Chapter 19: Handling of Arrays, Strings and Other Data Structures

Up to this point, we have studied simple data types and basic arrays built on those simple data types. Some of the simple data types studied include.

a) Integers: both halfword and fullword.
b) Packed decimal
c) Character data.

This lecture will cover the following:

1. A generalized "self describing" array that includes limits on the permitted index values. Only 1–D and 2–D arrays will be considered.
2. Options for a string data type and how that differs from a character array.
3. Use of indirect addressing with pointer structures generalized to include descriptions of the data item pointed to.

Structures of Arrays

We first consider the problem of converting an index in a one–dimensional array into an byte displacement. We then consider two ways of organizing a two–dimensional array, and proceed to convert the index pair into a byte displacement.

The simple array type has two variants:

0–based:	The first element in the array is either AR[0] for a singly dimensioned array or AR[0][0] for a 2–D array.
1–based:	The first element in the array is either AR[1] for a singly dimensioned array or AR[1][1] for a 2–D array.

We shall follow the convention of using only 0–based arrays. One reason is that it allows for efficient conversion from a set of indices into a displacement from the base address.
By definition, the base address of an array will be the address of its first element: either the address of AR[0] or AR[0][0].

Byte Displacement and Addressing Array Elements: The General Case

We first consider addressing issues for an array that contains either character halfword, or fullword data. It will be constrained to one of these types. The addressing issue is well illustrated for a singly dimensioned array.

Byte Offset	0	1	2	3	4	5	6	7
Characters	C[0]	C[1]	C[2]	C[3]	C[4]	C[5]	C[6]	C[7]
Halfwords	HW[0]		HW[1]		HW[2]		HW[3]	
Fullwords	FW[0]				FW[1]			

For each of these examples, suppose that the array begins at address X.
In other words, the address declared for the array is that of its element 0.

The character entries would be: C[0] at X, C[1] at X + 1, C[2] at X + 2, etc.
The halfword entries would be: HW[0] at X, HW[1] at X + 2, etc.
The fullword entries would be: FW[0] at X, FW[1] at X + 4, etc.

Byte Displacement and Addressing Array Elements: Our Case

I have decided not to write macros that handle the general case, but to concentrate on arrays that store 4–byte fullwords. The goal is to focus on array handling and not macro writing. The data structure for such an array will be designed under the following considerations.

1. It must have a descriptor specifying the maximum allowable index.
   In this data structure, I store the size and derive the maximum index.
2. It might store a descriptor specifying the minimum allowable index.
   For a 0–based array, that index is 0.
3. It should be created by a macro that allows the size to be specified
   at assembly time. Once specified, the array size will not change.

In this design, I assume the following:

1. The array is statically allocated; once loaded, its size is set.
2. The array is "zero based"; its first element has index 0. I decide to include this "base value" in the array declaration, just to show how to do it.
3. The array is self–describing for its maximum size.

Here is an example of the proposed data structure as it would be written in System 370 Assembler. The array is named "**ARRAY**".

```
ARBASE    DC F'0'         THE FIRST INDEX IS 0
ARSIZE    DC F'100'       SIZE OF THE ARRAY
ARRAY     DC 100F'0'      STORAGE FOR THE ARRAY
```

I want to generalize this to allow for a macro construction that will specify both the array name and its size.

The Constructor for a One–Dimensional Array

Here is the macro I used to construct a one–dimensional array while following the design considerations listed above.

```
33          MACRO
34 &L1      ARMAKE &NAME,&SIZE
35 &L1      B X&SYSNDX
36 &NAME.B  DC F'0'        ZERO BASED ARRAY
37 &NAME.S  DC F'&SIZE'
38 &NAME.V  DC &SIZE.F'0'
39 X&SYSNDX SLA R3,0
40          MEND
```

Line 34: The macro is named "**ARMAKE**" for "Array Make".
It takes two arguments: the array name and array size.
A typical invocation: **ARMAKE XX,20** creates an array called **XX**.

Note the "**&L1**" on line 34 and repeated on line 35. This allows a macro definition to be given a label that will persist into the generated code.

More on the 1–D Constructor

```
33            MACRO
34 &L1        ARMAKE &NAME,&SIZE
35 &L1        B X&SYSNDX
36 &NAME.B    DC F'0'        ZERO BASED ARRAY
37 &NAME.S    DC F'&SIZE'
38 &NAME.V    DC &SIZE.F'0'
39 X&SYSNDX SLA R3,0
40            MEND
```

Line 35: A macro is used to generate a code sequence. Since I am using it to create a data structure, I must provide code to jump around the data, so that the data will not be executed. While it might be possible to place all invocations of this macro in a program location that will not be executed, I do not assume that.

Line 36: I put in the lower bound on the index just to show a typical declaration.

Line 37 This holds the size of the array.

Label Concatenations in the Constructor

```
33            MACRO
34 &L1        ARMAKE &NAME,&SIZE
35 &L1        B X&SYSNDX
36 &NAME.B    DC F'0'        ZERO BASED ARRAY
37 &NAME.S    DC F'&SIZE'
38 &NAME.V    DC &SIZE.F'0'
39 X&SYSNDX SLA R3,0
40            MEND
```

Recall that the system variable symbol **&SYSNDX** in a counter that contains a four digit number unique to the macro expansion.

Line 39 uses one style of concatenation to produce a unique label. Note that in this more standard concatenation, the system variable symbol is the postfix of the generated symbol; it is the second part of a two–part concatenation. Recall that the symbol **&SYSNDX** counts total macro expansions. For the third macro expansion; the label would be "**X0003**".

Lines 36, 37, and 38 use another type of concatenation, based on the dot. This is due to the fact that the symbolic parameter **&NAME** is the prefix of the generated symbol; it is the first part of a two–part concatenation. If **&NAME** is **XX**, then the labels are **XXB**, **XXS**, and **XXV**.

As always, it is desirable to provide a few macro expansions just to show that all of the process, as described above, really works. What follows is a sequence of two array constructions using the macro just discussed.

Sample Expansions of the 1–D Constructor Macro

```
                                    90          ARMAKE XX,20
000014 47F0 C06A           00070    91+         B X0003
000018 00000000                     92+XXB      DC F'0'
00001C 00000014                     93+XXS      DC F'20'
000020 0000000000000000             94+XXV      DC 20F'0'
000070 8B30 0000           00000    95+X0003    SLA R3,0

                                    96          ARMAKE YY,40
000074 47F0 C11A           00120    97+         B X0004
000078 00000000                     98+YYB      DC F'0'
00007C 00000028                     99+YYS      DC F'40'
000080 0000000000000000            100+YYV      DC 40F'0'
000120 8B30 0000           00000   101+X0004    SLA R3,0
```

Notice the labels generated. Note also the unconditional branch statements in lines 91 and 97; these prevent the accidental execution of data. The target for each of the branch statements is a do–nothing shift of a register by zero spaces; it might have been written using another construct had your author known of that construct at the time. Anyway, this works.

Two More Macros for 1–D Arrays

I now define two macros to use the data structure defined above. I call these **ARPUT** and **ARGET**. Each will use **R4** as a working register.

Macro **ARPUT &NAME,&INDX** stores the contents of register R4 into the indexed element of the named 1–D array. Consider the high–level language statement **A2[10] = Y**.

This becomes
```
L   R4,Y
ARPUT A2,=F'10'   CHANGE ELEMENT 10
```

Consider the high–level language statement **Y = A3[20]**.

This becomes
```
ARGET A3,=F'20'   GET ELEMENT 20
ST R4,Y
```

NOTE: For some reason, I decided to implement the index as a fullword when I wrote the code. I just continue the practice, though a halfword index would make more sense.

Design of the Macros

The two macros, **ARPUT** and **ARGET**, share much of the same design. Much is centered on proper handling of the index, passed as a fullword. Here are the essential processing steps.

1. The index value is examined. If it is negative, the macro exits.
2. If the value in the index is not less than the number of elements in the array, the macro exits. For N elements, valid indices are $0 \le K < N$.
3. Using the SLA instruction, the index value is multiplied by 4 in order to get a byte offset from the base address.
4. **ARPUT** stores the value in R4 into the indexed address.
   ARGET retrieves the value at the indexed address and loads R4.

The ARPUT Macro

Here is the definition of the macro to store a value into the named array.

```
              MACRO
   &L2        ARPUT  &NAME,&INDX
   &L2        ST     R3,S&SYSNDX
              L      R3,&INDX
              C      R3,&NAME.B
              BL     Z&SYSNDX
              C      R3,&NAME.S
              BNL    Z&SYSNDX
              SLA    R3,2
              ST     R4,&NAME.V(R3)
              B      Z&SYSNDX
   S&SYSNDX   DC     F'0'
   Z&SYSNDX   L      R3,S&SYSNDX
              MEND
```

Note the two labels, **S&SYSNDX** and **Z&SYSNDX**, generated by concatenation with the System Variable Symbol **&SYSNDX**. This allows the macro to use conditional branching.

