Chapter 19: Distributed Databases

Database System Concepts, 6th Ed.

Chapter 19: Distributed Databases

- Heterogeneous and Homogeneous Databases
- Distributed Data Storage
- Distributed Transactions
- Commit Protocols
- Concurrency Control in Distributed Databases
- Availability
- Distributed Query Processing
- Heterogeneous Distributed Databases
- Directory Systems

Distributed Database System

- A distributed database system consists of loosely coupled sites that share no physical component
- Database systems that run on each site are independent of each other
- Transactions may access data at one or more sites

Homogeneous Distributed Databases

- In a homogeneous distributed database
  - All sites have identical software
  - Are aware of each other and agree to cooperate in processing user requests.
  - Each site surrenders part of its autonomy in terms of right to change schemas or software
  - Appears to user as a single system
- In a heterogeneous distributed database
  - Different sites may use different schemas and software
    - Difference in schema is a major problem for query processing
    - Difference in software is a major problem for transaction processing
  - Sites may not be aware of each other and may provide only limited facilities for cooperation in transaction processing

Distributed Data Storage

- Assume relational data model
- Replication
  - System maintains multiple copies of data, stored in different sites, for faster retrieval and fault tolerance.
- Fragmentation
  - Relation is partitioned into several fragments stored in distinct sites
- Replication and fragmentation can be combined
  - Relation is partitioned into several fragments: system maintains several identical replicas of each such fragment.

Data Replication

- A relation or fragment of a relation is **replicated** if it is stored redundantly in two or more sites.
- Full replication of a relation is the case where the relation is stored at all sites.
- Fully redundant databases are those in which every site contains a copy of the entire database.

Data Replication (Cont.)

- Advantages of Replication
  - **Availability**: failure of site containing relation *r* does not result in unavailability of *r* is replicas exist.
  - **Parallelism**: queries on *r* may be processed by several nodes in parallel.
  - **Reduced data transfer**: relation *r* is available locally at each site containing a replica of *r*.
- Disadvantages of Replication
  - Increased cost of updates: each replica of relation *r* must be updated.
  - Increased complexity of concurrency control: concurrent updates to distinct replicas may lead to inconsistent data unless special concurrency control mechanisms are implemented.
    - One solution: choose one copy as **primary copy** and apply concurrency control operations on primary copy

Data Fragmentation

- Division of relation r into fragments $r_1, r_2, \ldots, r_n$ which contain sufficient information to reconstruct relation r.
- **Horizontal fragmentation**: each tuple of *r* is assigned to one or more fragments
- **Vertical fragmentation**: the schema for relation *r* is split into several smaller schemas
  - All schemas must contain a common candidate key (or superkey) to ensure lossless join property.
  - A special attribute, the tuple-id attribute may be added to each schema to serve as a candidate key.

Horizontal Fragmentation of *account* Relation

branch_name	*account_number*	*balance*
Hillside	A-305	500
Hillside	A-226	336
Hillside	A-155	62

$$account_1 = \sigma_{branch\_name=\text{“Hillside”}}(account)$$

branch_name	*account_number*	*balance*
Valleyview	A-177	205
Valleyview	A-402	10000
Valleyview	A-408	1123
Valleyview	A-639	750

$$account_2 = \sigma_{branch\_name=\text{“Valleyview”}}(account)$$

Vertical Fragmentation of *employee_info* Relation

branch_name	*customer_name*	*tuple_id*
Hillside	Lowman	1
Hillside	Camp	2
Valleyview	Camp	3
Valleyview	Kahn	4
Hillside	Kahn	5
Valleyview	Kahn	6
Valleyview	Green	7

$$deposit_1 = \Pi_{branch\_name,\ customer\_name,\ tuple\_id}\ (employee\_info\ )$$

account_number	*balance*	*tuple_id*
A-305	500	1
A-226	336	2
A-177	205	3
A-402	10000	4
A-155	62	5
A-408	1123	6
A-639	750	7

$$deposit_2 = \Pi_{account\_number,\ balance,\ tuple\_id}\ (employee\_info\ )$$

Advantages of Fragmentation

- Horizontal:
  - allows parallel processing on fragments of a relation
  - allows a relation to be split so that tuples are located where they are most frequently accessed
- Vertical:
  - allows tuples to be split so that each part of the tuple is stored where it is most frequently accessed
  - tuple-id attribute allows efficient joining of vertical fragments
  - allows parallel processing on a relation
- Vertical and horizontal fragmentation can be mixed.
  - Fragments may be successively fragmented to an arbitrary depth.

Data Transparency

- **Data transparency**: Degree to which system user may remain unaware of the details of how and where the data items are stored in a distributed system
- Consider transparency issues in relation to:
  - Fragmentation transparency
  - Replication transparency
  - Location transparency

Naming of Data Items - Criteria

1. Every data item must have a system-wide unique name.
2. It should be possible to find the location of data items efficiently.
3. It should be possible to change the location of data items transparently.
4. Each site should be able to create new data items autonomously.

Centralized Scheme - Name Server

- Structure:
  - name server assigns all names
  - each site maintains a record of local data items
  - sites ask name server to locate non-local data items
- Advantages:
  - satisfies naming criteria 1-3
- Disadvantages:
  - does not satisfy naming criterion 4
  - name server is a potential performance bottleneck
  - name server is a single point of failure

Use of Aliases

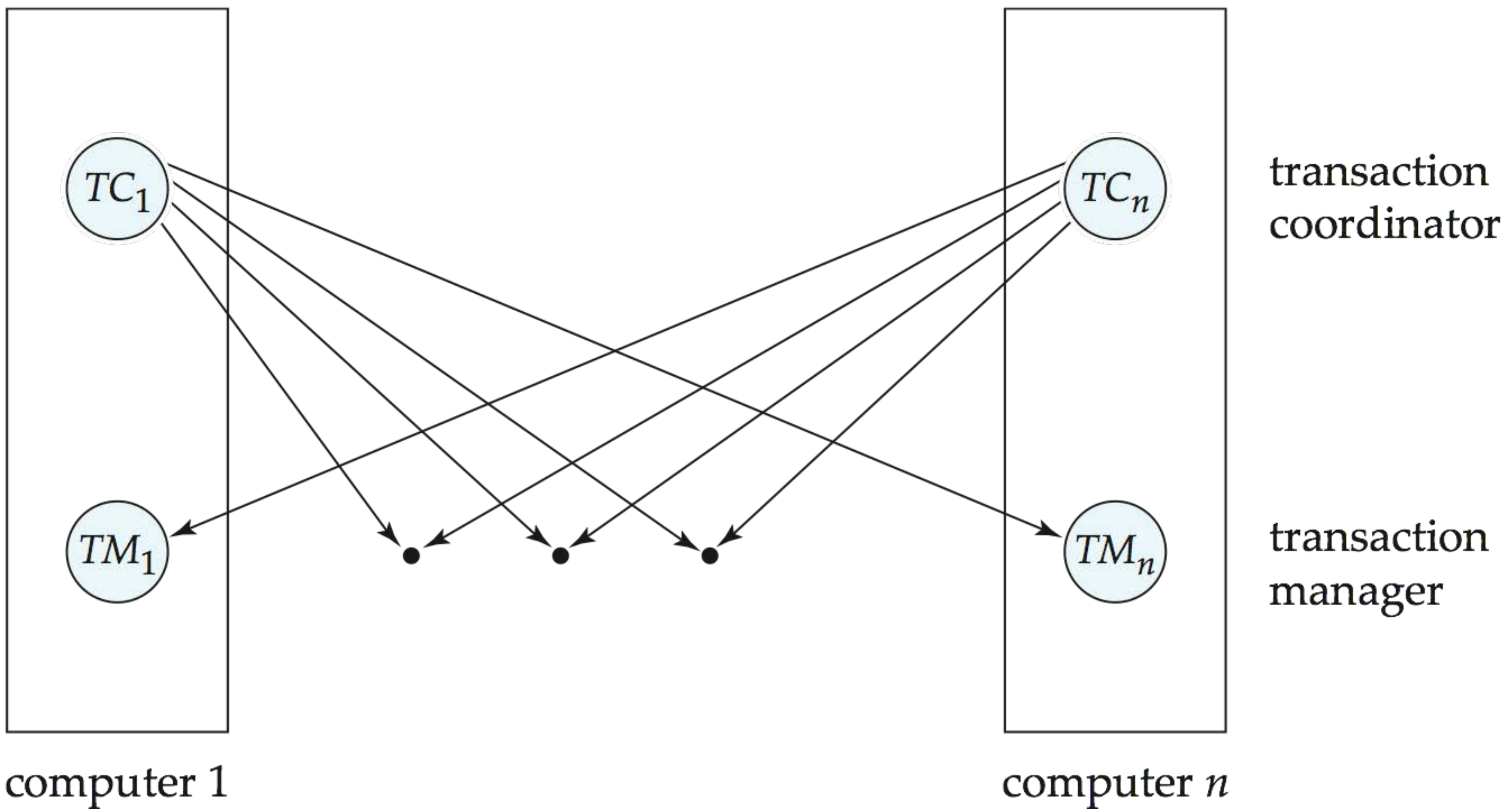
- Alternative to centralized scheme: each site prefixes its own site identifier to any name that it generates i.e., *site* 17.*account.*
  - Fulfills having a unique identifier, and avoids problems associated with central control.
  - However, fails to achieve network transparency.
- Solution: Create a set of **aliases** for data items; Store the mapping of aliases to the real names at each site.
- The user can be unaware of the physical location of a data item, and is unaffected if the data item is moved from one site to another.

Distributed Transactions and 2 Phase Commit

Distributed Transactions

- Transaction may access data at several sites.
- Each site has a local transaction manager responsible for:
  - Maintaining a log for recovery purposes
  - Participating in coordinating the concurrent execution of the transactions executing at that site.
- Each site has a transaction coordinator, which is responsible for:
  - Starting the execution of transactions that originate at the site.
  - Distributing subtransactions at appropriate sites for execution.
  - Coordinating the termination of each transaction that originates at the site, which may result in the transaction being committed at all sites or aborted at all sites.

Transaction System Architecture



System Failure Modes

- Failures unique to distributed systems:
  - Failure of a site.
  - Loss of massages
    - Handled by network transmission control protocols such as TCP-IP
  - Failure of a communication link
    - Handled by network protocols, by routing messages via alternative links
  - **Network partition**
    - A network is said to be **partitioned** when it has been split into two or more subsystems that lack any connection between them
      - Note: a subsystem may consist of a single node
- Network partitioning and site failures are generally indistinguishable.

Commit Protocols

- Commit protocols are used to ensure atomicity across sites
  - a transaction which executes at multiple sites must either be committed at all the sites, or aborted at all the sites.
  - not acceptable to have a transaction committed at one site and aborted at another
- The *two-phase commit* (2PC) protocol is widely used
- The *three-phase commit* (3PC) protocol is more complicated and more expensive, but avoids some drawbacks of two-phase commit protocol. This protocol is not used in practice.

