Computer Organization & Assembly Languages

Loader and Linker

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Adapted from the slides prepared by Beck for the book,
System Software: An Intro. to Systems Programming , 3rd Ed.

Overview

- Basic Loader Functions
  - Design of an Absolute Loader
  - A Simple Bootstrap Loader
- Machine-dependent Loader Features
  - Relocation
  - Program Linking

Introduction

- To execute an object program, we needs
  - Relocation, which modifies the object program so that it can be loaded at an address different from the location originally specified
  - Linking, which combines two or more separate object programs and supplies the information needed to allow references between them
  - Loading and Allocation, which allocates memory location and brings the object program into memory for execution

Assemble-and-go Loader

- Characteristic
  - The object code is stored in memory after assembly
  - Single JUMP instruction
- Advantage
  - Simple, developing environment
- Disadvantage
  - Whenever the assembly program is to be executed, it has to be assembled again

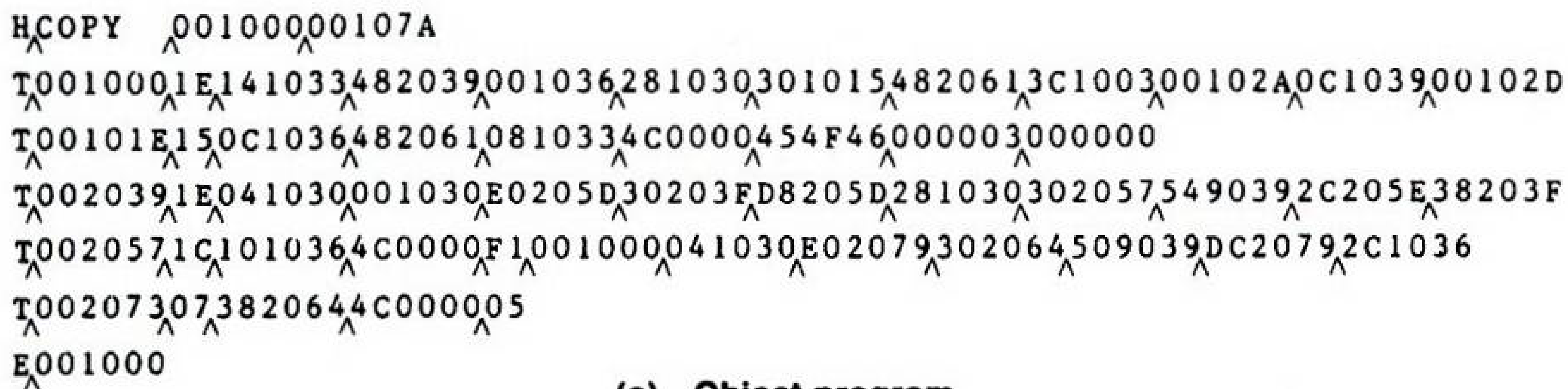
Design of an Absolute Loader

- Absolute Program
  - Advantage
    - Simple and efficient
  - Disadvantage
    - The need for programmer to specify the actual address
    - Difficult to use subroutine libraries

Algorithm for an Absolute Loader

```
begin
  read Header record
  verify program name and length
  read first Text record
  while record type <> ’E’ do
    begin
      {if object code is in character form, convert into
        internal representation}
      move object code to specified location in memory
      read next object program record
    end
  jump to address specified in End record
end
```

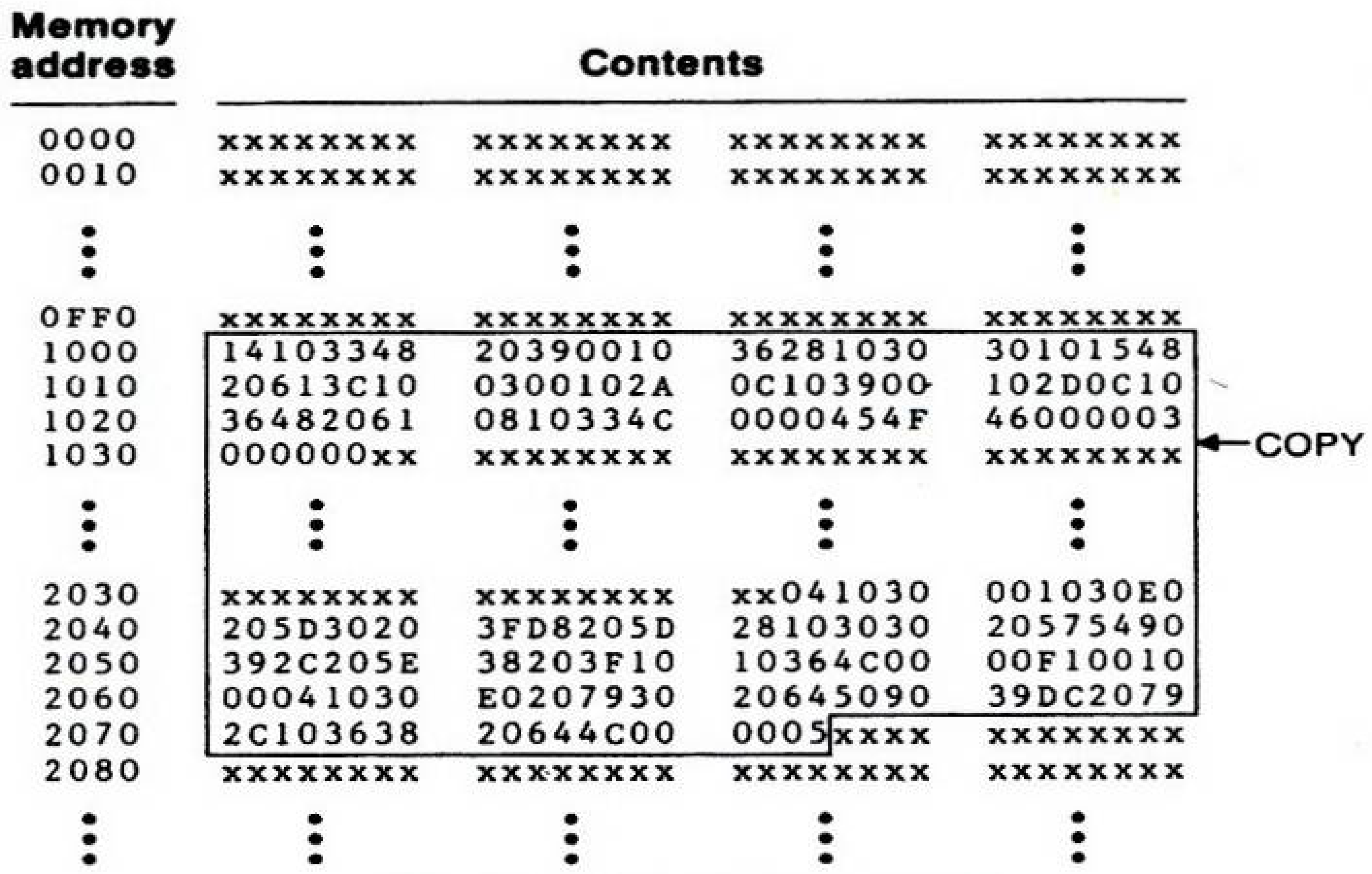
Loading of an Absolute Program



```
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
```

