Assemblers

System Software

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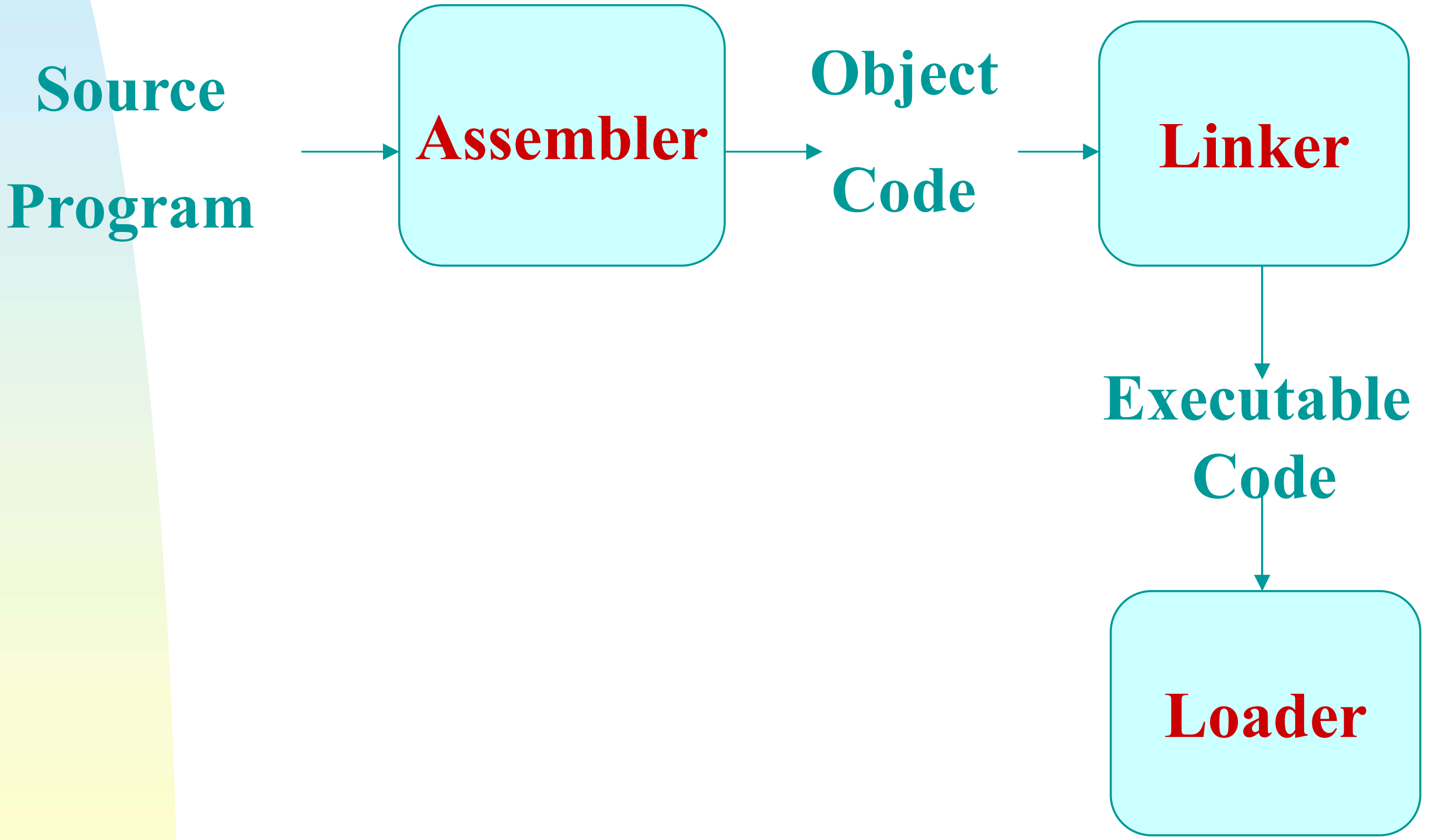
Chapter 2

Role of Assembler



Chapter 2 -- Outline

- Basic Assembler Functions
- Machine-dependent Assembler Features
- Machine-independent Assembler Features
- Assembler Design Options

Introduction to Assemblers

- **Fundamental functions**
  - translating mnemonic operation codes to their machine language equivalents
  - assigning machine addresses to symbolic labels
- **Machine dependency**
  - different machine instruction formats and codes

