part 7

# File Structures, Hashing, Indexing, and Physical Database Design

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chapter 16

# Disk Storage, Basic File Structures, Hashing, and Modern Storage Architectures

Databases are stored physically as files of records, which are typically stored on magnetic disks. This chapter and the next deal with the organization of databases in storage and the techniques for accessing them efficiently using various algorithms, some of which require auxiliary data structures called *indexes*. These structures are often referred to as **physical database file structures** and are at the physical level of the three-schema architecture described in Chapter 2. We start in Section 16.1 by introducing the concepts of computer storage hierarchies and how they are used in database systems. Section 16.2 is devoted to a description of magnetic disk storage devices and their characteristics, flash memory, and solid-state drives and optical drives and magnetic tape storage devices used for archiving data. We also discuss techniques for making access from disks more efficient. After discussing different storage technologies, we turn our attention to the methods for physically organizing data on disks. Section 16.3 covers the technique of double buffering, which is used to speed retrieval of multiple disk blocks. We also discuss buffer management and buffer replacement strategies. In Section 16.4 we discuss various ways of formatting and storing file records on disk. Section 16.5 discusses the various types of operations that are typically applied to file records. We present three primary methods for organizing file records on disk: unordered records, in Section 16.6; ordered records, in Section 16.7; and hashed records, in Section 16.8.

Section 16.9 briefly introduces files of mixed records and other primary methods for organizing records, such as B-trees. These are particularly relevant for storage of object-oriented databases, which we discussed in Chapter 11. Section 16.10

describes RAID (redundant arrays of inexpensive (or independent) disks)—a data storage system architecture that is commonly used in large organizations for better reliability and performance. Finally, in Section 16.11 we describe modern developments in the storage architectures that are important for storing enterprise data: storage area networks (SANs), network-attached storage (NAS), iSCSI (Internet SCSI—small computer system interface), and other network-based storage protocols, which make storage area networks more affordable without the use of the Fibre Channel infrastructure and hence are becoming widely accepted in industry. We also discuss storage tiering and object-based storage. Section 16.12 summarizes the chapter. In Chapter 17 we discuss techniques for creating auxiliary data structures, called indexes, which speed up the search for and retrieval of records. These techniques involve storage of auxiliary data, called index files, in addition to the file records themselves.

Chapters 16 and 17 may be browsed through or even omitted by readers who have already studied file organizations and indexing in a separate course. The material covered here, in particular Sections 16.1 through 16.8, is necessary for understanding Chapters 18 and 19, which deal with query processing and optimization, as well as database tuning for improving performance of queries.

## 16.1 Introduction

The collection of data that makes up a computerized database must be stored physically on some computer **storage medium**. The DBMS software can then retrieve, update, and process this data as needed. Computer storage media form a *storage hierarchy* that includes two main categories:

- **Primary storage.** This category includes storage media that can be operated on directly by the computer's *central processing unit* (CPU), such as the computer's main memory and smaller but faster cache memories. Primary storage usually provides fast access to data but is of limited storage capacity. Although main memory capacities have been growing rapidly in recent years, they are still more expensive and have less storage capacity than demanded by typical enterprise-level databases. The contents of main memory are lost in case of power failure or a system crash.
- **Secondary storage.** The primary choice of storage medium for online storage of enterprise databases has been magnetic disks. However, flash memories are becoming a common medium of choice for storing moderate amounts of permanent data. When used as a substitute for a disk drive, such memory is called a **solid-state drive** (SSD).
- **Tertiary storage.** Optical disks (CD-ROMs, DVDs, and other similar storage media) and tapes are removable media used in today's systems as offline storage for archiving databases and hence come under the category called tertiary storage. These devices usually have a larger capacity, cost less, and provide slower access to data than do primary storage devices. Data in secondary or tertiary storage cannot be processed directly by the CPU; first it must be copied into primary storage and then processed by the CPU.

We first give an overview of the various storage devices used for primary, secondary, and tertiary storage in Section 16.1.1, and in Section 16.1.2 we discuss how databases are typically handled in the storage hierarchy.

### 16.1.1 Memory Hierarchies and Storage Devices[1]

In a modern computer system, data resides and is transported throughout a hierarchy of storage media. The highest-speed memory is the most expensive and is therefore available with the least capacity. The lowest-speed memory is offline tape storage, which is essentially available in indefinite storage capacity.

At the *primary storage level,* the memory hierarchy includes, at the most expensive end, **cache memory**, which is a static RAM (random access memory). Cache memory is typically used by the CPU to speed up execution of program instructions using techniques such as prefetching and pipelining. The next level of primary storage is DRAM (dynamic RAM), which provides the main work area for the CPU for keeping program instructions and data. It is popularly called **main memory**. The advantage of DRAM is its low cost, which continues to decrease; the drawback is its volatility[2] and lower speed compared with static RAM.

At the *secondary and tertiary storage level,* the hierarchy includes magnetic disks; **mass storage** in the form of CD-ROM (compact disk–read-only memory) and DVD (digital video disk or digital versatile disk) devices; and finally tapes at the least expensive end of the hierarchy. The **storage capacity** is measured in kilobytes (Kbyte or 1,000 bytes), megabytes (MB or 1 million bytes), gigabytes (GB or 1 billion bytes), and even terabytes (1,000 GB). The word *petabyte* (1,000 terabytes or 10**15 bytes) is now becoming relevant in the context of very large repositories of data in physics, astronomy, earth sciences, and other scientific applications.

Programs reside and execute in dynamic random-access memory ( DRAM ). Generally, large permanent databases reside on secondary storage (magnetic disks), and portions of the database are read into and written from buffers in main memory as needed. Nowadays, personal computers and workstations have large main memories of hundreds of megabytes of RAM and DRAM, so it is becoming possible to load a large part of the database into main memory. Eight to sixteen GB of main memory is becoming commonplace on laptops, and servers with 256 GB capacity are not uncommon. In some cases, entire databases can be kept in main memory (with a backup copy on magnetic disk), which results in **main memory databases**; these are particularly useful in real-time applications that require extremely fast response times. An example is telephone switching applications, which store databases that contain routing and line information in main memory.

**Flash Memory.** Between DRAM and magnetic disk storage, another form of memory, **flash memory**, is becoming common, particularly because it is nonvolatile.

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[1]The authors appreciate the valuable input of Dan Forsyth regarding the current status of storage systems in enterprises. The authors also wish to thank Satish Damle for his suggestions.

[2]Volatile memory typically loses its contents in case of a power outage, whereas nonvolatile memory does not.

Flash memories are high-density, high-performance memories using EEPROM (electrically erasable programmable read-only memory) technology. The advantage of flash memory is the fast access speed; the disadvantage is that an entire block must be erased and written over simultaneously. Flash memories come in two types called NAND and NOR flash based on the type of logic circuits used. The NAND flash devices have a higher storage capacity for a given cost and are used as the data storage medium in appliances with capacities ranging from 8 GB to 64 GB for the popular cards that cost less than a dollar per GB. Flash devices are used in cameras, MP3/MP4 players, cell phones, PDAs (personal digital assistants), and so on. USB (universal serial bus) flash drives or USB sticks have become the most portable medium for carrying data between personal computers; they have a flash memory storage device integrated with a USB interface.

**Optical Drives.** The most popular form of optical removable storage is CDs (compact disks) and DVDs. CDs have a 700-MB capacity whereas DVDs have capacities ranging from 4.5 to 15 GB. CD-ROM(compact disk – read only memory) disks store data optically and are read by a laser. CD-ROMs contain prerecorded data that cannot be overwritten. The version of compact and digital video disks called CD-R (compact disk recordable) and DVD-R or DVD+R, which are also known as WORM (write-once-read-many) disks, are a form of optical storage used for archiving data; they allow data to be written once and read any number of times without the possibility of erasing. They hold about half a gigabyte of data per disk and last much longer than magnetic disks.[3] A higher capacity format for DVDs called Blu-ray DVD can store 27 GB per layer, or 54 GB in a two-layer disk. **Optical jukebox memories** use an array of CD-ROM platters, which are loaded onto drives on demand. Although optical jukeboxes have capacities in the hundreds of gigabytes, their retrieval times are in the hundreds of milliseconds, quite a bit slower than magnetic disks. This type of **tertiary storage** is continuing to decline because of the rapid decrease in cost and the increase in capacities of magnetic disks. Most personal computer disk drives now read CD-ROM and DVD disks. Typically, drives are CD-R (compact disk recordable) that can create CD-ROMs and audio CDs, as well as record on DVDs.

**Magnetic Tapes.** Finally, **magnetic tapes** are used for archiving and backup storage of data. **Tape jukeboxes**—which contain a bank of tapes that are catalogued and can be automatically loaded onto tape drives—are becoming popular as **tertiary storage** to hold terabytes of data. For example, NASA's EOS (Earth Observation Satellite) system stores archived databases in this fashion.

Many large organizations are using terabyte-sized databases. The term **very large database** can no longer be precisely defined because disk storage capacities are on

[3]Their rotational speeds are lower (around 400 rpm), giving higher latency delays and low transfer rates (around 100 to 200 KB/second) for a 1X drive. *n*X drives (e.g., 16X (*n* = 16) are supposed to give *n* times higher transfer rate by multiplying the rpm *n* times. The 1X DVD transfer rate is about 1.385 MB/s.

**Table 16.1** Types of Storage with Capacity, Access Time, Max Bandwidth (Transfer Speed), and Commodity Cost

| Type | Capacity* | Access Time | Max Bandwidth | Commodity Prices (2014)** |
|---|---|---|---|---|
| Main Memory- RAM | 4GB–1TB | 30ns | 35GB/sec | $100–$20K |
| Flash Memory- SSD | 64 GB–1TB | 50μs | 750MB/sec | $50–$600 |
| Flash Memory- USB stick | 4GB–512GB | 100μs | 50MB/sec | $2–$200 |
| Magnetic Disk | 400 GB–8TB | 10ms | 200MB/sec | $70–$500 |
| Optical Storage | 50GB–100GB | 180ms | 72MB/sec | $100 |
| Magnetic Tape | 2.5TB–8.5TB | 10s–80s | 40–250MB/sec | $2.5K–$30K |
| Tape jukebox | 25TB–2,100,000TB | 10s–80s | 250MB/sec–1.2PB/sec | $3K–$1M+ |

*Capacities are based on commercially available popular units in 2014.

**Costs are based on commodity online marketplaces.

the rise and costs are declining. Soon the term *very large database* may be reserved for databases containing hundreds of terabytes or petabytes.

To summarize, a hierarchy of storage devices and storage systems is available today for storage of data. Depending upon the intended use and application requirements, data is kept in one or more levels of this hierarchy. Table 16.1 summarizes the current state of these devices and systems and shows the range of capacities, average access times, bandwidths (transfer speeds), and costs on the open commodity market. Cost of storage is generally going down at all levels of this hierarchy.

### 16.1.2 Storage Organization of Databases

Databases typically store large amounts of data that must persist over long periods of time, and hence the data is often referred to as **persistent data**. Parts of this data are accessed and processed repeatedly during the storage period. This contrasts with the notion of **transient data**, which persists for only a limited time during program execution. Most databases are stored permanently (or *persistently*) on magnetic disk secondary storage, for the following reasons:

- Generally, databases are too large to fit entirely in main memory.[4]
- The circumstances that cause permanent loss of stored data arise less frequently for disk secondary storage than for primary storage. Hence, we refer to disk—and other secondary storage devices—as **nonvolatile storage**, whereas main memory is often called **volatile storage**.
- The cost of storage per unit of data is an order of magnitude less for disk secondary storage than for primary storage.

[4]This statement is being challenged by recent developments in main memory database systems. Examles of prominent commercial systems include HANA by SAP and TIMESTEN by Oracle.

Some of the newer technologies—such as solid-state drive (SSD) disks are likely to provide viable alternatives to the use of magnetic disks. In the future, databases may therefore reside at different levels of the memory hierarchy from those described in Section 16.1.1. The levels may range from the highest speed main memory level storage to the tape jukebox low speed offline storage. However, it is anticipated that magnetic disks will continue to be the primary medium of choice for large databases for years to come. Hence, it is important to study and understand the properties and characteristics of magnetic disks and the way data files can be organized on disk in order to design effective databases with acceptable performance.

Magnetic tapes are frequently used as a storage medium for backing up databases because storage on tape costs much less than storage on disk. With some intervention by an operator—or an automatic loading device—tapes or optical removable disks must be loaded and read before the data becomes available for processing. In contrast, disks are **online** devices that can be accessed directly at any time.

The techniques used to store large amounts of structured data on disk are important for database designers, the DBA, and implementers of a DBMS. Database designers and the DBA must know the advantages and disadvantages of each storage technique when they design, implement, and operate a database on a specific DBMS. Usually, the DBMS has several options available for organizing the data. The process of **physical database design** involves choosing the particular data organization techniques that best suit the given application requirements from among the options. DBMS system implementers must study data organization techniques so that they can implement them efficiently and thus provide the DBA and users of the DBMS with sufficient options.

Typical database applications need only a small portion of the database at a time for processing. Whenever a certain portion of the data is needed, it must be located on disk, copied to main memory for processing, and then rewritten to the disk if the data is changed. The data stored on disk is organized as **files** of **records**. Each record is a collection of data values that can be interpreted as facts about entities, their attributes, and their relationships. Records should be stored on disk in a manner that makes it possible to locate them efficiently when they are needed. We will discuss some of the techniques for making disk access more efficient in Section 17.2.2.

There are several **primary file organizations**, which determine how the file records are *physically placed* on the disk, *and hence how the records can be accessed.* A *heap file* (or *unordered file*) places the records on disk in no particular order by appending new records at the end of the file, whereas a *sorted file* (or *sequential file*) keeps the records ordered by the value of a particular field (called the *sort key*). A *hashed file* uses a hash function applied to a particular field (called the *hash key*) to determine a record's placement on disk. Other primary file organizations, such as *B-trees,* use tree structures. We discuss primary file organizations in Sections 16.6 through 16.9. A **secondary organization** or **auxiliary access structure** allows efficient access to file records based on *alternate fields* than those that have been used for the primary file organization. Most of these exist as indexes and will be discussed in Chapter 17.

## 16.2 Secondary Storage Devices

In this section, we describe some characteristics of magnetic disk and magnetic tape storage devices. Readers who have already studied these devices may simply browse through this section.

### 16.2.1 Hardware Description of Disk Devices

Magnetic disks are used for storing large amounts of data. The device that holds the disks is referred to as a **hard disk drive**, or **HDD**. The most basic unit of data on the disk is a single **bit** of information. By magnetizing an area on a disk in certain ways, one can make that area represent a bit value of either 0 (zero) or 1 (one). To code information, bits are grouped into **bytes** (or **characters**). Byte sizes are typically 4 to 8 bits, depending on the computer and the device; 8 bits is the most common. We assume that one character is stored in a single byte, and we use the terms *byte* and *character* interchangeably. The **capacity** of a disk is the number of bytes it can store, which is usually very large. Small floppy disks were used with laptops and desktops for many years—they contained a single disk typically holding from 400 KB to 1.5 MB; they are almost completely out of circulation. Hard disks for personal computers currently hold from several hundred gigabytes up to a few terabytes; and large disk packs used with servers and mainframes have capacities of hundreds of gigabytes. Disk capacities continue to grow as technology improves.

Whatever their capacity, all disks are made of magnetic material shaped as a thin circular disk, as shown in Figure 16.1(a), and protected by a plastic or acrylic cover. A disk is **single-sided** if it stores information on one of its surfaces only and **double-sided** if both surfaces are used. To increase storage capacity, disks are assembled into a **disk pack**, as shown in Figure 16.1(b), which may include many disks and therefore many surfaces. The two most common form factors are 3.5 and 2.5 inch diameter. Information is stored on a disk surface in concentric circles of *small width*,[5] each having a distinct diameter. Each circle is called a **track**. In disk packs, tracks with the same diameter on the various surfaces are called a **cylinder** because of the shape they would form if connected in space. The concept of a cylinder is important because data stored on one cylinder can be retrieved much faster than if it were distributed among different cylinders.

The number of tracks on a disk ranges from a few thousand to 152,000 on the disk drives shown in Table 16.2, and the capacity of each track typically ranges from tens of kilobytes to 150 Kbytes. Because a track usually contains a large amount of information, it is divided into smaller blocks or sectors. The division of a track into **sectors** is hard-coded on the disk surface and cannot be changed. One type of sector organization, as shown in Figure 16.2(a), calls a portion of a track that subtends a fixed angle at the center a sector. Several other sector organizations are possible, one of which is to have the sectors subtend smaller angles at the center as one moves

[5]In some disks, the circles are now connected into a kind of continuous spiral.

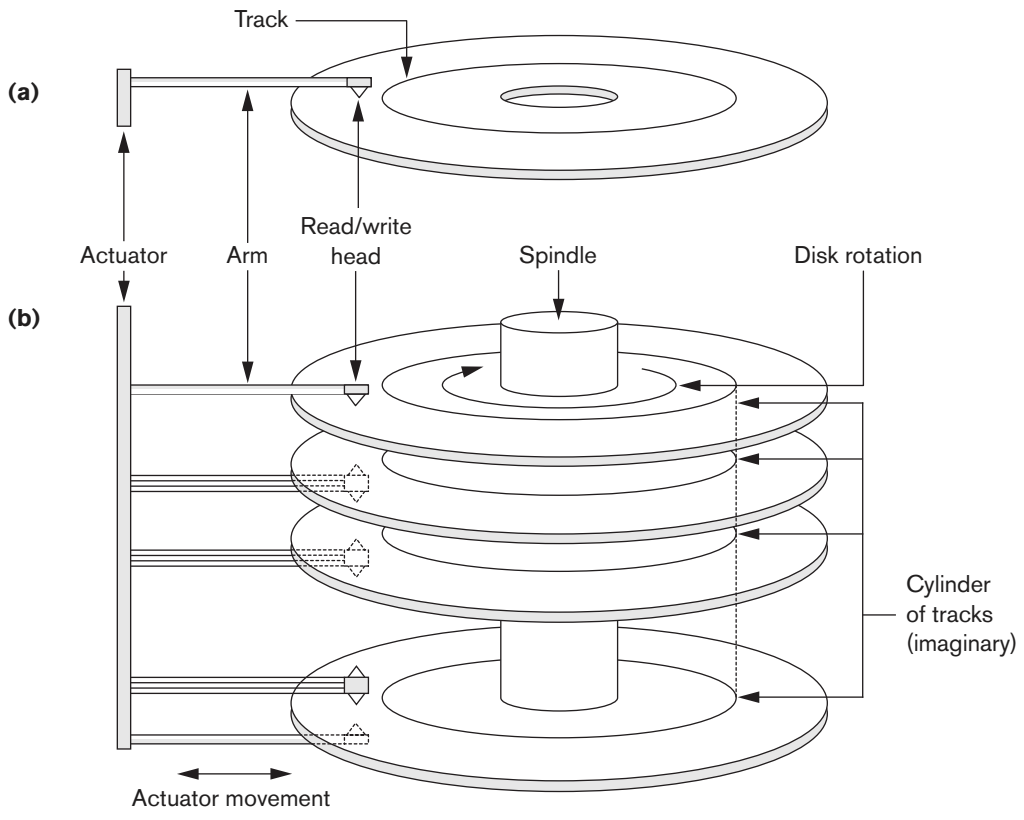


**Figure 16.1**
(a) A single-sided disk with read/write hardware. (b) A disk pack with read/write hardware.

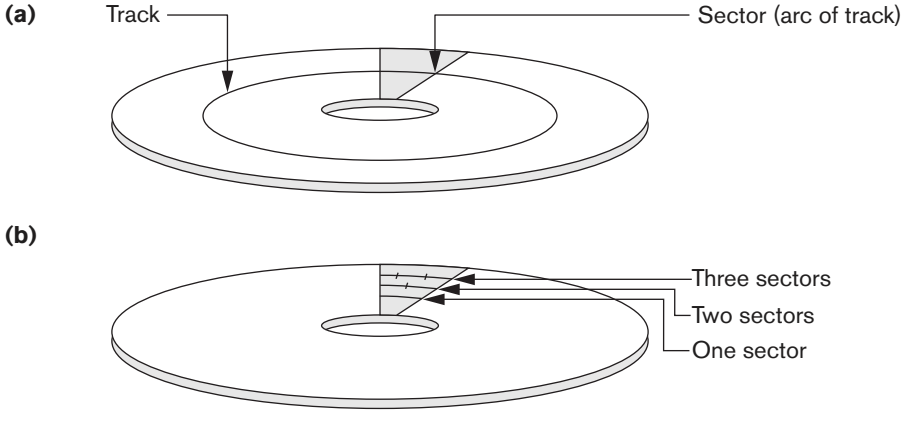


**Figure 16.2**
Different sector organizations on disk. (a) Sectors subtending a fixed angle. (b) Sectors maintaining a uniform recording density.

away, thus maintaining a uniform density of recording, as shown in Figure 16.2(b). A technique called ZBR (zone bit recording) allows a range of cylinders to have the same number of sectors per arc. For example, cylinders 0–99 may have one sector per track, 100–199 may have two per track, and so on. A common sector size is 512 bytes. Not all disks have their tracks divided into sectors.

The division of a track into equal-sized **disk blocks** (or **pages**) is set by the operating system during disk **formatting** (or **initialization**). Block size is fixed during initialization and cannot be changed dynamically. Typical disk block sizes range

**Table 16.2** Specifications of Typical High-End Enterprise Disks from Seagate (a) Seagate Enterprise Performance 10 K HDD - 1200 GB

| Specifications | 1200GB |
|---|---|
| SED Model Number | ST1200MM0017 |
| SED FIPS 140-2 Model Number | ST1200MM0027 |
| Model Name | Enterprise Performance 10K HDD v7 |
| Interface | 6Gb/s SAS |
| **Capacity** | |
| Formatted 512 Bytes/Sector (GB) | 1200 |
| External Transfer Rate (MB/s) | 600 |
| **Performance** | |
| Spindle Speed (RPM) | 10K |
| Average Latency (ms) | 2.9 |
| Sustained Transfer Rate Outer to Inner Diameter (MB/s) | 204 to 125 |
| Cache, Multisegmented (MB) | 64 |
| **Configuration/Reliability** | |
| Disks | 4 |
| Heads | 8 |
| Nonrecoverable Read Errors per Bits Read | 1 per 10E16 |
| Annualized Failure Rate (AFR) | 0.44% |
| **Physical** | |
| Height (in/mm, max) | 0.591/15.00 |
| Width (in/mm, max) | 2.760/70.10 |
| Depth (in/mm, max) | 3.955/100.45 |
| Weight (lb/kg) | 0.450/0.204 |

Courtesy Seagate Technology

(*Continued*)

**Table 16.2** (b) Internal Drive Characteristics of 300 GB–900 GB Seagate Drives

| | **ST900MM0006 ST900MM0026 ST900MM0046 ST900MM0036** | **ST600MM0006 ST600MM0026 ST600MM0046** | **ST450MM0006 ST450MM0026 ST450MM0046** | **ST300MM0006 ST300MM0026 ST300MM0046** | |
|---|---|---|---|---|---|
| Drive capacity | 900 | 600 | 450 | 300 | GB (formatted, rounded off value) |
| Read/write data heads | 6 | 4 | 3 | 2 | |
| Bytes per track | 997.9 | 997.9 | 997.9 | 997.9 | KBytes (avg, rounded off values) |
| Bytes per surface | 151,674 | 151,674 | 151,674 | 151,674 | MB (unformatted, rounded off value) |
| Tracks per surface (total) | 152 | 152 | 152 | 152 | KTracks (user accessible) |
| Tracks per inch | 279 | 279 | 279 | 279 | KTPI (average) |
| Peak bits per inch | 1925 | 1925 | 1925 | 1925 | KBPI |
| Areal density | 538 | 538 | 538 | 538 | Gb/in2 |
| Disk rotation speed | 10K | 10K | 10K | 10K | rpm |
| Avg rotational latency | 2.9 | 2.9 | 2.9 | 2.9 | ms |

from 512 to 8192 bytes. A disk with hard-coded sectors often has the sectors subdivided or combined into blocks during initialization. Blocks are separated by fixed-size **interblock gaps**, which include specially coded control information written during disk initialization. This information is used to determine which block on the track follows each interblock gap. Table 16.2 illustrates the specifications of typical disks used on large servers in industry. The 10K prefix on disk names refers to the rotational speeds in rpm (revolutions per minute.

There is continuous improvement in the storage capacity and transfer rates associated with disks; they are also progressively getting cheaper—currently costing only a fraction of a dollar per megabyte of disk storage. Costs are going down so rapidly that costs as low as $100/TB are already on the market.

A disk is a *random access* addressable device. Transfer of data between main memory and disk takes place in units of disk blocks. The **hardware address** of a block—a combination of a cylinder number, track number (surface number within the cylinder on which the track is located), and block number (within the track)—is supplied to the disk I/O (input/output) hardware. In many modern disk drives, a single number called LBA (logical block address), which is a number between 0 and $n$ (assuming the total capacity of the disk is $n + 1$ blocks), is mapped automatically to the right block by the disk drive controller. The address of a **buffer**—a contiguous

reserved area in main storage that holds one disk block—is also provided. For a **read** command, the disk block is copied into the buffer; whereas for a **write** command, the contents of the buffer are copied into the disk block. Sometimes several contiguous blocks, called a **cluster**, may be transferred as a unit. In this case, the buffer size is adjusted to match the number of bytes in the cluster.

The actual hardware mechanism that reads or writes a block is the disk **read/write head**, which is part of a system called a **disk drive**. A disk or disk pack is mounted in the disk drive, which includes a motor that rotates the disks. A read/write head includes an electronic component attached to a **mechanical arm**. Disk packs with multiple surfaces are controlled by several read/write heads—one for each surface, as shown in Figure 16.1(b). All arms are connected to an **actuator** attached to another electrical motor, which moves the read/write heads in unison and positions them precisely over the cylinder of tracks specified in a block address.

Disk drives for hard disks rotate the disk pack continuously at a constant speed (typically ranging between 5,400 and 15,000 rpm). Once the read/write head is positioned on the right track and the block specified in the block address moves under the read/write head, the electronic component of the read/write head is activated to transfer the data. Some disk units have fixed read/write heads, with as many heads as there are tracks. These are called **fixed-head** disks, whereas disk units with an actuator are called **movable-head disks**. For fixed-head disks, a track or cylinder is selected by electronically switching to the appropriate read/write head rather than by actual mechanical movement; consequently, it is much faster. However, the cost of the additional read/write heads is high, so fixed-head disks are not commonly used.

**Interfacing Disk Drives to Computer Systems.** A **disk controller**, typically embedded in the disk drive, controls the disk drive and interfaces it to the computer system. One of the standard interfaces used for disk drives on PCs and workstations was called **SCSI** (small computer system interface). Today to connect HDDs, CDs, and DVDs to a computer, the interface of choice is SATA. **SATA** stands for serial ATA, wherein ATA represents attachment; so SATA becomes serial AT attachment. It has its origin in PC/AT attachment, which referred to the direct attachment to the 16-bit bus introduced by IBM. The AT referred to advanced technology but is not used in the expansion of SATA due to trademark issues. Another popular interface used today is called **SAS** (serial attached SCSI). SATA was introduced in 2002 and allows the disk controller to be in the disk drive; only a simple circuit is required on the motherboard. SATA transfer speeds underwent an evolution from 2002 to 2008, going from 1.5 Gbps (gigabits per second) to 6 Gbps. SATA is now called NL-SAS for nearline SAS. The largest 3.5-inch SATA and SAS drives are 8TB, whereas 2.5-inch SAS drives are smaller and go up to 1.2TB. The 3.5-inch drives use 7,200 or 10,000 rpm speed whereas 2.5-inch drives use up to 15,000 rpm. In terms of IOPs (input/output operations) per second as a price to performance index, SAS is considered superior to SATA.

The controller accepts high-level I/O commands and takes appropriate action to position the arm and causes the read/write action to take place. To transfer a disk block, given its address, the disk controller must first mechanically position the

read/write head on the correct track. The time required to do this is called the **seek time**. Typical seek times are 5 to 10 msec on desktops and 3 to 8 msec on servers. Following that, there is another delay—called the **rotational delay** or **latency**—while the beginning of the desired block rotates into position under the read/write head. It depends on the rpm of the disk. For example, at 15,000 rpm, the time per rotation is 4 msec and the average rotational delay is the time per half revolution, or 2 msec. At 10,000 rpm the average rotational delay increases to 3 msec. Finally, some additional time is needed to transfer the data; this is called the **block transfer time**. Hence, the total time needed to locate and transfer an arbitrary block, given its address, is the sum of the seek time, rotational delay, and block transfer time. The seek time and rotational delay are usually much larger than the block transfer time. To make the transfer of multiple blocks more efficient, it is common to transfer several consecutive blocks on the same track or cylinder. This eliminates the seek time and rotational delay for all but the first block and can result in a substantial saving of time when numerous contiguous blocks are transferred. Usually, the disk manufacturer provides a **bulk transfer rate** for calculating the time required to transfer consecutive blocks. Appendix B contains a discussion of these and other disk parameters.

The time needed to locate and transfer a disk block is in the order of milliseconds, usually ranging from 9 to 60 msec. For contiguous blocks, locating the first block takes from 9 to 60 msec, but transferring subsequent blocks may take only 0.4 to 2 msec each. Many search techniques take advantage of consecutive retrieval of blocks when searching for data on a disk. In any case, a transfer time in the order of milliseconds is considered high compared with the time required to process data in main memory by current CPUs. Hence, locating data on disk is a *major bottleneck* in database applications. The file structures we discuss here and in Chapter 17 attempt to *minimize the number of block transfers* needed to locate and transfer the required data from disk to main memory. Placing "related information" on contiguous blocks is the basic goal of any storage organization on disk.

### 16.2.2 Making Data Access More Efficient on Disk

In this subsection, we list some of the commonly used techniques to make accessing data more efficient on HDDs.

1. **Buffering of data:** In order to deal with the incompatibility of speeds between a CPU and the electromechanical device such as an HDD, which is inherently slower, buffering of data is done in memory so that new data can be held in a buffer while old data is processed by an application. We discuss the double buffering strategy followed by general issues of buffer management and buffer replacement strategies in Section 16.3.
2. **Proper organization of data on disk:** Given the structure and organization of data on disk, it is advantageous to keep related data on contiguous blocks; when multiple cylinders are needed by a relation, contiguous cylinders should be used. Doing so avoids unnecessary movement of the read/write arm and related seek times.

3. **Reading data ahead of request:** To minimize seek times, whenever a block is read into the buffer, blocks from the rest of the track can also be read even though they may not have been requested yet. This works well for applications that are likely to need consecutive blocks; for random block reads this strategy is counterproductive.
4. **Proper scheduling of I/O requests:** If it is necessary to read several blocks from disk, total access time can be minimized by scheduling them so that the arm moves only in one direction and picks up the blocks along its movement. One popular algorithm is called the elevator algorithm; this algorithm mimics the behavior of an elevator that schedules requests on multiple floors in a proper sequence. In this way, the arm can service requests along its outward and inward movements without much disruption.
5. **Use of log disks to temporarily hold writes:** A single disk may be assigned to just one function called logging of writes. All blocks to be written can go to that disk sequentially, thus eliminating any seek time. This works much faster than doing the writes to a file at random locations, which requires a seek for each write. The log disk can order these writes in (cylinder, track) ordering to minimize arm movement when writing. Actually, the log disk can only be an area (extent) of a disk. Having the data file and the log file on the same disk is a cheaper solution but compromises performance. Although the idea of a log disk can improve write performance, it is not feasible for most real-life application data.
6. **Use of SSDs or flash memory for recovery purposes:** In applications where updates occur with high frequency, updates can be lost from main memory if the system crashes. A preventive measure would be to increase the speed of updates/writes to disk. One possible approach involves writing the updates to a nonvolatile SSD buffer, which may be a flash memory or battery-operated DRAM, both of which operate at must faster speeds (see Table 16.1). The disk controller then updates the data file during its idle time and also when the buffer becomes full. During recovery from a crash, unwritten SSD buffers must be written to the data file on HDD. For further discussion of recovery and logs, consult Chapter 22.

### 16.2.3 SolidState Device (SSD) Storage

This type of storage is sometimes known as flash storage because it is based on the flash memory technology, which we discussed in Section 16.1.1.

The recent trend is to use flash memories as an intermediate layer between main memory and secondary rotating storage in the form of magnetic disks (HDDs). Since they resemble disks in terms of the ability to store data in secondary storage without the need for continuous power supply, they are called **solid-state disks** or **solid-state drives (SSDs)**. We will discuss SSDs in general terms first and then comment on their use at the enterprise level, where they are sometimes referred to as **enterprise flash drives (EFDs),** a term first introduced by EMC Corporation.

The main component of an SSD is a controller and a set of interconnected flash memory cards. Use of NAND flash memory is most common. Using form factors compatible with 3.5 inch or 2.5 inch HDDs makes SSDs pluggable into slots already available for mounting HDDs on laptops and servers. For ultrabooks, tablets, and the like, card-based form factors such as mSATA and M.2 are being standardized. Interfaces like **SATA express** have been created to keep up with advancements in SSDs. Because there are no moving parts, the unit is more rugged, runs silently, is faster in terms of access time and provides higher transfer rates than HDD. As opposed to HDDs, where related data from the same relation must be placed on contiguous blocks, preferably on contiguous cylinders, there is no restriction on placement of data on an SSD since any address is directly addressable. As a result, the data is less likely to be fragmented; hence no reorganization is needed. Typically, when a write to disk occurs on an HDD, the same block is overwritten with new data. In SDDs, the data is written to different NAND cells to attain **wear-leveling**, which prolongs the life of the SSD. The main issue preventing a wide-scale adoption of SSDs today is their prohibitive cost (see Table 16.1), which tends to be about 70 to 80 cents per GB as opposed to about 15 to 20 cents per GB for HDDs.

In addition to flash memory, DRAM-based SSDs are also available. They are costlier than flash memory, but they offer faster access times of around 10 μs (microseconds) as opposed to 100 μs for flash. Their main drawback is that they need an internal battery or an adapter to supply power.

As an example of an enterprise level SSD, we can consider CISCO's UCS (Unified Computing System©) Invicta series SSDs. They have made it possible to deploy SSDs at the data center level to unify workloads of all types, including databases and virtual desktop infrastructure (VDI), and to enable a cost-effective, energy-efficient, and space-saving solution. CISCO's claim is that Invicta SSDs offer a better price-to-performance ratio to applications in a multitenant, multinetworked architecture because of the advantages of SSDs stated above. CISCO states that typically four times as many HDD drives may be needed to match an SSD-based RAID in performance.[6] The SSD configuration can have a capacity from 6 to 144 TB, with up to 1.2 million I/O operations/second, and a bandwidth of up to 7.2 GB/sec with an average latency of 200 μs.[7] Modern data centers are undergoing rapid transformation and must provide real-time response using cloud-based architectures. In this environment, SSDs are likely to play a major role.

### 16.2.4 Magnetic Tape Storage Devices

Disks are **random access** secondary storage devices because an arbitrary disk block may be accessed *at random* once we specify its address. Magnetic tapes are sequential access devices; to access the *n*th block on tape, first we must scan the preceding

[6]Based on the CISCO White Paper (CISCO, 2014)

[7]Data sheet for CISCO UCS Invicta Scaling System.

$n - 1$ blocks. Data is stored on reels of high-capacity magnetic tape, somewhat similar to audiotapes or videotapes. A tape drive is required to read the data from or write the data to a **tape reel**. Usually, each group of bits that forms a byte is stored across the tape, and the bytes themselves are stored consecutively on the tape.

A read/write head is used to read or write data on tape. Data records on tape are also stored in blocks—although the blocks may be substantially larger than those for disks, and interblock gaps are also quite large. With typical tape densities of 1,600 to 6,250 bytes per inch, a typical interblock gap[8] of 0.6 inch corresponds to 960 to 3,750 bytes of wasted storage space. It is customary to group many records together in one block for better space utilization.

The main characteristic of a tape is its requirement that we access the data blocks in **sequential order**. To get to a block in the middle of a reel of tape, the tape is mounted and then scanned until the required block gets under the read/write head. For this reason, tape access can be slow and tapes are not used to store online data, except for some specialized applications. However, tapes serve a very important function—**backing up** the database. One reason for backup is to keep copies of disk files in case the data is lost due to a disk crash, which can happen if the disk read/write head touches the disk surface because of mechanical malfunction. For this reason, disk files are copied periodically to tape. For many online critical applications, such as airline reservation systems, to avoid any downtime, mirrored systems are used to keep three sets of identical disks—two in online operation and one as backup. Here, offline disks become a backup device. The three are rotated so that they can be switched in case there is a failure on one of the live disk drives. Tapes can also be used to store excessively large database files. Database files that are seldom used or are outdated but required for historical recordkeeping can be **archived** on tape. Originally, half-inch reel tape drives were used for data storage employing the so-called nine-track tapes. Later, smaller 8-mm magnetic tapes (similar to those used in camcorders) that can store up to 50 GB, as well as 4-mm helical scan data cartridges and writable CDs and DVDs, became popular media for backing up data files from PCs and workstations. They are also used for storing images and system libraries.

Backing up enterprise databases so that no transaction information is lost is a major undertaking. Tape libraries were in vogue and featured slots for several hundred cartridges; these tape libraries used digital and superdigital linear tapes (DLTs and SDLTs), both of which have capacities in the hundreds of gigabytes and record data on linear tracks. These tape libraries are no longer in further development. The LTO (Linear Tape Open) consortium set up by IBM, HP, and Seagate released the latest LTO-6 standard in 2012 for tapes. It uses ½-inch-wide magnetic tapes like those used in earlier tape drives but in a somewhat smaller, single-reel enclosed cartridge. Current generation of libraries use LTO-6 drives, at 2.5-TB cartridge with 160 MB/s transfer rate. Average seek time is about 80 seconds. The T10000D drive of Oracle/StorageTek handles 8.5 TB on a single cartridge with transfer rate upto 252 MB/s.

[8]Called *interrecord gaps* in tape terminology.

Robotic arms write on multiple cartridges in parallel using multiple tape drives and automatic labeling software to identify the backup cartridges. An example of a giant library is the SL8500 model of Sun Storage Technology. The SL8500 scales from 1,450 to just over 10,000 slots and from 1 to 64 tape drives within each library. It accepts both DLT/SDLT and LTO tapes. Up to 10 SL8500s can be connected within a single library complex for over 100,000 slots and up to 640 drives. With 100,000 slots, the SL8500 can store 2.1 exabytes (exabyte = 1,000 petabytes, or million TB = 10**18 bytes). We defer the discussion of disk storage technology called RAID, and of storage area networks, network-attached storage, and iSCSI storage systems, to the end of the chapter.

## 16.3 Buffering of Blocks

When several blocks need to be transferred from disk to main memory and all the block addresses are known, several buffers can be reserved in main memory to speed up the transfer. While one buffer is being read or written, the CPU can process data in the other buffer because an independent disk I/O processor (controller) exists that, once started, can proceed to transfer a data block between memory and disk independent of and in parallel to CPU processing.

Figure 16.3 illustrates how two processes can proceed in parallel. Processes A and B are running **concurrently** in an **interleaved** fashion, whereas processes C and D are running **concurrently** in a **parallel** fashion. When a single CPU controls multiple processes, parallel execution is not possible. However, the processes can still run concurrently in an interleaved way. Buffering is most useful when processes can run concurrently in a parallel fashion, either because a separate disk I/O processor is available or because multiple CPU processors exist.

Figure 16.4 illustrates how reading and processing can proceed in parallel when the time required to process a disk block in memory is less than the time required to

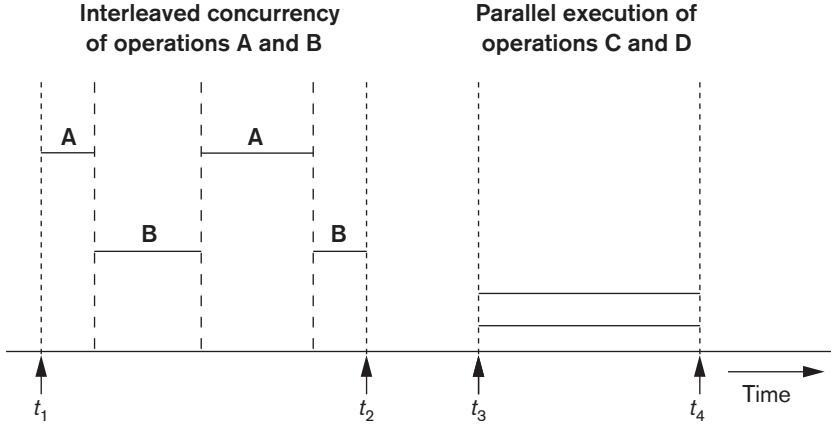


**Figure 16.3**
Interleaved concurrency versus parallel execution.

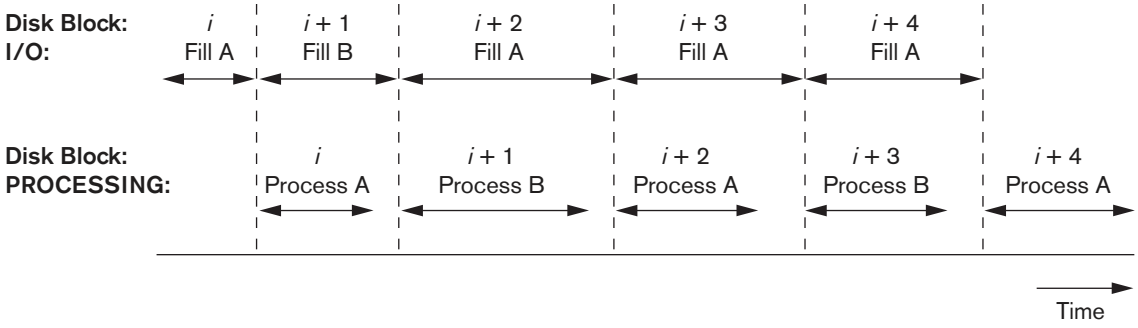


**Figure 16.4**
Use of two buffers, A and B, for reading from disk.

read the next block and fill a buffer. The CPU can start processing a block once its transfer to main memory is completed; at the same time, the disk I/O processor can be reading and transferring the next block into a different buffer. This technique is called **double buffering** and can also be used to read a continuous stream of blocks from disk to memory. Double buffering permits continuous reading or writing of data on consecutive disk blocks, which eliminates the seek time and rotational delay for all but the first block transfer. Moreover, data is kept ready for processing, thus reducing the waiting time in the programs.

### 16.3.1 Buffer Management

**Buffer management and Replacement Strategies.** For most large database files containing millions of pages, it is not possible to bring all of the data into main memory at the same time. We alluded to double buffering as a technique whereby we can gain efficiency in terms of performing the I/O operation between the disk and main memory into one buffer area concurrently with processing the data from another buffer. The actual management of buffers and decisions about what buffers to use to place a newly read page in the buffer is a more complex process. We use the term **buffer** to refer to a part of main memory that is available to receive blocks or pages of data from disk.[9] **Buffer manager** is a software component of a DBMS that responds to requests for data and decides what buffer to use and what pages to replace in the buffer to accommodate the newly requested blocks. The buffer manager views the available main memory storage as a **buffer pool**, which has a collection of pages. The size of the shared buffer pool is typically a parameter for the DBMS controlled by DBAs. In this section, we briefly discuss the workings of the buffer manager and discuss a few replacement strategies.

[9]We use the terms page and block interchangeably in the current context.

There are two kinds of buffer managers; the first kind controls the main memory directly, as in most RDBMSs. The second kind allocates buffers in virtual memory, which allows the control to transfer to the operating system (OS). The OS in turn controls which buffers are actually in main memory and which ones are on disk under the control of OS. This second kind of buffer manager is common in main memory database systems and some object-oriented DBMSs. The overall goal of the buffer manager is twofold: (1) to maximize the probability that the requested page is found in main memory, and (2) in case of reading a new disk block from disk, to find a page to replace that will cause the least harm in the sense that it will not be required shortly again.

To enable its operation, the buffer manager keeps two types of information on hand about each page in the buffer pool:

1. A **pin-count**: the number of times that page has been requested, or the number of current users of that page. If this count falls to zero, the page is considered **unpinned**. Initially the pin-count for every page is set to zero. Incrementing the pin-count is called **pinning**. In general, a pinned block should not be allowed to be written to disk.
2. A **dirty bit**, which is initially set to zero for all pages but is set to 1 whenever that page is updated by any application program.

In terms of storage management, the buffer manager has the following responsibility: It must make sure that the number of buffers fits in main memory. If the requested amount of data exceeds available buffer space, the buffer manager must select what buffers must be emptied, as governed by the buffer replacement policy in force. If the buffer manager allocates space in virtual memory and all buffers in use exceed the actual main memory, then the common operating system problem of "thrashing" happens and pages get moved back and forth into the swap space on disk without performing useful work.

When a certain page is requested, the buffer manager takes following actions: it checks if the requested page is already in a buffer in the buffer pool; if so, it increments its pin-count and releases the page. If the page is not in the buffer pool, the buffer manager does the following:

a. It chooses a page for replacement, using the replacement policy, and increments its pin-count.
b. If the dirty bit of the replacement page is on, the buffer manager writes that page to disk by replacing its old copy on disk. If the dirty bit is not on, this page is not modified and the buffer manager is not required to write it back to disk.
c. It reads the requested page into the space just freed up.
d. The main memory address of the new page is passed to the requesting application.

If there is no unpinned page available in the buffer pool and the requested page is not available in the buffer pool, the buffer manager may have to wait until a page gets released. A transaction requesting this page may go into a wait state or may even be aborted.

### 16.3.2 Buffer Replacement Strategies:

The following are some popular replacement strategies that are similar to those used elsewhere, such as in operating systems:

1. Least recently used (LRU): The strategy here is to throw out that page that has not been used (read or written) for the longest time. This requires the buffer manager to maintain a table where it records the time every time a page in a buffer is accessed. Whereas this constitutes an overhead, the strategy works well because for a buffer that is not used for a long time, its chance of being accessed again is small.
2. Clock policy: This is a round-robin variant of the LRU policy. Imagine the buffers are arranged like a circle similar to a clock. Each buffer has a flag with a 0 or 1 value. Buffers with a 0 are vulnerable and may be used for replacement and their contents read back to disk. Buffers with a 1 are not vulnerable. When a block is read into a buffer, the flag is set to 1. When the buffer is accessed, the flag is set to 1 also. The clock hand is positioned on a "current buffer." When the buffer manager needs a buffer for a new block, it rotates the hand until it finds a buffer with a 0 and uses that to read and place the new block. (If the dirty bit is on for the page being replaced, that page will be written to disk, thus overwriting the old page at its address on disk.) If the clock hand passes buffers with 1s, it sets them to a zero. Thus, a block is replaced from its buffer only if it is not accessed until the hand completes a rotation and returns to it and finds the block with the 0 that it set the last time.
3. First-in-first-out (FIFO): Under this policy, when a buffer is required, the one that has been occupied the longest by a page is used for replacement. Under this policy, the manager notes the time each page gets loaded into a buffer; but it does not have to keep track of the time pages are accessed. Although FIFO needs less maintenance than LRU, it can work counter to desirable behavior. A block that remains in the buffer for a long time because it is needed continuously, such as a root block of an index, may be thrown out but may be immediately required to be brought back.

LRU and clock policies are not the best policies for database applications if they require sequential scans of data and the file cannot fit into the buffer at one time. There are also situations when certain pages in buffers cannot be thrown out and written out to disk because certain other pinned pages point to those pages. Also, policies like FIFO can be modified to make sure that pinned blocks, such as root block of an index, are allowed to remain in the buffer. Modification of the clock policy also exists where important buffers can be set to higher values than 1 and therefore will not be subjected to replacement for several rotations of the hand. There are also situations when the DBMS has the ability to write certain blocks to disk even when the space occupied by those blocks is not needed. This is called **force-writing** and occurs typically when log records have to be written to disk ahead of the modified pages in a transaction for recovery purposes. (See Chapter 22.) There are some other replacement strategies such as **MRU (most recently used)**

that work well for certain types of database transactions, such as when a block that is used most recently is not needed until all the remaining blocks in the relation are processed.

## 16.4 Placing File Records on Disk

Data in a database is regarded as a set of records organized into a set of files. In this section, we define the concepts of records, record types, and files. Then we discuss techniques for placing file records on disk. Note that henceforth in this chapter we will be referring to the random access persistent secondary storage as "disk drive" or "disk." The disk may be in different forms; for example, magnetic disks with rotational memory or solid-state disks with electronic access and no mechanical delays.

### 16.4.1 Records and Record Types

Data is usually stored in the form of **records**. Each record consists of a collection of related data **values** or **items**, where each value is formed of one or more bytes and corresponds to a particular **field** of the record. Records usually describe entities and their attributes. For example, an EMPLOYEE record represents an employee entity, and each field value in the record specifies some attribute of that employee, such as Name, Birth_date, Salary, or Supervisor. A collection of field names and their corresponding data types constitutes a **record type** or **record format** definition. A **data type**, associated with each field, specifies the types of values a field can take.

The data type of a field is usually one of the standard data types used in programming. These include numeric (integer, long integer, or floating point), string of characters (fixed-length or varying), Boolean (having 0 and 1 or TRUE and FALSE values only), and sometimes specially coded **date** and **time** data types. The number of bytes required for each data type is fixed for a given computer system. An integer may require 4 bytes, a long integer 8 bytes, a real number 4 bytes, a Boolean 1 byte, a date 10 bytes (assuming a format of YYYY-MM-DD), and a fixed-length string of $k$ characters $k$ bytes. Variable-length strings may require as many bytes as there are characters in each field value. For example, an EMPLOYEE record type may be defined—using the C programming language notation—as the following structure:

```
struct employee{
    char name[30];
    char ssn[9];
    int salary;
    int job_code;
    char department[20];
} ;
```

In some database applications, the need may arise for storing data items that consist of large unstructured objects, which represent images, digitized video or audio streams, or free text. These are referred to as **BLOB**s (binary large objects). A BLOB data item is typically stored separately from its record in a pool of disk blocks, and

a pointer to the BLOB is included in the record. For storing free text, some DBMSs (e.g., Oracle, DB2, etc.) provide a data type called CLOB (character large object); some DBMSs call this data type text.

### 16.4.2 Files, Fixed-Length Records, and Variable-Length Records

A **file** is a *sequence* of records. In many cases, all records in a file are of the same record type. If every record in the file has exactly the same size (in bytes), the file is said to be made up of **fixed-length records**. If different records in the file have different sizes, the file is said to be made up of **variable-length records**. A file may have variable-length records for several reasons:

- The file records are of the same record type, but one or more of the fields are of varying size (**variable-length fields**). For example, the Name field of EMPLOYEE can be a variable-length field.
- The file records are of the same record type, but one or more of the fields may have multiple values for individual records; such a field is called a **repeating field** and a group of values for the field is often called a **repeating group**.
- The file records are of the same record type, but one or more of the fields are **optional**; that is, they may have values for some but not all of the file records (**optional fields**).
- The file contains records of *different record types* and hence of varying size (**mixed file**). This would occur if related records of different types were *clustered* (placed together) on disk blocks; for example, the GRADE_REPORT records of a particular student may be placed following that STUDENT's record.

The fixed-length EMPLOYEE records in Figure 16.5(a) have a record size of 71 bytes. Every record has the same fields, and field lengths are fixed, so the system can identify the starting byte position of each field relative to the starting position of the record. This facilitates locating field values by programs that access such files. Notice that it is possible to represent a file that logically should have variable-length records as a fixed-length records file. For example, in the case of optional fields, we could have *every field* included in *every file record* but store a special NULL value if no value exists for that field. For a repeating field, we could allocate as many spaces in each record as the *maximum possible number of occurrences* of the field. In either case, space is wasted when certain records do not have values for all the physical spaces provided in each record. Now we consider other options for formatting records of a file of variable-length records.

For *variable-length fields,* each record has a value for each field, but we do not know the exact length of some field values. To determine the bytes within a particular record that represent each field, we can use special **separator** characters (such as ? or % or $)—which do not appear in any field value—to terminate variable-length fields, as shown in Figure 16.5(b), or we can store the length in bytes of the field in the record, preceding the field value.

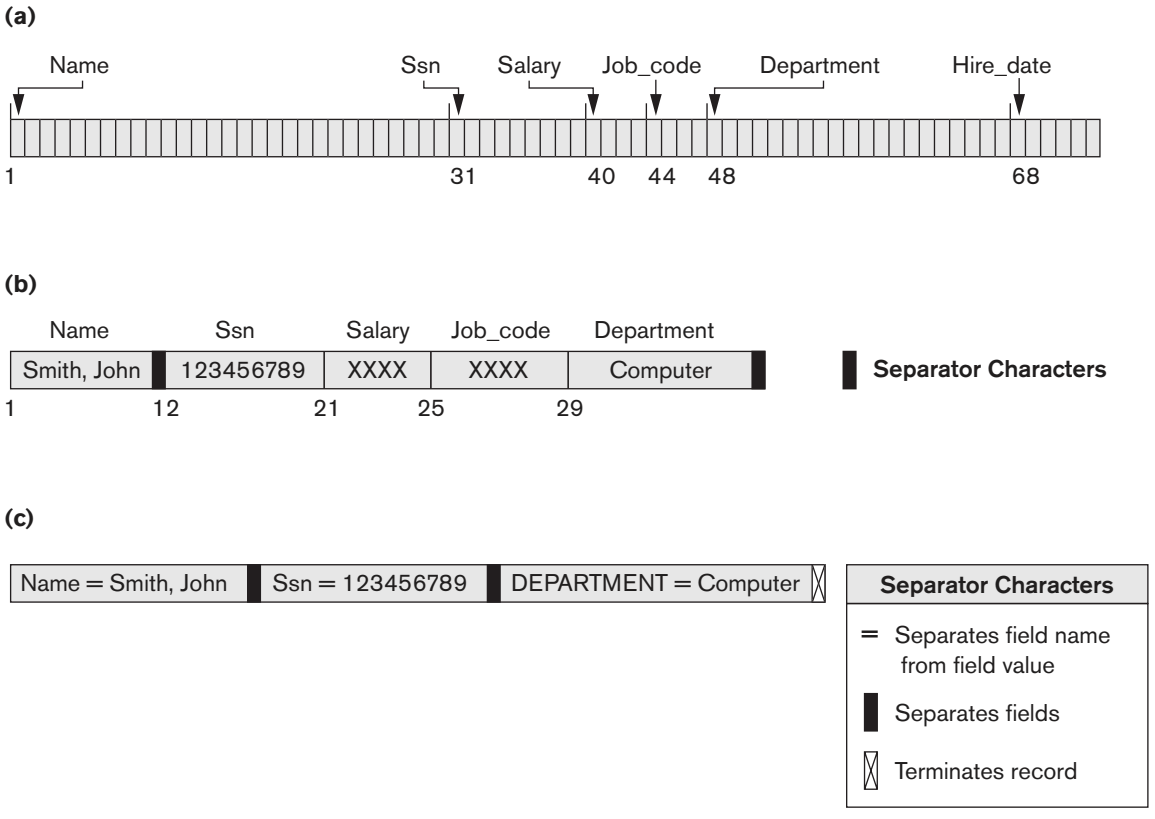


**Figure 16.5**
Three record storage formats. (a) A fixed-length record with six fields and size of 71 bytes. (b) A record with two variable-length fields and three fixed-length fields. (c) A variable-field record with three types of separator characters.

A file of records with *optional fields* can be formatted in different ways. If the total number of fields for the record type is large, but the number of fields that actually appear in a typical record is small, we can include in each record a sequence of <field-name, field-value> pairs rather than just the field values. Three types of separator characters are used in Figure 16.5(c), although we could use the same separator character for the first two purposes—separating the field name from the field value and separating one field from the next field. A more practical option is to assign a short **field type** code—say, an integer number—to each field and include in each record a sequence of <field-type, field-value> pairs rather than <field-name, field-value> pairs.

A *repeating field* needs one separator character to separate the repeating values of the field and another separator character to indicate termination of the field. Finally, for a file that includes *records of different types,* each record is preceded by a **record**

**type** indicator. Understandably, programs that process files of variable-length records—which are usually part of the file system and hence hidden from the typical programmers—need to be more complex than those for fixed-length records, where the starting position and size of each field are known and fixed.[10]

### 16.4.3 Record Blocking and Spanned versus Unspanned Records

The records of a file must be allocated to disk blocks because a block is the *unit of data transfer* between disk and memory. When the block size is larger than the record size, each block will contain numerous records, although some files may have unusually large records that cannot fit in one block. Suppose that the block size is $B$ bytes. For a file of fixed-length records of size $R$ bytes, with $B \geq R$, we can fit $bfr = \lfloor B/R \rfloor$ records per block, where the $\lfloor (x) \rfloor$ (*floor function*) *rounds down* the number $x$ to an integer. The value *bfr* is called the **blocking factor** for the file. In general, $R$ may not divide $B$ exactly, so we have some unused space in each block equal to

$$B - (bfr * R) \text{ bytes}$$

To utilize this unused space, we can store part of a record on one block and the rest on another. A **pointer** at the end of the first block points to the block containing the remainder of the record in case it is not the next consecutive block on disk. This organization is called **spanned** because records can span more than one block. Whenever a record is larger than a block, we *must* use a spanned organization. If records are not allowed to cross block boundaries, the organization is called **unspanned**. This is used with fixed-length records having $B > R$ because it makes each record start at a known location in the block, simplifying record processing. For variable-length records, either a spanned or an unspanned organization can be used. If the average record is large, it is advantageous to use spanning to reduce the lost space in each block. Figure 16.6 illustrates spanned versus unspanned organization.

For variable-length records using spanned organization, each block may store a different number of records. In this case, the blocking factor *bfr* represents the *average*

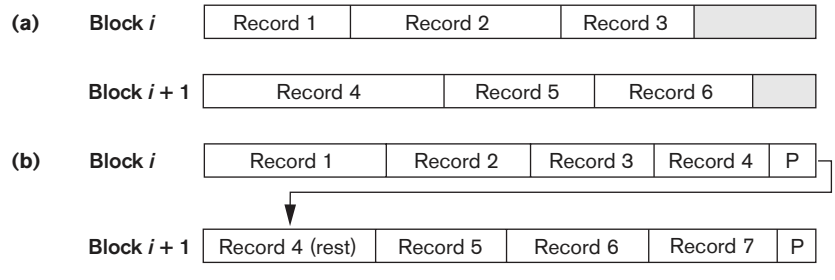


**Figure 16.6**
Types of record organization. (a) Unspanned. (b) Spanned.

[10]Other schemes are also possible for representing variable-length records.

number of records per block for the file. We can use *bfr* to calculate the number of blocks *b* needed for a file of *r* records:

$$b = \lceil (r/bfr) \rceil \text{ blocks}$$

where the $\lceil (x) \rceil$ (*ceiling function*) rounds the value $x$ up to the next integer.

### 16.4.4 Allocating File Blocks on Disk

There are several standard techniques for allocating the blocks of a file on disk. In **contiguous allocation**, the file blocks are allocated to consecutive disk blocks. This makes reading the whole file very fast using double buffering, but it makes expanding the file difficult. In **linked allocation**, each file block contains a pointer to the next file block. This makes it easy to expand the file but makes it slow to read the whole file. A combination of the two allocates **clusters** of consecutive disk blocks, and the clusters are linked. Clusters are sometimes called **file segments** or **extents**. Another possibility is to use **indexed allocation**, where one or more **index blocks** contain pointers to the actual file blocks. It is also common to use combinations of these techniques.

### 16.4.5 File Headers

A **file header** or **file descriptor** contains information about a file that is needed by the system programs that access the file records. The header includes information to determine the disk addresses of the file blocks as well as to record format descriptions, which may include field lengths and the order of fields within a record for fixed-length unspanned records and field type codes, separator characters, and record type codes for variable-length records.

To search for a record on disk, one or more blocks are copied into main memory buffers. Programs then search for the desired record or records within the buffers, using the information in the file header. If the address of the block that contains the desired record is not known, the search programs must do a **linear search** through the file blocks. Each file block is copied into a buffer and searched until the record is located or all the file blocks have been searched unsuccessfully. This can be very time-consuming for a large file. The goal of a good file organization is to avoid linear search or full scan of the file and to locate the block that contains a desired record with a minimal number of block transfers.

## 16.5 Operations on Files

Operations on files are usually grouped into **retrieval operations** and **update operations**. The former do not change any data in the file, but only locate certain records so that their field values can be examined and processed. The latter change the file by insertion or deletion of records or by modification of field values. In either case, we may have to **select** one or more records for retrieval, deletion, or modification based on a **selection condition** (or **filtering condition**), which specifies criteria that the desired record or records must satisfy.

Consider an EMPLOYEE file with fields Name, Ssn, Salary, Job_code, and Department. A **simple selection condition** may involve an equality comparison on some field value—for example, (Ssn = '123456789') or (Department = 'Research'). More complex conditions can involve other types of comparison operators, such as > or ≥ ; an example is (Salary ≥ 30000). The general case is to have an arbitrary Boolean expression on the fields of the file as the selection condition.

Search operations on files are generally based on simple selection conditions. A complex condition must be decomposed by the DBMS (or the programmer) to extract a simple condition that can be used to locate the records on disk. Each located record is then checked to determine whether it satisfies the full selection condition. For example, we may extract the simple condition (Department = 'Research') from the complex condition ((Salary ≥ 30000) AND (Department = 'Research')); each record satisfying (Department = 'Research') is located and then tested to see if it also satisfies (Salary ≥ 30000).

When several file records satisfy a search condition, the *first* record—with respect to the physical sequence of file records—is initially located and designated the **current record**. Subsequent search operations commence from this record and locate the *next* record in the file that satisfies the condition.

Actual operations for locating and accessing file records vary from system to system. In the following list, we present a set of representative operations. Typically, high-level programs, such as DBMS software programs, access records by using these commands, so we sometimes refer to **program variables** in the following descriptions:

- **Open.** Prepares the file for reading or writing. Allocates appropriate buffers (typically at least two) to hold file blocks from disk, and retrieves the file header. Sets the file pointer to the beginning of the file.
- **Reset.** Sets the file pointer of an open file to the beginning of the file.
- **Find (or Locate).** Searches for the first record that satisfies a search condition. Transfers the block containing that record into a main memory buffer (if it is not already there). The file pointer points to the record in the buffer and it becomes the *current record.* Sometimes, different verbs are used to indicate whether the located record is to be retrieved or updated.
- **Read (or Get).** Copies the current record from the buffer to a program variable in the user program. This command may also advance the current record pointer to the next record in the file, which may necessitate reading the next file block from disk.
- **FindNext.** Searches for the next record in the file that satisfies the search condition. Transfers the block containing that record into a main memory buffer (if it is not already there). The record is located in the buffer and becomes the current record. Various forms of FindNext (for example, FindNext record within a current parent record, FindNext record of a given type, or FindNext record where a complex condition is met) are available in legacy DBMSs based on the hierarchical and network models.

- **Delete.** Deletes the current record and (eventually) updates the file on disk to reflect the deletion.
- **Modify.** Modifies some field values for the current record and (eventually) updates the file on disk to reflect the modification.
- **Insert.** Inserts a new record in the file by locating the block where the record is to be inserted, transferring that block into a main memory buffer (if it is not already there), writing the record into the buffer, and (eventually) writing the buffer to disk to reflect the insertion.
- **Close.** Completes the file access by releasing the buffers and performing any other needed cleanup operations.

The preceding (except for Open and Close) are called **record-at-a-time** operations because each operation applies to a single record. It is possible to streamline the operations Find, FindNext, and Read into a single operation, Scan, whose description is as follows:

- **Scan.** If the file has just been opened or reset, *Scan* returns the first record; otherwise it returns the next record. If a condition is specified with the operation, the returned record is the first or next record satisfying the condition.

In database systems, additional **set-at-a-time** higher-level operations may be applied to a file. Examples of these are as follows:

- **FindAll.** Locates *all* the records in the file that satisfy a search condition.
- **Find (or Locate)** $n$**.** Searches for the first record that satisfies a search condition and then continues to locate the next $n - 1$ records satisfying the same condition. Transfers the blocks containing the $n$ records to the main memory buffer (if not already there).
- **FindOrdered.** Retrieves all the records in the file in some specified order.
- **Reorganize.** Starts the reorganization process. As we shall see, some file organizations require periodic reorganization. An example is to reorder the file records by sorting them on a specified field.

At this point, it is worthwhile to note the difference between the terms *file organization* and *access method.* A **file organization** refers to the organization of the data of a file into records, blocks, and access structures; this includes the way records and blocks are placed on the storage medium and interlinked. An **access method**, on the other hand, provides a group of operations—such as those listed earlier—that can be applied to a file. In general, it is possible to apply several access methods to a file organized using a certain organization. Some access methods, though, can be applied only to files organized in certain ways. For example, we cannot apply an indexed access method to a file without an index (see Chapter 17).

Usually, we expect to use some search conditions more than others. Some files may be **static**, meaning that update operations are rarely performed; other, more **dynamic** files may change frequently, so update operations are constantly applied to them. If a file is not updatable by the end user, it is regarded as a read-only file.

Most data warehouses (see Chapter 29) predominantly contain read-only files. A successful file organization should perform as efficiently as possible the operations we expect to *apply frequently* to the file. For example, consider the EMPLOYEE file, as shown in Figure 16.5(a), which stores the records for current employees in a company. We expect to insert records (when employees are hired), delete records (when employees leave the company), and modify records (for example, when an employee's salary or job is changed). Deleting or modifying a record requires a selection condition to identify a particular record or set of records. Retrieving one or more records also requires a selection condition.

If users expect mainly to apply a search condition based on Ssn, the designer must choose a file organization that facilitates locating a record given its Ssn value. This may involve physically ordering the records by Ssn value or defining an index on Ssn (see Chapter 17). Suppose that a second application uses the file to generate employees' paychecks and requires that paychecks are grouped by department. For this application, it is best to order employee records by department and then by name within each department. The clustering of records into blocks and the organization of blocks on cylinders would now be different than before. However, this arrangement conflicts with ordering the records by Ssn values. If both applications are important, the designer should choose an organization that allows both operations to be done efficiently. Unfortunately, in many cases a single organization does not allow all needed operations on a file to be implemented efficiently. Since a file can be stored only once using one particular organization, the DBAs are often faced with making a difficult design choice about the file organization. They make it based on the expected importance and mix of retrieval and update operations.

In the following sections and in Chapter 17, we discuss methods for organizing records of a file on disk. Several general techniques, such as ordering, hashing, and indexing, are used to create access methods. Additionally, various general techniques for handling insertions and deletions work with many file organizations.

## 16.6 Files of Unordered Records (Heap Files)

In this simplest and most basic type of organization, records are placed in the file in the order in which they are inserted, so new records are inserted at the end of the file. Such an organization is called a **heap** or **pile file**.[11] This organization is often used with additional access paths, such as the secondary indexes discussed in Chapter 17. It is also used to collect and store data records for future use.

Inserting a new record is *very efficient*. The last disk block of the file is copied into a buffer, the new record is added, and the block is then **rewritten** back to disk. The address of the last file block is kept in the file header. However, searching for a record using any search condition involves a **linear search** through the file block by block—an expensive procedure. If only one record satisfies the search condition, then, on the average, a program will read into memory and search half the file

[11]Sometimes this organization is called a **sequential file**.

blocks before it finds the record. For a file of $b$ blocks, this requires searching $(b/2)$ blocks, on average. If no records or several records satisfy the search condition, the program must read and search all $b$ blocks in the file.

To delete a record, a program must first find its block, copy the block into a buffer, delete the record from the buffer, and finally **rewrite the block** back to the disk. This leaves unused space in the disk block. Deleting a large number of records in this way results in wasted storage space. Another technique used for record deletion is to have an extra byte or bit, called a **deletion marker**, stored with each record. A record is deleted by setting the deletion marker to a certain value. A different value for the marker indicates a valid (not deleted) record. Search programs consider only valid records in a block when conducting their search. Both of these deletion techniques require periodic **reorganization** of the file to reclaim the unused space of deleted records. During reorganization, the file blocks are accessed consecutively, and records are packed by removing deleted records. After such a reorganization, the blocks are filled to capacity once more. Another possibility is to use the space of deleted records when inserting new records, although this requires extra bookkeeping to keep track of empty locations.

We can use either spanned or unspanned organization for an unordered file, and it may be used with either fixed-length or variable-length records. Modifying a variable-length record may require deleting the old record and inserting a modified record because the modified record may not fit in its old space on disk.

To read all records in order of the values of some field, we create a sorted copy of the file. Sorting is an expensive operation for a large disk file, and special techniques for **external sorting** are used (see Chapter 18).

For a file of unordered *fixed-length records* using *unspanned blocks* and *contiguous allocation,* it is straightforward to access any record by its **position** in the file. If the file records are numbered 0, 1, 2, … , $r - 1$ and the records in each block are numbered 0, 1, …, $bfr - 1$, where $bfr$ is the blocking factor, then the $i$th record of the file is located in block $\lfloor (i/bfr) \rfloor$ and is the ($i$ mod $bfr$)th record in that block. Such a file is often called a **relative** or **direct file** because records can easily be accessed directly by their relative positions. Accessing a record by its position does not help locate a record based on a search condition; however, it facilitates the construction of access paths on the file, such as the indexes discussed in Chapter 17.

## 16.7 Files of Ordered Records (Sorted Files)

We can physically order the records of a file on disk based on the values of one of their fields—called the **ordering field**. This leads to an **ordered** or **sequential** file.[12] If the ordering field is also a **key field** of the file—a field guaranteed to have a unique value in each record—then the field is called the **ordering key** for the file. Figure 16.7

[12]The term *sequential file* has also been used to refer to unordered files, although it is more appropriate for ordered files.

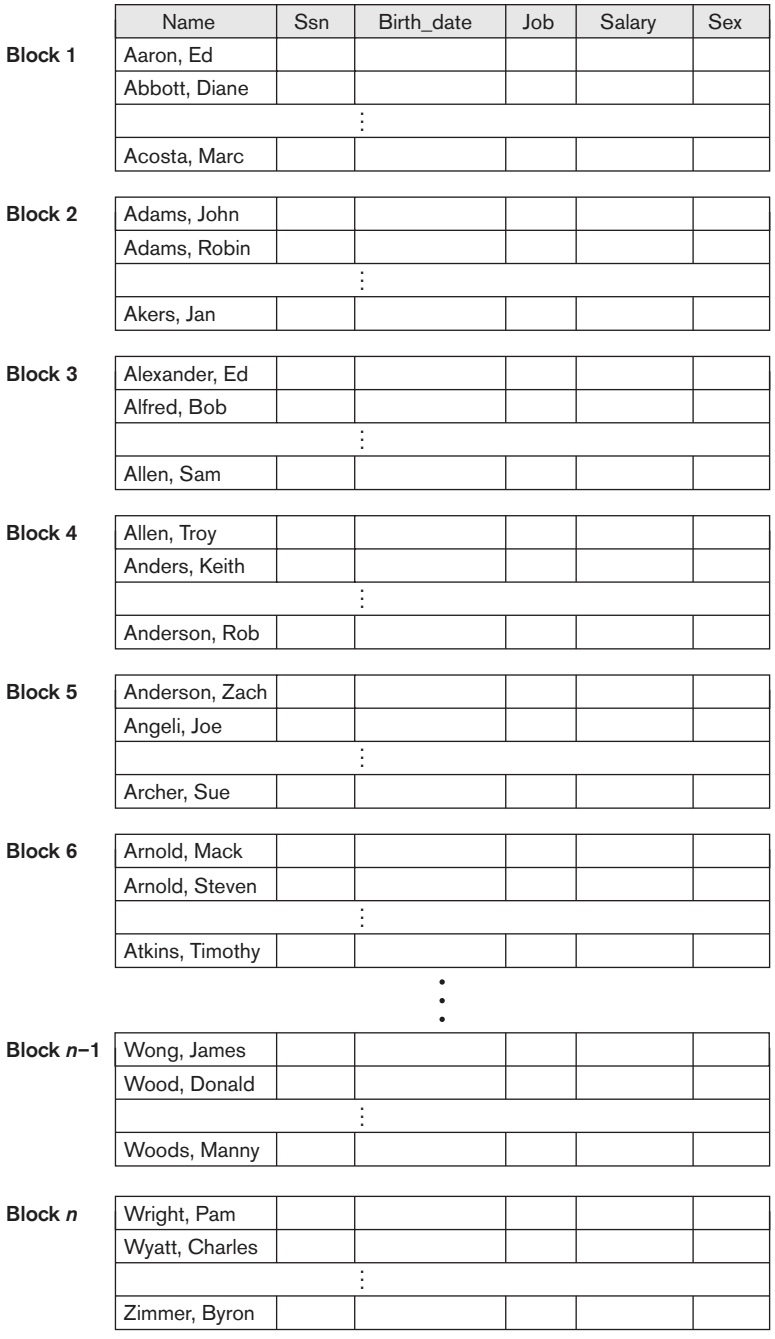


**Figure 16.7**
Some blocks of an ordered (sequential) file of EMPLOYEE records with Name as the ordering key field.

shows an ordered file with Name as the ordering key field (assuming that employees have distinct names).

Ordered records have some advantages over unordered files. First, reading the records in order of the ordering key values becomes extremely efficient because no sorting is required. The search condition may be of the type < key = value>, or a range condition such as < value1 < key < value2>. Second, finding the next record from the current one in order of the ordering key usually requires no additional block accesses because the next record is in the same block as the current one (unless the current record is the last one in the block). Third, using a search condition based on the value of an ordering key field results in faster access when the binary search technique is used, which constitutes an improvement over linear searches, although it is not often used for disk files. Ordered files are blocked and stored on contiguous cylinders to minimize the seek time.

