Principles of Distributed Database Systems

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Outline

- Introduction
- Distributed and parallel database design
- Distributed data control
- Distributed Transaction Processing
- Data Replication
- Database Integration – Multidatabase Systems
- Parallel Database Systems
- Peer-to-Peer Data Management
- Big Data Processing
- NoSQL, NewSQL and Polystores
- Web Data Management

Outline

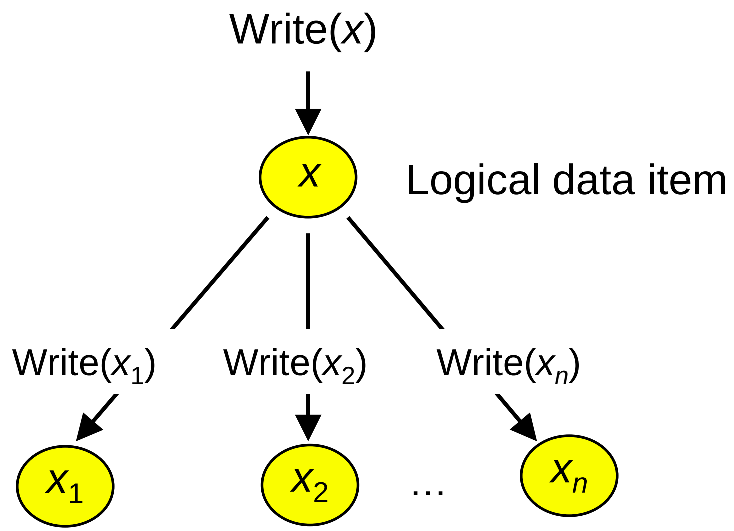
- Data Replication
  - Consistency criteria
  - Update Management Strategies
  - Replication Protocols
  - Replication and Failure Management

Replication

- Why replicate?
  - System availability
    - Avoid single points of failure
  - Performance
    - Localization
  - Scalability
    - Scalability in numbers and geographic area
  - Application requirements
- Why not replicate?
  - Replication transparency
  - Consistency issues
    - Updates are costly
    - Availability may suffer if not careful

Execution Model

- There are physical copies of logical objects in the system.
- Operations are specified on logical objects, but translated to operate on physical objects.
- One-copy equivalence
  - Transaction effects on replicated objects should be the same as if they had been performed on a single set of objects.



Physical data item (replicas, copies)

Replication Issues

- Consistency models - how do we reason about the consistency of the “global execution state”?
  - Mutual consistency
  - Transactional consistency
- Where are updates allowed?
  - Centralized
  - Distributed
- Update propagation techniques – how do we propagate updates to one copy to the other copies?
  - Eager
  - Lazy

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Consistency

- Mutual Consistency
  - How do we keep the values of physical copies of a logical data item synchronized?
  - Strong consistency
    - All copies are updated within the context of the update transaction
    - When the update transaction completes, all copies have the same value
    - Typically achieved through 2PC
  - Weak consistency
    - Eventual consistency: the copies are not identical when update transaction completes, but they eventually converge to the same value
    - Many versions possible:
      - Time-bounds
      - Value-bounds
      - Drifts

Transactional Consistency

- How can we guarantee that the global execution history over replicated data is serializable?
- One-copy serializability (1SR)
  - The effect of transactions performed by clients on replicated objects should be the same as if they had been performed *one at-a-time* on a single set of objects.
- Weaker forms are possible
  - Snapshot isolation
  - RC-serializability

Example 1

Site A	Site B	Site C
x	x, y	x, y, z

T_1: $x \leftarrow 20$
Write(x)
Commit

T_2: Read(x)
$x \leftarrow x+y$
Write(y)
Commit

T_3: Read(x)
Read(y)
$z \leftarrow (x*y)/100$
Write(z)
Commit

Consider the three histories:

$H_A=\{W_1(x_A), C_1\}$
$H_B=\{W_1(x_B), C_1, R_2(x_B), W_2(y_B), C_2\}$
$H_C=\{W_2(y_C), C_2, \mathrm{R}_3(x_C), R_3(y_C), W_3(z_C), C_3, W_1(x_C), C_1\}$

Global history non-serializable: H_B: $T_1 \rightarrow T_2$, H_C: $T_2 \rightarrow T_3 \rightarrow T_1$

Mutually consistent: Assume $x_A=x_B=x_C=10$, $y_B=y_C=15$, $y_C=7$ to begin; in the end $x_A=x_B=x_C=20$, $y_B=y_C=35$, $y_C=3.5$

Example 2

Site A		Site B	
	x		x
T_1:	Read(x) $x \leftarrow x+5$ Write(x) Commit	T_2:	Read(x) $x \leftarrow x*10$ Write(x) Commit

Consider the two histories:

$$H_A=\{R_1(x_A), W_1(x_A), C_1, R_2(x_A), W_2(x_A), C_2\}$$
$$H_B=\{R_2(x_B), W_2(x_B), C_2, R_1(x_B), W_1(x_B), C_1\}$$

Global history non-serializable: H_A: $T_1 \rightarrow T_2$, H_B: $T_2 \rightarrow T_1$

Mutually inconsistent: Assume $x_A=x_B=1$ to begin; in the end $x_A=15$, $x_B=60$

