CompSci 516
Database Systems

Lecture 18
Distributed DBMS

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Announcements

- HW3 on NOSQL and MongoDB to be released soon
  - Install the system first
  - Due in two weeks after NOSQL in class
  - Keep working on the project in the meantime!

Where are we now?

We learnt

- ✓ Relational Model and Query Languages
  - ✓ SQL, RA, RC
  - ✓ Postgres (DBMS)
  - HW1
- ✓ Map-reduce and spark
  - HW2
- ✓ DBMS Internals
  - ✓ Storage
  - ✓ Indexing
  - ✓ Query Evaluation
  - ✓ Operator Algorithms
  - ✓ External sort
  - ✓ Query Optimization
- ✓ Database Normalization

- ✓ Transactions
  - ✓ Basic concepts
  - ✓ Concurrency control
  - ✓ Recovery

Next

- Distributed DBMS
- NOSQL

- (ARIES protocol of transactions to be covered later)

Reading Material

- [RG]
  - Parallel DBMS: Chapter 22.1-22.5
  - Distributed DBMS: Chapter 22.6 – 22.14

- [GUW]
  - Parallel DBMS and map-reduce: Chapter 20.1-20.2
  - Distributed DBMS: Chapter 20.3, 20.4.1-20.4.2, 20.5-20.6

- Other recommended readings:
  - Chapter 2 (Sections 1,2,3) of Mining of Massive Datasets, by Rajaraman and Ullman: http://i.stanford.edu/~ullman/mmds.html
  - Original Google MR paper by Jeff Dean and Sanjay Ghemawat, OSDI' 04: http://research.google.com/archive/mapreduce.html

Acknowledgement:
The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.

Parallel and Distributed Data Processing

- So far, query processing on a single machine
  - Query Execution and Optimization
  - Transaction CC and Recovery
- Now: data and operation distribution
- Parallelism
  - performance
  - Parallel databases (will be covered soon)
- Data distribution
  - increased availability, e.g. when a site goes down
  - distributed local access to data (e.g. an organization may have branches in several cities)
  - analysis of distributed data
  - Distributed DBMS (today)

Topics in Distributed DBMS

- Architecture
- Data Storage
- Query Execution
- Transactions – updates
- Recovery – Two Phase Commit (2PC)

- Warning! Many concepts and terminology

Introduction: Distributed Databases

- Data is stored at several sites, each managed by a DBMS that can run independently

- Desired properties
  1. Distributed Data Independence
  2. Distributed Transaction Atomicity

Distributed Data Independence

- Users should not have to know where data is located
  - no need to know the locations of references relations, their copies or fragments (later)
  - extends Physical and Logical Data Independence principles

- Queries spanning multiple sites should be optimized in a cost-based manner
  - taking into account communication costs and differences in local computation costs

Distributed Transaction Atomicity

1. Users should be able to write transactions accessing multiple sites just like local transactions

2. The effects of a transaction across sites should be atomic
   - all changes persist if transaction commits
   - none persist if transaction aborts

Recent Trends on These Two Properties

- These two properties are in general desirable
- But not always efficiently achievable
  - e.g. when sites are connected by a slow long-distance network
- Even sometimes not desirable for globally distributed sites
  - too much administrative overhead of making location of data "transparent" (not visible to user)
- Therefore not always supported
  - Users have to be aware of where data is located
  - Not much consensus on the design objectives on distributed databases

Types of Distributed Databases

- Homogeneous:
  - Every site runs same type of DBMS
- Heterogeneous:
  - Different sites run different DBMSs
  - different RDBMSs or even non-relational DBMSs
  - RDBMS = Relational DBMS

More on Heterogeneous Distributed Databases

- Database servers are accessed through well-accepted and standard Gateway protocols
  - masks the differences of DBMSs (capability, data format etc.)
  - e.g. ODBC, JDBC
- However, can be expensive and may not be able to hide all differences
  - e.g. when a server is not capable of supporting distributed transaction management

