COURSE MANUAL CF20

INTRODUCTION TO ASSEMBLY PROGRAMMING

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COURSE MANUAL
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1. ASSEMBLERS

During execution of a program, the instruction sequence is represented inside the computer by binary instructions in successive registers. However, the programmer specifies instructions symbolically. The conversion from a symbolic representation of a program to its binary representation inside the computer can itself be performed by a computer program. This is referred to as the assembly process, and the program which performs the conversion is called an assembler.

An assembler is a program that accepts a program written in assembly language as input and produces its machine language equivalent. Each instruction word in an assembly language program is translated to only one instruction word in machine language.

Thus, we can think of an assembler as a function, the domain of which is the set of all legal assembly language instructions, and the range of which is the corresponding set of machine language instructions. Operation of the assembler A on a symbolic assembly language program S produces a machine language program M, i.e., M = A (S).

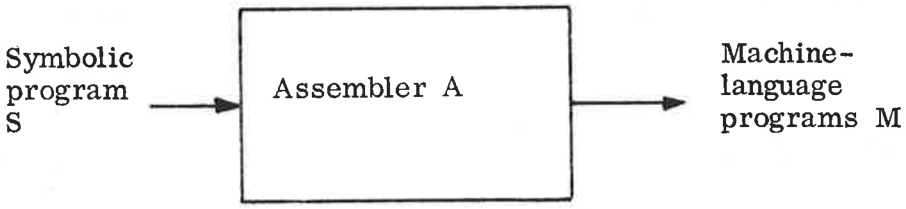


Figure 1.1: The operation of an assembler.

1.1 Basic Concepts of Scanning and Assembly

1.1.1 External Instruction Format

Input to an assembler consists of sequences of symbolic instructions each of which consists of a number of symbolic fields. It will be assumed that symbolic instructions consist of a location field followed by an operation field, followed by an address field.

<instruction> :: = <location field><operation field><address field>

The location field contains the instruction label, if there is any. It is used to give symbolic names to locations in order to be able to refer to these locations by name. The operation field contains the symbolic operation code. The address field contains the symbolic operand address. This is a reference to that location which has the address as location name.

1.1.2 Operation Codes and Address Symbols

The assembler basically has to deal with two kinds of symbols:

i. operation code symbols
ii. address symbols.

The internal binary codes corresponding to operation code symbols are specified by a mnemonic table. When the binary code corresponding to an operation code symbol is required, it is determined by a table look-up in the mnemonic table.

Address symbols do not have fixed internal values. Their values are assigned by the assembler.

Instructions are normally assembled assuming that they will be placed in a set of contiguous locations during execution. However, the value of the location in which the first instruction will be placed is left open. Addresses are normally relative addresses, relative to the first instruction of the instruction block.

1.1.3 Two-Pass and One-Pass Assembly

Addresses to locations are specified by the defined symbol table, DST, constructed during the assembly process. In order to insure that all symbols are defined before they are referred to, early assemblers were designed to perform assembly in two passes over the instruction sequence. The first pass reads only the location field and builds the symbol table. In both passes a simulated location counter keeps track over the address of the instruction currently being scanned relative to the beginning of the instruction sequence. The location counter will be referred to as current location counter, CLC, or program counter, P.

If the binary instructions of the assembled program can be stored in core during assembly, then assembly can be performed in a single pass by partial translation of instructions which contain references to undefined symbols as they are encountered. Reference addresses of undefined symbols are noted down in an undefined symbol table, UST, and are fixed up as location symbols get defined.