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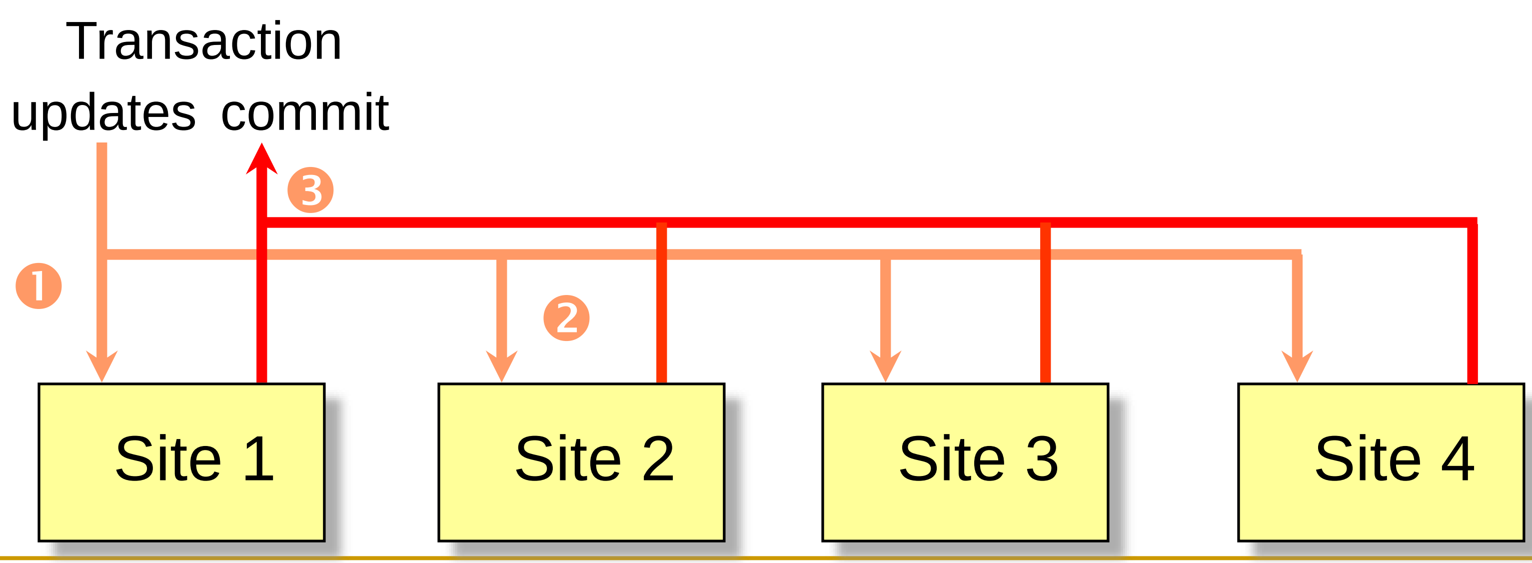
Update Management Strategies

- Depending on when the updates are propagated
  - Eager
  - Lazy
- Depending on where the updates can take place
  - Centralized
  - Distributed

	Centralized	**Distributed**
Eager		
Lazy		

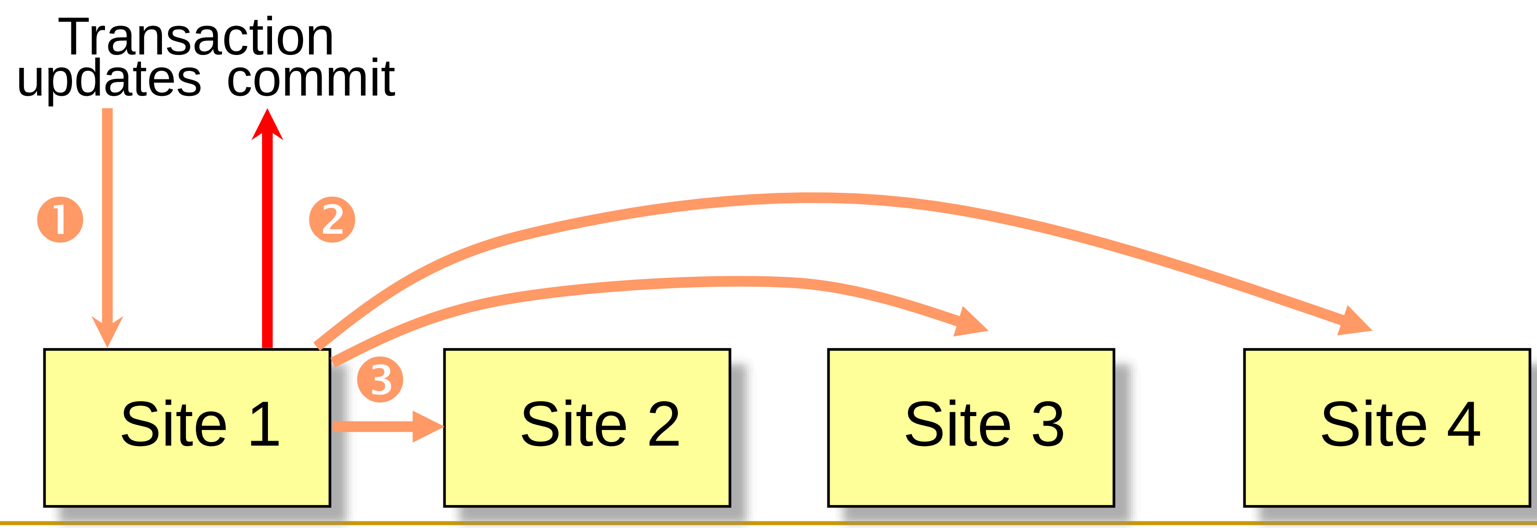
Eager Replication

- Changes are propagated within the scope of the transaction making the changes. The ACID properties apply to all copy updates.
  - Synchronous
  - Deferred
- ROWA protocol: Read-one/Write-all



