Chapter 10: Storage and File Structure

- Overview of Physical Storage Media

- Magnetic Disks

- RAID

- Tertiary Storage

- Storage Access

- File Organization

- Organization of Records in Files

- Data-Dictionary Storage

Classification of Physical Storage Media

- Speed with which data can be accessed

- Cost per unit of data

- Reliability
  - data loss on power failure or system crash
  - physical failure of the storage device

- Can differentiate storage into:
  - **volatile storage:** loses contents when power is switched off
  - **non-volatile storage:**
    - Contents persist even when power is switched off.
    - Includes secondary and tertiary storage, as well as batter-backed up main-memory.

Physical Storage Media

■ **Cache** – fastest and most costly form of storage; volatile; managed by the computer system hardware. Several levels of cache.

■ **Main memory**:

   ● fast access (10s to 100s of nanoseconds; 1 nanosecond = 10^{-9} seconds)

   ● generally too small (or too expensive) to store the entire database

      ‣ capacities of up to a few Gigabytes widely used currently

      ‣ Capacities have gone up and per-byte costs have decreased steadily and rapidly (roughly factor of 2 every 2 to 3 years)

   ● **Volatile** — contents of main memory are usually lost if a power failure or system crash occurs.

Physical Storage Media (Cont.)

■ **Flash memory**

- Data survives power failure

- Data can be written at a location only once, but location can be erased and written to again

  ▸ Can support only a limited number (10K – 1M) of write/erase cycles.

  ▸ Erasing of memory has to be done to an entire bank of memory

- Reads are almost as fast as main memory (but not quite)

- But writes are slow (few microseconds), erase is slower

- Actual performance depends on file system and details

- Widely used in embedded devices such as digital cameras, phones, and USB keys

Physical Storage Media (Cont.)

- **Magnetic-disk**
  - Data is stored on spinning disk, and read/written magnetically
  - Primary medium for the long-term storage of data; typically stores entire database.
  - Data must be moved from disk to main memory for access, and written back for storage
    - Much slower access than main memory (more on this later)
  - **direct-access** – possible to read data on disk in any order, unlike magnetic tape
  - Capacities range up to roughly 1.5 TB as of 2009
    - Much larger capacity and cost/byte than main memory/flash memory
    - Growing constantly and rapidly with technology improvements (factor of 2 to 3 every 2 years)
  - Survives power failures and system crashes
    - disk failure can destroy data, but is rare

Physical Storage Media (Cont.)

- **Optical storage**
  - non-volatile, data is read optically from a spinning disk using a laser
  - CD-ROM (640 MB) and DVD (4.7 to 17 GB) most popular forms
  - Blu-ray disks: 27 GB to 54 GB
  - Write-one, read-many (WORM) optical disks used for archival storage (CD-R, DVD-R, DVD+R)
  - Multiple write versions also available (CD-RW, DVD-RW, DVD+RW, and DVD-RAM)
  - Reads and writes are slower than with magnetic disk
  - **Juke-box** systems, with large numbers of removable disks, a few drives, and a mechanism for automatic loading/unloading of disks available for storing large volumes of data

Physical Storage Media (Cont.)

- **Tape storage**

  - non-volatile, used primarily for backup (to recover from disk failure), and for archival data

  - **sequential-access** – much slower than disk

  - very high capacity (40 to 300 GB tapes available)

  - tape can be removed from drive $\Rightarrow$ storage costs much cheaper than disk, but drives are expensive

  - Tape jukeboxes available for storing massive amounts of data

    - hundreds of terabytes (1 terabyte = 10^9 bytes) to even multiple **petabytes** (1 petabyte = 10^{12} bytes)

Storage Hierarchy

cache

main memory

flash memory

magnetic disk

optical disk

magnetic tapes
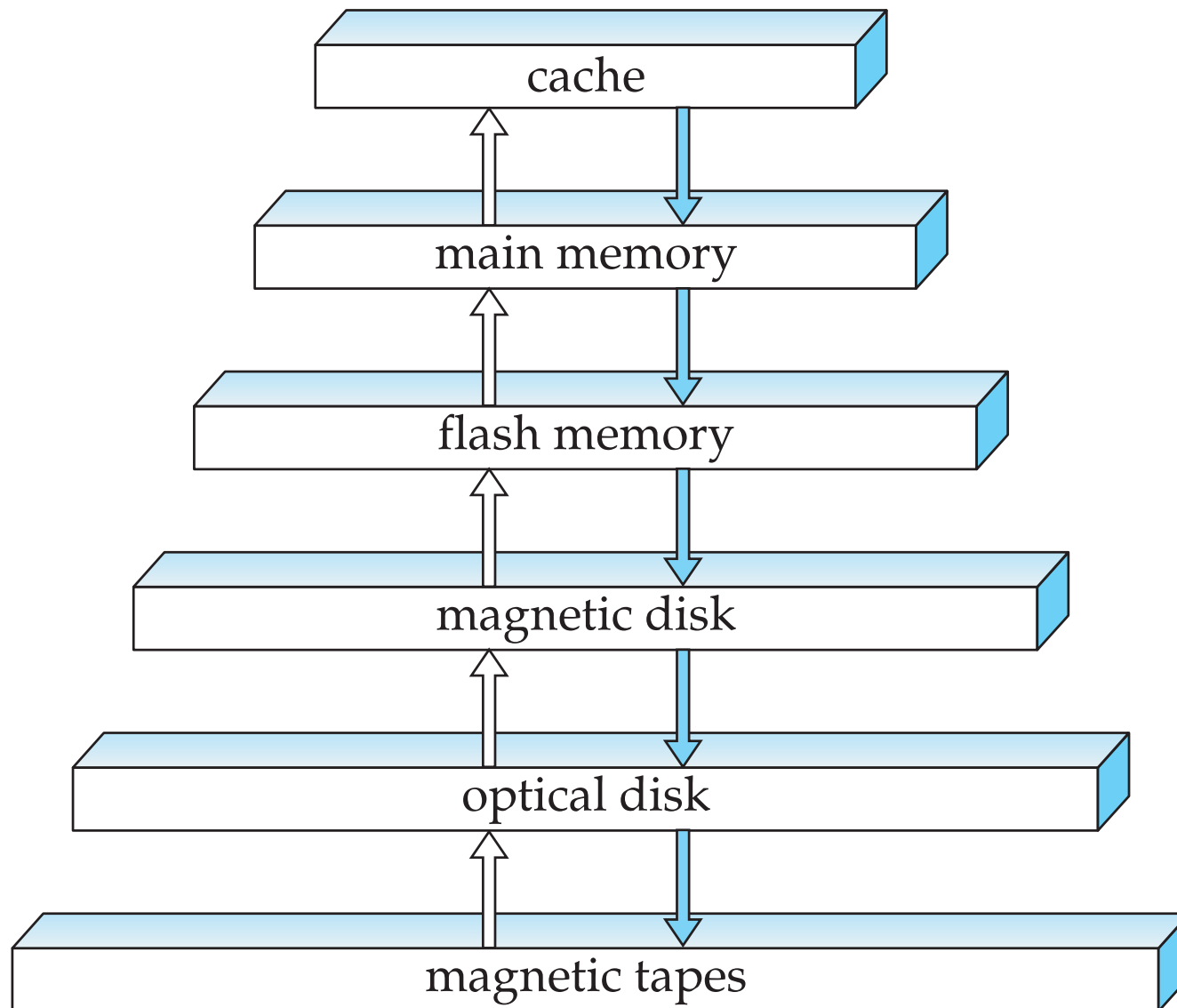
Storage Hierarchy (Cont.)

■ **primary storage**: Fastest media but volatile (cache, main memory).

■ **secondary storage**: next level in hierarchy, non-volatile, moderately fast access time

- also called **on-line storage**
- E.g. flash memory, magnetic disks

■ **tertiary storage**: lowest level in hierarchy, non-volatile, slow access time

- also called **off-line storage**
- E.g. magnetic tape, optical storage

■ Another issue: remote storage, clouds, etc.

Magnetic Hard Disk Mechanism
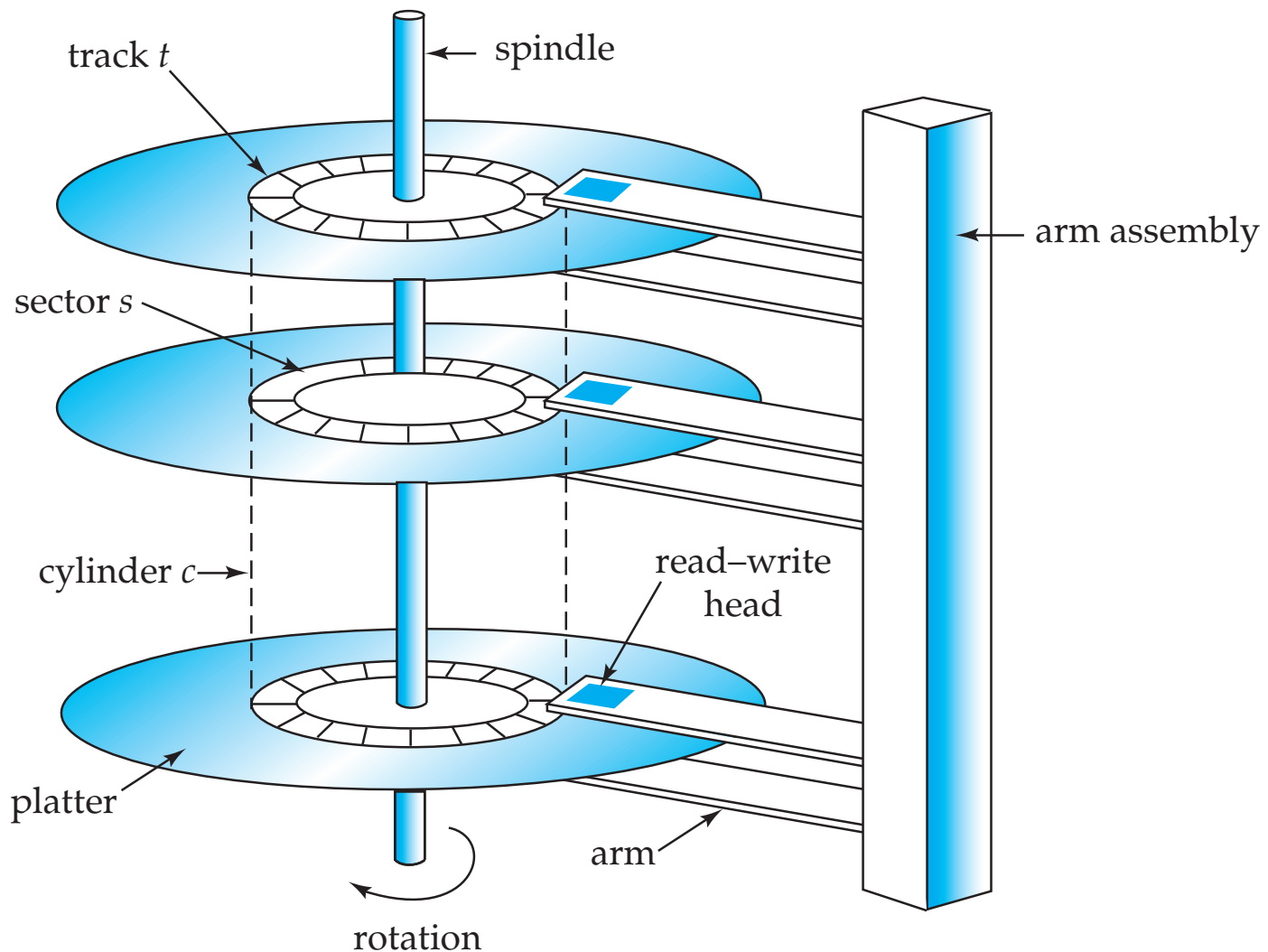
NOTE: Diagram is schematic, and simplifies the structure of actual disk drives

Magnetic Disks

- **Read-write head**
  - Positioned very close to the platter surface (almost touching it)
  - Reads or writes magnetically encoded information.
- Surface of platter divided into circular **tracks**
  - Over 50K-100K tracks per platter on typical hard disks
- Each track is divided into **sectors**.
  - A sector is the smallest unit of data that can be read or written.
  - Sector size typically 512 bytes
  - Typical sectors per track: 500 to 1000 (on inner tracks) to 1000 to 2000 (on outer tracks)
- To read/write a sector
  - disk arm swings to position head on right track
  - platter spins continually; data is read/written as sector passes under head
- Head-disk assemblies
  - multiple disk platters on a single spindle (1 to 5 usually)
  - one head per platter, mounted on a common arm.
- **Cylinder** i consists of ith track of all the platters

Magnetic Disks (Cont.)

