```
#include <stdio.h>

/* printd:  print n in decimal */
void printd(int n)
{
    if (n < 0) {
        putchar('-');
        n = -n;
    }
    if (n / 10)
        printd(n / 10);
    putchar(n % 10 + '0');
}
```

When a function calls itself recursively, each invocation gets a fresh set of all the automatic variables, independent of the previous set. Thus in `printd(123)` the first `printd` receives the argument `n = 123`. It passes `12` to a second `printd`, which in turn passes `1` to a third. The third-level `printd` prints `1`, then returns to the second level. That `printd` prints `2`, then returns to the first level. That one prints `3` and terminates.

Another good example of recursion is quicksort, a sorting algorithm developed by C. A. R. Hoare in 1962. Given an array, one element is chosen and the others are partitioned into two subsets—those less than the partition element and those greater than or equal to it. The same process is then applied recursively to the two subsets. When a subset has fewer than two elements, it doesn't need any sorting; this stops the recursion.

Our version of quicksort is not the fastest possible, but it's one of the simplest. We use the middle element of each subarray for partitioning.

```
/* qsort:  sort v[left]...v[right] into increasing order */
void qsort(int v[], int left, int right)
{
    int i, last;
    void swap(int v[], int i, int j);

    if (left >= right)    /* do nothing if array contains */
        return;           /* fewer than two elements */
    swap(v, left, (left + right)/2); /* move partition elem */
    last = left;                     /* to v[0] */
    for (i = left+1; i <= right; i++)   /* partition */
        if (v[i] < v[left])
            swap(v, ++last, i);
    swap(v, left, last);           /* restore partition elem */
    qsort(v, left, last-1);
    qsort(v, last+1, right);
}
```

We moved the swapping operation into a separate function `swap` because it occurs three times in `qsort`.

```
/* swap:  interchange v[i] and v[j] */
void swap(int v[], int i, int j)
{
    int temp;

    temp = v[i];
    v[i] = v[j];
    v[j] = temp;
}
```

The standard library includes a version of `qsort` that can sort objects of any type.

Recursion may provide no saving in storage, since somewhere a stack of the values being processed must be maintained. Nor will it be faster. But recursive code is more compact, and often much easier to write and understand than the non-recursive equivalent. Recursion is especially convenient for recursively defined data structures like trees; we will see a nice example in Section 6.5.

Exercise 4-12. Adapt the ideas of `printd` to write a recursive version of `itoa`; that is, convert an integer into a string by calling a recursive routine. □

Exercise 4-13. Write a recursive version of the function `reverse(s)`, which reverses the string `s` in place. □

4.11 The C Preprocessor

C provides certain language facilities by means of a preprocessor, which is conceptually a separate first step in compilation. The two most frequently used features are `#include`, to include the contents of a file during compilation, and `#define`, to replace a token by an arbitrary sequence of characters. Other features described in this section include conditional compilation and macros with arguments.

4.11.1 File Inclusion

File inclusion makes it easy to handle collections of `#define`s and declarations (among other things). Any source line of the form

`#include` "*filename*"

or

`#include` <*filename*>

is replaced by the contents of the file *filename*. If the *filename* is quoted, searching for the file typically begins where the source program was found; if it is not found there, or if the name is enclosed in < and >, searching follows an implementation-defined rule to find the file. An included file may itself contain

`#include` lines.

There are often several `#include` lines at the beginning of a source file, to include common `#define` statements and `extern` declarations, or to access the function prototype declarations for library functions from headers like `<stdio.h>`. (Strictly speaking, these need not be files; the details of how headers are accessed are implementation-dependent.)

`#include` is the preferred way to tie the declarations together for a large program. It guarantees that all the source files will be supplied with the same definitions and variable declarations, and thus eliminates a particularly nasty kind of bug. Naturally, when an included file is changed, all files that depend on it must be recompiled.

4.11.2 Macro Substitution

A definition has the form

`#define` *name* *replacement text*

It calls for a macro substitution of the simplest kind—subsequent occurrences of the token *name* will be replaced by the *replacement text*. The name in a `#define` has the same form as a variable name; the replacement text is arbitrary. Normally the replacement text is the rest of the line, but a long definition may be continued onto several lines by placing a \ at the end of each line to be continued. The scope of a name defined with `#define` is from its point of definition to the end of the source file being compiled. A definition may use previous definitions. Substitutions are made only for tokens, and do not take place within quoted strings. For example, if `YES` is a defined name, there would be no substitution in `printf("YES")` or in `YESMAN`.

Any name may be defined with any replacement text. For example,

```
#define  forever  for (;;)   /* infinite loop */
```

defines a new word, `forever`, for an infinite loop.

It is also possible to define macros with arguments, so the replacement text can be different for different calls of the macro. As an example, define a macro called `max`:

```
#define  max(A, B)  ((A) > (B) ? (A) : (B))
```

Although it looks like a function call, a use of `max` expands into in-line code. Each occurrence of a formal parameter (here `A` or `B`) will be replaced by the corresponding actual argument. Thus the line

```
x = max(p+q, r+s);
```

will be replaced by the line

```
x = ((p+q) > (r+s) ? (p+q) : (r+s));
```

So long as the arguments are treated consistently, this macro will serve for any data type; there is no need for different kinds of `max` for different data types, as there would be with functions.

