Chapter

6

Compiling to the Assembly Level

The theme of this book is the application of the concept of levels of abstraction to computer science. This chapter continues the theme by showing the relationship between the high-order languages level and the assembly level. It examines features of the C++ language at level HOL6 and shows how a compiler might translate programs that use those features to the equivalent program at level Asmb5.

One major difference between level-HOL6 languages and level-Asmb5 languages is the absence of extensive data types at level Asmb5. In C++, you can define integers, reals, arrays, booleans, and structures in almost any combination. But assembly language has only bits and bytes. If you want to define an array of structures in assembly language, you must partition the bits and bytes accordingly. The compiler does that job automatically when you program at level HOL6.

Another difference between the levels concerns the flow of control. C++ has `if`, `while`, `do`, `for`, `switch`, and function statements to alter the normal sequential flow of control. You will see that assembly language is limited by the basic von Neumann design to more primitive control statements. This chapter shows how the compiler must combine several primitive level-Asmb5 control statements to execute a single, more powerful level-HOL6 control statement.

6.1 Stack Addressing and Local Variables

When a program calls a function, the program allocates storage on the run-time stack for the returned value, the parameters, and the return address. Then the function allocates storage for its local variables. Stack-relative addressing allows the function to access the information that was pushed onto the stack.

You can consider `main()` of a C++ program to be a function that the operating system calls. You might be familiar with the fact that the main program can have parameters named `argc` and `argv` as follows:

```
int main (int argc, char* argv[])
```

With main declared this way, `argc` and `argv` are pushed onto the run-time stack, along with the return address and any local variables.

A simplification with `main()`

To keep things simple, this book always declares `main()` without the parameters, and it ignores the fact that storage is allocated for the integer returned value and the return address. Hence, the only storage allocated for `main()` on the run-time stack is for local variables. This section describes how the compiler translates main programs that have local variables.

Stack-Relative Addressing

In stack-relative addressing, the relationship between the operand and the operand specifier is

Stack-relative addressing

Oprnd = Mem [SP + OprndSpec]

The stack grows upward in main memory.

The stack pointer acts as a memory address to which the operand specifier is added. Figure 4.39 shows that the user stack grows upward in main memory starting at address FBCF. When an item is pushed onto the run-time stack, its address is less than the address of the item that was on the top of the stack.

You can think of the operand specifier as the offset from the top of the stack. If the operand specifier is 0, the instruction accesses Mem [SP], the value on top of the stack. If the operand specifier is 2, it accesses Mem [SP + 2], the value two bytes below the top of the stack.

The `ADDSP` instruction

The Pep/8 instruction set has two instructions for manipulating the stack pointer directly, `ADDSP` and `SUBSP`. (`CALL`, `RETn`, and `RETTR` manipulate the stack pointer indirectly.) `ADDSP` simply adds a value to the stack pointer and `SUBSP` subtracts a value. The RTL specification of `ADDSP` is

$$\mathrm{SP} \leftarrow \mathrm{SP} + \mathrm{Oprnd};\ \mathrm{N} \leftarrow \mathrm{SP} < 0,\ \mathrm{Z} \leftarrow \mathrm{SP} = 0,\ \mathrm{V} \leftarrow \{\mathit{overflow}\},\ \mathrm{C} \leftarrow \{\mathit{carry}\}$$

The `SUBSP` instruction

and the RTL specification of SUBSP is

$$\mathrm{SP} \leftarrow \mathrm{SP} - \mathrm{Oprnd};\ \mathrm{N} \leftarrow \mathrm{SP} < 0,\ \mathrm{Z} \leftarrow \mathrm{SP} = 0,\ \mathrm{V} \leftarrow \{\mathit{overflow}\},\ \mathrm{C} \leftarrow \{\mathit{carry}\}$$

Even though you can add to and subtract from the stack pointer, you cannot set the stack pointer with a load instruction. There is no `LDSP` instruction. Then how is the stack pointer ever set? When you select the execute option in the Pep/8 simulator the following two actions occur:

SP ← Mem [FFF8]
PC ← 0000

The first action sets the stack pointer to the content of memory location FFF8. That location is part of the operating system ROM, and it contains the address of the top of the application's run-time stack. Therefore, when you select the execute option the stack pointer is initialized correctly. The default Pep/8 operating system initializes SP to FBCF. The application never needs to set it to anything else. In general, the application only needs to add to the stack pointer to push items onto the run-time stack, and subtract from the stack pointer to pop items off of the run-time stack.

Accessing the Run-Time Stack

Figure 6.1 shows how to push data onto the stack, access it with stack-relative addressing, and pop it off the stack. The program pushes the string `"BMW"` onto the stack followed by the decimal integer 325 followed by the character `'i'`. Then it outputs the items and pops them off the stack.

```
0000   C00042 LDA     'B',i       ;push B
0003   F3FFFF STBYTEA -1,s
0006   C0004D LDA     'M',i       ;push M
0009   F3FFFE STBYTEA -2,s
000C   C00057 LDA     'W',i       ;push W
000F   F3FFFD STBYTEA -3,s
0012   C00145 LDA     325,i       ;push 325
0015   E3FFFB STA     -5,s
0018   C00069 LDA     'i',i       ;push i
001B   F3FFFA STBYTEA -6,s
001E   680006 SUBSP   6,i         ;6 bytes on the run-time stack
0021   530005 CHARO   5,s         ;output B
0024   530004 CHARO   4,s         ;output M
0027   530003 CHARO   3,s         ;output W
002A   3B0001 DECO    1,s         ;output 325
002D   530000 CHARO   0,s         ;output i
0030   600006 ADDSP   6,i         ;deallocate stack storage
0033   00     STOP
0034          .END
```

Output

```
BMW325i
```

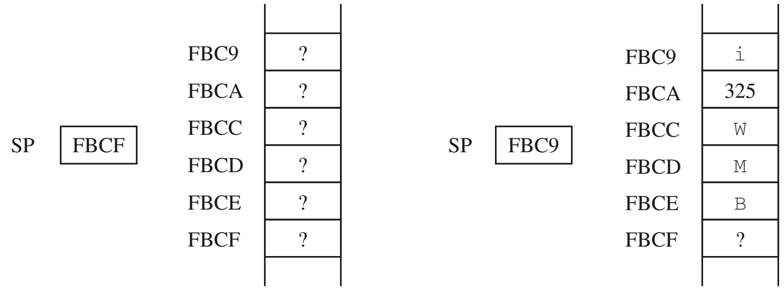
Figure 6.1

Stack-relative addressing.

Figure 6.2(a) shows the values in the stack pointer (SP) and main memory before the program executes. The machine initializes the stack pointer to FBCF from the vector at Mem [FFF8].

The first two instructions,

```
LDA 'B',i
STBYTEA -1,s
```



(a) Before the program executes. (b) After `SUBSP` executes.

Figure 6.2

Pushing BMW325i onto the run-time stack in Figure 6.1.

put an ASCII 'B' character in the byte just above the top of the stack. `LDA` puts the 'B' byte in the right half of the accumulator, and `STBYTEA` puts it above the stack. The store instruction uses stack-relative addressing with an operand specifier of –1 (dec) = FFFF (hex). Because the stack pointer has the value FBCF, the 'B' is stored at Mem [FBCF + FFFF] = Mem [FBCE]. The next two instructions put 'M' and 'W' at Mem [FBCD] and Mem [FBCC], respectively.

The decimal integer 325, however, occupies two bytes. The program must store it at an address that differs from the address of the 'W' by two. That is why the instruction to store the 325 is

```
STA -5,s
```

and not

```
STA -4,s
```

In general, when you push items onto the run-time stack you must take into account how many bytes each item occupies and set the operand specifier accordingly.

The `SUBSP` instruction subtracts 6 from the stack pointer, as Figure 6.2(b) shows. That completes the push operation.

Tracing a program that uses stack-relative addressing does not require you to know the absolute value in the stack pointer. The push operation would work the same if the stack pointer were initialized to some other value, say FA18. In that case, 'B', 'M', 'W', 325, and 'i' would be at Mem [FA17], Mem [FA16], Mem [FA15], Mem [FA13], and Mem [FA12], respectively, and the stack pointer would wind up with a value of FA12. The values would be at the same locations relative to the top of the stack, even though they would be at different absolute memory locations.

Figure 6.3 is a more convenient way of tracing the operation and makes use of the fact that the value in the stack pointer is irrelevant. Rather than show the value in the stack pointer, it shows an arrow pointing to the memory cell whose address is contained in the stack pointer. Rather than show the address of the cells in memory, it shows their offsets from the stack pointer. Figures depicting the state of the run-time stack will use this drawing convention from now on.

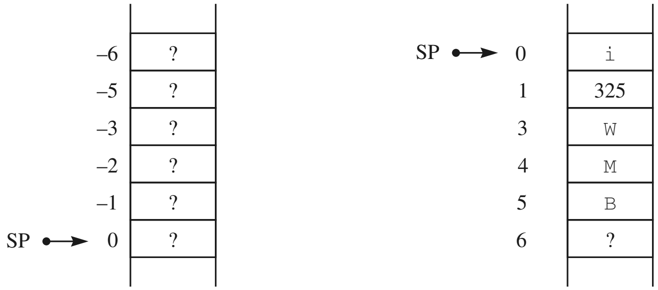


Figure 6.3

The stack of Figure 6.2 with relative addresses.

The instruction

```
CHARO 5,s
```

outputs the ASCII ‘B’ character from the stack. Note that the stack-relative address of the ‘B’ before `SUBSP` executes is –1, but its address after `SUBSP` executes is 5. Its stack-relative address is different because the stack pointer has changed. Both

```
STBYTEA -1,s
```

and

```
CHARO 5,s
```

access the same memory cell. The other items are output similarly using their stack offsets shown in Figure 6.3(b).

The instruction

```
ADDSP 6,i
```

deallocates six bytes of storage from the run-time stack by adding 6 to SP. Because the stack grows upward toward smaller addresses, you allocate storage by subtracting from the stack pointer and you deallocate storage by adding to the stack pointer.

Local Variables

The previous chapter shows how the compiler translates programs with global variables. It allocates storage for a global variable with a `.BLOCK` dot command and it accesses it with direct addressing. Local variables, however, are allocated on the run-time stack. To translate a program with local variables the compiler

The rules for accessing local variables

- allocates local variables with `SUBSP`,
- accesses local variables with stack-relative addressing, and
- deallocates storage with `ADDSP`.

An important difference between global and local variables is the time at which the allocation takes place. The `.BLOCK` dot command is not an executable statement. Storage for global variables is reserved at a fixed location before the program executes. In contrast, the `SUBSP` statement is executable. Storage for local variables is created on the run-time stack during program execution.

The memory model for global versus local variables

Figure 6.4 is identical to the program of Figure 5.26 except that the variables are declared local to `main()`. Although this difference is not perceptible to the user

Figure **6.4**

A program with local variables.

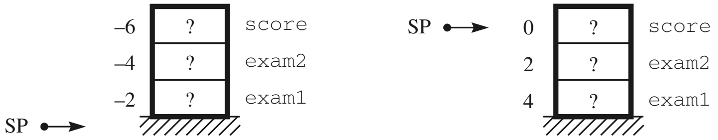
High-Order Language

```
#include <iostream>
using namespace std;

int main () {
   const int bonus = 5;
   int exam1;
   int exam2;
   int score;
   cin >> exam1 >> exam2;
   score = (exam1 + exam2) / 2 + bonus;
   cout << "score = " << score << endl;
   return 0;
}
```

Assembly Language

```
0000  040003          BR      main
             bonus:   .EQUATE 5          ;constant
             exam1:   .EQUATE 4          ;local variable
             exam2:   .EQUATE 2          ;local variable
             score:   .EQUATE 0          ;local variable
             ;
0003  680006 main:    SUBSP   6,i        ;allocate locals
0006  330004          DECI    exam1,s    ;cin >> exam1
0009  330002          DECI    exam2,s    ;   >> exam2
000C  C30004          LDA     exam1,s    ;score = (exam1
000F  730002          ADDA    exam2,s    ;   + exam2)
0012  1E              ASRA               ;   / 2
0013  700005          ADDA    bonus,i    ;   + bonus
0016  E30000          STA     score,s
0019  410026          STRO    msg,d      ;cout << "score = "
001C  3B0000          DECO    score,s    ;   << score
001F  50000A          CHARO   '\n',i     ;   << endl
0022  600006          ADDSP   6,i        ;deallocate locals
0025  00              STOP
0026  73636F msg:     .ASCII  "score = \x00"
      726520
      3D2000
002F                  .END
```



(a) Before `SUBSP` executes.

(a) After `SUBSP` executes.

Figure **6.5**

The run-time stack for the program of Figure 6.4.

of the program, the translation performed by the compiler is significantly different. Figure 6.5 shows the run-time stack for the program. As in Figure 5.26, `bonus` is a constant and is defined with the `.EQUATE` command. However, local variables are also defined with `.EQUATE`. With a constant, `.EQUATE` specifies the value of the constant, but with a local variable, `.EQUATE` specifies the stack offset on the run-time stack. For example, Figure 6.5 shows that the stack offset for local variable `exam1` is 6. Therefore, the assembly language program equates the symbol `exam1` to 6. Note from the assembly language listing that `.EQUATE` does not generate any code for the local variables.

`.EQUATE` specifies the stack offset for a local variable.

Translation of the executable statements in `main()` differs in two respects from the version with global variables. First, `SUBSP` and `ADDSP` allocate and deallocate storage on the run-time stack for the locals. Second, all accesses to the variables use stack-relative addressing instead of direct addressing. Other than these differences, the translation of the assignment and output statements is the same.

6.2 Branching Instructions and Flow of Control

The Pep/8 instruction set has eight conditional branches:

`BRLE`	Branch on less than or equal to
`BRLT`	Branch on less than
`BREQ`	Branch on equal to
`BRNE`	Branch on not equal to
`BRGE`	Branch on greater than or equal to
`BRGT`	Branch on greater than
`BRV`	Branch on V
`BRC`	Branch on C

Each of these conditional branches tests one or two of the four status bits, N, Z, V, and C. If the condition is true, the operand is placed in PC, causing the branch. If the condition is not true, the operand is not placed in PC, and the instruction following the conditional branch executes normally. You can think of them as comparing a 16-bit result to 0000 (hex). For example, `BRLT` checks whether a result is less than zero, which happens if N is 1. `BRLE` checks whether a result is less than or equal to zero, which happens if N is 1 or Z is 1. Here is the Register Transfer Language (RTL) specification of each conditional branch instruction.

The conditional branch instructions

`BRLE`	$\mathrm{N} = 1 \vee \mathrm{Z} = 1 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$
`BRLT`	$\mathrm{N} = 1 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$
`BREQ`	$\mathrm{Z} = 1 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$
`BRNE`	$\mathrm{Z} = 0 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$
`BRGE`	$\mathrm{N} = 0 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$
`BRGT`	$\mathrm{N} = 0 \wedge \mathrm{Z} = 0 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$
`BRV`	$\mathrm{V} = 1 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$
`BRC`	$\mathrm{C} = 1 \Rightarrow \mathrm{PC} \leftarrow \mathrm{Oprnd}$

Whether a branch occurs depends on the value of the status bits. The status bits are in turn affected by the execution of other instructions. For example,

```
LDA num,s
BRLT place
```

causes the content of `num` to be loaded into the accumulator. If the word represents a negative number, that is, if its sign bit is 1, then the N bit is set to 1. `BRLT` tests the N bit and causes a branch to the instruction at `place`. On the other hand, if the word loaded into the accumulator is not negative, then the N bit is cleared to 0. When `BRLT` tests the N bit, the branch does not occur and the instruction after `BRLT` executes next.

Translating the If Statement

Figure 6.6 shows how a compiler would translate an `if` statement from C++ to assembly language. The program computes the absolute value of an integer.

The assembly language comments show the statements that correspond to the high-level program. The `cin` statement translates to `DECI` and the `cout` statement translates to `DECO`. The assignment statement translates to the sequence `LDA`, `NEGA`, `STA`.

The compiler translates the `if` statement into the sequence `LDA`, `BRGE`. When `LDA` executes, if the value loaded into the accumulator is positive or zero, the N bit is cleared to 0. That condition calls for skipping the body of the `if` statement. Figure 6.7(a) shows the structure of the `if` statement at level HOL6. S1 represents the

High-Order Language

```
#include <iostream>
using namespace std;

int main () {
   int number;
   cin >> number;
   if (number < 0) {
      number = -number;
   }
   cout << number;
   return 0;
}
```

Assembly Language

```
0000  040003          BR      main
             number:  .EQUATE 0          ;local variable
             ;
0003  680002 main:    SUBSP   2,i        ;allocate local
0006  330000          DECI    number,s   ;cin >> number
0009  C30000 if:      LDA     number,s   ;if (number < 0)
000C  0E0016          BRGE    endIf
000F  C30000          LDA     number,s   ;   number = -number
0012  1A              NEGA
0013  E30000          STA     number,s
0016  3B0000 endIf:   DECO    number,s   ;cout << number
0019  600002          ADDSP   2,i        ;deallocate local
001C  00              STOP
001D                  .END
```

Figure **6.6**

The `if` statement at level HOL6 and level Asmb5.

statement `cin >> number`, C1 represents the condition `number < 0`, S2 represents the statement `number = -number`, and S3 represents the statement `cout << number`. Figure 6.7(b) shows the structure with the more primitive branching

(a) The structure at Level HOL6.

(b) The structure at level Asmb5 for Figure 6.6.

Figure **6.7**

The structure of the `if` statement at level Asmb5.

instructions at level Asmb5. The dot following C1 represents the conditional branch, `BRGE`.

The braces `{` and `}` for delimiting a compound statement have no counterpart in assembly language. The sequence

```
Statement 1
if (number >= 0) {
   Statement 2
   Statement 3
}
Statement 4
```

translates to

```
        Statement 1
if:     LDA number,d
        BRLT endIf
        Statement 2
        Statement 3
endIf:  Statement 4
```

Optimizing Compilers

You may have noticed an extra load statement that was not strictly required in Figure 6.6. You can eliminate the `LDA` at 000F because the value of `number` will still be in the accumulator from the previous load at 0009.

The question is, what would a compiler do? The answer is that it depends on the compiler. A compiler is a program that must be written and debugged. Imagine that you must design a compiler to translate from C++ to assembly language. When the compiler detects an assignment statement, you program it to generate the following sequence: (a) load accumulator, (b) evaluate expression if necessary, (c) store result to variable. Such a compiler would generate the code of Figure 6.6, with the `LDA` at 000F.

Imagine how difficult your compiler program would be if you wanted it to eliminate the unnecessary load. When your compiler detected an assignment statement, it would not always generate the initial load. Instead, it would analyze the previous instructions generated and remember the content of the accumulator. If it determined that the value in the accumulator was the same as the value that the initial load put there, it would not generate the initial load. In Figure 6.6, the compiler would need to remember that the value of `number` was still in the accumulator from the code generated for the `if` statement.

The purpose of an optimizing compiler

A compiler that expends extra effort to make the object program shorter and faster is called an optimizing compiler. You can imagine how much more difficult an optimizing compiler is to design than a nonoptimizing one. Not only are optimizing compilers more difficult to write, they also take longer to compile because they must analyze the source program in much greater detail.

The advantages and disadvantages of an optimizing compiler

Which is better, an optimizing or a nonoptimizing compiler? That depends on the use to which you put the compiler. If you are developing software, a process that requires many compiles for testing and debugging, then you would want a compiler that translates quickly, that is, a nonoptimizing compiler. If you have a large fixed program that will be executed repeatedly by many users, you would want fast execution of the object program, hence, an optimizing compiler. Frequently, software is developed and debugged with a nonoptimizing compiler and then translated one last time with an optimizing compiler for the users.

Real compilers come in all shades of gray between these two extremes. The examples in this chapter occasionally present object code that is partially optimized. Most assignment statements, such as the one in Figure 6.6, are presented in nonoptimized form.

Translating the If/Else Statement

Figure 6.8 illustrates the translation of the `if/else` statement. The C++ program is identical to the one in Figure 2.9. The `if` body requires an extra unconditional branch around the `else` body. If the compiler omitted the `BR` at 0015 and the input were 127, the output would be `highlow`.