(a) Object program

Loading of an Absolute Program



```
Memory
address                    Contents

 0000     xxxxxxxx  xxxxxxxx  xxxxxxxx  xxxxxxxx
 0010     xxxxxxxx  xxxxxxxx  xxxxxxxx  xxxxxxxx
  ⋮          ⋮         ⋮         ⋮         ⋮
 0FF0     xxxxxxxx  xxxxxxxx  xxxxxxxx  xxxxxxxx
 1000     14103348  20390010  36281030  30101548
 1010     20613C10  0300102A  0C103900  102D0C10
 1020     36482061  0810334C  0000454F  46000003
 1030     000000xx  xxxxxxxx  xxxxxxxx  xxxxxxxx  ←COPY
  ⋮          ⋮         ⋮         ⋮         ⋮
 2030     xxxxxxxx  xxxxxxxx  xx041030  001030E0
 2040     205D3020  3FD8205D  28103030  20575490
 2050     392C205E  38203F10  10364C00  00F10010
 2060     00041030  E0207930  20645090  39DC2079
 2070     2C103638  20644C00  0005xxxx  xxxxxxxx
 2080     xxxxxxxx  xxxxxxxx  xxxxxxxx  xxxxxxxx
  ⋮          ⋮         ⋮         ⋮         ⋮
```

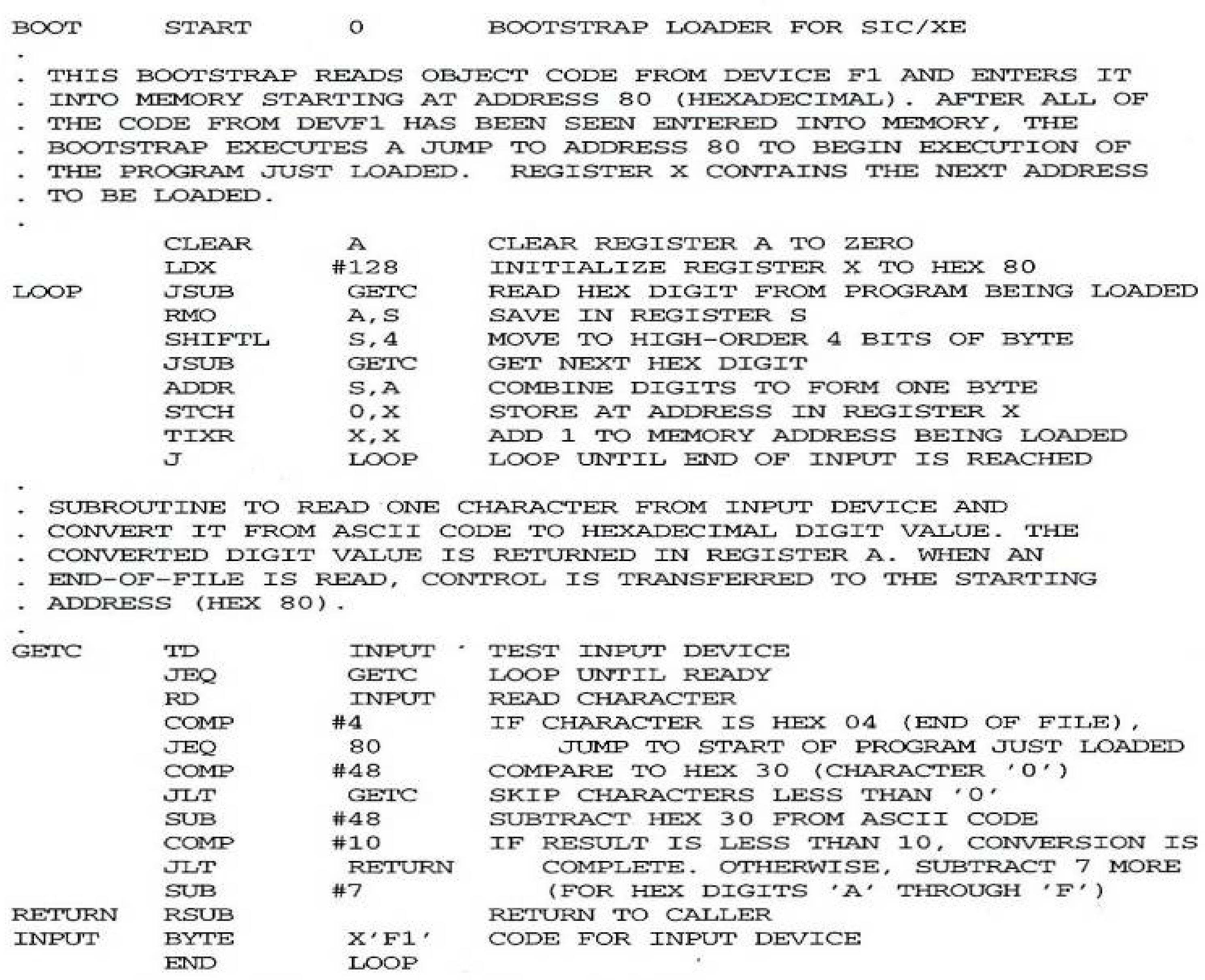
(b) Program loaded in memory

Figure 3.1 Loading of an absolute program.

A Simple Bootstrap Loader

- Bootstrap Loader
  - When a computer is first tuned on or restarted, a special type of absolute loader, called *bootstrap loader* is executed
  - This bootstrap loads the first program to be run by the computer -- usually an operating system
- Example (SIC bootstrap loader)
  - The bootstrap itself begins at address 0
  - It loads the OS starting address 0x80
  - No header record or control information, the object code is consecutive bytes of memory

Bootstrap Loader for SIC/XE



```
BOOT     START    0        BOOTSTRAP LOADER FOR SIC/XE
.
. THIS BOOTSTRAP READS OBJECT CODE FROM DEVICE F1 AND ENTERS IT
. INTO MEMORY STARTING AT ADDRESS 80 (HEXADECIMAL). AFTER ALL OF
. THE CODE FROM DEVF1 HAS BEEN SEEN ENTERED INTO MEMORY, THE
. BOOTSTRAP EXECUTES A JUMP TO ADDRESS 80 TO BEGIN EXECUTION OF
. THE PROGRAM JUST LOADED.  REGISTER X CONTAINS THE NEXT ADDRESS
. TO BE LOADED.
.
         CLEAR     A       CLEAR REGISTER A TO ZERO
         LDX      #128     INITIALIZE REGISTER X TO HEX 80
LOOP     JSUB      GETC    READ HEX DIGIT FROM PROGRAM BEING LOADED
         RMO       A,S     SAVE IN REGISTER S
         SHIFTL    S,4     MOVE TO HIGH-ORDER 4 BITS OF BYTE
         JSUB      GETC    GET NEXT HEX DIGIT
         ADDR      S,A     COMBINE DIGITS TO FORM ONE BYTE
         STCH      0,X     STORE AT ADDRESS IN REGISTER X
         TIXR      X,X     ADD 1 TO MEMORY ADDRESS BEING LOADED
         J         LOOP    LOOP UNTIL END OF INPUT IS REACHED
.
. SUBROUTINE TO READ ONE CHARACTER FROM INPUT DEVICE AND
. CONVERT IT FROM ASCII CODE TO HEXADECIMAL DIGIT VALUE. THE
. CONVERTED DIGIT VALUE IS RETURNED IN REGISTER A. WHEN AN
. END-OF-FILE IS READ, CONTROL IS TRANSFERRED TO THE STARTING
. ADDRESS (HEX 80).
.
GETC     TD        INPUT   TEST INPUT DEVICE
         JEQ       GETC    LOOP UNTIL READY
         RD        INPUT   READ CHARACTER
         COMP     #4       IF CHARACTER IS HEX 04 (END OF FILE),
         JEQ       80          JUMP TO START OF PROGRAM JUST LOADED
         COMP     #48      COMPARE TO HEX 30 (CHARACTER '0')
         JLT       GETC    SKIP CHARACTERS LESS THAN '0'
         SUB      #48      SUBTRACT HEX 30 FROM ASCII CODE
         COMP     #10      IF RESULT IS LESS THAN 10, CONVERSION IS
         JLT       RETURN     COMPLETE. OTHERWISE, SUBTRACT 7 MORE
         SUB      #7          (FOR HEX DIGITS 'A' THROUGH 'F')
RETURN   RSUB              RETURN TO CALLER
INPUT    BYTE      X'F1'   CODE FOR INPUT DEVICE
         END       LOOP
```

Figure 3.3 Bootstrap loader for SIC/XE.

