between the letter 'ell' and the digit 'one' - be sure always to type the one you really mean.

To the right of the main keyboard are, at the top, a few more typing keys - notice the [ and ] - and also some blue keys for control actions. You will be using the ones marked CR, DEL, CAN, and ESC.

Still further to the right, there is a box next to the keyboard with a couple of switches controlling the operation of the terminal.

### 3. Logging on to EMAS

(a) First turn on the terminal, using the switches mounted on the box to the right of the keyboard: turn the power switch to ON, which should "bring the machine to life"; then make sure the black switch is set at FULL DUPLEX.

(b) Press the space bar. The system should respond by typing out:  
HOST:

(c) Type in EMAS followed by the CR key

i.e. HOST: EMAS CR

(the bits you type are underlined)

(d) The system will respond with

USER:

Type in your user code followed by the CR key

e.g. USER: ECMU13 CR

(e) The system will respond with

PASS:

Now type in your password, again followed by CR. Your password will not be "echoed", in other words it will not be typed on the paper. This is to prevent other people from learning your password by looking at your listing.

Initially your password is TERM, but there are ways of changing it if you wish to.

(f) If either the name or the password is invalid, the system types an appropriate message, and you may then try the whole sequence again.

If correct the system responds (after a while) with a message like

PROCESS STARTED date time

SUBSYSTEM version date

COMMAND:

(the bits in lower case vary of course)

(g) You are now logged into the EMAS system, and there are a number of things you can do, which you may find out about in due course.

For the moment, though, we concentrate on running LOGO - see below.

### 4. Starting LOGO

(a) When prompted by COMMAND: you simply type AI2LOGO.

COMMAND: AI2LOGO

After a pause, LOGO will report itself by:

LOGO-VERSION m.n(date) time

1:

and from this point on, you will be communicating with LOGO.

(b) Make a habit of giving as your first instruction:

1: LIBRARY ^ECMI02 ^AI2

This will load some useful LOGO procedures not normally available.

- (c) When you want to end the session, type:

1: GOODBYE

This returns you to EMAS, so logoff by typing:

COMMAND: STOP

Some information will be printed out, and the terminal will be disconnected. Remember to switch it off before you leave.

### 5. Summary

The complete sequence is given below. The conventions used are that the things you type are underlined and bits of the sequence that vary between users or with time are in lower case letters.

SWITCH ON

FULL DUPLEX

SPACE BAR

HOST: EMAS CR

USER: user code CR

PASS: password CR

PROCESS STARTED date time

SUBSYSTEM version date

COMMAND: AI2LOGO CR

LOGO-VERSION m.n (date) time

1: LIBRARY 'ECMI02 'AI2

LIB DEFINED

etc.

.....

1:  
your LOGO session

1: GOODBYE

STOPPED AT LINE n

COMMAND: STOP

date time continue connect time page turns charge

CONSOLE DISCONNECTED date time

SWITCH OFF

## 6. Password

Passwords are to prevent other people stealing your nuts or secrets, or sabotaging your programs. Initially everybodys password is set to be TERM. You can change this to any set of 4 printable characters other than a comma. To do this log on to EMAS and in response to

COMMAND:

type PASSWORD (new password, new password)

e.g. COMMAND: PASSWORD (FRED, FRED)

Then inform Dr. Bundy what your new password is. It will be kept confidential. It is necessary for our systems staff to be able to log on as you, to keep your version of LOGO up to date.

## 7. Typing in lines

It is important to realise that EMAS (and LOGO) look only at complete lines of input. So, every line you type in must be terminated by CR (for Carriage Return). It is impossible for EMAS (or LOGO) to respond to what you have typed until you have given the CR.

If you make a typing error on a line and notice it before you give the CR, you can correct it by either of two methods:

1. If you press the DEL key (for DELETE) the system deletes the most recent character typed in and responds with a \ followed by that character. Each time you press DEL another character is deleted and the system responds with the deleted character. When you start typing normally again the system responds with a second \.

e.g. L A G \ G A \ O G O is the same as LOGO

G deleted A deleted O typed

2. You can ignore the whole line typed so far, and start over, by pressing the CAN key (for CANcel). The system responds with a + and gives you a new line,

e.g. TXIS LOIN IS B MISS CAN +

THIS LINE IS A MESS

## 8. Limitations on use

Because computing is expensive there are various limitations on your usage. The limitations are the:

- (a) Rationing of Nuts;
- (b) Log-on limit of 22 students;
- (c) Availability of terminals

and (d) Withdrawal of Service.

- (a) Rationing of Nuts A Nut is a unit of computer power (about 10p worth)



based on a function of connect time, page turns and cputime. You have an allowance of 250 nuts per week. When you have exceeded this you will get a message

#### USE EXCEEDED

To get your allowance increased apply to Alan Bundy.

- (b) Log on limit Only 22 students may be logged on at any one time. During the times when an AI demonstrator is on duty, AI2 students have priority. To claim your priority, approach the demonstrator. Conversely, you may be thrown off yourself in a non-priority period.
- (c) Availability of consoles In exceptional circumstances you can get permission from the demonstrator to use a terminal in Alison House, Forrest Hill or Hope Park Square.
- (d) Withdrawal of Service The computer may be unavailable for a variety of reasons. For instance, it is broken down or being maintained. You will get the message.

#### NO USER SERVICE

Inform the demonstrator and get him to ask when the service will be available again.

### 9. Mistakes (bugs)

If this is your first programming experience you will be surprised how many mistakes you make - everybody is! Do not worry about them because:

- (a) Nothing you can do will damage the computer, and you will need at least a small hammer to damage the terminal.
- (b) Making mistakes is beneficial. It will help you to learn. People who do not make mistakes are obviously not stretching themselves.
- (c) If you get in a mess, ask the demonstrator. That is what he is there for. If he decides there is a fault in the system, you should send your entire terminal listing for the session, annotated if necessary, to Rosemary Robinson, Dept. of Artificial Intelligence, Forrest Hill.

A "bug" is a computing term meaning a mistake in your program.

### 10. Interrupts

If you make a mistake and want to interrupt the computer, because it is doing something you do not want it to do, press the ESC button. The computer will respond fairly quickly with the prompt

INT: ( )

Now type Q (for Quit), this will cause the program to stop what it was doing and allow you to start over again. It will respond with the

prompt

1:

If the program was typing to you when you interrupted it, this typing may continue for a short while after you have typed either ESC or Q. The reason is that the computer has a, half full, buffer of characters, which it wants to empty before it responds.

The complete sequence is

interrupt with ESC

..... perhaps more typeout

INT: Q CR

..... perhaps more typeout

1: now continue.

Some errors will (unfortunately) throw you out of LOGO and back to EMAS. You will recognise these because the message

MONITOR ENTERED FROM IMP

followed by a lot of meaningless rubbish, will be typed on your terminal.

Interrupt as soon as possible. In answer to the INT: prompt type A (for Abort). EMAS will respond with:

COMMAND:

You must now type AI2LOGO to re-enter LOGO.

### 11. Terminal Listing

The piece of paper with typewriting on it that comes from your terminal is called "listing". It is solely for your benefit. The computer keeps its own record. You will normally throw it away except for bits on which you have

- (a) The final record of your program.
- (b) The results of the program.
- (c) Some particular sequence (e.g. Logging on)
- that you want to remember.
- (d) The record of an unsolved bug.

Keep your records tidy or you will be swamped. Do not leave the listing hanging from the terminal - it is a fire hazard!

### 12. Having Fun

In order to give you the feel of computing, here are some exercises to try. First logon to LOGO and do LIBRARY ECMI02 AI2.

1. Solve the "tea ceremony" puzzle. Do LIB CEREMONY and then CEREMONY.

2. Play a game with the computer. Do LIB 'GAME123 and then GAME123 to play a matchsticks game. You can win if you play correctly!
- \* 3. Can you guess what makes ELL1 like things? Do LIB 'ELL1 and then ELL1 to try.
- \* 4. Play "Guess the number". Do LIB 'GUESSNUM and then GUESSNUM. Explain how you think this program works.
5. Play the "Animal" game. Do LIB 'ANIMAL and then ANIMAL. Teach the computer zoology.

#### LOGO objects

LOGO deals with two different kinds of objects: lists and words.

Lists contain words and other lists as their elements:

```
[THIS IS [A LIST] [OF [4 ELEMENTS]]]
```

Words can be numbers or non-numbers. Numbers are written as integers:

```
23 17 104
```

and non-numbers outside of lists are written with a prime:

```
'WORD1 'CAT 'LONGERWORD.
```

(Words inside lists are written as themselves, as in the example above).

6. SUM is a procedure which takes in 2 numbers and outputs a third. Can you guess what the third number is? Test your guess by typing

```
PRINT(SUM 2 3)
```

What happens if you omit the word PRINT?

7. FIRST is a procedure which takes in a list and outputs something. Can you guess what this is? Experiment by typing

```
PRINT(FIRST [THIS IS A LIST])
```

Now try

```
PRINT(FIRST [[THIS IS A LIST] OF [3 ELEMENTS]])
```

Were you surprised at the result?

8. Repeat exercises 6 and 7 with the procedures

```
DIFF PROD DIV (take 2 numbers)
```

```
BUTFIRST LAST COUNT (take 1 list)
```

- \* 9. Write an essay describing your initial experiences of computing in LOGO.

You are not expected to do all these exercises. Your tutor may suggest some, otherwise do those that appeal to you most.

Good luck.

## Procedures

### Introduction

In the LOGO programming language there are two kinds of beast:

- (1) Objects these can be numbers (like 2,13, 105), words (like CAT, or TRIANGLE2) or lists (like [ON THE MAT] or [ON [THE MAT]]).
- (2) Procedures these are instructions or recipes which allow us to manipulate objects

e.g. PRINT 4

causes 4 to be printed on the terminal.

### Synonyms

Not everybody uses the same notation as us. Objects are sometimes called datastructures; data or items. Procedures are sometimes called: programs; functions; routines; operations; commands or predicates. A process is a procedure which is running.

### What is provided?

Numbers must be non-negative; whole numbers. Words can be any string of letters or digits, containing a letter. Lists are any sequence of objects (i.e. numbers, words or sublists) separated by spaces and surrounded by brackets. Lists can be as nested as you like.

e.g. [THIS [IS [A]].[[VERY NESTED] LIST]]

Quite a lot of procedures are provided by LOGO

e.g. PRINT, FIRST, FIRSTPUT, COUNT, SUM, DIFF, NL, VALUE etc.

A complete list and definitions can be found in the reference manual.

An additional lot of procedures can be obtained by typing

LIBRARY 'ECMI02 'AI2

when you log on to LOGO. These are: LIB; LIBPAIR; ANDALSO; THAN; OR and AMONGQ.

Exercise 2.1 PRINT, TYPE and SAY are very similar procedures. Find out how they differ by experimenting at the terminal.

### Quotes

Each procedure has a name, which must be a word. To distinguish words as objects from procedure names, words intended as objects have a quote sign ' in front of them

e.g. PRINT 'HI

PRINT is a procedure name, 'HI is an object.

PRINT HI

would cause an error, unless HI was the name of a procedure.

Exceptions to this rule are words in lists, since these could not possibly be intended as procedure names.

e.g. PRINT [HI THERE] will work alright.

### Procedure Calls

We communicate with the computer by typing in procedure calls

e.g. PRINT 4 is a procedure call.

The procedure PRINT prints one LOGO object (number, word or list) on the terminal listing. This LOGO object is called its argument

e.g. 4 is the argument of PRINT in PRINT 4.

Some procedures, like SUM, take 2 arguments. Some, like GOODBYE, take none. Some take 3 or more. The number of arguments a procedure takes is fixed. Arguments are always LOGO objects.

Sometimes arguments are not given explicitly but are the result of some other procedure call.

e.g. PRINT SUM 2 3

the arguments of SUM are 2 and 3.

the argument of PRINT is 5, the result of SUM 2 3.

This nesting of procedure calls can get arbitrarily deep.

e.g. 1: PRINT FIRST BUTFIRST BUTFIRST [A B C D]  
C

The decisions about which procedure calls provide the arguments to which procedures, are called the calling pattern of the procedure call. In the above examples the calling patterns are obvious. In some examples it can be non-obvious

e.g. PRINT SUM COUNT [A B C] FIRST [2 4 5]

When we write a procedure call we can try to make the calling pattern clearer by putting brackets around sub-procedure calls and using new lines and indentation for the second and consecutive arguments of a procedure

e.g. PRINT (SUM (COUNT [A B C])  
(FIRST [2 4 5]))

In fact these are not strictly necessary for the computer. Provided:

- (a) The procedure name comes first, followed by its arguments.
- (b) The computer knows how many arguments each procedure takes;
- (c) The computer can distinguish between procedure names and objects;

it can always fix the calling pattern in a unique way.

Can you do it?

Exercise 2.2 What will the computer type out if you type in each of the following commands?



```

PRINT FIRST [A B C]
PRINT COUNT FIRST [[UP DOWN] [NORTH SOUTH EAST WEST]]
PRINT BUTFIRST FIRST BUTFIRST [[X] [Y Z] [U V W]]
PRINT SUM COUNT [1 2 3] FIRST [1 2 3]
PRINT SUM LAST FIRST [[2 1] [4 3]] FIRST
      LAST [[3 4] [1 2]]
PRINT DIFF FIRST BUTFIRST [10 9 8 7] COUNT
      BUTFIRST BUTFIRST [1 2 3 4 5 6]

```

Now logon to LOGO and check your answers.

### Evaluation

We communicate with the computer by typing procedure calls at the terminal. Each procedure call is evaluated by the computer which causes LOGO procedures to be run on LOGO objects. The evaluation process is as follows:

1. The computer works along the line from left to right.
2. When it sees an unquoted word it knows this must be a procedure name. The definition of this procedure is recovered from the computer's memory. It decides how many arguments the procedure takes, and looks further along the line to find out what these are. The procedure is then run on these arguments and the result is stored in memory.
3. When it sees a number, list or quoted word, it knows that these must be the arguments of some procedure. These LOGO objects are stored in a special place where the procedure can find them when it runs.

### User Defined Procedures

In LOGO you can define your own procedures and add them to the ones already provided. For the mechanics of doing this see the handout entitled "How to define procedures".

### Simple Procedures

Suppose, we have a longish message we often want to have typed out on the terminal. We can define a procedure to do this.

```

. . e.g.  TO HELP
          10 PRINT [TO LOGOFF TYPE]
          20 PRINT 'GOODBYE
          30 PRINT [THEN TYPE]
          40 PRINT /STOP
          END

```

The words TO and END mark the beginning and end of the procedure definition. the first line



## TO HELP

is the title line. It consists of TO followed by the procedure name, HELP. The middle 4 lines are the body of the procedure. Each line starts with a number. When the procedure is called, the lines are executed in numerical order. If they have bugs in, procedures can be edited by inserting, changing or deleting lines. A line can be inserted between lines 20 and 30 by giving it a number between 20 and 30

e.g. 25 PRINT [WAIT FOR THE PROMPT COMMAND]

Exercise 2.3 Write a procedure called HELLO which will type out

HELLO

[HOW ARE YOU]

Procedures with arguments

Procedures like HELP and HELLO always behave in an identical way each time they are called. We would like to be able to write procedures like PRINT and SUM which are given as arguments objects which they manipulate. Such procedures behave differently according to the object they are given. Procedures with arguments are defined in a similar way to simple procedures except that they involve words (called parameters or input variables) which stand for the arguments.

e.g. TO PRINTENDS 'LIST

10 PRINT FIRST (VALUE 'LIST)

20 PRINT LAST (VALUE 'LIST)

END

LIST is a parameter in the above example. In the title line we put all the parameters just after the procedure name. So LOGO knows how many parameters there are and what their names are. VALUE 'LIST will give the particular object which is input at any one time. The effect of typing

PRINTENDS [SUNDAY MONDAY . . . . . SATURDAY]

will be that

SUNDAY

SATURDAY

is printed on the terminal.