Unlike Figure 6.6, the `if` statement in Figure 6.8 does not compare a variable's value with zero. It compares it with another nonzero value using `CPA`, which stands for compare accumulator. `CPA` subtracts the operand from the accumulator and sets the NZVC status bits accordingly. `CPr` is identical to `SUBr` except that `SUBr` stores the result of the subtraction in register r (accumulator or index register), whereas `CPr` ignores the result of the subtraction. The RTL specification of `CPr` is

The `CPr` instruction

$$T \leftarrow r - \text{Oprnd};\ N \leftarrow T < 0,\ Z \leftarrow T = 0,\ V \leftarrow \{\mathit{overflow}\},\ C \leftarrow \{\mathit{carry}\}$$

where T represents a temporary value.

This program computes `num - limit` and sets the NZVC bits. `BRLT` tests the N bit, which is set if

```
num - limit < 0
```

that is, if

```
num < limit
```

That is the condition under which the `else` part must execute.

Figure **6.8**

The `if/else` statement at level HOL6 and level Asmb5.

High-Order Language

```
#include <iostream>
using namespace std;

int main () {
   const int limit = 100;
   int num;
   cin >> num;
   if (num >= limit) {
      cout << "high";
   }
   else {
      cout << "low";
   }
   return 0;
}
```

Assembly Language

```
0000   040003          BR      main
              limit:   .EQUATE 100         ;constant
              num:     .EQUATE 0           ;local variable
              ;
0003   680002 main:    SUBSP   2,i         ;allocate local
0006   330000          DECI    num,s       ;cin >> num
0009   C30000 if:      LDA     num,s       ;if (num >= limit)
000C   B00064          CPA     limit,i
000F   080018          BRLT    else
0012   41001F          STRO    msg1,d      ;   cout << "high"
0015   04001B          BR      endIf       ;else
0018   410024 else:    STRO    msg2,d      ;   cout << "low"
001B   600002 endIf:   ADDSP   2,i         ;deallocate local
001E   00              STOP
001F   686967 msg1:    .ASCII  "high\x00"
       6800
0024   6C6F77 msg2:    .ASCII  "low\x00"
       00
0028                   .END
```

Figure 6.9 shows the structure of the control statements at the two levels. Part a shows the level-HOL6 control statement, and part b shows the level-Asmb5 translation for this program.

(a) The structure at Level HOL6.

(b) The structure at level Asmb5 for Figure 6.8.

Figure **6.9**

The structure of the `if/else` statement at level Asmb5.

Translating the While Loop

Translating a loop requires branches to previous instructions. Figure 6.10 shows the translation of a `while` statement. The C++ program is identical to the one in Figure 2.12. It echoes ASCII input characters to the output, using the sentinel technique with `*` as the sentinel. If the input is `happy*`, the output is `happy`.

The test for a `while` statement is made with a conditional branch at the top of the loop. This program tests a character value, which is a byte quantity. The load instruction at 0007 clears both bytes in the accumulator, so the most significant byte will be 00 (hex) after the load byte instruction at 000A executes. You must guarantee that the most significant byte is 0 because the compare instruction compares a whole word.

Every `while` loop ends with an unconditional branch to the test at the top of the loop. The branch at 0019 brings control back to the initial test. Figure 6.11 shows the structure of the `while` statement at the two levels.

Figure **6.10**

The `while` statement at level HOL6 and level Asmb5.

High-Order Language

```
#include <iostream>
using namespace std;

char letter;

int main () {
   cin >> letter;
   while (letter != '*') {
      cout << letter;
      cin >> letter;
   }
   return 0;
}
```

Assembly Language

```
0000  040004           BR      main
0003  00      letter:  .BLOCK  1           ;global variable
              ;
0004  490003 main:     CHARI   letter,d    ;cin >> letter
0007  C00000           LDA     0x0000,i
000A  D10003 while:    LDBYTEA letter,d    ;while (letter != '*')
000D  B0002A           CPA     '*',i
0010  0A001C           BREQ    endWh
0013  510003           CHARO   letter,d    ;    cout << letter
0016  490003           CHARI   letter,d    ;    cin >> letter
0019  04000A           BR      while
001C  00      endWh:   STOP
001D                   .END
```

Figure 6.10

(Continued)

(a) The structure at level HOL6.

(b) The structure at level Asmb5 for Figure 6.10.

Figure 6.11

The structure of the `while` statement at level Asmb5.

Translating the Do Loop

A highway patrol officer parks behind a sign. A driver passes by, traveling 20 meters per second, which is faster than the speed limit. When the driver is 40 meters down the road, the officer gets his car up to 25 meters per second to pursue the offender. How far from the sign does the officer catch up to the speeder?

The program in Figure 6.12 solves the problem by simulation. It is identical to the one in Figure 2.13. The values of `cop` and `driver` are the positions of the two motorists, initialized to 0 and 40, respectively. Each execution of the `do` loop represents one second of elapsed time, during which the officer travels 25 meters and the driver 20, until the officer catches the driver.

A `do` statement has its test at the bottom of the loop. In this program, the compiler translates the `while` test to the sequence `LDA`, `CPA`, `BRLT`. `BRLT` executes the branch if N is set to 1. Because `CPA` computes the difference, `cop - driver`, N will be 1 if

```
cop - driver < 0
```

Figure **6.12**

The `do` statement at level HOL6 and level Asmb5.

High-Order Language

```
#include <iostream>
using namespace std;

int cop;
int driver;

int main () {
   cop = 0;
   driver = 40;
   do {
      cop += 25;
      driver += 20;
   }
   while (cop < driver);
   cout << cop;
   return 0;
}
```

Assembly Language

```
0000  040007          BR      main
0003  0000    cop:    .BLOCK  2          ;global variable
0005  0000    driver: .BLOCK  2          ;global variable
              ;
0007  C00000 main:    LDA     0,i        ;cop = 0
000A  E10003          STA     cop,d
000D  C00028          LDA     40,i       ;driver = 40
0010  E10005          STA     driver,d
0013  C10003 do:      LDA     cop,d      ;   cop += 25
0016  700019          ADDA    25,i
0019  E10003          STA     cop,d
001C  C10005          LDA     driver,d   ;   driver += 20
001F  700014          ADDA    20,i
0022  E10005          STA     driver,d
0025  C10003 while:   LDA     cop,d      ;while (cop < driver)
0028  B10005          CPA     driver,d
002B  080013          BRLT    do
002E  390003          DECO    cop,d      ;cout << cop
0031  00              STOP
0032                  .END
```

that is, if

```
cop < driver
```

That is the condition under which the loop should repeat. Figure 6.13 shows the structure of the `do` statement at levels 6 and 5.

(a) The structure at level HOL6.

(b) The structure at level Asmb5 for Figure 6.12.

Figure 6.13

The structure of the `do` statement at level Asmb5.

Translating the For Loop

`for` statements are similar to `while` statements because the test for both is at the top of the loop. The compiler must generate code to initialize and to increment the control variable. The program in Figure 6.14 shows how a compiler would generate code for the `for` statement. It translates the `for` statement into the following sequence at level Asmb5:

- Initialize the control variable.
- Test the control variable.
- Execute the loop body.
- Increment the control variable.
- Branch to the test.

Figure 6.14

The `for` statement at level HOL6 and level Asmb5.

High-Order Language

```
#include <iostream>
using namespace std;

int main () {
   int i;
   for (i = 0; i < 3; i++) {
      cout << "i = " << i << endl;
   }
   cout << "i = " << i << endl;
   return 0;
}
```

Figure **6.14**

(Continued)

Assembly Language

```
0000  040003          BR      main
             i:       .EQUATE 0          ;local variable
             ;
0003  680002 main:    SUBSP   2,i        ;allocate local
0006  C00000          LDA     0,i
0009  E30000          STA     i,s
000C  B00003 for:     CPA     3,i
000F  0E0027          BRGE    endFor
0012  410034          STRO    msg,d      ;   cout << "i = "
0015  3B0000          DECO    i,s        ;      << i
0018  50000A          CHARO   '\n',i     ;      << endl
001B  C30000          LDA     i,s
001E  700001          ADDA    1,i
0021  E30000          STA     i,s
0024  04000C          BR      for
0027  410034 endFor:  STRO    msg,d      ;cout << "i = "
002A  3B0000          DECO    i,s        ;   << i
002D  50000A          CHARO   '\n',i     ;   << endl
0030  600002          ADDSP   2,i        ;deallocate local
0033  00              STOP
0034  69203D msg:     .ASCII  "i = \x00"
      2000
0039                  .END
```

In this program, `CPA` computes the difference, `i - 3`. `BRGE` branches out of the loop if N is 0, that is, if

```
i - 3 >= 0
```

or, equivalently,

```
i >= 3
```

The body executes once each for `i` having the values 0, 1, and 2. The last time through the loop, `i` increments to 3, which is the value written by the output statement following the loop.

Spaghetti Code

At the assembly level, a programmer can write control structures that do not correspond to the control structures in C++. Figure 6.15 shows one possible flow of control that is not directly possible in many level-HOL6 languages. Condition *C1* is

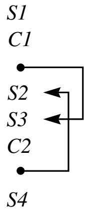


Figure **6.15**

A flow of control not possible directly in many HOL6 languages.

tested, and if it is true, a branch is taken to the middle of a loop whose test is *C2*. This control flow cannot be written directly in C++.

Assembly language programs generated by a compiler are usually longer than programs written by humans directly in assembly language. Not only that, but they often execute more slowly. If human programmers can write shorter, faster assembly language programs than compilers, why does anyone program in a high-order language? One reason is the ability of the compiler to perform type checking, as mentioned in Chapter 5. Another is the additional burden of responsibility that is placed on the programmer when given the freedom of using primitive branching instructions. If you are not careful when you write programs at level Asmb5, the branching instructions can get out of hand, as the next program shows.

The program in Figure 6.16 is an extreme example of the problem that can occur with unbridled use of primitive branching instructions. It is difficult to understand because of its lack of comments and indentation and its inconsistent branching style. Actually, the program performs a very simple task. Can you discover what it does?

```
0000  040009           BR      main
0003  0000    n1:      .BLOCK  2
0005  0000    n2:      .BLOCK  2
0007  0000    n3:      .BLOCK  2
              ;
0009  310005  main:    DECI    n2,d
000C  310007           DECI    n3,d
000F  C10005           LDA     n2,d
0012  B10007           CPA     n3,d
0015  08002A           BRLT    L1
0018  310003           DECI    n1,d
001B  C10003           LDA     n1,d
001E  B10007           CPA     n3,d
0021  080074           BRLT    L7
0024  040065           BR      L6
0027  E10007           STA     n3,d
002A  310003  L1:      DECI    n1,d
002D  C10005           LDA     n2,d
0030  B10003           CPA     n1,d
0033  080053           BRLT    L5
0036  390003           DECO    n1,d
0039  390005           DECO    n2,d
003C  390007  L2:      DECO    n3,d
003F  00               STOP
0040  390005  L3:      DECO    n2,d
0043  390007           DECO    n3,d
0046  040081           BR      L9
```

Figure **6.16**

A mystery program.

```
0049  390003 L4:     DECO    n1,d
004C  390005         DECO    n2,d
004F  00             STOP
0050  E10003         STA     n1,d
0053  C10007 L5:     LDA     n3,d
0056  B10003         CPA     n1,d
0059  080040         BRLT    L3
005C  390005         DECO    n2,d
005F  390003         DECO    n1,d
0062  04003C         BR      L2
0065  390007 L6:     DECO    n3,d
0068  C10003         LDA     n1,d
006B  B10005         CPA     n2,d
006E  080049         BRLT    L4
0071  04007E         BR      L8
0074  390003 L7:     DECO    n1,d
0077  390007         DECO    n3,d
007A  390005         DECO    n2,d
007D  00             STOP
007E  390005 L8:     DECO    n2,d
0081  390003 L9:     DECO    n1,d
0084  00             STOP
0085                 .END
```

Figure **6.16**

(Continued)

The body of an `if` statement or a loop in C++ is a block of statements, sometimes contained in a compound statement delimited by braces `{}`. Additional `if` statements and loops can be nested entirely within these blocks. Figure 6.17(a) pictures this situation schematically. A flow of control that is limited to nestings of the `if/else`, `switch`, `while`, `do`, and `for` statements is called structured flow of control.

Structured flow of control

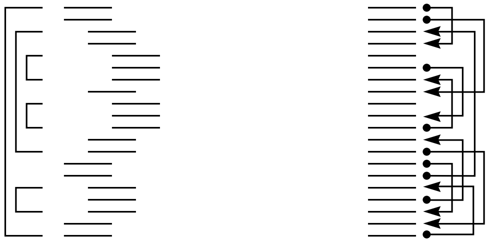
The branches in the mystery program do not correspond to the structured control constructs of C++. Although the program's logic is correct for performing its intended task, it is difficult to decipher because the branching statements branch all over the place. This kind of program is called spaghetti code. If you draw an arrow from each branch statement to the statement to which it branches, the picture looks rather like a bowl of spaghetti, as shown in Figure 6.17(b).

Spaghetti code

It is often possible to write efficient programs with unstructured branches. Such programs execute faster and require less memory for storage than if they were written in a high-order language with structured flow of control. Some specialized applications require this extra measure of efficiency and are therefore written directly in assembly language.

Advantages and disadvantages of programming at level Asmb5

Balanced against this savings in execution time and memory space is difficulty in comprehension. When programs are hard to understand, they are hard to write, debug, and modify. The problem is economic. Writing, debugging, and modifying



(a) Structured flow. (b) Spaghetti code.

Figure 6.17

Two different styles of flow of control.

are all human activities, which are labor intensive and, therefore, expensive. The question you must ask is whether the extra efficiency justifies the additional expense.

Flow of Control in Early Languages

Computers had been around for many years before structured flow of control was discovered. In the early days there were no high-order languages. Everyone programmed in assembly language. Computer memories were expensive, and CPUs were slow by today's standards. Efficiency was all-important. Because a large body of software had not yet been generated, the problem of program maintenance was not appreciated.

The first widespread high-order language was FORTRAN, developed in the 1950s. Because people were used to dealing with branch instructions, they included them in the language. An unconditional branch in FORTRAN is

```
GOTO 260
```

A goto statement at level HOL6

where 260 is the statement number of another statement. It is called a goto statement. A conditional branch is

```
IF (NUMBER .GE. 100) GOTO 500
```

where `.GE.` means "is greater than or equal to." This statement compares the value of variable `NUMBER` with 100. If it is greater than or equal to 100, the next statement executed is the one with a statement number of 500. Otherwise the statement after the `IF` is executed.

FORTRAN's conditional `IF` is a big improvement over level-Asmb5 branch instructions. It does not require a separate compare instruction to set the status bits. But notice how the flow of control is similar to level-Asmb5 branching: If the test is true, do the `GOTO`. Otherwise continue to the next statement.

As people developed more software, they noticed that it would be convenient to group statements into blocks for use in `if` statements and loops. The most notable language to make this advance was ALGOL-60, developed in 1960. It was the first widespread block-structured language, although its popularity was limited mainly to Europe.

The Structured Programming Theorem

The preceding sections show how high-level structured control statements translate into primitive branch statements at a lower level. They also show how you can write branches at the lower level that do not correspond to the structured constructs. That raises an interesting and practical question: Is it possible to write an algorithm with goto statements that will perform some processing that is impossible to perform with structured constructs? That is, if you limit yourself to structured flow of control, are there some problems you will not be able to solve that you could solve if unstructured goto's were allowed?

The structured programming theorem

Corrado Bohm and Giuseppe Jacopini answered this important question in a computer science journal article in 1966.[1] They proved mathematically that any algorithm containing goto's, no matter how complicated or unstructured, can be written with only nested `if` statements and `while` loops. Their result is called the structured programming theorem.

Bohm and Jacopini's paper was highly theoretical. It did not attract much attention at first because programmers generally had no desire to limit the freedom they had with goto statements. Bohm and Jacopini showed what could be done with nested `if` statements and `while` loops, but left unanswered why programmers would want to limit themselves that way.

People experimented with the concept anyway. They would take an algorithm in spaghetti code and try to rewrite it using structured flow of control without goto statements. Usually the new program was much clearer than the original. Occasionally it was even more efficient.

The Goto Controversy

Two years after Bohm and Jacopini's paper appeared, Edsger W. Dijkstra of the Technological University at Eindhoven, the Netherlands, wrote a letter to the editor of the same journal in which he stated his personal observation that good programmers used fewer goto's than poor programmers.[2]

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[1] Corrado Bohm and Giuseppe Jacopini, "Flow-Diagrams, Turing Machines and Languages with Only Two Formation Rules," *Communications of the ACM 9* (May 1966): 366–371.

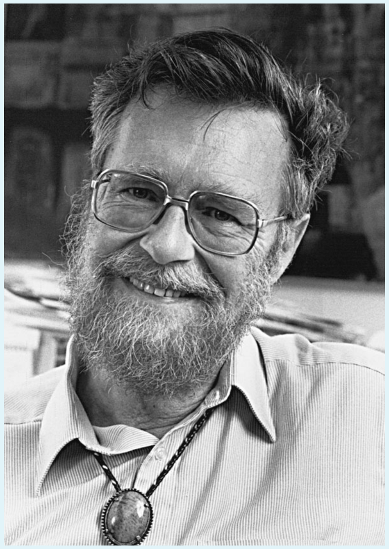
[2] Edsger W. Dijkstra, "Goto Statement Considered Harmful," *Communications of the ACM 11* (March 1968): 147–648. Reprinted by permission.

Edsger Dijkstra

Born to a Dutch chemist in Rotterdam in 1930, Dijkstra grew up with a formalist predilection toward the world. While studying at the University of Leiden in the Netherlands, Dijkstra planned to take up physics as his career. But his father heard about a summer course on computing in Cambridge, England, and Dijkstra jumped aboard the computing bandwagon just as it was gathering speed around 1950.

One of Dijkstra's most famous contributions to programming was his strong advocacy of structured programming principles, as exemplified by his famous letter that disparaged the goto statement. He developed a reputation for speaking his mind, often in inflammatory or dramatic ways that most of us couldn't get away with. For example, Dijkstra once remarked that "the use of COBOL cripples the mind; its teaching should therefore be regarded as a criminal offence." Not one to single out only one language for his criticism, he also said that "it is practically impossible to teach good programming to students that have had a prior exposure to BASIC; as potential programmers they are mentally mutilated beyond hope of regeneration."

Besides his work in language design, Dijkstra is also noted for his work in proofs of program correctness. The field of program correctness is an application of mathematics to computer programming. Researchers are trying to construct a language and proof technique that might be used to certify unconditionally that a program will perform according to its specifications—entirely free of bugs. Needless to say, whether your application is customer billing or flight control systems, this would be an extremely valuable claim to make about a program.



Dijkstra worked in practically every area within computer science. He invented the semaphore, described in Chapter 8 of this book, and invented a famous algorithm to solve the shortest path problem. In 1972 the Association for Computing Machinery acknowledged Dijkstra's rich contributions to the field by awarding him the distinguished Turing Award. Dijkstra died after a long struggle with cancer in 2002 at his home in Nuenen, the Netherlands.

"The question of whether computers can think is like the question of whether submarines can swim."

—Edsger Dijkstra

In his opinion, a high density of goto's in a program indicated poor quality. He stated in part:

An excerpt from Dijkstra's famous letter

> For a number of years I have been familiar with the observation that the quality of programmers is a decreasing function of the density of goto statements in the programs they produce. More recently I discovered why the use of the goto state-

> ment has such disastrous effects, and I became convinced that the goto statement should be abolished from all "higher level" programming languages (i.e., everything except, perhaps, plain machine code). . . . The goto statement as it stands is just too primitive; it is too much an invitation to make a mess of one's program.

To justify these statements, Dijkstra developed the idea of a set of coordinates that are necessary to describe the progress of the program. When a human tries to understand a program, he must maintain this set of coordinates mentally, perhaps unconsciously. Dijkstra showed that the coordinates to be maintained with structured flow of control were vastly simpler than those with unstructured goto's. Thus he was able to pinpoint the reason that structured flow of control is easier to understand.

Dijkstra acknowledged that the idea of eliminating goto's was not new. He mentioned several people who influenced him on the subject, one of whom was Niklaus Wirth, who had worked on the ALGOL-60 language.