ARPUT Expanded

Here is an invocation of **ARPUT** and its expansion.

```
                                107         ARPUT XX,=F'10'
000126 5030 C146        0014C   108+        ST    R3,S0005
00012A 5830 C46A        00470   109+        L     R3,=F'10'
00012E 5930 C012        00018   110+        C     R3,XXB
000132 4740 C14A        00150   111+        BL    Z0005
000136 5930 C016        0001C   112+        C     R3,XXS
00013A 47B0 C14A        00150   113+        BNL   Z0005
00013E 8B30 0002        00002   114+        SLA   R3,2
000142 5043 C01A        00020   115+        ST    R4,XXV(R3)
000146 47F0 C14A        00150   116+        B     Z0005
00014A 0000
00014C 00000000                 117+S0005   DC    F'0'
000150 5830 C146        0014C   118+Z0005   L     R3,S0005
```

Note the **labels generated** by use of the System Variable Symbol **&SYSNDX**.

We now examine the actions of the macro **ARPUT**.

```
108+         ST     R3,S0005
```

Register R3 will be used to hold the index into the array. This line saves the value so that it can be restored at the end of the macro. Here we note that the generated line does not have a label; this reflects the fact that line 107, the macro invocation, is not labeled.

```
109+         L      R3,=F'10'
```

Register R3 is loaded with the index to be used for the macro. As the index was specified as a literal in the invocation, this is copied in the macro expansion. Were this a keyword macro, the literal would have to be specified in a different manner. This is a positional macro, which does not require special handling of literals.

ARPUT: Checking the Index Value

We continue our analysis of the macro. At this point, the value of the array index has been loaded into register R3, the original contents having been saved.

```
110+            C      R3,XXB
111+            BL     Z0005
112+            C      R3,XXS
113+            BNL    Z0005
```

This code checks that the index value is within permissible bounds.
The requirement is that **XXB** ≤ Index < **XXS**.

If this is not met, the macro restores the value of R3 and exits. If the requirement is met, the index is multiplied by 4 in order to convert it into a byte displacement from element 0.

```
114+            SLA    R3,2
```

Here is the code to store the value into the array, called **XXV**.

```
115+            ST     R4,XXV(R3)
116+            B      Z0005
117+S0005       DC     F'0'
118+Z0005       L      R3,S0005
```

Line 115 This is the actual store command.

Line 116 Note the necessity of branching around the stored value,
so that the data will not be executed as if it were code.

Line 117 The save area for the macro.

Line 118 This restores the original value of R3. The macro can now exit.

The ARGET Macro

Here is the definition of the macro to retrieve a value from the named array.

```
         MACRO
&L3      ARGET &NAME,&INDX
&L3      ST    R3,S&SYSNDX
         L     R3,&INDX
         C     R3,&NAME.B
         BL    Z&SYSNDX
         C     R3,&NAME.S
         BNL   Z&SYSNDX
         SLA   R3,2
         L     R4,&NAME.V(R3)
         B     Z&SYSNDX
S&SYSNDX DC    F'0'
Z&SYSNDX L     R3,S&SYSNDX
         MEND
```

ARGET Expanded

Here is an invocation of the macro and its expansion.

```
                                        119          ARGET YY,=F'20'
000154 5030 C172            00178       120+         ST    R3,S0006
000158 5830 C46E            00474       121+         L     R3,=F'20'
00015C 5930 C072            00078       122+         C     R3,YYB
000160 4740 C176            0017C       123+         BL    Z0006
000164 5930 C076            0007C       124+         C     R3,YYS
000168 47B0 C176            0017C       125+         BNL   Z0006
00016C 8B30 0002            00002       126+         SLA   R3,2
000170 5843 C07A            00080       127+         L     R4,YYV(R3)
000174 47F0 C176            0017C       128+         B     Z0006
000178 00000000                         129+S0006    DC    F'0'
00017C 5830 C172            00178       130+Z0006    L     R3,S0006
```

The only difference between this macro and **ARPUT** occurs in line 127 of the expansion. Here the value is loaded into register R4. Note that, in the sequence of macro expansions, **ARPUT** was expansion number 5 and **ARGET** was expansion number six; hence the labels here are "**S0006**" and "**Z0006**" rather than "**S0005**" and "**Z0005**".