Example Program (Fig. 2.1)

- **Purpose**
  - reads records from input device (code F1)
  - copies them to output device (code 05)
  - at the end of the file, writes EOF on the output device, then RSUB to the operating system
  - program

Example Program (Fig. 2.1)

- **Data transfer (RD, WD)**
  - a buffer is used to store record
  - buffering is necessary for different I/O rates
  - the end of each record is marked with a null character (00_{16})
  - the end of the file is indicated by a zero-length record
- **Subroutines (JSUB, RSUB)**
  - RDREC, WRREC
  - save link register first before nested jump

Assembler Directives

- **Pseudo-Instructions**
  - Not translated into machine instructions
  - Providing information to the assembler
- **Basic assembler directives**
  - START
  - END
  - BYTE
  - WORD
  - RESB
  - RESW

Object Program

- **Header**

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**

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 (69-10+1)/6=10 instructions

- **End**

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

Fig. 2.3

```
H COPY  001000 00107A
T 001000 1E 141033 482039 001036 281030 301015 482061 ...
T 00101E 15 0C1036 482061 081044 4C0000 454F46 000003 000000
T 002039 1E 041030 001030 E0205D 30203F D8205D 281030 …
T 002057 1C 101036 4C0000 F1 001000 041030 E02079 302064 …
T 002073 07 382064 4C0000 05
E 001000
```

Figure 2.1 (Pseudo code)

```
Program copy {
          save return address;
  cloop:   call subroutine RDREC to read one record;
           if length(record)=0 {
              call subroutine WRREC to write EOF;
          }  else {
              call subroutine WRREC to write one record;
              goto cloop;
           }
           load return address
           return to caller
  }
```

An Example (Figure 2.1, Cont.)

EOR:
character x‘00’

```
Subroutine RDREC {
            clear A, X register to 0;
 rloop:     read character from input device to A register
            if not EOR {
                    store character into buffer[X];
                    X++;
                    if X < maximum length
                         goto rloop;
            }
            store X to length(record);
            return
}
```

An Example (Figure 2.1, Cont.)

```
Subroutine WDREC {
            clear X register to 0;
  wloop:    get character from buffer[X]
            write character from X to output device
            X++;
            if X < length(record)
                 goto wloop;
            return
  }
```

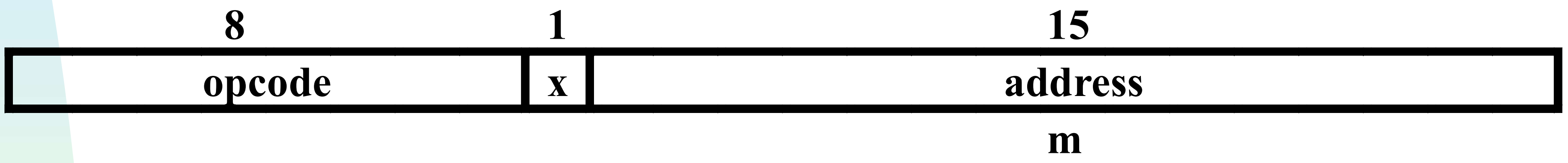
Assembler's functions

- Convert mnemonic operation codes to their machine language equivalents
- Convert symbolic operands to their equivalent machine addresses ✓
- Build the machine instructions in the proper format
- Convert the data constants to internal machine representations
- Write the object program and the assembly listing

Break...

Example of Instruction Assemble

STCH BUFFER,X 549039



$(54)_{16}$ 1 $(001)_2$ $(039)_{16}$

- **Forward reference**

Difficulties: Forward Reference

- **Forward reference: reference to a label that is defined later in the program.**

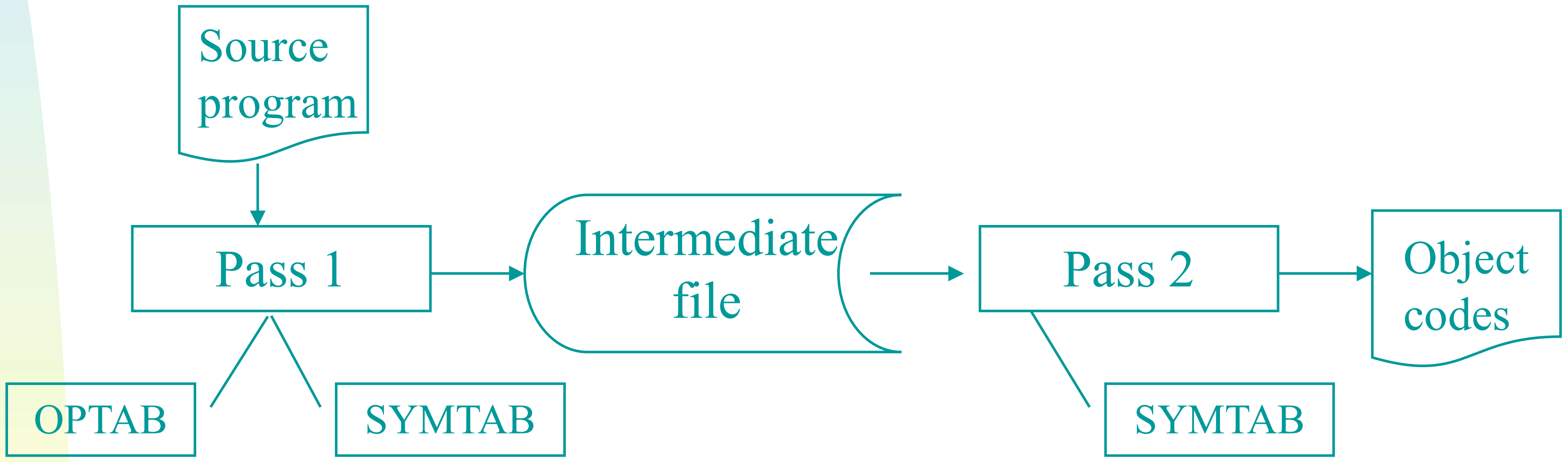
Loc	Label	Operator	Operand	
1000	FIRST	STL	RETADR	
1003	CLOOP	JSUB	RDREC	
…	…	…	…	…
1012		J	CLOOP	
…	…	…	…	…
1033	RETADR	RESW	1	

Two Pass Assembler

- **Pass 1**
  - Assign addresses to all statements in the program
  - Save the values assigned to all labels for use in Pass 2
  - Perform some processing of assembler directives
- **Pass 2**
  - Assemble instructions
  - Generate data values defined by BYTE, WORD
  - Perform processing of assembler directives not done in Pass 1
  - Write the object program and the assembly listing

Two Pass Assembler

- **Read from input line**
  - LABEL, OPCODE, OPERAND



Data Structures

- Operation Code Table (OPTAB)
- Symbol Table (SYMTAB)
- Location Counter(LOCCTR)

OPTAB (operation code table)

- **Content**
  - menmonic, machine code (instruction format, length) etc.
- **Characteristic**
  - static table
- **Implementation**
  - array or hash table, easy for search

SYMTAB (symbol table)

- **Content**
  - label name, value, flag, (type
- **Characteristic**
  - dynamic table (insert, delete
- **Implementation**
  - hash table, non-random key n

COPY	1000
FIRST	1000
CLOOP	1003
ENDFIL	1015
EOF	1024
THREE	102D
ZERO	1030
RETADR	1033
LENGTH	1036
BUFFER	1039
RDREC	2039

Homework #3

```
SUM       START   4000
FIRST     LDX     ZERO
          LDA     ZERO
LOOP      ADD     TABLE,X
          TIX     COUNT
          JLT     LOOP
          STA     TOTAL
          RSUB
TABLE     RESW    2000
COUNT     RESW    1
ZERO      WORD    0
TOTAL     RESW    1
          END     FIRST
```

End of Sec 2-1

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

Machine-dependent Assembler Features

Sec. 2-2

- Instruction formats and addressing modes
- Program relocation

Instruction Format and Addressing Mode

- **SIC/XE**
  - PC-relative or Base-relative addressing: op m
  - Indirect addressing: op @m
  - Immediate addressing: op #c
  - Extended format: +op m
  - Index addressing: op m,x
  - register-to-register instructions
  - larger memory -> multi-programming (program allocation)
- **Example program**

Translation

- **Register translation**
  - register name (A, X, L, B, S, T, F, PC, SW) and their values (0,1, 2, 3, 4, 5, 6, 8, 9)
  - preloaded in SYMTAB
- **Address translation**
  - Most register-memory instructions use program counter relative or base relative addressing
  - Format 3: 12-bit address field
    - base-relative: 0~4095
    - pc-relative: -2048~2047
  - Format 4: 20-bit address field

