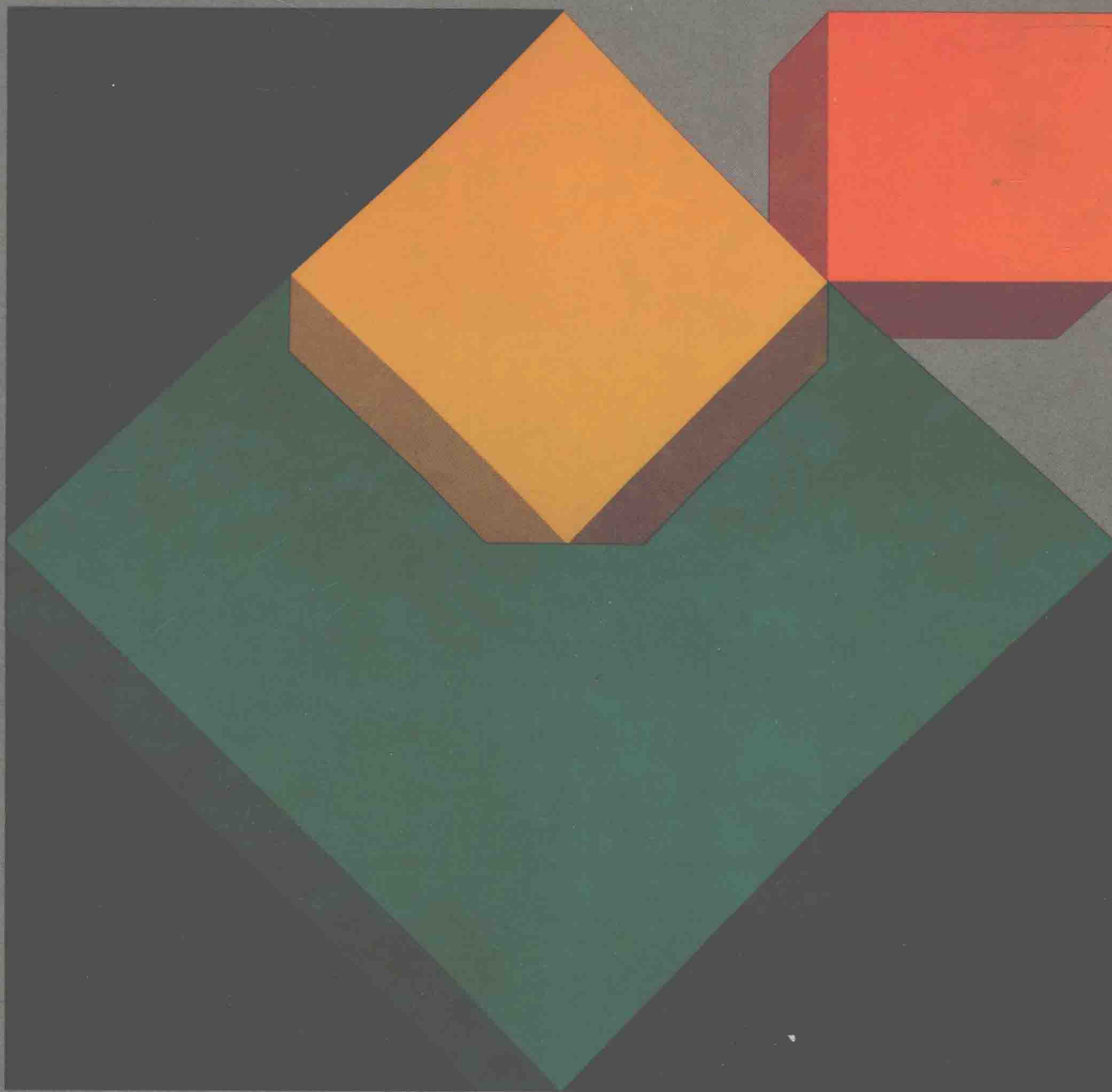
Daniel D. McCracken

A SECOND COURSE IN COMPUTER SCIENCE WITH PASCAL



A SECOND COURSE IN COMPUTER SCIENCE WITH PASCAL

Daniel D. McCracken
City College of New York

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To Ruth, Harvey, David, Horace,
and the memory of John

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PREFACE

This is an introductory text on the central subject of computer science—the theory, implementation, and applications of data structures and algorithms.