- Earlier generation disks were susceptible to head-crashes
  - Surface of earlier generation disks had metal-oxide coatings which would disintegrate on head crash and damage all data on disk
  - Current generation disks are less susceptible to such disastrous failures, although individual sectors may get corrupted
- **Disk controller** – interfaces between the computer system and the disk drive hardware.
  - accepts high-level commands to read or write a sector
  - initiates actions such as moving the disk arm to the right track and actually reading or writing the data
  - Computes and attaches **checksums** to each sector to verify that data is read back correctly
    - ‣ If data is corrupted, with very high probability stored checksum won't match recomputed checksum
  - Ensures successful writing by reading back sector after writing it
  - Performs remapping of bad sectors

Disk Subsystem
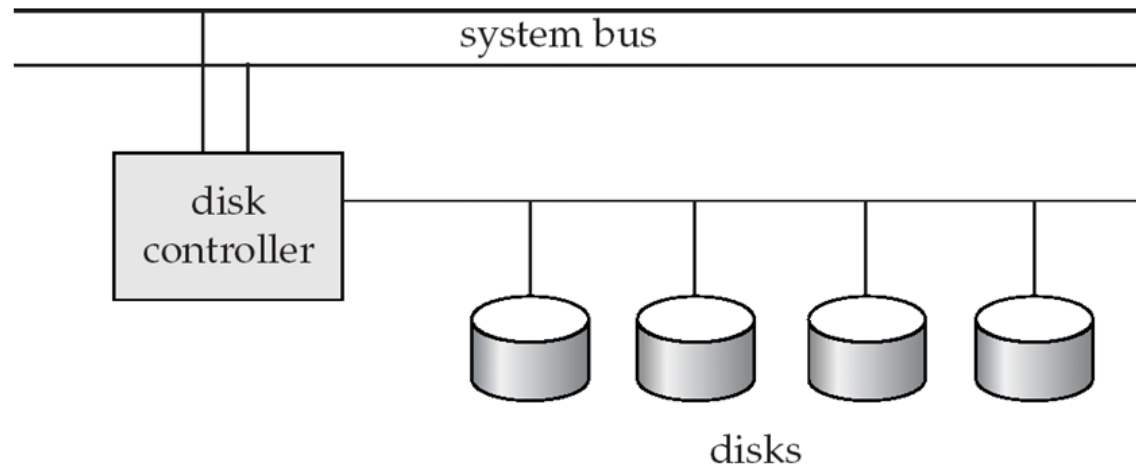
- Multiple disks connected to a computer system through a controller
  - Controllers functionality (checksum, bad sector remapping) often carried out by individual disks; reduces load on controller
- Disk interface standards families
  - ATA (AT adaptor) range of standards
  - SATA (Serial ATA)
  - SCSI (Small Computer System Interconnect) range of standards
  - SAS (Serial Attached SCSI)
  - Several variants of each standard (different speeds and capabilities)

Performance Measures of Disks

- **Access time** – the time it takes from when a read or write request is issued to when data transfer begins. Consists of:
  - **Seek time** – time it takes to reposition the arm over the correct track.
    - Average seek time is 1/2 the worst case seek time.
      - Would be 1/3 if all tracks had the same number of sectors, and we ignore the time to start and stop arm movement
    - 4 to 10 milliseconds on typical disks
  - **Rotational latency** – time it takes for the sector to be accessed to appear under the head.
    - Average latency is 1/2 of the worst case latency.
    - 4 to 11 milliseconds on typical disks (5400 to 15000 r.p.m.)
- **Data-transfer rate** – the rate at which data can be retrieved from or stored to the disk.
  - 25 to 100 MB per second max rate, lower for inner tracks
  - Multiple disks may share a controller, so rate that controller can handle is also important
    - E.g. SATA: 150 MB/sec, SATA-II 3Gb (300 MB/sec)
    - Ultra 320 SCSI: 320 MB/s, SAS (3 to 6 Gb/sec)
    - Fiber Channel (FC2Gb or 4Gb): 256 to 512 MB/s

Performance Measures (Cont.)

■ **Mean time to failure (MTTF)** – the average time the disk is expected to run continuously without any failure.

- Typically 3 to 5 years

- Probability of failure of new disks is quite low, corresponding to a "theoretical MTTF" of 500,000 to 1,200,000 hours for a new disk

  ‣ E.g., an MTTF of 1,200,000 hours for a new disk means that given 1000 relatively new disks, on an average one will fail every 1200 hours

- MTTF decreases as disk ages

Disk Subsystem

■ Disks usually connected directly to computer system

■ In **Storage Area Networks (SAN)**, a large number of disks are connected by a high-speed network to a number of servers

■ In **Network Attached Storage (NAS)** networked storage provides a file system interface using networked file system protocol, instead of providing a disk system interface

Optimization of Disk-Block Access

- **Block** – a contiguous sequence of sectors from a single track
  - data is transferred between disk and main memory in blocks
  - sizes range from 512 bytes to several kilobytes
    - Smaller blocks: more transfers from disk
    - Larger blocks: more space wasted due to partially filled blocks
    - Typical block sizes today range from 4 to 16 kilobytes
- **Disk-arm-scheduling** algorithms order pending accesses to tracks so that disk arm movement is minimized
  - **elevator algorithm**
- **File organization** – optimize block access time by organizing the blocks to correspond to how data will be accessed
  - E.g. Store related information on the same or nearby cylinders.
  - Files may get **fragmented** over time
    - Sequential access to fragmented file means increased arm movement
  - Some systems have utilities to defragment the file system, in order to speed up file access

Optimization of Disk Block Access (Cont.)