A **binary search** for disk files can be done on the blocks rather than on the records. Suppose that the file has $b$ blocks numbered 1, 2, …, $b$; the records are ordered by ascending value of their ordering key field; and we are searching for a record whose ordering key field value is $K$. Assuming that disk addresses of the file blocks are available in the file header, the binary search can be described by Algorithm 16.1. A binary search usually accesses $\log_2(b)$ blocks, whether the record is found or not—an improvement over linear searches, where, on the average, $(b/2)$ blocks are accessed when the record is found and $b$ blocks are accessed when the record is not found.

**Algorithm 16.1.** Binary Search on an Ordering Key of a Disk File
$l \leftarrow 1$; $u \leftarrow b$; (*b is the number of file blocks*)
while ($u \geq l$) do
    **begin** $i \leftarrow (l + u)$ div 2;
    read block $i$ of the file into the buffer;
    if $K <$ (ordering key field value of the *first* record in block $i$)
        then $u \leftarrow i - 1$
    else if $K >$ (ordering key field value of the *last* record in block $i$)
        then $l \leftarrow i + 1$
    else if the record with ordering key field value = $K$ is in the buffer
        then goto found
    else goto notfound;
    **end**;
goto notfound;

A search criterion involving the conditions >, <, ≥, and ≤ on the ordering field is efficient, since the physical ordering of records means that all records satisfying the condition are contiguous in the file. For example, referring to Figure 16.7, if the search criterion is (Name > 'G')—where > means *alphabetically before*—the records satisfying the search criterion are those from the beginning of the file up to the first record that has a Name value starting with the letter 'G'.

Ordering does not provide any advantages for random or ordered access of the records based on values of the other *nonordering fields* of the file. In these cases, we

do a linear search for random access. To access the records in order based on a nonordering field, it is necessary to create another sorted copy—in a different order—of the file.

Inserting and deleting records are expensive operations for an ordered file because the records must remain physically ordered. To insert a record, we must find its correct position in the file, based on its ordering field value, and then make space in the file to insert the record in that position. For a large file this can be very time-consuming because, on the average, half the records of the file must be moved to make space for the new record. This means that half the file blocks must be read and rewritten after records are moved among them. For record deletion, the problem is less severe if deletion markers and periodic reorganization are used.

One option for making insertion more efficient is to keep some unused space in each block for new records. However, once this space is used up, the original problem resurfaces. Another frequently used method is to create a temporary *unordered* file called an **overflow** or **transaction** file. With this technique, the actual ordered file is called the **main** or **master** file. New records are inserted at the end of the overflow file rather than in their correct position in the main file. Periodically, the overflow file is sorted and merged with the master file during file reorganization. Insertion becomes very efficient, but at the cost of increased complexity in the search algorithm. One option is to keep the highest value of the key in each block in a separate field after taking into account the keys that have overflown from that block. Otherwise, the overflow file must be searched using a linear search if, after the binary search, the record is not found in the main file. For applications that do not require the most up-to-date information, overflow records can be ignored during a search.

Modifying a field value of a record depends on two factors: the search condition to locate the record and the field to be modified. If the search condition involves the ordering key field, we can locate the record using a binary search; otherwise we must do a linear search. A nonordering field can be modified by changing the record and rewriting it in the same physical location on disk—assuming fixed-length records. Modifying the ordering field means that the record can change its position in the file. This requires deletion of the old record followed by insertion of the modified record.

Reading the file records in order of the ordering field is efficient if we ignore the records in overflow, since the blocks can be read consecutively using double buffering. To include the records in overflow, we must merge them in their correct positions; in this case, first we can reorganize the file, and then read its blocks sequentially. To reorganize the file, first we sort the records in the overflow file, and then merge them with the master file. The records marked for deletion are removed during the reorganization.

Table 16.3 summarizes the average access time in block accesses to find a specific record in a file with $b$ blocks.

Ordered files are rarely used in database applications unless an additional access path, called a **primary index**, is used; this results in an **indexed-sequential file**.

**Table 16.3** Average Access Times for a File of *b* Blocks under Basic File Organizations

| Type of Organization | Access/Search Method | Average Blocks to Access a Specific Record |
|---|---|---|
| Heap (unordered) | Sequential scan (linear search) | $b/2$ |
| Ordered | Sequential scan | $b/2$ |
| Ordered | Binary search | $\log_2 b$ |

This further improves the random access time on the ordering key field. (We discuss indexes in Chapter 17.) If the ordering attribute is not a key, the file is called a **clustered file**.

# 16.8 Hashing Techniques

Another type of primary file organization is based on hashing, which provides very fast access to records under certain search conditions. This organization is usually called a **hash file**.[13] The search condition must be an equality condition on a single field, called the **hash field**. In most cases, the hash field is also a key field of the file, in which case it is called the **hash key**. The idea behind hashing is to provide a function *h*, called a **hash function** or **randomizing function**, which is applied to the hash field value of a record and yields the *address* of the disk block in which the record is stored. A search for the record within the block can be carried out in a main memory buffer. For most records, we need only a single-block access to retrieve that record.

Hashing is also used as an internal search structure within a program whenever a group of records is accessed exclusively by using the value of one field. We describe the use of hashing for internal files in Section 16.8.1; then we show how it is modified to store external files on disk in Section 16.8.2. In Section 16.8.3 we discuss techniques for extending hashing to dynamically growing files.

## 16.8.1 Internal Hashing

For internal files, hashing is typically implemented as a **hash table** through the use of an array of records. Suppose that the array index range is from 0 to $M - 1$, as shown in Figure 16.8(a); then we have $M$ **slots** whose addresses correspond to the array indexes. We choose a hash function that transforms the hash field value into an integer between 0 and $M - 1$. One common hash function is the $h(K) = K$ **mod** $M$ function, which returns the remainder of an integer hash field value $K$ after division by $M$; this value is then used for the record address.

[13] A hash file has also been called a *direct file*.

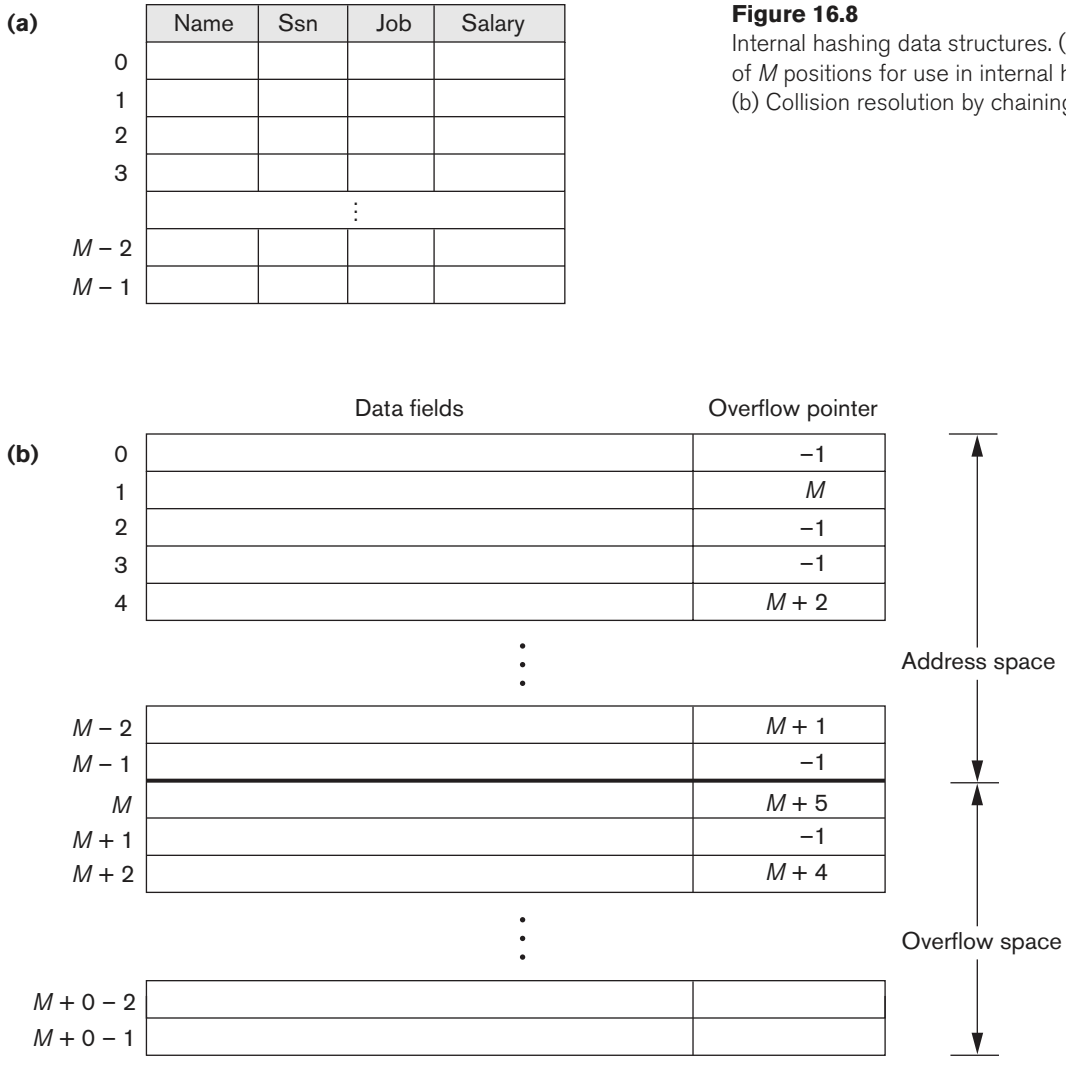


**Figure 16.8**
Internal hashing data structures. (a) Array of $M$ positions for use in internal hashing. (b) Collision resolution by chaining records.

Noninteger hash field values can be transformed into integers before the mod function is applied. For character strings, the numeric (ASCII) codes associated with characters can be used in the transformation—for example, by multiplying those code values. For a hash field whose data type is a string of 20 characters, Algorithm 16.2(a) can be used to calculate the hash address. We assume that the code function returns the numeric code of a character and that we are given a hash field value $K$ of type *K: array* [1..20] *of char* (in Pascal) or *char K*[20] (in C).

**Algorithm 16.2.** Two simple hashing algorithms: (a) Applying the mod hash function to a character string K. (b) Collision resolution by open addressing.

**(a)** *temp* ← 1;
for *i* ← 1 to 20 do *temp* ← *temp* * code(*K*[*i* ] ) mod *M* ;
*hash_address* ← *temp* mod *M*;

**(b)** *i* ← *hash_address*(*K*); *a* ← *i*;
if location *i* is occupied
then **begin** *i* ← (*i* + 1) mod *M*;
while (*i* ≠ *a*) and location *i* is occupied
do *i* ← (*i* + 1) mod *M*;
if (*i* = *a*) then all positions are full
else *new_hash_address* ← *i*;
**end**;

Other hashing functions can be used. One technique, called **folding**, involves applying an arithmetic function such as *addition* or a logical function such as *exclusive or* to different portions of the hash field value to calculate the hash address (for example, with an address space from 0 to 999 to store 1,000 keys, a 6-digit key 235469 may be folded and stored at the address: (235+964) mod 1000 = 199). Another technique involves picking some digits of the hash field value—for instance, the third, fifth, and eighth digits—to form the hash address (for example, storing 1,000 employees with Social Security numbers of 10 digits into a hash file with 1,000 positions would give the Social Security number 301-67-8923 a hash value of 172 by this hash function).[14] The problem with most hashing functions is that they do not guarantee that distinct values will hash to distinct addresses, because the **hash field space**—the number of possible values a hash field can take—is usually much larger than the **address space**—the number of available addresses for records. The hashing function maps the hash field space to the address space.

A **collision** occurs when the hash field value of a record that is being inserted hashes to an address that already contains a different record. In this situation, we must insert the new record in some other position, since its hash address is occupied. The process of finding another position is called **collision resolution**. There are numerous methods for collision resolution, including the following:

- **Open addressing.** Proceeding from the occupied position specified by the hash address, the program checks the subsequent positions in order until an unused (empty) position is found. Algorithm 16.2(b) may be used for this purpose.
- **Chaining.** For this method, various overflow locations are kept, usually by extending the array with a number of overflow positions. Additionally, a pointer field is added to each record location. A collision is resolved by placing the new record in an unused overflow location and setting the pointer of the occupied hash address location to the address of that overflow location.

[14] A detailed discussion of hashing functions is outside the scope of our presentation.

A linked list of overflow records for each hash address is thus maintained, as shown in Figure 16.8(b).

- **Multiple hashing.** The program applies a second hash function if the first results in a collision. If another collision results, the program uses open addressing or applies a third hash function and then uses open addressing if necessary. Note that the series of hash functions are used in the same order for retrieval.

Each collision resolution method requires its own algorithms for insertion, retrieval, and deletion of records. The algorithms for chaining are the simplest. Deletion algorithms for open addressing are rather tricky. Data structures textbooks discuss internal hashing algorithms in more detail.

The goal of a good hashing function is twofold: first, to distribute the records uniformly over the address space so as to minimize collisions, thus making it possible to locate a record with a given key in a single access. The second, somewhat conflicting, goal is to achieve the above yet occupy the buckets fully, thus not leaving many unused locations. Simulation and analysis studies have shown that it is usually best to keep a hash file between 70 and 90% full so that the number of collisions remains low and we do not waste too much space. Hence, if we expect to have $r$ records to store in the table, we should choose $M$ locations for the address space such that $(r/M)$ is between 0.7 and 0.9. It may also be useful to choose a prime number for $M$, since it has been demonstrated that this distributes the hash addresses better over the address space when the mod hashing function is used modulo a prime number. Other hash functions may require $M$ to be a power of 2.

### 16.8.2 External Hashing for Disk Files

Hashing for disk files is called **external hashing**. To suit the characteristics of disk storage, the target address space is made of **buckets**, each of which holds multiple records. A bucket is either one disk block or a cluster of contiguous disk blocks. The hashing function maps a key into a relative bucket number rather than assigning an absolute block address to the bucket. A table maintained in the file header converts the bucket number into the corresponding disk block address, as illustrated in Figure 16.9.

The collision problem is less severe with buckets, because as many records as will fit in a bucket can hash to the same bucket without causing problems. However, we must make provisions for the case where a bucket is filled to capacity and a new record being inserted hashes to that bucket. We can use a variation of chaining in which a pointer is maintained in each bucket to a linked list of overflow records for the bucket, as shown in Figure 16.10. The pointers in the linked list should be **record pointers**, which include both a block address and a relative record position within the block.

Hashing provides the fastest possible access for retrieving an arbitrary record given the value of its hash field. Although most good hash functions do not maintain

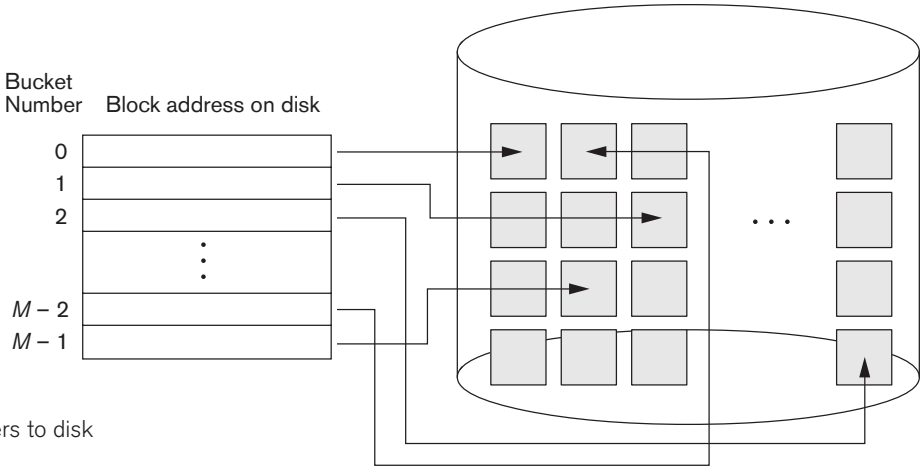


**Figure 16.9**
Matching bucket numbers to disk block addresses.

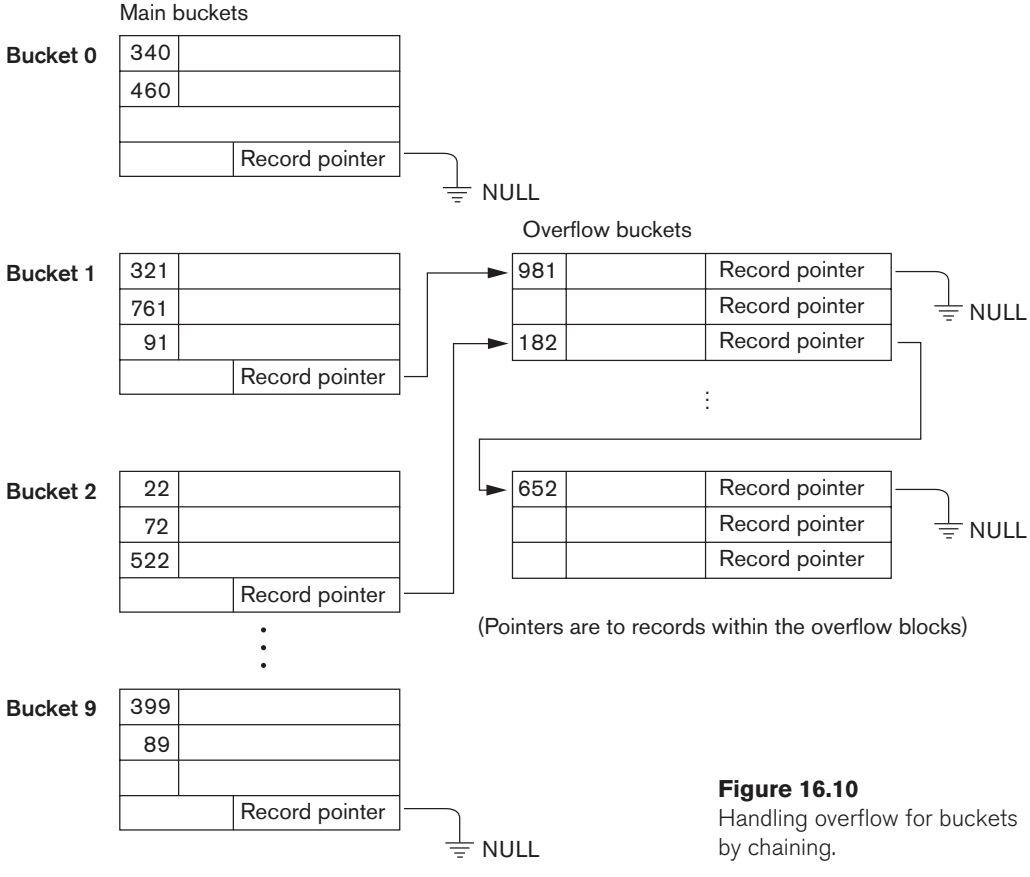


**Figure 16.10**
Handling overflow for buckets by chaining.

records in order of hash field values, some functions—called **order preserving**—do. A simple example of an order-preserving hash function is to take the leftmost three digits of an invoice number field that yields a bucket address as the hash address and keep the records sorted by invoice number within each bucket. Another example is to use an integer hash key directly as an index to a relative file, if the hash key values fill up a particular interval; for example, if employee numbers in a company are assigned as 1, 2, 3, … up to the total number of employees, we can use the identity hash function (i.e., Relative Address = Key) that maintains order. Unfortunately, this only works if sequence keys are generated in order by some application.

The hashing scheme described so far is called **static hashing** because a fixed number of buckets $M$ is allocated. The function does key-to-address mapping, whereby we are fixing the address space. This can be a serious drawback for dynamic files. Suppose that we allocate $M$ buckets for the address space and let $m$ be the maximum number of records that can fit in one bucket; then at most ($m * M$) records will fit in the allocated space. If the number of records turns out to be substantially fewer than ($m * M$), we are left with a lot of unused space. On the other hand, if the number of records increases to substantially more than ($m * M$), numerous collisions will result and retrieval will be slowed down because of the long lists of overflow records. In either case, we may have to change the number of blocks $M$ allocated and then use a new hashing function (based on the new value of $M$) to redistribute the records. These reorganizations can be quite time-consuming for large files. Newer dynamic file organizations based on hashing allow the number of buckets to vary dynamically with only localized reorganization (see Section 16.8.3).

When using external hashing, searching for a record given a value of some field other than the hash field is as expensive as in the case of an unordered file. Record deletion can be implemented by removing the record from its bucket. If the bucket has an overflow chain, we can move one of the overflow records into the bucket to replace the deleted record. If the record to be deleted is already in overflow, we simply remove it from the linked list. Notice that removing an overflow record implies that we should keep track of empty positions in overflow. This is done easily by maintaining a linked list of unused overflow locations.

Modifying a specific record's field value depends on two factors: the search condition to locate that specific record and the field to be modified. If the search condition is an equality comparison on the hash field, we can locate the record efficiently by using the hashing function; otherwise, we must do a linear search. A nonhash field can be modified by changing the record and rewriting it in the same bucket. Modifying the hash field means that the record can move to another bucket, which requires deletion of the old record followed by insertion of the modified record.

### 16.8.3 Hashing Techniques That Allow Dynamic File Expansion

A major drawback of the *static* hashing scheme just discussed is that the hash address space is fixed. Hence, it is difficult to expand or shrink the file dynamically. The schemes described in this section attempt to remedy this situation. The first

scheme—extendible hashing—stores an access structure in addition to the file, and hence is somewhat similar to indexing (see Chapter 17). The main difference is that the access structure is based on the values that result after application of the hash function to the search field. In indexing, the access structure is based on the values of the search field itself. The second technique, called linear hashing, does not require additional access structures. Another scheme, called **dynamic hashing**, uses an access structure based on binary tree data structures.

These hashing schemes take advantage of the fact that the result of applying a hashing function is a nonnegative integer and hence can be represented as a binary number. The access structure is built on the **binary representation** of the hashing function result, which is a string of **bits**. We call this the **hash value** of a record. Records are distributed among buckets based on the values of the *leading bits* in their hash values.

**Extendible Hashing.** In extendible hashing, proposed by Fagin (1979), a type of directory—an array of $2^d$ bucket addresses—is maintained, where $d$ is called the **global depth** of the directory. The integer value corresponding to the first (high-order) $d$ bits of a hash value is used as an index to the array to determine a directory entry, and the address in that entry determines the bucket in which the corresponding records are stored. However, there does not have to be a distinct bucket for each of the $2^d$ directory locations. Several directory locations with the same first $d'$ bits for their hash values may contain the same bucket address if all the records that hash to these locations fit in a single bucket. A **local depth** $d'$—stored with each bucket—specifies the number of bits on which the bucket contents are based. Figure 16.11 shows a directory with global depth $d = 3$.

The value of $d$ can be increased or decreased by one at a time, thus doubling or halving the number of entries in the directory array. Doubling is needed if a bucket, whose local depth $d'$ is equal to the global depth $d$, overflows. Halving occurs if $d > d'$ for all the buckets after some deletions occur. Most record retrievals require two block accesses—one to the directory and the other to the bucket.

To illustrate bucket splitting, suppose that a new inserted record causes overflow in the bucket whose hash values start with 01—the third bucket in Figure 16.11. The records will be distributed between two buckets: the first contains all records whose hash values start with 010, and the second all those whose hash values start with 011. Now the two directory locations for 010 and 011 point to the two new distinct buckets. Before the split, they pointed to the same bucket. The local depth $d'$ of the two new buckets is 3, which is one more than the local depth of the old bucket.

If a bucket that overflows and is split used to have a local depth $d'$ equal to the global depth $d$ of the directory, then the size of the directory must now be doubled so that we can use an extra bit to distinguish the two new buckets. For example, if the bucket for records whose hash values start with 111 in Figure 16.11 overflows, the two new buckets need a directory with global depth $d = 4$, because the two buckets are now labeled 1110 and 1111, and hence their local depths are both 4. The directory size is hence doubled, and each of the other original locations in the

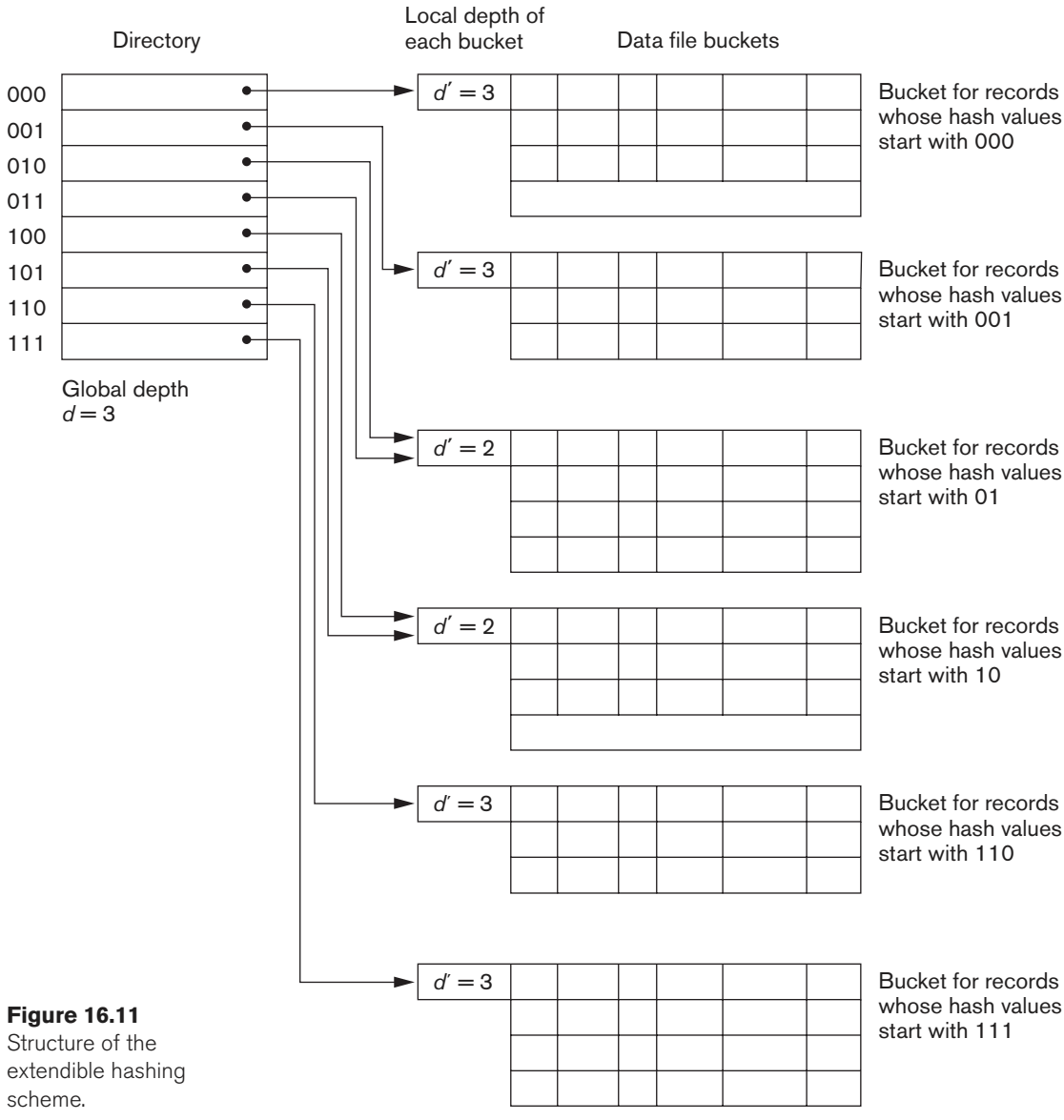


**Figure 16.11**
Structure of the extendible hashing scheme.

directory is also split into two locations, both of which have the same pointer value as did the original location.

The main advantage of extendible hashing that makes it attractive is that the *performance of the file does not degrade as the file grows*, as opposed to static external hashing, where collisions increase and the corresponding chaining effectively increases the average number of accesses per key. Additionally, no space is allocated in extendible hashing for future growth, but additional buckets can be allocated

dynamically as needed. The space overhead for the directory table is negligible. The maximum directory size is $2^k$, where $k$ is the number of bits in the hash value. Another advantage is that splitting causes minor reorganization in most cases, since only the records in one bucket are redistributed to the two new buckets. The only time reorganization is more expensive is when the directory has to be doubled (or halved). A disadvantage is that the directory must be searched before accessing the buckets themselves, resulting in two block accesses instead of one in static hashing. This performance penalty is considered minor and thus the scheme is considered quite desirable for dynamic files.

**Dynamic Hashing.** A precursor to extendible hashing was dynamic hashing proposed by Larson (1978), in which the addresses of the buckets were either the $n$ high-order bits or $n - 1$ high-order bits, depending on the total number of keys belonging to the respective bucket. The eventual storage of records in buckets for dynamic hashing is somewhat similar to extendible hashing. The major difference is in the organization of the directory. Whereas extendible hashing uses the notion of global depth (high-order $d$ bits) for the flat directory and then combines adjacent collapsible buckets into a bucket of local depth $d - 1$, dynamic hashing maintains a tree-structured directory with two types of nodes:

- Internal nodes that have two pointers—the left pointer corresponding to the 0 bit (in the hashed address) and a right pointer corresponding to the 1 bit.
- Leaf nodes—these hold a pointer to the actual bucket with records.

An example of the dynamic hashing appears in Figure 16.12. Four buckets are shown ("000", "001", "110", and "111") with high-order 3-bit addresses (corresponding to the global depth of 3), and two buckets ("01" and "10") are shown with high-order 2-bit addresses (corresponding to the local depth of 2). The latter two are the result of collapsing the "010" and "011" into "01" and collapsing "100" and "101" into "10". Note that the directory nodes are used implicitly to determine the "global" and "local" depths of buckets in dynamic hashing. The search for a record given the hashed address involves traversing the directory tree, which leads to the bucket holding that record. It is left to the reader to develop algorithms for insertion, deletion, and searching of records for the dynamic hashing scheme.

**Linear Hashing.** The idea behind linear hashing, proposed by Litwin (1980), is to allow a hash file to expand and shrink its number of buckets dynamically *without* needing a directory. Suppose that the file starts with $M$ buckets numbered 0, 1, … , $M - 1$ and uses the mod hash function $h(K) = K \bmod M$; this hash function is called the **initial hash function** $h_i$. Overflow because of collisions is still needed and can be handled by maintaining individual overflow chains for each bucket. However, when a collision leads to an overflow record in *any* file bucket, the *first* bucket in the file—bucket 0—is split into two buckets: the original bucket 0 and a new bucket $M$ at the end of the file. The records originally in bucket 0 are distributed between the two buckets based on a different hashing function $h_{i+1}(K) = K \bmod 2M$. A key property of the two hash functions $h_i$ and $h_{i+1}$ is that any records that hashed to bucket 0

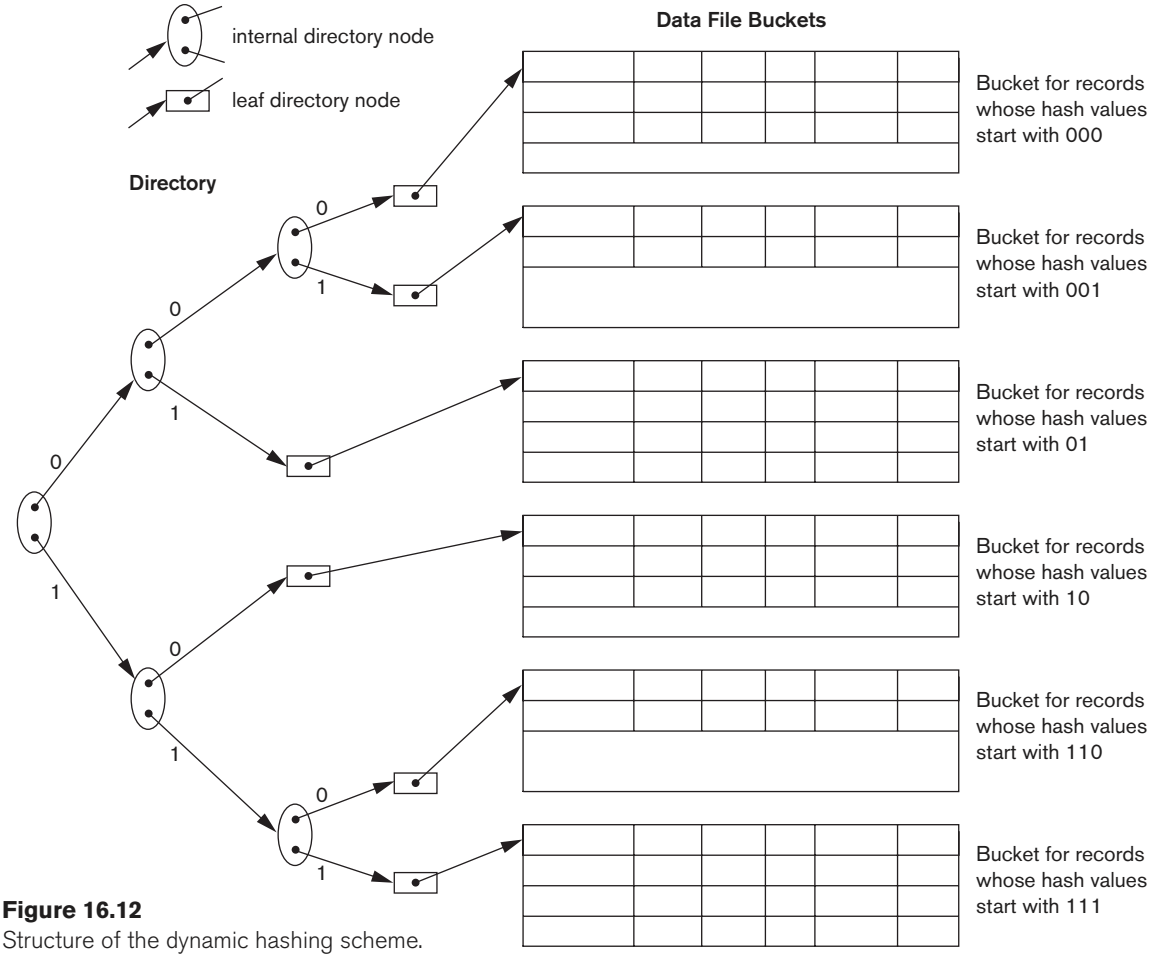


**Figure 16.12**
Structure of the dynamic hashing scheme.

based on $h_i$ will hash to either bucket 0 or bucket $M$ based on $h_{i+1}$; this is necessary for linear hashing to work.

As further collisions lead to overflow records, additional buckets are split in the *linear* order 1, 2, 3, … . If enough overflows occur, all the original file buckets 0, 1, … , $M - 1$ will have been split, so the file now has $2M$ instead of $M$ buckets, and all buckets use the hash function $h_{i+1}$. Hence, the records in overflow are eventually redistributed into regular buckets, using the function $h_{i+1}$ via a *delayed split* of their buckets. There is no directory; only a value $n$—which is initially set to 0 and is incremented by 1 whenever a split occurs—is needed to determine which buckets have been split. To retrieve a record with hash key value $K$, first apply the function $h_i$ to $K$; if $h_i(K) < n$, then apply the function $h_{i+1}$ on $K$ because the bucket is already split. Initially, $n = 0$, indicating that the function $h_i$ applies to all buckets; $n$ grows linearly as buckets are split.

When $n = M$ after being incremented, this signifies that all the original buckets have been split and the hash function $h_{i+1}$ applies to all records in the file. At this point, $n$ is reset to 0 (zero), and any new collisions that cause overflow lead to the use of a new hashing function $h_{i+2}(K) = K \bmod 4M$. In general, a sequence of hashing functions $h_{i+j}(K) = K \bmod (2^j M)$ is used, where $j = 0, 1, 2, \ldots$ ; a new hashing function $h_{i+j+1}$ is needed whenever all the buckets 0, 1, …, $(2^j M) - 1$ have been split and $n$ is reset to 0. The search for a record with hash key value $K$ is given by Algorithm 16.3.

Splitting can be controlled by monitoring the file load factor instead of by splitting whenever an overflow occurs. In general, the **file load factor** $l$ can be defined as $l = r/(bfr * N)$, where $r$ is the current number of file records, $bfr$ is the maximum number of records that can fit in a bucket, and $N$ is the current number of file buckets. Buckets that have been split can also be recombined if the load factor of the file falls below a certain threshold. Blocks are combined linearly, and $N$ is decremented appropriately. The file load can be used to trigger both splits and combinations; in this manner the file load can be kept within a desired range. Splits can be triggered when the load exceeds a certain threshold—say, 0.9—and combinations can be triggered when the load falls below another threshold—say, 0.7. The main advantages of linear hashing are that it maintains the load factor fairly constantly while the file grows and shrinks, and it does not require a directory.[15]

**Algorithm 16.3.** The Search Procedure for Linear Hashing

```
if n = 0
    then m ← h_j (K) (*m is the hash value of record with hash key K*)
    else begin
        m ← h_j (K);
        if m < n then m ← h_{j+1} (K)
        end;
```

search the bucket whose hash value is $m$ (and its overflow, if any);

# 16.9 Other Primary File Organizations

## 16.9.1 Files of Mixed Records

The file organizations we have studied so far assume that all records of a particular file are of the same record type. The records could be of EMPLOYEEs, PROJECTs, STUDENTs, or DEPARTMENTs, but each file contains records of only one type. In most database applications, we encounter situations in which numerous types of entities are interrelated in various ways, as we saw in Chapter 7. Relationships among records in various files can be represented by **connecting fields**.[16] For example, a

[15]For details of insertion and deletion into Linear hashed files, refer to Litwin (1980) and Salzberg (1988).

[16]The concept of foreign keys in the relational data model (Chapter 3) and references among objects in object-oriented models (Chapter 11) are examples of connecting fields.

STUDENT record can have a connecting field Major_dept whose value gives the name of the DEPARTMENT in which the student is majoring. This Major_dept field *refers* to a DEPARTMENT entity, which should be represented by a record of its own in the DEPARTMENT file. If we want to retrieve field values from two related records, we must retrieve one of the records first. Then we can use its connecting field value to retrieve the related record in the other file. Hence, relationships are implemented by **logical field references** among the records in distinct files.

File organizations in object DBMSs, as well as legacy systems such as hierarchical and network DBMSs, often implement relationships among records as **physical relationships** realized by physical contiguity (or clustering) of related records or by physical pointers. These file organizations typically assign an **area** of the disk to hold records of more than one type so that records of different types can be **physically clustered** on disk. If a particular relationship is expected to be used frequently, implementing the relationship physically can increase the system's efficiency at retrieving related records. For example, if the query to retrieve a DEPARTMENT record and all records for STUDENTs majoring in that department is frequent, it would be desirable to place each DEPARTMENT record and its cluster of STUDENT records contiguously on disk in a mixed file. The concept of **physical clustering** of object types is used in object DBMSs to store related objects together in a mixed file. In data warehouses (see Chapter 29), the input data comes from a variety of sources and undergoes an integration initially to collect the required data into an **operational data store (ODS)**. An ODS typically contains files where records of multiple types are kept together. It is passed on to a data warehouse after **ETL** (extract, transform and load) processing operations are performed on it.

To distinguish the records in a mixed file, each record has—in addition to its field values—a **record type** field, which specifies the type of record. This is typically the first field in each record and is used by the system software to determine the type of record it is about to process. Using the catalog information, the DBMS can determine the fields of that record type and their sizes, in order to interpret the data values in the record.

### 16.9.2 B-Trees and Other Data Structures as Primary Organization

Other data structures can be used for primary file organizations. For example, if both the record size and the number of records in a file are small, some DBMSs offer the option of a B-tree data structure as the primary file organization. We will describe B-trees in Section 17.3.1, when we discuss the use of the B-tree data structure for indexing. In general, any data structure that can be adapted to the characteristics of disk devices can be used as a primary file organization for record placement on disk. Recently, column-based storage of data has been proposed as a primary method for storage of relations in relational databases. We will briefly introduce it in Chapter 17 as a possible alternative storage scheme for relational databases.

## 16.10 Parallelizing Disk Access Using RAID Technology

With the exponential growth in the performance and capacity of semiconductor devices and memories, faster microprocessors with larger and larger primary memories are continually becoming available. To match this growth, it is natural to expect that secondary storage technology must also take steps to keep up with processor technology in performance and reliability.

A major advance in secondary storage technology is represented by the development of **RAID**, which originally stood for **redundant arrays of inexpensive disks**. More recently, the *I* in RAID is said to stand for *independent*. The RAID idea received a very positive industry endorsement and has been developed into an elaborate set of alternative RAID architectures (RAID levels 0 through 6). We highlight the main features of the technology in this section.

The main goal of RAID is to even out the widely different rates of performance improvement of disks against those in memory and microprocessors.[17] Although RAM capacities have quadrupled every two to three years, disk *access times* are improving at less than 10% per year, and disk *transfer rates* are improving at roughly 20% per year. Disk *capacities* are indeed improving at more than 50% per year, but the speed and access time improvements are of a much smaller magnitude.

A second qualitative disparity exists between the ability of special microprocessors that cater to new applications involving video, audio, image, and spatial data processing (see Chapters 26 for details of these applications), with corresponding lack of fast access to large, shared data sets.

The natural solution is a large array of small independent disks acting as a single higher performance logical disk. A concept called data striping is used, which utilizes *parallelism* to improve disk performance. **Data striping** distributes data transparently over multiple disks to make them appear as a single large, fast disk. Figure 16.13 shows a file distributed or *striped* over four disks. In **bit-level striping**, a byte is split and individual bits are stored on independent disks. Figure 16.13(a) illustrates bit-striping across four disks where the bits (0, 4) are assigned to disk 0, bits (1, 5) to disk 1, and so on. With this striping, every disk participates in every read or write operation; the number of accesses per second would remain the same as on a single disk, but the amount of data read in a given time would increase fourfold. Thus, striping improves overall I/O performance by providing high overall transfer rates. **Block-level striping** stripes blocks across disks. It treats the array of disks as if it is one disk. Blocks are logically numbered from 0 in sequence. Disks in an $m$-disk array are numbered 0 to $m$ – 1. With striping, block j goes to disk (j mod $m$). Figure 16.13(b) illustrates block striping with four disks ($m$ = 4). Data striping also accomplishes load balancing among disks. Moreover, by storing redundant information on

[17]This was predicted by Gordon Bell to be about 40% every year between 1974 and 1984 and is now supposed to exceed 50% per year.

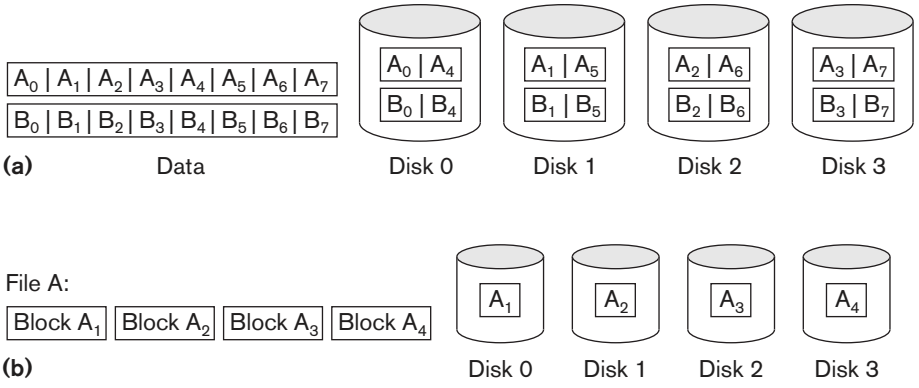


**Figure 16.13**
Striping of data across multiple disks. (a) Bit-level striping across four disks. (b) Block-level striping across four disks.

disks using parity or some other error-correction code, reliability can be improved. In Sections 16.10.1 and 16.10.2, we discuss how RAID achieves the two important objectives of improved reliability and higher performance. Section 16.10.3 discusses RAID organizations and levels.

### 16.10.1 Improving Reliability with RAID

For an array of $n$ disks, the likelihood of failure is $n$ times as much as that for one disk. Hence, if the MTBF (mean time between failures) of a disk drive is assumed to be 200,000 hours or about 22.8 years (for the disk drive in Table 16.1 called Seagate Enterprise Performance 10K HDD, it is 1.4 million hours), the MTBF for a bank of 100 disk drives becomes only 2,000 hours or 83.3 days (for a bank of 1,000 Seagate Enterprise Performance 10K HDD disks it would be 1,400 hours or 58.33 days). Keeping a single copy of data in such an array of disks will cause a significant loss of reliability. An obvious solution is to employ redundancy of data so that disk failures can be tolerated. The disadvantages are many: additional I/O operations for write, extra computation to maintain redundancy and to do recovery from errors, and additional disk capacity to store redundant information.

One technique for introducing redundancy is called **mirroring** or **shadowing**. Data is written redundantly to two identical physical disks that are treated as one logical disk. When data is read, it can be retrieved from the disk with shorter queuing, seek, and rotational delays. If a disk fails, the other disk is used until the first is repaired. Suppose the mean time to repair is 24 hours; then the mean time to data loss of a mirrored disk system using 100 disks with MTBF of 200,000 hours each is $(200{,}000)^2/(2 * 24) = 8.33 * 10^8$ hours, which is 95,028 years.[18] Disk mirroring also doubles the rate at which read requests are handled, since a read can go to either disk. The transfer rate of each read, however, remains the same as that for a single disk.

[18]The formulas for MTBF calculations appear in Chen et al. (1994).

Another solution to the problem of reliability is to store extra information that is not normally needed but that can be used to reconstruct the lost information in case of disk failure. The incorporation of redundancy must consider two problems: selecting a technique for computing the redundant information, and selecting a method of distributing the redundant information across the disk array. The first problem is addressed by using error-correcting codes involving parity bits, or specialized codes such as Hamming codes. Under the parity scheme, a redundant disk may be considered as having the sum of all the data in the other disks. When a disk fails, the missing information can be constructed by a process similar to subtraction.

For the second problem, the two major approaches are either to store the redundant information on a small number of disks or to distribute it uniformly across all disks. The latter results in better load balancing. The different levels of RAID choose a combination of these options to implement redundancy and improve reliability.

### 16.10.2 Improving Performance with RAID

The disk arrays employ the technique of data striping to achieve higher transfer rates. Note that data can be read or written only one block at a time, so a typical transfer contains 512 to 8,192 bytes. Disk striping may be applied at a finer granularity by breaking up a byte of data into bits and spreading the bits to different disks. Thus, **bit-level data striping** consists of splitting a byte of data and writing bit $j$ to the $j$th disk. With 8-bit bytes, eight physical disks may be considered as one logical disk with an eightfold increase in the data transfer rate. Each disk participates in each I/O request and the total amount of data read per request is eight times as much. Bit-level striping can be generalized to a number of disks that is either a multiple or a factor of eight. Thus, in a four-disk array, bit $n$ goes to the disk which is ($n$ mod 4). Figure 16.13(a) shows bit-level striping of data.

The granularity of data interleaving can be higher than a bit; for example, blocks of a file can be striped across disks, giving rise to **block-level striping**. Figure 16.13(b) shows block-level data striping assuming the data file contains four blocks. With block-level striping, multiple independent requests that access single blocks (small requests) can be serviced in parallel by separate disks, thus decreasing the queuing time of I/O requests. Requests that access multiple blocks (large requests) can be parallelized, thus reducing their response time. In general, the more the number of disks in an array, the larger the potential performance benefit. However, assuming independent failures, the disk array of 100 disks collectively has 1/100th the reliability of a single disk. Thus, redundancy via error-correcting codes and disk mirroring is necessary to provide reliability along with high performance.

### 16.10.3 RAID Organizations and Levels

Different RAID organizations were defined based on different combinations of the two factors of granularity of data interleaving (striping) and pattern used to compute redundant information. In the initial proposal, levels 1 through 5 of RAID were proposed, and two additional levels—0 and 6—were added later.

RAID level 0 uses data striping, has no redundant data, and hence has the best write performance since updates do not have to be duplicated. It splits data evenly across two or more disks. However, its read performance is not as good as RAID level 1, which uses mirrored disks. In the latter, performance improvement is possible by scheduling a read request to the disk with shortest expected seek and rotational delay. RAID level 2 uses memory-style redundancy by using Hamming codes, which contain parity bits for distinct overlapping subsets of components. Thus, in one particular version of this level, three redundant disks suffice for four original disks, whereas with mirroring—as in level 1—four would be required. Level 2 includes both error detection and correction, although detection is generally not required because broken disks identify themselves.

RAID level 3 uses a single parity disk relying on the disk controller to figure out which disk has failed. Levels 4 and 5 use block-level data striping, with level 5 distributing data and parity information across all disks. Figure 16.14(b) shows an illustration of RAID level 5, where parity is shown with subscript p. If one disk fails, the missing data is calculated based on the parity available from the remaining disks. Finally, RAID level 6 applies the so-called $P + Q$ redundancy scheme using Reed-Soloman codes to protect against up to two disk failures by using just two redundant disks.

Rebuilding in case of disk failure is easiest for RAID level 1. Other levels require the reconstruction of a failed disk by reading multiple disks. Level 1 is used for critical applications such as storing logs of transactions. Levels 3 and 5 are preferred for large volume storage, with level 3 providing higher transfer rates. Most popular use of RAID technology currently uses level 0 (with striping), level 1 (with mirroring), and level 5 with an extra drive for parity. A combination of multiple RAID levels are also used—for example, 0 + 1 combines striping and mirroring

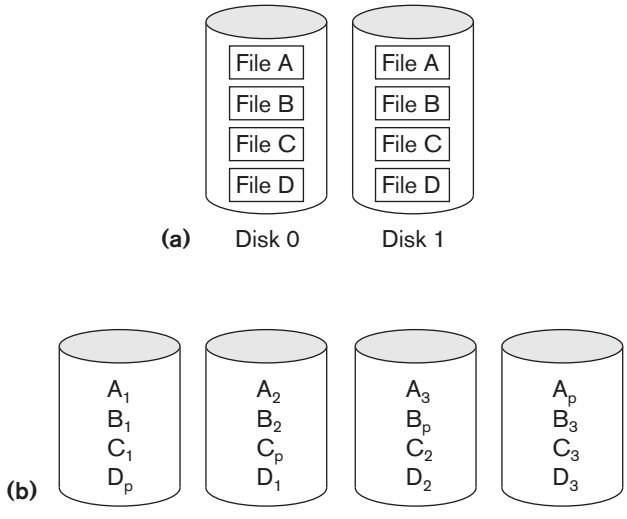


**Figure 16.14**
Some popular levels of RAID. (a) RAID level 1: Mirroring of data on two disks. (b) RAID level 5: Striping of data with distributed parity across four disks.

using a minimum of four disks. Other nonstandard RAID levels include: RAID 1.5, RAID 7, RAID-DP, RAID S or Parity RAID, Matrix RAID, RAID-K, RAID-Z, RAIDn, Linux MD RAID 10, IBM ServeRAID 1E, and unRAID. A discussion of these nonstandard levels is beyond the scope of this text. Designers of a RAID setup for a given application mix have to confront many design decisions such as the level of RAID, the number of disks, the choice of parity schemes, and grouping of disks for block-level striping. Detailed performance studies on small reads and writes (referring to I/O requests for one striping unit) and large reads and writes (referring to I/O requests for one stripe unit from each disk in an error-correction group) have been performed.

## 16.11 Modern Storage Architectures

In this section, we describe some recent developments in storage systems that are becoming an integral part of most enterprise's information system architectures. We already mentioned the SATA and SAS interface, which has almost replaced the previously popular SCSI (small computer system interface) in laptops and small servers. The Fibre Channel (FC) interface is the predominant choice for storage networks in data centers. We review some of the modern storage architectures next.

### 16.11.1 Storage Area Networks

With the rapid growth of electronic commerce, enterprise resource planning (ERP) systems that integrate application data across organizations, and data warehouses that keep historical aggregate information (see Chapter 29), the demand for storage has gone up substantially. For today's Internet-driven organizations, it has become necessary to move from a static fixed data center-oriented operation to a more flexible and dynamic infrastructure for the organizations' information processing requirements. The total cost of managing all data is growing so rapidly that in many instances the cost of managing server-attached storage exceeds the cost of the server itself. Furthermore, the procurement cost of storage is only a small fraction—typically, only 10 to 15% of the overall cost of storage management. Many users of RAID systems cannot use the capacity effectively because it has to be attached in a fixed manner to one or more servers. Therefore, most large organizations have moved to a concept called **storage area networks (SANs)**. In a SAN, online storage peripherals are configured as nodes on a high-speed network and can be attached and detached from servers in a very flexible manner.

Several companies have emerged as SAN providers and supply their own proprietary topologies. They allow storage systems to be placed at longer distances from the servers and provide different performance and connectivity options. Existing storage management applications can be ported into SAN configurations using Fibre Channel networks that encapsulate the legacy SCSI protocol. As a result, the SAN-attached devices appear as SCSI devices.

Current architectural alternatives for SAN include the following: point-to-point connections between servers and storage systems via Fiber Channel; use of a Fiber

Channel switch to connect multiple RAID systems, tape libraries, and so on to servers; and the use of Fiber Channel hubs and switches to connect servers and storage systems in different configurations. Organizations can slowly move up from simpler topologies to more complex ones by adding servers and storage devices as needed. We do not provide further details here because they vary among SAN vendors. The main advantages claimed include:

- Flexible many-to-many connectivity among servers and storage devices using Fiber Channel hubs and switches
- Up to 10 km separation between a server and a storage system using appropriate fiber optic cables
- Better isolation capabilities allowing nondisruptive addition of new peripherals and servers
- High-speed data replication across multiple storage systems. Typical technologies use synchronous replication for local and asynchronous replication for disaster recovery (DR) solutions.

SANs are growing very rapidly but are still faced with many problems, such as combining storage options from multiple vendors and dealing with evolving standards of storage management software and hardware. Most major companies are evaluating SANs as a viable option for database storage.

### 16.11.2 Network-Attached Storage

With the phenomenal growth in digital data, particularly generated from multimedia and other enterprise applications, the need for high-performance storage solutions at low cost has become extremely important. **Network-attached storage** (NAS) devices are among the storage devices being used for this purpose. These devices are, in fact, servers that do not provide any of the common server services, but simply allow the addition of storage for **file sharing**. NAS devices allow vast amounts of hard-disk storage space to be added to a network and can make that space available to multiple servers without shutting them down for maintenance and upgrades. NAS devices can reside anywhere on a local area network (LAN) and may be combined in different configurations. A single hardware device, often called the **NAS box** or **NAS head**, acts as the interface between the NAS system and network clients. These NAS devices require no monitor, keyboard, or mouse. One or more disk or tape drives can be attached to many NAS systems to increase total capacity. Clients connect to the NAS head rather than to the individual storage devices. A NAS can store any data that appears in the form of files, such as e-mail boxes, Web content, remote system backups, and so on. In that sense, NAS devices are being deployed as a replacement for traditional file servers.

NAS systems strive for reliable operation and easy administration. They include built-in features such as secure authentication, or the automatic sending of e-mail alerts in case of error on the device. The NAS devices (or *appliances*, as some vendors refer to them) are being offered with a high degree of scalability, reliability,

flexibility, and performance. Such devices typically support RAID levels 0, 1, and 5. Traditional storage area networks (SANs) differ from NAS in several ways. Specifically, SANs often utilize Fibre Channel rather than Ethernet, and a SAN often incorporates multiple network devices or *endpoints* on a self-contained or *private* LAN, whereas NAS relies on individual devices connected directly to the existing public LAN. Whereas Windows, UNIX, and NetWare file servers each demand specific protocol support on the client side, NAS systems claim greater operating system independence of clients. In summary, NAS provides a file system interface with support for networked files using protocols such as common internet file system (CIFS) or network file system (NFS).

### 16.11.3 iSCSI and Other Network-Based Storage Protocols

A new protocol called **iSCSI** (Internet SCSI) has been proposed recently. It is a block-storage protocol like SAN. It allows clients (called *initiators*) to send SCSI commands to SCSI storage devices on remote channels. The main advantage of iSCSI is that it does not require the special cabling needed by Fibre Channel and it can run over longer distances using existing network infrastructure. By carrying SCSI commands over IP networks, iSCSI facilitates data transfers over intranets and manages storage over long distances. It can transfer data over local area networks (LANs), wide area networks (WANs), or the Internet.

iSCSI works as follows. When a DBMS needs to access data, the operating system generates the appropriate SCSI commands and data request, which then go through encapsulation and, if necessary, encryption procedures. A packet header is added before the resulting IP packets are transmitted over an Ethernet connection. When a packet is received, it is decrypted (if it was encrypted before transmission) and disassembled, separating the SCSI commands and request. The SCSI commands go via the SCSI controller to the SCSI storage device. Because iSCSI is bidirectional, the protocol can also be used to return data in response to the original request. Cisco and IBM have marketed switches and routers based on this technology.

**iSCSI storage** has mainly impacted small- and medium-sized businesses because of its combination of simplicity, low cost, and the functionality of iSCSI devices. It allows them not to learn the ins and outs of Fibre Channel (FC) technology and instead benefit from their familiarity with the IP protocol and Ethernet hardware. iSCSI implementations in the data centers of very large enterprise businesses are slow in development due to their prior investment in Fibre Channel–based SANs.

iSCSI is one of two main approaches to storage data transmission over IP networks. The other method, **Fibre Channel over IP (FCIP)**, translates Fibre Channel control codes and data into IP packets for transmission between geographically distant Fibre Channel storage area networks. This protocol, known also as *Fibre Channel tunneling* or *storage tunneling*, can only be used in conjunction with Fibre Channel technology, whereas iSCSI can run over existing Ethernet networks.

The latest idea to enter the enterprise IP storage race is **Fibre Channel over Ethernet (FCoE)**, which can be thought of as iSCSI without the IP. It uses many

elements of SCSI and FC (just like iSCSI), but it does not include TCP/IP components. FCoE has been successfully productized by CISCO (termed "Data Center Ethernet") and Brocade. It takes advantage of a reliable ethernet technology that uses buffering and end-to-end flow control to avoid dropped packets. This promises excellent performance, especially on 10 Gigabit Ethernet (10GbE), and is relatively easy for vendors to add to their products.

### 16.11.4 Automated Storage Tiering

Another trend in storage is automated storage tiering (AST), which automatically moves data between different storage types such as SATA, SAS, and solid-state drives (SSDs) depending on the need. The storage administrator can set up a tiering policy in which less frequently used data is moved to slower and cheaper SATA drives and more frequently used data is moved up to solid-state drives (see Table 16.1 for the various tiers of storage ordered by increasing speed of access). This automated tiering can improve database performance tremendously.

EMC has an implementation of this technology called FAST (fully automated storage tiering) that does continuous monitoring of data activity and takes actions to move the data to the appropriate tier based on the policy.

### 16.11.5 Object-Based Storage

During the last few years, there have been major developments in terms of rapid growth of the cloud concept, distributed architectures for databases and for analytics, and development of data-intensive applications on the Web (see Chapters 23, 24, and 25). These developments have caused fundamental changes in enterprise storage infrastructure. The hardware-oriented file-based systems are evolving into new open-ended architectures for storage. The latest among these is object-based storage. Under this scheme, data is managed in the form of objects rather than files made of blocks. Objects carry metadata that contains properties that can be used for managing those objects. Each object carries a unique global identifier that is used to locate it. Object storage has its origins in research projects at CMU (Gibson et al., 1996) on scaling up of network attached storage and in the Oceanstore system at UC Berkeley (Kubiatowicz et al., 2000), which attempted to build a global infrastructure over all forms of trusted and untrusted servers for continuous access to persistent data. There is no need to do lower level storage operations in terms of capacity management or making decisions like what type of RAID architecture should be used for fault protection.

Object storage also allows additional flexibility in terms of interfaces—it gives control to applications that can control the objects directly and also allows the objects to be addressable across a wide namespace spanning multiple devices. Replication and distribution of objects is also supported. In general, object storage is ideally suited for scalable storage of massive amounts of unstructured data such as Web pages, images, and audio/video clips and files. Object-based storage device commands (OSDs) were proposed as part of SCSI protocol a long time ago but did not

become a commercial product until Seagate adopted OSDs in its Kinetic Open Storage Platform. Currently, Facebook uses an object storage system to store photos at the level of over 350 Petabytes of storage; Spotify uses an object storage system for storing songs; and Dropbox uses it for its storage infrastructure. Object storage is the choice of many cloud offerings, such as Amazon's AWS (Amazon Web Service) S3, and Microsoft's Azure, which stores files, relations, messages, and so on as objects. Other examples of products include Hitachi's HCP, EMC's Atmos, and Scality's RING. Openstack Swift is an open source project that allows one to use HTTP GET and PUT to retrieve and store objects—that's basically the whole API. Openstack Swift uses very cheap hardware, is fully fault resistant, automatically takes advantage of geographic redundancy, and scales to very large numbers of objects. Since object storage forces locking to occur at the object level, it is not clear how suitable it is for concurrent transaction processing in high-throughput transaction-oriented systems. Therefore, it is still not considered viable for mainstream enterprise-level database applications.

## 16.12 Summary

We began this chapter by discussing the characteristics of memory hierarchies and then concentrated on secondary storage devices. In particular, we focused on magnetic disks because they are still the preferred medium to store online database files. Table 16.1 presented a perspective on the memory hierarchies and their current capacities, access speeds, transfer rates, and costs.

Data on disk is stored in blocks; accessing a disk block is expensive because of the seek time, rotational delay, and block transfer time. To reduce the average block access time, double buffering can be used when accessing consecutive disk blocks. (Other disk parameters are discussed in Appendix B.) We introduced the various interface technologies in use today for disk drives and optical devices. We presented a list of strategies employed to improve access of data from disks. We also introduced solid-state drives, which are rapidly becoming popular, and optical drives, which are mainly used as tertiary storage. We discussed the working of the buffer manager, which is responsible for handling data requests and we presented various buffer replacement policies. We presented different ways of storing file records on disk. File records are grouped into disk blocks and can be fixed length or variable length, spanned or unspanned, and of the same record type or mixed types. We discussed the file header, which describes the record formats and keeps track of the disk addresses of the file blocks. Information in the file header is used by system software accessing the file records.

Then we presented a set of typical commands for accessing individual file records and discussed the concept of the current record of a file. We discussed how complex record search conditions are transformed into simple search conditions that are used to locate records in the file.

Three primary file organizations were then discussed: unordered, ordered, and hashed. Unordered files require a linear search to locate records, but record

insertion is very simple. We discussed the deletion problem and the use of deletion markers.

Ordered files shorten the time required to read records in order of the ordering field. The time required to search for an arbitrary record, given the value of its ordering key field, is also reduced if a binary search is used. However, maintaining the records in order makes insertion very expensive; thus the technique of using an unordered overflow file to reduce the cost of record insertion was discussed. Overflow records are merged with the master file periodically, and deleted records are physically dropped during file reorganization.

Hashing provides very fast access to an arbitrary record of a file, given the value of its hash key. The most suitable method for external hashing is the bucket technique, with one or more contiguous blocks corresponding to each bucket. Collisions causing bucket overflow are handled by open addressing, chaining, or multiple hashing. Access on any nonhash field is slow, and so is ordered access of the records on any field. We discussed three hashing techniques for files that grow and shrink in the number of records dynamically: extendible, dynamic, and linear hashing. The first two use the higher-order bits of the hash address to organize a directory. Linear hashing is geared to keep the load factor of the file within a given range and adds new buckets linearly.

We briefly discussed other possibilities for primary file storage and organization, such as B-trees, and files of mixed records, which implement relationships among records of different types physically as part of the storage structure. We reviewed the recent advances in disk technology represented by RAID (redundant arrays of inexpensive (or independent) disks), which has become a standard technique in large enterprises to provide better reliability and fault tolerance features in storage. Finally, we reviewed some modern trends in enterprise storage systems: storage area networks (SANs), network-attached storage (NAS), iSCSI and other network based protocols, automatic storage tiering, and finally object-based storage, which is playing a major role in storage architecture of data centers offering cloud-based services.

## Review Questions

**16.1.** What is the difference between primary and secondary storage?

**16.2.** Why are disks, not tapes, used to store online database files?

**16.3.** Define the following terms: *disk, disk pack, track, block, cylinder, sector, interblock gap, and read/write head.*

**16.4.** Discuss the process of disk initialization.

**16.5.** Discuss the mechanism used to read data from or write data to the disk.

**16.6.** What are the components of a disk block address?

**16.7.** Why is accessing a disk block expensive? Discuss the time components involved in accessing a disk block.

**16.8.** How does double buffering improve block access time?

**16.9.** What are the reasons for having variable-length records? What types of separator characters are needed for each?

**16.10.** Discuss the techniques for allocating file blocks on disk.

**16.11.** What is the difference between a file organization and an access method?

**16.12.** What is the difference between static and dynamic files?

**16.13.** What are the typical record-at-a-time operations for accessing a file? Which of these depend on the current file record?

**16.14.** Discuss the techniques for record deletion.

**16.15.** Discuss the advantages and disadvantages of using (a) an unordered file, (b) an ordered file, and (c) a static hash file with buckets and chaining. Which operations can be performed efficiently on each of these organizations, and which operations are expensive?

**16.16.** Discuss the techniques for allowing a hash file to expand and shrink dynamically. What are the advantages and disadvantages of each?

**16.17.** What is the difference between the directories of extendible and dynamic hashing?

**16.18.** What are mixed files used for? What are other types of primary file organizations?

**16.19.** Describe the mismatch between processor and disk technologies.

**16.20.** What are the main goals of the RAID technology? How does it achieve them?

**16.21.** How does disk mirroring help improve reliability? Give a quantitative example.

**16.22.** What characterizes the levels in RAID organization?

**16.23.** What are the highlights of the popular RAID levels 0, 1, and 5?

**16.24.** What are storage area networks? What flexibility and advantages do they offer?

**16.25.** Describe the main features of network-attached storage as an enterprise storage solution.

**16.26.** How have new iSCSI systems improved the applicability of storage area networks?

**16.27.** What are SATA, SAS, and FC protocols?

**16.28.** What are solid-state drives (SSDs) and what advantage do they offer over HDDs?

**16.29.** What is the function of a buffer manager? What does it do to serve a request for data?

**16.30.** What are some of the commonly used buffer replacement strategies?

**16.31.** What are optical and tape jukeboxes? What are the different types of optical media served by optical drives?

**16.32.** What is automatic storage tiering? Why is it useful?

**16.33.** What is object-based storage? How is it superior to conventional storage systems?

## Exercises

**16.34.** Consider a disk with the following characteristics (these are not parameters of any particular disk unit): block size $B = 512$ bytes; interblock gap size $G = 128$ bytes; number of blocks per track = 20; number of tracks per surface = 400. A disk pack consists of 15 double-sided disks.

a. What is the total capacity of a track, and what is its useful capacity (excluding interblock gaps)?

b. How many cylinders are there?

c. What are the total capacity and the useful capacity of a cylinder?

d. What are the total capacity and the useful capacity of a disk pack?

e. Suppose that the disk drive rotates the disk pack at a speed of 2,400 rpm (revolutions per minute); what are the transfer rate (*tr*) in bytes/msec and the block transfer time (*btt*) in msec? What is the average rotational delay (*rd*) in msec? What is the bulk transfer rate? (See Appendix B.)

f. Suppose that the average seek time is 30 msec. How much time does it take (on the average) in msec to locate and transfer a single block, given its block address?

g. Calculate the average time it would take to transfer 20 random blocks, and compare this with the time it would take to transfer 20 consecutive blocks using double buffering to save seek time and rotational delay.

**16.35.** A file has $r = 20{,}000$ STUDENT records of *fixed length*. Each record has the following fields: Name (30 bytes), Ssn (9 bytes), Address (40 bytes), PHONE (10 bytes), Birth_date (8 bytes), Sex (1 byte), Major_dept_code (4 bytes), Minor_dept_code (4 bytes), Class_code (4 bytes, integer), and Degree_program (3 bytes). An additional byte is used as a deletion marker. The file is stored on the disk whose parameters are given in Exercise 16.27.

a. Calculate the record size *R* in bytes.

b. Calculate the blocking factor *bfr* and the number of file blocks *b*, assuming an unspanned organization.

c. Calculate the average time it takes to find a record by doing a linear search on the file if (i) the file blocks are stored contiguously, and double buffering is used; (ii) the file blocks are not stored contiguously.

d. Assume that the file is ordered by Ssn; by doing a binary search, calculate the time it takes to search for a record given its Ssn value.

**16.36.** Suppose that only 80% of the STUDENT records from Exercise 16.28 have a value for Phone, 85% for Major_dept_code, 15% for Minor_dept_code, and 90% for Degree_program; and suppose that we use a variable-length record file. Each record has a 1-byte *field type* for each field in the record, plus the 1-byte deletion marker and a 1-byte end-of-record marker. Suppose that we use a *spanned* record organization, where each block has a 5-byte pointer to the next block (this space is not used for record storage).

a. Calculate the average record length $R$ in bytes.

b. Calculate the number of blocks needed for the file.

**16.37.** Suppose that a disk unit has the following parameters: seek time $s = 20$ msec; rotational delay $rd = 10$ msec; block transfer time $btt = 1$ msec; block size $B = 2400$ bytes; interblock gap size $G = 600$ bytes. An EMPLOYEE file has the following fields: Ssn, 9 bytes; Last_name, 20 bytes; First_name, 20 bytes; Middle_init, 1 byte; Birth_date, 10 bytes; Address, 35 bytes; Phone, 12 bytes; Supervisor_ssn, 9 bytes; Department, 4 bytes; Job_code, 4 bytes; deletion marker, 1 byte. The EMPLOYEE file has $r = 30{,}000$ records, fixed-length format, and unspanned blocking. Write appropriate formulas *and* calculate the following values for the above EMPLOYEE file:

a. Calculate the record size $R$ (including the deletion marker), the blocking factor $bfr$, and the number of disk blocks $b$.

b. Calculate the wasted space in each disk block because of the unspanned organization.

c. Calculate the transfer rate $tr$ and the bulk transfer rate $btr$ for this disk unit (see Appendix B for definitions of $tr$ and $btr$).

d. Calculate the average *number of block accesses* needed to search for an arbitrary record in the file, using linear search.

e. Calculate in msec the average *time* needed to search for an arbitrary record in the file, using linear search, if the file blocks are stored on consecutive disk blocks and double buffering is used.

f. Calculate in msec the average *time* needed to search for an arbitrary record in the file, using linear search, if the file blocks are *not* stored on consecutive disk blocks.

g. Assume that the records are ordered via some key field. Calculate the average *number of block accesses* and the *average time* needed to search for an arbitrary record in the file, using binary search.

**16.38.** A PARTS file with Part# as the hash key includes records with the following Part# values: 2369, 3760, 4692, 4871, 5659, 1821, 1074, 7115, 1620, 2428,

3943, 4750, 6975, 4981, and 9208. The file uses eight buckets, numbered 0 to 7. Each bucket is one disk block and holds two records. Load these records into the file in the given order, using the hash function $h(K) = K \bmod 8$. Calculate the average number of block accesses for a random retrieval on Part#.

**16.39.** Load the records of Exercise 16.31 into expandable hash files based on extendible hashing. Show the structure of the directory at each step, and the global and local depths. Use the hash function $h(K) = K \bmod 128$.

**16.40.** Load the records of Exercise 16.31 into an expandable hash file, using linear hashing. Start with a single disk block, using the hash function $h_0 = K \bmod 2^0$, and show how the file grows and how the hash functions change as the records are inserted. Assume that blocks are split whenever an overflow occurs, and show the value of $n$ at each stage.

**16.41.** Compare the file commands listed in Section 16.5 to those available on a file access method you are familiar with.

**16.42.** Suppose that we have an unordered file of fixed-length records that uses an unspanned record organization. Outline algorithms for insertion, deletion, and modification of a file record. State any assumptions you make.

**16.43.** Suppose that we have an ordered file of fixed-length records and an unordered overflow file to handle insertion. Both files use unspanned records. Outline algorithms for insertion, deletion, and modification of a file record and for reorganizing the file. State any assumptions you make.

**16.44.** Can you think of techniques other than an unordered overflow file that can be used to make insertions in an ordered file more efficient?

**16.45.** Suppose that we have a hash file of fixed-length records, and suppose that overflow is handled by chaining. Outline algorithms for insertion, deletion, and modification of a file record. State any assumptions you make.

**16.46.** Can you think of techniques other than chaining to handle bucket overflow in external hashing?

**16.47.** Write pseudocode for the insertion algorithms for linear hashing and for extendible hashing.

**16.48.** Write program code to access individual fields of records under each of the following circumstances. For each case, state the assumptions you make concerning pointers, separator characters, and so on. Determine the type of information needed in the file header in order for your code to be general in each case.

a. Fixed-length records with unspanned blocking
b. Fixed-length records with spanned blocking
c. Variable-length records with variable-length fields and spanned blocking
d. Variable-length records with repeating groups and spanned blocking
e. Variable-length records with optional fields and spanned blocking
f. Variable-length records that allow all three cases in parts c, d, and e

**16.49.** Suppose that a file initially contains $r = 120{,}000$ records of $R = 200$ bytes each in an unsorted (heap) file. The block size $B = 2{,}400$ bytes, the average seek time $s = 16$ ms, the average rotational latency $rd = 8.3$ ms, and the block transfer time $btt = 0.8$ ms. Assume that 1 record is deleted for every 2 records added until the total number of active records is 240,000.

a. How many block transfers are needed to reorganize the file?

b. How long does it take to find a record right before reorganization?

c. How long does it take to find a record right after reorganization?

**16.50.** Suppose we have a sequential (ordered) file of 100,000 records where each record is 240 bytes. Assume that $B = 2{,}400$ bytes, $s = 16$ ms, $rd = 8.3$ ms, and $btt = 0.8$ ms. Suppose we want to make $X$ independent random record reads from the file. We could make $X$ random block reads or we could perform one exhaustive read of the entire file looking for those $X$ records. The question is to decide when it would be more efficient to perform one exhaustive read of the entire file than to perform $X$ individual random reads. That is, what is the value for $X$ when an exhaustive read of the file is more efficient than random $X$ reads? Develop this as a function of $X$.

