

A *computer system* consists of hardware and systems software that work together to run application programs. Specific implementations of systems change over time, but the underlying concepts do not. All computer systems have similar hardware and software components that perform similar functions. This book is written for programmers who want to get better at their craft by understanding how these components work and how they affect the correctness and performance of their programs.

You are poised for an exciting journey. If you dedicate yourself to learning the concepts in this book, then you will be on your way to becoming a rare “power programmer,” enlightened by an understanding of the underlying computer system and its impact on your application programs.

You are going to learn practical skills such as how to avoid strange numerical errors caused by the way that computers represent numbers. You will learn how to optimize your C code by using clever tricks that exploit the designs of modern processors and memory systems. You will learn how the compiler implements procedure calls and how to use this knowledge to avoid the security holes from buffer overflow vulnerabilities that plague network and Internet software. You will learn how to recognize and avoid the nasty errors during linking that confound the average programmer. You will learn how to write your own Unix shell, your own dynamic storage allocation package, and even your own Web server. You will learn the promises and pitfalls of concurrency, a topic of increasing importance as multiple processor cores are integrated onto single chips.

In their classic text on the C programming language [61], Kernighan and Ritchie introduce readers to C using the `hello` program shown in Figure 1.1. Although `hello` is a very simple program, every major part of the system must work in concert in order for it to run to completion. In a sense, the goal of this book is to help you understand what happens and why when you run `hello` on your system.

We begin our study of systems by tracing the lifetime of the `hello` program, from the time it is created by a programmer, until it runs on a system, prints its simple message, and terminates. As we follow the lifetime of the program, we will briefly introduce the key concepts, terminology, and components that come into play. Later chapters will expand on these ideas.

```
1  #include <stdio.h>
2
3  int main()
4  {
5      printf("hello, world\n");
6      return 0;
7  }
```

code/intro/hello.c

code/intro/hello.c

Figure 1.1 The `hello` program. (Source: [60])

#	i	n	c	l	u	d	e	SP	<	s	t	d	i	o	.
35	105	110	99	108	117	100	101	32	60	115	116	100	105	111	46
h	>	\n	\n	i	n	t	SP	m	a	i	n	()	\n	{
104	62	10	10	105	110	116	32	109	97	105	110	40	41	10	123
\n	SP	SP	SP	SP	p	r	i	n	t	f	("	h	e	l
10	32	32	32	32	112	114	105	110	116	102	40	34	104	101	108
l	o	,	SP	w	o	r	l	d	\	n	")	;	\n	SP
108	111	44	32	119	111	114	108	100	92	110	34	41	59	10	32
SP	SP	SP	r	e	t	u	r	n	SP	0	;	\n	}	\n	
32	32	32	114	101	116	117	114	110	32	48	59	10	125	10	

Figure 1.2 The ASCII text representation of `hello.c`.

1.1 Information Is Bits + Context

Our `hello` program begins life as a *source program* (or *source file*) that the programmer creates with an editor and saves in a text file called `hello.c`. The source program is a sequence of bits, each with a value of 0 or 1, organized in 8-bit chunks called *bytes*. Each byte represents some text character in the program.

Most computer systems represent text characters using the ASCII standard that represents each character with a unique byte-size integer value.¹ For example, Figure 1.2 shows the ASCII representation of the `hello.c` program.

The `hello.c` program is stored in a file as a sequence of bytes. Each byte has an integer value that corresponds to some character. For example, the first byte has the integer value 35, which corresponds to the character ‘#’. The second byte has the integer value 105, which corresponds to the character ‘i’, and so on. Notice that each text line is terminated by the invisible *newline* character ‘\n’, which is represented by the integer value 10. Files such as `hello.c` that consist exclusively of ASCII characters are known as *text files*. All other files are known as *binary files*.

The representation of `hello.c` illustrates a fundamental idea: All information in a system—including disk files, programs stored in memory, user data stored in memory, and data transferred across a network—is represented as a bunch of bits. The only thing that distinguishes different data objects is the context in which we view them. For example, in different contexts, the same sequence of bytes might represent an integer, floating-point number, character string, or machine instruction.

As programmers, we need to understand machine representations of numbers because they are not the same as integers and real numbers. They are finite

1. Other encoding methods are used to represent text in non-English languages. See the aside on page 86 for a discussion on this.

Aside Origins of the C programming language

C was developed from 1969 to 1973 by Dennis Ritchie of Bell Laboratories. The American National Standards Institute (ANSI) ratified the ANSI C standard in 1989, and this standardization later became the responsibility of the International Standards Organization (ISO). The standards define the C language and a set of library functions known as the *C standard library*. Kernighan and Ritchie describe ANSI C in their classic book, which is known affectionately as “K&R” [61]. In Ritchie’s words [92], C is “quirky, flawed, and an enormous success.” So why the success?

- *C was closely tied with the Unix operating system.* C was developed from the beginning as the system programming language for Unix. Most of the Unix kernel (the core part of the operating system), and all of its supporting tools and libraries, were written in C. As Unix became popular in universities in the late 1970s and early 1980s, many people were exposed to C and found that they liked it. Since Unix was written almost entirely in C, it could be easily ported to new machines, which created an even wider audience for both C and Unix.
- *C is a small, simple language.* The design was controlled by a single person, rather than a committee, and the result was a clean, consistent design with little baggage. The K&R book describes the complete language and standard library, with numerous examples and exercises, in only 261 pages. The simplicity of C made it relatively easy to learn and to port to different computers.
- *C was designed for a practical purpose.* C was designed to implement the Unix operating system. Later, other people found that they could write the programs they wanted, without the language getting in the way.

C is the language of choice for system-level programming, and there is a huge installed base of application-level programs as well. However, it is not perfect for all programmers and all situations. C pointers are a common source of confusion and programming errors. C also lacks explicit support for useful abstractions such as classes, objects, and exceptions. Newer languages such as C++ and Java address these issues for application-level programs.

approximations that can behave in unexpected ways. This fundamental idea is explored in detail in Chapter 2.

1.2 Programs Are Translated by Other Programs into Different Forms

The `hello` program begins life as a high-level C program because it can be read and understood by human beings in that form. However, in order to run `hello.c` on the system, the individual C statements must be translated by other programs into a sequence of low-level *machine-language* instructions. These instructions are then packaged in a form called an *executable object program* and stored as a binary disk file. Object programs are also referred to as *executable object files*.

On a Unix system, the translation from source file to object file is performed by a *compiler driver*: