The Practice of Programming

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Contents

Preface

The presentation is organized into nine chapters, each focusing on one major aspect of programming practice.

Chapter 1 discusses programming style. Good style is so important to good programming that we have chosen to cover it first. Well-written programs are better than badly-written ones, they have fewer errors and are easier to debug and to modify, so it is import to think about style from the beginning. This chapter also introduces an important theme in good programming, the use of idioms (惯用语法) appropriate to the language being used.

Algorithms and data structures, the topics of Chapter 2, are the core of the computer science curriculum (课程) and a major part of programming courses. Since most readers will already be familiar with this material, our treatment is intended as a brief review of the handful of algorithms and data structures that show up in almost every program. More complex algorithms and data structures usually evolve from these building blocks, so one should master the basics.

Chapter 3 describes the design and implementation of a small program that illustrates algorithm and data structure issues in a realistic setting. The program is implemented in five language; comparing the versions shows how the same data structures are handled in each, and how expressiveness (表现力) and performance vary across a spectrum (系列) languages.

Interfaces between users, programs, and parts of programs are fundamental in programming and much of the success of software is determined by how well interfaces are designed and implemented. Chapter 4 show the evolution of a small library for parsing a widely used data format. Even though the example is small, it illustrates many of the concerns of interfaces design: abstraction, information hiding, resource management and error handling.

Much as we try to write a programs correctly the first time, bugs, and therefore debugging are inevitable. Chapter 5 gives strategies and tactics (策略) for systematic and effective debugging. Among the topics are the signatures of common bugs and the importance of "numerology" (命理学), where patterns in debugging often indicates where a problem lies.

Testing is an attempt to develop a reasonable assurance that a program is wording correctly and that it stays correct as it evolves. The emphasis in Chapter 6 is on systematic testing by hand and machine. Boundary condition tests probe at potential weak spots. Mechanization (机械化) and test scaffolds (脚手架) make it easy to do extensive testing with modest effort. Stress tests provide a different kind of testing than typical users do and ferret out (揪出) a different class of bugs.

Computers are so fast and compilers are so good that many programs are fast enough the day they are written. But others are too slow, or they use too much memory, or both. Chapter 7 presents an orderly way to approach the task of making a program use resources efficiently, so that the program remains correct and sound as it is made more efficient.

Chapter 8 covers portability. Successful programs live long enough that their environment changes, or they must be moved to new system or new hardware or new countries. The goal of portability is to reduce the maintenance of a program by minimizing the amount of change necessary to adapt it to a new environment.

Computing is rich in languages, not just the general-purpose ones that we use for the bulk of programming, but also many specialized languages that focus on narrow domains. Chapter 9 presents several examples of the importance of notation in computing, and shows how we can use it to simplify programs, to guide implementations, and even to help us write programs that write programs.

1

Style

It is an old observation that the best writers sometimes disregard the rules of rhetoric (修辞学). When they do so, however, the reader will usually find in the sentence some compensating (补偿) merit (优点), attained at the cost of the violation (违反). Unless he is certain of doing as well, he will probably do best to follow the rules.

William Strunk and E. B. White, *The Elements of Style*

This fragment of code comes from a large program written many years ago:

```
if ((country == SING) || (country == BRNI) ||
    (country == POL) || (country == ITALY))
{
    /*
     * If the country is Singapore, Brunei or Poland
     * then the current time is the answer time
     * rather than the off hook time.
     * Reset answer time and set day of week.
     */
     ...
}
```

It's carefully written, formatted, and commented, and the program it comes from works extremely well; the programmers who create these system are rightly proud of what they built. But this except is puzzling to the casual reader. What relationship links Singapore, Brunei, Poland and Italy? Why isn't Italy mentioned in the comment? Since the comment and the code differ, one of them must be wrong. Maybe both are. The code is what gets executed and tested, so it's more likely to be right; probably the comment didn't get updated when the code did. The comment doesn't say enough about the relationship among the three countries it does mention; if you had to maintain this code, you would need to know more.

The few lines above are typical of much real code: mostly well done, but with some things could be improved.

This book is about the practice of programming -- how to write programs for real. Our purpose is to help you to write software that works at least as well as the program this example was take from, while avoiding trouble spots and weakness. We will talk about writing better code from the beginning and improving it as it evolves.

We are going to start in an unusual place, however, by discussing programming style. The purpose of style is to make the code easy to read for yourself and others, and good style is crucial to good programming. We want to talk about it first so you will be sensitive to it as you read the code in the rest of the book.

These is more to writing a program than getting the syntax right, fixing the bugs, and making it run fast enough. Programs are read not only by computers but also by programmers. A well-written program is easier to understand and to modify than a poorly-written one. The discipline of writing well leads to code that is more like to be correct. Fortunately, this discipline is not hard.

The principles of programming style are based on common sense guided experience, not on arbitrary rules and prescriptions (命令). Code should be clear and simple -- straightforward login, natural expression, conventional language use, meaningful names, neat formatting, helpful comments -- and it should be avoid clever tricks and unusual constructions. Consistency is important because others will find it easier to read your code, and you theirs, if you all stick to the same style. Detail many be imposed by local conventions, management edict (法令), or a program, but even if not, but if even not, it is best to obey a set of widely shared conventions. We follow the style used in the book *The C Programming Language*, with minor adjustments for C++ and Java.

We will often illustrate rules of style by small example of bad and good programming, since the contrast between two ways of saying the same thing is instructive. These example are not artificial. The "bad" ones are all adapted from real code, written by ordinary programmers (occasionally yourselves) working under the common pressures of too much work and too little time. Some will be distilled (提取) for brevity (简短), but they will not be misrepresented (错误的叙述). Then we will rewrite the bad excerpts (摘录) to show how they could be improved. Since they are real code, however, they may exhibit (展现) multiple problems. Addressing every shortcoming would take us too far off topics, so some of the good examples will still harbor (隐藏) other, unremarked flaws (缺点).

To distinguish bad examples from good, throughout the book we will place question marks in the questionable code, as in this real excerpt (摘录):

```
?   #define ONE 1
?   #define TEN 10
?   #define TWENTY  20
```

Why are these `#defines` questionable? Consider the modification that will be necessary if an array of `TWENTY` elements must be made larger. At the very least (至少), each name should be replaced by one that indicates the role of the specific value in the program:

```
    #define INPUT_MODE  1
    #define INPUT_BUFSIZE   10
    #define OUTPUT_BUFSIZE  20
```

1.1 Names

What's in a name? A variable or function name labels an object and conveys information about its purpose. A name should be informative, concise, memorable, and pronounceable if possible. Much information comes from context and scope; the broader the scope of a variable, the more information should be conveyed by it's name.

Use descriptive names for globals, short names for locals. Global variables, by definition, can crop up (突然出现) anywhere in a program, so they need names long enough and descriptive enough to remind the reader of their meaning. It's also helpful to include a brief comment with the declaration of each global:

```
    int npending = 0;   // current length of input queue
```

Global functions, classes and structures should also have descriptive names that suggest their role in a program.

By contrast, shorter names suffice (足够) for local variables; within a function, `n` may be sufficient, `npoints` is fine, and `numberOfPoints` is overkill.

Local variables used in conventional way can have very short names. The use of `i` and `j` for loop indices, `p` and `q` for pointers, and `s` and `t` for strings is so frequent that there is little profit and perhaps some loss in longer names. Compare

```
?   for (theElementIndex = 0; theElementIndex < numberOfElements;
?           theElementIndex++)
?       elementArray[theElementIndex] = theElementIndex;
```

to

```
    for (i = 0; i < nelems; i++)
        elem[i] = i;
```

Programmers are often encouraged to use long variable names regardless of context. That is s mistake: clarity is often achieved through brevity.

There are many naming conventions and local customs. Common ones include using names that begin or end with `p`, such as `nodep`, for pointer; initial capital letters for `Globals`; and all capital for `CONSTANTs`. Some programming shop use more sweeping (彻底的) rules, such as notation to encode type and usage information in the variable, perhaps `pch` to mean a pointer to a character and `strTo` and `strFrom` to mean strings that will be written to and read from. As for the spelling of the names themselves, whether to use `npending` or `numPending` or `num_pending` is a matter of taste; specific rules are much less important than consistent adherence (坚持) to a sensible convention.

Naming conventions make it easier to understand your own code, as well as code written by others. They also make it easier to invent new names as the code is being written. The longer the program, the more important is the choice of good, descriptive, systematic names.

Namespaces in C++ and packages in Java provide ways to manage the scope of names and help to keep meanings clear without unduly (过度的) long names.

Be consistent. Give related things related names that show their relationship and highlight their difference.

Besides being much too long, the member names in this Java class are wildly (鲁莽地) inconsistent:

```
?   class UserQueue {
?       int noOfItemsInQ, frontOfTheQueue, queueCapacity;
?       public int noOfUserInQueue() { ... }
?   }
```

The word "queue" appears as Q, Queue and queue. But since queues can only be accessed from a variable of type `UserQueue`, member names do not need to mention "queue" at all; context suffices, so

```
?   queue.queueCapacity
```

is redundant. This version is better:

```
class UserQueue {
    int nitems, front, capacity;
    public int nusers() { ... }
}
```

since it leads to statements like

```
queue.capacity++;
n = queue.nusers();
```

No clarity is lost. This example still needs work, however, "items" and "users" are the same thing, so only one term should be used for a single concept.

Use active names for functions. Function names should be based on active verbs, perhaps followed by nouns:

```
now = data.getTime();
putchar('\n');
```

Functions that return boolean(true or false) value should be named so that return value is unambiguous. Thus

```
?   if (checkoctal(c)) ...
```

does not indicate which value is true and which is false, while

```
    if (isoctal(c)) ...
```

makes it clear that the function return true if argument is octal and false if not.

Be accurate. A name not only labels, it conveys information to the reader. A misleading names can result in mystifying (模糊的) bugs.

One of us wrote and distributed for years a macro called `isoctal` with this incorrect implementation:

```
?   #define isoctal(c) ((c) >= '0' && (c) <= '8')
```

instead of the proper

```
    #define isoctal(c) ((c) >= '0' && (c) <= '7')
```

In this case, the name conveyed the correct intent but the implementation was wrong; it's easy for a sensible name to disguise a broken implementation.

Here is an example in which the name and the code are in complete contradiction (矛盾):

```
?   public boolean inTable(Object obj) {
?       int j = this.getIndex(obj);
?       return(j == nTable);
?   }
```

The function `getIndex` returns a value between zero and `nTable-1` if it finds the object, and returns `nTable` if not. The boolean value returned by `inTable` is thus the opposite of what the name implies. At the time code is written, this might not cause trouble, but it the program is modified later, perhaps by a different programmer, the name is sure to confuse.

Exercise 1-1 . Comment on the choice of names and values in the following code.

```
?   #define TRUE    0
?   #define FALSE   1
?
?   if ((ch = getchar()) == EOF)
?       not_eof = FALSE;
```

□

Exercise 1-2 . Improve this function:

```
?   int smaller(char *s, char *t) {
?       if (strcmp(s, t) < 1)
?           return 1;
?       else
?           return 0;
?   }
```

□

Exercise 1-3 . Read this code aloud:

```
?   if ((falloc(SMRHSHSCRTCH, S_IFEXT|0644, MAXRODDHSH)) < 0)
?       ...
```

□

1.2 Expression and Statements

By analogy (类比) with choosing names to aid the reader's understanding, write expressions and statements in a way that makes their meaning as transport as possible. Write the clearest code that does the job. Use spaces around operators to suggest grouping; more generally, format to help readability. This is trivial (琐细的) but valuable, like keeping a neat desk so you can find things. Unlike your desk, your programs are likely to be examined by others.

Indent to show structure. A consistent indentation style is the lowest-energy way to make a program's structure self-evident (不言自明的). This example is badly formatted:

```
?   for(n++;n<100;field[n++]='\0');
?   *i = '\0'; return('\n');
```

Reformatting improves it somewhat:

```
?   for (n++; n < 100; field[n++] = '\0')
?       ;
?   *i = '\0';
?   return('\n');
```

Even better is to put the assignment in the body and separate the increment, so the loop takes a more conventional form and is thus easier to grasp (抓取):

```
    for (n++; n < 100; n++)
        field[n] = '\0';
    *i = '\0';
    return '\n';
```

Use the natural form for expressions. Write expressions as you might speak them aloud. Conditional expressions that include negations are always hard to understand:

```
?   if (!(block-id < actblks) || !(block-id >= unblocks))
?       ...
```

Each test is stated negatively, though there is no need for either to be. Turing the relations around lets us state the tests positively:

```
    if ((block-id >= actblks) || (block - id < unblocks))
        ...
```

Now the code reads naturally.

Parenthesize to resolves ambiguity. Parentheses specify grouping and can be used to make the intent clear event when they are not required. The inner parentheses in the previous example are not necessary, but they don't hurt, either. Seasoned (经验丰富的) programmers might omit them, because the relational operators(`< <= == != >= >`) have higher precedence than the logical operators(`&&` and `||`).

When mixing unrelated operators, though, it's a good idea to parenthesize. C and it's friends present pernicious (恶劣的) precedence problems, and it's easy to make a mistake. Because the logical operators bind tighter than assignment, parentheses are mandatory for most expressions that combine them:

```
    while ((c = getchar()) != EOF)
        ...
```

The bitwise operators `&` and `|` have lower precedence than relational operators like `==`, so despite it's appearance,

```
?   if (x&MASK == BITS)
?       ...
```

actually means

```
?   if (x & (MASK==BITS))
?       ...
```

which is certainly not the programmer's intent. Because it combines bitwise and relational operators, the expression need parentheses:

```
    if ((x&MASK) == BITS)
        ...
```

Even if parentheses aren't necessary, they can help if the grouping is hard to grasp at first glance. This code doesn't need parentheses:

```
?   leap_year = y % 4 == 0 && y % 100 != 0 || y % 400 == 0;
```

but they make it easier to understand:

```
    leap_year = ((y%4 == 0) && (y%100 != 0)) || (y%400 == 0);
```

We also removed some of the blanks: grouping the operands of higher-precedence operators helps the readers to see the structure more quickly.

Break up complex expressions. C, C++ and Java have rich expression syntax and operators, and it's easy to get carried away by cramming (塞满) everything into one construction. An expression like the following is compact (紧凑的) but it packs too many operations into a single statement:

```
?   *x += (*xp=(2*k < (n-m) ? c[k+1] : d[k--]));
```

It's easier to grasp when broken into several pieces:

```
    if (2*k < n-m)
        *xp = c[k+1];
    else
        *xp = d[k--];
    *x += *xp;
```

Be clear. Programmers' endless creative energy is sometimes used to write the most concise code possible, or to find clever ways to achieve a result. Sometimes these skills are misapplied, though, since the goal is to write clear code, not clever code.

What does this intricate (复杂的) calculation do?

```
?   subkey = subkey >> (bitoff - ((bitoff >> 3) << 3));
```

The innermost expression shifts `bitoff` three bits to the right. The result is shifted left again, thus replacing the three shifted bits by zeros. This result in turn is subtracted from the original value, yielding the bottom three bits of `bitoff`. These three bits are used to shift `subkey` to the right.

Thus the original expression is equivalent to

```
    subkey = subkey >> (bitoff & 0x7);
```

It takes a while to puzzle out what the first version is doing; the second is shorter and clearer. Experienced programmers make it ever shorter by using assignment operator:

```
    subkey >>= bitoff & 0x7;
```

Some constructs seem to invite abuse. The `?:` operator can lead to mysterious code:

```
?   child=(!LC&&!RC)?0:(!LC?RC:LC);
```

It's almost impossible to figure out what this code without following all the possible paths through the expression. This form is longer, but much easier to follow because it makes the paths explicit:

```
    if (LC == 0 && RC == 0)
        child = 0;
    else if (LC == 0)
        child = RC;
    else
        child = LC;
```

The `?:` operator is fine for short expressions where it can replace four lines of if-else with one, as in

```
    max = (a > b) ? a : b;
```

or perhaps

```
    printf("The list has %d item%s\n", n, n==1 ? "" : "s");
```

but it is not a general replacement for conditional statements.

Be careful with side effect. Operators like ++ have side effects: besides returning a value, they also modify an underlying variable. Side effects can be extremely convenient, but they can also cause trouble because the actions of retrieving the value and updating the variable might not happen at the same time. In C and C++, the order of execution of side effects is undefined, so this multiple assignment is likely to produce the wrong answer:

```
?   str[i++] = str[i++] = ' ';
```

The intent is to store blanks at the next two position in `str`. But depending on when `i` is updated, a position in `str` could be skipped and `i` might end up increased only by 1. Break it into two statements:

```
    str[i++] = ' ';
    str[i++] = ' ';
```

Even though it contains only one increment, this assignment can also give varying results:

```
?   array[i++] = i;
```

If `i` is initially 3, the array element might be set to 3 or 4.

It's not just increment and decrement that have side effects; I/O is another source of behind-the-scenes (幕后的) action. This example is an attempt to read two related numbers from standard input:

```
?   scanf("%d %d", &yr, &profit[yr]);
```

It is broken because part of the expression modifies `yr` and another part uses it. The value of `profit[yr]` can never be right unless the new value of `yr` is the same as the old one. You might think that the answer depends on the order in which the arguments are evaluated, but the real issue is that all the arguments to `scanf` are evaluated before the routine is called, so `&profit[yr]` will always be evaluated using the old value of `yr`. This sort of problem can occur in almost any language. The fix is, as usual, to break up the expression:

```
    scanf("%d", &yr);
    scanf("%d", &profit[yr]);
```

Exercises caution in any expression with side effects.

Exercise 1-4 . Improves each of these fragments:

```
?   if (!(c == 'y' || c == 'Y'))
?       return;
?   length = (length < BUFSIZE) ? length : BUFSIZE;
?   flag = flag ? 0 : 1;
?   quote = (*line == '"') ? 1 : 0;
?   if (val & 1)
?       bit = 1;
?   else
?       bit = 0;
```

□

Exercise 1-5 . What is wrong with this excerpt (摘录)?

```
?   int read(int *ip) {
?       scanf("%d", ip);
?       return *ip;
?   }
?       ...
?   insert(&graph[vert], read(&val), read(&ch));
```

□

Exercise 1-6 . List all the different output this could produce with various orders of evaluation:

```
?   n = 1;
?   printf("%d %d\n", n++, n++);
```

Try it on as many compilers as you can, to see what happens in practice. □

1.3 Consistency and Idioms (习惯用法)

Consistency leads to better programs. If formatting varies unpredictably, or loop over an array runs until this time and downhill the next, or strings are copied with `strcpy` and a `for` loop there, the variations make it harder to see what's really going on. But if the same computation is done the same way every time it appears, any variation suggests a genuine (真正的) difference, one worth nothing.

Use a consistent indentation and brace style. Indentation show structure, but which indentation style is best? Should the opening brace go one the same line as the `if` for on the next? Programmers have always argued about the layout of program, but the specific style is much less important than its consistent application. Pick one style, preferably (更合意地) ours, use it consistently, and don't waste time arguing.

Should you include braces even when they are not needed? Like parentheses, braces can resolve ambiguity and occasionally make the code clearer. For consistency, many experienced programmers always put braces around loop or `if` bodies. But if the body is a single statement they are unnecessary, so we tend to omit them. If you also choose to leave them out, make sure you don't drop them when they are needed to resolve the "dangling (悬挂的) else" ambiguity exemplified (示例) by this excerpt (摘录):

```
?   if (month == FEB) {
?       if (year%4 == 0)
?           if (day > 29)
?               legal = FALSE;
?       else
?           if (day > 28)
?               legal = FALSE;
?   }
```

The indentation is misleading, since the `else` is actually attached to the line

```
?   if (day > 29)
```

and the code is wrong. When one `if` immediately follows another, always use braces:

```
?   if (month == FEB) {
?       if (year%4 == 0) {
?           if (day > 29)
?               legal = FALSE;
?       } else {
?           if (day > 28)
?               legal = FALSE;
?       }
?   }
```

Syntax-driven tools make this sort of mistake less likely.

Even with the bug fixed, though, the code is hard to follow. The computation is easier to grasp if we use a variable to hold the number of days in February:

```
?   if (month == FEB) {
?       int nday;
?
?       nday = 28;
?       if (year%4 == 0)
?           nday == 29;
?       if (day > nday)
```

```
?           legal = FALSE;
?   }
```

The code still wrong -- 2000 is a leap year, while 1900 and 2100 are not -- but this structure is much easier to adapt to make it absolutely right.

By the way, if you work on a program you didn't write, preserve the style you find there. When you make a change, don't use your own style even though you prefer it. The program's consistency is more important than your own, because it makes life easier for those who follow.

Use idioms for consistency. Like natural language, programming languages have idioms, conventional ways that experienced programmers write common pieces of code. A central part of learning any language is developing a familiarity with its idioms.

One of the most common idioms is the form of a loop. Consider the C, C++, or Java code for stepping through the `n` elements of an array, for example to initialize them. Someone might write the loop like this:

```
?   i = 0;
?   while (i <= n-1)
?       array[i++] = 1.0;
```

or perhaps like this:

```
?   for (i = 0; i < n; )
?       array[i++] = 1.0;
```

or even:

```
?   for (i = 0; --i >= 0; )
?       array[i] = 1.0;
```

All of these are correct, but the idiomatic form is like this:

```
    for (i = 0; i < n; i++)
        array[i] = 1.0;
```

This is not an arbitrary choice. It visits each member of an n-element array indexed from `0` to `n-1`. It places all the loop control in the `for` itself, runs in increasing order, and uses the very idiomatic ++ operator to update the loop variable. It leaves the index variable at a known value just beyond the last array element. Native speakers recognize it which study and write it correctly without a moment's thought.

In C++ or Java, a common variant includes the declaration of the loop variable:

```
    for (int i = 0; i < n; i++)
        array[i] = 1.0;
```

Here is the standard loop for walking along a list in C:

```
    for (p = list; p != NULL; p = p->next)
        ...
```

Again, all the loop control is in the `for`.

For an infinite loop, we prefer

```
    for (;;)
        ...
```

but

```
while (1)
    ...
```

is also popular. Don't use anything other than these forms.

Indentation should be idiomatic, too. This unusual vertical layout detracts (贬低) from readability; it looks like three statements, not a loop:

```
?   for (
?       ap = arr;
?       ap < arr + 128;
?       *ap++ = 0
?       )
?   {
?       ;
?   }
```

A standard loop is much easier to read:

```
for (ap = arr; ap < arr+128; ap++)
    *ap = 0;
```

Sprawling (蔓延的) layout also force code onto multiple screens or pages, and thus detract from readability.

Another common idiom is to nest an assignment inside a loop condition, as in

```
while ((c = getchar()) != EOF)
    putchar(c);
```

The `do-while` statement is used much less often than `for` and `while`, because it always executes at least once, testing at the bottom of the loop instead of the top. In many cases, that behavior is a bug waiting to bite, as in this rewrite of the `getchar` loop:

```
?   do {
?       c = getchar();
?       putchar(c);
?   } while (c != EOF);
```

It write a spurious (假的) output character because the test occurs after the call to `putchar`. The `do-while` loop is the right one only when the body of the loop must always be executed at least once; we'll see some examples later.

One advantage of the consistent use of idioms is that it draws attentions to non-standard loops, a frequent sign of trouble:

```
int i, *iArray, nmemb;

iArray = malloc(nmemb * sizeof(int));
for (i = 0; i <= nmemb; i++)
    iArray[i] = i;
```

Space is allocated for `nmemb` items, `iArray[0]` through `iArray[nmemb-1]`, but since the loop test is <= the loop walks off the end of array and overwrites whatever is stored next in memory. Unfortunately, error like this are often not detected until long after the damage has been done.

C and C++ also have idioms for allocating space for strings and then manipulating it, and code that doesn't use them often harbors (隐藏) a bug:

```
?   char *p, buf[256];
?
?   gets(buf);
?   p = malloc(strlen(buf));
?   strcpy(p, buf);
```

One should never use `gets`, since there is no way to limit the amount of input it will read. This leads to security problems that we'll return to in Chapter 6, where we will show that `fgets` is always a better choice. But there is another problem as well: `strlen` does not count the `'\0'` that terminates a string, while `strcpy` copies it. So not enough space is allocated, and `strcpy` writes past the end of allocated space. The idiom is

```
p = malloc(strlen(buf) + 1);
strcpy(p, buf);
```

or

```
p = new char[strlen(buf) + 1];
strcpy(p, buf);
```

in C++. If you don't see the `+1`, beware.

Java doesn't suffer from this specific problem, since string are not represented as null-terminated arrays. Array subscripts are checked as well, so it is not possible to access outside the bounds of an array in Java.

Most C and C++ environments provide a library function, `strdup`, that creates a copy of a string using `malloc` and `strcpy`, making it easy to avoid this bug. Unfortunately, `strdup` is not part of the ANSI C standard.

By the way, neither the original code nor the corrected version check the value returned by `malloc`. We omitted this improvement to focus on the main point, but in a real program the return value from `malloc`, `realloc`, `strdup`, or any other allocation routine should always be checked.

Use else-ifs for multi-way decisions. Multi-way decisions are idiomatically expressed as a chain of `if .. else if .. else`, like this:

```
if (condition1)
    statement1
else if (condition2)
    statement2
...
else if (condition_i)
    statement_i
else
    default-statement
```

The *conditions* read from top to bottom; at the first *condition* that is satisfied, the *statement* that follows is executed, and then rest of the construct is skipped. The *statement* part may be a single statement or group of statements enclosed in braces. The last `else` handles the "default" situation, where none of the other alternatives was chosen. This trailing (拖尾的) `else` part may be omitted if there is no action for the default, although leaving it with an error message may help to catch conditions that "can't happen".

Align all of the `else` clauses (子句) vertically rather than lining up (排列) each `else` with the corresponding `if`. Vertical alignment emphasizes that test are done in sequence and keep them from marching off (步进, 越来越近) the right side of the page.

A sequence of nested `if` statement is often a warning of awkward (笨拙的) code, if not outright (显示) errors:

```
?   if (argc == 3)
?       if ((find == fopen(argv[1], "r")) != NULL)
?           if ((fout = fopen(argv[2], "w")) != NULL) {
?               while ((c = getc(find)) != EOF)
?                   putc(c, fout);
?               fclose(fin); fclose(fout);
?           } else
?               printf("Can't open output file %s\n", argv[1]);
?       else
?           printf("Can't open input file %s\n", argv[1]);
?   else
?       printf("Usage: cp inputfile outputfile\n");
```

The sequence of `ifs` requires us to maintain a mental (心理的) pushdown (推进) stack of what tests were make, so that at the appropriate point we can pop them until we determine the corresponding action (if we can still remember). Since at most one action will be performed, we really want an `else if`. Changing the order in which the decisions are made leads to a clearer version, in which we have also corrected the resource leak (泄漏) in the original:

```
    if (argc != 3)
        printf("Usage: cp inputfile outputfile\n");
    else if ((fin = fopen(argv[1], "r")) == NULL)
        printf("Can't open input file %s\n", argv[1]);
    else if ((fout = fopen(argv[2], "w")) == NULL) {
        printf("Can't open output file %s\n", argv[2]);
        fclose(fin);
    } else {
        while ((c = getc(fin)) != EOF)
            putc(c, fout);
        fclose(fin);
        fclose(fout);
    }
```

We read down the tests until the first one that is true, do the corresponding action, and continue after the last `else`. The rule is to follow each decision as closely as possible by it's associated action. Or, to put it another way, each time you make a test, do something.

Attempts to re-use pieces of code often lead to tightly knotted (纠缠的) programs.

```
?   switch (c) {
?   case '-': sign = -1;
?   case '+': c = getchar();
?   case '.': break;
?   default: if (!isdigit(c))
?                return 0;
?   }
```

This uses a tricky sequence of fall-through in the `switch` statement to avoid duplicating one line of code. It's also not idiomatic; cases should almost always end with a `break`, with the rare exceptions commented. A more traditional layout and structure is easier to read, though longer:

```
?   switch (c) {
?   case '-':
```

```
?       sign = -1;
?       /* fall through */
?   case '+':
?       c = getchar();
?       break;
?   case '.':
?       break;
?   default:
?       if (!isdigit(c))
?           return 0;
?       break;
?   }
```

The increase in size is more than offset by the increase in clarity. However, for such an unusual structure, a sequence of `else-if` is even clearer:

```
    if (c == '-') {
        sign = -1;
        c = getchar();
    } else if (c == '+') {
        c = getchar();
    } else if (c != '.' && !isdigit(c)) {
        return 0;
    }
```

The braces around the one-line blocks highlight the parallel structure.

An acceptable use of a fall-through occurs when several cases have identical code; the conventional layout is like this:

```
    case '0':
    case '1':
    case '2':
        ...
        break;
```

and no comment is required.

Exercise 1-7 . Rewrite these C/C++ excerpts more clearly:

```
?       if (istty(stdin)) ;
?       else if (istty(stdout)) ;
?           else if (istty(stderr)) ;
?               else return(0);

?       if (retval != SUCCESS)
?           return(retval);
?       /* All went well */
?       return SUCCESS;

?       for (k = 0; k++ < 5; x += dx)
?           scanf("%lf", &dx);
```

□

Exercise 1-8 . Identify the errors in this Java fragment and repair it by rewriting with an idiomatic loop:

```
?       int count = 0;
?       while (count < total) {
?           count++;
?           if (this.getName(count) == nametable.userName()) {
?               return (true);
?           }
?       }
```

□

1.4 Function Macros

There is a tendency among older C programmers to write macros instead of function for very short computations that will be executed frequently; I/O operations such as `getchar` and character test like `isdigit` are officially sanctioned (认可的) examples. The reason is performance: a macro avoids the overhead of a function call. This argument was weak even when C was first defined, a time of slow machines and expensive function calls; today it is irrelevant. With modern machines and compilers, the drawbacks of function macros outweigh (超过) their benefits.

Avoid function macros. In C++, `inline` functions render (补偿) function macros unnecessary; in Java, there are no macros. In C, they cause more problems than they solve.

One of the most serious problem with function macros is that a *parameter* that appears more than once in the definition might be evaluated more than once; if the argument in the call includes an expression with side effect, the result is a subtle (微妙的) bug. This code attempts to implement one of the character tests from `<ctype.h>`:

```
?   #define isupper(c) ((c) >= 'A' && (c) <= 'Z')
```

Note that the parameter `c` occurs twice in the body of the macro. If `isupper` is called in a context like this,

```
?   while (isupper(c = getchar()))
?       ...
```

then each time an input character is greater than or equal to `A`, it will be discarded and another character read to be tested against `Z`. The C standard is carefully written to permit `isupper` and analogous functions to be macros, but only if they guarantee to evaluate the argument only once, so this implementation is broken.

It's always better to use the `ctype` function than to implement them yourself, and it's safer not to nest routine like `getchar` that have side effects. Rewriting the test to use two expressions rather one makes it clearer and also gives an opportunity to catch end-of-file explicitly:

```
    while ((c = getchar()) != EOF && isupper(c))
        ...
```

Sometimes multiple evaluation causes a performance problem rather than an outright error. Consider this example:

```
?   #define ROUND_TO_INT(x) ((int) ((x)+(((x)>0)?0.5:-0.5)))
?       ...
?   size = ROUND_TO_INT(sqrt(dx*dx + dy*dy));
```

This will perform the square root computation twice as often as necessary. Even given simple arguments, a complex expression like the body of `ROUND_TO_INT` translates into many instructions, which should be housed (收藏) in a single function to be called when needed. Instantiating a macro at every occurrence makes the compiled program larger. (C++ `inline` functions have this drawback, too.)

Parenthesize the macro body and arguments. If you insist on using function macros, be careful. Macros work by textual substitution: the parameters in the definition are replaced by the arguments of the call and the result replaces the original call, as text. This is a troublesome difference from function. This expression

```
    1 / square(x)
```

works fine if square is a function, but if it's a macro like this,

```
?   #define square(x) (x) * (x)
```

the expression will be expanded to the erroneous

```
?   1 / (x) * (x)
```

The macro should be rewritten as

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

All those parentheses are necessary. Even parenthesizing the macro properly does not address the multiple evaluation problem. If an operation is expensive or common enough to be wrapped up, use a function.

In C++, `inline` functions avoid the syntactic trouble while offering whatever performance advantage macros might provide. They are appropriate for short functions that set or retrieve a single value.

Exercise 1-9 . Identify the problems with this macro definition:

```
?       #define ISDIGIT(c) ((c >= '0') && (c <= '9')) 1 : 0
```

□

1.5 Magic Numbers

Magic numbers are the constants, array sizes, character positions, conversion factors, and other literal numeric values that appear in programs.

Give names to magic numbers. As a guideline, any number other than 0 or 1 is likely to be magic and should have a name of its own. A raw number in program source gives no indication of its importance or derivation (来历), making the program harder to understand and modify. This excerpt from a program to print a histogram of letter frequencies on a 24 by 80 cursor-addressed terminal is needlessly opaque (不透明的) because of a host of magic numbers:

```
?   fac = lim / 20;      /* set scale factor */
?   if (fac < 1)
?       fac = 1;
?
?                        /* generate histogram */
?   for (i = 0, col = 0; i < 27; i++, j++) {
?       col += 3;
?       k = 21 - (let[i] / fac);
```

```
?       star = (let[i] == 0) ? ' ' : '*';
?       for (j = k; j < 22; j++)
?           draw(j, col, star);
?   }
?   draw(23, 2, ' '); /* label x axis */
?   for (i = 'A'; i <= 'Z'; i++)
?       printf("%c ", i);
```

The code includes, among others, the number 20, 21, 22, 23. They're clearly related... or are they? In fact, there are only three numbers critical to this program: 24, the number of rows on the screen; 80, the number of column; and 26, the number of letters in the alphabet. But none of these appears in the code, which makes the numbers that do even more magical.

By giving names to the principal (主要的) numbers in the calculation, we can make the code easier to follow. We discover, for instance, that the number 3 comes from (80-1)/26 and that `let` should have 26 entries, not 27 (an off-by-one error perhaps caused by 1-indexed screen coordinates). Making a couple of other simplifications, this is the result:

```
enum {
    MINROW   = 1,                   /* top edge */
    MINCOL   = 1,                   /* left edge */
    MAXROW   = 24,                  /* bottom edge (<=) */
    MAXCOL   = 80,                  /* right edge (<=) */
    LABELROW = 1,                   /* position of labels */
    NLET     = 26,                  /* size of alphabet */
    HEIGHT   = MAXROW - 4,          /* height of bars */
    WIDTH    = (MAXCOL-1)/NLET,     /* width of bars */
};

...
fac = (lim + HEIGHT - 1) / HEIGHT;  /* set scale factor */
if (fac < 1)
    fac = 1;
for (i = 0; i < NLET; i++) { /* generate histogram */
    if (let[i] == 0)
        continue;
    for (j = HEIGHT - let[i]/fac; j < HEIGHT; j++)
        draw(j+1+LABELROW, (i+1)*WIDTH, '*');
}
draw(MAXROW-1, MINCOL+1, ' '); /* label x axis */
for (i = 'A'; i <= 'Z'; i++)
    printf("%c ", i);
```

Now it's clearer what the main loop does: it's an idiomatic loop from 0 to `NLET`, indicating that the loop is over the elements of the data. Also the calls to `draw` are easier to understand because words like `MAXROW` and `MINCOL` remind us of the order of arguments. Most important, it's now feasible to adapt the program to another size of display or different data. The numbers are demystified (易懂的) and so is the code.

Define numbers as constants, not macros. C programmers have traditional used `#define` to manage magic number values. The C preprocessor is a powerful but blunt (愚蠢的) tool, however, and macros are a dangerous way to program because they change the lexical structure of the program underfoot (碍事的). Let the language proper do the work. In C and C++, integer constants can be defined with an `enum` statement, as we say in the previous example. Constants of any type can be declared with `const` in C++:

```
const int MAXROW = 24, MAXCOL = 80;
```

or `final` in Java:

```
    static final int MAXROW = 24, MAXCOL = 80;
```

C also has `const` values but they cannot be used as array bounds, so the `enum` statement remains the method of choice in C.

Use character constants, not integers. The functions in `<ctype.h>` or their equivalent should be used to test the properties of character. A test like this:

```
?   if (c >= 65 && c <= 90)
?       ...
```

depends completely on a particular character representation. It's better to use

```
?   if (c >= 'A' && c <= 'Z')
?       ...
```

but that may not have the desired effect if the letters are not contiguous in the character set encoding or if the alphabet include other letters. Best is to use the library:

```
    if (isupper(c))
        ...
```

in C or C++, or

```
    if (Character.isUpperCase(c))
        ...
```

in Java.

A related issue is that the number 0 appears often in programs, in many contexts. The compiler will convert the number into the appropriate type, but it helps the reader to understand the role of each 0 if the type is explicit. For example, use `(void *)0` or `NULL` to represent a zero pointer in C, and `'\0'` instead of `0` to represent the null byte at the end of a string. In other words, don't write

```
?   str = 0;
?   name[i] = 0;
?   x = 0;
```

but rather:

```
    str = NULL;
    name[i] = '\0';
    x = 0.0;
```

We prefer to use different explicit constants, reserving 0 for a literal integer zero, because they indicate the use of the value and thus provide a bit of documentation. In C++, however, `0` rather than `NULL` is the acceptable notation for a null pointer. Java solves the problem best by defining the keyword `null` for an object reference that doesn't refer to anything.

Use the language to calculate the size of an object. Don't use an explicit size for any data type; use `sizeof(int)` instead of `2` or `4`, for instance. For similar reasons, `sizeof(array[0])` may be better than `sizeof(int)` because it's one less thing to change if the type of the array changes.

The `sizeof` operator is sometimes a convenient way to avoid inventing names for the numbers that determine array size. For example, if we write

```
char    buf[1024];
fgets(buf, sizeof(buf), stdin);
```

the buffer size is still a magic number, but it occurs only once, in the declaration. It may not be worth inventing a name for the size of a local array, but it is definitely worth writing code that does not have to change if the size or type changes.

Java arrays have `length` that gives the numbers of elements:

```
char buf[] = new char[1024];
for (int i = 0; i < buf.length; i++)
    ...
```

There is no equivalent of `.length` in C and c++, but for an array (not a pointer) whose declaration is visible, this macro computes the number of elements in the array:

```
#define NELEMS(array) (sizeof(array) / sizeof(array[0]))

double dbuf[100];
for (i = 0; i < NELEMS(dbuf); i++)
    ...
```

The array size is set in only one place; the rest of the code not change if the size does. There is no problem with multiple evaluation of the macro argument here, since there can be no side effects, and in fact the computation is done as the program is being compiled. This is an appropriate use for a macro because it does something that a function cannot: compute the size of an array from its declaration.

Exercise 1-10 . How would you rewrite these definitions to minimize potential errors?

```
?       #define FTZMETER    0.3048
?       #define METERZFT    328084
?       #define MIZFT       5280.0
?       #define MIZKM       1.609344
?       #define SQMIZSQKM   2.589988
```

□

1.6 Comments

Comments are meant to help the reader of a program. They do not help by saying things the code already plainly (清楚地) says, or by contradicting (矛盾) the code, or by distracting (分心) the reader with elaborate (详细说明) typographical (印刷的) displays. The best comments aid the understanding of a program by briefly pointing out salient (突出的) details or by providing a larger-scale view of the proceedings (进程, 进行).

Don't belabor (痛打) the obvious. Comments shouldn't report self-evident information, such as the fact that `i++` increments `i`. Here are some of our favorite worthless comments:

```
?   /*
?    * default
?    */
?   default:
?       break;
```

```
?   /* return SUCCESS */
?   return SUCCESS;

?   zerocount++;    /* increment zero entry counter */

?   /* initialize "total" to "number_received" */
?   node->total = node->number_received;
```

All of these comments should be deleted; they're just clutter (杂物).

Comments should add something that is not immediately evident from the code, or collect into one place information that is spread through the source. When something subtle (微妙的) is happening, a comment may clarify, but if the actions are obvious already, restating them in words is pointless:

```
?   while ((c = getchar()) != EOF && isspace(c))
?       ;   /* skip white space */
?   if (c == EOF)   /* end of file */
?       type = endoffile;
?   else if (c == '(')  /* left parenthesis */
?       type = leftparen;
?   else if (c == ';')  /* semicolon */
?       type = semicolon;
?   else if (isdigit(c))    /* number */
?       ...
```

These comments should also be deleted, since the well-chosen names already convey the information.

Comment functions and global data. Comments can be useful, of course. We comment functions, global variables, constant definitions, fields in structures and classes, and anything else where a brief summary can aid understanding.

Global variables have a tendency to crop up (突然出现) intermittently (间歇地) throughout a program; a comment serves as a reminder to be referred to as needed. Here's an example from a program in Chapter 3 of this book:

```
    struct State { /* prefix + suffix list */
        char    *pref[NPREF];   /* prefix words */
        Suffix  *suf;           /* list of suffixes */
        State   *next;          /* next in hash table */
    };
```

A comment that introduces each function set the stage for reading the code itself. If the code isn't too long or technical, a single line is enough:

```
    // random: return an integer in the range [0, r-1].
    int random(int r)
    {
        return (int)(Math.floor(Math.random() * r));
    }
```

Sometimes code is genuinely (真正地) difficult, perhaps because the algorithm is complicated or the data structure are intricate (复杂的). In that case, a comment that points to a source of understanding can aid the reader. It may also be valuable to suggest why particular decisions were made. This comment introduces an extremely efficient implementation of an inverse (反转) discrete (离散) cosine transform (DCT) used in JPEG image decoder:

```
/*
 * idct: Scaled integer implementation of
 * inverse two dimensional 8*8 Discrete Cosine Transform,
 * Chen-Wang algorithm (IEEE ASSP-32, pp 803-816, Aug 1984)
 *
 * 32-bit integer arithmetic (8-bit coefficients)
 * 11 multiplies, 29 adds per DCT
 *
 * coefficients extended to 12 bits for IEEE 1180-1990 compliance.
 */
 static void dict(int b[8*8])
 {
     ...
 }
```

This helpful comments cites the reference, briefly describes the data used, indicates the performance of the algorithm, and tells how and why the original algorithm has been modified.

Don't comment bad code, rewrite it. Comment anything unusual or potentially confusing, but when the comment outweigh the code, the code probably needs fixing. This example uses a long, muddled (胡乱对付的) comment and a conditional-compiled debugging print statement to explain to a single statement:

```
?   /* if "result" is 0, a match was found, so return true.
?    * otherwise, "result" is non-zero, so return false
?    */
?   #ifdef DEBUG
?   printf("*** isword returns !result = %d\n", !result);
?   fflush(stdout);
?   #endif
?
?   return(!result);
```

Negation is hard to understand and should be avoided. Part of the problem is the uninformative (无法提供信息的) variable name, `result`. A more descriptive name, `matchfound`, makes the comment unnecessary and cleans up the print statement, too.

```
#ifdef DEBUG
printf("*** isword returns matchfound = %d\n", matchfound);
fflush(stdout);
#endif

return(matchfound);
```

Don't contradict the code. Most comments agree with code when they are written, but as bugs are fixed and the program evolves, the comments are often left in their original form, resulting in disagreement with the code. This is the likely explanation for the inconsistentency in the example that opens this chapter.

Whatever the source of the disagreement, a comment that contradicts the code is confusing, and many a debugging session has been needlessly protracted (拖延) because a mistaken comment was taken as truth. When you change the code, make sure the comments are still accurate.

Comments should not only agree with code, they should support it. The comment in this example is correct -- it explains the purpose of the next two lines -- but it appears to contradict the code; the comment talks about newline and the code talks about blanks:

```
?   time(&now);
?   strcpy(date, ctime(&now));
?   /* get rid of trailing newline character copied from ctime */
?   i = 0;
?   while (date[i] != ' ') i++;
?   date[i] = 0;
```

One improvement is to rewrite the code more idiomatically:

```
?   time(&now);
?   strcpy(date, ctime(&now));
?   /* get rid of trailing newline character copied from ctime */
?   i = 0;
?   while (date[i] != '\n') i++;
?   date[i] = '\0';
```

Code and comment now agree, but both can be improved by being made more direct. The problem is to delete the newline that `ctime` puts on the end of the string it returns. The comment should say so, and the code should do so:

```
    time(&now);
    strcpy(date, ctime(&now));
    /* ctime() puts newline at end of string, delete it */
    date[strlen(data) - 1] = '\0';
```

This last expression is the C idiom for removing the last character from a string. The code is now short, idiomatic and clear, and the comment support it by explaining why it needs to be there.

Clarify, don't confuse. Comments are supposed to help readers over the hard parts, not create more obstacles. This example follows our guidelines of commenting the function and explaining unusual properties; on other hand, the function is `strcmp` and the unusual properties are peripheral(无关紧要的) to the job at hand, which is the implementation of a standard and familiar interface:

```
?   int strcmp(char *s1, char *s2)
?   /* string comparison routine returns -1 if s1 is
?    * above s2 in an ascending order list, 0 if equal,
?    * 1 if s1 below s2
?    */
?   {
?       while (*s1 == *s2) {
?           if (*s1 == '\0') return(0);
?           s1++;
?           s2++;
?       }
?       if (*s1 > *s2) return(1);
?       return(-1);
?   }
```

When it takes more than a few words to explain what's happening,it's often and indication that the code should be rewriting. Here, the code could perhaps be improved but the real problem is the comment, which is nearly as long as the implementation and confusing. too (which way is "above"?). We're stretching (伸展) the point to say this routine is hard to understand, but since it implements a standard function, its comment can help by summarizing the behavior and telling us where the definition originates; that's all that's needed:

```
/*
 * strcmp: return <0 if s1 < s2, > 0 if s1 > s2, 0 if equal.
 * ANSI C, section 4.11.4.2
 */
int strcmp(const char *s1, const char *s2)
{
    ...
}
```

Students are taught that it's important to comment everything. Professional programmers are often require to comment all their code. But the purpose of commenting can be lost in blindly following rules. Comments are meant to help a reader understand pans (全景) of the program that are not readily understood from the code itself. As much as possible, write code that is easy to understand; the better you do this, the fewer comments you need. Good code needs fewer comments than bad code.

Exercise 1-11 . Comment on these comments.

```
?       void dict::insert(string& w)
?       // returns 1 if w in dictionary, otherwise returns 0.

?       if (n > MAX || n % 2 > 0) // test for even number

?       // write a message
?       // Add to line counter for each line written
?       void write_message()
?       {
?           // increment line counter
?           line_number = line_number + 1;
?           fprintf(fout, "%d %s\n%d %s\n%d %s\n",
?               line_number, HEADER,
?               line_number + 1, BODY,
?               line_number + 2, TRAILER);
?           // increment line counter
?           line_number = line_number + 2;
?       }
```

□

1.7 Why Bother?

In this chapter, we've talked about the main concerns of programming style: descriptive names, clarity in expressions, straightforward control flow, readability of code and comments, and the important of consistent use of conventions and idioms in achieving all of these. It's hard to argue that these are bad things.

But why worry about style? Who cares what a program looks like if it works? Doesn't it take too much time to make it look pretty? Aren't the rules arbitrary anyway?

The answer is that well-written code is easier to read and to understand, almost surely has fewer errors, and is likely to be smaller than code that has been carelessly tossed (摇摆) and never polished. In the rush to get programs out the door to met some deadline, it's easy to push style aside, to worry about it later. This can be a costly decision. Some of the examples in this chapter show what can go wrong if there isn't enough attention to good style. Sloppy (粗心的) code is bad code -- not just awkward and hard to read, but often broken.

The key observation is that good style should be a matter of habit. If you think about style as you write the code originally, and if you take the time to revise and improve it, you will develop good habits. Once they become automatic, your subconscious will take care of many of the details for you, and even the code you produce under pressure will be better.

Supplementary (补充的) Reading

As we said at the beginning of the chapter, writing good code has much in common with writing good English. Strunk and White's *The Elements of Style* (Allyn & Bacon) is still the best short book on how to write English well.

This chapter draw on the approach of *The Elements of Programming Style* by Brian Kernighan and P. J. Plauger (McGraw-Hill, 1978). Steve Maguire's *Writing Solid Code* (Microsoft Press, 1993) is an excellent source of programming advise. There are also helpful discussions of style in Steve McConnell's *Code Complete* (Microsoft Press, 1993) and Peter van der Linder's *Expert C Programming: Deep C Secrets* (Prentice Hall, 1994).

2

Algorithms and Data Structures

In the end, only familiarity with the tools and techniques of the field will provide right solution for a particular problem, and only a certain amount of experience will provide consistently professional result.

Raymond Fielding.*The Technique of Special Effects Cinematography*

The study of algorithms and data structures is one of the foundations of computer science, a rich field elegant (一流的) techniques and sophisticated (老成的) mathematical analyses. And it's more than just fun and games for the theoretically inclined: a good algorithm or data structure might make it possible to solve a problem in seconds that could otherwise take years.

In specialized areas like graphics, databases, parsing, numerical analysis, and simulation, the ability to solve problems depends critically on state-of-the-artalgorithms and data structures. If you are developing your programs in a field that's new to you, you ***must*** find out what is already known, lest (免得) you waste your time doing poorly what others have already done well.

Every program depends on algorithms and data structures, but few programs depend on the invention of brand new ones. Even within an intricate (错综复杂的) program like a compiler or a web browser, most of the data structures are arrays, lists, trees and hash tables. When a program needs something more elaborate(详细), it will likely be based on these simpler ones. Accordingly, for most programmers, the task is to know what appropriate algorithms and data structures are available and to understand how to choose among alternatives.

Here is the story in a nutshell. There are only a handful of basic algorithms that show up in almost every program -- primarily searching and sorting -- and even those are often included in libraries. Similarly, almost every data structure is derived (起源) from a few fundamental ones. Thus the material covered in this chapter will be familiar to almost all programmers. We have written working versions to make the discussion concrete, and you can lift code verbatim (逐字的) if necessary, but do so only after you have investigated what the programming language and its libraries have to offer.

2.1 Searching

Nothing beats an array for storing static tabular data. Compile-time initialization makes it cheap and easy to construct such arrays. (In Java, the initialization occurs at run-time, but this is an unimportant implementation detail unless the arrays are large.) In a program to detect words that are used rather too much in bad prose, we can write

```
char *flab[] = {
    "actually",
    "just",
    "quite",
    "really",
    NULL
};
```

The search routines needs to know how many elements are in the array. One way to tell it is to pass length as an argument; another, used here, is to place a `NULL` marker at the end of the array:

```
/* lookup: sequential search for word in array */
int lookup(char *word, char *array[])
{
    int i;
    for (i = 0; array[i] != NULL; i++)
       if (strcmp(word, array[i]) == 0)
            return i;
    return -1;
}
```

In C and C++, a parameter that is an array of strings can be declared as `char *array[]` or `char **array`. Although these forms are equivalent, the first makes it clearer how the parameter will be used.

This search algorithm is called ***sequential search*** because it looks at each element in turn to see if it's the desired one. When the amount of data is small, sequential search is fast enough. There are standard library routines to do sequential search for specific data types; for example, functions like `strchr` and `strstr` search for the first instance of a given character or substring in a C or C++ string. The Java `String` class has an `indexOf` method, and the generic C++ `find` algorithms apply to most data types. If such a function exists for the data type you've got, use it.

Sequential search is easy but the amount of work is directly proportional (成比例的) to the amount of data to be searched; doubling the number of elements will double the time to search if the desired item is not present. This is a linear relationship -- run-time is a linear function of data size -- so this method is also known as ***linear search***.

Here's an excerpt (引用) from an array of more realistic size from a program that parses HTML, which defines textual names for well over a hundred individual characters:

```
typedef struct Nameval Nameval;
struct Nameval{
    char *name;
    int value;
};
/* HTML characters, e.g. AElig is ligature of A and E. */
/* Values are Unicode/ISO10646 encoding. */
Nameval htmlchars[] = {
    "AElig",    0x00c6,
    "Aacute",   0x00c1,
    "Acirc",    0x00c2,
    /* ... */
    "zeta",     0x03b6,
};
```

For a larger array like this, it's more efficient to use *binary* search. The binary search algorithm is an orderly version of the way we look up words in a dictionary. Check the middle element. If that value is bigger than what we are looking for, look in the first half; otherwise, look in the second half. Repeat until the desired item is found or determined not to be present.

For binary search, the table must be sorted, as it is here (that's good style anyway; people find things faster in sorted tables too), and we must know how long the table is. The `NELEMS` macro from Chapter 1 can help:

```
printf("The HTML table has %d words\n", NELEMS(htmlchars));
```

A binary search function for this table might look like this:

```
/* lookup: binary search for name in tab; return index */
int lookup(char *name, NameVal tab[], int ntab)
{
    int low, high, mid, cmp;
    low = 0;
    high = ntab - 1;
    while (low <= high){
        mid = (low + high)/2;
        cmp = strcmp(name, tab[mid].name);
        if (cmp < 0){
            high = mid - 1;
        }
        else if (cmp > 0){
            low = mid + 1;
        }
        else{   /* found match */
            return mid;
        }
    }
    return -1;  /* no match */
}
```

Putting all this together, to search `htmlchars` we write

```
half = lookup("frac12", htmlchars, NELEMS(htmlchars));
```

to find the array index of the character $1/2$.

Binary search eliminates half the data at each step. The number of steps is therefore proportional to the number of times we can divide n by 2 before we're left with a single element. Ignoring roundoff, this is $\log_2 n$. If we have 1000 items to search, linear search takes up to 1000 steps, while binary search takes about 10; if we have a million items, linear takes a million steps and binary takes 20. The more items, the greater the advantage of binary search. Beyond some size of input (which varies with the implementation), binary search is faster than linear search.

2.2 Sorting

Binary search works only if the elements are sorted. If repeated searches are going to be made in some data set, it will be profitable to sort once and then use binary search. If the data set is known in advance, it can be sorted when the program is written and built using compile-time initialization. If not, it must be sorted when the program is run.

One of the best all-round sorting algorithms is quicksort, which was invented in 1960 by C. A. R. Hoare. Quicksort is a fine example of how to avoid extra computing. It works by partitioning an array into little and big elements:

> pick one element of the array (the "pivot").
> partition the other elements into two groups:
>   "little ones" that are less than the pivot value, and
>   "big ones" that are greater than or equal to the pivot value.
> recursively sort each group.

When this process is finished, the array is in order. Quicksort is fast because once an element is known to be less than the pivot value, we don't have to compare it to any of the big ones; similarly, big ones are not compared to little ones. This makes it much faster than the simple sorting methods such as insertion sort and bubble sort that compare each element directly to all the others.

Quicksort is practical and efficient; it has been extensively studied and myriad variations (各式变种) exist. The version that we present here is just about the simplest implementation but it is certainly not the quickest.

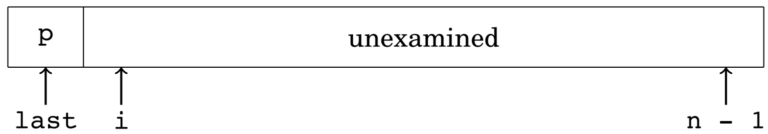
This `quicksort` function sorts an array of integers:

```
/* quicksort: sort v[0]..v[n-1] into increasing order */
void quicksort(int v[], int n)
{
    int i, last;
    if(n <= 1) /* nothing to do */
        return;
    swap(v, 0, rand() % n); /* move pivot elem to v[0] */
    last = 0;
    for(i = 1; i < n; i++)  /*partition */
        if(v[i] < v[0])
            swap(v, ++last, i);
    swap(v, 0, last);   /* restore pivot */
    quicksort(v, last); /* recursively sort */
    quicksort(v + last + 1, n - last - 1); /* each part */
}
```

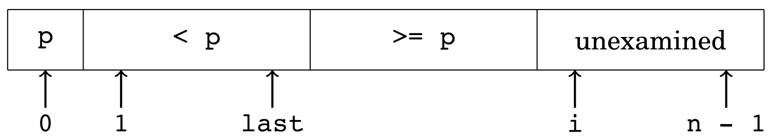
The swap operation, which interchanges two elements, appears three times in `quicksort`, so it is best made into a separate function:

```
/* 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;
}
```

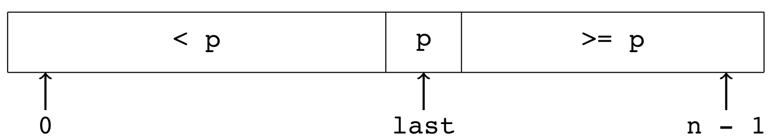
Partitioning selects a random element as the pivot, swaps it temporarily to the front, then sweeps through the remaining elements, exchanging those smaller than the pivot ("little ones") towards the beginning (at location `last`) and big ones towards the end (at location `i`), At the beginning of the process, just after the pivot has been swapped to the front, `last=0` and elements `i=1` through `n-1` are unexamined:



At the top of the `for` loop, elements `1` through `last` are strictly less than the pivot (中枢), elements `last+1` through `i-1` are greater than or equal to the pivot, and elements `i` through `n-1` have not been examined yet. Until `v[i] >= v[0]`, the algorithm may swap `v[i]` with itself; this wastes some time but not enough to worry about.



After all elements have been partitioned, element `0` is swapped with the `last` element to put the pivot element in its final position; this maintains the correct ordering. Now the array looks like this:



The same process is applied to the left and right sub-arrays; when this has finished, the whole array has been sorted.

How fast is quicksort? In the best possible case,

- the first pass partitions n elements into two groups of about $n/2$ each.
- the second level partitions two groups, each of about $n/2$ elements, into four groups each of about $n/4$.
- the next level partitions four groups of about $n/4$ into eight of about $n/8$.
- and so on.

This goes on for about $\log_2 n$ levels, so the total amount of work in the best case is proportional to $n + 2 \times n/2 + 4 \times n/4 + 8 \times n/8...$ ($\log_2 n$ terms), which is $n \log_2 n$. On the average, it does only a little more work. It is customary to use base 2 logarithms; thus we say that quicksort takes time proportional to $n \log n$.

This implementation of quicksort is the clearest for exposition, but it has a weakness. If each choice of pivot splits the element values into two nearly equal groups, our analysis is correct, but if the split is uneven too often, the run-time can grow more like n^2. Our implementation uses a random element as the pivot to reduce the chance that unusual input data will cause too many uneven splits. But if all the input values are the same, our implementation splits off only one element each time and will thus run in time proportional to n^2.

The behavior of some algorithms depends strongly on the input data. Perverse or unlucky inputs may cause an otherwise well-behaved algorithm to run extremely slowly or use a lot of memory. In the case of quicksort, although a simple implementation like ours might sometimes run slowly, more sophisticated implementations can reduce the chance of pathological behavior to almost zero.

2.3 Libraries

The standard libraries for C and C++ include sort functions that should be robust against adverse inputs, and tuned to run as fast as possible.

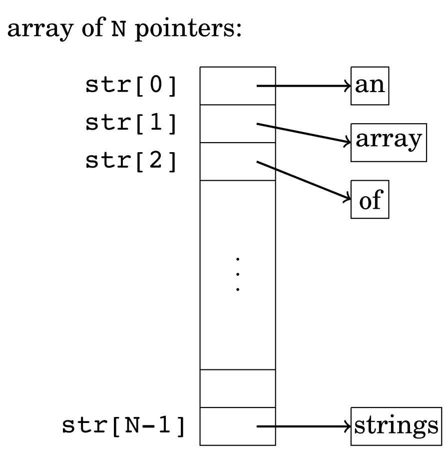
Library routines are prepared to son any data type, but in return we must adapt to their interface, which may be somewhat more complicated than what we showed above. In C, the library function is named `qsort`, and we need to provide a comparison function to be called by `qsort` whenever it needs to compare two values. Since the values might be of any type, the comparison function is handed two `void *` pointers to the data items to be compared. The function casts the pointers to the proper type, extracts the data values, compares them, and returns the result (negative, zero, or positive according to whether the first value is less than, equal to, or greater than the second).

Here's an implementation for sorting an array of strings, which is a common case. We define a function `scmp` to cast the arguments and call `strcmp` to do the comparison.

```
/* scmp: string compare of *p1 and *p2 */
int scmp(const void *p1, const void *p2)
{
    char *v1, *v2;
    v1 = *(char **) p1;
    v2 = *(char **) p2;
    return strcmp(v1, v2);
}
```

We could write this as a one-line function, but the temporary variables make the code easier to read.

We can't use `strcmp` directly as the comparison function because `qsort` passes the address of each entry in the array, `&str[i]` (of type `char**`), not `str[i]` (of type `char*`), as shown in this figure:



To sort elements `str[0]` through `str[N-1]` of an array of strings, `qsort` must be called with the array, its length, the size of the items being sorted, and the comparison function:

```
char *str[N];
qsort(str, N, sizeof(str[0]), scmp);
```

Here's a similar function `icmp` for comparing integers:

```
/* icmp: integer compare of *p1 and *p2 */
int icmp(const void *p1, const void *p2)
{
    int v1, v2;
    v1 = *(int *) p1;
    v2 = *(int *) p2;
    if (v1 < v2)
        return -1;
    else if (v1 == v2)
        return 0;
    else
        return 1;
}
```

We could write

```
?   return v1 - v2;
```

but if `v2` is large and positive and `v1` is large and negative or vice versa (反过来), the resulting overflow would produce an incorrect answer. Direct comparison is longer but safe.

Again, the call to `qsort` requires the array, its length, the size of the items being sorted, and the comparison function:

```
int arr[N];
qsort(arr, N, sizeof(arr[0]), icmp);
```

ANSI C also defines a binary search routine, `bsearch`. Like `qsort`, `bsearch` requires a pointer to a comparison function (often the same one used for `qsort`); it returns a pointer to the matching element or `NULL` if not found. Here is our HTML `lookup` routine, rewritten to use `bsearch`:

```
/* lookup: use bsearch to find name in tab, return index*/
int lookup(char *name, Nameval tab[], int ntab)
{
    Nameval key, *np;
    key.name = name;
    key.value = 0;  /* unused; anything will do*/
    np = (Nameval *) bsearch(&key, tab, ntab, sizeof(tab[0]), nvcmp);
    if(np == NULL)
        return -1;
    else
        return np - tab;
}
```

As with `qsort`, the comparison routine receives the address of the items to be compared, so the key must have that type; in this example, we need to construct a fake `Nameval` entry that is passed to the comparison routine. The comparison routine itself is a function `nvcmp` that compares two `Nameval` items by calling `strcmp` on their string components, ignoring their values:

```
/* nvcmp: compare two Nameval names */
int nvcmp(const void *va, const void *vb)
{
    const Nameval *a, *b;
    a = (Nameval *) va;
    b = (Nameval *) vb;
    return strcmp(a->name, b->name);
}
```

This is analogous (相似) to `scmp` but differs because the strings are stored as members of a structure.

The clumsiness(笨拙) of providing the key means that `bsearch` provides less leverage(杠杆作用) than `qsort`. A good general-purpose sort routine takes a page or two of code, while binary search is not much longer than the code it takes to interface to `bsearch`. Nevertheless, it's a good idea to use `bsearch` instead of writing your own. Over the years, binary search has proven surprisingly hard for programmers to get right.

The standard C++ library has a generic algorithm called `sort` that guarantees $O(n \log n)$ behavior. The code is easier because it needs no casts or element sizes, and it does not require an explicit comparison function for types that have an order relation.

```
int arr[N];
sort(arr, arr + N);
```

The C++ library also has generic binary search routines, with similar notational advantages.

Exercise 2-1 . Quicksort is most naturally expressed recursively. Write it iteratively and compare the two versions. (Hoare describes how hard it was to work out quicksort iteratively, and how neatly it fell into place when he did it recursively.) □

2.4 A Java Quicksort

3

Design and Implementation

Show me your flowcharts and conceal your tables, and I shall continue to be mystijied. Show me your tables, and I won't usually need your flowcharts; they'll be obvious.

Frederick P.Brooks, Jr.,*The Mythical Man Month*

As the quotation from Brooks's classic book suggests, the design of the data structures is the central decision in the creation of a program. Once the data structures are laid out, the algorithms tend to fall into place, and the coding is comparatively easy.

This point of view is oversimplified but not misleading. In the previous chapter we examined the basic data structures that are the building blocks of most programs. In this chapter we will combine such structures as we work through the design and implementation of a modest-sized program. We will show how the problem influences the data structures, and how the code that follows is straightforward once we have the data structures mapped out.

One aspect of this point of view is that the choice of programming Language is relatively unimportant to the overall design. We will design the program in the abstract and then write it in C, Java, C++, Awk, and perl. Comparing the implementations demonstrates how languages can help or hinder, and ways in which they are unimportant. Program design can certainly be colored by a language but is not usually dominated by it.

The problem we have chosen is unusual, but in basic from it is typical of many programs: some data comes in, some data goes out, and the processing depends on a little ingenuity.

Specifically, we're going to generate random English text that reads well. If we emit random letters or random words, the result will be nonsense. For example, a program that randomly selects letters(and blanks. to separate words)might produce this:

```
xptmxgn xusaja afqnzgxl lhidwed rjdjuvpydrlwnjy
```

which is not very convincing. If we weight the letters by their frequency of appearance in English text, we might get this:

```
idtefoae tcs trder jcii ofdslnqetacp t ola
```

which isn't a great deal better. Words chosen from the dictionary at random don't make much more sense:

```
polydactyl equatorial splashily jowl verandah circumscribe
```

For better results, we need a statistical model with more structure.Such as the frequency of appearance of whole phrases. But where can we find such statistics?

We could grab a large body of English and study it in detail, but there is an easier and more entertaining approach. The key observation is that we can use any existing text to construct a statistical model of the language *as used* in *that text*, and from that generate random text that has similar statistics to the original.

3.1 The Markov Chain Algorithm

An elegant way to do this sort of processing is a technique called a *Markov chain algorithm*. If we imagine the input as a sequence of overlapping phrases, the algorithm divides each phrase into two parts, a multi-word *prefix* and a single *suffix* word that follows the prefix. A Markov chain algorithm emits output phrases by randomly choosing the suffix that follows the prefix, according to the statistics of(in our case)the original text. Three-word phrases work well a two-word prefix is used to select the suffix word:

set w_1 and w_2 to the first two words in the text
print w_1 and w_2
loop:
  randomly choose w_3, one of the successors of prefix w_1 w_2 in the text
  print w_3
  replace *w* and w_2 by w_2 and w_3
  repeat loop

To illustrate, suppose we want to generate random text base on a few sentences paraphrased from the epigraph above, using-word prefixes:

Show your flowcharts and conceal your tables and I will be mystified. Show your tables and you flowcharts will be obvious.*(end)*

These are some of the pairs of input words and the words that follow them:

Input prefix:	*Suffix words that follow:*
Show your	flowcharts tables
your flowcharts	and will
flowcharts and	conceal
flowcharts will	be
your tables	and and
will be	mystified. obvious.
be mystified.	Show
be obvious.	*(end)*

A Markov algorithm processing this text will begin by printing *Show your* and will then randomly pick either *flowcharts* or *tables*. If it choose the former, the current prefix becomes *your flowcharts* and next word will be *and* or *will*. If it chooses *tables*, the next word will be *and*. This continues until enough output has been generated or until the end-marker is encountered as a suffix.

Our program will read a piece of English text and use a Markov chain algorithm to generate new text based on the frequency of appearance of phrases of a fixed length. The number of words in the prefix, which is two in our example, is a parameter. Making the prefix shorter tends to produce less coherent prose; making it longer tends to reproduce the input text varbatim. For English text, using two words to select a third is a good compromise; it seems to recreate the flavor of the input while adding its own whimsical touch.

What is a word? The obvious answer is a sequence of alphabetic characters, but it is desirable to leave punctuation attached to the words so *"words"* and *"words."* are different. This helps to improve the quality of the generated prose by letting punctuation, and therefore(indirectly)grammar, influence the word choice, althought it also permits unbalanced quotes and parentheses to sneak in. We will therefore define a "word" as anything between white space, a decision that places no *restriction* on input language and leaves punctuation attached to the words. Since most programming languages have facilities to split text into white-space-sepatated words, this is also e

4 Interfaces

Before I build a wall I'd ask to know
What I was walling in or walling out,
And to whom I was like to give offence.
Somthing there is that doesn't love a wall.
That wants it down.

Robert Frost, *Mending Wall*

The essence (精髓) of design is to balance competing goals and constraints. Although there may be many tradeoffs when one is writing a small self-contained system, the ramifications (分叉) of particular choices remain within the system and affect only the individual programmer. But when code is to be used by others, decisions have wider repercussions (反响).

Among the issues to be worked out in a design are

- Interfaces: what services and access are provided? The interface is in effect a contract between supplier and customer. The desire is to provide services that are uniform and convenient, with enough functionality to be easy to use but not so much as to become unwieldy (笨拙).

- Information hiding: what information is visible and what is private? An interface must provide straightforward access to the components while hiding details of the implementation so they can be changed without affecting users.

- Resource management: who is responsible for managing memory and other limited resources? Here, the main problems are allocating and freeing storage, and managing shared copies of information.

- Error handling: who detects errors, who reports them, and how? When an error is detected, what recovery is attempted?

In Chapter 2 we looked at the individual pieces -- the data structures -- from which a system is built. In Chapter 3, we looked at how to combine those into a small program. The topic now turns to the interfaces between components that might come from different sources. In this chapter we illustrate interface design by building a library of functions and data structures for a common task. Along the way, we will present some principles of design. Typically there are an enormous number of decisions to be made, but most are made almost unconsciously. Without these principles, the result is often the sort of haphazard (无计划的) interfaces that frustrate and impede (妨碍) programmers every day.

5 Debugging

Bug, a defect or fault in a machine, plan, or the like. orig.U.S. 1889 Pall Mall Gaz. 11 Mar: 1/1 Mr. Edison, I was informed, has been up the two previous nights discovering 'a bug' in his phonograph -- an expression for solving a difficulty, implying that some imaginary insect has secreted itself inside and is causing all the trouble.

Oxford English Dictionary. 2nd Edition

We have presented a lot of code in the past four chapters, and we've pretended that it all pretty much worked the first time. Naturally this wasn't true; there were plenty of bugs. The word "bug" didn't originate with programmers, but it is certainly one of the most common terms in computing. Why should software be so hard?

One reason is that the complexity of a program is related to the number of ways that its components can interact, and software is full of components and interactions. Many techniques attempt to reduce the connections between components so there are fewer pieces to interact; examples include information hiding, abstraction and interfaces, and the language features that support them. There are also techniques for ensuring the integrity of a software design -- program proofs, modeling, requirements analysis, formal verification -- but none of these has yet changed the way software is built; they have been successful only on small problems. The reality is that there will always be errors that we find by testing and eliminate by debugging.

Good programmers know that they spend as much time debugging as writing so they try to learn from their mistakes. Every bug you find can teach you how to prevent a similar bug from happening again or to recognize it if it does.

Debugging is hard and can take long and unpredictable amount of time, so the goal is to avoid having to do much of it. Techniques that help reduce debugging time include good design, good style, boundary condition tests, assertions (断言) and sanity (完整性) checks in the code, defensive (防御性) programming, well-designed interfaces, limited global data, and checking tools. An ounce (盎司) of prevention really is worth a pound (磅) of cure.

What is the role of language? A major force in the evolution of programming language has been the attempt to prevent bugs through language features. Some features make classes of errors less likely: range checking on subscript, restricted pointers or no pointers at all, garbage collection, string data types, typed

UO, and strong type-checking. On the opposite side of the coin, some features are prone (倾向的) error, like `goto` statements, global variables, unrestricted pointers, and automatic type conversions. Programmers should know the potentially risky bits of their languages and take extra care when using them. They should also enable all compiler checks and heed (注意) warnings.

Each language feature that prevents some problem has a cost of its own. If a higher-level language makes the simple bugs disappear automatically, the price is that it makes it easier to create higher-level bugs. No language prevents you from making mistakes.

Even though we wish it were otherwise, a majority of programming time is spent testing and debugging. In this chapter, we'll discuss how to make your debugging time as short and productive as possible; we'll come back to testing in Chapter 6.

5.1 Debuggers

Compiler for major languages usually come with sophisticated (复杂的) debuggers, often packaged as part of a development environment that integrates creation and edition of source code, compilation, execution, and debugging, all in a single system. Debuggers include graphical interfaces for stepping through a program one statement or function at a time, stopping at particular lines or when a specific condition occurs. They also provide facilities for formatting and displaying the values of variables.

A debugger can be invoked directly when a problem is known to exist. Some debuggers take over automatically when something unexpectedly goes wrong during program execution. It's usually easy to find out where the program was executing when it died, examine the sequence of functions that were active (the stack trace), and display the values of local and global variables. That much information may be sufficient to identify a bug. If not, breakpoints and stepping make it possible to re-run a failing program one step at a time to find the first place where something goes wrong.

In the right environment and in the hands of an experienced user, a good debugger can make debugging effective and efficient, if not exactly painless. With such powerful tools at one's disposal, why would anyone ever debug without them? Why do we need a whole chapter on debugging?

There are several good reasons, some objective and some based on personal experience. Some languages outside the mainstream have no debugger or provide only rudimentary (基本的) debugging facilities. Debuggers are system-dependent, so you may not have access to the familiar debugger from one system when you work on another. Some programs are not handled well by debuggers: multi-process or multi-thread programs, operating systems, and distributed systems must often be debugged by lower-level approaches. In such situations, you're on your own, without much help besides print statements and your own experience and ability to reason about code.

As a personal choice, we tend not to use debuggers beyond getting a stack trace or the value of a variable or two. One reason is that it is easy to et lost in details of complicated data structures and control flow; we find stepping through a program less productive than thinking harder and adding out statements and self-checking code at critical places. Clicking over statements takes longer than scanning the output of judiciously-placed (精心放置的) displays. It takes less time to decide where to put print statements than to single-step to the critical section of code, even assuming we know where that is. More important, debugging statements stay with the program; debugger sessions are transient.

Blind probing with a debugger is not likely to be productive. It is more helpful to use the debugger to discover the state of the program when it fails, then think about how the failure could have happened. Debuggers can be arcane (晦涩难解的) and difficult programs, and especially for beginners may provide more confusion than help. If you ask the wrong question, they will probably give you an answer, but you may not know it's misleading.

A debugger can be of enormous (庞大的) value, however, and you should certainly include one in your debugging toolkit; it is likely to be the first thing you turn to. But if you don't have a debugger, or if you're stuck on an especially hard problem, the techniques in this chapter will help you to debug effectively and efficiently anyway. They should make your use of your debugger more productive as well, since they are largely concerned with how to reason about errors and probable causes.

5.2 Good Clues, Easy Bugs

Oops! Something is badly wrong. My program crashed, or printed nonsense, or seems to be running forever. Now what?

Beginners have a tendency to blame the compiler, the library, or anything other than their own code. Experienced programmers would love to do the same, but they know that, realistically, most problems are their own fault.

Fortunately, most bugs are simple and can be found with simple techniques. Examine the evidence in the erroneous output and try to infer (推论) how it could have been produced. Look at any debugging output before the crash; if possible get a stack trace from a debugger. Now you know something of what happened, and where. Pause to reflect. How could that happen? Reason back from the state of the crashed program to determine what could have caused this.

Debugging involves backwards reasoning, like solving murder mysteries. Something impossible occurred, and the only solid information is that it really did occur. So we must think backwards from the result to discover the reasons. Once we have a full explanation, we'll know what to fix and, along the way, likely discover a few other things we hadn't expected.

Look for familiar patterns. Ask yourself whether this is familiar pattern. "I've seen that before" is often the beginning of understanding, or even the whole answer. Common bugs have distinctive signatures. For instance, novice (新手) C programmers often write:

```
?   int n;
?   scanf("%d", n);
```

instead of

```
    int n;
    scanf("%d", &n);
```

and this typically causes an attempt to access out-of-bounds memory when a line of input is read. People who teach C recognize the symptom instantly.

Mismatched types and conversion in `printf` and `scanf` are an endless source of easy bugs:

```
?   int n = 1;
?   double d = PI;
?   printf("%d %f\n", d, n);
```

The signature of this error is sometimes the appearance of preposterous (反常的) values: huge integers or improbably large or small floating-point values. On a Sun SPARC, the output from this program is a huge number and an astronomical (天文的) one[1] (folded to fit):

```
107434034 26815 ... 30144.000000
```

Another common error is using `%f` instead of `%lf` to read a `double` with `scanf`. Some compilers catch such mistakes by verifying that the type of `scanf` and `printf` arguments match their format string; if all warnings are enabled. for the `printf` above, the GNU compiler gcc reports that

```
x.c:9: warning: int format, double arg (arg 2)
x.c:9: warning: double format, different type arg (arg 3)
```

Failing to initialize a local variable give rise to another distinctive error. The result often an extremely large value, the garbage left over from whatever previous value was stored in the same memory location. Some compilers will warn you, though you may have enable the compile-time check, and they can never catch all cases. Memory returned by allocators like `malloc`, `realloc`, and `new` is likely to be garbage too; be sure to initialize it.

Examine the most recent change. What was the last change? If you're changing only one at a time as a program evolves, the bug most likely is either in the new code or has been exposed by it. Looking carefully at recent changes helps to localize the problem. If the bug appears in the new version and not in the old, the new code is part of the problem. This means that you should preserve at least the previous version of the program, which you believe to be correct, so that you can compare behaviors. It also means that you should keep records of the changes made and bugs fixed, so you don't have to rediscover this vital information while you're trying to fix a bug. Source code control systems and other history mechanisms are helpful here.

Don't make the same mistake twice. After you fix a bug, ask whether you might have made the same mistake somewhere else. This happened to one of us just days before beginning to write this chapter. The program was a quick prototype for a colleague, and included some boilerplate (样板) for optional arguments:

```
?   for (i = 1; i < argc; i++) {
?       if (argv[i][0] != '-')  /* options finished */
?           break;
?       switch (argv[i][1]) {
?       case 'o':           /* output filename */
?           outname = argv[i];
?           break;
?       case 'f':
?           from = atoi(argv[i]);
?           break;
?       case 't':
?           to = atoi(argv[i]);
?           break;
?       ...
```

Shortly after our colleague tried it, he reported that the output file name always had the prefix `-o` attached to it. This was embarrassing but easy to repair; the code should have read

```
outname = &argv[i][2];
```

[1]It's hard to type a long number, so I omit most of digits.

So that was fixed up and shipped off, and back came another report that the program failed to handle an argument like `-f123` properly: the converted numeric value was always zero. This is the same error; the next case in the `switch` should have read

```
from = atoi(&argv[i][2]);
```

Because the author was still in a hurry, he failed to notice that the same blunder (错误) occurred twice more and it took another round before all of the fundamentally identical errors were fixed.

Easy code can have bugs if its familiarity causes us to let down our guard. Even when code is so simple you could write it in your sleep, don't fall asleep while writing it.

Debug it now, not later. Being in too much of a hurry can hurt in other situations as well. Don't ignore a crash when it happens; track it down right away, since it may not happen again until it's too late. A famous example occurred on the Mars Pathfinder mission. After the flawless (完美的) landing in July 1977 the spacecraft's computers tended to reset once a day or so, and the engineer were baffled (困惑). Once they tracked down the problem, they realized that they had seed that problem before. During pre-launch tests the resets had occurred, but had been ignored because the engineers were working on unrelated problems. So they were forced to deal with the problem later when the machine was tens of millions of miles away and much harder to fix.

Get a stack trace. Although debuggers can probe running programs, one of their most common uses is to examine the state of a program after death. The source line number of the failure, often part of a stack trace, is the most useful single piece of debugging information; improbable (不太可能的) values of arguments are also a big clue (zero pointers, integers that are huge when they should be small, or negative when they should be positive, character strings that aren't alphabetic).

Here is a typical example, based on the discussion of sorting in Chapter 2. To sort an array of integers, we should call `qsort` with the integer comparison function `icmp`:

```
int arr[N];
qsort(arr, N, sizeof(arr[0]), icmp);
```

but suppose it is inadvertently (粗心地) passed the name of the string comparison function `scmp` instead:

```
?   int arr[N];
?   qsort(arr, n, sizeof(arr[0]), scmp);
```

A compiler can't detect the mismatch of types here, so disasters awaits. When we run the program, it crashes by attempting to access an illegal memory location. Running the `dbx` debugger produces a stack trace like this, edited to fit[2]:

```
0 strcmp(0x1a2, 0x1c2) ["strcmp.s":31]
1 scmp(p1 = 0x10001048, p2 = 0x1000105c) ["badqs.c":31]
2 qst(0x10001048, 0x10001074, 0x400b20, 0x4) ["qsort.c":147]
3 qsort(0x10001048, 0x1c2,0x4, 0x400b20) ["qsort.c",63]
4 main() ["badqs.c":45]
5 __istart() ["crtltinit.s":13]
```

This says that the program died in strcmp; by inspection, the two pointers passed to `strcmp` are much too small, a clear sign of trouble. The stack trace gives a trail (痕迹) of line numbers where each function was called. Line 13 in our test file `badqs.c` is the call

[2]The source pdf is blurry (模糊的), so the stack trace may contain some typing errors

```
    return strcmp(v1, v2);
```

which identifies the failing call and points towards the error.

A debugger can also be used to display values of local or global variables that will give additional information about what went wrong.

Read before typing. One effective but under-appreciated debugging technique is to read the code very carefully and think about it for a while without making changes. There's a powerful urge to get to the keyboard and start modifying the program to see if the bug goes away. But chances are that you don't know what's really broken and will change the wrong thing, perhaps breaking something something else. A listing of the critical part of program on paper can give a different perspective than what you see on the screen, and encourages you to take more time for reflection. Don't make listings as a matter of routine, though. Printing a complete program wastes trees since it's hard to see the structure when it's spread across many pages and the listing will be obsolete (荒废的) the moment you start editing again.

Take a break for while; sometimes what you see in the source code is what you meant rather than what you wrote, and an interval away from it can soften your misconception (误解) and help the code speak for itself when you return.

Resist the urge to start typing; thinking is a worthwhile alternative.

Explain your code to someone else. Another effective technique is to explain your code to someone else. This will often cause you to explain the bug to yourself. Sometimes it takes no more than a few sentences, followed by an embarrassed "Never mind, I see what's wrong. Sorry to bother you." This works remarkably well; you can even use non-programmer as listeners. One university computer center kept a teddy bear near the help desk. Students with mysterious bugs were required to explain to the bear before they could speak to a human counselor (顾问).

5.3 No Clues, Hard Bugs

"I haven't got a clue. What on earth is going on?" If you really haven't any idea what could be wrong, life get tougher.

Make the bug reproducible. The first step is to make sure you can make the bug appear on demand. It's frustrating to chase down a bug that doesn't happen every time. Spend some time constructing input and parameter settings that reliably cause the problem, then wrap up the recipe (处方) so it can be run with a button push or a few keystrokes. If it's a hard bug, you'll be making it happen over and over as you track down the problem, so you'll save yourself time by making it easy to reproduce.

If the bug can't be made to happen every time, try to understand why not. Does some set of conditions make it happen more often than others? Even if you can't make it happen every time, if you can decrease the time spent waiting for it, you'll find it faster.

If a program provides debugging output, enable it. Simulation program like the Markov chain program in Chapter 3 should include an option that produces debugging information such as the seed of the random number generator so that output can be reproduced; another option should allow for setting the seed. Many programs include such options and it is a good idea to include similar facilities in your own programs.

Divide and conquer (分而治之). Can the input that causes the program to fail be made smaller or more focused? Narrow down the possibilities by creating the smallest input where the bug still shows up. What changes make the error go way? Try to find crucial (决定性的) test cases that focus on the error.

Each test case should aim at a definitive outcome that confirms or denies hypotheses (假说) about what is wrong.

Proceed by binary search. Throw away half the input and see if the output is still wrong; if not, go back to the previous state and discard the other half of the input. The same binary search process can be used on the program text itself: eliminate some part of the program that should have no relationship to the bug and see if the bug is still there. An editor with undo is helpful in reducing big test cases and big programs without losing the bug.

Study the numerology (命理) of failures. Sometimes a pattern in the numerology of failing examples give a clue that focus the search. We found some spelling mistakes in a newly written section of this book, where occasional letters had simply disappeared. this was mystifying (迷惑的). The text had been created by cutting and pasting from another file, so it seemed possible that something was wrong with the cut or paste commands in the text editor. But where to start looking for the problem? For clues we looked at the data, and noticed that the missing characters seemed uniformly (均匀地) distributed through the text. We measured the intervals and found that the distance between dropped characters was always 1023 bytes, a suspiciously non-random value. A search through the editor source code for numbers near 1024 found a couple of candidates. One of those was in new code, so we examined that first, and the bug was easy to spot, a classic off-by-one error where a null byte overwrote the last character in a 1024-byte buffer.

Studying the patterns of numbers related to the failure pointed us right at the bug. Elapsed time? A couple of minutes of mystification, five minutes of looking at the data to discover the pattern of missing characters, a minute to search for likely places to fix, and another minute to identify and eliminate the bug. This one would have been hopeless to find with a debugger, since it involved two multiprocess programs, driven by mouse clicks, communicating through a file system.

Display output to localize your search. If you don't understand what the program is doing, adding statements to display more information can be the easiest, most cost-effective way to find out. Put them in to verify your understanding or refine your ideas of what's wrong. For example, display "can't get here" if you think it's not possible to reach a certain point in the code; then if you see that message, move the output statements back towards the start to figure out where things first begin to go wrong. Or show "got here" messages going forward, to find the last place where things seem to be working. Each message should be distinct so you can tell which one you're looking at.

Display messages in a compact fixed format so they are easy to scan by eye or with programs like the pattern-matching tool `grep`. (A grep-like program is invaluable (无价的) for searching text. Chapter 9 includes a simple implementation.) If you're displaying the value of a variable, format it the same way each time. In C and C++, show pointers as hexadecimal numbers with `%x` or `%p`; this will help you to see whether two pointers have the same value or are related. Learn to read pointer values and recognize likely and unlikely ones, like zero, negative numbers, odd numbers, and small numbers. Familiarity with the form of address will pay off (获益) when you're using a debugger, too.

If output is potentially voluminous (长篇的), it might be sufficient to print single-letter outputs like `A`, `B`, `...`, as a compact display of where the program went.

Write self-checking code. If more information is needed, you can write your own check function to test a condition, dump relevant variables, and abort the programs:

```
/* check: test condition, print and dir */
void check(char *s)
{
```

```
        if (var1 > var2) {
            printf("%s, var1 %d var2 %d\n", s, var1, var2);
            fflush(stdout); /* make sure all output is out */
            abort();        /* signal abnormal termination */
        }
    }
```

We wrote `check` to call `abort`, a standard C library function that causes program execution to be terminated abnormally for analysis with a debugger. In a different application, you might want `check` to carry on after printing.

Next, add calls to `check` wherever they might be useful in your code:

```
check("before suspect");
/* ... suspect code ... */
check("after suspect");
```

After a bug is fixed, don't throw `check` away. Leave it in the source, commented out or controlled by a debugging option, so that it can be turned on again when the next difficult problem appears.

For harder problems, `check` might evolve to do verification and display of data structures. This approach can be generalized to routine that perform ongoing (进行中) consistency checks of data structures and other information. In a program with intricate (复杂的) data structures, it's good idea to write these checks ***before*** problems happen, as components of the program proper (适当的), so they can be turned on when trouble starts. Don't use then only when debugging; leave them installed during all stages of program development. If they're not expensive, it might be wise to leave them always enables. Large programs like telephone switching systems often devote a significant amount of code to "audit" (审计) subsystems that monitor information and equipment, and report or even fix problems if they occur.

Write a log file. Another tactic (策略) is to write a ***log file*** containing a fixed-format stream of debugging output. When a crash occurs, the log records what happened just before the crash. Web servers and other network programs maintain extensive logs of traffic so they can monitor themselves and their clients; this fragment (edited to fit) comes from a local system:

```
[Sun Dec 27 16:19:24 1998]
HTTPd: access to /usr/local/httpd/cgi-bin/test.html
    failed for m1.cs.bell-labs.com,
    reason: client denied by server (CGI non-executable)
    from http://m2.cs.bell-labs.com/cgi-bin/test.pl
```

Be sure to flush I/O buffers so the final log records appear in the log file. Output functions like `printf` normally buffer their output to print it efficiently; abnormal termination may discard this buffered output. In C, a call to `fflush` guarantees that all output is written before the program dies; there are analogous `flush` function for output streams in C++ and Java. Or, if you can afford the overhead, you can avoid the flushing problem altogether by using unbuffered I/O for log files. The standard functions `setbuf` and `setvbuf` control buffering; `setbuf(fp, NULL)` turns off buffering on the stream `fp`. The standard error streams (`stderr`, `cerr`, `System.err`) are normally unbuffered by default.

Draw a picture. Sometimes pictures are more effective than text for testing and debugging. Pictures are especially helpful for understanding data structures, as we say in Chapter 2, and of course when writing graphics software, but they can be used for all kinds of programs. Scatter (散点) plots display misplaced values more effectively than columns of numbers. A histogram of data reveals anomalies in exam grades, random numbers, bucket sizes in allocators and hash tables, and the like.

If you don't understand what's happening inside your program, try annotating the data structures with statistics and plotting the result. The following graphs plot[3], for the C `markov` program in Chapter 3, hash chain lengths on the x axis and the number of elements in chains of that length on the y axis. The input data is our standard test, *The Book of Psalms* (42685 words, 22482 prefixes). The first two graphs are for the good hash multipliers of 31 and 37 and the third is for the awful multiplier of 128. In the first two cases, no chain is longer than 15 or 16 elements and most elements are in chains of length 5 or 6. In the third, the distribution is broader, the longest chain has 187 elements, and there are thousands of elements in chains longer than 20.

Use tools. Make good use of the facilities of the environment where you are debugging. For example, a file comparison program like `diff` compares the outputs from successful and failed debugging runs so you can focus on what has changed. If your debugging output is long, use `grep` to search it or an editor to examine it. Resist the temptation to send the debugging output to a printer: computers scan voluminous output better than people do. Use shell scripts and other tools to automate the processing of the output from debugging runs.

Write trivial programs to test hypotheses or confirm your understanding of how something works. For instance, is it valid to free a `NULL` pointer?

```
int main(void)
{
    free(NULL);
    return 0;
}
```

Source code control programs like RCS keep track of versions of code so you can see what has changed and revert to previous to restore a known state. Besides indicating what has changed recently, they can identify sections of code that have a long history of frequent modification; these are often a good place for bugs to lurk (潜伏).

Keep records. If the search for a bug goes on for any length of time, you will begin to lose track of what you tried and what you learned. If you record your tests and results, you are less likely to overlook something or to think that you have checked some possibility when you haven't. The act of writing will help you remember the problem the next time something similar comes up, and will also serve when you're explaining it to someone else.

5.4 Last Resorts (手段)

What do you do if none of this advice help? This may be the time to use a good debugger to step through the program. If your mental (精神上的) model of how something works is just pain wrong, so you're looking in the wrong place entirely, or looking in the right place but not seeing the problem, a debugger forces you to think differently. These "mental model" bugs are among the hardest to find; the mechanical aid is invaluable.

Sometimes the misconception (误解) is simple: incorrect operator precedence, or the wrong operator, or indentation that doesn't match the actual structure, or a scope error where a local name hides a global name or a global name introduces into a local scope. For example, programmers often forget that `&` and `|` have lower precedence than `==` and `!=`. They write

[3] Lack of graphs, because the graph is too blurry and ugly to represent.

```
?   if (x & 1 == 0)
?       ...
```

and can't figure out why this is always false. Occasionally a slip of the finger converts a single = into two or vice versa:

```
?   while ((c == getchar()) != EOF)
?       if (c = '\n')
?           break;
```

Or extra code is left behind during editing:

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

Or hasty typing creates a problem:

```
?   switch (c) {
?       case '<':
?           mode = LESS;
?           break;
?       case '>':
?           mode = GREATER;
?           break;
?       default:
?           mode = EQUAL;
?           break;
?   }
```

Sometimes the error involves arguments in the wrong order in a situation where type-checking can't help, like writing

```
?   memset(p, n, 0);    /* store n 0's in p */
```

instead of

```
    memset(p, 0, n);    /* store n 0's in p */
```

Sometimes something changes behind your back -- global or shared variables are modified and you don't realize that some other routine can touch them.

Sometimes your algorithms or data structure has a fatal flaw (缺陷) and you just can't see it. While preparing material on linked lists, we wrote a package of list functions to create new elements, link them to the front or back of lists, and so on; these functions appear in Chapter 2. Of course we wrote a test program to make sure everything was correct. The first few tests worked but then one failed spectacularly (惊人地). In essence (基本), this was the testing program:

```
?   while (scanf(%s %d", name, &value) != EOF) {
?       p = newitem(name, value);
?       list1 = addfront(list1, p);
?       list2 - addend(list2, p);
?   }
?   for (p = list1; p != NULL; p = p->next)
?       printf("%s %d\n", p->name, p->value);
```

It was surprisingly difficult to see that the first loop was putting the same node p on both lists so the pointers were hopelessly scrambled (扰乱) by the time we got to printing.

It's tough to find this kind of bug, because your brain takes you right around the mistake. Thus a debugger is a help, since it forces you to go in a different direction, to follow what the program is doing, not what you think it is doing. Often the underlying problem is something wrong with the structure of the whole program, and to see the error you need to return to your starting assumptions.

Notice, by the way, that in the list example the error was in the test code, which made the bug that much harder to find. It is frustratingly easy to waste time chasing bugs that aren't there, because the test program is wrong, or by testing the wrong version of the program, or by failing go update or recompile before testing.

If you can't find a bug after considerable work, take a break. Clear your mind, do something else. Talk to a friend and ask for help. The answer might appear out of the blue, but if not, you won't be stuck in the same rut (凹槽) in the next debugging session.

Once in a long while, the problem really is the compiler or a library or the operating system or even the hardware, especially if something changed in the environment just before a bug appeared. You should never start by blaming one of these, but when everything else has been eliminated, that might be all that's left. We once had to move a large text-formatting program from its original Unix home to a PC. The program compiled without incident, but behaved in an extremely odd way: it dropped roughly every second (次要的) character of its input. Our first thought was that this must be some property of using 16-bit integers instead of 32-bit, or perhaps some strange byte-order problem. But by printing out the characters seen by the main loop, we finally tracked it down to an error in the standard header file `ctype.h` provided by the compiler vendor. It implemented `isprint` as a function macro:

```
?   #define isprint(c) ((c) >= 040 && (c) < 0177)
```

and the main input loop was basically

```
?   while (isprint(c = getchar()))
?        ...
```

Each time an input character was blank (octal 40, a poor way to write ' ') or greater, which was most of the time, `getchar` was called a second time because the macro evaluated its argument twice, and the first input character disappeared forever. The original code was not as clean as it should have been -- there's too much in the loop condition -- but the vendor's header file was inexcusably (无法容许地) wrong.

One can still find instances of this problem today; this macro comes from a different vendor's current header files:

```
?   #define __iscsym(c) (isalnum(c) || ((c) == '_'))
```

Memory "leaks" -- the failure to reclaim memory that is no longer in use -- are a significant source of erratic behavior. Another problem is forgetting to close files, until the table of open files is full and the program cannot open any more. Programs with leaks tend to fail mysteriously because they run out of some resource but the specific failure can't be reproduced.

Occasionally hardware itself goes bad. The floating-point flaw (缺陷) in the 1994 Pentium processor that caused certain computations to produce wrong answers was a highly publicized (广为宣传的) and costly bug in the design of the hardware, but once it had been identified, it was of course reproducible. One of the strangest bugs we ever saw involved a calculator program, long ago on a two-processor system. Sometimes the expression $1/2$ would print 0.5 and sometimes it would print some consistent but utterly (完全) wrong value like 0.7432; there was no pattern as to whether one got the right answer or the wrong one. The problem was eventually traced to a failure of the floating-point unit in one of the processors. As the calculator program was randomly executed on one processor or the other, answers were either correct or nonsense.

Many years ago we used a machine whose internal temperature could be estimated from the number of low-order bits it got wrong in floating-point calculations. One of the circuit cards was loose; as the machine got warmer, the card tilted (倾斜的) further out of its socket, and more data bits were disconnected from the backplane (基架).

5.5 Non-reproducible Bugs

Bugs that won't stand still are the most difficult to deal with, and usually the problem isn't as obvious as failing hardware. The very fact that the behavior is non- deterministic is itself information, however; it means that the error is not likely to be a flaw (缺陷) in your algorithm but that in some way your code is using information that changes each time the program runs.

Check whether all variables have been initialized; you may be picking up a random value from whatever was previously stored in the same memory location. Local variables of functions and memory obtained from allocators are the most likely culprits (罪魁祸首) in C and C++. Set all variables to known values; if there's a random number seed that is normally set from the time of day, force it to a constant, like zero.

If the bug changes behavior or even disappears when debugging code is added, it may be a memory allocation error -- somewhere you have written outside of allocated memory, and the addition of debugging code changes the layout of storage enough to change the effect of the bug. Most output functions, from `printf` to dialog windows, allocate memory themselves, further muddying the waters (进一步把水搅混).

If the crash site seems far away from anything that could be wrong, the most likely problem is overwriting memory by storing into a memory location that isn't used until much later. Sometimes this is a dangling (悬挂) pointer problem, where a pointer to a local variable is inadvertently (不慎地) returned from a function, then used. Returning the address of a local variable is a recipe (秘诀) for delayed disaster:

```
?   char *msg(int n, char *s)
?   {
?       char buf[100];
?
?       sprintf(buf, "error %d: %s\n", n, s);
?       return buf;
?   }
```

By the time the pointer returned by `msg` is used, it no longer points to meaningful storage. You must allocate storage with `malloc`, use a static array, or require the caller to provide the space.

Using a dynamically allocated value after it has been freed has similar symptoms. We mentioned this in Chapter 2 when we wrote `freeall`. This code is wrong:

```
?   for (p = listp; p != NULL; p = p->next)
?       free(p);
```

Once memory has been freed, it must not be used since its contents may have changed and there is no guarantee that `p->next` still points to the right place.

In some implementations of `malloc` and `free`, freeing an item twice corrupts the internal data structures but doesn't cause trouble until much later, when a subsequent call slips (滑过) on the mess made earlier. Some allocators come with debugging options that can be set to check the consistency of the arena (竞技场) at each call; turn them on if you have a non-deterministic bug. Failing that, you can write your own allocator that does some of its own consistency checking or logs all calls for separate analysis. An allocator that doesn't have to run fast is easy to write, so this strategy is feasible when the situation is dire (可怕的). There are also excellent commercial products that check memory management and catch errors and leaks: writing your own `malloc` and `free` can give you some of their benefits if you don't have access to them.

When a program works for one person but fails for another, something must depend on the external environment of the program. This might include files read by the program, file permissions, environment variables, search path for commands, defaults, or startup files. It's hard to be a consultant for these situations, since you have to become the other person to duplicate the environment of the broken program.

Exercise 5-1 . Write a version of `malloc` and `free` that can be used for debugging storage-management problems. One approach is to check the entire workspace on each call of `malloc` and `free`; another is to write logging information that can be processed by another program. Either way, add markers to the beginning and end of each allocated block to detect overruns (超限) at either end. □

5.6 Debugging Tools

Debuggers aren't the only tools that help find bugs. A variety of programs can help us wade through voluminous output to select important bits, find anomalies, or rearrange data to make it easier to see what's going on. Many of these programs are part of the standard toolkit; some are written to help find a particular bug or to analyze a specific program.

In this section we will describe a simple program called `strings` that is especially useful for looking at files that are mostly non-printing characters, such as executables or the mysterious binary formats favored by some word processors. There is often valuable information hidden within, like the text of a document, or error messages and undocumented options, or the names of files and directories, or the names of functions a program might call.

We also find `strings` helpful for locating text in other binary files. Image files often contain ASCII strings that identify the program that created them, and compressed files and archives (such as zip files) may contain file names; `strings` will find these too.

Unix systems provide an implementation of `strings` already. although it's a little different from this one. It recognizes when its input is a program and examines only the text and data segments, ignoring the symbol table. Its `-a` option forces it to read the whole file.

In effect, `strings` extracts the ASCII text from a binary file so the text can be read or processed by other programs. If an error message carries no identification, it may not be evident what program produced it, let alone why. In that case, searching through likely directories with a command like

```
% strings *.exe *.dll | grep 'mystery message'
```

might locate the producer.

The `strings` function reads a file and prints all run of at least `MINLEN = 6` printable characters:

```
/* strings: extract printable strings from stream */
void strings(char *name, FILE *fin)
{
```

```
        int c, i;
        char buf[BUFSIZ];

        do {    /* once for each string */
            for (i = 0; (c = getc(fin)) != EOF;  ) {
                if (!isprint(c))
                    break;
                buf[i++] = c;
                if (i >= BUFSIZ)
                    break;
            }
            if (i >= MINLEN) /* print if long enough */
                printf("%s: %.*s\n", name, i, buf);
        } while (c != EOF);
    }
```

The `printf` format string `%.*s` takes the string length from the next argument (`i`), since the string (`buf`) is not null-terminated.

The `do-while` loop finds and then prints each string, terminating at `EOF`. Checking for end of file at the bottom allows the `getc` and `string` loops to share a termination condition and lets a single `printf` handle end of string, end of file, and string too long.

A standard-issue outer loop with a test at the top, or a single `getc` loop with a more complex body, would require duplicating the `printf`. This function started life that way, but it had a bug in the `printf` statement. We fixed that in one place but forgot to fix two others. ("Did I make the same mistake somewhere else?") At that point, it became clear that the program needed to be rewritten so there was less duplicated code; that led to the `do-while`.

The main routine of `strings` calls the `strings` function for each of its argument files:

```
    /* strings main: find printable strings in files */
    int main(int argc, char *argv[])
    {
        int     i;
        FILE    *fin;

        setprogname("strings");
        if (argc == 1)
            printf("usage: strings filenames");
        else {
            for (i = 1; i < argc; i++) {
                if ((fin = fopen(argv[i], "rb")) == NULL)
                    printf("can't open %s: ", argv[i]);
                else {
                    strings(argv[i], fin);
                    fclose(fin);
                }
            }
        }
        return 0;
    }
```

You might be surprised that `strings` doesn't read its standard input if no files are named. Originally it did. To explain why it doesn't now, we need to tell a debugging story.

The obvious test case for `strings` is to run the program on itself. This worked fine on Unix, but under Windows 95 the command

```
C:\> strings < strings.exe
```

produced exactly five lines of output[4]:

```
!This program cannot be run in DOS mode
.rdata
@.data
.idata
.reloc
```

The first line looks like an error message and we wasted some time before realizing it's actually a string in the program, and the output is correct, at least as far as it goes. It's not unknown to have a debugging session derailed (转移) by misunderstanding the source of a message.

But there should be more output. Where is it? Late one night, the light finally dawned. ("I've seen that before!") This is a portability problem that is described in more detail in Chapter 8. We had originally written the program to read only from its standard input using `getchar`. On Windows. however, `getchar` returns `EOF` when it encounters a particular byte (`Ox1A` or `Ctrl-Z`) in text mode input and this was causing the early termination.

This is absolutely legal behavior, but not what we were expecting given our Unix background. The solution is to open the file in binary mode using the mode `"rb"`. But `stdin` is already open and there is no standard way to change its mode. (Functions like `fdopen` or `setmode` could be used but they are not part of the C standard.) Ultimately we face a set of unpalatable (不可口的) alternatives: force the user to provide a file name so it works properly on Windows but is unconventional on Unix; silently produce wrong answers if a Windows user attempts to read from standard input; or use conditional compilation to make the behavior adapt to different systems, at the price of reduced portability. We chose the first option so the same program works the same way everywhere.

Exercise 5-2 . The `strings` program prints strings with `MINLEN` or more characters, which sometimes produces more output than is useful. Provide `strings` with an optional argument to define the minimum string length. □

Exercise 5-3 . Write `vis`, which copies input to output, except that it displays non-printable bytes like backspace, control characters, and non-ASCII characters as `\Xhh` where `hh` is the hexadecimal representation of the non-printable byte. By contrast with `strings`, `vis` is most useful for examing input that contain only a few non-printable characters. □

Exercise 5-4 . What does `vis` produce if the input is `\X0A`? How could you make the output `vis` unambiguous? □

Exercise 5-5 . Extend `vis` to process a sequence of files, fold long lines at any desired column, and remove non-printable characters entirely. What other features might be consistent with the role of the program? □

[4]The message maybe contains errors, because the source is blurry.

5.7 Other People's Bugs

Realistically, most programmers do not have the fun of developing a brand new system from the ground up. Instead, they spend much of their time using, maintaining. modifying and thus, inevitably, debugging code written by other people.

When debugging others' code, everything that we have said about how to debug your own code applies. Before starting, though, you must first acquire some understanding of how the program is organized and how the original programmers thought and wrote. The term used in one very large software project is "discovery," which is not a bad metaphor (隐喻). The task is discovering what on earth is going on in something that you didn't write.

This is a place where tools can help significantly. Text-search programs like grep can find all the occurrences of names. Cross-reference give some idea of the program's structure. A display of the graph of function calls is valuable if it isn't too big. Stepping through a program a function call at a time with a debugger can reveal the sequence of events. A revision history of the program may give some clues by showing what has been done to the program over time. Frequent changes are often a sign of code that is poorly understood or subject (屈服于) to changing requirements. and thus potentially buggy.

Sometimes you need to track down errors in software you are not responsible for and d o not have the source code for. In that case, the task is to identify and characterize the bug sufficiently well that you can report it accurately. and at the same time perhaps find a "work-around" (迂回路线) that avoids the problem.

If you think that you have found a bug in someone else's program, the first step is to make absolutely sure it is a genuine (真正的) bug, so you don't waste the author's time and lose your own credibility.

When you find a compiler bug, make sure that the error is really in the compiler and not in your own code. For example, whether a right shift operation fills with zero bits (logical shift) or propagates (蔓延) the sign bit (arithmetic shift) is unspecified in C and C++, so novices (新手) sometimes think it's an error if a construct like

```
?   i = -1;
?   printf("%d\n", i >> 1);
```

yields an unexpected answer. But this is a portability issue, because this statement can legitimately (合法地) behave differently on different systems. Try your test on multiple systems and be sure you understand what happens; check the language definition to be sure.

Make sure the bug is new. Do you have the latest version of the program? Is there a list of bug fixes? Most software goes through multiple releases; if you find a bug in version 4.0b1, it might well be fixed or replaced by a new one in version 4.04b2. In any case, few programmers have much enthusiasm for fixing bugs in any- thing but the current version of a program.

Finally, put yourself in the shoes of the person who receives your report. You want to provide the owner with as good a test case as you can manage. It's not very helpful if the bug can be demonstrated (示范) only with large inputs, or an elaborate (复杂的) environment, or multiple supporting files. Strip the test down to a minimal and self-contained case. Include other information that could possibly be relevant, like the version of the program itself, and of the compiler, operating system, and hardware. For the buggy version of `isprint` mentioned in Section 5.4, we could provide this as a test program:

```
    /* test program for isprint bug */
```

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

    while (isprint(c = getchar()) || c != EOF)
        print("%c", c);
    return 0;
}
```

Any line of printable text will serve as a test case, since the output will contain only half the input:

```
% echo 1234567890 | isprint_test
24680
%
```

The best bug reports are the ones that need only a line or two of input on a plain vanilla system to demonstrate the fault, and that include a fix. Send the kind of bug report you'd like to receive yourself.

5.8 Summary

With the right attitude debugging can be fun, like solving a puzzle, but whether we enjoy it or not, debugging is an art that we will practice regularly. Still, it would be nice if bugs didn't happen, so we try to avoid them by writing code well in the first place. Well-written code has fewer bugs to begin with and those that remain are easier to find. Once a bug has been seen, the first thing to do is to think hard about the clues it presents. How could it have come about? Is it something familiar? Was something just changed in the program? Is there something special about the input data that provoked (触发) it? A few well-chosen test cases and a few print statements in the code may be enough.

If there aren't good clues, hard thinking is still the best first step, to be followed by systematic attempts to narrow down the location of the problem. One step is cutting down the input data to make a small input that fails; another is cutting out code to eliminate regions that can't be related. It's possible to insert checking code that gets turned on only after the program has executed some number of steps, again to try to localize the problem. All of these are instances of a general strategy, divide and conquer, which is as effective in debugging as it is in politics and war.

Use other aids as well. Explaining your code to someone else (even a teddy bear) is wonderfully effective. Use a debugger to get a stack trace. Use some of the commercial tools that check for memory leaks, array bounds violations, suspect (可疑的) code, and the like. Step through your program when it has become clear that you have the wrong mental picture of how the code works.

Know yourself, and the kinds of errors you make. Once you have found and fixed a bug, make sure that you eliminate other bugs that might be similar. Think about what happened so you can avoid making that kind of mistake again.

Supplementary Reading

Steve Maguire's *Writing Solid Code* (Microsoft Press, 1993) and Steve McConnell's *Code Complete* (Microsoft Press, 1993) both have much good advice on debugging.

6 Testing

In ordinary computational practice by hand or by desk mtichines[1]*, it is the custom to check every step of the computation and, when an error is found, to localize it by a backward process starting from the first point where the error is noted.*

Norbert Wiener, *Cybernetics*[2]

Testing and debugging are often spoken as a single phrase but they are not the same thing. To oversimplify, debugging is what you do when you know that a program is broken. Testing is a determined, systematic attempt to break a program that you think is working.

Edsger Dijkstra made the famous observation that testing can demonstrate the presence of bugs, but not their absence. His hope is that programs can be made correct by construction, so that there are no errors and thus no need for testing. Though this is a fine goal, it is not yet realistic for substantial (大量的) programs. So in this chapter we'll focus on how to test to find errors rapidly, efficiently, and effectively.

Thinking about potential problems as you code is a good start. Systematic testing, from easy tests to elaborate (详尽的) ones, helps ensure that programs begin life working correctly and remain correct as they grow. Automation helps to eliminate manual processes and encourages (促进) extensive (多方面的) testing. And there are plenty of tricks of the trade that programmers have learned from experience.

One way to write bug-free code is to generate it by a program. If some programming task is understood so well that writing the code seems mechanical, then it should be mechanized (机械化的). A common case occurs when a program can be generated from a specification in some specialized language. For example, we compile high-level languages into assembly code; we use regular expressions to specify patterns of text; we use notations like `SUM(A1:A50)` to represent operations over a range of cells in a spreadsheet. In such cases, if the generator or translator is correct and if the specification is correct, the resulting program will be correct too. We will cover this rich topic in more detail in Chapter 9; in this chapter we will talk briefly about ways to create tests from compact specifications.

[1] Unrecognized word
[2] 控制论.

6.1 Test as You Write the Code

The earlier a problem is found, the better. If you think systematically about what you are writing as you write it, you can verify simple properties of the program as it is being constructed, with the result that your code will have gone through one round of testing before it is even compiled. Certain kinds of bugs never come to life.

Test code at its boundaries. One technique is *boundary condition* testing: as each small piece of code is written -- a loop or a conditional statement, for example -- check right then that the condition branches the right way or that the loop goes through the proper number of times. This process is called boundary condition testing because you are probing at the natural boundaries within the program and data, such as non-existent or empty input, a single input item, an exactly full array, and so on. The idea is that most bugs occur at boundaries. If a piece of code is going to fail, it will likely fail at a boundary. Conversely (相反), if it works at its boundaries, it's likely to work elsewhere too.

This fragment, modeled on `fgets`, reads characters until it finds a newline or fills a buffer:

```
?   int     i;
?   char    s[MAX];
?
?   for (i = 0; (s[i] = getchar()) != '\n' && i < MAX - 1; ++i)
?       ;
?   s[--i] = '\0';
```

Imagine that you have just written this loop. Now simulate it mentally as it reads a line. The first boundary to test is the simplest: an empty line. If you start with a line that contains only a single newline, it's easy to see that the loop stops on the first iteration with `i` set to zero, so the last line decrements `i` to `-1` and thus writes a null byte into `s[-1]`, which is before the beginning of the array. Boundary condition testing finds the error.

If we rewrite the loop to use the conventional idiom for filling an array with input characters, it looks likes this:

```
    for (i = 0; i < MAX - 1; i++)
        if ((s[i] = getchar()) == '\n')
            break;
    s[i] = '\0';
```

Repeating the original boundary test, it's easy to verify that a line with just a newline is handled correctly: `i` is zero, the first input character breaks out of the loop, and `'\0'` is stored in `s[0]`. Similar checking for inputs of one and two characters followed by a newline give us confidence that the loop works near that boundary.

Boundary condition testing can catch lots of bugs, but not all of them. We will return to this example in Chapter 8, where we will show that it still has a portability bug.

The next step is to check input at the other boundary, where the array is nearly full, exactly full, and over-full, particularly if the newline arrives at the same time. We won't write out the details here, but it's a good exercise. Thinking about the boundaries raises the question of what to do when the buffer fills before a `'\n'` occurs; this gap (缺口) in the specification should be resolved early, and testing boundaries helps to identify it.

Boundary condition checking is effective for finding off-by-one (单一断接) errors. With practice, it becomes second nature, and many trivial (琐碎的) bugs are eliminated before they ever happen.

Test pre- and post-conditions. Another way to head off (拦截) problems is to verify that expected or necessary properties hold before (pre-condition) and after (post-condition) some piece of code executes. Making sure that input values are within range is a common example of testing a pre-condition. This function for computing the average of n elements in an array has a problem if n is less than or equal to zero:

```
?   double avg(double a[], int n)
?   {
?       int     i;
?       double  sum;
?
?       sum = 0.0;
?       for (i = 0; i < n; i++)
?           sum += a[i];
?       return sum / n;
?   }
```

What should avg do if n is zero? An array with no elements is a meaningful concept although its average value is not. Should avg let the system catch the division by zero? Abort? Complain? Quietly return some innocuous (无害的) value? What if n is negative, which is nonsensical (无意义) but not impossible? As suggested in Chapter 4, our preference would probably be to return 0 as the average if n is less than or equal to zero:

```
return n <= 0 ? 0.0 : sum/n;
```

but there's no single right answer.

The one guaranteed wrong answer is to ignore the problem. An article in the November, 1998 *Scientific American* describes an incident (事件) aboard (在... 之上) the USS Yorktown, a guided-missile cruiser (导弹巡洋舰). A crew member mistakenly entered a zero for a data value, which resulted in a division by zero, an error that cascaded and eventually shut down the ship's propulsion (推进) system. The Yorktown was dead in the water for a couple of hours because a program didn't check for valid input.

Use assertions. C and C++ provide an assertion facility in `assert.h` that encourages adding pre- and post-condition tests. Since a failed assertion aborts the program, these are usually reserved for situations where a failure is really unexpected and there's no way to recover. We might augment (增加) the code above with an assertion before the loop:

```
assert(n > 0);
```

If the assertion is violated, it will cause the program to abort with a standard message:

```
Assertion failed: n > 0, file avgtest.c, line 7
Abort(crash)
```

Assertions are particularly helpful for validating properties of interfaces because they draw attention to inconsistencies between caller and callee and may even indicate who's at fault. If the assertion that n is greater than zero fails when the function is called, it points the finger (手指) at the caller rather than at avg itself as the source of trouble. If an interface changes but we forget to fix some routine that depends on it, an assertion may catch the mistake before it causes real trouble.

Program defensively. A useful technique is to add code to handle "can't happen" cases, situations where it is not logically possible for something to happen but (because of some failure elsewhere) it might anyway. Adding a test for zero or negative array lengths to avg was one example. As another example, a program processing grades might expect that there would be no negative or huge values but should check anyway:

```
if (grade < 0 || grade > 100) /* can't happen */
    letter = '?';
else if (grade >= 90)
    letter = 'A';
else
    ...
```

This is an example of defensive programming: making sure that a program protects itself against incorrect use or illegal data. Null pointers, out of range subscripts, division by zero, and other errors can be detected early and warned about or deflected (转移). Defensive programming (no pun intended (没有双关语意)) might well have caught the zero-divide problem on the Yorktown.

Check error returns. One often-overlooked (常常被忽视的) defense is to check the error returns from library functions and system calls. Return values from input routines such as `fread` and `fscanf` should always be checked for errors, as should any file open call such as `fopen`. If a read or open fails, computation cannot proceed correctly.

Checking the return code from output functions like `fprintf` or `fwrite` will catch the error that results from trying to write a file when there is no space left on the disk. It may be sufficient to check the return value from `fclose`, which returns `EOF` if any error occurred during any operation, and zero otherwise.

```
fp = fopen(outfile, "w");
while (...)                 /* write output to outfile */
    fprintf(fp, ...);
if (fclose(fp) == EOF) {    /* any errors? */
    /* some output error occurred */
}
```

Output errors can be serious. If the file being written is the new version of a precious file, this check will save you from removing the old file if the new one was not written successfully.

The effort of testing as you go is minimal and pays off handsomely (优厚地). Thinking about testing as you write a program will lead to better code, because that's when you know best what the code should do. If instead you wait until something breaks, you will probably have forgotten how the code works. Working under pressure, you will need to figure it out again, which takes time, and the fixes will be less thorough and more fragile because your refreshed understanding is likely to be incomplete.

Exercise 6-1 . Check out these examples at their boundaries, then fix them as necessary according to the principles of style in Chapter 1 and the advice in this chapter.

a. This is supposed to compute factorials:

```
?           int factorial(int n)
?           {
?               int fac;
?               fac = 1;
?               while (n--)
?                   fac *= n;
?               return fac;
?           }
```

b. This is supposed to print the characters of a string one per line:

```
?           i = 0;
?           do {
?               putchar(s[i++];
?               putchar('\n');
?           } while (s[i] != '\0');
```

c. This is meant to copy a string from source to destination:

```
?           void strcpy(char *dest, char *src)
?           {
?               int i;
?
?               for (i = 0; src[i] != '\0'; i++)
?                   dest[i] = src[i];
?           }
```

d. Another string copy, which attempts to copy `n` characters from `s` to `t`:

```
?           void strncpy(char *s, char *t, int n)
?           {
?               while (n > 0 && *s != '\0') {
?                   *t = *s;
?                   t++;
?                   s++;
?                   n--;
?               }
?           }
```

e. A numerical comparison:

```
?           if (i > j)
?               printf("%d is greater than %d.\n", i, j);
?           else
?               printf("%d is smaller than %d.\n", i, j);
```

f. A character class test:

```
?           if (c >= 'A' && c <= 'Z') {
?               if (c >= 'L')
?                   cout << "first half of alphabet";
?               else
?                   cout << "second half of alphabet";
?           }
```

□

Exercise 6-2 . As we are writing this book in late 1998, the Year 2000 problem looms (若隐若现) as perhaps the biggest boundary condition problem ever.

a. What dates would you use to check whether a system is likely to work in the year 2000? Supposing that test are expensive to perform, in what order would you do your tests after trying January 1, 2000 itself?

b. How would you test the standard function `ctime`, which returns a string representation of the date in this form:

```
Fri Dec 31 23:58:27 EST 1999\n\0
```

Suppose your program calls `ctime`. How would you write your code to defend against a flawed (缺陷的) implementation?

c. Describe how you would test a calendar program that prints output like this:

```
      July 2015
Su Mo Tu We Th Fr Sa
          1  2  3  4
5  6  7  8  9  10 11
12 13 14 15 16 17 18
19 20 21 22 23 24 25
26 27 28 29 30 31
```

d. What other time boundaries can you think of in systems that you use, and how would you test to see whether they are handled correctly?

□

6.2 Systematic Testing

It's important to test a program systematically so you know at each step what you are testing and what results you expect. You need to be orderly so you don't overlook (忽略) anything, and you must keep records so you know how much you have done.

Test incrementally. Testing should go hand in hand (联合) with program construction. A "big bang" (大撞击) where one writes the whole program, then tests it all at once, is much harder and more time-consuming than an incremental approach. Write part of a program, test it, add some more code, test that, and so on. If you have two packages that have been written and tested independently, test that they work together when you finally connect them.

For instance, when we were testing the CSV programs in Chapter 4, the first step was to write just enough code to read the input; this let us validate input processing. The next step was to split input lines at commas. Once these parts were working, we moved on to fields with quotes, and then gradually worked up to testing everything.

Test simple parts first. The incremental approach also applies to how you test features. Tests should focus first on the simplest and most commonly executed features of a program; only when those are working properly should you move on. This way, at each stage, you expose more to testing and build confidence that basic mechanisms are working correctly. Easy tests find the easy bugs. Each test does the minimum to ferret out (查获) the next potential problem. Although each bug is harder to trigger than its predecessor, it is not necessarily harder to fix.

In this section, we'll talk about ways to choose effective tests and in what order to apply them; in the next two sections, we'll talk about how to mechanize (使机械化) the process so that it can be carried out efficiently. The first step, at least for small programs or individual functions, is an extension of the boundary condition testing that we described in the previous section: systematic testing of small cases.

Suppose we have a function that performs binary search in an array of integers. We would begin with these tests, arranged in order of increasing complexity:

- search an array with noelements
- search an array with one element and a trial (试验的) value this is
  - less than the single element in the array
  - equal to the single element
  - greater than the single element
- search an array with two elements and trial values that
  - check all five possible positions
- check behavior with duplicate elements in the array and trial values
  - less than the value in the array
  - equal to the value
  - greater than the value
- search an array with three elements as with two elements
- search an array with four elements as with two and three

If the function gets past this unscathed (未受损伤的), it's likely to be in good shape, but it could still be tested further.

This set of tests is small enough to perform by hand, but it is better to create a test scaffold (脚手架) to mechanize the process. The following driver program is about as simple as we can manage. It reads input lines that contain a key to search for and an array size; it creates an array of that size containing values `1, 3, 5, ...`, and it searches the array for the key.

```
/* bintest main: scaffold for testing binsearch */
int main(void)
{
    int i, key, nelem, arr[1000];

    while (scanf("%d %d", &key, &nelem) != EOF) {
        for (i = 0; i < nelem; i++)
            arr[i] = 2 * i + 1;
        printf("%d\n", binsearch(key, arr, nelem));
    }
    return 0;
}
```

This is simpleminded but it shows that a useful test scaffold need not be big, and it is easily extended to perform more of these tests and require less manual intervention (介入).

Know what output to expect. For all tests, it's necessary to know what the right answer is; if you don't, you're wasting your time. This might seem obvious, since for many programs it's easy to tell whether the program is working. For example, either a copy of a tile (瓦片) is a copy or it isn't. The output from a sort is sorted or it isn't; it must also be a permutation (排列) of the original input.

Most programs are more difficult to characterize (描绘特性) -- compilers (does the output properly translate the input?), numerical algorithms (is the answer within error tolerance?), graphics (are the pixels in the right places?), and so on. For these, it's especially important to validate the output by comparing it with known values.

- To test a compiler, compile and run the test files. The test programs should in turn generate output, and their results should be compared to known ones.
- To test a numerical program, generate test cases that explore the edges of the algorithm, trivial (琐细的) cases as well as hard ones. Where possible, write code that verifies that output properties are sane (合理的). For example, the output of a numerical integrator can be tested for continuity (连续性), and for agreement with closed-form (封闭形式) solutions.
- To test a graphics program, it's not enough to see if it can draw a box; instead read the box back from the screen and check that its edges are exactly where they should be.

If the program has an inverse (相反的), check that its application recovers the input. Encryption and decryption are inverses, so if you encrypt something and can't decrypt it, something is wrong. Similarly, lossless compression and expansion algorithms should be inverses. Programs that bundle (打包) files together should extract them unchanged. Sometimes there are multiple methods for inversion: check all combinations.

Verify conservation (保存) properties. Many programs preserve some property of their inputs. Tools like `wc` (count lines, words, and characters) and `sum` (compute a checksum) can verify that outputs are of the same size, have the same number of words, contain the same bytes in some order, and the like. Other programs compare files for identity (`cmp`) or report differences (`diff`). These programs or similar ones are readily (轻易的) available for most environments, and are well worth acquiring.

A byte-frequency program can be used to check for conservation of data and also to spot anomalies (反常) like non-text characters in supposedly text-only files; here's a version that we call `freq`:

```
#include <stdio.h>
#include <ctype.h>
#include <limits.h>

unsigned long count[UCHAR_MAX+1];

/* freq main: display byte frequency counts */
int main(void)
{
    int c;

    while ((c = getchar()) != EOF)
        count[c]++;
    for (c = 0; c <= UCHAR_MAX; c++)
        if (count[c] != 0)
            printf("%.2x %c %lu\n",
                    c, isprint(c) ? c : '-', count[c]);
    return 0;
}
```

Conservation properties can be verified within a program, too. A function that counts the elements in a data structure provides a trivial (平常的) consistency check. A hash table should have the property that every element inserted into it can be retrieved. This condition is easy to check with a function that dumps the contents of the table into a file or an array. At any time, the number of insertions into a data structure minus the number of deletions must equal the number of elements contained, a condition that is easy to verify.

Compare independent implementations. Independent implementations of a library or program should produce the same answers. For example, two compilers should produce programs that behave the same way on the same machine, at least in most situations.

Sometimes an answer can be computed in two different ways, or you might be able to write a trivial version of a program to use as a slow but independent comparison. If two unrelated programs get the same answers, there is a good chance that they are correct; if they get different answers, at least one is wrong.

One of the authors once worked with another person on a compiler for a new machine. The work of debugging the code generated by the compiler was split: one person wrote the software that encoded instructions for the target machine, and the other wrote the disassembler for the debugger. This meant that any error of interpretation or implementation of the instruction set was unlikely to be duplicated between the two components. When the compiler miscoded an instruction, the disassembler was sure to notice. All the early output of the compiler was run through the disassembler and verified against the compiler's own debugging printouts. This strategy worked very well in practice, instantly catching mistakes in both pieces. The only difficult, protracted (拖延的) debugging occurred when both people interpreted an ambiguous phrase in the architecture description in the same incorrect way.

Measure test coverage (覆盖范围). One goal of testing is to make sure that every statement of a program has been executed sometime during the sequence of tests; testing cannot be considered complete unless every line of the program has been exercised by at least one test. Complete coverage is often quite difficult to achieve. Even leaving aside "can't happen" statements, it is hard to use normal inputs to force a program to go through particular statements.

There are commercial tools for measuring coverage. Profilers (探查程序), often included as part of compiler suites, provide a way to compute a statement frequency count for each program statement that indicates the coverage achieved by specific tests.

We tested the `Markov` program of Chapter 3 with a combination of these techniques. The last section of this chapter describes those tests in detail.

Exercise 6-3 . Describe how you would test `freq`. □

Exercise 6-4 . Design and implement a version of `freq` that measures the frequencies of other types of data values, such as 32-bit integers or floating-point numbers. Can you make one version of the program handle a variety of types elegantly? □

6.3 Test Automation

It's tedious and unreliable to do much testing by hand; proper testing involves lots of tests, lots of inputs, and lots of comparisons of outputs. Testing should therefore be done by programs, which don't get tired or careless. It's worth taking the time to write a script or trivial program that encapsulates all the tests, so a complete test suite can be run by (literally (从字面上) or figuratively (比喻)) pushing a single button.

The easier a test suite is to run, the more often you'll run it and the less likely you'll skip it when time is short. We wrote a test suite that verifies all the programs we wrote for this book, and ran it every time we made changes; parts of the suite ran automatically after each successful compilation.

Automate regression testing. The most basic form of automation is regression testing, which performs a sequence of tests that compare the new version of something with the previous version. When fixing problems, there's a natural tendency to check only that the fix works; it's easy to overlook the possibility that the fix broke something else. The intent of regression testing is to make sure that the behavior hasn't changed except in expected ways.

Some systems are rich in tools that help with such automation; scripting languages allow us to write short scripts to run test sequences. On Unix, file comparators like `diff` and `cmp` compare outputs; `sort` brings common elements together; `grep` filters test outputs; `wc`, `sum`, and `freq` summarize outputs. Together, these make it easy to create ad hoc (特别定制地) test scaffolds, maybe not enough for large programs but entirely adequate for a program maintained by an individual or a small group.

Here is a script for regression testing a killer application program called `ka`. It runs the old version (`old_ka`) and the new version (`new_ka`) for a large number of different test data files, and complains about each one for which the outputs are not identical. It is written for a Unix shell but could easily be transcribed to Perl or other scripting language:

```
for i in ka_data.*              # loop over test data files
do
    old_ka $i > out1            # run the old version
    new_ka $i > out2            # run the new version
    if ! cmp -s out1 out2       # compare output files
    then
        echo $BAD               # different: print error message
    fi
done
```

A test script should usually run silently, producing output only if something unexpected occurs, as this one does. We could instead choose to print each file name as it is being tested, and to follow it with an error message if something goes wrong. Such indications of progress help to identify problems like an infinite loop or a test script that is failing to run the right tests, but the extra chatter (喋喋不休) is annoying if the tests are running properly.

The `-s` argument causes `cmp` to report status but produce no output. If the files compare equal, `cmp` returns a true status, `!cmp` is false, and nothing is printed. If the old and new outputs differ, however, `cmp` returns false and the file name and a warning are printed.

There is an implicit assumption in regression testing that the previous version of the program computes the right answer. This must be carefully checked at the beginning of time, and the invariant (不变的) scrupulously (审慎地) maintained. If an erroneous answer ever sneaks (偷偷地) into a regression test, it's very hard to detect and everything that depends on it will be wrong thereafter (其后). It's good practice to check the regression test itself periodically to make sure it is still valid.

Create self-contained tests. Self-contained tests that carry their own inputs and expected outputs provide a complement (补充) to regression tests. Our experience testing Awk may be instructive (有益的). Many language constructions are tested by running specified inputs through tiny programs and checking that the right output is produced. The following part of a large collection of miscellaneous tests verifies one tricky (狡猾的) increment expression. This test runs the new version of Awk (`newawk`) on a short Awk program to produce output in one file, writes the correct output to another file with echo, compares the files, and reports an error if they differ.

```
# field increment test: $i++ means ($i)++, not $(i++)

echo 3 5 | newawk '{i = 1; print $i++; print $1, i}' > out1
echo '3
4 1' > out2     # correct answer
if ! cmp -s out1 out2   # outputs are different
then
    echo 'BAD: field increment test failed'
fi
```

The first comment is part of the test input; it documents what the test if testing.

Sometimes it is possible to construct a large number of tests with modest effort. For simple expressions, we created a small, specialized language for describing tests, input data, and expected outputs. Here is a short sequence that tests some of the ways that the numeric value 1 can be represented in Awk:

```
try {if ($1 == 1) print "yes"; else print "no"}
1       yes
1.0     yes
1E0     yes
0.1E1   yes
10E-1   yes
01      yes
+1      yes
10E-2   no
10      no
```

The first line is a program to be tested (everything after the word try). Each subsequent line is a set of inputs and the expected output, separated by tabs. The first test says that if the first input field is 1 the output should be yes. The first seven tests should all print yes and the last two tests should print no.

An Awk program (what else?) converts each test into a complete Awk program, then runs each input through it, and compares actual output to expected output; it reports only those cases where the answer is wrong.

Similar mechanisms are used to test the regular expression matching and substitution commands. A little language for writing tests makes it easy to create a lot of them; using a program to write a program to test a program has high leverage (杠杆效率). (Chapter 9 has more to say about little languages and the use of programs that write programs.)

Overall, there are about a thousand tests for Awk; the whole set can be run with a single command, and if everything goes well, no output is produced. Whenever a feature is added or a bug is fixed, new tests are added to verify correct operation. When ever the program is changed, even in a trivial (琐碎的) way, the whole test suite is run; it takes only a few minutes. It sometimes catches completely unexpected errors, and has saved the authors of Awk from public embarrassment many times.

What should you do when you discover an error? If it was not found by an existing test, create a new test that does uncover the problem and verify the test by running it with the broken version of the code. The error may suggest further tests or a whole new class of things to check. Or perhaps it is possible to add defenses to the program that would catch the error internally.

Never throw away a test. It can help you decide whether a bug report is valid or describes something already fixed. Keep a record of bugs, changes, and fixes; it will help you identify old problems and fix new ones. In most commercial programming shops (工作室), such records are mandatory. For your personal programming, they are a small investment that will pay off repeatedly.

✎ **Exercise 6-5** . Design a test suite for `printf`, using as many mechanical aids as possible. □

6.4 Test Scaffolds

Our discussion so far is based largely on testing a single stand-alone program in its completed form. This is not the only kind of test automation, however, nor is it the most likely way to test parts of a big program during construction, especially if you are part of a team. Nor is it the most effective way to test small components that are buried in something larger.

To test a component in isolation, it's usually necessary to create some kind of framework or scaffold that provides enough support and interface to the rest of the system that the part under test will run. We showed a tiny example for testing binary search earlier in this chapter.

It's easy to build scaffolds for testing mathematical functions, string functions, sort routines, and so on, since the scaffolding is likely to consist mostly of setting up input parameters, calling the functions to be tested, then checking the results. It's a bigger job to create scaffolding for testing a partly-completed program.

To illustrate, we'll walk through building a test for `memset`, one of the `mem...` functions in the C/C++ standard library. These functions are often written in assembly language for a specific machine, since their performance is important. The more carefully tuned they are, however, the more likely they are to be wrong and thus the more thoroughly they should be tested.

The first step is to provide the simplest possible C versions that are known to work; these provide a benchmark for performance and, more important, for correctness. To move to a new environment, one carries the simple versions and uses them until the tuned ones are working.

The function `memset(s, c, n)` sets `n` bytes of memory to the byte `c`, starting at address `s`, and returns `s`. This function is easy if speed is not an issue:

```
/* memset: set first n bytes of s to c */
void *memset(void *s, int c, size_t n)
{
    size_t  i;
    char    *p;

    p = (char *)s;
    for (i = 0; i < n; i++)
        p[i] = c;
    return s;
}
```

But when speed is an issue, tricks like writing full words of 32 or 64 bits at a time are used. These can lead to bugs, so extensive (广泛的) testing is mandatory.

Testing is based on a combination of exhaustive (彻底的) and boundary-condition checks at likely points of failure. For `memset`, the boundaries include obvious values of `n` such as zero, one and two, but also values that are powers of two or nearby values. including both small ones and large ones like 2^{16}, which corresponds to a natural boundary in many machines, a 16-bit word. Powers of two deserve attention because one way to make `memset` faster is to set multiple bytes at one time; this might be done by special instructions or by trying to store a word at a time instead of a byte. Similarly, we want to check array origins with a variety of alignments in case there is some error based on starting address or length. We will place the target array inside a larger array, thus creating a buffer zone or safety margin on each side and giving us an easy way to vary the alignment.

We also want to check a variety of values for `c`, including zero, `0x7F` (the largest signed value, assuming 8-bit bytes), `0x80` and `0xFF` (probing at potential errors involving signed and unsigned characters), and some values much bigger than one byte (to be sure that only one byte is used). We should also initialize memory to some known pattern that is different from any of these character values so we can check whether `memset` wrote outside the valid area.

We can use the simple implementation as a standard of comparison in a test that allocates two arrays, then compares behaviors on combinations of `n`, `c` and offset within the array:

`big` = maximum left margin + maximum `n` + maximum right margin
`s0 = malloc(big)`
`s1 = malloc(big)`
for each combination of test parameters `n`, `c`, and `offset`:
  set all of `s0` and `s1` to knwon pattern
  run slow `memset(s0 + offset, c, n)`
  run fast `memset(s1 + offset, c, n)`
  check return values
  copare all of `s0` and `s1` byte by byte

An error that causes `memset` to write outside the limits of its array is most likely to affect bytes near the beginning or the end of the array, so leaving a buffer zone makes it easier to see damaged bytes and makes it less likely that an error will overwrite some other part of the program. To check for writing out of bounds, we compare all the bytes of `s0` and `s1`, not just the `n` bytes that should be written.

Thus a reasonalbe set of tests might include all combinations of:

```
offset = 10, 11, ..., 20
c = 0, 1, 0x7F, 0x80, 0xFF, 0x11223344
n = 0, 1, 2, 3, 4, 5, 7, 8, 9, 15, 16, 17,
    31, 32, 33, ..., 65535, 65536, 65537
```

The values of `n` would include at least $2^i - 1$, 2^i and $2^i + 1$ for i from 0 to 16.

These values should not be wired into the main part of the test scaffold, but should appear in arrays that might be created by hand or by program. Generating them automatically is better; that makes it easy to specify more powers of two or to include more offsets and more characters.

These tests will give `memset` a thorough workout (试验) yet cost very little time even to create, let alone run, since there are fewer than 3500 cases for the values above. The tests are completely portable, so they can be carried to a new environment as necessary.

As a warning, consider this story. We once gave a copy of a `memset` tester to someone developing an operating system and libraries for a new processor. Months later, we (the authors of the original test) started using the machine and had a large application fail its test suite. We traced the problem to a subtle (微妙的) bug involving sign extension in the assembly language implementation of `memset`. For reasons unknown, the library implementer had changed the `memset` tester so it did not check values of `c` above `0x7F`. Of course, the bug was isolated by running the original, working tester, once we realized that `memset` was a suspect.

Functions like `memset` are susceptible (容许... 的) to exhaustive tests because they are simple enough that one can prove that the test cases exercise all possible execution paths through the code, thus giving complete coverage. For example, it is possible to test `memmove` for all combinations of overlap, direction, and alignment. This is not exhaustive in the sense of testing all possible copy operations, but it is an exhaustive test of representatives (代表) of each kind of distinct input situation.

As in any testing method, test scaffolds need the correct answer to verify the operations they are testing. An important technique, which we used in testing `memset`, is to compare a simple version that is believed correct against a new version that may be incorrect. This can be done in stages, as the following example shows.

One of the authors implemented a raster (光栅) graphics library involving an operator that copied blocks of pixels from one image to another. Depending on the parameters, the operation could be a simple memory copy, or it could require converting pixel values from one color space to another, or it could require "tiling" (盖瓦) where the input was copied repeatedly throughout a rectangular area, or combinations of these and other features. The specification of the operator was simple, but an efficient implementation would require lots of special code for the many cases. To make sure all that code was right demanded a sound (可靠的) testing strategy.

First, simple code was written by hand to perform the correct operation for a single pixel. This was used to test the library version's handling of a single pixel. Once this stage was working, the library could be trusted for single-pixel operations.

Next, hand-written code used the library a pixel at a time to build a very slow version of the operator that worked on a single horizontal row of pixels, and that was compared with the library's much more efficient handling of a row. With that working, the library could be trusted for horizontal lines.

This sequence continued, using lines to build rectangles, rectangles to build tiles (瓦片), and so on. Along the way, many bugs were found, including some in the tester itself, but that's part of the effectiveness of the method: we were testing two independent implementations, building confidence in both as we went. If a test failed, the tester printed out a detailed analysis to aid understanding what went wrong, and also to verify that the tester was working properly itself.

As the library was modified and ported over the years, the tester repeatedly proved invaluable for finding bugs.

Because of its layer-by-layer approach, this tester needed to be run from scratch (擦除) each time, to verify its own trust of the library. Incidentally, the tester was not exhaustive, but probabilistic (概率性的): it generated random test cases which, for long enough runs, would eventually explore every cranny (缝隙) of the code. With the huge number of possible test cases, this strategy was more effective than trying to construct a thorough test set by hand, and much more efficient than exhaustive testing.

Exercise 6-6 . Create the test scaffold for `memset` along the lines that we indicated. □

Exercise 6-7 . Create tests for the rest of the `mem...` family. □

Exercise 6-8 . Specify a testing regime (体制) for numerical routines like `sqrt`, `sin`, and so on, as found in `math.h`. What input values make sense? What independent checks can be performed? □

✎ **Exercise 6-9** . Define mechanisms for testing the functions of the C `str...` family, like `strcmp`. Some of these functions, especially tokenizers like `strtok` and `strcspn`, are significantly more complicated than the `mem...` family, so more sophiscated test will be called for. □

6.5 Stress Tests

High volumes of machine-generated input are another effective testing technique. Machine-generated input stresses programs differently than input written by people does. Higher volume in itself tends to break things because very large inputs cause overflow of input buffers, arrays, and counters, and are effective at finding unchecked fixed-size storage within a program. People tend to avoid "impossible" cases like empty inputs or input that is out of order or out of range, and are unlikely to create very long names or huge data values. Computers, by contrast, produce output strictly according to their programs and have no idea of what to avoid.

To illustrate, here is a single line of output produced by the Microsoft Visual C++ Version 5.0 compiler while compiling the C++ STL implementation of `markov`; we have edited the line so it fits:

```
xtree(114) : warning C4786: 'std::_Tree<std::deque<std::
basic_string<char, std::char_traits<char>,std::allocator
<char>>,std::allocator<std::basic_string<char,std::
... 1420 characters ommited
allocator<char>>>>>::iterator' : identifer was
truncated to '255' characters in the debug information
```

The compiler is warning us that it has generated a variable name that is a remarkable 1594 characters long but that only 255 characters have been preserved as debugging information. Not all programs defend themselves against such unusually long strings.

Random inputs (not necessarily legal) are another way to assault (攻击) a program in the hope of breaking something. This is a logical extension of "people don't do that" reasoning. For example, some commercial C compilers are tested with randomly-generated but syntactically valid programs. The trick is to use the specification of the problem -- in this case, the C standard -- to drive a program that produces valid but bizarre (奇异的) test data.

Such tests rely on detection by built-in checks and defenses in the program, since it may not be possible to verify that the program is producing the right output; the goal is more to provoke (诱导) a crash or a "can't happen" than to uncover (揭开) straightforward errors. It's also a good way to test that error-handling code works. With sensible input, most errors don't happen and code to handle them doesn't get exercised: by nature, bugs tend to hide in such corners. At some point, though, this kind of testing reaches diminishing (逐渐减小的) returns: it finds problems that are so unlikely to happen in real life they may not be worth fixing.

Some testing is based on explicitly malicious (恶意的) inputs. Security attacks often use big or illegal inputs that overwrite precious data; it is wise to look for such weak spots. A few standard library functions are vulnerable to this sort of attack. For instance, the standard library function `gets` provides no way to limit the size of an input line, so it should ***never*** be used; always use `fgets(buf, sizeof(buf), stdin)` instead. A bare (无遮蔽的) `scanf("%s", buf)` doesn't limit the length of an input line either; it should therefore usually be used with an explicit length, such as `scanf("%20s", buf)`. In Section **??** we showed how to address this problem for a general buffer size.

Any routine that might receive values from outside the program, directly or indirectly, should validate its input values before using them. The following program from a textbook is supposed to read an integer typed by a user, and warn if the integer is too long. Its goal is to demonstrate how to overcome the `gets` problem, but the solution doesn't always work.

```
?   #define MAXNUM 10
?
?   int main(void)
?   {
?       char    num[MAXNUM];
?
?       memset(num, 0, sizeof(num));
?       printf("Type a number: ");
?       gets(num);
?       if (num[MAXNUM - 1] != 0)
?           printf("Number too bit.\n");
?       /* ... */
?   }
```

If the input number is ten digits long, it will overwrite the last zero in array num with a non-zero value, and in theory this will be detected after the return from gets. Unfortunately, this is not sufficient. A malicious attacker can provide an even longer input string that overwrites some critical value, perhaps the return address for the call, so the program never returns to the `if` statement but instead executes something nefarious (恶毒的). Thus this kind of unchecked input is a potential security problem.

Lest (免得) you think that this is an irrelevant textbook example, in July, 1998 an error of this form was uncovered in several major electronic mail programs. As the *New York Times* reported,

> The security hole is caused by what is known as a "buffer overflow error." Programmers are supposed to include code in their software to check that incoming data are of a safe type and that the units are arriving at the right length. If a unit of data is too long, it can overrun the "buffer" -- the chunk of memory set aside to hold it. In that case, the E-mail program will crash, and a hostile (怀有敌意的) programmer can trick the computer into running a malicious program in its place.

This was also one of the attacks in the famous "Internet Worm" incident of 1988.

Programs that parse HTML forms can also be vulnerable to attacks that store very long input strings in small arrays:

```
?   static char query[1024];
?
?   char *read_form(void)
?   {
?       int qsize;
?
?       qsize = atoi(getenv("CONTENT_LENGTH"));
?       fread(query, qsize, 1, stdin);
?       return query;
?   }
```

The code assumes that the input will never be more than 1024 bytes long so, like `gets`, it is open to an attack that overflows its buffer.

More familiar kinds of overflow can cause trouble, too. If integers overflow silently, the result can be disastrous. Consider an allocation like

```
?   char *p;
?   p = (char *)malloc(x * y * z);
```

If the product of `x`, `y`, and `z` overflows, the call to `malloc` might produce a reasonable-sized array, but `p[x]` might refer to memory outside the allocated region. Suppose that `int`s are 16 bits and `x`, `y`, and `z` are each 41. Then `x*y*z` is 68921, which is 3385 module 2^{16}. So the call to `malloc` allocates only 3385 bytes; any reference with a subscript beyond that value will be out of bounds.

Conversion between types is another source of ovefflow, and catching the error may not be good enough. The Ariane 5 rocket exploded on its maiden (首次) flight in June, 1996 because the navigation package was inherited from the Ariane 4 without proper testing. The new rocket flew faster, resulting in larger values of some variables in the navigation software. Shortly after launch, an attempt to convert a 64-bit floating-point number into a 16-bit signed integer generated an overflow. The error was caught, but the code that caught it elected to shut down the subsystem. The rocket veered off course (冲出航线) and exploded. It was unfortunate that the code that failed generated inertial (惯性的) reference information useful only before lift-off (起飞); had it been turned off at the moment of launch, there would have been no trouble.

On a more mundane (世俗的) level, binary inputs sometimes break programs that expect text inputs, especially if they assume that the input is in the 7-bit ASCII character set. It is instructive (有益的) and sometimes sobering (合理的) to pass binary input (such as a compiled program) to an unsuspecting program that expects text input.

Good test cases can often be used on a variety of programs. For example, any program that reads files should be tested on an empty file. Any program that reads text should be tested on binary files. Any program that reads text lines should be tested on huge lines and empty lines and input with no newlines at all. It's a good idea to keep a collection of such test files handy, so you can test any program with them without having to recreate the tests. Or write a program to create test files upon demand.

When Steve Bourne was writing his Unix shell (which came to be known as the Bourne shell), he made a directory of 254 files with one-character names, one for each byte value except `'\0'` and slash, the two characters that cannot appear in Unix file names. He used that directory for all manner (方式) of tests of pattern-matching and tokenization. (The test directory was of course created by a program.) For years afterwards, that directory was the bane (祸根) of file-tree-walking programs; it tested them to destruction (破坏).

Exercise 6-10. Try to create a file that will crash your favorite text editor, compiler or other program. □

6.6 Tips for Testing

Experienced testers use many tricks and techniques to make their work more productive; this section includes some of our favorites.

Programs should check array bounds (if the language doesn't do it for them), but the checking code might not be tested if the array sizes are large compared to typical input. To exercise the checks, temporarily make the array sizes very small, which is easier than creating large test cases. We used a related trick in the array-growing code in Chapter 2 and in the CSV library in Chapter 4. In fact, we left the tiny initial values in place, since the additional startup cost is negligible (可以忽略的).

Make the hash function return a constant, so every element gets installed in the same hash bucket. This will exercise the chaining mechanism; it also provides an indication (指示) of worst-case performance.

Write a version of your storage allocator that intentionally fails early, to test your code for recovering from out-of-memory errors. This version returns NULL after 10 calls:

```
/* testmalloc: returns NULL after 10 calls */
void *testmalloc(size_t n)
{
    static int count = 0;
    if (++count > 10)
        return NULL;
    else
        return malloc(n);
}
```

Before you ship (发布) your code, disable testing limitations that will affect performance. We once tracked down a performance problem in a production compiler to a hash function that always returned zero because testing code had been left installed.

Initialize arrays and variables with some distinctive (有特色的) value, rather than the usual default of zero; then if you access out of bounds or pick up an uninitialized variable, you are more likely to notice it. The constant 0xDEADBEEF is easy to recognize in a debugger; allocators sometimes use such values to help catch uninitialized data.

Vary your test cases, especially when making small tests by hand -- it's easy to get into a rut (车辙) by always testing the same thing, and you may not notice that something else has broken.

Don't keep on implementing new features or even testing existing ones if there are known bugs; they could be affecting the test results.

Test output should include all input parameter settings, so the tests can be reproduced exactly. If your program uses random numbers, have a way to set and print the starting seed, independent of whether the tests themselves are random. Make sure that test inputs and corresponding outputs are properly identified, so they can be understood and reproduced.

It's also wise to provide ways to make the amount (总数) and type of output controllable when a program is run; extra output can help during testing.

Test on multiple machines, compilers, and operating systems. Each combination potentially reveals errors that won't be seen on others, such as dependencies on byte-order, sizes of integers, treatment of null pointers, handling of carriage return and newline, and specific properties of libraries and header files. Testing on multiple machines also uncovers problems in gathering the components of a program for shipment and, as we will discuss in Chapter 8, may reveal unwitting (没有意识到的) dependencies on the development environment.

We will discuss performance testing in Chapter 7.

6.7 Who Does the Testing?

Testing that is done by the implementer or someone else with access to the source code is sometimes called white box testing. (The term is a weak analogy to black box testing, where the tester does not know how the component is implemented; "clear box" might be more evocative (恰当).) It is important to test your own code: don't assume that some testing organization or user will find things for you. But it's easy to delude (蛊惑) yourself about how carefully you are testing, so try to ignore the code and think of hard cases, not easy ones. To quote Don Knuth describing how he creates tests for the TEX formatter, "I get into the meanest (低劣的), nastiest (污秽的) frame of mind that I can manage, and I write the nastiest [testing] code I can think of; then I turn around and embed (嵌入) that in even nastier constructions that are almost obscene (可憎的)." The reason for testing is to find bugs, not to declare the program working. Therefore the tests should be tough, and when they find problems, that is a vindication (辩护) of your methods, not a cause for alarm.

Black box testing means that the tester has no knowledge of or access to the innards (内脏) of the code. It finds different kinds of errors, because the tester has different assumptions about where to look. Boundary conditions are a good place to begin black box testing; high-volume, perverse (错误的), and illegal inputs are good follow-ons (后续). Of course you should also test the ordinary "middle of the road" or conventional uses of the program to verify basic functionality.

Real users are the next step. New users find new bugs, because they probe the program in unexpected ways. It is important to do this kind of testing before the program is released to the world though, sadly, many programs are shipped without enough testing of any kind. Beta releases of software are an attempt to have numerous real users test a program before it is finalized, but beta releases should not be used as a substitute for thorough testing. As software systems get larger and more complex, and development schedules get shorter, however, the pressure to ship without adequate testing increases.

It's hard to test interactive programs, especially if they involve mouse input. Some testing can be done by scripts (whose properties depend on language, environment, and the like). Interactive programs should be controllable from scripts that simulate user behaviors so they can be tested by programs. One technique is to capture the actions of real users and replay them; another is to create a scripting language that describes sequences and timing of events.

Finally, give some thought to how to test the tests themselves. We mentioned in Chapter 5 the confusion caused by a faulty test program for a list package. A regression suite infected by an error will cause trouble for the rest of time. The results of a set of tests will not mean much if the tests themselves are flawed (有缺陷的).

6.8 Testing the Markov Program

The Markov program of Chapter 3 is sufficiently intricate (复杂) that it needs careful testing. It produces nonsense, which is hard to analyze for validity, and we wrote multiple versions in several languages. As a final complication, its output is random and different each time. How can we apply some of the lessons of this chapter to testing this program?

The first set of tests consists of a handful of tiny files that check boundary conditions, to make sure the program produces the right output for inputs that contain only a few words. For prefixes of length two, we use five files that contain respectively (with one word per line)

```
(empty file)
a
a b
a b c
a b c d
```

For each file, the output should be identical to the input. These checks uncovered several off-by-one (单一断接) errors in initializing the table and starting and stopping the generator.

A second test verified conservation (保存) properties. For two-word prefixes, every word, every pair, and every triple that appears in the output of a run must occur in the input as well. We wrote an Awk program that reads the original input into a giant array, builds arrays of all pairs and triples, then reads the Markov output into another array and compares the two:

```
# markov test: check that all words, pairs, triples in
# output ARGV[2] are in original input ARGV[1]
BEGIN {
    while (getline <ARGV[1] > 0)
        for (i = 1; i <= NF; i++) {
            wd[++nw] = $i   # input words
            single[$i]++
        }
    for (i = 1; i < nw; i++)
        pair[wd[i],wd[i+1]]++
    for (i = 1; i < nw-1; i++)
        triple[wd[i],wd[i+1],wd[i+2]]++

    while (getline <ARGV[2] > 0) {
        outwd[++ow] = $0    # output words
        if (!($0 in single))
            print "unexpected word", $0
    }
    for (i = 1; i < ow; i++)
        if (!((outwd[i],outwd[i+1]) in pair))
            print "unexpected pair", outwd[i], outwd[i+1]
    for (i = 1; i < ow-1; i++)
        if (!((outwd[i],outwd[i+1],outwd[i+2]) in triple))
            print "unexpected triple",
                outwd[i], outwd[i+1], outwd[i+2]
}
```

We made no attempt to build an efficient test, just to make the test program as simple as possible. It takes six or seven seconds to check a 10,000 word output file against a 42,685 word input file, not much longer than some versions of Markov take to generate it. Checking conservation caught a major error in our Java implementation: the program sometimes overwrote (重写) hash table entries because it used references instead of making copies of prefixes.

This test illustrates the principle that it can be much easier to verify a property of the output than to create the output itself. For instance it is easier to check that a file is sorted than to sort it in the first place.

A third test is statistical in nature. The input consists of the sequence