**16.51.** Suppose that a static hash file initially has 600 buckets in the primary area and that records are inserted that create an overflow area of 600 buckets. If we reorganize the hash file, we can assume that most of the overflow is eliminated. If the cost of reorganizing the file is the cost of the bucket transfers (reading and writing all of the buckets) and the only periodic file operation is the fetch operation, then how many times would we have to perform a fetch (successfully) to make the reorganization cost effective? That is, the reorganization cost and subsequent search cost are less than the search cost before reorganization. Support your answer. Assume $s = 16$ msec, $rd = 8.3$ msec, and $btt = 1$ msec.

**16.52.** Suppose we want to create a linear hash file with a file load factor of 0.7 and a blocking factor of 20 records per bucket, which is to contain 112,000 records initially.

a. How many buckets should we allocate in the primary area?

b. What should be the number of bits used for bucket addresses?

## Selected Bibliography

Wiederhold (1987) has a detailed discussion and analysis of secondary storage devices and file organizations as a part of database design. Optical disks are described in Berg and Roth (1989) and analyzed in Ford and Christodoulakis (1991). Flash memory is discussed by Dipert and Levy (1993). Ruemmler and Wilkes (1994) present a survey of the magnetic-disk technology. Most textbooks on databases include discussions of the material presented here. Most data structures textbooks, including Knuth (1998), discuss static hashing in more detail; Knuth has

a complete discussion of hash functions and collision resolution techniques, as well as of their performance comparison. Knuth also offers a detailed discussion of techniques for sorting external files. Textbooks on file structures include Claybrook (1992), Smith and Barnes (1987), and Salzberg (1988); they discuss additional file organizations including tree-structured files, and have detailed algorithms for operations on files. Salzberg et al. (1990) describe a distributed external sorting algorithm. File organizations with a high degree of fault tolerance are described by Bitton and Gray (1988) and by Gray et al. (1990). Disk striping was proposed in Salem and Garcia Molina (1986). The first paper on redundant arrays of inexpensive disks (RAID) is by Patterson et al. (1988). Chen and Patterson (1990) and the excellent survey of RAID by Chen et al. (1994) are additional references. Grochowski and Hoyt (1996) discuss future trends in disk drives. Various formulas for the RAID architecture appear in Chen et al. (1994).

Morris (1968) is an early paper on hashing. Extendible hashing is described in Fagin et al. (1979). Linear hashing is described by Litwin (1980). Algorithms for insertion and deletion for linear hashing are discussed with illustrations in Salzberg (1988). Dynamic hashing, which we briefly introduced, was proposed by Larson (1978). There are many proposed variations for extendible and linear hashing; for examples, see Cesarini and Soda (1991), Du and Tong (1991), and Hachem and Berra (1992).

Gibson et al. (1997) describe a file server scaling approach for network-attached storage, and Kubiatowicz et al. (2000) decribe the Oceanstore system for creating a global utility infrastructure for storing persistent data. Both are considered pioneering approaches that led to the ideas for object-based storage. Mesnier et al. (2003) give an overview of the object storage concept. The Lustre system (Braam & Schwan, 2002) was one of the first object storage products and is used in the majority of supercomputers, including the top two, namely China's Tianhe-2 and Oakridge National Lab's Titan.

Details of disk storage devices can be found at manufacturer sites (for example, http://www.seagate.com, http://www.ibm.com, http://www.emc.com, http://www.hp.com, http://www.storagetek.com). IBM has a storage technology research center at IBM Almaden (http://www.almaden.ibm.com). Additional useful sites include CISCO storage solutions at cisco.com; Network Appliance (NetApp) at www.netapp.com; Hitachi Data Storage (HDS) at www.hds.com, and SNIA (Storage Networking Industry Association) at www.snia.org. A number of industry white papers are available at the aforementioned sites.

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chapter 17

# Indexing Structures for Files and Physical Database Design

In this chapter, we assume that a file already exists with some primary organization such as the unordered, ordered, or hashed organizations that were described in Chapter 16. We will describe additional auxiliary **access structures** called **indexes**, which are used to speed up the retrieval of records in response to certain search conditions. The index structures are additional files on disk that provide **secondary access paths**, which provide alternative ways to access the records without affecting the physical placement of records in the primary data file on disk. They enable efficient access to records based on the **indexing fields** that are used to construct the index. Basically, *any field* of the file can be used to create an index, and *multiple indexes* on different fields—as well as indexes on *multiple fields*—can be constructed on the same file. A variety of indexes are possible; each of them uses a particular data structure to speed up the search. To find a record or records in the data file based on a search condition on an indexing field, the index is searched, which leads to pointers to one or more disk blocks in the data file where the required records are located. The most prevalent types of indexes are based on ordered files (single-level indexes) and use tree data structures (multilevel indexes, $B^+$-trees) to organize the index. Indexes can also be constructed based on hashing or other search data structures. We also discuss indexes that are vectors of bits called *bitmap indexes*.

We describe different types of single-level ordered indexes—primary, secondary, and clustering—in Section 17.1. By viewing a single-level index as an ordered file, one can develop additional indexes for it, giving rise to the concept of multilevel indexes. A popular indexing scheme called **ISAM (indexed sequential access method)** is based on this idea. We discuss multilevel tree-structured indexes in Section 17.2. In Section 17.3, we describe B-trees and $B^+$-trees, which are data structures that are commonly used in DBMSs to implement dynamically changing

multilevel indexes. $B^+$-trees have become a commonly accepted default structure for generating indexes on demand in most relational DBMSs. Section 17.4 is devoted to alternative ways to access data based on a combination of multiple keys. In Section 17.5, we discuss hash indexes and introduce the concept of logical indexes, which give an additional level of indirection from physical indexes and allow the physical index to be flexible and extensible in its organization. In Section 17.6, we discuss multikey indexing and bitmap indexes used for searching on one or more keys. Section 17.7 covers physical design and Section 7.8 summarizes the chapter.

## 17.1 Types of Single-Level Ordered Indexes

The idea behind an ordered index is similar to that behind the index used in a textbook, which lists important terms at the end of the book in alphabetical order along with a list of page numbers where the term appears in the book. We can search the book index for a certain term in the textbook to find a list of *addresses*—page numbers in this case—and use these addresses to locate the specified pages first and then *search* for the term on each specified page. The alternative, if no other guidance is given, would be to sift slowly through the whole textbook word by word to find the term we are interested in; this corresponds to doing a *linear search*, which scans the whole file. Of course, most books do have additional information, such as chapter and section titles, which help us find a term without having to search through the whole book. However, the index is the only exact indication of the pages where each term occurs in the book.

For a file with a given record structure consisting of several fields (or attributes), an index access structure is usually defined on a single field of a file, called an **indexing field** (or **indexing attribute**).[1] The index typically stores each value of the index field along with a list of pointers to all disk blocks that contain records with that field value. The values in the index are *ordered* so that we can do a *binary search* on the index. If both the data file and the index file are ordered, and since the index file is typically much smaller than the data file, searching the index using a binary search is a better option. Tree-structured multilevel indexes (see Section 17.2) implement an extension of the binary search idea that reduces the search space by two-way partitioning at each search step to an *n*-ary partitioning approach that divides the search space in the file *n*-ways at each stage.

There are several types of ordered indexes. A **primary index** is specified on the *ordering key field* of an **ordered file** of records. Recall from Section 16.7 that an ordering key field is used to *physically order* the file records on disk, and every record has a *unique value* for that field. If the ordering field is not a key field—that is, if numerous records in the file can have the same value for the ordering field—another type of index, called a **clustering index**, can be used. The data file is called a **clustered file** in this latter case. Notice that a file can have at most one physical ordering field, so it can have at most one primary index or one clustering index, *but*

[1]We use the terms *field* and *attribute* interchangeably in this chapter.

*not both*. A third type of index, called a **secondary index**, can be specified on any *nonordering* field of a file. A data file can have several secondary indexes in addition to its primary access method. We discuss these types of single-level indexes in the next three subsections.

### 17.1.1 Primary Indexes

A **primary index** is an ordered file whose records are of fixed length with two fields, and it acts like an access structure to efficiently search for and access the data records in a data file. The first field is of the same data type as the ordering key field—called the **primary key**—of the data file, and the second field is a pointer to a disk block (a block address). There is one **index entry** (or **index record**) in the index file for each *block* in the data file. Each index entry has the value of the primary key field for the *first* record in a block and a pointer to that block as its two field values. We will refer to the two field values of index entry $i$ as $<K(i), P(i)>$. In the rest of this chapter, we refer to different types of index **entries** $< K(i), X >$ as follows:

- $X$ may be the physical address of a block (or page) in the file, as in the case of $P(i)$ above.
- $X$ may be the record address made up of a block address and a record id (or offset) within the block.
- $X$ may be a logical address of the block or of the record within the file and is a relative number that would be mapped to a physical address (see further explanation in Section 17.6.1).

To create a primary index on the ordered file shown in Figure 16.7, we use the Name field as primary key, because that is the ordering key field of the file (assuming that each value of Name is unique). Each entry in the index has a Name value and a pointer. The first three index entries are as follows:

$<K(1) =$ (Aaron, Ed), $P(1) =$ address of block 1$>$
$<K(2) =$ (Adams, John), $P(2) =$ address of block 2$>$
$<K(3) =$ (Alexander, Ed), $P(3) =$ address of block 3$>$

Figure 17.1 illustrates this primary index. The total number of entries in the index is the same as the *number of disk blocks* in the ordered data file. The first record in each block of the data file is called the **anchor record** of the block, or simply the **block anchor**.[2]

Indexes can also be characterized as dense or sparse. A **dense index** has an index entry for *every search key value* (and hence every record) in the data file. A **sparse** (or **nondense**) **index**, on the other hand, has index entries for only some of the search values. A sparse index has fewer entries than the number of records in the file. Thus, a primary index is a nondense (sparse) index, since it includes an

[2]We can use a scheme similar to the one described here, with the last record in each block (rather than the first) as the block anchor. This slightly improves the efficiency of the search algorithm.

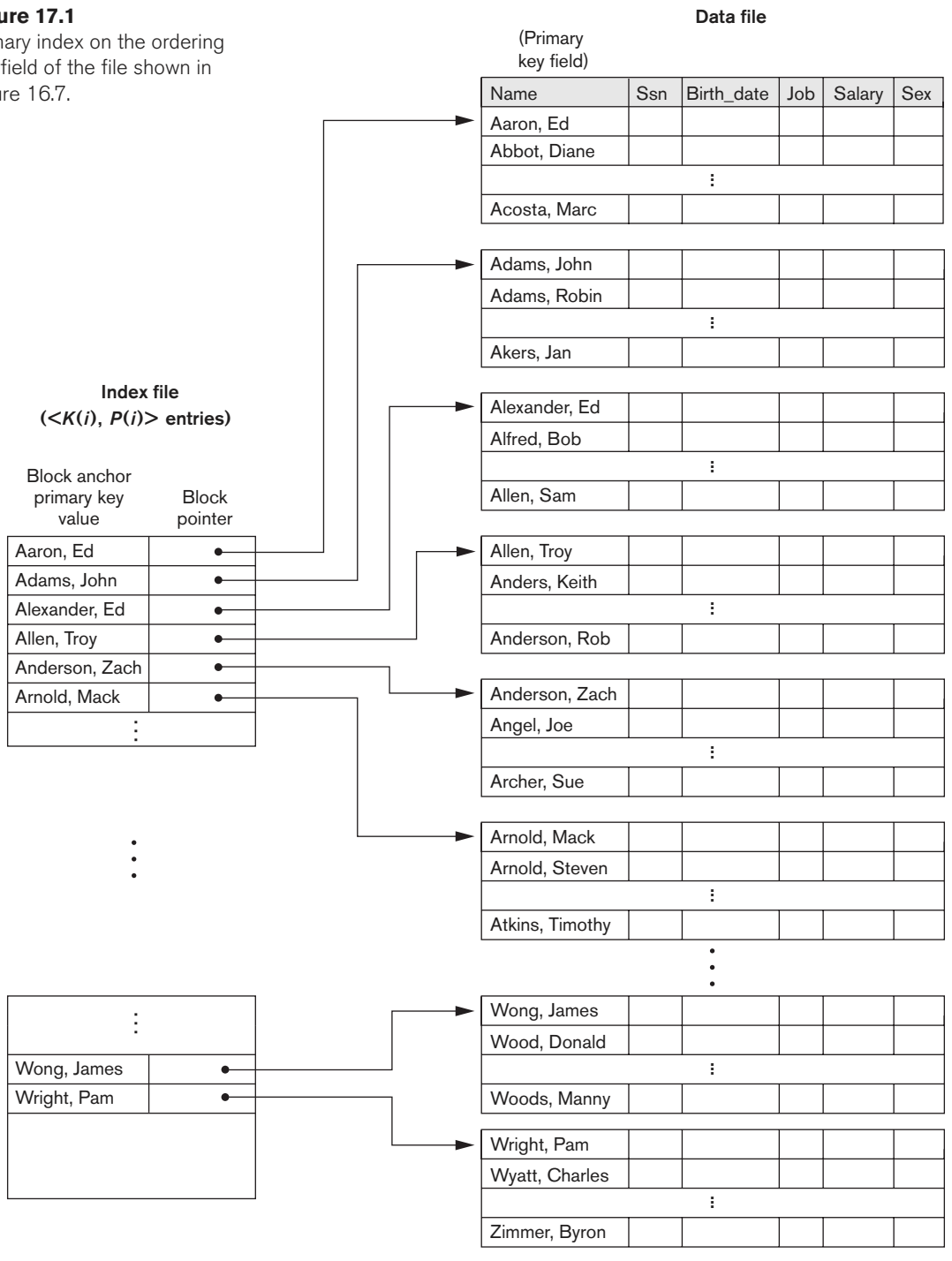



**Figure 17.1**
Primary index on the ordering key field of the file shown in Figure 16.7.

entry for each disk block of the data file and the keys of its anchor record rather than for every search value (or every record).[3]

The index file for a primary index occupies a much smaller space than does the data file, for two reasons. First, there are *fewer index entries* than there are records in the data file. Second, each index entry is typically *smaller in size* than a data record because it has only two fields, both of which tend to be short in size; consequently, more index entries than data records can fit in one block. Therefore, a binary search on the index file requires fewer block accesses than a binary search on the data file. Referring to Table 16.3, note that the binary search for an ordered data file required $\log_2 b$ block accesses. But if the primary index file contains only $b_i$ blocks, then to locate a record with a search key value requires a binary search of that index and access to the block containing that record: a total of $\log_2 b_i + 1$ accesses.

A record whose primary key value is $K$ lies in the block whose address is $P(i)$, where $K(i) \leq K < K(i + 1)$. The $i$th block in the data file contains all such records because of the physical ordering of the file records on the primary key field. To retrieve a record, given the value $K$ of its primary key field, we do a binary search on the index file to find the appropriate index entry $i$, and then retrieve the data file block whose address is $P(i)$.[4] Example 1 illustrates the saving in block accesses that is attainable when a primary index is used to search for a record.

**Example 1.** Suppose that we have an ordered file with $r = 300{,}000$ records stored on a disk with block size $B = 4{,}096$ bytes.[5] File records are of fixed size and are unspanned, with record length $R = 100$ bytes. The blocking factor for the file would be $bfr = \lfloor (B/R) \rfloor = \lfloor (4{,}096/100) \rfloor = 40$ records per block. The number of blocks needed for the file is $b = \lceil (r/bfr) \rceil = \lceil (300{,}000/40) \rceil = 7{,}500$ blocks. A binary search on the data file would need approximately $\lceil \log_2 b \rceil = \lceil (\log_2 7{,}500) \rceil = 13$ block accesses.

Now suppose that the ordering key field of the file is $V = 9$ bytes long, a block pointer is $P = 6$ bytes long, and we have constructed a primary index for the file. The size of each index entry is $R_i = (9 + 6) = 15$ bytes, so the blocking factor for the index is $bfr_i = \lfloor (B/R_i) \rfloor = \lfloor (4{,}096/15) \rfloor = 273$ entries per block. The total number of index entries $r_i$ is equal to the number of blocks in the data file, which is 7,500. The number of index blocks is hence $b_i = \lceil (r_i/bfr_i) \rceil = \lceil (7{,}500/273) \rceil = 28$ blocks. To perform a binary search on the index file would need $\lceil (\log_2 b_i) \rceil = \lceil (\log_2 28) \rceil = 5$ block accesses. To search for a record using the index, we need one additional block access to the data file for a total of 5 + 1 = 6 block accesses—an improvement over binary search on the data file, which required 13 disk block accesses. Note that the index with 7,500 entries of 15 bytes each is rather small (112,500 or 112.5 Kbytes) and would typically be kept in main memory thus requiring negligible time to search with binary search. In that case we simply make one block access to retrieve the record.

---

[3]The sparse primary index has been called clustered (primary) index in some books and articles.

[4]Notice that the above formula would not be correct if the data file were ordered on a *nonkey field*; in that case the same index value in the block anchor could be repeated in the last records of the previous block.

[5]Most DBMS vendors, including Oracle, are using 4K or 4,096 bytes as a standard block/page size.

A major problem with a primary index—as with any ordered file—is insertion and deletion of records. With a primary index, the problem is compounded because if we attempt to insert a record in its correct position in the data file, we must not only move records to make space for the new record but also change some index entries, since moving records will change the *anchor records* of some blocks. Using an unordered overflow file, as discussed in Section 16.7, can reduce this problem. Another possibility is to use a linked list of overflow records for each block in the data file. This is similar to the method of dealing with overflow records described with hashing in Section 16.8.2. Records within each block and its overflow linked list can be sorted to improve retrieval time. Record deletion is handled using deletion markers.

### 17.1.2 Clustering Indexes

If file records are physically ordered on a nonkey field—which *does not* have a distinct value for each record—that field is called the **clustering field** and the data file is called a **clustered file.** We can create a different type of index, called a **clustering index**, to speed up retrieval of all the records that have the same value for the clustering field. This differs from a primary index, which requires that the ordering field of the data file have a *distinct value* for each record.

A clustering index is also an ordered file with two fields; the first field is of the same type as the clustering field of the data file, and the second field is a disk block pointer. There is one entry in the clustering index for each *distinct value* of the clustering field, and it contains the value and a pointer to the *first block* in the data file that has a record with that value for its clustering field. Figure 17.2 shows an example. Notice that record insertion and deletion still cause problems because the data records are physically ordered. To alleviate the problem of insertion, it is common to reserve a whole block (or a cluster of contiguous blocks) for *each value* of the clustering field; all records with that value are placed in the block (or block cluster). This makes insertion and deletion relatively straightforward. Figure 17.3 shows this scheme.

A clustering index is another example of a *nondense* index because it has an entry for every *distinct value* of the indexing field, which is a nonkey by definition and hence has duplicate values rather than a unique value for every record in the file.

**Example 2.** Suppose that we consider the same ordered file with $r$ = 300,000 records stored on a disk with block size $B$ = 4,096 bytes. Imagine that it is ordered by the attribute Zipcode and there are 1,000 zip codes in the file (with an average 300 records per zip code, assuming even distribution across zip codes.) The index in this case has 1,000 index entries of 11 bytes each (5-byte Zipcode and 6-byte block pointer) with a blocking factor $bfr_i = \lfloor (B/R_i) \rfloor = \lfloor (4{,}096/11) \rfloor = 372$ index entries per block. The number of index blocks is hence $b_i = \lceil (r_i/bfr_i) \rceil = \lceil (1{,}000/372) \rceil = 3$ blocks. To perform a binary search on the index file would need $\lceil (\log_2 b_i) \rceil = \lceil (\log_2 3) \rceil = 2$ block accesses. Again, this index would typically be loaded in main memory (occupies 11,000 or 11 Kbytes) and takes negligible time to search in memory. One block access to the data file would lead to the first record with a given zip code.

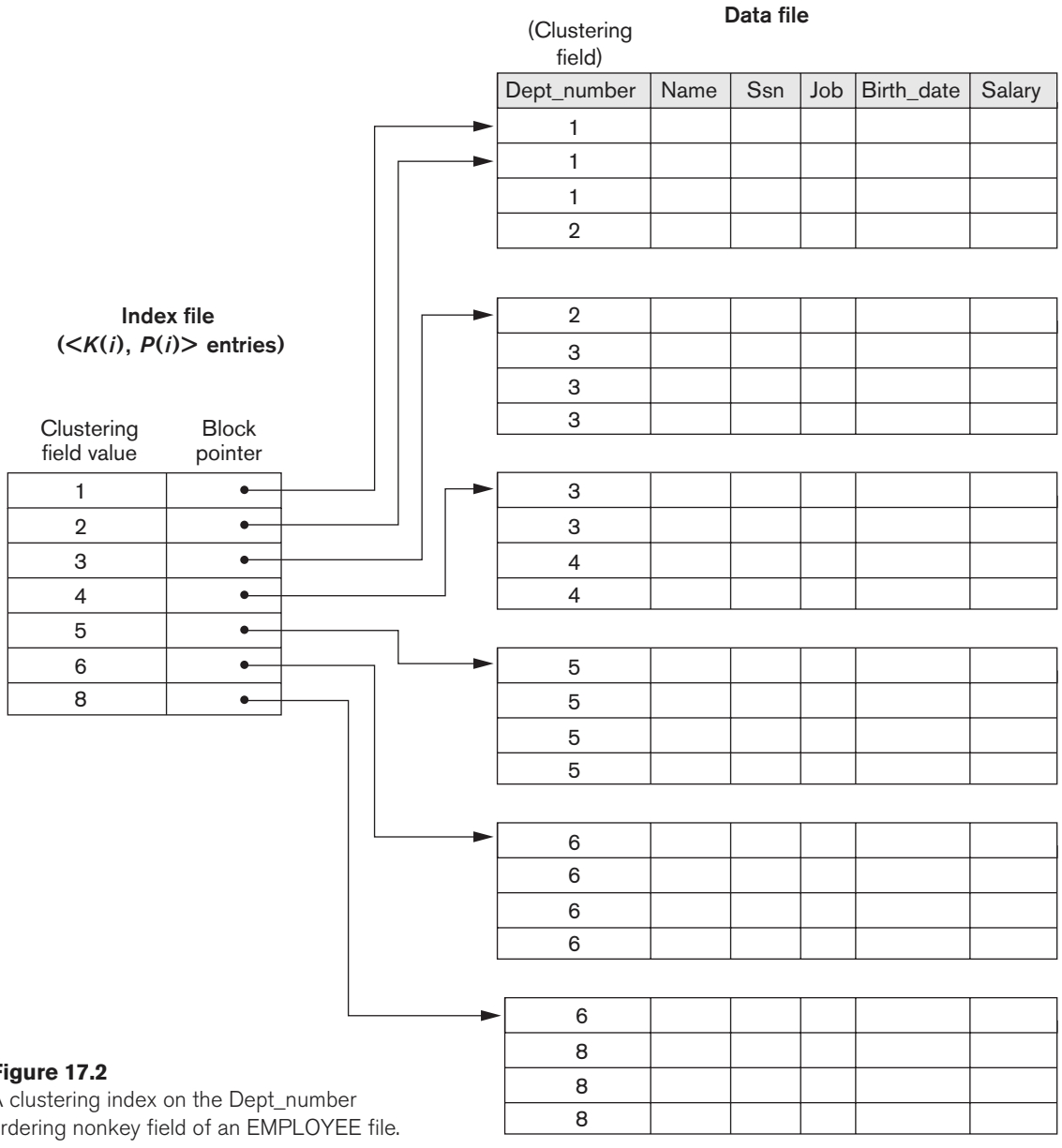



**Figure 17.2**
A clustering index on the Dept_number ordering nonkey field of an EMPLOYEE file.

There is some similarity between Figures 17.1, 17.2, and 17.3 and Figures 16.11 and 16.12. An index is somewhat similar to dynamic hashing (described in Section 16.8.3) and to the directory structures used for extendible hashing. Both are searched to find a pointer to the data block containing the desired record. A main difference is that an index search uses the values of the search field itself, whereas a hash directory search uses the binary hash value that is calculated by applying the hash function to the search field.

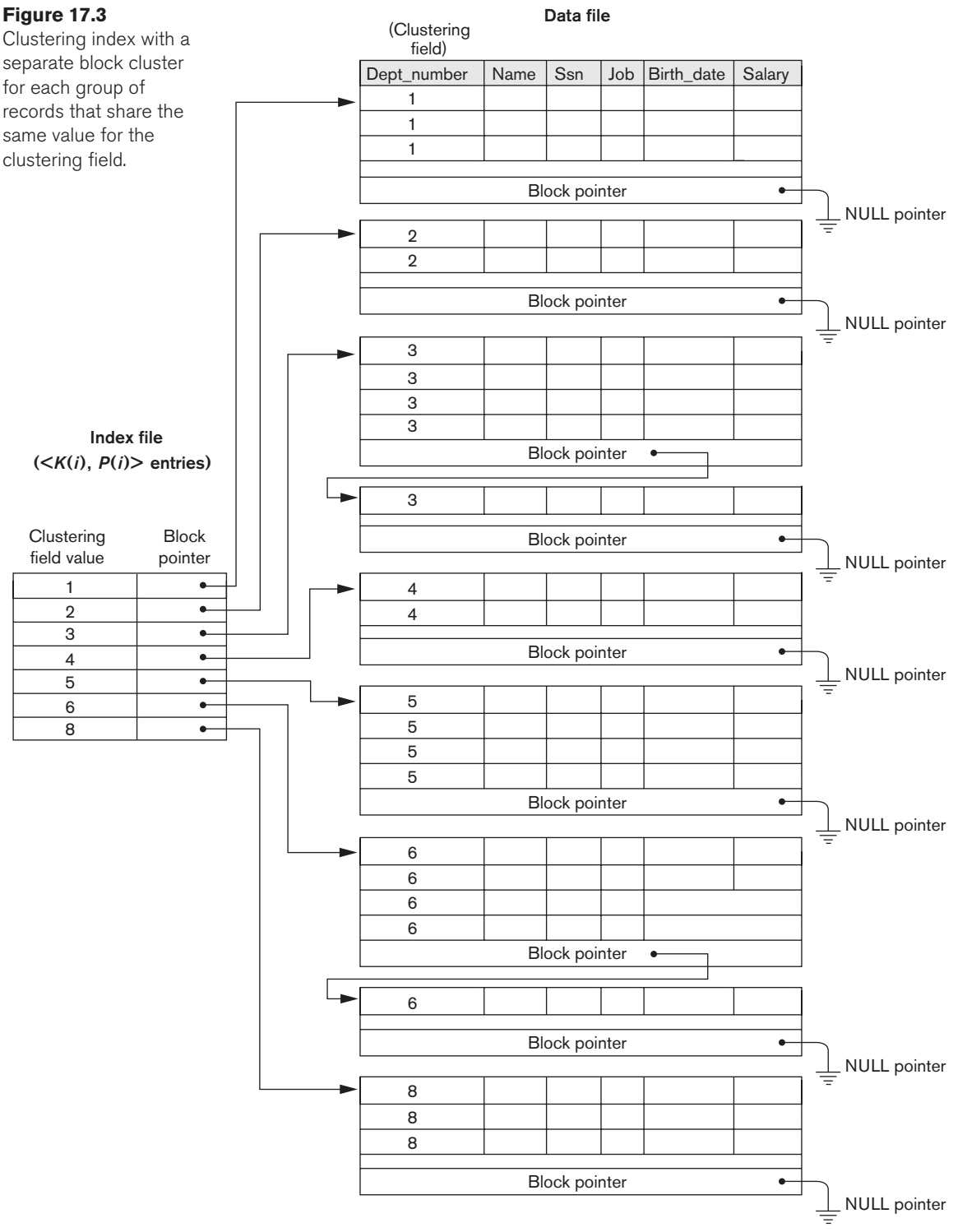



**Figure 17.3**
Clustering index with a separate block cluster for each group of records that share the same value for the clustering field.

### 17.1.3 Secondary Indexes

A **secondary index** provides a secondary means of accessing a data file for which some primary access already exists. The data file records could be ordered, unordered, or hashed. The secondary index may be created on a field that is a candidate key and has a unique value in every record, or on a nonkey field with duplicate values. The index is again an ordered file with two fields. The first field is of the same data type as some *nonordering field* of the data file that is an **indexing field**. The second field is either a *block* pointer or a *record* pointer. *Many* secondary indexes (and hence, indexing fields) can be created for the same file—each represents an additional means of accessing that file based on some specific field.

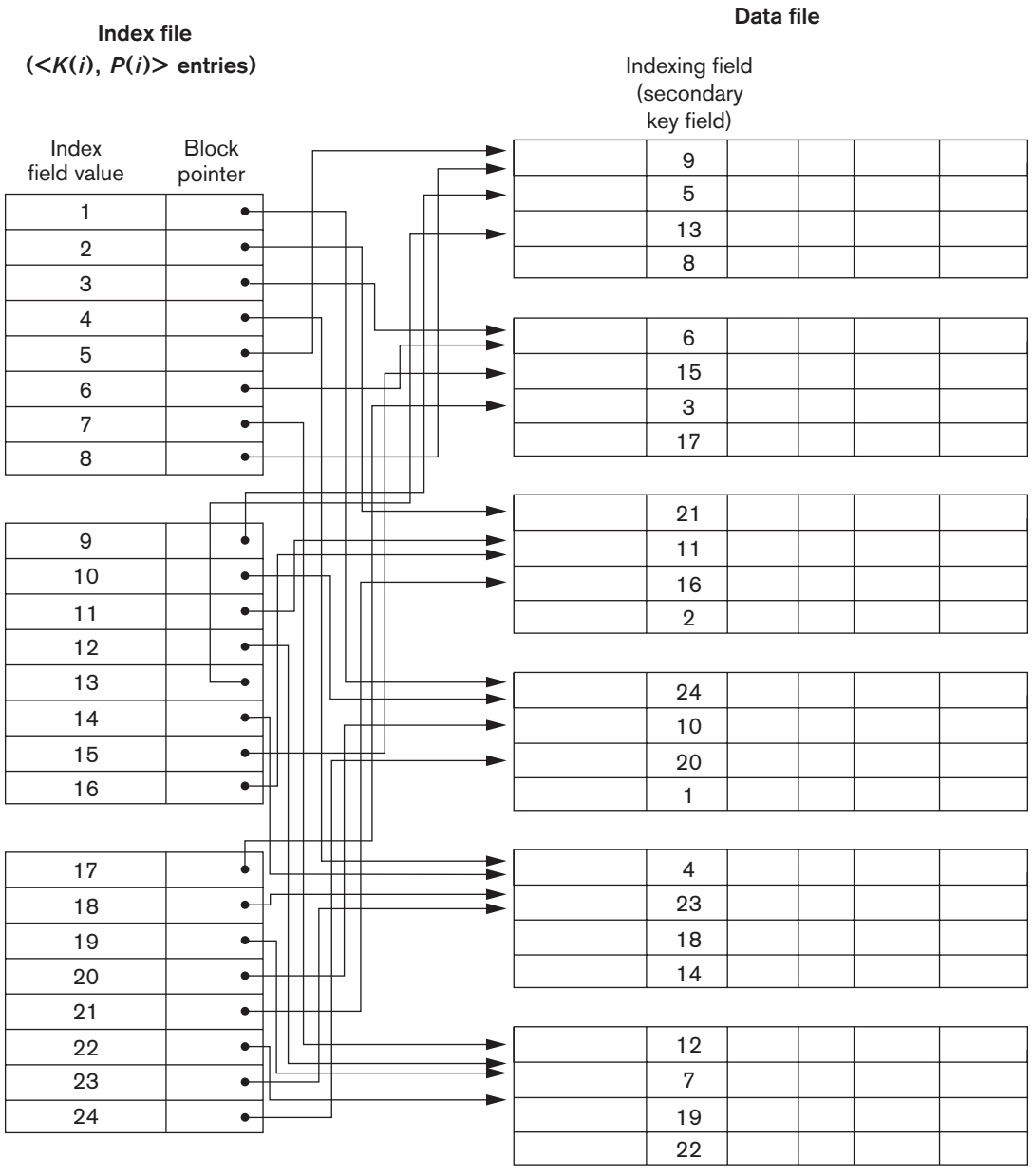
First we consider a secondary index access structure on a key (unique) field that has a *distinct value* for every record. Such a field is sometimes called a **secondary** key; in the relational model, this would correspond to any UNIQUE key attribute or to the primary key attribute of a table. In this case there is one index entry for *each record* in the data file, which contains the value of the field for the record and a pointer either to the block in which the record is stored or to the record itself. Hence, such an index is **dense**.

Again we refer to the two field values of index entry $i$ as $<K(i), P(i)>$. The entries are **ordered** by value of $K(i)$, so we can perform a binary search. Because the records of the data file are *not* physically ordered by values of the secondary key field, we *cannot* use block anchors. That is why an index entry is created for each record in the data file, rather than for each block, as in the case of a primary index. Figure 17.4 illustrates a secondary index in which the pointers $P(i)$ in the index entries are *block pointers,* not record pointers. Once the appropriate disk block is transferred to a main memory buffer, a search for the desired record within the block can be carried out.

A secondary index usually needs more storage space and longer search time than does a primary index, because of its larger number of entries. However, the *improvement* in search time for an arbitrary record is much greater for a secondary index than for a primary index, since we would have to do a *linear search* on the data file if the secondary index did not exist. For a primary index, we could still use a binary search on the main file, even if the index did not exist. Example 3 illustrates the improvement in number of blocks accessed.

**Example 3.** Consider the file of Example 1 with $r = 300{,}000$ fixed-length records of size $R = 100$ bytes stored on a disk with block size $B = 4{,}096$ bytes. The file has $b = 7{,}500$ blocks, as calculated in Example 1. Suppose we want to search for a record with a specific value for the secondary key—a nonordering key field of the file that is $V = 9$ bytes long. Without the secondary index, to do a linear search on the file would require $b/2 = 7{,}500/2 = 3{,}750$ block accesses on the average. Suppose that we construct a secondary index on that *nonordering key* field of the file. As in Example 1, a block pointer is $P = 6$ bytes long, so each index entry is $R_i = (9 + 6) = 15$ bytes, and the blocking factor for the index is $bfr_i = \lfloor (B/R_i) \rfloor = \lfloor (4{,}096/15) \rfloor = 273$ index entries per block. In a dense secondary index such as this, the total number of index entries $r_i$ is equal to the *number of records* in the data file, which is 300,000. The number of blocks needed for the index is hence $b_i = \lceil (r_i/bfr_i) \rceil = \lceil (300{,}000/273) \rceil = 1{,}099$ blocks.

**Figure 17.4**
A dense secondary index (with block pointers) on a nonordering key field of a file.



A binary search on this secondary index needs $\lceil (\log_2 b_i) \rceil = \lceil (\log_2 1{,}099) \rceil = 11$ block accesses. To search for a record using the index, we need an additional block access to the data file for a total of 11 + 1 = 12 block accesses—a vast improvement over the 3,750 block accesses needed on the average for a linear search, but slightly worse than the 6 block accesses required for the primary index. This difference arose because the primary index was nondense and hence shorter, with only 28 blocks in length as opposed to the 1,099 blocks dense index here.

We can also create a secondary index on a *nonkey, nonordering field* of a file. In this case, numerous records in the data file can have the same value for the indexing field. There are several options for implementing such an index:

- Option 1 is to include duplicate index entries with the same $K(i)$ value—one for each record. This would be a dense index.
- Option 2 is to have variable-length records for the index entries, with a repeating field for the pointer. We keep a list of pointers $<P(i, 1), \ldots, P(i, k)>$ in the index entry for $K(i)$—one pointer to each block that contains a record whose indexing field value equals $K(i)$. In either option 1 or option 2, the binary search algorithm on the index must be modified appropriately to account for a variable number of index entries per index key value.
- Option 3, which is more commonly used, is to keep the index entries themselves at a fixed length and have a single entry for each *index field value*, but to create *an extra level of indirection* to handle the multiple pointers. In this nondense scheme, the pointer $P(i)$ in index entry $<K(i), P(i)>$ points to a disk block, which contains a *set of record pointers*; each record pointer in that disk block points to one of the data file records with value $K(i)$ for the indexing field. If some value $K(i)$ occurs in too many records, so that their record pointers cannot fit in a single disk block, a cluster or linked list of blocks is used. This technique is illustrated in Figure 17.5. Retrieval via the index requires one or more additional block accesses because of the extra level, but the algorithms for searching the index and (more importantly) for inserting of new records in the data file are straightforward. The binary search algorithm is directly applicable to the index file since it is ordered. For range retrievals such as retrieving records where $V_1 \leq K \leq V_2$, block pointers may be used in the pool of pointers for each value instead of the record pointers. Then a union operation can be used on the pools of block pointers corresponding to the entries from $V_1$ to $V_2$ in the index to eliminate duplicates and the resulting blocks can be accessed. In addition, retrievals on complex selection conditions may be handled by referring to the record pointers from multiple non-key secondary indexes, without having to retrieve many unnecessary records from the data file (see Exercise 17.24).

Notice that a secondary index provides a **logical ordering** on the records by the indexing field. If we access the records in order of the entries in the secondary index, we get them in order of the indexing field. The primary and clustering indexes assume that the field used for **physical ordering** of records in the file is the same as the indexing field.