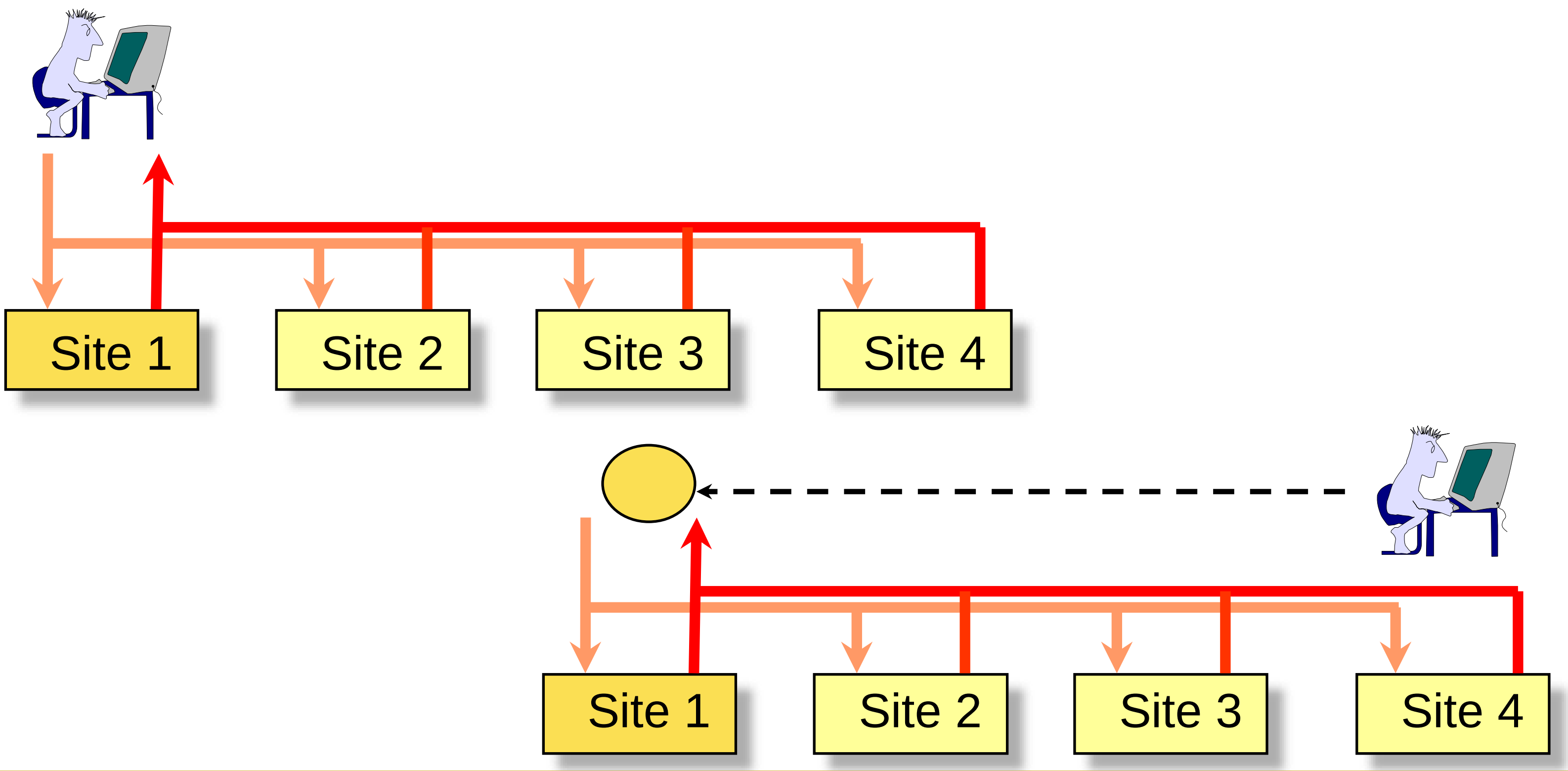
Lazy Replication

- Lazy replication first executes the updating transaction on one copy. After the transaction commits, the changes are propagated to all other copies (refresh transactions)
- While the propagation takes place, the copies are mutually inconsistent.
- The time the copies are mutually inconsistent is an adjustable parameter which is application dependent.