VALUE LIST gives the list [SUNDAY . . . . . SATURDAY]

Here is another example

TO PRINTTOTAL 'NUM1 'NUM2

10 PRINT (SUM (VALUE 'NUM1) (VALUE 'NUM2))

END

Exercises 2.4 What would be the effect of typing

(a) PRINTTOTAL 2 3

(b) PRINTTOTAL (SUM 2 3) 1

In (b) what are VALUE 'NUM2 and VALUE 'NUM1?

2.5 Write a procedure which takes a list as argument and prints the number of elements in it (use COUNT).

### Results and Effects

In LOGO there is a sharp distinction between two different aspects of a procedure's behaviour, namely its result (or output) and its effect (or side-effect). To understand the difference consider the LOGO line

```
PRINT FIRST [A B C]
```

The job of FIRST is to take one LOGO object, [A B C], and calculate another, A. "A" is the result of this application of FIRST. It is stored away in a special place, where it is later collected to be the VALUE of the parameter of PRINT. LOGO procedures always produce exactly one result, and this must be a LOGO object. Some procedures, like PRINT, are executed mainly for their effect, which in this case is to cause the terminal to work and start printing characters. Other effects might be to cause the computer to read some characters from the teletype or to log you off LOGO (e.g. GOODBYE). PRINT does produce a result, which is identical to its input, but this is very rarely used.

LOGO procedures which are executed mainly for their effect (like PRINT) we will call commands. LOGO procedures which are executed mainly for their result (like FIRST), we will call functions.

Note that the leftmost procedure in a line will usually be a command and that the rest will be functions.

Exercise 2.6 Classify the following procedures into commands and functions: SAY; LAST; COUNT; SUM; DIFF; NL; VALUE; FIRSTPUT.

### Little MEN

It is sometimes useful to think of each call of a procedure as a "little man".

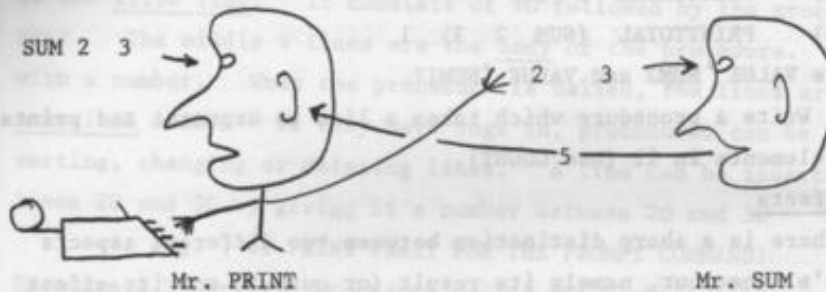
e.g. [A B C] → Mr. FIRST



Arguments to the little man go in through his eyes. Results come from his mouth. Other things he does, like effects, are achieved by other organs. We can use this analogy to visualize what happens when, say,

```
PRINT (SUM 2 3)
```

is evaluated



### Procedures which produce results

So far all the procedures we have defined (HELP, PRINTENDS etc.) have been commands. By using the command RESULT we can also define functions. RESULT takes 1 input and stores it in the special place. For instance, suppose we wanted to write a procedure to find the second element of a list, we could write

```
TO SECOND 'LIST
  10 RESULT FIRST BUTFIRST VALUE 'LIST
END
```

Exercises 2.7 Define a procedure FOURTH for finding the fourth element of a list.

2.8 Define a procedure SUM3 which takes 3 numbers and outputs their sum.

### Sub-procedures

We have seen plenty of examples in procedure definitions where one procedure calls another

```
e.g. TO THIRD 'LIST
      10 OUTPUT FIRST BUTFIRST BUTFIRST VALUE 'LIST
END
```

OUTPUT, FIRST, BUTFIRST and VALUE are called sub-procedures of THIRD.

We can use user-defined procedures as sub-procedures.

```
e.g. 10 OUTPUT SECOND BUTFIRST VALUE LIST
      ↑
      user defined
```

### Variables and Assignment

It is often useful to have variables in addition to the parameters. For instance, as place holders for partial results. Consider the following arithmetic procedure, DIFFSQ, for calculating the difference of 2 squares.

```

TO DIFFSQ 'N1 'N2
10 NEW [S D]
20 MAKE 'S (SUM VALUE 'N1 VALUE 'N2)
30 MAKE 'D (DIFF VALUE 'N1 VALUE 'N2)
40 OUTPUT (PROD VALUE 'S VALUE 'D)
END

```

Line 10 declares that S and D are to be new local-variables within the procedure DIFFSQ. S and D are very similar to the parameters N1 and N2 except that they are not assigned VALUE's when the procedure is entered. The VALUES of S and D are assigned (we say S and D are bound) in lines 20 and 30 by the command MAKE. MAKE takes 2 arguments, a word and an object and assigns the object to be the VALUE of the word.

e.g. after MAKE 'S 3  
then PRINT VALUE 'S  
causes 3 to be printed.

Of course we could have written DIFFSQ without using local variables, but it would have been a little difficult to read. We will soon meet examples where they are not so easy to dispense with.

The variable declaration (e.g. NEW [N1 N2]) and the assignment statement (e.g. MAKE 'N1 8) are not required for parameters (e.g. N1 and N2). They are implicitly made when the procedure is entered.

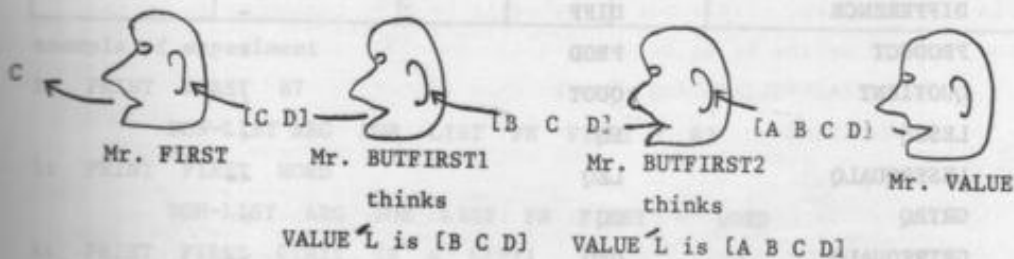
When the procedure is exited (i.e. when it is finished) the assignments of the parameters and local variables are cancelled, e.g. outside of DIFFSQ the VALUES of N1, N2, S and D are undefined. This is important because it allows the same variable name to be used in different procedures which call each other. Consider the procedure THIRD

```

TO THIRD 'LIST
10 OUTPUT FIRST BUTFIRST BUTFIRST VALUE 'LIST
END

```

It is vital that the 2 different versions of BUTFIRST have different ideas about the VALUE's of their parameter (called say, L.). Consider the following "little man" diagram.



What each little man thinks are the VALUE's of his parameters and local variables is called conceptual cloud

Principle of Reincarnation Each time we call a procedure we get a new little man with his own conceptual cloud.

### Abbreviations

Some of the LOGO procedure names are a bit longwinded, e.g., BUTFIRST, FIRSTPUT. We want to minimise typing as much as possible, so each of the LOGO procedure names has an abbreviation.

e.g. The abbreviation of

FIRST is F

BUTFIRST is BF

FIRSTPUT is FPUT

For a complete list see the reference manual.

There is also a facility for creating new abbreviations of LOGO or user-defined procedures. The command ABBREV is used. It takes as input the old procedure name and the new abbreviation.

e.g. Calling ABBREV 'LONGPROCEDURENAME 'LPN

will make LPN the abbreviation for LONGPROCEDURENAME

There is a special kind of abbreviation for VALUE. If VALUE is being called on some quoted word, VALUE is omitted and the quote is replaced by a colon.

e.g. :FRED is an abbreviation for VALUE 'FRED

### Infix Procedures

Some mathematical function names are usually written between the parameters rather than in front of them.

e.g. we usually write  $2 + 3$

rather than SUM 2 3

+ is called an infix function.

Many LOGO functions have an equivalent infix form.

i.e. Function	Abbreviation	Infix Form
SUM	SUM	+
DIFFERENCE	DIFF	-
PRODUCT	PROD	*
QUOTIENT	QUOT	/
LESSQ	LQ	<
LESSEQUALQ	LEQ	<=
GRTRQ	GQ	>
GRTREQUALQ	GEQ	>=
EQUALQ	EQ	=



Take care when you use infix function, because the calling pattern can be ambiguous.

e.g. `FIRST :LIST1 = FIRST :LIST2`

will be interpreted (parsed) by LOGO as

`FIRST (:LIST1 = (FIRST :LIST2))`

which will result in an error. When using infix form always use plenty of brackets and this will remove the ambiguity.

e.g. `(FIRST :LIST1) = (FIRST :LIST2)`

will be parsed correctly.

For similar reasons always put brackets around negative numbers

e.g. `(-23)`

Exercise 2.9 The following is an uncompleted table of LOGO functions.

Fill in the rest of the table by performing experiments at the terminal.

Name of function	Number of inputs	Type of Input			Result
		Number	Word	List	
FIRST	1	X	X	✓	First element of list
BUTFIRST					
LAST					
BUTLAST					
SUM					
DIFF					
PROD					
QUOT					
WORD					
EQUALQ					
WORDQ					
NUMBERQ					
LISTQ					
EMPTYQ					
JOIN					

example of experiment

1: PRINT FIRST 87

NON-LIST ARG FOR LIST FN FIRST - 87

1: PRINT FIRST WORD

NON-LIST ARG FOR LIST FN FIRST - WORD

1: PRINT FIRST [THIS IS A LIST]  
THIS.

1:



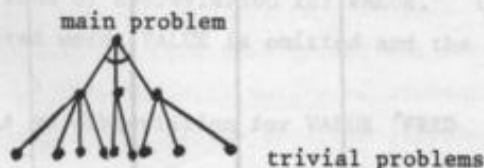
### How to define a procedure

#### The Procedure

To define a procedure  
10 design the procedure and write it on paper  
20 type it into the computer  
30 show it  
40 save it  
50 test it  
60 If procedure works perfectly then stop  
70 debug it  
80 edit it  
90 go back to line 30  
End

#### Designing Procedures

Analyse the problem and break it into parts, then analyse these parts. Continue this process until all the problems are trivial. You should now have a tree structured plan



Always work from the top down. You will gradually develop intuitions about what is trivial at the lower levels and about how to break problems down.

Write the top level procedure first and its subprocedures next. The top level procedure can be tested before the subprocedures are written, by using the CALLUSER facility. For instance, suppose you needed a subprocedure ISITANGLISHWORDQ, which checked whether words were in a dictionary. This would obviously be time consuming to write. However, we can define it as follows:

```
TO ISITANGLISHWORDQ 'WORD
10 CALLUSER
END
```

When this procedure is called processing is temporarily halted and you get a message and the prompt RESULT: . You now type in the result

you think the procedure should return, this is evaluated and processing will continue.

Find a procedure which does a similar task to the one you want done, and use it as a model.

Keep your procedures short i.e. less than 9 lines long.

Use mnemonics for procedure names and variables. ABBREVIATE them afterwards if necessary.

#### Typing in the procedure

Logon to LOGO and type the title line of your procedure

e.g. TO SECOND LIST

After this, the "prompt" that LOGO gives you at the beginning of each line changes from its usual "1:" to a "&:". This reminds you that you are defining a procedure. If there is a mistake in the format of the title line you will get an error message. Try again.

Each line of the procedure must begin with a line number. Lines can be typed-in in any order, and will be stored not necessarily in the order you type them but in the order of their line numbers. If you forget the line number you will get an error message. Try again.

In order to change a line already typed, merely type a new line with the same line number. To remove a line, say line 30, type

&: DELETE 30

To type in a command that is longer than a single physical line, towards the end of the first line type @ CR. LOGO will respond with "C:" and you can then type in the continuation.

When you have finished defining the procedure, type

&: END

and the prompt will then revert to "1".

e.g. 1: TO SECOND LIST

&: 10 RESULT FIRST BUTFIRST :LIST

&: END

1: PRINT SECOND [A B C]

B

1:

When you are defining (or editing) procedures the lines you type in are not run, they are merely stored away in the computer's memory for future reference.

#### Saving Procedures

If you are writing a program you do not want to have to retype all your procedures every time you use LOGO. So there is a way to get LOGO to remember your procedures at one session, so that you can use them again at a later session. Procedures can be stored in a "file" by

analogy with storing objects in a file drawer. You can have several different files - one for each program you are writing.

The procedure GETFILE is used for creating a new file or getting an old one. It takes as input the name of your file and makes this the currently active file.

e.g. GETFILE 'JIM

The procedure SAVE is used to save procedures on the currently active file.

e.g. SAVE 'SECOND

stores the procedure SECOND on file JIM.

e.g. SAVE [SECOND PRINTENDS HELP]

stores all three named procedures.

There is also a useful command

1: SAVENEW

which saves all procedures which have been typed in or EDITed, and not yet SAVED.

FORGET can be used to remove procedures from a file:

e.g. 1: FORGET 'PRINTENDS

OR 1: FORGET [SECOND HELP]

To recover the procedures at a later session, we first GETFILE the relevant file, and then use LOAD:

e.g. 1: LOAD 'SECOND

1: LOAD [PRINTENDS HELP]

or more simply

1: LOADSAVED

which loads all the procedures in the current file.

You can access someone else's file using the command LIBRARY. You must give LIBRARY the other users code number as well as the name of the file.

e.g. LIBRARY 'ECMI02 'AI2

will load all the procedures in Alan Bundy's file AI2.

#### Showing Procedures

To get a procedure typed on the terminal use the procedure SHOW.

e.g. SHOW 'SECOND will type procedure SECOND

SHOW [SECOND PRINTENDS HELP] will type all 3

SHOWALL will type all procedures currently loaded

SHOWTITLES will type just the titles

#### Testing Procedures

If you are an inexperienced programmer your procedures are much more likely to be wrong than right.

To test a procedure call it on some of the arguments you expect it to be receiving in practice. Try a wide range of types of arguments. Do not forget "awkward" cases like: the empty list; especially long lists; negative numbers etc.

You will notice a bug because either the procedure does not produce the result you expected or you get an error message.

#### Debugging Procedures

There are two types of bug: syntax errors and run-time errors. Syntax errors are ungrammatical LOGO procedure calls. They always result in error messages, either when the procedure is typed in, or when it is run. Run-time errors come from procedures which do not do what you expected them to. These can sometimes give error messages if they cause a procedure to receive an argument it is not equipped to deal with.

If you get an error message, make sure you understand what it means, and what typical kinds of bug cause it. Ask the demonstrator if necessary. If the error message tells you the line in error examine this line and possibly one or two lines before.

Make sure you have a listing of the most recent version of the procedure at fault.

Follow the execution of the procedure through with your finger, playing "devils advocate".

Execute each line of the procedure in turn. Does it work as expected. Make sure lines containing infix procedures are being interpreted properly.

Sometimes the error will leave you in the middle of executing the procedure which failed. You will recognise this because the prompt will change from 1: to 2: , (or 2: to 3: etc.). You can now PRINT the current VALUES of the local variables and parameters. Are they what you expected? You can cause execution of your own procedures to be suspended by inserting the command BREAK into them. CONTINUE will cause the processing to continue, QUIT will cause it to be abandoned.