Two Phase Commit Protocol (2PC)

- Assumes **fail-stop** model – failed sites simply stop working, and do not cause any other harm, such as sending incorrect messages to other sites.
- Execution of the protocol is initiated by the coordinator after the last step of the transaction has been reached.
- The protocol involves all the local sites at which the transaction executed
- Let T be a transaction initiated at site S_i, and let the transaction coordinator at S_i be C_i

Phase 1: Obtaining a Decision

- Coordinator asks all participants to *prepare* to commit transaction T_i.
  - C_i adds the records <**prepare** *T*> to the log and forces log to stable storage
  - sends **prepare** *T* messages to all sites at which *T* executed
- Upon receiving message, transaction manager at site determines if it can commit the transaction
  - if not, add a record <**no** *T*> to the log and send **abort** *T* message to C_i
  - if the transaction can be committed, then:
  - add the record <**ready** *T*> to the log
  - force *all records* for *T* to stable storage
  - send **ready** *T* message to C_i

Phase 2: Recording the Decision

- *T* can be committed of C_i received a **ready** *T* message from all the participating sites: otherwise *T* must be aborted.
- Coordinator adds a decision record, <**commit** *T*> or <a**bort** *T*>, to the log and forces record onto stable storage. Once the record stable storage it is irrevocable (even if failures occur)
- Coordinator sends a message to each participant informing it of the decision (commit or abort)
- Participants take appropriate action locally.

Handling of Failures - Site Failure

When site S_i recovers, it examines its log to determine the fate of transactions active at the time of the failure.

- Log contain <**commit** *T*> record: txn had completed, nothing to be done
- Log contains <**abort** *T*> record: txn had completed, nothing to be done
- Log contains <**ready** *T*> record: site must consult C_i to determine the fate of *T*.
  - If *T* committed, **redo** (*T*); write <**commit** *T*> record
  - If *T* aborted, **undo** (*T*)
- The log contains no log records concerning *T*:
  - Implies that S_k failed before responding to the **prepare** *T* message from C_i
  - since the failure of S_k precludes the sending of such a response, coordinator C_1 must abort *T*
  - S_k must execute **undo** (*T*)

Handling of Failures- Coordinator Failure

- If coordinator fails while the commit protocol for *T* is executing then participating sites must decide on *T*'s fate:
  1. If an active site contains a <**commit** *T*> record in its log, then *T* must be committed.
  2. If an active site contains an <**abort** *T*> record in its log, then *T* must be aborted.
  3. If some active participating site does not contain a <**ready** *T*> record in its log, then the failed coordinator C_i cannot have decided to commit *T*.
     - Can therefore abort *T;* however, such a site must reject any subsequent <**prepare** *T*> message from C_i
  4. If none of the above cases holds, then all active sites must have a <**ready** *T*> record in their logs, but no additional control records (such as <**abort** *T*> of <**commit** *T*>).
     - In this case active sites must wait for C_i to recover, to find decision.
- **Blocking problem**: active sites may have to wait for failed coordinator to recover.

Handling of Failures - Network Partition

- If the coordinator and all its participants remain in one partition, the failure has no effect on the commit protocol.
- If the coordinator and its participants belong to several partitions:
  - Sites that are not in the partition containing the coordinator think the coordinator has failed, and execute the protocol to deal with failure of the coordinator.
    - No harm results, but sites may still have to wait for decision from coordinator.
- The coordinator and the sites are in the same partition as the coordinator think that the sites in the other partition have failed, and follow the usual commit protocol.
    - Again, no harm results

Recovery and Concurrency Control

- **In-doubt transactions** have a <**ready** *T*>, but neither a <**commit** *T*>, nor an <**abort** *T*> log record.
- The recovering site must determine the commit-abort status of such transactions by contacting other sites; this can slow and potentially block recovery.
- Recovery algorithms can note lock information in the log.
  - Instead of <**ready** *T*>, write out <**ready** *T*, *L*> *L* = list of locks held by *T* when the log is written (read locks can be omitted).
  - For every in-doubt transaction *T*, all the locks noted in the <**ready** *T*, *L*> log record are reacquired.
- After lock reacquisition, transaction processing can resume; the commit or rollback of in-doubt transactions is performed concurrently with the execution of new transactions.

Three Phase Commit (3PC)

- Assumptions:
  - No network partitioning
  - At any point, at least one site must be up.
  - At most K sites (participants as well as coordinator) can fail
- Phase 1: Obtaining Preliminary Decision: Identical to 2PC Phase 1.
  - Every site is ready to commit if instructed to do so
- Phase 2 of 2PC is split into 2 phases, Phase 2 and Phase 3 of 3PC
  - In phase 2 coordinator makes a decision as in 2PC (called the pre-commit decision) and records it in multiple (at least K) sites
  - In phase 3, coordinator sends commit/abort message to all participating sites,
- Under 3PC, knowledge of pre-commit decision can be used to commit despite coordinator failure
  - Avoids blocking problem as long as < K sites fail
- Drawbacks:
  - higher overheads
  - assumptions may not be satisfied in practice

Alternative Models of Transaction Processing

- Notion of a single transaction spanning multiple sites is inappropriate for many applications
  - E.g. transaction crossing an organizational boundary
  - No organization would like to permit an externally initiated transaction to block local transactions for an indeterminate period
- Alternative models carry out transactions by sending messages
  - Code to handle messages must be carefully designed to ensure atomicity and durability properties for updates
    - Isolation cannot be guaranteed, in that intermediate stages are visible, but code must ensure no inconsistent states result due to concurrency
  - Persistent messaging systems are systems that provide transactional properties to messages
    - Messages are guaranteed to be delivered exactly once
    - Will discuss implementation techniques later

Alternative Models (Cont.)

- Motivating example: funds transfer between two banks
  - Two phase commit would have the potential to block updates on the accounts involved in funds transfer
  - Alternative solution:
    - Debit money from source account and send a message to other site
    - Site receives message and credits destination account
  - Messaging has long been used for distributed transactions (even before computers were invented!)
- Atomicity issue
  - once transaction sending a message is committed, message must guaranteed to be delivered
    - Guarantee as long as destination site is up and reachable, code to handle undeliverable messages must also be available
      - e.g. credit money back to source account.
  - If sending transaction aborts, message must not be sent

Error Conditions with Persistent Messaging

- Code to handle messages has to take care of variety of failure situations (even assuming guaranteed message delivery)
  - E.g. if destination account does not exist, failure message must be sent back to source site
  - When failure message is received from destination site, or destination site itself does not exist, money must be deposited back in source account
    - Problem if source account has been closed
      - get humans to take care of problem
- User code executing transaction processing using 2PC does not have to deal with such failures
- There are many situations where extra effort of error handling is worth the benefit of absence of blocking
  - E.g. pretty much all transactions across organizations

Persistent Messaging and Workflows

- **Workflows** provide a general model of transactional processing involving multiple sites and possibly human processing of certain steps
  - E.g. when a bank receives a loan application, it may need to
    - Contact external credit-checking agencies
    - Get approvals of one or more managers

    and then respond to the loan application
  - We study workflows in Chapter 25
  - Persistent messaging forms the underlying infrastructure for workflows in a distributed environment

Implementation of Persistent Messaging

- **Sending site protocol.**
  - When a transaction wishes to send a persistent message, it writes a record containing the message in a special relation *messages_to_send;* the message is given a unique message identifier.
  - A message delivery process monitors the relation, and when a new message is found, it sends the message to its destination.
  - The message delivery process deletes a message from the relation only after it receives an acknowledgment from the destination site.
    - If it receives no acknowledgement from the destination site, after some time it sends the message again. It repeats this until an acknowledgment is received.
    - If after some period of time, that the message is undeliverable, exception handling code provided by the application is invoked to deal with the failure.
- Writing the message to a relation and processing it only after the transaction commits ensures that the message will be delivered if and only if the transaction commits.

Implementation of Persistent Messaging (Cont.)

- **Receiving site protocol.**
  - When a site receives a persistent message, it runs a transaction that adds the message to a *received_messages* relation
    - provided message identifier is not already present in the relation
  - After the transaction commits, or if the message was already present in the relation, the receiving site sends an acknowledgment back to the sending site.
    - Note that sending the acknowledgment before the transaction commits is not safe, since a system failure may then result in loss of the message.
  - In many messaging systems, it is possible for messages to get delayed arbitrarily, although such delays are very unlikely.
    - Each message is given a timestamp, and if the timestamp of a received message is older than some cutoff, the message is discarded.
    - All messages recorded in the received messages relation that are older than the cutoff can be deleted.

Concurrency Control

Concurrency Control

- Modify concurrency control schemes for use in distributed environment.
- We assume that each site participates in the execution of a commit protocol to ensure global transaction automicity.
- We assume all replicas of any item are updated
  - Will see how to relax this in case of site failures later

Single-Lock-Manager Approach

- System maintains a *single* lock manager that resides in a *single* chosen site, say S_i
- When a transaction needs to lock a data item, it sends a lock request to S_i and lock manager determines whether the lock can be granted immediately
  - If yes, lock manager sends a message to the site which initiated the request
  - If no, request is delayed until it can be granted, at which time a message is sent to the initiating site

Single-Lock-Manager Approach (Cont.)

- The transaction can read the data item from *any* one of the sites at which a replica of the data item resides.
- Writes must be performed on all replicas of a data item
- Advantages of scheme:
  - Simple implementation
  - Simple deadlock handling
- Disadvantages of scheme are:
  - Bottleneck: lock manager site becomes a bottleneck
  - Vulnerability: system is vulnerable to lock manager site failure.

Distributed Lock Manager

- In this approach, functionality of locking is implemented by lock managers at each site
  - Lock managers control access to local data items
    - But special protocols may be used for replicas
- Advantage: work is distributed and can be made robust to failures
- Disadvantage: deadlock detection is more complicated
  - Lock managers cooperate for deadlock detection
    - More on this later
- Several variants of this approach
  - Primary copy
  - Majority protocol
  - Biased protocol
  - Quorum consensus

Primary Copy

- Choose one replica of data item to be the **primary copy**.
  - Site containing the replica is called the **primary site** for that data item
  - Different data items can have different primary sites
- When a transaction needs to lock a data item *Q*, it requests a lock at the primary site of *Q*.
  - Implicitly gets lock on all replicas of the data item
- Benefit
  - Concurrency control for replicated data handled similarly to unreplicated data - simple implementation.
- Drawback
  - If the primary site of *Q* fails, *Q* is inaccessible even though other sites containing a replica may be accessible.

Majority Protocol

- Local lock manager at each site administers lock and unlock requests for data items stored at that site.
- When a transaction wishes to lock an unreplicated data item *Q* residing at site S_i, a message is sent to S_i ‘s lock manager.
  - If *Q* is locked in an incompatible mode, then the request is delayed until it can be granted.
  - When the lock request can be granted, the lock manager sends a message back to the initiator indicating that the lock request has been granted.