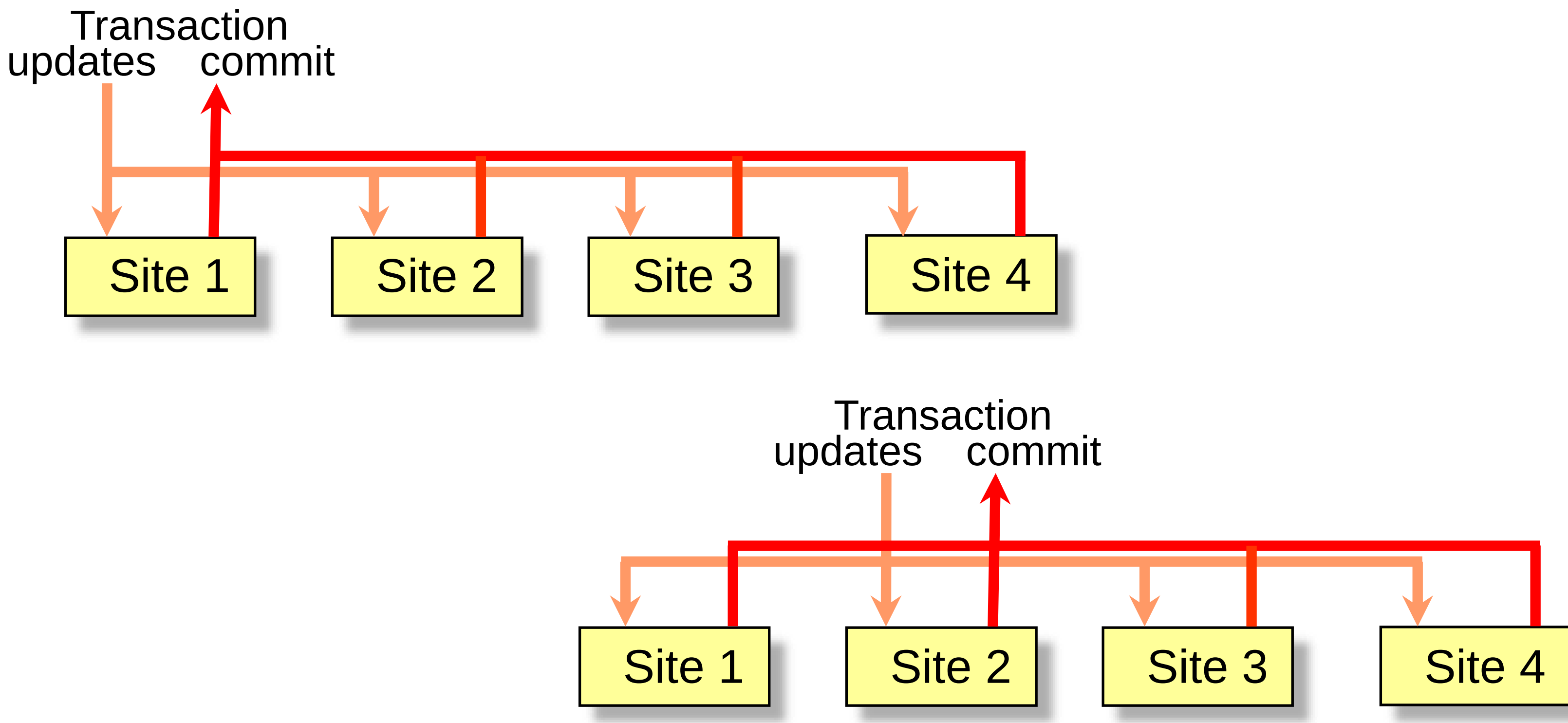
Centralized

- There is only one copy which can be updated (the master), all others (slave copies) are updated reflecting the changes to the master.



Distributed

- Changes can be initiated at any of the copies. That is, any of the sites which owns a copy can update the value of the data item.



Forms of Replication

Eager

+ No inconsistencies (identical copies)
+ Reading the local copy yields the most up to date value
+ Changes are atomic
− A transaction has to update all sites
  − Longer execution time
  − Lower availability

Lazy

+ A transaction is always local (good response time)
− Data inconsistencies
− A local read does not always return the most up-to-date value
− Changes to all copies are not guaranteed
− Replication is not transparent

Centralized

+ No inter-site synchronization is necessary (it takes place at the master)
+ There is always one site which has all the updates
− The load at the master can be high
− Reading the local copy may not yield the most up-to-date value

Distributed

+ Any site can run a transaction
+ Load is evenly distributed
− Copies need to be synchronized

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Replication Protocols

The previous ideas can be combined into 4 different replication protocols:

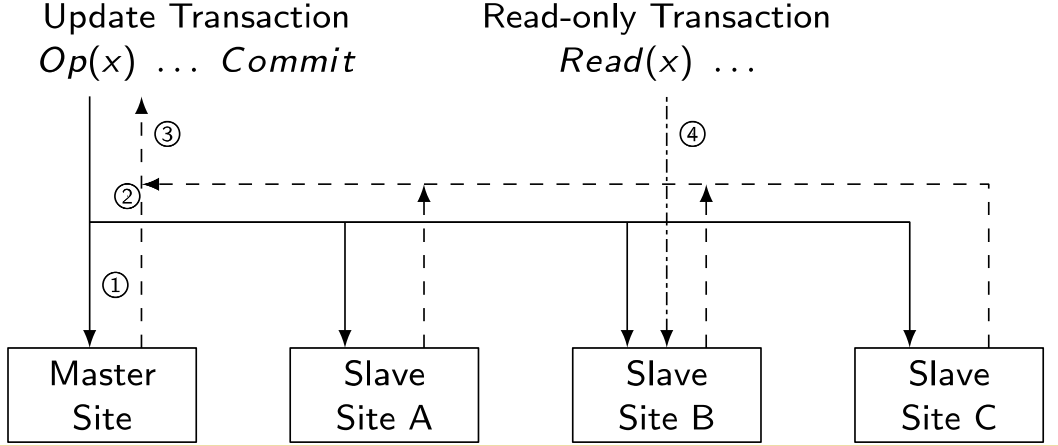
	Centralized	Distributed
Eager	Eager centralized	Eager distributed
Lazy	Lazy centralized	Lazy distributed

Eager Centralized Protocols

- Design parameters:
  - Distribution of master
    - Single master: one master for all data items
    - Primary copy: different masters for different (sets of) data items
  - Level of transparency
    - Limited: applications and users need to know who the master is
      - Update transactions are submitted directly to the master
      - Reads can occur on slaves
    - Full: applications and users can submit anywhere, and the operations will be forwarded to the master
      - Operation-based forwarding
- Four alternative implementation architectures, only three are meaningful:
  - Single master, limited transparency
  - Single master, full transparency
  - Primary copy, full transparency

