Chapter 9

Functions

Introduction

- A function is a series of statements that have been grouped together and given a name.
- Each function is essentially a small program, with its own declarations and statements.
- Advantages of functions:
  - A program can be divided into small pieces that are easier to understand and modify.
  - We can avoid duplicating code that's used more than once.
  - A function that was originally part of one program can be reused in other programs.

Defining and Calling Functions

- Before we go over the formal rules for defining a function, let’s look at three simple programs that define functions.

Program: Computing Averages

- A function named `average` that computes the average of two `double` values:

```
double average(double a, double b)
{
  return (a + b) / 2;
}
```

- The word `double` at the beginning is the ***return type*** of `average`.
- The identifiers `a` and `b` (the function's ***parameters***) represent the numbers that will be supplied when `average` is called.

Program: Computing Averages

- Every function has an executable part, called the ***body,*** which is enclosed in braces.
- The body of `average` consists of a single `return` statement.
- Executing this statement causes the function to "return" to the place from which it was called; the value of `(a + b) / 2` will be the value returned by the function.

Program: Computing Averages

- A function call consists of a function name followed by a list of ***arguments.***
  - `average(x, y)` is a call of the `average` function.
- Arguments are used to supply information to a function.
  - The call `average(x, y)` causes the values of `x` and `y` to be copied into the parameters `a` and `b`.
- An argument doesn't have to be a variable; any expression of a compatible type will do.
  - `average(5.1, 8.9)` and `average(x/2, y/3)` are legal.

Program: Computing Averages

- We'll put the call of `average` in the place where we need to use the return value.
- A statement that prints the average of `x` and `y`:

```
printf("Average: %g\n", average(x, y));
```

  The return value of `average` isn't saved; the program prints it and then discards it.
- If we had needed the return value later in the program, we could have captured it in a variable:

```
avg = average(x, y);
```

Program: Computing Averages

- The `average.c` program reads three numbers and uses the `average` function to compute their averages, one pair at a time:

```
Enter three numbers: 3.5 9.6 10.2
Average of 3.5 and 9.6: 6.55
Average of 9.6 and 10.2: 9.9
Average of 3.5 and 10.2: 6.85
```

average.c

```
/* Computes pairwise averages of three numbers */

#include <stdio.h>

double average(double a, double b)
{
  return (a + b) / 2;
}

int main(void)
{
  double x, y, z;

  printf("Enter three numbers: ");
  scanf("%lf%lf%lf", &x, &y, &z);
  printf("Average of %g and %g: %g\n", x, y, average(x, y));
  printf("Average of %g and %g: %g\n", y, z, average(y, z));
  printf("Average of %g and %g: %g\n", x, z, average(x, z));

  return 0;
}
```

Program: Printing a Countdown

- To indicate that a function has no return value, we specify that its return type is `void`:

```
void print_count(int n)
{
  printf("T minus %d and counting\n", n);
}
```

- `void` is a type with no values.
- A call of `print_count` must appear in a statement by itself:

```
print_count(i);
```

- The `countdown.c` program calls `print_count` 10 times inside a loop.

countdown.c

```
/* Prints a countdown */

#include <stdio.h>

void print_count(int n)
{
  printf("T minus %d and counting\n", n);
}

int main(void)
{
  int i;

  for (i = 10; i > 0; --i)
    print_count(i);

  return 0;
}
```

Program: Printing a Pun (Revisited)

- When a function has no parameters, the word `void` is placed in parentheses after the function's name:

```
void print_pun(void)
{
  printf("To C, or not to C: that is the question.\n");
}
```

- To call a function with no arguments, we write the function's name, followed by parentheses:

```
print_pun();
```

  The parentheses *must* be present.

- The `pun2.c` program tests the `print_pun` function.

pun2.c

```c
/* Prints a bad pun */

#include <stdio.h>

void print_pun(void)
{
  printf("To C, or not to C: that is the question.\n");
}

int main(void)
{
  print_pun();
  return 0;
}
```

Function Definitions

- General form of a ***function definition:***

```
return-type  function-name  (  parameters  )
{
    declarations
    statements
}
```

Function Definitions

- The return type of a function is the type of value that the function returns.
- Rules governing the return type:
  - Functions may not return arrays.
  - Specifying that the return type is `void` indicates that the function doesn’t return a value.
- If the return type is omitted in C89, the function is presumed to return a value of type `int`.
- In C99, omitting the return type is illegal.