Dijkstra's letter set off a storm of protest, now known as the famous goto controversy. To theoretically be able to program without goto was one thing. But to advocate that goto be abolished from high-order languages such as FORTRAN was altogether something else.

Old ideas die hard. However, the controversy has died down and it is now generally recognized that Dijkstra was, in fact, correct. The reason is cost. When software managers began to apply the structured flow of control discipline, along with other structured design concepts, they found that the resulting software was much less expensive to develop, debug, and maintain. It was usually well worth the additional memory requirements and extra execution time.

FORTRAN 77 is a more recent version of FORTRAN standardized in 1977. The goto controversy influenced its design. It contains a block style `IF` statement with an `ELSE` part similar to C++. For example,

```
IF (NUMBER .GE. 100) THEN
   Statement 1
ELSE
   Statement 2
ENDIF
```

You can write the `IF` statement in FORTRAN 77 without goto.

One point to bear in mind is that the absence of goto's in a program does not guarantee that the program is well structured. It is possible to write a program with three or four nested `if` statements and `while` loops when only one or two are necessary. Also, if a language at any level contains only goto statements to alter the flow of control, they can always be used in a structured way to implement `if` statements and `while` loops. That is precisely what a C++ compiler does when it translates a program from level HOL6 to level Asmb5.

6.3 Procedure Calls and Parameters

A C++ procedure call changes the flow of control to the first executable statement in the procedure. At the end of the procedure, control returns to the statement following the procedure call. The compiler implements procedure calls with the `CALL` instruction, which has a mechanism for storing the return address on the run-time stack. It implements the return to the calling statement with `RETn`, which uses the saved return address on the run-time stack to determine which instruction to execute next.

Translating a Procedure Call

Figure 6.18 shows how a compiler translates a procedure call without parameters. The program outputs three triangles of asterisks.

The `CALL` instruction pushes the content of the program counter onto the runtime stack, and then loads the operand into the program counter. Here is the RTL specification of the `CALL` instruction:

The `CALL` instruction

$$SP \leftarrow SP - 2;\ Mem[SP] \leftarrow PC;\ PC \leftarrow Opernd$$

In effect, the return address for the procedure call is pushed onto the stack and a branch to the procedure is executed.

As with the branch instructions, `CALL` usually executes in the immediate addressing mode, in which case the operand is the operand specifier. If you do not specify the addressing mode, the Pep/8 assembler will assume immediate addressing.

The default addressing mode for `CALL` is immediate.

Figure 5.2 shows that the `RETn` instruction has a three-bit nnn field. In general, a procedure can have any number of local variables. There are eight versions of the `RETn` instruction, namely `RET0`, `RET1`, …, `RET7`, where `n` is the number of bytes occupied by the local variables in the procedure. Procedure `printTri` in Figure 6.18 has no local variables. That is why the compiler generated the `RET0` instruction at 0015. Here is the RTL specification of `RETn`:

The `RETn` instruction

$$SP \leftarrow SP + n;\ PC \leftarrow Mem[SP];\ SP \leftarrow SP + 2$$

First, the instruction deallocates storage for the local variables by adding n to the stack pointer. After the deallocation, the return address should be on top of the runtime stack. Then, the instruction moves the return address from the top of the stack into the program counter. Finally, it adds two to the stack pointer, which completes the pop operation. Of course, it is possible for a procedure to have more than seven bytes of local variables. In that case, the compiler would generate an `ADDSP` instruction to deallocate the storage for the local variables.

In Figure 6.18,

```
BR main
```

Figure **6.18**

A procedure call at level HOL6 and level Asmb5.

High-Order Language

```
#include <iostream>
using namespace std;

void printTri () {
   cout << "*" << endl;
   cout << "**" << endl;
   cout << "***" << endl;
   cout << "****" << endl;
}

int main () {
   printTri ();
   printTri ();
   printTri ();
   return 0;
}
```

Assembly Language

```
0000  04001F           BR      main
              ;
              ;******* void printTri ()
0003  410016 printTri:STRO    msg1,d      ;cout << "*"
0006  50000A           CHARO   '\n',i      ;   << endl
0009  410018           STRO    msg2,d      ;cout << "**"
000C  50000A           CHARO   '\n',i      ;   << endl
000F  41001B           STRO    msg3,d      ;cout << "***"
0012  50000A           CHARO   '\n',i      ;   << endl
0015  58               RET0
0016  2A00   msg1:     .ASCII  "*\x00"
0018  2A2A00 msg2:     .ASCII  "**\x00"
001B  2A2A2A msg3:     .ASCII  "***\x00"
      00
              ;
              ;******* int main ()
001F  160003 main:     CALL    printTri    ;printTri ()
0022  160003           CALL    printTri    ;printTri ()
0025  160003           CALL    printTri    ;printTri ()
0028  00               STOP
0029                   .END
```

puts 001F into the program counter. The next statement to execute is, therefore, the one at 001F, which is the first `CALL` instruction. The discussion of the program in Figure 6.1 explains how the stack pointer is initialized to FBCF. Figure 6.19 shows the runtime stack before and after execution of the first `CALL` statement. As usual, the initial value of the stack pointer is FBCF.

(a) Before execution of the first `CALL`.

(b) After execution of the first `CALL`.

Figure 6.19

Execution of the first `CALL` instruction in Figure 6.18.

The operations of `CALL` and `RETn` crucially depend on the von Neumann execution cycle: fetch, decode, increment, execute, repeat. In particular, the increment step happens before the execute step. As a consequence, the statement that is executing is not the statement whose address is in the program counter. It is the statement that was fetched before the program counter was incremented and that is now contained in the instruction register. Why is that so important in the execution of `CALL` and `RETn`?

Figure 6.19(a) shows the content of the program counter as 0022 before execution of the first `CALL` instruction. It is not the address of the first `CALL` instruction, which is 001F. Why not? Because the program counter was incremented to 0022 before execution of the `CALL`. Therefore, during execution of the first `CALL` instruction the program counter contains the address of the instruction in main memory located just after the first `CALL` instruction.

What happens when the first `CALL` executes? First, SP ← SP – 2 subtracts two from SP, giving it the value FBCD. Then, Mem[SP] ← PC puts the value of the program counter, 0022, into main memory at address FBCD, that is, on top of the run-time stack. Finally, PC ← Oprnd puts 0003 into the program counter, because the operand specifier is 0003 and the addressing mode is immediate. The result is Figure 6.19(b).

The von Neumann cycle continues with the next fetch. But now the program counter contains 0003. So, the next instruction to be fetched is the one at address 0003, which is the first instruction of the `printTri` procedure. The output instructions of the procedure execute, producing the pattern of a triangle of asterisks.

Eventually the `RET0` instruction at 0015 executes. Figure 6.20(a) shows the content of the program counter as 0016 just before execution of `RET0`. This might

(a) Before the first execution of `RET0`.

(b) After the first execution of `RET0`.

Figure 6.20

The first execution of the `RET0` instruction in Figure 6.18.

seem strange, because 0016 is not even the address of an instruction. It is the address of the string `"*\x00"`. Why? Because `RET0` is a unary instruction and the CPU incremented the program counter by one. The first step in the execution of `RET0` is SP ← SP + n, which adds zero to SP because n is zero. Then, PC ← Mem[SP] puts 0022 into the program counter. Finally, SP ← SP + 2 changes the stack pointer back to FBCF.

The von Neumann cycle continues with the next fetch. But now the program counter contains the address of the second `CALL` instruction. The same sequence of events happens as with the first call, producing another triangle of asterisks in the output stream. The third call does the same thing, after which the `STOP` instruction executes. Note that the value of the program counter after the `STOP` instruction executes is 0029 and not 0028, which is the address of the `STOP` instruction.

Now you should see why increment comes before execute in the von Neumann execution cycle. To store the return address on the run-time stack, the `CALL` instruction needs to store the address of the instruction following the `CALL`. It can only do that if the program counter has been incremented before the `CALL` statement executes.

The reason increment must come before execute in the von Neumann execution cycle

Translating Call-By-Value Parameters with Global Variables

The allocation process when you call a void function in C++ is

- Push the actual parameters.
- Push the return address.
- Push storage for the local variables.

At level HOL6, the instructions that perform these operations on the stack are hidden. The programmer simply writes the function call, and during execution the stack allocation occurs automatically.

At the assembly level, however, the translated program must contain explicit instructions for the allocation. The program in Figure 6.21, which is identical to the program in Figure 2.15, is a level-HOL6 program that prints a bar chart, and the program's corresponding level-Asmb5 translation. It shows the level-Asmb5 statements, not explicit at level HOL6, that are required to push the parameters.

Figure **6.21**

Call-by-value parameters with global variables.

High-Order Language

```
#include <iostream>
using namespace std;

int numPts;
int value;
int i;
```

```
void printBar (int n) {
   int j;
   for (j = 1; j <= n; j++) {
      cout << '*';
   }
   cout << endl;
}

int main () {
   cin >> numPts;
   for (i = 1; i <= numPts; i++) {
      cin >> value;
      printBar (value);
   }
   return 0;
}
```

Figure 6.21

(Continued)

Assembly Language

```
0000  04002B          BR      main
0003  0000   numPts:  .BLOCK  2           ;global variable
0005  0000   value:   .BLOCK  2           ;global variable
0007  0000   i:       .BLOCK  2           ;global variable
             ;
             ;******* void printBar (int n)
             n:       .EQUATE 4           ;formal parameter
             j:       .EQUATE 0           ;local variable
0009  680002 printBar:SUBSP   2,i         ;allocate local
000C  C00001          LDA     1,i         ;for (j = 1
000F  E30000          STA     j,s
0012  B30004 for1:    CPA     n,s         ;j <= n
0015  100027          BRGT    endFor1
0018  50002A          CHARO   '*',i       ;   cout << '*'
001B  C30000          LDA     j,s         ;j++)
001E  700001          ADDA    1,i
0021  E30000          STA     j,s
0024  040012          BR      for1
0027  50000A endFor1: CHARO   '\n',i      ;cout << endl
002A  5A              RET2                ;deallocate local, pop retAddr
```

```
                ;
                ;******* main ()
002B  310003  main:    DECI    numPts,d    ;cin >> numPts
002E  C00001           LDA     1,i         ;for (i = 1
0031  E10007           STA     i,d
0034  B10003  for2:    CPA     numPts,d    ;i <= numPts
0037  100058           BRGT    endFor2
003A  310005           DECI    value,d     ;   cin >> value
003D  C10005           LDA     value,d     ;   call by value
0040  E3FFFE           STA     -2,s
0043  680002           SUBSP   2,i         ;   push parameter
0046  160009           CALL    printBar    ;   push retAddr
0049  600002           ADDSP   2,i         ;   pop parameter
004C  C10007           LDA     i,d         ;i++)
004F  700001           ADDA    1,i
0052  E10007           STA     i,d
0055  040034           BR      for2
0058  00      endFor2: STOP
0059                   .END
```

Figure **6.21**

(Continued)

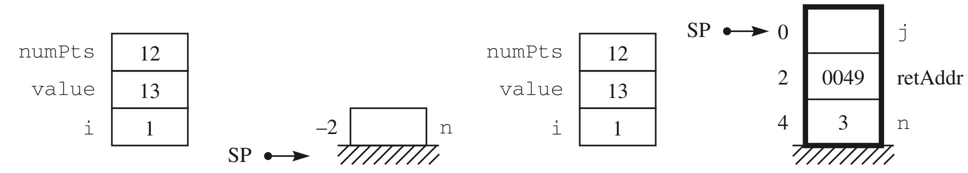
The calling procedure is responsible for pushing the actual parameters and executing `CALL`, which pushes the return address onto the stack. The called procedure is responsible for allocating storage on the stack for its local variables. After the called procedure executes, it must deallocate the storage for the local variables, and then pop the return address by executing `RETn`. Before the calling procedure can continue, it must deallocate the storage for the actual parameters.

In summary, the calling and called procedures do the following:

- Calling pushes actual parameters (executes `SUBSP`).
- Calling pushes return address (executes `CALL`).
- Called allocates local variables (executes `SUBSP`).
- Called executes its body.
- Called deallocates local variables and pops return address (executes `RETn`).
- Calling pops actual parameters (executes `ADDSP`).

Note the symmetry of the operations. The last two operations undo the first three operations in reverse order. That order is a consequence of the last-in, first-out property of the stack.

The global variables in the level-HOL6 main program—`numPts`, `value`, and `i`—correspond to the identical level-Asmb5 symbols, whose symbol values are 0003, 0005, and 0007, respectively. These are the addresses of the memory cells that will hold the run-time values of the global variables. Figure 6.22(a) shows the



(a) After `cin >> value`. (b) After allocation with `SUBSP` in `printBar`.

Figure 6.22

Call-by-value parameters with global variables.

global variables on the left with their symbols in place of their addresses. The values for the global variables are the ones after

```
cin >> value;
```

executes for the first time.

What do the formal parameter, `n`, and the local variable, `j`, correspond to at level Asmb5? Not absolute addresses, but stack-relative addresses. Procedure `printBar` defines them with

```
n: .EQUATE 4
j: .EQUATE 0
```

Remember that `.EQUATE` does not generate object code. The assembler does not reserve storage for them at translation time. Instead, storage for `n` and `j` is allocated on the stack at run time. The decimal numbers 4 and 0 are the stack offsets appropriate for `n` and `j` during execution of the procedure, as Figure 6.22(b) shows. The procedure refers to them with stack-relative addressing.

The statements that correspond to the procedure call in the calling procedure are

```
LDA   value,d
STA   -2,s
SUBSP 2,i
CALL  printBar
ADDSP 2,i
```

Because the parameter is a global variable that is called by value, `LDA` uses direct addressing. That puts the run-time value of variable `value` in the accumulator, which `STA` then pushes onto the stack. The offset is –2 because `value` is a two-byte integer quantity, as Figure 6.22(a) shows.

The statements that correspond to the procedure call in the called procedure are

```
SUBSP 2,i
.
.
.
RET2
```

The `SUBSP` subtracts 2 because the local variable, `j`, is a two-byte integer quantity. Figure 6.22(a) shows the run-time stack just after the first input of global variable `value` and just before the first procedure call. It corresponds directly to Figure 2.16(d) (page 49). Figure 6.22(b) shows the stack just after the procedure call and corresponds directly to Figure 2.16(g). Note that the return address, which is labeled ra1 in Figure 2.16, is here shown to be 0049, which is the assembly language address of the instruction following the `CALL` instruction.

The stack address of `n` is 4 because both `j` and the return address occupy two bytes on the stack. If there were more local variables, the stack address of `n` would be correspondingly greater. The compiler must compute the stack addresses from the number and size of the quantities on the stack.

In summary, to translate call-by-value parameters with global variables the compiler generates code as follows:

The translation rules for call-by-value parameters with global variables

- To push the actual parameter, it generates a load instruction with direct addressing.
- To access the formal parameter, it generates instructions with stack-relative addressing.

Translating Call-By-Value Parameters with Local Variables

The program in Figure 6.23 is identical to the one in Figure 6.21 except that the variables in `main()` are local instead of global. Although the program behaves like the one in Figure 6.21, the memory model and the translation to level Asmb5 are different.

Figure **6.23**

Call-by-value parameters with local variables.

High-Order Language

```
#include <iostream>
using namespace std;

void printBar (int n) {
   int j;
   for (j = 1; j <= n; j++) {
      cout << '*';
   }
   cout << endl;
}

int main () {
   int numPts;
   int value;
   int i;
```

```
   cin >> numPts;
   for (i = 1; i <= numPts; i++) {
      cin >> value;
      printBar (value);
   }
   return 0;
}
```

Figure 6.23

(Continued)

Assembly Language

```
0000  040025         BR      main
             ;
             ;******* void printBar (int n)
             n:       .EQUATE 4          ;formal parameter
             j:       .EQUATE 0          ;local variable
0003  680002 printBar:SUBSP   2,i        ;allocate local
0006  C00001          LDA     1,i        ;for (j = 1
0009  E30000          STA     j,s
000C  B30004 for1:    CPA     n,s        ;j <= n
000F  100021          BRGT    endFor1
0012  50002A          CHARO   '*',i      ;   cout << '*'
0015  C30000          LDA     j,s        ;j++)
0018  700001          ADDA    1,i
001B  E30000          STA     j,s
001E  04000C          BR      for1
0021  50000A endFor1: CHARO   '\n',i     ;cout << endl
0024  5A              RET2               ;deallocate local,
                                         ;pop retAddr
             ;
             ;******* main ()
             numPts:  .EQUATE 4          ;local variable
             value:   .EQUATE 2          ;local variable
             i:       .EQUATE 0          ;local variable
0025  680006 main:    SUBSP   6,i        ;allocate locals
0028  330004          DECI    numPts,s   ;cin >> numPts
002B  C00001          LDA     1,i        ;for (i = 1
002E  E30000          STA     i,s
0031  B30004 for2:    CPA     numPts,s   ;i <= numPts
0034  100055          BRGT    endFor2
0037  330002          DECI    value,s    ;   cin >> value
003A  C30002          LDA     value,s    ;   call by value
003D  E3FFFE          STA     -2,s
0040  680002          SUBSP   2,i        ;   push parameter
0043  160003          CALL    printBar   ;   push retAddr
0046  600002          ADDSP   2,i        ;   pop parameter
```

```
0049  C30000           LDA     i,s          ;i++)
004C  700001           ADDA    1,i
004F  E30000           STA     i,s
0052  040031           BR      for2
0055  600006 endFor2:  ADDSP   6,i          ;deallocate locals
0058  00               STOP
0059                   .END
```

Figure **6.23**

(Continued)

You can see that the versions of void function `printTri` at level HOL6 are identical in Figure 6.21 and Figure 6.23. Hence, it should not be surprising that the compiler generates identical object code for the two versions of `printTri` at level Asmb5. The only difference between the two programs is in the definition of `main()`. Figure 6.24(a) shows the allocation of `numPts`, `value`, and `i` on the run-time stack in the main program. Figure 6.24(b) shows the stack after `printTri` is called for the first time. Because `value` is a local variable, the compiler generates `LDA value,s` with stack-relative addressing to push the actual value of `value` into the stack cell of formal parameter `n`.

In summary, to translate call-by-value parameters with local variables the compiler generates code as follows:

- To push the actual parameter, it generates a load instruction with stack-relative addressing.
- To access the formal parameter, it generates instructions with stack-relative addressing.

The translation rules for call-by-value parameters with local variables

Translating Non-Void Function Calls

The allocation process when you call a function is

- Push storage for the returned value.
- Push the actual parameters.
- Push the return address.
- Push storage for the local variables.

(a) After `cin >> value`.

(b) After allocation with `SUBSP` in `printBar`.

Figure **6.24**

The first execution of the `RET0` instruction in Figure 6.23.

Allocation for a non-void function call differs from that for a procedure (void function) call by the extra value that you must allocate for the returned function value.

Figure 6.25 shows a program that computes a binomial coefficient recursively and is identical to the one in Figure 2.24. It is based on Pascal's triangle of coefficients, shown in Figure 2.25. The recursive definition of the binomial coefficient is

$$\begin{cases} b(n,0)=1 \\ b(k,k)=1 \\ b(n,k)=b(n-1,k)+b(n-1,k-1) \quad \text{for } 0 \le k \le n \end{cases}$$

The function tests for the base cases with an `if` statement, using the OR boolean operator. If neither base case is satisfied, it calls itself recursively twice—once to compute $b(n-1, k)$ and once to compute $b(n-1, k-1)$. Figure 6.26 shows the run-time stack produced by a call from the main program with actual parameters (3, 1). The function is called twice more with parameters (2, 1) and (1, 1), followed by a return. Then a call with parameters (1, 0) is executed, followed by a second return, and so on. Figure 6.26 shows the run-time stack at the assembly level immediately after the second return. It corresponds directly to the level-HOL6 diagram of Figure 2.28(g) (page 65). The return address labeled ra2 in Figure 2.28(g) is 0031 in Figure 6.26, the address of the instruction after the first `CALL` in the function. Similarly, the address labeled ra1 in Figure 2.28 is 007A in Figure 6.26.

