Database Technology
Database Architectures

Heiko Paulheim
Today

• So far, we have treated Database Systems as a “black box”
  – We can define a schema
  – ...and write data into it…
  – ...and read data from it

• Today
  – Opening the “black box”
  – How is data stored?
  – Architectures for larger database systems
Physical Data Storage

• A manifold of options
  – Hard disks, flash memory, magnetic tape, CDs, DVDs, BluRays, …

• Considerations
  – 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
      – secondary & tertiary storage, battery backed up main-memory
Storage Hierarchy

- cache
- main memory
- flash memory
- magnetic disk
- optical disk
- magnetic tapes

Higher speed of access vs. lower cost per unit of data
Storage Hierarchy

- **primary storage**: Fastest media but volatile (cache, main memory)
  - data on which the processor operates
- **secondary storage**: next level in hierarchy, non-volatile, moderately fast access time
  - also called on-line storage
  - e.g., flash memory, magnetic disks
  - needs to be loaded in memory for processing
- **tertiary storage**: lowest level in hierarchy, non-volatile, slow access time
  - also called off-line storage
  - e.g., magnetic tape, optical storage
  - typically used for backup
Physical Storage

- **Cache**
  - fastest and most costly form of storage; volatile; managed by the computer system hardware

- **Main memory**
  - fast access (10s to 100s of nanoseconds (1 ns = $10^{-9}$ seconds))
  - generally too small (or too expensive) to store the entire database
    - typically: gigabyte capacity
    - 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

• **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 roughly as fast as main memory
  – But writes are slow (few microseconds), erase is slower
  – Widely used in embedded devices such as digital cameras, phones, and USB keys
Physical Storage

- **Magnetic disk (hard 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
  - **direct-access** – possible to read data on disk in any order, unlike magnetic tape
  - Terabyte sized
    - Much larger capacity and lower cost/byte than (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

• **Optical storage**
  
  • non-volatile, data is read optically from a spinning disk using a laser
  
  • CD-ROM (640 MB), DVD (4.7 to 17 GB), Blu-ray (27 to 54 GB)
  
  • Write-once, read-many (WORM) optical disks for archival storage
    
    • 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

  • for storing large volumes of data
  
  • large numbers of removable disks
  
  • a few drives
  
  • mechanism for automatic loading/unloading of disks
Physical Storage

- **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 (terabyte scale)
  - tape can be removed from drive
    - storage costs much cheaper than disk, but drives are expensive
  - Tape jukeboxes available for storing massive amounts of data
Physical Storage

• Modern, experimental and exotic trends
• Molecular memory
  – bits are stored as charge of single molecules
  – using polymer molecules for storage
  – experimental state (NASA, Hewlett Packard…)
• DNA storage
  – idea: DNA stores information
    (i.e.: genetic instructions)
  – synthesizing DNA for data storage
  – in theory, 1g of DNA can store 215 PB
Anatomy of a Hard Disk Drive

• Schematic view
  – sectors are the smallest unit to be read or written
  – also called blocks

• Goal for storage
  – minimize number of blocks transferred
File Organization

• The database is stored as a collection of *files*
  – each file is a sequence of *records*
  – each record is a sequence of *fields*

• Simple 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.
File Organization

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

- Deletion of record $i$:
  - 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

<table>
<thead>
<tr>
<th>Record</th>
<th>Name</th>
<th>Department</th>
<th>Salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10101</td>
<td>Srinivasan</td>
<td>Comp. Sci.</td>
</tr>
<tr>
<td>1</td>
<td>12121</td>
<td>Wu</td>
<td>Finance</td>
</tr>
<tr>
<td>2</td>
<td>15151</td>
<td>Mozart</td>
<td>Music</td>
</tr>
<tr>
<td>3</td>
<td>22222</td>
<td>Einstein</td>
<td>Physics</td>
</tr>
<tr>
<td>4</td>
<td>32343</td>
<td>El Said</td>
<td>History</td>
</tr>
<tr>
<td>5</td>
<td>33456</td>
<td>Gold</td>
<td>Physics</td>
</tr>
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<td>6</td>
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<td>Katz</td>
<td>Comp. Sci.</td>
</tr>
<tr>
<td>7</td>
<td>58583</td>
<td>Califieri</td>
<td>History</td>
</tr>
<tr>
<td>8</td>
<td>76543</td>
<td>Singh</td>
<td>Finance</td>
</tr>
<tr>
<td>9</td>
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<td>Crick</td>
<td>Biology</td>
</tr>
<tr>
<td>10</td>
<td>83821</td>
<td>Brandt</td>
<td>Comp. Sci.</td>
</tr>
<tr>
<td>11</td>
<td>98345</td>
<td>Kim</td>
<td>Elec. Eng.</td>
</tr>
</tbody>
</table>
## Record Deletion – Compacting