Key features:

- There is a strong Abstract Data Type (ADT) approach. For each of the major data types the sequence is: a definition in terms of objects and operations, an illustration of usefulness, *then* one or more possible implementations, followed by larger applications and/or an overview of related issues.
- Almost all implementations are informally analyzed using the Big-Oh notation. The concept is introduced in the first chapter, and applied throughout.
- Recursion receives heavy emphasis. One chapter is devoted to its explanation and it offers many examples. Recursion is then used freely in the book, where it makes the presentation of other ideas clearer.
- There is heavy emphasis on program readability as a key feature of good programming style. The point is made explicitly in the first chapter and reinforced by example throughout. All programs have been tested and run, to produce the results shown and explained in the text.
- Program verification, through assertions and loop invariants, is introduced and explained at an informal level.
- The major illustrations are chosen with an eye to making the course serve, among other things, as an overview of what computer science is about. Parsing, simulation, expression simplification, BNF, state transition diagrams, backtracking, the database concept, solving recurrence relations, and several graph algorithms are introduced in this way, at a level appropriate to a second course.

It will be seen that the coverage is that recommended in the Koffman Committee report on a revision for CS2 of the ACM Curriculum 78.

I believe I have written a text that is in the spirit of the best recent work on curriculum revision; I have tried not to fall into the trap of trying to cover everything. The examples, along with their underlying abstract and implemented data structures, provide real-life applications of many theoretical topics. Thus the text complements a separate course in discrete mathematics but can be used separately.

About 15 percent of the entire text is devoted to a variety of exercises. Some test mastery of concepts; some are programming exercises that reinforce the data structures and algorithms covered in the chapter; some extend the mathematics and/or computer science topics of the chapter; and, some are suitable for projects that require consideration of software engineering issues. Many make most sense if programmed and run, but many others will help the student master the material

with only paper and pencil to support careful study. About a quarter of them involve discrete mathematics, permitting the instructor to give that emphasis if desired.

Every chapter concludes with a "Suggestions for Further Study" section, which is a selective annotated bibliography. The references chosen include other texts covering about the same material, for comparison and alternative exposition; primary sources; standard works that every student should know (e.g., Knuth); and indications of applications.

An Instructor's Manual will provide answers to exercises, suggestions for teaching the material, a sample syllabus, sample examinations, and ideas for larger projects for those who wish to emphasize the software engineering component of the course. A disk containing all programs and data from the book may be obtained by writing me care of John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158.

Daniel D. McCracken
New York, New York
January, 1987

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D.D.M.

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CHAPTER 1

THE PROGRAM DEVELOPMENT PROCESS

1.1 TO THE READER: ABOUT THIS BOOK

We begin this text with the assumption that you have had one computer science course on algorithm development, with programming in Pascal. You may, we hope, have had a course in discrete mathematics or you may know other programming languages. You may also know something about how computers operate at a level below programming languages like Pascal. But that you have had one good Pascal-based computer science course in which you wrote five to ten programs and ran them—that is our starting assumption.

Building on that background, study of this book will advance your growth in computer science in four areas:

1. **Abstract data types (ADTs).** You have been introduced to arrays, records, sets, and strings in your previous study. We shall look at those topics afresh, taking a broader viewpoint, and study five others: stacks, queues, linked lists, trees, and graphs. Our major new viewpoint will be to distinguish between the *concept* of a given abstract data type and the various possibilities for its *implementation*. We call this the *abstract data type* (ADT) approach.
2. **Algorithms.** An algorithm is a precisely stated set of steps that terminates in finite time, the execution of which solves a stated problem. You are probably already accustomed to simple algorithms, perhaps when you had to evaluate a polynomial, find the roots of a polynomial, solve a small system of simultaneous equations, or find the greatest common divisor of two integers.