PC-Relative Addressing Modes

- **PC-relative**
  - 10 0000 FIRST STL RETADR 17202D

op(6)	n	I	x	b	p	e	disp(12)
$(14)_{16}$	1	1	0	0	1	0	$(02D)_{16}$

    - displacement= RETADR - PC = 30-3 = 2D
  - 40 0017 J CLOOP 3F2FEC

op(6)	n	I	x	b	p	e	disp(12)
$(3C)_{16}$	1	1	0	0	1	0	$(FEC)_{16}$

    - displacement= CLOOP-PC= 6 - 1A= -14= FEC

Base-Relative Addressing Modes

- **Base-relative**
  - base register is under the control of the programmer
  - 12 LDB #LENGTH
  - 13 BASE LENGTH
  - 160 104E STCH BUFFER, X 57C003

op(6)	n	I	x	b	p	e	disp(12)
$(54)_{16}$	1	1	1	1	0	0	$(003)_{16}$
(54)	1	1	1	0	1	0	0036-1051= $-101B_{16}$

  - displacement= BUFFER - B = 0036 - 0033 = 3
- NOBASE is used to inform the assembler that the contents of the base register no longer be relied upon for addressing

Immediate Address Translation

- Immediate addressing
  - 55 0020 LDA #3 010003

op(6)	n	I	x	b	p	e	disp(12)
$(00)_{16}$	0	1	0	0	0	0	$(003)_{16}$

  - 133 103C +LDT #4096 75101000

op(6)	n	I	x	b	p	e	disp(20)
$(74)_{16}$	0	1	0	0	0	1	$(01000)_{16}$

Immediate Address Translation (Cont.)

- **Immediate addressing**
  - 12 0003 LDB #LENGTH 69202D

op(6)	n	I	x	b	p	e	disp(12)	
$(68)_{16}$	0	1	0	0	1	0	$(02D)_{16}$	
$(68)_{16}$	0	1	0	0	0	0	$(033)_{16}$	690033

  - the immediate operand is the symbol LENGTH
  - the address of this symbol LENGTH is loaded into register B
  - LENGTH=0033=PC+displacement=0006+02D
  - if immediate mode is specified, the target address becomes the operand

Indirect Address Translation

- **Indirect addressing**
  - target addressing is computed as usual (PC-relative or BASE-relative)
  - only the n bit is set to 1
  - 70 002A J @RETADR 3E2003

op(6)	n	I	x	b	p	e	disp(12)

$(3C)_{16}$ 1 0 0 0 1 0 $(003)_{16}$

- TA=RETADR=0030
- TA=(PC)+disp=002D+0003

Program Relocation

- **Example Fig. 2.1**
  - *Absolute program*, starting address 1000

    e.g. 55 101B LDA THREE 00102D
  - Relocate the program to 2000

    e.g. 55 101B LDA THREE 00202D
  - Each Absolute address should be modified
- **Example Fig. 2.5:**
  - Except for absolute address, the rest of the instructions need not be modified
    - not a memory address (immediate addressing)
    - PC-relative, Base-relative
  - The only parts of the program that require modification at load time are those that specify direct addresses

