Chapter 2
Assemblers

Outline

- 2.1 Basic Assembler Functions
- 2.2 Machine-Dependent Assembler Features
- 2.3 Machine-Independent Assembler Features
- 2.4 Assembler Design Options
- 2.5 Implementation Examples

Introduction to Assemblers

- Fundamental functions
  - Translate mnemonic operation codes to their *machine language* equivalents
  - Assign *machine addresses* to *symbolic labels* used by the programmer
- The feature and design of an assembler depend
  - *Source language* it translate
  - The *machine language* it produce

2.1 Basic Assembler Functions

- ***Assembler***
  - A program that accepts an *assembly language program* as input and produces its *machine language equivalent* along with *information for the loader*

2.1 Basic Assembler Functions (Cont.)

- Constructions of assembly language program
  - ***Instruction***

    Label mnemonic operand
    - Operand
      - Direct addressing
        - E.g. LDA ZERO
      - Immediate addressing
        - E.g. LDA #0
      - Indexed addressing
        - E.g. STCH BUFFER, X
      - Indirect addressing
        - E.g J @RETADR

2.1 Basic Assembler Functions (Cont.)

- Constructions of assembly language program (Cont.)
  - ***Data***

    Label BYTE value

    Label WORD value

    Label RESB value

    Label RESW value

    - Label: name of operand
    - value: integer, character
    - E.g. EOF BYTE C'EOF'
    - E.g. FIVE WORD 5

Assembler Directives

- **Pseudo-instructions**
  - Not translated into machine instructions
  - Provide instructions to the assembler itself
- Basic assembler directives
  - **START:** specify *name* and *starting address of the program*
  - **END:** specify *end of program* and (option) *the first executable instruction in the program*
    - If not specified, use the address of the first executable instruction
  - **BYTE:** direct the assembler to *generate constants*
  - **WORD**
  - **RESB:** : instruct the assembler to *reserve memory location* without generating data values
  - **RESW**

Example of a SIC Assembler Language Program

- Show the generated *object code* for each statement in Fig. 2.1
- ***Loc*** column shows the *machine address* for each part of the assembled program
  - Assume program starts at address 1000
  - All instructions, data, or reserved storage are *sequential arranged* according to their order in source program.
  - A ***location counter*** is used to keep track the address changing

Example of a SIC Assembler Language Program (Fig 2.1,2.2)

Loc	Source statement			Object code
1000	COPY	START	1000	
1000	FIRST	STL	RETADR	141033
1003	CLOOP	JSUB	RDREC	482039
1006		LDA	LENGTH	001036
1009		COMP	ZERO	281030
100C		JEQ	ENDFIL	301015
100F		JSUB	WRREC	482061
1012		J	CLOOP	3C1003
1015	ENDFIL	LDA	EOF	00102A
1018		STA	BUFFER	0C1039
101B		LDA	THREE	00102D
101E		STA	LENGTH	0C1036
1021		JSUB	WRREC	482061
1024		LDL	RETADR	081033
1027		RSUB		4C0000
102A	EOF	BYTE	C'EOF'	454F46
102D	THREE	WORD	3	000003
1030	ZERO	WORD	0	000000
1033	RETADR	RESW	1	
1036	LENGTH	RESW	1	
1039	BUFFER	RESB	4096	

Example of a SIC Assembler Language Program (Fig 2.1,2.2) (Cont.)

```
                .
                .        SUBROUTINE TO READ RECORD INTO BUFFER
                .
        2039    RDREC    LDX      ZERO          041030
        203C             LDA      ZERO          001030
        203F    RLOOP    TD       INPUT         E0205D
        2042             JEQ      RLOOP         30203F
        2045             RD       INPUT         D8205D
        2048             COMP     ZERO          281030
        204B             JEQ      EXIT          302057
        204E             STCH     BUFFER,X      549039
        2051             TIX      MAXLEN        2C205E
        2054             JLT      RLOOP         38203F
        2057    EXIT     STX      LENGTH        101036
        205A             RSUB                   4C0000
        205D    INPUT    BYTE     X'F1'         F1
        205E    MAXLEN   WORD     4096          001000
```

Example of a SIC Assembler Language Program (Fig 2.1,2.2) (Cont.)

```
                .
                .       SUBROUTINE TO WRITE RECORD FROM BUFFER
                .
2061    WRREC   LDX     ZERO            041030
2064    WLOOP   TD      OUTPUT          E02079
2067            JEQ     WLOOP           302064
206A            LDCH    BUFFER,X        509039
206D            WD      OUTPUT          DC2079
2070            TIX     LENGTH          2C1036
2073            JLT     WLOOP           382064
2076            RSUB                    4C0000
2079    OUTPUT  BYTE    X'05'           05
                END     FIRST
```

Figure 2.2 Program from Fig. 2.1 with object code.

Functions of a Basic Assembler

- Convert *mnemonic operation codes* to their *machine language equivalents*
  - E.g. STL -> 14 (line 10)
- Convert *symbolic operands* to their equivalent *machine addresses*
  - E.g. RETADR -> 1033 (line 10)
- Build the machine instructions in the proper format
- Convert the *data constants* to *internal machine representations*
  - E.g. EOF -> 454F46 (line 80)
- Write the *object program* and the *assembly listing*

Functions of a Basic Assembler (Cont.)

- All of above functions can be accomplished by *sequential processing* of the source program
  - *Except number 2 in processing symbolic operands*
- Example
  - **10 STL RETADR**
    - *RETADR* is not yet defined when we encounter *STL* instruction
    - Called *forward reference*

Symbolic Operands (Renew)

- We're not likely to write *memory addresses* directly in our code.
  - Instead, we will define *variable names*.
- Other examples of symbolic operands
  - Labels (for jump instructions)
  - Subroutines
  - Constants

Address Translation Problem

- *Forward reference*
  - A reference to a label that is defined later in the program
    - We will be unable to process this statement
- As a result, most assemblers make 2 passes over the source program
  - ***1st pass***: scan *label definitions* and *assign addresses*
  - ***2nd pass***: actual translation (object code)

Functions of Two Pass Assembler

- **Pass 1 - define symbols (assign addresses)**
  - Assign addresses to all statements in the program
  - Save the values assigned to all labels for use in Pass 2
  - Process some assembler directives
- **Pass 2 - assemble instructions and generate object program**
  - Assemble instructions
  - Generate data values defined by BYTE, WORD, etc.
  - Process the assembler directives not done in Pass 1
  - Write the object program and the assembly listing

Object Program

- Finally, assembler must write the generated object code to some output device
  - Called *object program*
  - Will be later loaded into memory for execution

Object Program (Cont.)

- Contains 3 types of records:
  - **Header record:**

Col. 1	H
Col. 2-7	Program name
Col. 8-13	Starting address (hex)
Col. 14-19	Length of object program in bytes (hex)

  - **Text record**

Col.1	T
Col.2-7	Starting address in this record (hex)
Col. 8-9	Length of object code in this record in bytes (hex)
Col. 10-69	Object code (hex) (2 columns per byte)

  - **End record**

Col.1	E
Col.2~7	Address of first executable instruction (hex) (END program_name)

Object Program for Fig 2.2 (Fig 2.3)

Program name,Starting address (hex),Length of object program in bytes (hex)

```
H^COPY  ^001000^00107A
T^001000^1E^141033^482039^001036^281030^301015^482061^3C1003^00102A^0C1039^00102D
T^00101E^15^0C1036^482061^081033^4C0000^454F46^000003^000000
T^002039^1E^041030^001030^E0205D^30203F^D8205D^281030^302057^549039^2C205E^38203F
T^002057^1C^101036^4C0000^F1^001000^041030^E02079^302064^509039^DC2079^2C1036
T^002073^07^382064^4C0000^05
E^001000
```

2.3 Object program corresp

Address of first executable instruction (hex)

Starting address (hex),Length of object code in this record (hex),Object code (hex)

2.1.2 Assembler Algorithm and Data Structures

- Algorithm
  - Two-pass assembler
- Data Structures
  - Operation Code Table (OPTAB)
  - Symbol Table (SYMTAB)
  - Location Counter (LOCCTR)

Internal Data Structures

- **OPTAB (operation code table)**
  - Content
    - Menmonic machine code and its machine language equivalent
    - May also include instruction format, length etc.
  - Usage
    - Pass 1: used to loop up and validate operation codes in the source program
    - Pass 2: used to translate the operation codes to machine language
  - Characteristics
    - Static table, predefined when the assembler is written
  - Implementation
    - Array or hash table with mnemonic operation code as the key (preferred)
  - Ref. Appendix A

Internal Data Structures (Cont.)

- **SYMTAB (symbol table)**
  - Content
    - Label name and its value (address)
    - May also include flag (type, length) etc.
  - Usage
    - Pass 1: labels are entered into SYMTAB with their address (from LOCCTR) as they are encountered in the source program
    - Pass 2: symbols used as operands are looked up in SYMTAB to obtain the address to be inserted in the assembled instruction
  - Characteristic
    - Dynamic table (insert, delete, search)
  - Implementation
    - Hash table for efficiency of *insertion* and *retrieval*

Internal Data Structures (Cont.)

- **Location Counter**
  - A variable used to help in *assignment of addresses*
  - Initialized to the beginning address specified in the START statement
  - Counted in bytes

Algorithm for 2 Pass Assembler (Fig 2.4)

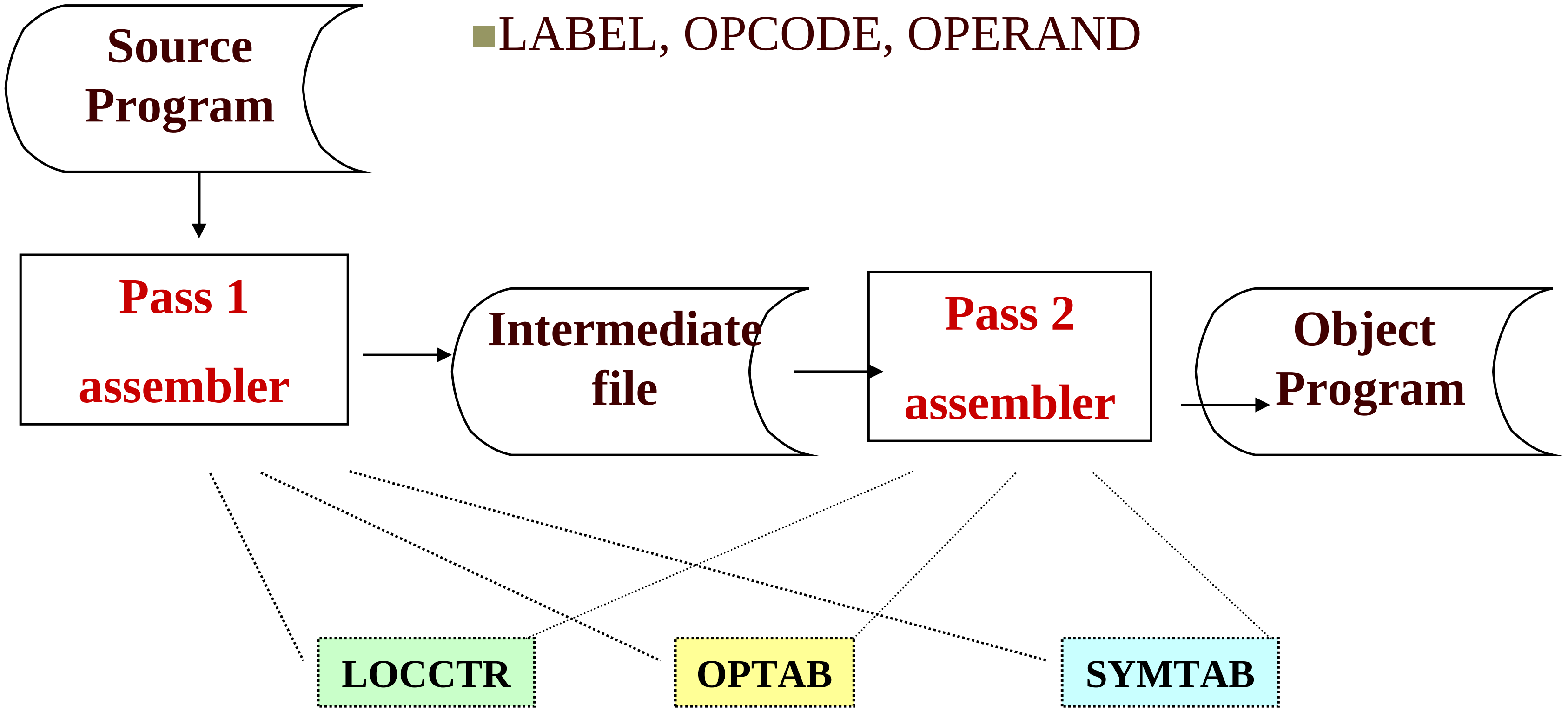
- Figure 2.4 (a): algorithm for pass 1 of assembler
- Figure 2.4 (b): algorithm for pass 2 of assembler