Majority Protocol (Cont.)

- In case of replicated data
  - If *Q* is replicated at n sites, then a lock request message must be sent to more than half of the n sites in which *Q* is stored.
  - The transaction does not operate on *Q* until it has obtained a lock on a majority of the replicas of *Q*.
  - When writing the data item, transaction performs writes on *all* replicas.
- Benefit
  - Can be used even when some sites are unavailable
    - details on how handle writes in the presence of site failure later
- Drawback
  - Requires 2(*n*/2 + 1) messages for handling lock requests, and (*n*/2 + 1) messages for handling unlock requests.
  - Potential for deadlock even with single item - e.g., each of 3 transactions may have locks on 1/3rd of the replicas of a data.

Biased Protocol

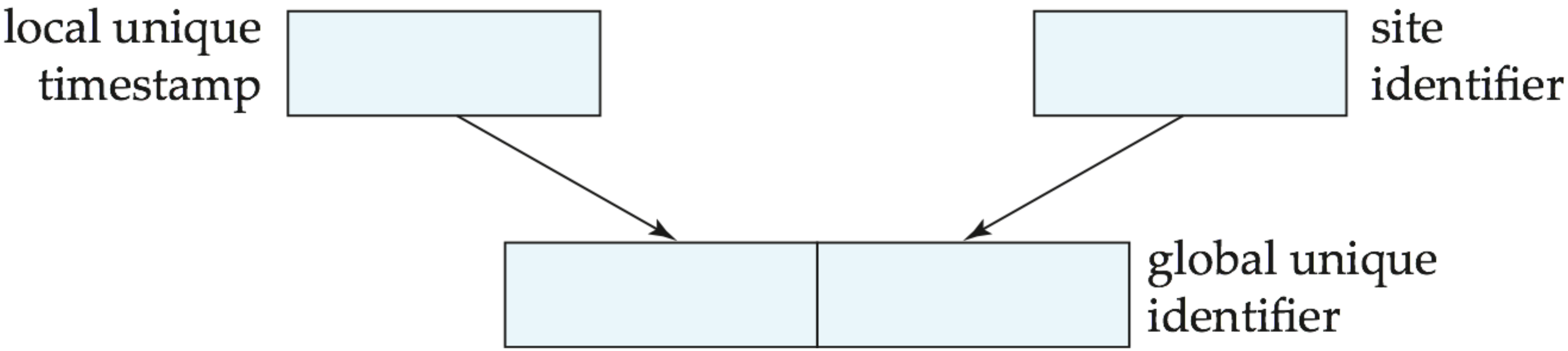
- Local lock manager at each site as in majority protocol, however, requests for shared locks are handled differently than requests for exclusive locks.
- **Shared locks**. When a transaction needs to lock data item *Q*, it simply requests a lock on *Q* from the lock manager at one site containing a replica of *Q*.
- **Exclusive locks**. When transaction needs to lock data item *Q*, it requests a lock on *Q* from the lock manager at all sites containing a replica of *Q*.
- Advantage - imposes less overhead on **read** operations.
- Disadvantage - additional overhead on writes

Quorum Consensus Protocol

- A generalization of both majority and biased protocols
- Each site is assigned a weight.
  - Let S be the total of all site weights
- Choose two values read quorum Q_r and write quorum Q_w
  - Such that $Q_r + Q_w > S$ and $2 * Q_w > S$
  - Quorums can be chosen (and S computed) separately for each item
- Each read must lock enough replicas that the sum of the site weights is >= Q_r
- Each write must lock enough replicas that the sum of the site weights is >= Q_w
- For now we assume all replicas are written
  - Extensions to allow some sites to be unavailable described later

Timestamping

- Timestamp based concurrency-control protocols can be used in distributed systems
- Each transaction must be given a unique timestamp
- Main problem: how to generate a timestamp in a distributed fashion
  - Each site generates a unique local timestamp using either a logical counter or the local clock.
  - Global unique timestamp is obtained by concatenating the unique local timestamp with the unique identifier.



Timestamping (Cont.)

- A site with a slow clock will assign smaller timestamps
  - Still logically correct: serializability not affected
  - But: "disadvantages" transactions
- To fix this problem
  - Define within each site S_i a **logical clock** (LC_i), which generates the unique local timestamp
  - Require that S_i advance its logical clock whenever a request is received from a transaction Ti with timestamp < *x,y*> and x is greater that the current value of LC_i.
  - In this case, site S_i advances its logical clock to the value $x + 1$.

Replication with Weak Consistency

- Many commercial databases support replication of data with weak degrees of consistency (I.e., without a guarantee of serializabiliy)
- E.g.: **master-slave replication**: updates are performed at a single “master” site, and propagated to “slave” sites.
  - Propagation is not part of the update transaction: its is decoupled
    - May be immediately after transaction commits
    - May be periodic
  - Data may only be read at slave sites, not updated
    - No need to obtain locks at any remote site
  - Particularly useful for distributing information
    - E.g. from central office to branch-office
  - Also useful for running read-only queries offline from the main database

Replication with Weak Consistency (Cont.)

- Replicas should see a **transaction-consistent snapshot** of the database
  - That is, a state of the database reflecting all effects of all transactions up to some point in the serialization order, and no effects of any later transactions.
- E.g. Oracle provides a **create snapshot** statement to create a snapshot of a relation or a set of relations at a remote site
  - snapshot refresh either by recomputation or by incremental update
  - Automatic refresh (continuous or periodic) or manual refresh

Multimaster and Lazy Replication

- With multimaster replication (also called update-anywhere replication) updates are permitted at any replica, and are automatically propagated to all replicas
  - Basic model in distributed databases, where transactions are unaware of the details of replication, and database system propagates updates as part of the same transaction
    - Coupled with 2 phase commit
- Many systems support **lazy propagation** where updates are transmitted after transaction commits
  - Allows updates to occur even if some sites are disconnected from the network, but at the cost of consistency

Deadlock Handling

Consider the following two transactions and history, with item X and transaction T_1 at site 1, and item Y and transaction T_2 at site 2:

T_1:	write (X)	T_2:	write (Y)
	write (Y)		write (X)

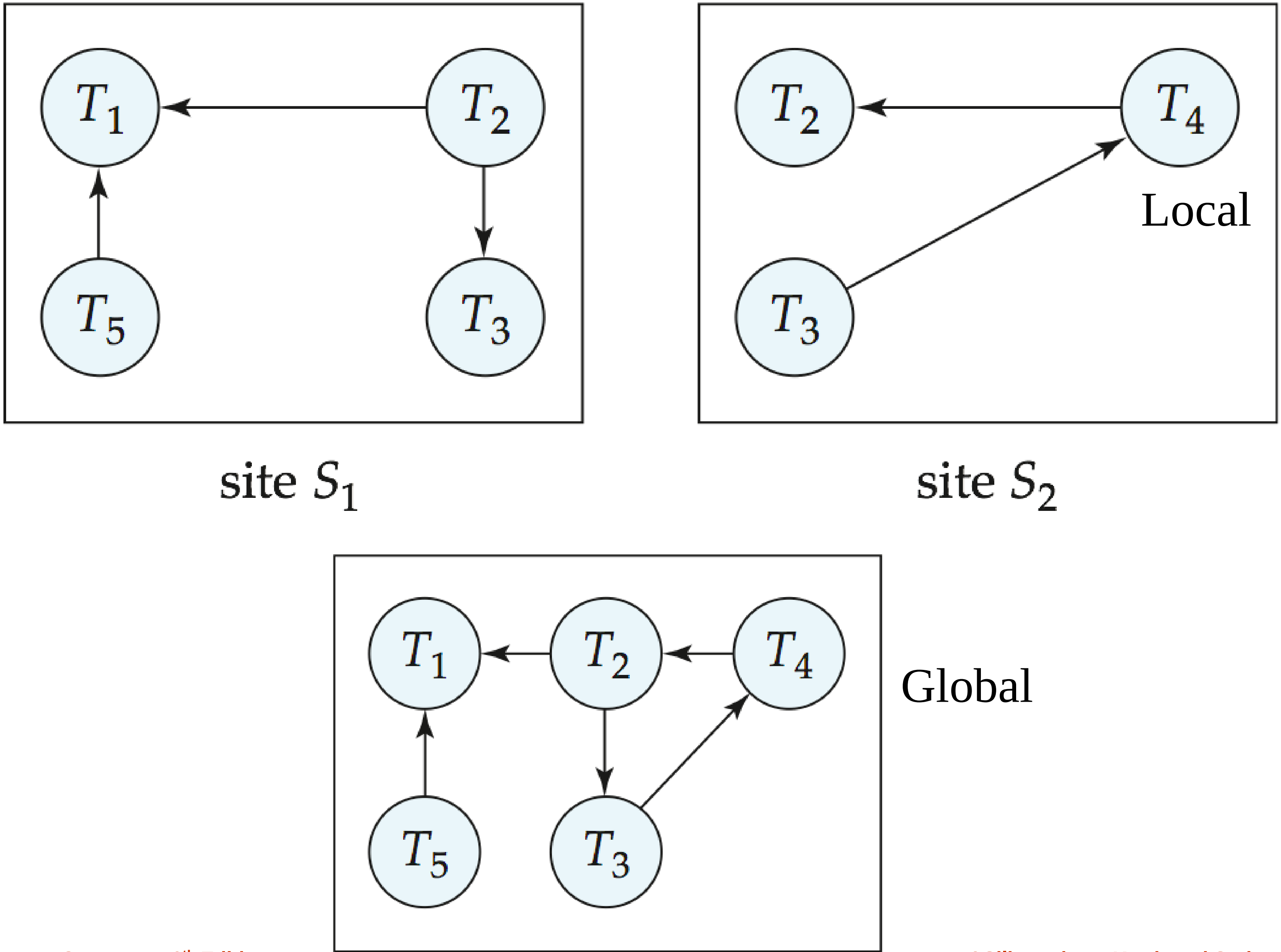
X-lock on X	
write (X)	
	X-lock on Y
	write (Y)
	wait for X-lock on X
Wait for X-lock on Y	