Example

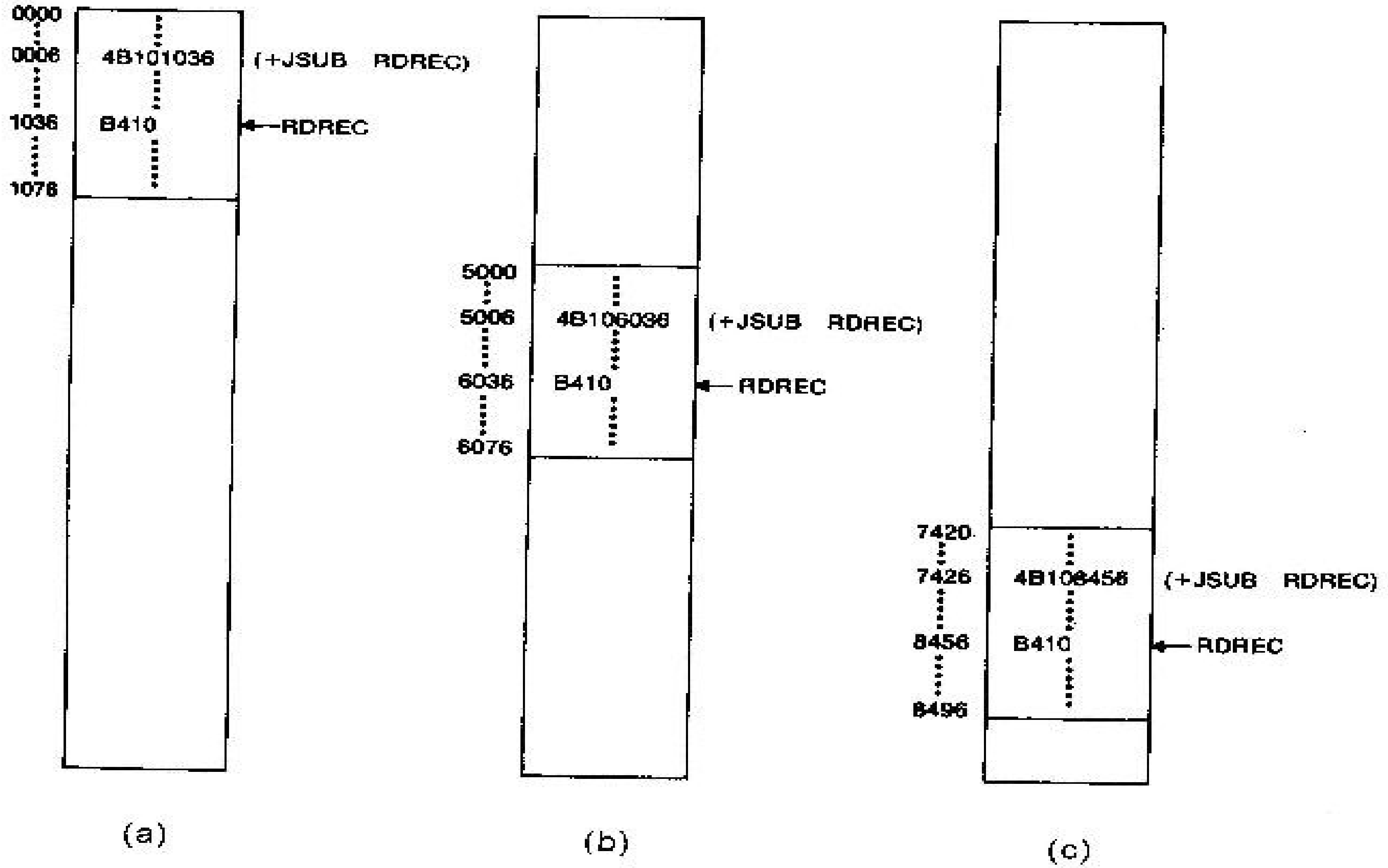
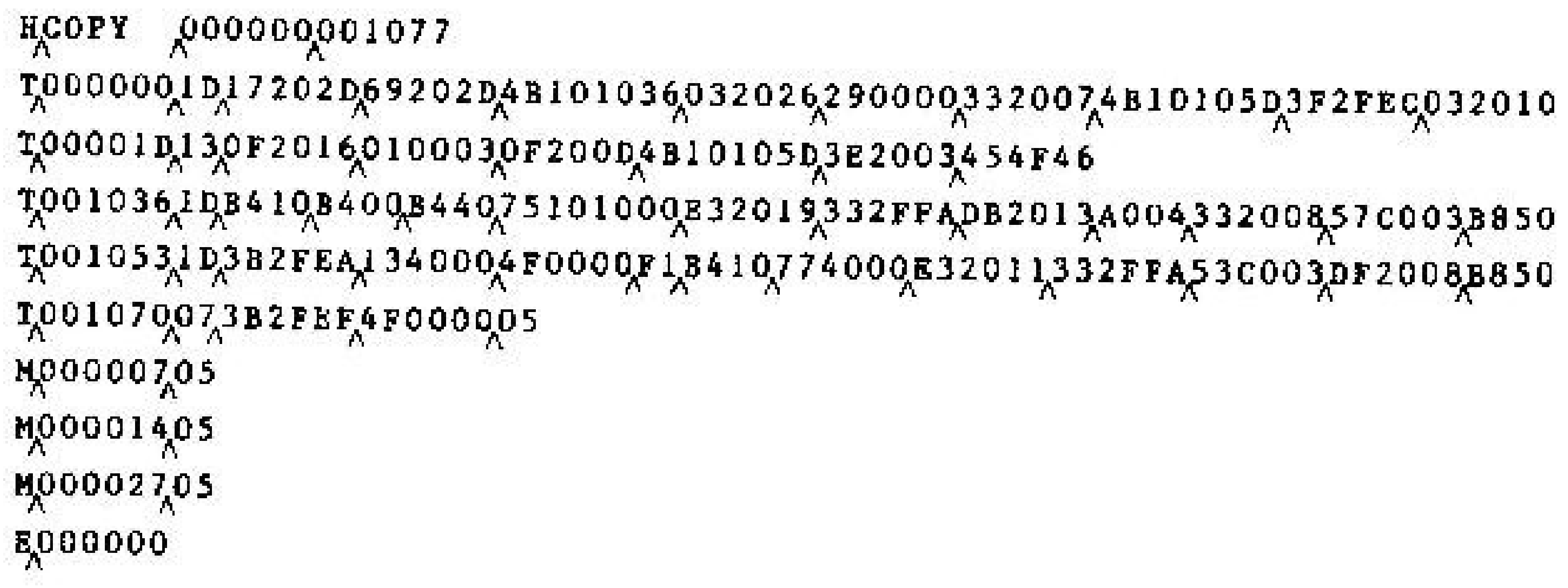