Algorithm for 2 Pass Assembler (Fig 2.4)

- Both pass1 and pass 2 need to read the source program.
  - However, pass 2 needs more information
    - Location counter value, error flags
- **Intermediate file**
  - Contains each source statement with its assigned address, error indicators, etc
  - Used as the input to Pass 2

Intermediate File

- LABEL, OPCODE, OPERAND



Algorithm for Pass 1 of Assembler (Fig 2.4a)

Pass 1:

```
begin
  read first input line
  if OPCODE = 'START' then
     begin
        save #[OPERAND] as starting address
        initialize LOCCTR to starting address
        write line to intermediate file
        read next input line
     end {if START}
  else
     initialize LOCCTR to 0
```

```
    while OPCODE ≠ 'END' do
        begin
            if this is not a comment line then
                begin
                    if there is a symbol in the LABEL field then
                        begin
                            search SYMTAB for LABEL
                            if found then
                                set error flag (duplicate symbol)
                            else
                                insert (LABEL,LOCCTR) into SYMTAB
                        end {if symbol}
                    search OPTAB for OPCODE
                    if found then
                        add 3 {instruction length} to LOCCTR
                    else if OPCODE = 'WORD' then
                        add 3 to LOCCTR
                    else if OPCODE = 'RESW' then
                        add 3 * #[OPERAND] to LOCCTR
                    else if OPCODE = 'RESB' then
                        add #[OPERAND] to LOCCTR
                    else if OPCODE = 'BYTE' then
                        begin
                            find length of constant in bytes
                            add length to LOCCTR
                        end {if BYTE}
                    else
                        set error flag (invalid operation code)
                end {if not a comment}
            write line to intermediate file
            read next input line
        end {while not END}
    write last line to intermediate file
    save (LOCCTR - starting address) as program length
end {Pass 1}
```

Figure 2.4(a) Algorithm for Pass 1 of assembler.

Algorithm for Pass 2 of Assembler (Fig 2.4b)

Pass 2:

```
begin
   read first input line {from intermediate file}
   if OPCODE = 'START' then
      begin
         write listing line
         read next input line
      end {if START}
   write Header record to object program
   initialize first Text record
```

```
while OPCODE ≠ 'END' do
    begin
        if this is not a comment line then
            begin
                search OPTAB for OPCODE
                if found then
                    begin
                        if there is a symbol in OPERAND field then
                            begin
                                search SYMTAB for OPERAND
                                if found then
                                    store symbol value as operand address
                                else
                                    begin
                                        store 0 as operand address
                                        set error flag (undefined symbol)
                                    end
                            end {if symbol}
                        else
                            store 0 as operand address
                        assemble the object code instruction
                    end {if opcode found}
                else if OPCODE = 'BYTE' or 'WORD' then
                    convert constant to object code
                if object code will not fit into the current Text record then
                    begin
                        write Text record to object program
                        initialize new Text record
                    end
                add object code to Text record
            end {if not comment}
        write listing line
        read next input line
    end {while not END}
  write last Text record to object program
  write End record to object program
  write last listing line
end {Pass 2}
```

Figure 2.4(b) Algorithm for Pass 2 of assembler.

Assembler Design

- Machine Dependent Assembler Features
  - instruction formats and addressing modes
  - program relocation
- Machine Independent Assembler Features
  - literals
  - symbol-defining statements
  - expressions
  - program blocks
  - control sections and program linking
- Assembler design Options
  - one-pass assemblers
  - multi-pass assemblers

2.2 Machine Dependent Assembler Features

- Machine Dependent Assembler Features
  - SIC/XE
  - Instruction formats and addressing modes
  - Program relocation

SIC/XE Assembler

- Previous, we know how to implement the 2-pass SIC assembler.

- What’s new for SIC/XE?
  - More addressing modes.
  - Program Relocation.

SIC/XE Assembler (Cont.)

- SIC/XE
  - Immediate addressing: op #c
  - Indirect addressing: op @m
  - PC-relative or Base-relative addressing: op m
    - The assembler directive **BASE** is used with base-relative addressing
    - If displacements are too large to fit into a 3-byte instruction, then 4-byte extended format is used
  - Extended format: +op m
  - Indexed addressing: op m, **x**
  - Register-to-register instructions
  - Large memory
    - Support multiprogramming and need *program reallocation* capability

Example of a SIC/XE Program (Fig 2.5)

- Improve the execution speed
  - Register-to-register instructions
  - Immediate addressing: op #c
    - Operand is already present as part of the instruction
  - Indirect addressing: op @m
    - Often avoid the need of another instruction

Example of a SIC/XE Program (Fig 2.5,2.6)

Line	Loc	Source statement			Object code
5	0000	COPY	START	0	
10	0000	FIRST	STL	RETADR	17202D
12	0003		LDB	#LENGTH	69202D
13			BASE	LENGTH	
15	0006	CLOOP	+JSUB	RDREC	4B101036
20	000A		LDA	LENGTH	032026
25	000D		COMP	#0	290000
30	0010		JEQ	ENDFIL	332007
35	0013		+JSUB	WRREC	4B10105D
40	0017		J	CLOOP	3F2FEC
45	001A	ENDFIL	LDA	EOF	032010
50	001D		STA	BUFFER	0F2016
55	0020		LDA	#3	010003
60	0023		STA	LENGTH	0F200D
65	0026		+JSUB	WRREC	4B10105D
70	002A		J	@RETADR	3E2003
80	002D	EOF	BYTE	C'EOF'	454F46
95	0030	RETADR	RESW	1	
100	0033	LENGTH	RESW	1	
105	0036	BUFFER	RESB	4096	

Example of a SIC/XE Program (Fig 2.5,2.6) (Cont.)

```
110              .
115              .        SUBROUTINE TO READ RECORD INTO BUFFER
120              .
125    1036      RDREC    CLEAR    X              B410
130    1038               CLEAR    A              B400
132    103A               CLEAR    S              B440
133    103C              +LDT      #4096          75101000
135    1040      RLOOP    TD       INPUT          E32019
140    1043               JEQ      RLOOP          332FFA
145    1046               RD       INPUT          DB2013
150    1049               COMPR    A,S            A004
155    104B               JEQ      EXIT           332008
160    104E               STCH     BUFFER,X       57C003
165    1051               TIXR     T              B850
170    1053               JLT      RLOOP          3B2FEA
175    1056      EXIT     STX      LENGTH         134000
180    1059               RSUB                    4F0000
185    105C      INPUT    BYTE     X'F1'          F1
```

Example of a SIC/XE Program (Fig 2.5,2.6) (Cont.)

195		.			
200		.	SUBROUTINE TO WRITE RECORD FROM BUFFER		
205		.			
210	105D	WRREC	CLEAR	X	B410
212	105F		LDT	LENGTH	774000
215	1062	WLOOP	TD	OUTPUT	E32011
220	1065		JEQ	WLOOP	332FFA
225	1068		LDCH	BUFFER,X	53C003
230	106B		WD	OUTPUT	DF2008
235	106E		TIXR	T	B850
240	1070		JLT	WLOOP	3B2FEF
245	1073		RSUB		4F0000
250	1076	OUTPUT	BYTE	X'05'	05
255			END	FIRST	

Figure 2.6 Program from Fig. 2.5 with object code.

2.2.1 Instruction Formats and Addressing Modes

- START now specifies a beginning program address of 0
  - Indicate a *relocatable program*
- Register translation
  - For example: *COMPR A, S => A004*
  - Must keep the register name (A, X, L, B, S, T, F, PC, SW) and their values (0,1, 2, 3, 4, 5, 6, 8, 9)
    - Keep in SYMTAB

Address Translation

- Most register-to-memory instructions are assembled using *PC relative* or *base relative* addressing
  - Assembler must calculate a *displacement* as part of the object instruction
  - If displacement can be fit into 12-bit field, format 3 is used.
  - Format 3: 12-bit address field
    - Base-relative: 0~4095
    - PC-relative: -2048~2047
  - Assembler attempts to translate using PC-relative first, then base-relative
    - If displacement in PC-relative is out of range, then try base-relative

Address Translation (Cont.)

- If displacement can not be fit into 12-bit field in the object instruction, format 4 must be used.
  - Format 4: 20-bit address field
  - No displacement need to be calculated.
    - 20-bit is large enough to contain the full memory address
  - Programmer must specify extended format: +op m
  - For example: +*JSUB RDREC => 4B101036*
    - *LOC(RDREC) = 1036, get it from SYMTAB*

PC-Relative Addressing Modes

- *10 0000 FIRST STL RETADR 17202D*
  - Displacement= RETADR – (PC) = 30-**3** = 2D
  - Opcode (6 bits) $=14_{16}=00010100_2$
  - nixbpe=110010
    - n=1, i = 1: indicate neither *indirect* nor *immediate* addressing
    - p = 1: indicate *PC-relative* addressing

OPCODE	n	i	x	b	p	e	Address
0001 01	1	1	0	0	1	0	$(02D)_{16}$

Object Code = 17202D

PC-Relative Addressing Modes (Cont.)

- 40 0017 J CLOOP 3F2FEC
  - Displacement= CLOOP - (PC) = 6 - **1A** = -14 = FEC (2's complement for negative number)
  - Opcode=$3C_{16}$ = 00111100_2
  - nixbpe=110010

OPCODE	n	i	x	b	p	e	Address
0011 11	1	1	0	0	1	0	$(FEC)_{16}$

Object Code = 3F2FEC

Base-Relative Addressing Modes

- Base register is under the control of the programmer
  - Programmer use assembler directive ***BASE*** to specify which value to be assigned to base register (B)
  - Assembler directive ***NOBASE***: inform the assembler that the contents of base register no longer be used for addressing
  - ***BASE*** and ***NOBASE*** produce no executable code

Base-Relative Addressing Modes (Cont.)

- *12 LDB #LENGTH*
- *13 BASE LENGTH ;no object code*
- *160 104E STCH BUFFER, X 57C003*
  - Displacement= BUFFER – (B) = 0036 – 0033(=LOC(LENGTH)) = 3
  - Opcode=54=01010100
  - nixbpe=111100
    - n=1, i = 1: indicate neither *indirect* nor *immediate* addressing
    - x = 1: *indexed* addressing
    - b = 1: *base-relative* addressing

OPCODE	n	i	x	b	p	e	Address
0101 01	1	1	1	1	0	0	$(003)_{16}$

Object Code = 57C003

Address Translation

- Assembler attempts to translate using *PC-relative* first, then *base-relative*
  - e.g. 175 1056 STX LENGTH 134000
    - Try PC-relative first
      - Displacement= LENGTH - (PC) = 0033 - 1056 = -1026 (hex)
    - Try base-relative next
      - displacement= LENGTH – (B) = 0033 – 0033 =0
      - Opcode=10
      - nixbpe=110100
        - n=1, i = 1: indicate neither *indirect* nor *immediate* addressing
        - b = 1: *base-relative* addressing

Immediate Address Translation

- Convert the *immediate* operand to its internal representation and insert it into the instruction
- 55 0020 LDA #3 010003
  - Opcode=00
  - nixbpe=010000
    - i = 1: *immediate addressing*

OPCODE	n	i	x	b	p	e	Address
0000 00	0	1	0	0	0	0	$(003)_{16}$

Object Code = 010003

Immediate Address Translation (Cont.)