Relocating Loaders

- Motivation
  - Efficient sharing of the machine with larger memory and when several independent programs are to be run together
  - Support the use of subroutine libraries efficiently
- Two methods for specifying relocation
  - Modification record
  - Relocation bit
    - Each instruction is associated with one relocation bit
    - These relocation bits in a Text record is gathered into bit masks

Modification Record

- For complex machines
- Also called RLD specification
  - Relocation and Linkage Directory

Modification record

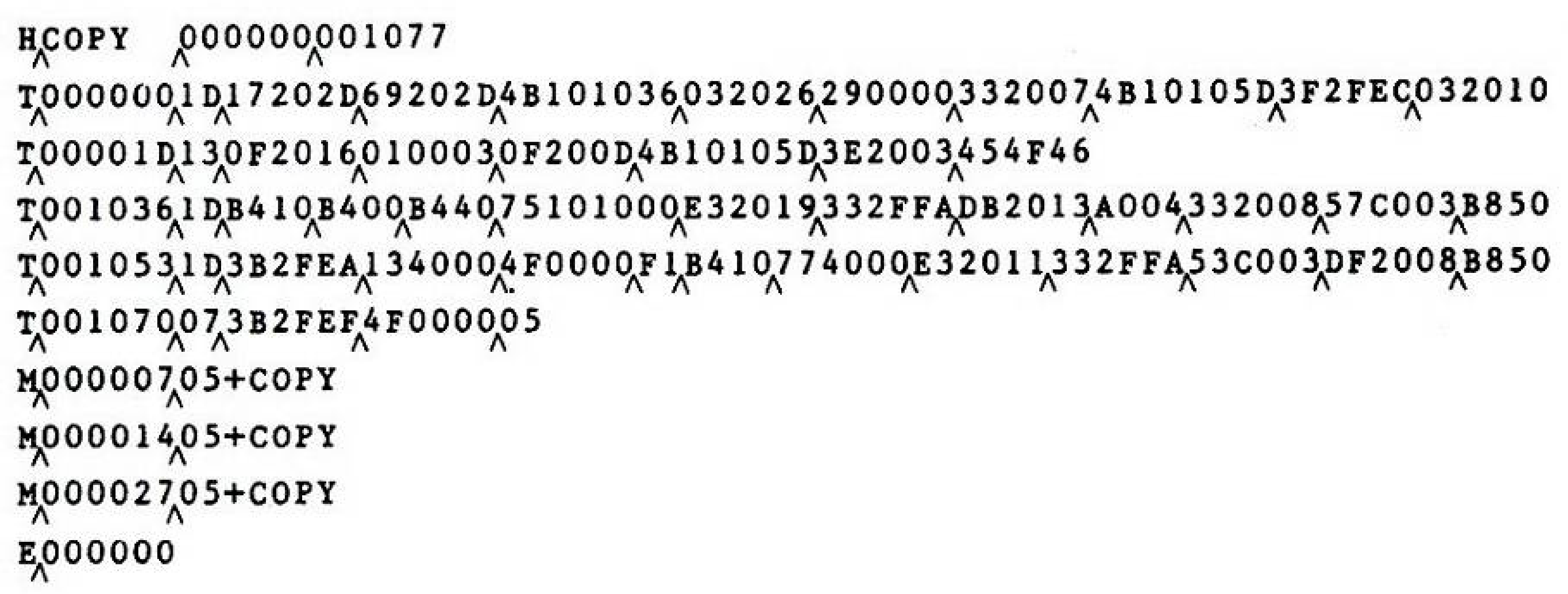
- col 1: M
- col 2-7: relocation address
- col 8-9: length (halfbyte)
- col 10: flag (+/-)
- col 11-17: segment name

An SIC/XE Example

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	

```
115              .        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
195              .
200              .        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
             ...(omitted)
```

Object Code with Modification Records



```
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+COPY
M^000014^05+COPY
M^000027^05+COPY
E^000000
```

Figure 3.5 Object program with relocation by Modification records.

Relocation Bit

- For simple machines
- Relocation bit
  - 0: No modification is necessary
  - 1: Modification is needed

Text record
col 1: T
col 2-7: starting address
col 8-9: length (byte)
col 10-12: relocation bits
col 13-72: object code

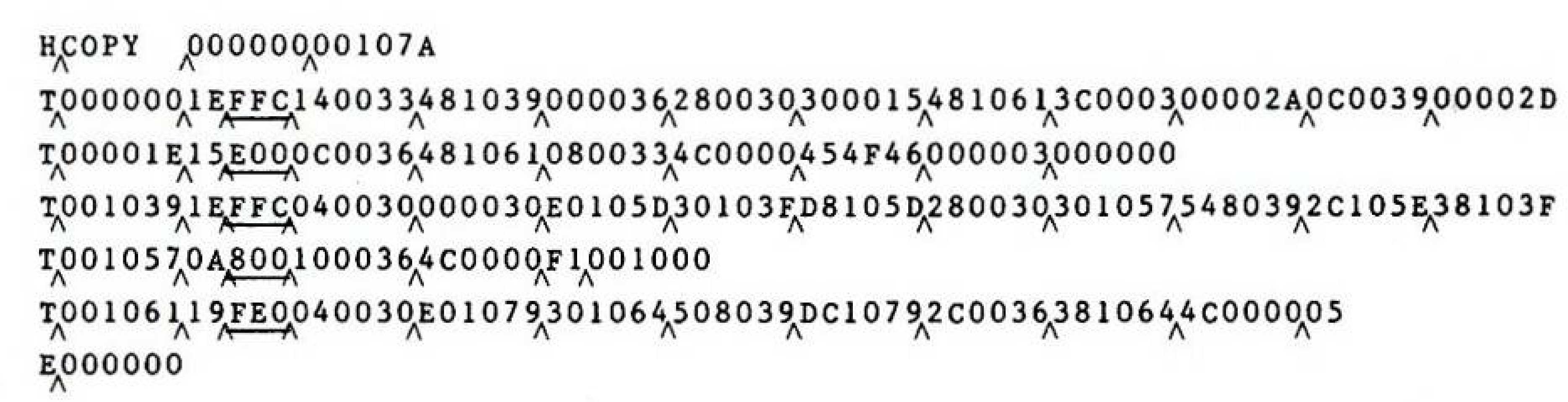
- Twelve-bit mask is used in each Text record
  - Since each text record contains less than 12 words
  - Unused words are set to 0
  - Any value that is to be modified during relocation must coincide with one of these 3-byte segments
    - e.g. line 210