Function Definitions

- As a matter of style, some programmers put the return type *above* the function name:

```
double
average(double a, double b)
{
  return (a + b) / 2;
}
```

- Putting the return type on a separate line is especially useful if the return type is lengthy, like `unsigned long int`.

Function Definitions

- After the function name comes a list of parameters.
- Each parameter is preceded by a specification of its type; parameters are separated by commas.
- If the function has no parameters, the word `void` should appear between the parentheses.

Function Definitions

- The body of a function may include both declarations and statements.
- An alternative version of the average function:

```
double average(double a, double b)
{
  double sum;         /* declaration */

  sum = a + b;        /* statement */
  return sum / 2;     /* statement */
}
```

Function Definitions

- Variables declared in the body of a function can’t be examined or modified by other functions.
- In C89, variable declarations must come first, before all statements in the body of a function.
- In C99, variable declarations and statements can be mixed, as long as each variable is declared prior to the first statement that uses the variable.

Function Definitions

- The body of a function whose return type is `void` (a "`void` function") can be empty:

```
void print_pun(void)
{
}
```

- Leaving the body empty may make sense as a temporary step during program development.

Function Calls

- A function call consists of a function name followed by a list of arguments, enclosed in parentheses:

```
average(x, y)
print_count(i)
print_pun()
```

- If the parentheses are missing, the function won't be called:

```
print_pun;    /*** WRONG ***/
```

This statement is legal but has no effect.

Function Calls

- A call of a `void` function is always followed by a semicolon to turn it into a statement:

```
print_count(i);
print_pun();
```

- A call of a non-`void` function produces a value that can be stored in a variable, tested, printed, or used in some other way:

```
avg = average(x, y);
if (average(x, y) > 0)
  printf("Average is positive\n");
printf("The average is %g\n", average(x, y));
```

Function Calls

- The value returned by a non-`void` function can always be discarded if it's not needed:

```
average(x, y);  /* discards return value */
```

  This call is an example of an expression statement: a statement that evaluates an expression but then discards the result.

Function Calls

- Ignoring the return value of `average` is an odd thing to do, but for some functions it makes sense.
- `printf` returns the number of characters that it prints.
- After the following call, `num_chars` will have the value 9:

```
num_chars = printf("Hi, Mom!\n");
```

- We'll normally discard `printf`'s return value:

```
printf("Hi, Mom!\n");
  /* discards return value */
```

Function Calls

- To make it clear that we're deliberately discarding the return value of a function, C allows us to put `(void)` before the call:

```
(void) printf("Hi, Mom!\n");
```

- Using `(void)` makes it clear to others that you deliberately discarded the return value, not just forgot that there was one.

Program: Testing Whether a Number Is Prime

- The `prime.c` program tests whether a number is prime:

```
Enter a number: 34
Not prime
```

- The program uses a function named `is_prime` that returns `true` if its parameter is a prime number and `false` if it isn’t.
- `is_prime` divides its parameter `n` by each of the numbers between 2 and the square root of `n`; if the remainder is ever 0, `n` isn’t prime.

prime.c

```
/* Tests whether a number is prime */

#include <stdbool.h>   /* C99 only */
#include <stdio.h>

bool is_prime(int n)
{
  int divisor;

  if (n <= 1)
    return false;
  for (divisor = 2; divisor * divisor <= n; divisor++)
    if (n % divisor == 0)
      return false;
  return true;
}
```

```
int main(void)
{
  int n;

  printf("Enter a number: ");
  scanf("%d", &n);
  if (is_prime(n))
    printf("Prime\n");
  else
    printf("Not prime\n");
  return 0;
}
```

Function Declarations

- C doesn’t require that the definition of a function precede its calls.
- Suppose that we rearrange the `average.c` program by putting the definition of `average` *after* the definition of `main`.