圖2.7 程式重定位範例

Relocatable Program

- **Modification record**
  - Col 1 M
  - Col 2-7 Starting location of the address field to be modified, relative to the beginning of the program
  - Col 8-9 length of the address field to be modified, in half-bytes

Object Code



```
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
```

圖2.8　相對於圖2.6的目的程式

End of Sec 2-2

Machine-Independent Assembler Features

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

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.
- **Example**

```
e.g. 45    001A    ENDFIL    LDA      =C'EOF'      032010
     93                      LTORG
           002D    *         =C'EOF'               454F46
e.g. 215   1062    WLOOP     TD       =X'05'       E32011
```

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**
  - The assembler generates the specified value as a constant at some other memory location
  - e.g. 45 001A ENDFILLDA =C'EOF' 032010
- **Compare (Fig. 2.6)**
  - e.g. 45 001A ENDFIL LDA EOF 032010
  - 80 002D EOF BYTE C'EOF' 454F46

Literal - Implementation (1/3)

- **Literal pools**
  - Normally literals are placed into a pool at the end of the program
    - see Fig. 2.10 (END statement)
  - In some cases, it is desirable to place literals into a pool at some other location in the object program
    - assembler directive LTORG
    - reason: keep the literal operand close to the instruction

Literal - Implementation (2/3)

- **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
    - Comparison of the defining expression
      - Same literal name with different value, e.g. LOCCTR=*
    - Comparison of the generated data value
      - The benefits of using generate data value are usually not great enough to justify the additional complexity in the assembler

Literal - Implementation (3/3)

- **LITTAB**
  - literal name, the operand value and length, the address assigned to the operand
- **Pass 1**
  - build LITTAB with literal name, operand value and length, leaving the address unassigned
  - when LTORG statement is encountered, assign an address to each literal not yet assigned an address
- **Pass 2**
  - search LITTAB for each literal operand encountered
  - generate data values using BYTE or WORD statements
  - generate modification record for literals that represent an address in the program

Symbol-Defining Statements

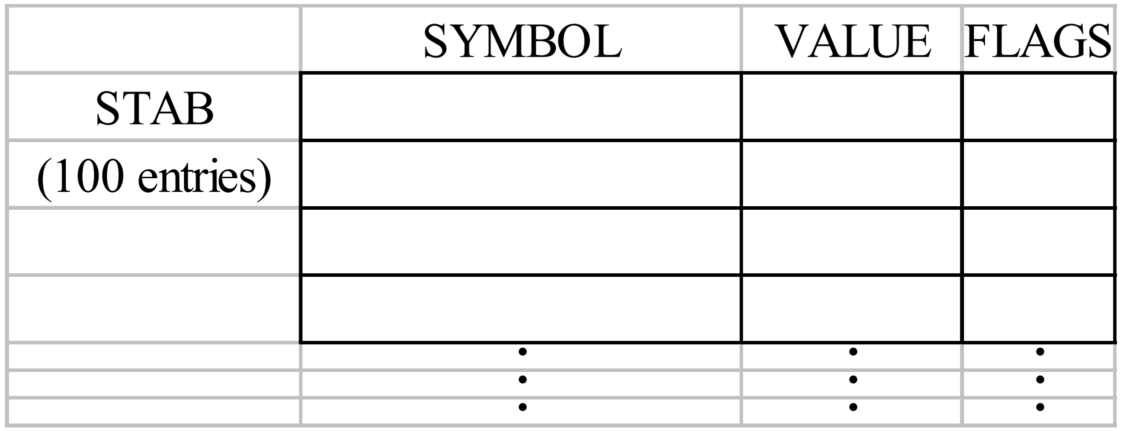
- **Labels on instructions or data areas**
  - the value of such a label is the address assigned to the statement
- **Defining symbols**
  - symbol EQU value
  - value can be: constant, other symbol, expression
  - making the source program easier to understand
  - no forward reference