```
a b a b c ... a b d ...
```

with ten occurrences of `abc` for each `abd`. The output should have about 10 times as many `c`'s as `d`'s if the random selection is working properly. We confirm this with `freq`, of course.

The statistical test showed that an early version of the Java program, which associated counters with each suffix, produced 20 `c`'s for every `d`, twice as many as it should have. After some head scratching, we realized that Java's random number generator returns negative as well as positive integers; the factor of two occurred because the range of values was twice as large as expected, so twice as many values would be zero modulo the counter; this favored the first element in the list, which happened to be `c`. The fix was to take the absolute value before the modulus[3]. Without this test, we would never have discovered the error; to the eye, the output looked fine.

Finally, we gave the Markov program plain English text to see that it produced beautiful nonsense. Of course, we also ran this test early in the development of the program. But we didn't stop testing when the program handled regular input, because nasty cases will come up in practice. Getting the easy cases right is seductive (富有魅力的); hard cases must be tested too. Automated, systematic testing is the best way to avoid this trap.

All of the testing was mechanized. A shell script generated necessary input data, ran and timed the tests, and printed any anomalous output. The script was configurable so the same tests could be applied to any version of Markov, and every time we made a set of changes to one of the programs, we ran all the tests again to make sure that nothing was broken.

6.9 Summary

The better you write your code originally, the fewer bugs it will have and the more confident you can be that your testing has been thorough. Testing boundary conditions as you write is an effective way to eliminate a lot of silly little bugs. Systematic testing tries to probe at potential trouble spots in an orderly way; again, failures are most commonly found at boundaries, which can be explored by hand or by program. As much as possible, it is desirable to automate testing, since machines don't make mistakes or get tired or fool themselves into thinking that something is working when it isn't. Regression tests check that the program still produces the same answers as it used to. Testing after each small change is a good technique for localizing the source of any problem because new bugs are most likely to occur in new code.

The single most important rule of testing is to do it.

Supplementary Reading

One way to learn about testing is to study examples from the best freely available software. Don Knuth's "The Errors of TEX," in *Software -- Practice and Experience*, 19, 7, pp. 607-685, 1989, describes every error found to that point in the TEX formatter, and includes a discussion of Knuth's testing methods. The TRIP test for TEX is an excellent example of a thorough test suite. Perl also comes with an extensive test suite that is meant to verify its correctness after compilation and installation on a new system, and includes modules such as `MakeMaker` and `TestHarness` that aid in the construction of tests for Perl extensions.

Jon Bentley wrote a series of articles in *Communications of the ACM* that were subsequently collected in *Programming Pearls* and *More Programming Pearls*, published by Addison-Wesley in 1986 and 1988 respectively. They often touch on testing, especially frameworks for organizing and mechanizing extensive tests.

[3]Unrecognized word.

7 Performance

His promises were, as he then was, mighty; But his performance, as he is now, nothing.

Shakespeare, *King Henry VIII*

Long ago, programmers went to great effort to make their programs efficient because computers were slow and expensive. Today, machines are much cheaper and faster, so the need for absolute efficiency is greatly reduced. Is it still worth worrying about performance?

Yes, but only if the problem is important, the program is genuinely too slow, and there is some expectation that it can be made faster while maintaining correctness, robustness, and clarity. A fast program that gets the wrong answer doesn't save any time.

Thus the first principle of optimization is don't. Is the program good enough already? Knowing how a program will be used and the environment it runs in, is there any benefit to making it faster? Programs written for assignments in a college class are never used again; speed rarely matters. Nor will speed matter for most personal programs, occasional tools, test frameworks, experiments, and prototypes. The run-time of a commercial product or a central component such as a graphics library can be critically important, however, so we need to understand how to think about performance issues.

When should we try to speed up a program? How can we do so? What can we expect to gain? This chapter discusses how to make programs run faster or use less memory. Speed is usually the most important concern, so that is mostly what we'll talk about. Space (main memory, disk) is less frequently an issue but can be crucial, so we will spend some time and space on that too.

As we observed in Chapter 2, the best strategy is to use the simplest, cleanest algorithms and data structures appropriate for the task. Then measure performance to see if changes are needed; enable compiler options to generate the fastest possible code; assess what changes to the program itself will have the most effect; make changes one at a time and re-assess; and keep the simple versions for testing revisions against.

Measurement is a crucial component of performance improvement since reasoning and intuition are fallible (易错的) guides and must be supplemented with tools like timing commands and profilers (探查). Performance improvement has much in common with testing, including such techniques as automation, keeping careful records, and using regression (回归) tests to make sure that changes preserve correctness and do not undo previous improvements.

If you choose your algorithms wisely and write well originally you may find no need for further speedups. Often minor changes will fix any performance problems in well-designed code, while badly-designed code will require major rewriting.

7.1 A Bottleneck

Let us begin by describing how a bottleneck was removed from a critical program in our local environment.

Our incoming mail funnels (漏斗) through a machine, called a gateway, that connects our internal network with the external Internet. Electronic mail messages from outside -- tens of thousands a day for a community of a few thousand people -- arrive at the gateway and are transferred to the internal network; this separation isolates our private network from the public Internet and allows us to publish a single machine name (that of the gateway) for everyone in the community.

One of the services of the gateway is to filter out "spam (罐头猪肉)." unsolicited (未经同意的) mail that advertises services of dubious (可疑的) merit (值得). After successful early trials of the spam filter, the service was installed as a permanent feature for all users of the mail gateway, and a problem immediately became apparent. The gateway machine, antiquated (老旧的) and already very busy, was overwhelmed (倾覆) because the filtering program was taking so much time -- much more time than was required for all the other processing of each message -- that the mail queues filled and message delivery was delayed by hours while the system struggled to catch up.

This is an example of a true performance problem: the program was not fast enough to do its job, and people were inconvenienced by the delay. The program simply had to run much faster.

Simplifying quite a bit, the spam filter runs like this. Each incoming message is treated as a single string, and a textual pattern matcher examines that string to see if it contains any phrases from known spam, such as "Make millions in your spare time" or "XXX-rated." Messages tend to recur (重发), so this technique is remarkably effective, and if a spam message is not caught, a phrase is added to the list to catch it next time.

None of the existing string-matching tools, such as `grep`, had the right combination of performance and packaging (封装), so a special-purpose spam filter was written. The original code was very simple; it looked to see if each message contained any of the phrases (patterns):

```
/* isspam: test mesg for occurrence of any pat */
int isspam(char *mesg)
{
    int i;

    for (i = 0; i < npat; i++)
        if (strstr(mesg, pat[i]) != NULL) {
            printf("spam: match for '%s'\n", pat[i]);
            return 1;
        }

    return 0;
}
```

How could this be made faster? The string must be searched, and the `strstr` function from the C library is the best way to search: it's standard and efficient.

Using profiling (靠模切削), a technique we'll talk about in the next section, it became clear that the implementation of `strstr` had unfortunate properties when used in a spam filter. By changing the way `strstr` worked, it could be made more efficient ***for this particular problem***.

The existing implementation of `strstr` looked something like this:

```
/* simple strstr: use strchr to look for first character */
char *strstr(const char *s1, const char *s2)
{
    int n;

    n = strlen(s2);
    for (;;) {
        s1 = strchr(s1, s2[0]);
        if (s1 == NULL)
            return NULL;
        if (strncmp(s1, s2, n) == 0)
            return s1;
        s1++;
    }
}
```

It had been written with efficiency in mind, and in fact for typical use it was fast because it used highly-optimized library routines to do the work. It called `strchr` to find the next occurrence of the first character of the pattern, and then called `strncmp` to see if the rest of the string matched the rest of the pattern. Thus it skipped quickly over most of the message looking for the first character of the pattern. and then did a fast scan to check the rest. Why would this perform badly?

There are several reasons. First, strncmp takes as an argument the length of the pattern. which must be computed with `strlen`. But the patterns are fixed, so it shouldn't be necessary to recompute their lengths for each message.

Second, `strncmp` has a complex inner loop. It must not only compare the bytes of the two strings, it must look for the terminating `\0` byte on both strings while also counting down the length parameter. Since the lengths of all the strings are known in advance (though not to strncmp), this complexity is unnecessary; we know the counts are right so checking for the `\n` wastes time.

Third, `strchr` is also complex, since it must look for the character and also watch for the `\0` byte that terminates the message. For a given call to `isspam`, the message is fixed, so time spent looking for the `\0` is wasted since we know where the message ends.

Finally, although `strncmp`, `strchr` , and `strlen` are all efficient in isolation, the overhead of calling these functions is comparable to the cost of the calculation they will perform. It's more efficient to do all the work in a special, carefully written version of `strstr` and avoid calling other functions altogether.

These sorts of problems are a common source of performance trouble -- a routine or interface works well for the typical case, but performs poorly in an unusual case that happens to be central to the program at issue. The existing `strstr` was fine when both the pattern and the string were short and changed each call, but when the string is long and fixed, the overhead is prohibitive (可抑制的).

With this in mind, `strstr` was rewritten to walk the pattern and message strings together looking for matches, without calling subroutines. The resulting implementation has predictable behavior: it is slightly slower in some cases, but much faster in the spam filter and, most important, is never terrible. To verify the new implementation's correctness and performance, a performance test suite was built. This suite included not only simple examples like searching for a word in a sentence, but also pathological (病态

的) cases such as looking for a pattern of a single x in a string of a thousand e's and a pattern of a thousand x's in a string of a single e, both of which can be handled badly by naive implementations. Such extreme cases are a key part of performance evaluation.

The library was updated with the new `strstr` and the spam filter ran about 30% faster, a good payoff for rewriting a single routine.

Unfortunately, it was still too slow.

When solving problems, it's important to ask right question. Up to now, we've been asking for the fastest way to search for a textual pattern in a string. But the real problem is to search for a large, fixed set of textual patterns in a long, variable string. Put that way, `strstr` is not so obviously the right solution.

The most effective way to make a program faster is to use a better algorithm. With a clearer idea of the problem, it's time to think about what algorithm would work best.

The basic loop,

```
for (i = 0; i < npat; i++)
    if (strstr(mesg, pat[i]) != NULL)
        return 1;
```

scans down the message `npat` independent times; assuming it doesn't find any matches, it examines each byte of the message `npat` times, for a total of `strlen(mesg)*npat` comparisons.

A better approach is to invert the loops, scanning the message once in the outer loop while searching for all the patterns in parallel in the inner loop:

```
for (j = 0; mesg[j] != '\0'; j++)
    if (some pattern matches starting at mesg[j])
        return 1;
```

The performance improvement stems from (主要来源于) a simple observation. To see if any pattern matches the message at position `j`, we don't need to look at all patterns, only those that begin with the same character as `mesg[j]`. Roughly, with 52 upper and lower-case letters we might expect to do only `strlen(mesg)*npat/52` comparisons. Since the letters are not evenly distributed -- words with `s` more often than `x` -- we won't see a factor of 52 improvement, but we should see some. In effect, we construct a hash table using the first character of the pattern as the key.

Given some precomputation to construct a table of which patterns begin with each character, `isspam` is still short:

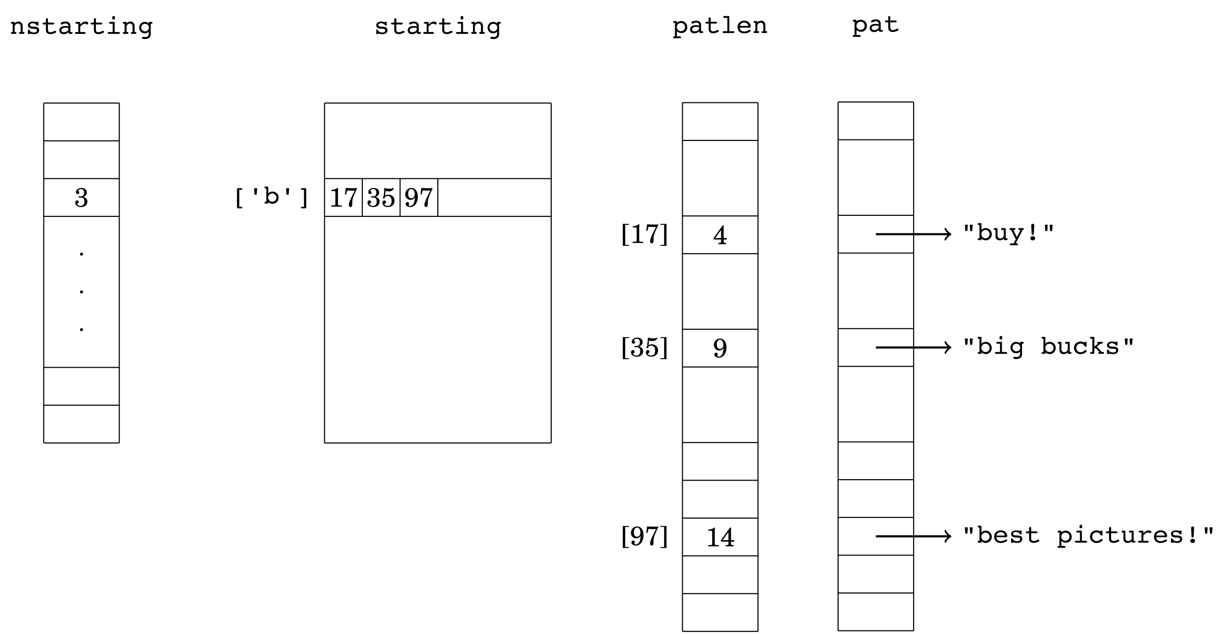
```
int patlen[NPAT];                   /* length of pattern */
int starting[UCHAR_MAX+1][NSTART];  /* pats starting with char */
int nstarting[UCHAR_MAX+1];         /* number of such patterns */
...
/* isspam: test mesg for occurrence of any pat */
int isspam(char *mesg)
{
    int i, j, k;
    unsigned char c;

    for (j = 0; (c = mesg[j]) != '\0'; j++) {
        for (i = 0; i < nstarting[c]; i++) {
            k = starting[c][i];
            if (memcmp(mesg+j, pat[k], patlen[k]) == 0) {
                printf("spam: match for '%s'\n", pat[k]);
```

```
                    return 1;
                }
            }
        }
        return 0;
    }
```

The two-dimensional array `starting[c][]` stores, for each character `c`, the indices of those patterns that begin with that character. Its companion `nstarting[c]` records how many patterns begin with `c`. Without these tables, the inner loop would run from 0 to `npat`, about a thousand; instead it runs from 0 something like 20. Finally, the array element `patlen[k]` stores the precomputed result of `strlen(pat[k])`.

The following figure sketches (概括) these data structures for a set of three pattern that begin with the letter `b`:



The code to build these tables is easy:

```
int i;
unsigned char c;

for (i = 0; i < npat; i++) {
    c = pat[i][0];
    if (nstarting[c] >= NSTART)
        printf("too many patterns (>=%d) begin '%c'",
                NSTART, c);
    starting[c][nstarting[c]++] = i;
    patlen[i] = strlen(pat[i]);
}
```

Depending on the input, the spam filter is now five to ten times faster than it was using the improved `strstr`, and seven to fifteen times faster than the original implementation. We didn't get a factor of 52, partly because of the non-uniform distribution of letters, partly because the loop is more complicated in the new program, and partly because there are still many failing string comparisons to execute, but the spam filter is no longer the bottleneck for mail delivery. Performance problem solved.

The rest of this chapter will explore the techniques used to discover performance problems, isolate the slow code. and speed it up. Before moving on, though, it's worth looking back at the spam filter to see what lessons it teaches. Most important, make sure performance matters. It wouldn't have been worth all the effort if spam filtering wasn't a bottleneck. Once we knew it was a problem, we used profiling and other techniques to study the behavior and learn where the problem really lay. Then we made sure we were solving the right problem, examining the overall program rather than just focusing on `strstr`, the obvious but incorrect suspect. Finally, we solved the correct problem using a better algorithm, and checked that it really was faster. Once it was fast enough, we stopped; why over-engineer?

Exercise 7-1 . A table that maps a single character to the set of patterns that begin with that character gives an order of magnitude (巨大的) improvement. Implement a version of `isspam` that uses two characters as the index. How much improvement does that lead to? These are simple special cases of a data structure called a trie. Most such data structures are based on trading (交易) space for time. □

7.2 Timing and Profiling

Automate timing measurements. Most systems have a command to measure how long a program takes. On Unix, the command is called `time`:

```
% time slowprogram
real    7.0
user    6.2
sys     0.1
%
```

This runs the command and reports three numbers, all in seconds: "real" time, the elapsed time for the program to complete; "user" CPU time, time spent executing the user's program; and "system" CPU time, time spent within the operating system on the program's behalf. If your system has a similar command, use it; the numbers will be more informative, reliable, and easier to track than time measured with a stopwatch. And keep good notes. As you work on the program, making modifications and measurements, you will accumulate a lot of data that can become confusing a day or two later. (Which version was it that ran 20% faster?) Many of the techniques we discussed in the chapter on testing can be adapted for measuring and improving performance. Use the machine to run and measure your test suites and, most important, use regression (回归) testing to make sure your modifications don't break the program.

If your system doesn't have a `time` command, or if you're timing a function in isolation, it's easy to construct a timing scaffold (脚手架) analogous to a testing scaffold. C and C++ provide a standard routine, clock, that reports how much CPU time the program has consumed so far. It can be called before and after a function to measure CPU usage:

```
#include <time.h>
#include <stdio.h>
    ...
    clock_t before;
    double  elapsed;

    before = clock();
    long_running_function();
    elapsed = clock() - before;
```

```
        printf("function used %.3f seconds\n",
                elapsed / CLOCKS_PER_SEC);
```

The scaling (定比) term, `CLOCKS_PER_SEC`, records the resolutions of the timer as reported by clock. If the function takes only a small fraction of a second, run it in a loop, but be sure to compensate (补偿) for loop overhead if that is significant:

```
    before = clock();
    for (i = 0; i < 1000; i++)
        short_running_function();
    elapsed = (clock(0 - before) / (double)i;
```

In Java, functions in the `Date` class give wall clock time, which is an approximation to CPU time:

```
    Date before = new Date();
    long_running_function();
    Date after = new Date();
    long elapsed = after.getTime() - before.getTime();
```

The return value of `getTime` is in milliseconds.

Use a profiler (*刻画器*). Besides a reliable timing method, the most important tool for performance analysis is a system for generating profiles. A profile is a measurement of where a program spends its time. Some profiles list each function, the number of times it is called, and the fraction of execution time it consumes. Others show counts of how many times each statement was executed. Statements that are executed frequently contribute more to run-time, while statements that are never executed may indicate useless code or code that is not being tested adequately.

Profiling is an effective tool for finding *hot spots* in a program, the functions or sections of code that consume most of the computing time. Profiles should be interpreted with care, however. Given the sophistication of compilers and the complexity of caching and memory effects, as well as the fact that profiling a program affects its performance, the statistics in a profile can be only approximate.

In the 1971 paper that introduced the term profiling, Don Knuth wrote that "less than 4 percent of a program generally accounts for more than half of its running time." This indicates that the way to use profiling is to identify the critical time-consuming parts of the program, improve them to the degree possible, and then measure again to see if a new hot spot has surfaced. Eventually, often after only one or two iterations, there is no obvious hot spot left.

Profiling is usually enabled with a special compiler flat or option. The program is run, and then an analysis tool shows the results. On Unix, the flag is usually `-p` and the tool is called `prof`[1]:

```
    % cc -p spamtest.c -o spamtest
    % spamtest
    % prof spamtest
```

The following table shows the profile generated by a special version of the spam filter we built to understand its behavior. It uses a fixed message and a fixed set of 217 phrases, which it matches against the message 10000 times. This run on a 250 MHz MIPS R 10000 used the original implementation of `strstr` that calls other standard functions. The output has been edited reformatted so it fits the page. Notice how sizes of input (217 phrases) and the number of runs (10000) show up as consistency checks in the "calls" column, which counts the number of calls of each function.

[1] `gprof` in Linux

```
12234768552: Total number of instructions executed
13961810001: Total computed cycles
55.847: Total computed execution time (secs)
1.141: Average cycles per instruction
```

secs	%	cum%	cycles	instructions	calls	function
45.260	81.0%	81.0%	11314990000	9440110000	48350000	strchr
6.081	10.9%	91.9%	1520280000	1566460000	46180000	strncmp
2.592	4.6%	94.6%	648080000	854500000	2170000	strstr
1.825	3.3%	99.8%	456225559	344882213	21704435	strlen
0.088	0.2%	100.0%	21950000	28510000	10000	isspam
0.000	0.0%	100.0%	100025	100028	1	main
0.000	0.0%	100.0%	53677	70268	219	_memcopy
0.000	0.0%	100.0%	48888	46403	217	strcpy
0.000	0.0%	100.0%	17989	19894	219	fgets
0.000	0.0%	100.0%	16798	17547	230	__malloc
0.000	0.0%	100.0%	10305	10900	204	realfree
0.000	0.0%	100.0%	6293	7161	217	estrdup
0.000	0.0%	100.0%	6032	8575	231	cleanfree
0.000	0.0%	100.0%	5932	5729	1	readpat
0.000	0.0%	100.0%	5899	6339	219	getline
0.000	0.0%	100.0%	5500	5720	220	_malloc

It's obvious that strchr and strncmp, both called by strstr, completely dominate the performance. Knuth's guideline is right: a small part of the program consumes most of the run-time. When a program is first profiled, it's common to see the top-running function at 50 percent or more, as it is here, making it easy to decide where to focus attention.

Concentrate on the hot spots. After rewriting strstr, we profiled spamtest again and found that 99.8% of the time was now spent in strstr alone, even though the whole program was considerable faster. When a single function is so overwhelmingly (压倒性的) the bottleneck, there are only two ways to go: improve the function to use a better algorithm, or eliminate the function altogether by rewriting the surrounding program.

In this case, we rewrote the program. Here are the first few lines of the profile for spamtest using the final, fast implementation of isspam. Notice that the overall time is much less, that memcmp is now the hot spot, and that isspam now consumes a significant fraction of the computation. It is more complex than the version that called strstr, but its cost is more than compensated for by eliminating strlen and strchr from isspam and by replacing strncmp with memcmp, which does less work per byte.

secs	%	cum%	cycles	instructions	calls	function
3.524	56.9%	56.9%	880890000	1027590000	46180000	memcmp
2.662	43.04%	100.0%	665550000	902920000	10000	isspam
0.001	0.0%	100.0%	140304	106043	652	strlen
0.000	0.0%	100.0%	100025	100028	1	main

It's instructive (有益的) to spend some time comparing the cycle counts and number of calls in the two profiles. Notice that strlen went from a couple of million calls to 652, and that strncmp and memcmp are called the same number of times. Also notice that isspam. which now incorporates (吸收) the function of `strchr`, still manages to use far fewer cycles than `strchr` did before because it examines only the relevant patterns at each step. Many more details of the execution can be discovered by examining the numbers.

A hot spot can often be eliminated, or at least cooled, by much simpler engineering than we undertook for the spam filter. Long ago, a profile of Awk indicated that one function was begin called about a million times over the course of a regression (回归) test, in this loop:

```
?   for (j = i; j < MAXFLD; j++)
?       clear(j);
```

The loop, which clears fields before each new input line is read, was taking as much as 50 percent of the run-time. The constant `MAXFLD`. the maximum number of fields permitted in an input line, was 200. But in most uses of Awk, the actual number of fields was only two or three. Thus an enormous amount of time was being wasted clearing fields that had never been set. Replacing the constant by the previous value of the maximum number of fields gave a 25 percent overall speedup. The fix was to change the upper limit of the loop:

```
    for (j = i; j < maxfld; j++)
        clear(j);
    maxfld = i;
```

Draw a picture. Pictures are especially good for presentating performance measurements. They can convey information about the effects of parameter changes, compare algorithms and data structures, and sometimes point to unexpected behavior. The graphs of chain length counts for several hash multipliers in Chapter 5 showed clearly that some multipliers were better than others.

The following graph[2] shows the effect of the size of the hash table array on run-time for the C version of `markov` with Psalms as input (42685 words, 22482 prefixes). We did two experiments. One set of runs used array sizes that are powers of two from 2 to 16384; the other used sizes that are the largest prime less than each power of two. We wanted to see if a prime array size made any measurable difference to the performance.

The graph shows that run-time for this input is not sensitive to the table size once the size is above 1000 elements, nor is there a discernible (可辨别的) difference between prime and power-of-two table sizes.

✎ **Exercise 7-2** . Whether or not your system has a `time` command, use `clock` or `getTime` to write a timing facility for your own use. Compare its times t a wall clock. How does other activity on the machine affect the timing? □

✎ **Exercise 7-3** . In the first profile, `strchr` was called 48,350,000 times and `strncmp` only 46,180,000. Explain the difference. □

7.3 Strategies for Speed

Before changing a program to make it faster, be certain that it really is too slow, and use timing tools and profilers to discover where the time is going. Once you know what's happening, there are a number of strategies to follow. We list a few here in decreasing order of profitability (收益性).

[2]Lack of graphs, because the graph is too blurry and ugly to represent.

Use a better algorithm or data structure. The most important factor in making a program faster is the choice of algorithm and data structure; there can be a huge difference between an algorithm that is efficient and one that is not. Our spam filter saw a change in data structure that was worth a factor of ten; even greater improvement is possible if the new algorithm reduces the order (阶数) of computation, say from $O(n^2)$ to $O(n \log n)$. We covered this topic in Chapter 2, so we won't dwell on (详述) it here.

Be sure that the complexity is really what you expect; if not, there might be a hidden performance bug. This apparently linear algorithm for scanning a string,

```
?   for (i = 0; i < strlen(s); i++)
?       if (s[i] == c)
?           ...
```

is in fact quadratic (平方的): if `s` has `n` characters, each call to `strlen` walks down the `n` characters of the string and the loop is performed `n` times.

Enable compiler optimizations. One zero-cost change that usually produces a reasonable improvement is to turn on whatever optimization the compiler provides. Modern compilers do sufficiently well that they obviate (排除) much of the need for small-scale changes by programmers.

By default, most C and C++ compilers do not attempt much optimization. A compiler option enables the optimizer ("improver" would be a more accurate term). It should probably be the default except that the optimizations tend to confuse source-level debuggers, so programmers must enable the optimizer explicitly once they believe the program has been debugged.

Compiler optimization usually improves run-time anywhere from a few percent to a factor of two. Sometimes, though, it slows the program down, so measure the improvement before shipping (装运) your product. We compared unoptimized and optimized compilation on a couple of versions of the spam filter. For the test suite using the final version of the matching algorithm, the original run-time was 8.1 seconds, which dropped to 5.9 seconds when optimization was enabled, an improvement of over 25%. On the other hand, the version that used the fixed-up `strstr` showed no improvement under optimization, because `strstr` had already been optimized when it was installed in the library; the optimizer applies only to the source code being compiled now and not to the system libraries. However, some compilers have global optimizer -- which analyze the entire program for potential improvements. If such a compiler is available on your system, try it; it might squeeze out a few more cycles.

One thing to be aware of is that the more aggressively the compiler optimizes, the more likely it is to introduce bugs into the compiled program. After enabling the optimizer, re-run your regression test suite, as you should for any other modification.

Tune the code. The right choice of algorithm matters if data sizes are big enough. Furthermore, algorithmic improvements work across different machines, compilers and languages. But once the right algorithm is in place, if speed is still an issue the next thing to try is tuning the code: adjusting the details of loops and expressions to make things go faster.

The version of `isspam` we showed at the end of Section 7.1 hadn't been tuned. Here, we'll show what further improvements can be achieved by tweaking (扭) the loop. As a reminder, this is how we left it:

```
    for (j = 0; (c = mesg[j]) != '\0'; j++) {
        for (i = 0; i < nstarting[c]; i++) {
            k = starting[c][i];
            if (memcmp(mesg+j, pat[k], patlen[k]) == 0) {
                printf("spam: match for '%s'\n", pat[k]);
                return 1;
```

```
            }
        }
    }
```

This initial version takes 6.6 seconds in our test suite when compiled using the optimizer. The inner loop has an array index (`nstarting[c]`) in its loop condition whose value is fixed for each iteration of the outer loop. We can avoid recalculating it by saving the value in a local variable:

```
    for (j = 0; (c = mesg[j]) != '\0'; j++) {
        n = nstarting[c];
        for (i = 0; i < n; i++) {
            k = starting[c][i];
            ...
```

This drops the time to 5.9 seconds, about 10% faster, a speedup typical of what tuning can achieve. There's another variable we can pull out: `starting[c]` is also fixed. It seems like pulling that computation out of the loop would also help, but in our tests it made no measurable difference. This, too, is typical of tuning: some things help, some things don't, and one must measure to find out which. And results will vary with different machines or compilers.

There is another change we could make to the spam filter. The inner loop compares the entire pattern against the string, but the algorithm ensures that the first character already matches. We can therefore tune the code to start `memcmp` one byte further along. We tried this and found it gave about 3% improvement, which is slight but it requires modifying only three lines of the program, one of them in precomputation.

Don't optimize what doesn't matter. Sometimes tuning achieves nothing because it is applied where it makes no difference. Make sure the code you're optimizing is where time is really spent. The following story might be apocryphal (不可信的), but we'll tell it anyway. An early machine from a now-defunct (现已倒闭的) company was analyzed with a hardware performance monitor and discovered to be spending 50 percent of its time executing the same sequence of several instructions. The engineers built a special instruction to encapsulate the function of the sequence, rebuilt the system, and found it made no difference at all; they had optimized the idle loop of the operating system.

How much effort should you spend making a program run faster? The main criterion (标准) is whether the changes will yield enough to be worthwhile. As a guideline, the personal time spent making a program faster should not be more than the time the speedup will recover during the lifetime of the program. By this rule, the algorithmic improvement to `isspam` was worthwhile: it took a day of work but saved (and continues to save) hours every day. Removing the array index from the inner loop was less dramatic (戏剧性的) but still worth doing, since the program provides a service to a large community. Optimizing public services like the spam filter or a library is almost always worthwhile; speeding up test programs is almost never worthwhile. And for a program that runs for a year, squeeze out everything you can. It may be worth restarting if you find a way to make a ten percent improvement even after the program has been running for a month.

Competitive programs -- games, compilers. word processors, spreadsheets, database systems -- fall into this category as well, since commercial success is often to the swiftest, at least in published benchmark results.

It's important to time programs as changes are being made, to make sure that things are improving. Sometimes two changes that each improve a program will interact, negating (否定) their individual effects.

It's also the case that timing mechanisms can be so erratic (不稳定的) that it's hard to draw firm conclusions about the effect of changes. Even on single-user systems, times can fluctuate (波动) unpredictably. If the variability of the internal timer (or at least what is reported back to you) is ten percent, changes that yield improvements of only ten percent are hard to distinguish from noise.

7.4 Tuning the Code

There are many techniques to reduce run-time when a hot spot is found. Here are some suggestions, which should be applied with care, and with regression testing after each to be sure that the code still works. Bear in mind that good compilers will do some of these for you, and in fact you may impede (阻止) their efforts by complicating the program. Whatever you try, measure its effect to make sure it helps.

Collect common subexpressions. If an expensive computation appears multiple time, do it in only one place and remember the result. For example, in Chapter 1 we showed a macro that computed a distance by calling `sqrt` twice in a row with the same values; in effect the computation was

```
?   sqrt(dx*dx + dy*dy) + ((sqrt(dx*dx + dy*dy) > 0) ? ...)
```

Compute the square root once and use its value in two places.

If a computation is done within a loop but does not depend on anything that changes within the loop, move the computation outside, as when we replaced

```
    for (i = 0; i < nstarting[c]; i++) {
```

by

```
    n = nstarting[c];
    for (i = 0; i < n; i++) {
```

Replace expensive operations by cheap ones. The term *reduction in strength* refers to optimizations that replace an expensive operation by a cheaper one. In olden times, this used to mean replacing multiplications by additions or shifts, but that rarely buys much now. Division and remainder are much slower than multiplication, however, so there may be improvement if a division can be replaced with multiplication by the inverse, or a remainder by a masking operation if the divisor (除数) is a power of two. Replacing array indexing by pointers in C or C++ might speed things up, although most compilers do this automatically. Replacing a function call by a simpler calculation can still be worthwhile. Distance in the plane (平面) is determined by the formula `sqrt(dx*dx+dy*dy)`, so to decide which of two points is further away would normally involve calculating two square roots. But the same decision can be made by comparing the squares of the distances:

```
    if (dx1*dx1 + dy1*dy1 < dx2*dx2 + dy2*dy2)
        ...
```

gives the same result as comparing the square roots of the expressions.

Another instance occurs in textual pattern matchers such as our spam filter or `grep`. If the pattern begins with a literal character, a quick search is made down the input text for that character; if no match is found, the more expensive search machinery (结构)is not invoked at all.

Unroll (展开) or eliminate loops. There is a certain overhead in setting up and running a loop. If the body of the loop isn't too long and doesn't iterate too many times, it can be more efficient to write out each iteration in sequence. Thus, for example:

```
for (i = 0; i < 3; i++)
    a[i] = b[i] + c[i];
```

becomes

```
a[0] = b[0] + c[0];
a[1] = b[1] + c[1];
a[2] = b[2] + c[2];
```

This eliminates loop overhead, particularly branching, which can slow modern processors by interrupting the flow of execution.

If the loop is longer, the same kind of transformation can be used to amortize (分摊) the overhead over fewer iterations:

```
for (i = 0; i < 3*n; i++)
    a[i] = b[i] + c[i];
```

becomes

```
for (i = 0; i < 3*n; i += 3) {
    a[i+0] = b[i+0] + c[i+0];
    a[i+1] = b[i+1] + c[i+1];
    a[i+2] = b[i+2] + c[i+2];
}
```

Note that this works only if the length is a multiple of the step size; otherwise additional code is needed to fix up the ends, which is a place for mistakes to creep in (潜入) and for some of the efficiency to be lost again.

Cache frequently-used values. Cached values don't have to be recomputed. Caching takes advantage of *locality*, the tendency for programs (and people) to re-use recently accessed or nearby items in preference to (优先于) older or distant data. Computing hardware makes extensive use of caches; indeed. adding cache memory to a computer can make great improvements in how fast a machine appears. The same is true of software. Web browsers, for instance, cache pages and images to avoid the slow transfer of data over the Internet. In a print preview program we wrote years ago, non-alphabetic special characters like $^1/_2$ had to be looked up in a table. Measurement showed that much of the use of special characters involved drawing lines with long sequences of the same single character. Caching just the single most recently used character made the program significantly faster on typical inputs.

It's best if the caching operation is invisible from outside, so that it doesn't affect the rest of the program except for making it run faster. Thus in the case of the print previewer, the interface to the character drawing function didn't change; it was always

```
drawchar(c);
```

The original version of `drawchar` called `show(lookup(c))`. The cache implementation used internal static variables to remember the previous character and its code:

```
if (c != lastc) { /* update the cache */
    lastc = c;
    lastc = lookup(c);
}
show(lastc);
```

Write a special-purpose allocator. Often the single hot spot in a program is memory allocation, which manifests (表明) itself as lots of calls on `malloc` or new. When most requests are for blocks of the same size, substantial (实质的) speedups are possible by replacing calls to the general-purpose allocator by calls to a special-purpose one. The special-purpose allocator makes one call to `malloc` to fetch a big array of items, then hands them out one at a time as needed, a cheaper operation. Freed items are placed back in a free list so they can be reused quickly.

If the requested sizes are similar, you can trade space for time by always allocating enough for the largest request. This can be effective for managing short strings if you use the same size for all strings up to a specified length.

Some algorithms can use stack-based allocation, where a whole sequence of allocations is done, and then the entire set is freed at once. The allocator obtains one big chunk for itself and treats it as a stack, pushing allocated items on as needed and popping them all off in a single operation at the end. Some C libraries offer a function `alloca` for this kind of allocation, though it is not standard. It uses the local call stack as the source of memory, and frees all the items when the function that calls `alloca` returns.

Buffer input and output. Buffering batches transactions so that frequent operations are done with as little overhead as possible, and the high-overhead operations are done only when necessary. The cost of an operation is thereby spread over multiple data values. When a C program calls `printf`, for example, the characters are stored in a buffer but not passed to the operating system until the buffer is full or flushed explicitly. The operating system itself may in turn (轮流) delay writing the data to disk. The drawback is the need to flush output buffers to make data visible; in the worst case, information still in a buffer will be lost if a program crashes.

Handle special cases separately. By handling same-sized objects in separate code, special-purpose allocators reduce time and space overhead in the general allocator and incidentally (顺便) reduce fragmentation. In the graphics library for the Inferno system, the basic draw function was written to be as simple and straightforward as possible. With that working, optimizations for a variety of cases (chosen by profiling) were added one at a time; it was always possible to test the optimized version against the simple one. In the end, only a handful of cases were optimized because the dynamic distribution of calls to the drawing function was heavily skewed towards (为了) displaying characters; it wasn't worth writing clever code for all the cases.

Precompute results. Sometimes it is possible to make a program run faster by precomputing values so they are ready when they are needed. We saw this in the spam filter, which precomputed `strlen(pat[i])` and stored it in the array at `patlen[i]`. If a graphics system needs to repeatedly compute a mathematical function like sine but only for a discrete (离散的) set of values, such as integer degrees, it will be faster to precompute a table with 360 entries (or provide it as data) and index into it as needed. This is an example of trading space for time. There are many opportunities to replace code by data or to do computation during compilation, to save time and sometimes space as well. For example, the `ctype` functions like `isdigit` are almost always implemented by indexing into a table of bit flags rather than by evaluating a sequence of tests.

Use approximate values. If accuracy isn't an issue, use lower-precision data types. On older or smaller machines, or machines that simulate floating point in software, single-precision floating-point arithmetic is often faster than double-precision, so use `float` instead of `double` to save time. Some modern graphics processors use a related trick. The IEEE floating-point standard requires "graceful underflow" as calculations approach the low end of representable values, but this is expensive to compute.

For images, the feature is unnecessary, and it is faster and perfectly acceptable to truncate to zero. This not only saves time when the numbers underflow, it can simplify the hardware for all arithmetic. The use of integer `sin` and `cos` routines is another example of using approximate values.

Rewrite in a lower-level language. Lower-level languages tend to be more efficient, although at a cost in programmer time. Thus rewriting some critical part of a C++ or Java program in C or replacing an interpreted script by a program in a compiled language may make it run much faster.

Occasionally, one can get significant speedups with machine-dependent code. This is a last resort (手段), not a step to be taken lightly, because it destroys portability and makes future maintenance and modifications much harder. Almost always, operations to be expressed in assembly language are relatively small functions that should be embedded in a library; `memset` and `memmove`, or graphics operations, are typical examples. The approach is to write the code as cleanly as possible in a high-level language and make sure it's correct by testing it as we described for `memset` in Chapter 6. This is your portable version, which will work everywhere, albeit (虽然) slowly. When you move to a new environment, you can start with a version that is known to work. Now when you write an assembly-language version, test it exhaustively (彻底地) against (针对) the portable one. When bugs occur, non-portable code is always suspect: it's comforting (令人鼓舞的) to have a comparison implementation.

Exercise 7-4 . One way to make a function like `memset` run faster is to have it write in word-sized chunks instead of byte-sized; this is likely to match the hardware better and might reduce the loop overhead by a factor of four or eight. The downside is that there are now a variety of end effects to deal with if the target is not aligned on a word boundary and if the length is not a multiple of the word size. Write a version of `memset` that does this optimization. Compare its performance to the existing library version and to a straightforward byte-at-a-time loop. □

Exercise 7-5 . Write a memory allocator `smalloc` for C strings that uses a special-purpose allocator for small strings but calls `malloc` directly for large ones. You will need to define a `struct` to represent the strings in either case. How do you decide where to switch from calling `smalloc` to `malloc`? □

7.5 Space Efficiency

Memory used to be the most precious computing resource, always in short supply, and much bad programming was done in an attempt to squeeze the most out of what little there was. The infamous (声名狼藉的) "Year 2000 Problem" is frequently cited as an example of this; when memory was truly scarce (稀有), even the two bytes needed to store 19 were deemed (认为) too expensive. Whether or not space is the true reason for the problem -- such code may simply reflect the way people use dates in everyday life, where the century is commonly omitted -- it demonstrates the danger inherent (固有的) in short-sighted (短浅的) optimization.

In any case, times have changed, and both main memory and secondary storage are amazingly cheap. Thus the first approach to optimizing space should be the same as to improving speed: don't bother.

There are still situations, however, where space efficiency matters. If a program doesn't fit into the available main memory, parts of it will be paged out, and that will make its performance unacceptable. We see this when new versions of software squander (使分散) memory; it is a sad reality that software upgrades are often followed by the purchase of more memory.

Save space by using the smallest-possible data type. One step to space efficiency is to make minor changes to use existing memory better, for example by using the smallest data type that will work. This might mean replacing `int` with `short` if the data will fit; this is a common technique for coordinates (协调) in 2-D graphics systems, since 16 bits are likely to handle any expected range of screen coordinates. Or it might mean replacing `double` with `float`; the potential problem is loss of precision, since `float`s usually hold only 6 or 7 decimal digits.

In these cases and analogous ones, other changes may be required as well, notably (特别是) format specifications in `printf` and especially `scanf` statements.

The logical extension of this approach is to encode information in a byte or even fewer bits, say a single bit where possible. Don't use C or C++ bit-fields; they are highly non-portable and tend to generate voluminous (长篇的) and inefficient code. Instead, encapsulate the operations you want in functions that fetch and set individual bits within words or an array of words with shift and mask operations. This function returns a group of contiguous bits from the middle of a word:

```
/* getbits: get n bits from position p */
/* bits are numbered from 0 (least significant) up */
unsigned int getbits(unsigned int x, int p, int n)
{
    return (x >> (p+1-n)) & ~(~0 << n);
}
```

If such functions turn out to be too slow, they can be improved with the techniques described earlier in this chapter. In C++, operator overloading can be used to make bit accesses look like regular subscripting.

Don't store what you can easily recompute. Changes like these are minor, however; they are analogous to code tuning. Major improvements are more likely to come from better data structures, perhaps coupled with algorithm changes. Here's an example. Many years ago, one of us was approached (商量) by a colleague who was trying to do a computation on a matrix so large that it was necessary to shut down the machine and reload a stripped-down (精简的) operating system so the matrix would fit. He wanted to know if there was an alternative, since this was an operational nightmare. We asked what the matrix was like, and learned that it contained integer values, *most of which were zero.* In fact, fewer than five percent of the matrix elements were non-zero. This immediately suggested a representation in which only the non-zero elements of the matrix were stored, and each matrix access like `m[i][j]` would be replaced by a function call `m(i,j)`. There are several ways to store the data; the easiest is probably an array of pointers, one for each row, each of which points to a compact array of column numbers and corresponding values. This has higher space overhead per non-zero item but requires much less space overall, and although individual accesses will be slower, they will be noticeably faster than reloading the operating system. To complete the story: the colleague applied the suggestion and went away completely satisfied.

We used a similar approach to solve a modern version of the same problem. A radio design system needed to represent terrain (地形) and radio signal strengths over a very large geographical area (100 to 200 kilometers on a side) to a resolution of 100 meters. Storing this as a large rectangular array exceeded the memory available on the target machine and would have caused unacceptable paging behavior. But over large regions, the terrain and signal strength values are likely to be the same, so a hierarchical representation that coalesces (联合) regions of the same value into a single cell makes the problem manageable.

Variations on this theme are frequent, and so are specific representations, but all share the same basic idea: store the common value or values implicitly or in a compact form, and spend more time and space on the remaining values. If the most common values are really common, this is a win.

The program should be organized so that the specific data representation of complex types is hidden in a class or set of functions operating on a private data type. This precaution (预防措施) ensures that the rest of the program will not be affected if the representation changes.

Space efficiency concerns sometimes manifest (表现) themselves in the external representation of information as well, both conversion (转换) and storage. In general, it is best to store information as text wherever feasible rather than in some binary representation. Text is portable, easy to read, and amenable (服从的) to processing by all kinds of tools; binary representations have none of these advantages. The argument in favor of binary is usually based on "speed," but this should be treated with some skepticism (批判思想), since the disparity (差异) between text and binary forms may not be all that great.

Space efficiency often comes with a cost in run-time. One application had to transfer a big image from one program to another. Images in a simple format called PPM were typically a megabyte, so we thought it would be much faster to encode them for transfer in the compressed GIF format instead; those files were more like 50K bytes. But the encoding and decoding of GIF took as much time as was saved by transferring a shorter file, so nothing was gained. The code to handle the GIF format is about 500 lines long; the PPM source is about 10 lines. For ease of maintenance, therefore, the GIF encoding was dropped and the application continues to use PPM exclusively. Of course the tradeoff would be different if the file were to be sent across a slow network instead; then a GIF encoding would be much more cost-effective.

7.6 Estimation

It's hard to estimate ahead of time how fast a program will be, and it's doubly hard to estimate the cost of specific language statements or machine instructions. It's easy, though, to create a cost model for a language or a system, which will give you at least a rough idea of how long a important operations take.

One approach that is often used for conventional programming languages is a program that times representative code sequences. There are operational difficulties, like getting reproducible results and canceling out irrelevant overheads, but it is possible to get useful insights without much effort. For example, we have a C and C++ cost model program that estimates the costs of individual statements by enclosing them in a loop that runs them many millions of times, then computes an average time. On a 250 MHz MIPS R10000, it produces this data, with times in nanoseconds per operation.