Function Declarations

```
#include <stdio.h>

int main(void)
{
  double x, y, z;

  printf("Enter three numbers: ");
  scanf("%lf%lf%lf", &x, &y, &z);
  printf("Average of %g and %g: %g\n", x, y, average(x, y));
  printf("Average of %g and %g: %g\n", y, z, average(y, z));
  printf("Average of %g and %g: %g\n", x, z, average(x, z));

  return 0;
}

double average(double a, double b)
{
  return (a + b) / 2;
}
```

Function Declarations

- When the compiler encounters the first call of `average` in `main`, it has no information about the function.
- Instead of producing an error message, the compiler assumes that `average` returns an `int` value.
- We say that the compiler has created an ***implicit declaration*** of the function.

Function Declarations

- The compiler is unable to check that we're passing `average` the right number of arguments and that the arguments have the proper type.
- Instead, it performs the default argument promotions and hopes for the best.
- When it encounters the definition of `average` later in the program, the compiler notices that the function's return type is actually `double`, not `int`, and so we get an error message.

Function Declarations

- One way to avoid the problem of call-before-definition is to arrange the program so that the definition of each function precedes all its calls.
- Unfortunately, such an arrangement doesn't always exist.
- Even when it does, it may make the program harder to understand by putting its function definitions in an unnatural order.

Function Declarations

- Fortunately, C offers a better solution: declare each function before calling it.
- A ***function declaration*** provides the compiler with a brief glimpse at a function whose full definition will appear later.
- General form of a function declaration:

  return-type function-name `(` *parameters* `) ;`

- The declaration of a function must be consistent with the function’s definition.
- Here’s the `average.c` program with a declaration of `average` added.

Function Declarations

```
#include <stdio.h>

double average(double a, double b);    /* DECLARATION */

int main(void)
{
  double x, y, z;

  printf("Enter three numbers: ");
  scanf("%lf%lf%lf", &x, &y, &z);
  printf("Average of %g and %g: %g\n", x, y, average(x, y));
  printf("Average of %g and %g: %g\n", y, z, average(y, z));
  printf("Average of %g and %g: %g\n", x, z, average(x, z));

  return 0;
}

double average(double a, double b)     /* DEFINITION */
{
  return (a + b) / 2;
}
```

Function Declarations

- Function declarations of the kind we're discussing are known as ***function prototypes.***
- C also has an older style of function declaration in which the parentheses are left empty.
- A function prototype doesn't have to specify the names of the function's parameters, as long as their types are present:

```
double average(double, double);
```

- It's usually best not to omit parameter names.

Function Declarations

- C99 has adopted the rule that either a declaration or a definition of a function must be present prior to any call of the function.
- Calling a function for which the compiler has not yet seen a declaration or definition is an error.

Arguments

- In C, arguments are ***passed by value:*** when a function is called, each argument is evaluated and its value assigned to the corresponding parameter.
- Since the parameter contains a copy of the argument's value, any changes made to the parameter during the execution of the function don't affect the argument.

Arguments

- The fact that arguments are passed by value has both advantages and disadvantages.
- Since a parameter can be modified without affecting the corresponding argument, we can use parameters as variables within the function, reducing the number of genuine variables needed.

Arguments

- Consider the following function, which raises a number `x` to a power `n`:

```
int power(int x, int n)
{
  int i, result = 1;

  for (i = 1; i <= n; i++)
    result = result * x;

  return result;
}
```

Arguments

- Since `n` is a *copy* of the original exponent, the function can safely modify it, removing the need for `i`:

```
int power(int x, int n)
{
  int result = 1;

  while (n-- > 0)
    result = result * x;

  return result;
}
```

Arguments

- C's requirement that arguments be passed by value makes it difficult to write certain kinds of functions.
- Suppose that we need a function that will decompose a `double` value into an integer part and a fractional part.
- Since a function can't *return* two numbers, we might try passing a pair of variables to the function and having it modify them:

```
void decompose(double x, long int_part,
               double frac_part)
{
  int_part = (long) x;
  frac_part = x - int_part;
}
```

Arguments

- A call of the function:

  ```
  decompose(3.14159, i, d);
  ```

- Unfortunately, `i` and `d` won't be affected by the assignments to `int_part` and `frac_part`.
- Chapter 11 shows how to make `decompose` work correctly.

Argument Conversions

- C allows function calls in which the types of the arguments don't match the types of the parameters.
- The rules governing how the arguments are converted depend on whether or not the compiler has seen a prototype for the function (or the function's full definition) prior to the call.

Argument Conversions

- ***The compiler has encountered a prototype prior to the call.***
- The value of each argument is implicitly converted to the type of the corresponding parameter as if by assignment.
- Example: If an `int` argument is passed to a function that was expecting a `double`, the argument is converted to `double` automatically.

Argument Conversions

- ***The compiler has not encountered a prototype prior to the call.***
- The compiler performs the ***default argument promotions:***
  - `float` arguments are converted to `double`.
  - The integral promotions are performed, causing `char` and `short` arguments to be converted to `int`. (In C99, the integer promotions are performed.)

Argument Conversions

- Relying on the default argument promotions is dangerous.
- Example:

```
#include <stdio.h>

int main(void)
{
  double x = 3.0;
  printf("Square: %d\n", square(x));

  return 0;
}

int square(int n)
{
  return n * n;
}
```

- At the time `square` is called, the compiler doesn't know that it expects an argument of type `int`.

Argument Conversions

- Instead, the compiler performs the default argument promotions on `x`, with no effect.
- Since it's expecting an argument of type `int` but has been given a `double` value instead, the effect of calling `square` is undefined.
- The problem can be fixed by casting `square`'s argument to the proper type:

```
printf("Square: %d\n", square((int) x));
```

- A much better solution is to provide a prototype for `square` before calling it.
- In C99, calling `square` without first providing a declaration or definition of the function is an error.

Array Arguments

- When a function parameter is a one-dimensional array, the length of the array can be left unspecified:

```
int f(int a[])  /* no length specified */
{
  …
}
```

- C doesn’t provide any easy way for a function to determine the length of an array passed to it.
- Instead, we’ll have to supply the length—if the function needs it—as an additional argument.

Array Arguments

- Example:

```
int sum_array(int a[], int n)
{
  int i, sum = 0;

  for (i = 0; i < n; i++)
    sum += a[i];

  return sum;
}
```

- Since `sum_array` needs to know the length of `a`, we must supply it as a second argument.

Array Arguments

- The prototype for `sum_array` has the following appearance:

```
int sum_array(int a[], int n);
```

- As usual, we can omit the parameter names if we wish:

```
int sum_array(int [], int);
```

Array Arguments

- When `sum_array` is called, the first argument will be the name of an array, and the second will be its length:

```
#define LEN 100

int main(void)
{
  int b[LEN], total;
  …
  total = sum_array(b, LEN);
  …
}
```

- Notice that we don't put brackets after an array name when passing it to a function:

```
total = sum_array(b[], LEN);   /*** WRONG ***/
```

Array Arguments

- A function has no way to check that we've passed it the correct array length.
- We can exploit this fact by telling the function that the array is smaller than it really is.
- Suppose that we've only stored 50 numbers in the `b` array, even though it can hold 100.
- We can sum just the first 50 elements by writing

```
total = sum_array(b, 50);
```

Array Arguments

- Be careful not to tell a function that an array argument is *larger* than it really is:

  ```
  total = sum_array(b, 150);    /*** WRONG ***/
  ```

  `sum_array` will go past the end of the array, causing undefined behavior.

Array Arguments

- A function is allowed to change the elements of an array parameter, and the change is reflected in the corresponding argument.
- A function that modifies an array by storing zero into each of its elements:

```
void store_zeros(int a[], int n)
{
  int i;

  for (i = 0; i < n; i++)
    a[i] = 0;
}
```

Array Arguments

- A call of `store_zeros`:

```
store_zeros(b, 100);
```

- The ability to modify the elements of an array argument may seem to contradict the fact that C passes arguments by value.
- Chapter 12 explains why there's actually no contradiction.

Array Arguments

- If a parameter is a multidimensional array, only the length of the first dimension may be omitted.
- If we revise `sum_array` so that `a` is a two-dimensional array, we must specify the number of columns in `a`:

```
#define LEN 10

int sum_two_dimensional_array(int a[][LEN], int n)
{
  int i, j, sum = 0;

  for (i = 0; i < n; i++)
    for (j = 0; j < LEN; j++)
      sum += a[i][j];

  return sum;
}
```

Array Arguments

- Not being able to pass multidimensional arrays with an arbitrary number of columns can be a nuisance.
- We can often work around this difficulty by using arrays of pointers.
- C99's variable-length array parameters provide an even better solution.

Variable-Length Array Parameters (C99)

- C99 allows the use of variable-length arrays as parameters.
- Consider the `sum_array` function:

  ```
  int sum_array(int a[], int n)
  {
    …
  }
  ```

  As it stands now, there’s no direct link between `n` and the length of the array `a`.
- Although the function body treats `n` as `a`’s length, the actual length of the array could be larger or smaller than `n`.

Variable-Length Array Parameters (C99)

- Using a variable-length array parameter, we can explicitly state that a's length is n:

```
int sum_array(int n, int a[n])
{
  …
}
```

- The value of the first parameter (n) specifies the length of the second parameter (a).
- Note that the order of the parameters has been switched; order is important when variable-length array parameters are used.

Variable-Length Array Parameters (C99)

- There are several ways to write the prototype for the new version of `sum_array`.
- One possibility is to make it look exactly like the function definition:

```
int sum_array(int n, int a[n]);  /* Version 1 */
```

- Another possibility is to replace the array length by an asterisk (`*`):

```
int sum_array(int n, int a[*]);  /* Version 2a */
```

Variable-Length Array Parameters (C99)

- The reason for using the `*` notation is that parameter names are optional in function declarations.
- If the name of the first parameter is omitted, it wouldn't be possible to specify that the length of the array is `n`, but the `*` provides a clue that the length of the array is related to parameters that come earlier in the list:

```
int sum_array(int, int [*]);    /* Version 2b */
```

Variable-Length Array Parameters (C99)

- It’s also legal to leave the brackets empty, as we normally do when declaring an array parameter:

```
int sum_array(int n, int a[]);  /* Version 3a */
int sum_array(int, int []);     /* Version 3b */
```

- Leaving the brackets empty isn’t a good choice, because it doesn’t expose the relationship between `n` and `a`.

Variable-Length Array Parameters (C99)

- In general, the length of a variable-length array parameter can be any expression.
- A function that concatenates two arrays `a` and `b`, storing the result into a third array named `c`:

```
int concatenate(int m, int n, int a[m], int b[n],
                int c[m+n])
{
  …
}
```

- The expression used to specify the length of `c` involves two other parameters, but in general it could refer to variables outside the function or even call other functions.

Variable-Length Array Parameters (C99)

- Variable-length array parameters with a single dimension have limited usefulness.
- They make a function declaration or definition more descriptive by stating the desired length of an array argument.
- However, no additional error-checking is performed; it’s still possible for an array argument to be too long or too short.

Variable-Length Array Parameters (C99)

- Variable-length array parameters are most useful for multidimensional arrays.
- By using a variable-length array parameter, we can generalize the `sum_two_dimensional_array` function to any number of columns:

```
int sum_two_dimensional_array(int n, int m, int a[n][m])
{
  int i, j, sum = 0;

  for (i = 0; i < n; i++)
    for (j = 0; j < m; j++)
      sum += a[i][j];

  return sum;
}
```

Variable-Length Array Parameters (C99)

- Prototypes for this function include:

```
int sum_two_dimensional_array(int n, int m, int a[n][m]);
int sum_two_dimensional_array(int n, int m, int a[*][*]);
int sum_two_dimensional_array(int n, int m, int a[][m]);
int sum_two_dimensional_array(int n, int m, int a[][*]);
```

Using `static` in Array Parameter Declarations (C99)

- C99 allows the use of the keyword `static` in the declaration of array parameters.
- The following example uses `static` to indicate that the length of `a` is guaranteed to be at least 3:

```
int sum_array(int a[static 3], int n)
{
  …
}
```

Using `static` in Array Parameter Declarations (C99)

- Using `static` has no effect on program behavior.
- The presence of `static` is merely a "hint" that may allow a C compiler to generate faster instructions for accessing the array.
- If an array parameter has more than one dimension, `static` can be used only in the first dimension.

Compound Literals (C99)

- Let's return to the original `sum_array` function.
- When `sum_array` is called, the first argument is usually the name of an array.
- Example:

```
int b[] = {3, 0, 3, 4, 1};
total = sum_array(b, 5);
```

- `b` must be declared as a variable and then initialized prior to the call.
- If `b` isn't needed for any other purpose, it can be annoying to create it solely for the purpose of calling `sum_array`.

Compound Literals (C99)

- In C99, we can avoid this annoyance by using a ***compound literal:*** an unnamed array that's created "on the fly" by simply specifying which elements it contains.
- A call of `sum_array` with a compound literal (shown in **bold**) as its first argument:

```
total = sum_array((int []){3, 0, 3, 4, 1}, 5);
```

- We didn't specify the length of the array, so it's determined by the number of elements in the literal.
- We also have the option of specifying a length explicitly:

```
(int [4]){1, 9, 2, 1}
```

  is equivalent to

```
(int []){1, 9, 2, 1}
```

Compound Literals (C99)

- A compound literal resembles a cast applied to an initializer.
- In fact, compound literals and initializers obey the same rules.
- A compound literal may contain designators, just like a designated initializer, and it may fail to provide full initialization (in which case any uninitialized elements default to zero).
- For example, the literal `(int [10]){8, 6}` has 10 elements; the first two have the values 8 and 6, and the remaining elements have the value 0.

Compound Literals (C99)

- Compound literals created inside a function may contain arbitrary expressions, not just constants:

```
total = sum_array((int []){2 * i, i + j, j * k}, 3);
```

- A compound literal is an lvalue, so the values of its elements can be changed.
- If desired, a compound literal can be made "read-only" by adding the word `const` to its type:

```
(const int []){5, 4}
```

The `return` Statement

- A non-`void` function must use the `return` statement to specify what value it will return.
- The `return` statement has the form

  `return` *expression* `;`

- The expression is often just a constant or variable:

```
return 0;
return status;
```

- More complex expressions are possible:

```
return n >= 0 ? n : 0;
```

The `return` Statement

- If the type of the expression in a `return` statement doesn't match the function's return type, the expression will be implicitly converted to the return type.
  - If a function returns an `int`, but the `return` statement contains a `double` expression, the value of the expression is converted to `int`.

The `return` Statement

- `return` statements may appear in functions whose return type is `void`, provided that no expression is given:

```
return;  /* return in a void function */
```

- Example:

```
void print_int(int i)
{
  if (i < 0)
    return;
  printf("%d", i);
}
```

The **`return`** Statement

- A `return` statement may appear at the end of a `void` function:

  ```
  void print_pun(void)
  {
    printf("To C, or not to C: that is the question.\n");
    return;    /* OK, but not needed */
  }
  ```

  Using `return` here is unnecessary.

- If a non-`void` function fails to execute a `return` statement, the behavior of the program is undefined if it attempts to use the function's return value.

Program Termination

- Normally, the return type of `main` is `int`:

```
int main(void)
{
   …
}
```

- Older C programs often omit `main`'s return type, taking advantage of the fact that it traditionally defaults to `int`:

```
main()
{
   …
}
```

Program Termination

- Omitting the return type of a function isn't legal in C99, so it's best to avoid this practice.
- Omitting the word `void` in `main`'s parameter list remains legal, but—as a matter of style—it's best to include it.

Program Termination

- The value returned by `main` is a status code that can be tested when the program terminates.
- `main` should return 0 if the program terminates normally.
- To indicate abnormal termination, `main` should return a value other than 0.
- It’s good practice to make sure that every C program returns a status code.

The **exit** Function

- Executing a `return` statement in `main` is one way to terminate a program.
- Another is calling the `exit` function, which belongs to `<stdlib.h>`.
- The argument passed to `exit` has the same meaning as `main`'s return value: both indicate the program's status at termination.
- To indicate normal termination, we'd pass 0:

```
exit(0);    /* normal termination */
```

The `exit` Function

- Since 0 is a bit cryptic, C allows us to pass `EXIT_SUCCESS` instead (the effect is the same):

```
exit(EXIT_SUCCESS);
```

- Passing `EXIT_FAILURE` indicates abnormal termination:

```
exit(EXIT_FAILURE);
```

- `EXIT_SUCCESS` and `EXIT_FAILURE` are macros defined in `<stdlib.h>`.
- The values of `EXIT_SUCCESS` and `EXIT_FAILURE` are implementation-defined; typical values are 0 and 1, respectively.