Distributed DBMS Architecture

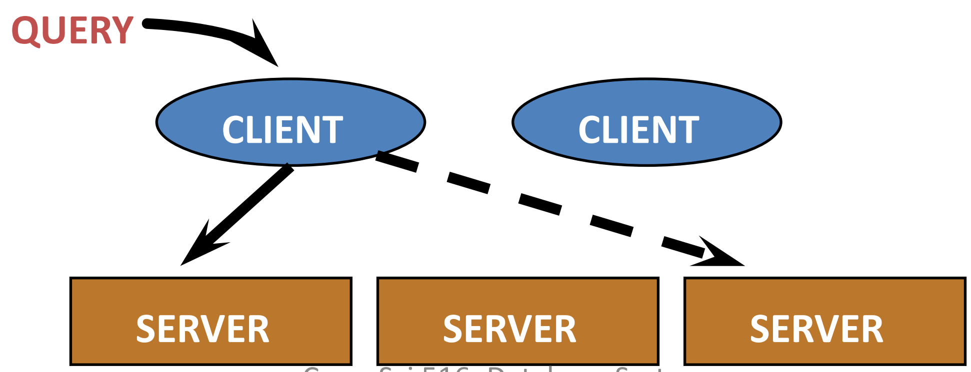
Distributed DBMS Architectures

- Three alternative approaches

1. Client-Server
2. Collaborating Server
3. Middleware

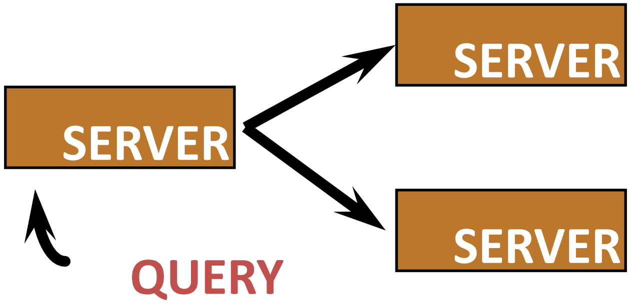
Client-Server Systems

- One or more client (e.g. personal computer) and one or more server processes (e.g. a mainframe)
  - A client process can ship a query to any server process
  - Clients are responsible for user interfaces
  - Server manages data and executes queries
- Advantages
  - clean separation and centralized server
  - expensive server machines are not underutilized by simple user interactions
  - users can run GUI on clients that they are familiar with
- Challenges
  - need to carefully handle communication costs
  - e.g. fetching tuples one at a time might be bad – need to do caching on client side



Collaborating Server Systems

- Queries can span multiple sites
  - not allowed in client-servers as the clients would have had to break queries and combine the results
- When a server receives a query that requires access to data at other servers
  - it generates appropriate subqueries
  - puts the result together
- Eliminates distinction between client and server



Middleware Systems

- Allows a single query to span multiple servers
- But does not require all db servers to be capable of handling multi-site execution strategies
  - need just one db server capable of managing queries and transactions spanning multiple servers (called middleware)
  - the remaining servers can handle only the local queries and transactions
- The middleware layer is capable of executing joins and other operations on data obtained from other servers, but typically does not maintain any data
- Useful when trying to integrate several "legacy systems"
  - whose basic capabilities cannot be extended

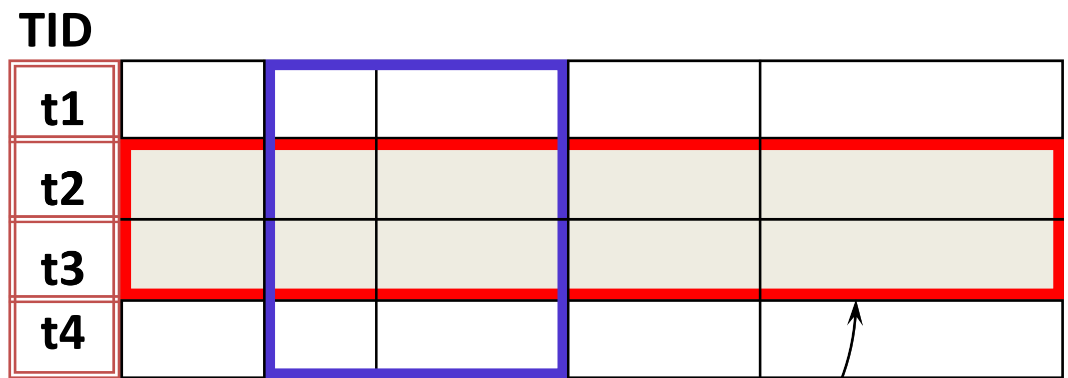
Storing Data in Distributed DBMS

Storing Data in a Distributed DBMS

- Relations are stored across several sites
- Accessing data at a remote site incurs message-passing costs
- To reduce this overhead, a single relation may be partitioned or fragmented across several sites
  - typically at sites where they are most often accessed
- The data can be replicated as well
  - when the relation is in high demand