- 133 103C +LDT #4096 75101000
  - Opcode=74=01110100
  - nixbpe=010001
    - i = 1: *immediate addressing*
    - e = 1: *extended instruction format* since 4096 is too large to fit into the 12-bit displacement field

OPCODE	n	i	x	b	p	e	Address
0111 01	0	1	0	0	0	1	$(01000)_{16}$

Object Code = 75101000

Immediate Address Translation (Cont.)

- 12 0003 LDB #LENGTH 69202D
  - The immediate operand is the symbol LENGTH
    - The address of LENGTH is loaded into register B
  - Displacement=LENGTH – (PC) = 0033 – 0006 = 02D
  - Opcode=68_{16} = 01101000_2
  - nixbpe=010010
    - Combined *PC relative* (p=1) with *immediate addressing* (i=1)

OPCODE	n	i	x	b	p	e	Address
0110 10	0	1	0	0	1	0	$(02D)_{16}$

Indirect Address Translation

- Indirect addressing
  - The contents stored at the location represent the *address* of the operand, not the operand itself
  - Target addressing is computed as usual (PC-relative or BASE-relative)
  - *n* bit is set to 1

Indirect Address Translation (Cont.)

- 70 002A J @RETADR 3E2003
  - Displacement= RETADR- (PC) = 0030 – 002D =3
  - Opcode= 3C=00111100
  - nixbpe=100010
    - n = 1: *indirect addressing*
    - p = 1: *PC-relative addressing*

OPCODE	n	i	x	b	p	e	Address
0011 11	1	0	0	0	1	0	$(003)_{16}$

Note

- Ref: ***Appendix A***

2.2.2 Program Relocation

- The larger main memory of SIC/XE
  - Several programs can be loaded and run at the same time.
  - This kind of sharing of the machine between programs is called ***multiprogramming***
- To take full advantage
  - Load programs into memory wherever there is room
  - Not specifying a fixed address at assembly time
  - Called ***program relocation***

2.2.2 Program Relocation (Cont.)

- *Absolute program* (or *absolute assembly*)
  - Program must be loaded at the address specified *at assembly time.*
  - E.g. Fig. 2.1

program loading starting address 1000

```
COPY   START   1000
FIRST  STL     RETADR
          :
          :
```

  - e.g. 55 101B LDA THREE 00102D

  - What if the program is loaded to 2000

    e.g. 55 101B LDA THREE 00202D

    - Each absolute address should be modified

Example of Program Relocation (Fig 2.7)

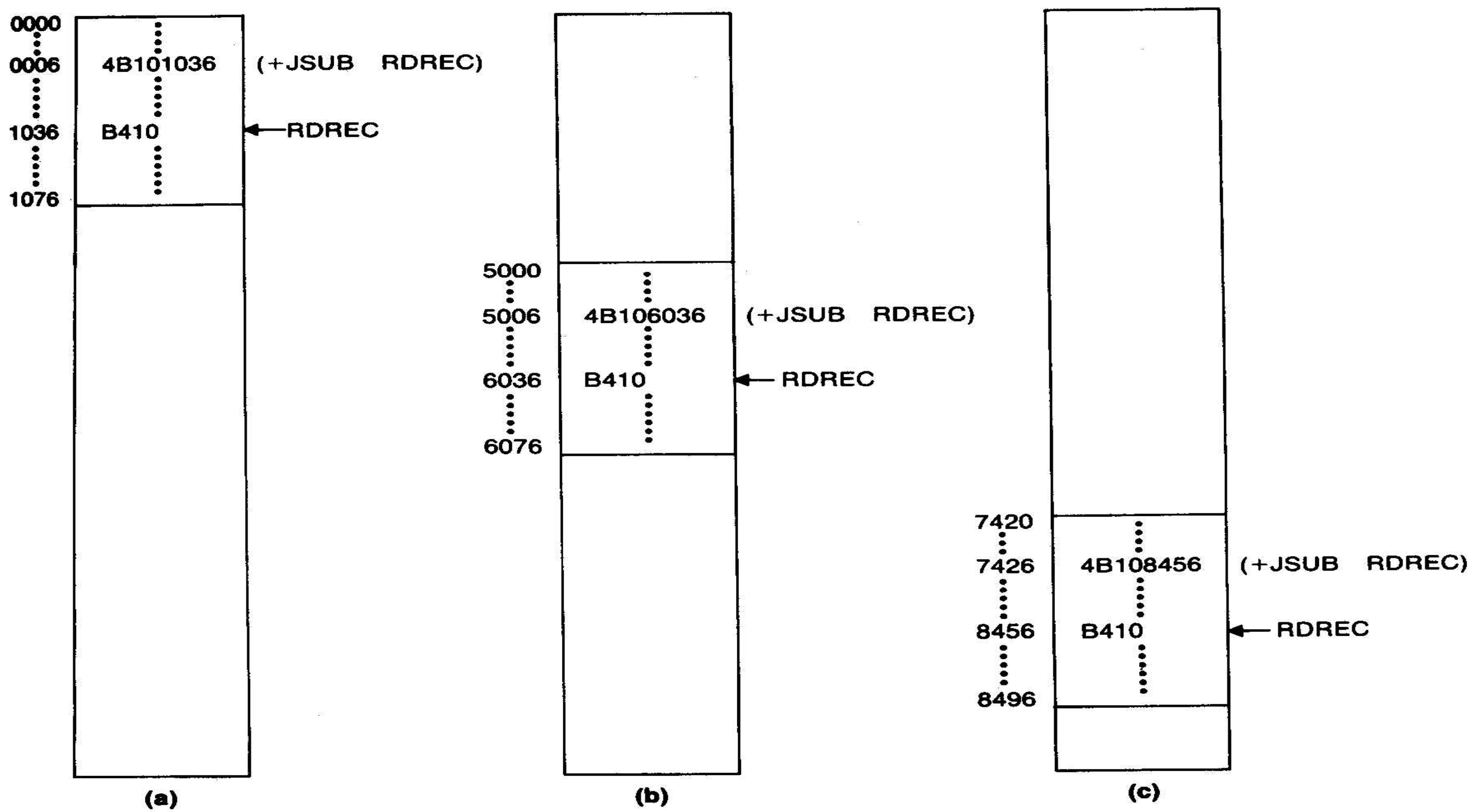


Figure 2.7 Examples of program relocation.

2.2.2 Program Relocation (Cont.)

- *Relocatable* program

```
COPY    START   0
FIRST   STL     RETADR
                :
                :
```

program loading starting address is determined *at load time*

  - An object program that contains the information necessary to perform *address modification* for relocation
  - The **assembler** must identify for the **loader** those parts of object program that need modification.
  - No instruction modification is needed for
    - Immediate addressing (not a memory address)
    - PC-relative, Base-relative addressing
  - The only parts of the program that require modification at load time are those that specify *direct addresses*
    - In SIC/XE, only found in extended format instructions

Instruction Format vs. Relocatable Loader

- In SIC/XE
  - Format 1, 2, 3
    - Not affect
  - Format 4
    - Should be modified
- In SIC
  - Format with address field
    - Should be modified
    - SIC does not support PC-relative and base-relative addressing

Relocatable Program

- We use modification records that are added to the object files.

Pass the *address–modification* information to the relocatable loader

- *Modification record*
  - Col 1 M
  - Col 2-7 Starting location of the address field to be modified, relative to the beginning of the program (hex)
  - Col 8-9 length of the address field to be modified, in half-bytes
  - E.g M$_\wedge$000007$_\wedge$05

Beginning address of the program is to be added to a field that begins at addr ox000007 and is 2.5 bytes in length.

Object Program for Fig 2.6 (Fig 2.8)

```
H^COPY  ^000000^001077
T^000000^1D^17202D^69202D^4B101036^032026^290000^332007^4B10105D^3F2FEC^032010
T^00001D^13^0F2016^010003^0F200D^4B10105D^3E2003^454F46
T^001036^1D^B410^B400^B440^75101000^E32019^332FFA^DB2013^A004^332008^57C003^B850
T^001053^1D^3B2FEA^134000^4F0000^F1^B410^774000^E32011^332FFA^53C003^DF2008^B850
T^001070^07^3B2FEF^4F0000^05
M^000007^05
M^000014^05
M^000027^05
E^000000
```

Figure 2.8 Object program corresponding to Fig. 2.6.

2.3 Machine-Independent Assembler Features

- Literals
- Symbol-Defining Statements
- Expressions
- Program Blocks
- Control Sections and Program Linking

2.3.1 Literals

- Design idea
  - Let programmers to be able to write the value of a constant operand as a part of the instruction that uses it.
  - This avoids having to define the constant elsewhere in the program and make up a label for it.
  - Such an operand is called a ***literal*** because the value is stated “literally” in the instruction.
  - A literal is identified with the prefix **=**
- Examples

45	001A	ENDFILLDA	=C’EOF’	032010
215	1062	WLOOPTD	=X’05’	E32011

Original Program (Fig. 2.6)

```
0000    COPY      START    0
0000    FIRST     STL      RETADR       17202D
0003              LDB      #LENGTH      69202D
                  BASE     LENGTH
0006    CLOOP    +JSUB     RDREC        4B101036
000A              LDA      LENGTH       032026
000D              COMP     #0           290000
0010              JEQ      ENDFIL       332007
0013             +JSUB     WRREC        4B10105D
0017              J        CLOOP        3F2FEC
001A    ENDFIL    LDA      EOF          032010
001D              STA      BUFFER       0F2016
0020              LDA      #3           010003
0023              STA      LENGTH       0F200D
0026             +JSUB     WRREC        4B10105D
002A              J        @RETADR      3E2003
002D    EOF       BYTE     C'EOF'       454F46
0030    RETADR    RESW     1
0033    LENGTH    RESW     1
0036    BUFFER    RESB     4096
```

Using Literal (Fig. 2.9)

```
  5    COPY     START    0             COPY FILE FROM INPUT TO OUTPUT
 10    FIRST    STL      RETADR        SAVE RETURN ADDRESS
 13             LDB      #LENGTH       ESTABLISH BASE REGISTER
 14             BASE     LENGTH
 15    CLOOP   +JSUB     RDREC         READ INPUT RECORD
 20             LDA      LENGTH        TEST FOR EOF (LENGTH = 0)
 25             COMP     #0
 30             JEQ      ENDFIL        EXIT IF EOF FOUND
 35            +JSUB     WRREC         WRITE OUTPUT RECORD
 40             J        CLOOP         LOOP
 45    ENDFIL   LDA      =C'EOF'       INSERT END OF FILE MARKER
 50             STA      BUFFER
 55             LDA      #3            SET LENGTH = 3
 60             STA      LENGTH
 65            +JSUB     WRREC         WRITE EOF
 70             J        @RETADR       RETURN TO CALLER
 93             LTORG
 95    RETADR   RESW     1
100    LENGTH   RESW     1             LENGTH OF RECORD
105    BUFFER   RESB     4096          4096-BYTE BUFFER AREA
106    BUFEND   EQU      *
107    MAXLEN   EQU      BUFEND-BUFFER MAXIMUM RECORD LENGTH
```

Object Program Using Literal

5	0000	COPY	START	0	
10	0000	FIRST	STL	RETADR	17202D
13	0003		LDB	#LENGTH	69202D
14			BASE	LENGTH	
15	0006	CLOOP	+JSUB	RDREC	4B101036
20	000A		LDA	LENGTH	032026
25	000D		COMP	#0	290000
30	0010		JEQ	ENDFIL	332007
35	0013		+JSUB	WRREC	4B10105D
40	0017		J	CLOOP	3F2FEC
45	001A	ENDFIL	LDA	=C'EOF'	032010
50	001D		STA	BUFFER	0F2016
55	0020		LDA	#3	010003
60	0023		STA	LENGTH	0F200D
65	0026		+JSUB	WRREC	4B10105D
70	002A		J	@RETADR	3E2003
93			LTORG		
	002D	*	=C'EOF'		454F46
95	0030	RETADR	RESW	1	