The `exit` Function

- The statement

  `return` *expression*`;`

  in `main` is equivalent to

  `exit(`*expression*`);`
- The difference between `return` and `exit` is that `exit` causes program termination regardless of which function calls it.
- The `return` statement causes program termination only when it appears in the `main` function.

Recursion

- A function is ***recursive*** if it calls itself.
- The following function computes $n!$ recursively, using the formula $n! = n \times (n - 1)!$:

```
int fact(int n)
{
  if (n <= 1)
    return 1;
  else
    return n * fact(n - 1);
}
```

Recursion

- To see how recursion works, let's trace the execution of the statement

  `i = fact(3);`

`fact(3)` finds that 3 is not less than or equal to 1, so it calls

`fact(2)`, which finds that 2 is not less than or equal to 1, so it calls

`fact(1)`, which finds that 1 is less than or equal to 1, so it returns 1, causing

`fact(2)` to return 2 × 1 = 2, causing

`fact(3)` to return 3 × 2 = 6.

Recursion

- The following recursive function computes x^n, using the formula $x^n = x \times x^{n-1}$.

```
int power(int x, int n)
{
  if (n == 0)
    return 1;
  else
    return x * power(x, n - 1);
}
```

Recursion

- We can condense the `power` function by putting a conditional expression in the `return` statement:

```
int power(int x, int n)
{
  return n == 0 ? 1 : x * power(x, n - 1);
}
```

- Both `fact` and `power` are careful to test a "termination condition" as soon as they're called.
- All recursive functions need some kind of termination condition in order to prevent infinite recursion.

The Quicksort Algorithm

- Recursion is most helpful for sophisticated algorithms that require a function to call itself two or more times.
- Recursion often arises as a result of an algorithm design technique known as ***divide-and-conquer,*** in which a large problem is divided into smaller pieces that are then tackled by the same algorithm.

The Quicksort Algorithm

- A classic example of divide-and-conquer can be found in the popular ***Quicksort*** algorithm.
- Assume that the array to be sorted is indexed from 1 to *n*.

Quicksort algorithm

1. Choose an array element *e* (the "partitioning element"), then rearrange the array so that elements 1, …, *i* – 1 are less than or equal to *e*, element *i* contains e, and elements *i* + 1, …, *n* are greater than or equal to *e*.
2. Sort elements 1, …, *i* – 1 by using Quicksort recursively.
3. Sort elements *i* + 1, …, *n* by using Quicksort recursively.

The Quicksort Algorithm

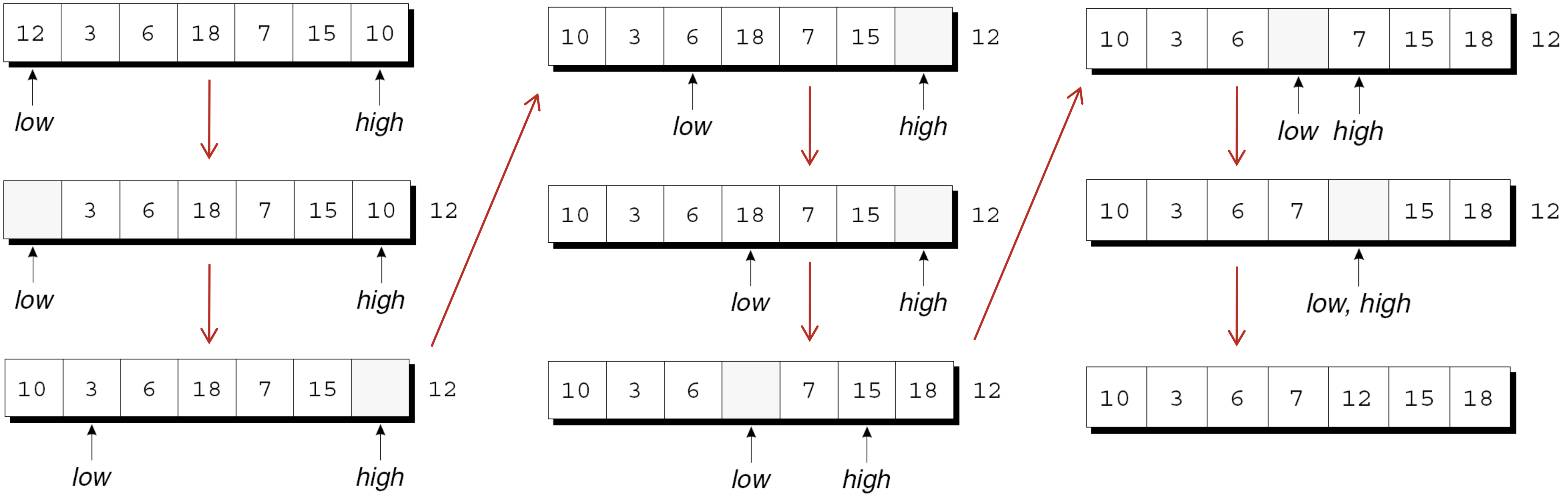
- Step 1 of the Quicksort algorithm is obviously critical.
- There are various methods to partition an array.
- We'll use a technique that's easy to understand but not particularly efficient.
- The algorithm relies on two "markers" named *low* and *high*, which keep track of positions within the array.