```
int operations:
    i1++                  8
    i1 = i2 + i3         12
    i1 = i2 - i3         12
    i1 = i2 * i3         12
    i1 = i2 / i3        114
    i1 = i2 % i3        114

float operations
    f1 = f2               8
    f1 = f2 + f3         12
    f1 = f2 - f3         12
    f1 = f2 * f3         11
    f1 = f2 / f3         28

double operations
    d1 = d2               8
    d1 = d2 + d3         12
```

```
        d1 = d2 - d3           12
        d1 = d2 * d3           11
        d1 = d2 / d3           58

    numeric conversions
        i1 = f1                 8
        f1 = i1                 8
```

Integer operations are fast, except for division and modulus (取模). Floating-point operations are as fast or faster, a surprise to people who grew up at a time when floating point operations were much more expensive than integer operations.

Other basic operations are also quite fast, including function calls, the last three lines of this group:

```
    integer vector operations
        v[i] = i               49
        v[v[i]] = i            81
        v[v[v[i]]] = i        100

    control structures
        if (i == 5) i1++        4
        if (i != 5) i1++       12
        while (i < 0) i1++      3
        i1 = sum1(i2)          57
        i1 = sum2(i2, i3)      58
        i1 = sum3(i2, i3, i4)  54
```

But input and output are not so cheap, nor are most other library function:

```
    input/output
        fputs(s, fp)                       270
        fgets(s, 9, fp)                    222
        fprintf(fp, "%d\n", i)            1820
        fscanf(fp, "%d", &i1)             2070

    malloc
        free(malloc(8))                    342

    string functions
        strcpy(s, "0123456789")            157
        i1 = strcmp(s, s)                  176
        i1 = strcmp(s, "a123456789")        64

    string/number conversions
        i1 = atoi("12345")                 402
        sscanf("12345", "%d", &i1)        2376
        sprintf(s, "%d", i)               1492
        f1 = atof("123.45")               4098
        sscanf("123.45", "%f", &f1)       6438
        sprintf(s, "%6.2f", 123.45)       3902
```

The time for `malloc` and `free` are probably not indicative of true performance, since freeing immediately after allocating is not a typical pattern.

Finally, math functions:

```
    math functions
        i1 = rand()             135
        f1 = log(f2)            418
```

```
f1 = exp(f2)          462
f1 = sin(f2)          514
f1 = sqrt(f2)         112
```

These values would be different on different hardware, of course, but the trends can be used for back-of-the-envelope (粗略) estimates of how long something might take, or for comparing the relative costs of I/O versus basic operations, or for deciding whether to rewrite an expression or use an inline function.

There are many sources of variability. One is compiler optimization level. Modern compilers can find optimizations that elude most programmers. Furthermore, current CPUs are so complicated that only a good compiler can take advantage of their ability to issue multiple instructions concurrently, pipeline their execution, fetch instructions and data before they are needed, and the like.

Computer architecture itself is another major reason why performance numbers are hard to predict. Memory caches make a great difference in speed, and much cleverness in hardware design goes into hiding the fact that main memory is quite a bit slower than cache memory. Raw processor clock rates (频率) like "400 MHz" are suggestive (提示性的) but don't tell the whole story; one of our old 200 MHz Pentium is significantly slower than an even older 100 MHz Pentium because the latter has a big second-level cache and the former has none. And different generations of processor, even for the same instruction set, take different numbers of clock cycles to do a particular operation.

✎ **Exercise 7-6** . Create a set of tests for estimating the costs of basic operations for computers and compilers near you, and investigates and differences in performance. □

✎ **Exercise 7-7** . Create a cost model for higher-level operations in C++. Among the features that might be included are construction, copying, and deletion of class objects; member function calls; virtual functions; inline functions; the `iostream` library; the STL. This exercise is open-ended (开放式的), so Concentrate on a small set of representative operations. □

✎ **Exercise 7-8** . Repeat the previous exercise for Java. □

7.7 Summary

Once you have chosen the right algorithm, performance optimization is generally the last thing to worry about as you write a program. If you must undertake it, however, the basic cycle is to measure, focus on the few places where a change will make the most difference, verify the correctness of your changes, then measure again. Stop as soon as you can, and preserve the simplest version as a baseline (基准) for timing and correctness.

When you're trying to improve the speed or space consumption of a program, it's a good idea to make up some benchmark tests and problems so you can estimate and keep track of performance for yourself. If there are already standard benchmarks for your task, use them too. If the program is relatively self-contained, one approach is to find or create a collection of "typical" inputs; these might well be part of a test suite as well. This is the genesis (起源) of benchmark suites for commercial and academic systems like compilers, computers, and the like. For example, Awk comes with about 20 small programs that together cover most of the commonly-used language features; these programs are run over a very large input file to assure that the same results are computed and that no performance bug has been introduced. We also have a collection of standard large data files that can be used for timing tests. In some cases it might help that such files have easily verified properties, for example a size that is a power of ten or of two.

Benchmarking can be managed with the same kind of scaffolding (脚手架) as we recommended for testing in Chapter 6. Timing tests are run automatically; outputs include enough identification that they can be understood and replicated (复制); records are kept so that trends and significant changes can be observed.

By the way, it's extremely difficult to do good benchmarking, and it is not unknown for companies to tune their products to show up well on benchmarks, so it is wise to take all benchmark results with a grain of salt.

Supplementary Reading

Our discussion of the spam filter is based on work by Bob Handrena and Ken Thompson. Their filter includes regular expressions for more sophisticated matching and automatically classifies messages (certainly spam, possibly spam, not spam) according to the strings they match.

Knuth's profiling paper, "An Empirical (经验主义的) Study of FORTRAN Programs," appeared in *Software -- Practice and Experience, 1, 2*, PP.105-133, 1971. The core of the paper is a statistical analysis of a set of programs found by rummaging (仔细搜索) in waste basket (篮子) and publicly-visible directories on the computer center's machines.

Jon Bentley's *Programming Pearls* and *More Programming Pearls* (Addison-Wesley, 1986 and 1988) have several fine example of algorithmic and code-tuning improvements; there are also good essays (短文) on scaffolds for performance improvements and the use of profiles.

Inner Loops, by Rick Booth (Addison-Wesley, 1997), is a good reference on tuning PC programs, although processors evolve so fast that specific details age quickly.

John Hennessy and David Patterson's family of books on computer architecture (for example, *Computer Organization and Design: The Hardware/Software Interface*, Morgan Kaufman, 1997) contain thorough discussions of performance considerations for modern computers.

8

Portability

Finally, standardization, like convention, can be another manifestation (证明) of the strong older. But unlike convention it has been accepted in Modern architecture as an enriching (丰富) product of our technology, yet dreaded (可怕的) for its potential domination and brutality.

Robert Venturi, *Complexity and Contradiction (矛盾) in Architecture*

It's hard to write software that runs correctly and efficiently. So once a program works in one environment, you don't want to repeat much of the effort if you move it to a different compiler or processor or operating system. Ideally (理想地), it should need no changes whatsoever (无论什么).

This ideal is called ***portability***. In practice, "portability" more often stands for the weaker concept that it will be easier to modify the program as it moves than to rewrite it from scratch (擦除). The less revision it needs, the more portable it is.

You may wonder why we worry about portability at all. If software is going to run in only one environment, under specified conditions, why spend time giving it broader applicability? First, any successful program, almost by definition, gets used in unexpected ways and unexpected places. Building software to be more general than its original specification will result in less maintenance and more utility down the road. Second, environments change. When the compiler or operating system or hardware is upgraded, features may change. The less the program depends on special features, the less likely it is to break and the more easily it will adapt to changing circumstances. Finally, and most important, a portable program is a better program. The effort invested to make a program portable also makes it better designed, better constructed, and more thoroughly tested. The techniques of portable programming are closely related to the techniques of good programming in general.

Of course the degree of portability must be tempered (调和) by reality. There is no such thing as an absolutely portable program, only a program that hasn't yet been tried in enough environments. But we can keep portability as our goal by aiming towards software that runs without change almost everywhere. Even if this goal isn't met completely, time spent on portability as the program is created will pay off when the software must be updated.

Our message is this: try to write software that works within the intersection of the various standards, interfaces and environments it must accommodate. Don't fix every portability problem by adding special code; instead, adapt the software to work within the new constraints. Use abstraction and encapsulation to restrict and control unavoidable non-portable code. By staying within the intersection of constraints and by localizing (局部化) system dependencies, your code will become cleaner and more general as it is ported (移植).

8.1 Language

Stick to the standard. The first step to portable code is of course to program in a high-level language, and within the language standard if there is one. Binaries don't port well, but source code does. Even so, the way that a compiler translates a program into machine instructions is not precisely defined, even for standard languages. Few languages in wide use have only a single implementation; there are usually multiple suppliers, or versions for different operating systems, or releases that have evolved over time. How they interpret your source code will vary.

Why isn't a standard a strict definition? Sometimes a standard is incomplete and fails to define the behavior when features interact (互相干扰). Sometimes it's deliberately (故意地) indefinite (不确定); for example, the `char` type in C and C++ may be signed or unsigned, and need not even have exactly 8 bits. Leaving such issues up to the compiler writer may allow more efficient implementations and avoid restricting the hardware the language will run on, at the risk of making life harder for programmers. Politics and technical compatibility issues may lead to compromises that leave details unspecified. Finally, languages are intricate (复杂的) and compilers are complex; there will be errors in the interpretation and bugs in the implementation.

Sometimes the languages aren't standardized at all. C has an official ANSI/ISO standard issued in 1988, but the ISO C++ standard was ratified (批准) only in 1998; at the time we are writing this, not all compilers in use support the official definition. Java is new and still years away from standardization. A language standard is usually developed only after the language has a variety of conflicting (互相矛盾的) implementations to unify (统一), and is in wide enough use to justify the expense of standardization. In the meantime, there are still programs to write and multiple environments to support.

So although reference manuals and standards give the impression (印象) of rigorous (严格的) specification, they never define a language fully, and different implementations may make valid but incompatible interpretations. Sometimes there are even errors. A small illustration showed up while we were first writing this chapter. This external declaration is illegal in C and C++:

```
?   *x[] = {"abc"};
```

A test of a dozen compilers turned up a few that correctly diagnosed the missing `char` type specifier for `x`, a fair number that warned of mismatched types (apparently using an old definition of the language to infer (推断) incorrectly that `x` is an array of `int` pointers), and a couple that compiled the illegal code without a murmur (低语) of complaint.

Program in the mainstream. The inability of some compilers to flag this error is unfortunate, but it also indicates an important aspect of portability. Languages have dark comers (死角) where practice varies -- bit-fields in C and C++, for example -- and it is prudent (谨慎的) to avoid them. Use only those features for which the language definition is unambiguous and well understood. Such features are more likely to be widely available and to behave the same way everywhere. We call this the mainstream of the language.

It's hard to know just where the mainstream is, but it's easy to recognize constructions that are well outside it. Brand new features such as `//` comments and `complex` in C, or features specific to one architecture such as the keywords `near` and `far`, are guaranteed to cause trouble. If a feature is so unusual or unclear that to understand it you need to consult a "language lawyer" -- an expert in reading language definitions -- don't use it.

In this discussion, we'll focus on C and C++, general-purpose languages commonly used to write portable software. The C standard is more than a decade old and the language is very stable, but a new standard is in the works, so upheaval (变动) is coming. Meanwhile, the C++ standard is hot off the press (刚刚出炉), so not all implementations have had time to converge (聚合).

What is the C mainstream? The term usually refers to the established style of use of the language, but sometimes it's better to plan for the future. For example, the original version of C did not require function prototypes. One declared `sqrt` to be a function by saying

```
?   double sqrt();
```

which defines the type of the return value but not of the parameters. ANSI C added function prototypes, which specify everything:

```
    double sqrt(double);
```

ANSI C compilers are required to accept the earlier syntax, but you should nonetheless (仍然) write prototypes for all your functions. Doing so will guarantee safer code -- function calls will be fully type-checked -- and if interfaces change, the compiler will catch them. If your code calls

```
    func(7, PI);
```

but func has no prototype, the compiler might not verify that `func` is being called correctly. If the library later changes so that `func` has three arguments, the need to repair the software might be missed because the old-style syntax disables type checking of function arguments.

C++ is a larger language with a more recent standard, so its mainstream is harder to identify. For example, although we expect the STL to become mainstream, this will not happen immediately, and some current implementations do not support it completely.

Beware of language trouble spots (故障点). As we mentioned, standard leave some things intentionally undefined or unspecified, usually to give compiler writers more flexibility. The list of such behaviors is discouragingly long.

Size of data types. The sizes of basic data types in C and C++ are not defined; other than (除了) the basic rules that

```
    sizeof(char) <= sizeof(short) <= sizeof(int) <= sizeof(long)
    sizeof(float) <= sizeof(double)
```

and that `char` must have at least 8 bit, `short` and `int` at least 16, and `long` at least 32, there are no guaranteed properties. It's not even required that a pointer value fit in an `int`.

It's easy enough to find out what the sizes are for a specific compiler:

```
    /* sizeof: display sizes of basic types */
    int main(void)
    {
        printf("char %d, short %d, int %d, long %d",
                sizeof(char), sizeof(short),
```

```
            sizeof(int), sizeof(long));
    printf(" float %d, double %d, void* %d\n",
            sizeof(float), sizeof(double), sizeof(void *));
    return 0;
}
```

The output is the same on most of the machines we use regularly:

```
char 1, short 2, int 4, long 4, float 4, double 8, void* 4
```

but other values are certainly possible. Some 64-bit machines produce this:

```
char 1, short 2, int 4, long 8, float 4, double 8, void* 8
```

and early PC compilers typically produced this:

```
char 1, short 2, int 2, long 4, float 4, double 8, void* 2
```

In the early days of PCs, the hardware supported several kinds of pointers. Coping with this mess (混乱) caused the invention (发明) of pointer modifiers like `far` and `near`, neither of which is standard, but whose reserved-word ghosts (灵魂) still haunt (出没于) current compilers. If your compiler can change the sizes of basic types, or if you have machines with different sizes, try to compile and test your program in these different configurations.

The standard header file `stddef.h` defines a number of types that can help with portability. The most commonly-used of these is `size_t`, which is the unsigned integer type returned by the `sizeof` operator. Values of this type are returned by functions like `strlen` and used as arguments by many functions, including `malloc`.

Learning from some of these experiences, Java defines the sizes of all basic data types: `byte` is 8 bits, `char` and `short` are 16, `int` is 32, and `long` is 64.

We will ignore the rich set of potential issues related to floating-point computation since that is a book-sized topic in itself. Fortunately, most modern machines support the IEEE standard for floating-point hardware, and thus the properties of floating-point arithmetic are reasonably well defined.

Order of evaluation. In C and C++, the order of evaluation of operands of expressions, side effects, and function arguments is not defined. For example, in the assignment

```
?   n = (getchar() << 8) | getchar();
```

the second `getchar` could be called first: the way the expression is written is not necessarily the way it executes. In the statement

```
?   ptr[count] = name[++count];
```

`count` might be incremented before or after it is used to index `ptr`, and in

```
?   printf("%c %c\n", getchar(), getchar());
```

the first input character could be printed second instead of first. In

```
?   printf("%f %s\n", log(-1.23), strerror(errno));
```

the value of `errno` may be evaluated before `log` is called.

There are rules for when certain expressions are evaluated. By definition, all side effects and function calls must be completed at each semicolon, or when a function is called. The `&&` and `||` operators execute left to right and only as far as necessary to determine their truth value (including side effects). The condition in a `?:` operator is evaluated (including side effects) and then exactly one of the two expressions that follow is evaluated.

Java has a stricter definition of order of evaluation. It requires that expressions, including side effects, be evaluated left to right, though (虽然) one authoritative (权威的) manual advises not writing code that depends "crucially (重要的)" on this behavior. This is sound (合理的) advice if there's any chance that Java code will be converted to C or C++, which make no such promises (约定). Converting between languages is an extreme but occasionally reasonable test of portability.

Signedness of `char`. In C and C++, it is not specified whether the `char` data type is signed or unsigned. This can lead to trouble when combining `char`s and `int`s, such as in code that calls the `int`-valued routine `getchar()`. If you say

```
char    c;  /* should be int */
c = getchar();
```

the value of `c` will be between 0 and 255 if `char` is unsigned, and between -128 and 127 if `char` is signed, for the almost universal configuration of 8-bit characters on a two's complement machine. This has implications if the character is to be used as an array subscript or if it is to be tested against `EOF`, which usually has value -1 in `stdio`. For instance, we had developed this code in Section 6.1 after fixing a few boundary conditions in the original version. The comparison `s[i] == EOF` will always fail if `char` is unsigned:

```
?   int i;
?   char s[MAX];
?
?   for (i = 0; i < MAX - 1; i++)
?       if ((s[i] = getchar()) == '\n' || s[i] == EOF)
?           break;
?   s[i] = '\0';
```

When `getchar` returns `EOF`, the value `255` (`0xff`, the result of converting `-1` to `unsigned char`) will be stored in `s[i]`, If `s[i]` is unsigned, this will remain 255 for the comparison with `EOF`, which will fail.

Even if `char` is signed, however, the code isn't correct. The comparison will succeed at `EOF`, but a valid input byte of `0xff` will look just like `EOF` ad terminate the loop prematurely (过早). So regardless of the sign of `char`, you must always store the return value of `getchar` in an `int` for comparison with `EOF`. Here is how to write the loop portably:

```
int c, i;
char s[MAX];

for (i = 0; i < MAX - 1; i++) {
    if ((c = getchar()) == '\n' || c == EOF)
        break;
    s[i] = c;
}
s[i] = '\0';
```

Java has no `unsigned` qualifier; integral types are signed and the (16-bit) `char` type is not.

Arithmetic or logical shift. Right shifts of signed quantities with >> operator may be arithmetic (a copy of the sign bit is propagated (可繁殖的) during the shift) or logical (zeros fill the vacated (空出的) bits during the shift). Again, learning from the problems with C and C++, Java reserves >> for arithmetic right shift and provides a separate operator >>> for logical right shift.

Byte order. The byte order within `short`, `int`, and `long` is not defined; the byte with the lowest address may be the most significant byte or the least significant byte. This is a hardware-dependent issue that we'll discuss later in this chapter.

Alignment of structure and class members. The alignment of items within structures, classes, and unions is not defined, except that members are laid out in the order of declaration. For example, in this structure

```
struct X {
    char    c;
    int     i;
};
```

the address of `i` could be 2,4, or 8 bytes from the beginning of the structure. A few machines allow `int`s to be stored on odd boundaries, but most demand that an n-byte primitive data type be stored at an n-byte boundary, for example that `double`s, which are usually 8 bytes long, are stored at addresses that are multiples of 8. On top of this, the compiler writer may make further (更多的) adjustments, such as forcing alignment for performance reasons.

You should never assume that the elements of a structure occupy contiguous memory. Alignment restrictions introduce "holes"; `struct X` will have at least one byte of unused space. These holes imply that a structure may be bigger than the sum of its member sizes, and will vary from machine to machine. If you're allocating memory to hold one, you must ask for `sizeof (struct X)` bytes, not `sizeof(char) + sizeof(int)`.

Bitfields. Bitfields are so machine-dependent that no one should use them.

This long list of perils (危险) can be skirted (绕过) by following a few rules. Don't use side effects except for a very few idiomatic constructions like

```
a[i++] = 0;
c = *p++;
*s++ = *t++;
```

Don't compare a `char` to `EOF`. Always use `sizeof` to compute the size of types and objects. Never right shift a signed value. Make sure the data type is big enough for the range of values you are storing in it.

Try several compilers. It's easy to think that you understand portability, but compilers will see problems that you don't, and different compilers sometimes see your program differently, so you should take advantage of their help. Turn on all compiler warnings. Try multiple compilers on the same machine and on different machines. Try a C++ compiler on a C program.

Since the language accepted by different compilers varies, the fact that your program compiles with one compiler is no guarantee that it is even syntactically correct. If several compilers accept your code, however, the odds (奇怪的事情) improve. We have compiled every C program in this book with three C compilers on three unrelated operating systems (Unix, Plan 9, Windows) and also a couple of C++ compilers. This was a sobering (合理的) experience, but it caught dozens of portability errors that no amount of human scrutiny (检查) would have uncovered. They were all trivial (琐细的) to fix.

Of course, compilers cause portability problems too, by making different choices for unspecified behaviors. But our approach still gives us hope. Rather than writing code in a way that amplifies (放大) the differences among systems, environments, and compilers, we strive (争取) to create software that behaves independently of the variations. In short, we steer clear of (避开) features and properties that are likely to vary.

8.2 Headers and Libraries

Headers and libraries provide services that augment (增加) the basic language. Examples include input and output through `stdio` in C, `iostream` in C++, and `java.io` in Java. Strictly speaking, these are not part of the language, but they are defined along with the language itself and are expected to be part of any environment that claims to support it. But because libraries cover a broad spectrum (范围) of activities, and must often deal with operating system issues, they can still harbor (港湾) non-portabilities.

Use standard libraries. The same general advice applies here as for the core language: stick to the standard, and within its older, well-established components. C defines a standard library of functions for input and output, string operations, character class tests, storage allocation, and a variety of other tasks. If you confine (禁止) your operating system interactions to these functions, there is a good chance that your code will behave the same way and perform well as it moves from system to system. But you must still be careful, because there are many implementations of the library and some of them contain features that are not defined in the standard.

ANSI C does not define the string-copying function `strdup`, yet most environments provide it, even those that claim to conform (一致) to the standard. A seasoned (老练的) programmer may use `strdup` out of habit (出于习惯), and not be warned that it is non-standard. Later, the program will fail to compile when ported to an environment that does not provide the function. This sort of problem is the major portability headache introduced by libraries; the only solution is to stick to the standard and test your program in a wide variety of environments.

Header files and package definitions declare the interface to standard functions. One problem is that headers tend to be cluttered (杂乱的) because they are trying to cope (应付) with several languages in the same file. For example, it is common to find a single header file like `stdio.h` serving pre-ANSI C, ANSI C, and even C++ compilers. In such cases, the file is littered (弄乱) with conditional compilation directives like `#if` and `#ifdef`. Because the preprocessor language is not very flexible, the files are complicated and hard to read, and sometimes contain errors.

This excerpt (摘录) from a header file on one of our systems is better than most, because it is neatly formatted:

```
#ifdef __OLD_C
    extern int fread();
    extern int fwrite();
#else
    #if defined(__STDC__) || defined(__cplusplus)
        extern size_t fread(void *, size_t, size_t, FILE *);
        extern size_t fwrite(const void *, size_t, size_t, FILE *);
    #else /* not __STDC__ __cplusplus */
        extern size_t fread();
        extern size_t fwrite();
    #endif /* else not __STDC__ || __cplusplus */
#endif
```

Even though the example is relatively clean, it demonstrates that header files (and programs) structured like this are intricate (复杂的) and hard to maintain. It might be easier to use a different header for each compiler or environment. This would require maintaining separate files, but each would be self-contained and appropriate for a particular system, and would reduce the likelihood of errors like including `strdup` in a strict ANSI C environment.

Header files also can "pollute" the name space by declaring a function with the same name as one in your program. For example, our warning-message function `weprintf` was originally called `wprintf`, but we discovered that some environments, in anticipation (预测) of the new C standard, define a function with that name in `stdio.h`. We needed to change the name of our function in order to compile on those systems and be ready for the future. If the problem was an erroneous implementation rather than a legitimate (合法的) change of specification, we could work around it by redefining the name when including the header:

```
?   /* some versions of stdio use wprintf so define it away */
?   #define wprintf stdio_wprintf
?   #undef wprintf
?   /* code using our wprintf() follows ... */
```

This maps all occurrences of `wprintf` in the header file to `stdio_wprintf` so they will not interfere with our version. We can then use our own `wprintf` without changing its name, at the cost of some clumsiness (笨拙) and the risk that a library we link with will call our `wprintf` expecting to get the official one. For a single function, it's probably not worth the trouble, but some systems make such a mess of the environment that one must resort to (采取) extremes (极端方法) to keep the code clean. Be sure to comment what the construction is doing, and don't make it worse by adding conditional compilation. If some environments define `wprintf`, assume they all do; then the fix is permanent and you won't have to maintain the `#ifdef` statements as well. It may be easier to switch than fight and it's certainly safer, so that's what we did when we changed the name to `weprintf`.

Even if you try to stick to the rules and the environment is clean, it is easy to step outside the limits by implicitly assuming that some favorite property is true everywhere. For instance, ANSI C defines six signals that can be caught with `signal`; the POSIX standard defines 19; most Unix systems support 32 or more. If you want to use a non-ANSI signal, there is clearly a tradeoff (交易) between functionality and portability, and you must decide which matters more.

There are many other standards that are not part of a programming language definition; examples include operating system and network interfaces, graphics interfaces, and the like. Some are meant to carry across more than one system, like POSIX; others are specific to one system, like the various Microsoft Windows APIs. Similar advice holds here as well. Your programs will be more portable if you choose widely used and well-established standards, and if you stick to the most central and commonly used aspects.

8.3 Program Organization

There are two major approaches to portability, which we will call union and intersection. The union approach is to use the best features of each particular system, and make the compilation and installation process conditional on properties of the local environment. The resulting code handles the union of all scenarios (方案), taking advantage of the strengths of each system. The drawbacks include the size and complexity of the installation process and the complexity of code riddled (充塞) with compile-time conditionals.

Use only features available everywhere. The approach we recommend is intersection: use only those features that exist in all target systems; don't use a feature if it isn't available everywhere. One danger is that the requirement of universal availability of features may limit the range of target systems or the capabilities of the program; another is that performance may suffer in some environments.

To compare these approaches, let's look at a couple of examples that use union code and rethink them using intersection. As you will see, union code is by design unportable, despite (不管) its stated goal, while intersection code is not only portable but usually simpler.

This small example attempts to cope with (应付) an environment that for some reason doesn't have the standard header file `stdlib.h`:

```
#if defined(STDC_HEADERS) || defined(_LIBC)
    #include <stdlib.h>
#else
    extern void *malloc(unsigned int);
    extern void *realloc(void *, unsigned int);
#endif
```

This style of defense (防御) is acceptable if used occasionally, but not if it appears often. It also begs the question of how many other functions from `stdlib` will eventually find their way into this or similar conditional code. If one is using `malloc` and `realloc`, surely `free` will be needed as well, for instance. What if `unsigned int` is not the same as `size_t`, the proper type of the argument to `malloc` and `realloc`? Moreover, how do we know that `STDC_HEADERS` or `_LIBC` are defined, and defined correctly? How can we be sure that there is no other name that should trigger (触发) the substitution in some environment? Any conditional code like this is incomplete-unportable -- because eventually a system that doesn't match the condition will come along (出现), and we must edit the `#ifdefs`. If we could solve the problem without conditional compilation, we would eliminate the ongoing (进行中的) maintenance headache.

Still, the problem this example is solving is real, so how can we solve it once and for all? Our preference would be to assume that the standard headers exist; it's someone else's problem if they don't. Failing that, it would be simpler to ship with (装载) the software a header file that defines `malloc`, `realloc`, and `free`, exactly as ANSI C defines them. This file can always be included, instead of applying band-aids (创可帖) throughout the code. Then we will always know that the necessary interface is available.

Avoid conditional compilation. Conditional compilation with `#ifdef` and similar preprocessor directives is hard to manage, because information tends to get sprinkled (点缀) throughout the source.

```
?   #ifdef NATIVE
?       char *astring = "convert ASCII to native character set";
?   #else
?   #ifdef MAC
?       char *astring = "convert to Mac text file format";
?   #else
?   #ifdef DOS
?       char *astring = "convert to DOS text file format";
?   #else
?       char *astring = "convert to Unix text file format";
?   #endif /* DOS */
?   #endif /* MAC */
?   #endif /* NATIVE */
```

This excerpt (摘录) would have been better with `#elif` after each definition, rather than having `#endifs` pile up (堆积) at the end. But the real problem is that, despite its intention, this code is highly non-portable because it behaves differently on each system and needs to be updated with a new `#ifdef` for every new environment. A single string with more general wording would be simpler, completely portable, and just as informative (提供消息的):

```
char *astring = "convert to local text format";
```

This needs no conditional code since it is the same on all systems.

Mixing compile-time control flow (determined by `#ifdef` statements) with run-time control flow is much worse, since it is very difficult to read.

```
?   #ifndef DISKSYS
?       for (i = 1; i <= msg->dbgmsg.msg_total; i++)
?   #endif
?   #ifdef DISKSYS
?       i = dbgmsgno;
?       if (i <= msg->dbgmsg.msg_total)
?   #endif
?       {
?           ...
?           if (msg->dbgmsg.msg_total == i)
?   #ifndef DISKSYS
?               break; /* no more messages to wait for */
?           /*
?            * about 30 more lines, with further Conditional
?            * compilation.
?            */
?   #endif
?       }
```

Even when apparently innocuous (无害的), conditional compilation can frequently be replaced be cleaner methods. For instance, `#ifdefs` are often used to control debugging code:

```
?   #ifdef DEBUG
?       printf(...);
?   #endif
```

but a regular `if` statement with a constant condition may work just as well:

```
    enum { DEBUG = 0 };
    ...
    if (DEBUG) {
        printf(...);
    }
```

If `DEBUG` is zero, most compilers won't generate any code for this, but they will check the syntax of the excluded (排除的) code. An `#ifdef`, by contrast, can conceal (掩盖) syntax errors that will prevent compilation if the `#ifdef` is later enabled.

Sometimes conditional compilation excludes large blocks of code:

```
    #ifdef notdef   /* undefined symbol */
        ...
    #endif

    #if 0
        ...
    #endif
```

but conditional code can often be avoided altogether by using files that are conditionally substituted during compilation. We will return to this topic in the next section.

When you must modify a program to adapt to a new environment, don't begin by making a copy of the entire program. Instead, adapt the existing source. You will probably need to make changes to the main body of the code, and if you edit a copy, before long (不久以后) you will have divergent (分散的) versions. As much as possible, there should only be a single source for a program; if you find you need to change something to port to a particular environment, find a way to make the change work everywhere. Change internal interfaces if you need to, but keep the code consistent and `#ifdef`-free. This will make your code more portable over time, rather than more specialized. Narrow the intersection, don't broaden the union.

We have spoken out against conditional compilation and shown some of the problems it causes. But the nastiest (污秽的) problem is one we haven't mentioned: it is almost impossible to test. An `#ifdef` turns a single program into two separately-compiled programs. It is difficult to know whether all the variant programs have been compiled and tested. If a change is made in one `#ifdef` block, we may need to make it in others, but the changes can be verified only within the environment that causes those `#ifdefs` to be enabled. If a similar change needs to be made for other configurations, it cannot be tested. Also, when we add a new `#ifdef` block, it is hard to isolate the change to determine what other conditions need to be satisfied to get here, and where else this problem might need to be fixed. Finally, if something is in code that is conditionally omitted, the compiler doesn't see it. It could be utter (完全) nonsense (说不通) and we won't know until some unlucky customer tries to compile it in the environment that triggers that condition. This program compiles when `_MAC` is defined and fails when it is not:

```
#ifdef _MAC
    printf("This is Macintosh\r");
#else
    This will give a syntax error on other systems
#endif
```

So our preference is to use only features that are common to all target environments. We can compile and test all the code. If something is a portability problem, we rewrite to avoid it rather than adding conditional code; this way, portability will steadily increase and the program itself will improve rather than becoming more complicated.

Some large systems are distributed with a configuration script to tailor (裁减) code to the local environment. At compilation time, the script tests the environment properties -- location of header files and libraries, byte order within words, size of types, implementations known to be broken (surprisingly common), and so on -- and generates configuration parameters or makefiles that will give the right configuration settings for that situation, These scripts can be large and intricate (复杂的), a significant fraction (成分) of a software distribution, and require continual (持续的) maintenance to keep them working. Sometimes such techniques are necessary but the more portable and `#ifdef`-free the code is, the simpler and more reliable the configuration and installation will be.

Exercise 8-1 . Investigate how your compiler handles code contained within a conditional block like

```
const int DEBUG = 0;
/* or enum { DEBUG = 0 }; */
/* or final boolean DEBUG = false; */

if (DEBUG) {
    ...
}
```

Under what circumstances does it check syntax? When does it generate code? If you have access to more than one compiler, how do the results compare? □

8.4 Isolation

Although we would like to have a single source that compiles without change on all systems, that may be unrealistic. But it is a mistake to have non-portable code scattered (分散) throughout a program: that is one of the problems that conditional compilation creates.

Localize system dependencies in separate files. When different code is needed for different systems, the differences should be localized in separate files, one file for each system. For example, the text editor Sam runs on Unix, Windows, and several other operating systems. The system interfaces for these environments vary widely, but most of the code for Sam is identical everywhere. A single file captures the system variations for a particular environment; `unix.c` provides the interface code for Unix systems, and `windows.c` for the Windows environment. These files implement a portable interface to the operating system and hide the differences. Sam is, in effect, written to its own virtual operating system, which is ported to various real systems by writing a couple of hundred lines of C to implement half a dozen small but non-portable operations using locally available system calls.

The graphics environments of these operating systems are almost unrelated. Sam copes (应付) by having a portable library for its graphics. Although it's a lot more work to build such a library than to hack (劈砍) the code to adapt to a given system -- the code to interface to the X Window system, for example, is about half as big as the rest of Sam put together -- the cumulative (累积的) effort is less in the long run. And as a side benefit, the graphics library is itself valuable, and has been used separately to make a number of other programs portable, too.

Sam is an old program; today, portable graphics environments such as OpenGL, Tcl/Tk and Java are available for a variety of platforms. Writing your code with these rather than a proprietary (私有的) graphics library will give your programs wider utility.

Hide system dependencies behind interfaces. Abstraction is a powerful technique for creating boundaries between portable and non-portable parts of a program. The I/O libraries that accompany (伴随) most programming languages provide a good example: they present an abstraction of secondary storage in terms of (在... 方面) files to be opened and closed, read and written, without any reference to their physical location or structure. Programs that adhere (依附) to the interface will run on any system that implements it.

The implementation of Sam provides another example of abstraction. An interface is defined for the file system and graphics operations and the program uses only features of the interface. The interface itself uses whatever facilities are available in the underlying system. That might require significantly different implementations on different systems, but the program that uses the interface is independent of that and should require no changes as it is moved.

The Java approach to portability is a good example of how far this can be carried. A Java program is translated into operations in a "virtual machine." that is, a simulated computer that can be implemented to run on any real machine. Java libraries provide uniform access to features of the underlying system, including graphics, user interface, networking, and the like; the libraries map into whatever the local system provides. In theory, it should be possible to run the same Java program (even after translation) everywhere without change.

8.5 Data Exchange

Textual data moves readily (迅速地) from one system to another and is the simplest portable way to exchange arbitrary information between systems.

Use text for data exchange. Text is easy to manipulate with other tools and to process in unexpected ways. For example, if the output of one program isn't quite right as input for another, an Awk or Perl script can be used to adjust it; `grep` can be used to select or discard lines; your favorite editor can be used to make more complicated changes. Text files are also much easier to document and may not even need much documentation, since people can read them. A comment in a text file can indicate what version of software is needed to process the data; the first line of a Postscript file, for instance, identifies the encoding:

```
%!PS-Adobe-2.0
```

By contrast, binary files need specialized tools and rarely can be used together even on the same machine. A variety of widely-used programs convert arbitrary binary data into text so it can be shipped (传送) with less chance of corruption; these include `binhex` for Macintosh systems, `uuencode` and `uudecode` for Unix, and various tools that use MIME encoding for transferring binary data in mail messages. In Chapter 9, we show a family of pack and unpack routines to encode binary data portably for transmission. The sheer (全然的) variety of such tools speaks to the problems of binary formats.

There is one continuing (持续的) irritation (烦恼) with exchanging text: PC systems use a carriage return `'\r'` and a newline or line-feed `'\n'` to terminate each line, while Unix systems use only newline. The carriage return is an artifact (人工产物) of an ancient device called a Teletype that had a carriage-return (CR) operation to return the typing mechanism to the beginning of a line, and a separate line-feed operation (LF) to advance it to the next line.

Even though today's computers have no carriages to return, PC software for the most part continues to expect the combination (familiarly known as CRLF, pronounced "curliff") on each line. If there are no carriage returns, a file may be interpreted as one giant line. Line and character counts can be wrong or change unexpectedly. Some software adapts gracefully, but much does not. PCs are not the only culprits (罪魁祸首); thanks to a sequence of incremental compatibilities, some modern networking standards such as HTTP also use CRLF to delimit lines.

Our advice is to use standard interfaces, which will treat CRLF consistently on any given system, either (on PCs) by removing `\r` on input and adding it back on output, or (on Unix) by always using `\n` rather than CRLF to delimit lines in files. For files that must be moved back and forth, a program to convert files from each format to the other is a necessity.

Exercise 8-2 . Write a program to remove spurious (伪造的) carriage returns from a file. Write a second program to add them by replacing each newline with a carriage return and newline. How would you test these programs? □

8.6 Byte Order

Despite the disadvantages discussed above, binary data is sometimes necessary. It can be significantly more compact and faster to decode, factors that make it essential (本质) for many problems in computer networking. But binary data has severe portability problems.

At least one issue is decided: all modern machines have 8-bit bytes. Different machines have different representations of any object larger than a byte, however, so relying on specific properties is a mistake. A short integer (typically 16 bits, or two bytes) may have its low-order byte stored at a lower address than the high-order byte (little-endian), or at a higher address (big-endian). The choice is arbitrary, and some machines even support both modes.

Therefore, although big-endian and little-endian machines see memory as a sequence of words in the same order, they interpret the bytes within a word in the opposite order. In this diagram, the four bytes starting at location 0 will represent the hexadecimal integer `0x11223344` on a big-endian machine and `0x44332211` on a little-endian.

0	1	2	3	4	5	6	7
11	22	33	44				

To see byte order in action, try this program:

```
/* byte order: display bytes of a long */
int main(void)
{
    unsigned long x;
    unsigned char *p;
    int i;

    /* 11 22 33 44 => big-endian */
    /* 44 33 22 11 => little-endian */

    x = 0x11223344;
    p = (unsigned char *)&x;
    for (i = 0; i < sizeof(long); i++)
        printf("%x ", *p++);
    printf("\n");
    return 0;
}
```

On a 32-bit big-endian machine, the output is

```
11 22 33 44
```

but on a little-endian machine, it is

```
44 33 22 11
```

and on the PDP-11 (a vintage (古老的) 16-bit machine still found in embedded systems), it is

```
22 11 44 33
```

On machines with 64-bit longs, we can make the constant bigger and see similar behaviors.

This may seem like a silly (愚蠢的) program, but if we wish to send an integer down a byte-wide interface such as a network connection, we need to choose which byte to send first, and that choice is in essence (本质上) the big-endian and little-endian decision. In other words, this program is doing explicitly what

```
fwrite(&x, sizeof(x), 1, stdout);
```

does implicitly. It is not safe to write an `int` (or `short` or `long`) from one computer and read it as an `int` on another computer.

For example, if the source computer writes with

```
unsigned short x;
fwrite(&x, sizeof(x), 1, stdout);
```

and the receiving computer reads with

```
unsigned short x;
fread(&x, sizeof(x), 1, stdin);
```

the value of `x` will not be preserved if the machines have different byte orders. If `x` starts as `0x1000` it may arrive as `0x0010`.

This problem is frequently solved using conditional compilation and "byte swapping," something like this:

```
?   short x;
?   fread(&x, sizeof(x), 1, stdin);
?   #ifdef BIG_ENDIAN
?   /* swap bytes */
?   x = ((x&0xff) << 8) | ((x>>8) & 0xff);
?   #endif
```

This approach becomes unwieldy (笨拙的) when many two-byte and four-byte integers are being exchanged. In practice, the bytes end up being swapped more than once as they pass from place to place.

If the situation is bad for `short`, it's worse for longer data types, because there are more ways to permute (变更) the bytes. Add in the variable padding between structure members, alignment restrictions, and the mysterious byte orders of older machines, and the problem looks intractable (棘手的).

Use a fixed byte order for data exchange. There is a solution. Write the bytes in a canonical order using portable code:

```
unsigned short x;
putchar(x >> 8);    /* write high-order byte */
putchar(x & 0xff);  /* write low-order byte */
```

then read it back a byte at a time and reassemble it:

```
unsigned short x;
x = getchar() << 8);    /* read high-order byte */
x |= getchar() & 0xff;  /* read low-order byte */
```

The approach generalizes to structures if you write the values of the structure members in a defined sequence, a byte at a time, without padding. It doesn't matter what byte order you pick; anything consistent will do. The only requirement is that sender and receiver agree on the byte order in transmission and on the number of bytes in each object. In the next chapter we show a pair of routines to wrap up (掩饰) the packing and unpacking of general data.

Byte-at-a-time processing may seem expensive, but relative to (涉及) the I/O that makes the packing and unpacking necessary, the penalty (成本) is minute. Consider the X Window system, in which the client writes data in its native byte order and the server must unpack whatever the client sends. This may save a few instructions on the client end, but the server is made larger and more complicated by the necessity of handling multiple byte orders at the same time -- it may well have concurrent big-endian and little-endian clients -- and the cost in complexity and code is much more significant. Besides, this is a graphics environment where the overhead to pack bytes will be swamped (淹没) by the execution of the graphical operation it encodes.

The X Window system negotiates (协商) a byte order for the client and requires the server to be capable of both. By contrast, the Plan 9 operating system defines a byte order for messages to the file server (or the graphics server) and data is packed and unpacked with portable code, as above. In practice the run-time effect is not detectable; compared to I/O, the cost of packing the data is insignificant.

Java is a higher-level language than C or C++ and hides byte order completely. The libraries provide a `Serializable` interface that defines how data items are packed for exchange.

If you're working in C or C++, however, you must do the work yourself. The key point about the byte-at-a-time approach is that it solves the problem without `#ifdefs`, for any machines that have 8-bit bytes. We'll discuss this further in the next chapter.

Still, the best solution is often to convert information to text format, which (except for the CRLF problem) is completely portable; there is no ambiguity about representation. It's not always the right answer, though. Time or space can be critical, and some data, particularly floating point, can lose precision due to roundoff (四舍五入) when passed through `printf` and `scanf`. If you must exchange floating-point values accurately, make sure you have a good formatted I/O library; such libraries exist, but may not be part of your existing environment. It's especially hard to represent floating-point values portably in binary, but with care, text will do the job.

There is one subtle (微妙的) portability issue in using standard function to handle binary file -- it is necessary to open such files in binary mode:

```
FILE *fin;

fin = fopen(binary_file, "rb");
c = getc(fin);
```

If the `'b'` is omitted, it typically makes no difference at all on Unix systems, but on Windows systems the first control-Z byte (octal `032`, hex `1A`) of input will terminate reading (we saw this happen to the strings program in Chapter 5). On the other hand, using binary mode to read text files will cause `\r` to be preserved on input, and not generated on output.

8.7 Portability and Upgrade

One of the most frustrating sources of portability problems is system software that changes during its lifetime. These changes can happen at any interface in the system, causing gratuitous (无理由的) incompatibilities between existing versions of programs.

Change the name if you change the specification. Our favorite (if that is the word) example is the changing properties of the Unix `echo` command, whose initial design was just to echo its arguments:

```
% echo hello, world
hello, world
%
```

However, echo became a key part of many shell scripts, and the need to generate formatted output became important. So echo was changed to interpret its arguments, somewhat like printf:

```
% echo 'hello\nworld'
hello
world
%
```

This new feature is useful, but causes portability problems for any shell script that depends on the echo command to do nothing more than echo. The behavior of

```
% echo BPATH
```

now depends on which version of echo we have. If the variable happens by accident to contain a backslash, as may happen on DOS or Windows, it may be interpreted by echo. The difference is similar to that between the output from printf(str) and printf("%s", str) if the string str contains a percent sign (百分号).

We've told only a fraction of the full echo story, but it illustrates the basic problem: changes to systems can generate different versions of software that intentionally behave differently, leading to unintentional portability problems. And the problems are very hard to work around. It would have caused much less trouble had the new version of echo been given a distinct name.

As a more direct example, consider the Unix command sum, which prints the size and a checksum of a file. It was written to verify that a transfer (转送) of information was successful:

```
% sum file
52313 2 file
% copy file to other_machine
%
% telnet other_machine
>
> sum file
52313 2 file
>
```

The checksum is the same after the transfer, so we can be reasonably confident that the old and new copies are identical.

Then systems proliferated (扩散), versions mutated (变异), and someone observed that the checksum algorithm wasn't perfect, so sum was modified to use a better algorithm. Someone else made the same observation and gave sum a different better algorithm. And so on, so that today there are multiple versions of sum, each giving a different answer. We copied one file to nearby machines to see what sum computed:

```
% sum file
52313 2 file
% copy file to machine2
% copy file to machine3
% telnet machine2
>
> sum file
eaa0d468 713 file
```

```
> telnet  machine3
>
> sum file
62992 1 file
>
```

Is the `file` corrupted, or do we just have different versions of `sum`? Maybe both.

Thus `sum` is the perfect portability disaster: a program intended to aid in the copying of software from one machine to another has different incompatible versions that render (给予) it useless for its original purpose.

For its simple task, the original `sum` was fine; its low-tech (技术含量低) checksum algorithm was adequate. "Fixing" it may have made it a better program, but not by much, and certainly not enough to make the incompatibility worthwhile. The problem is not the enhancements but that incompatible programs have the same name. The change introduced a versioning problem that will plague (折磨) us for years.

Maintain compatibility with existing programs and data. When a new version of software such as a word processor is shipped, it's common for it to read files produced by the old version. That's what one would expect: as unanticipated (意外的) features are added, the format must evolve (演化). But new versions sometimes fail to provide a way to write the previous file format. Users of the new version, even if they don't use the new features, cannot share their files with people using the older software and everyone is forced to upgrade. Whether an engineering oversight (疏忽) or a marketing strategy, this design is most regrettable (可悲的).

Backwards compatibility is the ability of a program to meet its older specification. If you're going to change a program, make sure you don't break old software and data that depend on it. Document the changes well, and provide ways to recover the original behavior. Most important, consider whether the change you're proposing is a genuine (真正的) improvement when weighed against the cost of any non-portability you will introduce.

8.8 Internationalization

If one lives in the United States, it's easy to forget that English is not the only language, ASCII is not the only character set, `$` is not the only currency symbol, dates can be written with the day first, times can be based on a 24-hour clock, and so on. So another aspect of portability, taken broadly, deals with making programs portable across language and cultural boundaries. This is potentially a very big topic, but we have space to point out only a few basic concerns.

Internationalization is the term for making a program run without assumptions about its cultural environment. The problems are many, ranging from character sets to the interpretation of icons in interfaces.

Don't assume ASCII. Character sets are richer than ASCII in most parts of the world. The standard character-testing functions in `ctype.h` generally hide these differences:

```
if (isalpha(c)) ...
```

is independent of the specific encoding of characters, and in addition will work correctly in locales where there are more or fewer letters than those from `a` to `z` if the program is compiled in that locale. Of course, even the name `isalpha` speaks to its origins; some languages don't have alphabets at all.

Most European countries augment (扩展) the ASCII encoding, which defines values only up to `0x7F` (7 bits), with extra characters to represent the letters of their language. The Latin-1 encoding, commonly used throughout Western Europe, is an ASCII superset that specifies byte values from `0x80` to `0xFF` for symbols and accented (重音) characters; `0xE7`, for instance, represents the accented letter `c`. The English word "boy" is represented in ASCII (or Latin-1) by three bytes with hexadecimal values `62 6F 79`, while the French word "garcon" is represented in Latin-1 by the bytes `67 61 72 E7 6F 6E`. Other languages define other symbols, but they can't all fit in the 128 values left unused by ASCII, so there are a variety of conflicting standards for the characters assigned to bytes `0x80` through `0xFF`.

Some languages don't fit in 8 bits at all; there are thousands of characters in the major Asian languages. The encodings used in China, Japan, and Korea all have 16 bits per character. As a result, to read a document written in one language on a computer set up for another is a major portability problem. Assuming the characters arrive intact (原封不动地), to read a Chinese document on an American computer involves, at a minimum, special software and fonts. If we want to use Chinese, English, and Russian together, the obstacles are formidable (可怕的).

The Unicode character set is an attempt to ameliorate (改善) this situation by providing a single encoding for all languages throughout the world. Unicode, which is compatible with the 16-bit subset of the IS0 10646 standard, uses 16 bits per character, with values `00FF` and below corresponding to Latin-1. Thus the word "garcon" is represented by the 16-bit values `0067 0061 0072 00E7 006F 006E`, while the Cyrillic (西里尔) alphabet occupies values `0401` through `04FF`, and the ideographic (表意的) languages occupy a large block starting at `3000`. All well-known languages, and many not so well-known, are represented in Unicode, so it is the encoding of choice for transferring documents between countries or for storing multilingual (多语言的) text. Unicode is becoming popular on the Internet and some systems even support it as a standard format; Java, for example, uses Unicode as its native character set for strings. The Plan 9 and Inferno operating systems use Unicode throughout, even for the names of files and users. Microsoft Windows supports the Unicode character set, but does not mandate (强制的) it; most Windows applications still work best in ASCII but practice is rapidly evolving towards Unicode.

Unicode introduces a problem, though: characters no longer fit in a byte, so Unicode text suffers from the byte-order confusion. To avoid this, Unicode documents are usually translated into a byte-stream encoding called UTF-8 before being sent between programs or over a network. Each 16-bit character is encoded as a sequence of 1, 2, or 3 bytes for transmission. The ASCII character set uses values `00` through `7F`, all of which fit in a single byte using UTF-8, so UTF-8 is backwards compatible with ASCII. Values between `80` and `7FF` are represented in two bytes, and values `800` and above are represented in three bytes. The word "garcon" appears in UTF-8 as the bytes `67 61 72 C3 A7 6F 6E`; Unicode value `E7`, the 'ç' character, is represented as the two bytes `C3 A7` in UTF-8.

The backwards compatibility of UTF-8 and ASCII is a boon (恩惠), since it permits programs that treat text as an uninterpreted byte stream to work with Unicode text in any language. We tried the `Markov` programs from Chapter 3 on UTF-8 encoded text in Russian, Greek, Japanese, and Chinese, and they ran without problems. For the European languages, whose words are separated by ASCII space, tab, or newline. the output was reasonable nonsense. For the others, it would be necessary to change the word-breaking rules to get output closer in spirit (在精神上) to the intent of the program.

C and C++ support "wide characters," which are 16-bit or larger integers and some accompanying functions that can be used to process characters in Unicode or other large character sets. Wide character string literals are written as `L"..."`, but they introduce further portability problems: a program with wide character constants can only be understood when examined on a display that uses that character set. Since characters must be converted into byte streams such as UTF-8 for portable transmission between machines. C provides functions to convert wide characters to and from bytes. But which conversion do we use? The interpretation of the character set and the definition of the byte-stream encoding are hidden in the libraries and difficult to extract (抽取); the situation is unsatisfactory (不令人满意的) at best (最多). It is possible that in some rosy (理想的) future everyone will agree on which character set to use but a likelier scenario (方案) will be confusion reminiscent (回忆) of the byte-order problems that still pester (纠缠) us.

Don't assume English. Creators of interfaces must keep in mind that different languages often take significantly different numbers of characters to say the same thing, so there must be enough room on the screen and in arrays.

What about error messages? At the very least (最起码), they should be free of jargon (术语) and slang (俚语) that will be meaningful only among a selected population; writing them in simple language is a good start. One common technique is to collect the text of all messages in one spot so that they can be replaced easily by translations into other languages.

There are plenty of cultural dependencies, like the `mm/dd/yy` date format that is used only in North America. If there is any prospect (可能) that software will be used in another country, this kind of dependency should be avoided or minimized. Icons in graphical interfaces are often culture-dependent; many icons are inscrutable (难以理解的) to natives of the intended environment, let alone (更不用说) people from other backgrounds.

8.9 Summary

Portable code is an ideal that is well worth striving for, since so much time is wasted making changes to move a program from one system to another or to keep it running as it evolves and the systems it runs on changes. Portability doesn't come for free, however. It requires care in implementation and knowledge of portability issues in all the potential target systems.

We have dubbed (轻点) the two approaches to portability union and intersection. The union approach amounts to (相当于) writing versions that work on each target, merging the code as much as possible with mechanisms like conditional compilation. The drawbacks are many: it takes more code and often more complicated code, it's hard to keep up to date, and it's hard to test.

The intersection approach is to write as much of the code as possible in a form that will work without change on each system. Inescapable (不可避免的) system dependencies are encapsulated in single source files that act as an interface between the program and the underlying system. The intersection approach has drawbacks too, including potential loss of efficiency and even of features, but in the long run, the benefits outweigh the costs.

Supplementary Reading

There are many descriptions of programming languages, but few are precise enough to serve as definitive references. The authors admit to a personal bias towards *The C Programming Language* by Brian Kernighan and Dennis Ritchie (Prentice Hall, 1988), but it is not a replacement for the standard. Sam Harbison and Guy Steele's *C: A Reference Manual* (Prentice Hall, 1994), now in its fourth edition, has good advice on C portability. The official C and C++ standards are available from ISO, the International Organization for Standardization. The closest thing to an official standard for Java is *The Java Language*

Specification, by James Gosling, Bill Joy, and Guy Steele (Addison-Wesley, 1996).

Rich Stevens's *Advanced Programming in the Unix Environment* (Addison-Wesley, 1992) is an excellent resource for Unix programmers, and provides thorough coverage of portability issues among Unix variants.

POSIX, the Portable Operating System Interface, is an international standard defining commands and libraries based on Unix. It provides a standard environment, source code portability for applications, and a uniform interface to I/O, file systems and processes. It is described in a series of books published by the IEEE.

The term "big-endian" was coined by Jonathan Swift in 1726. The article by Danny Cohen, "On holy wars and a plea (请求) for peace," *IEEE Computer*, October 1981, is a wonderful fable (寓言) about byte order that introduced the "endian (尾端)" terms to computing.

The Plan 9 system developed at Bell Labs has made portability a central priority. The system compiles from the same `#ifdef`-free source on a variety of processors and uses the Unicode character set throughout. Recent versions of Sam (first described in "The Text Editor sam," *Software -- Practice and Experience, 17, 11*, pp. 813-845, 1987) use Unicode, but run on a wide variety of systems. The problems of dealing with 16-bit character sets like Unicode are discussed in the paper by Rob Pike and Ken Thompson, "Hello World or[1]" *Proceedings of the Winter 1993 USENIX Conference*, San Diego, 1993, pp. 43-50. The UTF-8 encoding made its first appearance in this paper. This paper is also available at the Plan 9 web site at Bell Labs, as is the current version of Sam.

The Inferno system, which is based on the Plan 9 experience, is somewhat analogous to Java, in that it defines a virtual machine that can be implemented on any real machine, provides a language (Limbo) that is translated into instructions for this virtual machine, and uses Unicode as its native character set. It also includes a virtual operating system that provides a portable interface to a variety of commercial systems. It is described in "The Inferno Operating System," by Sean Dorward, Rob Pike, David Leo Presotto, Dennis M. Ritchie, Howard W. Trickey, and Philip Winterbottom, *Bell Labs Technical Journal, 2, 1*, Winter, 1997.

[1]Unrecognized characters.

9 Notation

Perhaps of all the creations of man language is the most astonishing (惊讶的).

Giles Lytton Strachey, *Words and Poetry*

The right language can make all the difference in how easy it is to write a program. This is why a practicing programmer's arsenal holds not only general-purpose languages like C and its relatives, but also programmable shells, scripting languages, and lots of application-specific languages

The power of good notation reaches beyond traditional programming into specialized problem domains. Regular expressions let us write compact (if occasionally cryptic (神秘的)) definitions of classes of strings; HTML lets us define the layout of interactive documents, often using embedded programs in other languages such as JavaScript; Postscript expresses an entire document -- this book, for example -- as a stylized program. Spreadsheets and word processors often include programming languages like Visual Basic to evaluate expressions, access information, or control layout.

If you find yourself writing too much code to do a mundane (平凡的) job, or if you have trouble expressing the process comfortably, maybe you're using the wrong language. If the right language doesn't yet exist, that might be an opportunity to create it yourself. Inventing a language doesn't necessarily mean building the successor to Java; often a thorny (多刺的) problem can be cleared up by a change of notation. Consider the format strings in the `printf` family, which are a compact and expressive way to control the display of printed values.

In this chapter, we'll talk about how notation can solve problems, and demonstrate some of the techniques you can use to implement your own special-purpose languages. We'll even explore the possibilities of having one program write another program, an apparently extreme use of notation that happens more often, and is far easier to do, than many programmers realize.

9.1 Formatting Data

There is always a gap between what we want to say to the computer ("solve my problem") and what we are required to say to get a job done. The narrower this gap, the better. Good notation makes it easier to say what we want and harder to say the wrong thing by mistake. Sometimes, good notation can provide new insight (见识, 洞察), allowing us to solve problems that seemed too difficult, or even lead us to new discoveries.

Little languages are specialized notations for narrow domains. They not only provide a good interface but also help organize the program that implements them. The `printf` control sequences are a good example:

```
printf("%d %6.2f %-10.10s\n", i, f, s);
```

Each `%` in the format string signals a place to interpolate (插入) the value of the next `printf` argument; after some optional flags and field widths, the terminating letter says what kind of parameter to expect. This notation is compact, intuitive, and easy to write, and the implementation is straightforward. The alternatives in C++ (`iostream`) and Java (`java.io`) seem more awkward (笨拙) since they don't provide special notation, although they extend to user-defined types and offer type-checking.

Some non-standard implementations of `printf` let you add your own conversions to the built-in set. This is convenient if you have other data types that need output conversion. For example, a compiler might use `%L` for line number and file name; a graphics system might use `%P` for a point and `%R` for a rectangle. The cryptic string of letters and numbers for retrieving stock quotes (股价报价) that we saw in Chapter 4 was in the same spirit, a compact notation for arranging (编排) combinations of stock data.

We can synthesize similar examples in C and C++. Suppose we want to send packets containing various combinations of data types from one system to another. As we saw in Chapter 8, the cleanest solution may be to convert to a textual representation. For a standard network protocol, though, the format is likely to be binary for reasons of efficiency or size. How can we write the packet-handling code to be portable, efficient, and easy to use?

To make this discussion concrete, imagine that we plan to send packets of 8-bit, 16-bit, and 32-bit data items from system to system. ANSI C says that we can always store at least 8 bits in a `char`, 16 bits in a `short`, and 32 bits in a `long`, so we will use these data types to represent our values. There will be many types of packets; packet type 1 might have a 1-byte type specifier, a 2-byte count, a 1-byte value and a 4-byte data item:

0x01	cnt_1	cnt_0	val	$data_3$	$data_2$	$data_1$	$data_0$

Packet type 2 might contain a short and two long data words:

0x02	cnt_1	cnt_0	$dw1_3$	$dw1_2$	$dw1_1$	$dw1_0$	$dw2_3$	$dw2_2$	$dw2_1$	$dw2_0$

One approach is to write pack and unpack functions for each possible packet type:

```
int pack_type1(unsigned char *buf, unsigned short count,
        unsigned char val, unsigned long data)
{
    unsigned char *bp;

    bp = buf;
    *bp++ = 0x01;
    *bp++ = count >> 8;
    *bp++ = count;
    *bp++ = val;
    *bp++ = data >> 24;
    *bp++ = data >> 16;
    *bp++ = data >> 8;
```

```
        *bp++ = data;
        return bp - buf;
    }
```

For a realistic protocol, there will be dozens of such routines, all variations on a theme. The routines could be simplified by using macros or functions to handle the basic data types (`short`, `long`, and so on), but even so, such repetitive code is easy to get wrong, hard to read, and hard to maintain.

The inherent (固有的) repetitiveness (重复性) of the code is a clue that notation can help. Borrowing the idea from `printf`, we can define a tiny specification language in which each packet is described by a brief string that captures the packet layout. Successive elements of the packet are encoded with `c` for an 8-bit character, `s` for a 16-bit short integer, and `l` for a 32-bit long integer. Thus, for example, the packet type 1 built by our example above, including the initial type byte, might be described by the format string `cscl`. Then we can use a single pack function to create packets of any type; this packet would be created with

```
pack(buf, "cscl", 0x01, count, val, data);
```

Because our format string contains only data definitions, there's no need for the `%` character used by `printf`.

In practice, information at the beginning of the packet might tell the recipient (接受者) how to decode the rest, but we'll assume the first byte of the packet can be used to determine the layout. The sender encodes the data in this format and ships it; the receiver reads the packet, picks off the first byte, and uses that to decode what follows.

Here is an implementation of `pack`, which fills `buf` with the encoded representation of its arguments as determined by the format. We make all values unsigned, including the bytes in the packet buffer, to avoid sign-extension problems. We also use some conventional `typedef`s to keep the declarations short:

```
typedef unsigned char   uchar;
typedef unsigned short  ushort;
typedef unsigned long   ulong;
```

Like `sprintf`, `strcpy`, and similar functions, `pack` assumes that the buffer is big enough to hold the result; it is the caller's responsibility to ensure this. There is also no attempt to detect mismatches between the format and the argument list.

```
#include <stdarg.h>

/* pack: pack binary items into buf, return length */
int pack(uchar *buf, char *fmt, ...)
{
    va_list args;
    char    *p;
    uchar   *bp;
    ushort  s;
    ulong   l;
    bp = buf;
    va_start(args, fmt);
    for (p = fmt; *p != '\0'; p++) {
        switch (*p) {
        case 'c':   /* char */
            *bp++ = va_arg(args, int);
            break;
        case 's':   /* short */
```

```
            s = va_arg(args, int);
            *bp++ = s >> 8;
            *bp++ = s;
            break;
        case 'l':   /* long */
            l = va_arg(args, ulong);
            *bp++ = l >> 24;
            *bp++ = l >> 16;
            *bp++ = l >> 8;
            *bp++ = l;
            break;
        default:    /* illegal type character */
            va_end(args);
            return -1;
        }
    }
    va_end(args);
    return bp - buf;
}
```

The pack routine uses the stdarg.h header more extensively than eprintf did in Chapter 4. The successive arguments are extracted using the macro va_arg, with first operand the variable of type va_list set up by calling va_start and second operand the type of the argument (this is why va_arg is a macro, not a function). When processing is done, va_end must be called. Although the arguments for 'c' and 's' represent char and short values, they must be extracted as ints because C promotes (提升) char and short arguments to int when they are represented by an ellipsis ... parameter.

Each pack_type routine will now be one line long, marshaling (封装处理) its arguments into a call of pack:

```
/* pack_type1: pack format 1 packet */
int pack_type1(uchar *buf, ushort count, uchar val, ulong data)
{
    return pack(buf, "cscl", 0x01, count, val, data);
}
```

To unpack, we can do the same thing: rather than write separate code to crack each packet format, we call a single unpack with a format string. This centralizes the conversion in one place:

```
/* unpack: unpack packed items from buf, return length */
int unpack(uchar *buf, char *fmt, ...)
{
    va_list args;
    char    *p;
    uchar   *bp, *pc;
    ushort  *ps;
    ulong   *pl;

    bp = buf;
    va_start(args, fmt);
    for (p = fmt; *p != '\0'; p++) {
        switch (*p) {
        case 'c':   /* char */
            pc = va_arg(args, uchar *);
            *pc = *bp++;
            break;
```

```
        case 's':   /* short */
            ps = va_arg(args, ushort *);
            *ps = *bp++ << 8;
            *ps |= *bp++;
            break;
        case 'l':   /* long */
            pl = va_arg(args, ulong *);
            *pl = *bp++ << 24;
            *pl |= *bp++ << 16;
            *pl |= *bp++ << 8;
            *pl |= *bp++;
            break;
        default:    /* illegal type character */
            va_end(args);
            return -1;
        }
    }
    va_end(args);
    return bp - buf;
}
```

Like `scanf`, `unpack` must return multiple values to its caller, so its arguments are pointers to the variables where the results are to be stored. Its function value is the number of bytes in the packet, which can be used for error checking.

Because the values are unsigned and because we stayed within the sizes that ANSI C defines for the data types, this code transfers data portably even between machines with different sizes for `short` and `long`. Provided (倘若) the program that uses `pack` does not try to send as a long (for example) a value that cannot be represented in 32 bits, the value will be received correctly. In effect, we transfer the low 32 bits of the value. If we need to send larger values, we could define another format.

The type-specific unpacking routines that call `unpack` are easy:

```
/* unpack_type2: unpack and process type 2 packet */
int unpack_type2(int n, uchar *buf)
{
    uchar   c;
    ushort  count;
    ulong   dw1, dw2;

    if (unpack(buf, "csll", &c, &count, &dw1, &dw2) != n)
        return -1;
    assert(c == 0x02);
    return process_type2(count, dw1, dw2);
}
```

To call `unpack_type2`, we must first recognize that we have a type 2 packet, which implies a receiver loop something like this:

```
while ((n = readpacket(network, buf, BUFSIZ)) > 0) {
    switch (buf[0]) {
    default:
        eprintf("bad packet type 0x%x", buf[0]);
        break;
    case 1:
        unpack_type1(n, buf);
        break;
```

```
        case 2:
            unpack_type2(n, buf);
            break:
        ...
        }
    }
```

This style of programming can get long-winded (冗长的). A more compact method is to define a table of function pointers whose entries are the unpacking routines indexed by type:

```
    int (*unpackfn[])(int, uchar *) = {
        unpack_type0,
        unpack_type1,
        unpack_type2,
    };
```

Each function in the table parses a packet, checks the result, and initiates further processing for that packet. The table makes the recipient's job straightforward:

```
    /* receive: read packets from network, process them */
    void receive(int network)
    {
        uchar   type, buf[BUFSIZ];
        int     n;

        while ((n = readpacket(network, buf, BUFSIZ)) > 0) {
            type = buf[0];
            if (type >= NELEMS(unpackfn))
                eprintf("bad packet type 0x%x", type);
            if ((*unpackfn[type](n, buf) < 0)
                eprintf("protocol error, type %x length %d",
                        type, n);
        }
    }
```

Each packet's handling code is compact, in a single place, and easy to maintain. The receiver is largely independent of the protocol itself; it's clean and fast, too.

This example is based on some real code for a commercial networking protocol. Once the author realized this approach could work, a few thousand repetitive, error-prone (容易出错的) lines of code shrunk (压缩) to a few hundred lines that are easily maintained. Notation reduced the mess enormously.

Exercise 9-1 . Modify `pack` and `unpack` to transmit signed values correctly, even between machines with different sizes for `short` and `long`. How should you modify the format strings to specify a signed data item? How can you test the code to check, for example, that it correctly transfers a `-1` from a computer with 32-bit `long`s to one with 64-bit `long`s? □

Exercise 9-2 . Extend `pack` and `unpack` to handle strings; one possibility is to include the length of the string in the format string. Extend them to handle repeated items with a count. How does this interact with the encoding of strings? □

Exercise 9-3 . The table of function pointers in the C program above is at the heart of C++'s virtual function mechanism. Rewrite `pack` and `unpack` and `receive` in C++ to take advantage of this notational convenience. □

Exercise 9-4 . Write a command-line version of `printf` that prints its second and subsequent arguments in the format given by its first argument. Some shells already provide this as a built-in. □

Exercise 9-5 . Write a function that implements the format specifications found in spreadsheet programs or in Java's `DecimalFormat` class, which display numbers according to patterns that indicate mandatory and optional digits, location of decimal points and commas, and so on. To illustrate, the format

```
##,##0.00
```

specifies a number with two decimal places, at least one digit to the left of the decimal point, a comma after the thousands digit, and blank-filling up to the ten-thousands It would represent `12345.67` as `12,345.67` and `.4` as `␣␣␣␣0.4` (using ␣ to stand for blanks). For a full specification, look at the definition of `DecimalFormat` or a spreadsheet program. □

9.2 Regular Expressions

The format specifiers (说明) for `pack` and `unpack` are a very simple notation for defining the layout of packets. Our next topic is a slightly more complicated but much more expressive notation, ***regular expressions***, which specify patterns of text. We've used regular expressions occasionally throughout the book without defining them precisely; they are familiar enough to be understood without much explanation. Although regular expressions are pervasive (无孔不入的) in the Unix programming environment, they are not as widely used in other systems, so in this section we'll demonstrate some of their power. In case you don't have a regular expression library handy, we'll also show a rudimentary (低级的) implementation.

There are several flavors (滋味) of regular expressions, but in spirit they are all the same, a way to describe patterns of literal characters, along with repetitions, alternatives, and shorthands (简写) for classes of characters like digits or letters. One familiar example is the so-called "wildcards" used in command-line processors or shells to match patterns of file names. Typically a is taken to mean "any string of characters" so, for example, a command like

```
C:\>del *.exe
```

uses a pattern that matches all files whose names consist of any string ending in `".exe"`. As in often the case, details differ from system to system, and even from program to program.

Although the vagaries (奇特行为) of different programs may suggest that regular expressions are an ad hoc (特别设的) mechanism, in fact they are a language with a formal grammar and a precise meaning for each utterance (言辞) in the language. Furthermore, the right implementation can run very fast; a combination of theory and engineering practice makes a lot of difference (造成了很多差异), an example of the benefit of specialized algorithms that we alluded (提及) to in Chapter 2.

A regular expression is a sequence of characters that defines a set of matching strings. Most characters simply match themselves, so the regular expression `abc` will match that string of letters wherever it occurs. In addition a few metacharacters indicate repetition or grouping or positioning. In conventional Unix regular expressions, `^` stands for the beginning of a string and `$` for the end, so `^x` matches an `x` only at the beginning of a string. `x$` matches an `x` only at the end, `^x$` matches `x` only if it is the sole (仅有的) character of the string, and `^$` matches the empty string.

The character "." matches any character, so `x.y` matches `xay`, `x2y` and so on, but not `xy` or `xaby`, and `^.$` matches a string with a single arbitrary character.

A set of characters inside brackets `[]` matches any one of the enclosed characters, so `[0123456789]` matches a single digit; it may be abbreviated `[0-9]`.

These building blocks are combined with parentheses for grouping, | for alternatives, `*` for zero or more occurrences, + for one or more occurrences, and `?` for zero or one occurrences. Finally, \ is used as a prefix to quote a metacharacter and turn off its special meaning; `\*` is a literal `*` and `\\` is a literal backslash.

The best-known regular expression tool is the program `grep` that we've mentioned several times. The program is a marvelous (了不起的) example of the value of notation. It applies a regular expression to each line of its input files and prints those lines that contain matching strings. This simple specification, plus the power of regular expressions, lets it solve many day-to-day (日复一日) tasks. In the following examples, note that the regular expression syntax used in the argument to `grep` is different from the wildcards used to specify a set of file names; this difference reflects the different uses.

Which source file uses class `Regexp`?

```
% grep Regexp *.java
```

Which implements it?

```
% grep 'class.*Regexp' *.java
```

Where did I save that mail from Bob?

```
grep '^From:.* bob@' mail/*
```

How many non-blank source lines are there in this program?

```
% grep '.' *.cpp | wc
```

With flags to print line numbers of matched lines, count matches, do case- insensitive matching, invert the sense (select lines that don't match the pattern), and perform other variations of the basic idea, `grep` is so widely used that it has become the classic example of tool-based programming.

Unfortunately, not every system comes with `grep` or an equivalent. Some systems include a regular expression library, usually called `regex` or `regexp`, that you can use to write a version of `grep`. If neither option is available, it's easy to implement a modest (适度的) subset of the full regular expression language. Here we present an implementation of regular expressions, and `grep` to go along with it; for simplicity, the only metacharacters are `^ $`. and `*`, with `*` specifying a repetition of the single previous period (片段) or literal character. This subset provides a large fraction of the power with a tiny fraction of the programming complexity of general expressions.

Let's start with the `match` function itself, Its job is to determine whether a text string matches a regular expression:

```
/* match: search for regexp anywhere in text */
int match(char *regexp, char *text)
{
    if (regexp[0] == '^')
        return matchhere(regexp+1, text);
    do {    /* must look even if string is empty */
        if (matchhere(regexp, text))
```

```
                return 1;
        } while (*text++ != '\0');
        return 0;
    }
```

If the regular expression begins with ^, the text must begin with a match of the remainder of the expression. Otherwise, we walk along the text, using `matchhere` to see if the text matches at any position. As soon as we find a match, we're done. Note the use of a `do-while`: expressions can match the empty string (for example, `$` matches the empty string at the end of a line and `.*` matches any number of characters, including zero), so we must call matchhere even if the text is empty.

The recursive function `matchhere` does most of the work:

```
/* matchhere: search for regexp at beginning of text */
int matchhere(char *regexp, char *text)
{
    if (regexp[0] == '\0')
        return 1;
    if (regexp[1] == '*')
        return matchstar(regexp[0], regexp+2, text);
    if (regexp[0] == '$' && regexp[1] == '\0')
        return *text == '\0';
    if (*text != '\0' && (regexp[0] == '.' || regexp[0] == *text))
        return matchhere(regexp+1, text+1);
    return 0;
}
```

If the regular expression is empty, we have reached the end and thus have found a match. If the expression ends with `$`, it matches only if the text is also at the end. If the expression begins with a period, that matches any character. Otherwise the expression begins with a plain character that matches itself in the text. A ^ or `$` that appears in the middle of a regular expression is thus taken as a literal character, not a metacharacter.

Notice that matchhere calls itself after matching one character of pattern and string, so the depth of recursion can be as much as the length of the pattern.

The one tricky case occurs when the expression begins with a starred character, for example `x*`. Then we call `matchstar`, with first argument the operand of the star (`x`) and subsequent arguments the pattern after the star and the text.

