2.4 Control Statements

This section introduces four concepts to control the execution of a program: selection, iteration, blocks, and jumps. These concepts enable us to deviate from the default linear control flow which executes statement by statement from top to bottom. You will learn how these concepts are implemented in C++, and how to apply them to create interesting programs.

The programs we have seen so far are all pretty simple. They consist of a sequence of statements that are executed one by one from the first to the last. Such a program is said to have a linear control flow. This type of control flow is quite restrictive, as each statement in the source code is executed at most once during the execution of the program. Suppose you want to implement an algorithm that performs 10,000 steps for some input. Then you would have to write a program with at least 10,000 lines of code. Obviously this is undesirable. Therefore, in order to implement non-trivial algorithms, more powerful mechanisms to control the flow of a program are needed.

2.4.1 Selection: if- and if-else statements

One particularly simple way to deviate from linear control flow is to select whether or not a particular statement is executed. In C++ this can be done via an if statement. The syntax is

```
if (condition) statement
```

where condition is an expression or variable declaration of a type whose values can be converted to bool, and statement — as the name suggests — is a statement. The semantics is the following: condition is evaluated; if and only if its value is true, statement is executed afterwards. In other words, an if statement splits the control flow into two branches. The value of condition selects which of these branches is executed. For example, the following line of code

```cpp
if (a % 2 == 0) std::cout << "even";
```

reads a number from standard input into the variable a, and prints "even" to standard output if and only if \(a\) is even.

Optionally, an if statement can be complemented by an else-branch. The syntax is

```
if (condition) statement1
else statement2
```

and the semantics is as follows: condition is evaluated; if its value is true, statement1 is executed afterwards; otherwise, statement2 is executed afterwards. For example, the following line of code

```cpp
int a;
std::cin >> a;
if (a % 2 == 0) std::cout << "even";
else
    std::cout << "odd";
```

reads a number from standard input into the variable \(a\). Then if \(a\) is even, "even" is written to standard output; otherwise, "odd" is written to standard output.

When formatting an if statement, it is common to insert a line break before statement1, before else, and before statement2. Moreover, statement1 and statement2 are indented and else is aligned with if, as shown in the example above. If the whole statement fits on a single line then it can also be typeset as a single line.

Collectively, if- and if-else statements are known as selection statements.

2.4.2 Iteration: for statements

A much more powerful way of manipulating the control flow is provided by iteration statements. Iteration allows to execute a statement many times, possibly with different parameters each time. Iteration statements are also called loops, as they "loop through" a statement (potentially) several times. Selection and iteration statements are collectively referred to as control statements.

Consider the problem of computing the sum \(S_n = \sum_{i=1}^{n} i\) of the first \(n\) natural numbers, for a given \(n \in \mathbb{N}\). Program 6 reads in a variable \(n\) from standard input, defines another variable \(s\) to contain the result, computes the result and finally outputs it. In order to understand why the program sum_n_C indeed behaves as claimed, we have to explain the different parts of a for statement.

```cpp
1 // Program: sum_n.C
2 // Compute the sum of the first n natural numbers.
3 #include <iostream>
4 5 int main()
6 {  
```

[1] In case you are missing a semicolon after statement: recall that this semicolon is part of the statement,
2.4. CONTROL STATEMENTS

Each single iteration of a for statement consists of first executing statement and then evaluating expression. After each iteration, condition is evaluated again. If it returns true, another iteration follows. If condition returns false, the for statement terminates. The execution order is therefore init-statement, condition, statement, expression, condition, statement, expression, . . . until condition returns false.

Let’s see this in action: Consider the for statement

```
for (unsigned int i = 1; i <= n; ++i) a = i;
```

in sum_.c and suppose n == 2. First, the variable i is defined and initialized to 1. Then it is tested whether i <= n. As 1 <= 2 is true, the first iteration starts. The statement a += 1 is executed, setting a to 1, and thereafter i is incremented by one such that i == 2. One iteration is now complete. As a next step, the condition i <= n is evaluated again. As 2 <= 2 is true, another iteration follows. First n += 1 is executed, setting n to 3. Thereafter, i is incremented by one such that i == 3. The second iteration is now complete. The subsequent evaluation of i <= n entails 3 <= 2 which is false. Thus, no further iteration takes place and the processing of the for statement ends. The value of a is now 3, the sum of the first n == 2 natural numbers.

Infinite loops. It is easily possible to create loops that do not terminate. For example, recall that both condition and expression may be empty. Moreover, both init statement and condition can be the null statement. In this case we get the for statement

```
for ( ; ; )
```

As the empty condition has value true, executing this statement runs through iteration after iteration without actually doing anything. Therefore, for ( ; ; ) may be read as “forever”. In general, a statement which does not terminate is called an infinite loop.

Clearly, infinite loops are extremely undesirable and programmers try hard to avoid them. Nevertheless, sometimes such loops occur even in real life software. If you regularly use a computer, you have probably experienced this kind of phenomenon: a program “hangs”.

You may ask: Why doesn’t the compiler simply detect infinite loops and warns me about them just as it complains about syntax error? Indeed, this would be a great thing to have and it would solve many problems in software development. The problem is that infinite loops are not always as easy to spot as in the above example. Loops can be pretty complicated, and possibly they loop infinitely when executed in certain program states only.