If you examine the expansion of `max`, you will notice some pitfalls. The expressions are evaluated twice; this is bad if they involve side effects like increment operators or input and output. For instance,

```
max(i++, j++)   /* WRONG */
```

will increment the larger value twice. Some care also has to be taken with parentheses to make sure the order of evaluation is preserved; consider what happens when the macro

```
#define  square(x)  x * x    /* WRONG */
```

is invoked as `square(z+1)`.

Nonetheless, macros are valuable. One practical example comes from <stdio.h>, in which `getchar` and `putchar` are often defined as macros to avoid the run-time overhead of a function call per character processed. The functions in <ctype.h> are also usually implemented as macros.

Names may be undefined with `#undef`, usually to ensure that a routine is really a function, not a macro:

```
#undef getchar

int getchar(void) { ... }
```

Formal parameters are not replaced within quoted strings. If, however, a parameter name is preceded by a `#` in the replacement text, the combination will be expanded into a quoted string with the parameter replaced by the actual argument. This can be combined with string concatenation to make, for example, a debugging print macro:

```
#define  dprint(expr)  printf(#expr " = %g\n", expr)
```

When this is invoked, as in

```
dprint(x/y);
```

the macro is expanded into

```
printf("x/y" " = %g\n", x/y);
```

and the strings are concatenated, so the effect is

```
printf("x/y = %g\n", x/y);
```

Within the actual argument, each `"` is replaced by `\"` and each `\` by `\\`, so the result is a legal string constant.

The preprocessor operator `##` provides a way to concatenate actual arguments during macro expansion. If a parameter in the replacement text is adjacent to a `##`, the parameter is replaced by the actual argument, the `##` and surrounding white space are removed, and the result is re-scanned. For example, the macro `paste` concatenates its two arguments:

```
#define  paste(front, back)  front ## back
```

so `paste(name, 1)` creates the token `name1`.

The rules for nested uses of `##` are arcane; further details may be found in Appendix A.

Exercise 4-14. Define a macro `swap(t,x,y)` that interchanges two arguments of type `t`. (Block structure will help.) □

4.11.3 Conditional Inclusion

It is possible to control preprocessing itself with conditional statements that are evaluated during preprocessing. This provides a way to include code selectively, depending on the value of conditions evaluated during compilation.

The `#if` line evaluates a constant integer expression (which may not include `sizeof`, casts, or `enum` constants). If the expression is non-zero, subsequent lines until an `#endif` or `#elif` or `#else` are included. (The preprocessor statement `#elif` is like `else if`.) The expression `defined(`*name*`)` in a `#if` is 1 if the *name* has been defined, and 0 otherwise.

For example, to make sure that the contents of a file `hdr.h` are included only once, the contents of the file are surrounded with a conditional like this:

```
#if !defined(HDR)
#define HDR

/* contents of hdr.h go here */

#endif
```

The first inclusion of `hdr.h` defines the name `HDR`; subsequent inclusions will find the name defined and skip down to the `#endif`. A similar style can be used to avoid including files multiple times. If this style is used consistently, then each header can itself include any other headers on which it depends, without the user of the header having to deal with the interdependence.

This sequence tests the name `SYSTEM` to decide which version of a header to include:

```
#if SYSTEM == SYSV
    #define HDR "sysv.h"
#elif SYSTEM == BSD
    #define HDR "bsd.h"
#elif SYSTEM == MSDOS
    #define HDR "msdos.h"
#else
    #define HDR "default.h"
#endif
#include HDR
```

The `#ifdef` and `#ifndef` lines are specialized forms that test whether a name is defined. The first example of `#if` above could have been written

```
#ifndef HDR
#define HDR

/* contents of hdr.h go here */

#endif
```

CHAPTER 5: Pointers and Arrays

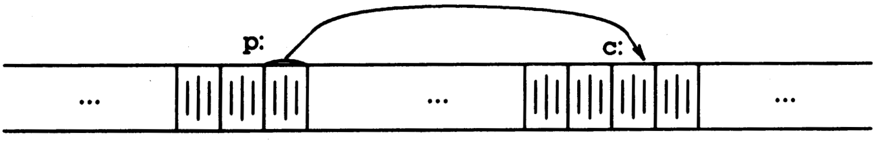
A pointer is a variable that contains the address of a variable. Pointers are much used in C, partly because they are sometimes the only way to express a computation, and partly because they usually lead to more compact and efficient code than can be obtained in other ways. Pointers and arrays are closely related; this chapter also explores this relationship and shows how to exploit it.

Pointers have been lumped with the `goto` statement as a marvelous way to create impossible-to-understand programs. This is certainly true when they are used carelessly, and it is easy to create pointers that point somewhere unexpected. With discipline, however, pointers can also be used to achieve clarity and simplicity. This is the aspect that we will try to illustrate.

The main change in ANSI C is to make explicit the rules about how pointers can be manipulated, in effect mandating what good programmers already practice and good compilers already enforce. In addition, the type `void *` (pointer to `void`) replaces `char *` as the proper type for a generic pointer.

5.1 Pointers and Addresses

Let us begin with a simplified picture of how memory is organized. A typical machine has an array of consecutively numbered or addressed memory cells that may be manipulated individually or in contiguous groups. One common situation is that any byte can be a `char`, a pair of one-byte cells can be treated as a `short` integer, and four adjacent bytes form a `long`. A pointer is a group of cells (often two or four) that can hold an address. So if `c` is a `char` and `p` is a pointer that points to it, we could represent the situation this way:



The unary operator `&` gives the address of an object, so the statement

```
p = &c;
```

assigns the address of c to the variable p, and p is said to "point to" c. The & operator only applies to objects in memory: variables and array elements. It cannot be applied to expressions, constants, or `register` variables.