If you want a record of which procedures are called and by whom, before the error, call the command TRACE on each procedure you want recorded, and then call your procedure

e.g. TRACE [SECOND HELP]

Using FULLTRACE instead will give the VALUES of parameters on entry, and result on exit. To stop procedures being TRACEd call UNTRACE on them. Do not TRACE too many procedures, or you will be swamped.

To see whether a procedure reaches a certain point edit a PRINT or BREAK command into that point.

For further advice see the reference manual or ask a demonstrator.

Editing Procedures

To change a procedure which has already been defined call the command EDIT on that procedure. You will get the prompt &: and will be back in the mode in which you defined the procedure.

e.g. EDIT 'SECOND

&: 5 PRINT 'ENTER

&: 15 PRINT [TOO FAR]

&: END

1:

Exercises

3.1 Type in definitions of HELP, SECOND and PRINTENDS; and then try them out.

3.2 LIB 'BUGS will get you some procedures with bugs in them. Can you correct them?

3.3 Make sure you understand the procedure FIRSTPUT. Use it to define a procedure BACKTOFRONT which outputs a list with the last element moved to the front,

e.g. BACKTOFRONT [A B C D] is [D A B C].

3.4 Write a procedure QUERY which switches the first two elements of a list, so that

PRINT QUERY[BILL CAN FIX IT]

gives

[CAN BILL FIX IT].

Hints: What gives the list [FIX IT]? What gives the list [BILL FIX IT]?

What is QUERY [DOGS LIKE CHEESE]? Or QUERY [THE CAT CHASED THE SQUIRREL]? How would you set about improving the procedure QUERY?



## Control Structures

### Introduction

So far all our procedures have consisted of a simple sequence of instructions, to be obeyed in order. Sometimes we will want the order to be variable according to the circumstances, or we will want some instructions to be repeated several times.

### Conditionals

For instance suppose we wanted to amend the procedure SECOND so that it produced an error message if its input was not a list. We can do this with the conditional IF.....THEN.....ELSE.....

i.e.

```
TO SECOND LIST
```

```
10 IF LISTQ :LIST THEN RESULT FIRST BUTFIRST :LIST  
   ELSE SECERR :LIST
```

```
END
```

```
TO SECERR PARA
```

```
10 SAY [NON LIST PARAMETER FOR SECOND]
```

```
20 PRINT 'PARA
```

```
END
```

The general form of the conditional is

```
IF condition THEN instruction1 ELSE instruction2
```

It is a funny kind of procedure. It's name is split into 3 parts, IF, THEN and ELSE, and distributed between the 3 arguments. The first argument must return as result either the word TRUE or the word FALSE. Procedures like this are called predicates.

Examples are:

```
EQUALQ :A :B - tests whether :A and :B are equal
```

```
ZEROQ :NUMBER - tests whether the :NUMBER is zero
```

```
EMPTYQ :LIST - tests whether the list is empty
```

```
LISTQ :THING - tests whether the :THING is a list
```

```
WORDQ :THING - tests whether the :THING is a word
```

```
NUMBERQ :THING - tests whether the :THING is a number
```

We will adopt the convention that predicate names, even user defined ones, end in a Q (for Question).



Normally procedures evaluate all their inputs before they are called themselves. However, when

```
IF condition THEN instruction1 ELSE instruction2
```

is called only "condition" is evaluated. If "condition" returns TRUE "instruction1" is evaluated. If "condition" returns FALSE, "instruction2" is evaluated, otherwise an error message is called.

There is a shortened version

```
IF condition THEN instruction
```

RESULT not only causes its argument to be stored in the special place for results, it also causes the current procedure to be exited. So an alternative form for SECOND would be

```
TO SECOND LIST
  10 IF LISTQ :LIST THEN RESULT FIRST BUTFIRST :LIST
  20 SECERR
END
```

Exercises 4.1 Write a version of SECOND which does not check that it's argument is a list, but does check that it is at least 2 elements long.

\*4.2 Write a version of SECOND which performs both checks.

#### Linking Procedure Calls Together

The arguments of IF-THEN-ELSE-, like the arguments of any other procedure, must be a LOGO object or a single procedure call. However, if a conditional test succeeds we often want to do a sequence of instructions.

e.g.

```
IF SUNNY :DAY THEN HANGOUT :WASHING
                     WEED :FLOWERBEDS
                     SUNBATH
```

As it stands this is illegal LOGO syntax. What we need is a way of linking together the last 3 LOGO procedure calls into one procedure call. This is provided by the infix command AND. AND causes the procedure calls it links to be evaluated simply by having them as arguments, but it does nothing further to them.

The following is legal LOGO syntax.

```
IF SUNNY :DAY THEN HANGOUT :WASHING
                     AND WEED :FLOWERBEDS
                     AND SUNBATH
```

Exercise 4.3 Write a version of SECOND which prints out a message "SECOND CALLED SUCCESSFULLY" whenever it is called successfully.

Repetition

Suppose we wanted to repeat an instruction several times. It would be tedious to have to write the instruction several times. Instead we can use the command REPEAT.

e.g.

```
TO LOVE
  10 REPEAT 3 SAY [I LOVE YOU]
END
```

This will print "I LOVE YOU" 3 times.

We can REPEAT things a variable number of times by having the first input of REPEAT be a procedure call or variable.

e.g.

```
TO MUCHLOVE NUM
  10 REPEAT :NUM SAY [I LOVE YOU]
END
```

MUCHLOVE 1000 will now print "I LOVE YOU" 1000 times etc.

Exercises 4.4 Write a procedure, PRIDE, which prints

```
COMPUTERS NEVER MAKE
MISTAKES
MISTAKES
MISTAKES
```

MISTAKES

4.5 Write a procedure which prints 3 times

```
I LOVE YOU
VERY MUCH
```

Warning You now have the facility to define procedures which may go on for a long time. Before running one, make sure you understand how to interrupt (with ESC) and QUIT. Otherwise it will be very boring for you waiting for the procedure to finish and you will needlessly use up your allocation of nuts. There is a facility to prevent this kind of accident called the EVALIMIT. This will prevent you doing too much processing, by setting a limit on the depth to which you can have sub-procedures calling each other. EVALIMIT is currently 500. You can increase or decrease this with the command SETELIM, which takes 1 argument, the new limit.

Running down lists

We will sometimes want to do something to each member of a list in turn. For instance PRINT each member of the list on a new line. The easiest way to do this is with the command APPLIST.

i.e. 1: APPLIST [SUNDAY MONDAY .....SATURDAY] 'PRINT

SUNDAY

MONDAY

.

.

.

SATURDAY

APPLIST applies the command PRINT to each member of the list in turn. Since PRINT always prints it's arguments and then does a new line, a new line is inserted between every member.

The second argument of APPLIST can be the name of any system or user defined, one argument, procedure (though it is usually a command). Sometimes we do not have the appropriate command already defined, and we do not need it except for this APPLIST. In this case the definition can be made implicitly in the second argument to APPLIST. For instance, suppose we wanted a procedure which printed TRUE for each word in a list and FALSE for each list or number. It could be done as follows:

1: APPLIST [JOHN 23 MALE] [PRINT WORDQ EACH]

TRUE

FALSE

TRUE

For each member of the list, [JOHN 23 MALE], EACH finds the VALUE of that member, WORDQ works on that VALUE returning as result TRUE or FALSE and PRINT prints that result.

[PRINT WORDQ EACH] is an alternative to some procedure name, say 'FOO, where FOO is defined by

TO FOO 'ARG

10 PRINT WORDQ :ARG

END

Corresponding to the command APPLIST there is a function MAPLIST. This takes a list and a function name and produces as a result the new list obtained from applying the function to each member of the old list

e.g. 1: PRINT MAPLIST [JOHN 23 MALE] 'WORDQ

[TRUE FALSE TRUE]

As in APPLIST the second argument of MAPLIST can be a procedure call in the form of a list.

e.g.

```
1: PRINT MAPLIST [1 2 3] [SUM 1 EACH]
[2 3 4]
```

Exercises 4.6 What would be the effect of typing

```
1: PRINT MAPLIST [1 0 3] ZEROQ
```

```
1: APPLIST [JOHN 23 MALE] [PRINT NUMBERQ EACH]
```

```
1: PRINT MAPLIST [1 2 3] [PROD 2 EACH]
```

4.7. Write a function, DOUBLELIST, which takes a list of numbers and returns a list with each member doubled.

#### Conditional Loops

Sometimes we cannot say in advance how often we would like to repeat a command, we just want to go on repeating it until some goal has been achieved (like hitting a nail repeatedly until it has sunk right into the wood). This facility is provided in LOGO by the construction, WHILE condition THEN instruction.

e.g.

```
WHILE OUT :NAIL THEN HIT :NAIL
```

WHILE combines the ideas of conditionals and repetition. As in IF-THEN-, the condition is evaluated. If it returns TRUE the instruction is evaluated. Then the process is repeated until the condition returns FALSE. Clearly evaluating the instruction should have some effect upon whatever the condition is testing or this process will never stop.

We can use the WHILE-THEN- procedure to define a procedure SUMFROMITON which adds up all the numbers from 1 to some number N, say.

e.g.

```
1: PRINT SUMFROMITON 2
3 (i.e., 1+2 )
```

```
1: PRINT SUMFROMITON 5
15 (i.e., 1+2+3+4+5)
```

```
TO SUMFROMITON N
  10 NEW [TALLY TOTAL]
  20 MAKE TALLY 1
  30 MAKE TOTAL 1
  40 WHILE NOT EQUALQ :TALLY :N
```

THEN MAKE TALLY SUM :TALLY 1

AND MAKE TOTAL SUM :TOTAL :TALLY

50 RESULT :TOTAL

END

Note the use of local variables

(a) to keep a running score (TOTAL)

(b) to count how many times something was done (TALLY)

Note also the use of AND to enable us both to do something and to record we did it, each time round the loop. It is nearly always necessary to use AND in WHILE loops.

Exercise 4.8. Write a procedure SUMOFLIST which adds up all the numbers in a list of numbers

e.g.

1: PRINT SUMOFLIST [5 7 3]

15

(a) Using APPLIST

(b) Using WHILE- THEN-

# Recursion

## Breaking problems into parts

So far most of the problems we have tackled have been fairly easy. It has been possible to break the problem down into a short sequence of instructions, each of which can be written with the LOGO procedures currently available. Sometimes these instructions cannot be written using existing procedures. Then writing these instructions becomes a new problem and we begin to build up a hierarchical structure of procedures

e.g.

```
TO SINGSONG
10 SINGVERSE1
20 SINGCHORUS
30 SINGVERSE2
40 SINGCHORUS
```

etc.

.

.

END

```
TO SINGVERSE1
10 SAY [RICH GIRL WEARS A ..... ]
20 SAY [POOR GIRL ..... ]
....
END
```

```
TO SINGCHORUS
10 SAY [DINAH DINAH .. .. ]
.
.
.
.
END
```

etc.

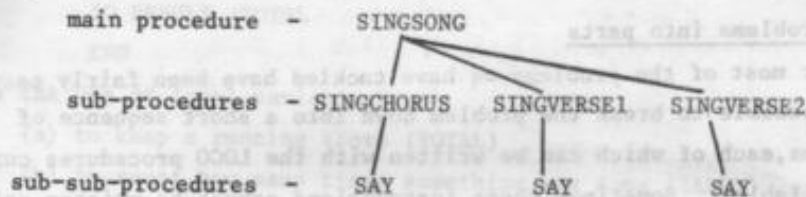
This device of "divide and conquer", the breaking of a problem into parts, is one of the main weapons of program writing. We will be develop-



ing it further in our "little man methods".

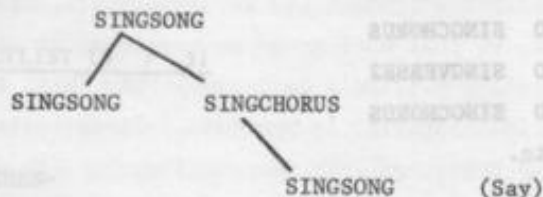
Until now the break down of the task has been strictly hierarchical.

e.g.



In fact there is nothing in LOGO to stop one of the sub-procedures or sub-sub-procedures being the same as the main procedures. When this happens it is called recursion.

e.g.



In the rest of this handout we will be exploring this possibility; seeing how it is possible and when it is useful.

Many of the examples we will be using could also be done using REPEAT, APPLIST, MAPLIST or WHILE. For expository purposes we will be ignoring these alternatives in this handout. When designing your own procedures you should choose the alternative which reflects the way you naturally break down the task. Recursion is a very powerful programming device. It can always replace, REPEAT, APPLIST, MAPLIST and WHILE, but not vice versa.

#### Indefinite Repetition

Using REPEAT we can repeat an instruction a finite number of times, but suppose we want to go on repeating something indefinitely? We can do this using recursion.

Consider, if we tell LOGO how to LAUGH:

```

TO LAUGH
  10 PRINT 'HAHAHA
  20 PRINT 'HOHOHO
END
  
```

If we use this procedure

```
1: LAUGH
```

then LOGO will laugh just once

HAHAHA

HOOHO

1:

But suppose we want LOGO to laugh again and again and again? We could try

TO LAUGHALOT

10 LAUGH

20 LAUGH

-----

END

but these do not look promising because (a) it's a nuisance to have to write out all these LAUGHS, and (b) it still doesn't make LOGO laugh indefinitely.

Instead, try this:

TO KEEPLAUGHING

10 LAUGH

20 KEEPLAUGHING + KEEPLAUGHING calls itself.

END

This has the desired effect:

1: KEEPLAUGHING

HAHAHA

HOOHO

HAHAHA

HOOHO

-----

----- (indefinitely)

### The "little man" method

We give two ways of understanding how KEEPLAUGHING works. We've simplified the task from the one large problem given to: a small problem we can solve + another large problem. We were asked to produce:

HAHAHA )

HOOHO )

HAHAHA )

HOOHO )

----- )

----- )

indefinite number of times

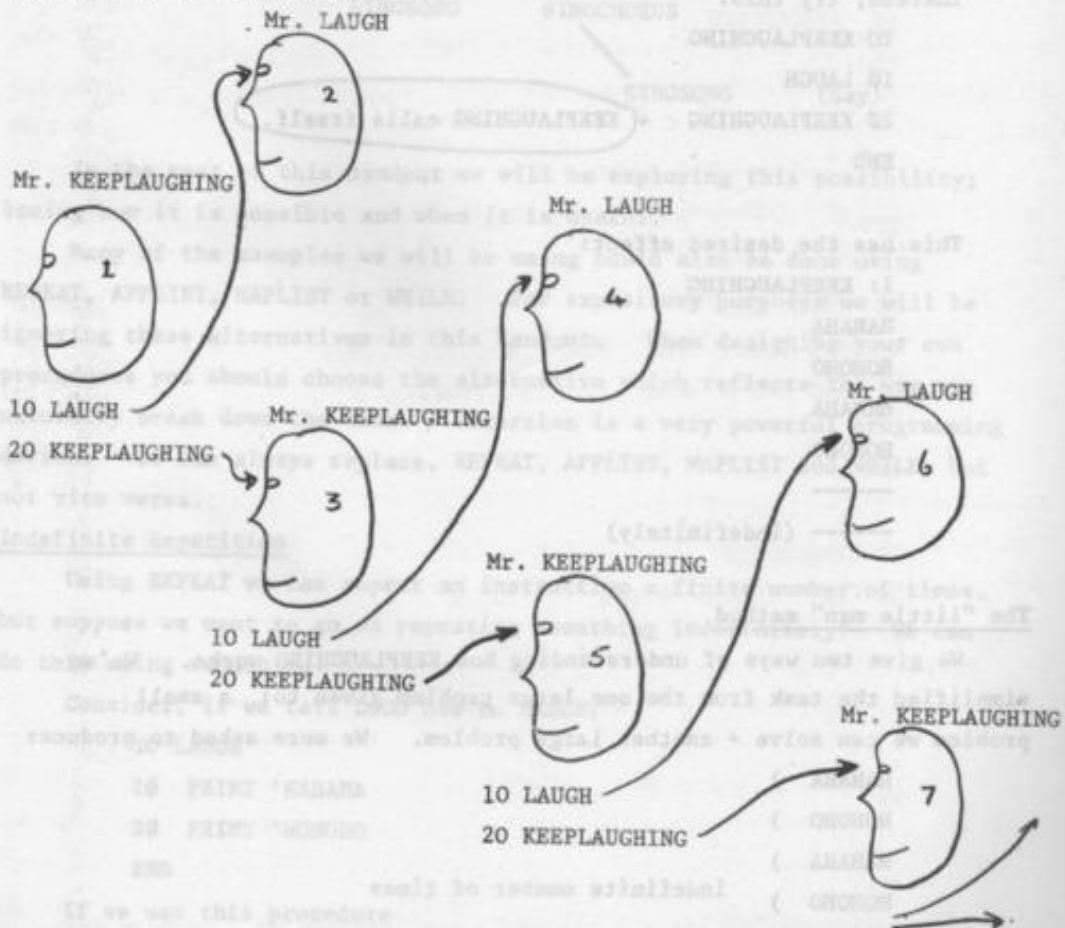
We tackle it by breaking it into two parts:

HAHAHA )  
HOHOHO ) (A) produce a single laugh

HAHAHA )  
HOHOHO ) (B) produce the rest of the laughs  
----- ) (an indefinite number)  
----- )

But now we can easily write the procedure **KEEPLAUGHING**, since task (A) is what **LAUGH** is designed to do, and task (B) is identical to what **KEEPLAUGHING** is meant to do! So these become lines 10 and 20 of the procedure.