High-Order Language

```
#include <iostream>
using namespace std;

int binCoeff (int n, int k) {
   int y1, y2;
   if ((k == 0) || (n == k)) {
      return 1;
   }
   else {
      y1 = binCoeff (n - 1, k); // ra2
      y2 = binCoeff (n - 1, k - 1); // ra3
      return y1 + y2;
   }
}

int main () {
   cout << "binCoeff (3, 1) = " << binCoeff (3, 1); // ra1
   cout << endl;
   return 0;
}
```

Figure 6.25

A recursive nonvoid function at level HOL6 and level Asmb5.

Figure 6.25

(Continued)

Assembly Language

```
0000  040065         BR      main
                ;
                ;******* int binomCoeff (int n, int k)
                retVal:  .EQUATE 10          ;returned value
                n:       .EQUATE 8           ;formal parameter
                k:       .EQUATE 6           ;formal parameter
                y1:      .EQUATE 2           ;local variable
                y2:      .EQUATE 0           ;local variable
0003  680004 binCoeff:SUBSP   4,i            ;allocate locals
0006  C30006 if:      LDA     k,s            ;if ((k == 0)
0009  0A0015          BREQ    then
000C  C30008          LDA     n,s            ;|| (n == k))
000F  B30006          CPA     k,s
0012  0C001C          BRNE    else
0015  C00001 then:    LDA     1,i            ;return 1
0018  E3000A          STA     retVal,s
001B  5C              RET4                   ;deallocate locals, pop retAddr
001C  C30008 else:    LDA     n,s            ;push n - 1
001F  800001          SUBA    1,i
0022  E3FFFC          STA     -4,s
0025  C30006          LDA     k,s            ;push k
0028  E3FFFA          STA     -6,s
002B  680006          SUBSP   6,i            ;push params and retVal
002E  160003          CALL    binCoeff       ;binomCoeff (n - 1, k)
0031  600006 ra2:     ADDSP   6,i            ;pop params and retVal
0034  C3FFFE          LDA     -2,s           ;y1 = binomCoeff (n - 1, k)
0037  E30002          STA     y1,s
003A  C30008          LDA     n,s            ;push n - 1
003D  800001          SUBA    1,i
0040  E3FFFC          STA     -4,s
0043  C30006          LDA     k,s            ;push k - 1
0046  800001          SUBA    1,i
0049  E3FFFA          STA     -6,s
004C  680006          SUBSP   6,i            ;push params and retVal
004F  160003          CALL    binCoeff       ;binomCoeff (n - 1, k - 1)
0052  600006 ra3:     ADDSP   6,i            ;pop params and retVal
0055  C3FFFE          LDA     -2,s           ;y2 = binomCoeff (n - 1, k - 1)
0058  E30000          STA     y2,s
005B  C30002          LDA     y1,s           ;return y1 + y2
005E  730000          ADDA    y2,s
0061  E3000A          STA     retVal,s
0064  5C     endIf:   RET4                   ;deallocate locals, pop retAddr
```

```
             ;
             ;******* main ()
0065  410084 main:    STRO    msg,d      ;cout << "binCoeff (3, 1) = "
0068  C00003          LDA     3,i        ;push 3
006B  E3FFFC          STA     -4,s
006E  C00001          LDA     1,i        ;push 1
0071  E3FFFA          STA     -6,s
0074  680006          SUBSP   6,i        ;push params and retVal
0077  160003          CALL    binCoeff   ;binomCoeff (3, 1)
007A  600006 ra1:     ADDSP   6,i        ;pop params and retVal
007D  3BFFFE          DECO    -2,s       ;<< binCoeff (3, 1)
0080  50000A          CHARO   '\n',i     ;cout << endl
0083  00              STOP
0084  62696E msg:     .ASCII  "binCoeff (3, 1) = \x00"
      ...
0097                  .END
```

Figure 6.25

(Continued)

At the start of the main program when the stack pointer has its initial value, the first actual parameter has a stack offset of –4, and the second has a stack offset of –6. In a procedure call (a void function), these offsets would be –2 and –4, respectively. Their magnitudes are greater by 2 because of the two-byte value returned on the stack by the function. The `SUBSP` instruction at 0074 allocates six bytes, two each for the actual parameters and two for the returned value.

When the function returns control to `ADDSP` at 007A, the value it returns will be on the stack below the two actual parameters. `ADDSP` pops the parameters and returned value by adding 6 to the stack pointer, after which it points to the cell directly below the returned value. So `DECO` outputs the value with stack-relative addressing and an offset of –2.

The function calls itself by allocating actual parameters according to the standard technique. For the first recursive call, it computes `n` - 1 and `k` and pushes those values onto the stack along with storage for the returned value. After the return, the sequence

```
ADDSP  6,i    ;pop params and retVal
LDA   -2,s    ;y1 = binomCoeff (n - 1, k)
STA    y1,s
```

pops the two actual parameters and returned value and assigns the returned value to `y1`. For the second call, it pushes `n` – 1 and `k` – 1 and assigns the returned value to `y2` similarly.

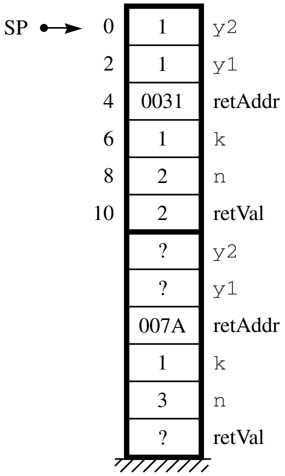


Figure 6.26

The run-time stack of Figure 6.25 immediately after the second return.

Translating Call-By-Reference Parameters with Global Variables

C++ provides call-by-reference parameters so that the called procedure can change the value of the actual parameter in the calling procedure. Figure 2.19 shows a program at level HOL6 that uses call by reference to put two global variables `a` and `b` in order. Figure 6.27 shows the same program together with the object program that a compiler would produce.

High-Order Language

```
#include <iostream>
using namespace std;

int a, b;

void swap (int& r, int& s) {
   int temp;
   temp = r;
   r = s;
   s = temp;
}

void order (int& x, int& y) {
   if (x > y) {
      swap (x, y);
   }  // ra2
}

int main () {
   cout << "Enter an integer: ";
   cin >> a;
   cout << "Enter an integer: ";
   cin >> b;
   order (a, b);
   cout << "Ordered they are: " << a << ", " << b << endl; // ra1
   return 0;
}
```

Figure **6.27**

Call-by-reference parameters with global variables.

Figure 6.27

(Continued)

Assembly Language

```
0000  04003C          BR      main
0003  0000   a:       .BLOCK  2           ;global variable
0005  0000   b:       .BLOCK  2           ;global variable
             ;
             ;******* void swap (int& r, int& s)
             r:       .EQUATE 6           ;formal parameter
             s:       .EQUATE 4           ;formal parameter
             temp:    .EQUATE 0           ;local variable
0007  680002 swap:    SUBSP   2,i         ;allocate local
000A  C40006          LDA     r,sf        ;temp = r
000D  E30000          STA     temp,s
0010  C40004          LDA     s,sf        ;r = s
0013  E40006          STA     r,sf
0016  C30000          LDA     temp,s      ;s = temp
0019  E40004          STA     s,sf
001C  5A              RET2                ;deallocate local, pop retAddr
             ;
             ;******* void order (int& x, int& y)
             x:       .EQUATE 4           ;formal parameter
             y:       .EQUATE 2           ;formal parameter
001D  C40004 order:   LDA     x,sf        ;if (x > y)
0020  B40002          CPA     y,sf
0023  06003B          BRLE    endIf
0026  C30004          LDA     x,s         ;   push x
0029  E3FFFE          STA     -2,s
002C  C30002          LDA     y,s         ;   push y
002F  E3FFFC          STA     -4,s
0032  680004          SUBSP   4,i         ;   push params
0035  160007          CALL    swap        ;   swap (x, y)
0038  600004          ADDSP   4,i         ;   pop params
003B  58     endIf:   RET0                ;pop retAddr
             ;
             ;******* main ()
003C  41006D main:    STRO    msg1,d      ;cout << "Enter an integer: "
003F  310003          DECI    a,d         ;cin >> a
0042  41006D          STRO    msg1,d      ;cout << "Enter an integer: "
0045  310005          DECI    b,d         ;cin >> b
0048  C00003          LDA     a,i         ;push the address of a
004B  E3FFFE          STA     -2,s
004E  C00005          LDA     b,i         ;push the address of b
0051  E3FFFC          STA     -4,s
0054  680004          SUBSP   4,i         ;push params
```

```
0057  16001D          CALL    order       ;order (a, b)
005A  600004 ra1:     ADDSP   4,i         ;pop params
005D  410080          STRO    msg2,d      ;cout << "Ordered they are: "
0060  390003          DECO    a,d         ;     << a
0063  410093          STRO    msg3,d      ;     << ", "
0066  390005          DECO    b,d         ;     << b
0069  50000A          CHARO   '\n',i      ;     << endl
006C  00              STOP
006D  456E74 msg1:    .ASCII  "Enter an integer: \x00"
      ...
0080  4F7264 msg2:    .ASCII  "Ordered they are: \x00"
      ...
0093  2C2000 msg3:    .ASCII  ", \x00"
0096                  .END
```

Figure **6.27**

(Continued)

The main program calls a procedure named `order` with two formal parameters `x` and `y` that are called by reference. `order` in turn calls `swap`, which makes the actual exchange. `swap` has call-by-reference parameters `r` and `s`. Parameter `r` refers to `s`, and `s` refers to `a`. The programmer used call by reference so that when procedure swap changes `r` it really changes `a`, because `r` refers to `a` (via `s`).

Parameters called by reference differ from parameters called by value in C++ because the actual parameter provides a reference to a variable in the calling routine instead of a value. At the assembly level, the code that pushes the actual parameter onto the stack pushes the address of the actual parameter. When the actual parameter is a global variable, its address is available as the value of its symbol. So, the code to push the address of a global variable is a load instruction with immediate addressing. In Figure 6.27, the code to push the address of `a` is

```
LDA a,i ;push the address of a
```

The value of the symbol `a` is 0003, the address of where the value of `a` is stored. The machine code for this instruction is

```
C00003
```

C0 is the instruction specifier for the load accumulator instruction with addressing-aaa field of 000 to indicate immediate addressing. With immediate addressing, the operand specifier is the operand. Consequently, this instruction loads 0003 into the accumulator. The following instruction pushes it onto the run-time stack.

Similarly, the code to push the address of `b` is

```
LDA b,i ;push the address of b
```

The machine code for this instruction is

```
C00005
```

where 0005 is the address of `b`. This instruction loads 0005 into the accumulator with immediate addressing, after which the next instruction puts it on the run-time stack.

In Figure 6.27 at 0026, procedure `order` calls `swap (x, y)`. It must push `x` onto the run-time stack. `x` is called by reference. Consequently, the address of `x` is on the run-time stack. The corresponding formal parameter `r` is also called by reference. Consequently, procedure `swap` expects the address of `r` to be on the run-time stack. Procedure `order` simply transfers the address for `swap` to use. The statement

```
LDA x,s ;push x
```

at 0026 uses stack-relative addressing to put the address in the accumulator. The next instruction puts it on the run-time stack.

In procedure order, however, the compiler must translate

```
temp = r
```

It must load the value of `r` into the accumulator, and then store it in `temp`. How does the called procedure access the value of a formal parameter whose address is on the run-time stack? It uses stack-relative deferred addressing.

Remember that the relation between the operand and the operand specifier with stack-relative addressing is

Oprnd = Mem [SP + OprndSpec]

Stack-relative addressing

The operand is on the run-time stack. But with call-by-reference parameters, the address of the operand is on the run-time stack. The relation between the operand and the operand specifier with stack-relative deferred addressing is

Oprnd = Mem [Mem [SP + OprndSpec]]

Stack-relative deferred addressing

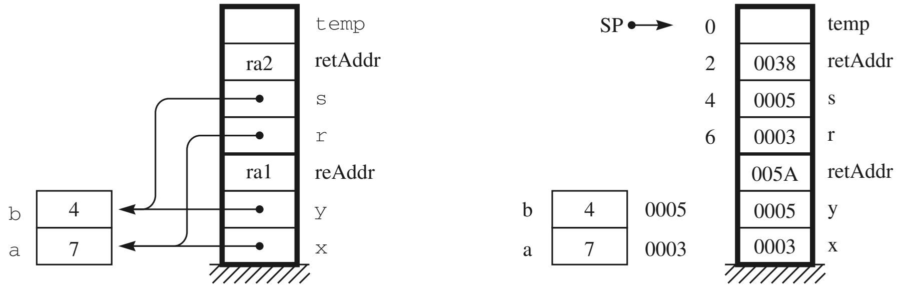
In other words, Mem [SP + OprndSpec] is the address of the operand, rather than the operand itself.

At lines 000A and 000D, the compiler generates the following object code to translate the assignment statement:

```
LDA r,sf
STA temp,s
```

The letters `sf` with the load instruction indicate stack-relative deferred addressing. The object code for the load instruction is

```
C40006
```



(a) The run-time stack at level HOL6.

(b) The run-time stack at level Asmb5.

Figure 6.28

The run-time stack for Figure 6.27 at level HOL6 and level Asmb5.

0006 is the stack relative address of parameter `r`, as Figure 6.28(b) shows. It contains 0003, the address of `a`. The load instruction loads 7, which is the value of `a`, into the accumulator. The store instruction puts it in `temp` on the stack.

The next assignment statement in procedure `swap`

```
r = s;
```

has parameters on both sides of the assignment operator. The compiler generates `LDA` to load the value of `s` and `STA` to store the value to `r`, both with stack-relative addressing.

```
LDA s,sf
STA r,sf
```

In summary, to translate call-by-reference parameters with global variables the compiler generates code as follows:

- To push the actual parameter, it generates a load instruction with immediate addressing.
- To access the formal parameter, it generates instructions with stack-relative deferred addressing.

The translation rules for call-by-reference parameters with global variables

Translating Call-By-Reference Parameters with Local Variables

Figure 6.29 shows a program that computes the perimeter of a rectangle given its width and height. The main program prompts the user for the width and the height, which it inputs into two local variables named `width` and `height`. A third local variable is named `perim`. The main program calls a procedure (a void function) named `rect` passing `width` and `height` by value and `perim` by reference. The figure shows the input and output when the user enters 8 for the width and 5 for the height.

Figure **6.29**

Call-by-reference parameters with local variables.

High-Order Language

```
#include <iostream>
using namespace std;

void rect (int& p, int w, int h) {
   p = (w + h) * 2;
}

int main () {
   int perim, width, height;
   cout << "Enter width: ";
   cin >> width;
   cout << "Enter height: ";
   cin >> height;
   rect (perim, width, height);
   // ra1
   cout << "perim = " << perim << endl;
   return 0;
}
```

Assembly Language

```
0000  04000E          BR      main
             ;
             ;******* void rect (int& p, int w, int h)
             p:       .EQUATE 6          ;formal parameter
             w:       .EQUATE 4          ;formal parameter
             h:       .EQUATE 2          ;formal parameter
0003  C30004 rect:    LDA     w,s        ;p = (w + h) * 2
0006  730002          ADDA    h,s
0009  1C              ASLA
000A  E40006          STA     p,sf
000D  58     endIf:   RET0               ;pop retAddr
             ;
             ;******* main ()
             perim:   .EQUATE 4          ;local variable
             width:   .EQUATE 2          ;local variable
             height:  .EQUATE 0          ;local variable
000E  680006 main:    SUBSP   6,i        ;allocate locals
0011  410046          STRO    msg1,d     ;cout << "Enter width: "
0014  330002          DECI    width,s    ;cin >> width
0017  410054          STRO    msg2,d     ;cout << "Enter height: "
```

```
001A  330000          DECI    height,s   ;cin >> height
001D  02              MOVSPA             ;push the address of perim
001E  700004          ADDA    perim,i
0021  E3FFFE          STA     -2,s
0024  C30002          LDA     width,s    ;push the value of width
0027  E3FFFC          STA     -4,s
002A  C30000          LDA     height,s   ;push the value of height
002D  E3FFFA          STA     -6,s
0030  680006          SUBSP   6,i        ;push params
0033  160003          CALL    rect       ;rect (perim, width, height)
0036  600006 ra1:     ADDSP   6,i        ;pop params
0039  410063          STRO    msg3,d     ;cout << "perim = "
003C  3B0004          DECO    perim,s    ;      << perim
003F  50000A          CHARO   '\n',i     ;      << endl
0042  600006          ADDSP   6,i        ;deallocate locals
0045  00              STOP
0046  456E74 msg1:    .ASCII  "Enter width: \x00"
      ...
0054  456E74 msg2:    .ASCII  "Enter height: \x00"
      ...
0063  706572 msg3:    .ASCII  "perim = \x00"
      ...
006C                  .END
```

Input/Output

```
Enter width: 8
Enter height: 5
perim = 26
```

Figure 6.30 shows the run-time stack at level HOL6 for the program. Compare it to Figure 6.28(a) for a program with global variables that are called by reference. In that program, formal parameters `x`, `y`, `r`, and `s` refer to global variables `a` and `b`. At level Asmb5, `a` and `b` are allocated at translation time with the `.EQUATE` dot command. Their symbols are their addresses. However, Figure 6.30 shows `perim` to be allocated on the run-time stack. The statement

```
main: SUBSP 6,i
```

at 000E allocates storage for `perim`, and its symbol is defined by

```
perim: .EQUATE 4
```

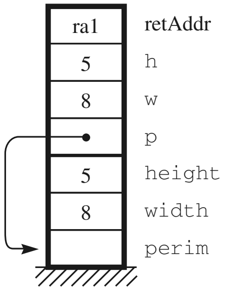
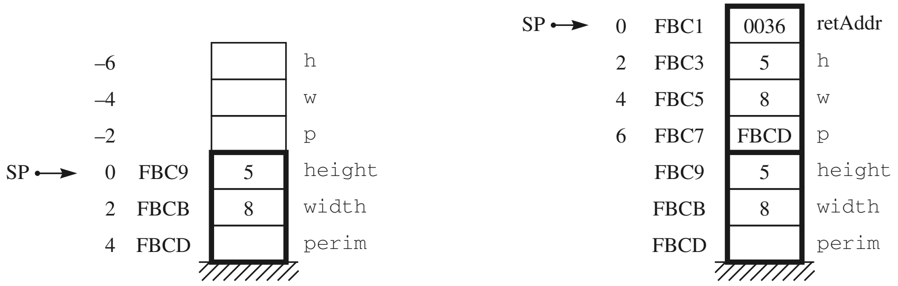


Figure 6.30

The run-time stack for Figure 6.29 at level HOL6.



(a) Before the procedure call. (b) After the procedure call.

Figure **6.31**

The run-time stack for Figure 6.29 at level Asmb5.

Its symbol is not its absolute address. Its symbol is its address relative to the top of the run-time stack, as Figure 6.31(a) shows. Its absolute address is FBCD. Why? Because that is the location of the bottom of the application run-time stack, as the memory map in Figure 4.39 shows.

So, the compiler cannot generate code to push parameter `perim` with

```
LDA perim,i
STA -2,s
```

as it does for global variables. If it generated those instructions, procedure `rect` would modify the content of Mem [0004], and 0004 is not where `perim` is located.

The absolute address of `perim` is FBCD. Figure 6.31(a) shows that you could calculate it by adding the value of `perim`, 4, to the value of the stack pointer. Fortunately, there is a unary instruction `MOVSPA` that moves the content of the stack pointer to the accumulator. The RTL specification of `MOVSPA` is

The `MOVSPA` instruction

$$A \leftarrow SP$$

To push the address of `perim` the compiler generates the following instructions at 001D in Figure 6.29:

```
MOVSPA
ADDA   perim,i
STA    -2,s
```

The first instruction moves the content of the stack pointer to the accumulator. The accumulator then contains FBC9. The second instruction adds the value of `perim`, which is 4, to the accumulator, making it FBCD. The third instruction puts the address of `perim` in the cell for `p`, which procedure `rect` uses to store the perimeter. Figure 6.31(b) shows the result.

Procedure `rect` uses `p` as any procedure would use any call-by-reference parameter. Namely, at 000A it stores the value using stack-relative deferred addressing.

```
STA p,sf
```

With stack-relative deferred addressing, the address of the operand is on the stack. The operand is

Stack-relative deferred addressing

Oprnd = Mem [Mem [SP + OprndSpec]]

This instruction adds the stack pointer FBC1 to the operand specifier 6 yielding FBC7. Because Mem [FBC7] is FBCD, it stores the accumulator at Mem [FBCD].