The same as before

Original Program (Fig. 2.6)

```
                 .
        105D     WRREC    CLEAR    X            B410
        105F              LDT      LENGTH       774000
        1062     WLOOP    TD       OUTPUT       E32011
        1065              JEQ      WLOOP        332FFA
        1068              LDCH     BUFFER,X     53C003
        106B              WD       OUTPUT       DF2008
        106E              TIXR     T            B850
        1070              JLT      WLOOP        3B2FEF
        1073              RSUB                  4F0000
        1076     OUTPUT   BYTE     X'05'        05
                          END      FIRST
```

Using Literal (Fig. 2.9)

```
       .
       .        SUBROUTINE TO WRITE RECORD FROM BUFFER
       .
WRREC           CLEAR   X               CLEAR LOOP COUNTER
                LDT     LENGTH
WLOOP           TD      =X'05'          TEST OUTPUT DEVICE
                JEQ     WLOOP           LOOP UNTIL READY
                LDCH    BUFFER,X        GET CHARACTER FROM BUFFER
                WD      =X'05'          WRITE CHARACTER
                TIXR    T               LOOP UNTIL ALL CHARACTERS
                JLT     WLOOP             HAVE BEEN WRITTEN
                RSUB                    RETURN TO CALLER
                END     FIRST
```

Object Program Using Literal

205		.			
210	105D	WRREC	CLEAR	X	B410
212	105F		LDT	LENGTH	774000
215	1062	WLOOP	TD	=X'05'	E32011
220	1065		JEQ	WLOOP	332FFA
225	1068		LDCH	BUFFER,X	53C003
230	106B		WD	=X'05'	DF2008
235	106E		TIXR	T	B850
240	1070		JLT	WLOOP	3B2FEF
245	1073		RSUB		4F0000
255			END	FIRST	
	1076	*	=X'05'		05

The same as before

Object Program Using Literal (Fig 2.9 & 2.10)

Line	Loc	Source statement			Object code
5	0000	COPY	START	0	
10	0000	FIRST	STL	RETADR	17202D
13	0003		LDB	#LENGTH	69202D
14			BASE	LENGTH	
15	0006	CLOOP	+JSUB	RDREC	4B101036
20	000A		LDA	LENGTH	032026
25	000D		COMP	#0	290000
30	0010		JEQ	ENDFIL	332007
35	0013		+JSUB	WRREC	4B10105D
40	0017		J	CLOOP	3F2FEC
45	001A	ENDFIL	LDA	=C'EOF'	032010
50	001D		STA	BUFFER	0F2016
55	0020		LDA	#3	010003
60	0023		STA	LENGTH	0F200D
65	0026		+JSUB	WRREC	4B10105D
70	002A		J	@RETADR	3E2003
93			LTORG		
	002D	*	=C'EOF'		454F46
95	0030	RETADR	RESW	1	
100	0033	LENGTH	RESW	1	
105	0036	BUFFER	RESB	4096	
106	1036	BUFEND	EQU	*	
107	1000	MAXLEN	EQU	BUFEND-BUFFER	
110		.			

Object Program Using Literal (Fig 2.9 & 2.10) (Cont.)

110		.			
115		.	SUBROUTINE TO READ RECORD INTO BUFFER		
120		.			
125	1036	RDREC	CLEAR	X	B410
130	1038		CLEAR	A	B400
132	103A		CLEAR	S	B440
133	103C		+LDT	#MAXLEN	75101000
135	1040	RLOOP	TD	INPUT	E32019
140	1043		JEQ	RLOOP	332FFA
145	1046		RD	INPUT	DB2013
150	1049		COMPR	A,S	A004
155	104B		JEQ	EXIT	332008
160	104E		STCH	BUFFER,X	57C003
165	1051		TIXR	T	B850
170	1053		JLT	RLOOP	3B2FEA
175	1056	EXIT	STX	LENGTH	134000
180	1059		RSUB		4F0000
185	105C	INPUT	BYTE	X'F1'	F1
195					

Object Program Using Literal (Fig 2.9 & 2.10) (Cont.)

195		.			
200		.	SUBROUTINE TO WRITE RECORD FROM BUFFER		
205		.			
210	105D	WRREC	CLEAR	X	B410
212	105F		LDT	LENGTH	774000
215	1062	WLOOP	TD	=X'05'	E32011
220	1065		JEQ	WLOOP	332FFA
225	1068		LDCH	BUFFER,X	53C003
230	106B		WD	=X'05'	DF2008
235	106E		TIXR	T	B850
240	1070		JLT	WLOOP	3B2FEF
245	1073		RSUB		4F0000
255			END	FIRST	
	1076	*	=X'05'		05

Figure 2.10 Program from Fig. 2.9 with object code.

Literals vs. Immediate Operands

- Immediate Operands
  - The operand value is assembled as *part of the machine instruction*
  - e.g. 55 0020 LDA #3 010003
- Literals ← Similar to define constant
  - The assembler generates the specified value as a constant *at some other memory location*
  - The effect of using a literal is exactly the same as if the programmer had *defined the constant* and used the *label* assigned to the constant as the instruction operand.
  - e.g. 45 001A ENDFIL LDA =C'EOF' 032010 (Fig. 2.9)
- Compare (Fig. 2.6)
  - e.g. 45 001A ENDFIL LDA EOF 032010
    80 002D EOF BYTE C'EOF' 454F46

Literal - Implementation

- *Literal pools*
  - All of the literal operands are gathered together into one or more *literal pools*
  - Normally, literal are placed at the end of the object program, i.e., following the END statement by the *assembler*
  - E.g., Fig. 2.10 (END statement)

255		END	FIRST	
	1076	*	=X'05'	05

Literal – Implementation (Cont.)

- In some case, *programmer* would like to place literals into a pool at some other location in the object program
  - Using assembler directive **LTORG** (see Fig. 2.10)
  - Create a literal pool that contains all of the literal operands used since the previous LTORG
  - e.g.,

45	001A	ENDFIL	LDA	=C'EOF'	032010 (Fig.2.10)
93			**LTORG**		
	002D	*	=C'EOF'		454F46

  - Reason: keep the literal operand close to the instruction referencing it
    - Allow *PC-relative addressing* possible

Literal - Implementation (Cont.)

- Duplicate literals
  - e.g. 215 1062 WLOOP TD =X'05'
  - e.g. 230 106B WD =X'05'
  - The assemblers should recognize duplicate literals and store only one copy of the specified data value
    - Compare the character strings defining them
      - E.g., =X'05'
      - Easier to implement, but has potential problem (see next)
    - Or compare the generated data value
      - E.g.the literals =C'EOF' and =X'454F46' would specify identical operand value.
      - Better, but will increase the complexity of the assembler

Same symbols, only one address is assigned

Basic Data Structure for Assembler to Handle Literal Operands

- *Data Structure: literal table* - *LITTAB*
  - Content
    - Literal name
    - The operand value and length
    - Address assigned to the operand
  - Implementation
    - Organized as a hash table, using literal name or value as key.

How the Assembler Handles Literals?

- Pass 1
  - Build LITTAB with literal name, operand value and length, (leaving the address unassigned).
  - Handle duplicate literals. (Ignore duplicate literals)
  - When encounter LTORG statement or end of the program, assign an address to each literal not yet assigned an address
    - Remember to update the PC value to assign each literal's address
- Pass 2
  - Search LITTAB for each literal operand encountered
  - Generate data values in the object program exactly as if they are generated by BYTE or WORD statements
  - Generate modification record for literals that represent an *address* in the program (e.g. a location counter value)

2.3.2 Symbol-Defining Statements

- ***Labels*** on instructions or data areas
  - The value of such a label is the *address* assigned to the statement on which it appears
- Defining symbols
  - All programmer to define symbols and specify their values
  - Format: symbol **EQU** value
    - Value can be *constant* or *expression involving constants and previously defined symbols*
  - Example
    - MAXLEN EQU 4096
    - +LDT #MAXLEN

2.3.2 Symbol-Defining Statements (Cont.)

- Usage:
  - Make the source program easier to understand
- How assembler handles it?
  - In pass 1: when the assembler encounters the EQU statement, it enters the symbol into SYMTAB for later reference.
  - In pass 2: assemble the instruction with the *value* of the symbol
    - Follow the previous approach

Examples of Symbol-Defining Statements

- E.g. +LDT #4096 (Fig 2.5)
  - MAXLEN EQU 4096
  - +LDT #MAXLEN
- E.g. define mnemonic names for registers
  - A EQU 0
  - X EQU 1
  - L EQU 2
  - …
- E.g. define names that reflect the logical function of the registers in the program
  - BASE EQU R1
  - COUNT EQU R2
  - INDEX EQU R3

Forward Reference

- All ***symbol-defining directives*** do ***not*** allow forward reference for 2-pass assembler
  - e.g., EQU…
  - All symbols used on the *right-hand side* of the statement must have been defined previously

E.g. (Cannot be assembled in 2-pass assm.)

```
ALPHA    EQU     BETA
BETA     EQU     DELTA
DELTA    RESW    1
```

2.3.3 Expressions

- Most assemblers allow the use of *expression* to replace symbol in the operand field.
  - Expression is evaluated by the assembler
  - Formed according to the rules using the operators +, -, *, /
    - Division is usually defined to produce an integer result
    - Individual terms can be
      - Constants
      - User-defined symbols
      - Special terms: e.g., * (= current value of location counter)

2.3.3 Expressions (Cont.)

- Review
  - Values in the object program are
    - *relative* to the beginning of the program or
    - *absolute* (independent of program location)
  - For example
    - Constants: absolute
    - Labels: relative

2.3.3 Expressions (Cont.)

- **Expressions can also be classified as *absolute expressions* or *relative expressions***
  - E.g. (Fig 2.9)

    107 MAXLEN EQU BUFEND-BUFFER

    - Both BUFEND and BUFFER are *relative terms*, representing addresses within the program
    - However the expression BUFEND-BUFFER represents an *absolute value: the difference between the two addresses*
  - When relative terms are paired with opposite signs
    - The dependency on the program starting address is canceled out
    - The result is an ***absolute value***

2.3.3 Expressions (Cont.)

- Absolute expressions
  - An expression that contains only absolute terms
  - An expression that contain relative terms but *in pairs* and the terms in each such pair have *opposite* signs
- Relative expressions
  - All of the relative terms *except one* can be paired and the remaining *unpaired relative terms* must have a *positive sign*
- ***No*** *relative terms* can enter into a multiplication or division operation no matter in absolute or relative expression

2.3.3 Expressions (Cont.)

- Errors: **(represent neither absolute values nor locations within the program)**
  - BUFEND+BUFFER // not opposite terms
  - 100-BUFFER // not in pair
  - 3*BUFFER // multiplication

2.3.3 Expressions (Cont.)

- Assemblers should determine the type of an expression
  - Keep track of the *types* of all symbols defined in the program in the symbol table.
  - Generate *Modification records* in the object program for relative values.

SYMTAB for Fig. 2.10

Symbol	Type	Value
RETADR	R	30
BUFFER	R	36
BUFEND	R	1036
MAXLEN	A	1000

2.3.4 Program Blocks

- Previously, main program, subroutines, and data area are treated as a unit and are assembled at the same time.
  - Although the source program logically contains subroutines, data area, etc, they were assembled into a single block of object code
  - To improve memory utilization, main program, subroutines, and data blocks may be allocated in separate areas.
- Two approaches to provide such a flexibility:
  - Program blocks
    - Segments of code that are rearranged within a single object program unit
  - Control sections
    - Segments of code that are translated into independent object program units

2.3.4 Program Blocks

- *Solution 1: Program blocks*
  - Refer to segments of code that are rearranged within a single object program unit
  - **Assembler directive: USE blockname**
    - Indicates which portions of the source program belong to which blocks.
  - Codes or data with same block name will allocate together
  - At the beginning, statements are assumed to be part of the unnamed (default) block
  - If no USE statements are included, the entire program belongs to this single block.