Row–Major and Column–Major 2–D Arrays

The mapping of a one–dimensional array to linear address space is simple. How do we map a two–dimensional array? There are three standard options: The two that we shall consider are called **row–major order** and **column–major order**.

Consider the array declared as **INT A[2][3]**, using 32–bit integers, which occupy four bytes. In this array the first index can have values 0 or 1 and the second 0, 1, or 2. Suppose the first element is found at address A. The following table shows the allocation of these elements to the linear address space.

Address	Row Major	Column Major
A	A[0][0]	A[0][0]
A + 4	A[0][1]	A[1][0]
A + 8	A[0][2]	A[0][1]
A + 12	A[1][0]	A[1][1]
A + 16	A[1][1]	A[0][2]
A + 20	A[1][2]	A[1][2]

The mechanism for Java arrays is likely to be somewhat different.

Addressing Elements in Arrays of 32–Bit Fullwords

Consider first a singly dimensioned array that holds 4–byte fullwords. The addressing is simple: **Address (A[K]) = Address (A[0]) + 4•K**.

Suppose that we have a two dimensional array declared as **A[M][N]**, where each of M and N has a fixed positive integer value. Again, we assume 0–based arrays and ask for the address of an element **A[K][J]**, assuming that **0** ≤ **K** < **M** and **0** ≤ **J** < **N**.
At this point, I must specify either row–major or column–major ordering.

As FORTRAN is the only major language to use column–major ordering, I shall assume row–major. The formula is as follows.
Element offset = **`K•N + J`**, which leads to a byte offset of **`4•(K•N + J)`**; hence
Address (**`A[K][J]`**) = Address (**`A[0][0]`**) + **`4•(K•N + J)`**

Suppose that the array is declared as **A[2][3]** and that element **`A[0][0]`** is at address A.
Address (**`A[K][J]`**) = Address (**`A[0][0]`**) + **`4•(K•3 + J)`**.
Element **`A[0][0]`** is at offset **`4•(0•3 + 0) = 0,`** or address **`A + 0.`**
Element **`A[0][1]`** is at offset **`4•(0•3 + 1) = 4,`** or address **`A + 4.`**
Element **`A[0][2]`** is at offset **`4•(0•3 + 2) = 8,`** or address **`A + 8.`**
Element **`A[1][0]`** is at offset **`4•(1•3 + 0) = 12,`** or address **`A + 12.`**
Element **`A[1][1]`** is at offset **`4•(1•3 + 1) = 16,`** or address **`A + 16.`**
Element **`A[1][2]`** is at offset **`4•(1•3 + 1) = 20,`** or address **`A + 20.`**

Here is a first cut at what we might want the data structure to look like.
```
ARRB     DC F‘0’      ROW INDEX STARTS AT 0
ARRCNT   DC F‘30’     NUMBER OF ROWS
ARCB     DC F‘0’      COLUMN INDEX STARTS AT 0
ARCCNT   DC F‘20’     NUMBER OF COLUMNS
ARRAY    DC 600F‘0’   STORAGE FOR THE ARRAY
```

NOTE: The number 600 in the declaration of the storage for the array is not independent of the row and column count. It is the product of the row and column count.

We need a way to replace the number 600 by 30•20, indicating that the size of the array is a computed value. This leads us to the Macro feature called “SET Symbols”.

SET Symbols

The feature called “SET Symbols” allows for computing values in a macro, based on the values or attributes of the symbolic parameters. There are three basic types of SET symbols.

1.	Arithmetic	These are 32–bit numeric values, initialized to 0.
2.	Binary	These are 1–bit values, initialized to 0.
3.	Character	These are strings of characters, initialized to the null string.

Each of these comes in two varieties: local and global.

The **local** SET symbols have meaning only within the macro in which they are defined.
In terms used by programming language textbooks, these symbols have scope that is local to the macro invocation. Declarations in different macro expansions are independent.

The **global** SET symbols specify values that are to be known in other macro expansions within the same assembly. In other words, the scope of such a symbol is probably the entire unit that is assembled independently; usually this is a CSECT.

A proper use of a global SET symbol demands the use of conditional assembly to insure that the symbol is defined once and only once.

Local and Global Set Declarations
Here are the instructions used to declare the SET symbols.