In this book we shall study a number of algorithms for solving some of the "standard" problems that arise frequently in computer science. You have probably seen simple examples of some of these, such as elementary sorting methods or binary search. Here we shall not only investigate sorting and searching in greater depth, but also study a variety of algorithms that arise in connection with the new (to you) ADTs. These involve, for example, ways of "visiting" all the nodes of a binary tree or finding the shortest path between two vertices in a graph. Several of the algorithms will have the dual purpose of illustrating a new ADT and introducing a fundamental area of computer science study.

3. **Better programming.** Computer science is more than the amassing of programming skills and languages, but programming is nonetheless one of the essential tools of a computer scientist. Consequently, in this book we will help you improve your programming skills in a number of ways. One major way is to give you many examples to read and study.
4. **The use of mathematics in computer science.** Computer science as a discipline is in the process of becoming more firmly grounded in mathematics. In various ways, appropriate to your background, we shall demonstrate some of the ways mathematics is useful in computer science and deepen your ability to work with the combination of the two.

In other words, you are going to learn some of the tools of the trade of a computer scientist. Many of these tools have direct application; others are building blocks that will find full value after study of more advanced topics such as compiler construction, database implementation, or computer graphics. A number of the applications that we use to illustrate data structures and algorithms provide "sneak preview" of some of the areas of computer science that you will be studying later.

1.2 THE SOFTWARE DEVELOPMENT CYCLE

In writing programs to this stage, you have probably gone through a process something like this:

1. Get the assignment. The instructor states a problem to be solved.
2. Devise an algorithm. With more or less help depending on your experience, and with more or less difficulty depending on the problem, devise an algorithm for solving the problem.
3. Express the algorithm as a computer program, using the programming language specified for the course. Type the program into the computer.
4. Compile the program. Revise it to correct errors detected by the compiler, run it with sample data for which you know the correct answers, and correct errors discovered in testing. Run the program with actual data and turn in program and results.

And, typically, *never so much as look at the program, ever again.*

This is an acceptable way to start learning about programming, computer science, and software engineering. However, software development outside of the classroom is vastly different. Many organizations develop programs that are far too large to be written by one person or even by one small team. In projects of such size, a majority of the effort may be devoted primarily to communication among team members. Any one team member may be working on a procedure of only a few hundred lines, but that procedure must *interface* (communicate correctly) with other procedures in the program. As a result, interface standards and programming style standards are rigidly enforced. When all the costs have been tallied, including the planning, the waste caused by bad planning, and the meetings to coordinate interface definitions, etc., the cost of a program can easily be in excess of $100 *per line.*

If you have ever written a 200-line program by staying up the night before an assignment was due, you may find this figure incomprehensible. That is because you have seen only a part of the whole job of program development so far.

You are not expected to make the transition from writing "student-sized" programs to the industrial world of multi-person projects in one giant leap. For the purposes of this book, you will be writing programs of a few hundred lines, for the most part, and working alone. But one major goal of the book is to help you make several big steps—if not the entire journey—toward your ability to develop software of realistic size.

One of the essentials you will have to acquire is how to become much more systematic about the program development *process.* It won't do, for instance, to approach program development in an informal way. Rather, you will have to start going through a series of well-defined steps, using the intellectual tools that are the main subject of the book, in which the coding is only one phase.

There is no single formula that fits every situation, but we can list a sequence of steps that will provide a starting outlook—a framework that will serve in many cases—and that is a good foundation for discussion of the variations.

Here, then, is a listing of the steps in developing a software system.

1. **User requirements analysis.** The software developer or development team, working closely with the *user* (also called the *client* or *customer*—the person or group requesting the software), produces a definition of the problem. A document called the *user requirements statement* is jointly agreed to by the user and the developer, and becomes a sort of contract stating what the program is to accomplish. However, this document contains essentially nothing about how the requirements are to be met, which is worked out later. "What, not how" summarizes this step.
2. **Functional specification.** Next comes a technical statement that shows the major components of the system, data flows between them, required outputs, errors to be checked for and procedures to follow after detection, and any constraints such as required processing rates. A formal document is also produced at this stage, part of which is a first draft of the *User's Guide,* which is what the end users will work from when using the system.
3. **Design.** For each of the major components identified in the functional specification, the developer now chooses data types and algorithms, and breaks

the processing into precisely defined subprograms (procedures or functions, in Pascal). Key algorithms may be subjected to *verification* at this stage, to build confidence that they are correct.