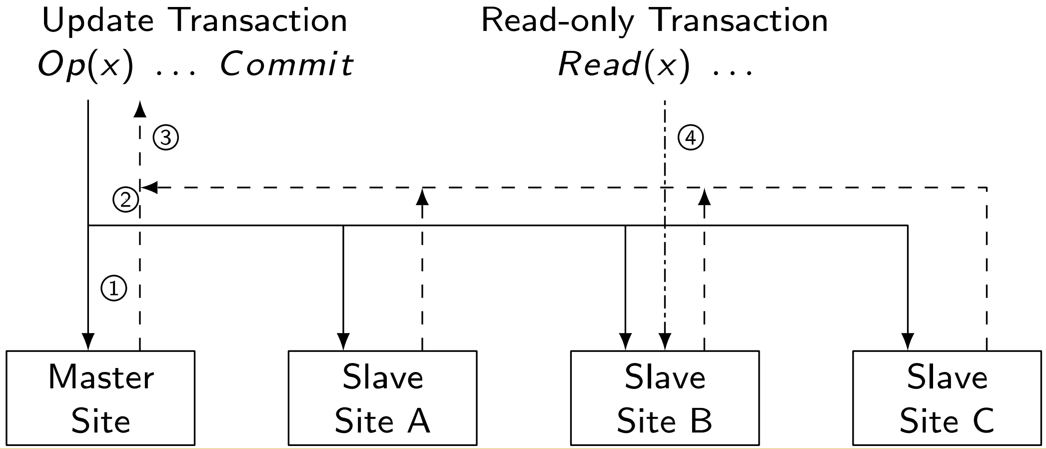
Eager Single Master/Limited Transparency

- Applications submit update transactions directly to the master
- Master:
  - Upon read: read locally and return to user
  - Upon write: write locally, multicast write to other replicas (in FFO timestamps order)
  - Upon commit request: run 2PC coordinator to ensure that all have really installed the changes
  - Upon abort: abort and inform other sites about abort
- Slaves install writes that arrive from the master



Eager Single Master/Limited Transparency (cont'd)

- Applications submit read transactions directly to an appropriate slave
- Slave
  - Upon read: read locally
  - Upon write from master copy: execute conflicting writes in the proper order (FIFO or timestamp)
  - Upon write from client: refuse (abort transaction; there is error)
  - Upon commit request from read-only: commit locally
  - Participant of 2PC for update transaction running on primary



Eager Single Master/Full Transparency

Applications submit all transactions to the Transaction Manager at their own sites (Coordinating TM)

<u>Coordinating TM</u>

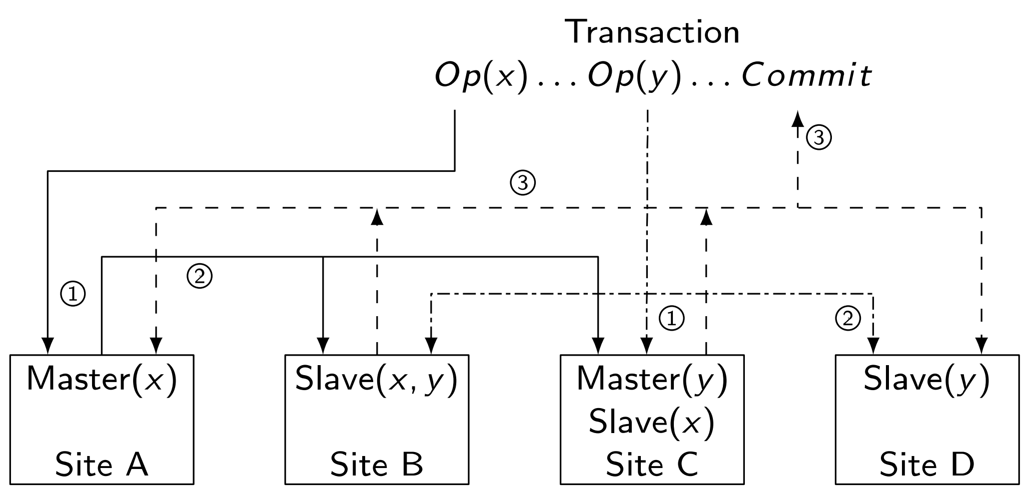
1. Send *op*(*x*) to the master site
2. Send *Read*(*x*) to any site that has *x*
3. Send *Write*(*x*) to all the slaves where a copy of *x* exists
4. When Commit arrives, act as coordinator for 2PC

<u>Master Site</u>

1. If *op*(*x*) = *Read*(*x*): set read lock on *x* and send "lock granted" msg to the coordinating TM
2. If *op*(*x*) = *Write*(*x*)
   1. Set write lock on *x*
   2. Update local copy of *x*
   3. Inform coordinating TM
3. Act as participant in 2PC