The Quicksort Algorithm

- Initially, *low* points to the first element; *high* points to the last.
- We copy the first element (the partitioning element) into a temporary location, leaving a “hole” in the array.
- Next, we move *high* across the array from right to left until it points to an element that’s smaller than the partitioning element.
- We then copy the element into the hole that *low* points to, which creates a new hole (pointed to by *high*).
- We now move *low* from left to right, looking for an element that’s larger than the partitioning element. When we find one, we copy it into the hole that *high* points to.
- The process repeats until *low* and *high* meet at a hole.
- Finally, we copy the partitioning element into the hole.

The Quicksort Algorithm

- Example of partitioning an array:



The Quicksort Algorithm

- By the final figure, all elements to the left of the partitioning element are less than or equal to 12, and all elements to the right are greater than or equal to 12.
- Now that the array has been partitioned, we can use Quicksort recursively to sort the first four elements of the array (10, 3, 6, and 7) and the last two (15 and 18).

Program: Quicksort

- Let’s develop a recursive function named `quicksort` that uses the Quicksort algorithm to sort an array of integers.
- The `qsort.c` program reads 10 numbers into an array, calls `quicksort` to sort the array, then prints the elements in the array:

```
Enter 10 numbers to be sorted: 9 16 47 82 4 66 12 3 25 51
In sorted order: 3 4 9 12 16 25 47 51 66 82
```

- The code for partitioning the array is in a separate function named `split`.

qsort.c

```
/* Sorts an array of integers using Quicksort algorithm */

#include <stdio.h>

#define N 10

void quicksort(int a[], int low, int high);
int split(int a[], int low, int high);

int main(void)
{
  int a[N], i;

  printf("Enter %d numbers to be sorted: ", N);
  for (i = 0; i < N; i++)
    scanf("%d", &a[i]);
  quicksort(a, 0, N - 1);

  printf("In sorted order: ");
  for (i = 0; i < N; i++)
    printf("%d ", a[i]);
  printf("\n");

  return 0;
}
```

```
void quicksort(int a[], int low, int high)
{
  int middle;

  if (low >= high) return;
  middle = split(a, low, high);
  quicksort(a, low, middle - 1);
  quicksort(a, middle + 1, high);
}
```

```
int split(int a[], int low, int high)
{
  int part_element = a[low];

  for (;;) {
    while (low < high && part_element <= a[high])
      high--;
    if (low >= high) break;
    a[low++] = a[high];

    while (low < high && a[low] <= part_element)
      low++;
    if (low >= high) break;
    a[high--] = a[low];
  }

  a[high] = part_element;
  return high;
}
```

Program: Quicksort

- Ways to improve the program's performance:
  - Improve the partitioning algorithm.
  - Use a different method to sort small arrays.
  - Make Quicksort nonrecursive.