<table>
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<td>Music</td>
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# Record Deletion – Moving Last Record

<table>
<thead>
<tr>
<th>record 0</th>
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</thead>
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<td>record 4</td>
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<td>El Said</td>
<td>History</td>
<td>60000</td>
</tr>
<tr>
<td>record 5</td>
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<td>record 7</td>
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<td>record 10</td>
<td>83821</td>
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Record Deletion – 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
• Insertion:
  – find last deleted record and fill in data there
  – remove previous pointer

<table>
<thead>
<tr>
<th></th>
<th>header</th>
<th>record 0</th>
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Storing Variable Length Records

- Variable-length records arise in database systems in several ways:
  - e.g., storage of multiple record types in a file.
  - e.g., record types that allow variable lengths for one or more fields such as strings (varchar)
- 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

<table>
<thead>
<tr>
<th>Bytes</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>20</th>
<th>21</th>
<th>26</th>
<th>36</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>21, 5</td>
<td>26, 10</td>
<td>36, 10</td>
<td>65000</td>
<td>10101</td>
<td>Srinivasan</td>
<td>Comp. Sci.</td>
<td>Null bitmap (stored in 1 byte)</td>
<td>0000</td>
</tr>
</tbody>
</table>
Storing Variable Length Records

- **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 (e.g., foreign keys) should not point directly to record, but to 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
  – requires re-organizations

• **Hashing**
  – a hash function computed on some attribute(s) of each record
  – the result specifies in which block of the file the record should be placed

• Records of different relations
  – stored either in separate files
  – or: store related relations in one file (called: **multitable clustering file organization**)
    • 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

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Sequential File Organization

- 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
Multitable Clustering File Organization

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

<table>
<thead>
<tr>
<th>dept_name</th>
<th>building</th>
<th>budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp. Sci.</td>
<td>Taylor</td>
<td>100000</td>
</tr>
<tr>
<td>Physics</td>
<td>Watson</td>
<td>70000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>name</th>
<th>dept_name</th>
<th>salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>10101</td>
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<td>92000</td>
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</table>

multitable clustering of department and instructor
Multitable Clustering File Organization

- good for queries
  - involving department $\wedge$ instructor
  - involving one single department (and its instructors)
  - involving only the instructor relation
- bad for queries involving only the department relation
- results in variable size records
- can add pointer chains to link records of a particular relation

<table>
<thead>
<tr>
<th>Comp. Sci.</th>
<th>Taylor</th>
<th>100000</th>
</tr>
</thead>
<tbody>
<tr>
<td>45564</td>
<td>Katz</td>
<td>75000</td>
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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
Data Dictionary Storage

- Many RDBMS use relations also for the data dictionary
- Those relations are typically held in memory for fast access
- Details may vary
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
  – simple: by keeping as many blocks as possible in main memory
  – advanced: planning which blocks to keep in 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
  – If the block is already in the buffer, buffer manager returns the address of the block in main memory
  – If the block is not in the buffer, the buffer manager
    • Allocates space in the buffer for the block
    • Replaces (i.e., removes) some other block, if required, to make space for the new block
      – If replaced block was changed: write back to disk
      – Read the block from the disk to the buffer
      – return the address of the block in main memory to requester
Buffer Replacement Strategies

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

  - 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 Strategies

- **Pinned block** – memory block that is not allowed to be replaced
- **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 processing the final tuple, 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 (coming back to this in a few weeks)
Database System Architectures

• Variants for creating a database system
  – Centralized and Client-Server Systems
  – Server System Architectures
  – Parallel Systems
  – Distributed Systems
Centralized Systems

• Run on a single computer system
  – and do not interact with other computer systems

• General-purpose computer system
  – one to a few CPUs and a number of device controllers
  – shared memory

• Single-user system
  – e.g., personal computer or workstation
  – desk-top unit, single user, usually one CPU and one or two hard disks

• Multi-user system
  – more disks, more memory, multiple CPUs
  – serve a large number of users, usually connected to the system via terminals
  – also called server systems
Centralized Systems

- Simplified Architecture
Client Server Systems

- Server systems satisfy requests generated at $m$ client systems
- They are connected to the server via a network
  - local or internet
  - LAN or WIFI
  - ...

```
client          client          client          ...
            /                /                /
           /                /                /
          /                /                /
 network
```
Client Server Systems

- Database functionality can be divided into:
  - **Back-end**: manages access structures, query evaluation and optimization, concurrency control and recovery
  - **Front-end**: consists of tools such as *forms*, *report-writers*, and graphical user interface facilities

- The interface between the front-end and the back-end is through SQL or through an application program interface.
Client-Server Systems

• Advantages of client-server systems over single machine systems:
  – better functionality for the cost
  – flexibility in locating resources and expanding facilities
  – better user interfaces
  – easier maintenance