Fragmentation

- Break a relation into smaller relations or fragments
  - store them in different sites as needed

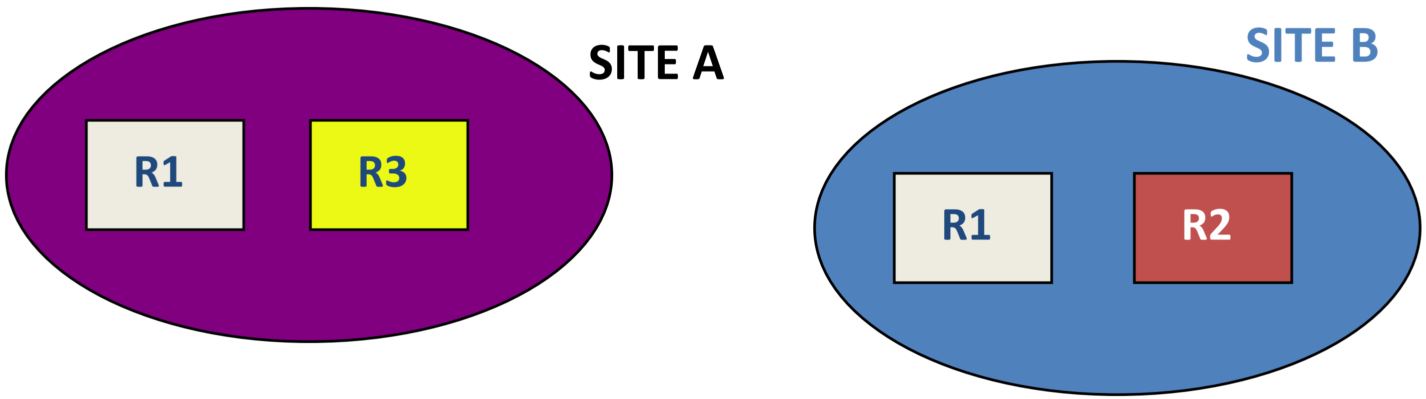


- Horizontal:
  - Usually disjoint
  - Can often be identified by a selection query (employees in a city – locality of reference)
  - To retrieve the full relation, need a union

- Vertical:
  - Identified by projection queries
  - Typically unique TIDs added to each tuple
  - TIDs replicated in each fragments
  - Ensures that we have a Lossless Join

Replication

- When we store several copies of a relation or relation fragments
  - can be replicated at one or more sites
  - e.g. R is fragmented into R1, R2, R3; one copy of R2, R3; but two copies at R1 at two sites
- Advantages
  - Gives increased availability – e.g. when a site or communication link goes down
  - Faster query evaluation – e.g. using a local copy
- Synchronous and Asynchronous (later)
  - Vary in how current different copies are when a relation is modified



Distributed Catalog Management

- Must keep track of how data is fragmented and replicated across sites
  - in addition to usual schema, authorization, and statistical information
- Must be able to uniquely identify each replica of each fragment
  - Globally unique name may compromise autonomy of servers
  - To preserve local autonomy: Global relation name = <local-name, birth-site>
  - To identify a replica, add a replica-id field (now called global replica name)
- Site Catalog: Describes all objects (fragments, replicas) at a site + Keeps track of replicas of relations created at this site
  - To find a relation, look up its birth-site catalog
  - Birth-site never changes, even if relation is moved

Distributed Query Processing

No joins

Join

Non-Join Distributed Queries

```
SELECT AVG(S.age)
FROM Sailors S
WHERE S.rating > 3
   AND S.rating < 7
```

tid	sid	sname	rating	age
T1			4	
T2			5	
T3			9	

T1: stored at Shanghai

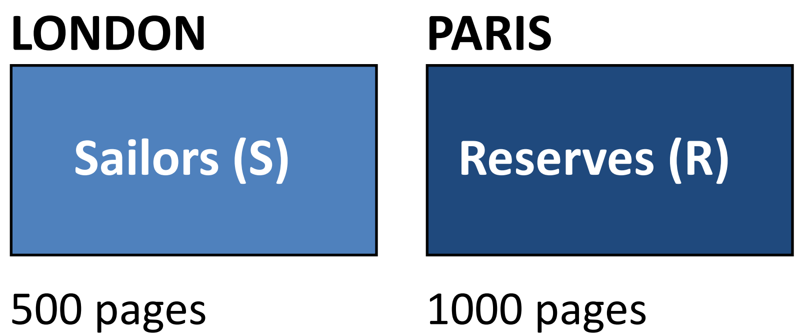
T2, T3: stored at Tokyo

- Horizontally Fragmented: Tuples with rating < 5 at Shanghai, >= 5 at Tokyo.
  - Must compute SUM(age), COUNT(age) at both sites.
  - If WHERE contained just S.rating > 6, just one site
- Vertically Fragmented: sid and rating at Shanghai, sname and age at Tokyo, tid at both.
  - Must reconstruct relation by join on tid, then evaluate the query
  - if no tid, decomposition would be lossy
- Replicated: Sailors copies at both sites.
  - Choice of site based on local costs (e.g. index), shipping costs