Result: deadlock which cannot be detected locally at either site

Centralized Approach

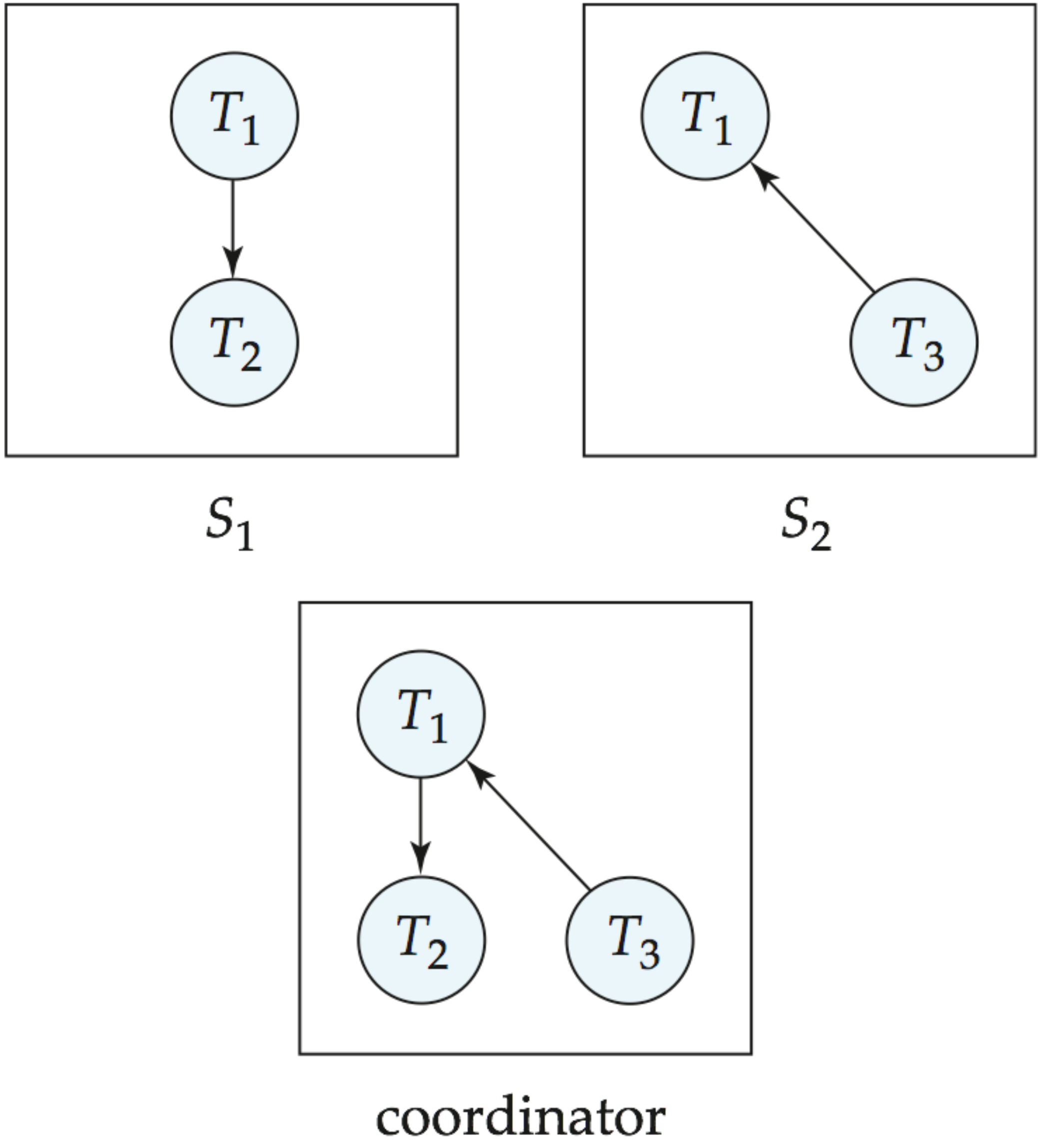
- A global wait-for graph is constructed and maintained in a *single* site; the deadlock-detection coordinator
  - *Real graph*: Real, but unknown, state of the system.
  - *Constructed graph*:Approximation generated by the controller during the execution of its algorithm .
- the global wait-for graph can be constructed when:
  - a new edge is inserted in or removed from one of the local wait-for graphs.
  - a number of changes have occurred in a local wait-for graph.
  - the coordinator needs to invoke cycle-detection.
- If the coordinator finds a cycle, it selects a victim and notifies all sites. The sites roll back the victim transaction.

Local and Global Wait-For Graphs



Example Wait-For Graph for False Cycles

Initial state:



False Cycles (Cont.)

- Suppose that starting from the state shown in figure,

  1. T_2 releases resources at S_1
     - resulting in a message remove $T_1 \rightarrow T_2$ message from the Transaction Manager at site S_1 to the coordinator)
  2. And then T_2 requests a resource held by T_3 at site S_2
     - resulting in a message insert $T_2 \rightarrow T_3$ from S_2 to the coordinator
- Suppose further that the insert message reaches before the **delete** message
  - this can happen due to network delays
- The coordinator would then find a false cycle

$$T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_1$$

- The false cycle above never existed in reality.
- False cycles cannot occur if two-phase locking is used.

Unnecessary Rollbacks

- Unnecessary rollbacks may result when deadlock has indeed occurred and a victim has been picked, and meanwhile one of the transactions was aborted for reasons unrelated to the deadlock.
- Unnecessary rollbacks can result from false cycles in the global wait-for graph; however, likelihood of false cycles is low.

Availability

Availability

- High availability: time for which system is not fully usable should be extremely low (e.g. 99.99% availability)
- Robustness: ability of system to function spite of failures of components
- Failures are more likely in large distributed systems
- To be robust, a distributed system must
  - Detect failures
  - Reconfigure the system so computation may continue
  - Recovery/reintegration when a site or link is repaired
- Failure detection: distinguishing link failure from site failure is hard
  - (partial) solution: have multiple links, multiple link failure is likely a site failure

Reconfiguration

- Reconfiguration:
  - Abort all transactions that were active at a failed site
    - Making them wait could interfere with other transactions since they may hold locks on other sites
    - However, in case only some replicas of a data item failed, it may be possible to continue transactions that had accessed data at a failed site (more on this later)
  - If replicated data items were at failed site, update system catalog to remove them from the list of replicas.
    - This should be reversed when failed site recovers, but additional care needs to be taken to bring values up to date
  - If a failed site was a central server for some subsystem, an **election** must be held to determine the new server
    - E.g. name server, concurrency coordinator, global deadlock detector

Reconfiguration (Cont.)

- Since network partition may not be distinguishable from site failure, the following situations must be avoided
  - Two ore more central servers elected in distinct partitions
  - More than one partition updates a replicated data item
- Updates must be able to continue even if some sites are down
- Solution: majority based approach
  - Alternative of "read one write all available" is tantalizing but causes problems

Majority-Based Approach

- The majority protocol for distributed concurrency control can be modified to work even if some sites are unavailable
  - Each replica of each item has a **version number** which is updated when the replica is updated, as outlined below
  - A lock request is sent to at least ½ the sites at which item replicas are stored and operation continues only when a lock is obtained on a majority of the sites
  - Read operations look at all replicas locked, and read the value from the replica with largest version number
    - May write this value and version number back to replicas with lower version numbers (no need to obtain locks on all replicas for this task)

Majority-Based Approach

- Majority protocol (Cont.)
  - Write operations
    - find highest version number like reads, and set new version number to old highest version + 1
    - Writes are then performed on all locked replicas and version number on these replicas is set to new version number
  - Failures (network and site) cause no problems as long as
    - Sites at commit contain a majority of replicas of any updated data items
    - During reads a majority of replicas are available to find version numbers
    - Subject to above, 2 phase commit can be used to update replicas
  - Note: reads are guaranteed to see latest version of data item
  - Reintegration is trivial: nothing needs to be done
- Quorum consensus algorithm can be similarly extended

Read One Write All (Available)

- Biased protocol is a special case of quorum consensus
  - Allows reads to read any one replica but updates require all replicas to be available at commit time (called **read one write all**)
- Read one write all available (ignoring failed sites) is attractive, but incorrect
  - If failed link may come back up, without a disconnected site ever being aware that it was disconnected
  - The site then has old values, and a read from that site would return an incorrect value
  - If site was aware of failure reintegration could have been performed, but no way to guarantee this
  - With network partitioning, sites in each partition may update same item concurrently
    - believing sites in other partitions have all failed

Site Reintegration

- When failed site recovers, it must catch up with all updates that it missed while it was down
  - Problem: updates may be happening to items whose replica is stored at the site while the site is recovering
  - Solution 1: halt all updates on system while reintegrating a site
    - Unacceptable disruption
  - Solution 2: lock all replicas of all data items at the site, update to latest version, then release locks
    - Other solutions with better concurrency also available

Comparison with Remote Backup

- Remote backup (hot spare) systems (Section 17.10) are also designed to provide high availability
- Remote backup systems are simpler and have lower overhead
  - All actions performed at a single site, and only log records shipped
  - No need for distributed concurrency control, or 2 phase commit
- Using distributed databases with replicas of data items can provide higher availability by having multiple (> 2) replicas and using the majority protocol
  - Also avoid failure detection and switchover time associated with remote backup systems

Coordinator Selection

- Backup coordinators
  - site which maintains enough information locally to assume the role of coordinator if the actual coordinator fails
  - executes the same algorithms and maintains the same internal state information as the actual coordinator fails executes state information as the actual coordinator
  - allows fast recovery from coordinator failure but involves overhead during normal processing.
- Election algorithms
  - used to elect a new coordinator in case of failures
  - Example: Bully Algorithm - applicable to systems where every site can send a message to every other site.

Bully Algorithm

- If site S_i sends a request that is not answered by the coordinator within a time interval *T*, assume that the coordinator has failed S_i tries to elect itself as the new coordinator.
- S_i sends an election message to every site with a higher identification number, S_i then waits for any of these processes to answer within *T*.
- If no response within *T*, assume that all sites with number greater than *i* have failed, S_i elects itself the new coordinator.
- If answer is received S_i begins time interval *T*', waiting to receive a message that a site with a higher identification number has been elected.

Bully Algorithm (Cont.)

- If no message is sent within *T*', assume the site with a higher number has failed; S_i restarts the algorithm.
- After a failed site recovers, it immediately begins execution of the same algorithm.
- If there are no active sites with higher numbers, the recovered site forces all processes with lower numbers to let it become the coordinator site, even if there is a currently active coordinator with a lower number.

Trading Consistency for Availability

What is Consistency?

- Consistency in Databases (ACID):
  - Database has a set of integrity constraints
  - A consistent database state is one where all integrity constraints are satisfied
  - Each transaction run individually on a consistent database state must leave the database in a consistent state
- Consistency in distributed systems with replication
  - Strong consistency: a schedule with read and write operations on a replicated object should give results and final state equivalent to some schedule on a single copy of the object, with order of operations from a single site preserved
  - Weak consistency (several forms)

Availability

- Traditionally, availability of centralized server
- For distributed systems, availability of system to process requests
  - For large system, at almost any point in time there's a good chance that
    - a node is down or even
    - Network partitioning
- Distributed consensus algorithms will block during partitions to ensure consistency
  - Many applications require continued operation even during a network partition
    - Even at cost of consistency

Brewer's CAP Theorem

- Three properties of a system
  - Consistency (all copies have same value)
  - Availability (system can run even if parts have failed)
    - Via replication
  - Partitions (network can break into two or more parts, each with active systems that can't talk to other parts)
- Brewer's CAP "Theorem": You can have at most two of these three properties for any system
- Very large systems will partition at some point

➔Choose one of consistency or availablity
  - Traditional database choose consistency
  - Most Web applications choose availability
    - Except for specific parts such as order processing

Replication with Weak Consistency

- Many systems support replication of data with weak degrees of consistency (I.e., without a guarantee of serializabiliy)
  - i.e. $Q_R + Q_W \le S$ or $2 * Q_W < S$
  - Usually only when not enough sites are available to ensure quorum
    - But sometimes to allow fast local reads
  - Tradeoff of consistency versus availability or latency
- Key issues:
  - Reads may get old versions
  - Writes may occur in parallel, leading to inconsistent versions
    - Question: how to detect, and how to resolve
      - Version vector scheme, Section 25.5.4

Eventual Consistency

- When no updates occur for a long period of time, eventually all updates will propagate through the system and all the nodes will be consistent
- For a given accepted update and a given node, eventually either the update reaches the node or the node is removed from service
- Known as **BASE** (**B**asically **A**vailable, **S**oft state, **E**ventual consistency), as opposed to ACID
  - **Soft state**: copies of a data item may be inconsistent
  - **Eventually Consistent** – copies becomes consistent at some later time if there are no more updates to that data item

Availability vs Latency

- CAP theorem only matters when there is a partition
  - Even if partitions are rare, applications may trade off consistency for latency
    - E.g. PNUTS allows inconsistent reads to reduce latency
      - Critical for many applications
    - But update protocol (via master) ensures consistency over availability
  - Thus there are two questions :
    - If there is partitioning, how does system tradeoff *availability* for *consistency*
    - else how does system trade off *latency* for *consistency*

Distributed Query Processing

Distributed Query Processing

- For centralized systems, the primary criterion for measuring the cost of a particular strategy is the number of disk accesses.
- In a distributed system, other issues must be taken into account:
  - The cost of a data transmission over the network.
  - The potential gain in performance from having several sites process parts of the query in parallel.

Query Transformation

- Translating algebraic queries on fragments.
  - It must be possible to construct relation *r* from its fragments
  - Replace relation *r* by the expression to construct relation *r* from its fragments
- Consider the horizontal fragmentation of the *account* relation into

  $account_1 = \sigma_{branch\_name = \text{"Hillside"}} (account)$

  $account_2 = \sigma_{branch\_name = \text{"Valleyview"}} (account)$
- The query $\sigma_{branch\_name = \text{"Hillside"}} (account)$ becomes

  $\sigma_{\text{branch\_name} = \text{"Hillside"}} (account_1 \cup account_2)$

  which is optimized into

  $\sigma_{branch\_name = \text{"Hillside"}} (account_1) \cup \sigma_{branch\_name = \text{"Hillside"}} (account_2)$

Example Query (Cont.)

- Since $account_1$ has only tuples pertaining to the Hillside branch, we can eliminate the selection operation.
- Apply the definition of $account_2$ to obtain

  $\sigma_{\ branch\_name\ =\ \text{"Hillside"}}\ (\sigma_{\ branch\_name\ =\ \text{"Valleyview"}}\ (account\ )$

- This expression is the empty set regardless of the contents of the *account* relation.
- Final strategy is for the Hillside site to return $account_1$ as the result of the query.

Simple Join Processing

- Consider the following relational algebra expression in which the three relations are neither replicated nor fragmented

  account ⋈ *depositor* ⋈ *branch*
- *account* is stored at site S_1
- *depositor* at S_2
- *branch* at S_3
- For a query issued at site S_I, the system needs to produce the result at site S_I

Possible Query Processing Strategies

- Ship copies of all three relations to site S_I and choose a strategy for processing the entire locally at site $S_{I.}$
- Ship a copy of the account relation to site S_2 and compute $temp_1$ = *account* ⋈ *depositor at* S_2. Ship $temp_1$ from S_2 to S_3, and compute $temp_2 = temp_1$ *branch* at S_3. Ship the result $temp_2$ to S_I.
- Devise similar strategies, exchanging the roles S_1, S_2, S_3
- Must consider following factors:
  - amount of data being shipped
  - cost of transmitting a data block between sites
  - relative processing speed at each site

Semijoin Strategy

- Let r_1 be a relation with schema R_1 stores at site S_1

  Let r_2 be a relation with schema R_2 stores at site S_2
- Evaluate the expression $r_1 \ltimes r_2$ and obtain the result at S_1.

1. Compute $temp_1 \leftarrow \prod_{R1 \cap R2} (r1)$ at $S1$.

- 2. Ship $temp_1$ from S_1 to S_2.
- 3. Compute $temp_2 \leftarrow r_2 \ltimes$ temp1 at S_2
- 4. Ship $temp_2$ from S_2 to S_1.
- 5. Compute $r_1 \ltimes temp_2$ at S_1. This is the same as $r_1 \ltimes r_2$.

Formal Definition

- The **semijoin** of r_1 with r_2, is denoted by:

  $$r_1 \ltimes r_2$$

- it is defined by:

  $$\Pi_{R1} (r_1 \bowtie r_2)$$

- Thus, $r_1 \ltimes r_2$ selects those tuples of r_1 that contributed to $r_1 \bowtie r_2$.
- In step 3 above, $temp_2 = r_2 \ltimes r_1$.
- For joins of several relations, the above strategy can be extended to a series of semijoin steps.

Join Strategies that Exploit Parallelism

- Consider $r_1 \bowtie r_2 \bowtie r_3 \bowtie r_4$ where relation ri is stored at site S_i. The result must be presented at site S_1.
- r_1 is shipped to S_2 and $r_1 \bowtie r_2$ is computed at S_2: simultaneously r_3 is shipped to S_4 and $r_3 \bowtie r_4$ is computed at S_4
- S_2 ships tuples of $(r_1 \bowtie r_2)$ to S_1 as they produced;
  S_4 ships tuples of $(r_3 \bowtie r_4)$ to S_1
- Once tuples of $(r_1 \bowtie r_2)$ and $(r_3 \bowtie r_4)$ arrive at S_1 $(r_1 \bowtie r_2) \bowtie (r_3 \bowtie r_4)$ is computed in parallel with the computation of $(r_1 \bowtie r_2)$ at S_2 and the computation of $(r_3 \bowtie r_4)$ at S_4.

Heterogeneous Distributed Databases

- Many database applications require data from a variety of preexisting databases located in a heterogeneous collection of hardware and software platforms
- Data models may differ (hierarchical, relational , etc.)
- Transaction commit protocols may be incompatible
- Concurrency control may be based on different techniques (locking, timestamping, etc.)
- System-level details almost certainly are totally incompatible.
- A **multidatabase system** is a software layer on top of existing database systems, which is designed to manipulate information in heterogeneous databases
  - Creates an illusion of logical database integration without any physical database integration

Advantages

- Preservation of investment in existing
  - hardware
  - system software
  - Applications
- Local autonomy and administrative control
- Allows use of special-purpose DBMSs
- Step towards a unified homogeneous DBMS
  - Full integration into a homogeneous DBMS faces
    - Technical difficulties and cost of conversion
    - Organizational/political difficulties
      - Organizations do not want to give up control on their data
      - Local databases wish to retain a great deal of **autonomy**

Unified View of Data

- Agreement on a common data model
  - Typically the relational model
- Agreement on a common conceptual schema
  - Different names for same relation/attribute
  - Same relation/attribute name means different things
- Agreement on a single representation of shared data
  - E.g. data types, precision,
  - Character sets
    - ASCII vs EBCDIC
    - Sort order variations
- Agreement on units of measure
- Variations in names
  - E.g. Köln vs Cologne, Mumbai vs Bombay

Query Processing

- Several issues in query processing in a heterogeneous database
- Schema translation
  - Write a **wrapper** for each data source to translate data to a global schema
  - Wrappers must also translate updates on global schema to updates on local schema
- Limited query capabilities
  - Some data sources allow only restricted forms of selections
    - E.g. web forms, flat file data sources
  - Queries have to be broken up and processed partly at the source and partly at a different site
- Removal of duplicate information when sites have overlapping information
  - Decide which sites to execute query
- Global query optimization

Mediator Systems

- **Mediator** systems are systems that integrate multiple heterogeneous data sources by providing an integrated global view, and providing query facilities on global view
  - Unlike full fledged multidatabase systems, mediators generally do not bother about transaction processing
  - But the terms mediator and multidatabase are sometimes used interchangeably
  - The term **virtual database** is also used to refer to mediator/multidatabase systems

Transaction Management in Multidatabases

- **Local transactions** are executed by each local DBMS, outside of the MDBS system control.
- **Global transactions** are executed under multidatabase control.
- Local autonomy - local DBMSs cannot communicate directly to synchronize global transaction execution and the multidatabase has no control over local transaction execution.
  - local concurrency control scheme needed to ensure that DBMS's schedule is serializable
  - in case of locking, DBMS must be able to guard against local deadlocks.
  - need additional mechanisms to ensure global serializability

Local vs. Global Serializability

- The guarantee of local serializability is not sufficient to ensure global serializability.
  - As an illustration, consider two global transactions T1 and T2 , each of which accesses and updates two data items, A and B, located at sites S1 and S2 respectively.
  - It is possible to have a situation where, at site S1 , T2 follows T1 , whereas, at S2 , T1 follows T2, resulting in a nonserializable global schedule.
- If the local systems permit control of locking behavior and all systems follow two-phase locking
  - the multidatabase system can ensure that global transactions lock in a two-phase manner
  - the lock points of conflicting transactions would then define their global serialization order.

Cloud Databases

Data Storage on the Cloud

- Need to store and retrieve massive amounts of data
- Traditional parallel databases not designed to scale to 1000's of nodes (and expensive)
- Initial needs did not include full database functionality
  - Store and retrieve data items by key value is minimum functionality
    - **Key-value stores**
- Several implementations
  - Bigtable from Google,
  - HBase, an open source clone of Bigtable
  - Dynamo, which is a key-value storage system from Amazon
  - Cassandra, from FaceBook
  - Sherpa/PNUTS from Yahoo!