• Server systems can be broadly categorized into two kinds:
  – transaction servers (used for RDBMS)
  – data servers (used for object-oriented databases)
Transaction Servers

• Also called query server systems or SQL server systems
  – Clients send requests to the server
  – Transactions are executed at the server
  – Results are shipped back to the client

• Requests are specified in SQL, and communicated to the server through a remote procedure call (RPC) mechanism

• Transactional RPC allows many RPC calls to form a transaction

• Open Database Connectivity (ODBC) is a C language application program interface standard from Microsoft for connecting to a server, sending SQL requests, and receiving results

• JDBC standard is similar to ODBC, for Java
  – similar implementations exist for Python etc.
Transaction Server Processes

• A typical transaction server consists of multiple processes accessing data in shared memory

• Server processes
  – These receive user queries (transactions), execute them and send results back
  – Processes may be **multithreaded**, allowing a single process to execute several user queries concurrently
  – Typically multiple multithreaded server processes

• Lock manager process
  – More on this later

• Database writer process
  – Output modified buffer blocks to disks continually
Transaction Server Processes

- **Log writer process**
  - Server processes simply add log records to log record buffer
  - Log writer process outputs log records to stable storage

- **Checkpoint process**
  - Performs periodic checkpoints

- **Process monitor process**
  - Monitors other processes, and takes recovery actions if any of the other processes fail
  - e.g., aborting any transactions being executed by a server process and restarting it
Transaction Server Processes: Overview
Transaction Server Processes: Overview

• Shared memory contains shared data
  – Buffer pool
  – Lock table
  – Log buffer
  – Cached query plans (reused if same query submitted again)
• All database processes can access shared memory
• To avoid concurrency, DBMS implement *mutual exclusion* using either
  – Operating system semaphores
  – Atomic instructions such as test-and-set
• To avoid overhead of interprocess communication for lock request/grant
  – each database process operates directly on the lock table
  – instead of sending requests to lock manager process
• Lock manager process still used for deadlock detection
Data Servers

- Used in high-speed LANs, in cases where
  - The clients are comparable in processing power to the server
  - The tasks to be executed are compute intensive
- Data are shipped to clients where processing is performed, and then shipped results back to the server
- This architecture requires full back-end functionality at the clients
- Used in many object-oriented database systems

Issues:
- Page-Shipping versus Item-Shipping
- Locking
- Data Caching
- Lock Caching
Data Servers: Issues

- **Page-shipping** versus **item-shipping**
  - Smaller unit of shipping $\Rightarrow$ more messages
  - Worth **prefetching** related items along with requested item
  - Page shipping can be thought of as a form of prefetching

- **Locking**
  - Overhead of requesting and getting locks from server is high (message delays)
  - Item-shipping: locks on prefetched items
    - can be *called back* by the server, or returned by the client
  - Page-shipping: locks on page level
    - transaction is granted lock on entire page
    - can be deescalated to item level in case of lock conflicts
    - locks on unused items are then returned
Data Servers: Issues

• **Data Caching**
  – Data can be cached at client even in between transactions
  – But check that data is up-to-date before it is used (cache coherency)
  – Check can be done when requesting lock on data item

• **Lock Caching**
  – Locks can be retained by client system even in between transactions
  – Transactions can acquire cached locks locally, without contacting server
  – Server **calls back** locks from clients when it receives conflicting lock request
  – Client returns lock once no local transaction is using it
  – Similar to deescalation, but across transactions
Parallel Database Systems

• Parallel database systems consist of multiple processors and multiple disks connected by a fast interconnection network

• A **coarse-grain parallel** machine consists of a small number of powerful processors

• A **massively parallel** or **fine grain parallel** machine utilizes thousands of smaller processors

• Two main performance measures:
  – **throughput** – the number of tasks that can be completed in a given time interval
  – **response time** – the amount of time it takes to complete a single task from the time it is submitted
Speedup and Scaleup

- Question: how much performance do we gain by enlarging the system?
  - Optimum: linear scalability: doubling the system doubles the performance
- **Speedup**: a fixed-sized problem executing on a small system is given to a system which is $N$-times larger
  - Measured by: $speedup = \frac{\text{small system elapsed time}}{\text{large system elapsed time}}$
  - Speedup is **linear** if equation equals $N$.
- **Scaleup**: increase the size of both the problem and the system
  - $N$-times larger system used to perform $N$-times larger job
  - Measured by: $scaleup = \frac{\text{small system small problem elapsed time}}{\text{big system big problem elapsed time}}$
  - Scale up is **linear** if equation equals 1.
Speedup

- Linear speedup
- Sublinear speedup

(speed) vs (resources)
Batch and Transaction Scaleup

- **Batch scaleup:**
  - A single large job
  - Use an $N$-times larger computer on $N$-times larger problem