- **Nonvolatile write buffers** speed up disk writes by writing blocks to a non-volatile RAM buffer immediately
  - Non-volatile RAM: battery backed up RAM or flash memory
    - Even if power fails, the data is safe and will be written to disk when power returns
  - Controller then writes to disk whenever the disk has no other requests or request has been pending for some time
  - Database operations that require data to be safely stored before continuing can continue without waiting for data to be written to disk
  - *Writes can be reordered to minimize disk arm movement*
- **Log disk** – a disk devoted to writing a sequential log of block updates
  - Used exactly like nonvolatile RAM
    - Write to log disk is very fast since no seeks are required
    - No need for special hardware (NV-RAM)
- File systems typically reorder writes to disk to improve performance
  - **Journaling file systems** write data in safe order to NV-RAM or log disk
  - Reordering without journaling: risk of corruption of file system data

RAID

- **RAID: Redundant Arrays of Independent Disks**
  - disk organization techniques that manage a large numbers of disks, providing a view of a single disk of
    - high capacity and high speed by using multiple disks in parallel,
    - high reliability by storing data redundantly, so that data can be recovered even if a disk fails
- The chance that some disk out of a set of *N* disks will fail is much higher than the chance that a specific single disk will fail.
  - E.g., a system with 100 disks, each with MTTF of 100,000 hours (approx. 11 years), will have a system MTTF of 1000 hours (approx. 41 days)
  - Techniques for using redundancy to avoid data loss are critical with large numbers of disks
- Originally a cost-effective alternative to large, expensive disks
  - I in RAID originally stood for ``inexpensive'' (now "independent")
  - Today RAIDs are used for their higher reliability and bandwidth.

Improvement of Reliability via Redundancy

- **Redundancy** – store extra information that can be used to rebuild information lost in a disk failure

- E.g., **Mirroring** (or **shadowing**)
  - Duplicate every disk. Logical disk consists of two physical disks.
  - Every write is carried out on both disks
    - Reads can take place from either disk
  - If one disk in a pair fails, data still available in the other
    - Data loss would occur only if a disk fails, and its mirror disk also fails before the system is repaired
      - Probability of combined event is very small
        - » Except for dependent failure modes such as fire or building collapse or electrical power surges

- **Mean time to data loss** depends on mean time to failure, and **mean time to repair**
  - E.g. MTTF of 100,000 hours, mean time to repair of 10 hours gives mean time to data loss of $500*10^6$ hours (or 57,000 years) for a mirrored pair of disks (ignoring dependent failure modes)

Improvement in Performance via Parallelism

- Two main goals of parallelism in a disk system:

  1. Load balance multiple small accesses to increase throughput

  2. Parallelize large accesses to reduce response time.

- Improve transfer rate by striping data across multiple disks.

- **Bit-level striping** – split the bits of each byte across multiple disks

  - In an array of eight disks, write bit i of each byte to disk i.

  - Each access can read data at eight times the rate of a single disk.

  - But seek/access time worse than for a single disk

    ‣ Bit level striping is not used much any more

- **Block-level striping** – block i of a file goes to disk (i mod n) + 1

  - Requests for different blocks can run in parallel if the blocks reside on different disks

  - A request for a long sequence of blocks can utilize all disks in parallel

Main Ideas in RAID

- **Striping: Dividing data between several disks round-robin**
  - E.g., 4 disks: first 8KB of file goes to disk 1, next 8KB to disk 2,
  - Small accesses go to one disk, large ones get parallelized

- **Mirroring: keeping two or more copies of the data**
  - E.g., 2 disks containing the same data
  - Read accesses can be satisfied by either or both disks
  - 4 disks: stripe data between disks 1 & 2, then mirror on disks 3 & 4

- **Parity: Instead of keeping full copies, use checksums/XOR of bits**
  - E.g., 4 disks: stripe data between disks 1, 2, 3, and store checksum (XOR of corresponding bits on disks 1, 2, 3) on disk 4
  - If one disk fails, can reconstruct data, but at cost; if 2 fail, data loss

- **Error-Correcting Codes**
 - To survive more than 2 disk failures

RAID Schemas (Levels)

- **RAID levels are determined by:**
  - **Choice of redundancy scheme:**
    - none, mirror, parity, ECC
  - **Choice of stripe size:**
    - bit-wise or maybe a few or few hundred KB
  - **If parity used, layout of checksum blocks:**
    - All checksums on one disk, or cycling among disks

RAID Levels

- Schemes to provide redundancy at lower cost by using disk striping combined with parity bits
  - Different RAID organizations, or RAID levels, have differing cost, performance and reliability characteristics
- **RAID Level 0**: Block striping; non-redundant.
  - Used in high-performance applications where data loss is not critical.
- **RAID Level 1**: Mirrored disks with block striping
  - Offers best write performance.
  - Popular for applications such as storing log files in a database system.
  - Sometimes called Raid 10, as it combines Levels 0 and 1
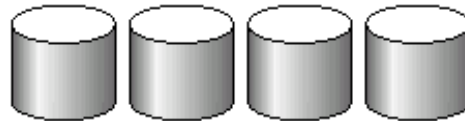
(a) RAID 0: nonredundant striping

(b) RAID 1: mirrored disks

RAID Levels (Cont.)

- **RAID Level 2**: Memory-Style Error-Correcting-Codes (ECC) with bit striping.

- **RAID Level 3**: Bit-Interleaved Parity
  - a single parity bit is enough for error correction, not just detection, since we know which disk has failed
    - When writing data, corresponding parity bits must also be computed and written to a parity bit disk
    - To recover data in a damaged disk, compute XOR of bits from other disks (including parity bit disk)

(c) RAID 2: memory-style error-correcting codes
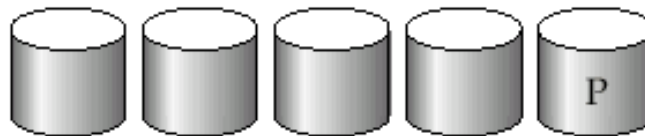
(d) RAID 3: bit-interleaved parity

RAID Levels (Cont.)

- **RAID Level 3** (Cont.)
  - Faster data transfer than with a single disk, but fewer I/Os per second since every disk has to participate in every I/O.
  - Subsumes Level 2 (provides all its benefits, at lower cost).

- **RAID Level 4:** Block-Interleaved Parity; uses block-level striping, and keeps a parity block on a separate disk for corresponding blocks from *N* other disks.
  - When writing data block, corresponding block of parity bits must also be computed and written to parity disk
  - To find value of a damaged block, compute XOR of bits from corresponding blocks (including parity block) from other disks.

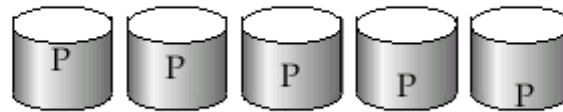
(e) RAID 4: block-interleaved parity

RAID Levels (Cont.)

- **RAID Level 4** (Cont.)
  - Provides higher I/O rates for independent block reads than Level 3
    - ▸ block read goes to a single disk, so blocks stored on different disks can be read in parallel
  - Provides high transfer rates for reads of multiple blocks than no-striping
  - Before writing a block, parity data must be computed
    - ▸ Can be done by using old parity block, old value of current block and new value of current block (2 block reads + 2 block writes)
    - ▸ Or by recomputing the parity value using the new values of blocks corresponding to the parity block
      - – More efficient for writing large amounts of data sequentially
  - Parity block becomes a bottleneck for independent block writes since every block write also writes to parity disk

RAID Levels (Cont.)

- **RAID Level 5:** Block-Interleaved Distributed Parity; partitions data and parity among all $N + 1$ disks, rather than storing data in N disks and parity in 1 disk.

  - E.g., with 5 disks, parity block for nth set of blocks is stored on disk $(n \bmod 5) + 1$, with the data blocks stored on the other 4 disks.

(f) RAID 5: block-interleaved distributed parity

P0	0	1	2	3
4	P1	5	6	7
8	9	P2	10	11
12	13	14	P3	15
16	17	18	19	P4

RAID Levels (Cont.)

- **RAID Level 5** (Cont.)
  - Higher I/O rates than Level 4.
    - Block writes occur in parallel if the blocks and their parity blocks are on different disks.
  - Subsumes Level 4: provides same benefits, but avoids bottleneck of parity disk.

- **RAID Level 6**: P+Q Redundancy scheme; similar to Level 5, but stores extra redundant information to guard against multiple disk failures.
  - Better reliability than Level 5 at a higher cost; not used as widely.

(g) RAID 6: P + Q redundancy

Choice of RAID Level

- Factors in choosing RAID level
  - Monetary cost
  - Performance: Number of I/O operations per second, and bandwidth during normal operation
  - Performance during failure
  - Performance during rebuild of failed disk
    - Including time taken to rebuild failed disk
- RAID 0 is used only when data safety is not important
  - E.g. data can be recovered quickly from other sources
- Level 3 and 4 never used since they are subsumed by level 5
- Level 2 is never used, and subsumed by level 6 for scenarios where several disks can fail. This has become more important recently as the number of disks increases.
- In general, bit striping is a terrible idea, and having dedicated disks for parity and ECC as in Levels 2 and 4 is also not good.
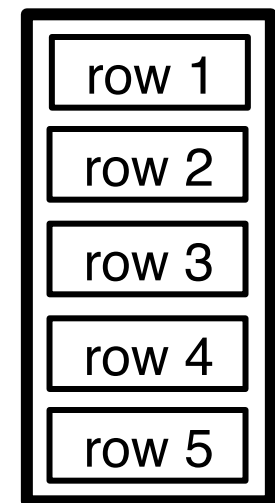
Hardware Issues

- **Software RAID**: RAID implementations done entirely in software, with no special hardware support

- **Hardware RAID**: RAID implementations with special hardware
  - Use non-volatile RAM to record writes that are being executed
  - Beware: power failure during write can result in corrupted disk
    - E.g. failure after writing one block but before writing the second in a mirrored system
    - Such corrupted data must be detected when power is restored
      - Recovery from corruption is similar to recovery from failed disk
      - NV-RAM helps to efficiently detected potentially corrupted blocks
        - » Otherwise all blocks of disk must be read and compared with mirror/parity block

Hardware Issues (Cont.)

- **Latent failures**: data successfully written earlier gets damaged
- **Data scrubbing:**
  - continually scan for latent failures, and recover from copy/parity
- **Hot swapping**: replacement of disk while system is running, without power down
  - Supported by some hardware RAID systems,
  - reduces time to recovery, and improves availability greatly
- Many systems maintain spare disks which are kept online, and used as replacements for failed disks immediately on detection of failure
  - Reduces time to recovery greatly
- Many hardware RAID systems ensure that a single point of failure will not stop the functioning of the system by using
  - Redundant power supplies with battery backup
  - Multiple controllers and multiple interconnections to guard against controller/interconnection failures

Next Topic: How are Tables Stored on Disk?

- The database is stored as a collection of *files*.

- In fact, each table is stored in one or more files, where each file consists of multiple 4KB or 16KB pages (blocks).

- E.g., 1GB relation = 50 files of 20MB each: file1, file2, file3, ..

- Simple solution: each page has 20 rows of size 200 bytes:

- But this is too naive:
  - How about insertions and deletions?
  - How about sorted tables?
  - How about variable-length rows?

- Need to use more complicated schemes

- Compare to memory allocation (but on disk)

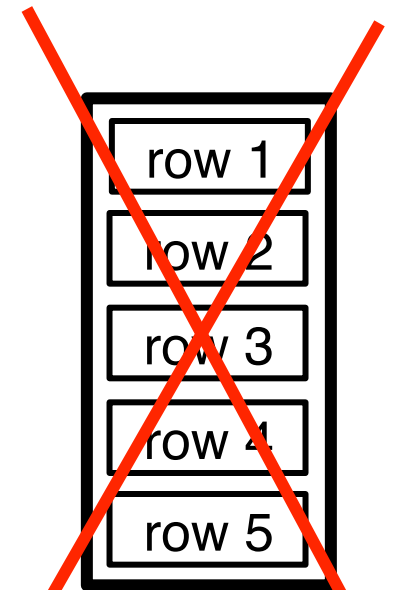| row 1 |
| row 2 |
| row 3 |
| row 4 |
| row 5 |

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row 1
row 2
row 3
row 4
row 5

File Organization

■ The database is stored as a collection of *files*. Each file is a sequence of *records.* A record is a sequence of fields.

■ One approach:

● assume record size is fixed

● each file has records of one particular type only

● different files are used for different relations

This case is easiest to implement; will consider variable length records later.

Fixed-Length Records

- Simple approach:
  - Store record i starting from byte $n * (i - 1)$, where n is the size of each record.
  - Record access is simple but records may cross blocks
    - Modification: do not allow records to cross block boundaries

- Deletion of record i: alternatives:
  - move records $i + 1, \ldots, n$ to $i, \ldots, n - 1$
  - move record n to i
  - do not move records, but link all free records on a *free list*

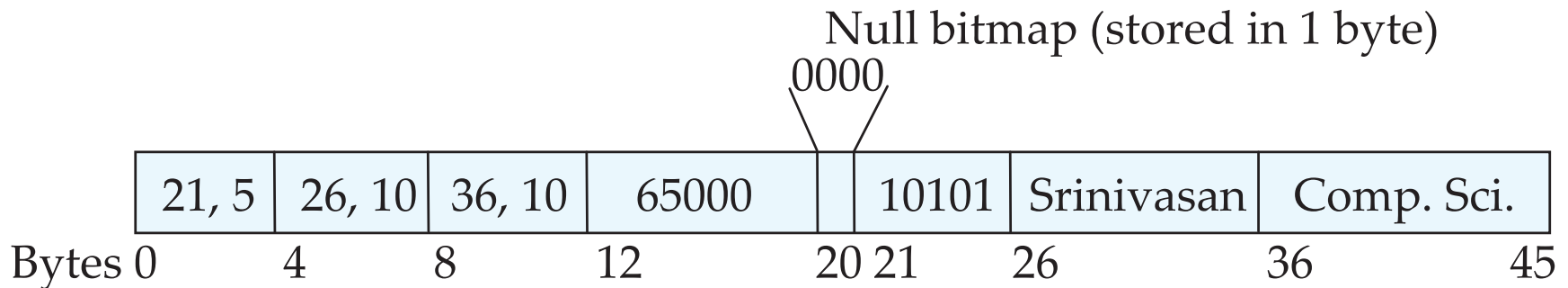|				
record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4	32343	El Said	History	60000
record 5	33456	Gold	Physics	87000
record 6	45565	Katz	Comp. Sci.	75000
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology	72000
record 10	83821	Brandt	Comp. Sci.	92000
record 11	98345	Kim	Elec. Eng.	80000

Free Lists

- Store the address of the first deleted record in the file header.
- Use this first record to store the address of the second deleted record, and so on
- Can think of these stored addresses as pointers since they "point" to the location of a record.
- More space efficient representation: reuse space for normal attributes of free records to store pointers. (No pointers stored in in-use records.)

header				
record 0	10101	Srinivasan	Comp. Sci.	65000
record 1				
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4				
record 5	33456	Gold	Physics	87000
record 6				
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology	72000
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record 11	98345	Kim	Elec. Eng.	80000

Variable-Length Records

■ Variable-length records arise in database systems in several ways:

- Storage of multiple record types in a file.

- Record types that allow variable lengths for one or more fields such as strings (**varchar**)

- Record types that allow repeating fields (used in some older data models).

■ Attributes are stored in order

■ Variable length attributes represented by fixed size (offset, length), with actual data stored after all fixed length attributes

■ Null values represented by null-value bitmap

Null bitmap (stored in 1 byte)

0000

21, 5	26, 10	36, 10	65000		10101	Srinivasan	Comp. Sci.

Bytes 0   4   8   12   20 21   26   36   45

Variable-Length Records: Slotted Page Structure

Block Header   Records

Size
Location | # Entries | ... Free Space ----
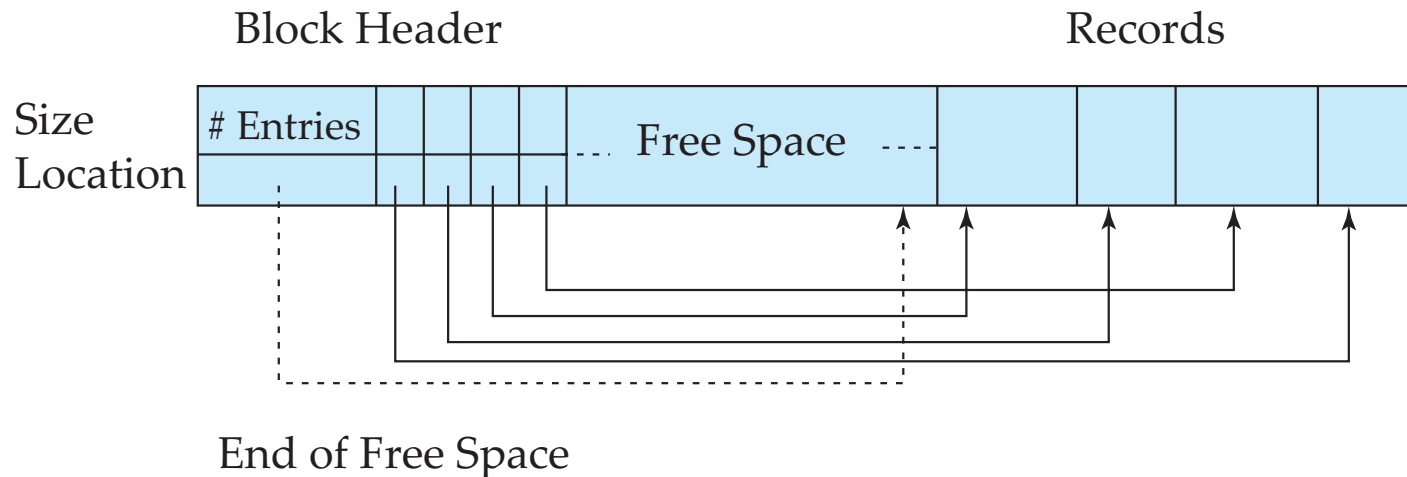
End of Free Space

- **Slotted page** header contains:
  - number of record entries
  - end of free space in the block
  - location and size of each record
- Records can be moved around within a page to keep them contiguous with no empty space between them; entry in the header must be updated.
- Pointers should not point directly to record — instead they should point to the entry for the record in header.
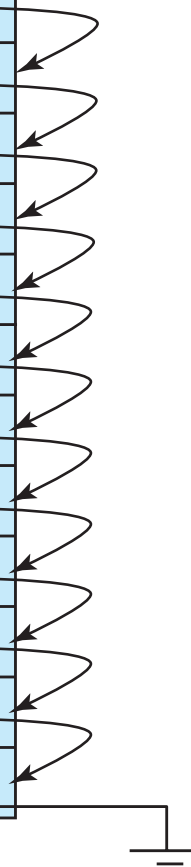
Organization of Records in Files

- **Heap** – a record can be placed anywhere in the file where there is space

- **Sequential** – store records in sequential order, based on the value of the search key of each record

- **Hashing** – a hash function computed on some attribute of each record; the result specifies in which block of the file the record should be placed

- Records of each relation may be stored in a separate file. In a **multitable clustering file organization** records of several different relations can be stored in the same file

  - Motivation: store related records on the same block to minimize I/O

Sequential File Organization

- Suitable for applications that require sequential processing of the entire file

- The records in the file are ordered by a search-key

10101	Srinivasan	Comp. Sci.	65000	
12121	Wu	Finance	90000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
32343	El Said	History	60000	
33456	Gold	Physics	87000	
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76543	Singh	Finance	80000	
76766	Crick	Biology	72000	
83821	Brandt	Comp. Sci.	92000	
98345	Kim	Elec. Eng.	80000	

Sequential File Organization (Cont.)