The unary operator * is the *indirection* or *dereferencing* operator; when applied to a pointer, it accesses the object the pointer points to. Suppose that x and y are integers and `ip` is a pointer to `int`. This artificial sequence shows how to declare a pointer and how to use & and *:

```
int x = 1, y = 2, z[10];
int *ip;            /* ip is a pointer to int */

ip = &x;            /* ip now points to x */
y = *ip;            /* y is now 1 */
*ip = 0;            /* x is now 0 */
ip = &z[0];         /* ip now points to z[0] */
```

The declarations of x, y, and z are what we've seen all along. The declaration of the pointer `ip`,

```
int *ip;
```

is intended as a mnemonic; it says that the expression `*ip` is an `int`. The syntax of the declaration for a variable mimics the syntax of expressions in which the variable might appear. This reasoning applies to function declarations as well. For example,

```
double *dp, atof(char *);
```

says that in an expression `*dp` and `atof(s)` have values of type `double`, and that the argument of `atof` is a pointer to `char`.

You should also note the implication that a pointer is constrained to point to a particular kind of object: every pointer points to a specific data type. (There is one exception: a "pointer to `void`" is used to hold any type of pointer but cannot be dereferenced itself. We'll come back to it in Section 5.11.)

If `ip` points to the integer x, then `*ip` can occur in any context where x could, so

```
*ip = *ip + 10;
```

increments `*ip` by 10.

The unary operators * and & bind more tightly than arithmetic operators, so the assignment

```
y = *ip + 1
```

takes whatever `ip` points at, adds 1, and assigns the result to y, while

```
*ip += 1
```

increments what `ip` points to, as do

```
++*ip
```

and

```
(*ip)++
```

The parentheses are necessary in this last example; without them, the expression would increment `ip` instead of what it points to, because unary operators like `*` and `++` associate right to left.

Finally, since pointers are variables, they can be used without dereferencing. For example, if `iq` is another pointer to `int`,

```
iq = ip
```

copies the contents of `ip` into `iq`, thus making `iq` point to whatever `ip` pointed to.

5.2 Pointers and Function Arguments

Since C passes arguments to functions by value, there is no direct way for the called function to alter a variable in the calling function. For instance, a sorting routine might exchange two out-of-order elements with a function called `swap`. It is not enough to write

```
swap(a, b);
```

where the `swap` function is defined as

```
void swap(int x, int y)  /* WRONG */
{
    int temp;

    temp = x;
    x = y;
    y = temp;
}
```

Because of call by value, `swap` can't affect the arguments `a` and `b` in the routine that called it. The function above only swaps *copies* of `a` and `b`.

The way to obtain the desired effect is for the calling program to pass *pointers* to the values to be changed:

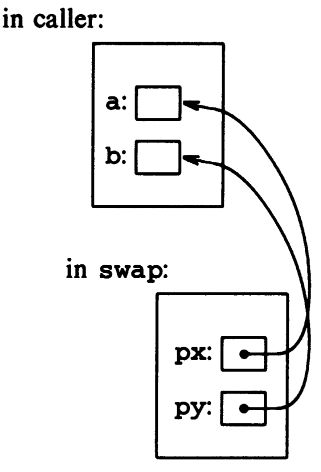
```
swap(&a, &b);
```

Since the operator `&` produces the address of a variable, `&a` is a pointer to `a`. In `swap` itself, the parameters are declared to be pointers, and the operands are accessed indirectly through them.

```
void swap(int *px, int *py)  /* interchange *px and *py */
{
    int temp;

    temp = *px;
    *px = *py;
    *py = temp;
}
```

Pictorially:



Pointer arguments enable a function to access and change objects in the function that called it. As an example, consider a function `getint` that performs free-format input conversion by breaking a stream of characters into integer values, one integer per call. `getint` has to return the value it found and also signal end of file when there is no more input. These values have to be passed back by separate paths, for no matter what value is used for `EOF`, that could also be the value of an input integer.

One solution is to have `getint` return the end of file status as its function value, while using a pointer argument to store the converted integer back in the calling function. This is the scheme used by `scanf` as well; see Section 7.4.

The following loop fills an array with integers by calls to `getint`:

```
int n, array[SIZE], getint(int *);

for (n = 0; n < SIZE && getint(&array[n]) != EOF; n++)
    ;
```

Each call sets `array[n]` to the next integer found in the input and increments `n`. Notice that it is essential to pass the address of `array[n]` to `getint`. Otherwise there is no way for `getint` to communicate the converted integer back to the caller.

Our version of `getint` returns `EOF` for end of file, zero if the next input is not a number, and a positive value if the input contains a valid number.

```
#include <ctype.h>

int getch(void);
void ungetch(int);

/* getint:  get next integer from input into *pn */
int getint(int *pn)
{
    int c, sign;

    while (isspace(c = getch()))   /* skip white space */
        ;
    if (!isdigit(c) && c != EOF && c != '+' && c != '-') {
        ungetch(c);    /* it's not a number */
        return 0;
    }
    sign = (c == '-') ? -1 : 1;
    if (c == '+' || c == '-')
        c = getch();
    for (*pn = 0; isdigit(c); c = getch())
        *pn = 10 * *pn + (c - '0');
    *pn *= sign;
    if (c != EOF)
        ungetch(c);
    return c;
}
```

Throughout `getint`, `*pn` is used as an ordinary `int` variable. We have also used `getch` and `ungetch` (described in Section 4.3) so the one extra character that must be read can be pushed back onto the input.

