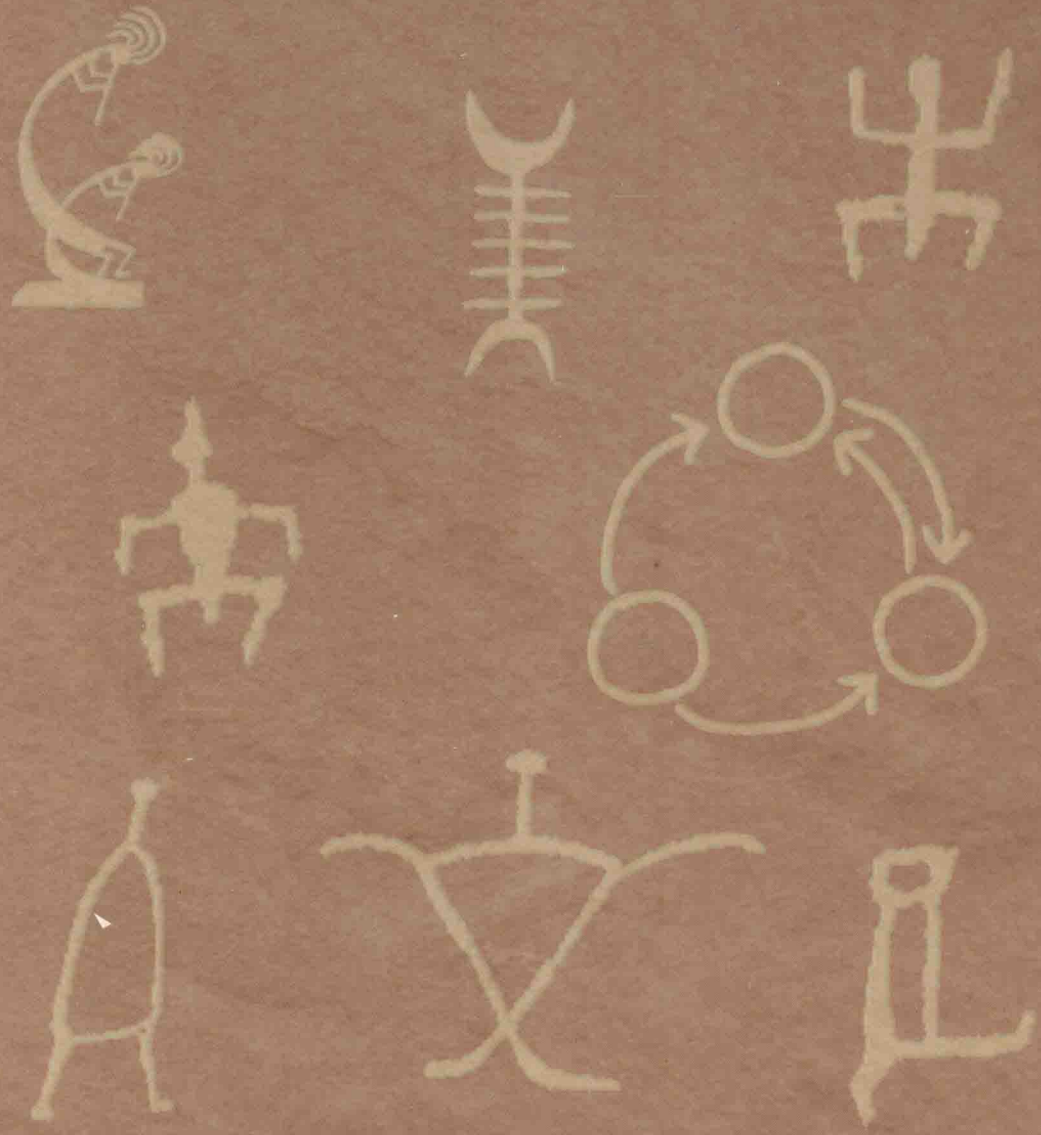
DATABASE SYSTEM IMPLEMENTATION



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Database System Implementation

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Preface

This book was designed for CS245, the second course in the database sequence at Stanford. Here, the first database course, CS145, covers database design and programming, for which the book *A First Course in Database Systems* by Jeff Ullman and Jennifer Widom, Prentice-Hall, 1997, was written. The CS245 course then covers implementation of a DBMS, notably storage structures, query processing, and transaction management.