Symbol-Defining Statements

- **Example 1**
  ```
  MAXLEN    EQU   4096
            +LDT  #MAXLEN
  ```
  ```
  +LDT    #4096
  ```
- **Example 2 (Many general purpose registers)**
  ```
  BASE  EQU  R1
  COUNT EQU  R2
  INDEX EQU  R3
  ```
- **Example 3**
  ```
  MAXLEN    EQU   BUFEND-BUFFER
  ```

ORG (origin)

- **Indirectly assign values to symbols**
- **Reset the location counter to the specified value**
    - ORG value
- **Value can be: □ constant, □ other symbol, □ expression**
- **No forward reference**
- **Example**
    - SYMBOL: 6bytes
    - VALUE: 1word
    - FLAGS: 2bytes
    - LDA VALUE, X



ORG Example

- **Using EQU statements**

```
STAB      RESB  1100
SYMBOL    EQU   STAB
VALUE     EQU   STAB+6
FLAG      EQU   STAB+9
```

- **Using ORG statements**

```
STAB      RESB  1100
          ORG   STAB
SYMBOL    RESB  6
VALUE     RESW  1
FLAGS     RESB  2
          ORG   STAB+1100
```

Expressions

- **Expressions can be classified as absolute expressions or relative expressions**
  - MAXLEN EQU BUFEND-BUFFER
  - BUFEND and BUFFER both are relative terms, representing addresses within the program
  - However the expression BUFEND-BUFFER represents an absolute value
- **When relative terms are paired with opposite signs, the dependency on the program starting address is canceled out; the result is an absolute value**

SYMTAB

- **None of the relative terms may enter into a multiplication or division operation**
- **Errors:**
  - BUFEND+BUFFER
  - 100-BUFFER
  - 3*BUFFER
- **The type of an expression**
  - keep track of the types of all symbols defined in the program

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

Example 2.9

SYMTAB

Name	Value
COPY	0
FIRST	0
CLOOP	6
ENDFIL	1A
RETADR	30
LENGTH	33
BUFFER	36
BUFEND	1036
MAXLEN	1000
RDREC	1036
RLOOP	1040
EXIT	1056
INPUT	105C
WREC	105D
WLOOP	1062

LITTAB

C'EOF'	454F46	3	002D
X'05'	05	1	1076

Program Blocks

- **Program blocks**
  - refer to segments of code that are rearranged within a single object program unit
  - **USE [blockname]**
  - Default block
  - Example: Figure 2.11
  - Each program block may actually contain several separate segments of the source program

Program Blocks - Implementation

- **Pass 1**
  - each program block has a separate location counter
  - each label is assigned an address that is relative to the start of the block that contains it
  - 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
- **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 that block

Figure 2.12

- Each source line is given a relative address assigned and a block number

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

- For absolute symbol, there is no block number
  - line 107
- Example
  - 20 0006 0 LDA LENGTH 032060
  - LENGTH=(Block 1)+0003= 0066+0003= 0069
  - LOCCTR=(Block 0)+0009= 0009

Program Readability

- **Program readability**
  - No extended format instructions on lines 15, 35, 65
  - No needs for base relative addressing (line 13, 14)
  - LTORG is used to make sure the literals are placed ahead of any large data areas (line 253)
- **Object code**
  - It is not necessary to physically rearrange the generated code in the object program
  - see Fig. 2.13, Fig. 2.14

```
H^COPY  ^000000^001071
T^000000^1E^172063^4B2021^032060^290000^332006^4B203B^3F2FEE^032055^0F2056^010
T^00001E^09^0F2048^4B2029^3E203F
T^000027^1D^B410^B400^B440^75101000^E32038^332FFA^DB2032^A004^332008^57A02F^B85
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
```