Type	Local		Global	
	Instruction	Example	Instruction	Example
Arithmetic	LCLA	LCLA &F1	GBLA	GBLA &G1
Binary	LCLB	LCLB &F2	GBLB	GBLB &G2
Character	LCLC	LCLC &F3	GBLC	GBLC &G3

Each of these instructions declares a SET symbol that can have its value assigned by one of the SET instructions. There are three SET instructions.

SETA	SET Arithmetic	Use with LCLA or GBLA SET symbols.
SETB	SET Binary	Use with LCLB or GBLB SET symbols.
SETC	SET Character String	Use with LCLC or GBLC SET symbols.

The requirements for placement of these instructions depend on the Operating System being run. The following standards have two advantages:

1. They are the preferred practice for clear programming, and
2. They seem to be accepted by every version of the Operating System.

Here is the sequence of declarations.

1. The macro prototype statement.
2. The global declarations used: GBLA, GBLB, or GBLC
3. The local declarations used:LCLA, LCLB, or LCLC
4. The appropriate SET instructions to give values to the SET symbols
5. The macro body.

Example of the Preferred Sequence
The following silly macro is not even complete. It illustrates the sequence for declaration, but might be incorrect in some details.

```
         MACRO
&NAME    HEDNG &HEAD, &PAGE
         GBLC &DATES          HOLDS THE DATE
         GBLB &DATEP          HAS DATES BEEN DEFINED
         LCLA &LEN, &MID      HERE IS A LOCAL DECLARATION
         AIF (&DATEP).N20     IS DATE DEFINED?
&DATES   DC C'&SYSDATE'       SET THE DATE
&DATEP   SETB (1)             DECLARE IT SET
.N20     ANOP
&LEN     SETA L'&HEAD         LENGTH OF THE HEADER
&MID     SETA (120-&LEN)/2    MID POINT
&NAME    Start of macro body.
```

A Constructor Macro for the 2–D Array

This macro uses one arithmetic SET symbol to calculate the array size. Note that this definition does away with the base for the row and column numbers, as I never use them.

```
*
*        MACRO DEFINITIONS
*
         MACRO
&L1      ARMAK2D &NAME,&ROWS,&COLS
         LCLA &SIZE
&SIZE    SETA (&ROWS*&COLS)
&L1      B X&SYSNDX
&NAME.RS DC H'&ROWS'
&NAME.CS DC H'&COLS'
&NAME.V  DC &SIZE.F'0'
X&SYSNDX SLA R3,0
         MEND
```

Here are two invocations of the macro **ARMAK2D** and their expansions.

```
                                    86           ARMAK2D XX,10,20
00004A 47F0 C36E           00374    87+          B X0009
00004E 000A                         88+XXRS      DC H'10'
000050 0014                         89+XXCS      DC H'20'
000052 0000
000054 0000000000000000             90+XXV       DC 200F'0'
000374 8B30 0000           00000    91+X0009     SLA R3,0

                                    92           ARMAK2D YY,4,8
000378 47F0 C3FA           00400    93+          B X0010
00037C 0004                         94+YYRS      DC H'4'
00037E 0008                         95+YYCS      DC H'8'
000380 0000000000000000             96+YYV       DC 32F'0'
000400 8B30 0000           00000    97+X0010     SLA R3,0
```

Please note the hexadecimal addresses at the left of the listing. Line 90 corresponds to byte address **X'0054'** and line 91 to byte address **X'0374'**. The difference is given by **X'320'**, which is decimal 800. Line 90 reserves 200 fullwords, which occupy 800 bytes.

The storage allocation indicated by lines 96 and 97 is similar. Line 96 sets aside thirty–two fullwords, for an allocation of 128 bytes. **X'400'** – **X'320'** = **X'80'** = 128 in decimal.

The **ARGET2D** and **ARPUT2D** macros would be based on the similar macros discussed above. Each would take three arguments, and have prototypes as follows:

```
ARGET2D &NAME,&ROW,&COL
ARPUT2D &NAME,&ROW,&COL
```

Each macro would insure that the row and column numbers were within bounds, and then calculate the offset into the block of storage set aside for the array. The writing of the actual code for each of these macros is left as an exercise for the reader.

Strings vs. Arrays of Characters

While a string may be considered an array of characters, this is not the normal practice.
A string is a sequence of characters with a fixed length. A string is stored in **"string space"**, which may be considered to be a large dynamically allocated array that contains all of the strings used. There are two ways to declare the length of a string.