In fact, the situation is hopeless: It can be shown that the problem of detecting infinite loops (commonly referred to as the halting problem) cannot be solved by a computer, as we have and understand it today (see the Details). Therefore, some care is needed when designing loops. We have to check “by hand” that the iteration statement terminates for all possible program states that can occur.
2.4. CONTROL STATEMENTS

Gauss. You may know or have realized that our program sum.n.C is actually a bad example. It is bad in the sense that it does not convincingly demonstrate the power of control statements.

In his primary school days, the German mathematician Carl Friedrich Gauss (1777–1855) was told to sum up the numbers 1, 2, 3, ..., 100. The teacher had planned to keep his students busy for a while, but Gauss came up with the correct result 5050 very quickly. He had imagined writing down the numbers in increasing order, and one line below once again in decreasing order. Clearly, the two numbers in each column sum up to 101; hence, the overall sum is 100 · 101 = 10100, half of which is the number that was asked for:

\[
\begin{array}{cccc}
1 & 2 & 3 & \ldots & 98 & 99 & 100 \\
100 & 99 & 98 & \ldots & 3 & 2 & 1 \\
\end{array}
\]

In this way, Gauss discovered the formula

\[
\sum_{i=1}^{n} i = \frac{n(n + 1)}{2},
\]

for any \( n \in \mathbb{N} \). The for statement in sum.n.C can therefore be replaced by the much more elegant and efficient statement:

\[
\texttt{s = n * (n + 1) / 2;}
\]

We next get to a real application of selection and iteration statements.

Prime numbers. In the introductory Section 1.1, we have talked a lot about prime numbers. How would a program look like that tests whether or not a given number is prime? According to the usual definition, a number \( n \in \mathbb{N} \), \( n \geq 2 \) is prime if and only if it is not divisible by any number \( d \in \{2, \ldots, n-1\} \). The strategy for our program is therefore clear: Write a loop that runs through all those numbers, and test each of them for being a divisor of \( n \). If a divisor is found, we can stop and output a factorization of \( n \) into two numbers, proving that \( n \) is not prime. Otherwise, we output that \( n \) is prime. Program 7 implements this strategy in C++, using one for statement, and one if statement. Remarkably, the for statement has an empty body, since we have put the divisibility test into the condition. The important observation is that the condition \( \% d \neq 0 \) definitely returns false for \( d = n \), so that the loop is guaranteed to terminate; if (and only if) condition returns false earlier, we have found a divisor of \( n \) in the range \( \{2, \ldots, n-1\} \).

1 // Program: prime.C
2 // Test if a given natural number is prime.
3

4 #include <iostream>
5
6 int main()
7 {
8     // Input
9     unsigned int n;
10     std::cin >> \"Test if n\>1 is prime for n = \\";
11     std::cin >> n;
12
13     // Computation: test possible divisors \( d \)
14     unsigned int d;
15     for (d = 2; n \% d != 0; ++d);
16
17     // Output
18     if (d < n)
19         // \( d \) is a divisor of \( n \) in \( \{2, \ldots, n-1\} \)
20         std::cout << \n << \" \% d >> 1 \% n / d << \"; \n
21     else
22         // no proper divisor found
23         std::cout << \n << \" is prime.\n\n\n24     return 0;
25 }

Program 7: prog/prime.C

2.4.3 Blocks

In C++ it is possible to group a sequence of one or more statements into one single statement that is then called a compound statement, or simply a block. This mechanism does not manipulate the control flow directly. Blocks allow to structure a program by grouping statements that logically belong together. In particular, they are a tool to design powerful and at the same time readable control statements.

Syntactically, a block is simply a sequence of zero or more statements that are enclosed in curly braces.

\[
\{ \text{statement1 \ statement2 \ldots \ statementN} \}
\]

Each of the statements may in particular be a block, so it is possible to have nested blocks. The simplest block is the empty block {}.

You have already seen blocks. Each program contains a special block, the so-called function body of the main function. This block encloses the sequence of statements that is executed when the main function is called by the operating system.

\[\text{\% & I} \]

---

18Note that in this statement, the integer division coincides with the real division, since for all \( n \), the product \( n(n+1) \) is even.
Using blocks, one can create selection and iteration statements whose body contains a sequence of two or more statements. For example, suppose that for testing purposes we would like to write out all partial sums during the computation in sum_n.c:

```c
int i = 2;
for (unsigned int = 1; i < n; ++i) {
    std::cerr << i << "-th partial sum is " << a << " \n";
}
```

Here two statements are executed in each iteration of the loop. First, the next summand is added to a, then the current value of a is written to standard error output.

Blocks should in general be formatted as shown above. That is, a line break appears after the opening and before the closing brace, and all lines in between are indented one level. Only if the block consists of just one single statement and it all fits on one line, the block can be formatted as one single line.

The type of test output we have created in the previous example is called debugging output. A bug is a commonly used term to denote a programming error, hence "debugging" is the process of finding and eliminating such errors. It is good practice to write debugging output to standard error output since it can then more easily be separated from the "real" program output that usually goes to standard output.

Visibility. Blocks do not only structure a program visually but they also provide a logical boundary around declarations (of variables, for example). Any declaration that appears inside a block is called local to that block. A local declaration extends only until the end of the block in which it appears. A name that is introduced by a local declaration is not "visible" outside of the block where it is declared. For example, in

```c
int i = 2;
std::cout << --i;
```

the statement ++i does not refer to the variable i declared inside the block. Thus, if you confront the compiler with this code, it issues a syntax error, unless...

Actually, the above code fragment may be correct in the context of the surrounding program: it is allowed to define two variables with the same name. For instance, embedding the above code as follows yields a perfectly correct program,

```c
#include <iostream>
int main() {
    int i = 5;
    std::cout << ++i; // outputs 6
}
```

Declarative region. After having seen these examples, we will now introduce the precise terminology. Each declaration has an associated declarative region. This region is part of the program in which the declaration appears. Such a region can be a block, a function definition, or a control statement. In all these cases the declaration is said to have local scope. A declaration can also have namespace scope, if it appears inside a namespace, see Section 2.1.2. Finally, a declaration that is outside of any particular other structure has global scope.

As we have seen, a program may contain several variable declarations that all define variables of the same name. This is only valid if no two of these declarations have the same declarative region. For example, the following code fragment is invalid, since both declarations of i have the same declarative region, namely the function body of the main function.

```c
int main() {
    int i = 5;
    int i = 6; // invalid redefinition of i
    return 0;
}
```

Program 8: prog/scope.c

The i in line 7 and line 11 refers to the declaration from line 5, whereas the i in line 9 refers to the declaration from line 8. Therefore, the program outputs first 6, then 1, and finally 7. In some sense, the declaration in line 8 temporarily hides the previous declaration of i from line 5. This phenomenon is called name hiding. But when the block that contains the second declaration ends in line 10, the second declaration "becomes invisible" (we say: "it runs out of scope") and the first declaration takes over again. In particular, since the modification in line 7 applies to the variable defined in line 5, we see the effect of this modification in line 11.

Please note: In order to explain the general visibility rules in the next three paragraphs, we have to talk about multiple declarations of the same name as in Program 8, and we sometimes have to use pretty artificial code fragments to make the point. In your own programs, however, you should avoid such multiple declarations whenever possible, as they make the code harder to read and more prone to errors.
Figure 5: Potential scopes of declarations D, E₁, E₂, E₃ of the same name, drawn as rectangles with the corresponding declaration in the upper left corner (left); on the right, we see the resulting scopes of D (dark gray), E₁, E₃ (light gray) and E₂ (white).

Scope. A name introduced by a declaration D is valid or visible in a part of its declaration's declarative region, called the scope of the declaration. Within the scope of D, the name introduced by D may be used and actually refers to the declaration D, and not to another declaration of the same name.

In order to define the scope, we need to introduce the term potential scope first. The potential scope of a declaration starts at the point where the declaration appears. For the name to be declared this is called its point of declaration. The potential scope extends until the end of the declarative region. The scope of a declaration D is obtained from its potential scope as follows: For each declaration D in the potential scope of D such that both D and E declare the same name, the potential scope of D is removed from the scope of D. Figure 5 gives a symbolic picture of the situation.

In Program 8, the declarative region of the declaration in line 5 is line 4-13, its potential scope is line 5-13, and its scope is line 5-7 plus line 11-13. For the declaration in line 8, the declarative region is line 6-10 and both potential scope and scope are line 8-10.

Breaking down the scopes into lines is in general not possible, of course, since line breaks may (or may not) appear almost anywhere. If we want to talk about scope on a line-by-line basis, we have to format the program accordingly.

Control statements and scope. As far as the rules for scopes are concerned, control statements act like blocks. They can also be thought of as grouping statements and, in fact, also a control statement forms a declarative region by itself.

Therefore any declaration appearing in a control statement is local to that control statement. In particular, this applies to a variable defined in the initialization of a for statement. For example, in

```c
for (unsigned int i = 0; i < 10; ++i) {
    std::cout << i << "\n";
}
```

the expression i in the second line does not refer to the variable i declared in the first line.

Storage duration. Related to the scope of a variable is its storage duration. This term denotes the time in which the address of the variable is valid, that is, some memory location is assigned to it.

For a variable with local scope, the storage duration is usually the time in which the program's control is in the variable's potential scope. During program execution, this means that whenever the variable declaration is reached, some memory location is assigned and the address becomes valid. And whenever the execution gets to the end of the declarative region, the associated memory is freed and the variable's address becomes invalid.\(^\text{14}\) We therefore get a "fresh instance" of the variable every time its declaration is executed.

This behavior is called automatic storage duration. For example, in

```c
for (unsigned int i = 0; i < 10; ++i) {
    int k = 3;
    // do something with k
}
```

the address of the variable k may change in each iteration of the loop. Also the initialization to 3 takes place in each iteration.

As a more concrete example, consider the following code fragment.

```c
1 int i = 5;
2 for (int j = 0; j < 5; ++j) {
3    std::cout << ++i; // outputs 6, 7, 8, 9, 10
4    int i = 2;
5    std::cout << --i; // outputs 1, 1, 1, 1, 1
6 }
```

Since line 3 belongs to the scope of the declaration in line 1, the effect of line 3 is to increment the variable defined in line 1 in every iteration of the for statement. Line 5, on the other hand, belongs to the scope of the declaration in line 5; the effect of line 5 is therefore to decrement the "fresh" variable i in every iteration, and this always results in value 1.

In contrast, a variable that is defined in a namespace scope or global scope has static storage duration. This means that its address is determined at the beginning of the program's execution, and it does not change (hence "static") nor become invalid until

\(^{14}\)Note that the address does not necessarily remain the same throughout the program's execution,
2.4. CONTROL STATEMENTS

the execution of the program ends. The variables `std::cin` and `std::cout`, for instance, have static storage duration. Variables with static storage duration are also referred to as static variables.