2.3.4 Program Blocks (Cont.)

- E.g: Figure 2.11
  - Three blocks
    - First: unnamed, i.e., default block
      - Line 5~ Line 70 + Line 123 ~ Line 180 + Line 208 ~ Line 245
    - Second: CDATA
      - Line 92 ~ Line 100 + Line 183 ~ Line 185 + Line 252 ~ Line 255
    - Third: CBLKS
      - Line 103 ~ Line 107
  - Each program block may actually contain *several separate segments* of the source program.
  - The assembler will (logically) rearrange these segments to gather together the pieces of each block.

Program with Multiple Program Blocks (Fig 2.11 & 2.12)

Line	Loc/Block		Source statement			Object code
5	0000	0	COPY	START	0	
10	0000	0	FIRST	STL	RETADR	172063
15	0003	0	CLOOP	JSUB	RDREC	4B2021
20	0006	0		LDA	LENGTH	032060
25	0009	0		COMP	#0	290000
30	000C	0		JEQ	ENDFIL	332006
35	000F	0		JSUB	WRREC	4B203B
40	0012	0		J	CLOOP	3F2FEE
45	0015	0	ENDFIL	LDA	=C'EOF'	032055
50	0018	0		STA	BUFFER	0F2056
55	001B	0		LDA	#3	010003
60	001E	0		STA	LENGTH	0F2048
65	0021	0		JSUB	WRREC	4B2029
70	0024	0		J	@RETADR	3E203F
92	0000	1		USE	CDATA	
95	0000	1	RETADR	RESW	1	
100	0003	1	LENGTH	RESW	1	
103	0000	2		USE	CBLKS	
105	0000	2	BUFFER	RESB	4096	
106	1000	2	BUFEND	EQU	*	
107	1000		MAXLEN	EQU	BUFEND-BUFFER	
110						

Program with Multiple Program Blocks (Fig 2.11 & 2.12) (Cont.)

110			.			
115			.	SUBROUTINE TO READ RECORD INTO BUFFER		
120			.			
123	0027	0		USE		
125	0027	0	RDREC	CLEAR	X	B410
130	0029	0		CLEAR	A	B400
132	002B	0		CLEAR	S	B440
133	002D	0		+LDT	#MAXLEN	75101000
135	0031	0	RLOOP	TD	INPUT	E32038
140	0034	0		JEQ	RLOOP	332FFA
145	0037	0		RD	INPUT	DB2032
150	003A	0		COMPR	A,S	A004
155	003C	0		JEQ	EXIT	332008
160	003F	0		STCH	BUFFER,X	57A02F
165	0042	0		TIXR	T	B850
170	0044	0		JLT	RLOOP	3B2FEA
175	0047	0	EXIT	STX	LENGTH	13201F
180	004A	0		RSUB		4F0000
183	0006	1		USE	CDATA	
185	0006	1	INPUT	BYTE	X'F1'	F1
195			.			

Program with Multiple Program Blocks (Fig 2.11 & 2.12)

195			.			
200			.	SUBROUTINE TO WRITE RECORD FROM BUFFER		
205			.			
208	004D	0		USE		
210	004D	0	WRREC	CLEAR	X	B410
212	004F	0		LDT	LENGTH	772017
215	0052	0	WLOOP	TD	=X'05'	E3201B
220	0055	0		JEQ	WLOOP	332FFA
225	0058	0		LDCH	BUFFER,X	53A016
230	005B	0		WD	=X'05'	DF2012
235	005E	0		TIXR	T	B850
240	0060	0		JLT	WLOOP	3B2FEF
245	0063	0		RSUB		4F0000
252	0007	1		USE	CDATA	
253				LTORG		
	0007	1	*	=C'EOF'		454F46
	000A	1	*	=X'05'		05
255				END	FIRST	

Figure 2.12 Program from Fig. 2.11 with object code.

Basic Data Structure for Assembler to Handle Program Blocks

- *Block name table*
  - Block name, block number, address, length

Block name	Block number	Address	Length
(default)	0	0000	0066
CDATA	1	0066	000B
CBLKS	2	0071	1000

How the Assembler Handles Program Blocks?

- Pass 1
  - Maintaining ***separate** location counter* for each program block
  - Each label is assigned an address that is relative to *the start of the block* that contains it
  - When labels are entered into SYMTAB, the *block name* or *number* is stored along with the assigned relative addresses.
  - At the end of Pass 1, the latest value of the location counter for each block indicates the length of that block
  - The assembler can then assign to each block a starting address in the object program

How the Assembler Handles Program Blocks? (Cont.)

- Pass 2
  - The address of each symbol can be computed by adding the *assigned block starting address* and the relative address of the symbol to the start of its block
    - The assembler needs the address for each symbol *relative to the start of the object program*, not the start of an individual program block

Table for Program Blocks

- At the end of Pass 1 in Fig 2.11:

Block name	Block number	Address	Length
(default)	0	0000	0066
CDATA	1	0066	000B
CBLKS	2	0071	1000

Example of Address Calculation

- Each source line is given a *relative address assigned* and a *block number*
  - ***Loc/Block*** Column in Fig. 2.11
- For an *absolute symbol* (whose value is not relative to the start of any program block), there is no block number
  - E.g. 107 1000 MAXLEN EQU BUFEND-BUFFER
- Example: calculation of address in Pass 2
  - 20 0006 0 LDA LENGTH 032060

LENGTH = (block 1 starting address)+0003 = 0066+0003= 0069

LOCCTR = (block 0 starting address)+0009 = 0009

PC-relative: Displacement = 0069 - (LOCCTR) = 0069-0009=0060

2.3.4 Program Blocks (Cont.)

- Program blocks reduce addressing problem:
  - No needs for extended format instructions (lines 15, 35, 65)
    - The larger buffer is moved to the end of the object program
  - No needs for base relative addressing (line 13, 14)
    - The larger buffer is moved to the end of the object program
  - LTORG is used to make sure the literals are placed ahead of any large data areas (line 253)
    - Prevent literal definition from its usage too far

2.3.4 Program Blocks (Cont.)

- Object code
  - It is not necessary to physically rearrange the generated code in the object program to place the pieces of each program block together.
  - Loader will load the object code from each record at the *indicated addresses*.
- For example (Fig. 2.13)
  - The first two Text records are generated from line 5~70
  - When the USE statement is recognized
    - Assembler writes out the current Text record, even if there still room left in it
    - Begin a new Text record for the new program block

Object Program Corresponding to Fig. 2.11 (Fig. 2.13)

```
H^COPY  ^000000^001071
T^000000^1E^172063^4B2021^032060^290000^332006^4B203B^3F2FEE^032055^0F2056^010003
T^00001E^09^0F2048^4B2029^3E203F
T^000027^1D^B410^B400^B440^75101000^E32038^332FFA^DB2032^A004^332008^57A02F^B850
T^000044^09^3B2FEA^13201F^4F0000
T^00006C^01^F1
T^00004D^19^B410^772017^E3201B^332FFA^53A016^DF2012^B850^3B2FEF^4F0000
T^00006D^04^454F46^05
E^000000
```

Figure 2.13 Object program corresponding to Fig. 2.11.

Program blocks for the Assembly and Loading Processes (Fig. 2.14)

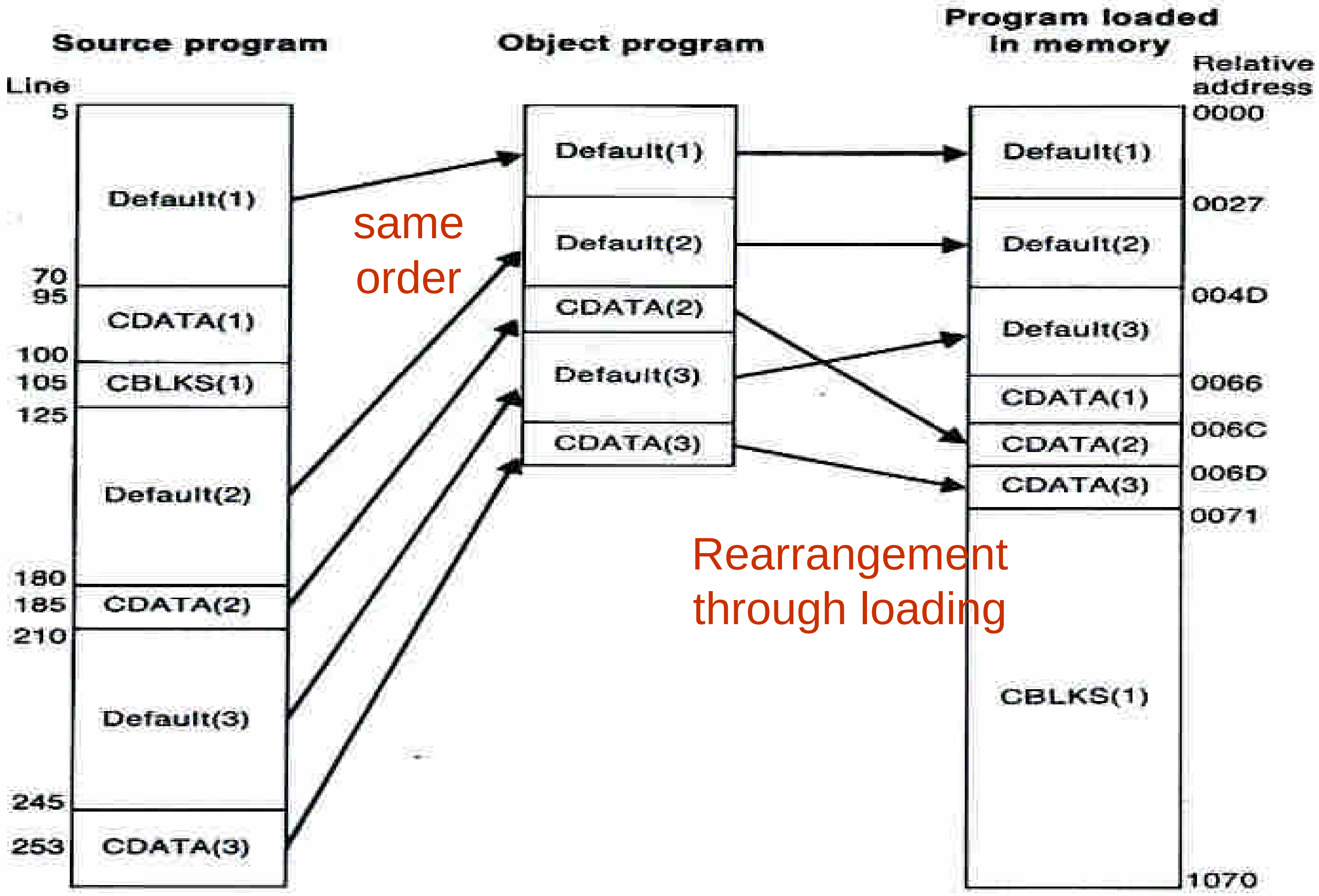


Figure 2.14 Program blocks from Fig. 2.11 traced through the assembly and loading processes.

2.3.5 Control Sections and Program Linking

- Control sections
  - A part of the program that maintains its *identity* after reassembly
    - Each control section can be loaded and relocated independently
    - Programmer can assemble, load, and manipulate each of these control sections separately
  - Often used for subroutines or other logical subdivisions of a program

2.3.5 Control Sections and Program Linking (Cont.)

- Instruction in one control section may need to refer to instructions or data located in another section
  - Called *external reference*
- However, assembler have no idea where any other control sections will be located at execution time
- The assembler has to generate information for such kind of references, called external references, that will allow the loader to perform the required linking.