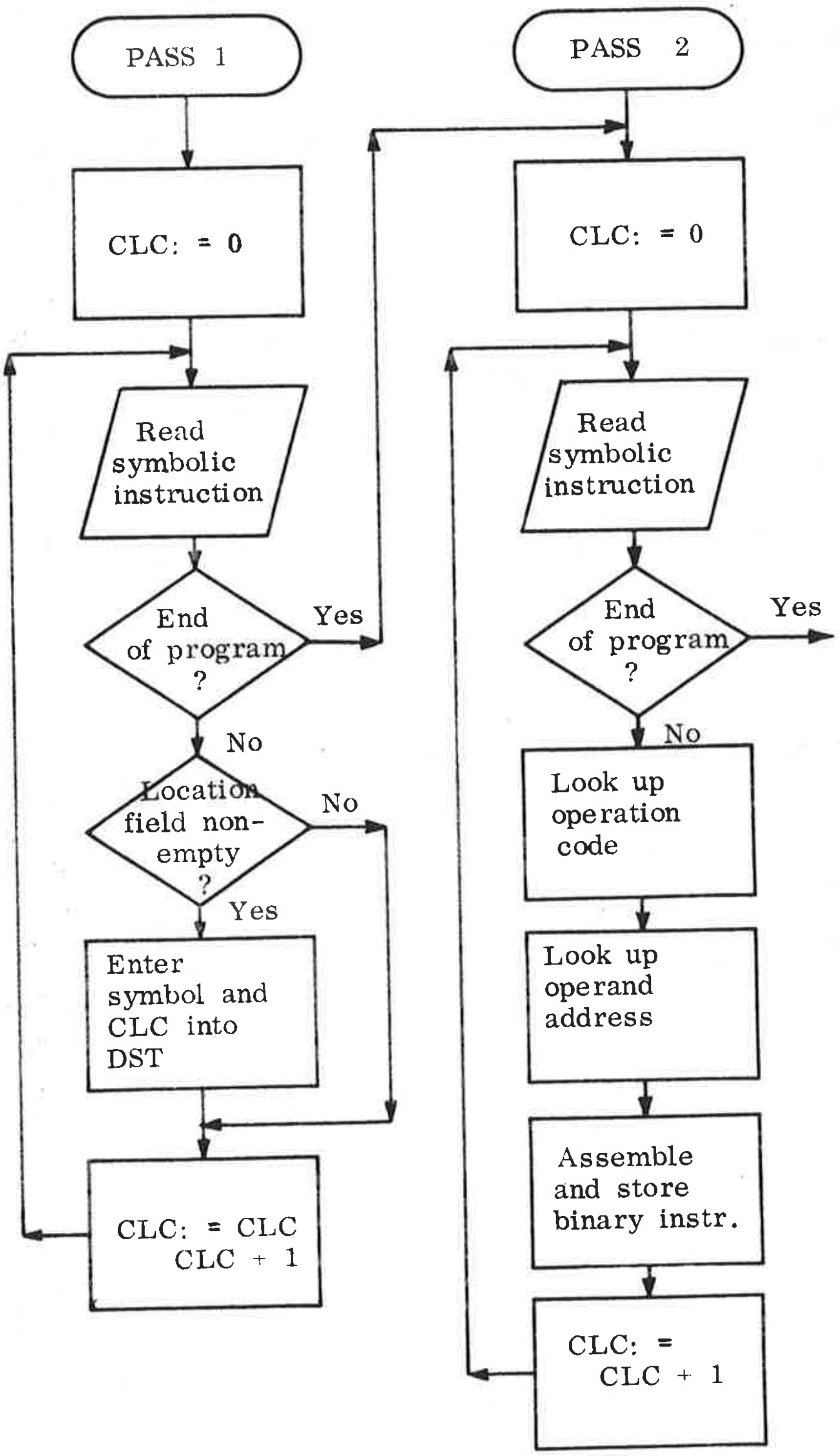


Figure 1.2: Operation of a simple two-pass assembler.

CLC	D	R
0	B	
1		A
2		B
3		A
4		
5		B
6		A
7		B
10	A	

Program P with definitions D and references R of symbols

Name	DA
B	0

DST contains symbol's name and definition address DA

Name	RA
A	1
A	3
A	6

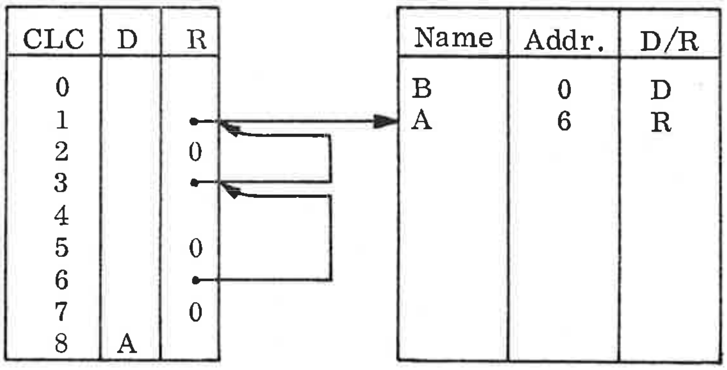
UST contains undefined symbol's name and reference address RA

Figure 1.3: One-pass assembly of a program P.
Situation before A gets defined in location 10 is shown.