```
/* matchstar: search for c*regexp at beginning of text */
int matchstar(int c, char *regexp, char *text)
{
    do {    /* a * matches zero or more instances */
        if (matchhere(regexp, text))
            return 1;
    } while (*text != '\0' && (*text++ == c || c == '.'));
    return 0;
}
```

Here is another `do-while`, again triggered by the requirement that the regular expression `x*` can match zero characters. The loop checks whether the text matches the remaining expression, trying at each position of the text as long as the first character matches the operand of the star.

This is an admittedly (诚然地) unsophisticated implementation, but it works, and at fewer than 30 lines of code, it shows that regular expressions don't need advanced techniques to be put to use.

We'll soon present some ideas for extending the code. For now, though, let's write a version of `grep` that uses `match`. Here is the main routine:

```
/* grep main: search for regexp in files */
int main(int argc, char *argv[])
{
    int     i, nmatch;
    FILE    *f;

    setprogname("grep");
    if (argc < 2)
        eprintf("usage: grep regexp [file ...]");
    nmatch = 0;
    if (argc == 2) {
        if (grep(argv[1], stdin, NULL))
            nmatch++;
    } else {
        for (i = 2; i < argc; i++) {
            f = fopen(argv[i], "r");
            if (f == NULL) {
                weprintf("can't open %s:", argv[i]);
                continue;
            }
            if (grep(argv[1], f, argc > 3 ? argv[i] : NULL) > 0)
                nmatch++;
            fclose(f);
        }
    }
    return nmatch == 0;
}
```

It is conventional that C programs return 0 for success and non-zero values for various failures. Our `grep`, like the Unix version, defines success as finding a matching line, so it returns `0` if there were any matches, `1` if there were none, and `2` (via `eprintf`) if an error occurred. These status values can be tested by other programs like a shell.

The function `grep` scans a single file, calling `match` on each line:

```
/* grep: search for regexp in file */
int grep(char *regexp, FILE *f, char *name)
{
    int     n, nmatch;
    char    buf[BUFSIZ];

    nmatch = 0;
    while (fgets(buf, sizeof(buf), f) != NULL) {
        n = strlen(buf);
        if (n > 0 && buf[n-1] == '\n')
            buf[n-1] = '\0';
        if (match(regexp, buf)) {
            nmatch++;
            if (name != NULL)
                printf("%s: ", name);
            printf("%s\n", buf);
        }
    }
    return nmatch;
}
```

The main routine doesn't quit if it fails to open a file. This design was chose because it's common to say something like

```
% grep herpolhode *.*
```

and find that one of the files in the directory can't be read. It's better for grep to keep going after reporting the problem, rather than to give up and force the user to type the file list manually to avoid the problem file. Also, notice that grep prints the file name and the matching line, but suppresses the name if it is reading standard input or a single file. This may seem an odd (古怪的) design, but it reflects an idiomatic style of use based on experience. When given only one input, grep's task is usually selection, and the file name would clutter (弄乱) the output. But if it is asked to search through many files, the task is most often to find all occurrences of something, and the names are informative. Compare

```
% strings markov.exe | grep 'DOS mode'
```

with

```
% grep grammer chapter*.txt
```

These touches are part of what makes grep so popular, and demonstrate that notation must be packaged with human engineering to build a natural, effective tool.

Our implementation of match returns as soon as it finds a match. For grep, that is a fine default. But for implementing a substitution (search-and-replace) operator in a text editor the ***leftmost longest*** match is more suitable. For example, given the text "aaaaa" the pattern a* matches the null string at the beginning of the text, but it seems more natural to match all five a's. To cause match to find the leftmost longest string, matchstar must be rewritten to be greedy: rather than looking at each character of the text from left to right, it should skip over the longest string that matches the starred operand, then back up (倒退) if the rest of the string doesn't match the rest of the pattern. In other words, it should run from right to left. Here is a version of matchstar that does leftmost longest matching:

```
/* matchstar: leftmost longest search for c*regexp */
int matchstar(int c, char *regexp, char *text)
{
    char    *t;

    for (t = text; *t != '\0' && (*t == c || c == '.');
            t++)
        ;
    do {    /* matches zero or more */
        if (matchhere(regexp, t))
            return 1;
    } while (t-- > text);
    return 0;
}
```

It doesn't matter which match grep finds, since it is just checking for the presence of any match and printing the whole line. So since leftmost longest matching does extra work, it's not necessary for grep, but for a substitution operator, it is essential.

Our grep is competitive with system-supplied versions, regardless of the regular expression. There are pathological (错误的) expressions that can cause exponential behavior, such as a*a*a*a*a*b when given the input aaaaaaaaac, but the exponential behavior is present in some commercial implementations too. A `grep` variant available on Unix, called `egrep`, uses a more sophisticated matching algorithm that guarantees linear performance by avoiding backtracking when a partial match fails.

What about making `match` handle full regular expressions? These would include character classes like `[a-zA-Z]` to match an alphabetic character, the ability to quote a metacharacter (for example to search for a literal period), parentheses for grouping, and alternatives (`abc` or `def`). The first step is to help `match` by compiling the pattern into a representation that is easier to scan. It is expensive to parse a character class every time we compare it against a character; a pre-computed representation based on bit vectors could make character classes much more efficient. For full regular expressions, with parentheses and alternatives, the implementation must be more sophisticated, but can use some of the techniques we'll talk about later in this chapter.

Exercise 9-6 . How does the performance of `match` compare to `strstr` when searching for plain text? □

Exercise 9-7 . Write a non-recursive version of `matchhere` and compare its performance to the recursive version. □

Exercise 9-8 . Add some options to `grep`. Popular ones include `-v` to invert the sense of the `match`. `-i` to do case-insensitive matching of alphabetics, and `-n` to include line numbers in the output. How should the line numbers be printed? Should they be printed on the same line as the matching text? □

Exercise 9-9 . Add the `+` (one or more) and `?` (zero or one) operators to `match`. The pattern `a+bb?` matches one or more `a`'s followed by one or two `b`'s. □

Exercise 9-10 . The current implementation of match turns off the special meaning of `^` and `$` if they don't begin or end the expression, and of `*` if it doesn't immediately follow a literal character or a period. A more conventional design is to quote a metacharacter by preceding it with a backslash. Fix `match` to handle backslashes this way. □

Exercise 9-11 . Add character classes to `match`. Character classes specify a match for any one of the characters in the brackets. They can be made more convenient by adding ranges, for example `[a-z]` to match any lower-case letter, and inverting the sense, for example `[^0-9]` to match any character except a digit. □

Exercise 9-12 . Change `match` to use the leftmost-longest version of `matchstar`, and modify it to return the character positions of the beginning and end of the matched text. Use that to build a program `gres` that is like `grep` but prints every input line after substituting new text for text that matches the pattern, as in

```
% grep 'homoiousian' 'homoousian' mission.stmt
```

□

Exercise 9-13 . Modify `match` and `grep` to work with UTF-8 strings of Unicode characters. Because UTF-8 and Unicode are a superset of ASCII, this change is upwardly compatible. Regular expressions, as well as the searched text, will also need to work properly with UTF-8. How should character classes be implemented? □

Exercise 9-14 . Write an automatic tester for regular expressions that generates test expressions and test strings to search. If you can, use an existing library as a reference implementation; perhaps you will find bugs in it too. □

9.3 Programmable Tools

Many tools are structured around a special-purpose language. The `grep` program is just one of a family of tools that use regular expressions or other languages to solve programming problems.

One of the first examples was the command interpreter or job control language. It was realized early that common sequences of commands could be placed in a file, and an instance of the command interpreter or *shell* could be executed with that file as input. From there it was a short step to adding parameters, conditionals, loops, variables, and all the other trappings of a conventional programming language. The main difference was that there was only one data type -- strings -- and the operators in shell programs tended to be entire programs that did interesting computations. Although shell programming has fallen out of favor (失宠), often giving ground to alternatives like Perl in command environments and to pushing buttons in graphical user interfaces, it is still an effective way to build up complex operations out of simpler pieces.

Awk is another programmable tool, a small, specialized pattern-action language that focuses on selection and transformation of an input stream. As we saw in Chapter 3, Awk automatically reads input files and splits each line into fields called `$1` through `$NF`, where `NF` is the number of fields on the line. By providing default behavior for many common tasks, it makes useful one-line programs possible. For example, this complete Awk program,

```
# split.awk: split input into one word per line
{ for (i = 1; i <= NF; i++) print $i }
```

prints the "words" of each input line one word per line. To go in the other direction, here is an implementation of `fmt`, which fills each output line with words, up to at most 60 characters; a blank line causes a paragraph break.

```
# fmt.awk: format into 60-character lines
/./  { for (i = 1; i <= NF; i++) addword($i) }  # non-blank line
/^$/ { printline(); print "" }                  # blank line
END  { printline() }

function addword(w) {
    if (length(line) + 1 + length(w) > 60)
        printline()
    if (length(line) == 0)
        line = w
    else
        line = line " " w
}

function printline() {
    if (length(line) > 0) {
        print line
        line = ""
    }
}
```

We often use `fmt` to re-paragraph mail messages and other short documents; we also use it to format the output of Chapter 3's Markov programs.

Programmable tools often originate in little language designed for natural expression of solutions to problems within a narrow domain. One nice example is the Unix tool `eqn`, which typesets (排版) mathematical formulas. Its input language is close to what a mathematician might say when reading equations aloud: $\frac{\pi}{2}$ is written `pi over 2`. TEX follows the same approach; its notation for this formula is `\pi \over 2`. If there is a natural or familiar notation for the problem you're solving, use it or adapt it; don't start from scratch.

Awk was inspired by a program that used regular expressions to identify anomalous (不规则的) data in telephone traffic records, but Awk includes variables, expressions, loops, and so on, to make it a real programming language. Perl and Tcl were designed from the beginning to combine the convenience and expressiveness of little languages with the power of big ones. They are true general-purpose languages, although they are most often used for processing text.

The generic term for such tools is ***scripting languages*** because they evolved from early command interpreters whose programmability was limited to executing canned (罐装) "scripts" of programs. Scripting languages permit creative use of regular expressions, not only for pattern matching -- recognizing that a particular pattern occurs -- but also for identifying regions of text to be transformed. This occurs in the two `regsub` (regular expression substitution) commands in the following Tcl program[1]. The program is a slight generalization of the program we showed in Chapter 4 that retrieves stock quotes; this one fetches the URL given by its first argument. The first substitution removes the string `http://` if it is present; the second replaces the first `/` by a blank, thereby splitting the argument into two fields. The `lindex` command retrieves fields from a string (starting with index 0). Text enclosed in `[]` is executed as a Tcl command and replaced by the resulting text; `$x` is replaced by the value of the variable `x`.

```
# geturl.tcl: retrieve document from URL
# input has form [http://labc.def.com[/whatever...]]
regsub "http://" $argv "" argv  ;# remove http:// if present
regsub "/" $argv " " argv       ;# replace leading / with blank
set so [socket [lindex $argv 0] 80];    ;# make network connection
set q "/[lindex $argv 1]

puts $so "GET $q HTTP/1.0\r\n"; ;# send request
flush $so
while {[gets Bso line] >= 0 && $line != ""} {} ;# skip header
puts [read $so]                 ;# read and print entire reply
```

This script typically produces voluminous output, much of which is HTML tags bracketed by < and >. Perl is good at text substitution, so our next tool is a Perl script[2] that uses regular expressions and substitutions to discard the tags:

```
# unhtml.pl: delete HTML tags
while (<>) {            # collect all input into single string
    $str .= $_;         # by concatenation input lines
}
$str =~ s/<[^>]*//g;    # delete <...>
$str =~ s/ / /g;   # replace   by blank
$str =~ s/\s+/\n/g;     # compress white space
print $str;
```

[1]Contains some errors, maybe, untested.
[2]Contains some errors, maybe, untested.

This example is cryptic if one does not speak Perl. The construction

```
$str =~ s/regexp/repl/g
```

substitutes the string `repl` for the text in `str` that matches (leftmost longest) the regular expression `regexp`; the trailing `g`, for "global," means to do so for all matches in the string rather than just the first. The metacharacter sequence `\s` is shorthand for a white space character (blank, tab, newline, and the like); `\n` is a newline. The string `" "` is an HTML character, like those in Chapter 2, that defines a non-breakable space character.

Putting all this together, here is a moronic (迟钝的) but functional web browser, implemented as a one-line shell script:

```
# web: retrieve web page and format its text, ignoring HTML
geturl.tcl $1 | unhtml.pl | fmt.awk
```

This retrieves the web page, discards all the control and formatting information, and formats the text by its own rules. It's a fast way to grab a page of text from the web.

Notice the variety of languages we cascade together, each suited to a particular task: Tcl, Perl, Awk and, within each of those, regular expressions. The power of notation comes from having a good one for each problem. Tcl is particularly good for grabbing text over the network; Perl and Awk are good at editing and formatting text; and of course regular expressions are good at specifying pieces of text for searching and modifying. These languages together are more powerful than any one of them in isolation. It's worth breaking the job into pieces if it enables you to profit from the right notation.

9.4 Interpreters, Compilers, and Virtual Machines

How does a program get from its source-code form into execution? If the language is simple enough, as in `printf` or our simplest regular expressions, we can execute straight from the source. This is easy and has very fast startup.

There is a tradeoff between setup time and execution speed. If the language is more complicated, it is generally desirable to convert the source code into a convenient and efficient internal representation for execution. It takes some time to process the source originally but this is repaid in faster execution. Programs that combine the conversion and execution into a single program that reads the source text, converts it, and runs it are called interpreters. Awk and Perl interpret, as do many other scripting and special-purpose languages.

A third possibility is to generate instructions for the specific kind of computer the program is meant to run on, as compilers do. This requires the most up-front (前期) effort and time but yields the fastest subsequent execution.

Other combinations exist. One that we will study in this section is compiling a program into instructions for a made-up computer (a ***virtual machine***) that can be simulated on any real computer. A virtual machine combines many of the advantages of conventional interpretation and compilation.

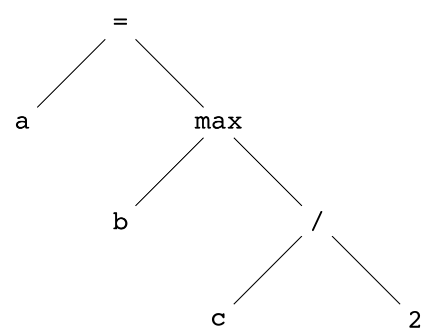
If a language is simple, it doesn't take much processing to infer (推论) the program structure and convert it to an internal form. If, however, the language has some complexity-declarations, nested structures, recursively-defined statements or expressions, operators with precedence, and the like -- it is more complicated to parse the input to determine the structure.

Parsers are often written with the aid of an automatic parser generator, also called a compiler-compiler, such as `yacc` or `bison`. Such programs translate a description of the language, called its ***grammar***, into (typically) a C or C++ program that, once compiled, will translate statements in the language into an internal representation. Of course, generating a parser directly from a grammar is another demonstration of the power of good notation.

The representation produced by a parser is usually a tree, with internal nodes containing operators and leaves containing operands. A statement such as

```
a = max(b, c/2);
```

might produce this parse (or syntax) tree:



Many of the tree algorithms described in Chapter 2 can be used to build and process parse trees.

Once the tree is built, there are a variety of ways to proceed. The most direct, used in Awk, is to walk the tree directly, evaluating the nodes as we go. A simplified version of such an evaluation routine for an integer-based expression language might involve a post-order traversal like this:

```
typedef struct Symbol Symbol;
typedef struct Tree Tree;

struct Symbol {
    int     value;
    char    *name;
};
struct Tree {
    int     op;          /* operation code */
    int     value;       /* value if number */
    Symbol  *symbol;     /* Symbol entry if variable */
    Tree    *left;
    Tree    *right;
};

/* eval: version 1: evaluate tree expression */
int eval(Tree *t)
{
    int left, right;

    switch (t->op) {
    case NUMBER:
        return t->value;
    case VARIABLE:
        return t->symbol->value;
    case ADD:
```

```
            return eval(t->left) + eval(t->right);
        case DIVIDE:
            left = eval(t->left);
            right = eval(t->right);
            if (right == 0)
                eprintf("divide %d by zero", left);
            return left / right;
        case MAX:
            left = eval(t->left);
            right = eval(t->right);
            return left > right ? left : right;
        case ASSIGN:
            t->left->symbol->value = eval(t->right);
            return t->left->symbol->value;
        /* ... */
        }
    }
```

The first few cases evaluate simple expressions like constants and values; later ones evaluate arithmetic expressions, and others might do special processing, conditionals, and loops. To implement control structures, the tree will need extra information, not shown here, that represents the control flow.

As in `pack` and `unpack`, we can replace the explicit `switch` with a table of function pointers. Individual operators are much the same as in the `switch` statement:

```
/* addop: return sum of two tree expressiions */
int addop(Tree *t)
{
    return eval(t->left) + eval(t->right);
}
```

The table of function pointers relates operators to the functions that perform the operations:

```
enum {  /* operation codes, Tree.op */
    NUMBER,
    VARIABLE,
    ADD,
    DIVIDE,
    /* ... */
}

/* optab: operator function table */
int (*optab[])(Tree *) = {
    pushop,     /* NUMBER */
    pushsymop,  /* VARIABLE */
    addop,      /* ADD */
    divop,      /* DIVIDE */
    /* ... */
}
```

Evaluation uses the operator to index into the table of function pointers to call the right functions; this version will invoke other functions recursively.

```
/* eval: version 2, evaluate tree from operator table */
int eval(Tree *t)
{
    return (*optab[t->op])(t);
}
```

Both these versions of eval are recursive. There are ways of eliminating recursion, including a clever technique called ***threaded*** code that flattens the call stack completely. The neatest method is to do away with the recursion altogether by storing the functions in an array that is then traversed sequentially to execute the program. This array becomes a sequence of instructions to be executed by a little special-purpose machine.

We still need a stack to represent the partially evaluated values in the computation, so the form of the functions changes, but the transformation is easy to see. In effect, we invent a ***stack machine*** in which the instructions are tiny functions and the operands are stored on a separate operand stack. It's not a real machine but we can program it as if it were, and we can implement it easily as an interpreter.

Instead of walking the tree to evaluate it, we walk it to generate the array of functions to execute the program. The array will also contain data values that the instructions use, such as constants and variables (symbols), so the type of the elements of the array should be a union:

```
typedef union Code Code;
union Code {
    void    (*op)(void);    /* function if operator */
    int     value;          /* value if number */
    Symbol  *symbol;        /* Symbol entry if variable */
};
```

Here is the routine to generate the function pointers and place them in an array, code, of these items. The return value of generate is not the value of the expression -- that will be computed when the generated code is executed -- but the index in code of the next operation to be generated:

```
/* generate: generate instructions by walking tree */
int generate(int codep, Tree *t)
{
    switch (t->op) {
    case NUMBER:
        code[codep++].op = pushop;
        code[codep++].value = t->value;
        return codep;
    case VARIABLE:
        code[codep++].op = pushsymop;
        code[codep++].symbol = t->symbol;
        return codep;
    case ADD:
        codep = generate(codep, t->left);
        codep = generate(codep, t->right);
        code[code++].op = addop;
        return codep;
    case DIVIDE:
        codep = generate(codep, t->left);
        codep = generate(codep, t->right);
        code[codep++].op = divop;
        return codep;
    case MAX:
        /* ... */
    }
}
```

For the statement a = max(b, c/2) the generated code would look like this:

```
pushsymop
```

```
b
pushsymop
c
pushop
2
divop
maxop
storesymop
a
```

The operator functions manipulate the stack, popping oprands and pushing results.

The interpreter is a loop that walks a program counter along the array of function pointer:

```
Code code[NCODE];
int stack[NSTACK];
int stackp;
int pc; /* program counter */

/* eval: version 3, evaluate expression from generated code */
int eval(Tree *t)
{
    pc = generate(0, t);
    code[pc].op = NULL;

    stackp = 0;
    pc = 0;
    while (code[pc].op != NULL)
        (*code[pc++].op)();
    return stack[0];
}
```

This loop simulates in software on our invented stack machine what happens in hardware on a real machine. Here are a couple of representative operators:

```
/* pushop: push number, value is next word in code stream */
void pushop(void)
{
    stack[stack++] = code[pc++].value;
}

/* divop: compute ration of two expressions */
void divop(void)
{
    int left, right;

    right = stack[--stackp];
    left = stack[--stackp];
    if (right == 0)
        eprintf("divide %d by zero\n", left);
    stack[stackp++] = left / right;
}
```

Notice that the check for zero divisors appears in `divop`, not `generate`.

Conditional execution, branches, and loops operate by modifying the program counter within an operator function, performing a branch to a different point in the array of functions. For example a `goto` operator always sets the value of the `pc` variable, while a conditional branch sets `pc` only if the condition is true.

The code array is internal to the interpreter, of course, but imagine we wanted to save the generated program in a file. If we wrote out the function addresses, the result would be unportable and fragile. But we could instead write out constants that represented the functions, say `1000` for `addop`. `1001` for `pushop`, and so on, and translate these back into the function pointers when we read the program in for interpretation.

If we examine a file this procedure produces, it looks like an instruction stream for a virtual machine whose instructions implement the basic operators of our little language, and the generate function is really a compiler that translates the language into the virtual machine. Virtual machines are a lovely old idea, recently made fashionable again by Java and the Java Virtual Machine (JVM); they give an easy way to produce portable, efficient representations of programs written in a high-level language.

9.5 Programs that Write Programs

Perhaps the most remarkable thing about the generate function is that it is a program that writes a program: its output is an executable instruction stream for another (virtual) machine. Compilers do this all the time, translating source code into machine instructions, so the idea is certainly familiar. In fact, programs that write programs appear in many forms.

One common example is the dynamic generation of HTML for web pages. HTML is a language, however limited, and it can contain JavaScript code as well. Web pages are often generated on the fly by Perl or C programs, with specific contents (for example, search results and targeted advertising) determined by incoming requests. We used specialized languages for the graphs, pictures, tables, mathematical expressions, and index in this book. As another example, PostScript is a programming language that is generated by word processors, drawing programs, and a variety of other sources; at the final stage of processing, this whole book is represented as a 57,000 line Postscript program.

A document is a static program, but the idea of using a programming language as notation for any problem domain is extremely powerful. Many years ago, programmers dreamt of having computers write all their programs for them. That will probably never be more than a dream, but today computers routinely (例行性的) write programs for us, often to represent things we would not previously have considered programs at all.

The most common program-writing program is a compiler that translates high- level language into machine code. It's often useful, though, to translate code into a mainstream programming language. In the previous section, we mentioned that parser generators convert a definition of a language's grammar into a C program that parses the language. C is often used in this way, as a kind of "high level assembly language." Modula-3 and C++ are among the general-purpose languages whose first compilers created C code, which was then compiled by a standard C compiler. The approach has several advantages, including efficiency -- because programs can in principle run as fast as C programs -- and portability -- because compilers can be carried to any system that has a C compiler. This greatly helped the early spread of these languages.

As another example, Visual Basic's graphical interface generates a set of Visual Basic assignment statements to initialize objects that the user has selected from menus and positioned on the screen with a mouse. A variety of other languages have "visual" development systems and "wizards" (魔力) that synthesize user-interface code out of mouse clicks.

In spite of the power of program generators, and in spite of the existence of many good examples, the notion (概念) is not appreciated as much as it should be and is infrequently used by individual programmers. But there are plenty of small-scale opportunities for creating code by a program, so that you can get some of the advantages for yourself. Here are several examples that generate C or C++ code.

The Plan 9 operating system generates error messages from a header file that contains names and comments; the comments are converted mechanically into quoted strings in an array that can be indexed by the enumerated value. This fragment shows the structure of the header file:

```
/* errors.h: standard error message */
enum {
    Eperm,      /* Permission denied */
    Eio,        /* I/O error */
    Efile,      /* File does not exist */
    Emem,       /* Memory limit reached */
    Espace,     /* Out of file space */
    Egrep,      /* It's all Greg's fault */
};
```

Given this input, a simple program can produce the following set of declarations for the error messages:

```
/* machine generated; do not edit. */
char *errs[] = {
    "Permission denied", /* Eperm */
    "I/O error", /* Eio */
    "File does not exist", /* Efile */
    "Memory limit reached", /* Espace */
    "Out of file space", /* Espace */
    "It's all Greg's fault", /* Egrep */
};
```

There are a couple of benefits to this approach. First, the relationship between the `enum` values and the strings they represent is literally self-documenting and easy to make natural-language independent. Also, the information appears only once, a "single point of truth" (单点真相) from which other code is generated, so there is only one place to keep information up to date. If instead there are multiple places, it is inevitable that they will get out of sync sometime. Finally, it's easy to arrange that the `.c` file will be recreated and recompiled whenever the header file is changed. When an error message must be changed, all that is needed is to modify the header file and compile the operating system. The messages are automatically updated.

The generator program can be written in any language. A string processing language like Perl makes it easy:

```
# enum.pl: generate error strings from enum+comments

print "/* machine generated; do not edit. */\n\n";
print "char *errs[] = {\n";
while (<>) {
    chop;                       # remove new line
    if (/^\s*(E[a-z0-9]+),?/) { # first word is E...
        $name = $1;             # save name
        s/.*\/\* *//;           # remove up to /*
        s/ *\*\///;             # remove */
        print "\t\"$_\",/* $name */\n";
    }
```

```
    }
    print "};\n";
```

Regular expressions are in action again. Lines whose first fields look like identifiers followed by a comma are selected. The first substitution deletes everything up to the first non-blank character of the comment, while the second removes the comment terminator and any blanks that precede it.

As part of a compiler-testing effort, Andy Koenig developed a convenient way to write C++ code to check that the compiler caught program errors. Code fragments that should cause a compiler diagnostic are decorated with magic comments to describe the expected messages. Each line has a comment that begins with `///` (to distinguish it from ordinary comments) and a regular expression that matches the diagnostics from that line. Thus, for example, the following two code fragments should generate diagnostics:

```
int f() {}
    /// warning.* non-void function .* should return a value

void g() { return 1; }
    /// error.* void function may not return a value
```

If we run the second test through our C++ compiler, it prints the expected message, which matches the regular expression:

Each such code fragment is given to the compiler, and the output is compared against the expected diagnostics, a process that is managed by a combination of shell and Awk programs. Failures indicate a test where the compiler output differed from what was expected. Because the comments are regular expressions there is some latitude (余地) in the output; they can be made more or less forgiving, depending on what is needed.

The idea of comments with semantics is not new. They appear in Postscript, where regular comments begin with `%`. Comments that begin with `%%` by convention may carry extra information about page numbers, bounding boxes, font names, and the like:

```
%%PageBoundingBox: 126 307 492 768
%%Pages:14
%%DocumentFonts: Helvetica Times-Italic Times-Roman
            LucidaSans-Typewriter
```

In Java, comments that begin with `/**` and end with `*/` are used to create documentation for the class definition that follows. The large-scale version of self-documenting code is ***literate programming***, which integrates a program and its documentation so one process prints it in a natural order for reading, and another arranges it in the right order for compilation.

In all of the examples above, it is important to observe the role of notation, the mixture of languages, and the use of tools. The combination magnifies the power of the individual components.

Exercise 9-15 . One of the old chestnuts (老办法) of computing is to write a program that when executed will reproduce itself exactly, in source form. This is a neat (灵巧的) special case of a program that writes a program. Give it a try in some of your favorite languages. □

9.6 Using Macros to Generate Code

Descending a couple of levels, it's possible to have macros write code at compile time. Throughout this book, we've cautioned against using macros and conditional compilation; they encourage a style of programming that is full of problems. But they do have their place; sometimes textual substitution is exactly the right answer to a problem. One example is using the C/C++ macro preprocessor to assemble pieces of a stylized (程式化的), repetitive program.

For instance, the program that estimated the speed of elementary language constructs for Chapter 7 uses the C preprocessor to assemble the tests by wrapping them in boilerplate (样板) code. The essence of the test is to encapsulate a code fragment in a loop that starts a timer, runs the fragment many times, stops the timer, and reports the results. All of the repeated code is captured in a couple of macros, and the code to be timed is passed in as an argument. The primary macro takes this form:

```
#define LOOP(CODE) {                    \
    t0 = clock();                       \
    for (i = 0; i < n; i++) { CODE; }   \
    printf("%7d ", clock() - t0);       \
}
```

The backslashes allow the macro body to span multiple lines. This macro is used in "statements" that typically look like this:

```
LOOP(f1 = f2)
LOOP(f1 = f2 + f3)
LOOP(f1 = f2 - f3)
```

There are sometimes other statements for initialization, but the basic timing part is represented in these single-argument fragments that expand to a significant amount of code.

Macro processing can be used to generate production code, too. Bart Locanthi once wrote an efficient version of a two-dimensional graphics operator. The operator, called `bitblt` or `rasterop`, is hard to make fast because there are many arguments that combine in complicated ways. Through careful case analysis, Locanthi reduced the combinations to individual loops that could be separately optimized. Each case was then constructed by macro substitution, analogous to the performance-testing example, with all the variants laid out in a single big switch statement. The original source code was a few hundred lines; the result of macro processing was several thousand. The macro-expanded code was not optimal but, considering the difficulty of the problem, it was practical and very easy to produce. Also, as high-performance code goes, it was relatively portable.

Exercise 9-16 . Exercise 7-7 involved writing a program to measure the cost of various operations in C++. Use the ideas of this section to create another version of the program. □

Exercise 9-17 . Exercise 7-8 involved doing a cost model for Java, which has no macro capability. Solve the problem by writing another program, in whatever language (or languages) you choose, that writes the Java version and automates the timing runs. □

9.7 Compiling on the Fly

In the previous section, we talked about programs that write programs. In each of the examples, the generated program was in source form; it still needed to be compiled or interpreted to run. But it is possible to generate code that is ready to run immediately by producing machine instructions rather than source. This is known as compiling "on the fly" or "just in time"; the first term is older but the latter. including its acronym (缩写), JIT, is more popular.

Although compiled code is necessarily non-portable -- it will run only on a single type of processor -- it can be extremely fast. Consider the expression

```
max(b, c/2)
```

The calculation must evaluate `c`, divide it by two, compare the result to `b`, and choose the larger. If we evaluate the expression using the virtual machine we sketched (描绘) earlier in the chapter, we could eliminate the check for division by zero in `divop`. Since `2` is never zero, the check is pointless. But given any of the designs we laid out for implementing the virtual machine, there is no way to eliminate the check; every implementation of the divide operation compares the divisor to zero.

This is where generating code dynamically can help. If we build the code for the expression directly, rather than just by stringing out predefined operations, we can avoid the zero-divide check for divisors that are known to be non-zero. In fact, we can go even further; if the entire expression is constant. such as `max(3*3, 4/2)`, we can evaluate it once when we generate the code, and replace it by the constant value `9`. If the expression appears in a loop, we save time each trip around the loop, and if the loop runs enough times, we will win back the overhead it took to study the expression and generate code for it.

The key idea is that the notation gives us a general way to express a problem, but the compiler for the notation can customize the code for the details of the specific calculation. For example, in a virtual machine for regular expressions, we would likely have an operator to match a `literal` character:

```
int matchchar(int literal, char *text)
{
    return *text == literal;
}
```

When we generate code for a particular pattern, however, the value of a given `literal` is fixed, say `'x'`, so we could instead use an operator like this:

```
int matchx(char *text)
{
    return *text == 'x';
}
```

And then, rather than predefining a special operator for each literal character value, we make things simpler by generating the code for the operators we really need for the current expression. Generalizing the idea for the full set of operations, we can write an on-the-fly compiler that translates the current regular expression into special code optimized for that expression.

Ken Thompson did exactly this for an implementation of regular expressions on the IBM 7094 in 1967. His version generated little blocks of binary 7094 instructions for the various operations in the expression, threaded them together, and then ran the resulting program by calling it, just like a regular function. Similar techniques can be applied to creating specific instruction sequences for screen updates in graphics systems, where there are so many special cases that it is more efficient to create dynamic code for each one that arises than to write them all out ahead of time or to include conditional tests in more general code.

To demonstrate what is involved in building a real on-the-fly compiler would take us much too far into the details of a particular instruction set, but it is worth spending some time to show how such a system works. The rest of this section should be read for ideas and insight but not for implementation details.

Recall that we left our virtual machine with a structure like this:

```
Code code[NCODE];
int stack[NSTACK];
int stackp;
int pc; /* program counter */

    ...
    Tree    *t;
    pc = generate(0,t );
    code[pc].op = NULL;

    stackp = 0;
    pc = 0;
    while (code[pc].op != NULL)
        (*code[pc++].op)();
    return stack[0];
```

To adapt this code to on-the-fly compilation, we must make some changes. First, the code array is no longer an array of function pointers, but an array of executable instructions. Whether the instructions will be of type `char`, `int`, or `long` will depend on the processor we're compiling for; we'll assume `int`. After the code is generated, we call it as a function. There will be no virtual program counter because the processor's own execution cycle will walk along the code for us; once the calculation is done, it will return, like a regular function. Also, we can choose to maintain a separate operand stack for the machine or use the processor's own stack. Each approach has advantages, but we've chosen to stick with a separate stack and concentrate on the details of the code itself. The implementation now looks like this:

```
typedef int Code;
Code    code[NCODE];
int codep;
int stack[NSTACK];
int stackp;
    ...
    Tree *t;
    void (*fn)(void);
    int pc;

    t = parse();
    pc = generate(0, t);
    genreturn(pc);      /* generate function return sequence */
    stackp = 0;
    flushcaches();      /* synchronize memory with processor */
    fn = (void (*)(void))code;  /* cast array to ptr to func */
    (*fn)();
    return stack[0];
```

After generate finishes, `genreturn` lays down (制定) the instructions that make the generated code return control to `eval`.

The function `flushcaches` stands for the steps needed to prepare the processor for running freshly generated code. Modern machines run fast in part because they have caches for instructions and data, and internal pipelines that overlap the execution of many successive instructions. These caches and pipelines expect the instruction stream to be static; if we generate code just before execution, the processor can become confused. The CPU needs to drain (排空) its pipeline and flush its caches before it can execute newly generated instructions. These are highly machine-dependent operations; the implementation of `flushcaches` will be different on each particular type of computer.

The remarkable expression `(void(*)(void))` code is a cast that converts the address of the array containing the generated instructions into a function pointer that can be used to call the code as a function.

Technically, it's not too hard to generate the code itself, though there is a fair amount of engineering to do so efficiently. We start with some building blocks. As before, a code array and an index into it are maintained during compilation. For simplicity, we'll make them both global, as we did earlier. Then we can write a function to lay down instructions:

```
/* emit (发射): append instruction to code stream */
void emit(Code inst)
{
    code[codep++] = inst;
}
```

The instructions themselves can be defined by processor-dependent macros or tiny functions that assemble the instructions by filling in the fields of the instruction word. Hypothetically (假设), we might have a function called `popreg` that generates code to pop a value off the stack and store it in a processor register, and another called `pushreg` that generates code to take the value stored in a register and push it onto the stack. Our revised (修订的) `addap` function would use them like this, given some defined constants that describe the instructions (like `ADDINST`) and their layout (the various (各自的) `SHIFT` positions that define the format):

```
/* addop: generate ADD instruction */
void addop(void)
{
    Code    inst;

    popreg(2);      /* pop stack into register 2 */
    popreg(1);      /* pop stack into register 1 */
    inst = ADDINST << INTSHIFT;
    inst |= (R1) << OP1SHIFT;
    inst |= (R2) << OP2SHIFT;
    emit(inst);     /* emit ADD R1, R2 */
    pushreg(2);     /* push val of register 2 onto stack */
}
```

This is only a starting point. If we were writing an on-the-fly compiler for real, we would employ optimizations. If we're adding a constant, we don't need to push the constant on the stack, pop it off, and add it; we can just add it directly. Similar thinking can eliminate more of the overhead. Even as written, however, `addop` will run much faster than the versions we wrote earlier because the various operators are not threaded together (穿在一起) by function calls. Instead, the code to execute them is laid out in memory as a single block of instructions, with the real processor's program counter doing all the threading (穿线) for us.

The `generate` function looks pretty much as it did for the virtual machine implementation. But this time, it lays out real machine instructions instead of pointers to predefined functions. And to generate efficient code, it should spend some effort looking for constants to eliminate and other optimizations.

Our whirlwind (旋风) tour of code generation has shown only glimpses (一瞥) of some of the techniques used by real compilers and entirely missed many more. It has also sidestepped (回避) many of the issues raised (带来) by the complexities of modern CPUs. But it does illustrate how a program can analyze the description of a problem to produce special purpose code for solving it efficiently. You can use these ideas to write a blazing (强烈的) fast version of `grep`, to implement a little language of your own devising (发明),

to design and build a virtual machine optimized for special-purpose calculation, or even, with a little help, to write a compiler for an interesting language.

A regular expression is a long way from a C++ program, but both are just notations for solving problems. With the right notation, many problems become easier. And designing and implementing the notation can be a lot of fun.

✎ **Exercise 9-18** . The on-the-fly compiler generates faster code if it can replace expressions that contain only constants, such as `max(3*3, 4/2)`, by their value. Once it has recognized such an expression, how should it compute its value? □

✎ **Exercise 9-19** . How would you test an on-the-fly compiler? □

Supplementary Reading

The Unix Programming Environment, by Brian Kemighan and Rob Pike (Prentice Hall, 1984), contains an extended discussion of the tool-based approach to computing that Unix supports so well. Chapter 8 of that book presents a complete implementation, from `yacc` grammar to executable code, of a simple programming language.

TEX: The Program, by Don Knuth (Addison-Wesley, 1986), describes a complex document formatter by presenting the entire program, about 13,000 lines of Pascal, in a "literate programming" style that combines explanation with program text and uses programs to format documentation and extract compilable code. *A Retargetable C Compiler: Design and Implementation* by Chris Fraser and David Hanson (Addison-Wesley, 1995) does the same for an ANSI C compiler.

The Java virtual machine is described in *The Java Virtual Machine Specification, 2nd Edition*, by Tim Lindholm and Frank Yellin (Addison-Wesley, 1999).

Ken Thompson's algorithm (one of the earliest software patents(专利)) was described in "Regular Expression Search Algorithm," *Communications of the ACM*, 11, 6, pp. 419-422, 1968. Jeffrey E. F. Friedl's *Mastering Regular Expressions* (O'Reilly, 1997) is an extensive treatment of the subject.

An on-the-fly compiler for two-dimensional graphics operations is described in "HardwareISoftware Tradeoffs for Bitmap Graphics on the Blit," by Rob Pike, Bart Locanthi, and John Reiser, *Software--Practice and Experience*, 15, 2, pp. 131-152, February 1985.