Relocatable Program for SIC

```
Line  Loc      Source statement              Object code

5     0000    COPY     START    0
10    0000    FIRST    STL      RETADR       140033
15    0003    CLOOP    JSUB     RDREC        481039
20    0006             LDA      LENGTH       000036
25    0009             COMP     ZERO         280030
30    000C             JEQ      ENDFIL       300015
35    000F             JSUB     WRREC        481061
40    0012             J        CLOOP        3C0003
45    0015    ENDFIL   LDA      EOF          00002A
50    0018             STA      BUFFER       0C0039
55    001B             LDA      THREE        00002D
60    001E             STA      LENGTH       0C0036
65    0021             JSUB     WRREC        481061
70    0024             LDL      RETADR       080033
75    0027             RSUB                  4C0000
80    002A    EOF      BYTE     C'EOF'       454F46
85    002D    THREE    WORD     3            000003
90    0030    ZERO     WORD     0            000000
95    0033    RETADR   RESW     1
100   0036    LENGTH   RESW     1
105   0039    BUFFER   RESB     4096
```

```
                .
                .         SUBROUTINE TO READ RECORD INTO BUFFER
                .
1039    RDREC   LDX       ZERO            040030
103C            LDA       ZERO            000030
103F    RLOOP   TD        INPUT           E0105D
1042            JEQ       RLOOP           30103D
1045            RD        INPUT           D8105D
1048            COMP      ZERO            280030
104B            JEQ       EXIT            301057
104E            STCH      BUFFER,X        548039
1051            TIX       MAXLEN          2C105E
1054            JLT       RLOOP           38103F
1057    EXIT    STX       LENGTH          100036
105A            RSUB                      4C0000
105D    INPUT   BYTE      X'F1'           F1
105E    MAXLEN  WORD      4096            001000
                .
                .         SUBROUTINE TO WRITE RECORD FROM BUFFER
                .
1061    WRREC   LDX       ZERO            040030
1064    WLOOP   TD        OUTPUT          E01079
1067            JEQ       WLOOP           301064
106A            LDCH      BUFFER,X        508039
106D            WD        OUTPUT          DC1079
1070            TIX       LENGTH          2C0036
1073            JLT       WLOOP           381064
1076            RSUB                      4C0000
1079    OUTPUT  BYTE      X'05'           05
                END       FIRST
```

Object Code with Bit Masks



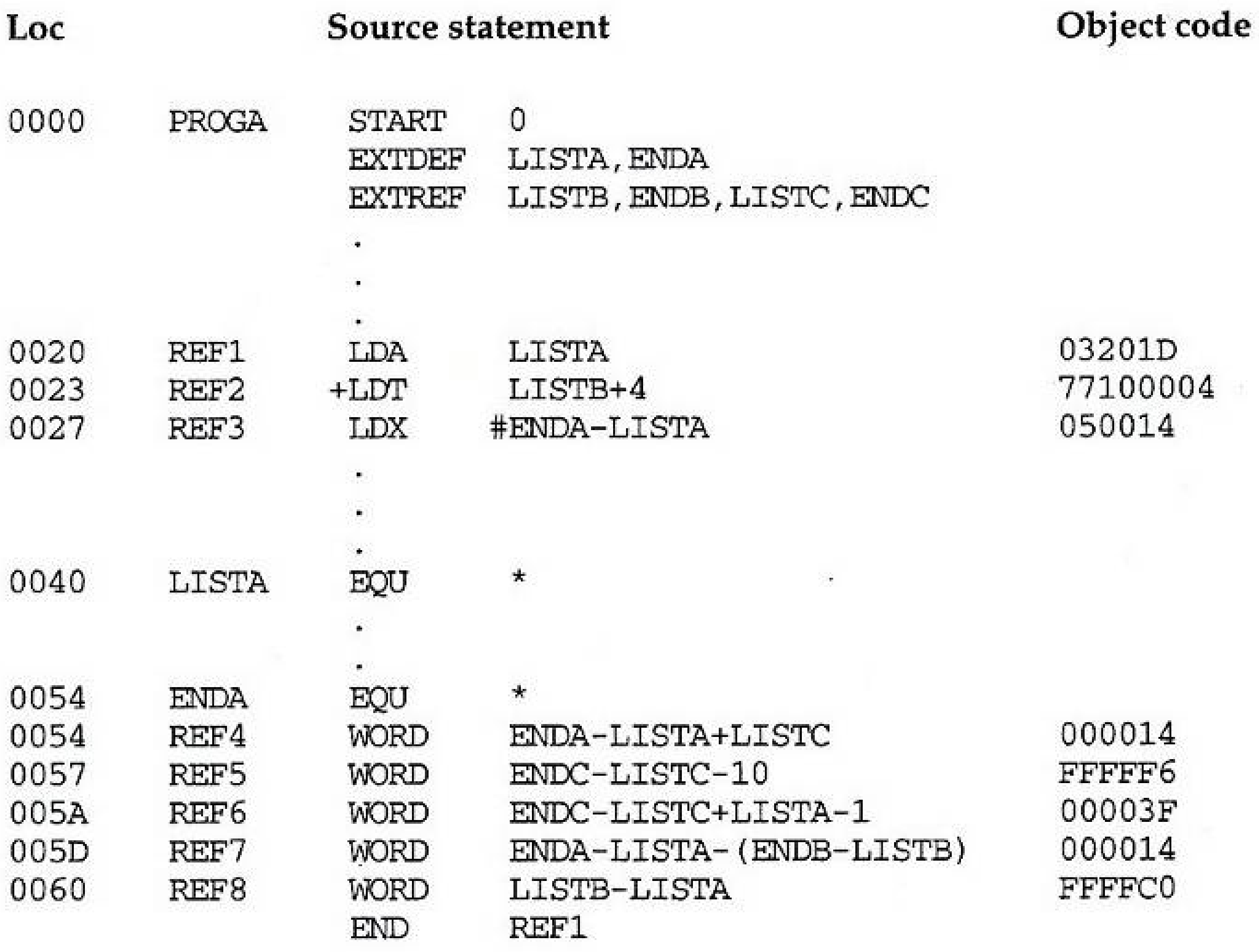
```
H^COPY  ^000000^00107A
T^000000^1E^FFC^140033^481039^000036^280030^300015^481061^3C0003^00002A^0C0039^00002D
T^00001E^15^E00^0C0036^481061^080033^4C0000^454F46^000003^000000
T^001039^1E^FFC^040030^000030^E0105D^30103F^D8105D^280030^301057^548039^2C105E^38103F
T^001057^0A^800^100036^4C0000^F1^001000
T^001061^19^FE0^040030^E01079^301064^508039^DC1079^2C0036^381064^4C0000^05
E^000000
```

Figure 3.7 Object program with relocation by bit mask.

Program Linking

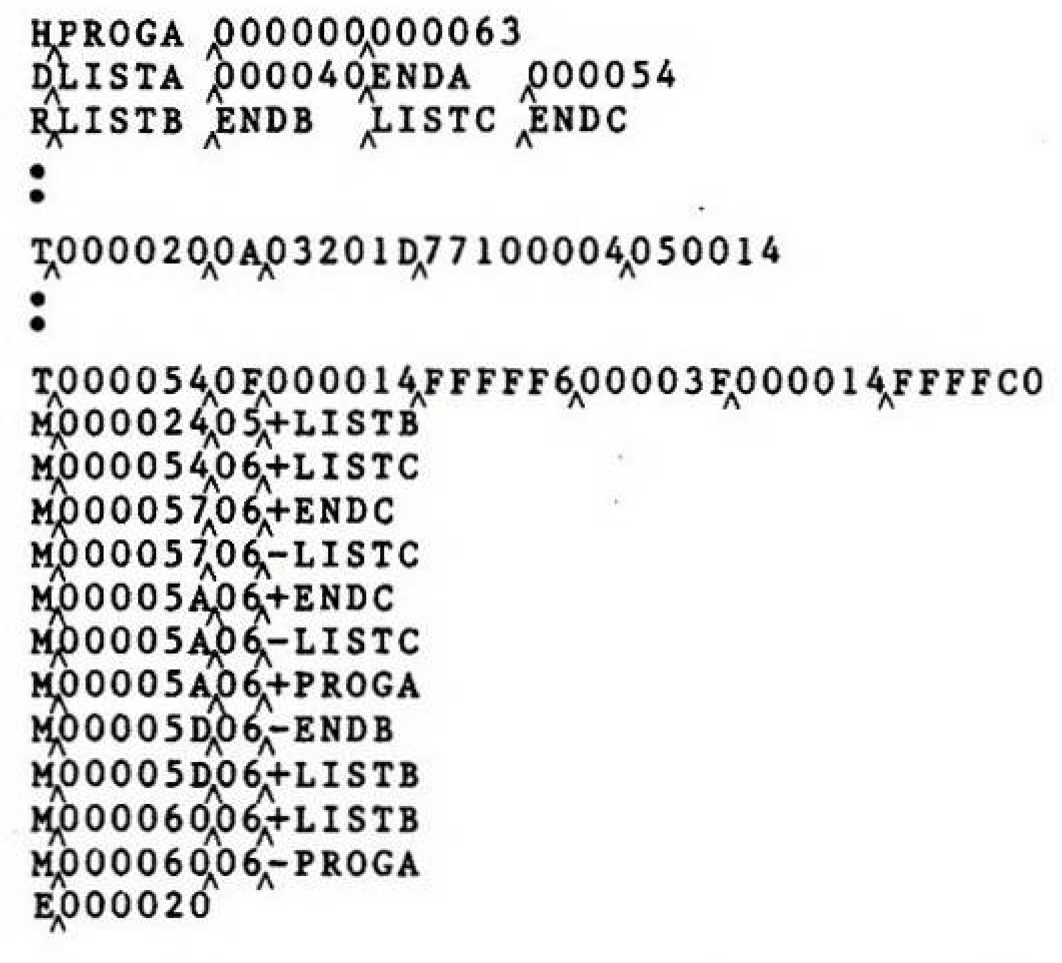
- Goal
  - Resolve the problems with EXTREF and EXTDEF from different control sections
- Use modification records for both relocation and linking
  - Address constant
  - External reference