The second way is to think about the "little men" involved. We have only two kinds of little man here, **LAUGH** and **KEEPLAUGHING**, but there may be many of each kind:



When we type KEEPLAUGHING we create l.m.1, who in turn creates (line 10) l.m.2 and asks him to "do his thing", then (line 20) creates l.m.3 and asks him to "do his thing". So l.m.3 first creates l.m.4---, etc.

We have here a powerful method of tackling problems involving repetition. We'll see soon that it's only half of an even more powerful method, so let's say:

(Second Half of) Little Man Method

- B. Can I break the task I'm given into two (or more) parts, such that
- (i) I can cope with one of the parts myself, and
  - (ii) I can give the other part(s) to someone else to deal with?

Be sure to understand how this applies to the case of KEEPLAUGHING.

Exercises 5.1 Write a procedure, STORY, which prints out the following monologue:

IT WAS A DARK AND STORMY NIGHT  
AND THE CAPTAIN SAID TO THE MATE  
TELL US A STORY  
AND THE MATE BEGAN  
IT WAS A DARK AND STORMY NIGHT  
.....  
..... etc.

5.2 Suppose you have procedures SING and DANCE. Define a procedure SINGANDDANCEFOREVER which will SING, then DANCE, then SING, then DANCE, etc.. Define appropriate procedures for SING and DANCE, and try them out.

Another example: COUNTUPFROM

Suppose we want to write a procedure which behaves as follows:

1: COUNTUPFROM 10	or	1: COUNTUPFROM 127
10		127
11		128
12		129
13		130
14		131
---		---
---		---

We can start with

```
TO COUNTUPFROM /GIVENNUMBER
```

Try same method as before. Break up the whole task into two parts:

```
1: COUNTUPFROM 127
```

```
127 ) ————— This line produced by PRINT 127
```

```
128 )
```

```
129 )
```

```
130 )
```

```
131 ) ————— The rest of the lines produced by  
--- ) COUNTUPFROM 128  
--- )
```

So, in terms of the Little Man Method,

(i) the subtask we can do ourselves is to print the given number:

```
10 PRINT :GIVENNUMBER
```

(ii) the rest of the task is given to someone else to do:

```
20 COUNTUPFROM SUM :GIVENNUMBER 1
```

i.e. one greater than the given number

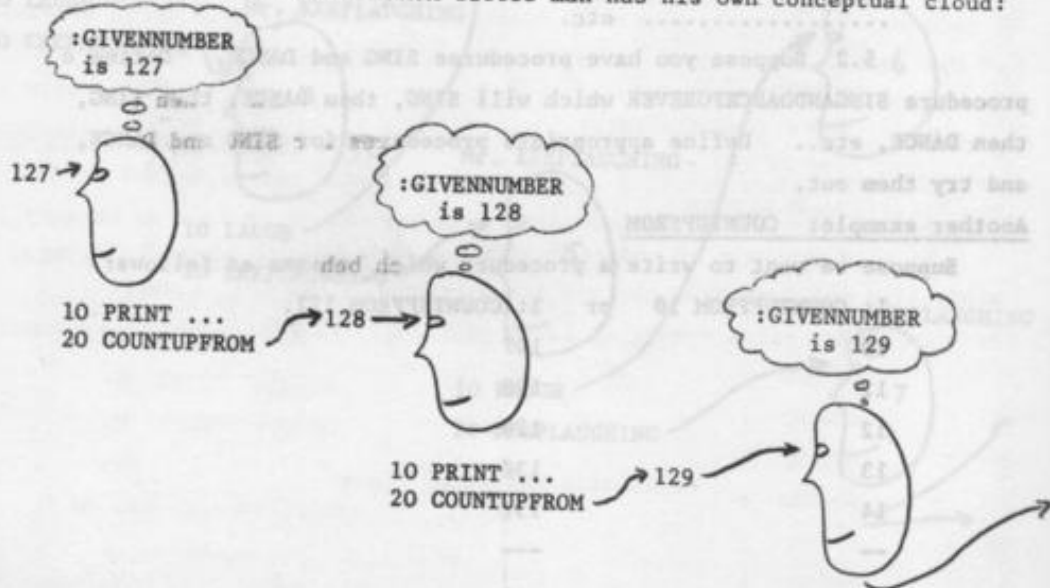
So, TO COUNTUPFROM /GIVENNUMBER

```
10 PRINT :GIVENNUMBER
```

```
20 COUNTUPFROM SUM :GIVEN NUMBER 1
```

```
END
```

Notice that each COUNTUPFROM little man has his own conceptual cloud:



Repeated WARNING Before trying these procedures on LOGO, make sure you understand about Interrupts.

Terminated recursion: COUNTDOWN

Try an example similar to the earlier procedure COUNTUPFROM but with an important difference:

```
1: COUNTDOWN 10
```

```
10
```

```
9
```

```
8
```

```
7
```

```
6
```

```
5
```

```
4
```

```
3
```

```
2
```

```
1
```

```
0
```

```
BLASTOFF
```

```
1: SHOW COUNTDOWN
```

How can we write COUNTDOWN using recursion? Most of it is easy, analogous to COUNTUPFROM. Applying the (second half of the) Little Man Method, we break the task into two parts, and realise that in the call of COUNTDOWN 10 above, the "10" in the typeout is printed directly by the COUNTDOWN little man, whereas the rest, 9 8 7 etc., are printed by a recursive call on COUNTDOWN 9. This gives us our first approximation:

```
TO COUNTDOWN /NUMBER
```

```
10 PRINT :NUMBER
```

```
20 COUNTDOWN DIFF :NUMBER 1
```

```
END
```

But when we try this we get

```
1: COUNTDOWN 3
```

```
3
```

```
2
```

```
1
```

```
0
```

```
-1
```

```
-2
```

```
...
```

Clearly, there is nothing to stop COUNTDOWN continuing indefinitely. After



printing zero, it will not print BLASTOFF and stop because we have nowhere asked it to. It's easy to correct this omission:

```
TO COUNTDOWN 'NUMBER
```

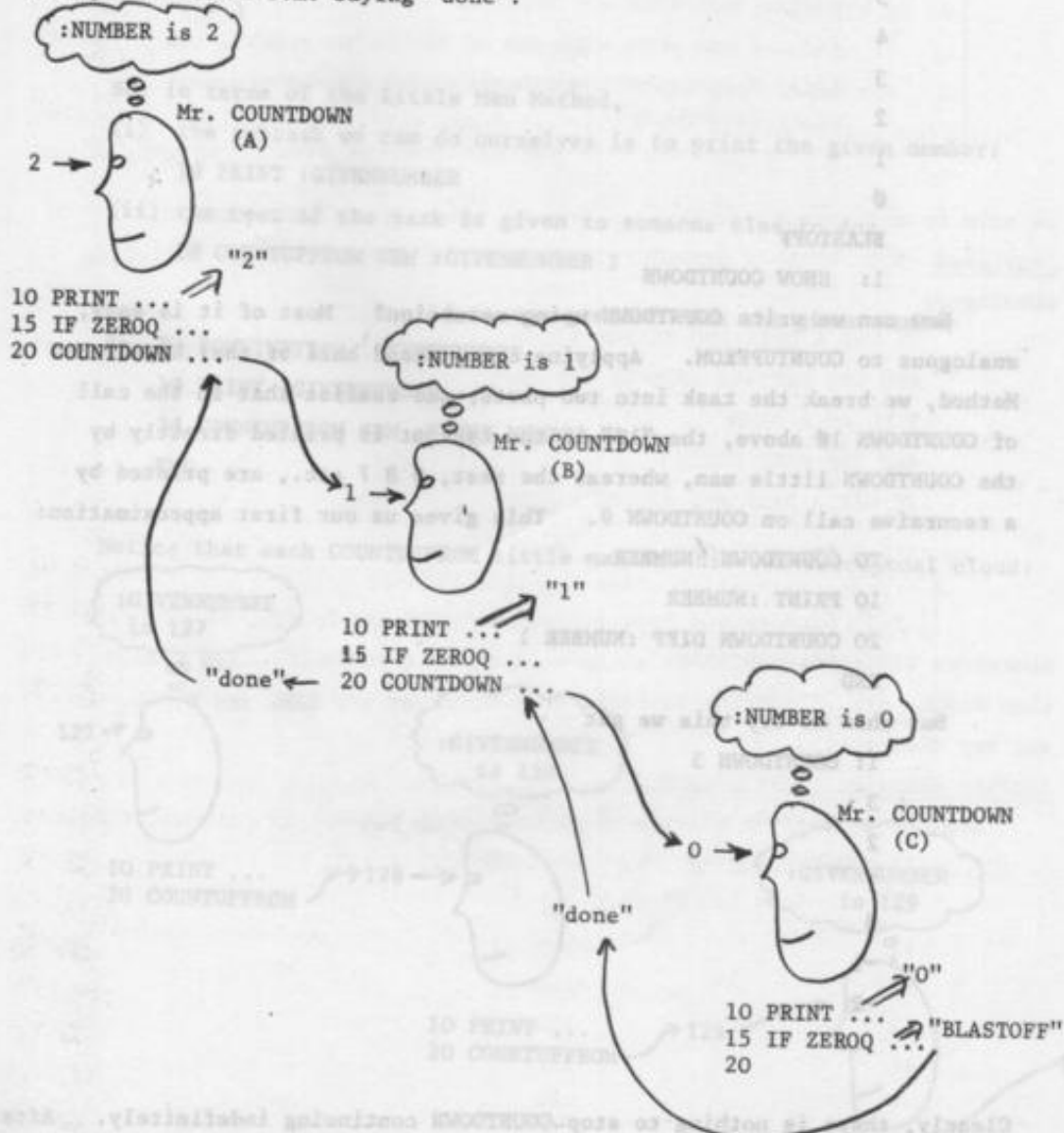
```
10 PRINT :NUMBER
```

```
→ 15 IF ZEROQ :NUMBER THEN PRINT 'BLASTOFF AND STOP
```

```
20 COUNTDOWN DIFF :NUMBER 1
```

```
END
```

This will now work correctly. ZEROQ is a predicate which tests whether or not a number is zero. Make sure you understand the little man structure of a call on COUNTDOWN. Here is a complete diagram of the little men for COUNTDOWN 2. This time we have added explicitly a line to represent each l.m. saying "done":



l.m.A prints "2" (line 10), which is not zero (line 15), so calls l.m.B, who similarly prints "1" and calls l.m. (c), l.m. C prints "0", which is zero so (line 15) he prints "BLASTOFF" and STOPS, i.e. tells l.m. B that he is done. l.m. B has already executed his last instruction (line 20), so he too is done, and so similarly is l.m. A.

#### Full Little Man Method

We have just used an application of our very powerful Little Man Method, which looks like this:

#### Little Man Method

- A. Is (are) there any special or simple case(s) that I can take care of myself?
- B. Otherwise, can I break the task into two (or more) parts, such that
  - (i) I can cope with one of the parts myself,
  - and (ii) I can give the other part(s) to someone else?

In the case of COUNTDOWN, the special case (A) is when the number is zero, the part the little man can do himself (B(i)) is to print the given number, and the part (B(ii)) that he gives to someone else is to COUNTDOWN one less than the given number.

It follows that the structure of a procedure written by this method is somewhat as follows:

1. Test for the special case; if so, take care of it, and stop.
2. Deal with the part to be handled directly.
3. Ask someone else to deal with the rest.

(Sometimes, as in COUNTDOWN, step 2 may precede step 1).

#### Another example: LAUGHNTIMES

Try the Little Man Method on another example. Remember the procedure LAUGH? How about a procedure LAUGH7TIMES, that will laugh exactly 7 times? We could have

TO LAUGH7TIMES

10 LAUGH

20 LAUGH

30 LAUGH

40 LAUGH

50 LAUGH

60 LAUGH

70 LAUGH

END

but this doesn't look too good, and is obviously hopeless for LAUGHing 2719 times. It's actually easier to write the more general procedure that can laugh any number of times, and then tell it how many times we want.

So let's try writing

TO LAUGHNTIMES /HOWMANY

We could follow the same argument as for COUNTDOWN, so that we first have a procedure that laughs indefinitely (cf. KEEPLAUGHING) and then we worry about how to stop it. Instead, apply the Little Man Method and try to get the procedure right directly.

So, is there any special case the l.m. can take care of himself?

Yes of course, if he is asked to laugh zero times then he simply stops:

10 IF ZEROQ :HOWMANY THEN STOP

Otherwise, can the l.m. break the task into two parts such that ... ?

Yes, for example if he is asked to laugh 19 times, he can laugh once himself and ask someone else to laugh the other 18 times:

TO LAUGHNTIMES /HOWMANY

10 IF ZEROQ :HOWMANY THEN STOP

→ 20 LAUGH

→ 30 LAUGHNTIMES DIFF :HOWMANY 1

END

Simple!

Exercises 5.3 Draw the little men diagram for LAUGHNTIMES 3.

5.4 Write a procedure to sing a simplified version of a well-known song:

e.g. 1: SIMPLEMOW 23

23 MEN WENT TO MOW

22 MEN WENT TO MOW

21 MEN WENT TO MOW

-----  
-----

Recursion along a list

In both COUNTDOWN and LAUGHTIMES, we have determined when to stop by counting. There is another important class of procedures where we control the recursion by doing something to each item on a list. The two kinds of procedures correspond directly:

For a counting recursion, where we do something N times,

- (a) we ask if N is zero, if so we stop;
- (b) we do it once;
- (c) someone else does it (N-1) times.