In summary, to translate call-by-reference parameters with local variables the compiler generates code as follows:

The translation rules for call-by-reference parameters with local variables

- To push the actual parameter, it generates the unary `MOVSPA` instruction followed by the `ADDA` instruction with immediate addressing.
- To access the formal parameter, it generates instructions with stack-relative deferred addressing.

Translating Boolean Types

Several schemes exist for storing boolean values at the assembly level. The one most appropriate for C++ is to treat the values true and false as integer constants. The values are

```
const int true = 1;
const int false = 0;
```

Figure 6.32 is a program that declares a boolean function named `inRange`. The compiler translates the function as if true and false were declared as above.

Figure **6.32**

Translation of a boolean type.

High-Order Language

```
#include <iostream>
using namespace std;

const int LOWER = 21;
const int UPPER = 65;

bool inRange (int a) {
   if ((LOWER <= a) && (a <= UPPER)) {
      return true;
   }
   else {
      return false;
   }
}
```

```
int main () {
   int age;
   cin >> age;
   if (inRange (age)) {
      cout << "Qualified\n";
   }
   else {
      cout << "Unqualified\n";
   }
   return 0;
}
```

Figure 6.32

(Continued)

Assembly Language

```
0000  040023          BR      main
             true:    .EQUATE 1
             false:   .EQUATE 0
             ;
             LOWER:   .EQUATE 21         ;const int
             UPPER:   .EQUATE 65         ;const int
             ;
             ;******* bool inRange (int a)
             retVal:  .EQUATE 4          ;returned value
             a:       .EQUATE 2          ;formal parameter
0003  C00015 inRange: LDA     LOWER,i    ;if ((LOWER <= a)
0006  B30002 if:      CPA     a,s
0009  10001C          BRGT    else
000C  C30002          LDA     a,s        ;    && (a <= UPPER))
000F  B00041          CPA     UPPER,i
0012  10001C          BRGT    else
0015  C00001 then:    LDA     true,i     ;    return true
0018  E30004          STA     retVal,s
001B  58              RET0
001C  C00000 else:    LDA     false,i    ;    return false
001F  E30004          STA     retVal,s
0022  58              RET0
             ;
             ;******* main ()
             age:     .EQUATE 0          ;local variable
0023  680002 main:    SUBSP   2,i        ;allocate local
0026  330000          DECI    age,s      ;cin >> age
```

```
0029  C30000 if2:    LDA     age,s       ;if (
002C  E3FFFC         STA     -4,s        ;store the value of age
002F  680004         SUBSP   4,i         ;push parameter and retVal
0032  160003         CALL    inRange     ;    (inRange (age))
0035  600004         ADDSP   4,i         ;pop parameter and retVal
0038  C3FFFE         LDA     -2,s        ;load retVal
003B  0A0044         BREQ    else2       ;branch if retVal == false (i.e., 0)
003E  41004B then2:  STRO    msg1,d      ;    cout << "Qualified\n"
0041  040047         BR      endif2
0044  410056 else2:  STRO    msg2,d      ;    cout << "Unqualified\n"
0047  600002 endif2: ADDSP   2,i         ;deallocate local
004A  00             STOP
004B  517561 msg1:   .ASCII  "Qualified\n\x00"
      ...
0056  556E71 msg2:   .ASCII  "Unqualified\n\x00"
      ...
0063                 .END
```

Figure 6.32

(Continued)

Representing false and true at the bit level as 0000 and 0001 (hex) has advantages and disadvantages. Consider the logical operations on boolean quantities and the corresponding assembly instructions `ANDr`, `ORr`, and `NOTr`. If `p` and `q` are global boolean variables, then

```
p && q
```

translates to

```
LDA  p,d
ANDA q,d
```

If you AND 0000 and 0001 with this object code, you get 0000 as desired. The OR operation `||` also works as desired. The NOT operation is a problem, however, because if you apply NOT to 0000, you get FFFF instead of 0001. Also, applying NOT to 0001 gives FFFE instead of 0000. Consequently, the compiler does not generate the `NOT` instruction when it translates the C++ assignment statement

```
p = !q
```

Instead, it uses the exclusive-or operation XOR, which has the mathematical symbol $\oplus$. It has the useful property that if you take the XOR of any bit value b with 0 you get b. And if you take the XOR of any bit value b with 1 you get the logical negation of b. Mathematically,

$$b \oplus 0 = b$$
$$b \oplus 1 = \neg b$$

Unfortunately, the Pep/8 computer does not have an `XORr` instruction in its instruction set. If it did have such an instruction, the compiler would generate the following code for the above assignment:

```
LDA  q,d
XORA 0x0001,i
STA  p,d
```

If `q` is false it has the representation 0000 (hex), and 0000 XOR 0001 equals 0001, as desired. Also, if `q` is true it has the representation 0001 (hex), and 0001 XOR 0001 equals 0000.

The type `bool` was not included in the C++ language standard until 1996. Older compilers use the convention that the boolean operators operate on integers. They interpret the integer value 0 as false and any nonzero integer value as true. To preserve backward compatibility, current C++ compilers maintain this convention.

6.4 Indexed Addressing and Arrays

A variable at level HOL6 is a memory cell at level ISA3. A variable at level HOL6 is referred to by its name, at level ISA3 by its address. A variable at level Asmb5 can be referred to by its symbolic name, but the value of that symbol is the address of the cell in memory.

What about an array of values? An array contains many elements, and so consists of many memory cells. The memory cells of the elements are contiguous; that is, they are adjacent to one another. An array at level HOL6 has a name. At level Asmb5, the corresponding symbol is the address of the first cell of the array. This section shows how the compiler translates source programs that allocate and access elements of one-dimensional arrays. It does so with several forms of indexed addressing.

At level Asmb5, the value of the symbol of an array is the address of the first cell of the array.

Figure 6.33 summarizes all the Pep/8 addressing modes. Previous programs illustrate immediate, direct, stack-relative, and stack-relative deferred addressing. Programs with arrays use indexed, stack-indexed, or stack-indexed deferred addressing. The column labeled aaa shows the address-aaa field at level ISA3. The column labeled Letters shows the assembly language designation for the addressing mode at level Asmb5. The column labeled Operand shows how the CPU determines the operand from the operand specifier (OprndSpec).

Addressing Mode	aaa	Letters	Operand
Immediate	000	i	OprndSpec
Direct	001	d	Mem [OprndSpec]
Indirect	010	n	Mem [Mem [OprndSpec]]
Stack-relative	011	s	Mem [SP + OprndSpec]
Stack-relative deferred	100	sf	Mem [Mem [SP + OprndSpec]]
Indexed	101	x	Mem [OprndSpec + X]
Stack-indexed	110	sx	Mem [SP + OprndSpec + X]
Stack-indexed deferred	111	sxf	Mem [Mem [SP + OprndSpec] + X]

Figure **6.33**

The Pep/8 addressing modes.

Translating Global Arrays

Figure 6.34 shows a program at level HOL6 that declares a global array of four integers named `vector` and a global integer named `i`. The main program inputs four integers into the array with a `for` loop and outputs them in reverse order together with their indexes.

High-Order Language

```
#include <iostream>
using namespace std;

int vector[4];
int i;

int main () {
   for (i = 0; i < 4; i++) {
      cin >> vector[i];
   }
   for (i = 3; i >= 0; i--) {
      cout << i  << ' ' << vector[i] << endl;
   }
   return 0;
}
```

Figure **6.34**

A global array.

Figure 6.34

(Continued)

Assembly Language

```
0000  04000D          BR      main
0003  000000 vector:  .BLOCK  8          ;global variable
      000000
      0000
000B  0000   i:       .BLOCK  2          ;global variable
             ;
             ;******* main ()
000D  C80000 main:    LDX     0,i        ;for (i = 0
0010  E9000B          STX     i,d
0013  B80004 for1:    CPX     4,i        ;   i < 4
0016  0E0029          BRGE    endFor1
0019  1D              ASLX               ;   an integer is two bytes
001A  350003          DECI    vector,x   ;   cin >> vector[i]
001D  C9000B          LDX     i,d        ;   i++)
0020  780001          ADDX    1,i
0023  E9000B          STX     i,d
0026  040013          BR      for1
0029  C80003 endFor1: LDX     3,i        ;for (i = 3
002C  E9000B          STX     i,d
002F  B80000 for2:    CPX     0,i        ;   i >= 0
0032  08004E          BRLT    endFor2
0035  39000B          DECO    i,d        ;   cout << i
0038  500020          CHARO   ' ',i      ;      << ' '
003B  1D              ASLX               ;   an integer is two bytes
003C  3D0003          DECO    vector,x   ;      << vector[i]
003F  50000A          CHARO   '\n',i     ;      << endl
0042  C9000B          LDX     i,d        ;   i--)
0045  880001          SUBX    1,i
0048  E9000B          STX     i,d
004B  04002F          BR      for2
004E  00     endFor2: STOP
004F                  .END
```

Input

```
60 70 80 90
```

Output

```
3 90
2 80
1 70
0 60
```

Figure 6.35 shows the memory allocation for integer `i` and array `vector`. As with all global integers, the compiler translates

```
int i;
```

at level HOL6 as the following statement at level Asmb5:

```
i: .BLOCK 2
```

The two-byte integer is allocated at address 000B. The compiler translates

```
int vector[4];
```

at level HOL6 as the following statement at level Asmb5:

```
vector: .BLOCK 8
```

It allocates eight bytes because the array contains four integers, each of which is two bytes. The `.BLOCK` statement is at 0003. Figure 6.35 shows that 0003 is the address of the first element of the array. The second element is at 0005, and each element is at an address two bytes greater than the previous element.

The compiler translates the first `for` statement

```
for (i = 0; i < 4; i++)
```

as usual. It accesses `i` with direct addressing because `i` is a global variable. But how does it access `vector[i]`? It cannot simply use direct addressing, because the value of symbol `vector` is the address of the first element of the array. If the value of `i` is 2, it should access the third element of the array, not the first.

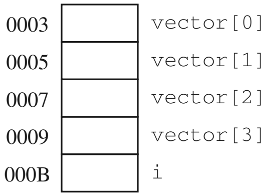


Figure **6.35**

Memory allocation for the global array of Figure 6.34.

The answer is that it uses indexed addressing. With indexed addressing, the CPU computes the operand as

Oprnd = Mem[OprndSpec + X]

Indexed addressing

It adds the operand specifier and the index register and uses the sum as the address in main memory from which it fetches the operand.

In Figure 6.34, the compiler translates

```
cin >> vector[i];
```

at level HOL6 as

```
ASLX
DECI vector,x
```

at level Asmb5. This is an optimized translation. The compiler analyzed the previous code generated and determined that the index register already contained the current value of `i`. A nonoptimizing compiler would generate the following code:

```
LDX   i,d
ASLX
DECI  vector,x
```

Suppose the value of `i` is 2. `LDX` puts the value of `i` in the index register. (Or, an optimizing compiler determines that the current value of `i` is already in the index register.) `ASLX` multiplies the 2 times 2, leaving 4 in the index register. `DECI` uses indexed addressing. So, the operand is computed as

Mem [OprndSpec + X]
Mem [0003 + 4]
Mem [0007]

which Figure 6.35 shows is `vector[2]`. Had the array been an array of characters, the `ASLX` operation would be unnecessary because each character occupies only one byte. In general, if each cell in the array occupies *n* bytes, the value of `i` is loaded into the index register, multiplied by *n*, and the array element is accessed with indexed addressing.

Similarly, the compiler translates the output of `vector[i]` as

```
ASLX
DECO   vector,x
```

with indexed addressing.

In summary, to translate global arrays the compiler generates code as follows:

The translation rules for global arrays

- It allocates storage for the array with `.BLOCK` *tot* where *tot* is the total number of bytes occupied by the array.
- It accesses an element of the array by loading the index into the index register, multiplying it by the number of bytes per cell, and using indexed addressing.

Translating Local Arrays

Like all local variables, local arrays are allocated on the run-time stack during program execution. The `SUBSP` instruction allocates the array and the `ADDSP` instruction deallocates it. Figure 6.36 is a program identical to the one of Figure 6.34 except that the index `i` and the array `vector` are local to `main()`.

High-Order Language

```
#include <iostream>
using namespace std;

int main () {
   int vector[4];
   int i;
```

Figure **6.36**

A local array.

```
   for (i = 0; i < 4; i++) {
      cin >> vector[i];
   }
   for (i = 3; i >= 0; i--) {
      cout << i  << ' ' << vector[i] << endl;
   }
   return 0;
}
```

Assembly Language

```
0000  040003          BR      main
             ;
             ;******* main ()
             vector:  .EQUATE 2          ;local variable
             i:       .EQUATE 0          ;local variable
0003  68000A main:    SUBSP   10,i       ;allocate locals
0006  C80000          LDX     0,i        ;for (i = 0
0009  EB0000          STX     i,s
000C  B80004 for1:    CPX     4,i        ;   i < 4
000F  0E0022          BRGE    endFor1
0012  1D              ASLX               ;   an integer is two bytes
0013  360002          DECI    vector,sx  ;   cin >> vector[i]
0016  CB0000          LDX     i,s        ;   i++)
0019  780001          ADDX    1,i
001C  EB0000          STX     i,s
001F  04000C          BR      for1
0022  C80003 endFor1: LDX     3,i        ;for (i = 3
0025  EB0000          STX     i,s
0028  B80000 for2:    CPX     0,i        ;   i >= 0
002B  080047          BRLT    endFor2
002E  3B0000          DECO    i,s        ;   cout << i
0031  500020          CHARO   ' ',i      ;      << ' '
0034  1D              ASLX               ;   an integer is two bytes
0035  3E0002          DECO    vector,sx  ;      << vector[i]
0038  50000A          CHARO   '\n',i     ;      << endl
003B  CB0000          LDX     i,s        ;   i--)
003E  880001          SUBX    1,i
0041  EB0000          STX     i,s
0044  040028          BR      for2
0047  60000A endFor2: ADDSP   10,i       ;deallocate locals
004A  00              STOP
004B                  .END
```

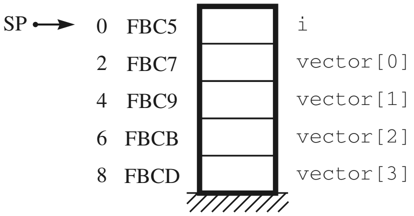


Figure **6.37**

Memory allocation for the local array of Figure 6.36.

Figure 6.37 shows the memory allocation on the run-time stack for the program of Figure 6.36. The compiler translates

```
int vector[4];
int i;
```

at level HOL6 as

```
main: SUBSP 10,i
```

at level Asmb5. It allocates eight bytes for `vector` and two bytes for `i`, for a total of 10 bytes. It sets the values of the symbols with

```
vector: .EQUATE 2
i:      .EQUATE 0
```

where 2 is the stack-relative address of the first cell of `vector` and 0 is the stack-relative address of `i` as Figure 6.37 shows

How does the compiler access `vector[i]`? It cannot use indexed addressing, because the value of symbol `vector` is not the address of the first element of the array. It uses stack-indexed addressing. With stack-indexed addressing, the CPU computes the operand as

Stack-indexed addressing

Oprnd = Mem[SP + OprndSpec + X]

It adds the stack pointer plus the operand specifier plus the index register and uses the sum as the address in main memory from which it fetches the operand.

In Figure 6.37, the compiler translates

```
cin >> vector[i];
```

at level HOL6 as

```
ASLX
DECI   vector,sx
```

at level Asmb5. As in the previous program, this is an optimized translation. A nonoptimizing compiler would generate the following code:

```
LDX    i,d
ASLX
DECI   vector,sx
```

Suppose the value of `i` is 2. `LDX` puts the value of `i` in the index register. `ASLX` multiplies the 2 times 2, leaving 4 in the index register. `DECI` uses stack-indexed addressing. So, the operand is computed as

Mem [SP + OprndSpec + X]
Mem [FBC5 + 2 + 4]
Mem [FBCB]

which Figure 6.37 shows is `vector[2]`. You can see how stack-indexed addressing is made for arrays on the run-time stack. SP is the address of the top of the stack. OprndSpec is the stack-relative address of the first cell of the array, so SP + OprndSpec is the absolute address of the first cell of the array. With `i` in the index register (multiplied by the number of bytes per cell of the array) the sum SP + OprndSpec + X is the address of cell `i` of the array.

In summary, to translate local arrays the compiler generates code as follows:

The translation rules for local arrays

- The array is allocated with `SUBSP` and deallocated with `ADDSP`.
- An element of the array is accessed by loading the index into the index register, multiplying it by the number of bytes per cell, and using stack-indexed addressing.

Translating Arrays Passed as Parameters

In C++, the name of an array is the address of the first element of the array. When you pass an array, even if you do not use the `&` designation in the formal parameter list, you are passing the address of the first element of the array. The effect is as if you call the array by reference. The designers of the C language, on which C++ is based, reasoned that programmers almost never want to pass an array by value because such calls are so inefficient. They require large amounts of storage on the run-time stack because the stack must contain the entire array. And they require a large amount of time because the value of every cell must be copied onto the stack. Consequently, the default behavior in C++ is for arrays to be called as if by reference.

Figure 6.38 shows how a compiler translates a program that passes a local array as a parameter. The main program passes an array of integers `vector` and an integer `numItms` to procedures `getVect` and `putVect`. `getVect` inputs values into the array and sets `numItms` to the number of items input. `putVect` outputs the values of the array.

Figure **6.38**

Passing a local array as a parameter.