2.4.4 Iteration: while statements

So far, we have seen one iteration statement, the for statement. The while statement is a simplified for statement, where both initialization and expression are omitted. Its syntax is

```
while ( condition )
  statement
```

where `condition` and `statement` are as in a for statement. As before, `statement` is referred to as the body of the while statement. Semantically, a while statement is equivalent to the corresponding for statement

```
for ( ; condition ; )
  statement
```

The execution order is therefore `condition`, `statement`, `condition`, ... until `condition` returns false.

Since while statements are so easy to rewrite as for statements, why do we need them? The main reason is readability. As its name suggests, a for statement is typically perceived as a counting loop in which the increment (or decrement) of a single variable is responsible for the progress towards termination. In this case, the progress is most conveniently made in the for statement’s expression. But the situation can be more complex: the progress may depend on the value of several variables, or on some condition that we check in the loop’s body. In some of these cases, a while statement is preferable. The next section describes an example.

The Collatz problem. Given a natural number \( n \in \mathbb{N} \), we consider the Collatz sequence \( n_0, n_1, n_2, \ldots \) with \( n_0 = n \) and

\[
  n_i = \begin{cases} 
    n_{i-1}/2, & \text{if } n_{i-1} \text{ is even} \\
    3n_{i-1} + 1, & \text{if } n_{i-1} \text{ is odd}
  \end{cases} \quad i \geq 1.
\]

For example, if \( n = 5 \), we get the sequence 5, 16, 8, 4, 2, 1, 4, 2, 1, ... Since the sequence gets repetitive as soon as 1 appears, we may stop at this point. Program 9 reads in a number \( n \) and outputs the elements of the sequence \( (n_i)_{i \geq 1} \) until the number 1 appears.

```
3 // Program: collatz.C
4 // Compute the Collatz sequence of a number n.

5 #include <iostream>
6 int main()
7 {
8  // Input
9    std::cin << "Compute the Collatz sequence for n = \? \n";
10   unsigned int n;
11   std::cin >> n;
12  // Iteration
13  while ( n > 1 ) {
14      if ( n % 2 == 0 )
15         n = n / 2;
16      else
17         n = 3 * n + 1;
18    std::cout << n << " \n";
19  }
20  std::cout << "\n";
21  return 0;
22 }
```

Program 9: `progs/collatz.C`

The loop can of course be written as a for statement with empty initialization and expression, but the resulting variant of the program is less readable since it tries to advertise the rather complicated iteration as a simple counting loop. As a rule of thumb, if there is a simple expression that captures the loop’s progress, use a for statement. Otherwise, consider formulating your loop as a while statement.

Talking about programs: is it clear that the number 1 always appears? If not, the program `collatz.C` contains an infinite loop for certain values of \( n \). If you play with the program, you will observe that 1 indeed appears for all numbers you try, although this may take a while. You will find, for example, that the Collatz sequence for \( n = 27 \) is

\[
\]

It is generally believed that 1 eventually comes up for all values of \( n \), but mathematicians have not yet been able to produce a proof of this conjecture. As innocent as
it looks, this problem seems to be a very hard mathematical nut to crack (see also the Details section), but you are certainly invited to give it a try!

2.4.5 **Iteration: do statements**

Do statements are similar to while statements, except that the condition is evaluated after every iteration of the loop instead of before every iteration. Therefore, in contrast to for and while statements, the body of a do statement is executed at least once. The syntax of a do statement is as follows:

```cpp
do
  statement;
while ( expression );
```

where `expression` is of a type whose values can be converted to bool.

The semantics is defined as follows. An iteration of the loop consists of first executing `statement` and then evaluating `expression`. If `expression` returns true then another iteration follows. Otherwise, the do statement terminates. The execution order is therefore `statement, expression, statement, expression, ...` until `expression` returns false.

Alternatively, the semantics could be defined in terms of the following equivalent for statement:

```cpp
for ( bool firsttime = true; firsttime || expression; firsttime = false )
  statement;
```

This behaves like our "simulation" of the while statement, except that in the first iteration, `expression` is not evaluated (due to short circuit evaluation, see Section 2.3.3), and statement is executed unconditionally.

Consider a simple calculator-type application in which the user enters a sequence of numbers, and after each number the program outputs the sum of the numbers entered so far. By entering 0, the user indicates that the program should stop. This is most naturally written using a do statement, since the termination condition can only be checked after the next number has been entered.

```cpp
int a; // next input value
int s = 0; // sum of values so far
do {
  std::cout << "next number =? ";
  std::cin >> a;
  s += a;
  std::cout << "sum = " << s << "\n";
} while (a != 0);
```

In this case, it is not possible to declare a where we would usually do it, namely immediately before the input statement. The reason is that a would then be local to the body of the do statement and would not be visible in the do statement's `expression a != 0`,

2.4.6 **Jump statements**

At this point, we would like to extend our arsenal of control statements with a special type of statements that are referred to as **jump statements**. These statements are not necessary in the sense that they would allow you to do something which is not possible otherwise. Instead, just like while- and do statements (which are also unnecessary in that sense), jump statements provide additional flexibility in designing iteration statements. You should use this flexibility wherever it allows you to improve your code. However, be also warned that jump statements should be used with care since they tend to complicate the control flow. The complication of the control flow has to be balanced by a significant gain in one of the other categories. Therefore, think carefully before introducing a jump statement!