Joins in a Distributed DBMS

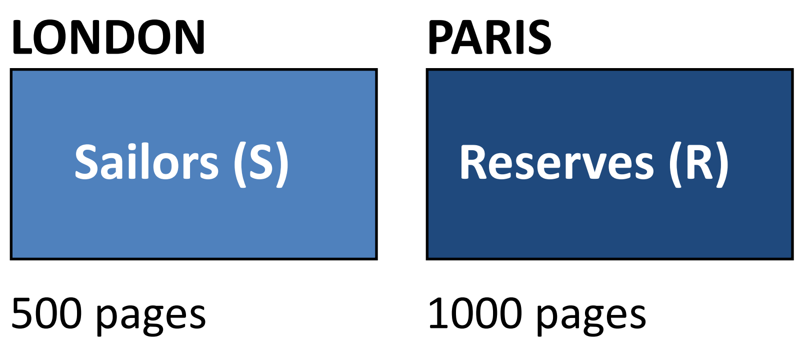
- Can be very expensive if relations are stored at different sites

1. Fetch as needed
2. Ship to one site
3. Semi-join
4. Bloom join



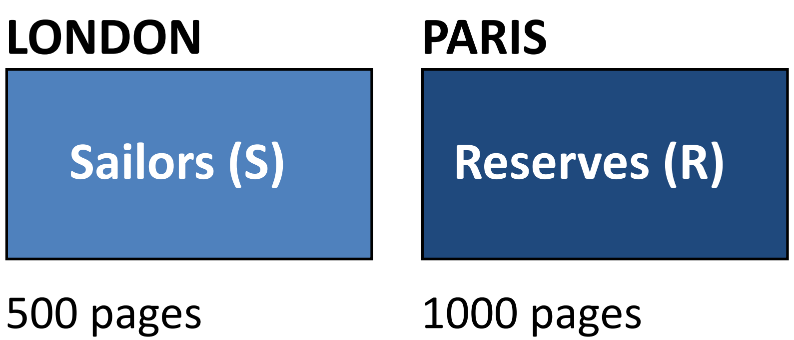
1. Fetch As Needed

- Page-oriented Nested Loop Join
  - Sailors as outer – for each S page, fetch all R pages from Paris
  - if cached at London, each R page fetched once
  - Otherwise, **Cost:** 500 d + 500 * 1000 (d+s)
  - **d** is cost to read/write page
  - **s** is cost to ship page
  - If query was not submitted at London, must add cost of shipping result to query site
  - Can also do Index NL at London, fetching matching Reserves tuples to London as needed



2. Ship To One Site

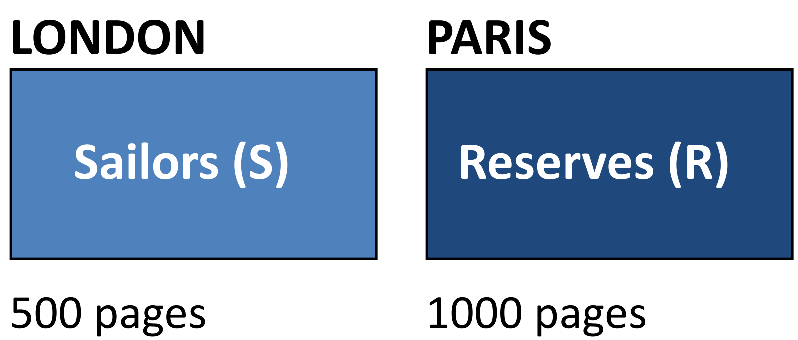
- Ship Sailors (S) to Paris
  - **Cost:** 500 (2d + s) + 4500 d
  - For relation S: reading in London, shipping to Paris, and saving it in Paris: 500 (2d + s)
  - Assume Sort-Merge Join with cost 3(M+N), i.e. enough memory
  - Then join cost = 3*(500+1000)d
  - If result size is very large, may be better to ship both relations to result site and then join them
- Not all tuples in S join with a tuple in R
  - unnecessary shipping
  - solution: Semi-join



3. Semijoin -1/2

- Suppose want to ship R to London and then do join with S at London. Instead,

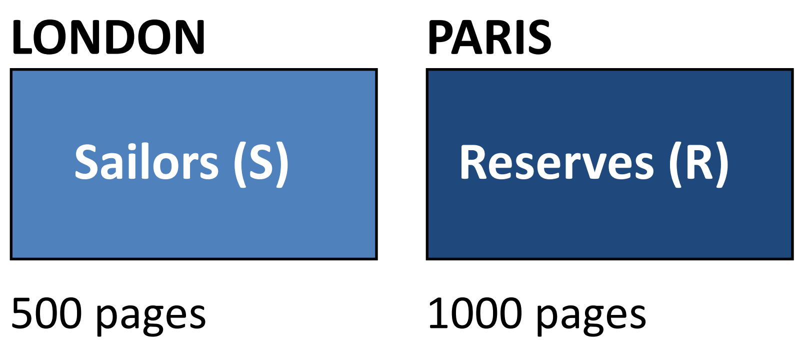
1. At London, project S onto join columns and ship this to Paris
   - Here foreign keys, but could be arbitrary join
2. At Paris, join S-projection with R
   - Result is called reduction of Reserves w.r.t. Sailors (only these tuples are needed)
3. Ship reduction of R to back to London
4. At London, join S with reduction of R



3. Semijoin – 2/2

End of Lecture 18

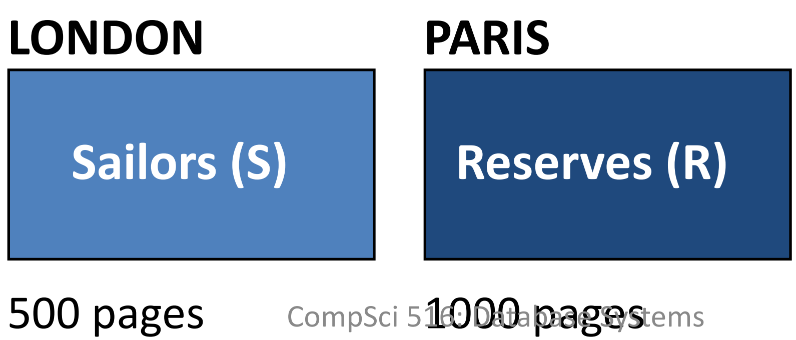
- Tradeoff the cost of computing and shipping projection for cost of shipping full R relation
- Especially useful if there is a selection on Sailors, and answer desired at London



4. Bloomjoin – 1/4

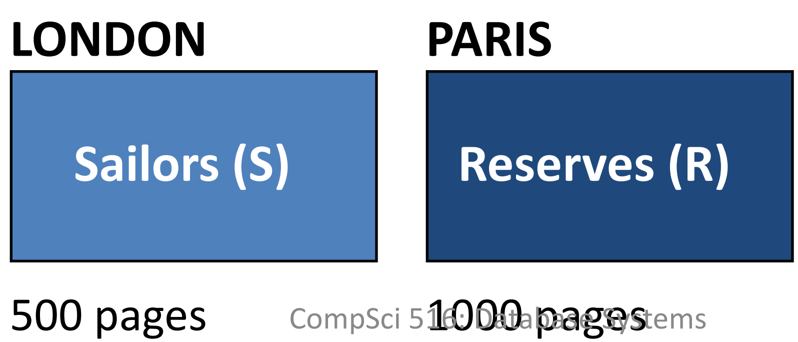
Start of Lecture 19

- Similar idea like semi-join
- Suppose want to ship R to London and then do join with S at London (like semijoin)



