6 Control Structures

Control statements are used to modify the order of execution. There are two classes of well-structured control statements: choice statements (if and case) which select one alternative from two or more possible execution sequences, and loop statements (for and while) which repeatedly execute a series of statements.

6.1 switch-/case-statements

A choice statement is used to select one of several possible paths for the computation to pursue (Figure 6.1).[1] The generalized choice statement is called a switch-statement in C and a case-

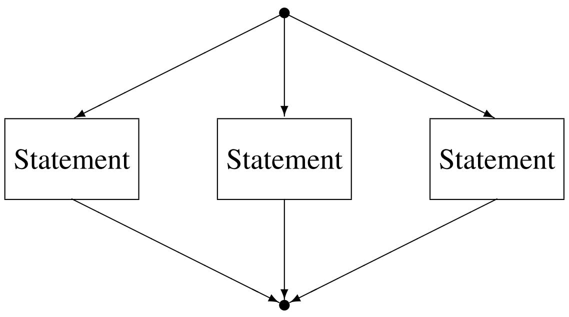


Figure 6.1: Choice statement

statement in other languages. A switch-statement is composed of an expression and a statement for each possible value of the expression:

C

```
switch (expression) {
    case value_1:
        statement_1;
        break;
    case value_2:
        statement_2;
        break;
    ...
```

[1]Throughout this chapter we will use the term "statement" to describe a path of the computation. This should be interpreted to include a *compound statement* which is a sequence of one or more statements.

```
    }
```

The expression is evaluated and the result of the expression is used to select a statement to execute; in terms of Figure 6.1, the selected statement represents a path. This requires that there be *exactly* one case alternative for each possible value of the expression. If the expression is of integer type, this is impossible since it is not practical to write a statement for each 32-bit integer value. In Pascal the case-statement is usable only for types which have a small number of values, while C and Ada provide a default alternative, so that the case-statement can be used even for types like Character that have hundreds of values:

C

```
        default:
            default_statement;
            break;
```

If the value of the expression is not explicitly listed, the default statement is executed. C actually assumes an empty default statement if the default alternative is missing. This option should not be used because the reader of the program has no way of knowing if an empty default statement is intended, or if the programmer has simply forgotten to provide the necessary statements.

In many cases, the statement for two or more alternatives is identical. C has no direct way of expressing this (see below); in Ada there is an extensive set of syntactical constructions for grouping alternatives:

Ada

```
    C: Character;
    case C is
        when 'A' .. 'Z'             => statement_1;
        when '0' .. '9'             => statement_2;
        when '+' | '−' | '*' | '/' => statement_3;
        when others                 => statement_4;
    end case;
```

In Ada the alternatives are introduced by the reserved keyword when, and the default alternative is called others. A case alternative may contain a range of values value_1..value_2, or it may contain a set of values separated by "|".

The break-statement in C

In C you must explicitly terminate each case alternative with the break-statement, otherwise the computation will "fall-through" to the next case alternative. A valid use of fall-through is to mimic the multiple-alternative construct in Ada:

C

```
    char c;
    switch (c) {
        case 'A':   case 'B':   . . .   case 'Z':
```

```
        statement_1;
        break;
    case '0':   ...  case '9':
        statement_2;
        break;
    case '+':   case '−':   case '*':   case '/':
        statement_3;
        break;
    default:
        statement_4;
        break;
}
```

Since each value must be explicitly written, the switch-statement in C is rather less convenient than the case-statement in Ada.

Fall-through should not be used in ordinary programming:

C

```
switch (e) {
    case value_1:
        statement_1;          /* After statement_1, */
    case value_2:
        statement_2;          /*    fall through to statement_2. */
        break;
}
```

Referring to Figure 6.1, the switch-statement is intended to be used to choose one of a set of possible paths. Fall-through is confusing because the end of a path loops back to the beginning of the tree of choices. Furthermore, no semantic importance should be attributed to the sequence in which the choices are written (though the order may be significant in terms of efficiency). Maintainers of the program should be free to rearrange existing choices, or to insert new choices, without fear of introducing a bug. This program is also difficult to test and debug: if a bug is traced to statement_2, it is difficult to know if the statement was reached by direct selection or by fall-through. Rather than using fall-through, common code should be placed in a procedure:

C

```
switch (e) {
    case value_1:
        statement_1;
        common_code( );
        break;
    case value_2:
        common_code( );
        break;
}
```

Implementation

The simplest way of compiling a case statement is as a sequence of tests:

```
          compute   R1,expr          Compute expression
          jump_eq   R1,#value_1,L1
          jump_eq   R1,#value_2,L2
          ...                        Other values
          default_statement          Instructions for default
          jump      End_Case

     L1:  statement_1                Instructions for statement_1
          jump      End_Case
     L2:  statement_2                Instructions for statement_2
          jump      End_Case
          ...                        Instructions for other statements
     End_Case:
```

In terms of efficiency, it is apparent that the closer an alternative is to the top of the statement, the more efficient it is to choose it; you can reorder the alternatives to take advantage of this fact (provided that you don't use fall-through!).

Certain case statements can be optimized to use jump tables. If the set of values of the expression form a short contiguous sequence, then the following code can be used (where we assume that the expression can take values from 0 to 3):

```
          compute   R1,expr
          mult      R1,#len_of_addr   expression*length_of_addr
          add       R1,&table        Start of table
          jump      (R1)             Jump to address in R1

     table:                          Jump table
          addr(L1)
          addr(L2)
          addr(L3)
          addr(L4)

     L1:  statement_1
          jump      End_Case
     L2:  statement_2
          jump      End_Case
     L3:  statement_3
          jump      End_Case
     L4:  statement_4
     End_Case:
```

The value of the expression is used as an index into a table of addresses of statements, and the jump instruction jumps to the address contained in the register. In terms of efficiency, the overhead of a jump-table implementation is fixed and small for *all* choices.

It is imperative that the value of the expression be within the expected range (here 0 to 3), otherwise an invalid address will be computed and the computation will jump to a location that might not even be a valid instruction! In Ada, the expression can often be checked at compilation time:

Ada

```
type Status is (Off, Warm_Up, On, Automatic);
S: Status;
case S is ...                    -- There are exactly four values
```

In other cases, a run-time check will be needed to ensure that the value is within range. Jump tables are even compatible with a default alternative, provided that the explicit choices are contiguous. The compiler simply inserts the run-time check before attempting to use the jump table; if the check fails, the computation continues with the default alternative.

The choice of implementation is usually left to the compiler and there is no way of knowing which one is used without examining the machine code. The documentation of an optimizing compiler may inform its users under what circumstances it will compile into a jump table. Even if you take this knowledge into account when programming, your program is still portable, because the case-statement is portable; however, a different compiler may implement it in a different manner, so the improvement in efficiency is not portable.

6.2 if-statements

An if-statement is a special case of a case- or switch-statement where the expression is of Boolean type. Since Boolean types have only two possible values, an if-statement chooses between two possible paths. if-statements are probably the most frequently used control structures; the reason is that relational operators are extensively used and they return values of Boolean type:

C

```
if (x > y)
   statement-1;
else
   statement-2;
```

As we discussed in Section 4.4, C does not have a Boolean type. Instead, integer values are used with the convention that zero is false and non-zero is true.

A common mistake is to use an if-statement to create a Boolean value:

Ada

```
if X > Y then
   Result = True;
else
   Result = False;
end if;
```

instead of using a simple assignment statement:

Ada

```
Result := X > Y;
```

Remember that values and variables of Boolean type are first-class objects: in C they are just integers, and in Ada they are a distinct type but no different from any other enumeration type. The fact that Boolean types have a special status in if-statements does not otherwise restrict them.

Nested if-statements

The alternatives of an if-statement are themselves statements; in particular, they can also be if-statements:

C

```
if (x1 > y1)
    if (x2 > y2)
        statement-1;
    else
        statement-2;
else
    if (x3 > y3)
        statement-3;
    else
        statement-4;
```

It is best not to nest control structures (especially if-statements) too deeply, three or four levels at most. The reason is that it becomes difficult to follow the logic of the various paths. Furthermore, the indentation of the source code is only a guide: if you omit an else, the statement may still be syntactically valid even though the processing is no longer correct.

Another potential problem is that of the dangling else:

C

```
if (x1 > y1)
    if (x2 > y2)
        statement-1;
    else
        statement-2;
```

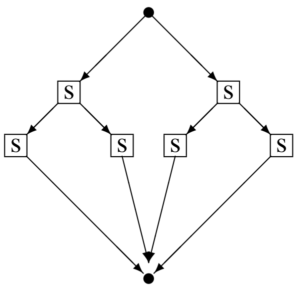
As implied by the indentation, the language definition associates the else with the inner-most if-statement. If you want to associate it with the outer if-statement, brackets must be used:

C

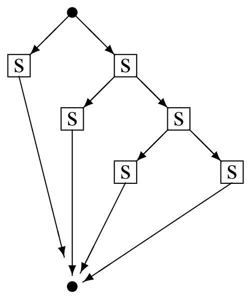
```
if (x1 > y1) {
    if (x2 > y2)
        statement-1;
}
```

```
else
    statement-2;
```

Nested if-statements can define a full binary tree of choices (Figure 6.2(a)), or any arbitrary subtree. In many cases, however, what is needed is to choose one of a sequence of outcomes (Fig-



(a) Fully nested



(b) Sequential

Figure 6.2: if-statements

ure 6.2(b)). If the selection is done on the basis of an expression, a switch-statement can be used. Otherwise, if the selection is done on the basis of a sequence of relational expressions, a sequence of nested if-statements is needed. In this case, it is conventional not to indent the statements:

C

```
if (x > y) {
    ...
} else if (x > z) {
    ...
} else if (y ¡ z) {
    ...
} else {
    ...
}
```

Explicit end if

The syntax of the if-statement in C (and Pascal) requires that each alternative be a single statement. If the alternative consists of a sequence of statements, they must be grouped into a single *compound* statement using braces ({, }) in C and (begin, end) in Pascal. The problem with this syntax is that if the terminating bracket is omitted, the compilation will continue without noticing the mistake. At best, the missing bracket will be noticed at the end of the compilation; at worst, a missing *opening* bracket will balance out the bracket count and an obscure run-time bug will be introduced.

This problem can be alleviated by explicitly terminating the if-statement. If the terminating bracket is omitted, it will be flagged as soon as another construct (a loop or procedure) is terminated with a different bracket. The if-statement syntax in Ada is:

Ada

```
if expression then
   statement-list-1;
else
   statement-list-2;
end if;
```

The problem with this construct is that in the case of a sequence of conditions (Figure 6.2(b)), there will be a confusing sequence of end if's at the end. To avoid this, a special construct is used; elsif introduces another condition and statement, but not another if-statement so no addition termination is required:

Ada

```
if x > y then
   ...
elsif x > z then
   ...
elsif y > z then
   ...
else
   ...
end if;
```

Implementation

The implementation of an if-statement is straightforward:

```
      compute    R1,expression
      jump_eq    R1,L1          False is represented as 0
      statement-1
      jump       L2
L1:   statement-2
L2:
```

Note that the False alternative is slightly more efficient than the True alternative since the latter executes an extra jump instruction.