Key Value Stores

- Key-value stores support
  - put(key, value): used to store values with an associated key,
  - get(key): which retrieves the stored value associated with the specified key.
- Some systems such as Bigtable additionally provide range queries on key values
- Multiple versions of data may be stored, by adding a timestamp to the key

Data Representation

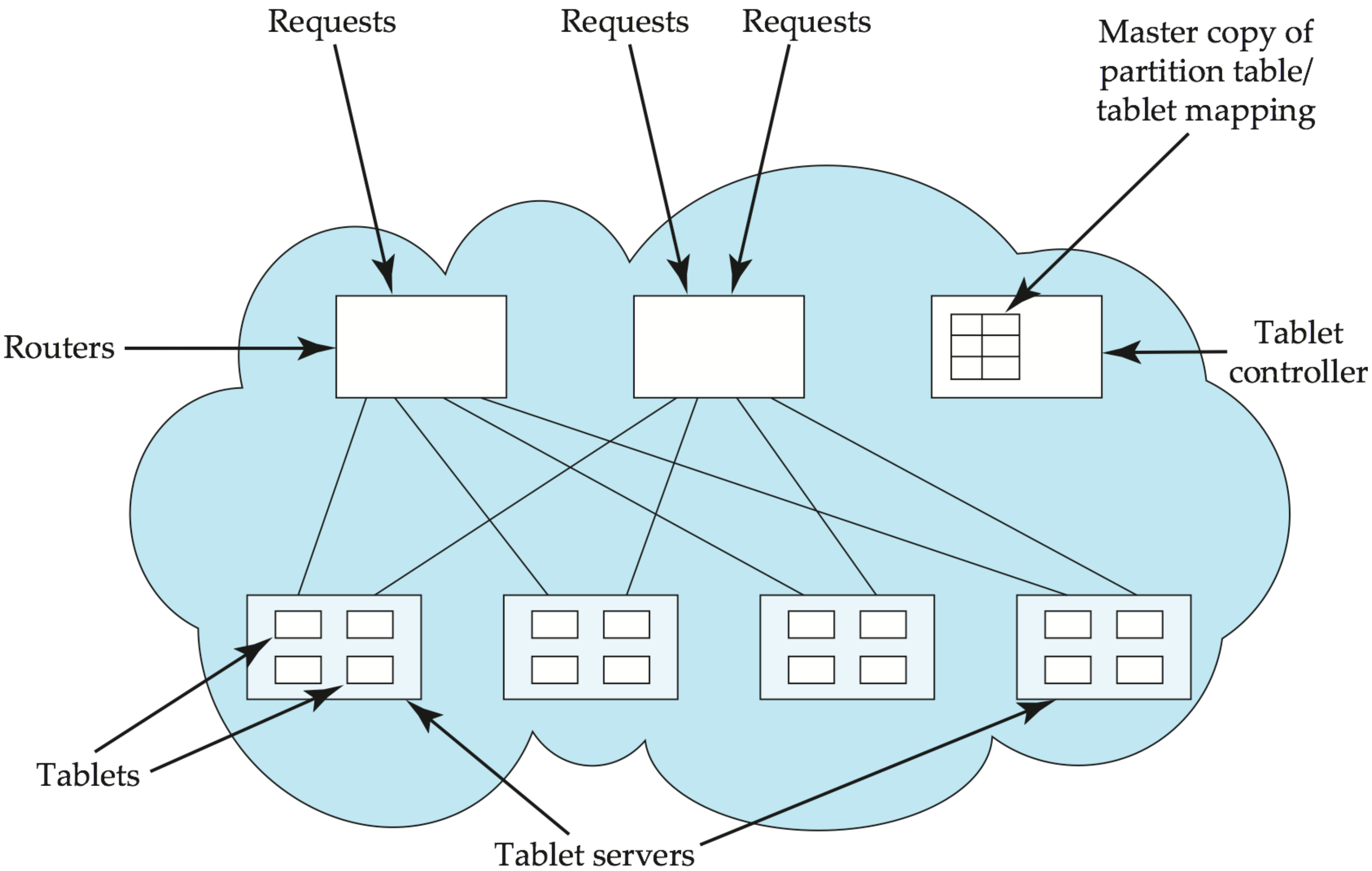
- Records in many big data applications need to have a flexible schema
  - Not all records have same structure
  - Some attributes may have complex substructure
- XML and JSON data representation formats widely used
- An example of a JSON object is:

```
{
    "ID": "22222",
    "name": {
          "firstname: "Albert",
          "lastname: "Einstein"
    },
    "deptname": "Physics",
    "children": [
          { "firstname": "Hans", "lastname": "Einstein" },
          { "firstname": "Eduard", "lastname": "Einstein" }
    ]
}
```

Partitioning and Retrieving Data

- Key-value stores partition data into relatively small units (hundreds of megabytes).
- These partitions are often called tablets (a tablet is a fragment of a table)
- Partitioning of data into tablets is dynamic:
  - as data are inserted, if a tablet grows too big, it is broken into smaller parts
  - if the load (get/put operations) on a tablet is excessive, the tablet may be broken into smaller tablets, which can be distributed across two or more sites to share the load.
  - the number of tablets is much larger than the number of sites
    - similar to virtual partitioning in parallel databases
- Each get/put request must be routed to the correct site
- **Tablet controller** tracks the partitioning function and tablet-to-site mapping
  - map a get() request to one or more tablets,
  - Tablet mapping function to track which site responsible for which tablet

PNUTS Parallel Storage System Architecture



Distributed Directory Systems

Directory Systems

- Typical kinds of directory information
  - Employee information such as name, id, email, phone, office addr, ..
  - Even personal information to be accessed from multiple places
    - e.g. Web browser bookmarks
- White pages
  - Entries organized by name or identifier
    - Meant for forward lookup to find more about an entry
- Yellow pages
  - Entries organized by properties
  - For reverse lookup to find entries matching specific requirements
- When directories are to be accessed across an organization
  - Alternative 1: Web interface. Not great for programs
  - Alternative 2: Specialized **directory access protocols**
    - Coupled with specialized user interfaces

Directory Access Protocols

- Most commonly used directory access protocol:
  - LDAP (Lightweight Directory Access Protocol)
  - Simplified from earlier X.500 protocol
- Question: Why not use database protocols like ODBC/JDBC?
- Answer:
  - Simplified protocols for a limited type of data access, evolved parallel to ODBC/JDBC
  - Provide a nice hierarchical naming mechanism similar to file system directories
    - Data can be partitioned amongst multiple servers for different parts of the hierarchy, yet give a single view to user
      - E.g. different servers for Bell Labs Murray Hill and Bell Labs Bangalore
  - Directories may use databases as storage mechanism

LDAP: Lightweight Directory Access Protocol

- LDAP Data Model
- Data Manipulation
- Distributed Directory Trees

LDAP Data Model

- LDAP directories store **entries**
  - Entries are similar to objects
- Each entry must have unique **distinguished name (DN)**
- DN made up of a sequence of **relative distinguished names (RDNs)**
- E.g. of a DN
  - cn=Silberschatz, ou-Bell Labs, o=Lucent, c=USA
  - Standard RDNs (can be specified as part of schema)
    - cn: common name ou: organizational unit
    - o: organization   c: country
  - Similar to paths in a file system but written in reverse direction

LDAP Data Model (Cont.)

- Entries can have attributes
  - Attributes are multi-valued by default
  - LDAP has several built-in types
    - Binary, string, time types
    - Tel: telephone number   PostalAddress: postal address
- LDAP allows definition of **object classes**
  - Object classes specify attribute names and types
  - Can use inheritance to define object classes
  - Entry can be specified to be of one or more object classes
    - No need to have single most-specific type

LDAP Data Model (cont.)

- Entries organized into a **directory information tree** according to their DNs
  - Leaf level usually represent specific objects
  - Internal node entries represent objects such as organizational units, organizations or countries
  - Children of a node inherit the DN of the parent, and add on RDNs
    - E.g. internal node with DN c=USA
      - Children nodes have DN starting with c=USA and further RDNs such as o or ou
    - DN of an entry can be generated by traversing path from root
  - Leaf level can be an alias pointing to another entry
    - Entries can thus have more than one DN
      - E.g. person in more than one organizational unit

LDAP Data Manipulation

- Unlike SQL, LDAP does not define DDL or DML
- Instead, it defines a network protocol for DDL and DML
  - Users use an API or vendor specific front ends
  - LDAP also defines a file format
    - LDAP Data Interchange Format (LDIF)
- Querying mechanism is very simple: only selection & projection

LDAP Queries

- LDAP query must specify
  - Base: a node in the DIT from where search is to start
  - A search condition
    - Boolean combination of conditions on attributes of entries
      - Equality, wild-cards and approximate equality supported
  - A scope
    - Just the base, the base and its children, or the entire subtree from the base
  - Attributes to be returned
  - Limits on number of results and on resource consumption
  - May also specify whether to automatically dereference aliases
- LDAP URLs are one way of specifying query
- LDAP API is another alternative

LDAP URLs

- First part of URL specifis server and DN of base
  - ldap:://aura.research.bell-labs.com/o=Lucent,c=USA
- Optional further parts separated by ? symbol
  - ldap:://aura.research.bell-labs.com/o=Lucent,c=USA??sub?cn=Korth
  - Optional parts specify
    1. attributes to return (empty means all)
    2. Scope (sub indicates entire subtree)
    3. Search condition (cn=Korth)

C Code using LDAP API

```
#include <stdio.h>
#include <ldap.h>
main( ) {
        LDAP *ld;
        LDAPMessage *res, *entry;
        char *dn, *attr, *attrList [ ] = {“telephoneNumber”, NULL};
        BerElement *ptr;
        int vals, i;
            // Open a connection to server
        ld = ldap_open(“aura.research.bell-labs.com”, LDAP_PORT);
        ldap_simple_bind(ld, “avi”, “avi-passwd”);
        … actual query (next slide) …
      ldap_unbind(ld);
}
```

C Code using LDAP API (Cont.)

```
ldap_search_s(ld, “o=Lucent, c=USA”, LDAP_SCOPE_SUBTREE,
                    “cn=Korth”, attrList, /* attrsonly*/ 0, &res);
          /*attrsonly = 1 => return only schema not actual results*/
printf(“found%d entries”, ldap_count_entries(ld, res));
for (entry=ldap_first_entry(ld, res); entry != NULL;
                    entry=ldap_next_entry(id, entry)) {
       dn = ldap_get_dn(ld, entry);
       printf(“dn: %s”, dn);    /* dn: DN of matching entry */
       ldap_memfree(dn);
       for(attr = ldap_first_attribute(ld, entry, &ptr); attr != NULL;
           attr = ldap_next_attribute(ld, entry, ptr))
       {                                    // for each attribute
          printf(“%s:”, attr);              // print name of attribute
          vals = ldap_get_values(ld, entry, attr);
          for (i = 0; vals[i] != NULL; i ++)
                 printf(“%s”, vals[i]);  // since attrs can be multivalued
          ldap_value_free(vals);
       }
}
ldap_msgfree(res);
```

LDAP API (Cont.)

- LDAP API also has functions to create, update and delete entries
- Each function call behaves as a separate transaction
  - LDAP does not support atomicity of updates

Distributed Directory Trees

- Organizational information may be split into multiple directory information trees
  - Suffix of a DIT gives RDN to be tagged onto to all entries to get an overall DN
    - E.g. two DITs, one with suffix o=Lucent, c=USA
      and another with suffix o=Lucent, c=India
  - Organizations often split up DITs based on geographical location or by organizational structure
  - Many LDAP implementations support replication (master-slave or multi-master replication) of DITs (not part of LDAP 3 standard)
- A node in a DIT may be a **referral** to a node in another DIT
  - E.g. Ou= Bell Labs may have a separate DIT, and DIT for o=Lucent may have a leaf with ou=Bell Labs containing a referral to the Bell Labs DIT
  - Referalls are the key to integrating a distributed collection of directories
  - When a server gets a query reaching a referral node, it may either
    - Forward query to referred DIT and return answer to client, or
    - Give referral back to client, which transparently sends query to referred DIT (without user intervention)

End of Chapter

Extra Slides on 3PC

Database System Concepts, 6th Ed.