Program Blocks v.s. Control Sections

- Program blocks
  - Refer to segments of code that are rearranged with *a single object program unit*
- Control sections
  - Refer to segments that are translated into *independent object program units*

Illustration of Control Sections and Program Linking (Fig 2.15 & 2.16)

First control section: COPY

Implicitly defined as an external symbol

Define external symbols

External reference

Line	Loc	Source statement			Object code
5	0000	COPY	START	0	
6			EXTDEF	BUFFER,BUFEND,LENGTH	
7			EXTREF	RDREC,WRREC	
10	0000	FIRST	STL	RETADR	172027
15	0003	CLOOP	+JSUB	RDREC	4B100000
20	0007		LDA	LENGTH	032023
25	000A		COMP	#0	290000
30	000D		JEQ	ENDFIL	332007
35	0010		+JSUB	WRREC	4B100000
40	0014		J	CLOOP	3F2FEC
45	0017	ENDFIL	LDA	=C'EOF'	032016
50	001A		STA	BUFFER	0F2016
55	001D		LDA	#3	010003
60	0020		STA	LENGTH	0F200A
65	0023		+JSUB	WRREC	4B100000
70	0027		J	@RETADR	3E2000
95	002A	RETADR	RESW	1	
100	002D	LENGTH	RESW	1	
103			LTORG		
	0030	*	=C'EOF'		454F46
105	0033	BUFFER	RESB	4096	
106	1033	BUFEND	EQU	*	
107	1000	MAXLEN	EQU	BUFEND-BUFFER	

Illustration of Control Sections and Program Linking (Fig 2.15 & 2.16) (Cont.)

Second control section: RDREC

External reference

```
109   0000   RDREC    CSECT
110                 .
115                 .         SUBROUTINE TO READ RECORD INTO BUFFER
120                 .
122                          EXTREF    BUFFER,LENGTH,BUFEND
125   0000                   CLEAR     X                       B410
130   0002                   CLEAR     A                       B400
132   0004                   CLEAR     S                       B440
133   0006                   LDT       MAXLEN                  77201F
135   0009   RLOOP           TD        INPUT                   E3201B
140   000C                   JEQ       RLOOP                   332FFA
145   000F                   RD        INPUT                   DB2015
150   0012                   COMPR     A,S                     A004
155   0014                   JEQ       EXIT                    332009
160   0017                  +STCH      BUFFER,X                57900000
165   001B                   TIXR      T                       B850
170   001D                   JLT       RLOOP                   3B2FE9
175   0020   EXIT           +STX       LENGTH                  13100000
180   0024                   RSUB                              4F0000
185   0027   INPUT           BYTE      X'F1'                   F1
190   0028   MAXLEN          WORD      BUFEND-BUFFER           000000
```

Illustration of Control Sections and Program Linking (Fig 2.15 & 2.16) (Cont.)

193	0000	WRREC	CSECT		
195		.			
200		.	SUBROUTINE TO WRITE RECORD FROM BUFFER		
205		.			
207			EXTREF	LENGTH,BUFFER	
210	0000		CLEAR	X	B410
212	0002		+LDT	LENGTH	77100000
215	0006	WLOOP	TD	=X'05'	E32012
220	0009		JEQ	WLOOP	332FFA
225	000C		+LDCH	BUFFER,X	53900000
230	0010		WD	=X'05'	DF2008
235	0013		TIXR	T	B850
240	0015		JLT	WLOOP	3B2FEE
245	0018		RSUB		4F0000
255			END	FIRST	
	001B	*	=X'05'		05

Figure 2.16 Program from Fig. 2.15 with object code.

2.3.5 Control Sections and Program Linking (Cont.)

- **Assembler directive: secname** CSECT
  - Signal the start of a new control section
  - e.g. 109 RDREC CSECT
  - e.g. 193 WRREC CSECT
  - **START** also identifies the beginning of a section
- *External references*
  - References between control sections
  - The assembler generates information for each external reference that will allows the loader to perform the required linking.

External Definition and References

- *External definition*
  - **Assembler directives: EXTDEF name [, name]**
  - EXTDEF names symbols, called ***external symbols***, that are defined in this control section and may be used by other sections
  - Control section names do not need to be named in an EXTDEF statement (e.g., COPY, RDREC, and WRREC)
    - They are automatically considered to be external symbols
- *External reference*
  - **Assembler directives: EXTREF name [,name]**
  - EXTREF names symbols that are used in this control section and are defined elsewhere

2.3.5 Control Sections and Program Linking (Cont.)

- Any instruction whose operand involves an external reference
  - Insert an address of zero and pass information to the loader
    - Cause the proper address to be inserted *at load time*
  - *Relative addressing* is not possible
    - The address of external symbol have no predictable relationship to anything in this control section
    - An *extended format instruction* must be used to provide enough room for the actual address to be inserted

Example of External Definition and References

- Example
  - 15 0003 CLOOP +JSUB RDREC 4B100000
  - 160 0017 +STCH BUFFER,X 57900000
  - 190 0028 MAXLEN WORD BUFEND-BUFFER 000000

How the Assembler Handles Control Sections?

- **The assembler must include information in the object program that will cause the loader to insert proper values where they are required**
- *Define record:* gives information about external symbols named by EXTDEF
  - Col. 1 D
  - Col. 2-7 Name of external symbol defined in this section
  - Col. 8-13 Relative address within this control section (hex)
  - Col.14-73 Repeat information in Col. 2-13 for other external symbols
- *Refer record:* lists symbols used as external references, i.e., symbols named by EXTREF
  - Col. 1 R
  - Col. 2-7 Name of external symbol referred to in this section
  - Col. 8-73 Name of other external reference symbols

How the Assembler Handles Control Sections? (Cont.)

- *Modification record* **(revised)**
  - Col. 1 M
  - Col. 2-7 Starting address of the field to be modified (hex)
  - Col. 8-9 Length of the field to be modified, in half-bytes (hex)
  - Col. 10 Modification flag (+ or -)
  - Col.11-16 External symbol whose value is to be added to or subtracted from the indicated field.
- Control section name is automatically an external symbol, it is available for use in Modification records.
- Example (Figure 2.17)
  - M000004^05^+RDREC
  - M000011^05^+WRREC
  - M000024^05^+WRREC
  - M000028^06^+BUFEND //Line 190 BUFEND-BUFFER
  - M000028^06^-BUFFER

Object Program Corresponding to Fig. 2.15 (Fig. 2.17)

```
HCOPY  000000001033
^      ^     ^
DBUFFER000033BUFEND001033LENGTH00002D
^      ^     ^     ^     ^     ^
RRDREC WRREC
^      ^
T0000001D1720274B1000000320232900003320074B1000003F2FEC0320160F2016
^      ^ ^     ^      ^     ^     ^     ^      ^     ^     ^
T00001D0D0100030F200A4B1000003E2000
^      ^ ^     ^     ^      ^
T00003003454F46
^      ^ ^
M00000405+RDREC
^      ^ ^
M00001105+WRREC
^      ^ ^
M00002405+WRREC
^      ^ ^
E000000
^
```

Object Program Corresponding to Fig. 2.15 (Fig. 2.17) (Cont.)

```
HRDREC 00000000002B
^      ^     ^
RBUFFERLENGTHBUFEND
^      ^     ^
T0000001DB410B400B44077201FE3201B332FFADB2015A00433200957900000B850
^      ^ ^   ^   ^   ^     ^     ^     ^     ^     ^     ^     ^
T00001D0E3B2FE9131000004F0000F1000000
^      ^ ^     ^     ^     ^ ^
M00001805+BUFFER
^      ^ ^
M00002105+LENGTH
^      ^ ^
M00002806+BUFEND
^      ^ ^
M00002806-BUFFER
^      ^ ^
E
```

Object Program Corresponding to Fig. 2.15 (Fig. 2.17) (Cont.)

```
H^WRREC ^000000^00001C
R^LENGTH^BUFFER
T^000000^1C^B410^77100000^E32012^332FFA^53900000^DF2008^B850^3B2FFE^4F0000^05
M^000003^05^+LENGTH
M^00000D^05^+BUFFER
E
```

Figure 2.17 Object program corresponding to Fig. 2.15.

2.4 Assembler Design Options

- One-pass assemblers
- Multi-pass assemblers

2.4.1 One-Pass Assemblers

- Goal: avoid a second pass over the source program
- Main problem
  - Forward references to *data items* or *labels on instructions*
- Solution
  - Data items: require all such areas be defined before they are referenced
  - Label on instructions: cannot be eliminated
    - E.g. the logic of the program often requires a forward jump
    - It is too inconvenient if forward jumps are not permitted

Two Types of One-Pass Assemblers:

- Load-and-go assembler
  - Produces object code directly in memory for immediate execution

- The other assembler
  - Produces usual kind of object code for later execution

Load-and-Go Assembler

- No object program is written out, no loader is needed
- Useful for program development and testing
  - Avoids the overhead of writing the object program out and reading it back in
- Both one-pass and two-pass assemblers can be designed as load-and-go
  - However, one-pass also avoids the overhead of an additional pass over the source program
- For a load-and-go assembler, the actual address must be known at assembly time.

Forward Reference Handling in One-pass Assembler

- When the assembler encounter an instruction operand that has not yet been defined:
  1. The assembler omits the translation of operand address
  2. Insert the symbol into SYMTAB, if not yet exist, and mark this symbol ***undefined***
  3. The address that refers to the undefined symbol is added to *a list of forward references* associated with the symbol table entry
  4. When the definition for a symbol is encountered
     1. The forward reference list for that symbol is scanned
     2. The proper address for the symbol is inserted into any instructions previous generated.

Handling Forward Reference in One-pass Assembler (Cont.)

- At the end of the program
  - Any SYMTAB entries that are still marked with * indicate *undefined symbols*
    - Be flagged by the assembler as errors
  - Search SYMTAB for the symbol named in the END statement and jump to this location to begin execution of the assembled program.

Sample Program for a One-Pass Assembler (Fig. 2.18)

Line	Loc	Source statement			Object code
0	1000	COPY	START	1000	
1	1000	EOF	BYTE	C'EOF'	454F46
2	1003	THREE	WORD	3	000003
3	1006	ZERO	WORD	0	000000
4	1009	RETADR	RESW	1	
5	100C	LENGTH	RESW	1	
6	100F	BUFFER	RESB	4096	
9		.			
10	200F	FIRST	STL	RETADR	141009
15	2012	CLOOP	JSUB	RDREC	48203D
20	2015		LDA	LENGTH	00100C
25	2018		COMP	ZERO	281006
30	201B		JEQ	ENDFIL	302024
35	201E		JSUB	WRREC	482062
40	2021		J	CLOOP	302012
45	2024	ENDFIL	LDA	EOF	001000
50	2027		STA	BUFFER	0C100F
55	202A		LDA	THREE	001003
60	202D		STA	LENGTH	0C100C
65	2030		JSUB	WRREC	482062
70	2033		LDL	RETADR	081009
75	2036		RSUB		4C0000
110					

Sample Program for a One-Pass Assembler (Fig. 2.18) (Cont.)

```
               .
               .        SUBROUTINE TO READ RECORD INTO BUFFE
               .
     2039      INPUT    BYTE     X'F1'           F1
     203A      MAXLEN   WORD     4096            001000
               .
     203D      RDREC    LDX      ZERO            041006
     2040               LDA      ZERO            001006
     2043      RLOOP    TD       INPUT           E02039
     2046               JEQ      RLOOP           302043
     2049               RD       INPUT           D82039
     204C               COMP     ZERO            281006
     204F               JEQ      EXIT            30205B
     2052               STCH     BUFFER,X        54900F
     2055               TIX      MAXLEN          2C203A
     2058               JLT      RLOOP           382043
     205B      EXIT     STX      LENGTH          10100C
     205E               RSUB                     4C0000
               .
```

Sample Program for a One-Pass Assembler (Fig. 2.18) (Cont.)

```
                .
                .       SUBROUTINE TO WRITE RECORD FROM BUFFER
                .
        2061    OUTPUT  BYTE    X'05'               05
                .
        2062    WRREC   LDX     ZERO                041006
        2065    WLOOP   TD      OUTPUT              E02061
        2068            JEQ     WLOOP               302065
        206B            LDCH    BUFFER,X            50900F
        206E            WD      OUTPUT              DC2061
        2071            TIX     LENGTH              2C100C
        2074            JLT     WLOOP               382065
        2077            RSUB                        4C0000
                        END     FIRST
```