For a list recursion, where we do something with each item on a list,

- (a) we ask if the list is empty, if so we stop;
- (b) we do it with the FIRST item of the list;
- (c) someone else does it with the rest (i.e. BUTFIRST) of the list.

An example: PRINTLIST

Most of our examples could be done with APPLIST or WHILE, but this will not always be possible. In order that we can explore recursion along a list in some simple cases we will suppress the APPLIST and WHILE solutions. Let us again try to write the procedure PRINTLIST, which prints each element of a list on a separate line. Assume we have

TO PRINTLIST 'ANYLIST

and apply the Little Man Method.

Is there any special case the l.m. can take care of himself? Yes, if the list is empty, then he has nothing to do:

10 IF EMPTYQ :ANYLIST THEN STOP

Otherwise, can he break the task into two parts ----? Yes, he himself can print the first item

20 PRINT FIRST :ANYLIST

and ask another l.m. to look after the rest of the list:

30 PRINTLIST BUTFIRST :ANYLIST

So we have:

TO PRINTLIST 'ANYLIST

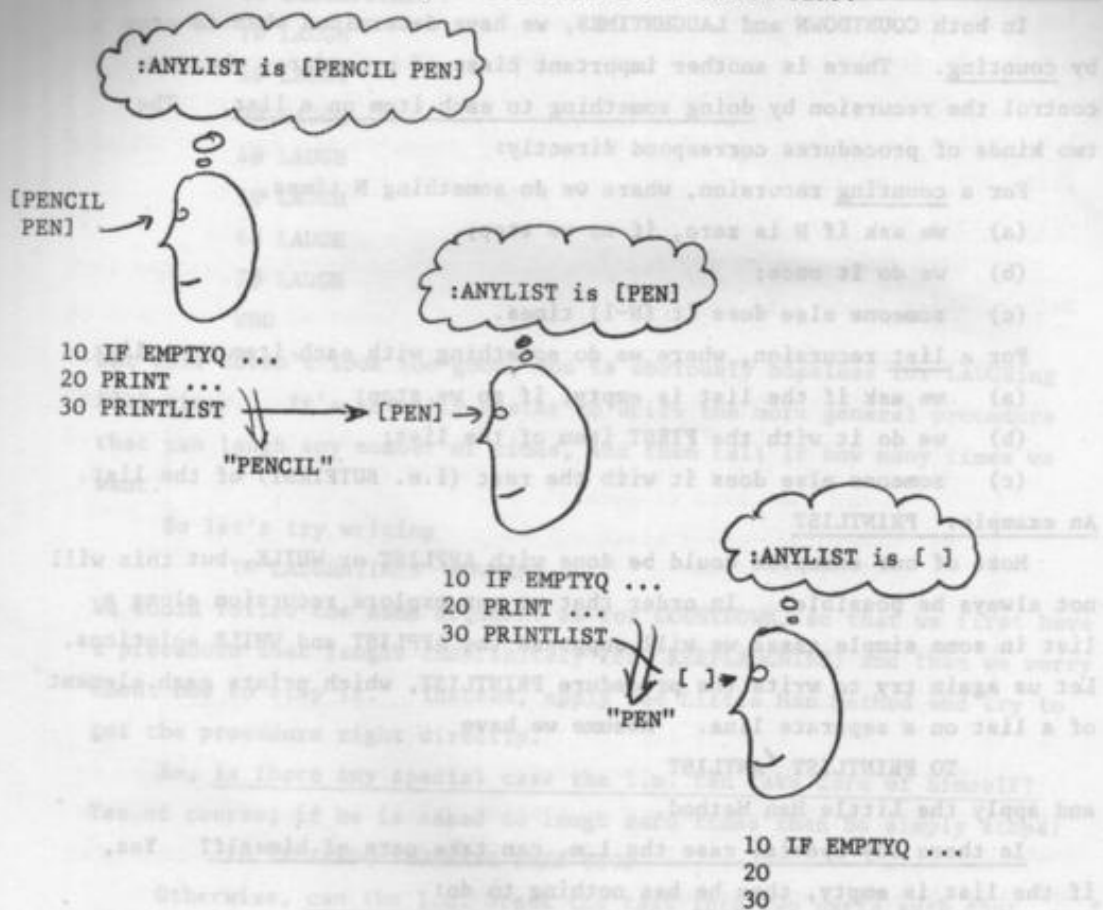
10 IF EMPTYQ :ANYLIST THEN STOP

20 PRINT FIRST :ANYLIST

30 PRINTLIST BUTFIRST :ANYLIST

END

Here is the l.m. diagram for PRINTLIST [PENCIL PEN]:



### Exegesis of the Little Man Method

Try summarizing our experience with the kind of procedures discussed above, as a commentary to help in the use of the Method:

For counting recursion, we often have:

Special case (A) consists of equality between two numbers (with zero as a particular instance).

Step B(i) consists of doing what was asked just once.

Step B(ii) consists of doing what was asked "N-1" times.

For list recursion, we often have:

Special case (A) consists of the empty list.

Step B(i) consists of doing something to FIRST of the list.

Step B(ii) consists of recursing on the BUTFIRST of the list.

### AMONGQ

We are now in a position to write the procedure AMONGQ:

TO AMONGQ 'ITEM 'LIST

Clearly, this involves some kind of a recursion down the list, though we may not have to go to the very end. What we have to "do" with each



element of the list is to check whether it is the same as the given item.  
Apply the Little Man Method:

Is there any special case ....? The commentary recommends checking for the empty list. If we have the empty list, then clearly the given item is not contained in it, so the result of the procedure must be FALSE:

```
10 IF EMPTYQ :LIST THEN RESULT FALSE
```

Break into two tasks ..... The commentary recommends dealing with the first element of the list. If it is the same as the given item, then the result of the procedure must be TRUE:

```
20 IF EQUALQ :ITEM FIRST :LIST THEN RESULT TRUE
```

Otherwise we need to go searching down the rest of the list:

```
30 RESULT AMONGQ :ITEM BUTFIRST :LIST
```

So we have:

```
TO AMONGQ /ITEM #LIST
```

```
10 IF EMPTYQ :LIST THEN RESULT FALSE
```

```
20 IF EQUALQ :ITEM FIRST :LIST THEN RESULT TRUE
```

```
30 RESULT AMONGQ :ITEM BUTFIRST :LIST
```

```
END
```

Exercise 5.5 Draw l.m. diagrams for AMONGQ 'HOUSE [DOG CAT COW] and AMONGQ 'CAT [DOG CAT COW].

Understanding recursion: TRIANGLE

Consider the procedure TRIANGLE

```
1: TRIANGLE [V W X Y Z]
```

```
[V W X Y Z]
```

```
[W X Y Z]
```

```
[X Y Z]
```

```
[Y Z]
```

```
[Z]
```

```
[ ]
```

```
1:
```

Writing this should now be a simple exercise:

```
TO TRIANGLE /LIST
```

```
10 PRINT :LIST
```

```
20 IF EMPTYQ :LIST THEN STOP
```

```
30 TRIANGLE BUTFIRST :LIST
```

```
END
```

But what happens if we add a new line:

```
40 PRINT :LIST ?
```

Try it and see!

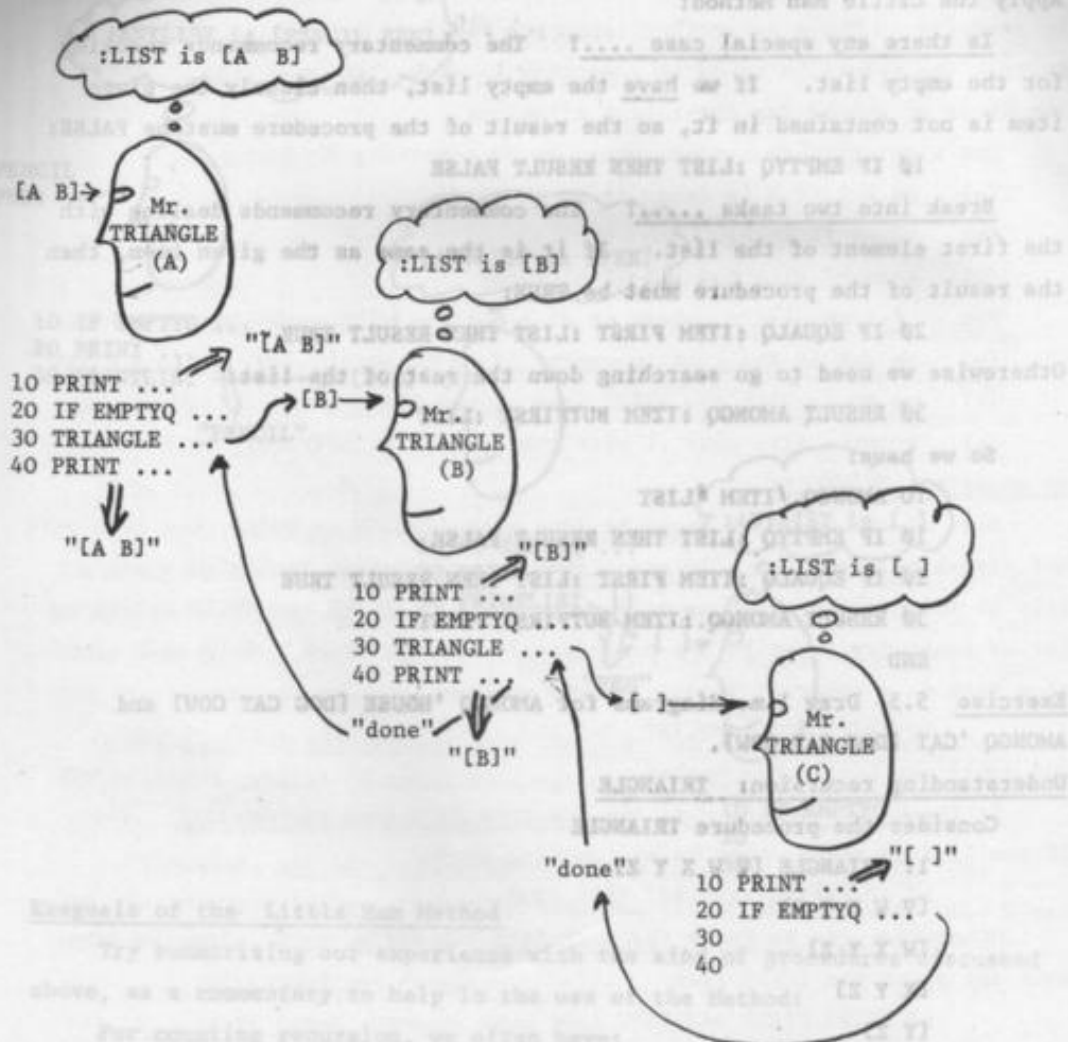
——part B(i)

——special case (a)

——the rest, B(ii)



Is the effect surprising? Try understanding it in terms of the little men involved:



When l.m. C stops (line 20), l.m. B resumes with his next instruction (line 40) and prints `"[B]"`, then he is finished so l.m. A resumes and prints `"[A B]"`.

**Exercises 5.6** What happens if we swap lines 10 and 15 of COUNTDOWN? Or lines 10 and 20 of TRIANGLE?

**5.7** Define the procedure COUNTUP which counts up from one number to another:

```
1: COUNTUP 8 11
```

```
8
```

```
9
```

```
10
```

```
11
```

5.8 Define the procedure NTH, which returns the Nth element of a list:

```
1: PRINT NTH 2 [COW DOG HORSE]
DOG
1: PRINT NTH 3 [ON CIRCLE SQUARE]
SQUARE
1: PRINT NTH 2 [PINK]
LIST TOO SHORT
```

5.9 The procedure RANDOM returns a random number between 0 and the number it is given as argument.

e.g. RANDOM 3 returns one of the numbers 0, 1, 2, or 3 with equal likelihood.

Use RANDOM and NTH to write a procedure RANDOMSELECT which returns a randomly chosen element of the list it is given:

```
1: PRINT RANDOMSELECT [BLUE GREEN RED YELLOW]
RED
1: PRINT RANDOMSELECT [BLUE GREEN RED YELLOW]
BLUE
```

### Constructing Recursive Objects

Just as we have used the Little Man Method to deal with tasks that have a recursive structure, so also we can use it to construct objects with a recursive structure. Adapt the wording of the l.m.m. appropriately.

e.g. we ask if there is a special case where we can construct the entire object immediately, otherwise we ask other Little Men to build parts of the object and then we put them together, etc.

In LOGO the "objects" we are constructing are usually numbers or lists.

e.g. in COUNTDOWN we analysed the task of doing something ten times as: doing it once, then doing it the remaining nine times:

$10 \rightarrow 1 + 9$  (recursive)

Similar, to construct an object of ten parts, we get someone else to build the object with nine parts and then we add the tenth part, an act of synthesis:

$1 + 9$  (recursive)  $\rightarrow 10$

SUMOF LIST Want a procedure whose input is a list of numbers, and which outputs the sum of all the numbers.

```
1: PRINT SUMOF LIST [5 7 9 11 13]
45
```

As usual, we break the list into its FIRST and BUTFIRST components:

$[5\ 7\ 9\ 11\ 13] \rightarrow 5 \ \& \ [7\ 9\ 11\ 13]$

There is a corresponding synthesis of the total sum we are seeking:

$$5 + \text{SUMOFLIST } [7 \ 9 \ 11 \ 13] \rightarrow 45$$

All we need now to apply the l.m.m. is the specially easy case, which as usual comes from the empty list.

Notice that SUMOFLIST [ ] is  $\emptyset$ . So we get

```

TO SUMOFLIST 'NUMBERLIST
10 IF EMPTYQ :NUMBERLIST THEN RESULT  $\emptyset$ 
20 RESULT SUM FIRST :NUMBERLIST
SUMOFLIST BUTFIRST :NUMBERLIST
END

```

Exercise 5.10 Draw the l.m. diagram for SUMOFLIST [10 17 23].

COUNT This is of course a built-in procedure, but how could we write it if it weren't already provided?

e.g. COUNT [A B C D E] ?

Apply the usual l.m. analysis of the list, and there is a corresponding synthesis of the number we want:

$$1 + \text{COUNT } [B \ C \ D \ E] \rightarrow \text{COUNT } [A \ B \ C \ D \ E]$$

And of course, COUNT [ ] is  $\emptyset$ .

```

TO COUNT 'LIST

```

```

10 IF EMPTYQ :LIST THEN RESULT  $\emptyset$ 

```

```

20 RESULT SUM 1 COUNT BUTFIRST :LIST

```

```

END

```

Exercise 5.11 NUMBEROF

e.g. NUMBEROF 'COW [HORSE COW DOG COW SHEEP] is 2.

What are the analysis/synthesis rules?

(a) NUMBEROF 'COW [HORSE COW DOG COW SHEEP]  $\leftarrow$

$\emptyset + \text{NUMBEROF 'COW [COW DOG COW SHEEP]}$

(b) NUMBEROF 'COW [COW DOG COW SHEEP]  $\leftarrow$

$1 + \text{NUMBEROF 'COW [DOG COW SHEEP]}$

(c) NUMBEROF 'COW [ ]  $\leftarrow \emptyset$

Can you write the procedure?

Constructing lists

To get the parts of a list, we have used the analysis

$\text{LIST} \xrightarrow{F, BF} F \text{ :LIST \& BF :LIST}$

To build up a list, we can use FIRSTPUT

$\text{:ITEM \& :LIST} \xrightarrow{\text{FPUT}} \text{FPUT :ITEM :LIST}$

e.g. FPUT 'A [B C D] is [A B C D].