Example Program



```
Loc              Source statement                          Object code

0000    PROGA    START    0
                 EXTDEF   LISTA,ENDA
                 EXTREF   LISTB,ENDB,LISTC,ENDC
                 .
                 .
                 .
0020    REF1     LDA      LISTA                            03201D
0023    REF2    +LDT      LISTB+4                          77100004
0027    REF3     LDX     #ENDA-LISTA                       050014
                 .
                 .
                 .
0040    LISTA    EQU      *
                 .
                 .
0054    ENDA     EQU      *
0054    REF4     WORD     ENDA-LISTA+LISTC                 000014
0057    REF5     WORD     ENDC-LISTC-10                    FFFFF6
005A    REF6     WORD     ENDC-LISTC+LISTA-1               00003F
005D    REF7     WORD     ENDA-LISTA-(ENDB-LISTB)          000014
0060    REF8     WORD     LISTB-LISTA                      FFFFC0
                 END      REF1
```

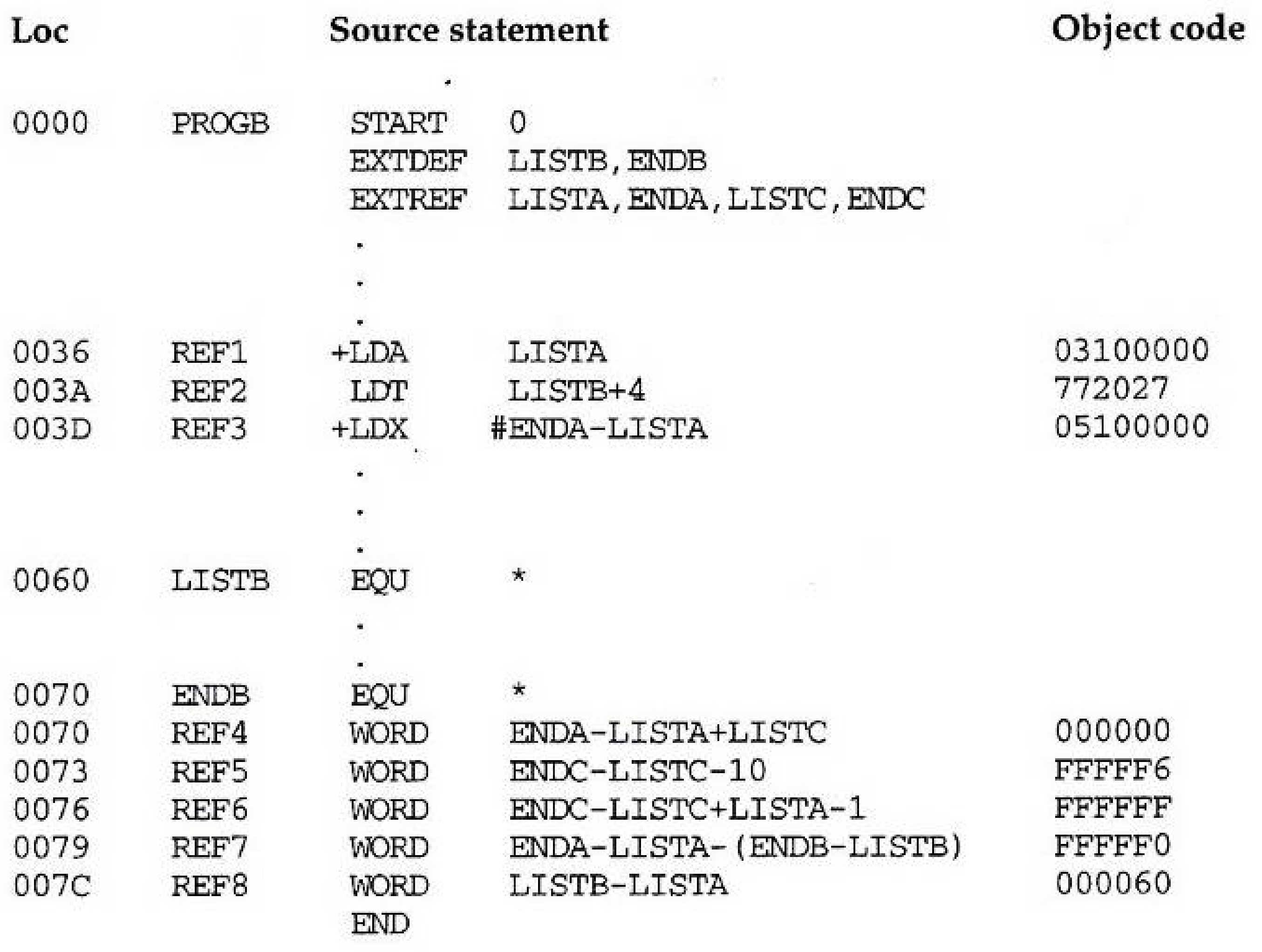
Object Code of Example Program



```
H^PROGA ^000000^000063
D^LISTA ^000040^ENDA  ^000054
R^LISTB ^ENDB  ^LISTC ^ENDC
•
•
T^000020^0A^03201D^77100004^050014
•
•
T^000054^0F^000014^FFFFF6^00003F^000014^FFFFC0
M^000024^05^+LISTB
M^000054^06^+LISTC
M^000057^06^+ENDC
M^000057^06^-LISTC
M^00005A^06^+ENDC
M^00005A^06^-LISTC
M^00005A^06^+PROGA
M^00005D^06^-ENDB
M^00005D^06^+LISTB
M^000060^06^+LISTB
M^000060^06^-PROGA
E^000020
```