When a jump statement is executed, the program flow unconditionally "jumps" to a certain point. There are two different jump statements that we want to discuss here.

The first jump statement is called a **break statement**, its syntax is rather simple:

```cpp
break;
```

When a break statement is executed within an iteration statement, it is the smallest enclosing iteration statement terminates immediately. The execution continues at the statement after the iteration statement (if any). For example,

```cpp
for (;;) break;
```

is not an infinite loop but rather a complicated way of writing a null statement. Here is a more useful appearance of `break`. In our calculator example from Page 81, it would be more elegant to suppress the irrelevant addition of 0 in the last iteration. This can be done with the following loop:

```cpp
for (;;) {
  std::cout << "next number =? ";
  std::cin >> a;
  if (a == 0) break;
  s += a;
  std::cout << "sum = " << s << "\n";
}
```

Here, we see the typical usage of `break`, namely the termination of a loop "somewhere in the middle". Note that we could equivalently write

```cpp
do {
  std::cout << "next number =? ";
  std::cin >> a;
  if (a == 0) break;
  s += a;
}
```

Otherwise, it can only occur in a switch statement, see the Details,
2.4. CONTROL STATEMENTS

std::cout << "sum = " << s << "\n";
) while (true);
In this case for is preferable, though, since it nicely reads as "forever". Of course, the same functionality is possible without break, but the resulting code requires an additional block and evaluates a != 0 twice.

do {
    std::cout << "next number =? \n";
    std::cin >> a;
    if (a != 0) {
        s += a;
    }
    std::cout << "sum = " << s << "\n";
} while (a != 0);

The second jump statement is called a continue statement; again the syntax is simple.

continue;

When a continue statement is executed, the remainder of the smallest enclosing iteration statement's body is skipped, and execution continues at the end of the body. The iteration statement itself is not terminated.

If the surrounding iteration statement is a while- or do statement, the execution therefore continues by evaluating its condition. If the surrounding iteration statement is a for statement, the execution continues by evaluating its expression and then its condition. Like the break statement, the continue statement can therefore be used to manipulate the control flow "in the middle" of a loop.

In our calculator example, the following variant of the loop ignores negative input. Again, it would be possible to do this without continue, at the expense of another nested block.

for (;;) {
    std::cout << "next number =? \n";
    std::cin >> a;
    if (a < 0) continue;
    if (a == 0) break;
    s += a;
    std::cout << "sum = " << s << "\n";
}

2.4.7 Equivalence of iteration statements
In terms of pure functionality, the while- and do statements are redundant, as both of them can equivalently be expressed using a for statement. This may create the impression that for statements have more expressive power than while- and do statements,

In this section we show that this is not the case: all three iteration statements are functionally equivalent. More precisely, we show how to use

- do statements to express while statements, and
- while statements to express for statements.

If we denote "A can be used to express B" by A ⇒ B, we therefore have

   do statement ⇒ while statement ⇒ for statement ⇒ do statement,

where we know the last implication from the previous section. Together, this clearly "proves" the claimed equivalence.

Note that we put the word proves in quotes, as our reasoning cannot be considered a formal proof. In order to really prove a statement like this, we first of all would have to be more formal in defining the semantics of statements. Semantics of programming languages is a subject of its own, and the formal treatment of semantics is way beyond what we can do here. In other words: The following is as much of a "proof" as you will get here, but it is sufficient to understand the relations between the three iteration statements.

do statement ⇒ while statement. Consider the while statement

    while ( condition )
    statement

Your first idea how to simulate this using a do statement might look like this:

    if ( condition )
    do
    statement
    while ( condition );

Indeed, this induces the execution order condition, statement, condition,... until condition returns false and the statement terminates. But there is a small technical problem: if condition is a variable declaration, we can't use it as the expression in the do statement. Here is a reformulation that works, 16

    do
    if ( condition )
    statement
    else
    break;
    while ( true );

This induces exactly the while statement's execution order condition, statement, condition,... until condition returns false and the loop is terminated using break.

16We are not saying that this should be done in practice. On the contrary, this should never be done in practice. This section is about conceptual equivalence, not about practical equivalence.
2.4. CONTROL STATEMENTS

while statement ⇒ for statement. Simulating the for statement
for ( init-statement condition; expression )
statement
by a while statement seems easy:

{ init-statement
  while ( condition )
  {statement
    expression;
  }
}

Indeed, this will work, unless statement contains a continue. In the for statement, execution would then proceed with the evaluation of expression, but in the simulating while statement, expression is skipped, and condition comes next. This reformulation is therefore wrong. Here is a version that works:

{ init-statement
  while ( condition )
  { bool b = false;
    while ( b = true )
      statement
      if ( b ) break;
    expression;
  }
}

This looks somewhat more complicated, so let us explain what is going on.

We may suppose that the identifier b does not appear in the given for statement (otherwise we choose a different name). Note that the whole statement forms a separate block, as does a for statement. A potential declaration in init-statement as well as the scope of b is thus limited to this block.

Consider an execution of the outer while statement. First, condition is evaluated, and if it returns false the statement terminates. Otherwise, the variable b is set to true in the inner while statement's condition, meaning that statement is executed next. If statement does not contain a break, the inner loop evaluates its condition for the second time. In doing so, b is set to false, and the condition returns false. Therefore, the inner loop terminates. Since b is now false, expression is evaluated next, followed by condition. This induces the for statement's execution order condition, statement, expression, condition... until condition returns false and the outer loop terminates.