On the surface it would seem that a condition of the form:

C

```
if (!expression) ...
```

would require an extra instruction to negate the value. However, compilers are smart enough just to change the initial jump_false instruction to jump_true.

Short circuit and full evaluation

Suppose that the expression in an if-statement is not just a simple relational expression, but a compound expression:

Ada

```
if (x > y) and (y > z) and (z ¡ 57) then...
```

There are two possible implementations of this statement. The first, called *full evaluation*, evaluates each of the components, then takes the Boolean and of the components and jumps according to the result. The second implementation, called *short-circuit evaluation*, evaluates the components one-by-one: if any component evaluates to False, a jump is executed to the False alternative since the entire expression must obviously be False. A similar situation occurs if the expression is a compound or-expression: if any component is True, the entire expression is obviously True.

The choice between the two implementations can usually be left to the compiler. Short-circuit evaluation will in general require fewer instructions to be executed. However, these instructions include many jumps and on a computer with a large instruction cache (see Section 1.7), it may be more efficient to compute all the components and only jump after the full evaluation.

Pascal specifies full evaluation because it was originally developed for a computer with a large cache. Other languages have two sets of operators: one for (full) evaluation of Boolean values and the other for short-circuit evaluation. For example, in Ada, and is used for fully evaluated Boolean operations on Boolean and modular types, while and then specifies short-circuit evaluation:

Ada

```
if (x > y) and then (y > z) and then (z < 57) then...
```

Similarly, or else is the short-circuit equivalent of or.

C contains three logical operators: "!" (not), "&&" (and), and "||" (or). Since C lacks a true Boolean type, these operators take integer operands and are defined in accordance with the interpretation described in Section 4.4. For example, a && b is equal to one if both operands are non-zero. Both "&&" and "||" use short-circuit evaluation. Also, be sure not to confuse these operators with the bitwise operators (Section 5.9).

In terms of programming style, Ada programmers should choose one style (either full evaluation or short circuit) for an entire program, using the other style only if necessary; C programmers always use the short-circuit operators.

Short-circuit evaluation is essential when the ability to evaluate one relation in a compound expression depends on a previous relation:

Ada

```
if (a /= 0) and then (b/a > 25) then ...
```

Such situations are also common when pointers (Chapter 8) are used:

Ada

```
if (ptr /= null) and then (ptr.value = key) then ...
```

6.3 Loop statements

Loop statements are the most difficult statements to program: they are prone to bugs especially at the boundaries of the loop, that is, the first and last executions of the loop body. Furthermore, an inefficient program is almost certainly spending most of its time in loops, so it is critical that their implementation be fully understood.

The structure of a loop statement is shown in Figure 6.3. A loop statement has an *entry* point,[2]

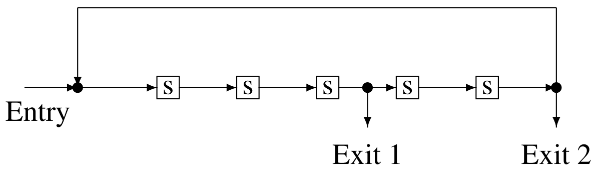


Figure 6.3: Loop statements

a sequence of statements that compose the loop, and one or more *exit* points. Since we (usually) want our loop statements to terminate, an exit point will have a *condition* associated with it, which decides if the exit should be taken, or if the execution of the loop should be continued. Loop statements are distinguished by the number, type and placement of the exit conditions. We will begin by discussing loops with arbitrary exit conditions, called while-statements, and in the next section discuss a specialization called for-statements.

The most common type of loop has its single exit point at the beginning of the loop, that is at its entry point. This is called a while-statement:

C

```
while (s[i].data != key)
   i++;
```

The while-statement is straightforward and reliable. Because the condition is checked at the beginning of the loop, we know that the loop body will be executed in its entirety a number of times that depends on the condition. If the exit condition is initially False, the loop body will not be executed and this simplifies the programming of boundary conditions:

C

```
while (count > 0)
   process(s[count].data);
```

If there is no data in the array, the loop will exit immediately.

In many cases, however, the exit from a loop is naturally written at the end of the loop. This is common when a variable must be initialized before any processing is done. Pascal has the repeat-statement:

[2]We will not even consider the possibility of jumping into a loop!

Pascal

```
repeat
    read(v);
    put_in_table(v)
until v = end_value;
```

The Pascal repeat terminates when the exit condition is True. Do not confuse it with the C do-statement, which terminates when the exit condition is False:

C

```
do {
    v = get( );
    put_in_table(v);
} while (v != end_value);
```

A pure approach to structured programming requires that all loops exit only at the beginning or the end of the loop. This makes a program much easier to analyze and verify, but in practice, exits from within a loop are commonly needed, especially when an error is detected:

Pascal

```
while not found do
    begin
    (* Long computation *)
    (* Error detected, terminate *)
    (* Long computation *)
    end
```

Pascal, which has no way of exiting from within a loop, uses the following unsatisfactory solution: set the exit condition and use an if-statement to skip the remainder of the loop body:

Pascal

```
while not found do
    begin
    (* Long computation *)
    if error_detected then found := True
    else
        begin
        (* Long computation *)
        end
    end
```

In C, the break-statement can be used:

C

```
while (!found) {
    /* Long computation */
    if (error_detected( )) break;
    /* Long computation */
}
```

Ada has the usual while-statement, as well as an exit-statement which is used to exit from an arbitrary location within the loop; the common occurrence of an if-statement together with an exit-statement can be conveniently expressed using a when-clause:

Ada

```
while not Found loop
    -- Long computation
    exit when error_detected;
    -- Long computation
end loop;
```

An operating system or real-time system is not intended to terminate, so there must be a way of indicating non-terminating loops. In Ada, this is directly expressed by a loop-statement with no exit condition:

Ada

```
loop
    ...
end loop;
```

Other languages require you to write an ordinary loop with an artificial exit condition that ensures that the loop does not terminate:

C

```
while (1==1) {
    ...
}
```

Implementation

The implementation of a while-loop:

C

```
while (expression)
    statement;
```

is as follows:

```
L1:  compute    R1,expr
     jump_zero  R1,L2         Skip statement if false
     statement                Loop body
     jump       L1            Jump to check for termination
L2:
```

Note that there are *two* jump instructions in the implementation of a while-statement! Surprisingly, if the loop exit is at the end of the loop, only one jump instruction is needed:

C

```
do {
   statement;
} while (expression);
```

compiles to:

```
L1:  statement
     compute   expr
     jump_nz   L1            Not zero is true
```

Even though the while-loop is a very clear construct, the efficiency of the loop can be improved by changing it to a do-loop. Exiting a loop in the middle requires two jumps just like a while-statement.

6.4 for-statements

Very often, we know the number of iterations that a loop requires: either it is a constant known when the program is written, or it is computed before the beginning of the loop. Counting loops can be programmed as follows:

C

```
int i;                    /* Loop index */
int low, high;            /* Loop limits */
i = low;                  /* Initialize index*/
while (i ¡= high) {       /* Evaluate exit expression */
   statement;
   i++;                   /* Increment index */
};
```

Since this paradigm is so common, all (imperative) programming languages supply a for-statement to simplify programming. In C the syntax is:

C

```
int i;                    /* Loop index */
int low, high;            /* Loop limits */

for (i = low; i ¡= high; i++) {
   statement;
}
```

The syntax in Ada is similar, except that the declaration and incrementation of the loop variable is implicit:

Ada

```
Low, High: Integer;

for I in Low .. High loop
   statement;
end loop;
```

Later in this section we will discuss the reasons for these differences.

for-statements are notorious for the bugs that they can introduce at the boundary values. The loop is executed for each of the values from low to high; thus the total number of iterations is $high - low + 1$. However, if the value of low is strictly greater than the value of high, the loop is executed zero times. If you wish to execute a loop exactly N times, the for-statement will be:

Ada

```
for I in 1..N loop ...
```

and the number of iterations is $N - 1 + 1 = N$. In C, because arrays are required to start from index zero, ordinary counting loops are usually written:

C

```
for (i = 0; i ¡ n; i++) ...
```

Since $i < n$ is the same as $i <= (n - 1)$, the loop is executed $(n - 1) - 0 + 1 = n$ times as required.

Generalized for-statements

Even though all imperative languages contain a for-statement, they differ greatly in the additional features that are provided. Two extremes are Ada and C.

Ada takes the point of view that a for-loop should be used *only* for loops with a fixed number of iterations, and that this number can be computed before starting the loop. The rationale for this point of view is: (1) most loops are in fact this simple, (2) other constructions can easily be explicitly programmed, and (3) for-loops are difficult enough to test and verify as it is. Ada even lacks the classic generalization: incrementing the loop variable by values other than 1 (or -1). In Algol, iteration over a sequence of odd numbers can be written:

Algol

```
for I := 1 to N step 2 do ...
```

while in Ada we have to explicitly program:

Ada

```
for I in 1 .. (N+1)/2 loop
   I1 = 2*I-1;
   ...
end loop;
```

In C, all three elements of the for-statement can be arbitrary expressions:

C

```
for ( i = j*k;   (i ¡ n) && (j+k > m);   i += 2*j ) ...
```

The definition of C specifies that:

C

```
for (expression_1; expression_2; expression_3) statement;
```

is equivalent to:

C

```
expression_1;
while (expression_2) {
    statement;
    expression_3;
}
```

In Ada, expressions are also permitted for the loop limits, but these are evaluated only once at the loop entry. That is:

Ada

```
for I in expression_1 .. expression_2 loop
    statement;
end loop
```

is equivalent to:

Ada

```
I = expression_1;
Temp = expression_2;
while (I ¡ Temp) loop
    statement;
    I := I + 1;
end loop;
```

If the body of the loop modifies the value of a variable used in computing expression_2, the upper limit of the Ada loop will not be modified. Compare this with the definition of the C for-loop above which re-evaluates the value of expression_2 on each iteration.

The generalizations in C are not just syntactic sugaring because of the possibility of side-effects, that is, statements within the loop that modify expression_2 and expression_3. Side-effects should be avoided for the following reasons:

- Side-effects make the loop difficult to fully verify and test.
- Side-effects adversely affect the readability and maintainability of the program.
- Side-effects make the loop much less efficient because expression_2 and expression_3 must be re-evaluated on each iteration. If side-effects are not used, an optimizing compiler will be able to move these evaluations outside the loop.

Implementation

for-statements are common sources of inefficiencies in programs because slight differences in language definition, or small changes in the use of the statement, can have significant consequences. In many cases, the optimizer can solve the problems, but it is better to be aware of and avoid problems, rather than to trust the optimizer. In this section, we will describe the implementation in greater detail at the register level.