Notice these relationships that hold for all lists:

FIRST FIRSTPUT :X :Y ..... is :X

BUTFIRST FIRSTPUT :X :Y ..... is :Y

### ADDLIST

Given a list of numbers, write a procedure to return the list with one added to each of the numbers:

e.g. ADDLIST [100 200 300] is ... [101 201 301].

ADDLIST could be easily written using MAPLIST, but this is not true of the next two examples, so we ignore the MAPLIST solution and concentrate on the recursive one.

We analyse the argument list as follows:

[100 200 300]  $\rightarrow$  100 & [200 300]

The corresponding synthesis of the result list is

ADDLIST [100 200 300]  $\leftarrow$  (100 + 1) & ADDLIST  
[200 300]

Unless this is the null list, in which case the synthesis is

ADDLIST [ ]  $\leftarrow$  [ ]

So we have,

```
TO ADDLIST LIST
10 IF EMPTYQ :LIST THEN RESULT [ ]
20 RESULT FPUT SUM 1 FIRST :LIST
   ADDLIST BF :LIST
END
```

Exercise 5.12 Write a procedure NEGSUBLIST which returns a list of those numbers on its argument list that are negative,

e.g. NEGSUBLIST [1 -2 3 -4 5] is ... [-2 -4].

### Example WITHOUT

In the M&C program we will need the procedure WITHOUT for changing one state description into another

i.e. MAKE LEFTBANK WITHOUT :MOVELIST :LEFTBANK

where WITHOUT is a procedure which removes a sublist from a list

e.g. 1: PRINT WITHOUT [M C BOAT] [M M C C BOAT]  
[M C]

We now tackle the problem of writing this procedure. Remember that the heart of programming is breaking tasks up into easier sub-tasks, so i.e. first tackle the easier problem of removing just a single item from a list.

e.g. WITHOUT1 'M [C M C BOAT] is ... [C C BOAT]

What are the synthesis rules? It must depend on whether or not the first of the list is the item we are trying to remove, e.g.

- (a) WITHOUT1 'M [C M C BOAT] ← 'C & WITHOUT1 'M [M C BOAT]  
 (b) WITHOUT1 'M [M C BOAT] ← [C BOAT]  
 (c) The empty list this time is a bit weird: if we can reach it it means that we haven't been able to find the item we're looking for. This may indicate an error.

So we have

```

TO WITHOUT1 'ITEM 'LIST
(case (c)): 10 IF EMPTYQ :LIST THEN BREAK ERROR
(case (b)): 20 IF EQ :ITEM FIRST :LIST THEN RESULT BF :LIST
(case (a)): 30 RESULT FPUT FIRST :LIST
              WITHOUT1 :ITEM BF :LIST
END
  
```

Exercise 5.13 Write WITHOUT, making use of the sub-procedure WITHOUT1.

A.I.2  
1975/76

15th October, 1975.

AB/11.

Programming Test - 1

Please answer the questions below and hand in your answers next Thursday, 30th October. This test will NOT BE USED FOR ASSESSMENT. It is purely to give us feedback on how you are finding the LOGO programming. Therefore - and unlike other programming exercises - it would be better if you do this test individually, without collaboration.

1. What is the result of the following LOGO commands:
  - (a) COUNT [DESK [TABLE CHAIR] CARPET]
  - (b) FIRST [CIRCLE SQUARE TRIANGLE]
  - (c) FIRST [[COLOUR RED] [SIZE BIG]]
  - (d) BUTFIRST [CIRCLE SQUARE TRIANGLE]
  - (e) BUTFIRST [[COLOUR RED] [SIZE BIG]]
  - (f) BUTFIRST [MAN WOMAN]
  - (g) SUM COUNT BUTFIRST [A B C] 7
2. Define a procedure CENSOR which checks on the public acceptability of lists. More precisely, the procedure CENSOR takes a list as argument, and if the word "SEX" occurs in the list it prints out the word "CENSORED", and if not it prints out the word "PASSED".  
e.g. 1: CENSOR [A PORNOGRAPHIC FILM]  
PASSED  
1: CENSOR [REPRESENTATIVE OF THE FAIR SEX]  
CENSORED  
-----

Hint Use the predicate AMONGQ - see previous handouts.

3. Suppose that we keep student records in the form of lists, containing the name, age, and department of each student,  
e.g. [BLOGGS 23 ASTROLOGY]  
[MCFINLAY 95 GERIATRICS]  
Write a procedure NICEPRINT that will type out one of these lists in a readable format:  
e.g. 1: NICEPRINT [BLOGGS 23 ASTROLOGY]  
NAME BLOGGS  
AGE 23  
DEPT ASTROLOGY



4. Define a predicate VOWELQ which decides whether a given word is one of A, E, I, O, or U.

e.g. 1: PRINT VOWELQ 'E

TRUE

1: PRINT VOWELQ 'F

FALSE

5. Define a predicate CONSONANTQ which tests for consonants.

## Behind the Scenes

### Introduction

A number of students have asked questions about what goes on behind the scenes in LOGO i.e. how do computers work etc. This handout is intended to give a simple and approximate answer to some of these questions and point you to the sources of more accurate answers.

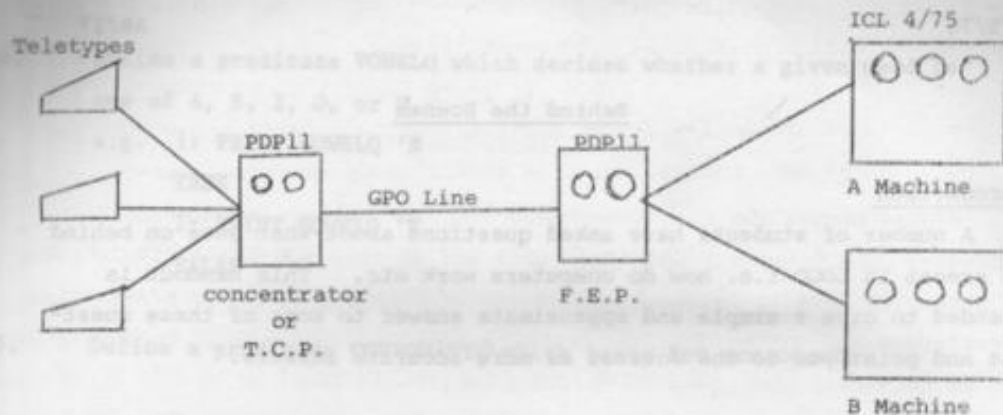
### The Physical Set-up

Some of you were surprised not to find a computer in the Appleton Tower, but just a lot of teletypes. The computer is actually located in the James Clerk Maxwell Building at King's Buildings, where it is run by the Edinburgh Regional Computer Centre (E.R.C.C.). The teletypes are connected to the computer by a high speed telephone line provided by the G.P.O. In order to save on telephone lines all the teletype signals are collected together at the Appleton Tower end by a mini-computer (called a PDP11) and sent down one line to K.B. At K.B. a similar mini-computer (the front end processor) decodes the separate signals and feeds them to the big computer where they are stored in a "buffer" until they can be processed. A similar process happens in the reverse direction when the computer talks to the teletypes.

In fact there are two computers at K.B., the I.C.L. 4-75 A and B machines. Your relationship with them is cunningly controlled by the front end processor, so that you should never notice that there are two machines.

The main computers are actually dealing with several users at any one time. They are running a main program called the operating system which divides the effort of the computer between the users on a "round robin" basis. The operating system also keeps each users program isolated from everyone elses in the computer's working memory. This is done in such a way that it should always appear to you that you have the computer all to yourself.

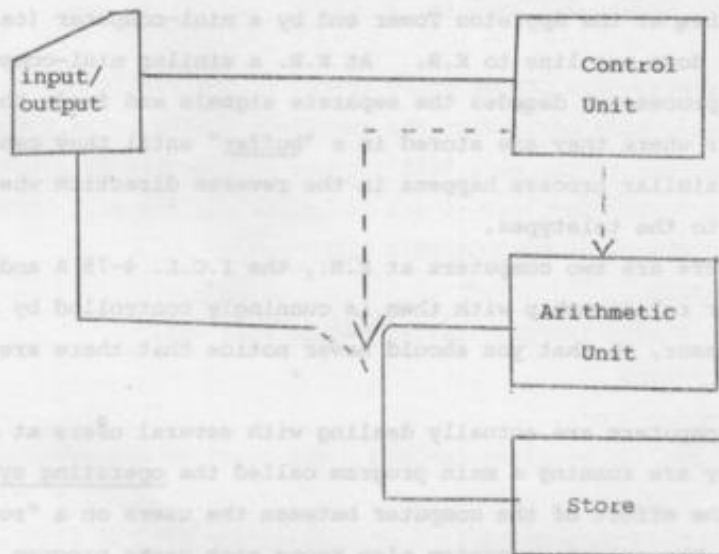
The set up is summed up in the following diagram.



For more information see: Frank Stacey in Comp. Sci. and various E.R.C.C. Newsletters.

#### How Computers Work

Computers can be conveniently divided into four components: the control unit; the arithmetic unit; the store and the input/output.



Reproduced from O.U. Television Notes on Mathematical Foundation Course.

The Arithmetic Unit is where the basic arithmetic operations, like adding two numbers, are performed. The store is where your programs and data are stored. Input/output covers a wide range of peripheral devices like: teletypes; line printers; card readers; disc files and even other computers. The control unit is the thing which decides what to do next, e.g. whether to: add two numbers; get something from

store or output to the line printer. It knows what to do because it feeds itself your program in a suitably coded form.

### Machine Code

The suitably coded form is called machine code. This is the only programming language which the control unit understands. All other languages: LOGO; IMP; FORTRAN; ALGOL etc. have first to be translated into machine code. The computer does this for itself by using either a compiler or an interpreter. These are programs which operate on your program as if it were a piece of data and produce a machine code translation. A compiler does this once, giving you the machine code in a form in which you can ask for it to be run. An interpreter translates your program as it is run.

LOGO procedures are currently interpreted into IMP by the LOGO system and thence into machine code. ERCC do not allow direct translation into machine code. Interpretation is much slower and more expensive than running an already compiled, machine code program. However, interpretation is much more convenient when a program is being developed, interactively because you do not have to recompile after every change. Compiling is best when a program has been completely developed and is now to be used for several "production runs".

Machine code is actually a sequence of binary numbers like:

```
0 1 1 0 0 0 1 1 1 1 1
0 0 1 1 1 0 0 0 0 1 1
0 1 0 0 0 1 1 1 0 0 0
-----
etc.
```



The control unit will break this into parts according to its own conventions. One part will tell it the instruction to be performed. One part will tell it where, in store, to find the thing to perform the instruction on

e.g. The first number might be broken into

```
0 1 1 0 and 0 0 1 1 1 1 1
```

The number 0 1 1 0 tells us this is a "fetch from store" instruction.

The number 0 0 1 1 1 1 1 is the address of some location in store.

Whatever is currently in that location is copied into a special place (the accumulator) in the arithmetic unit. The next number is broken down into

```
0 0 1 1 and 1 0 0 0 0 1 1
```

The number 0 0 1 1 tells us this is an "addition" instruction. The number

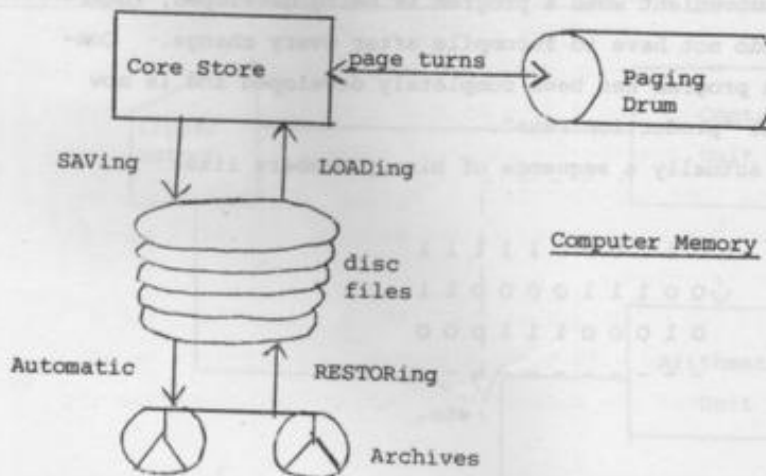
1 0 0 0 0 1 1 is the address of some place in store. The contents of that place are added to the number in the accumulator and the result is stored in the accumulator. The next instruction would be to store the result in some place in store.

For more information see the Open University introduction to computing or read:

Hollingdale, S.H. and Toothill, G. C. "Electronic Computers", Penguin Books, 1965.

### The Computer's Memory

So far we have discussed only one part of the computer's memory, the store (sometimes called core store). This is where the computer keeps the things it is currently working on. Information in core store can be accessed fast, but core store is expensive. Therefore the computer has a hierarchy of cheaper but slower memories. These are, in order of decreasing cost and speed: the paging drum; the disc files; the archives.



Computer Memory

All these extension memories are based on magnetic recording, like your home tape recorder. The archive store is in fact just that: a tape recorder. The disc files are a stack of magnetic discs: like a juke box for l.p.'s. The paging drum is a revolving magnetic drum.

The paging drum is an (optional) extension to the computer's core store. Users who are logged on but who are waiting to be worked on, will probably have their programs stored there. Even parts of a program, which is being worked on, may be there. You should not notice your program being put out or brought in from the drum, except that the number of "page turns", i.e. the number of times bits (or pages) of your program

are moved in and out, is recorded in your logoff message.

The disc files are where your programs are remembered when you are logged off. Procedures you want to be remembered are put onto the disc by the LOGO command SAVE. They are copied from the disc into the core store by the LOGO command LOAD.

Because space on the disc files is expensive, EMAS files which have not been used for four weeks are automatically archived onto magnetic tape. You only have one EMAS file, if it is archived it can be recovered and put back onto disc by the EMAS command RESTORE. This RESTORING is necessary because the file cannot be LOADED directly from archive:

For more information get the (out of print) EMAS User Manual or type HELP at monitor level, after the COMMAND: prompt.



Appendix 1 - Teaching and Assessment Methods

This appendix records the methods used to teach the course and assess the students. For opinions on the success of these methods see Appendix 6 on the student questionnaire.

Formal Lectures

The course ran for three terms (of 9, 9 and 6 weeks) and there were three lecture slots per week. Because of the difficulty of finding appropriate background reading, the lectures were accompanied by the extensive handouts bound in this volume. Not all the lecture slots were used for formal lectures. Some were used for: class discussions; problem classes; student presentations and an introductory teletype session. These are explained below.

Class Discussions

Three of the slots were used for holding general discussions on: Can Machines Think? Why is Understanding Natural Language so Hard? The Scope and Limitations of A.I.

Problem Classes

Because some of the skills we were trying to impart were too new to some of the students for them to make much initial progress, unassisted, we set aside some of the lecture time for them to do exercises, with the lecturer on hand to give assistance if needed.

Student Presentations

Each student was required to give a 25 minute talk on an A.I. topic of his choice, usually his project, to the whole class.

Introductory Teletype Session

The whole class was assembled in the terminal room for the second slot and nursed onto the computer by a large number of staff. A series of games and simple copied commands were devised for this (see pages P6-P7).

Audio Visual Aids

The overhead projector was universally used with prepared transparencies. Various films were shown including: Winograd's "Dialog with a Robot"; The MIT vision film "The Eye of a Robot"; SHAKEY and the Edinburgh Car/Ship assembly film.

### Tutorials

Weekly tutorials were held in the first term with small (i.e. 2 - 5 students), mixed ability groups. Exercises were set and marked by the lecturers, and were used by tutors as a basis in a variety of ways according to their style. These tutorials were replaced by individual project supervisions in the second and third terms.