17 Recall that the assignment operator returns the new value of its left operand.

In the case where statement contains a break, the inner loop terminates immediately, and b remains true. In this case, we also terminate the outer loop that represents our original for statement.

In retrospect, we should now check that jump statements cause no harm in our previous reformulation of the while statement in terms of the do statement. We leave this as an exercise.

2.4.8 Choosing the "right" iteration statements

We have seen that from a functional point of view, the for statement, the while statement and the do statement are equivalent. Moreover, the break and continue statements are redundant. Still, C++ offers all of these statements, and this gives you the freedom (but also the burden) of choosing the appropriate control statements for your particular program.

Writing programs is a dynamic process. Even though the program may do what you want at some point, the requirements change, and you will keep changing the program in the future. Even if there is currently no need to change the functionality of the program, you may want to replace a complicated iteration statement by an equivalent simpler formulation. The general theme here is refactoring: the process of rewriting a program to improve its readability or structure, while keeping its functionality unchanged.

Here is a simple guideline for writing "good" loops. Choose the loop that leads to the most readable and concise formulation. This means

- few statements,
- few lines of code,
- simple control flow, and
- simple expressions.

Almost never there is the one and only best formulation; however, there are always arguably bad choices which you should try to avoid. Usually, there are some tradeoffs, like fewer lines of code versus more complicated expressions, and there is also some amount of personal taste involved. You should experience and find out what suits you best.

Let us look at some examples to show what we mean. Suppose that you want to output the odd numbers between 0 and 100. Having just learned about the continue statement, you may write the following loop:

```c++
for (unsigned int i = 0; i < 100; ++i) {
    if (i % 2 == 0) continue;
    std::cout << i << "\n";
}
```

- Few statements,
- Few lines of code,
- Simple control flow, and
- Simple expressions.
This is perfectly correct, but the following version is preferable since it has fewer statements and fewer lines of code,

```cpp
for (unsigned int i = 0; i < 100; ++i)
  if (i % 2 != 0) std::cout << i << "\n";
```

This variant still contains nested control statements, but you can get rid of the if statement and obtain code with simpler control flow,

```cpp
for (unsigned int i = 1; i < 100; i += 2)
  std::cout << i << "\n";
```

The same output can be produced with a while statement and equally simple control flow,

```cpp
int i = -1;
while ((i += 2) < 100)
  std::cout << i << "\n";
```

But here, the condition is more complicated, since it combines assignment and comparison operators. Such expressions are comparatively difficult to understand due to the effect of the assignment operation. Also, the initialization of i to -1 is counter-intuitive, given that we deal with natural numbers.

You can solve the latter problem and at the same time get simpler expressions by writing

```cpp
unsigned int i = 1;
while (i < 100) {
  std::cout << i << "\n";
  i += 2;
}
```

The price to pay is that you get less concise code; there are now five lines instead of the two lines that the for statement needs. It seems that for the simple problem of writing out odd numbers, a for statement with `expression i += 2` is the loop of choice.

### 2.4.9 Details

#### Nested if-else statements

Consider the statement

```cpp
if(true) if (false); else std::cout << "Where do I belong?";
```

It is not a priori clear what its effect is: if the else branch belongs to the outer if, there will be no output (since the condition has value true), but if the else branch belongs to the inner if, we get the output where do I belong?

The intuitive rule is that the else branch belongs to the if immediately preceding it, in our case to the inner if. Therefore, the output is Where do I belong?, and we should actually format the statement like this:

```cpp
if(true)
  if (false)
```

The switch statement. Besides if...else there exists a second selection statement in C++: the switch statement. It is useful to select between many alternative statements, using the following syntax.

```cpp
switch (condition) {
  statement
}
```

The value of condition must be convertible to an integral type. This is in contrast to the other control statements where condition has to be convertible to bool.

statement is usually a block that contains several labels of the form case literal:

where literal is a literal of integral type. For no two labels shall these literals have the same value. There can also be a label default:

The semantics of a switch statement is the following: condition is evaluated and the result is compared to each of the literals which appear in a label in statement. If for any of them the value agrees, the execution continues at the statement immediately following the label. If there is no agreement but a default: label, the execution continues at the statement immediately following the default: label. Otherwise, statement is ignored and the execution continues after the switch statement.

Note that switch only selects an entry point for the processing of statement, it does not exit when the execution reaches another label. If one wants to separate the different alternatives, one has to use break (and this is the only legal use of break outside of a selection statement). Consider for example the following piece of code, and let us suppose that `x` is a variable of type `int`.

```cpp
switch (x) {
  case 0: std::cout << "0";
  case 1: std::cout << "1"; break;
```

; // null statement
else
  std::cout << "Where do I belong?";
```

Whenever you are unsure about rules like this, you can make the structure clear through explicit blocks:

```cpp
if (true) {
  if (false) {
    // null statement
  }
  else {
    std::cout << "Where do I belong?";
  }
}
```

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  case 0: std::cout << "0";
  case 1: std::cout << "1"; break;
```

; // null statement
else
  std::cout << "Where do I belong?";
```

Whenever you are unsure about rules like this, you can make the structure clear through explicit blocks:

```cpp
if (true) {
  if (false) {
    // null statement
  }
  else {
    std::cout << "Where do I belong?";
  }
}
```

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```cpp
switch (x) {
  case 0: std::cout << "0";
  case 1: std::cout << "1"; break;
```
default: std::cout << "whatever";
);
}

For x=0 the output is 0; for x=1 the output is 1; otherwise we get the output whatever.