Use of the Book

We're on a quarter system at Stanford, so the principal course using this book — CS245 — is only ten weeks long. In the Winter of 1999, Hector Garcia-Molina used a "beta" version of this book, and covered the following parts: Sections 2.1–2.4, all of Chapters 3 and 4, Sections 5.1 and 5.2, Sections 6.1–6.7, Sections 7.1–7.4, all of Chapter 8, Chapter 9 except for Section 9.8, Sections 10.1–10.3, Section 11.1, and Section 11.5.

The balance of Chapters 6 and 7 (query optimization) is covered in an advanced course, CS346, where students implement their own DBMS. Other portions of the book that are not covered in CS245 may appear in another advanced course, CS347, which talks about distributed databases and advanced transaction processing.

Schools that are on the semester system have the opportunity to combine the use of this book with its predecessor: *A First Course in Database Systems*. We recommend using that book in the first semester, coupled with a database-application programming project. The second semester could cover most or all of the content of this book. An advantage to splitting the study of databases into two courses is that students not planning to specialize in DBMS construction can take only the first course and be able to use databases in whatever branch of Computer Science they enter.

Prerequisites

The course on which the book is based is rarely taken before the senior year, so we expect the reader to have a fairly broad background in the traditional areas

of Computer Science. We assume that the reader has learned something about database programming, especially SQL. It is helpful to know about relational algebra and to have some familiarity with basic data structures. Likewise, some knowledge of file systems and operating systems is useful.

Exercises

The book contains extensive exercises, with some for almost every section. We indicate harder exercises or parts of exercises with an exclamation point. The hardest exercises have a double exclamation point.

Some of the exercises or parts are marked with a star. For these exercises, we shall endeavor to maintain solutions accessible through the book's Web page. These solutions are publicly available and should be used for self-testing. Note that in a few cases, one exercise B asks for modification or adaptation of your solution to another exercise A. If certain parts of A have Web-published solutions, then you should expect the corresponding parts of B to have solutions as well.

Support on the World-Wide Web

The book's home page is

`http://www-db.stanford.edu/~ullman/dbsi.html`

Here you will find solutions to starred exercises, errata as we learn of them, and backup materials. We hope to make available the notes for each offering of CS245 and relevant portions of other database courses, as we teach them, including homeworks, exams, and solutions.

Acknowledgements

Thanks go to Brad Adelberg, Karen Butler, Ed Chang, Surajit Chaudhuri, Rada Chirkova, Tom Dienstbier, Xavier Faz, Tracy Fujieda, Luis Gravano, Ben Holzman, Fabien Modoux, Peter Mork, Ken Ross, Mema Roussopolous, and Jonathan Ullman for assistance gathering material and/or discovering errors in earlier drafts of this work. Remaining errors are ours, of course.

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Table of Contents

Chapter 1

Introduction to DBMS Implementation

Databases today are essential to every business. They are used to maintain internal records, to present data to customers and clients on the World-Wide-Web, and to support many other commercial processes. Databases are likewise found at the core of many scientific investigations. They represent the data gathered by astronomers, by investigators of the human genome, and by biochemists exploring the medicinal properties of proteins, along with many other scientists.

The power of databases comes from a body of knowledge and technology that has developed over several decades and is embodied in specialized software called a *database management system*, or *DBMS*, or more colloquially a "database system." A DBMS is a powerful tool for creating and managing large amounts of data efficiently and allowing it to persist over long periods of time, safely. These systems are among the most complex types of software available. The capabilities that a DBMS provides the user are:

1. *Persistent storage.* Like a file system, a DBMS supports the storage of very large amounts of data that exists independently of any processes that are using the data. However, the DBMS goes far beyond the file system in providing flexibility, such as data structures that support efficient access to very large amounts of data.

2. *Programming interface.* A DBMS allows the user to access and modify data through a powerful query language. Again, the advantage of a DBMS over a file system is the flexibility to manipulate stored data in much more complex ways than the reading and writing of files.

3. *Transaction management.* A DBMS supports concurrent access to data, i.e., simultaneous access by many distinct processes (called "transactions") at once. To avoid some of the undersirable consequences of si-