High-Order Language

```
#include <iostream>
using namespace std;
```

Figure **6.38**

(Continued)

```
void getVect (int v[], int& n) {
   int i;
   cin >> n;
   for (i = 0; i < n; i++) {
      cin >> v[i];
   }
}

void putVect (int v[], int n) {
   int i;
   for (i = 0; i < n; i++) {
      cout << v[i] << ' ';
   }
   cout << endl;
}

int main () {
   int vector[8];
   int numItms;
   getVect (vector, numItms);
   putVect (vector, numItms);
   return 0;
}
```

Assembly Language

```
0000  040049          BR      main
             ;
             ;******* getVect (int v[], int& n)
             v:       .EQUATE 6           ;formal parameter
             n:       .EQUATE 4           ;formal parameter
             i:       .EQUATE 0           ;local variable
0003  680002 getVect: SUBSP   2,i         ;allocate local
0006  340004          DECI    n,sf        ;cin >> n
0009  C80000          LDX     0,i         ;for (i = 0
000C  EB0000          STX     i,s
000F  BC0004 for1:    CPX     n,sf        ;    i < n
0012  0E0025          BRGE    endFor1
0015  1D              ASLX                ;    an integer is two bytes
0016  370006          DECI    v,sxf       ;    cin >> v[i]
0019  CB0000          LDX     i,s         ;    i++)
001C  780001          ADDX    1,i
001F  EB0000          STX     i,s
0022  04000F          BR      for1
0025  5A     endFor1: RET2                ;pop local and retAddr
```

Figure 6.38

(Continued)

```
                 ;
                 ;******* putVect (int v[], int n)
                 v2:      .EQUATE 6           ;formal parameter
                 n2:      .EQUATE 4           ;formal parameter
                 i2:      .EQUATE 0           ;local variable
0026   680002 putVect: SUBSP   2,i         ;allocate local
0029   C80000          LDX     0,i         ;for (i = 0
002C   EB0000          STX     i2,s
002F   BB0004 for2:    CPX     n2,s        ;   i < n
0032   0E0048          BRGE    endFor2
0035   1D              ASLX                ;   an integer is two bytes
0036   3F0006          DECO    v2,sxf      ;   cout << v[i]
0039   500020          CHARO   ' ',i       ;      << ' '
003C   CB0000          LDX     i2,s        ;   i++)
003F   780001          ADDX    1,i
0042   EB0000          STX     i2,s
0045   04002F          BR      for2
0048   5A     endFor2: RET2                ;pop local and retAddr

                 ;
                 ;******* main ()
                 vector:  .EQUATE 2           ;local variable
                 numItms: .EQUATE 0           ;local variable
0049   680012 main:    SUBSP   18,i        ;allocate locals
004C   02              MOVSPA              ;push address of vector
004D   700002          ADDA    vector,i
0050   E3FFFE          STA     -2,s
0053   02              MOVSPA              ;push address of numItms
0054   700000          ADDA    numItms,i
0057   E3FFFC          STA     -4,s
005A   680004          SUBSP   4,i         ;push params
005D   160003          CALL    getVect     ;getVect (vector, numItms)
0060   600004          ADDSP   4,i         ;pop params
0063   02              MOVSPA              ;push address of vector
0064   700002          ADDA    vector,i
0067   E3FFFE          STA     -2,s
006A   C30000          LDA     numItms,s   ;push value of numItms
006D   E3FFFC          STA     -4,s
0070   680004          SUBSP   4,i         ;push params
0073   160026          CALL    putVect     ;putVect (vector, numItms)
0076   600004          ADDSP   4,i         ;pop params
0079   600012          ADDSP   18,i        ;deallocate locals
007C   00              STOP
007D                   .END
```

Input

```
5  40 50 60 70 80
```

Output

```
40 50 60 70 80
```

Figure 6.38

(Continued)

Figure 6.38 shows that the compiler translates the local variables

```
int vector[8];
int numItms;
```

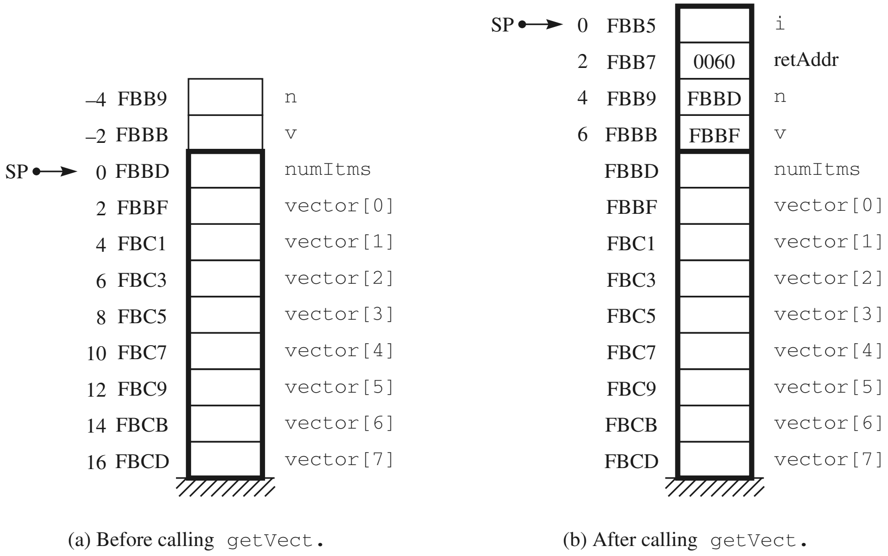
as

```
vector:   .EQUATE 2
numItms: .EQUATE 0
main:     SUBSP 18,i
```

The `SUBSP` instruction allocates 18 bytes on the run-time stack, 16 bytes for the eight integers of the array and 2 bytes for the integer. The `.EQUATE` dot commands set the symbols to their stack offsets, as Figure 6.39(a) shows.

The compiler translates

```
getVect (vector, numItms);
```



(a) Before calling `getVect`. (b) After calling `getVect`.

Figure 6.39

The run-time stack for the program of Figure 6.38.

by first generating code to push the address of the first cell of `vector`

```
MOVSPA
ADDA   vector,i
STA    -2,s
```

and then by generating code to push the address of `numItms`

```
MOVSPA
ADDA   numItms,i
STA    -4,s
```

Even though the signature of the function

```
void getVect (int v[], int& n)
```

does not have the `&` with parameter `v[]`, the compiler writes code to push the address of `v` with the `MOVSPA` and `ADDA` instructions. Because the signature does have the `&` with parameter `n`, the compiler writes code to push the address of `n` in the same way. Figure 6.39(b) shows `v` with FBBF, the address of `vector[0]` and `n` with FBBD, the address of `numItms`.

Figure 6.39(b) also shows the stack offsets for the parameters and local variables in `getVect`. The compiler defines the symbols

```
v: .EQUATE 6
n: .EQUATE 4
i: .EQUATE 0
```

accordingly. It translates the input statement

```
cin >> n;
```

as

```
DECI n,sf
```

where stack-relative deferred addressing is used because `n` is called by reference and the address of `n` is on the stack.

But how does the compiler translate

```
cin >> v[i];
```

It cannot use stack-indexed addressing, because the array of values is not in the stack frame for `getVect`. The value of `v` is 6, which means that the address of the first cell of the array is six bytes below the top of the stack. The array of values is in the stack frame for `main()`. Stack-indexed deferred addressing is designed to access the elements of an array whose address is in the top stack frame but whose actual collection of values is not. With stack-indexed deferred addressing, the CPU computes the operand as

Oprnd = Mem [Mem [SP + OprndSpec] + X]

Stack-indexed deferred addressing

It adds the stack pointer plus the operand specifier and uses the sum as the address of the first element of the array, to which it adds the index register. The compiler translates the input statement as

```
ASLX
DECI v,sxf
```

where the letters `sxf` indicate stack-indexed deferred addressing, and the compiler has determined that the index register will contain the current value of `i`.

For example, suppose the value of `i` is 2. The `ASLX` instruction doubles it to 4. The computation of the operand is

Mem [Mem[SP + OprndSpec] + X]
Mem [Mem[FBB5 + 6] + 4]
Mem [Mem[FBBB] + 4]
Mem [FBBF + 4]
Mem [FBC3]

which is `vector[2]` as expected from Figure 6.39(b).

The formal parameters in procedures `getVect` and `putVect` in Figure 6.39 have the same names. At level HOL6, the scope of the parameter names is confined to the body of the function. The programmer knows that a statement containing `n` in the body of `getVect` refers to the `n` in the parameter list for `getVect` and not to the `n` in the parameter list of `putVect`. The scope of a symbol name at level Asmb5, however, is the entire assembly language program. The compiler cannot use the same symbol for the `n` in `putVect` that it uses for the `n` in `getVect`, as duplicate symbol definitions would be ambiguous. All compilers must have some mechanism for managing the scope of name declarations in level-HOL6 programs when they transform them to symbols at level Asmb5. The compiler in Figure 6.38 makes the identifiers unambiguous by appending the digit 2 to the symbol name. Hence, the compiler translates variable name `n` in `putVect` at level HOL6 to symbol `n2` at level Asmb5. It does the same with `v` and `i`.

With procedure `putVect`, the array is passed as a parameter but `n` is called by value. In preparation for the procedure call, the address of `vector` is pushed onto the stack as before, but this time the value of `numItms` is pushed. In procedure `putVect`, `n2` is accessed with stack-relative addressing.

```
for2: CPX n2,s
```

because it is called by value. `v2` is accessed with stack-indexed deferred addressing

```
ASLX
DECO v2,sxf
```

as it is in `getVect`.

In Figure 6.38, `vector` is a local array. If it were a global array, the translations of `getVect` and `putVect` would be unchanged. `v[i]` would be accessed with stack-indexed deferred addressing, which expects the address of the first element of the array to be in the top stack frame. The only difference would be in the code to push the address of the first element of the array in preparation of the call. As in the program of Figure 6.34, the value of the symbol of a global array is the address of the first cell of the array. Consequently, to push the address of the first cell of the array the compiler would generate a `LDA` instruction with immediate addressing followed by a `STA` instruction with stack-relative addressing to do the push.

Passing global arrays as parameters

In summary, to pass an array as a parameter the compiler generates code as follows:

The translation rules for passing an array as a parameter

- The address of the first element of the array is pushed onto the run-time stack, either (a) with `MOVSPA` followed by `ADDA` with immediate addressing for a local array, or (b) with `LDA` with immediate addressing for a global array.
- An element of the array is accessed by loading the index into the index register, multiplying it by the number of bytes per cell, and using stack-indexed deferred addressing.

Translating the Switch Statement

The program in Figure 6.40, which is also in Figure 2.11, shows how a compiler translates the C++ `switch` statement. It uses an interesting combination of indexed addressing with the unconditional branch, `BR`. The `switch` statement is not the same as a nested `if` statement. If a user enters 2 for `guess`, the `switch` statement branches directly to the third alternative without comparing `guess` to 0 or 1. An array is a random access data structure because the indexing mechanism allows the programmer to access any element at random without traversing all the previous elements. For example, to access the third element of a vector of integers you can write `vector[2]` directly without having to traverse `vector[0]` and `vector[1]` first. Main memory is in effect an array of bytes whose addresses correspond to the indexes of the array. To translate the `switch` statement the compiler allocates an array of addresses called a jump table. Each entry in the jump table is the address of the first statement of a section of code that corresponds to one of the cases of the `switch` statement. With indexed addressing, the program can branch directly to case 2.

Figure **6.40**

Translation of a `switch` statement.

High-Order Language

```
#include <iostream>
using namespace std;

int main () {
   int guess;
   cout << "Pick a number 0..3: ";
   cin >> guess;
```

Figure **6.40**

(Continued)

```
   switch (guess) {
      case 0: cout << "Not close"; break;
      case 1: cout << "Close"; break;
      case 2: cout << "Right on"; break;
      case 3: cout << "Too high";
   }
   cout << endl;
   return 0;
}
```

Assembly Language

```
0000  040003          BR      main
             ;
             ;******* main ()
             guess:   .EQUATE 0           ;local variable
0003  680002 main:    SUBSP   2,i         ;allocate local
0006  410037          STRO    msgIn,d     ;cout << "Pick a number 0..3: "
0009  330000          DECI    guess,s     ;cin >> Guess
000C  CB0000          LDX     guess,s     ;switch (Guess)
000F  1D              ASLX                ;addresses occupy two bytes
0010  050013          BR      guessJT,x
0013  001B   guessJT: .ADDRSS case0
0015  0021            .ADDRSS case1
0017  0027            .ADDRSS case2
0019  002D            .ADDRSS case3
001B  41004C case0:   STRO    msg0,d      ;cout << "Not close"
001E  040030          BR      endCase     ;break
0021  410056 case1:   STRO    msg1,d      ;cout << "Close"
0024  040030          BR      endCase     ;break
0027  41005C case2:   STRO    msg2,d      ;cout << "Right on"
002A  040030          BR      endCase     ;break
002D  410065 case3:   STRO    msg3,d      ;cout << "Too high"
0030  50000A endCase: CHARO   '\n',i      ;count << endl
0033  600002          ADDSP   2,i         ;deallocate local
0036  00              STOP
0037  506963 msgIn:   .ASCII  "Pick a number 0..3: \x00"
      ...
004C  4E6F74 msg0:    .ASCII  "Not close\x00"
      ...
0056  436C6F msg1:    .ASCII  "Close\x00"
      ...
005C  526967 msg2:    .ASCII  "Right on\x00"
      ...
```

```
0065  546F6F msg3:    .ASCII  "Too high\x00"
      ...
006E                  .END
```

Figure 6.40

(Continued)

The .ADDRSS pseudo-op

Figure 6.40 shows the jump table at 0013 in the assembly language program. The code generated at 0013 is 001B, which is the address of the first statement of case 0. The code generated at 0015 is 0021, which is the address of the first statement of case 1, and so on. The compiler generates the jump table with `.ADDRSS` pseudo-ops. Every `.ADDRSS` command must be followed by a symbol. The code generated by `.ADDRSS` is the value of the symbol. For example, `case2` is a symbol whose value is 0027, the address of the code to be executed if `guess` has a value of 2. Therefore, the object code generated by

```
.ADDRSS case2
```

at 0017 is 0027.

Suppose the user enters 2 for the value of `guess`. The statement

```
LDX guess,s
```

puts 2 in the index register. The statement

```
ASLX
```

multiplies the 2, by two leaving 4 in the index register. The statement

```
BR guessJT,x
```

is an unconditional branch with indexed addressing. The value of the operand specifier `guessJT` is 0013, the address of the first word of the jump table. For indexed addressing, the CPU computes the operand as

Indexed addressing

Oprnd = Mem[OprndSpec + X]

Therefore, the CPU computes

Mem [OprndSpec + X]
Mem [0013 + 4]
Mem [0017]
0027

as the operand. The RTL specification for the `BR` instruction is

$PC \leftarrow Oprnd$

and so the CPU puts 0027 in the program counter. Because of the von Neumann cycle, the next instruction to be executed is the one at address 0027, which is precisely the first instruction for case 2.

The break statement in C++ is translated as a `BR` instruction to branch to the end of the `switch` statement. If you omit the `break` in your C++ program, the compiler will omit the `BR` and control will fall through to the next case.

If the user enters a number not in the range 0..3, a run-time error will occur. For example, if the user enters 4 for `guess` the `ASLX` instruction will multiply it by 2, leaving 8 in the index register, and the CPU will compute the operand as

Mem [OprndSpec + X]
Mem [0013 + 8]
Mem [001B]
4100

so the branch will be to memory location 4100 (hex). The problem is that the bits 001B were generated by the assembler for the `STRO` instruction and were never meant to be interpreted as a branch address. To prevent such indignities from happening to the user, C++ specifies that nothing should happen if the value of `guess` is not one of the cases. It also provides a `default` case for the `switch` statement to handle any case not encountered by the previous cases. The compiler must generate an initial conditional branch on `guess` to handle the values not covered by the other cases. The problems at the end of the chapter explore this characteristic of the `switch` statement.

6.5 Dynamic Memory Allocation

The purpose of a compiler is to create a high level of abstraction for the programmer. For example, it lets the programmer think in terms of a single `while` loop instead of the detailed conditional branches at the assembly level that are necessary to implement the loop on the machine. Hiding the details of a lower level is the essence of abstraction.

Abstraction of control

But abstraction of program control is only one side of the coin. The other side is abstraction of data. At the assembly and machine levels, the only data types are bits and bytes. Previous programs show how the compiler translates character, integer, and array types. Each of these types can be global, allocated with `.BLOCK`, or local, allocated with `SUBSP` on the run-time stack. But C++ programs can also contain structures and pointers, the basic building blocks of many data structures. At level HOL6, pointers access structures allocated from the heap with the `new` operator. This section shows the operation of a simple heap at level Asmb5 and how the compiler translates programs that contain pointers and structures. It concludes with a description of the translation of boolean values.

Abstraction of data

Translating Global Pointers

Figure 6.41 shows a C++ program with global pointers and its translation to Pep/8 assembly language. The C++ program is identical to the one in Figure 2.35, and

Figure 2.36 shows the allocation from the heap as the program executes. The heap is a region of memory different from the stack. The compiler, in cooperation with the operating system under which it runs, must generate code to perform the allocation and deallocation from the heap.

Figure 6.41

Translation of global pointers.

High-Order Language

```
#include <iostream>
using namespace std;

int *a, *b, *c;

int main () {
   a = new int;
   *a = 5;
   b = new int;
   *b = 3;
   c = a;
   a = b;
   *a = 2 + *c;
   cout << "*a = " << *a << endl;
   cout << "*b = " << *b << endl;
   cout << "*c = " << *c << endl;
   return 0;
}
```

Assembly Language

```
0000  040009          BR      main
0003  0000    a:      .BLOCK  2          ;global variable
0005  0000    b:      .BLOCK  2          ;global variable
0007  0000    c:      .BLOCK  2          ;global variable
              ;
              ;******* main ()
0009  C00002  main:   LDA     2,i        ;a = new int
000C  16006A          CALL    new
000F  E90003          STX     a,d
0012  C00005          LDA     5,i        ;*a = 5
0015  E20003          STA     a,n
0018  C00002          LDA     2,i        ;b = new int
001B  16006A          CALL    new
001E  E90005          STX     b,d
0021  C00003          LDA     3,i        ;*b = 3
0024  E20005          STA     b,n
0027  C10003          LDA     a,d        ;c = a
```

```
002A  E10007          STA     c,d
002D  C10005          LDA     b,d       ;a = b
0030  E10003          STA     a,d
0033  C00002          LDA     2,i       ;*a = 2 + *c
0036  720007          ADDA    c,n
0039  E20003          STA     a,n
003C  410058          STRO    msg0,d    ;cout << "*a = "
003F  3A0003          DECO    a,n       ;   << *a
0042  50000A          CHARO   '\n',i    ;   << endl
0045  41005E          STRO    msg1,d    ;cout << "*b = "
0048  3A0005          DECO    b,n       ;   << *b
004B  50000A          CHARO   '\n',i    ;   << endl
004E  410064          STRO    msg2,d    ;cout << "*c = "
0051  3A0007          DECO    c,n       ;   << *c
0054  50000A          CHARO   '\n',i    ;   << endl
0057  00              STOP
0058  2A6120 msg0:    .ASCII  "*a = \x00"
      3D2000
005E  2A6220 msg1:    .ASCII  "*b = \x00"
      3D2000
0064  2A6320 msg2:    .ASCII  "*c = \x00"
      3D2000
             ;
             ;******* operator new
             ;        Precondition: A contains number of bytes
             ;        Postcondition: X contains pointer to bytes
006A  C90074 new:     LDX     hpPtr,d   ;returned pointer
006D  710074          ADDA    hpPtr,d   ;allocate from heap
0070  E10074          STA     hpPtr,d   ;update hpPtr
0073  58              RET0
0074  0076   hpPtr:   .ADDRSS heap      ;address of next free byte
0076  00     heap:    .BLOCK  1         ;first byte in the heap
0077                  .END
```

Output

```
*a = 7
*b = 7
*c = 5
```

Figure 6.41 (Continued)

When you program with pointers in C++, you allocate storage from the heap with the `new` operator. When your program no longer needs the storage that was allocated, you deallocate it with the `delete` operator. It is possible to allocate several cells of memory from the heap and then deallocate one cell from the middle. The memory management algorithms must be able to handle that scenario. To keep things simple at this introductory level, the programs that illustrate the heap do not show the deallocation process. The heap is located in main memory at the end of the application program. Operator `new` works by allocating storage from the heap, so that the heap grows downward. Once memory is allocated it can never be deallocated. This feature of the Pep/8 heap is unrealistic but easier to understand than if it were presented more realistically.

Simplifications in the Pep/8 heap

The assembly language program in Figure 6.41 shows the heap starting at address 0076, which is the value of the symbol `heap`. The allocation algorithm maintains a global pointer named `hpPtr`, which stands for heap pointer. The statement

```
hpPtr: .ADDRSS heap
```

at 0074 initializes `hpPtr` to the address of the first byte in the heap. The application supplies the `new` operator with the number of bytes needed. The `new` operator returns the value of `hpPtr` and then increments it by the number of bytes requested. Hence, the invariant maintained by the `new` operator is that `hpPtr` points to the address of the next byte to be allocated from the heap.

The calling protocol for operator `new` is different from the calling protocol for functions. With functions, information is passed via parameters on the run-time stack. With operator `new`, the application puts the number of bytes to be allocated in the accumulator and executes the `CALL` statement to invoke the operator. The operator puts the current value of `hpPtr` in the index register for the application. So, the precondition for the successful operation of `new` is that the accumulator contains the number of bytes to be allocated from the heap. The postcondition is that the index register contains the address in the heap of the first byte allocated by `new`.

The calling protocol for operator `new`

The calling protocol for operator `new` is more efficient than the calling protocol for functions. The implementation of `new` requires only four lines of assembly language code including the `RET0` statement. At 006A, the statement

```
new: LDX hpPtr,d
```

puts the current value of the heap pointer in the index register. At 006D, the statement

```
ADDA hpPtr,d
```

adds the number of bytes to be allocated to the heap pointer, and at 0070, the statement

```
STA hpPtr,d
```

updates `hpPtr` to the address of the first unallocated byte in the heap.

This efficient protocol is possible for two reasons. First, there is no long parameter list as is possible with functions. The application only needs to supply one value to operator `new`. The calling protocol for functions must be designed to handle arbitrary numbers of parameters. If a parameter list had, say, four parameters there would not be enough registers in the Pep/8 CPU to hold them all. But the run-time stack can store an arbitrary number of parameters. Second, operator `new` does not call any other function. Specifically, it makes no recursive calls. The calling protocol for functions must be designed in general to allow for functions to call other functions recursively. The run-time stack is essential for such calls but unnecessary for operator `new`.