Exercise 5-1. As written, `getint` treats a `+` or `-` not followed by a digit as a valid representation of zero. Fix it to push such a character back on the input. □

Exercise 5-2. Write `getfloat`, the floating-point analog of `getint`. What type does `getfloat` return as its function value? □

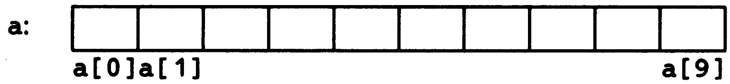
5.3 Pointers and Arrays

In C, there is a strong relationship between pointers and arrays, strong enough that pointers and arrays should be discussed simultaneously. Any operation that can be achieved by array subscripting can also be done with pointers. The pointer version will in general be faster but, at least to the uninitiated, somewhat harder to understand.

The declaration

```
int a[10];
```

defines an array a of size 10, that is, a block of 10 consecutive objects named a[0], a[1], ..., a[9].



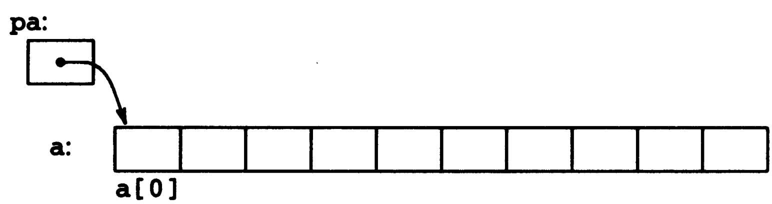
The notation a[i] refers to the i-th element of the array. If pa is a pointer to an integer, declared as

```
int *pa;
```

then the assignment

```
pa = &a[0];
```

sets pa to point to element zero of a; that is, pa contains the address of a[0].



Now the assignment

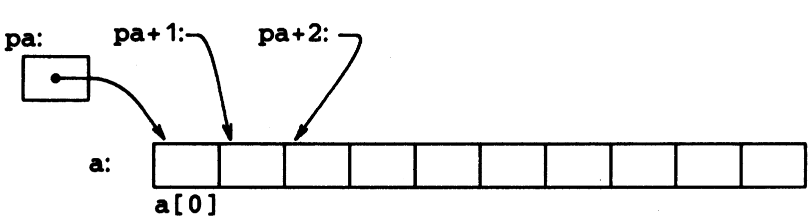
```
x = *pa;
```

will copy the contents of a[0] into x.

If pa points to a particular element of an array, then by definition pa+1 points to the next element, pa+i points i elements after pa, and pa-i points i elements before. Thus, if pa points to a[0],

```
*(pa+1)
```

refers to the contents of a[1], pa+i is the address of a[i], and *(pa+i) is the contents of a[i].



These remarks are true regardless of the type or size of the variables in the array a. The meaning of "adding 1 to a pointer," and by extension, all pointer arithmetic, is that pa+1 points to the next object, and pa+i points to the i-th object beyond pa.

The correspondence between indexing and pointer arithmetic is very close. By definition, the value of a variable or expression of type array is the address of element zero of the array. Thus after the assignment

```
pa = &a[0];
```

pa and a have identical values. Since the name of an array is a synonym for the location of the initial element, the assignment pa=&a[0] can also be written as

```
pa = a;
```

Rather more surprising, at least at first sight, is the fact that a reference to a[i] can also be written as *(a+i). In evaluating a[i], C converts it to *(a+i) immediately; the two forms are equivalent. Applying the operator & to both parts of this equivalence, it follows that &a[i] and a+i are also identical: a+i is the address of the i-th element beyond a. As the other side of this coin, if pa is a pointer, expressions may use it with a subscript; pa[i] is identical to *(pa+i). In short, an array-and-index expression is equivalent to one written as a pointer and offset.

There is one difference between an array name and a pointer that must be kept in mind. A pointer is a variable, so pa=a and pa++ are legal. But an array name is not a variable; constructions like a=pa and a++ are illegal.

When an array name is passed to a function, what is passed is the location of the initial element. Within the called function, this argument is a local variable, and so an array name parameter is a pointer, that is, a variable containing an address. We can use this fact to write another version of strlen, which computes the length of a string.

```
/* strlen:  return length of string s */
int strlen(char *s)
{
    int n;

    for (n = 0; *s != '\0'; s++)
        n++;
    return n;
}
```

Since s is a pointer, incrementing it is perfectly legal; s++ has no effect on the character string in the function that called strlen, but merely increments strlen's private copy of the pointer. That means that calls like

```
strlen("hello, world");   /* string constant */
strlen(array);            /* char array[100]; */
strlen(ptr);              /* char *ptr; */
```

all work.

As formal parameters in a function definition,

```
char s[];
```

and

```
char *s;
```

are equivalent; we prefer the latter because it says more explicitly that the parameter is a pointer. When an array name is passed to a function, the function can at its convenience believe that it has been handed either an array or a pointer, and manipulate it accordingly. It can even use both notations if it seems appropriate and clear.