Alternatively, each entry in the defined symbol table can contain one more field which indicates whether the symbol is defined or not. At any time, the last occurence of a reference to an undefined symbol is contained in the defined symbol tables, the address field in the instruction is used to chain references to the same undefined symbol.

CLC	D	R
0	B	
1		A
2		B
3		A
4		
5		B
6		A
7		B
10	A	

Program P, originally



CLC	D	R
0		
1		•
2		0
3		•
4		
5		0
6		•
7		0
8	A	

Name	Addr.	D/R
B	0	D
A	6	R

Program P before A gets defined

Table DST before A gets defined.

Figure 1.4: One-pass assembly by use of one table only.

2. AN IMAGINARY MACHINE

We shall now present an imaginary machine which consists of a processor, an internal memory of 1/4K 16 bits words and a Teletype as input/output unit.

Each location in the memory contains an octal number. The contents may be interpreted in two ways: either as an instruction or as an operand's value.

An instruction consists of two parts: a function code and a reference to an operand address.

The processor has two registers which have the same length as a memory location:

i. A-register is the accumulator
ii. P-register is the program counter. It is increased by one for each new instruction.

2.1 The Assembly Language MINI

The assembly language of the imaginary machine is called MINI. It is a somewhat extended subset of NORD computers' instruction repertoire.

Statements in MINI have one of following formats:

<instruction> :: = [<label>,] <operation> <operand>

or

<symbol definition> :: = <label>, <value>

where

<label> :: = <letter> | <label> <letter> | <label> <decimal digit>

<operand> :: = <label>
<value> :: = <label> | <octal number>

A <label>, which is a definition of a symbol's address, and an < operand > which is a reference to a symbol's value, may contain up to four alphanumberic characters. An < octal number> may contain up to six octal digits.

The < operation > must be one of the legal MINI operation listed below:

LDA	Load accumulator
STA	Store accumulator
ADD	Add to accumulator
SUB	Subtract from accumulator
JMP	Unconditional jump
JAP	Jump if accumulator is positive
JAZ	Jump if accumulator is zero
INP	Read an octal number into accumulator
OUT	Write the octal number contained in accumulator
HLT	Halt

2.2 Instruction Word

If a location contains an instruction, this is interpreted as a function code and a reference to an operand address, (see figure 2.1). Addressing is relative to the P-register. In other words: reference to an operand address is recomputed as a displacement from the definition address to the reference address:

displacement: = definition address - reference address

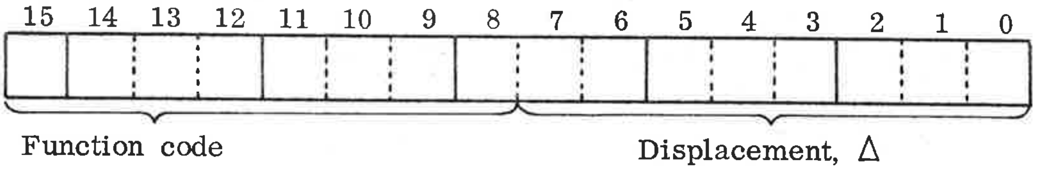


Figure 2.1: MINI's instruction word.

Both backward and foreward references are permitted such that the displacement may be negative or positive. Since the displacement must be represented by 8 bits, the sign inclusive, it is possible to refer to operands within an interval of 256 locations (the size of the memory). The displacement is limited by the following inequality:

$$-128 \leqslant \Delta \leqslant 127.$$

This means that the last reference to the defined symbol may not occur later than 128 locations after the corresponding < symbol definition > . On the other hand, reference to an undefined symbol must not occur earlier than 127 locations prior to the <symbol definition>.

2.3 Some Examples

2.3.1 Addition of 3 octal Numbers

MINI-program:

```
        INP
        STA     NUM1
        INP
        STA     NUM2
        INP
        STA     NUM3
        ADD     NUM1
        ADD     NUM2
        STA     SUM
        HLT
NUM1,   0
NUM2,   0
NUM3,   0
SUM,    0
```

2.3.2 Find the smallest Number of three octal Numbers

MINI-program:

```
        INP
        STA     NUM1
        INP
        STA     NUM2
        INP
        STA     NUM3
        SUB     NUM2
        JAP     SM2
        LDA     NUM3
        JMP     TST2
SM2,    LDA     NUM2
TST2,   SUB     NUM1
        JAP     FIN
        ADD     NUM1
        JMP     WRTE
FIN,    LDA     NUM1
WRTE,   OUT
        HLT
NUM1,   0
NUM2,   0
NUM3,   0
```