In Ada, the loop:

Ada

```
for I in expression_1 .. expression_2 loop
    statement;
end loop;
```

compiles to:

```
        compute    R1,expr_1
        store      R1,I           Lower bound to index
        compute    R2,expr_2
        store      R2,High        Upper bound to index
L1:     load       R1,I           Load index
        load       R2,High        Load upper bound
        jump_gt    R1,R2,L2       Terminate loop if greater
        statement                 Loop body
        load       R1,I           Increment index
        incr       R1
        store      R1,I
        jump       L1
L2:
```

An obvious optimization is to dedicate a register to the index variable I and, if possible, another register to High:

```
        compute    R1,expr_1      Lower bound to register
        compute    R2,expr_2      Upper bound to register
L1:     jump_gt    R1,R2,L2       Terminate loop if greater
        statement
        incr       R1             Increment index register
        jump       L1
L2:
```

Now consider a simple loop in C:

C

```
for (i = expression_1; expression_2; i++)
    statement;
```

This compiles to:

```
      compute    R1,expr_1
      store      R1,i          Lower bound to index
L1:   compute    R2,expr_2     Upper bound within loop !
      jump_gt    R1,R2,L2      Terminate loop if greater
      statement                Loop body
      load       R1,i          Increment index
      incr       R1
      store      R1,i
      jump       L1
L2:
```

Note that expression_2, which may be very complicated, is now computed inside the loop. Also, expression_2 necessarily uses the value of the index variable i which is changed each iteration. Thus the optimizer must be able to identify the non-changing part of the evaluation of expression_2 in order to extract it from the loop.

Can the index variable be stored in a register for greater efficiency? The answer is "maybe" and depends on two properties of the loop. In Ada, the index variable is considered to be constant and cannot be modified by the programmer. In C, the index variable is a normal variable; it can be kept in a register only if there is no possibility that its current value will be needed except within the loop. Never use a global variable as an index variable because another procedure may read or modify its value:[3]

C

```
int i;

void p2(void) {
   i = i + 5;
}

void p1(void) {
   for (i=0; i¡100; i++)          /* Global index variable */
      p2( );                      /* Side effect on index */
}
```

The second property that affects the ability to optimize the loop is the potential use of the index variable outside the loop. In Ada, the index variable is implicitly declared by the for-statement and is *not* accessible outside the loop. Thus no matter how the loop is exited, we do not have to save the value in the register. Consider the following loop which searches for a key value in an array a:

C

```
int a[100];
int i, key;
```

[3]Also, in a multi-processing environment, another process may access the value.

```
key = get_key( );
for (i = 0; i ¡ 100; i++)
    if (a[i] == key) break;
process(i);
```

The variable i must contain the correct value regardless of which exit is taken. This can cause difficulty when trying to optimize the code. Note that in Ada, explicit coding is required to achieve the same effect because the index variable does not exist outside the scope of the loop:

Ada

```
Found: Integer := False;

for I in 1..100 loop
    if A(I) = Key then
        Found = I;
        exit;
    end if;
end loop;
```

The definition of the scope of loop indices in C++ has changed over the years, but the final definition is the same as in Ada: the index does not exist outside the scope of the loop:

C++

```
for (int i=0; i¡100; i++) {
        // Index variable is local to loop
}
```

In fact, any statement controlled by a condition (including if- and switch-statements) can have several declarations appear in the condition; their scope is limited to the controlled statements. This feature can contribute to the readability and reliability of a program by preventing unintended use of a temporary name.

6.5 Sentinels

The following section is not about programming languages as such; rather it is intended to show that a program can be improved by using better algorithms and programming techniques instead of fiddling with language details. The section is included because the topic of loop exit in a linear search is the subject of intense debate, and yet there exists a different algorithm that is simultaneously clear, reliable and efficient.

In the last example of the previous section (searching an array), there are three jump instructions in every execution of the loop: the conditional jump of the for-statement, the conditional jump of the if-statement and the jump from the end of the loop back to the beginning. The problem with this search is that we are checking two conditions at once: have we found the key, and have we reached the end of the array? By using a *sentinel*, we can reduce the two conditions to one. The idea is to extend the array by one extra place at the beginning of the array, and to store the key we are searching for in that place (Figure 6.4). Since we will necessarily find the key, either as

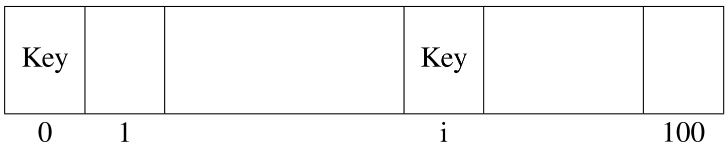


Figure 6.4: Sentinels

an occurrence within the array or as the artificial occurrence, only one condition need be checked within the loop:

Ada

```
type A_Type is array(0..100) of Integer;
         -- Extra place at zero for sentinel

function Find_Key(A: A_Type; Key: Integer)
      return Integer is
   I: Integer := 100;          -- Search from end
begin
   A(0) := Key;                -- Store sentinel
   while A(I) /= Key loop
      I := I - 1;
   end loop;
   return I;
end Find_Key;
```

Upon return from the function, if I is zero then the Key does not exist in the array; otherwise, I contains the index of the occurrence. Not only is this code more efficient, but the loop is extremely simple and can be easily verified.

6.6 * Invariants

The formal definition of the semantics of loop statements is based on the concept of an *invariant*: a formula which remains true after every execution of the loop body. Consider a simplistic program for computing integer division of a by b to obtain the result y:

C

```
y = 0;
x = a;
while (x >= b) {           /* As long as b "goes into" x, */
   x -= b;                 /*  subtracting b means that */
   y++;                    /*  result must be incremented */
}
```

and consider the formula:

$$a = yb + x$$

where an italic letter denotes the value of the corresponding program variable. After the initialization statements, this is certainly true since $y = 0$ and $x = a$. Furthermore, at the end of the program the formula *defines* what it means for y to be the result of integer division a/b, provided that the remainder x is less than the divisor b.

What is not so obvious is that the formula remains true after every execution of the loop body. In this trivial program, that fact is easy to see by simple arithmetic, given the changes to the values of x and y in the loop body:

$$(y+1)b + (x-b) = yb + b + x - b = yb + x = a$$

Thus the body of a loop statement transforms the state of a program from a state that satisfies the invariant to a different state that still satisfies the invariant.

Now note that for the loop to terminate, the Boolean condition in the while-statement must be False, that is the computation must be in a state such that $\neg(x \geq b)$ which is equivalent to $x < b$. Combining this formula with the invariant, we have shown that the program actually computes integer division.

More precisely, we have shown that *if* the program terminates, *then* the result is correct. This is called *partial correctness*. To prove *total correctness*, we must also show that the loop terminates.

This is done as follows. Since b is constant (and assumed positive!) during the execution of the program, what we have to show is that repeatedly decrementing x by b must eventually lead to a state in which $0 \leq x < b$. But (1) since x is repeatedly decremented, its value cannot stay indefinitely above that of b; (2) by the condition for terminating the loop and the computation in the loop body, x is never negative. These two facts imply that the loop must terminate.

Loop invariants in Eiffel

Eiffel supports the specification of assertions in general (see Section 11.5) and loop invariants in particular within the language:

Eiffel

```
from
    y = 0; x = a;
invariant
    a = yb + x
variant
    x
until
    x ¡ b
loop
    x := x − b;
    y := y + 1;
end
```

The from-clause establishes the initial condition, the until-clause gives the condition to terminate the loop, and the statements between loop and end form the loop body. The invariant-clause states the loop invariant and the variant-clause states the expression that will decrease (but stay non-negative) with each iteration of the loop. The correctness of the invariant is checked after each execution of the loop body.

6.7 goto-statements

In the original definition of Fortran there was only one structured control statement: the do-statement which is similar to the for-statement. All additional control used conditional or unconditional jumps to labels, called goto-statements:

Fortran

```
        if (a .eq. b) goto 12
        ...
        goto 5
4       ...
        ...
12      ...
        ...
5       ...
     if (x .gt. y) goto 4
```

In 1968, E. W. Dijkstra wrote a famous letter entitled “goto Considered Harmful” which launched a debate on structured programming. The main thrust of the “anti-goto” argument is that arbitrary jumps are not structured and create *spaghetti code*, that is, code whose possible threads of execution are so intertwined that it becomes impossible to understand or test the code. The “pro-goto” argument is that real programs often require control structures that are more general than those offered by structured statements, and that forcing programmers to use them results in artificial and complex code.

In retrospect, this debate was far too emotional and drawn-out because the basic principles are quite simple and are no longer seriously disputed. Furthermore, modern dialects of Fortran include more advanced control statements so that the goto-statement is no longer dominant.

It can be mathematically proven that if- and while-statements are sufficient to express any needed control structure. These statements are also easy to understand and use. Various syntactic extensions such as for-statements are well understood and if used properly pose no difficulty in understanding or maintaining a program. So why do programming languages (including Ada which was designed with reliability as the highest priority) retain the goto-statement?

The reason is that there are several well-defined situations where use of a goto-statement may be preferable. Firstly, many loops do not naturally terminate at their entry point as required by the while-statement. Attempting to force all loops into while-statements can lead to obscure code. With modern languages, the flexibility of exit- and break-statements means that goto-statements are usually unnecessary for this purpose. Nevertheless, the goto-statement still exists and can occasionally be useful. Note that both C and Ada limit the goto-statement by requiring that the label be in the same procedure.

A second situation that can be easily programmed using a goto-statement is an escape from a deeply nested computation. Suppose that deep within a series of procedure calls an error is detected that invalidates the entire computation. The natural way to program this requirement is to display an error message and terminate or reset the entire computation. However, this requires returning from many procedures, all of which have to know that an error has occurred. It is easier and more understandable just to goto a statement in the main program.

The C language has no means of dealing with this situation (not even with goto-statements which are limited to a single procedure), so facilities of the operating system must be used to handle serious errors. Ada, C++ and Eiffel have a language construct called *exceptions* (see Chapter 11) which directly solves this problem. Thus most of the uses of goto-statements have been superseded by improved language design.

Assigned goto-statements

Fortran includes a construct called an *assigned* goto-statement. A label variable can be defined and a label value assigned to the variable. When a jump is made to the label variable, the actual target of the jump is the current value of the label variable:

Fortran

```
   assign 5 to Label
   ...
   if (x .gt. y) assign 6 to Label
5  ...
6  ...
   goto Label
```

The problem, of course, is that the assignment of the label value could have been made millions of instructions before the goto is executed and it is practically impossible to verify or debug such code.

While assigned goto-statements do not exist in other languages, it is quite easy to simulate such a construct by defining many small subprograms and passing around pointers to the subprograms. You will find it difficult to relate a particular call with the pointer assignment that connected it to a specific subprogram. Thus pointers to subprograms should only be used in highly structured situations such as tables used by interpreters or callback mechanisms.

6.8 Exercises

1. Does your compiler implement all case-/switch-statements the same way, or does it try to choose an optimal implementation for each statement?

2. Simulate a Pascal repeat-statement in Ada and C.

3. The original definition of Fortran specified that a loop is executed at least one time even if the value of low is greater than the value of high! What could motivate this design?

4. The sequential search in C:

   C

   ```
   while (s[i].data != key)
       i++;
   ```

   might be written as follows:

   C

   ```
   while (s[i++].data != key)
       ;                           /* Null statement */
   ```

   What is the difference between the two computations?

5. Suppose that Ada did allow an index variable to exist after the scope of the loop. Show how optimization of a loop would be affected.