- **Transaction scaleup:**
  - Numerous small queries submitted by independent users to a shared database
  - $N$-times as many users submitting requests (hence, $N$-times as many requests) to an $N$-times larger database, on an $N$-times larger computer
  - Well-suited for parallel execution
Limitation of Speedup and Scaleup

Speedup and scaleup are often sublinear due to:

- **Startup costs**
  - cost of starting up multiple processes may dominate computation time
  - esp. if the degree of parallelism is high

- **Interference**
  - processes accessing shared resources (e.g., system bus, disks, or locks) compete with each other → bottlenecks
  - thus spending time waiting on other processes, rather than performing useful work

- **Skew**
  - Increasing the degree of parallelism increases the variance in service times of parallely executing tasks
  - Overall execution time determined by **slowest** of parallely executing task
Interconnection Networks

- Bus: does not scale well with increasing parallelism
- Mesh:
  - scalability grows with number of links
  - but number of hops grows at $O(\sqrt{n})$
- Hypercube:
  - good tradeoff
  - number of hops is $O(\log(n))$
Parallel Database Architectures

- **Shared memory** – processors share a common memory
- **Shared disk** – processors share a common disk
- **Shared nothing** – processors share neither a common memory nor common disk
- **Hierarchical** – hybrid of the above architectures
Parallel Database Architectures

(a) shared memory

(b) shared disk

(c) shared nothing

(d) hierarchical
Shared Memory

- Processors and disks have access to a common memory
  - typically via a bus or through an interconnection network
- Extremely efficient communication between processors
  - data in shared memory can be accessed by any processor
  - without having to move it using software
- Architecture is not scalable beyond 32 or 64 processors
  - interconnection network becomes a bottleneck
- Widely used for lower degrees of parallelism (4 to 8)
Shared Disk

- All processors can directly access all disks via an interconnection network, but the processors have private memories
  - i.e., the memory bus is not a bottleneck
- Downside
  - bottleneck now occurs at interconnection to the disk subsystem
- Shared-disk systems can scale to a somewhat larger number of processors, but communication between processors is slower

(b) shared disk
Shared Nothing

• Each node consists of a processor, memory, and one or more disks
• Node functions as the server for the data on the disk(s) it owns
• Data accessed from local disks (and local memory accesses) do not pass through interconnection network, thereby minimizing the interference of resource sharing
• Shared-nothing multiprocessors can be scaled up to thousands of processors without interference
• Main drawback:
  – cost of communication and non-local disk access;
  – sending data involves software interaction at both ends

(c) shared nothing
Hierarchical

- Combines characteristics of all three architectures
- Top level is a shared-nothing architecture
  - Each node of the system could be a shared-memory system or a shared-disk system
- Reduce the complexity of programming such systems by distributed virtual-memory architectures
- Also called non-uniform memory architecture (NUMA)

(d) hierarchical
Distributed Database Systems

- Data spread over multiple machines (also: *sites*)
- Network interconnects the machines
- Data shared by users on multiple machines
Distributed Database Systems

- Homogeneous distributed databases
  - Same software/schema on all sites, data may be partitioned among sites
  - Goal: provide a view of a single database, hiding details of distribution

- Heterogeneous distributed databases
  - Different software/schema on different sites
  - Goal: integrate existing databases to provide useful functionality

- Differentiate between local and global transactions
  - A local transaction accesses data in the single site at which the transaction was initiated
  - A global transaction either accesses data in a site different from the one at which the transaction was initiated or accesses data in several different sites
Trade Offs in Distributed Database Systems

• Sharing data
  – users at one site able to access the data residing at some other sites
• Autonomy
  – each site is able to retain a degree of control over data stored locally
• Higher system availability through redundancy
  – data can be replicated at remote sites, and system can function even if a site fails
• Disadvantage: added complexity required to ensure proper coordination among sites
  – Software development cost
  – Greater potential for bugs
  – Increased processing overhead
Implementation Issues

• Atomicity needed even for transactions that update data at multiple sites

• The two-phase commit protocol (2PC) is used to ensure atomicity
  – Basic idea: each site executes transaction until just before commit, and the leaves final decision to a coordinator
  – Each site must follow decision of coordinator, even if there is a failure while waiting for coordinators decision

• 2PC is not always appropriate: other transaction models based on persistent messaging, and workflows, are also used

• Distributed concurrency control (and deadlock detection) required

• Data items may be replicated to improve data availability
Summary

- Data storage is layered
  - trading off cost/byte vs. access speed
- Data organization in files
  - trading off disk usage vs. reorganization cost
  - minimize block transfer
- Database architectures
  - single machine vs. distributed
  - scalability of distributed databases (speedup/scaleup)
  - design issues of distributed databases
Questions?