Three Phase Commit (3PC)

- Assumptions:
  - No network partitioning
  - At any point, at least one site must be up.
  - At most K sites (participants as well as coordinator) can fail
- Phase 1: Obtaining Preliminary Decision: Identical to 2PC Phase 1.
  - Every site is ready to commit if instructed to do so
- Phase 2 of 2PC is split into 2 phases, Phase 2 and Phase 3 of 3PC
  - In phase 2 coordinator makes a decision as in 2PC (called the pre-commit decision) and records it in multiple (at least K) sites
  - In phase 3, coordinator sends commit/abort message to all participating sites,
- Under 3PC, knowledge of pre-commit decision can be used to commit despite coordinator failure
  - Avoids blocking problem as long as < K sites fail
- Drawbacks:
  - higher overheads
  - assumptions may not be satisfied in practice

Three Phase Commit (3PC)

- Assumptions:
  - No network partitioning
  - At any point, at least one site must be up.
  - At most K sites (participants as well as coordinator) can fail
- Phase 1: Obtaining Preliminary Decision: Identical to 2PC Phase 1.
  - Every site is ready to commit if instructed to do so
  - Under 2 PC each site is obligated to wait for decision from coordinator
  - Under 3PC, knowledge of pre-commit decision can be used to commit despite coordinator failure.

3PC: Phase 2. Recording the Preliminary Decision

- Coordinator adds a decision record (<**abort** *T*> or < **precommit** *T*>) in its log and forces record to stable storage.
- Coordinator sends a message to each participant informing it of the decision
- Participant records decision in its log
- If abort decision reached then participant aborts locally
- If pre-commit decision reached then participant replies with <**acknowledge** *T*>

3PC: Phase 3. Recording Decision in the Database

- Executed only if decision in phase 2 was to precommit
- Coordinator collects acknowledgements. It sends <**commit** *T*> message to the participants as soon as it receives K acknowledgements.
- Coordinator adds the record <**commit** *T*> in its log and forces record to stable storage.
- Coordinator sends a message to each participant to <**commit** *T*>
- Participants take appropriate action locally

3PC: Handling Site Failure

- **Site Failure.** Upon recovery, a participating site examines its log and does the following:
  - Log contains <**commit** *T*> record: no action
  - Log contains <**abort** *T*> record: no action
  - Log contains <**ready** *T*> record, but no <**abort** *T*> or <**precommit** *T*> record: site consults Ci to determine the fate of *T*.
    - if Ci says *T* aborted, site executes **undo** (*T*) (and writes <**abort** *T*> record)
    - if Ci says T committed, site executes **redo** (*T*) (and writes < **commit** *T*> record)
    - if *c* says *T* committed, site resumes the protocol from receipt of **precommit** *T* message (thus recording <**precommit** *T*> in the log, and sending **acknowledge** *T* message sent to coordinator).

3PC: Handling Site Failure (Cont.)

- Log contains <**precommit** *T*> record, but no <**abort** *T*> or <**commit** *T*>: site consults Ci to determine the fate of *T*.
  - if *Ci* says *T* aborted, site executes **undo** (*T*)
  - if Ci says *T* committed, site executes **redo** (*T*)
  - if Ci says *T* still in precommit state, site resumes protocol at this point
- Log contains no <**ready** *T*> record for a transaction *T*: site executes **undo** (*T*) writes <**abort** *T*> record

Figure 19.02

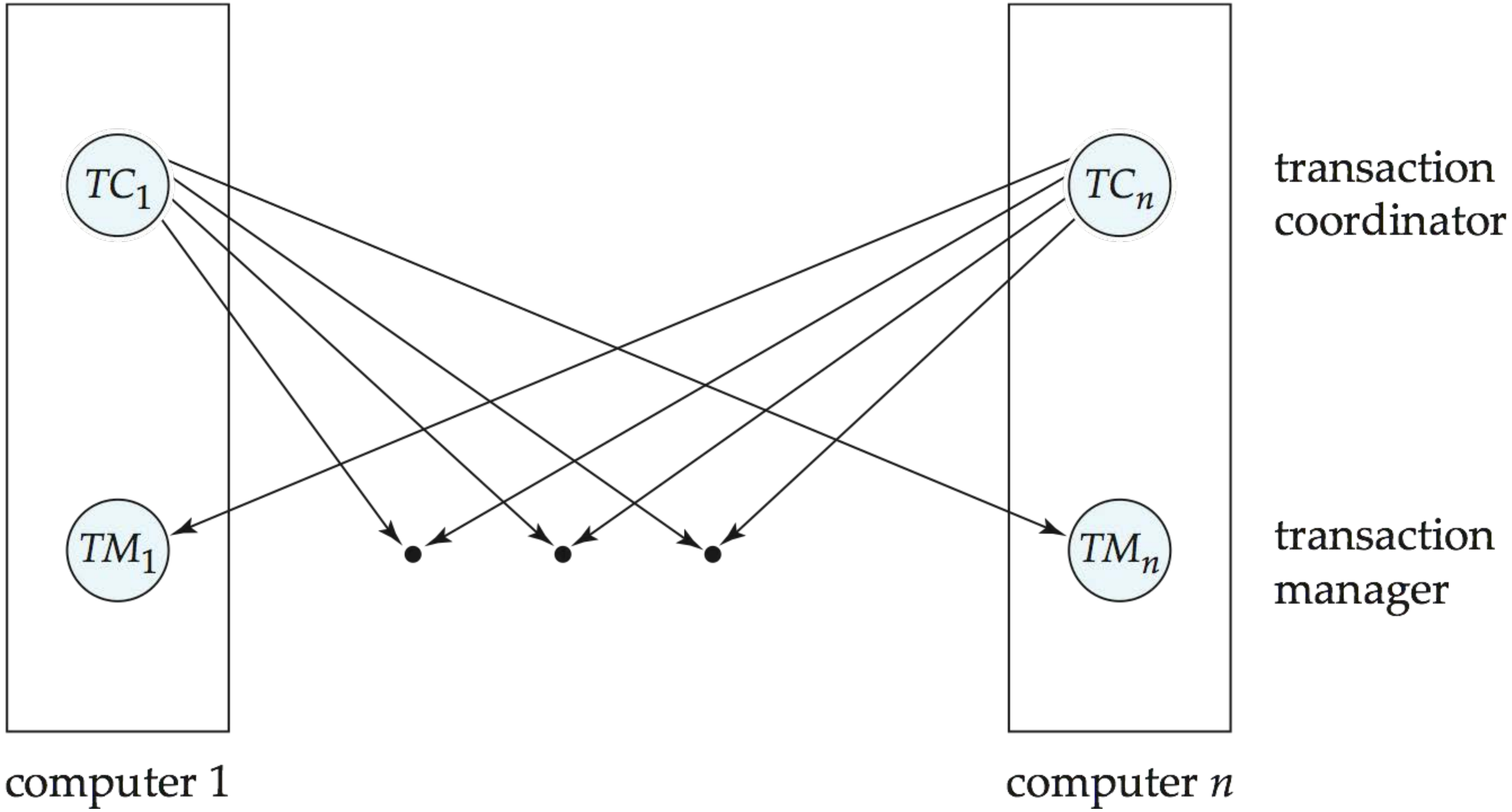

TC1
TCn
transaction coordinator
TM1
TMn
transaction manager
computer 1
computer n