6. Compare the code generated for a search implemented using a break- or exit-statement with the code generated for a sentinel search.

7. Write a sentinel search using do-while rather than while. Is it more efficient?

8. Why did we put the sentinel at the beginning of the array rather than at the end?

9. (Scholten) The game of Go is played with stones of two colors, black and white. Suppose that you have a can with an unknown mixture of stones and that you execute the following algorithm:

   Ada

   ```
   while Stones_Left_in_Can loop
       Remove_Two_Stones(S1, S2);
       if Color(S1) = Color(S2) then
           Add_Black_Stone;
       else
           Add_White_Stone;
       end if;
   end loop;
   ```

   Show that the loop terminates by identifying a value which is always decreasing but always non-negative. Can you say anything about the color of the last stone to be removed? (Hint: write a loop invariant on the number of white stones.)

7 Subprograms

7.1 Subprograms: procedures and functions

A *subprogram* is a segment of a program that can be invoked from elsewhere within the program. Subprograms are used for various reasons:

- A segment of a program that must be executed at various stages within the computation can be written once as a subprogram and then repeatedly invoked. This saves memory and prevents the possibility of errors caused by copying the code from one place to another.
- A subprogram is a logical unit of program decomposition. Even if a segment is executed only once, it is useful to identify it in a subprogram for purposes of testing, documentation and readability.
- A subprogram can also be used as a physical unit of program decomposition, that is, as a unit of compilation. In Fortran, subprograms (called *subroutines*) are the only units of decomposition and compilation. Modern languages use the module, a group of declarations and subprograms, as the unit of physical decomposition (Chapter 13).

A subprogram consists of:

- A declaration which defines the interface to the subprogram. The subprogram declaration includes the name of the subprogram, the list of parameters (if any)[1] and the type of the value returned (if any).
- Local declarations which are accessible only within the body of the subprogram.
- A sequence of executable statements.

The local declarations and the executable statements form the *body* of the subprogram.

Subprograms that return a value are called *functions*; those that do not are called *procedures*. C does not have a separate syntax for procedures; instead you must write a function that returns `void` which is a type with no values:

[1] As a point of syntax, subprograms without parameters are usually declared without a parameter list (Ada, Pascal) or with an empty list (C++). C uses the explicit keyword `void` to indicate an absence of parameters.

C

```
void proc(int a, float b);
```

Such a function has the same properties as a procedure in other languages, so we will use the term procedure even when discussing C.

A procedure is invoked by a *call* statement. In Fortran, there is a special syntax:

Fortran

```
call proc(x,y)
```

while in other languages you simply write the name of the procedure followed by the actual parameters:

C

```
proc(x,y);
```

The semantics of a procedure call is as follows: the current sequence of instructions is suspended; the sequence of instructions within the procedure body is executed; upon completing the procedure body, the execution continues with the first statement following the procedure call. This description ignores parameter passing and scopes which will be the subject of extensive discussion in the next sections.

Since a function returns a value, the function declaration must specify the type of the returned value. In C, the type of a function precedes the function declaration:

C

```
int func(int a, float b);
```

while Ada uses a distinctive syntax for functions:

Ada

```
function Func(A: Integer; B: Float) return Integer;
```

A function call appears not as a statement, but as an element of an *expression*:

C

```
a = x + func(r,s) + y;
```

The result type of the function must be consistent with the type expected in the expression. Note that C does implicit type conversions in many cases, while in Ada the result type must exactly match the context. The meaning of a function call is similar to that of a procedure call: the evaluation of the expression is suspended; the instructions of the function body are executed; the returned value is then used to continue the evaluation of the expression.

The term function is actually very inappropriate to use in the context of ordinary programming languages. When used in mathematics, a function is just a mapping from one set of values to another. To use the technical term, a mathematical function is *referentially transparent*, because its "computation" is transparent to the point at which it is "called". If you have a value 3.6 and you ask for the value of sin(3.6), you will get the same unique result every time that the function appears in an equation. In programming, a function can perform an arbitrary computation including input-output or modification of global data structures:

C

```
int x,y,z;
int func(void)
{
   y = get( );              /* Modifies a global variable */
   return x*y;              /* Value based on global variable */
}

z = x + func(void) + y;
```

If the optimizer rearranged the order of the computation so that x+y were computed before the function call, a different result will be obtained, because the function modifies the value of y.

Since all C subprograms are functions, C programming style extensively uses return values in non-mathematical situations like input-output subprograms. This is acceptable provided that the possible difficulties with order dependencies and optimization are understood. Programming language research has developed exciting languages that are based on the mathematically correct concept of functions (see Chapter 16).

7.2 Parameters

In the previous section, we defined subprograms as segments of code that may be repeatedly invoked. Almost always, each invocation will require that the code in the subprogram body be executed using different data. The way to influence the execution of a subprogram body is to "pass" it the data that it needs. Data is passed to a subprogram in the form of a sequence of values called *parameters*. The concept is taken from mathematics where a function is given a sequence of *arguments*:[2] $\sin(2\pi r)$.

There are two concepts that must be clearly distinguished:

- A *formal parameter* is a declaration that appears in the declaration of the subprogram. The computation in the body of the subprogram is written in terms of formal parameters.
- An *actual parameter* is a value that the calling program sends to the subprogram.

In the following example:

C

```
int i, j;
char a;
void p(int a, char b)
{
   i = a + (int) b;
}
```

[2]Mathematical terminology uses *argument* for the value passed to a function, while *parameter* is usually used for values that are constant for a specific problem! We will, of course, use the programming terminology.

```
p(i, a);
p(i+j, 'x');
```

the formal parameters of the subprogram p are a and b, while the actual parameters of the first call are i and a, and of the second call, i+j and 'x'.

There are several important points that can be noted from the example. The first is that since the actual parameters are values, they can be constants or expressions, and not just variables. In fact, even when a variable is used as a parameter, what we really mean is “the current value stored in the variable”. Secondly, the *name space* of each subprogram is distinct. The fact that the first formal parameter is called a is not relevant to the rest of the program, and it could be renamed, provided, of course, that all occurrences of the formal parameter in the subprogram body are renamed. The variable a declared outside the subprogram is totally independent from the variable of the same name declared within the subprogram. In Section 7.7, we will explore in great detail the relationship between variables declared in different subprograms.

Named parameter associations

Normally the actual parameters in a subprogram call are just listed and the matching with the formal parameters is done by position:

Ada

```
procedure Proc(First: Integer; Second: Character);
Proc(24, 'X');
```

However, in Ada it is possible to use named association in the call, where each actual parameter is preceded by the name of the formal parameter. The order of declaration of the parameters need not be followed:

Ada

```
Proc(Second => 'X', First => 24);
```

This is commonly used together with default parameters, where parameters that are not explicitly written receive the default values given in the subprogram declaration:

Ada

```
procedure Proc(First: Integer := 0; Second: Character := '*');
Proc(Second => 'X');
```

Named association and default parameters are commonly used in the command languages of operating systems, where each command may have dozens of options and normally only a few parameters need to be explicitly changed. However, there are dangers with this programming style. The use of default parameters can make a program hard to read because calls whose syntax is different actually call the same subprogram. Named associations are problematic because they bind the subprogram declaration and the calls more tightly than is usually needed. If you use only positional parameters in calling subprograms from a library, you could buy a competing library and just recompile or link:

Ada

```
X := Proc_1(Y) + Proc_2(Z);
```

However, if you use named parameters, then you might have to do extensive modifications to your program to conform to the new parameter names:

Ada

```
X := Proc_1(Parm => Y) + Proc_2(Parm => Z);
```

7.3 Passing parameters to a subprogram

The definition of the mechanism for passing parameters is one of the most delicate and important aspects of the specification of a programming language. Mistakes in parameter passing are a major source of difficult bugs, so we will go into great detail in the following description.

Let us start from the definition we gave above: the value of the actual parameter is passed to the formal parameter. The formal parameter is just a variable declared within the subprogram, so the obvious mechanism is to copy the value of the actual parameter into the memory location allocated to the formal parameter. This mechanism is called *copy-in semantics* or *call-by-value*. Figure 7.1 demonstrates copy-in semantics, given the procedure definition:

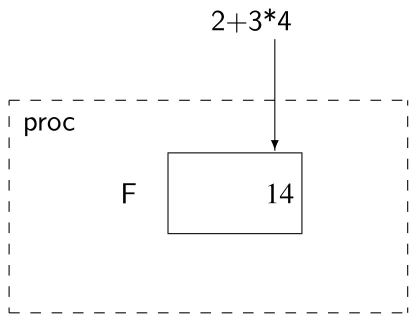


Figure 7.1: Copy-in semantics

Ada

```
procedure Proc(F: in Integer) is
begin
    . . . ;
end Proc;
```

and the call:

Ada

```
Proc(2+3*4);
```

The advantages of copy-in semantics are:

- Copy-in is the safest mechanism for parameter passing. Since only a copy of the actual parameter is passed, the subprogram cannot cause any damage to the actual parameter, which of course "belongs" to the calling program. If the subprogram modifies the formal parameter, only the copy is modified and not the original.
- Actual parameters can be constants, variables or expressions.
- Copy-in can be extremely efficient because once the initial overhead of the copy is done, all accesses to the formal parameter are to the local copy. As we shall see in Section 7.7, accesses to local variables are extremely efficient.

If copy-in semantics is so good, why are there other mechanisms? The reason is that we will often want to modify the actual parameter despite the fact that such modification is "unsafe":

- A function can only return a single result, so if the result of a computation is more complex, we may want to return several results. The way to do so is to provide a procedure with several actual parameters which can be assigned the results of the computation. Note that this situation can often be avoided by defining a function that returns a record as a result.
- Similarly, the purpose of the computation in the subprogram may be to modify data that is passed to it rather than to compute a result. This is common when a subprogram is maintaining a data structure. For example, a subprogram to sort an array does not compute a value; its only task is to modify the actual parameter. There is no point in sorting a copy of the actual parameter!
- A parameter may be so big that it is inefficient to copy. If copy-in is used for an array of 50,000 integers, there may simply not be enough memory available to make a copy, or the overhead of the copy may be excessive.

The first two situations can easily be solved using *copy-out semantics*. The actual parameter must be a variable, and the subprogram is passed the address of the actual parameter which it saves. A temporary local variable is used for the formal parameter, and a value must be assigned to the formal parameter[3] at least once during the execution of the subprogram. When the execution of the subprogram is completed, the value is copied into the variable pointed to by the saved address. Figure 7.2 shows copy-out semantics for the following subprogram:

Ada

```
procedure Proc(F: out Integer) is
begin
   F := 2+3*4;              -- Assign to copy-out parameter
end Proc;

A: Integer;
Proc(A);                    -- Call procedure with variable
```

[3]Ada 83 does not allow the subprogram to read the contents of the formal parameter. The more common definition of copy-out semantics, which is followed in Ada 95, allows normal computation on the (uninitialized) local variable.