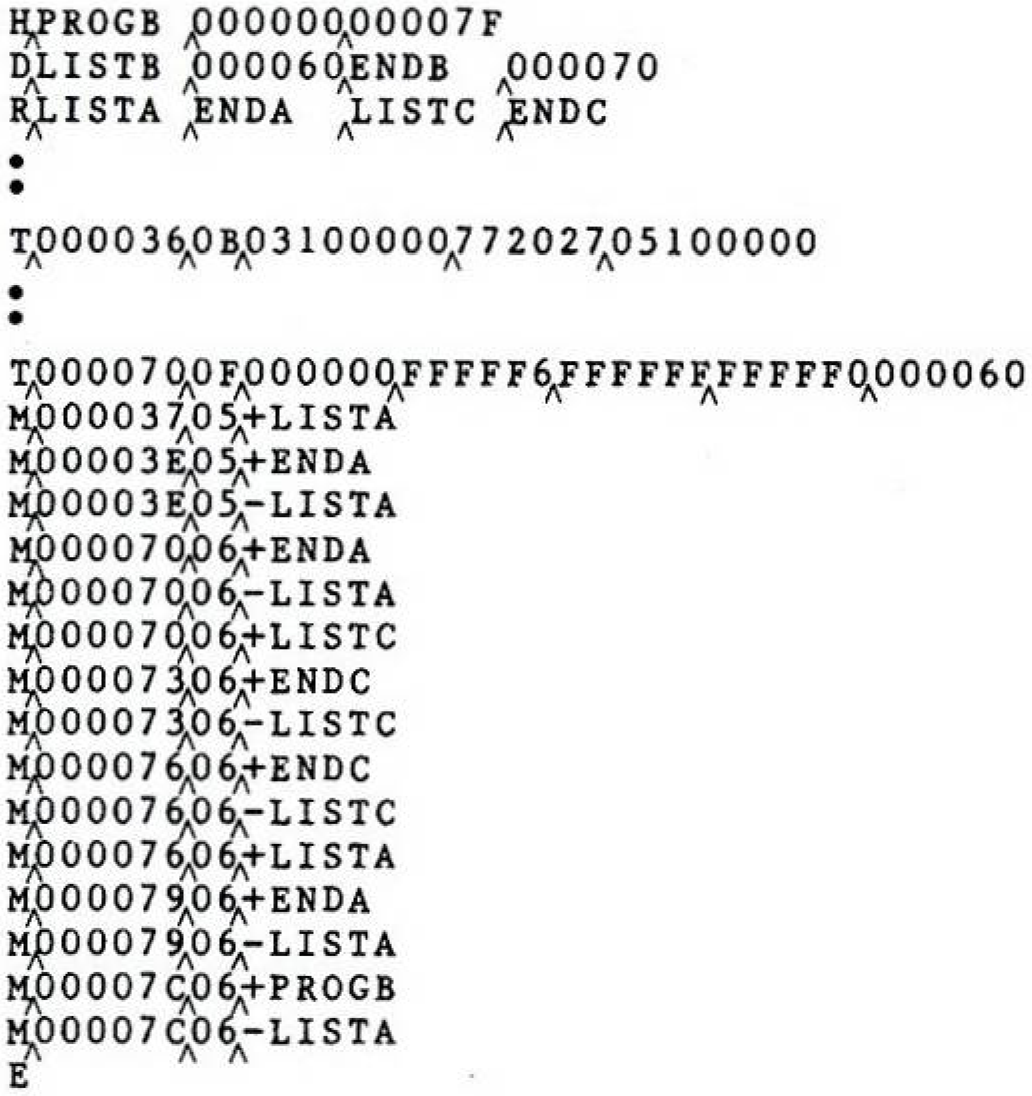
Figure 3.9 Object programs corresponding to Fig. 3.8.

Example Program



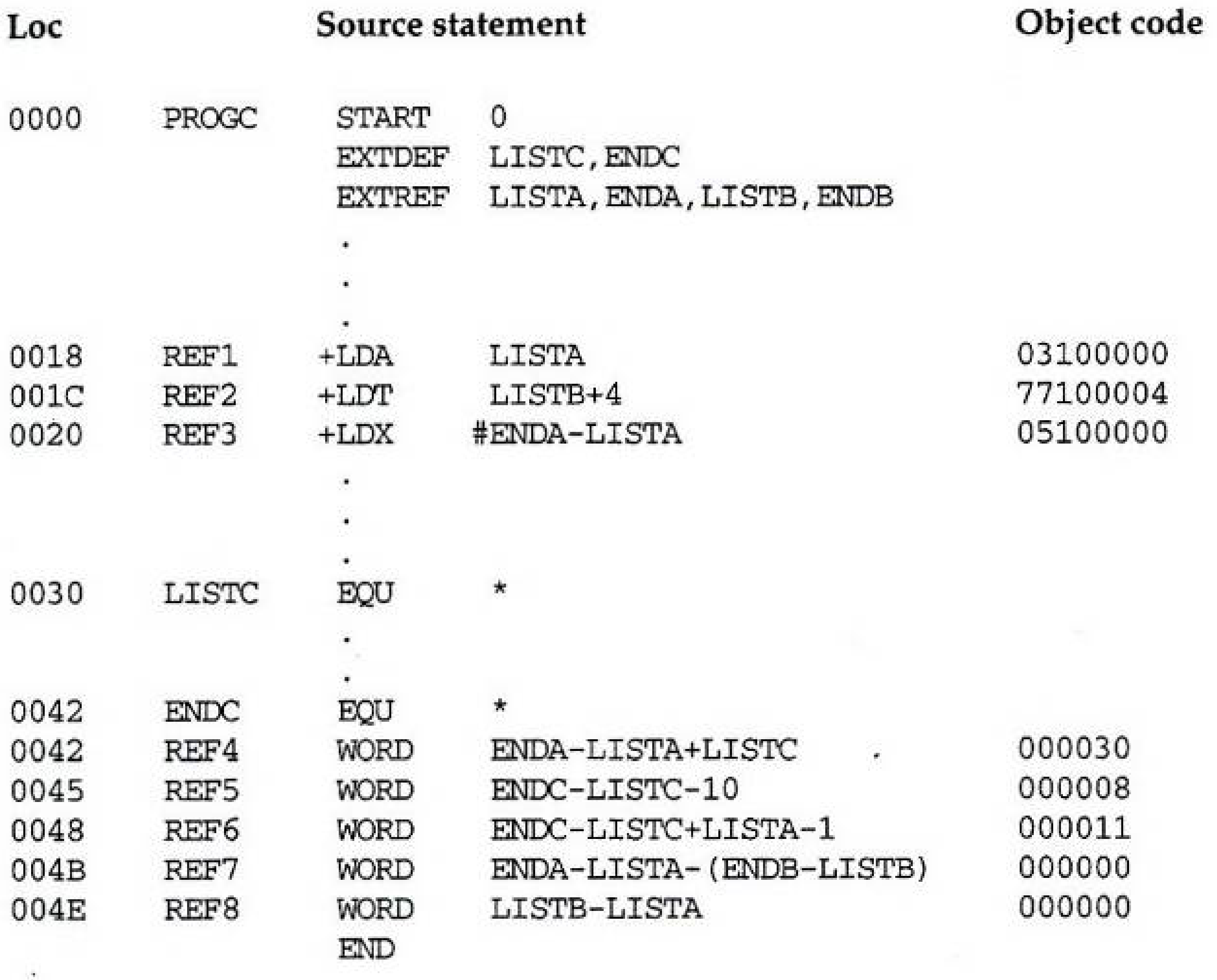
```
Loc        Source statement                                    Object code

0000   PROGB   START    0
               EXTDEF   LISTB,ENDB
               EXTREF   LISTA,ENDA,LISTC,ENDC
               .
               .
               .
0036   REF1   +LDA      LISTA                                  03100000
003A   REF2    LDT      LISTB+4                                772027
003D   REF3   +LDX     #ENDA-LISTA                             05100000
               .
               .
               .
0060   LISTB   EQU      *
               .
               .
0070   ENDB    EQU      *
0070   REF4    WORD     ENDA-LISTA+LISTC                       000000
0073   REF5    WORD     ENDC-LISTC-10                          FFFFF6
0076   REF6    WORD     ENDC-LISTC+LISTA-1                     FFFFFF
0079   REF7    WORD     ENDA-LISTA-(ENDB-LISTB)                FFFFF0
007C   REF8    WORD     LISTB-LISTA                            000060
               END
```

Figure 3.8 Sample programs illustrating linking and relocation.