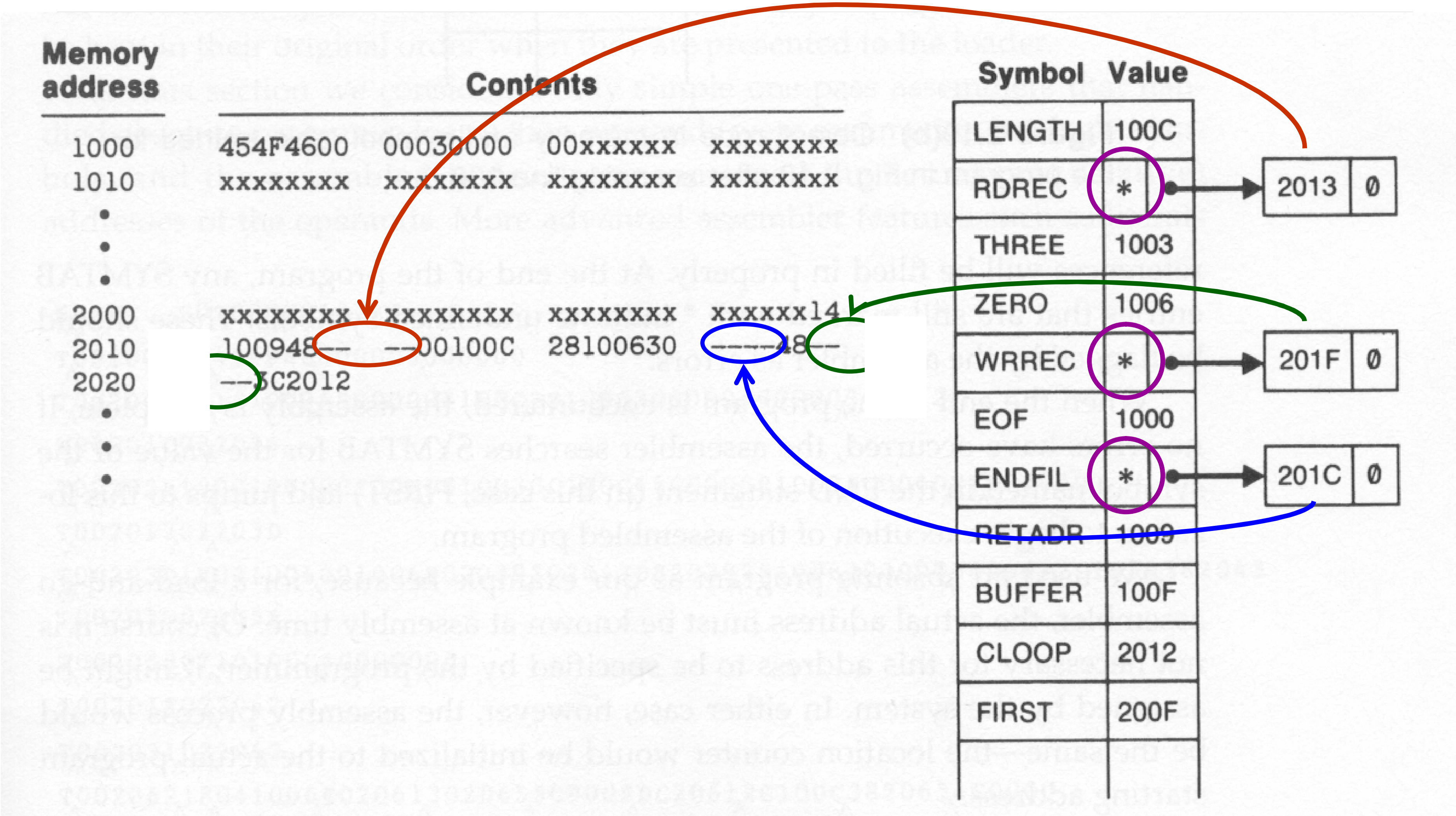
Figure 2.18 Sample program for a one-pass assembler.

Example

- Fig. 2.19 (a)
  - Show the object code in memory and symbol table entries after scanning line 40
  - Line 15: forward reference (RDREC)
    - Object code is marked ----
    - Value in symbol table is marked as * (undefined)
    - Insert *the address of operand* (2013) in a list associated with RDREC
  - Line 30 and Line 35: follow the same procedure

Object Code in Memory and SYMTAB

After scanning line 40 (Fig.2.19(a))

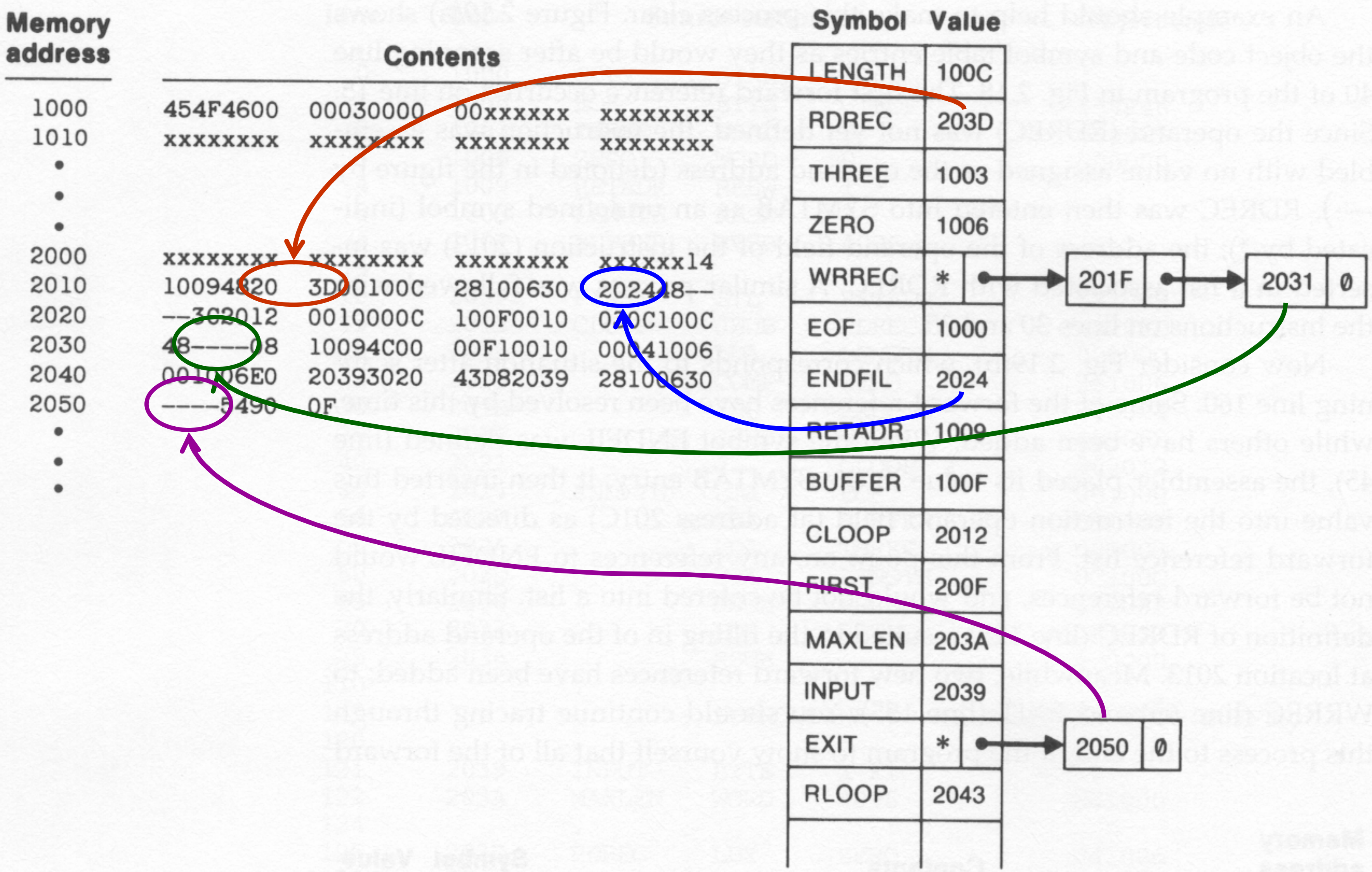


Example (Cont.)

- Fig. 2.19 (b)
  - Show the object code in memory and symbol table entries after scanning line 160
  - Line 45: ENDFIL was defined
    - Assembler place its value in the SYMTAB entry
    - Insert this value into the address (at 201C) as directed by the forward reference list
  - Line 125: RDREC was defined
    - Follow the same procedure
  - Line 65
    - A new forward reference (WRREC and EXIT)

Object Code in Memory and SYMTAB

After scanning line 160



One-Pass Assembler Producing Object Code

- Forward reference are entered into the symbol table's list as before
  - If the operand contains an undefined symbol, use 0 as the address and write the Text record to the object program.
- However, when definition of a symbol is encountered,
  - Assembler generate *another Text record* with the *correct operand address*.
- When the program is loaded, this address will be inserted into the instruction by *loader*.
- The object program records must be kept in their original order when they are presented to the loader

Example

- In Fig. 2.20
  - Second Text record contains the object code generated from lines 10 through 40
    - The operand addressed for the instruction on line 15, 30, 35 have been generated as 0000
  - When the definition of ENDFIL is encountered
    - Generate the third Text record
      - Specify the value 2024 (the address of ENDFIL) is to be loaded at location 201C (the operand field of JEQ in line 30)
      - Thus, the value 2024 will replace the 0000 previously loaded

Object Program from one-pass assembler for Fig 2.18 (Fig 2.20)

201C

```
H^COPY  ^001000^00107A
T^001000^09^454F46^000003^000000
T^00200F^15^141009^480000^00100C^281006^300000^480000^3C2012
T^00201C^02^2024
T^002024^19^001000^0C100F^001003^0C100C^480000^081009^4C0000^F1^001000
T^002013^02^203D
T^00203D^1E^041006^001006^E02039^302043^D82039^281006^300000^54900F^2C203A^382043
T^002050^02^205B
T^00205B^07^10100C^4C0000^05
T^00201F^02^2062
T^002031^02^2062
T^002062^18^041006^E02061^302065^50900F^DC2061^2C100C^382065^4C0000
E^00200F
```

Figure 2.20 Object program from one-pass assembler for program in Fig. 2.18.

2.4.2 Multi-Pass Assemblers

- Motivation: for a 2-pass assembler, any symbol used on the *right-hand side* should be defined previously.
  - No forward references since symbols' value can't be defined during the first pass
  - Reason: symbol definition must be completed in pass 1.
    - E.g.

```
APLHA   EQU   BETA
BETA    EQU   DELTA
DELTA   RESW  1
```

Not allowed !

Multi-Pass Assemblers (Cont.)

- Motivation for using a multi-pass assembler
  - DELTA can be defined in pass 1
  - BETA can be defined in pass 2
  - ALPHA can be defined in pass 3
- Multi-pass assemblers
  - Eliminate the restriction on EQU and ORG
  - Make as many passes as are needed to process the definitions of symbols.