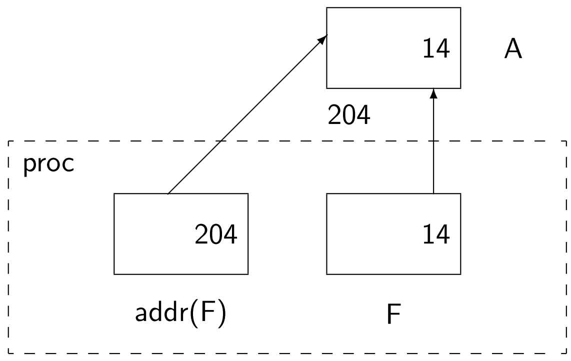


Figure 7.2: Copy-out semantics

When modification of the actual parameter is needed as in sort, *copy-in/out semantics* can be used: the actual parameter is copied into the subprogram when it is called and the final value is copied back upon completion.

However, copy-based parameter passing mechanisms cannot solve the efficiency problem caused by large parameters. The solution, which is known as *call-by-reference* or *reference semantics*, is to pass the address of the actual parameter and to access the parameter indirectly (Figure 7.3). Calling the subprogram is efficient because only a small, fixed-sized pointer is passed for each parameter; however, accessing the parameter can be inefficient because of the indirection.

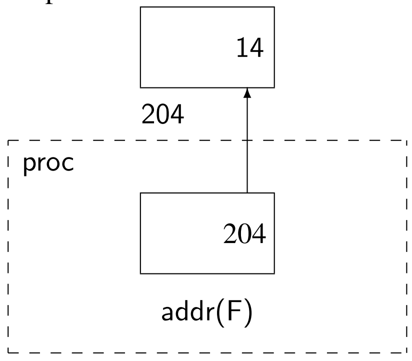


Figure 7.3: Reference semantics

In order to access the actual parameter, its address must be loaded and then an additional instruction is needed to load the value. Note that when using reference (or copy-out) semantics, the actual parameter must be a variable, not an expression, because a value will be assigned to it.

Another problem with call-by-reference is that it may result in *aliasing*: a situation in which the same variable is known by more than one name. In the following example, within the function f the variable global is also known by the alias *parm:

C

```
int global = 4;
int a[10];

int f(int *parm)
```

```
{
    *parm = 5;              /* Same variable as "global" */
    return 6;
}

x = a[global] + f(&global);
```

In the example, if the expression is evaluated in the order in which it is written, its value is a[4]+6, but because of aliasing, the value of the expression may be 6+a[5] if the compiler chooses to evaluate the function call before the array indexing. Aliasing is an important cause of non-portable behavior.

The real disadvantage of call-by-reference is that the mechanism is inherently unsafe. Suppose that for some reason the subprogram thinks that the actual parameter is an array whereas in fact it is just a single integer. This can cause an arbitrary amount of memory to be smeared, since the subprogram is working on the actual parameter, and not just on a local copy. This type of bug is extremely common, because the subprogram will typically have been written by a different programmer than the one calling the subprogram and misunderstandings always occur.

Safety of parameter passing can be improved by insisting on strong type checking which ensures that the types of the formal and actual parameters are compatible. Nevertheless, there is still room for misunderstanding between the programmer who wrote the subprogram and the programmer whose data is being modified. Thus we have an excellent parameter passing mechanism that is not always efficient enough (copy-in semantics), together with mechanisms that are necessary but unsafe (copy-out and reference semantics). The choice is complicated by constraints placed on the programmer by various programming languages. We will now describe the parameter passing mechanisms of several languages in detail.

Parameters in C and C++

C has only one parameter-passing mechanism, copy-in:

C

```
int i = 4;                  /* Global variables */

void proc(int i, float f)
{
    i = i + (int) f;        /* Local "i" */
}

proc(j, 45.0);              /* Function call */
```

In proc, the variable i that is modified is a local copy and not the global i.

In order to obtain the functionality of reference or copy-out semantics, a C programmer must resort to explicit use of pointers:

C

```
int i = 4;                      /* Global variables */

void proc(int *i, float f)
{
   *i = *i + (int) f;           /* Indirect access */
}

proc(&i, 45.0);                 /* Address operator needed */
```

After executing proc, the value of the global variable i will be modified. The requirement that pointers be used for reference semantics is unfortunate, because beginning programmers must learn this relatively advanced concept at an early stage of their studies.

C++ has corrected this problem so that true call-by-reference is available using *reference parameters*:

C++

```
int i = 4;                      // Global variables

void proc(int & i, float f)
{
   i = i + (int) f;             // By reference access
}

proc(i, 45.0);                  // No address operator needed
```

Note that the programming style is natural and does not use pointers artificially. This improvement in the parameter passing mechanism is so important that it justifies using C++ as a replacement for C.

You will often want to use pointers in C or references in C++ to pass large data structures. Of course, unlike copy-in parameters, there is a danger of accidental modification of the actual parameter. Read-only access to a parameter can be specified by declaring them const:

```
void proc(const Car_Data & d)
{
   d.fuel = 25;                 // Error, cannot modify const
}
```

const declarations should be used whenever possible both to clarify the meaning of parameters to readers of the program, and to catch potential bugs.

Another problem with parameters in C is that arrays cannot be parameters. If an array must be passed, the address of the first element of the array is passed, and the procedure has the responsibility for correctly accessing the array. As a convenience, using an array name as a parameter is automatically considered to be the use of a pointer to the first element:

C

```
int b[50];                  /* Array variable */

void proc(int a[])          /* "Array parameter" */
{
   a[100] = a[200];         /* How many components ? */
}

proc(&b[0]);                /* Address of first element */
proc(b);                    /* Address of first element */
```

C programmers quickly get used to this but it is a source of confusion and bugs. The problem is that since the parameter is actually a pointer to a single element, *any* pointer to a variable of a similar type is accepted:

C

```
int i;
void proc(int a[]);         /* "Array parameter" */
proc(&i);                   /* Any pointer to integer is OK !! */
```

Finally, in C no type checking is done between files so that it is possible to declare:

C

```
void proc(float f) { ... }  /* Procedure definition */
```

in one file and:

C

```
void proc(int i);           /* Procedure declaration */
proc(100);
```

in another file, and then spend a month looking for the bug.

The C++ language requires that parameter type checking be performed. However, the language does not require that implementations include a library facility as in Ada (see Section 13.3) that can ensure type checking across separately compiled files. C++ compilers implement type checking by cooperation with the linker: parameter types are encoded in the external name of the subprogram (a process called *name mangling*), and the linker will make sure that calls are linked only to subprograms with the correct parameter signature.[4] Unfortunately, this method cannot catch all type mismatches.

Parameters in Pascal

In Pascal, parameters are passed by value unless reference semantics is explicitly requested:

[4]For details, see Section 7.2c of the Annotated Reference Manual.

Pascal

```
procedure proc(P_Input: Integer; var P_Output: Integer);
```

The keyword var indicates that the following parameter is called by reference, otherwise call-by-value is used even if the parameter is very large. Parameters can be of any type including arrays, records or other complex data structures. The one limitation is that the result type of a function must be a scalar. The types of actual parameters are checked against the types of the formal parameters.

As we discussed in Section 5.4, there is a serious problem in Pascal because the array bounds are considered part of the type. The Pascal standard defines *conformant array parameters* to solve this problem.

Parameters in Ada

Ada takes a novel approach in defining parameter passing in terms of intended use rather than in terms of the implementation mechanism. For each parameter you must explicitly choose one of three possible *modes*:

in The parameter may be read but not written (default).

out The parameter may be written but not read.

in out The parameter may be both read and written.

For example:

Ada

```
procedure Put_Key(Key: in Key_Type);
procedure Get_Key(Key: out Key_Type);
procedure Sort_Keys(Keys: in out Key_Array);
```

In the first procedure, the parameter Key must be read so that it can be "put" into a data structure (or output device). In the second, a value is obtained from a data structure and upon completion of the procedure, the value is assigned to the parameter. The array Keys to be sorted must be passed as in out, because sorting involves both reading and writing the data of the array.

Ada restricts parameters of a function to be of mode in only. This does not make Ada functions referentially transparent because there is still no restriction on accessing global variables, but it can help the optimizer to improve the efficiency of expression evaluation.

Despite the fact that the modes are not defined in terms of implementation mechanisms, the Ada language does specify some requirements on the implementation. Parameters of elementary type (numbers, enumerations and pointers) must be implemented by copy semantics: copy-in for in parameters, copy-out for out parameters, and copy-in/out for in out parameters. The implementation of modes for composite parameters (arrays and records) is not specified, and a compiler may choose whichever mechanism it prefers. This introduces the possibility that the correctness of an

Ada program depends on the implementation-chosen mechanism, so such programs are simply not portable.[5]

Strong type checking is done between formal and actual parameters. The type of the actual parameter must be the same as that of the formal parameter; no implicit type conversion is ever performed. However, as we discussed in Section 5.4, the subtypes need not be identical as long as they are compatible; this allows an arbitrary array to be passed to an unconstrained formal parameter.

Parameters in Fortran

We will briefly touch on parameter passing in Fortran because it can cause spectacular bugs. Fortran can pass only scalar values; the interpretation of a formal parameter as an array is done by the called subroutine. Call-by-reference is used for all parameters. Furthermore, each subroutine is compiled independently and no checking is done for compatibility between the subroutine declaration and its call.

The language specifies that if a formal parameter is assigned to, the actual parameter must be a variable, but because of independent compilation this rule cannot be checked by the compiler. Consider the following example:

Fortran

```
Subroutine Sub(X, Y)
Real X,Y
X = Y
End

Call Sub(−1.0, 4.6)
```

The subroutine has two parameters of type Real. Since reference semantics is used, Sub receives pointers to the two actual parameters and the assignment is done directly on the actual parameters (Figure 7.4). The result is that the memory location storing the value −1.0 is modified! There

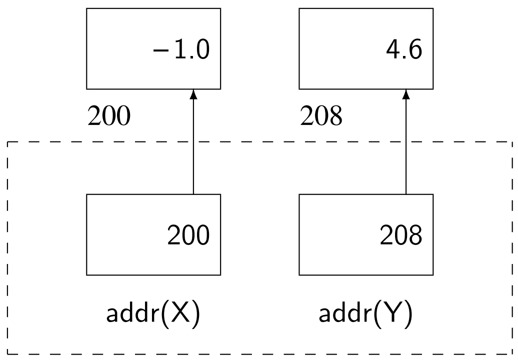


Figure 7.4: Smearing a constant in Fortran

[5]Ada 95 requires that certain categories of parameters be passed by reference; these include task types and tagged types (Section 14.5).

is literally no way to "debug" this bug, since debuggers only allow you to examine and trace variables, not constants. The point of the story is that correct matching of actual and formal parameters is a cornerstone of reliable programming.

7.4 Block structure

A *block* is an entity consisting of declarations and executable statements. A similar definition was given for a subprogram body and it is more precise to say that a subprogram body *is* a block. Blocks in general and procedures in particular can be nested within one another. This section will discuss the relationships among nested blocks.

Block structure was first defined in the Algol language which includes both procedures and unnamed blocks. Pascal contains nested procedures but not unnamed blocks; C contains unnamed blocks but not nested procedures; and Ada returns to support both.