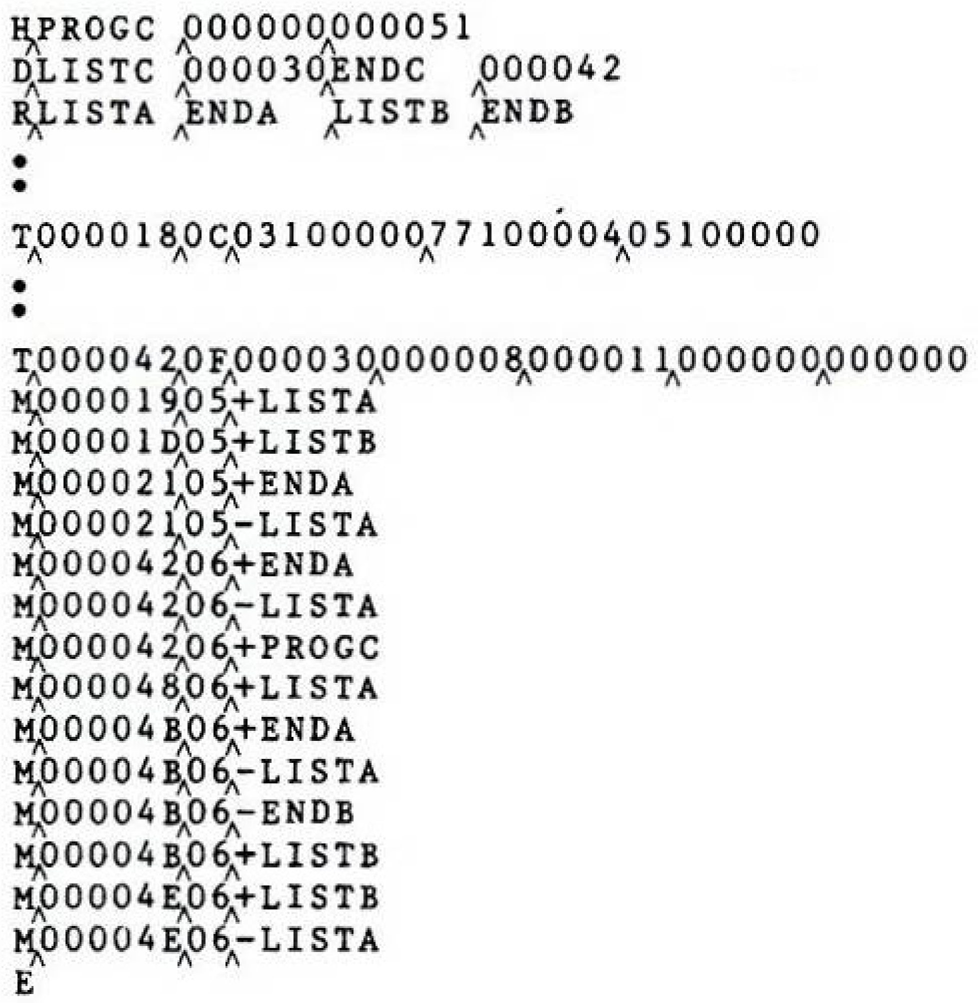
```
H^PROGB ^000000^00007F
D^LISTB ^000060^ENDB  ^000070
R^LISTA ^ENDA  ^LISTC ^ENDC
•
•
T^000036^0B^03100000^772027^05100000
•
•
T^000070^0F^000000^FFFFF6^FFFFFF^FFFFF0^000060
M^000037^05^+LISTA
M^00003E^05^+ENDA
M^00003E^05^-LISTA
M^000070^06^+ENDA
M^000070^06^-LISTA
M^000070^06^+LISTC
M^000073^06^+ENDC
M^000073^06^-LISTC
M^000076^06^+ENDC
M^000076^06^-LISTC
M^000076^06^+LISTA
M^000079^06^+ENDA
M^000079^06^-LISTA
M^00007C^06^+PROGB
M^00007C^06^-LISTA
E
```

Example Program



```
Loc              Source statement                           Object code

0000    PROGC     START    0
                  EXTDEF   LISTC,ENDC
                  EXTREF   LISTA,ENDA,LISTB,ENDB
                  .
                  .
                  .
0018    REF1     +LDA      LISTA                            03100000
001C    REF2     +LDT      LISTB+4                          77100004
0020    REF3     +LDX     #ENDA-LISTA                       05100000
                  .
                  .
                  .
0030    LISTC     EQU      *
                  .
                  .
0042    ENDC      EQU      *
0042    REF4      WORD     ENDA-LISTA+LISTC                 000030
0045    REF5      WORD     ENDC-LISTC-10                    000008
0048    REF6      WORD     ENDC-LISTC+LISTA-1               000011
004B    REF7      WORD     ENDA-LISTA-(ENDB-LISTB)          000000
004E    REF8      WORD     LISTB-LISTA                      000000
                  END
```

Figure 3.8 *(cont'd)*



```
H^PROGC ^000000^000051
D^LISTC ^000030^ENDC  ^000042
R^LISTA ^ENDA  ^LISTB ^ENDB
•
•
T^000018^0C^03100000^77100004^05100000
•
•
T^000042^0F^000030^000008^000011^000000^000000
M^000019^05^+LISTA
M^00001D^05^+LISTB
M^000021^05^+ENDA
M^000021^05^-LISTA
M^000042^06^+ENDA
M^000042^06^-LISTA
M^000042^06^+PROGC
M^000048^06^+LISTA
M^00004B^06^+ENDA
M^00004B^06^-LISTA
M^00004B^06^-ENDB
M^00004B^06^+LISTB
M^00004E^06^+LISTB
M^00004E^06^-LISTA
E
```