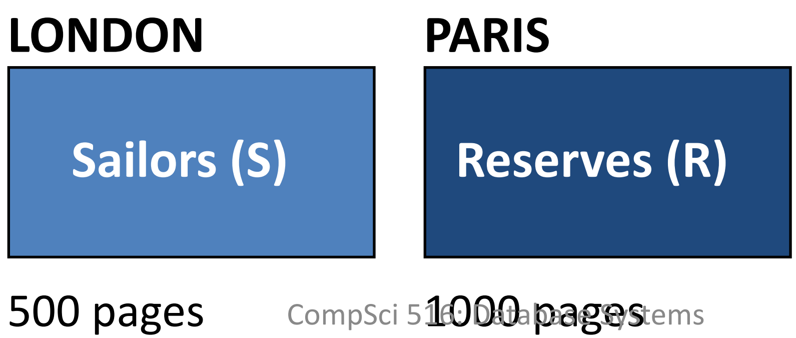
4. Bloomjoin – 2/4

1. At London, compute a bit-vector of some size k:
   – Hash column values into range 0 to k-1
   – If some tuple hashes to p, set bit p to 1 (p from 0 to k-1)
   – Ship bit-vector to Paris
2. At Paris, hash each tuple of R similarly
   – discard tuples that hash to 0 in S’s bit-vector
   – Result is called reduction of R w.r.t S



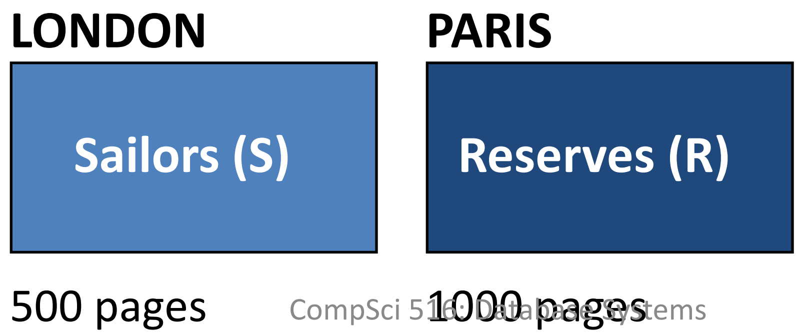
4. Bloomjoin – 3/4

3. Ship "bit-vector-reduced" R to London
4. At London, join S with reduced R



4. Bloomjoin – 4/4

- Bit-vector cheaper to ship, almost as effective
  - the size of the reduction of R shipped back can be larger. Why?



Distributed Query Optimization

- Cost-based approach
  - consider all plans
  - pick cheapest

- Similar to centralized optimization, but have differences
  1. Communication costs must be considered
  2. Local site autonomy must be respected
  3. New distributed join methods

- Query site constructs global plan, with suggested local plans describing processing at each site
  - If a site can improve suggested local plan, free to do so

Distributed transactions

Updating Distributed Data

Synchronous

Asynchronous

Updating distributed data

- Classical view says that it should be the same as a centralized DBMS from user's viewpoint and addressed at implementation level
- so far, we had this w.r.t. "queries"
- w.r.t "updates", this means transactions should be atomic regardless of data fragmentation and replication
- But there are other alternatives too

Updating Distributed Data

- Synchronous Replication: All copies of a modified relation (or fragment) must be updated before the modifying transaction commits
  - Data distribution is made "transparent" (not visible!) to users

- Asynchronous Replication: Copies of a modified relation are only periodically updated; different copies may get out of sync in the meantime
  - Users must be aware of data distribution
  - More efficient – many current products follow this approach

Synchronous Replication

- Voting: transaction must write a majority of copies to modify an object; must read enough copies to be sure of seeing at least one most recent copy
  - E.g., 10 copies; 7 written for update; 4 copies read (why 4?)
  - Each copy has version number – copy with the highest version number is current
  - Not attractive usually because reads are common
- Read-any Write-all: Read any copy, Write all copies
  - Writes are slower and reads are faster, relative to Voting
  - Most common approach to synchronous replication
  - A special case of voting (why?)
- Choice of technique determines which locks to set

Cost of Synchronous Replication

- Before an update transaction can commit, it must obtain locks on all modified copies
  - Sends lock requests to remote sites, and while waiting for the response, holds on to other locks
  - If sites or links fail, transaction cannot commit until they are back up
  - Even if there is no failure, committing must follow an expensive commit protocol with many messages (later)

- So the alternative of asynchronous replication is becoming widely used

Asynchronous Replication

- Allows modifying transaction to commit before all copies have been changed
  - readers nonetheless look at just one copy
  - Users must be aware of which copy they are reading, and that copies may be out-of-sync for short periods of time
- Two approaches: Primary Site and Peer-to-Peer replication
  - Difference lies in how many copies are “updatable" or “master copies"

Primary Site Replication

- Exactly one copy of a relation is designated the primary or master copy
  - Replicas at other sites cannot be directly updated
  - The primary copy is published
  - Other sites subscribe to this relation (or its fragments)
  - These are secondary copies
- How are changes to the primary copy propagated to the secondary copies?
  - Done in two steps
  - First, “capture” changes made by committed transactions
  - Then, “apply” these changes
    - more details in the [RG] book (optional reading)

Peer-to-Peer Replication

- More than one of the copies of an object can be a master
- Changes to a master copy must be propagated to other copies somehow
- If two master copies are changed in a conflicting manner, conflict resolution needed
  - e.g., Site 1: Joe's age changed to 35; Site 2: to 36
- Best used when conflicts do not arise:
  - E.g., Each master site owns a disjoint fragment
  - E.g., Updating rights held by one master at a time – then propagated to other sites

Distributed Transactions

Distributed CC
Distributed Recovery

Distributed Transactions

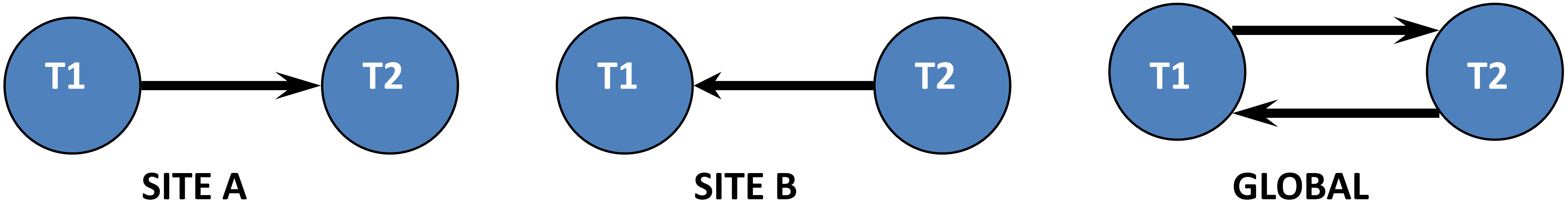
- Distributed CC
  - How can locks for objects stored across several sites be managed?
  - How can deadlocks be detected in a distributed database?
- Distributed Recovery
  - When a transaction commits, all its actions, across all the sites at which is executes must persist
  - When a transaction aborts, none of its actions must be allowed to persist

Distributed Locking

- How do we manage locks for objects across many sites?

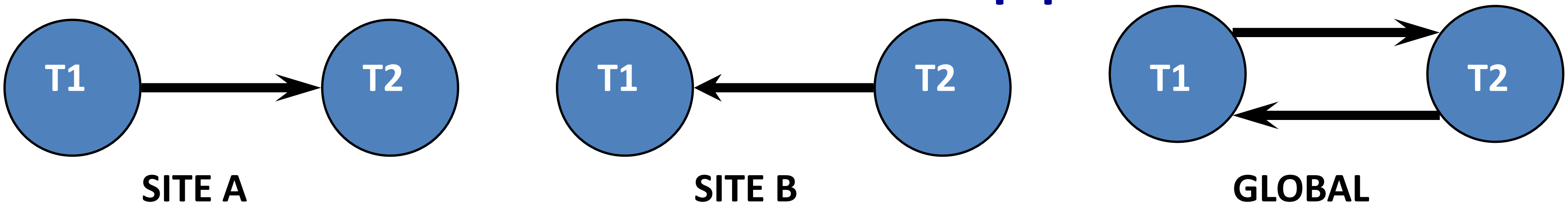
1. Centralized: One site does all locking
   - Vulnerable to single site failure
2. Primary Copy: All locking for an object done at the primary copy site for this object
   - Reading requires access to locking site as well as site where the object copy is stored
3. Fully Distributed: Locking for a copy done at site where the copy is stored
   - Locks at all sites while writing an object (unlike previous two)

Distributed Deadlock Detection



- Each site maintains a local waits-for graph
- A global deadlock might exist even if the local graphs contain no cycles
- Further, phantom deadlocks may be created while communicating
  - due to delay in propagating local information
  - might lead to unnecessary aborts

Three Distributed Deadlock Detection Approaches



1. Centralized
   - send all local graphs to one site periodically
   - A global waits-for graph is generated
2. Hierarchical
   - organize sites into a hierarchy and send local graphs to parent in the hierarchy
   - e.g. sites (every 10 sec)-> sites in a state (every min)-> sites in a country (every 10 min) -> global waits for graph
   - intuition: more deadlocks are likely across closely related sites
3. Timeout
   - abort transaction if it waits too long (low overhead)

Distributed Recovery

- Two new issues:
  - New kinds of failure, e.g., links and remote sites
  - If “sub-transactions” of a transaction execute at different sites, all or none must commit
  - Need a commit protocol to achieve this
  - Most widely used: Two Phase Commit (2PC)

- A log is maintained at each site
  - as in a centralized DBMS
  - commit protocol actions are additionally logged

Two Phase Commit (2PC)

Two-Phase Commit (2PC)

- Site at which transaction originates is coordinator
- Other sites at which it executes are subordinates
  - w.r.t. coordinarion of this transaction

Example on whiteboard

When a transaction wants to commit – 1/5

1. Coordinator sends prepare message to each subordinate

When a transaction wants to commit – 2/5

2. Subordinate receives the prepare message
   a) decides whether to abort or commit its subtransaction
   b) force-writes an abort or prepare log record
   c) then sends a no or yes message to coordinator

When a transaction wants to commit – 3/5

3. If coordinator gets unanimous yes votes from all subordinates
   a) it force-writes a commit log record
   b) then sends commit message to all subs

Else (if receives a no message or no response from some subordinate),

   a) it force-writes abort log record
   b) then sends abort messages

When a transaction wants to commit – 4/5

4. Subordinates force-write abort/commit log record based on message they get
   a) then send ack message to coordinator
   b) If commit received, commit the subtransaction
   c) write an end record

When a transaction wants to commit – 5/5

5. After the coordinator receives ack from all subordinates,
   – writes end log record

Transaction is officially committed when the coordinator’s commit log record reaches the disk

– subsequent failures cannot affect the outcomes

Comments on 2PC

- Two rounds of communication
  - first, voting
  - then, termination
  - Both initiated by coordinator
- Any site (coordinator or subordinate) can unilaterially decide to abort a transaction
  - but unanimity/consensus needed to commit
- Every message reflects a decision by the sender
  - to ensure that this decision survives failures, it is first recorded in the local log and is force-written to disk
- All commit protocol log records for a transaction contain tid and Coordinator-id
  - The coordinator's abort/commit record also includes ids of all subordinates.

Restart After a Failure at a Site – 1/4

- Recovery process is invoked after a sites comes back up after a crash
  - reads the log and executes the commit protocol
  - the coordinator or a subordinate may have a crash
  - one site can be the coordinator some transaction and subordinates for others

Restart After a Failure at a Site – 2/4

- If we have a commit or abort log record for transaction T, but not an end record, must redo/undo T respectively
  - If this site is the coordinator for T (from the log record), keep sending commit/abort messages to subs until acks received
  - then write an end log record for T

Restart After a Failure at a Site – 3/4

- If we have a prepare log record for transaction T, but not commit/abort
  - This site is a subordinate for T
  - Repeatedly contact the coordinator to find status of T
  - Then write commit/abort log record
  - Redo/undo T
  - and write end log record

Restart After a Failure at a Site – 4/4

- If we don't have even a prepare log record for T
  - T was not voted to commit before crash
  - unilaterally abort and undo T
  - write an end record
- No way to determine if this site is the coordinator or subordinate
  - If this site is the coordinator, it might have sent prepare messages
  - then, subs may send yes/no message – coordinator is detected – ask subordinates to abort

Blocking

- If coordinator for transaction T fails, subordinates who have voted yes cannot decide whether to commit or abort T until coordinator recovers.
  - T is blocked
  - Even if all subordinates know each other (extra overhead in prepare message) they are blocked unless one of them voted no
- Note: even if all subs vote yes, the coordinator then can give a no vote, and decide later to abort!

Link and Remote Site Failures

- If a remote site does not respond during the commit protocol for transaction T, either because the site failed or the link failed:
  - If the current site is the coordinator for T, should abort T
  - If the current site is a subordinate, and has not yet voted yes, it should abort T
  - If the current site is a subordinate and has voted yes, it is blocked until the coordinator responds
  - needs to periodically contact the coordinator until receives a reply

Observations on 2PC

- Ack messages used to let coordinator know when it can “forget” a transaction; until it receives all acks, it must keep T in the transaction Table
- If coordinator fails after sending prepare messages but before writing commit/abort log records, when it recovers, it aborts the transaction
- If a subtransaction does no updates, its commit or abort status is irrelevant

Other variants of 2PC

- 2PC with presumed abort
  - When coordinator aborts T, it undoes T and removes it from the transaction Table immediately (presumes abort). Doesn't wait for acks
- 3PC
  - prepare->precommit -> commit
- Not covered in class
  - discussed in the book