Implementation

- A symbol table is used
  - Store symbol definitions that *involve forward references*
  - Indicate *which symbols are dependant on the values of others*
  - Keep a *linking list* to keep track of whose symbols' value depend on an this entry

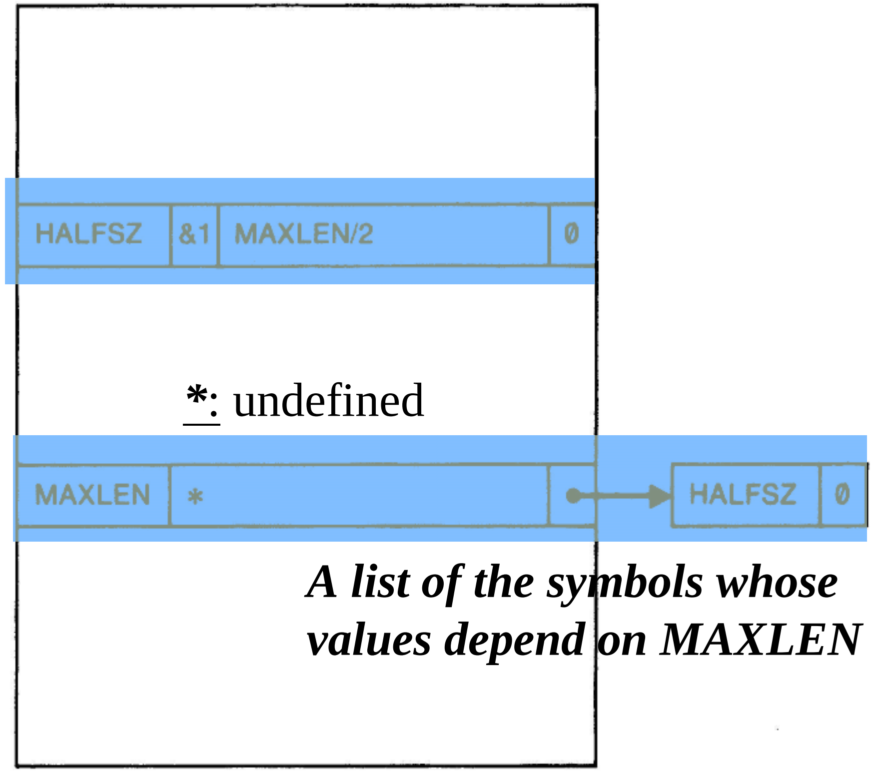
Example of Multi-pass Assembler Operation (fig 2.21a)

```
HALFSZ   EQU   MAXLEN/2
MAXLEN   EQU   BUFEND-BUFFER
PREVBT   EQU   BUFFER-1
    .
    .
    .
BUFFER   RESB  4096
BUFEND   EQU   *
```

Example of Multi-Pass Assembler Operation (Fig 2.21b)

&1: one symbol in the defining expression is undefined

```
HALFSZ   EQU     MAXLEN/2
MAXLEN   EQU     BUFEND-BUFFER
PREVBT   EQU     BUFFER-1
   .
   .
   .
BUFFER   RESB    4096
BUFEND   EQU     *
```

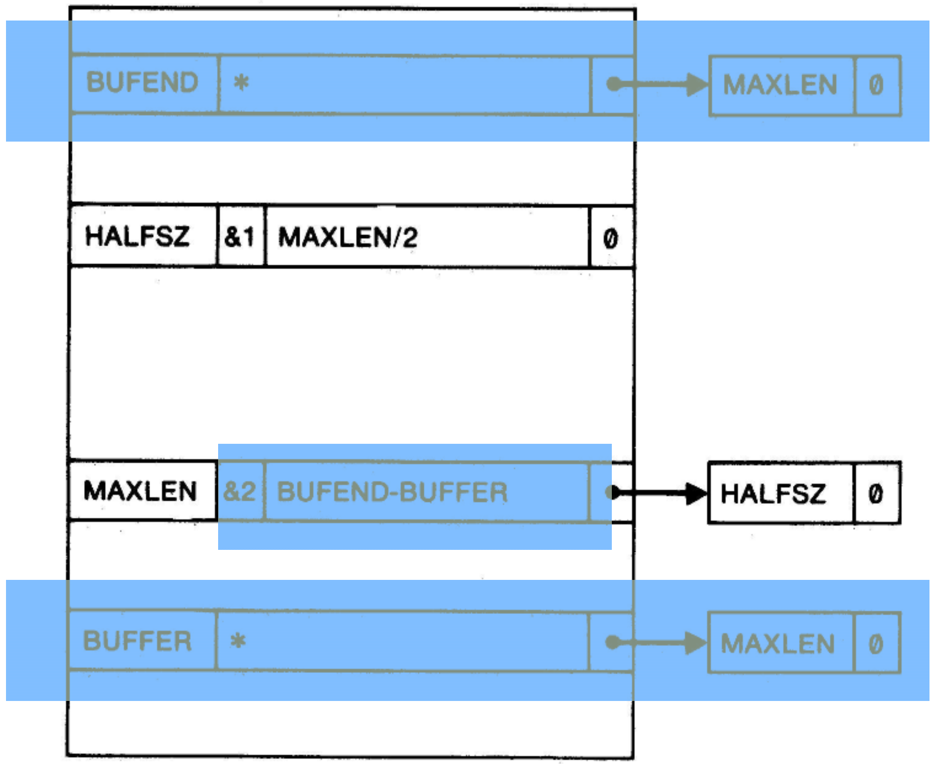


(b)

Figure 2.21 Example of multi-pass assembler operation.

Example of Multi-Pass Assembler Operation (Fig 2.21c)

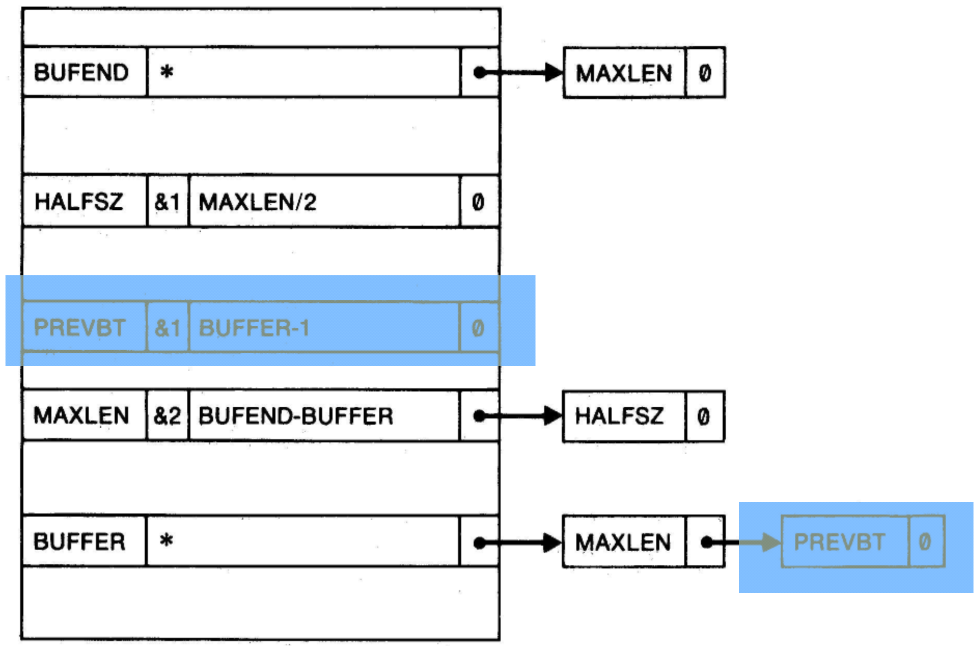
```
HALFSZ   EQU     MAXLEN/2
MAXLEN   EQU     BUFEND-BUFFER
PREVBT   EQU     BUFFER-1
    .
    .
    .
BUFFER   RESB    4096
BUFEND   EQU      *
```



(c)

Example of Multi-pass Assembler Operation (fig 2.21d)

```
HALFSZ   EQU     MAXLEN/2
MAXLEN   EQU     BUFEND-BUFFER
PREVBT   EQU     BUFFER-1
     .
     .
     .
BUFFER   RESB    4096
BUFEND   EQU     *
```

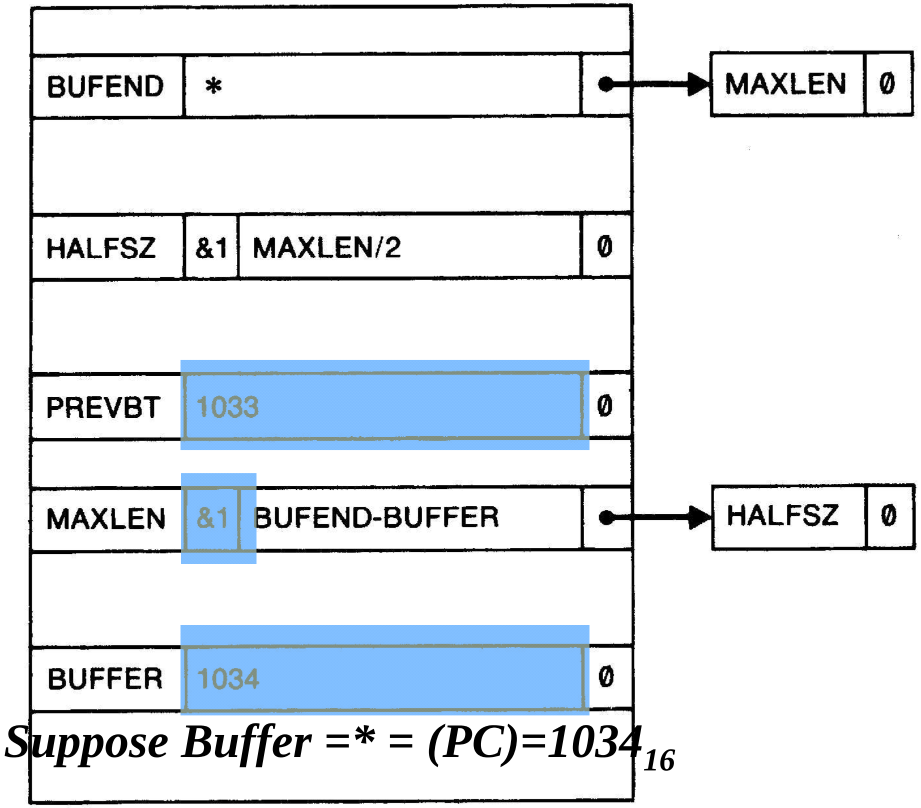


(d)

Figure 2.21 (*cont'd*)

Example of Multi-pass Assembler Operation (fig 2.21e)

```
HALFSZ   EQU    MAXLEN/2
MAXLEN  EQU    BUFEND-BUFFER
PREVBT   EQU    BUFFER-1
      .
      .
      .
BUFFER  RESB    4096
BUFEND  EQU     *
```



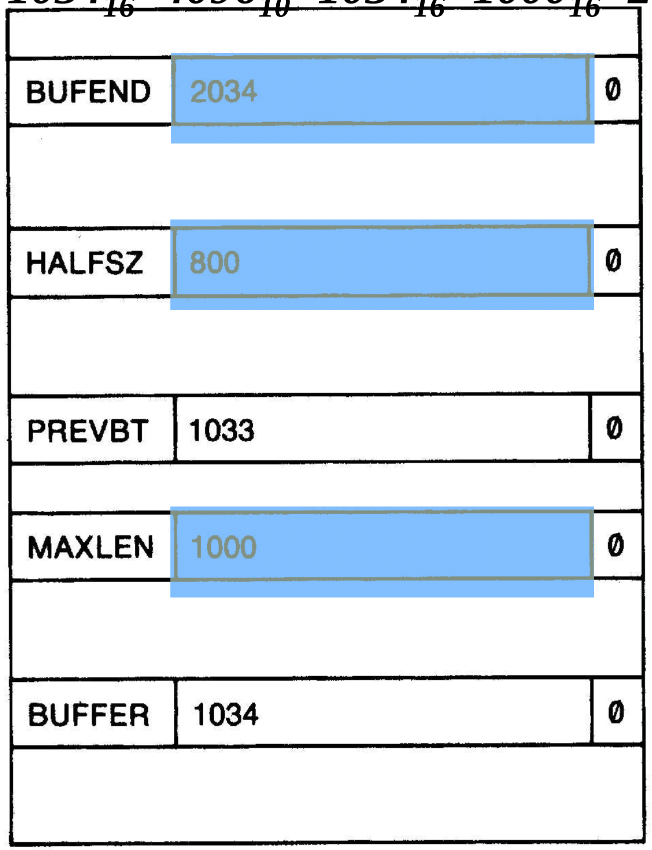
Suppose Buffer = = (PC)=1034*$_{16}$

(e)

Example of Multi-pass Assembler Operation (Fig 2.21f)

$BUFEND = *(PC) = 1034_{16} + 4096_{10} = 1034_{16} + 1000_{16} = 2034_{16}$

```
HALFSZ   EQU     MAXLEN/2
MAXLEN   EQU     BUFEND-BUFFER
PREVBT   EQU     BUFFER-1
           .
           .
           .
BUFFER   RESB    4096
BUFEND   EQU     *
```



(f)

Figure 2.21 *(con'd)*