2.3.3 Multiply two positive octal Numbers

MINI-program:

```
          INP
          STA     NUM1
          STA     PROD
          INP
          STA     NUM2
          JAZ     FIN1
CONT,     SUB     ONE
          STA     NUM2
          JAZ     FIN
          LDA     PROD
          ADD     NUM1
          STA     PROD
          LDA     NUM2
          JMP     CONT
FIN,      LDA     PROD
FIN1,     OUT
          HLT
NUM1,     0
NUM2,     0
PROD,     0
ONE,      1
```

2.4 Program Modification

In the previous examples we distinguished between words containing instructions and words containing data. It might be useful to be able to modify instructions, too, in order to be spared rewriting similar instructions.

2.4.1 Example:

Read n numbers into the locations NUM, NUM+1, NUM+2, ..., NUM+n-1. Compute their sum and place it in location SUM.

Instead of writing n input and store instructions and n-1 addition instructions, we may use loops where these instructions are repeated and modified.

MINI-program:

```
          INP     }
          STA     N }              Number of numbers
          STA     N1
```

```
READ  , INP          }    Read numbers
STRE  , STA   NUM    }
        LDA   N1     }
        SUB   ONE    }    Test if N numbers are read
        STA   N1     }
        JAZ   REST   }
        LDA   STRE   }
        ADD   ONE    }    Modify store instruction
        STA   STRE   }
        JMP   READ        Repeat
REST  , LDA   ORG1   }    Restore correct
        STA   STRE   }    instruction
        LDA   N      }    Restore number of
        STA   N1     }    numbers
        LDA   ZERO   }    Initiate summation
        STA   SUM    }
LOOP  , LDA   SUM    }
AD1   , ADD   NUM    }    Summation
        STA   SUM    }
        LDA   N1     }
        SUB   ONE    }    Test if finished
        STA   N1     }
        JAZ   FIN    }
        LDA   AD1    }
        ADD   ONE    }    Modify addition
        STA   AD1    }    instruction
        JMP   LOOP        Repeat
FIN   , LDA   ORG2   }    Restore original store
        STA   AD1    }    instruction
        LDA   SUM    }    Write result
        OUT          }
        HLT
ZERO  , 0
ONE   , 1
N     , 0
N1    , 0
ORG1  , 4046
ORG2  , 60026
SUM   , 0
NUM   , 0
```

2.4.2 "The Turtle"

The program moves itself further in memory.

MINI-program:

```
THIS  , LDA   THIS   }    Moves the i-th
STRE  , STA   NEXT   }    instruction
```

```
          LDA   THIS        Modify instruction in
          ADD   ONE         location THIS
          STA   THIS
          LDA   STRE        Modify instruction in
          ADD   ONE         location STRE
          STA   STRE
          LDA   PLEN
          SUB   ONE         Test if finished
          STA   PLEN
          JAZ   NEXT
          JMP   THIS        Repeat
ONE     , 1
PLEN    , 17
NEXT    , 0
```

2.5 Extension of the Imaginary Machine

Usually, programs consist of parts which are systematically repeated. In mathematics and high-level languages, we use indexes to refer to a given operand. An index may be a variable which changes its value.

In the preceding section, we saw examples of how to program loops. Indexing was implemented by changing the operand part of those instructions which refer to an indexed variable. This is clumsy and time-consuming. We now introduce a new register X, called the index register. It has the same length as the other two registers. There are three instructions to manipulate the X-register:

LDX	Load X-register
STX	Store X-register
JNC	Increment X-register and jump if it is negative.

2.5.1 Example

Alternative solution for the problem in example 2.4.1:

MINI-program:

```
          LDA   ADR
          ADD   N           Base address
          STA   ADR
          LDA   ZERO
          SUB   N           Negation of N
          STA   N
          LDX   N
```

```
              LDA    ZERO
              ADD    ADR,X  }           Summation
              JNC    NEXT               Test if finished
              STA    SUM
              OUT
              HLT
ADR   ,       NUM
ZERO  ,       0
N     ,       0
SUM   ,       0
NUM   ,       0
```

The effective address used in location NEXT is given by the contents of ADR plus the contents of the X-register, i.e., effective address: = contents (ADR) + X = (NUM + N) + X, where X = -N, -(N - 1), ..., -1.

2.6 Commands

Commands have a number of different formats. For the most part commands direct the assembler to take some action and cause no instructions to be assembled, but there are exceptions.

Three commands are of paramount importance; the define label command, the termination command and the execution command.

2.6.1 Define-label

This command is executed by writing a symbol at the beginning of a line followed by a comma (,). When this command is executed, the specified symbol is given as its value the current value of the location counter. Thus, if CLC = 400

```
          A,
```

gives A the value 400. The comma in a label definition must not be confused with the comma in the symbol ,X.

With the above command, instructions and constants, programs can be written. For example, if CLC = 400 in the beginning,

```
STRT,     LDA    F00
          STA    L
          HLT
F00  ,    3
L    ,    0
```

This is equivalent to

Location 400 →	044003
	004003
	146162
	000003
	000000

where STRT's address is 400, F00's address is 403 and L's address is 404.

The = command is another method of giving a value to a symbol. The way to use this command is to write a symbol at the beginning of a line and to immediately follow the symbol by the = sign (no intervening characters including spaces). The = sign is then followed by an expression composed of symbols and numbers. The arithmetic value of this expression is made the value of the symbol

```
A = STRT + 1
```

There may be no undefined symbols in the expression. This command us used to define symbols which are undefined after assembly has been terminated.

2.6.2 Termination

The termination command)END is used to terminate assembling. It must follow the last line in the program.

2.6.3 Execution

The execution command)RUN is used to start execution of a program. It must have been preceded by an)END command.

2.7 Exercises

2.7.1 Write a program that divides a number A by a number B. The quotient is placed in location Q and the rest in R.

2.7.2 Write a program that outputs 3 numbers in ascending order.

2.7.3 Write a program that reads another arbitrary program into the locations following your program and transfers control to it after instruction HLT has been read.

2.7.4 The "turtle" contains some mistakes. Write a correct "turtle"-program

i. without using the X-register.

ii. by using the X-register.

3. FUNCTIONAL DESCRIPTION OF AN ASSEMBLER

Each mnemonic has a unique binary value (See table 3.1). All the mnemonics and their binary or octal equivalents are stored in a table which is called the Mnemonic Table.

During assembly of an instruction, the assembler just adds the value of all the mnemonics which are encountered in the instruction. The total sum of this procedure is then the completely assembled instruction in binary or octal format. This sum which is now equal to the actual machine instruction, is now stored in memory.

The assembler employs a socalled Current Location Counter (CLC) to keep track of where in the memory an instruction is saved, and the value of the CLC is incremented by 1 for each instruction which is interpreted.

In this manner the instructions will be stored sequentially in memory during the assembly process.

3.1 Symbol Tables

The Defined-Symbol Table, DST, contains all symbols defined by "," during assembling or by "=" afterwards.

That is:

```
SYM, 2
SYM1 = SYM + 1
```

The symbols SYM and SYM1 are said to be local or user defined symbols.

When the assembler encounters SYM, 2, the symbol is first tested to see if it is already contained in the DST, thereby preventing the double definition of a symbol. If is not contained in DST, it is stored in DST with the octal value of CLC, i.e. its definition address.

If SYM has been defined before, an error message is printed out saying that the symbol SYM is double defined.

Next step in the processing of the symbol SYM is to see if it is part of the socalled Undefined Symbol Table, UST.

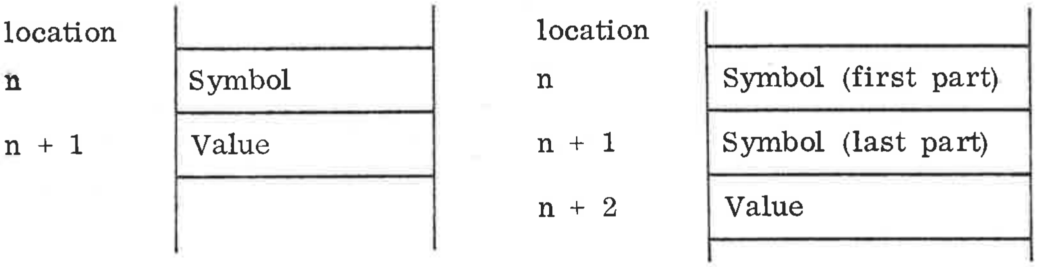
The Undefined Symbol Table is used for symbols which are referred to but not yet defined. If there are references to the symbol SYM prior to SYM, 2, all these references and their addresses are kept in the UST. If the symbol SYM has been referred to prior to the definition of SYM, the actual displacement is now calculated by the assembler and the displacement is now added into the instructions which have referred to SYM. After this has been done, the symbol SYM is deleted from the UST.