### Teletype sessions

Students were expected to put in about three hours a week at the terminal in interactive computing. This computing often involved preparation for tutorials. The terminal room was shared with the Computer Science Department. It could be used at any time, but the students were encouraged to use it during the four hours when an A.I. demonstrator was present.

### Assigned Reading

This was kept to a minimum (approximately one hour a week), because of the lack of suitable material and the pressure of other assigned work. The general reading list is given in Appendix 3. Specific reading is included in the handouts, usually at the end of each section.

### Reading Fortnight

At the end of the first term it became apparent that there were wide discrepancies in the progress being made by different students. It was decided to suspend all lectures and tutorials for a fortnight and run individual supervisions geared to each student's needs.

### Assessment

Assessment was by one three hour written examination and a project. The marks were split on a 60 (examination) - 40 (project) basis. Sample examination papers can be found in Appendix 4. Projects could be of three types: a programming project; the design of a program or a survey of a small set of A.I. programs. Students were expected to spend about 30/40 hours on them and write a report of 3-5000 words (some students spent much more time than this). The list of project titles for 1974/75 and 1975/76 is given in Appendix 5.

Appendix 2 - A Rough Timetable

<u>Number of Lectures</u>	<u>Subject</u>
1st term	
9 + 6	Representation of Knowledge (9 lectures) and Programming (6 lectures) in parallel.
7	Introductions to : Natural Language (2); Vision (3) and Learning (2).
1	Class Discussion "Can Machines be Intelligent".
4	Natural Language
2nd Term	
2 weeks	Reading Fortnight (no lectures)
11	Natural Language (including 3 guest lectures by Yorick Wilks, and class discussion on Natural Language).
5	Representation of Knowledge
4 + 1	Vision (4) and a Programming lecture.
3rd Term	
3	Vision
5	Learning
9	Student Presentations
1	Concluding Class Discussion.

Appendix 3 - General Reading List

In addition to the recommended reading on specific topics (to be found in the lecture notes), the students were required to read the following general references.

- Minsky, M. and Papert, S. 'Artificial Intelligence Progress Report'.  
AI Memo No. 252, MIT, January 1972.
- Nilsson, N.J. 'Artificial Intelligence'. IFIP Congress 1974, August.
- Turing, A.M. 'Computing Machinery and Intelligence' in Computers and Thought (eds. Feigenbaum, F.A. and Feldman, J.), McGraw Hill (1963), pp 11-35.
- Feigenbaum, F.A. 'Themes in the Second Decade'. Information Processing 68, Vol. 2, (ed. Morell, A.J.H.), North Holland (1969), pp. 1008-22.
- Longuet-Higgins, C. 'Artificial Intelligence'. Br. Med. Bull, vol.27, No. 3, pp. 218-221, (1972).

Four xerox copies of all reading material were made available in a central place (because this material is hard to track down and in short supply).

Appendix 4: Examination Questions

Here are the papers set for: the class examination 1974/1975;  
the degree examination 1974/1975 and the degree examination 1975/1976.  
(There was no class examination in 1975/1976).

ARTIFICIAL INTELLIGENCE 1

CLASS EXAMINATION

Monday 10th March 1975 9.00 a.m. - 12 noon

Instructions to Candidates

Answer any FOUR questions. All questions carry equal weight.

DEPARTMENT OF ARTIFICIAL INTELLIGENCE

UNIVERSITY OF EDINBURGH

ARTIFICIAL INTELLIGENCE 2

CLASS EXAMINATION

Monday 10th March 1975 9.00 a.m. - 12 noon

Instructions to Candidates

Answer any FOUR questions. All questions carry equal weight.

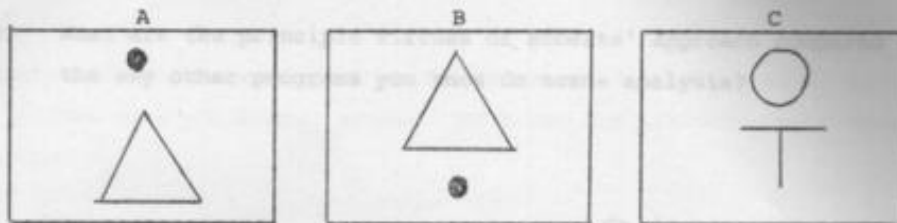
What happens when we try to apply the description of the rule to the description of Figure D? How might we amend the rule description so that it applies to the description of D and perhaps a description of Figure E?

Questions

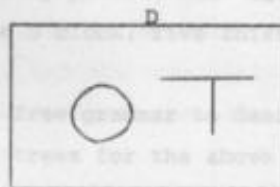
- (a) What does the Roberts' program use in order to select a picture fragment for matching to a model?
- (b) Show one possible decomposition of the scene depicted overlaid and one of the intermediate stages which would result from applying Roberts' program.



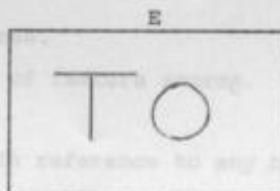
1.



- Give a symbolic description of figures A, B and C and description of the similarities between corresponding objects in A and B.
- Give a symbolic description of the rule which would change figure A into figure B.
- If the description of the rule were applied to the description of figure C what would be the description of the resulting answer figure?
- Suppose figure C had been



What goes wrong when we try to apply the description of the rule to the description of Figure D? How might we amend the rule description so that it applies to the description of D and produces a description of figure E?

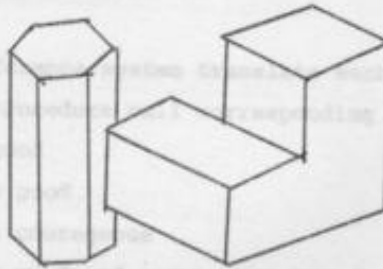


### Questions

2.

- What tests does Roberts' program use in order to select a picture fragment for matching to a model?
- Show one possible decomposition of the scene depicted overleaf and one of the intermediate stages which would result from applying Roberts' program?

- (c) What are the principle virtues of Roberts' approach compared to the way other programs you know do scene analysis?



3.

Times of day are expressed by phrases such as:-

- (a) twelve fifteen, three o'clock, five thirtyseven, a quarter to three, half past ten.
- (a) Make a context free grammar to describe such sentences.
- (b) Give the parse trees for the above phrases.
- (c) Indicate by writing typical procedures how you would write a LOGO program to take a list of words and return YES or NO according to whether it is described by your grammar. (You may assume procedures CHECK and TRY are provided).

4.

Discuss what is meant by:

- (a) A Look-Ahead tree.
- (b) A weighted sum of feature scores.
- (c) Mini-Maxing.

Illustrate your answer with reference to any board game of your choice except draughts (checkers).

5.

Explain how a syntactic production rule may have a semantic rule attached to it to compute the meaning of the phrases generated. Illustrate your answer by referring to the meanings of various kinds of phrase in the blocks world program described in the course.

6.

Discuss Guzman's use of picture junctions and linking rules to decompose a picture of a polyhedral scene. What are the limitations of such an approach?

SCHOOL OF SCIENCE

7.

- (a) Using the LOGO inference system translate each of the following sentences into a procedure call corresponding to its meaning:

The Pope is good

John Wayne is good 1972 2.30 p.m. - 3.00 p.m.

John Wayne is courageous

Anyone who is good and courageous is a hero

---

Who is a hero?

CHURCH OF ENGLAND

- (b) Suppose the translations of the sentences above the line were used to set up a database and the translation of the sentence below the line were used to interrogate that database. Draw the search tree of that interrogation.

INSTRUCTIONS TO CANDIDATES

1. Candidates in the third or later years for the degree of B.A. (Hons), B. Com., B.Sc. (Applied Science), B.Sc. (Science) and (B.Sc.) should put (a) after their name on the script book.

2. Answer any FOUR questions. All questions carry equal weight.

UNIVERSITY OF EDINBURGH

FACULTY OF SCIENCE

ARTIFICIAL INTELLIGENCE 2

Monday 9th June 1975 2.00 p.m. - 5.00 p.m.

Examiners:

Chairman B. Meltzer

External A. Sloman

Instructions to Candidates

1. Candidates in the third or later years for the degrees of B.A. (Arts), B. Com., B.Sc. (Social Science), B.Sc. (Science) and LL.B. should put (3) after their names on the script book.
2. Answer any FOUR questions. All questions carry equal weight.



1.

Suppose that a regular person is asked to take an simple direct-  
 ion map as the one below and check their correctness from a street map.  
 From a given starting place,

'To get to the school, take the first road on the left, then the  
 first road on the right after the bridge'

'To get to the hospital, take the second road on the left, then

Using the LOGO INFERENCE system:

- (a) Give a partial symbolic description of the above drawing of a face  
 sufficient to answer "yes" to the following questions, by direct  
 data-base lookup:

Is the mouth in the lower portion of the face?

- (a) Write Is the left eye in the upper portion of the face?

Is the nose in the centre of the face?

- (b) In addition represent the laws that:

Anything in the centre of the face is also in the middle

portion.

Anything in the middle portion of something is always above  
 anything in the lower portion.

Anything in the upper portion of something is always above  
 anything in the middle portion.

- (c) Represent the question:

Is the nose above the mouth?

Draw the complete search tree of its interrogation of the  
 database.

- (d) In addition represent the law:

To infer that x is above y show that x is above z and z is  
 above y.

and the question:

Is the mouth above the nose?

Draw some of the search tree of this interrogation. What  
 problem arises? How might it be overcome?

Does your solution involve changing the LOGO INFERENCE  
 system?

2.

Suppose that a computer program is to be written to take in simple directions such as the ones below and check their correctness from a street map from a given starting place.

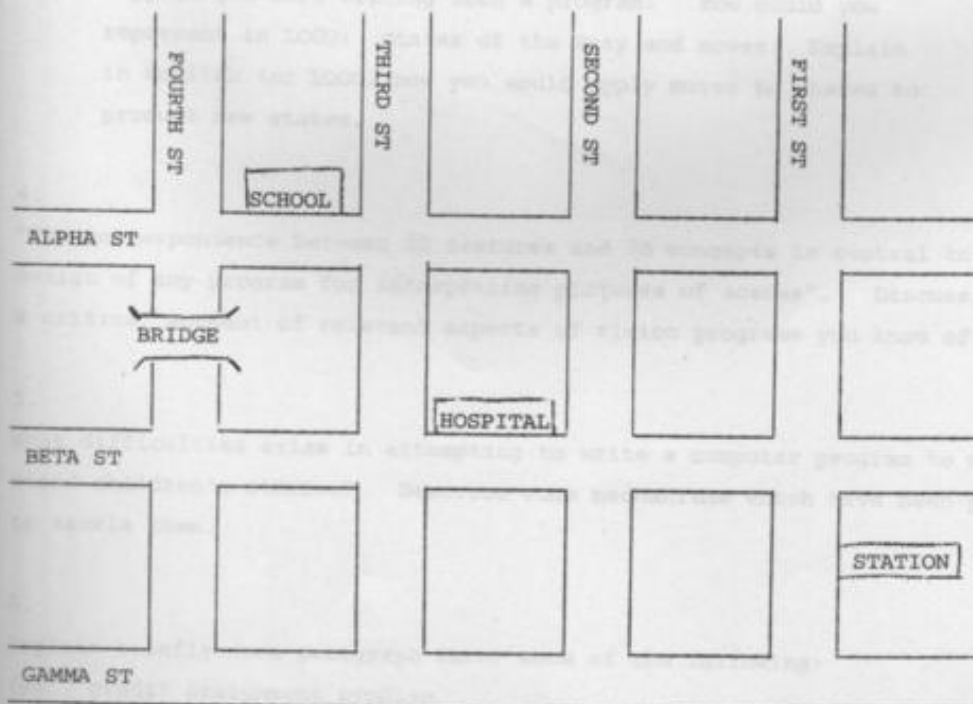
'To get to the school, take the first road on the left, then the first road on the right after the bridge'

'To get to the hospital, take the second road on the left, then the first road on the right'

'To get to the station, take the fourth road on the left'

'To get to the bridge, take the first road on the right after the school'

- (a) Write a context-free grammar to generate directions such as these, using the vocabulary in the above sentences.
- (b) Explain how the following simple street map might be represented in LOGO so as to be useable as a semantic model for such a checking program. (Hint: recall the list structure representations of the state of the blocks world described in the course).





3.

The "Eight-Puzzle" is played on the 3 x 3 tray illustrated below:

1	2	3
4		5
6	7	8

Mounted in the tray are eight 1 x 1 square pieces, which are free to slide left, right, up or down into an empty square. The standard position is illustrated in which the centre square is empty and the numbers are arranged in numerical order. The puzzle is played by initializing the pieces in some other order and then trying to get them back into the standard position.

- Explain how a course of play can be represented as a search through a tree or graph.
- How would this representation help you to design a computer program to solve eight-puzzle problems?
- Suppose you were writing such a program. How could you represent in LOGO: states of the tray and moves. Explain in English (or LOGO) how you would apply moves to states to produce new states.

4.

"The correspondence between 2D features and 3D concepts is central to the design of any program for interpreting pictures of scenes". Discuss, giving a critical account of relevant aspects of vision programs you know of.

5.

What difficulties arise in attempting to write a computer program to understand children's stories? Describe some mechanisms which have been proposed to tackle them.

6.

Explain briefly (one paragraph each) each of the following:

- credit assignment problem
- hill climbing
- near miss

- (d) Winston's notion of "appropriate generalization"
- (e) discrimination tree
- (f) diameter-limited perceptron

7.

Discuss up to four of the following statements. You may write at length on one of them or more briefly on two or more.

- (a) Representing the effects of operators by add and delete lists solves the frame problem.
- (b) Line-verifying is better than line-finding.
- (c) Alpha-beta pruning is a way to obtain a gain in efficiency in exchange for an increased danger of overlooking the best choice.
- (d) Since a program can now do analogy problems it makes no sense to use them on human intelligence tests.
- (e) Attempts to model human intelligence on a computer are doomed to failure since the human brain and the digital computer are based on different hardware.

UNIVERSITY OF EDINBURGH

FACULTY OF SCIENCE

ARTIFICIAL INTELLIGENCE 2

Monday : 7th June 1976

2.00.p.m. - 5.00.p.m.

Examiners: Chairman    B. Meltzer  
                                External    A. Sloman

INSTRUCTIONS TO CANDIDATES

1. Candidates in the third or later years for the degrees of B.A. (Arts), B. Com., B.Sc. (Social Science), B. Sc. (Science) and LL.B. should put (3) after their names on the script book.
2. You have been provided with a copy of the "AI2LOGO User's Guide and Manual".
3. Answer any FOUR questions. All questions carry equal weight.

1. The following context-free grammar generates linguistic descriptions of chess pieces in terms of their colour and board position.

Piecename → 'pawn

...

Piecename → 'king

Colour → 'black

Colour → 'white

Piece → Piecename

Piece → Colour Piecename

Nth → 'first

...

Nth → 'eight

Position → Nth 'rank

Position → Nth 'file

Position → Nth 'rank 'and Nth 'file

Description → 'the Piece

Description → 'the Piece 'on 'the Position

(terminal symbols are quoted)

- (i) Write out 5 descriptions generated by grammar.