Unnamed blocks are useful for restricting the scope of variables by declaring them only when needed, instead of at the beginning of a subprogram. The trend in programming is to reduce the size of subprograms, so the use of unnamed blocks is less useful than it used to be.

Nested procedures can be used to group statements that are executed at more than one location within a subprogram, but refer to local variables and so cannot be external to the subprogram. Before modules and object-oriented programming were introduced, nested procedures were used to structure large programs, but this introduces complications and is not recommended.

The following is an example of a complete Ada program:

Ada

```
procedure Main is
    Global: Integer;

    procedure Proc(Parm: in Integer) is
        Local: Integer;
    begin
        Global := Local + Parm;
    end Proc;

begin -- Main
    Global := 5;
    Proc(7);
    Proc(8);
end Main;
```

An Ada program is a *library* procedure, that is, a procedure that is not enclosed within any other entity and hence can be stored in the Ada library. The procedure begins with a procedure declaration for Main,[6] which serves as a definition of the interface to the procedure, in this case the

[6]Unlike C, the main procedure need not be called main.

external name of the program. Within the library procedure there are two declarations: a variable Global and a procedure Proc. Following the declarations is the sequence of executable statements for the main procedure. In other words, the procedure Main consists of a procedure declaration and a block. Similarly, the local procedure Proc consists of a procedure declaration (the procedure name and the parameters) and a block containing variable declarations and executable statements. Proc is said to be *local* to Main or *nested* within Main.

Each declaration has associated with it three properties:[7]

Scope The scope of a variable is the segment of the program within which it is defined.

Visibility A variable is visible within some subsegment of its scope if it can be directly accessed by name.

Lifetime The lifetime of a variable is the interval during the program's execution when memory is assigned to the variable.

Note that lifetime is a dynamic property of the run-time behavior of a program, while scope and visibility relate solely to the static program text.

Let us demonstrate these abstract definitions on the example above. The scope of a variable begins at the point of declaration and ends at the end of the block in which it is defined. The scope of Global includes the entire program while the scope of Local is limited to a single procedure. The formal parameter Parm is considered to be like a local variable and its scope is also limited to the procedure.[8]

The visibility of each variable in this example is identical to its scope: each variable can be directly accessed in its entire scope. Since the scope and visibility of the variable Local is limited to the local procedure, the following is not allowed:

Ada

```
begin -- Main
   Global := Local + 5;    -- Local is not in scope here
end Main;
```

However, the scope of Global includes the local procedure so the access within the procedure is correct:

Ada

```
   procedure Proc(Parm: in Integer) is
      Local: Integer;
   begin
      Global := Local + Parm;      -- Global is in scope here
   end Proc;
```

The lifetime of a variable is from the beginning of the execution of its block until the end of the execution of its block. The block of the procedure Main is the entire program so Global exists for

[7]To keep the discussion concrete, it will be given in terms of variables even though the concepts are more general.

[8]Ada allows named parameter associations, so this statement is not completely precise.

the duration of the execution of the program. Such a variable is called *static*: once it is allocated it lives until the end of the program. The local variable has two lifetimes corresponding to the two calls to the local procedure. Since these intervals do not overlap, the variable may be allocated at a different location each time it is created. Local variables are called *automatic* because they are automatically allocated when the procedure is called (the block is entered), and released when the procedure returns (the block is left).

Hiding

Suppose that a variable name that is used in the main program is repeated in a declaration in a local procedure:

Ada

```
procedure Main is
   Global: Integer;
   V: Integer;                        -- Declaration in Main

   procedure Proc(Parm: in Integer) is
      Local: Integer;
      V: Integer;                     -- Declaration in Proc
   begin
      Global := Local + Parm + V;-- Which V is used ?
   end Proc;

begin -- Main
   Global := Global + V;              -- Which V is used ?
end Main;
```

In this case, the local declaration is said to *hide* the global declaration. Within the procedure, any reference to V is a reference to the locally declared variable. In technical terms, the scope of the global V extends from the point of declaration to the end of Main, but its visibility does not include local procedure Proc.[9]

Hiding of variable names by inner declarations is convenient in that the programmer can reuse natural names like Current_Key and not have to invent strange-sounding names. Furthermore, it is always possible to add a global variable without worrying that this will clash with some local variable name used by one of the programmers on your team. The disadvantage is that a variable name could be accidentally hidden, especially if large include-files are used to centralize global declarations, so it is probably better to avoid hiding variable names. However, there is no objection to reusing a name in different scopes since there is no way of accessing both variables simultaneously, regardless of whether the names are the same or different:

[9] In Ada (but not in Pascal) the hidden variable is accessible using the syntax Main.V. Similarly, in C++ (but not in C), ::V can be used to access a hidden global variable.

Ada

```
procedure Main is
    procedure Proc_1 is
        Index: Integer;              -- One scope
        ...
    end Proc_1;
    procedure Proc_2 is
        Index: Integer;              -- Non-overlapping scope
        ...
    end Proc_2;
begin -- Main
    ...
end Main;
```

Depth of nesting

There is no conceptual limit to the depth of nesting, though a compiler may arbitrarily limit the depth. Scope and visibility are determined by applying the rules given above: a variable's scope is from its point of declaration to the end of the block, and its visibility is the same unless hidden by an inner declaration. For example:

Ada

```
procedure Main is
    Global: Integer;

    procedure Level_1 is
        Local: Integer;        -- Outer declaration of Local

        procedure Level_2 is
            Local: Integer;    -- Inner declaration of Local
        begin -- Level_2
            Local := Global;   -- Inner Local hides outer Local
        end Level_2;

    begin -- Level_1
        Local := Global;       -- Only outer Local in scope
        Level_2;
    end Level_1;

begin -- Main
    Level_1;
    Level_2;                   -- Error, procedure not in scope
end Main;
```

The scope of the variable Local defined in procedure Level_1 extends until the end of the procedure, but it is hidden within procedure Level_2 by the declaration of the same name.

The procedure declarations themselves are considered to have scope and visibility similar to variable declarations. Thus the scope of Level_2 is from its declaration in Level_1 until the end of Level_1. This means that Level_1 can *call* Level_2 even though it cannot access variables within Level_2. On the other hand, Main cannot call Level_2 directly, since it cannot access declarations that are local to Level_1.

Note the potential for confusion since the variable Local accessed by the statement in Level_1 is declared *further* away in the program text than the occurrence of Local enclosed within Level_2. If there were a lot of local procedures, it might be difficult to find the correct declaration. To prevent confusion, it is best to limit the depth of nesting to two or three levels below the main program.

Advantages and disadvantages of block structure

The advantage of block structure is that it provides an easy and efficient method of decomposing a procedure. If you avoid excessive nesting and hidden variables, block structure can be used to write reliable programs since related local procedures can be kept together. Block structuring is especially important when complex computations are being done:

Ada

```
procedure Proc(...) is
        -- Lots of declarations
begin
    -- Long computation 1
    if N ¡ 0 then
            -- Long computation 2 version 1
    elsif N = 0 then
            -- Long computation 2 version 2
    else
            -- Long computation 2 version 3
    end if;
    -- Long computation 3
end Proc;
```

In this example, we would like to avoid writing Long computation 2 three times and instead make it an additional procedure with a single parameter:

Ada

```
procedure Proc(...) is
        -- Lots of declarations
        procedure Long_2(I: in Integer) is
        begin
            -- Access declarations in Proc
        end Long_2;
begin
```

```
        -- Long computation 1
        if N ¡ 0 then Long_2(1);
        elsif N = 0 then Long_2(2);
        else Long_2(3);
        end if;
        -- Long computation 3
    end Proc;
```

However, it would be extremely difficult to make Long_2 an independent procedure because we might have to pass dozens of parameters so that it could access local variables. If Long_2 is nested, it needs just the one parameter, and the other declarations can be directly accessed according to normal scope and visibility rules.

The disadvantages of block structure become apparent when you try to program a large system in a language like standard Pascal that has no other means of program decomposition:

- Small procedures receive excessive "promotions". Suppose that a procedure to convert decimal digits to hexadecimal digits is used in many deeply-nested procedures. That utility procedure must be defined in some common ancestor. Practically, large block-structured programs tend to have many small utility procedures written at the highest level of declaration. This makes the program text awkward to work with because it is difficult to locate a specific procedure.

- Data security is compromised. Every procedure, even those declared deeply nested in the structure, can access global variables. In a large program being developed by a team, this makes it likely that errors made by one junior team member can cause obscure bugs. The situation is analogous to a company where every employee can freely examine the safe in the boss's office, but the boss has no right to examine the file cabinets of junior employees!

These problems are so serious that every commercial Pascal implementation defines a (non-standard) module structure to enable large projects to be constructed. In Chapter 13 we will discuss in detail constructs that are used for program decomposition in modern languages like Ada and C++. Nevertheless, block structure remains an important tool in the detailed programming of individual modules.

It is also important to understand block structure because programming languages are implemented using stack architecture, which directly supports block structure (Section 7.6).

7.5 Recursion

Most (imperative) programming is done using *iteration*, that is loops; however, *recursion*, the definition of an object or computation in terms of itself, is a more primitive mathematical concept, and is also a powerful, if often under-used, programming technique. Here we will survey how to program recursive subprograms.

The most elementary example of recursion is the factorial function, defined mathematically as:

$$\begin{aligned} 0! &= 1 \\ n! &= n \times (n-1)! \end{aligned}$$

This definition translates immediately into a program that uses a recursive function:

C

```
int factorial(int n)
{
   if (n == 0) return 1;
   else return n * factorial(n − 1);
}
```

What properties are required to support recursion?

- The compiler must emit *pure code*. Since the same sequence of machine instructions are used to execute each call to factorial, the code must not modify itself.
- During run-time, it must be possible to allocate an arbitrary number of memory cells for the parameters and local variables.

The first requirement is fulfilled by all modern compilers. Self-modifying code is an artifact of older programming styles and is rarely used. Note that if a program is to be stored in read-only memory (ROM), by definition it cannot modify itself.

The second requirement arises from consideration of the lifetime of the local variables. In the example, the lifetime of the formal parameter n is from the moment that the procedure is called until it is completed. But before the procedure is completed, another call is made and that call requires that memory be allocated for the new formal parameter. To compute factorial(4), a memory location is allocated for 4, then 3 and so on, five locations altogether. The memory cannot be allocated before execution, because the amount depends on the run-time parameter to the function. Section 7.6 shows how this allocation requirement is directly supported by the stack architecture.

At this point, most programmers will note that the factorial function could be written just as easily and far more efficiently using iteration:

C

```
int factorial(int n)
{
   int i = n;
   result = 1;
   while (i != 0) {
      result = result * i;
      i−−;
   }
   return result;
}
```

So why use recursion? The reason is that many algorithms can be elegantly and reliably written using recursion while an iterative solution is difficult to program and prone to bugs. Examples are the Quicksort algorithm for sorting and data structure algorithms based on trees. The language concepts discussed in Chapters 16 and 17 (functional and logic programming) use recursion exclusively instead of iteration. Even when using ordinary languages like C and Ada, recursion should probably be used more often than it is because of the concise, clear programs that result.

7.6 Stack architecture

A *stack* is a data structure that stores and retrieves data in a Last-In, First-Out (LIFO) order. LIFO constructions exist in the real world such as a stack of plates in a cafeteria, or a pile of newspapers in a store. A stack may be implemented using either an array or a list (Figure 7.5). The advantage of the list is that it is unbounded and its size is limited only by the total amount of

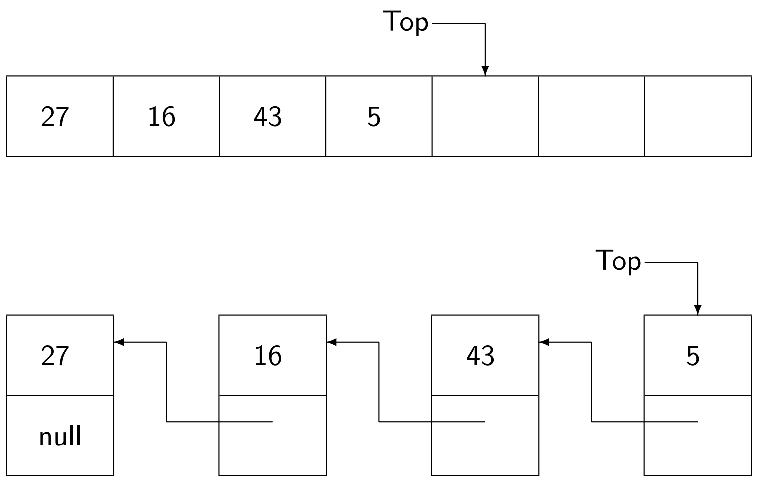


Figure 7.5: Stack implementation

available memory. Arrays are much more efficient and are implicitly used in the implementation of programming languages.

In addition to the array (or list), a stack contains an additional piece of data—the *top-of-stack pointer*. This is an index to the first available empty position in a stack. Initially, a variable top will point to the first position in the stack. The two possible operations on a stack are push and pop. push is a procedure that receives an element as a parameter, which it places on the top of the stack, incrementing top. pop is a function that returns the top element in the stack, decrementing top to indicate that that position is the new empty position.

The following C program implements a stack of integers as an array:

C

```
#define Stack_Size 100
int stack[Stack_Size];
int top = 0;

void push(int element)
{
   if (top == Stack_Size) /* Stack overflow, do something! */
   else stack[top++] = element;
}

int pop(void)
{
   if (top == 0) /* Stack underflow, do something! */
   else return stack[--top];
}
```

A stack can underflow if we try to pop from an empty stack, and it can overflow if we try to push onto a full stack. Underflow is always due to a programming error since you store something on a stack if and only if you intend to retrieve it later on. Overflow can occur even in a correct program if the amount of memory is not sufficient for the computation.

Stack allocation

How is a stack used in the implementation of a programming language? A stack is used to store information related to a procedure call, including the local variables and parameters that are automatically allocated upon entry to the procedure and released upon exit. The reason that a stack is the appropriate data structure is that procedures are entered and exited in a LIFO order, and any accessible data belongs to a procedure that occurs earlier in the chain of calls.

Consider a program with local procedures:

Ada

```
procedure Main is
   G: Integer;

   procedure Proc_1 is
      L1: Integer;
   begin ... end Proc_1;

   procedure Proc_2 is
      L2: Integer;
   begin ... end Proc_2;

begin
   Proc_1;
   Proc_2;
end Main;
```

When the Main begins executing, memory must be allocated for G. When Proc_1 is called, additional memory must be allocated for L1 without releasing the memory for G (Figure 7.6(a)). The memory for L1 is released before memory is allocated for L2, since Proc_1 terminates before

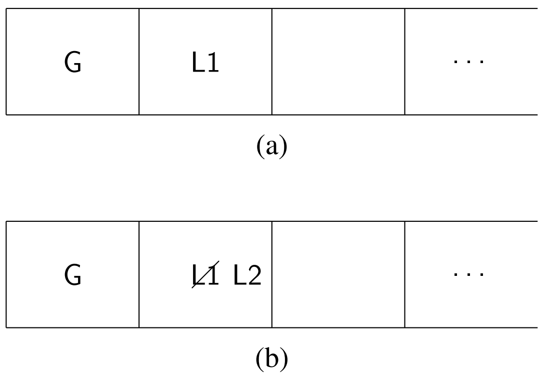


Figure 7.6: Allocating memory on a stack

Proc_2 is called (Figure 7.6(b)). In general, no matter how procedures call each other, the first memory element to be released is the last one allocated, so memory for variables and parameters can be allocated on a stack.

Consider now nested procedures:

Ada

```
procedure Main is
   G: Integer;

   procedure Proc_1(P1: Integer) is
      L1: Integer;

      procedure Proc_2(P2: Integer) is
         L2: Integer;
      begin
         L2 := L1 + G + P2;
      end Proc_2;

   begin -- Proc_1
      Proc_2(P1);
   end Proc_1;

begin -- Main
   Proc_1(G);
end Main;
```

Proc_2 can only be called from within Proc_1. This means that Proc_1 has not terminated yet, so its memory has not been released and the memory assigned to L1 must still be allocated (Figure 7.7). Of course, Proc_2 terminates before Proc_1 which in turn terminates before Main, so memory can be freed using the pop operation on the stack.

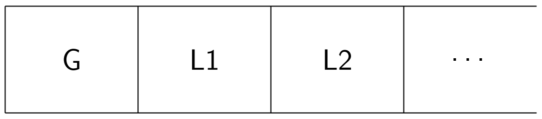


Figure 7.7: Nested procedures

Activation records

The stack is actually used to support the entire procedure call and not just the allocation of local variables. The segment of the stack associated with each procedure is called the *activation record* for the procedure. In outline,[10], a procedure call is implemented as follows (see Figure 7.8):

1. The actual parameters are pushed onto the stack. They can be accessed as offsets from the start of the activation record.
2. The *return address* is pushed onto the stack. The return address is the address of the statement following the procedure call.
3. The top-of-stack index is incremented by the total amount of memory required to hold the local variables.
4. A jump is made to the procedure code.

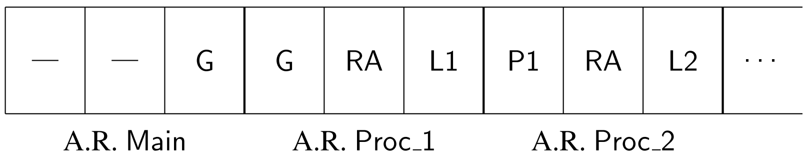


Figure 7.8: Activation records

Upon completion of the procedure the above steps are reversed:

1. The top-of-stack index is decremented by the amount of memory allocated for the local variables.
2. The return address is popped and the instruction pointer reset.
3. The top-of-stack index is decremented by the amount of memory allocated for the actual parameters.

[10]See Section 7.8 for more details.

While this code may seem complicated, it can actually be done very efficiently on most computers. The amount of memory needed for variables, parameters and call overhead is known at compile-time, and the above processing just requires modification of the stack index by a constant.

Accessing values on the stack

In a true stack, the only permissible operations are push and pop. The execution stack we have described is a more complex structure because we want to be able to efficiently access not only the most recent value pushed, but also all the local variables and all the parameters. One possibility would be to access these data relative to the top-of-stack index:

```
    stack[top – 25];                                                  C
```

However, the stack may hold other data besides that associated with a procedure call (such as temporary variables, see Section 4.7), so it is customary to maintain an additional index called the *bottom pointer* which points to the start of the activation record (see Section 7.7). Even if the top-of-stack index varies during the execution of the procedure, all the data in the activation record can be accessed at fixed offsets from the bottom pointer.

Parameters

There are two methods for implementing the passing of parameters. The simpler method is just to push the parameters themselves (whether values or references) onto the stack. This method is used in Pascal and Ada because in those languages the number and type of each parameter is known at compilation time. From this information, the offset of each parameter relative to the beginning of the activation record can be computed at compile-time, and each parameter can be accessed at this fixed offset from the bottom pointer index:

```
        load    R1,bottom-pointer
        add     R1,#offset-of-parameter
        load    R2,(R1)         Load value whose address is in R1
```

If the bottom pointer is kept in a register, this code can usually be collapsed into a single instruction. When leaving the subprogram, *stack clean-up* is done by having the subprogram reset the stack pointer so that the parameters are effectively no longer on the stack.

There is a problem using this method in C, because C allows a procedure to have a variable number of arguments:

```
    void proc(int num_args, . . . );                                  C
```

Since the subprogram does not know how many parameters there are, it cannot clean-up the stack. The responsibility for stack clean-up is thus shifted to the caller which does know how many parameters were passed. This causes some memory overhead because the clean-up code is duplicated at *every* call instead of being common to all calls.

When the number of parameters is not known, an alternative method of parameter passing is to store the actual parameters in a separate block of memory, and then to pass the address of this block on the stack. An additional indirection is required to access a parameter, so this method is less efficient than directly pushing parameters on the stack.

Note that it may not be possible to store a parameter directly on the stack. As you will recall, a formal parameter in Ada can be an unconstrained array type whose bounds are not known at compilation time:

Ada

```
procedure Proc(S: in String);
```

Thus the actual parameter cannot be pushed directly onto the stack. Instead a dope vector (Figure 5.5) which contains a pointer to the array parameter is placed on the stack.

Recursion

The stack architecture directly supports recursion because each call to a procedure automatically allocates a new copy of the local variables and parameters. For example, each recursive call of the function for factorial needs one memory word for the parameter and one memory word for the return address. The higher overhead of recursion relative to iteration comes from the extra instructions involved with the procedure entry and exit. Some compilers will attempt an optimization called *tail-recursion* or *last-call* optimization. If the only recursive call in a procedure is the last statement in the procedure, it is possible to automatically translate the recursion into iteration.

Stack size

If recursion is not used, the total stack usage can theoretically be computed before execution by adding the activation record requirements for each possible chain of procedure calls. Even in a complex program, it should not be hard to make a reasonable estimate of this figure. Add a few thousand spare words and you have computed a stack size that will probably not overflow.

However, if recursion is used, the stack size is theoretically unbounded at run-time:

C

```
i = get( );
j = factorial(i);
```

In the Exercises, we describe Ackermann's function which is unconditionally guaranteed to overflow any stack you allocate! In practice, it is usually not difficult to make an estimate of stack size even when recursion is used. Suppose the size of an activation record is about 10 and the depth of recursion no more than a few hundred. Adding an extra 10K to the stack will more than suffice.

Readers who have studied data structures will know that recursion is convenient to use on tree-structured algorithms like Quicksort and priority queues. The depth of recursion in tree algorithms is roughly $\log_2$ of the size of the data structure. For practical programs this bounds the depth of recursion to 10 or 20 so there is very little danger of stack overflow.

Whether recursion is used or not, the nature of the system will dictate the treatment of potential stack overflow. A program might completely ignore the possibility and accept the fact that in extreme circumstances the program will crash. Another possibility is to check the stack size before each procedure call, but this might be too inefficient. A compromise solution would be to check the stack size periodically and take some action if it fell below some threshold, say 1000 words.