The switch statement is powerful in the sense that it allows the different alternatives to share code. However, this power also makes switch statements hard to read and error prone. A frequent problem is that one forgets to put a break where there should be one. Therefore, we mention switch here for completeness only. Whenever there are only a few alternatives to be distinguished, play it safe and use if... else rather than switch.

The Halting Problem, Decidability, and Computability. The halting problem is one of the fundamental problems in the theory of computation. Informally speaking, the problem is to decide (using an algorithm) whether a given program halts (terminates) when executed on a given input (program state). The term "program" may refer to a C++ program, but also to a program in any other common programming language.

To attack the problem formally, the British mathematician Alan Turing (1912-1954) defined in a seminal paper a "minimal" programming language; a program in this language is known as a Turing machine.

Turing proved that the halting problem is undecidable for Turing machines, but the same argument can also be used to prove the same statement for C++ programs.

What does "undecidable" mean? We have seen a simple loop for which it was painfully evident that it is an infinite loop, haven't we? Yes, indeed one can decide the halting problem for many concrete programs. Undecidable means that (in a particular model of computation) there cannot be an algorithm that decides the halting problem for all possible programs.

Despite their simplicity, Turing machines are a widely accepted model of computation; in fact, just like machine language, Turing machines can do everything that C++ programs can do, except that they usually need a huge number of very primitive operations for that.

At the same time as Turing, the American mathematician Alonzo Church (1903-1995) developed a computational model called λ-calculus. As it turned out, his model is equivalent to Turing machines in terms of computational power. The Church-Turing thesis states that "every function that is naturally regarded as computable can be computed by a Turing machine". As there is no rigorous definition of what is "naturally regarded as computable", this statement is not a theorem but a hypothesis that cannot be proven mathematically. As of today, the hypothesis has not been disproved. In theoretical computer science the term computable used without further qualification is a synonym for "computable by a Turing machine" (equivalently, a C++ program).

Point of declaration. Our approach of defining potential scope and scope line by line is a simplification, even if the code is suitably formatted and we only have one declaration per line. The truth is that the point of declaration of 1 in

```cpp
int i = 5;
```

is in the middle of the declaration, after the name 1 has appeared. The potential scope therefore does not include the full line, but only the part starting from the. This explains what happens in the following code fragment, but fortunately this is consistent with our line-by-line approach. In

```cpp
1 int i = 5;
2 {
3   int i = 1;
4 }
```

the name i after the = in line 3 refers to the declaration in line 3. Consequently, i is initialized with itself in this line, meaning that its value will be undefined, and not 5.

In other situations it may happen, though, that the appearance of a name in the declaration of the same name refers to a previous declaration of this name. For now, we can easily avoid such subtleties by the following rule: any declaration should contain the name to be declared only once.

The Collatz problem and the if-operator. The Collatz sequence goes back to the German mathematician Lothar Collatz (1910-1990) who studied it in the 1930s. Several prizes have been offered to anyone who proves or disproves the conjecture that the number 1 appears in the Collatz sequence of every number n ≥ 1. The famous Hungarian mathematician Paul Erdős (1913-1996) offered $500, which is much by his standards (he used to offer much lower amounts for very difficult problems). Erdős said that "Mathematics is not yet ready for such problems", indeed, the conjecture is still unsolved.

We have presented the computation of the Collatz sequence as an application of the while statement, pointing out that the conditional change of n is too complicated to put it into a for statement's expression. Well, that's not exactly true: the designers of C, the precursor to C++, had a weakness for very compact code and came up with the `conditional operator` that allows us to simulate if statements by expressions. The syntax of this `ternary operator` (arity 3) is

```cpp
condition ? expression1 : expression2
```

Here, `condition` is an expression of a type whose values are convertible to bool, and `expression1` and `expression2` are expressions. The semantics is as follows. First, `condition` is evaluated. If it returns true, `expression1` is evaluated, and its value is returned as the value of the composite expression. Otherwise (if `condition` returns false), `expression2` is evaluated, and its value is returned. The `ternary operator` is a sequence point (see Section 2.2.10), meaning that all effects of `condition` are processed before either `expression1` or `expression2` are evaluated.

Using the conditional operator, the loop of Program 9 could quite compactly be written as follows.

```cpp
for ( ; n > 1; std::cout << (n % 2 == 0 ? n/=2 : n=3*n+1) << " ");
```

We leave it up to you to decide whether you like this variant better.
2.4. CONTROL STATEMENTS

Static variables. The discussion about storage duration above does not tell the whole story: it is also possible to define variables with local scope that have static storage duration.

This is done by prepending the keyword static to the variable declaration. For example, in

```
for (int i = 0; i < 5; ++i) {
    static int k = i;
    k += i;
    std::cout << k << "n";
}
```

the address of k remains the same during all iterations, and k is initialized to 0 once only, in the first iteration. The above piece of code will therefore output the sequence of values 0, 1, 3, 6, 10 (remember Gauss). Without the static keyword, the result would simply be the sequence of even numbers 0, 2, 4, 6, 8.

Static variables have been quite useful in C, for example to count how often a specific piece of code is executed; in C++, they are less important.

For variables of fundamental type the initial value may be undefined, as in the definition int y; However, the value is undefined only if x has automatic storage duration. In contrast, variables with static storage duration are always zero-initialized, that is, filled with a “zero” of the appropriate type.