The current state of a chess board can be represented, e.g. in LOGO, by a list of quadruples, where each quadruple represents a piece by a list of four elements, namely

PIECEKIND<sub>i</sub> which is 'PAWN or ... or 'KING

BLANKI which is 'BLACK or 'WHITE

RANKNO which is 1 or ... or 8

FILENO which is 1 or ... or 8

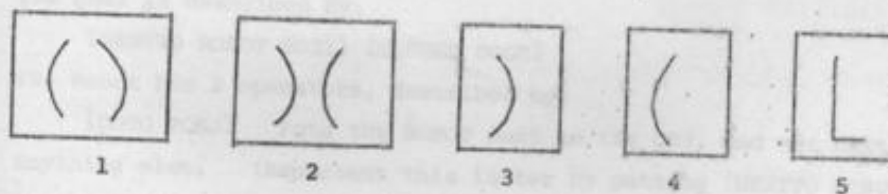
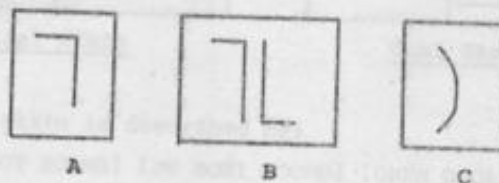
A chess playing program accepts linguistic descriptions of the above form and needs to find their meaning relative to the current state. For example, in the current state "The pawn on the first rank" might refer to [PAWN BLACK 1 8].

- (ii) What LOGO or other data structures could you use as the meaning of each of the six kinds of phrase: Piecename, Colour, ..., Description?

(iii) How could you write procedures to calculate the meaning of each phrase from the meaning of its components and (if necessary) the current state? (Say what these procedures would have to do; you need not write them.)

2. "Deduction is a formal, logical procedure with well-defined rules and can be carried out by a computer program. Induction, on the other hand, by its very nature involves a creative component and cannot even in principle be done by a machine."
- Discuss, with reference to computer programs you know of, that claim to do induction.

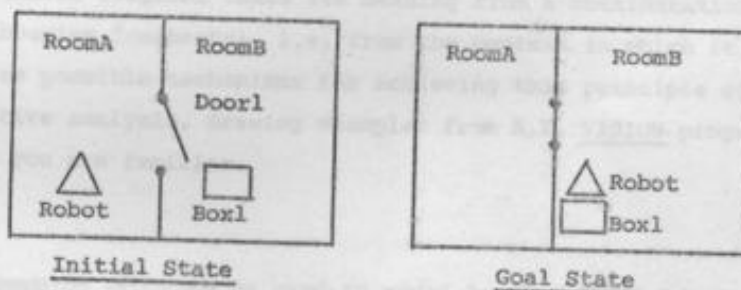
3. Below is a typical "Geometric Analogy Problem".



"Find the rule by which figure A has been changed to make figure B. Apply the rule to figure C. Select the resulting figure from figures 1 - 5."

- (a) Explain, briefly, how Evans' computer program, ANALOGY, could solve such problems.
- (b) Give an example of a geometric analogy problem which Evans' program would be unable to solve and explain why.

4. (i) Explain the distinction between forward inference and backward inference, giving as an example some AI tasks for which they might be used.
- (ii) What problems arise with the use of (a) forward inference and (b) backward inference? Illustrate your answer with examples. Suggest ways in which these problems might be overcome.
5. Consider the task defined by the following diagrams.



The initial state is described by:

[IN ROBOT ROOMA] [IN BOX1 ROOMB] [OPEN DOOR]

[IN DOOR1 ROOMA] [IN DOOR1 ROOMB] [CONNECTS DOOR1 ROOMA ROOMB]

The goal is described by:

[NEXTTO ROBOT BOX1] [CLOSED DOOR]

The Robot has 3 operators, described by:

[GOTO ?OBJ] Puts the ROBOT next to the OBJ, and not next to anything else. (Represent this latter by putting [NEXTTO ROBOT \*] in the delete list). It is applicable if the ROBOT and OBJ are in the same room.

[GOTHRU ?DOOR] Puts the ROBOT in the room which the DOOR connects to his present room. Initially the ROBOT must be next to the open DOOR.

[CLOSE ?DOOR] Closes the open DOOR. The ROBOT must be next to the DOOR.

- (a). Describe the 3 operators by drawing an Operator Table giving their preconditions, delete and add lists.



- (b) Describe a plan for achieving the goal, and draw a diagram giving symbolic descriptions of the sequence of states which would be achieved if the plan were executed.
- (c) What is subgoal protection? Why is subgoal protection sometimes needed by planning programs? If a robot plan formation program, which used subgoal protection, was given the above task, what difficulty would it encounter? How might this difficulty be overcome?
6. "A stimulus fragment takes its meaning from a consideration of its neighbouring fragments; i.e. from the context in which it occurs". Discuss possible mechanisms for achieving this principle of context-sensitive analysis, drawing examples from A.I. VISION programs with which you are familiar.
7. Can computer programs be used to model human intelligence? At what level can they be compared? Illustrate your answer with reference to GPS or some other program designed to simulate human behaviour.
8. Discuss the relevance of AI programs to either philosophy, psychology or linguistics.

Appendix 5: Student Project Titles1974/75

<u>Student</u>	<u>Title</u>
N. Conliffe	GRIP: Graphics Routines with Interpretive Parsing
C. Davie	Relation of work in AI and Psychology in Visual Perception
A. Fletcher	A Bidding Program in LOGO
T. Gayle	BUILD: A Lesson on Anarchism in the Blocks World
*S. Holtzman	A Program for Key Determination
I. Malcolm	Maze Traversing
D. Paterson	The Imitation Game: An Anti-Behaviourist Approach
P. Reddish	Approaching Perception
K. Schroeder	Models of Linguistic Description and Implications for Computer Programs involving Natural Language

\*Also available as DAI Research Report No. 20.

1975/76

<u>Student</u>	<u>Title</u>
R. Aikman	Generating English Sentences
J. Allan	Question Answering
M. Bennett	SUBSTITUTOR - CAI error analysis
M. Bottomley	Machine Translation reviewed: evaluation of selected programs
K. Chisholm	DRAFT4 - A Draughts program
A. Coldham	Date (and time) Translation Quizzing Machine
P. Dunne	Two Move Chess Problems
E. Doe	Fox and Hounds
D. Giles	Natural Language Analysis Using Case
V. Keir	Fugue Generation
J. Kennaway	Geometry theorem proving
E. Lawson	A Puzzle Solving System
G. Morris	P.A. Learning Models
M. Ferguson	Translation from Staff into Tablature (Music)
M. Schairer	Word into sentence: parsing an agglutinative language
S. Wigglesworth	A program to play Backgammon

The project reports are kept in the Library, Department of Artificial Intelligence, Forrest Hill.

# Appendix 6: Student Questionnaire Returns 1975/1976

In order to get feedback to help us improve the course we issued a questionnaire at the end of each year. The questions asked in 1975/76, together with a brief summary of the replies, are given below. All 21 students who started the course were circulated - we received 12 replies.

## Student Questionnaire

In order to get feedback to enable us to plan next year's course, we should be grateful if you would complete this questionnaire and give us your comments on any aspect of the course. Please be completely frank.

1. How did you find out about the course?  
Original source: Director of Studies, 2; Faculty Programme, 5;  
A Friend, 2; Noticeboard, 1; Lecture in Computer Science on AI, 2.
2. What factors influenced your decision to enrol in the course?  
Most frequently mentioned factors were: Looked interesting;  
Previous interest in AI; General interest in computers;  
Relevance to some other subject.
3. What do you think the objective of the course was? Did it succeed?  
Most answers centred on the "Introduction to AI" idea, mentioning some aspect like: past achievements, current developments or scope and limitations. A few answers mentioned our specific aims of teaching the methodology or establishing the relevance with soft sciences. Three gave no answer at all. Nearly everyone thought it succeeded.
4. Did you find the subject matter of the course
  - (i) Interesting?  
Nearly everyone found it interesting, some said "very".
  - (ii) Demanding?  
Reaction was mixed, from a non programmer "I still found myself completely out of my depth" through "Some of the programs particularly in Natural Language (parsing), were difficult to follow", to an experienced programmer "Most of the work I did was fun rather than 'real' work". Most people found it time consuming (too many exercises) whether or not they also found it demanding.
  - (iii) Relevant to other subjects you are studying (please specify)?  
People also doing computer science or linguistics found AI relevant to those subjects. Otherwise a fairly negative response (e.g. not much - but should it be), apart from one reference to psychology.

5. How do you think the teaching and assessment could be improved?

As an aid to thought we have listed the teaching and assessment methods below.

(i) Formal Lectures

(ii) Handouts

Much appreciation expressed. They found lectures well prepared and were able to give full attention to following them: "Handouts were better than those I got in any other course so far - complete and readable - and most of the lectures appeared to be well prepared".

(iii) Problem Classes

(iv) Class Discussions

More wanted of both. Several criticisms levelled at class discussions as being too infrequent, too general and class too large.

(v) Student Presentations

Welcomed but too late in term for feedback to be incorporated in projects.

(vi) Audio Visual Aids

Compliments expressed on films, videos, overheads etc.

(vii) Tutorials

(x) Other Assigned Work

Strong feeling that these should continue into second term. A suggestion that they should be streamed by programming ability.

(viii) Teletype Sessions

Too much programming in course. More personal tuition wanted.

(ix) Assigned Reading

Several suggestions for improving the method of access.

(xi) Informal contact with members of the department

Better than most departments but could be better. More information wanted about research work of department.

(xii) Examinations

(xiii) Project

Two requests for an extra class examination, balanced by one request for continuous assessment and one for exemptions for deserving cases. Opportunity to do project much appreciated but not enough time in course to do it justice (e.g. "why give 30-40 hours as a guide-line and then show previous examples which must have taken their authors about twice as long?").

6. (i) Was this your first opportunity to program a computer?  
 (ii) If so how hard did you find it?  
 (iii) Did any particular aspect of learning to program give you trouble, e.g., a particular concept, a misconception you harboured, a particular type of bug? (please specify).

People with no previous experience found programming very hard (typical comments were "very, very hard"; "Bad", etc.). Unfortunately (and significantly) they were unable to identify particular areas of difficulty, but just said "all of it (except the very early programming)" or "everything".

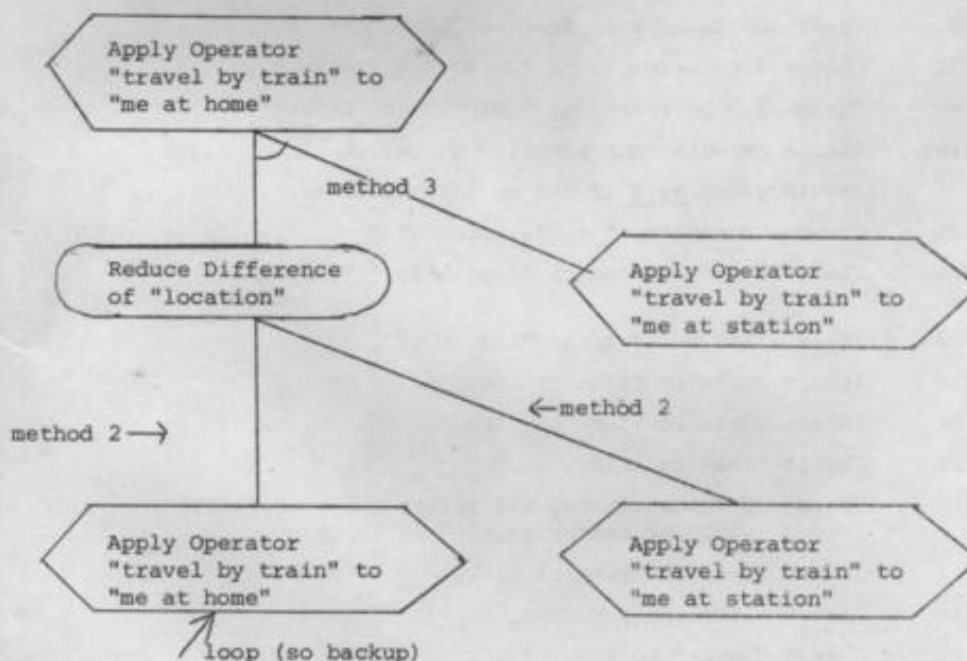
7. Please record any other comments you wish.

Mainly used to expand on above points. General mood was that course was good (e.g. "10/10 for effort put into 5(ii,vi,vii,viii, ix, xiii) etc."), but we had gone overboard with the imparting of specific skills (e.g. programming), to the detriment of general philosophical discussion (e.g. "more a series of intellectual exercises"; "even after deciding to drop the course it was stressed to me that AI was not a mathematical-type subject - but it is!"; "lack of spontaneous class discussion"). Some pointed out that the proper balance was difficult to strike while the class continued to contain a mixture of soft and hard scientists (e.g. "I don't think the same course should apply for people who have done computer science and also for people who have done nothing of this sort before"; "more places should be allocated to Psychologists, Philosophers, Linguists and other non-mathematicians").



Appendix 7: Errata

<u>Page</u>	<u>Line</u>	<u>Correction</u>
RK1	figure	Small rectangles should be squares
RK1	5	"fule" should be "rule"
RK1	9	delete "could involve some judgement". Insert "either straightforward or go back to beginning".
RK23	5	Insert line "LOO TRYMOVES"
RK24	14	Insert "AND STOP" at end of line.
RK42	table	"table" should be "cable"
RK44	5	"searched" should be "grown".
RK44	figure	tree all wrong — replace bottom half with:



RK46	2	Insert "RESULT" between "60" and "TRANSFORM".
RK66	13	"from" should be "form"
NL1	17	After 'IF :N=1 THEN', replace 'RETURN' by 'RESULT'
NL1	20	After '2Ø' insert 'RESULT'
NL3	20,22,24	Replace 'UMPHUM' by 'UMPHUN'
NL6	6	Replace 'semantics without' by 'syntax without'.
NL4	end	Insert '(This grammar example is essentially due to H.C. Longuet-Higgins)'



- NL13 13 should read '(3) (theoretical) it goes into an indefinite recursion if given'
- NL19 end Insert footnote 'LOGO programs given in lower case have not been tested in their present form'.
- NL23 -9 After '[A C] [B D] [C D] insert '[A D]'
- NL25 15 Should read  
'10 IF NOT EMPTYQ :XS THEN P 'CORRECT ELSE P 'LIAR'
- NL25 -11 Before line starting '10 NOUN' insert line  
'05 IF EMPTYQ :STATES THEN RESULT []'
- NL25 -5 Before line starting '10 JOIN' insert line as above.
- NL28 17 Replace ':(dimdf :b2)' by '+ (dimdf :b2)'
- NL31 7 After '[RED BLOCK ON' replace 'A' by 'THE'.
- NL32 17 After 'mkprop <(adj)> insert '<(simpnounphr)>'
- P1 end of page Insert "Pressing 2 keys at once causes locking.  
Unlock by pressing bar to right of space bar".
- P11 -5 Insert quote mark in front of LIST.
- P13 -7,9,11 Change 3 occurrences of "OUTPUT" to "RESULT".
- P14 5,-8 Change 2 occurrences of "OUTPUT" to "RESULT".
- P13 figures &14 Little men diagrams wrong. Output of men on right should go to eyes of men on left (not ears).
- P15 -15 Change "parameters" to "arguments".
- P16 heading of table Change 2 occurrences of "input" to "argument".
- P21 13 Insert "and BUGS" after "LIB 'BUGS'".
- P22 10 Insert quote in front of LIST.
- P22 14 Insert quote in front of PARA.
- P22 16 Change 'PARA to :PARA.  
(Note: for consistency all references to PARAMETER would be better changed to ARGUMENT).
- P22 12 Insert quote in front of LIST.
- P23 14 Insert :LIST after SECERR.
- P24 11 Change "input" to "argument".
- P24 13 Insert quote in front of NUM.