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

```
/* 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 (一瞥) 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 (真正的) 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 (利用) 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 (滋擾).
- 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.
  - (which can be used in optimizations).
- 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.
- Page 200. (If the compiler knows that an array will always have a certain minimum length, it can arrange to "prefetch" these elements from memory when the function is called, before the elements are actually needed by statements within the functioin.)
- 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.

```
int foo(){
  return 75.0;
}
```

- 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.

```
int main()
{
  …
}
```

```
int main(void)
{
     …
}
```


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*`);`

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

- The difference between `return` and `exit` is that `exit` causes program termination regardless of which function calls it.

```
int foo()
{
  return 0;
  exit(0);
}
```

- 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);
}
```

```
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
   1. elements 1, …, *i* – 1 are less than or equal to *e*,
   2. element *i* contains e, and
   3. 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.

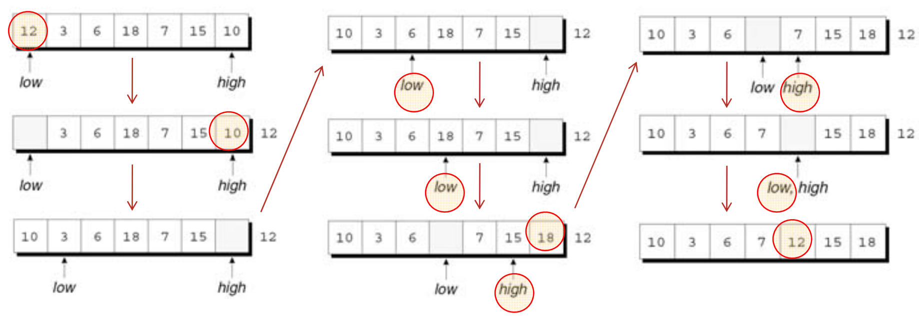
- The algorithm
  – relies on two "markers" named *low* and *high*,
  – which keep track of positions within the array.

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.