It is possible to pass part of an array to a function, by passing a pointer to the beginning of the subarray. For example, if `a` is an array,

```
f(&a[2])
```

and

```
f(a+2)
```

both pass to the function `f` the address of the subarray that starts at `a[2]`. Within `f`, the parameter declaration can read

```
f(int arr[]) { ... }
```

or

```
f(int *arr) { ... }
```

So as far as `f` is concerned, the fact that the parameter refers to part of a larger array is of no consequence.

If one is sure that the elements exist, it is also possible to index backwards in an array; `p[-1]`, `p[-2]`, and so on are syntactically legal, and refer to the elements that immediately precede `p[0]`. Of course, it is illegal to refer to objects that are not within the array bounds.

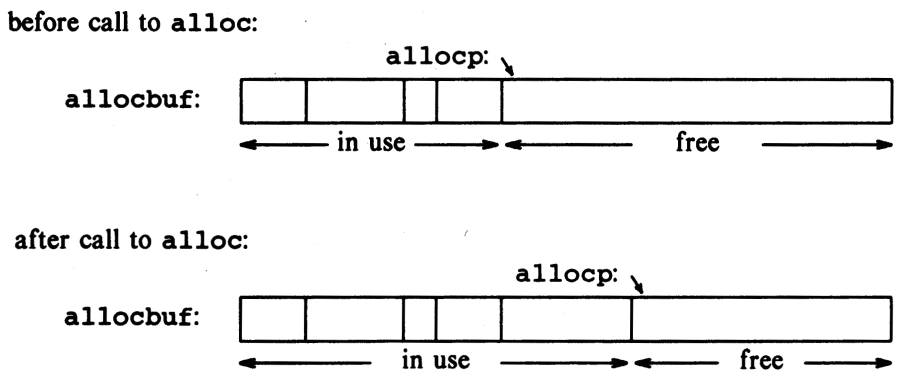
5.4 Address Arithmetic

If `p` is a pointer to some element of an array, then `p++` increments `p` to point to the next element, and `p+=i` increments it to point `i` elements beyond where it currently does. These and similar constructions are the simplest forms of pointer or address arithmetic.

C is consistent and regular in its approach to address arithmetic; its integration of pointers, arrays, and address arithmetic is one of the strengths of the language. Let us illustrate by writing a rudimentary storage allocator. There are two routines. The first, `alloc(n)`, returns a pointer `p` to `n` consecutive character positions, which can be used by the caller of `alloc` for storing characters. The second, `afree(p)`, releases the storage thus acquired so it can be re-used later. The routines are "rudimentary" because the calls to `afree` must be made in the opposite order to the calls made on `alloc`. That is, the storage managed by `alloc` and `afree` is a stack, or last-in, first-out list. The standard library provides analogous functions called `malloc` and `free` that have no such restrictions; in Section 8.7 we will show how they can be implemented.

The easiest implementation is to have `alloc` hand out pieces of a large character array that we will call `allocbuf`. This array is private to `alloc` and `afree`. Since they deal in pointers, not array indices, no other routine need know the name of the array, which can be declared `static` in the source file containing `alloc` and `afree`, and thus be invisible outside it. In practical implementations, the array may well not even have a name; it might instead be obtained by calling `malloc` or by asking the operating system for a pointer to some unnamed block of storage.

The other information needed is how much of `allocbuf` has been used. We use a pointer, called `allocp`, that points to the next free element. When `alloc` is asked for `n` characters, it checks to see if there is enough room left in `allocbuf`. If so, `alloc` returns the current value of `allocp` (i.e., the beginning of the free block), then increments it by `n` to point to the next free area. If there is no room, `alloc` returns zero. `afree(p)` merely sets `allocp` to `p` if `p` is inside `allocbuf`.




```
#define ALLOCSIZE 10000 /* size of available space */

static char allocbuf[ALLOCSIZE];  /* storage for alloc */
static char *allocp = allocbuf;   /* next free position */

char *alloc(int n)  /* return pointer to n characters */
{
    if (allocbuf + ALLOCSIZE - allocp >= n) { /* it fits */
        allocp += n;
        return allocp - n; /* old p */
    } else      /* not enough room */
        return 0;
}
```

```
void afree(char *p)  /* free storage pointed to by p */
{
    if (p >= allocbuf && p < allocbuf + ALLOCSIZE)
        allocp = p;
}
```

In general a pointer can be initialized just as any other variable can, though normally the only meaningful values are zero or an expression involving the addresses of previously defined data of appropriate type. The declaration

```
static char *allocp = allocbuf;
```

defines `allocp` to be a character pointer and initializes it to point to the beginning of `allocbuf`, which is the next free position when the program starts. This could have also been written

```
static char *allocp = &allocbuf[0];
```

since the array name *is* the address of the zeroth element.

The test

```
    if (allocbuf + ALLOCSIZE - allocp >= n) { /* it fits */
```

checks if there's enough room to satisfy a request for `n` characters. If there is, the new value of `allocp` would be at most one beyond the end of `allocbuf`. If the request can be satisfied, `alloc` returns a pointer to the beginning of a block of characters (notice the declaration of the function itself). If not, `alloc` must return some signal that no space is left. C guarantees that zero is never a valid address for data, so a return value of zero can be used to signal an abnormal event, in this case, no space.

Pointers and integers are not interchangeable. Zero is the sole exception: the constant zero may be assigned to a pointer, and a pointer may be compared with the constant zero. The symbolic constant `NULL` is often used in place of zero, as a mnemonic to indicate more clearly that this is a special value for a pointer. `NULL` is defined in `<stdio.h>`. We will use `NULL` henceforth.