As the last step in the assembly process of SYM, 2, the binary value of 2 is placed in the memory location the CLC is pointing to, and the CLC is incremented by 1.

3.2 Table Structure

The structure of the mnemonic, defined-symbol and undefined-symbol table is basically the same.

Each symbol in the mnemonic table will have an internal representation which require two memory locations. Symbols in DST and UST require three memory locations.



Mnemonic Table

DST and UST

Figure 2.1: Table Structure

In the mnemonic table only one location is used to store the symbol. Mnemonic symbols consist of three letters each of which are stored in five bits. The second location is used for the fixed binary value of the mnemonic symbol.

In DST and UST the two first locations are used to store the actual symbol itself. The third location is used for saving the value of CLC, either as definition address in DST or as reference address in UST.

3.3 Example of Assembly

Assume that the following instruction is to be assembled:

```
LDA NUM↲
```

To assemble this instruction, the assembler executes the following steps:

i. Each character of a symbol is read one by one. Space indicates to the assembler that it has read a complete symbol. This would first be LDA.

ii. Next, the symbol will be tested to see if it is found in the Mnemonics Table or not. It if is a mnemonic its octal value (in this example 044000_8) will be saved. If it is not a mnemonic, the assembler continues at step iv.

iii. On completion of step ii, the assembler continues reading characters of which constitutes the next symbol which is now NUM.

iv. The symbol NUM is tested for membership of the defined symbol table to see if NUM is already defined. If true, the displacement: = CLC - definition address is calculated and added to the instruction saved so far.

If the symbol NUM is not a member of the defined symbol table, NUM will be placed in the undefined symbol table together with the value of the CLC which now holds the value of memory location where the symbol NUM is being referred to by the instruction LDA NUM. Now, only the value of LDA is stored in the location where CLC is pointing to, and the assembly of the instruction LDA NUM will not be completed before NUM is defined.

v. The value of the complete instruction is stored in memory at the location given by CLC, and the assembler is ready to start the assembly process for the next instruction.

A complete flow diagram for any assembly process is shown in figure 3.2.