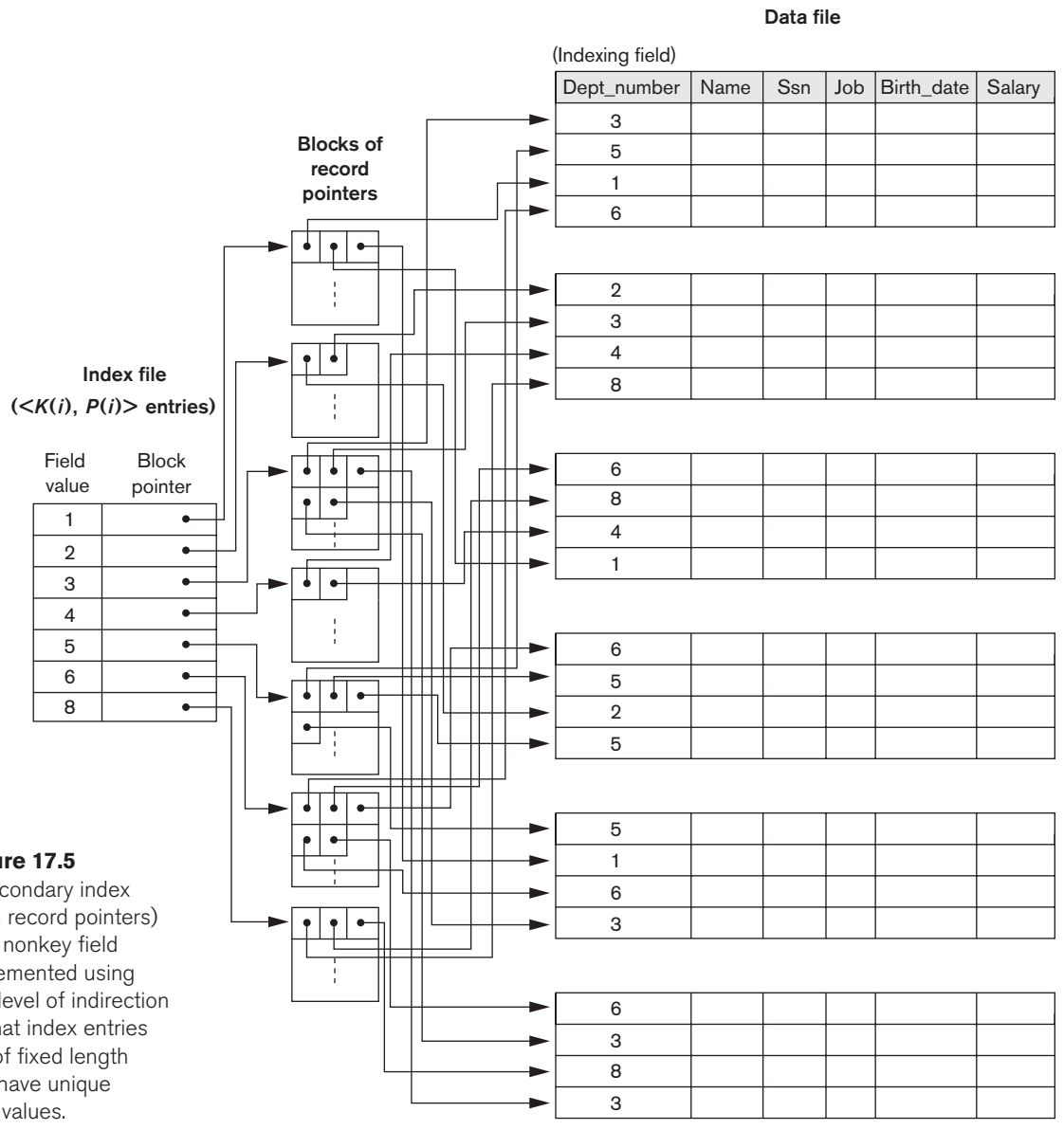



**Figure 17.5**
A secondary index (with record pointers) on a nonkey field implemented using one level of indirection so that index entries are of fixed length and have unique field values.

## 17.1.4 Summary

To conclude this section, we summarize the discussion of index types in two tables. Table 17.1 shows the index field characteristics of each type of ordered single-level index discussed—primary, clustering, and secondary. Table 17.2 summarizes the properties of each type of index by comparing the number of index entries and specifying which indexes are dense and which use block anchors of the data file.

**Table 17.1** Types of Indexes Based on the Properties of the Indexing Field

| | Index Field Used for Physical Ordering of the File | Index Field Not Used for Physical Ordering of the File |
|---|---|---|
| Indexing field is key | Primary index | Secondary index (Key) |
| Indexing field is nonkey | Clustering index | Secondary index (NonKey) |

**Table 17.2** Properties of Index Types

| Type of Index | Number of (First-Level) Index Entries | Dense or Nondense (Sparse) | Block Anchoring on the Data File |
|---|---|---|---|
| Primary | Number of blocks in data file | Nondense | Yes |
| Clustering | Number of distinct index field values | Nondense | Yes/no[a] |
| Secondary (key) | Number of records in data file | Dense | No |
| Secondary (nonkey) | Number of records[b] or number of distinct index field values[c] | Dense or Nondense | No |

[a]Yes if every distinct value of the ordering field starts a new block; no otherwise.
[b]For option 1.
[c]For options 2 and 3.

## 17.2 Multilevel Indexes

The indexing schemes we have described thus far involve an ordered index file. A binary search is applied to the index to locate pointers to a disk block or to a record (or records) in the file having a specific index field value. A binary search requires approximately ($\log_2 b_i$) block accesses for an index with $b_i$ blocks because each step of the algorithm reduces the part of the index file that we continue to search by a factor of 2. This is why we take the log function to the base 2. The idea behind a **multilevel index** is to reduce the part of the index that we continue to search by $bfr_i$, the blocking factor for the index, which is larger than 2. Hence, the search space is reduced much faster. The value $bfr_i$ is called the **fan-out** of the multilevel index, and we will refer to it by the symbol **fo**. Whereas we divide the *record search space* into two halves at each step during a binary search, we divide it $n$-ways (where $n$ = the fan-out) at each search step using the multilevel index. Searching a multilevel index requires approximately ($\log_{fo} b_i$) block accesses, which is a substantially smaller number than for a binary search if the fan-out is larger than 2. In most cases, the fan-out is much larger than 2. Given a blocksize of 4,096, which is most common in today's DBMSs, the fan-out depends on how many (key + block pointer) entries fit within a block. With a 4-byte block pointer (which would accommodate $2^{32} - 1 = 4.2 * 10^9$ blocks) and a 9-byte key such as SSN, the fan-out comes to 315.

A multilevel index considers the index file, which we will now refer to as the **first** (or **base**) **level** of a multilevel index, as an *ordered file* with a *distinct value* for each

$K(i)$. Therefore, by considering the first-level index file as a sorted data file, we can create a primary index for the first level; this index to the first level is called the **second level** of the multilevel index. Because the second level is a primary index, we can use block anchors so that the second level has one entry for *each block* of the first level. The blocking factor $bfr_i$ for the second level—and for all subsequent levels—is the same as that for the first-level index because all index entries are the same size; each has one field value and one block address. If the first level has $r_1$ entries, and the blocking factor—which is also the fan-out—for the index is $bfr_i = fo$, then the first level needs $\lceil (r_1/fo) \rceil$ blocks, which is therefore the number of entries $r_2$ needed at the second level of the index.

We can repeat this process for the second level. The **third level**, which is a primary index for the second level, has an entry for each second-level block, so the number of third-level entries is $r_3 = \lceil (r_2/fo) \rceil$. Notice that we require a second level only if the first level needs more than one block of disk storage, and, similarly, we require a third level only if the second level needs more than one block. We can repeat the preceding process until all the entries of some index level $t$ fit in a single block. This block at the $t$th level is called the **top** index level.[6] Each level reduces the number of entries at the previous level by a factor of $fo$—the index fan-out—so we can use the formula $1 \leq (r_1/((fo)^t))$ to calculate $t$. Hence, a multilevel index with $r_1$ first-level entries will have approximately $t$ levels, where $t = \lceil (\log_{fo}(r_1)) \rceil$. When searching the index, a single disk block is retrieved at each level. Hence, $t$ disk blocks are accessed for an index search, where $t$ is the *number of index levels*.

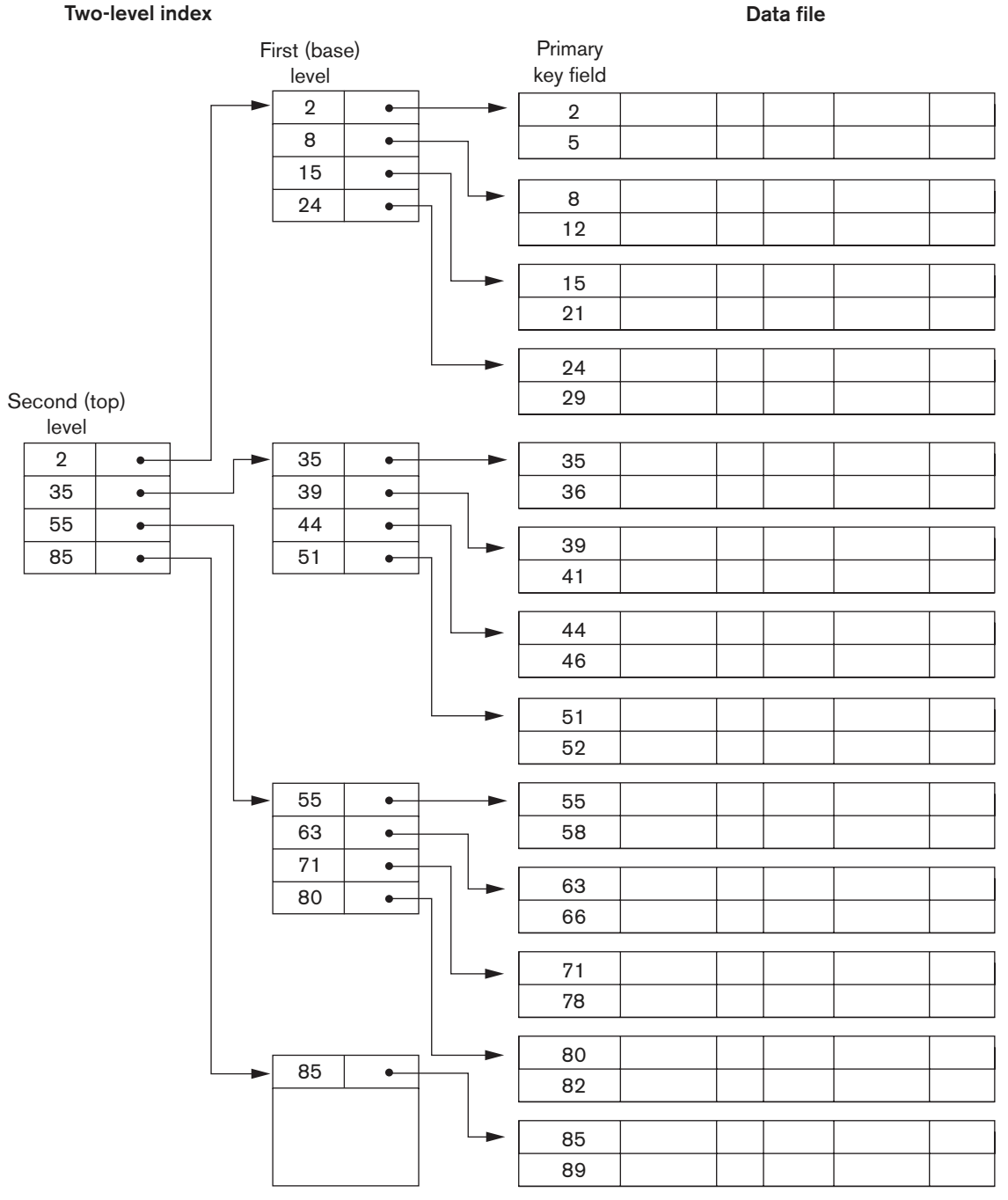
The multilevel scheme described here can be used on any type of index—whether it is primary, clustering, or secondary—as long as the first-level index has *distinct values for K(i) and fixed-length entries.* Figure 17.6 shows a multilevel index built over a primary index. Example 3 illustrates the improvement in number of blocks accessed when a multilevel index is used to search for a record.

**Example 4.** Suppose that the dense secondary index of Example 3 is converted into a multilevel index. We calculated the index blocking factor $bfr_i = 273$ index entries per block, which is also the fan-out $fo$ for the multilevel index; the number of first-level blocks $b_1 = 1{,}099$ blocks was also calculated. The number of second-level blocks will be $b_2 = \lceil (b_1/fo) \rceil = \lceil (1{,}099/273) \rceil = 5$ blocks, and the number of third-level blocks will be $b_3 = \lceil (b_2/fo) \rceil = \lceil (5/273) \rceil = 1$ block. Hence, the third level is the top level of the index, and $t = 3$. To access a record by searching the multilevel index, we must access one block at each level plus one block from the data file, so we need $t + 1 = 3 + 1 = 4$ block accesses. Compare this to Example 3, where 12 block accesses were needed when a single-level index and binary search were used.

Notice that we could also have a multilevel primary index, which would be non-dense. Exercise 17.18(c) illustrates this case, where we *must* access the data block from the file before we can determine whether the record being searched for is in the file. For a dense index, this can be determined by accessing the first index level

[6]The numbering scheme for index levels used here is the reverse of the way levels are commonly defined for tree data structures. In tree data structures, $t$ is referred to as level 0 (zero), $t - 1$ is level 1, and so on.

**Figure 17.6**
A two-level primary index resembling ISAM (indexed sequential access method) organization.



(without having to access a data block), since there is an index entry for *every* record in the file.

A common file organization used in business data processing is an ordered file with a multilevel primary index on its ordering key field. Such an organization is called an **indexed sequential file** and was used in a large number of early IBM systems. IBM's **ISAM** organization incorporates a two-level index that is closely related to the organization of the disk in terms of cylinders and tracks (see Section 16.2.1). The first level is a cylinder index, which has the key value of an anchor record for each cylinder of a disk pack occupied by the file and a pointer to the track index for the cylinder. The track index has the key value of an anchor record for each track in the cylinder and a pointer to the track. The track can then be searched sequentially for the desired record or block. Insertion is handled by some form of overflow file that is merged periodically with the data file. The index is re-created during file reorganization.

Algorithm 17.1 outlines the search procedure for a record in a data file that uses a nondense multilevel primary index with $t$ levels. We refer to entry $i$ at level $j$ of the index as $<K_j(i), P_j(i)>$, and we search for a record whose primary key value is $K$. We assume that any overflow records are ignored. If the record is in the file, there must be some entry at level 1 with $K_1(i) \leq K < K_1(i+1)$ and the record will be in the block of the data file whose address is $P_1(i)$. Exercise 17.23 discusses modifying the search algorithm for other types of indexes.

**Algorithm 17.1.** Searching a Nondense Multilevel Primary Index with $t$ Levels

```
(*We assume the index entry to be a block anchor that is the first key per block*)
p ← address of top-level block of index;
for j ← t step − 1 to 1 do
    begin
        read the index block (at jth index level) whose address is p;
        search block p for entry i such that K_j (i) ≤ K < K_j(i + 1)
    (* if K_j(i)
        is the last entry in the block, it is sufficient to satisfy K_j(i) ≤ K *);
        p ← P_j(i ) (* picks appropriate pointer at jth index level *)
    end;
    read the data file block whose address is p;
    search block p for record with key = K;
```

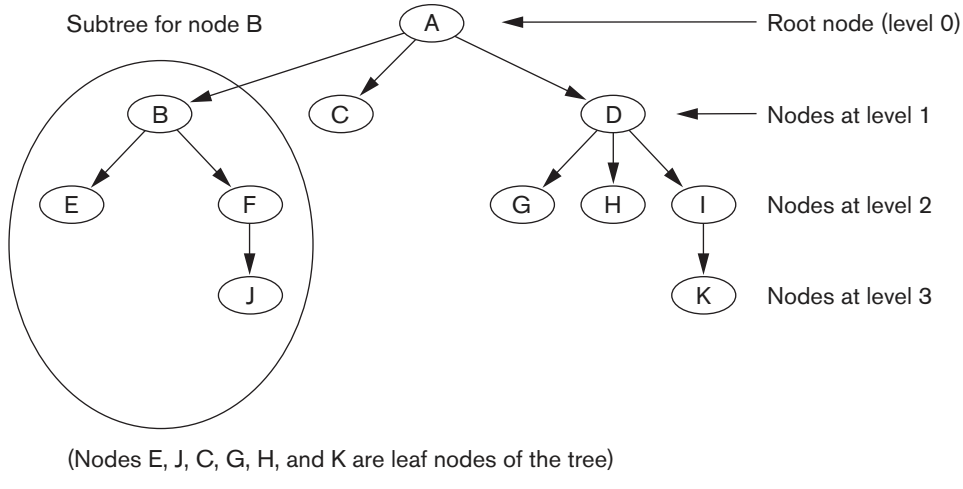
As we have seen, a multilevel index reduces the number of blocks accessed when searching for a record, given its indexing field value. We are still faced with the problems of dealing with index insertions and deletions, because all index levels are *physically ordered files.* To retain the benefits of using multilevel indexing while reducing index insertion and deletion problems, designers adopted a multilevel index called a **dynamic multilevel index** that leaves some space in each of its blocks for inserting new entries and uses appropriate insertion/deletion algorithms for creating and deleting new index blocks when the data file grows and shrinks. It is often implemented by using data structures called B-trees and $B^+$-trees, which we describe in the next section.

## 17.3 Dynamic Multilevel Indexes Using B-Trees and B+-Trees

B-trees and B+-trees are special cases of the well-known search data structure known as a **tree**. We briefly introduce the terminology used in discussing tree data structures. A **tree** is formed of **nodes**. Each node in the tree, except for a special node called the **root**, has one **parent** node and zero or more **child** nodes. The root node has no parent. A node that does not have any child nodes is called a **leaf** node; a nonleaf node is called an **internal** node. The **level** of a node is always one more than the level of its parent, with the level of the root node being *zero*.[7] A **subtree** of a node consists of that node and all its **descendant** nodes—its child nodes, the child nodes of its child nodes, and so on. A precise recursive definition of a subtree is that it consists of a node *n* and the subtrees of all the child nodes of *n*. Figure 17.7 illustrates a tree data structure. In this figure the root node is A, and its child nodes are B, C, and D. Nodes E, J, C, G, H, and K are leaf nodes. Since the leaf nodes are at different levels of the tree, this tree is called **unbalanced**.

In Section 17.3.1, we introduce search trees and then discuss B-trees, which can be used as dynamic multilevel indexes to guide the search for records in a data file. B-tree nodes are kept between 50 and 100 percent full, and pointers to the data blocks are stored in both internal nodes and leaf nodes of the B-tree structure. In Section 17.3.2 we discuss B+-trees, a variation of B-trees in which pointers to the data blocks of a file are stored only in leaf nodes, which can lead to fewer levels and

**Figure 17.7**
A tree data structure that shows an unbalanced tree.




[7]This standard definition of the level of a tree node, which we use throughout Section 17.3, is different from the one we gave for multilevel indexes in Section 17.2.

higher-capacity indexes. In the DBMSs prevalent in the market today, the common structure used for indexing is $B^+$-trees.

### 17.3.1 Search Trees and B-Trees

A **search tree** is a special type of tree that is used to guide the search for a record, given the value of one of the record's fields. The multilevel indexes discussed in Section 17.2 can be thought of as a variation of a search tree; each node in the multilevel index can have as many as *fo* pointers and *fo* key values, where *fo* is the index fan-out. The index field values in each node guide us to the next node, until we reach the data file block that contains the required records. By following a pointer, we restrict our search at each level to a subtree of the search tree and ignore all nodes not in this subtree.

**Search Trees.** A search tree is slightly different from a multilevel index. A **search tree of order** $p$ is a tree such that each node contains *at most* $p - 1$ search values and $p$ pointers in the order $<P_1, K_1, P_2, K_2, \ldots, P_{q-1}, K_{q-1}, P_q>$, where $q \leq p$. Each $P_i$ is a pointer to a child node (or a NULL pointer), and each $K_i$ is a search value from some ordered set of values. All search values are assumed to be unique.[8] Figure 17.8 illustrates a node in a search tree. Two constraints must hold at all times on the search tree:

1. Within each node, $K_1 < K_2 < \ldots < K_{q-1}$.
2. For all values $X$ in the subtree pointed at by $P_i$, we have $K_{i-1} < X < K_i$ for $1 < i < q$; $X < K_i$ for $i = 1$; and $K_{i-1} < X$ for $i = q$ (see Figure 17.8).

Whenever we search for a value $X$, we follow the appropriate pointer $P_i$ according to the formulas in condition 2 above. Figure 17.9 illustrates a search tree of order $p = 3$ and integer search values. Notice that some of the pointers $P_i$ in a node may be NULL pointers.

We can use a search tree as a mechanism to search for records stored in a disk file. The values in the tree can be the values of one of the fields of the file, called the

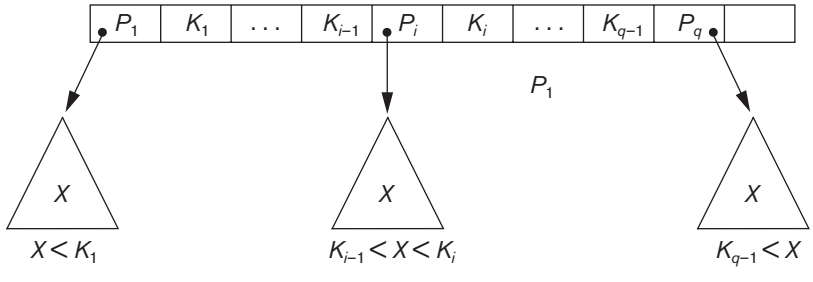



**Figure 17.8**
A node in a search tree with pointers to subtrees below it.

[8]This restriction can be relaxed. If the index is on a nonkey field, duplicate search values may exist and the node structure and the navigation rules for the tree may be modified.

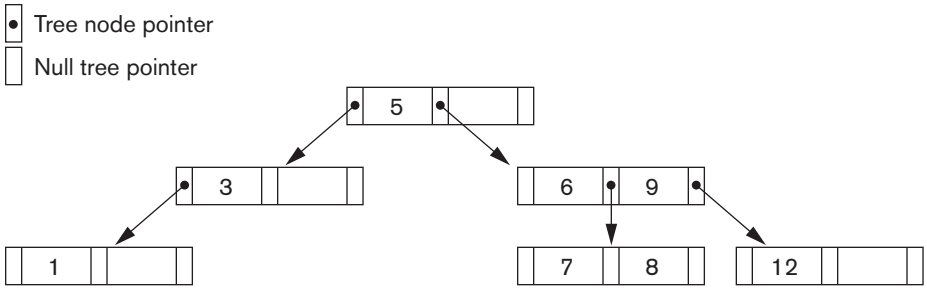



**Figure 17.9**
A search tree of order $p = 3$.

**search field** (which is the same as the index field if a multilevel index guides the search). Each key value in the tree is associated with a pointer to the record in the data file having that value. Alternatively, the pointer could be to the disk block containing that record. The search tree itself can be stored on disk by assigning each tree node to a disk block. When a new record is inserted in the file, we must update the search tree by inserting an entry in the tree containing the search field value of the new record and a pointer to the new record.

Algorithms are necessary for inserting and deleting search values into and from the search tree while maintaining the preceding two constraints. In general, these algorithms do not guarantee that a search tree is **balanced**, meaning that all of its leaf nodes are at the same level.[9] The tree in Figure 17.7 is not balanced because it has leaf nodes at levels 1, 2, and 3. The goals for balancing a search tree are as follows:

- To guarantee that nodes are evenly distributed, so that the depth of the tree is minimized for the given set of keys and that the tree does not get skewed with some nodes being at very deep levels
- To make the search speed uniform, so that the average time to find any random key is roughly the same

Minimizing the number of levels in the tree is one goal, another implicit goal is to make sure that the index tree does not need too much restructuring as records are inserted into and deleted from the main file. Thus we want the nodes to be as full as possible and do not want any nodes to be empty if there are too many deletions. Record deletion may leave some nodes in the tree nearly empty, thus wasting storage space and increasing the number of levels. The B-tree addresses both of these problems by specifying additional constraints on the search tree.

**B-Trees.** The B-tree has additional constraints that ensure that the tree is always balanced and that the space wasted by deletion, if any, never becomes excessive. The algorithms for insertion and deletion, though, become more complex in order to maintain these constraints. Nonetheless, most insertions and deletions are simple processes; they become complicated only under special circumstances—namely, whenever we attempt an insertion into a node that is already full or a deletion from

[9]The definition of *balanced* is different for binary trees. Balanced binary trees are known as *AVL trees*.

a node that makes it less than half full. More formally, a **B-tree of order** $p$, when used as an access structure on a *key field* to search for records in a data file, can be defined as follows:

1. Each internal node in the B-tree (Figure 17.10(a)) is of the form

   $$<P_1, <K_1, Pr_1>, P_2, <K_2, Pr_2>, \ldots, <K_{q-1}, Pr_{q-1}>, P_q>$$

   where $q \leq p$. Each $P_i$ is a **tree pointer**—a pointer to another node in the B-tree. Each $Pr_i$ is a **data pointer**[10]—a pointer to the record whose search key field value is equal to $K_i$ (or to the data file block containing that record).
2. Within each node, $K_1 < K_2 < \ldots < K_{q-1}$.
3. For all search key field values $X$ in the subtree pointed at by $P_i$ (the $i$th subtree, see Figure 17.10(a)), we have:

   $$K_{i-1} < X < K_i \text{ for } 1 < i < q; X < K_i \text{ for } i = 1; \text{ and } K_{i-1} < X \text{ for } i = q$$

4. Each node has at most $p$ tree pointers.
5. Each node, except the root and leaf nodes, has at least $\lceil (p/2) \rceil$ tree pointers. The root node has at least two tree pointers unless it is the only node in the tree.
6. A node with $q$ tree pointers, $q \leq p$, has $q - 1$ search key field values (and hence has $q - 1$ data pointers).
7. All leaf nodes are at the same level. Leaf nodes have the same structure as internal nodes except that all of their *tree pointers* $P_i$ are NULL.

Figure 17.10(b) illustrates a B-tree of order $p = 3$. Notice that all search values $K$ in the B-tree are unique because we assumed that the tree is used as an access structure on a key field. If we use a B-tree *on a nonkey field*, we must change the definition of the file pointers $Pr_i$ to point to a block—or a cluster of blocks—that contain the pointers to the file records. This extra level of indirection is similar to option 3, discussed in Section 17.1.3, for secondary indexes.

A B-tree starts with a single root node (which is also a leaf node) at level 0 (zero). Once the root node is full with $p - 1$ search key values and we attempt to insert another entry in the tree, the root node splits into two nodes at level 1. Only the middle value is kept in the root node, and the rest of the values are split evenly between the other two nodes. When a nonroot node is full and a new entry is inserted into it, that node is split into two nodes at the same level, and the middle entry is moved to the parent node along with two pointers to the new split nodes. If the parent node is full, it is also split. Splitting can propagate all the way to the root node, creating a new level if the root is split. We do not discuss algorithms for B-trees in detail in this text,[11] but we outline search and insertion procedures for $B^+$-trees in the next section.

[10]A data pointer is either a block address or a record address; the latter is essentially a block address and a record offset within the block.

[11]For details on insertion and deletion algorithms for B-trees, consult Ramakrishnan and Gehrke (2003).

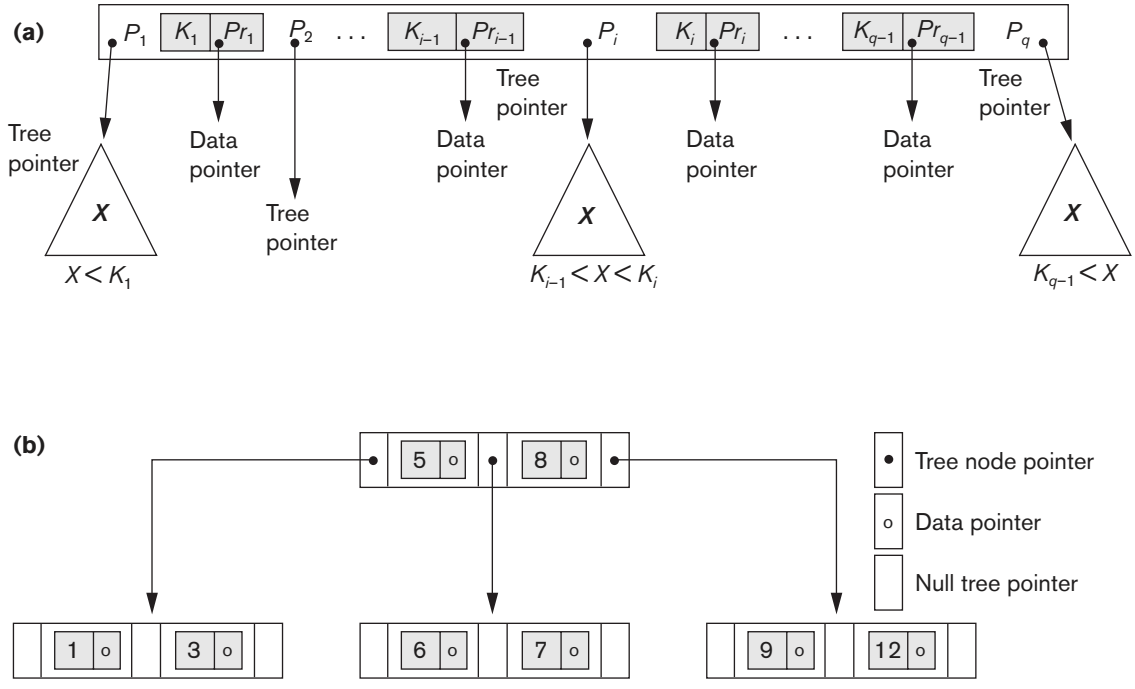



**Figure 17.10**
B-tree structures. (a) A node in a B-tree with $q - 1$ search values. (b) A B-tree of order $p = 3$. The values were inserted in the order 8, 5, 1, 7, 3, 12, 9, 6.

If deletion of a value causes a node to be less than half full, it is combined with its neighboring nodes, and this can also propagate all the way to the root. Hence, deletion can reduce the number of tree levels. It has been shown by analysis and simulation that, after numerous random insertions and deletions on a B-tree, the nodes are approximately 69% full when the number of values in the tree stabilizes. This is also true of $B^+$-trees. If this happens, node splitting and combining will occur only rarely, so insertion and deletion become quite efficient. If the number of values grows, the tree will expand without a problem—although splitting of nodes may occur, so some insertions will take more time. Each B-tree node can have *at most p* tree pointers, $p - 1$ data pointers, and $p - 1$ search key field values (see Figure 17.10(a)).

In general, a B-tree node may contain additional information needed by the algorithms that manipulate the tree, such as the number of entries $q$ in the node and a pointer to the parent node. Next, we illustrate how to calculate the number of blocks and levels for a B-tree.

**Example 5.** Suppose that the search field is a nonordering key field, and we construct a B-tree on this field with $p = 23$. Assume that each node of the B-tree is 69% full. Each node, on the average, will have $p * 0.69 = 23 * 0.69$ or approximately

16 pointers and, hence, 15 search key field values. The **average fan-out** *fo* = 16. We can start at the root and see how many values and pointers can exist, on the average, at each subsequent level:

| | | | |
|---|---|---|---|
| Root: | 1 node | 15 key entries | 16 pointers |
| Level 1: | 16 nodes | 240 key entries | 256 pointers |
| Level 2: | 256 nodes | 3,840 key entries | 4,096 pointers |
| Level 3: | 4,096 nodes | 61,440 key entries | |

At each level, we calculated the number of key entries by multiplying the total number of pointers at the previous level by 15, the average number of entries in each node. Hence, for the given block size (512 bytes), record/data pointer size (7 bytes), tree/block pointer size (6 bytes), and search key field size (9bytes), a two-level B-tree of order 23 with 69% occupancy holds 3,840 + 240 + 15 = 4,095 entries on the average; a three-level B-tree holds 65,535 entries on the average.

B-trees are sometimes used as **primary file organizations**. In this case, *whole records* are stored within the B-tree nodes rather than just the <search key, record pointer> entries. This works well for files with a relatively *small number of records* and a *small record size.* Otherwise, the fan-out and the number of levels become too great to permit efficient access.

In summary, B-trees provide a multilevel access structure that is a balanced tree structure in which each node is at least half full. Each node in a B-tree of order $p$ can have at most $p - 1$ search values.

### 17.3.2 $B^+$-Trees

Most implementations of a dynamic multilevel index use a variation of the B-tree data structure called a **$B^+$-tree**. In a B-tree, every value of the search field appears once at some level in the tree, along with a data pointer. In a $B^+$-tree, data pointers are stored *only at the leaf nodes* of the tree; hence, the structure of leaf nodes differs from the structure of internal nodes. The leaf nodes have an entry for *every* value of the search field, along with a data pointer to the record (or to the block that contains this record) if the search field is a key field. For a nonkey search field, the pointer points to a block containing pointers to the data file records, creating an extra level of indirection.

The leaf nodes of the $B^+$-tree are usually linked to provide ordered access on the search field to the records. These leaf nodes are similar to the first (base) level of an index. Internal nodes of the $B^+$-tree correspond to the other levels of a multilevel index. Some search field values from the leaf nodes are *repeated* in the internal nodes of the $B^+$-tree to guide the search. The structure of the *internal nodes* of a $B^+$-tree of order $p$ (Figure 17.11(a)) is as follows:

1. Each internal node is of the form

   $$<P_1, K_1, P_2, K_2, \ldots, P_{q-1}, K_{q-1}, P_q>$$

   where $q \leq p$ and each $P_i$ is a **tree pointer**.

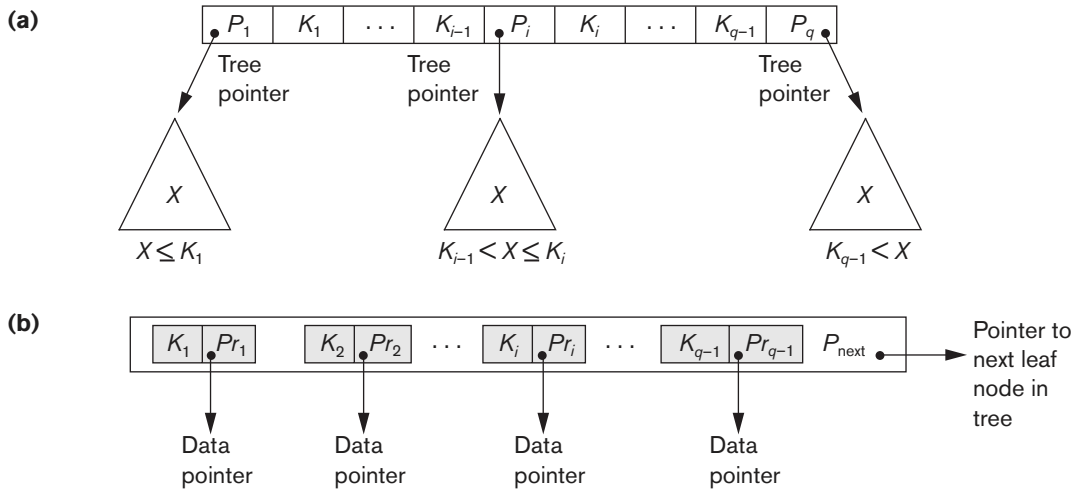



**Figure 17.11**
The nodes of a B+-tree. (a) Internal node of a B+-tree with $q - 1$ search values. (b) Leaf node of a B+-tree with $q - 1$ search values and $q - 1$ data pointers.

2. Within each internal node, $K_1 < K_2 < \ldots < K_{q-1}$.
3. For all search field values $X$ in the subtree pointed at by $P_i$, we have $K_{i-1} < X \leq K_i$ for $1 < i < q$; $X \leq K_i$ for $i = 1$; and $K_{i-1} < X$ for $i = q$ (see Figure 17.11(a)).[12]
4. Each internal node has at most $p$ tree pointers.
5. Each internal node, except the root, has at least $\lceil (p/2) \rceil$ tree pointers. The root node has at least two tree pointers if it is an internal node.
6. An internal node with $q$ pointers, $q \leq p$, has $q - 1$ search field values.

The structure of the *leaf nodes* of a B+-tree of order $p$ (Figure 17.11(b)) is as follows:

1. Each leaf node is of the form

   $<<K_1, Pr_1>, <K_2, Pr_2>, \ldots, <K_{q-1}, Pr_{q-1}>, P_{\text{next}}>$

   where $q \leq p$, each $Pr_i$ is a data pointer, and $P_{\text{next}}$ points to the next *leaf node* of the B+-tree.
2. Within each leaf node, $K_1 \leq K_2 \ldots, K_{q-1}, q \leq p$.
3. Each $Pr_i$ is a **data pointer** that points to the record whose search field value is $K_i$ or to a file block containing the record (or to a block of record pointers that point to records whose search field value is $K_i$ if the search field is not a key).
4. Each leaf node has at least $\lceil (p/2) \rceil$ values.
5. All leaf nodes are at the same level.