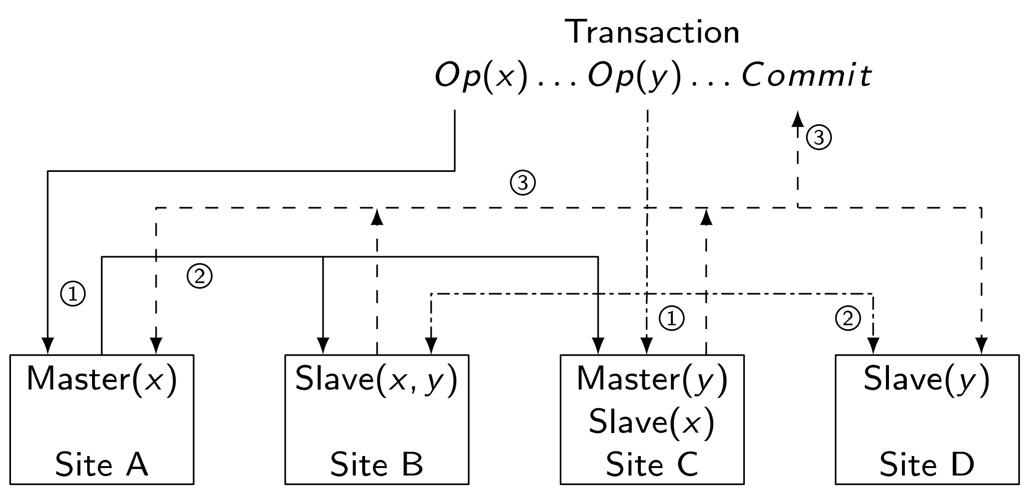
Eager Primary Copy/Full Transparency

- Applications submit transactions directly to their local TMs
- Local TM:
  - Forward each operation to the primary copy of the data item
  - Upon granting of locks, submit Read to any slave, Write to all slaves
  - Coordinate 2PC



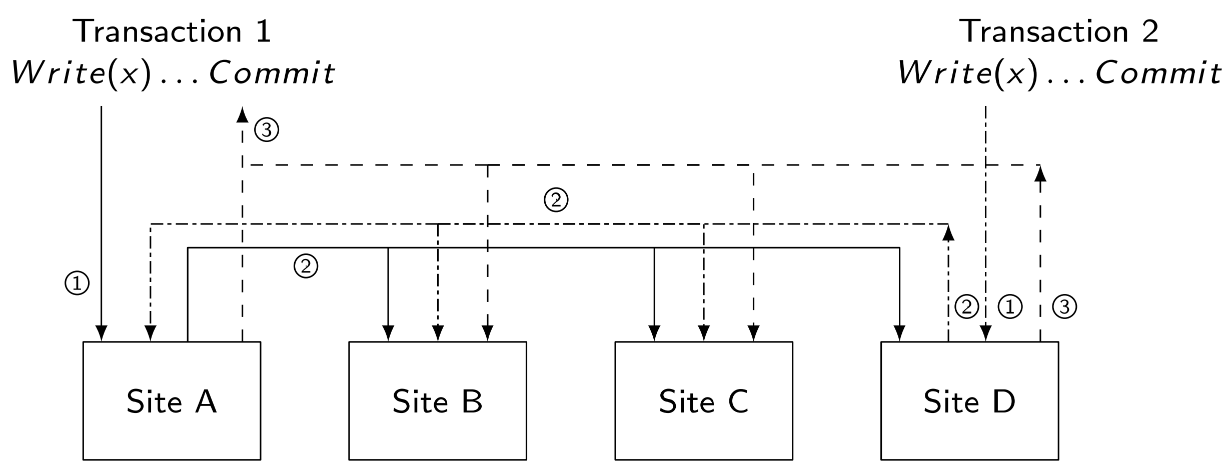
Eager Primary Copy/Full Transparency (cont'd)

- Primary copy site
  - Read(*x*): lock *x*and reply to TM
  - Write(*x*): lock *x*, perform update, inform TM
  - Participate in 2PC
- Slaves: as before



Eager Distributed Protocol

- Updates originate at any copy
  - Each sites uses 2 phase locking.
  - Read operations are performed locally.
  - Write operations are performed at all sites (using a distributed locking protocol).
  - Coordinate 2PC
- Slaves:
  - As before

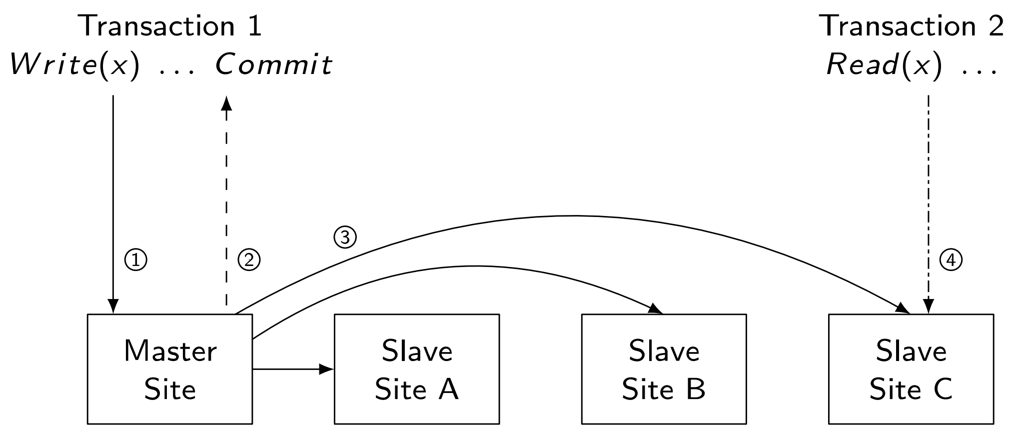


Eager Distributed Protocol (cont'd)

- Critical issue:
  - Concurrent Writes initiated at different master sites are executed in the same order at each slave site
  - Local histories are serializable (this is easy)
- Advantages
  - Simple and easy to implement
- Disadvantage
  - Very high communication overhead
    - *n* replicas; *m* update operations in each transaction: *n***m* messages (assume no multicasting)
    - For throughput of *k* tps: *k** *n***m* messages
- Alternative
  - Use group communication + deferred update to slaves to reduce messages