Figure 19.03

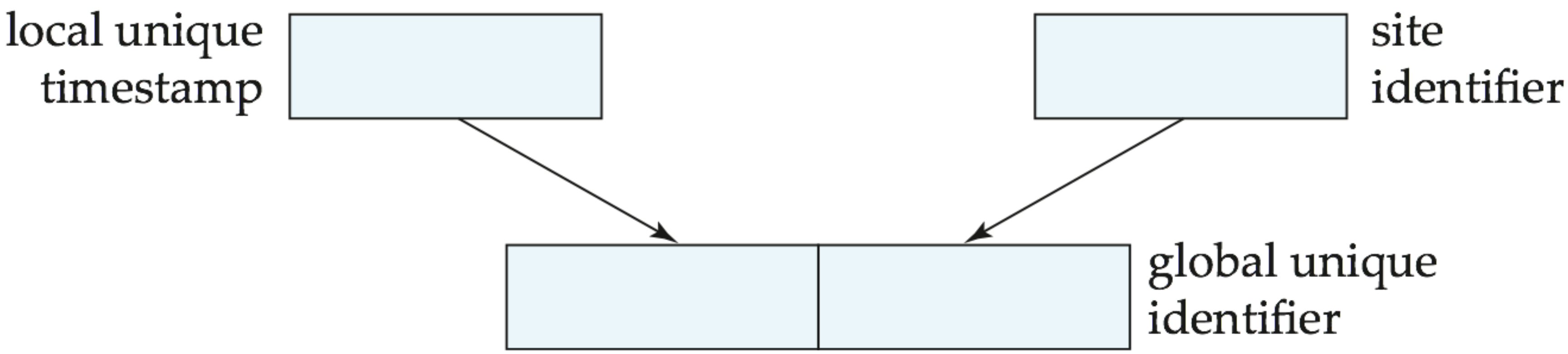

local unique
timestamp
site
identifier
global unique
identifier

Figure 19.04

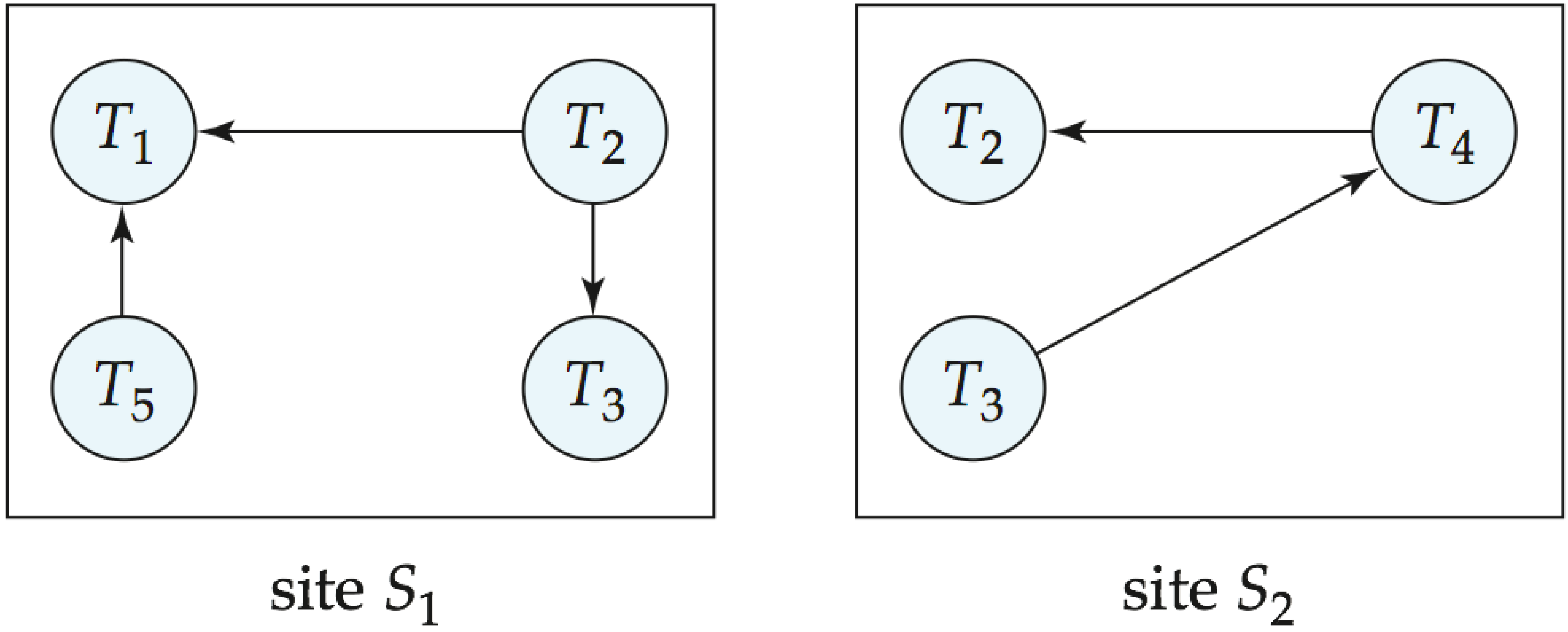


Figure 19.05

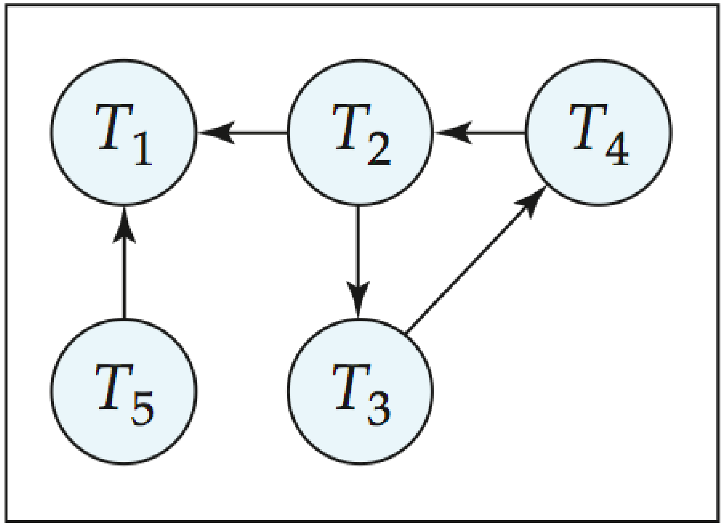


Figure 19.06

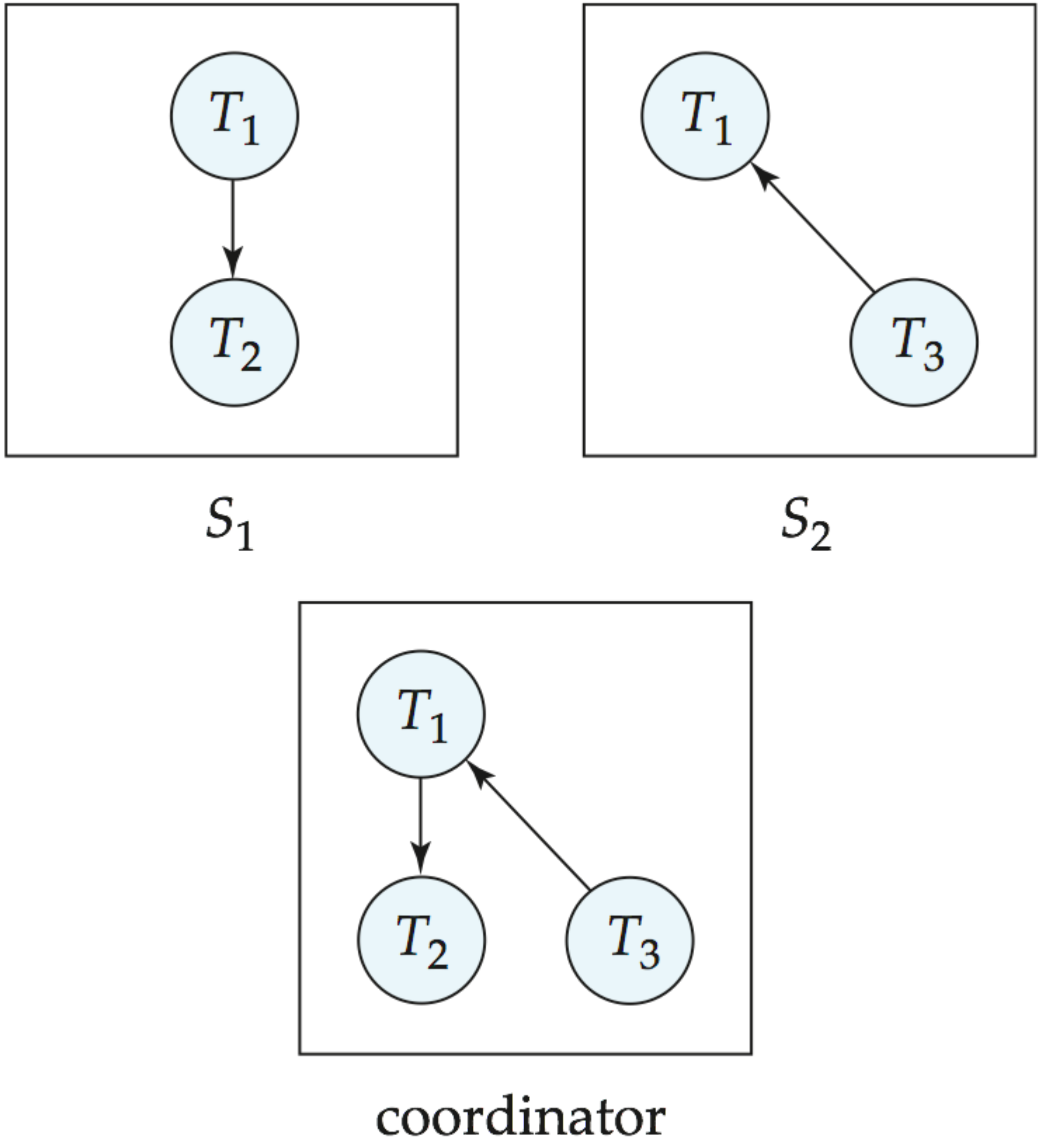
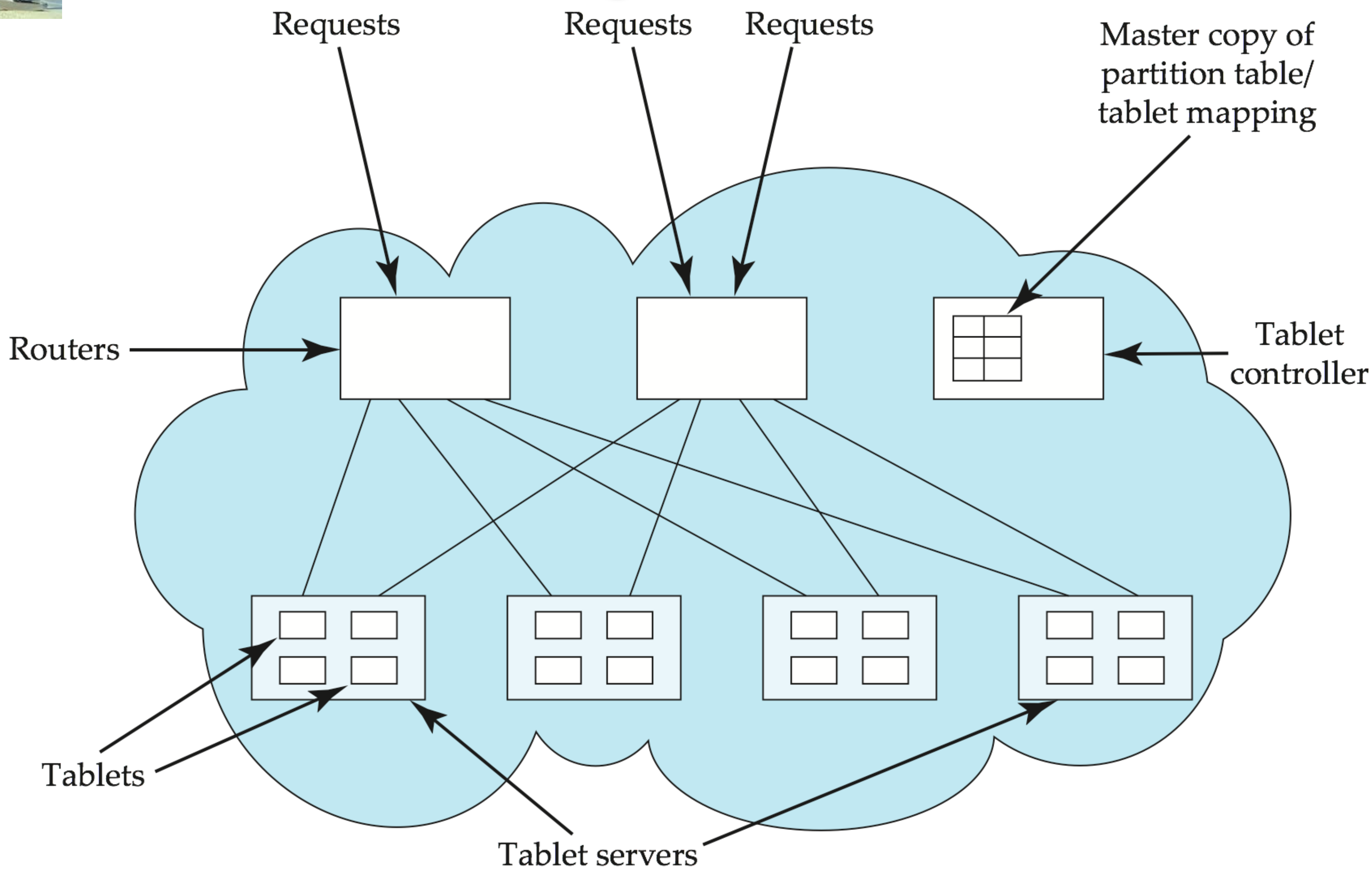


Figure 19.07


Requests
Requests
Requests
Master copy of
partition table/
tablet mapping
Routers
Tablet
controller
Tablets
Tablet servers