- Deletion – use pointer chains

- Insertion –locate the position where the record is to be inserted
  - if there is free space insert there
  - if no free space, insert the record in an overflow block
  - In either case, pointer chain must be updated

- Need to reorganize the file from time to time to restore sequential order

10101	Srinivasan	Comp. Sci.	65000	
12121	Wu	Finance	90000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
32343	El Said	History	60000	
33456	Gold	Physics	87000	
45565	Katz	Comp. Sci.	75000	
58583	Califieri	History	62000	
76543	Singh	Finance	80000	
76766	Crick	Biology	72000	
83821	Brandt	Comp. Sci.	92000	
98345	Kim	Elec. Eng.	80000	

| 32222 | Verdi | Music | 48000 | |
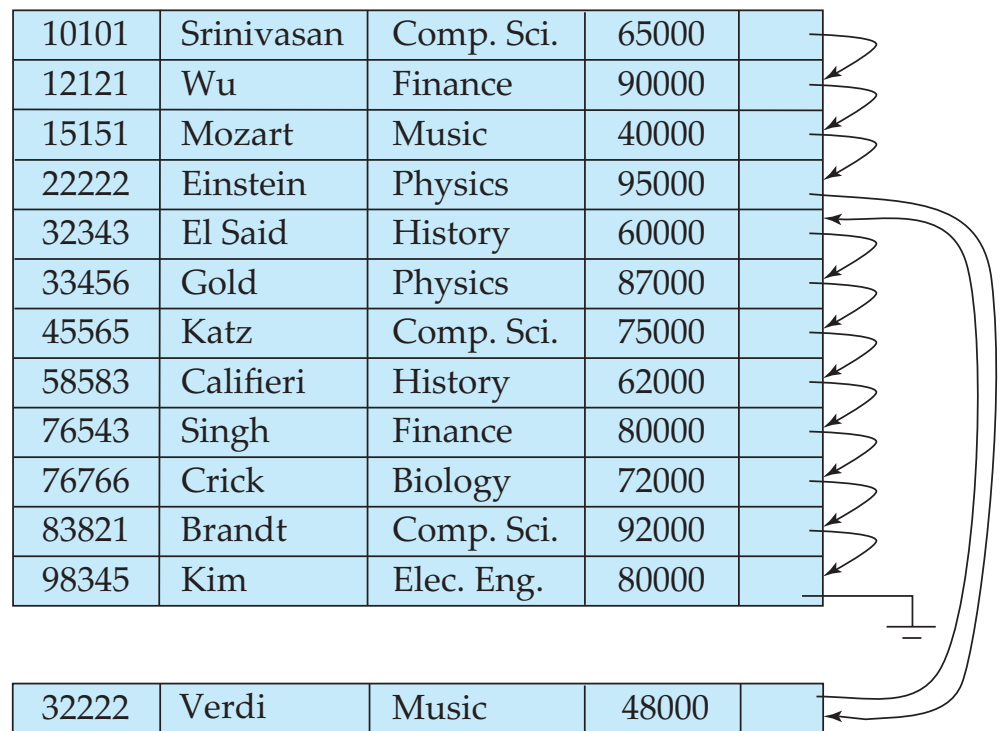
Multitable Clustering File Organization

Store several relations in one file using a **multitable clustering** file organization

department

dept_name	building	budget
Comp. Sci.	Taylor	100000
Physics	Watson	70000

instructor

ID	name	dept_name	salary
10101	Srinivasan	Comp. Sci.	65000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
83821	Brandt	Comp. Sci.	92000
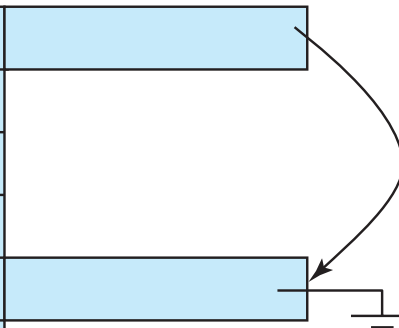
multitable clustering of *department* and *instructor*

Comp. Sci.	Taylor	100000
45564	Katz	75000
10101	Srinivasan	65000
83821	Brandt	92000
Physics	Watson	70000
33456	Gold	87000

Multitable Clustering File Organization (cont.)

- good for queries involving *department* ⋈ *instructor*, and for queries involving one single department and its instructors