Tests like

```
    if (allocbuf + ALLOCSIZE - allocp >= n) { /* it fits */
```

and

```
    if (p >= allocbuf && p < allocbuf + ALLOCSIZE)
```

show several important facets of pointer arithmetic. First, pointers may be compared under certain circumstances. If `p` and `q` point to members of the same array, then relations like `==`, `!=`, `<`, `>=`, etc., work properly. For example,

```
p < q
```

is true if `p` points to an earlier member of the array than `q` does. Any pointer can be meaningfully compared for equality or inequality with zero. But the behavior is undefined for arithmetic or comparisons with pointers that do not point to members of the same array. (There is one exception: the address of the first element past the end of an array can be used in pointer arithmetic.)

Second, we have already observed that a pointer and an integer may be added or subtracted. The construction

```
p + n
```

means the address of the n-th object beyond the one p currently points to. This is true regardless of the kind of object p points to; n is scaled according to the size of the objects p points to, which is determined by the declaration of p. If an `int` is four bytes, for example, the `int` will be scaled by four.

Pointer subtraction is also valid: if p and q point to elements of the same array, and p<q, then q-p+1 is the number of elements from p to q inclusive. This fact can be used to write yet another version of `strlen`:

```
/* strlen:  return length of string s */
int strlen(char *s)
{
    char *p = s;

    while (*p != '\0')
        p++;
    return p - s;
}
```

In its declaration, p is initialized to s, that is, to point to the first character of the string. In the `while` loop, each character in turn is examined until the `'\0'` at the end is seen. Because p points to characters, p++ advances p to the next character each time, and p-s gives the number of characters advanced over, that is, the string length. (The number of characters in the string could be too large to store in an `int`. The header `<stddef.h>` defines a type `ptrdiff_t` that is large enough to hold the signed difference of two pointer values. If we were being very cautious, however, we would use `size_t` for the return type of `strlen`, to match the standard library version. `size_t` is the unsigned integer type returned by the `sizeof` operator.)

Pointer arithmetic is consistent: if we had been dealing with `float`s, which occupy more storage than `char`s, and if p were a pointer to `float`, p++ would advance to the next `float`. Thus we could write another version of `alloc` that maintains `float`s instead of `char`s, merely by changing `char` to `float` throughout `alloc` and `afree`. All the pointer manipulations automatically take into account the size of the object pointed to.

The valid pointer operations are assignment of pointers of the same type, adding or subtracting a pointer and an integer, subtracting or comparing two pointers to members of the same array, and assigning or comparing to zero. All other pointer arithmetic is illegal. It is not legal to add two pointers, or to multiply or divide or shift or mask them, or to add `float` or `double` to them, or even, except for `void *`, to assign a pointer of one type to a pointer of another type without a cast.

5.5 Character Pointers and Functions

A *string constant*, written as

```
"I am a string"
```

is an array of characters. In the internal representation, the array is terminated with the null character `'\0'` so that programs can find the end. The length in storage is thus one more than the number of characters between the double quotes.

Perhaps the most common occurrence of string constants is as arguments to functions, as in

```
printf("hello, world\n");
```

When a character string like this appears in a program, access to it is through a character pointer; `printf` receives a pointer to the beginning of the character array. That is, a string constant is accessed by a pointer to its first element.

String constants need not be function arguments. If `pmessage` is declared as

```
char *pmessage;
```

then the statement

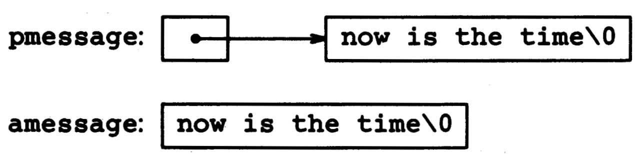
```
pmessage = "now is the time";
```

assigns to `pmessage` a pointer to the character array. This is *not* a string copy; only pointers are involved. C does not provide any operators for processing an entire string of characters as a unit.

There is an important difference between these definitions:

```
char amessage[] = "now is the time";   /* an array */
char *pmessage = "now is the time";    /* a pointer */
```

`amessage` is an array, just big enough to hold the sequence of characters and `'\0'` that initializes it. Individual characters within the array may be changed but `amessage` will always refer to the same storage. On the other hand, `pmessage` is a pointer, initialized to point to a string constant; the pointer may subsequently be modified to point elsewhere, but the result is undefined if you try to modify the string contents.



We will illustrate more aspects of pointers and arrays by studying versions of two useful functions adapted from the standard library. The first function is `strcpy(s,t)`, which copies the string `t` to the string `s`. It would be nice just to say `s=t` but this copies the pointer, not the characters. To copy the characters, we need a loop. The array version is first:

```
/* strcpy:  copy t to s; array subscript version */
void strcpy(char *s, char *t)
{
    int i;

    i = 0;
    while ((s[i] = t[i]) != '\0')
        i++;
}
```

For contrast, here is a version of `strcpy` with pointers:

```
/* strcpy:  copy t to s; pointer version 1 */
void strcpy(char *s, char *t)
{
    while ((*s = *t) != '\0') {
        s++;
        t++;
    }
}
```

Because arguments are passed by value, `strcpy` can use the parameters `s` and `t` in any way it pleases. Here they are conveniently initialized pointers, which are marched along the arrays a character at a time, until the `'\0'` that terminates `t` has been copied to `s`.