Lazy Single Master/Limited Transparency

- Update transactions submitted to master
- Master:
  - Upon read: read locally and return to user
  - Upon write: write locally and return to user
  - Upon commit/abort: terminate locally
  - Sometime after commit: multicast updates to slaves (in order)
- Slaves:
  - Upon read: read locally
  - Refresh transactions: install updates



Lazy Primary Copy/Limited Transparency

- There are multiple masters; each master execution is similar to lazy single master in the way it handles transactions
- Slave execution complicated: refresh transactions from multiple masters and need to be ordered properly

Lazy Primary Copy/Limited Transparency – Slaves

- Assign system-wide unique timestamps to refresh transactions and execute them in timestamp order
  - May cause too many aborts
- Replication graph
  - Similar to serialization graph, but nodes are transactions (*T*) + sites (*S*); edge $\langle T_i, S_j \rangle$ exists iff T_i performs a Write(*x*) and *x* is stored in S_j
  - For each operation (op_k), enter the appropriate nodes (T_k) and edges; if graph has no cycles, no problem
  - If cycle exists and the transactions in the cycle have been committed at their masters, but their refresh transactions have not yet committed at slaves, abort T_k; if they have not yet committed at their masters, T_k waits.
- Use group communication

Lazy Single Master/Full Transparency

- This is very tricky
  - Forwarding operations to a master and then getting refresh transactions cause difficulties
- Two problems:
  - Violation of 1SR behavior
  - A transaction may not see its own reads
- Problem arises in primary copy/full transparency as well

Example 3

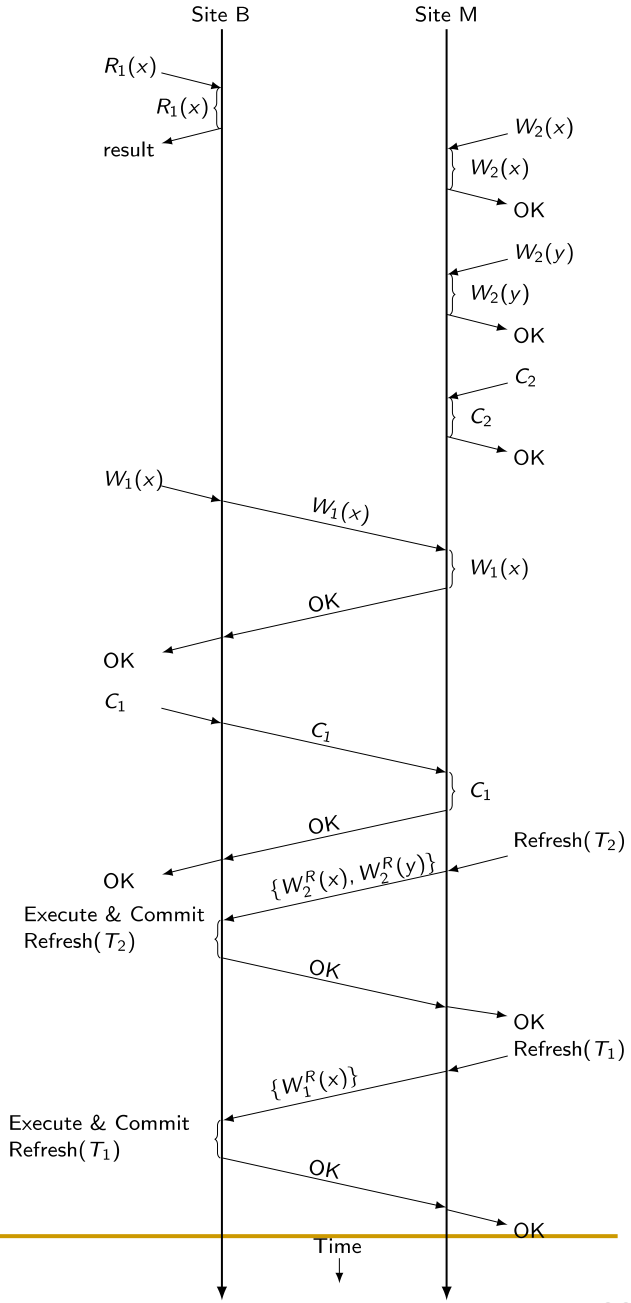
Site M (Master) holds x, y; SiteB holds slave copies of x, y