圖2.13　對應於圖2.11中的目的程式

Control Sections and Program Linking

- Control Sections
  - are most often used for subroutines or other logical subdivisions of a program
  - the programmer can assemble, load, and manipulate each of these control sections separately
  - instruction in one control section may need to refer to instructions or data located in another section
  - because of this, there should be some means for linking control sections together
  - Fig. 2.15, 2.16

External Definition and References

- **External definition**
  - **EXTDEF name [, name]**
  - EXTDEF names symbols that are defined in this control section and may be used by other sections
- **External reference**
  - **EXTREF name [,name]**
  - EXTREF names symbols that are used in this control section and are defined elsewhere
- **Example**

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

Implementation

- **The assembler must include information in the object program that will cause the loader to insert proper values where they are required**
- **Define record**

Col. 1	D
Col. 2-7	Name of external symbol defined in this control section
Col. 8-13	Relative address within this control section (hexadeccimal)
Col.14-73	Repeat information in Col. 2-13 for other external symbols

- **Refer record**

Col. 1	D
Col. 2-7	Name of external symbol referred to in this control section
Col. 8-73	Name of other external reference symbols

Modification Record

- **Modification record**
  - Col. 1 M
  - Col. 2-7 Starting address of the field to be modified (hexiadecimal)
  - Col. 8-9 Length of the field to be modified, in half-bytes (hexadeccimal)
  - Col.11-16 External symbol whose value is to be added to or subtracted from the indicated field
  - Note: control section name is automatically an external symbol, i.e. it is available for use in Modification records.
- **Example**
  - Figure 2.17
  - M00000405+RDREC
  - M00000705+COPY

External References in Expression

- **Earlier definitions**
  - required all of the relative terms be paired in an expression (an absolute expression), or that all except one be paired (a relative expression)
- **New restriction**
  - Both terms in each pair must be relative within the same control section
  - Ex: BUFEND-BUFFER
  - Ex: RDREC-COPY
- **In general, the assembler cannot determine whether or not the expression is legal at assembly time. This work will be handled by a linking loader.**

Assembler Design Options

One-pass assemblers

Multi-pass assemblers

Two-pass assembler with overlay structure

Two-Pass Assembler with Overlay Structure

- **For small memory**
  - pass 1 and pass 2 are never required at the same time
  - three segments
    - root: driver program and shared tables and subroutines
    - pass 1
    - pass 2
  - tree structure
  - overlay program

One-Pass Assemblers

- **Main problem**
  - forward references
    - data items
    - labels on instructions
- **Solution**
  - data items: require all such areas be defined before they are referenced
  - labels on instructions: no good solution

One-Pass Assemblers

- **Main Problem**
  - forward reference
    - data items
    - labels on instructions
- **Two types of one-pass assembler**
  - load-and-go
    - produces object code directly in memory for immediate execution
  - the other
    - produces usual kind of object code for later execution

Load-and-go Assembler

- **Characteristics**
  - Useful for program development and testing
  - Avoids the overhead of writing the object program out and reading it back
  - Both one-pass and two-pass assemblers can be designed as load-and-go.
  - However one-pass also avoids the over head of an additional pass over the source program
  - For a load-and-go assembler, the actual address must be known at assembly time, we can use an absolute program

Forward Reference in One-pass Assembler

- **For any symbol that has not yet been defined**
  1. omit the address translation
  2. insert the symbol into SYMTAB, 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, the proper address for the symbol is then inserted into any instructions previous generated according to the forward reference list

Load-and-go Assembler (Cont.)

- **At the end of the program**
  - any SYMTAB entries that are still marked with * indicate undefined symbols
  - search SYMTAB for the symbol named in the END statement and jump to this location to begin execution
- **The actual starting address must be specified at assembly time**
- **Example**
  - Figure 2.18, 2.19

Producing Object Code

- **When external working-storage devices are not available or too slow (for the intermediate file between the two passes**
- **Solution:**
  - When definition of a symbol is encountered, the assembler must generate another Tex record with the correct operand address
  - The loader is used to complete forward references that could not be handled by the assembler
  - The object program records must be kept in their original order when they are presented to the loader
- **Example: Figure 2.20**

Multi-Pass Assemblers

- **Restriction on EQU and ORG**
  - no forward reference, since symbols' value can't be defined during the first pass
- **Example**
  - Use link list to keep track of whose value depend on an undefined symbol
- **Figure 2.21**