In practice, `strcpy` would not be written as we showed it above. Experienced C programmers would prefer

```
/* strcpy:  copy t to s; pointer version 2 */
void strcpy(char *s, char *t)
{
    while ((*s++ = *t++) != '\0')
        ;
}
```

This moves the increment of `s` and `t` into the test part of the loop. The value of `*t++` is the character that `t` pointed to before `t` was incremented; the postfix `++` doesn't change `t` until after this character has been fetched. In the same way, the character is stored into the old `s` position before `s` is incremented. This character is also the value that is compared against `'\0'` to control the loop. The net effect is that characters are copied from `t` to `s`, up to and including the terminating `'\0'`.

As the final abbreviation, observe that a comparison against `'\0'` is redundant, since the question is merely whether the expression is zero. So the function would likely be written as

```
/* strcpy:  copy t to s; pointer version 3 */
void strcpy(char *s, char *t)
{
    while (*s++ = *t++)
        ;
}
```

Although this may seem cryptic at first sight, the notational convenience is considerable, and the idiom should be mastered, because you will see it frequently in C programs.

The `strcpy` in the standard library (`<string.h>`) returns the target string as its function value.

The second routine that we will examine is `strcmp(s,t)`, which compares the character strings `s` and `t`, and returns negative, zero or positive if `s` is lexicographically less than, equal to, or greater than `t`. The value is obtained by subtracting the characters at the first position where `s` and `t` disagree.

```
/* strcmp:  return <0 if s<t, 0 if s==t, >0 if s>t */
int strcmp(char *s, char *t)
{
    int i;

    for (i = 0; s[i] == t[i]; i++)
        if (s[i] == '\0')
            return 0;
    return s[i] - t[i];
}
```

The pointer version of `strcmp`:

```
/* strcmp:  return <0 if s<t, 0 if s==t, >0 if s>t */
int strcmp(char *s, char *t)
{
    for ( ; *s == *t; s++, t++)
        if (*s == '\0')
            return 0;
    return *s - *t;
}
```

Since `++` and `--` are either prefix or postfix operators, other combinations of `*` and `++` and `--` occur, although less frequently. For example,

```
*--p
```

decrements `p` before fetching the character that `p` points to. In fact, the pair of expressions

```
*p++ = val;     /* push val onto stack */
val = *--p;     /* pop top of stack into val */
```

are the standard idioms for pushing and popping a stack; see Section 4.3.

The header `<string.h>` contains declarations for the functions mentioned in this section, plus a variety of other string-handling functions from the standard library.

Exercise 5-3. Write a pointer version of the function `strcat` that we showed in Chapter 2: `strcat(s,t)` copies the string `t` to the end of `s`. □

Exercise 5-4. Write the function `strend(s,t)`, which returns 1 if the string `t` occurs at the end of the string `s`, and zero otherwise. □

Exercise 5-5. Write versions of the library functions `strncpy`, `strncat`, and `strncmp`, which operate on at most the first `n` characters of their argument strings. For example, `strncpy(s,t,n)` copies at most `n` characters of `t` to `s`. Full descriptions are in Appendix B. □

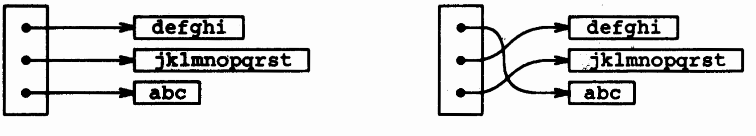
Exercise 5-6. Rewrite appropriate programs from earlier chapters and exercises with pointers instead of array indexing. Good possibilities include `getline` (Chapters 1 and 4), `atoi`, `itoa`, and their variants (Chapters 2, 3, and 4), `reverse` (Chapter 3), and `strindex` and `getop` (Chapter 4). □

5.6 Pointer Arrays; Pointers to Pointers

Since pointers are variables themselves, they can be stored in arrays just as other variables can. Let us illustrate by writing a program that will sort a set of text lines into alphabetic order, a stripped-down version of the UNIX program `sort`.

In Chapter 3 we presented a Shell sort function that would sort an array of integers, and in Chapter 4 we improved on it with a quicksort. The same algorithms will work, except that now we have to deal with lines of text, which are of different lengths, and which, unlike integers, can't be compared or moved in a single operation. We need a data representation that will cope efficiently and conveniently with variable-length text lines.

This is where the array of pointers enters. If the lines to be sorted are stored end-to-end in one long character array, then each line can be accessed by a pointer to its first character. The pointers themselves can be stored in an array. Two lines can be compared by passing their pointers to `strcmp`. When two out-of-order lines have to be exchanged, the pointers in the pointer array are exchanged, not the text lines themselves.



This eliminates the twin problems of complicated storage management and high overhead that would go with moving the lines themselves.

The sorting process has three steps:

read all the lines of input
sort them
print them in order

As usual, it's best to divide the program into functions that match this natural division, with the main routine controlling the other functions. Let us defer the sorting step for a moment, and concentrate on the data structure and the input and output.

The input routine has to collect and save the characters of each line, and build an array of pointers to the lines. It will also have to count the number of input lines, since that information is needed for sorting and printing. Since the input function can only cope with a finite number of input lines, it can return some illegal line count like -1 if too much input is presented.