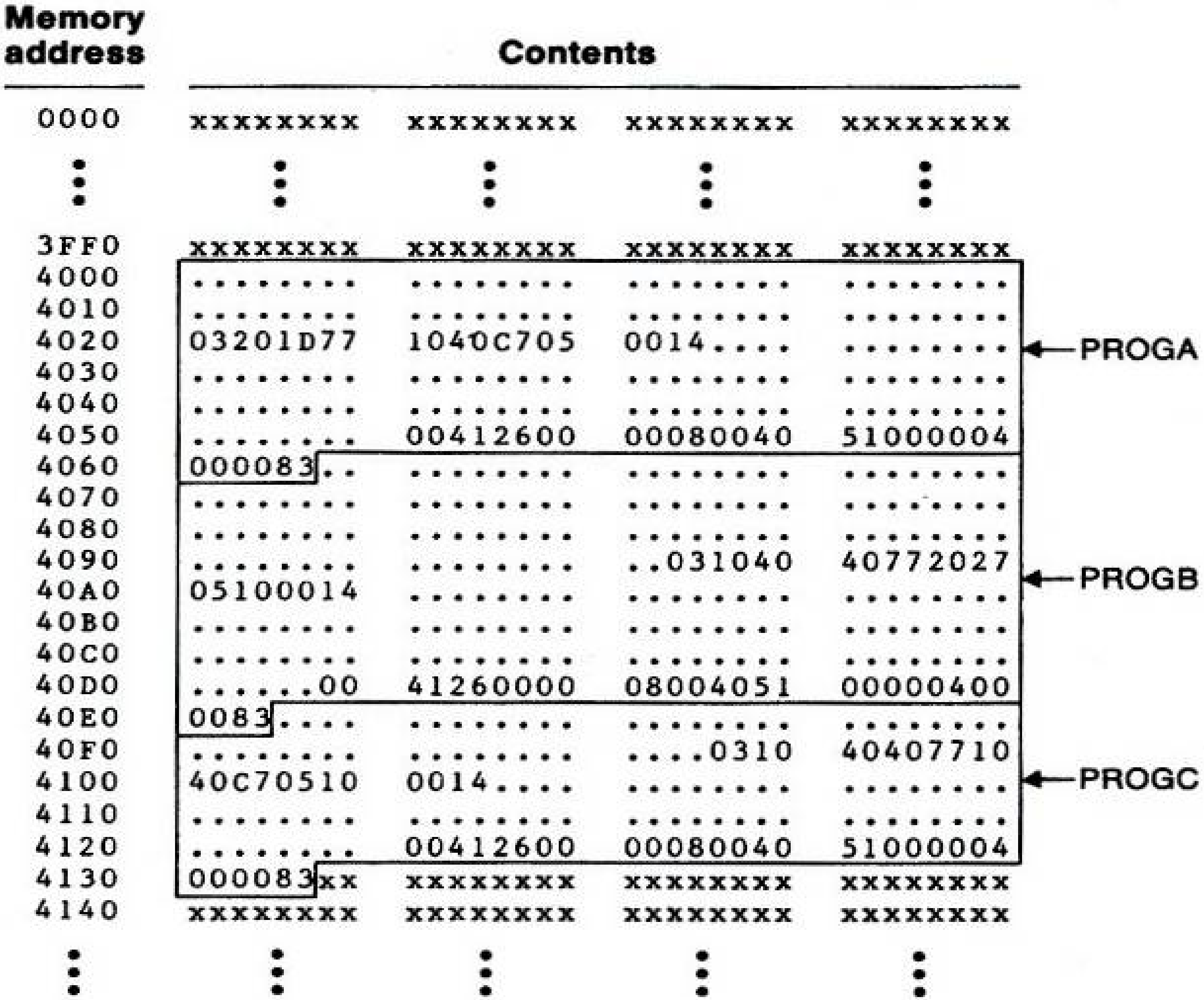
Figure 3.9 *(cont'd)*

Program Linking Example

- Load address for control sections

PROGA	004000	63
PROGB	004063	7F
PROGC	0040E2	51

- Load address for symbols
  - LISTA: PROGA+0040=4040
  - LISTB: PROGB+0060=40C3
  - LISTC: PROGC+0030=4112
- REF4 in PROGA
  - ENDA-LISTA+LISTC=14+4112=4126
  - T0000540F000014FFFFF600003F000014FFFFC0
  - M00005406+LISTC



```
Memory
address                        Contents
 0000     xxxxxxxx   xxxxxxxx   xxxxxxxx   xxxxxxxx
   :          :          :          :          :
 3FF0     xxxxxxxx   xxxxxxxx   xxxxxxxx   xxxxxxxx
 4000     ........   ........   ........   ........
 4010     ........   ........   ........   ........
 4020     03201D77   1040C705   0014....   ........   ←PROGA
 4030     ........   ........   ........   ........
 4040     ........   ........   ........   ........
 4050     ........   00412600   00080040   51000004
 4060     000083..   ........   ........   ........
 4070     ........   ........   ........   ........
 4080     ........   ........   ........   ........
 4090     ........   ........   ..031040   40772027   ←PROGB
 40A0     05100014   ........   ........   ........
 40B0     ........   ........   ........   ........
 40C0     ........   ........   ........   ........
 40D0     ......00   41260000   08004051   00000400
 40E0     0083....   ........   ........   ........
 40F0     ........   ........   ....0310   40407710
 4100     40C70510   0014....   ........   ........   ←PROGC
 4110     ........   ........   ........   ........
 4120     ........   00412600   00080040   51000004
 4130     000083xx   xxxxxxxx   xxxxxxxx   xxxxxxxx
 4140     xxxxxxxx   xxxxxxxx   xxxxxxxx   xxxxxxxx
   :          :          :          :          :
```

Figure 3.10(a) Programs from Fig. 3.8 after linking and loading.

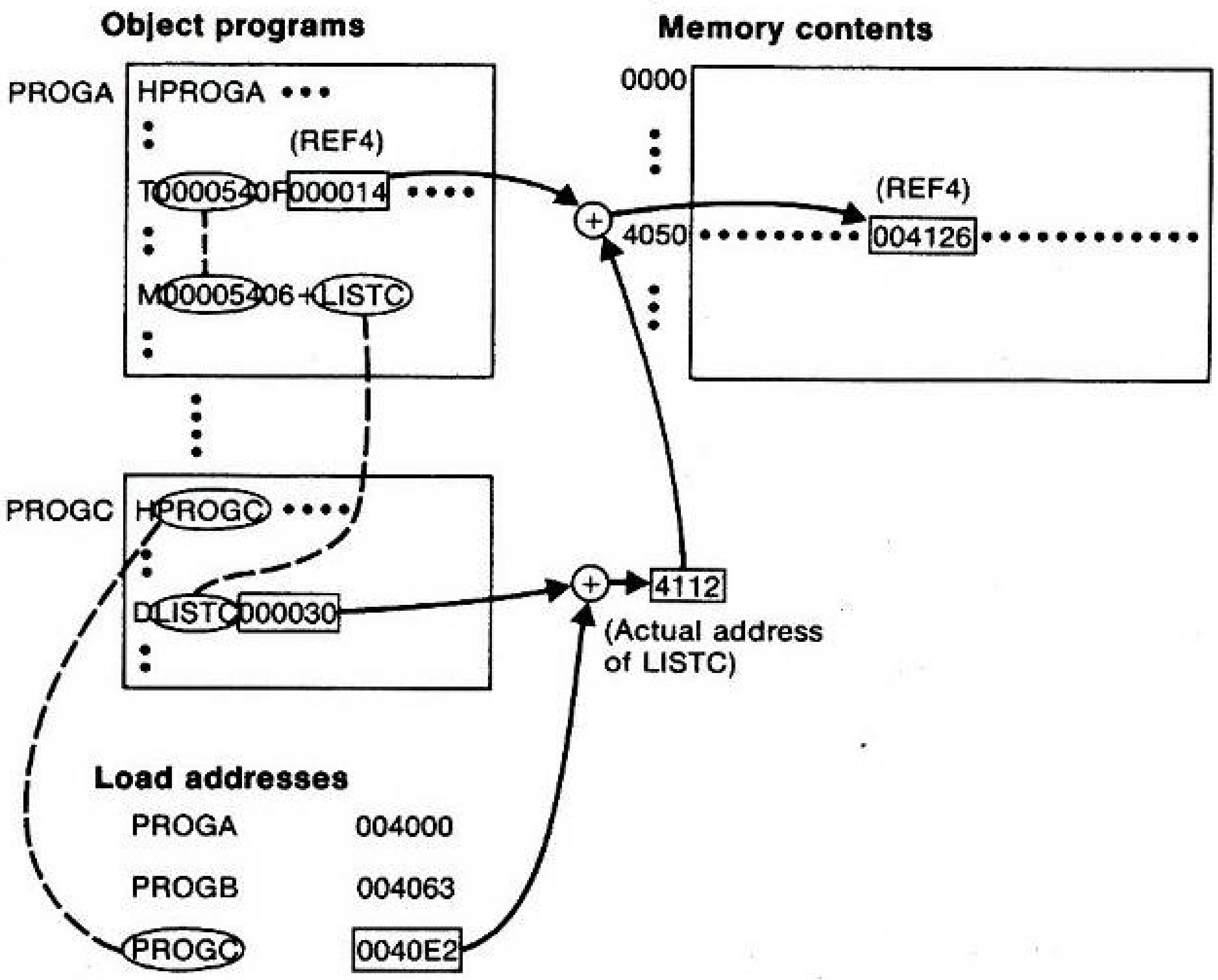


Figure 3.10(b) Relocation and linking operations performed on REF4 from PROGA.