Jump statements. There are two more jump statements in C++ that we haven’t discussed in this section. One of them is the return statement that you already know (Section 2.1.13); ist may occur only in a function, and its execution lets the program flow jump to the end of the corresponding function body. The other jump statement is the goto statement, but since this one is rarely needed (and somewhat difficult to use), we omit it.

2.4.10 Goals

Dispositional. At this point, you should ...

1) know the syntax and semantics of if, else, for, while, and do statements;
2) understand the concepts block, selection, iteration, declarative region, scope, and storage duration;
3) understand the concept of an infinite loop and be aware of the difficulty of detecting such loops;
4) understand the conceptual equivalence of for-, while-, and do statements;
5) know the syntax and semantics of continue- and break statements;
6) know at least four criteria to judge the code quality of iteration statements.

Operational. In particular, you should be able to...

(G1) check a given simple program (as defined below) for syntactical correctness and point out possible errors;
(G2) read and understand a given simple program and explain what happens during its execution;
(G3) find (potential) infinite loops in a given simple program;
(G4) find the matching declaration for a given identifier;
(G5) determine declarative region and scope of a given declaration;
(G6) reformulate a given for-, while-, or do statement equivalently using any of the other two statements;
(G7) compare the code quality of two given iteration statements and pick the one that is preferable (if any);
(G8) design simple programs for given tasks.

The term simple program refers to a program that consists of a main function in which up to three possibly nested control statements appear. Naturally, only the fundamental types and operations discussed in the preceding sections are used.

2.4.11 Exercises

Exercise 23 Correct all syntax errors in the program below. What does the resulting program output for the following inputs?

(a) +4 (b) 0 (c) 1 (d) 3

```
1 #include <iostream>
2 int main()
3 {
4    unsigned int x = +1;
5    ( std::cin >> x; )
6    for (int y = 0; y < x) {
7        std::cout << ++y;
8    return 0;
9 }
```

(G1)(G2)

Exercise 24 What is the problem with the code below? Fix it and explain what the resulting code computes.

```
1 unsigned int s = 0;
2 do {
3    int i = 1;
4    if (i % 2 == 1) s += i;
5    while (++i < 10);
```

(G2)(G3)
Exercise 25 For each variable declaration in the following program give its declarative region and its scope in the form “line x-y”. What is the output of the program? (G2)(G5)

```cpp
#include <iostream>
int main()
{
    int s = 0;
    int i = 0;
    while (i < 4)
    {
        ++i;
        int f = i + 1;
        s *= f;
    }
    unsigned int t = 2;
    std::cout << s + t << "\n";
    int k = 1;
    return 0;
}
```

Exercise 26 Consider the program given below for each of the listed input numbers, determine the values of x, s, and i at begin of the first five iterations of the for-loop, before the condition is evaluated. What does the program output for these inputs? (a) -1 (b) 1 (c) 2 (d) 3 (G2)(G3)

```cpp
#include <iostream>
int main()
{
    int x;
    std::cin >> x;
    unsigned int s = 0;
    for (int i = 0; i < x; ++i)
    {
        s += i;
        x *= s / 2;
    }
    std::cout << s << "\n";
    return 0;
}
```

Exercise 27 Find at least four problems in the code given below. (G3)(G4)(G5)

Exercise 28 For which input numbers is the output of the program given below well defined? List those input/output pairs and argue why your list is complete. (G3)(G4)(G5)

```cpp
#include <iostream>
int main()
{
    unsigned int x;
    std::cin >> x;
    unsigned int y = x;
    for (unsigned int s = 0; y > 0; --y)
    {
        s += y;
    }
    std::cout << s << y << "\n";
    return 0;
}
```

Exercise 29 Reformulate the code below equivalently in order to improve its readability. Describe the program’s output as a function of its input n. (G2)(G6)(G7)

```cpp
#include <iostream>
int main()
{
    unsigned int n;
    std::cin >> n;
    int x = 1;
    if (n > 0)
    {
        int k = 0;
        bool e = true;
        do {
            if (++k == n) e = false;
            x *= 2;
        } while (e);
    }
    std::cout << x;
    return 0;
}
```

Exercise 30 Reformulate the program below equivalently in order to improve its readability and efficiency. Describe the program’s output as a function of its input x. (G2)(G6)(G7)
#include <iostream>
int main()
{
    int x;
    std::cin >> x;
    int s = 0;
    int i = -10;
    do
        for (int j = 1;;)
            if (j ++ < i) s += j - 1; else break;
        while (++i <= x);
    std::cout << s << "\n";
    return 0;
}

Exercise 31 Write a program fak-1.C to compute the factorial n! of a given input number n.

Exercise 32 Write a program dec2bin.C that inputs a natural number n and outputs the binary digits of n in reverse order. For example, for n=2 the output is 01 and for n=11 the output is 101.

Exercise 33 Write a program cross_sum.C that inputs a natural number n and outputs the sum of the (decimal) digits of n. For example, for n=10 the output is 1 and for n=12 the output is 4.

Exercise 34 Write a program perfect.C to test whether a given natural number n is perfect. A number n ∈ N is called perfect if and only if it is equal to the sum of its proper divisors, that is, n = \sum_{k \mid n \land k < n} k. For example, 28 = 1 + 2 + 4 + 7 + 14 is perfect, while 12 = 1 + 2 + 3 + 4 + 6 is not.

Extend the program to find all perfect numbers between 1 and n. How many perfect numbers exist in the range [1,50000]?