1. Allot a special "end of string" character, such as the character with code **`X'00'`**, as done in C and C++.
2. Store an explicit string length code, usually as a single byte that prefixes the string. A single byte can store an unsigned integer in the range 0 through 255 inclusive.

   In this method, the maximum string length is 255 characters.

There are variants on these two methods; some are worth consideration.

Example String

In this example, I used strings of digits that are encoded in EBCDIC. The character sequence "**`12345`**" would be encoded as **`F1 F2 F3 F4 F5`**. This is a sequence of five characters. In either of the above methods, it would require six bytes to be stored.

Here is the string, as would be stored by C++.

Byte number	0	1	2	3	4	5
Contents	**F1**	**F2**	**F3**	**F4**	**F5**	**00**

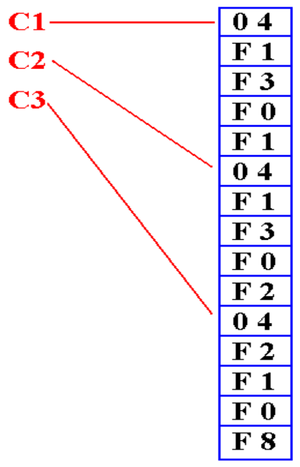
Here is the string, as might be stored by Visual Basic Version 6.

Byte number	0	1	2	3	4	5
Contents	**05**	**F1**	**F2**	**F3**	**F4**	**F5**

Each method has its advantages. The main difficulty with the first approach, as it is implemented in C and C++, is that the programmer is responsible for the terminating **`X'00'`**. Failing to place that can lead to strange run–time errors.

Sharing String Space

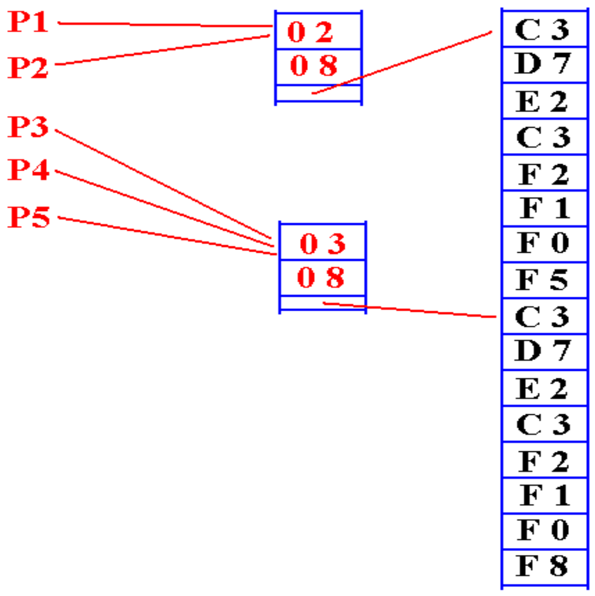
String variables usually are just pointers into string space.
Consider the following example in the style of Visual Basic.



Here, each of the symbols C1, C2, and C3 references a string of length 4.
C1 references the string "1301"
C2 references the string "1302"
C3 references the string "2108"

Using Indirect Pointers with Attributes

Another string storage method uses indirect pointers, as follows.



Here the intermediate node has the following structure.

1. A reference count
2. The string length
3. A pointer into string space.

There are two references to the first string, of length 8: "CPSC 2105".

There are three references to the second string, also of length 8: "CPSC 2108".

There are many advantages to this method of indirect reference, with attributes stored in the intermediate node. It may be the method used by Java.

There are a number of advantages associated with this approach to string storage. In general the use of indirection in pointers, as illustrated above, simplifies system programming. Here are a few illustrations of some of the standard considerations:

1. If pointer P1 is deallocated, the reference count for the string "CPSC 2105" is reduced by 1, but the string is not removed.
2. If pointer P2 is deallocated, then the reference count for the string goes to 0, and the string space can be reclaimed.

Reclamation of dynamic memory (string space in this example) is a tricky business and often is simply not done. However, the existence of the intermediate pointer facilitates such an operation. Suppose that the string "CPSC 2105" is removed and the string "CPSC2108" is moved up by eight positions. There is only one value that needs to be reassigned, and it is not the addresses associated with pointers P3, P4, or P5. It is the address in the intermediate node that each of P3, P4, and P5 reference. This intermediate node is easy to locate.