7.7 More on stack architecture

Accessing variables at intermediate levels

We have discussed how local variables are efficiently accessed at fixed offsets from the bottom pointer of an activation record. Global data, that is data declared in the main program, can also be accessed efficiently. The easiest way to see this is to imagine that global data is considered "local" to the main procedure; thus memory for the global data is allocated at the main procedure entry, that is, at the beginning of the program. Since this location is known at compile-time, or more exactly when the program is linked, the actual address of each element is known either directly or as an offset from a fixed location. In practice, global data is usually allocated separately (see Section 8.5), but in any case the addresses are fixed.

Variables at intermediate levels of nesting are more difficult to access:

Ada

```
procedure Main is
   G: Integer;

   procedure Proc_1 is
      L1: Integer;

      procedure Proc_2 is
         L2: Integer;
      begin L2 := L1 + G; end Proc_2;
      procedure Proc_3 is
         L3: Integer;
      begin L3 := L1 + G; Proc_2; end Proc_3;

   begin -- Proc_1
      Proc_3;
   end Proc_1;

begin -- Main
   Proc_1;
end Main;
```

We have seen that accessing the local variable L3 and the global variable G is easy and efficient, but how can L1 be accessed in Proc_3? The answer is that the value of the bottom pointer is stored at procedure entry and is used as a pointer to the activation record of the enclosing procedure Proc_1. The bottom pointer is stored at a known location and can be immediately loaded, so the overhead is an additional indirection.

If deeper nesting is used, each activation record contains a pointer to the previous one. These pointers to activation records form the *dynamic chain* (Figure 7.9). To access a *shallow variable* (one that is less deeply nested), instructions have to be executed to "climb" the dynamic chain. This potential inefficiency is the reason that accessing intermediate variables in deeply nested procedures is discouraged. Accessing the immediately previous level requires just one indirection and an occasional deep access should not cause any trouble, but a loop statement should not contain statements that reach far back in the chain.

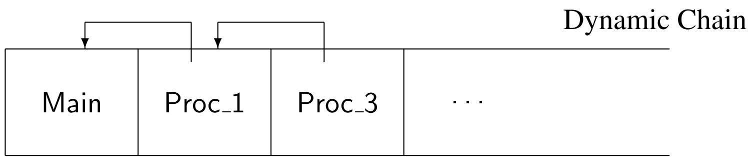


Figure 7.9: Dynamic chain

Calling shallow procedures

Accessing intermediate variables is actually more complicated than the discussion above would indicate because a procedure is allowed to call other procedures that are at the same level of nesting or lower. In the example, Proc_3 calls Proc_2. The activation record for Proc_2 will store the bottom pointer of Proc_3 so that it can be restored, but the variables of Proc_3 are *not* accessible in Proc_2 by the rules of scope.

Somehow the program must be able to identify the *static chain*, the link of activation records that defines the static context of the procedure according to the rules of scope, as opposed to the dynamic chain of procedure calls at execution time. As an extreme example, consider a recursive procedure: there may be dozens of activation records in the dynamic chain (one for each recursive call), but the static chain will consist only of the current record and the record for the main procedure.

One solution is to store the static level of nesting of each procedure in the activation record, because the compiler knows what level is needed for each access. In the example, if the main program is level 0, Proc_2 and Proc_3 are both at level 2. When searching up the dynamic chain, the level of nesting must decrease by one to be considered part of the static chain, thus the record for Proc_3 is skipped over and the next record, the one for Proc_1 at level 1, is used to obtain a bottom index.

Another solution is to explicitly include the static chain on the stack. Figure 7.10 shows the static chain just after Proc_3 calls Proc_2. Before the call, the static chain is the same as the dynamic chain while after the call, the static chain is shorter and contains just the main procedure and Proc_2.

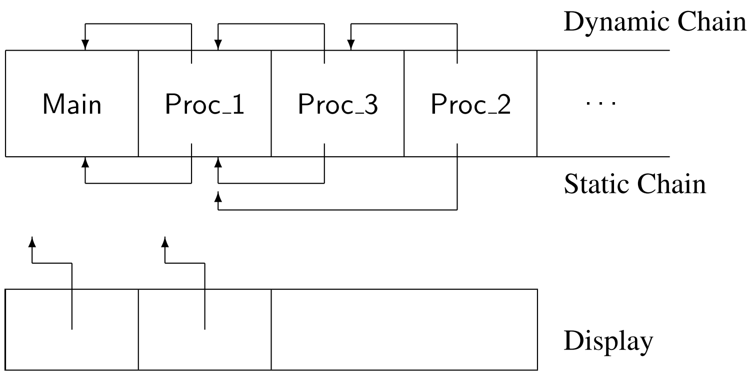


Figure 7.10: Variables at intermediate levels

The advantage of using an explicit static chain is that a static chain is often shorter than a dynamic chain (again think of a recursive procedure as an extreme case). However, we still have to do the search for each access of an intermediate variable. A solution that can be more efficient is to use a *display* which is an array that holds the current static chain, indexed by the nesting level (Figure 7.10). Thus to access a variable at an intermediate level, the nesting level is used as an index to obtain a pointer to the correct activation record, then the bottom pointer is obtained from the record and finally the offset is added to obtain the variable address. The disadvantage of a display is that additional overhead is needed to update the display at procedure entry and exit.

The potential inefficiencies of accessing intermediate variables should not deter the use of nested procedures, but programmers should carefully consider such factors as the depth of nesting and the trade-offs between using parameters as opposed to direct access to variables.

7.8 * Implementation on the 8086

To give a more concrete idea of how a stack architecture is implemented, we describe the actual machine code for procedure entry and exit on the Intel 8086 series of processors. The example program is:

Ada

```
procedure Main is
   Global: Integer;

   procedure Proc(Parm: in Integer) is
      Local1, Local2: Integer;
   begin
      Local2 := Global + Parm + Local1;
   end Proc;

begin
   Proc(15);
end Main;
```

The 8086 has built-in push and pop instructions which assume that the stack grows from higher to lower addresses. Two registers are dedicated to stack operations: the sp register which points to the "top" element in the stack, and the bp register which is the bottom pointer that identifies the location of the start of the activation record.

To call the procedure the parameter is pushed onto the stack and the call instruction executed:[11]

```
mov     ax,#15     Load value of parameter
push    ax         Store parameter on stack
call    Proc       Call the procedure
```

Figure 7.11 shows the stack after executing these instructions—the parameter and the return address have been pushed onto the stack.

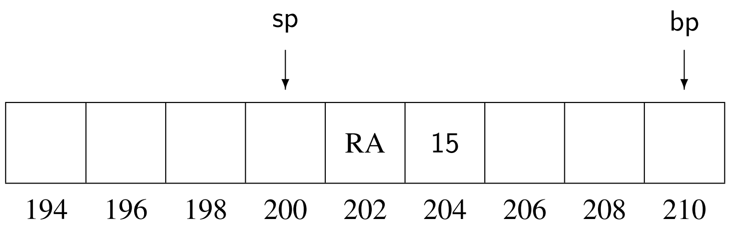


Figure 7.11: Stack before procedure entry

The next instructions are part of the code of the procedure and are executed at procedure entry; they store the old bottom pointer (the dynamic link), set up the new bottom pointer and allocate memory for the local variable by decrementing the stack pointer:

```
push    bp         Save the old dynamic pointer
mov     bp,sp      Set the new dynamic pointer
sub     sp,#4      Allocate the local variables
```

The stack now appears as shown in Figure 7.12.

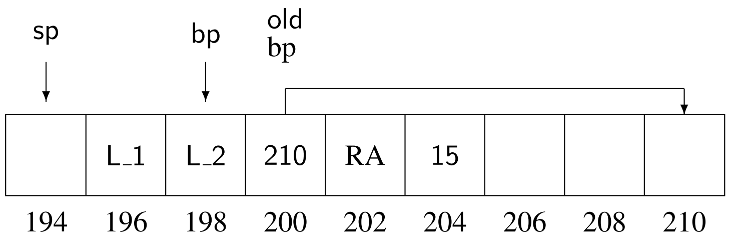


Figure 7.12: Stack after procedure entry

Now the body of the procedure can be executed:

[11]The extra mov instruction is there because stack operations work only to and from registers, in this case ax.

```
mov     ax,ds:[38]      Load the variable Global
add     ax,[bp+06]      Add the parameter Parm
add     ax,[bp-02]      Add the variable Local1
mov     ax,[bp]         Store in the variable Local2
```

Global variables are accessed as offsets from a special area of memory pointed to by the ds (data segment) register. The parameter Parm which is "lower" down in the stack than the start of the activation record is accessed at a *positive* offset from bp. The local variables which are "higher" up in the stack are accessed at a *negative* offset from bp. What is important to note is that since the 8086 processor has registers and addressing modes designed for common stack-oriented computations, all these variables can be accessed in a single instruction.

Procedure exit must reverse the effects of the procedure call:

```
mov     sp,bp           Release all local variables
pop     bp              Restore the old dynamic pointer
ret     2               Return and release parameters
```

The stack pointer is reset to the value of the bottom pointer thus effectively releasing memory allocated for the local variables. Then the old dynamic pointer is popped from the stack so that bp now points at the previous activation record. The only remaining tasks are to return from the procedure using the return address, and to release the memory allocated for the parameters. The ret instruction performs both of these tasks; the operand of the instruction indicates how many bytes of parameter memory must be popped from the stack. To summarize: procedure exit and entry require just three short instructions each, and access to local and global variables and to parameters is efficient.

7.9 Exercises

1. Does your Ada compiler use value or reference semantics to pass arrays and records?
2. Show how last-call optimization is implemented. Can last-call optimization be done on the factorial function?
3. McCarthy's function is defined by the following recursive function:

   Ada

   ```
   function M(I: Integer) return Integer is
   begin
      if I > 100 then return I-10;
      else return M(M(I+11));
   end M;
   ```

   (a) Write a program for McCarthy's function and compute M(I) for $80 \leq I \leq 110$.
   (b) Simulate by hand the computation for M(91) showing the growth of the stack.
   (c) Write an iterative program for McCarthy's function.
4. Ackermann's function is defined by the following recursive function:

Ada

```
function A(M, N: Natural) return Natural is
begin
   if M = 0 then return N + 1;
   elsif N = 0 then return A(M – 1, 1);
   else return A(M – 1, A(M, N – 1));
end A;
```

(a) Write a program for Ackermann's function and check that A(0,0)=1, A(1,1)=3, A(2,2)=7, A(3,3)=61.

(b) Simulate by hand the computation for A(2,2)=7 showing the growth of the stack.

(c) Try to compute A(4,4) and describe what happens. Try the computation using several compilers. Make sure you save your files before doing this!

(d) Write a non-recursive program for Ackermann's function.[12]

5. How are variables of intermediate scope accessed on an 8086?

6. There is a parameter passing mechanism called *call-by-name* in which each access of a formal parameter causes the actual parameter to be re-evaluated. This mechanism was first used in Algol but does not exist in most ordinary programming languages. What was the motivation for call-by-name in Algol and how was it implemented?

[12]Solutions can be found in: Z. Manna. *Mathematical Theory of Computation*. McGraw-Hill, 1974, p. 201 and p. 235.