- bad for queries involving only *department*

- results in variable size records

- Can add pointer chains to link records of a particular relation

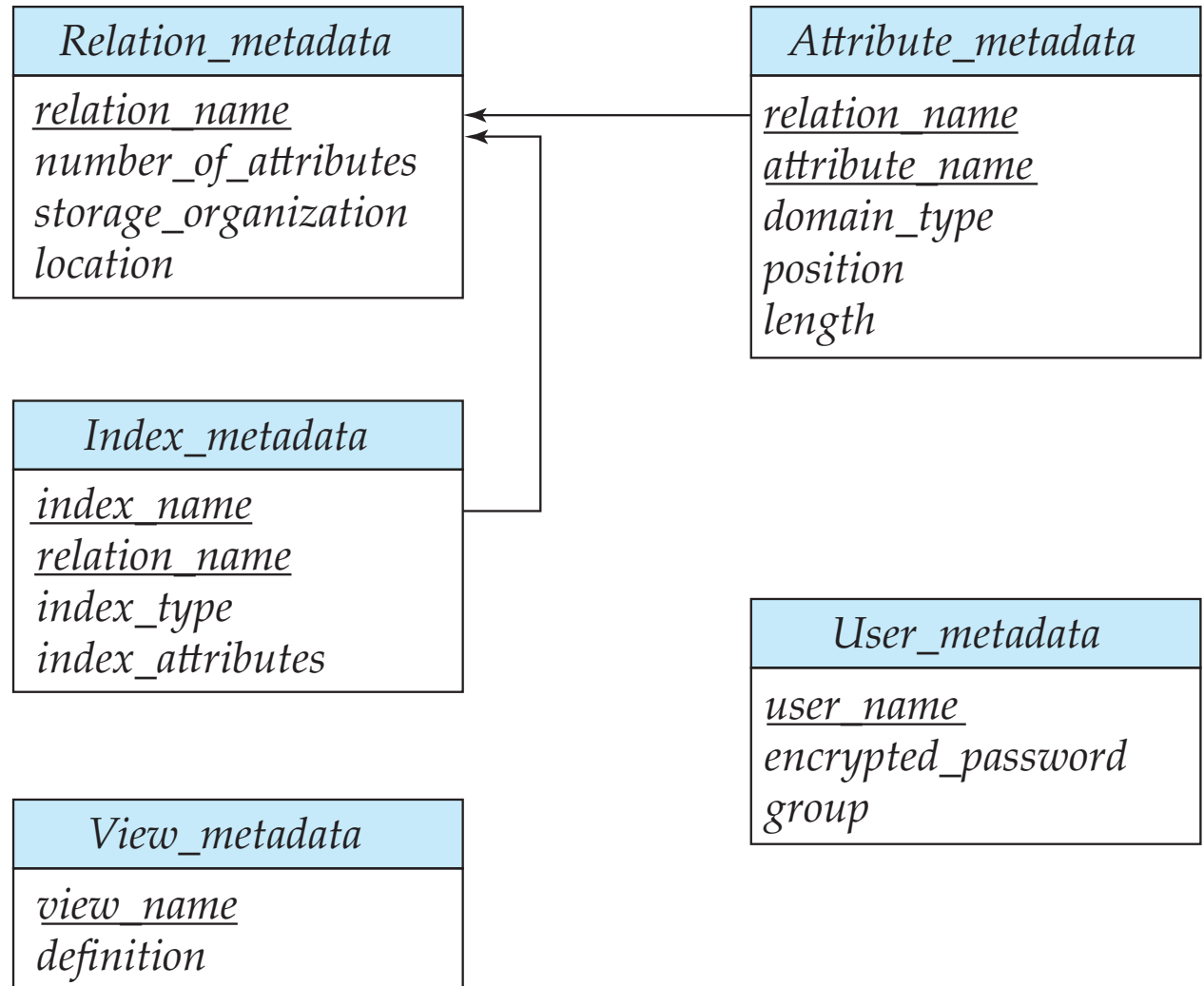|			
Comp. Sci.	Taylor	100000	
45564	Katz	75000	
10101	Srinivasan	65000	
83821	Brandt	92000	
Physics	Watson	70000	
33456	Gold	87000	

Data Dictionary Storage

The **Data dictionary** (also called **system catalog**) stores **metadata**; that is, data about data, such as

- Information about relations
    - names of relations
    - names, types and lengths of attributes of each relation
    - names and definitions of views
    - integrity constraints
- User and accounting information, including passwords
- Statistical and descriptive data
    - number of tuples in each relation
- Physical file organization information
    - How relation is stored (sequential/hash/…)
    - Physical location of relation
- Information about indices (Chapter 11)

Relational Representation of System Metadata

- Relational representation on disk

- Specialized data structures designed for efficient access, in memory

Relation_metadata

relation_name
number_of_attributes
storage_organization
location

Attribute_metadata

relation_name
attribute_name
domain_type
position
length

Index_metadata

index_name
relation_name
index_type
index_attributes

User_metadata

user_name
encrypted_password
group

View_metadata

view_name
definition

Storage Access

■ A database file is partitioned into fixed-length storage units called **blocks**. Blocks are units of both storage allocation and data transfer.

■ Database system seeks to minimize the number of block transfers between the disk and memory. We can reduce the number of disk accesses by keeping as many blocks as possible in main memory.

■ **Buffer** – portion of main memory available to store copies of disk blocks.

■ **Buffer manager** – subsystem responsible for allocating buffer space in main memory.

Buffer Manager

■ Programs call on the buffer manager when they need a block from disk.

1. If the block is already in the buffer, buffer manager returns the address of the block in main memory

2. If the block is not in the buffer, the buffer manager

   1. Allocates space in the buffer for the block

      1. Replacing (throwing out) some other block, if required, to make space for the new block.

      2. Replaced block written back to disk only if it was modified since the most recent time that it was written to/ fetched from the disk.

   2. Reads the block from the disk to the buffer, and returns the address of the block in main memory to requester.

Buffer-Replacement Policies

- Most operating systems replace the block **least recently used** (LRU strategy)

- Idea behind LRU – use past pattern of block references as a predictor of future references

- Queries have well-defined access patterns (such as sequential scans), and a database system can use the information in a user's query to predict future references

  - LRU can be a bad strategy for certain access patterns involving repeated scans of data

    - For example: when computing the join of 2 relations r and s by a nested loops
      for each tuple *tr* of *r* do
        for each tuple *ts* of *s* do
          if the tuples *tr* and *ts* match …

  - Mixed strategy with hints on replacement strategy provided by the query optimizer is preferable

Buffer-Replacement Policies

- Example where LRU is really bad:

  repeated scans of a relation slightly larger than the buffer

buffer

- LRU will evict data that will be revisited soon!

Buffer-Replacement Policies (Cont.)

■ **Pinned block** – memory block that is not allowed to be written back to disk.

■ **Toss-immediate** strategy – frees the space occupied by a block as soon as the final tuple of that block has been processed

■ **Most recently used (MRU) strategy** – system must pin the block currently being processed. After the final tuple of that block has been processed, the block is unpinned, and it becomes the most recently used block.

■ Buffer manager can use statistical information regarding the probability that a request will reference a particular relation

  ● E.g., the data dictionary is frequently accessed. Heuristic: keep data-dictionary blocks in main memory buffer

■ Buffer managers also support **forced output** of blocks for the purpose of recovery (more in Chapter 16)