4. **Implementation.** The design is translated into code, usually in a high-level language such as Pascal.
5. **Testing.** The developer then compiles the code and corrects errors detected by the compiler. Next, the compiled programs are run with data for which the correct results are known; errors detected in this stage are also corrected. The programs are then run with data containing all the errors that the requirements ask to be detected. (The programs may also be run with completely random data, to see if they reject unanticipated bad data.) The programs are finally run with real data supplied by the client, which will often disclose errors of understanding of user requirements.
6. **Installation.** The software is placed on the *target computer* (the client's machine, on which the application will run in regular use), which is usually not the one on which development (coding and testing) is done. The client personnel who will operate the system are trained. The system is run in parallel with the one it replaces, if that is the situation. (Discontinuing an old system before its replacement has been thoroughly proven has long been recognized as a recipe for disaster, but it still happens.)
7. **Maintenance.** This is an umbrella term for everything that is done to the software after the user has accepted the initial product—correction of errors not detected earlier, addition of new features, and modifications necessitated by hardware changes. "Maintenance" is a decidedly awkward term for this collection of almost unrelated activities, none of which is similar to the "maintenance" of a car or a TV set, but the terminology is entrenched.

The amount of time devoted to each of these steps obviously varies, but the following percentages of the total effort are generally indicative of what is needed:

User requirements: 10%

Functional specification: 30%

Design: 20%

Implementation: 15%

Testing: 15%

Installation: 10%.

No percentage has been shown for maintenance, which requires further explanation and emphasis. The trouble with trying to pin down a time allotment is that maintenance itself is poorly defined. Pragmatically, it often turns out to cover everything from the time the user accepts the system until an agreement is reached to undertake a major revision. By this definition, maintenance is usually reported as something in the range of 50–90% of the total cost of software development. Astonishing, perhaps, but generally accepted.

Several lessons may be drawn from this discussion.

1. Coding, possibly the only part to which you have given serious attention so far, is a relatively minor part of the job. One reason for this is that real life applications often require a great deal of effort just to get a good definition of what is to be done, in part because the user often doesn't really know at the outset. The user can't write the requirements in isolation, without knowing the constraints imposed by the computer, a subject about which he or she is not expert. Likewise, the software developer obviously can't define the task in isolation. Furthermore, the two people (or two groups) often have quite different vocabularies and areas of expertise, requiring considerable time, effort, and good will just to be sure they are really talking about the same thing. The draft of the User's Guide, which should be written long before coding begins, is an excellent device to help detect misunderstandings early in the development process.
2. Just about anything that can flush out errors of whatever type, *early in the development process,* is beneficial. The earlier an error is caught, the easier and cheaper it is to correct, sometimes even by a huge margin; correcting an error after installation may cost tens or even thousands of times as much as correcting it at the design stage. This is one reason that the percentages of project effort devoted to requirements analysis and functional specification are so much larger than you might have expected: much wasted effort can be saved by getting them right the first time. In sum, delay coding as long as possible.
3. We described this process as a linear sequence of separate steps, but it is really a *cycle:* normally there will be considerable looping back to repeat portions of earlier steps.
4. Because many people are involved in development over periods of months or years, with a great deal depending on an accurate understanding of what is to be accomplished and what has already been done, documentation is a crucial part of the software development process. Documentation does *not* mean a rushed, after-the-fact job that is done carelessly to meet contract requirements. Most of the stages of the development process haven't really been completed at all until an appropriate document has been created. The ability to communicate easily and clearly is a crucial vocational skill for a software developer.

Because so many people of diverse backgrounds and concerns use the computer for so many different applications, it is to be expected that there will be many variations of this process. In fact, some developers feel that there is *so much* variability that it is better not to pretend that there is a "standard" "life cycle" at all. Such an objection will be viewed with considerable sympathy in these quarters,[1] but you need to have an idea of the traditional approaches before you can deal with the variations. Consequently, we have presented one formulation of the conventional life cycle.

[1]See Daniel D. McCracken and Michael A. Jackson, "Life-Cycle Concept Considered Harmful," *Software Engineering Notes,* **7**, 2 (April 1982).

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