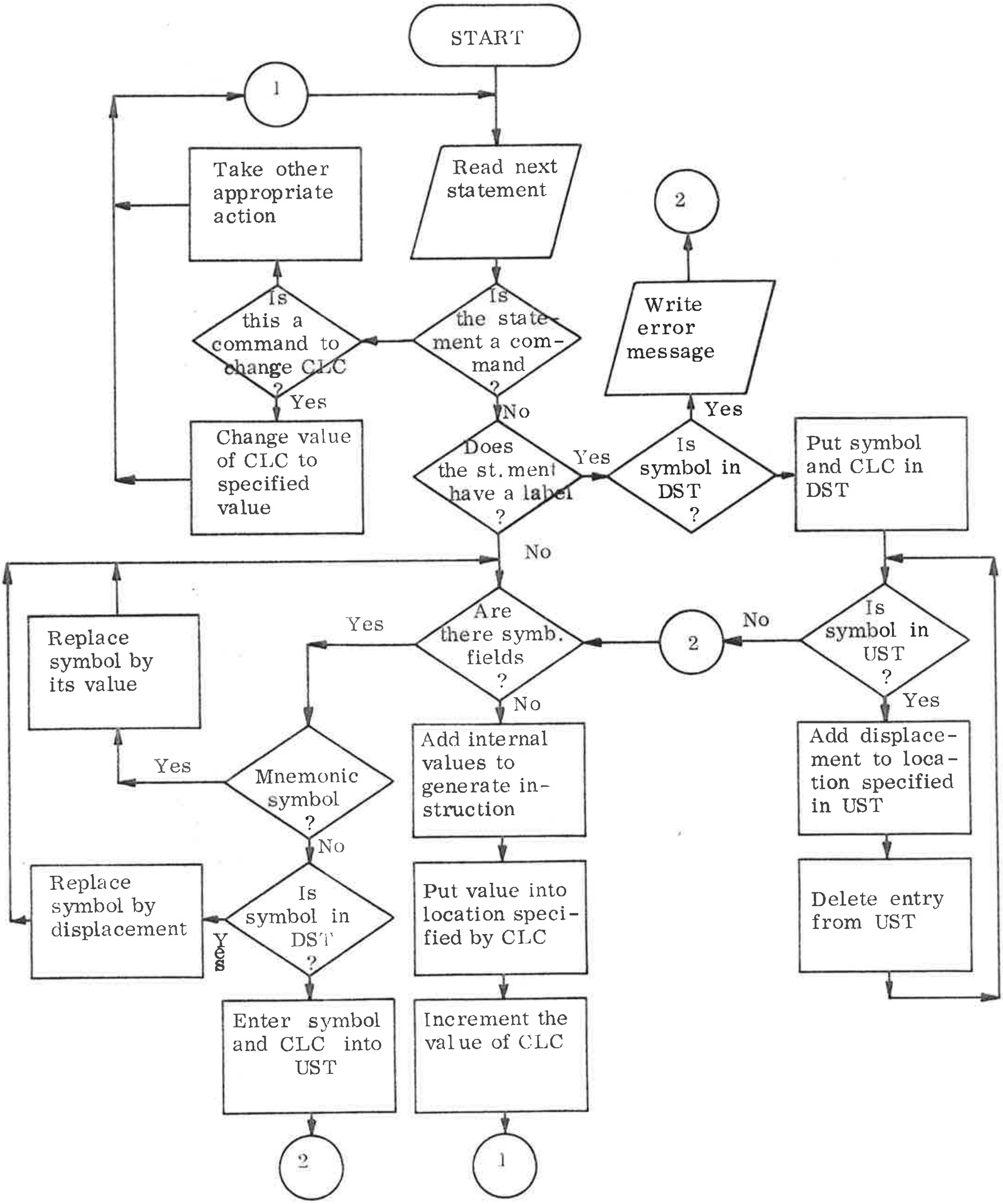

START
1
Read next statement
Is the statement a command ?
Is this a command to change CLC ?
Take other appropriate action
Yes
Change value of CLC to specified value
No
Does the st. ment have a label ?
Yes
Is symbol in DST ?
Yes
Write error message
2
Put symbol and CLC in DST
No
Is symbol in UST ?
No
2
Yes
Add displacement to location specified in UST
Delete entry from UST
Are there symb. fields ?
Yes
No
Add internal values to generate instruction
Put value into location specified by CLC
Increment the value of CLC
1
Mnemonic symbol ?
Yes
Replace symbol by its value
No
Is symbol in DST ?
Yes
Replace symbol by displacement
Enter symbol and CLC into UST
2

Figure 3.2: Simplified flow chart of assembling process

Octal value	Mnemonic	15	14	13	12	11	10	9	8	7 6 5 4 3 2 1 0
004000	STA	0	0	0	0	1	0	0	0	Displacement Δ
014000	STX	0	0	0	1	1	0	0	0	
044000	LDA	0	1	0	0	1	0	0	0	
054000	LDX	0	1	0	1	1	0	0	0	
060000	ADD	0	1	1	0	0	0	0	0	
064000	SUB	0	1	1	0	1	0	0	0	
124000	JMP	1	0	1	0	1	0	0	0	
130000	JAP	1	0	1	1	0	0	0	0	
131000	JAZ	1	0	1	1	0	0	1	0	
132400	JNC	1	0	1	1	0	1	0	1	
146162	HLT	1	1	0	0	1	1	0	0	0 1 1 1 0 0 1 0
160000	INP	1	1	1	0	0	0	0	0	
161000	OUT	1	1	1	0	0	0	1	0	
003000	,X	0	0	0	0	0	1	1	0	

Table 3.1: Summary of MINI instructions with internal representation

3.4 Exercises

3.4.1 Find the octal representation of the programs in example 2.3.2 and example 2.3.3.

3.4.2 Use the flow chart in figure 3.2 to trace the program of example 2.4.1. Build the defined- and undefined-symbol table.

3.4.3 Suppose we want to construct a one-pass assembler which uses only one table (see section 1.1.3). Change the flow chart in figure 3.2 to fit this demand.

4. INTRODUCTION TO MACRO INSTRUCTIONS

The assembly language programmer often finds it necessary to repeat some blocks of instructions many times within a program. Macro facilities allow the programmer to associate names with symbol strings. In employing a macro, the programmer essentially defines a single instruction to represent a block of code. For every occurence of this one-line macro instruction in a program, the macro processor (part of the assembler) will substitute the entire block.

4.1 Macro Definition, Macro Call and Macro Expansion

Macro facilities in an assembler allow the programmer to associate a name with a sequence of symbolic instructions and to subsequently use that name to denote the sequence of instructions.

Consider for example the following program:

```
          .
          .
          .
          .
          .
          .
          INP
          ADD X
          OUT
          .
          .
          .
          .
          .
          INP
          ADD X
          OUT
          .
          .
          .
          .
          .
          .
X,        .......
```

In the above program, the sequence

```
INP
ADD X
OUT
```

occurs twice. It is convenient to name frequent sequences of instructions and to denote their occurence by the abbreviated name. A name is attached to a sequence of instructions by means of a macro instruction which may be formed in the following way:

```
                 MACRO     <macro name>
                           <sequence of instructions>
                            END
```

A macro definition is introduced by the control operation MACRO followed by the <macro name>. The <sequence of instructions> constitutes the macro body. The macro definition is terminated by the control operation END.

When a macro gets defined, the name and the macro body are entered into the macro table. The macro table is a symbol table of name-value correspondence, just like the mnemonic table or the defined-symbol table. It is consulted when the value, the macro body, associated with a macro name is to be determined.

The macro definition does not give rise to any lines of generated code. The use of the macro name as an operation mnemonic in an assembly program causes substitution of the macro body for the macro name and subsequent assembly of the generated lines of instruction. This use of a macro name is referred to as a macro call. The instruction sequence substituted for the macro name is referred to as the macro expansion generated by a macro call.

Our example might be rewritten as follows, assigning the name INCR to the repeated sequence.

```
Source                          Expanded source

MACRO     INCR
          INP
          ADD X
          OUT
          END
          :
          :                       INP
          INCR                    ADD X
          :                       OUT
          :                       :
          :                       :
          :                       INP
          INCR                    ADD X
          :                       OUT
          :                       :
X       , .........             X , .........
```

4.2 Formal Parameters in Macro Instructions

So far, we have only discussed parameterless macros. All of the calls to any given macro will produce precisely the same macro expansion. This is unnecessarily restrictive. An important extension is to allow macro definitions with formal parameters which can be substituted by different actual parameters in different macro calls.

Different fields or an entire instruction may be treated as formal parameters.

Consider the following macro definition which treats the operand field as formal parameters:

```
MACRO    SUM       X, Y, Z
         LDA       X
         ADD       Y
         STA       Z
         END
```

Macro calls of this macro must contain three actual parameters. Two kinds of substitution are performed to obtain the macro expansion resulting from a macro call:

i. Actual parameters replace formal parameters

ii. The resulting macro body replaces the macro call.

Thus the macro call

```
         SUM       A, B, A
```

would result in the macro expansion

```
         LDA       A
         ADD       B
         STA       A
```

Similarly, the operation field or a complete instruction may be treated as formal parameters. The following example has a parameter which is a complete instruction, a parameter which is an operation field and a parameter which is an operand field:

```
MACRO    KAHU      X, Y, Z
         X
         Y         Z
         STA       Z
         END
```

The macro call

```
         KAHU   (LDA A), SUB, B
```

would give rise to the macro expansion

```
        LDA     A
        SUB     B
        STA     B
```

Actual parameters may in general be any strings which result in expansion of well-formed lines of instruction.

4.3 Remark

The macro facility is not part of the MINI assembly language.

4.4 Exercises

4.4.1 Define a macro which shortens the programs in example 2.3.2 and 2.3.3.

4.4.2 Consider the following program:

```
MACRO   READ    Z
        INP
        STA     Z
        END
MACRO   SEQ3    OP1, L, OP2
        STA     OP1
        JAZ     L
        LDA     OP2
        END
        READ    X
        STA     PROD
        READ    N
NEXT,   LDA     N
        SUB     ONE
        SEQ3    N, FIN, X
CONT,   SUB     ONE
        SEQ3    X1, NEXT, PROD
        ADD     X
        STA     PROD
        LDA     X1
        JMP     CONT
FIN,    LDA     PROD
        OUT
        HLT
```

```
X,        0
N,        0
PROD,     0
X1,       0
ONE,      1
```

How will the program be expanded? Trace the program for X=2 and N=3. Which values do X, N, PROD and X1 have after execution?

4.4.3 Write a MINI-program to find the greatest common divisor of two numbers X and Y.

Try to shorten your source program by introducing macros.

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COMMENT AND EVALUATION SHEET

CF20 - Introduction to Assembly Programming
January 1975

In order for this manual to develop to the point where it best suits your needs, we must have your comments, corrections, suggestions for additions, etc. Please write down your comments on this pre-addressed form and post it. Please be specific wherever possible.

FROM: ______________________________

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– we make bits for the future

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