Figure 6.42(a) shows the memory allocation for the C++ program at level HOL6 just before the first `cout` statement. It corresponds to Figure 2.36(h). Figure 6.42(b) shows the same memory allocation at level Asmb5. Global pointers `a`, `b`, and `c` are stored at 0003, 0005, and 0007. As with all global variables, they are allocated with `.BLOCK` by the statements

```
a: .BLOCK 2
b: .BLOCK 2
c: .BLOCK 2
```

Pointers are addresses.

A pointer at level HOL6 is an address at level Asmb5. Addresses occupy two bytes. Hence, each global pointer is allocated two bytes.

The compiler translates the statement

```
a = new int;
```

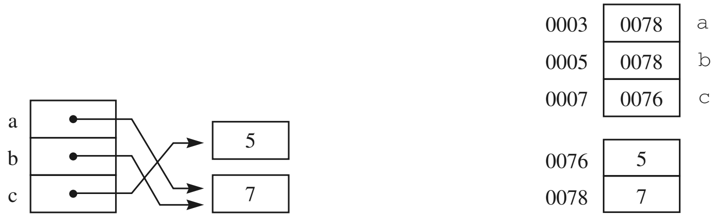
as

```
main: LDA  2,i
      CALL new
      STX  a,d
```

The `LDA` instruction puts 2 in the accumulator The `CALL` instruction calls the `new` operator, which allocates two bytes of storage from the heap, and puts the pointer to the allocated storage in the index register. The `STX` instruction stores the returned pointer in the global variable `a`. Because `a` is a global variable, `STX` uses direct addressing. After this sequence of statements executes, `a` has the value 0076, and `hpPtr` has the value 0078 because it has been incremented by two.

How does the compiler translate

```
*a = 5;
```



(a) Global pointers at level HOL6.

(b) The global pointers at level Asmb5.

Figure **6.42**

Memory allocation for Figure 6.41 just before the first `cout` statement.

At this point in the execution of the program, the global variable `a` has the address of where the 5 should be stored. (This point does *not* correspond to Figure 6.42, which is later.) The `store` instruction cannot use direct addressing, as that would replace the address with 5, which is not the address of the allocated cell in the heap. Pep/8 provides the indirect addressing mode, in which the operand is computed as

Indirect addressing

Oprnd = Mem[Mem[OprndSpec]]

With indirect addressing, the operand specifier is the address in memory of the address of the operand. The compiler translates the assignment statement as

```
LDA 5,i
STA a,n
```

where `n` in the `STA` instruction indicates indirect addressing. At this point in the program, the operand is computed as

Mem [Mem[OprndSpec]]
Mem [Mem[0003]]
Mem [0076]

which is the first cell in the heap. The `store` instruction stores 5 in main memory at address 0076.

The compiler translates the assignment of global pointers the same as it would translate the assignment of any other type of global variable. It translates

```
c = a;
```

as

```
LDA a,d
STA c,d
```

using direct addressing. At this point in the program, `a` contains 0076, the address of the first cell in the heap. The assignment gives `c` the same value, the address of the first cell in the heap, so that `c` points to the same cell to which `a` points.

Contrast the access of a global pointer to the access of the cell to which it points. The compiler translates

```
*a = 2 + *c;
```

as

```
LDA  2,i
ADDA c,n
STA  a,n
```

where the `add` and `store` instructions use indirect addressing. Whereas access to a global pointer uses direct addressing, access to the cell to which it points uses indirect addressing. You can see that the same principle applies to the translation of the `cout` statement. Because `cout` outputs `*a`, that is, the cell to which `a` points, the `DECO` instruction at 003F uses indirect addressing.

In summary, to access a global pointer the compiler generates code as follows:

The translation rules for global pointers

- It allocates storage for the pointer with `.BLOCK 2` because an address occupies two bytes.
- It accesses the pointer with direct addressing.
- It accesses the cell to which the pointer points with indirect addressing.

Translating Local Pointers

The program in Figure 6.43 is the same as the program in Figure 6.41 except that the pointers `a`, `b`, and `c` are declared to be local instead of global. There is no difference in the output of the program compared to the program where the pointers are declared to be global. But, the memory model is quite different because the pointers are allocated on the run-time stack.

Figure **6.43**

Translation of local pointers.

High-Order Language

```
#include <iostream>
using namespace std;

int main () {
   int *a, *b, *c;
   a = new int;
   *a = 5;
   b = new int;
   *b = 3;
   c = a;
   a = b;
   *a = 2 + *c;
   cout << "*a = " << *a << endl;
   cout << "*b = " << *b << endl;
   cout << "*c = " << *c << endl;
   return 0;
}
```

Figure 6.43

(Continued)

Assembly Language

```
0000  040003           BR      main
             ;
             ;******* main ()
             a:       .EQUATE 4          ;local variable
             b:       .EQUATE 2          ;local variable
             c:       .EQUATE 0          ;local variable
0003  680006 main:    SUBSP   6,i        ;allocate locals
0006  C00002          LDA     2,i        ;a = new int
0009  16006A          CALL    new
000C  EB0004          STX     a,s
000F  C00005          LDA     5,i        ;*a = 5
0012  E40004          STA     a,sf
0015  C00002          LDA     2,i        ;b = new int
0018  16006A          CALL    new
001B  EB0002          STX     b,s
001E  C00003          LDA     3,i        ;*b = 3
0021  E40002          STA     b,sf
0024  C30004          LDA     a,s        ;c = a
0027  E30000          STA     c,s
002A  C30002          LDA     b,s        ;a = b
002D  E30004          STA     a,s
0030  C00002          LDA     2,i        ;*a = 2 + *c
0033  740000          ADDA    c,sf
0036  E40004          STA     a,sf
0039  410058          STRO    msg0,d     ;cout << "*a = "
003C  3C0004          DECO    a,sf       ;   << *a
003F  50000A          CHARO   '\n',i     ;   << endl
0042  41005E          STRO    msg1,d     ;cout << "*b = "
0045  3C0002          DECO    b,sf       ;   << *b
0048  50000A          CHARO   '\n',i     ;   << endl
004B  410064          STRO    msg2,d     ;cout << "*c = "
004E  3C0000          DECO    c,sf       ;   << *c
0051  50000A          CHARO   '\n',i     ;   << endl
0054  600006          ADDSP   6,i        ;deallocate locals
0057  00              STOP
0058  2A6120 msg0:    .ASCII  "*a = \x00"
      3D2000
005E  2A6220 msg1:    .ASCII  "*b = \x00"
      3D2000
0064  2A6320 msg2:    .ASCII  "*c = \x00"
      3D2000
```

```
             ;
             ;******* operator new
             ;        Precondition: A contains number of bytes
             ;        Postcondition: X contains pointer to bytes
006A  C90074 new:     LDX     hpPtr,d     ;returned pointer
006D  710074          ADDA    hpPtr,d     ;allocate from heap
0070  E10074          STA     hpPtr,d     ;update hpPtr
0073  58              RET0
0074  0076   hpPtr:   .ADDRSS heap        ;address of next free byte
0076  00     heap:    .BLOCK  1           ;first byte in the heap
0077                  .END
```

Figure **6.43**

(Continued)

Figure 6.44 shows the memory allocation for the program in Figure 6.43 just before execution of the first `cout` statement. As with all local variables, `a`, `b`, and `c` are allocated on the run-time stack. Figure 6.44(b) shows their offsets from the top of the stack as 4, 2, and 0. Consequently, the compiler translates

```
int *a, *b, *c;
```

as

```
a: .EQUATE 4
b: .EQUATE 2
c: .EQUATE 0
```

Because `a`, `b`, and `c` are local variables, the compiler generates code to allocate storage for them with `SUBSP` and deallocates storage with `ADDSP`.

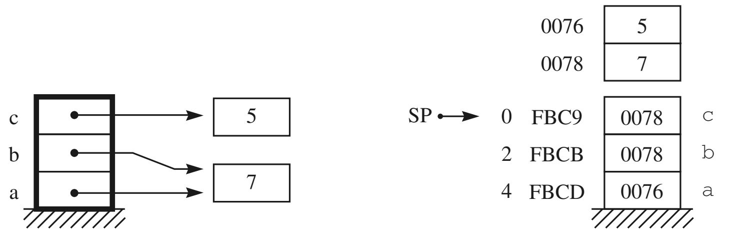
The compiler translates

```
a = new int;
```

as

```
LDA  2,i
CALL new
STX  a,s
```

The `LDA` instruction puts 2 in the accumulator in preparation for calling the `new` operator, because an integer occupies two bytes. The `CALL` instruction invokes the `new` operator, which allocates the two bytes from the heap and puts their address in the



(a) Local pointers at level HOL6.

(b) The local pointers at level Asmb5.

Figure **6.44**

Memory allocation for Figure 6.43 just before the `cout` statement.

index register. In general, assignments to local variables use stack-relative addressing. Therefore, the `STX` instruction uses stack-relative addressing to assign the address to `a`.

How does the compiler translate the assignment

```
*a = 5;
```

`a` is a pointer, and the assignment gives 5 to the cell to which a points. `a` is also a local variable. This situation is identical to the one where a parameter is called by reference in the programs of Figures 6.27 and 6.29. Namely, the address of the operand is on the run-time stack. The compiler translates the assignment statement as

```
LDA 5,i
STA a,sf
```

where the `store` instruction uses stack-relative deferred addressing.

The compiler translates the assignment of local pointers the same as it would translate the assignment of any other type of local variable. It translates

```
c = a;
```

as

```
LDA a,s
STA c,s
```

using stack-relative addressing. At this point in the program, `a` contains 0076, the address of the first cell in the heap. The assignment gives `c` the same value, the address of the first cell in the heap, so that `c` points to the same cell to which `a` points.

The compiler translates

```
*a = 2 + *c;
```

as

```
LDA  2,i
ADDA c,sf
STA  a,sf
```

where the `add` instruction uses stack-relative deferred addressing to access the cell to which `c` points and the `store` instruction uses stack-relative deferred addressing to access the cell to which `a` points. The same principle applies to the translation of `cout` statements where the `DECO` instructions also use stack-relative deferred addressing.

In summary, to access a local pointer the compiler generates code as follows:

The translation rules for local pointers

- It allocates storage for the pointer on the run-time stack with `SUBSP` and deallocates storage with `ADDSP`.
- It accesses the pointer with stack-relative addressing.
- It accesses the cell to which the pointer points with stack-relative deferred addressing.

Translating Structures

Structures are the key to data abstraction at level HOL6, the high-order languages level. They let the programmer consolidate variables with primitive types into a single abstract data type. The compiler provides the `struct` construct at level HOL6. At level Asmb5, the assembly level, a structure is a contiguous group of bytes, much like the bytes of an array. However, all cells of an array must have the same type and, therefore, the same size. Each cell is accessed by the numeric integer value of the index.

With a structure, the cells can have different types and, therefore, different sizes. The C++ programmer gives each cell, called a field, a field name. At level Asmb5, the field name corresponds to the offset of the field from the first byte of the structure. The field name of a structure corresponds to the index of an array. It should not be surprising that the fields of a structure are accessed much like the elements of an array. Instead of putting the index of the array in the index register, the compiler generates code to put the field offset from the first byte of the structure in the index register. Apart from this difference, the remaining code for accessing a field of a structure is identical to the code for accessing an element of an array.

Figure 6.45 shows a program that declares a `struct` named `person` that has four fields named `first`, `last`, `age`, and `gender`. It is identical to the program in Figure 2.37. The program declares a global variable name `bill` that has type `person`. Figure 6.46 shows the storage allocation for the structure at levels HOL6 and Asmb5. Fields `first`, `last`, and `gender` have type `char` and occupy one byte each. Field `age` has type `int` and occupies two bytes. Figure 6.46(b) shows the address of each field of the structure. To the left of the address is the offset from the first byte of the structure. The offset of a structure is similar to the offset of an element on the stack except that there is no pointer to the top of the structure that corresponds to SP.

High-Order Language

```
#include <iostream>
using namespace std;

struct person {
   char first;
   char last;
   int age;
   char gender;
};
person bill;
```

Figure **6.45**

Translation of a structure.

Figure **6.45**

(Continued)

```
int main () {
   cin >> bill.first >> bill.last >> bill.age >> bill.gender;
   cout << "Initials: " << bill.first << bill.last << endl;
   cout << "Age: " << bill.age << endl;
   cout << "Gender: ";
   if (bill.gender == 'm') {
      cout << "male\n";
   }
   else {
      cout << "female\n";
   }
   return 0;
}
```

Assembly Language

```
0000  040008          BR      main
             first:   .EQUATE 0           ;struct field
             last:    .EQUATE 1           ;struct field
             age:     .EQUATE 2           ;struct field
             gender:  .EQUATE 4           ;struct field
0003  000000 bill:    .BLOCK  5           ;global variable
      0000
             ;
             ;******* main ()
0008  C80000 main:    LDX     first,i     ;cin >> bill.first
000B  4D0003          CHARI   bill,x
000E  C80001          LDX     last,i      ;   >>bill.last
0011  4D0003          CHARI   bill,x
0014  C80002          LDX     age,i       ;   >>bill.age
0017  350003          DECI    bill,x
001A  C80004          LDX     gender,i    ;   >>bill.gender
001D  4D0003          CHARI   bill,x
0020  41005A          STRO    msg0,d      ;cout << "Initials: "
0023  C80000          LDX     first,i     ;   << bill.first
0026  550003          CHARO   bill,x
0029  C80001          LDX     last,i      ;   << bill.last
002C  550003          CHARO   bill,x
002F  50000A          CHARO   '\n',i      ;   << endl
0032  410065          STRO    msg1,d      ;cout << "Age: "
0035  C80002          LDX     age,i       ;   << bill.age
0038  3D0003          DECO    bill,x
003B  50000A          CHARO   '\n',i      ;   << endl;
003E  41006B          STRO    msg2,d      ;cout << "Gender: "
0041  C80004          LDX     gender,i    ;if (bill.gender == 'm')
0044  C00000          LDA     0,i
```

```
0047  D50003           LDBYTEA bill,x
004A  B0006D           CPA     'm',i
004D  0C0056           BRNE    else
0050  410074           STRO    msg3,d     ;   cout << "male\n"
0053  040059           BR      endIf
0056  41007A else:     STRO    msg4,d     ;   cout << "female\n"
0059  00     endIf:    STOP
005A  496E69 msg0:     .ASCII  "Initials: \x00"
      ...
0065  416765 msg1:     .ASCII  "Age: \x00"
      ...
006B  47656E msg2:     .ASCII  "Gender: \x00"
      ...
0074  6D616C msg3:     .ASCII  "male\n\x00"
      ...
007A  66656D msg4:     .ASCII  "female\n\x00"
      ...
0082                   .END
```

Input

```
bj 32 m
```

Output

```
Initials: bj
Age: 32
Gender: male
```

Figure 6.45

(Continued)

The compiler translates

```
struct person {
   char first;
   char last;
   int age;
   char gender;
};
```

with equate dot commands as

```
first:  .EQUATE 0
last:   .EQUATE 1
age:    .EQUATE 2
gender: .EQUATE 4
```

The name of a field equates to the offset of that field from the first byte of the structure. `first` equates to 0 because it is the first byte of the structure. `last`

(a) A global structure at level HOL6.

(b) The global structure at Asmb5.

Figure 6.46

Memory allocation for Figure 6.45 just after the `cin` statement.

equates to 1 because `first` occupies one byte. `age` equates to 2 because `first` and `last` occupy a total of two bytes. And `gender` equates to 4 because `first`, `last`, and `age` occupy a total of four bytes. The compiler translates the global variable

```
person bill;
```

as

```
bill: .BLOCK 5
```

It reserves five bytes because `first`, `last`, `age`, and `gender` occupy a total of five bytes.

To access a field of a global structure, the compiler generates code to load the index register with the offset of the field from the first byte of the structure. It accesses the field as it would the cell of a global array using indexed addressing. For example, the compiler translates

```
cin >> bill.age
```

as

```
LDX  age,i
DECI bill,x
```

The load instruction uses immediate addressing to load the offset of field `age` into the index register. The decimal input instruction uses indexed addressing to access the field.

The compiler translates

```
if (bill.gender == 'm')
```

similarly as

```
LDX     gender,i
LDA     0,i
LDBYTEA bill,x
CPA     'm',i
```

The first load instruction puts the offset of the `gender` field into the index register. The second load instruction clears the accumulator to ensure that its left-most byte is all zeros for the comparison. The load byte instruction accesses the field of the structure with indexed addressing and puts it into the right-most byte of the accumulator. Finally, the compare instruction compares `bill.gender` with the letter m.

In summary, to access a global structure the compiler generates code as follows:

The translation rules for global structures

- It equates each field of the structure to its offset from the first byte of the structure.
- It allocates storage for the structure with `.BLOCK` *tot* where *tot* is the total number of bytes occupied by the structure.
- It accesses a field of the structure by loading the offset of the field into the index register with immediate addressing followed by an instruction with indexed addressing.

The translation rules for local structures

In the same way that accessing the field of a global structure is similar to accessing the element of a global array, accessing the field of a local structure is similar to accessing the element of a local array. Local structures are allocated on the run-time stack. The name of each field equates to its offset from the first byte of the structure. The name of the local structure equates to its offset from the top of the stack. The compiler generates `SUBSP` to allocate storage for the structure and any other local variables, and `ADDSP` to deallocate storage. It accesses a field of the structure by loading the offset of the field into the index register with immediate addressing followed by an instruction with stack-indexed addressing. Translating a program with a local structure is a problem for the student at the end of this chapter.

Translating Linked Data Structures

Programmers frequently combine pointers and structures to implement linked data structures. The `struct` is usually called a node, a pointer points to a node, and the node has a field that is a pointer. The pointer field of the node serves as a link to another node in the data structure. Figure 6.47 is a program that implements a linked list data structure. It is identical to the program in Figure 2.38.

Figure **6.47**

Translation of a linked list.

High-Order Language

```
#include <iostream>
using namespace std;

struct node {
   int data;
   node* next;
};
```

Figure **6.47**

(Continued)

```
int main () {
   node *first, *p;
   int value;
   first = 0;
   cin >> value;
   while (value != -9999) {
      p = first;
      first = new node;
      first->data = value;
      first->next = p;
      cin >> value;
   }
   for (p = first; p != 0; p = p->next) {
      cout << p->data << ' ';
   }
   return 0;
}
```

Assembly Language

```
0000  040003          BR      main
             data:    .EQUATE 0          ;struct field
             next:    .EQUATE 2          ;struct field
             ;
             ;******* main ()
             first:   .EQUATE 4          ;local variable
             p:       .EQUATE 2          ;local variable
             value:   .EQUATE 0          ;local variable
0003  680006 main:    SUBSP   6,i        ;allocate locals
0006  C00000          LDA     0,i        ;first = 0
0009  E30004          STA     first,s
000C  330000          DECI    value,s    ;cin >> value
000F  C30000 while:   LDA     value,s    ;while (value != -9999)
0012  B0D8F1          CPA     -9999,i
0015  0A003F          BREQ    endWh
0018  C30004          LDA     first,s    ;    p = first
001B  E30002          STA     p,s
001E  C00004          LDA     4,i        ;    first = new node
0021  160067          CALL    new
0024  EB0004          STX     first,s
0027  C30000          LDA     value,s    ;    first->data = value
002A  C80000          LDX     data,i
002D  E70004          STA     first,sxf
0030  C30002          LDA     p,s        ;    first->next = p
0033  C80002          LDX     next,i
```

```
0036  E70004          STA     first,sxf
0039  330000          DECI    value,s    ;   cin >> value
003C  04000F          BR      while
003F  C30004 endWh:   LDA     first,s    ;for (p = first
0042  E30002          STA     p,s
0045  C30002 for:     LDA     p,s        ;   p != 0
0048  B00000          CPA     0,i
004B  0A0063          BREQ    endIf
004E  C80000          LDX     data,i     ;   cout << p->data
0051  3F0002          DECO    p,sxf
0054  500020          CHARO   ' ',i      ;      << ' '
0057  C80002          LDX     next,i     ;   p = p->next)
005A  C70002          LDA     p,sxf
005D  E30002          STA     p,s
0060  040045          BR      for
0063  600006 endIf:   ADDSP   6,i        ;deallocate locals
0066  00              STOP
             ;
             ;******* operator new
             ;        Precondition: A contains number of bytes
             ;        Postcondition: X contains pointer to bytes
0067  C90071 new:     LDX     hpPtr,d    ;returned pointer
006A  710071          ADDA    hpPtr,d    ;allocate from heap
006D  E10071          STA     hpPtr,d    ;update hpPtr
0070  58              RET0
0071  0073   hpPtr:   .ADDRSS heap       ;address of next free byte
0073  00     heap:    .BLOCK  1          ;first byte in the heap
0074                  .END
```

Input

```
10 20 30 40 -9999
```

Output

```
40 30 20 10
```

Figure 6.47

(Continued)

The compiler equates the fields of the struct

```
struct node {
   int data;
   node* next;
};
```

to their offsets from the first byte of the `struct`. `data` is the first field with an offset of 0. `next` is the second field with an offset of 2 because data occupies two bytes. The translation is

```
data: .EQUATE 0
next: .EQUATE 2
```

The compiler translates the local variables

```
node *first, *p;
int value;
```

as it does all local variables. It equates the variable names with their offsets from the top of the run-time stack. The translation is

```
first: .EQUATE 4
p:     .EQUATE 2
value: .EQUATE 0
```

Figure 6.48(b) shows the offsets for the local variables. The compiler generates `SUBSP` at 0003 to allocate storage for the locals and `ADDSP` at 0063 to deallocate storage.