[12]Our definition follows Knuth (1998). One can define a B+-tree differently by exchanging the $<$ and $\leq$ symbols ($K_{i-1} \leq X < K_i$; $K_{q-1} \leq$ X), but the principles remain the same.

The pointers in internal nodes are *tree pointers* to blocks that are tree nodes, whereas the pointers in leaf nodes are *data pointers* to the data file records or blocks—except for the $P_{next}$ pointer, which is a tree pointer to the next leaf node. By starting at the leftmost leaf node, it is possible to traverse leaf nodes as a linked list, using the $P_{next}$ pointers. This provides ordered access to the data records on the indexing field. A $P_{previous}$ pointer can also be included. For a $B^+$-tree on a nonkey field, an extra level of indirection is needed similar to the one shown in Figure 17.5, so the *Pr* pointers are block pointers to blocks that contain a set of record pointers to the actual records in the data file, as discussed in option 3 of Section 17.1.3.

Because entries in the *internal nodes* of a $B^+$-tree include search values and tree pointers without any data pointers, more entries can be packed into an internal node of a $B^+$-tree than for a similar B-tree. Thus, for the same block (node) size, the order $p$ will be larger for the $B^+$-tree than for the B-tree, as we illustrate in Example 6. This can lead to fewer $B^+$-tree levels, improving search time. Because the structures for internal and for leaf nodes of a $B^+$-tree are different, the order $p$ can be different. We will use $p$ to denote the order for *internal nodes* and $p_{leaf}$ to denote the order for *leaf nodes*, which we define as being the maximum number of data pointers in a leaf node.

**Example 6.** To calculate the order $p$ of a $B^+$-tree, suppose that the search key field is $V = 9$ bytes long, the block size is $B = 512$ bytes, a record pointer is $Pr = 7$ bytes, and a block pointer/tree pointer is $P = 6$ bytes. An internal node of the $B^+$-tree can have up to $p$ tree pointers and $p - 1$ search field values; these must fit into a single block. Hence, we have:

$$(p * P) + ((p - 1) * V) \leq B$$
$$(p * 6) + ((p - 1) * 9) \leq 512$$
$$(15 * p) \leq 512$$

We can choose $p$ to be the largest value satisfying the above inequality, which gives $p = 34$. This is larger than the value of 23 for the B-tree (it is left to the reader to compute the order of the B-tree assuming same size pointers), resulting in a larger fan-out and more entries in each internal node of a $B^+$-tree than in the corresponding B-tree. The leaf nodes of the $B^+$-tree will have the same number of values and pointers, except that the pointers are data pointers and a next pointer. Hence, the order $p_{leaf}$ for the leaf nodes can be calculated as follows:

$$(p_{leaf} * (Pr + V)) + P \leq B$$
$$(p_{leaf} * (7 + 9)) + 6 \leq 512$$
$$(16 * p_{leaf}) \leq 506$$

It follows that each leaf node can hold up to $p_{leaf} = 31$ key value/data pointer combinations, assuming that the data pointers are record pointers.

As with the B-tree, we may need additional information—to implement the insertion and deletion algorithms—in each node. This information can include the type of node (internal or leaf), the number of current entries $q$ in the node, and pointers to the parent and sibling nodes. Hence, before we do the above calculations for $p$

and $p_{leaf}$, we should reduce the block size by the amount of space needed for all such information. The next example illustrates how we can calculate the number of entries in a B+-tree.

**Example 7.** Suppose that we construct a B+-tree on the field in Example 6. To calculate the approximate number of entries in the B+-tree, we assume that each node is 69% full. On the average, each internal node will have 34 * 0.69 or approximately 23 pointers, and hence 22 values. Each leaf node, on the average, will hold 0.69 * $p_{leaf}$ = 0.69 * 31 or approximately 21 data record pointers. A B+-tree will have the following average number of entries at each level:

| | | | |
|---|---|---|---|
| Root: | 1 node | 22 key entries | 23 pointers |
| Level 1: | 23 nodes | 506 key entries | 529 pointers |
| Level 2: | 529 nodes | 11,638 key entries | 12,167 pointers |
| Leaf level: | 12,167 nodes | 255,507 data record pointers | |

For the block size, pointer size, and search field size as in Example 6, a three-level B+-tree holds up to 255,507 record pointers, with the average 69% occupancy of nodes. Note that we considered the leaf node differently from the nonleaf nodes and computed the data pointers in the leaf node to be 12,167 * 21 based on 69% occupancy of the leaf node, which can hold 31 keys with data pointers. Compare this to the 65,535 entries for the corresponding B-tree in Example 5. Because a B-tree includes a data/record pointer along with each search key at all levels of the tree, it tends to accommodate less number of keys for a given number of index levels. This is the main reason that B+-trees are preferred to B-trees as indexes to database files. Most DBMSs, such as Oracle, are creating all indexes as B+-trees.

**Search, Insertion, and Deletion with B+-Trees.** Algorithm 17.2 outlines the procedure using the B+-tree as the access structure to search for a record. Algorithm 17.3 illustrates the procedure for inserting a record in a file with a B+-tree access structure. These algorithms assume the existence of a key search field, and they must be modified appropriately for the case of a B+-tree on a nonkey field. We illustrate insertion and deletion with an example.

**Algorithm 17.2.** Searching for a Record with Search Key Field Value *K*, Using a B+-Tree

```
n ← block containing root node of B+-tree;
read block n;
while (n is not a leaf node of the B+-tree) do
    begin
    q ← number of tree pointers in node n;
    if K ≤ n.K1 (*n.Ki refers to the ith search field value in node n*)
        then n ← n.P1 (*n.Pi refers to the ith tree pointer in node n*)
        else if K > n.Kq–1
            then n ← n.Pq
```

```
            else begin
                search node n for an entry i such that n.K_{i-1} < K ≤ n.K_i;
                    n ← n.P_i
                    end;
        read block n
        end;
search block n for entry (K_i, Pr_i) with K = K_i; (* search leaf node *)
if found
    then read data file block with address Pr_i and retrieve record
    else the record with search field value K is not in the data file;
```

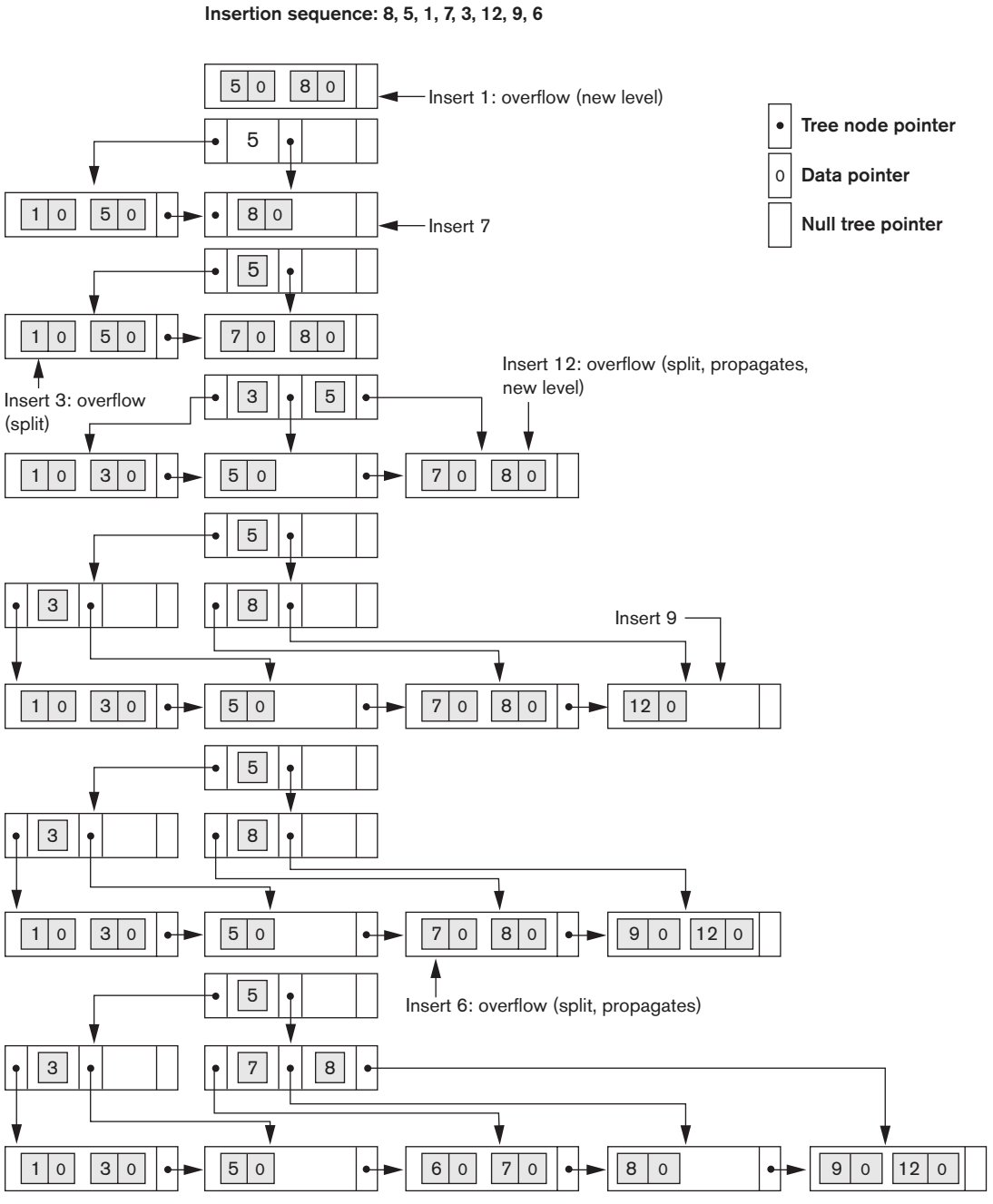
**Algorithm 17.3.** Inserting a Record with Search Key Field Value $K$ in a $B^+$-Tree of Order $p$

```
n ← block containing root node of B+-tree;
read block n; set stack S to empty;
while (n is not a leaf node of the B+-tree) do
    begin
    push address of n on stack S;
        (*stack S holds parent nodes that are needed in case of split*)
    q ← number of tree pointers in node n;
    if K ≤ n.K_1 (*n.K_i refers to the ith search field value in node n*)
        then n ← n.P_1 (*n.P_i refers to the ith tree pointer in node n*)
        else if K ← n.K_{q-1}
            then n ← n.P_q
            else begin
                search node n for an entry i such that n.K_{i-1} < K ≤ n.K_i;
                n ← n.P_i
                end;
        read block n
    end;
search block n for entry (K_i,Pr_i) with K = K_i; (*search leaf node n*)
if found
    then record already in file; cannot insert
    else (*insert entry in B+-tree to point to record*)
        begin
        create entry (K, Pr) where Pr points to the new record;
        if leaf node n is not full
            then insert entry (K, Pr) in correct position in leaf node n
            else begin (*leaf node n is full with p_leaf record pointers; is split*)
                copy n to temp (*temp is an oversize leaf node to hold extra entries*);
                insert entry (K, Pr) in temp in correct position;
                (*temp now holds p_leaf + 1 entries of the form (K_i, Pr_i)*)
                new ← a new empty leaf node for the tree; new.P_next ← n.P_next ;
                j ← ⌈ (p_leaf + 1)/2 ⌉ ;
                n ← first j entries in temp (up to entry (K_j, Pr_j)); n.P_next ← new;
```

```
            new ← remaining entries in temp; K ← K_j ;
            (*now we must move (K, new) and insert in parent internal node;
              however, if parent is full, split may propagate*)
            finished ← false;
            repeat
            if stack S is empty
                then (←no parent node; new root node is created for the tree*)
                    begin
                    root ← a new empty internal node for the tree;
                    root ← <n, K, new>; finished ← true;
                    end
                else begin
                    n ← pop stack S;
                    if internal node n is not full
                        then
                            begin (*parent node not full; no split*)
                            insert (K, new) in correct position in internal node n;
                            finished ← true
                            end
                        else begin (*internal node n is full with p tree pointers;
                                    overflow condition; node is split*)
                        copy n to temp (*temp is an oversize internal node*);
                        insert (K, new) in temp in correct position;
                        (*temp now has p + 1 tree pointers*)
                        new ← a new empty internal node for the tree;
                        j ← ⌊((p + 1)/2⌋ ;
                        n ← entries up to tree pointer P_j in temp;
                        (*n contains <P_1, K_1, P_2, K_2, ... , P_{j–1}, K_{j–1}, P_j >*)
                        new ← entries from tree pointer P_{j+1} in temp;
                        (*new contains < P_{j+1}, K_{j+1}, ... , K_{p–1}, P_p, K_p, P_{p+1} >*)
                        K ← K_j
                        (*now we must move (K, new) and insert in
                          parentinternal node*)
                    end
                end
            until finished
            end;
    end;
```

Figure 17.12 illustrates insertion of records in a B+-tree of order $p = 3$ and $p_{leaf} = 2$. First, we observe that the root is the only node in the tree, so it is also a leaf node. As soon as more than one level is created, the tree is divided into internal nodes and leaf nodes. Notice that *every key value must exist at the leaf level*, because all data pointers are at the leaf level. However, only some values exist in internal nodes to guide the search. Notice also that every value appearing in an internal node also appears as *the rightmost value* in the leaf level of the subtree pointed at by the tree pointer to the left of the value.

**Figure 17.12**
An example of insertion in a $B^+$-tree with $p = 3$ and $p_{leaf} = 2$.



When a *leaf node* is full and a new entry is inserted there, the node *overflows* and must be split. The first $j = \lceil ((p_{\text{leaf}} + 1)/2) \rceil$ entries in the original node are kept there, and the remaining entries are moved to a new leaf node. The $j$th search value is replicated in the parent internal node, and an extra pointer to the new node is created in the parent. These must be inserted in the parent node in their correct sequence. If the parent internal node is full, the new value will cause it to overflow also, so it must be split. The entries in the internal node up to $P_j$—the $j$th tree pointer after inserting the new value and pointer, where $j = \lfloor ((p + 1)/2) \rfloor$—are kept, whereas the $j$th search value is moved to the parent, not replicated. A new internal node will hold the entries from $P_{j+1}$ to the end of the entries in the node (see Algorithm 17.3). This splitting can propagate all the way up to create a new root node and hence a new level for the B+-tree.

Figure 17.13 illustrates deletion from a B+-tree. When an entry is deleted, it is always removed from the leaf level. If it happens to occur in an internal node, it must also be removed from there. In the latter case, the value to its left in the leaf node must replace it in the internal node because that value is now the rightmost entry in the subtree. Deletion may cause **underflow** by reducing the number of entries in the leaf node to below the minimum required. In this case, we try to find a sibling leaf node—a leaf node directly to the left or to the right of the node with underflow—and redistribute the entries among the node and its **sibling** so that both are at least half full; otherwise, the node is merged with its siblings and the number of leaf nodes is reduced. A common method is to try to **redistribute** entries with the left sibling; if this is not possible, an attempt to redistribute with the right sibling is made. If this is also not possible, the three nodes are merged into two leaf nodes. In such a case, underflow may propagate to **internal** nodes because one fewer tree pointer and search value are needed. This can propagate and reduce the tree levels.

Notice that implementing the insertion and deletion algorithms may require parent and sibling pointers for each node, or the use of a stack as in Algorithm 17.3. Each node should also include the number of entries in it and its type (leaf or internal). Another alternative is to implement insertion and deletion as recursive procedures.[13]

**Variations of B-Trees and B+-Trees.** To conclude this section, we briefly mention some variations of B-trees and B+-trees. In some cases, constraint 5 on the B-tree (or for the internal nodes of the B+–tree, except the root node), which requires each node to be at least half full, can be changed to require each node to be at least two-thirds full. In this case the B-tree has been called a **B*-tree**. In general, some systems allow the user to choose a **fill factor** between 0.5 and 1.0, where the latter means that the B-tree (index) nodes are to be completely full. It is also possible to specify two fill factors for a B+-tree: one for the leaf level and one for the internal nodes of the tree. When the index is first constructed, each node is filled up

[13]For more details on insertion and deletion algorithms for B+-trees, consult Ramakrishnan and Gehrke (2003).

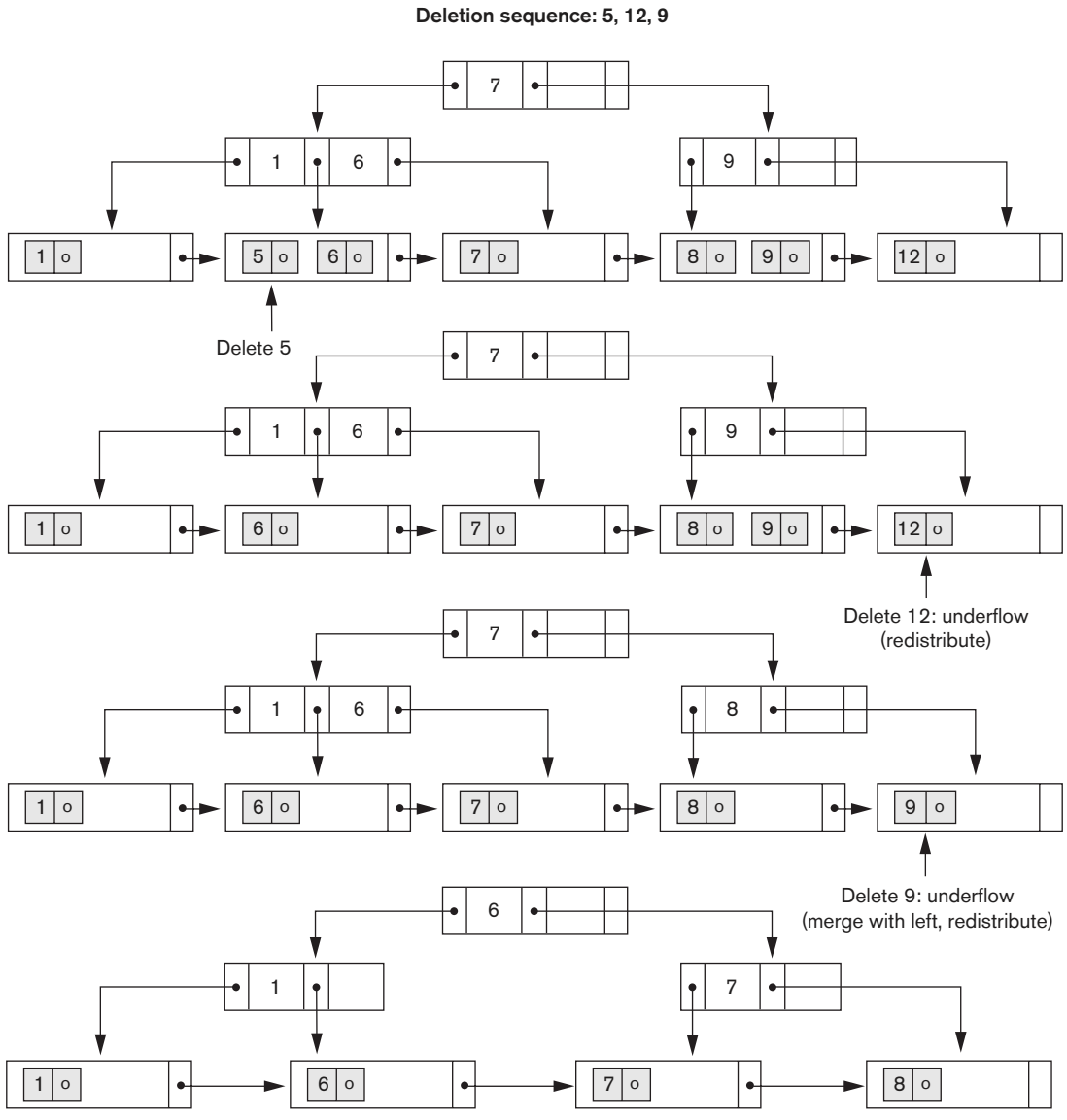



**Figure 17.13**
An example of deletion from a $B^+$-tree.

to approximately the fill factors specified. Some investigators have suggested relaxing the requirement that a node be half full, and instead allow a node to become completely empty before merging, to simplify the deletion algorithm. Simulation studies show that this does not waste too much additional space under randomly distributed insertions and deletions.

## 17.4 Indexes on Multiple Keys

In our discussion so far, we have assumed that the primary or secondary keys on which files were accessed were single attributes (fields). In many retrieval and update requests, multiple attributes are involved. If a certain combination of attributes is used frequently, it is advantageous to set up an access structure to provide efficient access by a key value that is a combination of those attributes.

For example, consider an EMPLOYEE file containing attributes Dno (department number), Age, Street, City, Zip_code, Salary and Skill_code, with the key of Ssn (Social Security number). Consider the query: *List the employees in department number 4 whose age is 59*. Note that both Dno and Age are nonkey attributes, which means that a search value for either of these will point to multiple records. The following alternative search strategies may be considered:

1. Assuming Dno has an index, but Age does not, access the records having Dno = 4 using the index, and then select from among them those records that satisfy Age = 59.
2. Alternately, if Age is indexed but Dno is not, access the records having Age = 59 using the index, and then select from among them those records that satisfy Dno = 4.
3. If indexes have been created on both Dno and Age, both indexes may be used; each gives a set of records or a set of pointers (to blocks or records). An intersection of these sets of records or pointers yields those records or pointers that satisfy both conditions.

All of these alternatives eventually give the correct result. However, if the set of records that meet each condition (Dno = 4 or Age = 59) individually are large, yet only a few records satisfy the combined condition, then none of the above is an efficient technique for the given search request. Note also that queries such as "find the minimum or maximum age among all employees" can be answered just by using the index on Age, without going to the data file. Finding the maximum or minimum age within Dno = 4, however, would not be answerable just by processing the index alone. Also, listing the departments in which employees with Age = 59 work will also not be possible by processing just the indexes. A number of possibilities exist that would treat the combination <Dno, Age> or <Age, Dno> as a search key made up of multiple attributes. We briefly outline these techniques in the following sections. We will refer to keys containing multiple attributes as **composite keys**.

### 17.4.1 Ordered Index on Multiple Attributes

All the discussion in this chapter so far still applies if we create an index on a search key field that is a combination of <Dno, Age>. The search key is a pair of values <4, 59> in the above example. In general, if an index is created on attributes $<A_1, A_2, \ldots, A_n>$, the search key values are tuples with $n$ values: $<v_1, v_2, \ldots, v_n>$.

A lexicographic ordering of these tuple values establishes an order on this composite search key. For our example, all of the department keys for department number

3 precede those for department number 4. Thus <3, *n*> precedes <4, *m*> for any values of *m* and *n*. The ascending key order for keys with Dno = 4 would be <4, 18>, <4, 19>, <4, 20>, and so on. Lexicographic ordering works similarly to ordering of character strings. An index on a composite key of *n* attributes works similarly to any index discussed in this chapter so far.

### 17.4.2 Partitioned Hashing

Partitioned hashing is an extension of static external hashing (Section 16.8.2) that allows access on multiple keys. It is suitable only for equality comparisons; range queries are not supported. In partitioned hashing, for a key consisting of *n* components, the hash function is designed to produce a result with *n* separate hash addresses. The bucket address is a concatenation of these *n* addresses. It is then possible to search for the required composite search key by looking up the appropriate buckets that match the parts of the address in which we are interested.

For example, consider the composite search key <Dno, Age>. If Dno and Age are hashed into a 3-bit and 5-bit address respectively, we get an 8-bit bucket address. Suppose that Dno = 4 has a hash address '100' and Age = 59 has hash address '10101'. Then to search for the combined search value, Dno = 4 and Age = 59, one goes to bucket address 100 10101; just to search for all employees with Age = 59, all buckets (eight of them) will be searched whose addresses are '000 10101', '001 10101', … and so on. An advantage of partitioned hashing is that it can be easily extended to any number of attributes. The bucket addresses can be designed so that high-order bits in the addresses correspond to more frequently accessed attributes. Additionally, no separate access structure needs to be maintained for the individual attributes. The main drawback of partitioned hashing is that it cannot handle range queries on any of the component attributes. Additionally, most hash functions do not maintain records in order by the key being hashed. Hence, accessing records in lexicographic order by a combination of attributes such as <Dno, Age> used as a key would not be straightforward or efficient.

### 17.4.3 Grid Files

Another alternative is to organize the EMPLOYEE file as a grid file. If we want to access a file on two keys, say Dno and Age as in our example, we can construct a grid array with one linear scale (or dimension) for each of the search attributes. Figure 17.14 shows a grid array for the EMPLOYEE file with one linear scale for Dno and another for the Age attribute. The scales are made in a way as to achieve a uniform distribution of that attribute. Thus, in our example, we show that the linear scale for Dno has Dno = 1, 2 combined as one value 0 on the scale, whereas Dno = 5 corresponds to the value 2 on that scale. Similarly, Age is divided into its scale of 0 to 5 by grouping ages so as to distribute the employees uniformly by age. The grid array shown for this file has a total of 36 cells. Each cell points to some bucket address where the records corresponding to that cell are stored. Figure 17.14 also shows the assignment of cells to buckets (only partially).

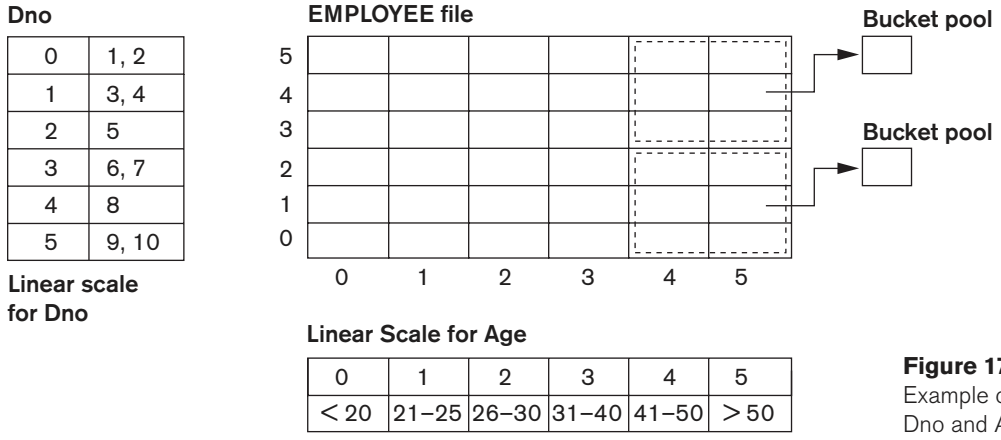



**Figure 17.14**
Example of a grid array on Dno and Age attributes.

Thus our request for Dno = 4 and Age = 59 maps into the cell (1, 5) corresponding to the grid array. The records for this combination will be found in the corresponding bucket. This method is particularly useful for range queries that would map into a set of cells corresponding to a group of values along the linear scales. If a range query corresponds to a match on the some of the grid cells, it can be processed by accessing exactly the buckets for those grid cells. For example, a query for Dno ≤ 5 and Age > 40 refers to the data in the top bucket shown in Figure 17.14.

The grid file concept can be applied to any number of search keys. For example, for *n* search keys, the grid array would have *n* dimensions. The grid array thus allows a partitioning of the file along the dimensions of the search key attributes and provides an access by combinations of values along those dimensions. Grid files perform well in terms of reduction in time for multiple key access. However, they represent a space overhead in terms of the grid array structure. Moreover, with dynamic files, a frequent reorganization of the file adds to the maintenance cost.[14]

# 17.5 Other Types of Indexes

## 17.5.1 Hash Indexes

It is also possible to create access structures similar to indexes that are based on *hashing*. The **hash index** is a secondary structure to access the file by using hashing on a search key other than the one used for the primary data file organization. The index entries are of the type <*K*, *Pr*> or <*K*, *P*>, where *Pr* is a pointer to the record containing the key, or *P* is a pointer to the block containing the record for that key. The index file with these index entries can be organized as a dynamically expandable hash file, using one of the techniques described in Section 16.8.3; searching for an entry uses the hash search algorithm on *K*. Once an entry is found, the pointer *Pr*

[14]Insertion/deletion algorithms for grid files may be found in Nievergelt et al. (1984).

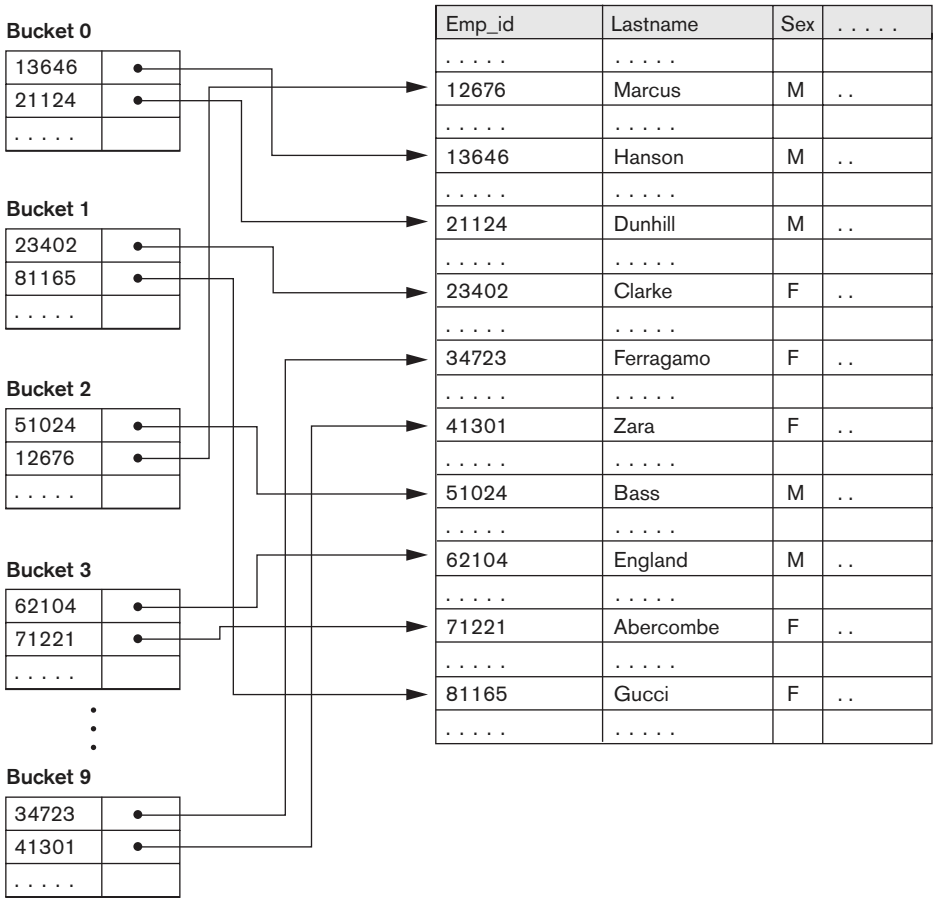



**Figure 17.15**
Hash-based indexing.

(or *P*) is used to locate the corresponding record in the data file. Figure 17.15 illustrates a hash index on the Emp_id field for a file that has been stored as a sequential file ordered by Name. The Emp_id is hashed to a bucket number by using a hashing function: the sum of the digits of Emp_id modulo 10. For example, to find Emp_id 51024, the hash function results in bucket number 2; that bucket is accessed first. It contains the index entry < 51024, *Pr* >; the pointer *Pr* leads us to the actual record in the file. In a practical application, there may be thousands of buckets; the bucket number, which may be several bits long, would be subjected to the directory schemes discussed in the context of dynamic hashing in Section 16.8.3. Other search structures can also be used as indexes.

### 17.5.2 Bitmap Indexes

The **bitmap index** is another popular data structure that facilitates querying on multiple keys. Bitmap indexing is used for relations that contain a large number of rows. It creates an index for one or more columns, and each value or value range in

**EMPLOYEE**

| Row_id | Emp_id | Lname | Sex | Zipcode | Salary_grade |
|---|---|---|---|---|---|
| 0 | 51024 | Bass | M | 94040 | .. |
| 1 | 23402 | Clarke | F | 30022 | .. |
| 2 | 62104 | England | M | 19046 | .. |
| 3 | 34723 | Ferragamo | F | 30022 | .. |
| 4 | 81165 | Gucci | F | 19046 | .. |
| 5 | 13646 | Hanson | M | 19046 | .. |
| 6 | 12676 | Marcus | M | 30022 | .. |
| 7 | 41301 | Zara | F | 94040 | .. |

**Bitmap index for Sex**

| M | F |
|---|---|
| 10100110 | 01011001 |

**Bitmap index for Zipcode**

| Zipcode 19046 | Zipcode 30022 | Zipcode 94040 |
|---|---|---|
| 00101100 | 01010010 | 10000001 |

**Figure 17.16**
Bitmap indexes for Sex and Zipcode.

those columns is indexed. Typically, a bitmap index is created for those columns that contain a fairly small number of unique values. To build a bitmap index on a set of records in a relation, the records must be numbered from 0 to $n$ with an id (a record id or a row id) that can be mapped to a physical address made of a block number and a record offset within the block.

A bitmap index is built on **one particular value** of a particular field (the column in a relation) and is just an array of bits. Thus, for a given field, there is one separate bitmap index (or a vector) maintained corresponding to each unique value in the database. Consider a bitmap index for the column $C$ and a value $V$ for that column. For a relation with $n$ rows, it contains $n$ bits. The $i$th bit is set to 1 if the row $i$ has the value $V$ for column $C$; otherwise it is set to a 0. If $C$ contains the valueset $<v_1, v_2, \ldots, v_m>$ with $m$ distinct values, then $m$ bitmap indexes would be created for that column. Figure 17.16 shows the relation EMPLOYEE with columns Emp_id, Lname, Sex, Zipcode, and Salary_grade (with just eight rows for illustration) and a bitmap index for the Sex and Zipcode columns. As an example, if the bitmap for Sex = F, the bits for Row_ids 1, 3, 4, and 7 are set to 1, and the rest of the bits are set to 0, the bitmap indexes could have the following query applications:

- For the query $C_1 = V_1$, the corresponding bitmap for value $V_1$ returns the Row_ids containing the rows that qualify.
- For the query $C_1 = V_1$ and $C_2 = V_2$ (a multikey search request), the two corresponding bitmaps are retrieved and intersected (logically AND-ed) to yield the set of Row_ids that qualify. In general, $k$ bitvectors can be intersected to deal with $k$ equality conditions. Complex AND-OR conditions can also be supported using bitmap indexing.
  - For the query $C_1 = V_1$ or $C_2 = V_2$ or $C_3 = V_3$ (a multikey search request), the three corresponding bitmaps for three different attributes are retrieved and unioned (logically OR-ed) to yield the set of Row ids that qualify.

- To retrieve a count of rows that qualify for the condition $C_1 = V_1$, the "1" entries in the corresponding bitvector are counted.
- Queries with negation, such as $C_1 \neg = V_1$, can be handled by applying the Boolean *complement* operation on the corresponding bitmap.

Consider the example relation EMPLOYEE in Figure 17.16 with bitmap indexes on Sex and Zipcode. To find employees with Sex = F and Zipcode = 30022, we intersect the bitmaps "01011001" and "01010010" yielding Row_ids 1 and 3. Employees who do not live in Zipcode = 94040 are obtained by complementing the bitvector "10000001" and yields Row_ids 1 through 6. In general, if we assume uniform distribution of values for a given column, and if one column has 5 distinct values and another has 10 distinct values, the join condition on these two can be considered to have a selectivity of 1/50 (= 1/5 * 1/10). Hence, only about 2% of the records would actually have to be retrieved. If a column has only a few values, like the Sex column in Figure 17.16, retrieval of the Sex = M condition on average would retrieve 50% of the rows; in such cases, it is better to do a complete scan rather than use bitmap indexing.

In general, bitmap indexes are efficient in terms of the storage space that they need. If we consider a file of 1 million rows (records) with record size of 100 bytes per row, each bitmap index would take up only one bit per row and hence would use 1 million bits or 125 Kbytes. Suppose this relation is for 1 million residents of a state, and they are spread over 200 ZIP Codes; the 200 bitmaps over Zipcodes contribute 200 bits (or 25 bytes) worth of space per row; hence, the 200 bitmaps occupy only 25% as much space as the data file. They allow an exact retrieval of all residents who live in a given ZIP Code by yielding their Row_ids.

When records are deleted, renumbering rows and shifting bits in bitmaps becomes expensive. Another bitmap, called the **existence bitmap**, can be used to avoid this expense. This bitmap has a 0 bit for the rows that have been deleted but are still physically present and a 1 bit for rows that actually exist. Whenever a row is inserted in the relation, an entry must be made in all the bitmaps of all the columns that have a bitmap index; rows typically are appended to the relation or may replace deleted rows to minimize the impact on the reorganization of the bitmaps. This process still constitutes an indexing overhead.

Large bitvectors are handled by treating them as a series of 32-bit or 64-bit vectors, and corresponding AND, OR, and NOT operators are used from the instruction set to deal with 32- or 64-bit input vectors in a single instruction. This makes bitvector operations computationally very efficient.