The output routine only has to print the lines in the order in which they appear in the array of pointers.

```
#include <stdio.h>
#include <string.h>

#define MAXLINES 5000       /* max #lines to be sorted */

char *lineptr[MAXLINES];    /* pointers to text lines */

int readlines(char *lineptr[], int nlines);
void writelines(char *lineptr[], int nlines);

void qsort(char *lineptr[], int left, int right);

/* sort input lines */
main()
{
    int nlines;     /* number of input lines read */

    if ((nlines = readlines(lineptr, MAXLINES)) >= 0) {
        qsort(lineptr, 0, nlines-1);
        writelines(lineptr, nlines);
        return 0;
    } else {
        printf("error: input too big to sort\n");
        return 1;
    }
}
```

```
#define MAXLEN 1000   /* max length of any input line */
int getline(char *, int);
char *alloc(int);

/* readlines:  read input lines */
int readlines(char *lineptr[], int maxlines)
{
    int len, nlines;
    char *p, line[MAXLEN];

    nlines = 0;
    while ((len = getline(line, MAXLEN)) > 0)
        if (nlines >= maxlines || (p = alloc(len)) == NULL)
            return -1;
        else {
            line[len-1] = '\0'; /* delete newline */
            strcpy(p, line);
            lineptr[nlines++] = p;
        }
    return nlines;
}

/* writelines:  write output lines */
void writelines(char *lineptr[], int nlines)
{
    int i;

    for (i = 0; i < nlines; i++)
        printf("%s\n", lineptr[i]);
}
```

The function `getline` is from Section 1.9.

The main new thing is the declaration for `lineptr`:

```
char *lineptr[MAXLINES]
```

says that `lineptr` is an array of `MAXLINES` elements, each element of which is a pointer to a `char`. That is, `lineptr[i]` is a character pointer, and `*lineptr[i]` is the character it points to, the first character of the `i`-th saved text line.

Since `lineptr` is itself the name of an array, it can be treated as a pointer in the same manner as in our earlier examples, and `writelines` can be written instead as

```
/* writelines:  write output lines */
void writelines(char *lineptr[], int nlines)
{
    while (nlines-- > 0)
        printf("%s\n", *lineptr++);
}
```

Initially `*lineptr` points to the first line; each increment advances it to the next line pointer while `nlines` is counted down.

With input and output under control, we can proceed to sorting. The quicksort from Chapter 4 needs minor changes: the declarations have to be modified, and the comparison operation must be done by calling `strcmp`. The algorithm remains the same, which gives us some confidence that it will still work.

```
/* qsort:  sort v[left]...v[right] into increasing order */
void qsort(char *v[], int left, int right)
{
    int i, last;
    void swap(char *v[], int i, int j);

    if (left >= right)   /* do nothing if array contains */
        return;          /* fewer than two elements */
    swap(v, left, (left + right)/2);
    last = left;
    for (i = left+1; i <= right; i++)
        if (strcmp(v[i], v[left]) < 0)
            swap(v, ++last, i);
    swap(v, left, last);
    qsort(v, left, last-1);
    qsort(v, last+1, right);
}
```

Similarly, the swap routine needs only trivial changes:

```
/* swap:  interchange v[i] and v[j] */
void swap(char *v[], int i, int j)
{
    char *temp;

    temp = v[i];
    v[i] = v[j];
    v[j] = temp;
}
```

Since any individual element of `v` (alias `lineptr`) is a character pointer, `temp` must be also, so one can be copied to the other.

Exercise 5-7. Rewrite `readlines` to store lines in an array supplied by `main`, rather than calling `alloc` to maintain storage. How much faster is the program? □

5.7 Multi-dimensional Arrays

C provides rectangular multi-dimensional arrays, although in practice they are much less used than arrays of pointers. In this section, we will show some of their properties.

Consider the problem of date conversion, from day of the month to day of the year and vice versa. For example, March 1 is the 60th day of a non-leap year, and the 61st day of a leap year. Let us define two functions to do the conversions: `day_of_year` converts the month and day into the day of the year, and `month_day` converts the day of the year into the month and day. Since this latter function computes two values, the month and day arguments will be pointers:

```
month_day(1988, 60, &m, &d)
```

sets `m` to 2 and `d` to 29 (February 29th).

These functions both need the same information, a table of the number of days in each month ("thirty days hath September ..."). Since the number of days per month differs for leap years and non-leap years, it's easier to separate them into two rows of a two-dimensional array than to keep track of what happens to February during computation. The array and the functions for performing the transformations are as follows:

```
static char daytab[2][13] = {
    {0, 31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31},
    {0, 31, 29, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31}
};

/* day_of_year:  set day of year from month & day */
int day_of_year(int year, int month, int day)
{
    int i, leap;

    leap = year%4 == 0 && year%100 != 0 || year%400 == 0;
    for (i = 1; i < month; i++)
        day += daytab[leap][i];
    return day;
}

/* month_day:  set month, day from day of year */
void month_day(int year, int yearday, int *pmonth, int *pday)
{
    int i, leap;

    leap = year%4 == 0 && year%100 != 0 || year%400 == 0;
    for (i = 1; yearday > daytab[leap][i]; i++)
        yearday -= daytab[leap][i];
    *pmonth = i;
    *pday = yearday;
}
```

Recall that the arithmetic value of a logical expression, such as the one for `leap`, is either zero (false) or one (true), so it can be used as a subscript of the array `daytab`.

The array `daytab` has to be external to both `day_of_year` and