When you use the `new` operator in C++, the computer must allocate enough memory from the heap to store the item to which the pointer points. In this program, a node occupies four bytes. Therefore, the compiler translates

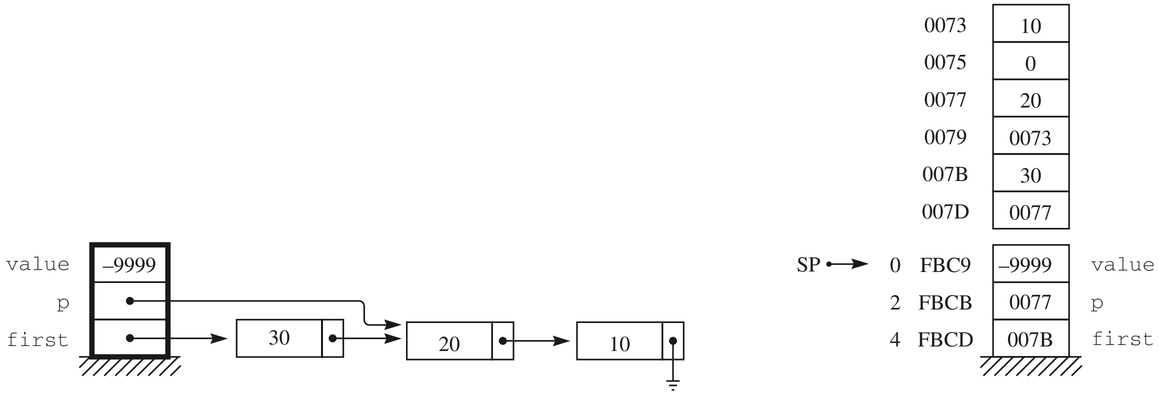
```
first = new node;
```

by allocating four bytes in the code it generates to call the `new` operator. The translation is

```
LDA  4,i
CALL new
STX  first,s
```

Figure 6.48

Memory allocation for Figure 6.47 just after the third execution of the `while` loop.



(a) The linked list at level HOL6.

(b) The linked list at level Asmb5.

The load instruction puts 4 in the accumulator in preparation for the call to `new`. The call instruction calls the `new` operator, which puts the address of the first byte of the allocated node in the index register. The store index instruction completes the assignment to local variable `first` using stack-relative addressing.

How does the compiler generate code to access the field of a node to which a local pointer points? Remember that a pointer is an address. A local pointer implies that the address of the node is on the run-time stack. Furthermore, the field of a `struct` corresponds to the index of an array. If the address of the first cell of an array is on the run-time stack, you access an element of the array with stack-indexed deferred addressing. That is precisely how you access the field of a node. Instead of putting the value of the index in the index register, you put the offset of the field in the index register. The compiler translates

```
first->data = value;
```

as

```
LDA value,s
LDX data,i
STA first,sxf
```

Similarly, it translates

```
first->next = p;
```

as

```
LDA p,s
LDX next,i
STA first,sxf
```

To see how stack-indexed deferred addressing works for a local pointer to a node, remember that the CPU computes the operand as

Stack-indexed deferred addressing

Oprnd = Mem[Mem[SP + OprndSpec] + X]

It adds the stack pointer plus the operand specifier and uses the sum as the address of the first field, to which it adds the index register. Suppose that the third node has been allocated as shown in Figure 6.48(b). The call to `new` has returned the address of the newly allocated node, 007B, and stored it in `first`. The `LDA` instruction above has put the value of `p`, 0077 at this point in the program, in the accumulator. The `LDX` instruction has put the value of `next`, offset 2, in the index register. The `STA` instruction executes with stack-indexed addressing. The operand specifier is 4, the value of `first`. The computation of the operand is

Mem[Mem[SP + OprndSpec] + X]
Mem[Mem[FBC9 + 4] + 2]
Mem[Mem[FBCD] + 2]
Mem[007B + 2]
Mem[007D]

which is the `next` field of the node to which `first` points.

In summary, to access a field of a node to which a local pointer points the compiler generates code as follows:

The translation rules for accessing the field of a node to which a local pointer points

- The field name of the node equates to the offset of the field from the first byte of the node. The offset is loaded into the index register.
- The instruction to access the field of the node uses stack-indexed deferred addressing.

You should be able to determine how the compiler translates programs with global pointers to nodes. Formulation of the translation rules is an exercise for the student at the end of this chapter. Translation of a C++ program that has global pointers to nodes is also a problem for the student.

SUMMARY

A compiler uses conditional branch instructions at the machine level to translate `if` statements and loops at the high-order languages level. An `if/else` statement requires a conditional branch instruction to test the `if` condition and an unconditional branch instruction to branch around the `else` part. The translation of a `while` or `do` loop requires a branch to a previous instruction. The `for` loop requires, in addition, instructions to initialize and increment the control variable.

The structured programming theorem, proved by Bohm and Jacopini, states that any algorithm containing goto's, no matter how complicated or unstructured, can be written with only nested `if` statements and `while` loops. The goto controversy was sparked by Dijkstra's famous letter, which stated that programs without goto's were not only possible but desirable.

The compiler allocates global variables at a fixed location in main memory. Procedures and functions allocate parameters and local variables on the run-time stack. Values are pushed onto the stack by incrementing the stack pointer (SP) and popped off the stack by decrementing SP. The subroutine call instruction pushes the contents of the program counter (PC), which acts as the return address, onto the stack. The subroutine return instruction pops the return address off the stack into the PC. Instructions access global values with direct addressing and values on the run-time stack with stack-relative addressing. A parameter that is called by reference has its address pushed onto the run-time stack. It is accessed with stack-relative deferred addressing. Boolean variables are stored with a value of 0 for false and a value of 1 for true.

Array values are stored in consecutive main memory cells. You access an element of a global array with indexed addressing, and an element of a local array with stack-indexed addressing. In both cases, the index register contains the index value of the array element. An array passed as a parameter always has the address of the first cell of the array pushed onto the run-time stack. You access an element of the array with stack-indexed deferred addressing. The compiler translates the `switch` statement with an array of addresses, each of which is the address of the first statement of a `case`.

Pointer and `struct` types are common building blocks of data structures. A pointer is an address of a memory location in the heap. The `new` operator allocates memory from the heap. You access a cell to which a global pointer points with indirect addressing. You access a cell to which a local pointer points with stack-relative deferred addressing. A `struct` has several named fields and is stored as a contiguous group of bytes. You access a field of a `global` struct with indexed addressing with the index register containing the offset of the field from the first byte of the `struct`. Linked data structures commonly have a pointer to a `struct` called a node, which in turn contains a pointer to yet another node. If a local pointer points to a node, you access a field of the node with stack-indexed deferred addressing.

EXERCISES

Section 6.1

1. Explain the difference in the memory model between global and local variables. How are each allocated and accessed?

Section 6.2

2. What is an optimizing compiler? When would you want to use one? When would you not want to use one? Explain.

*3. The object code for Figure 6.14 has a `CPA` at 000C to test the value of `i`. Because the program branches to that instruction from the bottom of the loop, why doesn't the compiler generate a `LDA i,d` at that point before `CPA`?

4. Discover the function of the mystery program of Figure 6.16, and state in one short sentence what it does.

5. Read the papers by Bohm and Jacopini and by Dijkstra that are referred to in this chapter and write a summary of them.

Section 6.3

*6. Draw the values just before and just after the `CALL` at 0022 of Figure 6.18 executes as they are drawn in Figure 6.19.

7. Draw the run-time stack, as in Figure 6.26, that corresponds to the time just before the second return.

Section 6.4

*8. In the Pep/8 program of Figure 6.40, if you enter 4 for `Guess`, what statement executes after the branch at 0010? Why?

9. Section 6.4 does not show how to access an element from a two-dimensional array. Describe how a two-dimensional array might be stored and the assembly language object code that would be necessary to access an element from it.

Section 6.5

10. What are the translation rules for accessing the field of a node to which a global pointer points?

PROBLEMS

Section 6.2

11. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

int main () {
   int number;
   cin >> number;
   if (number % 2 == 0) {
      cout << "Even\n";
   }
   else {
      cout << "Odd\n";
   }
   return 0;
}
```

12. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

const int limit = 5;

int main () {
   int number;
   cin >> number;
   while (number < limit) {
      number++;
      cout << number << ' ';
   }
   return 0;
}
```

13. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

int main () {
   char ch;
   cin >> ch;
   if ((ch >= 'A') && (ch <= 'Z')) {
      cout << 'A';
   }
   else if ((ch >= 'a') && (ch <= 'z')) {
```

```
         cout << 'a';
      }
      else {
         cout << '$';
      }
      cout << endl;
      return 0;
   }
```

14. Translate the C++ program in Figure 6.12 to Pep/8 assembly language but with the `do` loop test changed to

```
while (cop <= driver);
```

15. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

int main () {
   int numItms, i, data, sum;
   cin >> numItms;
   sum = 0;
   for (i = 1; i <= numItms; i++) {
      cin >> data;
      sum += data;
   }
   cout << "Sum: " << sum << endl;
   return 0;
}
```

Sample Input

```
4   8 -3 7 6
```

Sample Output

```
Sum: 18
```

Section 6.3

16. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

int myAge;

void putNext (int age) {
   int nextYr;
   nextYr = age + 1;
   cout << "Age: " << age << endl;
   cout << "Age next year: " << nextYr << endl;
}
```

```
int main () {
   cin >> myAge;
   putNext (myAge);
   putNext (64);
   return 0;
}
```

17. Translate the C++ program in Problem 16 to Pep/8 assembly language, but declare `myAge` to be a local variable in `main()`.

18. Translate the following C++ program to Pep/8 assembly language. It multiplies two integers using a recursive shift-and-add algorithm:

```
#include <iostream>
using namespace std;

int times (int mpr, int mcand) {
   if (mpr == 0) {
      return 0;
   }
   else if (mpr % 2 == 1) {
      return mcand + times (mpr / 2, mcand * 2);
   }
   else {
      return times (mpr / 2, mcand * 2);
   }
}

int main () {
   int n, m;
   cin >> n >> m;
   cout << "Product: " << times (n, m) << endl;
   return 0;
}
```

19. **(a)** Write a C++ program that converts a lowercase character to an uppercase character. Declare

```
char uppercase (char ch);
```

to do the conversion. If the actual parameter is not a lowercase character, the function should return that character value unchanged. Test your function in a main program with interactive I/O. **(b)** Translate your C++ program to Pep/8 assembly language.

20. **(a)** Write a C++ program that defines

```
int minimum (int i1, int i2)
```

which returns the smaller of `i1` and `i2`, and test it with interactive input. **(b)** Translate your C++ program to Pep/8 assembly language.

21. Translate to Pep/8 assembly language your C++ solution from Problem 2.14 that computes a Fibonacci term using a recursive function.

22. Translate to Pep/8 assembly language your C++ solution from Problem 2.15 that outputs the instructions for the Towers of Hanoi puzzle.

23. The recursive binomial coefficient function in Figure 6.25 can be simplified by omitting `y1` and `y2` as follows:

```
int binCoeff (int n, int k) {
   if ((k == 0) || (n == k)) {
      return 1;
   }
   else {
      return binCoeff (n - 1, k) + binCoeff (n - 1, k - 1);
   }
}
```

Write a Pep/8 assembly language program that calls this function. Keep the value returned from the `binCoeff (n - 1, k)` call on the stack and allocate the actual parameters for the `binCoeff (n - 1, k - 1)` call on top of it. Figure 6.49 shows a trace of the run-time stack where the stack frame contains four words (for `retVal`, `n`, `k`, and `retAddr`) and the shaded word is the value returned by a function call. The trace is for a call of `binCoeff (3,1)` from the main program.

24. Translate the following C++ program to Pep/8 assembly language. It multiplies two integers using an iterative shift-and-add algorithm.

```
#include <iostream>
using namespace std;

int product, n, m;

void times (int& prod, int mpr, int mcand) {
   prod = 0;
   while (mpr != 0) {
```

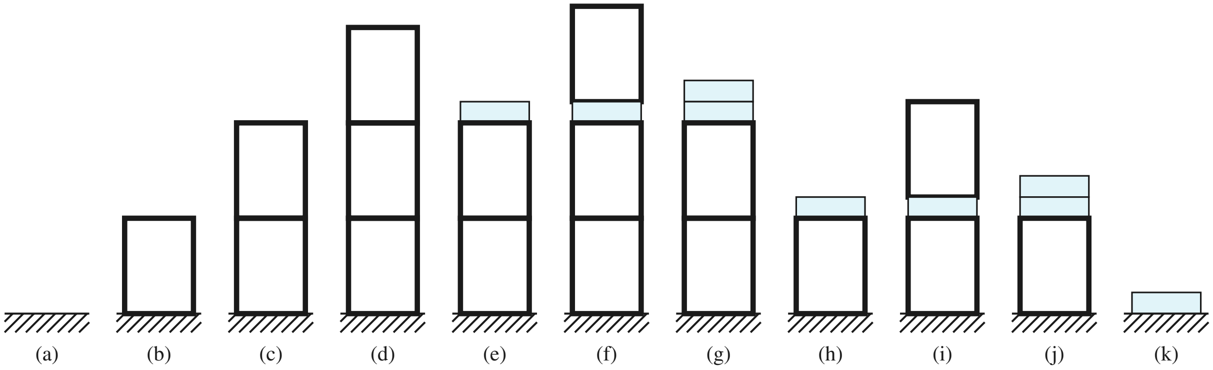


Figure **6.49**

Trace of the run-time stack for Figure 6.25

```
      if (mpr % 2 == 1) {
         prod = prod + mcand;
      }
      mpr /= 2;
      mcand *= 2;
   }
}

int main () {
   cin >> n >> m;
   times (product, n, m);
   cout << "Product: " << product << endl;
   return 0;
}
```

25. Translate the C++ program in Problem 24 to Pep/8 assembly language, but declare `product`, `n`, and `m` to be local variables in `main()`.

26. **(a)** Rewrite the C++ program of Figure 2.21 to compute the factorial recursively, but use procedure times in Problem 24 to do the multiplication. Use one extra local variable in `fact` to store the product. **(b)** Translate your C++ program to Pep/8 assembly language.

Section 6.4

27. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

int list[16];
int i, numItems;
int temp;

int main () {
   cin >> numItems;
   for (i = 0; i < numItems; i++) {
      cin >> list[i];
   }
   temp = list[0];
   for (i = 0; i < numItems - 1; i++) {
      list[i] = list[i + 1];
   }
   list[numItems - 1] = temp;
   for (i = 0; i < numItems; i++) {
      cout << list[i] << ' ';
   }
   cout << endl;
   return 0;
}
```

Sample Input

```
5
11 22 33 44 55
```

Sample Output

```
22 33 44 55 11
```

The test in the second `for` loop is awkward to translate because of the arithmetic expression on the right side of the < operator. You can simplify the translation by transforming the test to the following mathematically equivalent test.

```
i + 1 < numItems;
```

28. Translate the C++ program in Problem 27 to Pep/8 assembly language, but declare `list`, `i`, `numItems`, and `temp` to be local variables in `main()`.

29. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

void getList (int ls[], int& n) {
   int i;
   cin >> n;
   for (i = 0; i < n; i++) {
      cin >> ls[i];
   }
}

void putList (int ls[], int n) {
   int i;
   for (i = 0; i < n; i++) {
      cout << ls[i] << ' ';
   }
   cout << endl;
}

void rotate (int ls[], int n) {
   int i;
   int temp;
   temp = ls[0];
   for (i = 0; i < n - 1; i++) {
      ls[i] = ls[i + 1];
   }
   ls[n - 1] = temp;
}

int main () {
   int list[16];
   int numItems;
```

```
   getList (list, numItems);
   putList (list, numItems);
   rotate (list, numItems);
   putList (list, numItems);
   return 0;
}
```

Sample Input

```
5
11 22 33 44 55
```

Sample Output

```
11 22 33 44 55
22 33 44 55 11
```

30. Translate the C++ program in Problem 29 to Pep/8 assembly language but declare `list` and `numItems` to be global variables.

31. Translate to Pep/8 assembly language the C++ program from Figure 2.23 that adds four values in an array using a recursive procedure.

32. Translate to Pep/8 assembly language the C++ program from Figure 2.30 that reverses the elements of an array using a recursive procedure.

33. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

int main () {
   int guess;
   cout << "Pick a number 0..3: ";
   cin >> guess;
   switch (guess) {
      case 0: case 1: cout << "Too low"; break;
      case 2: cout << "Right on"; break;
      case 3: cout << "Too high";
   }
   cout << endl;
   return 0;
}
```

The program is identical to Figure 6.40 except that two of the cases execute the same code. Your jump table must have exactly four entries, but your program must have only three case symbols and three cases.

34. Translate the following C++ program to Pep/8 assembly language.

```
#include <iostream>
using namespace std;

int main () {
```

```
   int guess;
   cout << "Pick a number 0..3: ";
   cin >> guess;
   switch (guess) {
      case 0: cout << "Not close"; break;
      case 1: cout << "Too low"; break;
      case 2: cout << "Right on"; break;
      case 3: cout << "Too high"; break;
      default: cout << "Illegal input";
   }
   cout << endl;
   return 0;
}
```

Section 6.5

35. Translate to Pep/8 assembly language the C++ program from Figure 6.45 that accesses the fields of a structure, but declare `bill` as a local variable in `main()`.

36. Translate to Pep/8 assembly language the C++ program from Figure 6.47 that manipulates a linked list, but declare `first`, `p`, and `value` as global variables.

37. Insert the following C++ code fragment in `main()` of Figure 6.47 just before the `return` statement

```
sum = 0; p = first;
while (p != 0) {
   sum += p->data;
   p = p->next;
}
cout << "Sum: " << sum << endl;
```

and translate the complete program to Pep/8 assembly language. Declare `sum` to be a local variable along with the other locals as follows:

```
node *first, *p;
int value, sum;
```

38. Insert the following C++ code fragment between the declaration of `node` and `main()` in Figure 6.47

```
void reverse (node* list) {
   if (list != 0) {
      reverse (list->next);
      cout << list->data << ' ';
   }
}
```

and the following code fragment in `main()` just before the `return` statement.

```
cout << endl;
reverse (first);
```

Translate the complete C++ program to Pep/8 assembly language. The added code outputs the linked list in reverse order.

39. Insert the following C++ code fragment in `main()` of Figure 6.47 just before the `return` statement

```
first2 = 0; p2 = 0;
for (p = first; p != 0; p = p->next) {
   p2 = first2;
   first2 = new node;
   first2->data = p->data;
   first2->next = p2;
}
for (p2 = first2; p2 != 0; p2 = p2->next) {
   cout << p2->data << ' ';
}
```

Declare `first2` and `p2` to be local variables along with the other locals as follows:

```
node *first, *p, *first2, *p2;
int value;
```

Translate the complete program to Pep/8 assembly language. The added code creates a copy of the first list in reverse order and outputs it.

40. **(a)** Write a C++ program to input an unordered list of integers with –9999 as a sentinel into a binary search tree, then output them with an inorder traversal of the tree. **(b)** Translate your C++ program to Pep/8 assembly language.