**Bitmaps for B$^+$-Tree Leaf Nodes.** Bitmaps can be used on the leaf nodes of B$^+$-tree indexes as well as to point to the set of records that contain each specific value of the indexed field in the leaf node. When the B$^+$-tree is built on a nonkey search field, the leaf record must contain a list of record pointers alongside each value of the indexed attribute. For values that occur very frequently, that is, in a large percentage of the relation, a bitmap index may be stored instead of the pointers. As an

example, for a relation with $n$ rows, suppose a value occurs in 10% of the file records. A bitvector would have $n$ bits, having the "1" bit for those Row_ids that contain that search value, which is $n/8$ or $0.125n$ bytes in size. If the record pointer takes up 4 bytes (32 bits), then the $n/10$ record pointers would take up $4 * n/10$ or $0.4n$ bytes. Since $0.4n$ is more than 3 times larger than $0.125n$, it is better to store the bitmap index rather than the record pointers. Hence for search values that occur more frequently than a certain ratio (in this case that would be 1/32), it is beneficial to use bitmaps as a compressed storage mechanism for representing the record pointers in $B^+$-trees that index a nonkey field.

### 17.5.3 Function-Based Indexing

In this section, we discuss a new type of indexing, called **function-based indexing**, that has been introduced in the Oracle relational DBMS as well as in some other commercial products.[15]

The idea behind function-based indexing is to create an index such that the value that results from applying some function on a field or a collection of fields becomes the key to the index. The following examples show how to create and use function-based indexes.

**Example 1.** The following statement creates a function-based index on the EMPLOYEE table based on an uppercase representation of the Lname column, which can be entered in many ways but is always queried by its uppercase representation.

```
CREATE INDEX upper_ix ON Employee (UPPER(Lname));
```

This statement will create an index based on the function `UPPER(Lname)`, which returns the last name in uppercase letters; for example, `UPPER('Smith')` will return 'SMITH'.

Function-based indexes ensure that Oracle Database system will use the index rather than perform a full table scan, even when a function is used in the search predicate of a query. For example, the following query will use the index:

```
SELECT First_name, Lname
FROM Employee
WHERE UPPER(Lname)= "SMITH".
```

Without the function-based index, an Oracle Database might perform a full table scan, since a $B^+$-tree index is searched only by using the column value directly; the use of any function on a column prevents such an index from being used.

**Example 2.** In this example, the EMPLOYEE table is supposed to contain two fields—salary and commission_pct (commission percentage)—and an index is being created on the sum of salary and commission based on the commission_pct.

```
CREATE INDEX income_ix
ON Employee(Salary + (Salary*Commission_pct));
```

[15]Rafi Ahmed contributed most of this section.

The following query uses the `income_ix` index even though the fields salary and commission_pct are occurring in the reverse order in the query when compared to the index definition.

```
SELECT First_name, Lname
FROM Employee
WHERE ((Salary*Commission_pct) + Salary ) > 15000;
```

**Example 3.** This is a more advanced example of using function-based indexing to define conditional uniqueness. The following statement creates a unique function-based index on the ORDERS table that prevents a customer from taking advantage of a promotion id ("blowout sale") more than once. It creates a composite index on the Customer_id and Promotion_id fields together, and it allows only one entry in the index for a given Customer_id with the Promotion_id of "2" by declaring it as a unique index.

```
CREATE UNIQUE INDEX promo_ix ON Orders
(CASE WHEN Promotion_id = 2 THEN Customer_id ELSE NULL END,
CASE WHEN Promotion_id = 2 THEN Promotion_id ELSE NULL END);
```

Note that by using the `CASE` statement, the objective is to remove from the index any rows where Promotion_id is not equal to 2. Oracle Database does not store in the $B^+$-tree index any rows where all the keys are NULL. Therefore, in this example, we map both Customer_id and Promotion_id to NULL unless Promotion_id is equal to 2. The result is that the index constraint is violated only if Promotion_id is equal to 2, for two (attempted insertions of) rows with the same Customer_id value.

## 17.6 Some General Issues Concerning Indexing

### 17.6.1 Logical versus Physical Indexes

In the earlier discussion, we have assumed that the index entries <*K*, *Pr*> (or <*K*, *P*>) always include a physical pointer *Pr* (or *P*) that specifies the physical record address on disk as a block number and offset. This is sometimes called a **physical index**, and it has the disadvantage that the pointer must be changed if the record is moved to another disk location. For example, suppose that a primary file organization is based on linear hashing or extendible hashing; then, each time a bucket is split, some records are allocated to new buckets and hence have new physical addresses. If there was a secondary index on the file, the pointers to those records would have to be found and updated, which is a difficult task.

To remedy this situation, we can use a structure called a **logical index**, whose index entries are of the form <*K*, $K_p$>. Each entry has one value *K* for the secondary indexing field matched with the value $K_p$ of the field used for the primary file organization. By searching the secondary index on the value of *K*, a program can locate the corresponding value of $K_p$ and use this to access the record through the primary file organization, using a primary index if available. Logical indexes thus introduce an

additional level of indirection between the access structure and the data. They are used when physical record addresses are expected to change frequently. The cost of this indirection is the extra search based on the primary file organization.

### 17.6.2 Index Creation

Many RDBMSs have a similar type of command for creating an index, although it is not part of the SQL standard. The general form of this command is:

```
CREATE [ UNIQUE ] INDEX <index name>
ON <table name> ( <column name> [ <order> ] { , <column name> [ <order> ] } )
[ CLUSTER ] ;
```

The keywords UNIQUE and CLUSTER are optional. The keyword CLUSTER is used when the index to be created should also sort the data file records on the indexing attribute. Thus, specifying CLUSTER on a key (unique) attribute would create some variation of a primary index, whereas specifying CLUSTER on a nonkey (nonunique) attribute would create some variation of a clustering index. The value for <order> can be either ASC (ascending) or DESC (descending), and it specifies whether the data file should be ordered in ascending or descending values of the indexing attribute. The default is ASC. For example, the following would create a clustering (ascending) index on the nonkey attribute Dno of the EMPLOYEE file:

```
CREATE INDEX DnoIndex
ON EMPLOYEE (Dno)
CLUSTER ;
```

**Index Creation Process:** In many systems, an index is not an integral part of the data file but can be created and discarded dynamically. That is why it is often called an *access structure.* Whenever we expect to access a file frequently based on some search condition involving a particular field, we can request the DBMS to create an index on that field as shown above for the DnoIndex. Usually, a secondary index is created to avoid physical ordering of the records in the data file on disk.

The main advantage of secondary indexes is that—theoretically, at least—they can be created in conjunction with *virtually any primary record organization.* Hence, a secondary index could be used to complement other primary access methods such as ordering or hashing, or it could even be used with mixed files. To create a $B^+$-tree secondary index on some field of a file, if the file is large and contains millions of records, neither the file nor the index would fit in main memory. Insertion of a large number of entries into the index is done by a process called **bulk loading** the index. We must go through all records in the file to create the entries at the leaf level of the tree. These entries are then sorted and filled according to the specified fill factor; simultaneously, the other index levels are created. It is more expensive and much harder to create primary indexes and clustering indexes dynamically, because the records of the data file must be physically sorted on disk in order of the indexing field. However, some systems allow users to create these indexes dynamically on their files by sorting the file during index creation.

**Indexing of Strings:** There are a couple of issues that are of particular concern when indexing strings. Strings can be variable length (e.g., VARCHAR data type in SQL; see Chapter 6) and strings may be too long limiting the fan-out. If a $B^+$-tree index is to be built with a string as a search key, there may be an uneven number of keys per index node and the fan-out may vary. Some nodes may be forced to split when they become full regardless of the number of keys in them. The technique of **prefix compression** alleviates the situation. Instead of storing the entire string in the intermediate nodes, it stores only the prefix of the search key adequate to distinguish the keys that are being separated and directed to the subtree. For example, if Lastname was a search key and we were looking for "Navathe", the nonleaf node may contain "Nac" for Nachamkin and "Nay" for Nayuddin as the two keys on either side of the subtree pointer that we need to follow.

### 17.6.3 Tuning Indexes

The initial choice of indexes may have to be revised for the following reasons:

- Certain queries may take too long to run for lack of an index.
- Certain indexes may not get utilized at all.
- Certain indexes may undergo too much updating because the index is on an attribute that undergoes frequent changes.

Most DBMSs have a command or trace facility, which can be used by the DBA to ask the system to show how a query was executed—what operations were performed in what order and what secondary access structures (indexes) were used. By analyzing these execution plans (we will discuss this term further in Chapter 18), it is possible to diagnose the causes of the above problems. Some indexes may be dropped and some new indexes may be created based on the tuning analysis.

The goal of tuning is to dynamically evaluate the requirements, which sometimes fluctuate seasonally or during different times of the month or week, and to reorganize the indexes and file organizations to yield the best overall performance. Dropping and building new indexes is an overhead that can be justified in terms of performance improvements. Updating of a table is generally suspended while an index is dropped or created; this loss of service must be accounted for.

Besides dropping or creating indexes and changing from a nonclustered to a clustered index and vice versa, **rebuilding the index** may improve performance. Most RDBMSs use $B^+$-trees for an index. If there are many deletions on the index key, index pages may contain wasted space, which can be claimed during a rebuild operation. Similarly, too many insertions may cause overflows in a clustered index that affect performance. Rebuilding a clustered index amounts to reorganizing the entire table ordered on that key.

The available options for indexing and the way they are defined, created, and reorganized vary from system to system. As an illustration, consider the sparse and dense indexes we discussed in Section 17.1. A sparse index such as a primary index will have one index pointer for each page (disk block) in the data file; a

dense index such as a unique secondary index will have an index pointer for each record. Sybase provides clustering indexes as sparse indexes in the form of $B^+$-trees, whereas INGRES provides sparse clustering indexes as ISAM files and dense clustering indexes as $B^+$-trees. In some versions of Oracle and DB2, the option of setting up a clustering index is limited to a dense index, and the DBA has to work with this limitation.

### 17.6.4 Additional Issues Related to Storage of Relations and Indexes

**Using an Index for Managing Constraints and Duplicates:** It is common to use an index to enforce a *key constraint* on an attribute. While searching the index to insert a new record, it is straightforward to check at the same time whether another record in the file—and hence in the index tree—has the same key attribute value as the new record. If so, the insertion can be rejected.

If an index is created on a nonkey field, *duplicates* occur; handling of these duplicates is an issue the DBMS product vendors have to deal with and affects data storage as well as index creation and management. Data records for the duplicate key may be contained in the same block or may span multiple blocks where many duplicates are possible. Some systems add a row id to the record so that records with duplicate keys have their own unique identifiers. In such cases, the $B^+$-tree index may regard a <key, Row_id> combination as the de facto key for the index, turning the index into a unique index with no duplicates. The deletion of a key $K$ from such an index would involve deleting all occurrences of that key $K$—hence the deletion algorithm has to account for this.

In actual DBMS products, deletion from $B^+$-tree indexes is also handled in various ways to improve performance and response times. Deleted records may be marked as deleted and the corresponding index entries may also not be removed until a garbage collection process reclaims the space in the data file; the index is rebuilt online after garbage collection.

**Inverted Files and Other Access Methods:** A file that has a secondary index on every one of its fields is often called a **fully inverted file**. Because all indexes are secondary, new records are inserted at the end of the file; therefore, the data file itself is an unordered (heap) file. The indexes are usually implemented as $B^+$-trees, so they are updated dynamically to reflect insertion or deletion of records. Some commercial DBMSs, such as Software AG's Adabas, use this method extensively.

We referred to the popular IBM file organization called ISAM in Section 17.2. Another IBM method, the **virtual storage access method** (**VSAM**), is somewhat similar to the $B^+$–tree access structure and is still being used in many commercial systems.

**Using Indexing Hints in Queries:** DBMSs such as Oracle have a provision for allowing hints in queries that are suggested alternatives or indicators to the query

processor and optimizer for expediting query execution. One form of hints is called indexing hints; these hints suggest the use of an index to improve the execution of a query. The hints appear as a special comment (which is preceded by +) and they override all optimizer decisions, but they may be ignored by the optimizer if they are invalid, irrelevant, or improperly formulated. We do not get into a detailed discussion of indexing hints, but illustrate with an example query.

For example, to retrieve the SSN, Salary, and department number for employees working in department numbers with Dno less than 10:

```
SELECT /*+ INDEX (EMPLOYEE emp_dno_index ) */ Emp_ssn, Salary, Dno
FROM EMPLOYEE
WHERE Dno < 10;
```

The above query includes a hint to use a valid index called emp_dno_index (which is an index on the EMPLOYEE relation on Dno).

**Column-Based Storage of Relations:** There has been a recent trend to consider a column-based storage of relations as an alternative to the traditional way of storing relations row by row. Commercial relational DBMSs have offered $B^+$-tree indexing on primary as well as secondary keys as an efficient mechanism to support access to data by various search criteria and the ability to write a row or a set of rows to disk at a time to produce write-optimized systems. For data warehouses (to be discussed in Chapter 29), which are read-only databases, the column-based storage offers particular advantages for read-only queries. Typically, the column-store RDBMSs consider storing each column of data individually and afford performance advantages in the following areas:

- Vertically partitioning the table column by column, so that a two-column table can be constructed for every attribute and thus only the needed columns can be accessed
- Using column-wise indexes (similar to the bitmap indexes discussed in Section 17.5.2) and join indexes on multiple tables to answer queries without having to access the data tables
- Using materialized views (see Chapter 7) to support queries on multiple columns

Column-wise storage of data affords additional freedom in the creation of indexes, such as the bitmap indexes discussed earlier. The same column may be present in multiple projections of a table and indexes may be created on each projection. To store the values in the same column, strategies for data compression, null-value suppression, dictionary encoding techniques (where distinct values in the column are assigned shorter codes), and run-length encoding techniques have been devised. MonetDB/X100, C-Store, and Vertica are examples of such systems Some popular systems (like Cassandra, Hbase, and Hypertable) have used column-based storage effectively with the concept of **wide column-stores**. The storage of data in such systems will be explained in the context of NOSQL systems that we will discuss in Chapter 24.

# 17.7 Physical Database Design in Relational Databases

In this section, we discuss the physical design factors that affect the performance of applications and transactions, and then we comment on the specific guidelines for RDBMSs in the context of what we discussed in Chapter 16 and this chapter so far.

## 17.7.1 Factors That Influence Physical Database Design

Physical design is an activity where the goal is not only to create the appropriate structuring of data in storage, but also to do so in a way that guarantees good performance. For a given conceptual schema, there are many physical design alternatives in a given DBMS. It is not possible to make meaningful physical design decisions and performance analyses until the database designer knows the mix of queries, transactions, and applications that are expected to run on the database. This is called the **job mix** for the particular set of database system applications. The database administrators/designers must analyze these applications, their expected frequencies of invocation, any timing constraints on their execution speed, the expected frequency of update operations, and any unique constraints on attributes. We discuss each of these factors next.

**A. Analyzing the Database Queries and Transactions.** Before undertaking the physical database design, we must have a good idea of the intended use of the database by defining in a high-level form the queries and transactions that are expected to run on the database. For each **retrieval query**, the following information about the query would be needed:

1. The files (relations) that will be accessed by the query
2. The attributes on which any selection conditions for the query are specified
3. Whether the selection condition is an equality, inequality, or a range condition
4. The attributes on which any join conditions or conditions to link multiple tables or objects for the query are specified
5. The attributes whose values will be retrieved by the query

The attributes listed in items 2 and 4 above are candidates for the definition of access structures, such as indexes, hash keys, or sorting of the file.

For each **update operation** or **update transaction**, the following information would be needed:

1. The files that will be updated
2. The type of operation on each file (insert, update, or delete)
3. The attributes on which selection conditions for a delete or update are specified
4. The attributes whose values will be changed by an update operation

Again, the attributes listed in item 3 are candidates for access structures on the files, because they would be used to locate the records that will be updated or deleted. On

the other hand, the attributes listed in item 4 are candidates for *avoiding an access structure*, since modifying them will require updating the access structures.

**B. Analyzing the Expected Frequency of Invocation of Queries and Transactions.** Besides identifying the characteristics of expected retrieval queries and update transactions, we must consider their expected rates of invocation. This frequency information, along with the attribute information collected on each query and transaction, is used to compile a cumulative list of the expected frequency of use for all queries and transactions. This is expressed as the expected frequency of using each attribute in each file as a selection attribute or a join attribute, over all the queries and transactions. Generally, for large volumes of processing, the informal *80–20 rule* can be used: approximately 80% of the processing is accounted for by only 20% of the queries and transactions. Therefore, in practical situations, it is rarely necessary to collect exhaustive statistics and invocation rates on all the queries and transactions; it is sufficient to determine the 20% or so most important ones.

**C. Analyzing the Time Constraints of Queries and Transactions.** Some queries and transactions may have stringent performance constraints. For example, a transaction may have the constraint that it should terminate within 5 seconds on 95% of the occasions when it is invoked, and that it should never take more than 20 seconds. Such timing constraints place further priorities on the attributes that are candidates for access paths. The selection attributes used by queries and transactions with time constraints become higher-priority candidates for primary access structures for the files, because the primary access structures are generally the most efficient for locating records in a file.

**D. Analyzing the Expected Frequencies of Update Operations.** A minimum number of access paths should be specified for a file that is frequently updated, because updating the access paths themselves slows down the update operations. For example, if a file that has frequent record insertions has 10 indexes on 10 different attributes, each of these indexes must be updated whenever a new record is inserted. The overhead for updating 10 indexes can slow down the insert operations.

**E. Analyzing the Uniqueness Constraints on Attributes.** Access paths should be specified on all *candidate key* attributes—or sets of attributes—that are either the primary key of a file or unique attributes. The existence of an index (or other access path) makes it sufficient to search only the index when checking this uniqueness constraint, since all values of the attribute will exist in the leaf nodes of the index. For example, when inserting a new record, if a key attribute value of the new record *already exists in the index*, the insertion of the new record should be rejected, since it would violate the uniqueness constraint on the attribute.

Once the preceding information is compiled, it is possible to address the physical database design decisions, which consist mainly of deciding on the storage structures and access paths for the database files.

### 17.7.2 Physical Database Design Decisions

Most relational systems represent each base relation as a physical database file. The access path options include specifying the type of primary file organization for each relation and the attributes that are candidates for defining individual or composite indexes. At most, one of the indexes on each file may be a primary or a clustering index. Any number of additional secondary indexes can be created.

**Design Decisions about Indexing.** The attributes whose values are required in equality or range conditions (selection operation) are those that are keys or that participate in join conditions (join operation) requiring access paths, such as indexes.

The performance of queries largely depends upon what indexes or hashing schemes exist to expedite the processing of selections and joins. On the other hand, during insert, delete, or update operations, the existence of indexes adds to the overhead. This overhead must be justified in terms of the gain in efficiency by expediting queries and transactions.

The physical design decisions for indexing fall into the following categories:

1. **Whether to index an attribute.** The general rules for creating an index on an attribute are that the attribute must either be a key (unique), or there must be some query that uses that attribute either in a selection condition (equality or range of values) or in a join condition. One reason for creating multiple indexes is that some operations can be processed by just scanning the indexes, without having to access the actual data file.
2. **What attribute or attributes to index on.** An index can be constructed on a single attribute, or on more than one attribute if it is a composite index. If multiple attributes from one relation are involved together in several queries, (for example, (Garment_style_#, Color) in a garment inventory database), a multiattribute (composite) index is warranted. The ordering of attributes within a multiattribute index must correspond to the queries. For instance, the above index assumes that queries would be based on an ordering of colors within a Garment_style_# rather than vice versa.
3. **Whether to set up a clustered index.** At most, one index per table can be a primary or clustering index, because this implies that the file be physically ordered on that attribute. In most RDBMSs, this is specified by the keyword CLUSTER. (If the attribute is a *key*, *a primary index* is created, whereas a *clustering index* is created if the attribute is *not a key*.) If a table requires several indexes, the decision about which one should be the primary or clustering index depends upon whether keeping the table ordered on that attribute is needed. Range queries benefit a great deal from clustering. If several attributes require range queries, relative benefits must be evaluated before deciding which attribute to cluster on. If a query is to be answered by doing an index search only (without retrieving data records), the corresponding index should *not* be clustered, since the main benefit of clustering is achieved

when retrieving the records themselves. A clustering index may be set up as a multiattribute index if range retrieval by that composite key is useful in report creation (for example, an index on Zip_code, Store_id, and Product_id may be a clustering index for sales data).

4. **Whether to use a hash index over a tree index.** In general, RDBMSs use $B^+$-trees for indexing. However, ISAM and hash indexes are also provided in some systems. $B^+$-trees support both equality and range queries on the attribute used as the search key. Hash indexes work well with equality conditions, particularly during joins to find a matching record(s), but they do not support range queries.
5. **Whether to use dynamic hashing for the file.** For files that are very volatile—that is, those that grow and shrink continuously—one of the dynamic hashing schemes discussed in Section 16.9 would be suitable. Currently, such schemes are not offered by many commercial RDBMSs.

## 17.8 Summary

In this chapter, we presented file organizations that involve additional access structures, called indexes, to improve the efficiency of retrieval of records from a data file. These access structures may be used *in conjunction with* the primary file organizations discussed in Chapter 16, which are used to organize the file records themselves on disk.

Three types of ordered single-level indexes were introduced: primary, clustering, and secondary. Each index is specified on a field of the file. Primary and clustering indexes are constructed on the physical ordering field of a file, whereas secondary indexes are specified on nonordering fields as additional access structures to improve performance of queries and transactions. The field for a primary index must also be a key of the file, whereas it is a nonkey field for a clustering index. A single-level index is an ordered file and is searched using a binary search. We showed how multilevel indexes can be constructed to improve the efficiency of searching an index. An example is IBM's popular indexed sequential access method (ISAM), which is a multilevel index based on the cylinder/track configuration on disk.

Next we showed how multilevel indexes can be implemented as B-trees and $B^+$-trees, which are dynamic structures that allow an index to expand and shrink dynamically. The nodes (blocks) of these index structures are kept between half full and completely full by the insertion and deletion algorithms. Nodes eventually stabilize at an average occupancy of 69% full, allowing space for insertions without requiring reorganization of the index for the majority of insertions. $B^+$-trees can generally hold more entries in their internal nodes than can B-trees, so they may have fewer levels or hold more entries than does a corresponding B-tree.

We gave an overview of multiple key access methods, and we showed how an index can be constructed based on hash data structures. We introduced the concept of

**partitioned hashing**, which is an extension of external hashing to deal with multiple keys. We also introduced **grid files**, which organize data into buckets along multiple dimensions, We discussed the **hash index** in some detail—it is a secondary structure to access the file by using hashing on a search key other than that used for the primary organization. **Bitmap indexing** is another important type of indexing used for querying by multiple keys and is particularly applicable on fields with a small number of unique values. Bitmaps can also be used at the leaf nodes of $B^+$ tree indexes as well. We also discussed function-based indexing, which is being provided by relational vendors to allow special indexes on a function of one or more attributes.

We introduced the concept of a logical index and compared it with the physical indexes we described before. They allow an additional level of indirection in indexing in order to permit greater freedom for movement of actual record locations on disk. We discussed index creation in SQL, the process of bulk loading of index files and indexing of strings. We discussed circumstances that point to tuning of indexes. Then we reviewed some general topics related to indexing, including managing constraints, using inverted indexes, and using indexing hints in queries; we commented on column-based storage of relations, which is becoming a viable alternative for storing and accessing large databases. Finally, we discussed physical database design of relational databases, which involves decisions related to storage and accessing of data that we have been discussing in the current and the previous chapter. This discussion was divided into factors that influence the design and the types of decisions regarding whether to index an attribute, what attributes to include in an index, clustered versus nonclustered indexes, hashed indexes, and dynamic hashing.

## Review Questions

**17.1.** Define the following terms: *indexing field*, *primary key field*, *clustering field*, *secondary key field*, *block anchor*, *dense index*, and *nondense (sparse) index*.

**17.2.** What are the differences among primary, secondary, and clustering indexes? How do these differences affect the ways in which these indexes are implemented? Which of the indexes are dense, and which are not?

**17.3.** Why can we have at most one primary or clustering index on a file, but several secondary indexes?

**17.4.** How does multilevel indexing improve the efficiency of searching an index file?

**17.5.** What is the order $p$ of a B-tree? Describe the structure of B-tree nodes.

**17.6.** What is the order $p$ of a $B^+$-tree? Describe the structure of both internal and leaf nodes of a $B^+$-tree.

**17.7.** How does a B-tree differ from a $B^+$-tree? Why is a $B^+$-tree usually preferred as an access structure to a data file?

**17.8.** Explain what alternative choices exist for accessing a file based on multiple search keys.

**17.9.** What is partitioned hashing? How does it work? What are its limitations?

**17.10.** What is a grid file? What are its advantages and disadvantages?

**17.11.** Show an example of constructing a grid array on two attributes on some file.

**17.12.** What is a fully inverted file? What is an indexed sequential file?

**17.13.** How can hashing be used to construct an index?

**17.14.** What is bitmap indexing? Create a relation with two columns and sixteen tuples and show an example of a bitmap index on one or both.

**17.15.** What is the concept of function-based indexing? What additional purpose does it serve?

**17.16.** What is the difference between a logical index and a physical index?

**17.17.** What is column-based storage of a relational database?

## Exercises

**17.18.** Consider a disk with block size $B = 512$ bytes. A block pointer is $P = 6$ bytes long, and a record pointer is $P_R = 7$ bytes long. A file has $r = 30{,}000$ EMPLOYEE records of *fixed length*. Each record has the following fields: Name (30 bytes),Ssn (9 bytes), Department_code (9 bytes), Address (40 bytes), Phone (10 bytes), Birth_date (8 bytes), Sex (1 byte), Job_code (4 bytes), and Salary (4 bytes, real number). An additional byte is used as a deletion marker.

a. Calculate the record size $R$ in bytes.

b. Calculate the blocking factor *bfr* and the number of file blocks $b$, assuming an unspanned organization.

c. Suppose that the file is *ordered* by the key field Ssn and we want to construct a *primary index* on Ssn. Calculate (i) the index blocking factor $bfr_i$ (which is also the index fan-out *fo*); (ii) the number of first-level index entries and the number of first-level index blocks; (iii) the number of levels needed if we make it into a multilevel index; (iv) the total number of blocks required by the multilevel index; and (v) the number of block accesses needed to search for and retrieve a record from the file—given its Ssn value—using the primary index.

d. Suppose that the file is *not ordered* by the key field Ssn and we want to construct a *secondary index* on Ssn. Repeat the previous exercise (part c) for the secondary index and compare with the primary index.

e. Suppose that the file is *not ordered* by the nonkey field Department_code and we want to construct a *secondary index* on Department_code, using

option 3 of Section 17.1.3, with an extra level of indirection that stores record pointers. Assume there are 1,000 distinct values of Department_code and that the EMPLOYEE records are evenly distributed among these values. Calculate (i) the index blocking factor $bfr_i$ (which is also the index fan-out *fo*); (ii) the number of blocks needed by the level of indirection that stores record pointers; (iii) the number of first-level index entries and the number of first-level index blocks; (iv) the number of levels needed if we make it into a multilevel index; (v) the total number of blocks required by the multilevel index and the blocks used in the extra level of indirection; and (vi) the approximate number of block accesses needed to search for and retrieve all records in the file that have a specific Department_code value, using the index.

f. Suppose that the file is *ordered* by the nonkey field Department_code and we want to construct a *clustering index* on Department_code that uses block anchors (every new value of Department_code starts at the beginning of a new block). Assume there are 1,000 distinct values of Department_code and that the EMPLOYEE records are evenly distributed among these values. Calculate (i) the index blocking factor $bfr_i$ (which is also the index fan-out *fo*); (ii) the number of first-level index entries and the number of first-level index blocks; (iii) the number of levels needed if we make it into a multilevel index; (iv) the total number of blocks required by the multilevel index; and (v) the number of block accesses needed to search for and retrieve all records in the file that have a specific Department_code value, using the clustering index (assume that multiple blocks in a cluster are contiguous).

g. Suppose that the file is *not* ordered by the key field Ssn and we want to construct a $B^+$-tree access structure (index) on Ssn. Calculate (i) the orders $p$ and $p_{leaf}$ of the $B^+$-tree; (ii) the number of leaf-level blocks needed if blocks are approximately 69% full (rounded up for convenience); (iii) the number of levels needed if internal nodes are also 69% full (rounded up for convenience); (iv) the total number of blocks required by the $B^+$-tree; and (v) the number of block accesses needed to search for and retrieve a record from the file—given its Ssn value—using the $B^+$-tree.

h. Repeat part g, but for a B-tree rather than for a $B^+$-tree. Compare your results for the B-tree and for the $B^+$-tree.

**17.19.** A PARTS file with Part# as the key field includes records with the following Part# values: 23, 65, 37, 60, 46, 92, 48, 71, 56, 59, 18, 21, 10, 74, 78, 15, 16, 20, 24, 28, 39, 43, 47, 50, 69, 75, 8, 49, 33, 38. Suppose that the search field values are inserted in the given order in a $B^+$-tree of order $p = 4$ and $p_{\text{leaf}} = 3$; show how the tree will expand and what the final tree will look like.

**17.20.** Repeat Exercise 17.19, but use a B-tree of order $p = 4$ instead of a $B^+$-tree.

**17.21.** Suppose that the following search field values are deleted, in the given order, from the $B^+$-tree of Exercise 17.19; show how the tree will shrink and show the final tree. The deleted values are 65, 75, 43, 18, 20, 92, 59, 37.

**17.22.** Repeat Exercise 17.21, but for the B-tree of Exercise 17.20.

**17.23.** Algorithm 17.1 outlines the procedure for searching a nondense multilevel primary index to retrieve a file record. Adapt the algorithm for each of the following cases:

a. A multilevel secondary index on a nonkey nonordering field of a file. Assume that option 3 of Section 17.1.3 is used, where an extra level of indirection stores pointers to the individual records with the corresponding index field value.

b. A multilevel secondary index on a nonordering key field of a file.

c. A multilevel clustering index on a nonkey ordering field of a file.

**17.24.** Suppose that several secondary indexes exist on nonkey fields of a file, implemented using option 3 of Section 17.1.3; for example, we could have secondary indexes on the fields Department_code, Job_code, and Salary of the EMPLOYEE file of Exercise 17.18. Describe an efficient way to search for and retrieve records satisfying a complex selection condition on these fields, such as (Department_code = 5 AND Job_code = 12 AND Salary = 50,000), using the record pointers in the indirection level.

**17.25.** Adapt Algorithms 17.2 and 17.3, which outline search and insertion procedures for a $B^+$-tree, to a B-tree.

**17.26.** It is possible to modify the $B^+$-tree insertion algorithm to delay the case where a new level is produced by checking for a possible *redistribution* of values among the leaf nodes. Figure 17.17 illustrates how this could be done for our example in Figure 17.12; rather than splitting the leftmost leaf node when 12 is inserted, we do a *left redistribution* by moving 7 to the leaf node to its left (if there is space in this node). Figure 17.17 shows how the tree would look when redistribution is considered. It is also possible to consider *right redistribution*. Try to modify the $B^+$-tree insertion algorithm to take redistribution into account.

**17.27.** Outline an algorithm for deletion from a $B^+$-tree.

**17.28.** Repeat Exercise 17.27 for a B-tree.

## Selected Bibliography

**Indexing:** Bayer and McCreight (1972) introduced B-trees and associated algorithms. Comer (1979) provides an excellent survey of B-trees and their history, and variations of B-trees. Knuth (1998) provides detailed analysis of many search techniques, including B-trees and some of their variations. Nievergelt (1974) discusses the use of binary search trees for file organization. Textbooks on file structures, including Claybrook (1992), Smith and Barnes (1987), and Salzberg (1988); the algorithms and data structures textbook by Wirth (1985); as well as the database textbook by Ramakrihnan and Gehrke (2003) discuss indexing in detail and may be

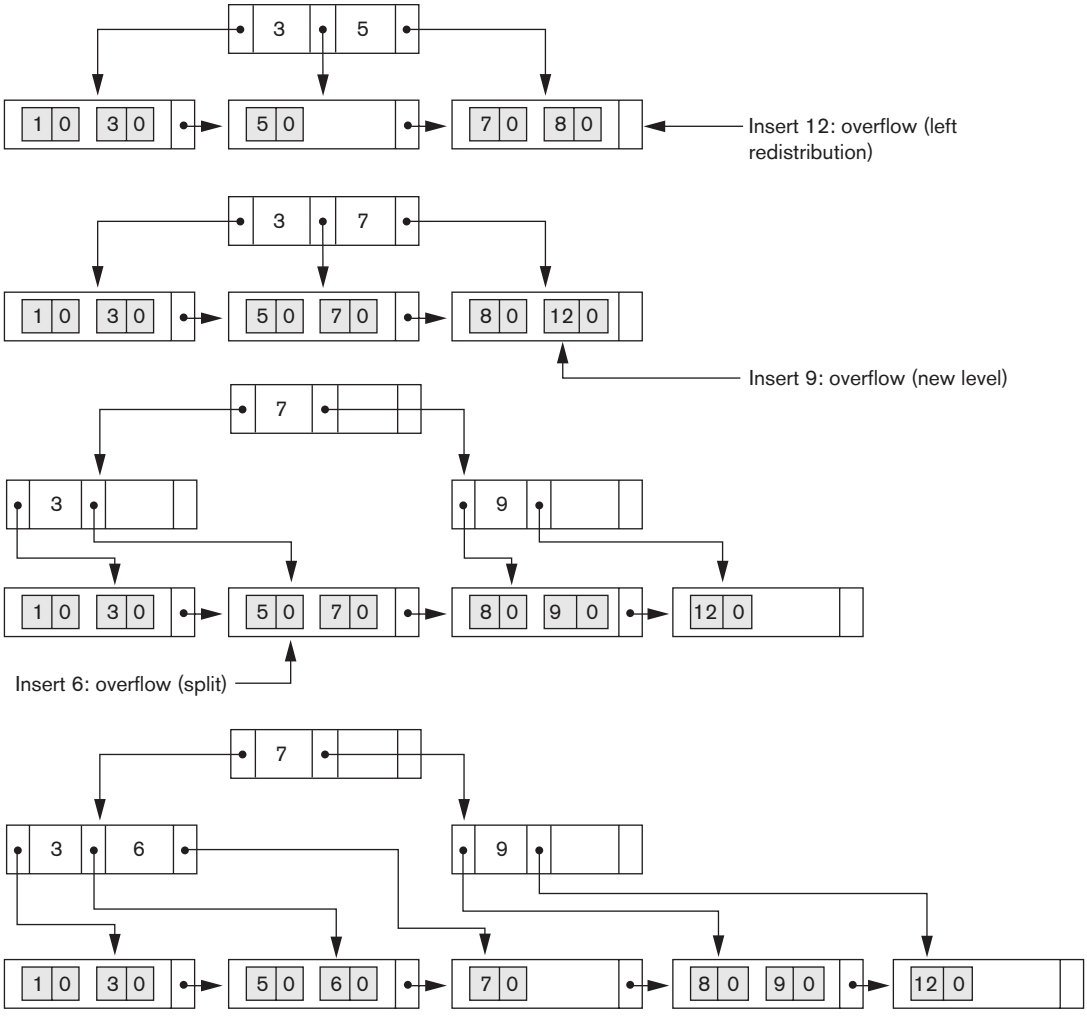



**Figure 17.17**
$B^+$-tree insertion with left redistribution.

consulted for search, insertion, and deletion algorithms for B-trees and $B^+$-trees. Larson (1981) analyzes index-sequential files, and Held and Stonebraker (1978) compare static multilevel indexes with B-tree dynamic indexes. Lehman and Yao (1981) and Srinivasan and Carey (1991) did further analysis of concurrent access to B-trees. The books by Wiederhold (1987), Smith and Barnes (1987), and Salzberg (1988), among others, discuss many of the search techniques described in this chapter. Grid files are introduced in Nievergelt et al. (1984). Partial-match retrieval, which uses partitioned hashing, is discussed in Burkhard (1976, 1979).

New techniques and applications of indexes and $B^+$-trees are discussed in Lanka and Mays (1991), Zobel et al. (1992), and Faloutsos and Jagadish (1992). Mohan

and Narang (1992) discuss index creation. The performance of various B–tree and $B^+$-tree algorithms is assessed in Baeza-Yates and Larson (1989) and Johnson and Shasha (1993). Buffer management for indexes is discussed in Chan et al. (1992). Column-based storage of databases was proposed by Stonebraker et al. (2005) in the C-Store database system; MonetDB/X100 by Boncz et al. (2008) is another implementation of the idea. Abadi et al. (2008) discuss the advantages of column stores over row-stored databases for read-only database applications.

**Physical Database Design:** Wiederhold (1987) covers issues related to physical design. O'Neil and O'Neil (2001) provides a detailed discussion of physical design and transaction issues in reference to commercial RDBMSs. Navathe and Kerschberg (1986) discuss all phases of database design and point out the role of data dictionaries. Rozen and Shasha (1991) and Carlis and March (1984) present different models for the problem of physical database design. Shasha and Bonnet (2002) offer an elaborate discussion of guidelines for database tuning. Niemiec (2008) is one among several books available for Oracle database administration and tuning; Schneider (2006) is focused on designing and tuning MySQL databases.