T_1: Read(x), Write(y), Commit

T_2: Read(x), Write(y), Commit

$$H_M = \{W_2(x_M), W_2(y_M), C_2, W_1(y_M), C_1\}$$

$$H_B = \{R_1(x_B), C_1, W_2^R(x_B), W_2^R(y_B), C_2^R, W_1^R(x_B), C_1^R\}$$



Example 4

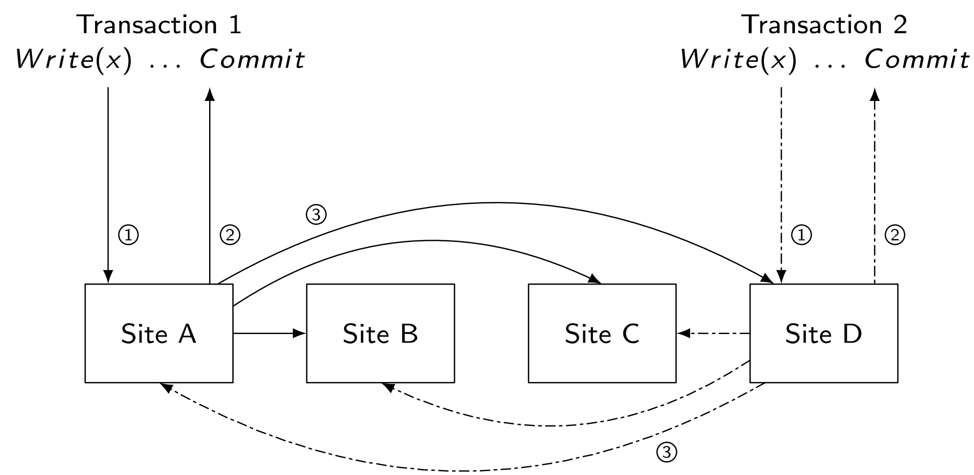
- Master site *M* holds *x*, site *C* holds slave copy of *x*
- T_3: Write(*x*), Read(*x*), Commit
- Sequence of execution
  1. $W_3(x)$ submitted at *C*, forwarded to *M* for execution
  2. $W_3(x)$ is executed at *M*, confirmation sent back to *C*
  3. $R_3(x)$ submitted at *C* and executed on the local copy
  4. T_3 submits Commit at *C*, forwarded to *M* for execution
  5. *M* executes Commit, sends notification to *C*, which also commits T_3
  6. *M* sends refresh transaction for T_3 to *C* (for $W_3(x)$ operation)
  7. *C* executes the refresh transaction and commits it
- When *C* reads *x* at step 3, it does not see the effects of Write at step 2

Lazy Single Master/ Full Transparency - Solution

- Assume T = Write(x)
- At commit time of transaction T, the master generates a timestamp for it [$ts(T)$]
- Master sets $last\_modified(x_M) \leftarrow ts(T)$
- When a refresh transaction arrives at a slave site i, it also sets $last\_modified(x_i) \leftarrow last\_modified(x_M)$
- Timestamp generation rule at the master:
  - $ts(T)$ should be greater than all previously issued timestamps and should be less than the *last_modified* timestamps of the data items it has accessed. If such a timestamp cannot be generated, then T is aborted.

Lazy Distributed Replication

- Any site:
  - Upon read: read locally and return to user
  - Upon write: write locally and return to user
  - Upon commit/abort: terminate locally
  - Sometime after commit: send refresh transaction
  - Upon message from other site
    - Detect conflicts
    - Install changes
    - Reconciliation may be necessary



Reconciliation

- Such problems can be solved using pre-arranged patterns:
  - Latest update win (newer updates preferred over old ones)
  - Site priority (preference to updates from headquarters)
  - Largest value (the larger transaction is preferred)
- Or using ad-hoc decision making procedures:
  - Identify the changes and try to combine them
  - Analyze the transactions and eliminate the non-important ones
  - Implement your own priority schemas

Replication Strategies

	Centralized	Distributed
Eager	+ Updates do not need to be coordinated + No inconsistencies - Longest response time - Only useful with few updates - Local copies are can only be read	+ No inconsistencies + Elegant (symmetrical solution) - Long response times - Updates need to be coordinated
Lazy	+ No coordination necessary + Short response times - Local copies are not up to date - Inconsistencies	+ No centralized coordination + Shortest response times - Inconsistencies - Updates can be lost (reconciliation)

Group Communication

- A node can multicast a message to all nodes of a group with a delivery guarantee
- Multicast primitives
  - There are a number of them
  - Total ordered multicast: all messages sent by different nodes are delivered in the same total order at all the nodes
- Used with deferred writes, can reduce communication overhead
  - Remember eager distributed requires *k*m* messages (with multicast) for throughput of *k*tps when there are *n* replicas and *m* update operations in each transaction
  - With group communication and deferred writes: 2*k* messages

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Failures

- So far we have considered replication protocols in the absence of failures
- How to keep replica consistency when failures occur
  - Site failures
    - Read One Write All Available (ROWAA)
  - Communication failures
    - Quorums
  - Network partitioning
    - Quorums

ROWAA with Primary Site

- READ = read any copy, if time-out, read another copy.
- WRITE = send *W*(*x*) to all copies. If one site rejects the operation, then abort. Otherwise, all sites not responding are "missing writes".
- VALIDATION = To commit a transaction
  - Check that all sites in "missing writes" are still down. If not, then abort the transaction.
    - There might be a site recovering concurrent with transaction updates and these may be lost
  - Check that all sites that were available are still available. If some do not respond, then abort.

Distributed ROWAA

- Each site has a copy of *V*
  - *V* represents the set of sites a site believes is available
  - *V*(*A*) is the "view" a site has of the system configuration.
- The view of a transaction *T* [*V*(*T*)] is the view of its coordinating site, when the transaction starts.
  - Read any copy within *V*; update all copies in *V*
  - If at the end of the transaction the view has changed, the transaction is aborted
- All sites must have the same view!
- To modify *V*, run a special atomic transaction at all sites.
  - Take care that there are no concurrent views!
  - Similar to commit protocol.
  - Idea: *V*s have version numbers; only accept new view if its version number is higher than your current one
- Recovery: get missed updates from any active node
  - Problem: no unique sequence of transactions

Quorum-Based Protocol

- Assign a vote to each copy of a replicated object (say V_i) such that $\sum_i V_i = V$
- Each operation has to obtain a read quorum (V_r) to read and a write quorum (V_w) to write an object
- Then the following rules have to be obeyed in determining the quorums:
  - $V_r + V_w > V$ — an object is not read and written by two transactions concurrently
  - $V_w > V/2$ — two write operations from two transactions cannot occur concurrently on the same object