Non-Standard Database Systems

Distributed Databases

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Sommersemester 2020

Version July 10, 2020

Adapted from slides for textbook "Database System Concepts"
by Silberschatz, Korth, Sudarshan
http://codex.cs.yale.edu/avi/db-book/db6/slide-dir/index.html

Introduction

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

Homogeneous vs. Heterogeneous 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

Outline

1. Distributed Data Storage
2. Distributed Transactions
3. Commit Protocols
   - Two Phase Commit (2PC)
   - Three Phase Commit (3PC)
   - Persistent Messaging
4. Concurrency Control
   - Locking
   - Deadlocks
   - Timestamping
   - Weak Consistency
5. Availability

Outline

Distributed Data Storage

- Assume relational data model
- Replication
  - system maintains multiple copies of data, stored in different sites
- 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/1

- A relation or fragment of a relation is replicated if it is stored redundantly in two or more sites.
- Full replication: relation is stored at all sites
- Fully redundant databases: every site contains copy of entire database

Data Replication/2

- Advantages of Replication
  - Availability: failure of site containing relation r does not result in unavailability of r as 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.

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:

$$r = \bigcup_{i=1}^{n} r_i$$

- Vertical fragmentation: schema of relation r is split into several smaller schemas.
  - All schemas must contain a common candidate key to ensure lossless join property.
  - A special attribute, the tuple-id attribute may be added to each schema to serve as a candidate key.
  - Let $sch(r_i) \cap sch(r_j)$ be the candidate key, then $r = r_1 \bowtie r_2 \bowtie \ldots \bowtie r_n$.

Horizontal Fragmentation of *account* Relation

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

Table: $account_1 = \sigma_{branch\_name='Hillside'}(account)$

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

Table: $account_2 = \sigma_{branch\_name='Valleyview'}(account)$

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

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

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

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

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.
  - 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, e.g., site17.account.
  - Fulfills having a unique identifier, and avoids problems associated with central control.
  - However, fails to achieve location 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.

Outline

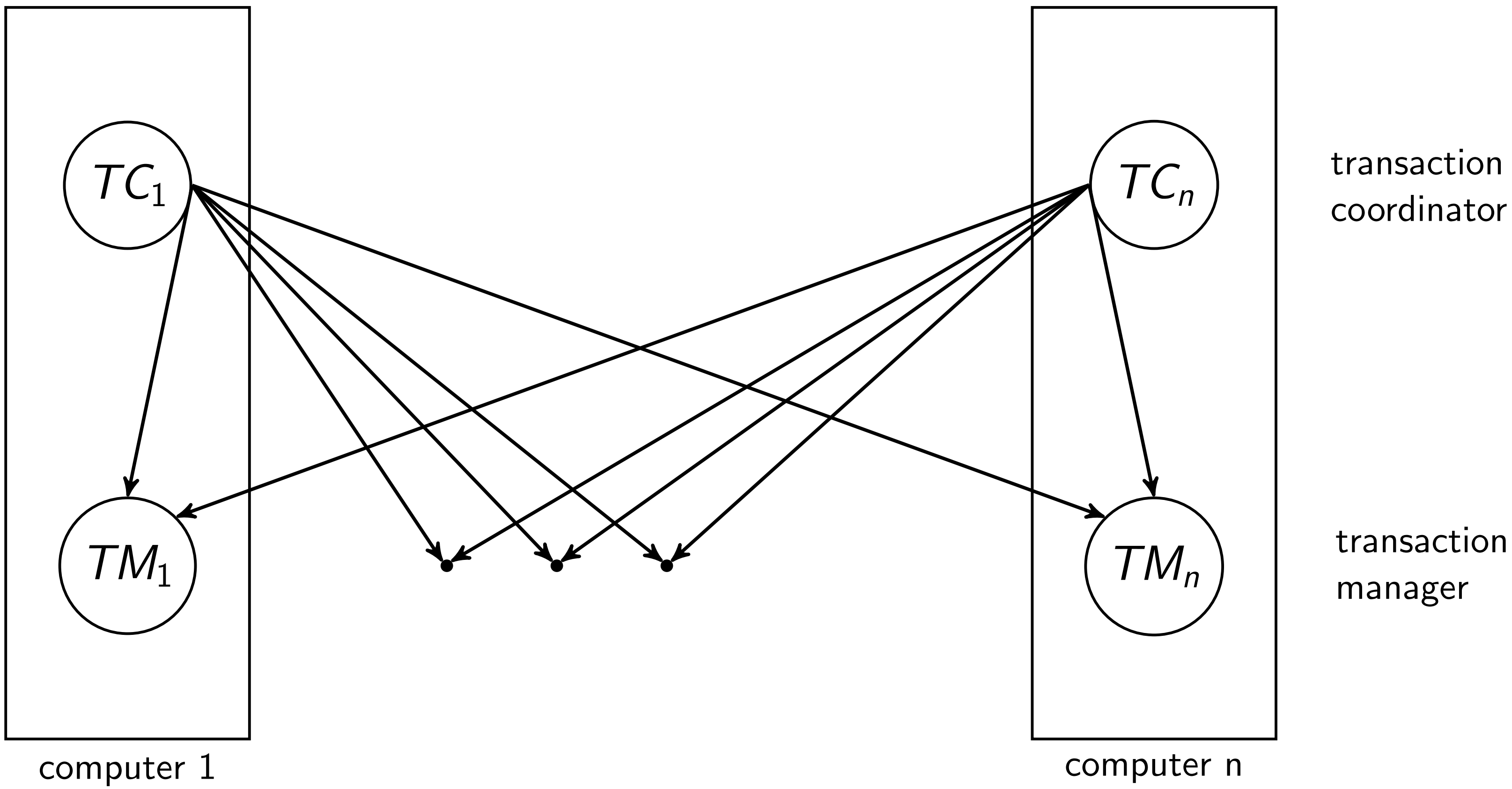
Local and Global Transactions

- Local transaction:
  - Accesses and/or updates data at only one site.
- Global transaction:
  - Accesses and/or updates data at several different sites.
  - Global transactions are split into local subtransactions for execution.

Distributed Transactions

- Each site has:
  - local transaction manager
  - transaction coordinator
- Local transaction manager:
  - ensures ACID for local transactions
  - maintains log for recovery purposes
  - coordinates concurrent execution of local transactions
- Transaction coordinator:
  - starts execution of transactions that originate at the site (local or global)
  - distributes subtransactions to appropriate sites for execution
  - coordinates termination of each transaction that originates at the site: either commit at all sites or aborted at all sites

Transaction System Architecture



System Failure Modes

- Failures unique to distributed systems:
  - site failure:
    - a site is down
  - loss of messages:
    - handled by network transmission control protocols such as TCP-IP
  - communication link failure:
    - handled by network protocols, by routing messages via alternative links
  - network partition:
    - network is split into two or more disconnected subsystems
    - a subsystem may consist of a single node
- Network partitioning and site failures are generally indistinguishable.

Outline

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 C_i asks all participants to prepare to commit transaction T.
  - C_i adds record `<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
  (a) if not, add a record `<abort T>` to the log and send abort T message to C_i
  (b) if the transaction can be committed, then:
    - add the record `<ready T>` to the log and force all records for T to stable storage
    - send ready T message to C_i

Phase 2: Recording the Decision

- T can be committed if 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 `<abort T>`, to the log and forces record onto stable storage. Once the record is on 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_k ($k \neq i$) recovers, it examines its log to determine the fate of transactions active at the time of the failure.

(a) Log contain `<commit T>` record: T had completed

(b) Log contains `<abort T>` record: T had failed

(c) 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, $undo(T)$

(d) The log contains none of the above log records concerning T:
- implies that S_k failed before responding to prepare T message from C_i
- since S_k did not send ready T message, coordinator C_i must have aborted T (or will abort after timeout)
- S_k executes $undo(T)$

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 in the same partition as the coordinator (and the coordinator) think that the sites in the other partitions have failed, and follow the usual commit protocol.
    - No harmful results
  - Sites that are not in the same partition as the coordinator think the coordinator has failed, and execute the protocol to deal with failure of the coordinator.
    - No harmful results, but sites may still have to wait for decision from coordinator.

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 be slow and potentially block recovery.
- Recovery algorithms can note lock information in the log.
  - Instead of `<ready T>`, write out `<ready T, L>`, where 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)/1

- 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: Identical to 2PC Phase 1.
  - Outcome: 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 additional) sites.
  - In Phase 3, coordinator sends commit/abort message to all participating sites.

Three Phase Commit (3PC)/2

- Under 3PC, knowledge of pre-commit decision can be used to commit despite coordinator failure
  - Avoids blocking problem as long as at most K sites fail
- Drawbacks:
  - higher overheads
  - assumptions may not be satisfied in practice

Three Phase Commit (3PC)/3

- Phase 1: Obtaining Preliminary Decision: Identical to 2PC Phase 1.
  - Every site is ready to commit if instructed to do so
  - Under 2PC 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 commit T message to each participant
- Participants take appropriate action locally

3PC: Handling Site Failure/1

- 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 C_i to determine the fate of T.
    - if C_i says T aborted, site executes *undo*(T) (and writes `<abort T>` record)
    - if C_i says T committed, site executes *redo*(T) (and writes `<commit T>` record)
    - if C_i says T pre-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/2

- Log contains `<precommit T>` record, but no `<abort T>` or `<commit T>`: site consults C_i to determine the fate of T.
  - if C_i says T aborted, site executes *undo* (T)
  - if C_i says T committed, site executes *redo* (T)
  - if C_i 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

Alternative Models of Transaction Processing/1

- Single transaction spanning multiple sites may be inappropriate for some 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.
- Persistent messaging systems:
  - provide transactional properties for messages
  - messages are guaranteed to be delivered exactly once

Alternative Models of Transaction Processing/2

- Example: funds transfer between two banks
  - 2PC potentially blocks 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 be 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
- Persistent messaging forms the underlying infrastructure for workflows in a distributed environment

Implementation of Persistent Messaging/1

- 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/2

- 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.
    - 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.

Outline

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 atomicity.
- 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/1

- 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/2

- 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
- Advantage: work is distributed and can be made robust to failures
- Disadvantage: deadlock detection is more complicated
  - Lock managers cooperate for deadlock detection
- 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/1

- 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/2

- 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 $1/3$rd 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
  - Suchthat $Q_r + Q_w > S$ 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 $\geq Q_r$
- Each write must lock enough replicas that the sum of the site weights is $\geq Q_w$
- For now we assume all replicas are written
  - Extensions to allow some sites to be unavailable described later

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:	$write(Y)$
	$write(Y)$		$write(X)$

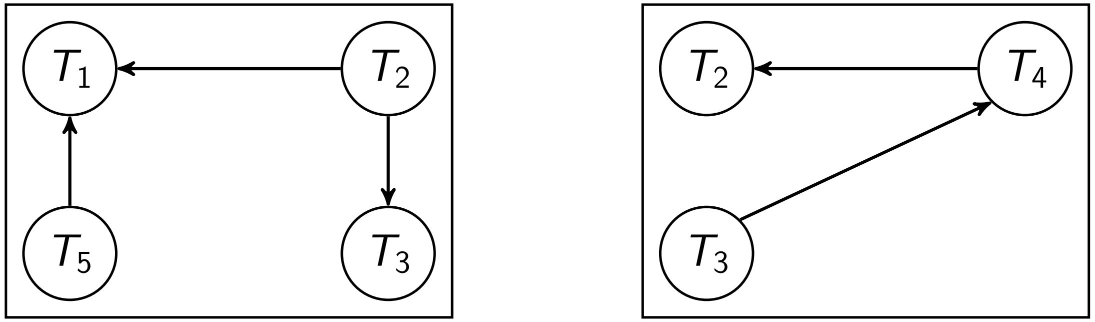
X-*lock* on X	
$write(X)$	X-*lock* on Y
	$write(Y)$
	wait for X-*lock* on X
wait for X-*lock* on Y	

Result: deadlock which cannot be detected locally at either site

Centralized Approach

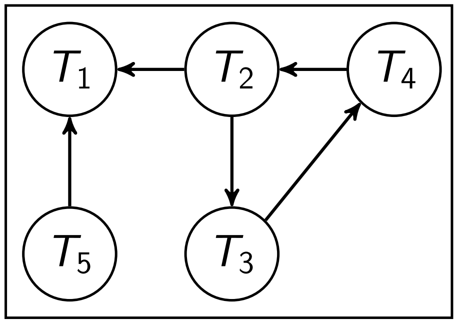
- A global wait-for graph is constructed and maintained in a single site: the deadlock-detection coordinator
  - Real graph: Real, but unknown, state of the system.
  - Constructed graph: Approximation generated by the controller during the execution of its algorithm.
- The global wait-for graph can 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



site S_1 site S_2

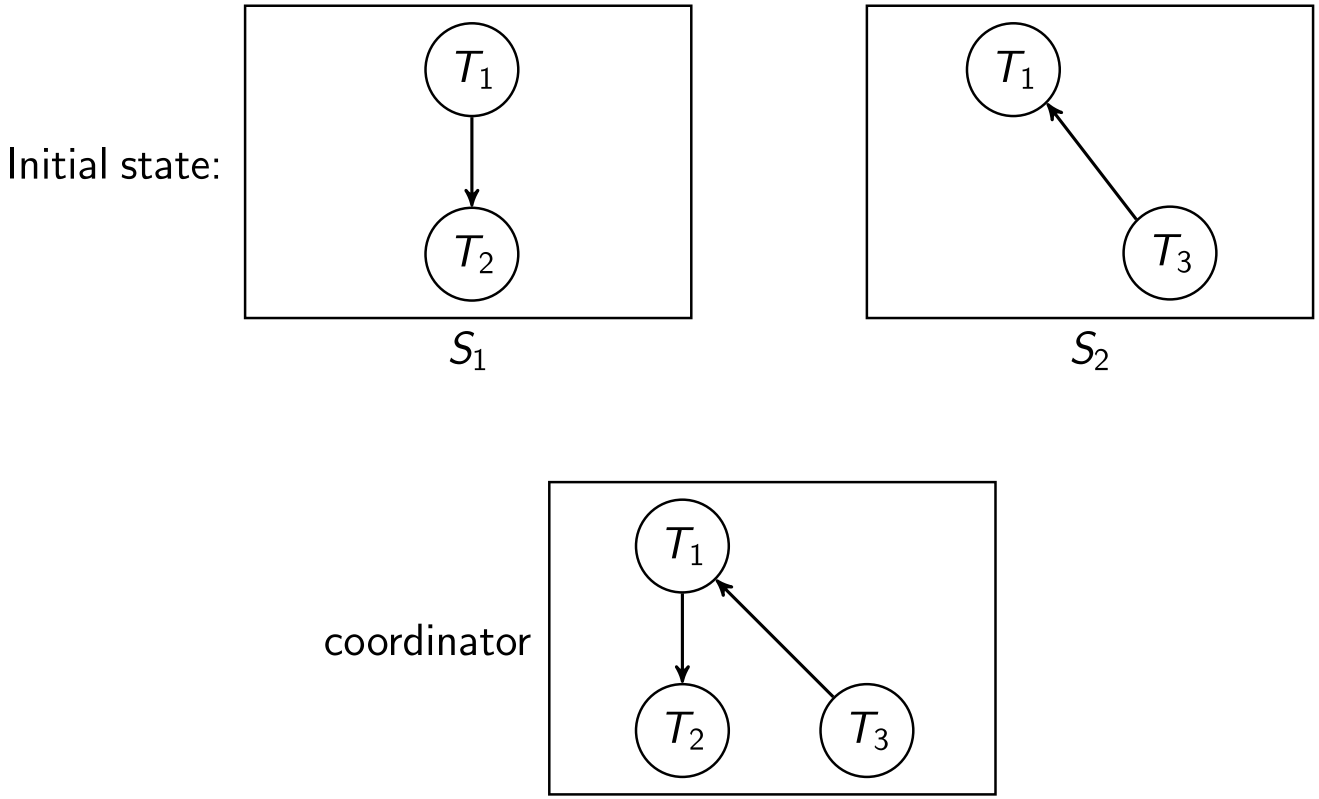
Local



Global

Example Wait-For Graph for False Cycles

Initial state:



False Cycles

- Suppose that starting from the state shown in figure,
  - 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)
  - 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.

Timestamp-Based Protocols/1

- Each transaction is issued a timestamp when it enters the system. If an old transaction T_i has time-stamp $TS(T_i)$, a new transaction T_j is assigned time-stamp $TS(T_j)$ such that $TS(T_i) < TS(T_j)$.
- The protocol manages concurrent execution such that the time-stamps determine the serializability order.
- In order to assure such behavior, the protocol maintains for each data Q two timestamp values:
  - $W\text{-}timestamp(Q)$ is the largest time-stamp of any transaction that executed **write(Q)** successfully.
  - $R\text{-}timestamp(Q)$ is the largest time-stamp of any transaction that executed **read(Q)** successfully.
- The timestamp ordering protocol ensures that any conflicting **read** and **write** operations are executed in timestamp order.

Timestamp-Based Protocols/2

- Transaction T_i issues a **read(Q)**:
  1. If $TS(T_i) < W\text{-}timestamp(Q)$, then T_i needs to read a value of Q that was already overwritten.
     - Hence, the **read** operation is rejected, and T_i is rolled back.
  2. Otherwise the **read** operation is executed, and $R\text{-}timestamp(Q)$ is set to $max(R\text{-}timestamp(Q), TS(T_i))$.
- Transaction T_i issues **write(Q)**:
  1. If $TS(T_i) < R\text{-}timestamp(Q)$, then the value of Q that T_i is producing was needed previously, and the system assumed that that value would never be produced.
     - Hence, the **write(Q)** operation is rejected, and T_i is rolled back.
  2. If $TS(T_i) < W\text{-}timestamp(Q)$, then T_i is attempting to write an obsolete value of Q.
     - Hence, this **write(Q)** operation is rejected, and T_i is rolled back.
  3. Otherwise, the **write(Q)** operation is executed, and $W\text{-}timestamp(Q)$ is set to $TS(T_i)$.

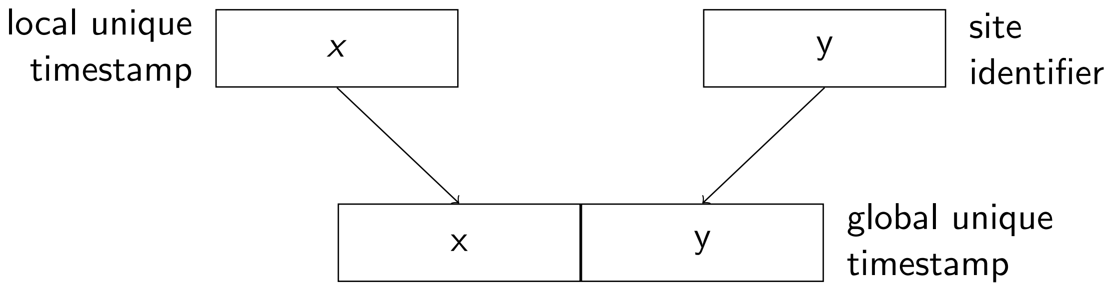
Example Use of the Protocol

A partial schedule for several data items for transactions with timestamps 1, 2, 3, 4, 5

T_1	T_2	T_3	T_4	T_5
				read(X)
	read(Y)			
read(Y)				
		write(Y)		
		write(Z)		
				read(Z)
	read(Z)			
	abort			
read(X)				
			read(W)	
		write(W)		
		abort		
				write(Y)
				write(Z)

Timestamping/1

- 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 $\langle x, y \rangle$ is obtained by concatenating the unique local timestamp x with the unique identifier y.



Timestamping/2

- A site with a slow clock will assign smaller timestamps
  - still logically correct: serializability not affected
  - but: "disadvantages" transactions
- Lamport-Clocks fix this problem:
  - each site S_i defines a logical clock LC_i, which generates the unique local timestamp;
  - increment timestamp LC_i for each new transactions issued by S_i;
  - whenever a read or write request is received from a transaction T_i with timestamp $\langle x, y \rangle$ and $x > LC_i$, then set LC_i to $x + 1$.

Replication with Weak Consistency/1

- Many commercial databases support replication of data with weak degrees of consistency (i.e., without a guarantee of serializabiliy)
- Example: 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/2

- 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.
- Example: 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 other replicas
  - basic model in distributed databases, where transactions are unaware of the details of replication
  - 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

Outline

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/1

- 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
  - 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/2

- 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 should 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/1

- 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 1/2 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/2

- Write operations
  - find highest version number like read, 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

Read One Write All (Available)

- Quorum consensus algorithm can be similarly extended
- 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

Link Failure and Network Partitioning

- Link failure:
  - 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.
- Network partitioning:
  - 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 are also designed to provide high availability.
    - simpler and lower overhead
    - all actions performed at a single site, and only log records shipped
    - no need for distributed concurrency control or 2 phase commit
- Distributed databases with replicas of data items
    - provide higher availability by having multiple (> 2) replicas and using the majority protocol
    - 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
  - 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

- Bully algorithm:
  - all nodes S_i are numbered
  - node with highest i-value is coordinator
- Coordinator election algorithm (started by S_i):
  - S_i sends an election message to every site S_k with $k > i$ and waits for response within T.
  - no response: S_i elects itself and informs all S_j, $j < i$.
  - response: Wait for the outcome of the coordinator election. (After timeout interval T', restart election from scratch.)
- S_i starts coordinator election (tries to elect itself coordinator) if
  - coordinator failure: coordinator does not answer within time interval T
  - recovery: when S_i recovers from failure
    $\rightarrow$ even if there is already a coordinator in the system
  - election message received: S_i is not coordinator and receives election message from some note S_j, $j < i$
    $\rightarrow$ if S_i is coordinator there is no need for election and S_j is informed

What is Consistency?

- Consistency in Databases (ACID):
  - database has a set of integrity constraints
  - a database state is consistent when 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[1]: 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 the order of operations from a single site preserved
    $\rightarrow$ replicated data item appears to be a single data item stored in shared memory to which different sites have sequential access
  - Weak consistency (several forms)

[1] Also "sequential consistency", defined by L. Lamport, 1979

Availability

- Traditionally, availability of centralized server
- For distributed systems: availability of system to process requests
- In large distributed system failures frequently happen:
  - a node is down
  - network partitioning
- Distributed consensus algorithms will block during partitions to ensure consistency
- Some applications require high availability 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 databases choose consistency
  - most Web applications choose availability (except for specific parts such as order processing)

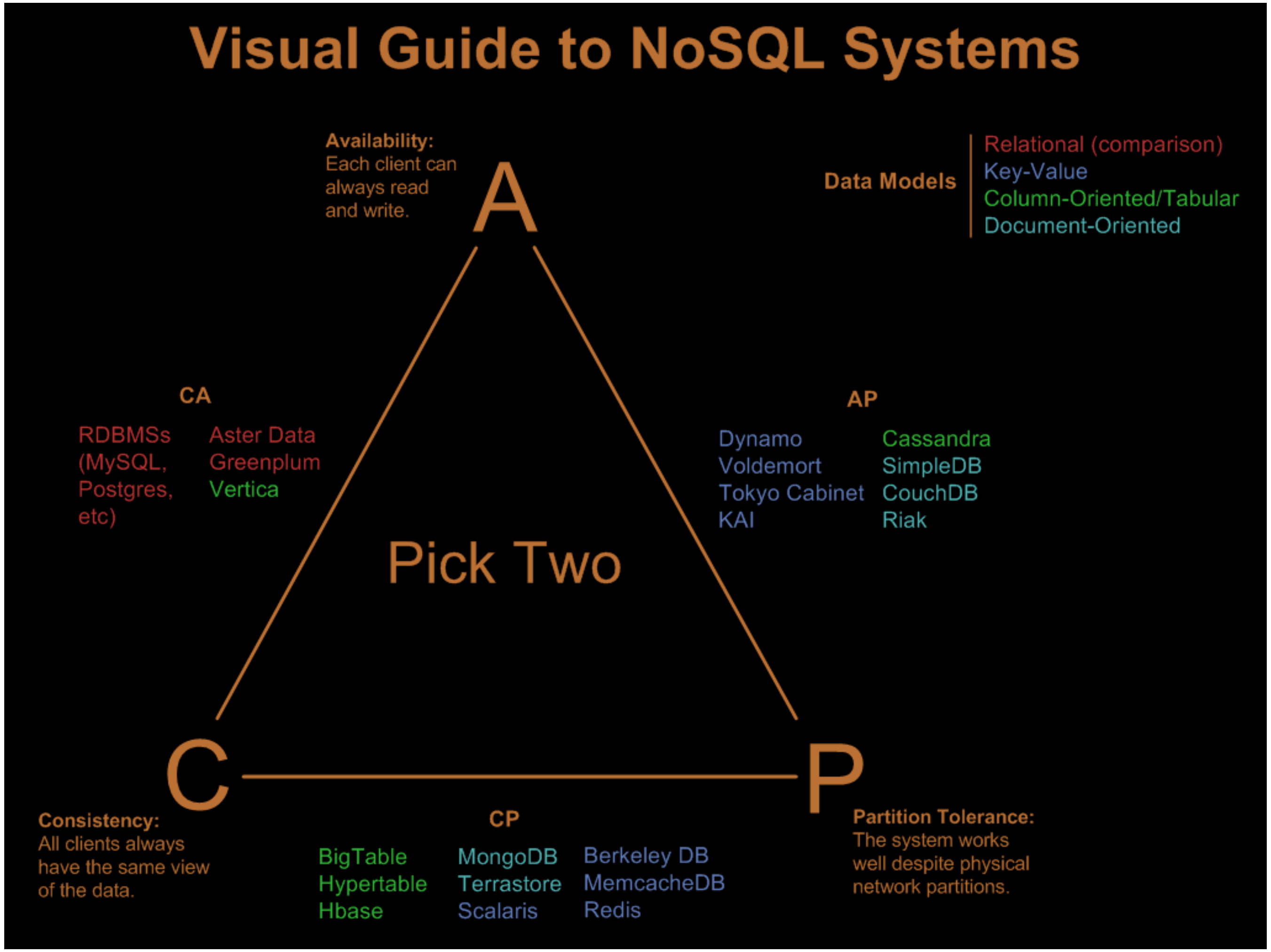
Replication with Weak Consistency

- Many systems support replication of data with weak degree of consistency (i.e., without a guarantee of serializability)
  - $Q_r + Q_w \leq S$ or $2 * Q_w < S$
- Trade off consistency for:
  - availability: when not enough sites are available to ensure quorum
  - low latency: small Q_r-values allow fast local reads
- Key issues:
  - Reads may get old versions
  - Writes may occur in parallel, leading to inconsistent versions
    - Question: how to detect, and how to resolve

Example: Trade off Consistency for Availability or Latency

- Real systems may use a mix of tradeoff options.
- Example: Yahoo!'s PNUTS distributed database
  - allows inconsistent reads to reduce latency (critical for many applications)
  - but consistent updates (via master) to ensures consistency over availability

Example: CAP Choice of Various Systems



Source: `http://blog.nahurst.com/visual-guide-to-nosql-systems`

BASE Properties

- BASE is an acronym for
  - Basically Available: availability is given priority over consistency
  - Soft state: copies of a data item may be inconsistent
  - Eventual Consistency: copies becomes consistent at some later time if there are no more updates to that data item.
- BASE is an alternative to ACID as used in traditional databases.

Eventual Consistency

- Definition 1: 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.
- Definition 2: For a given accepted update and a given node, eventually either the update reaches the node or the node is removed from service.

How to converge?

- Anti entropy: exchange versions
- Conflict detection:
  - timestamp: can identify last writer, but cannot distinguish sequential from branching version history
  - vector clocks: detects branching histories (i.e. conflicting updates)
- Reconciliation: decide on final state
  - last updater wins: data item with highest time stamp is final state
  - user defined: user must solve conflict
- When to reconcile?
  - read repair: fix conflicts at read time
  - write repair: fix conflicts at write time
  - asynchronous repair: separate process fixes conflicts

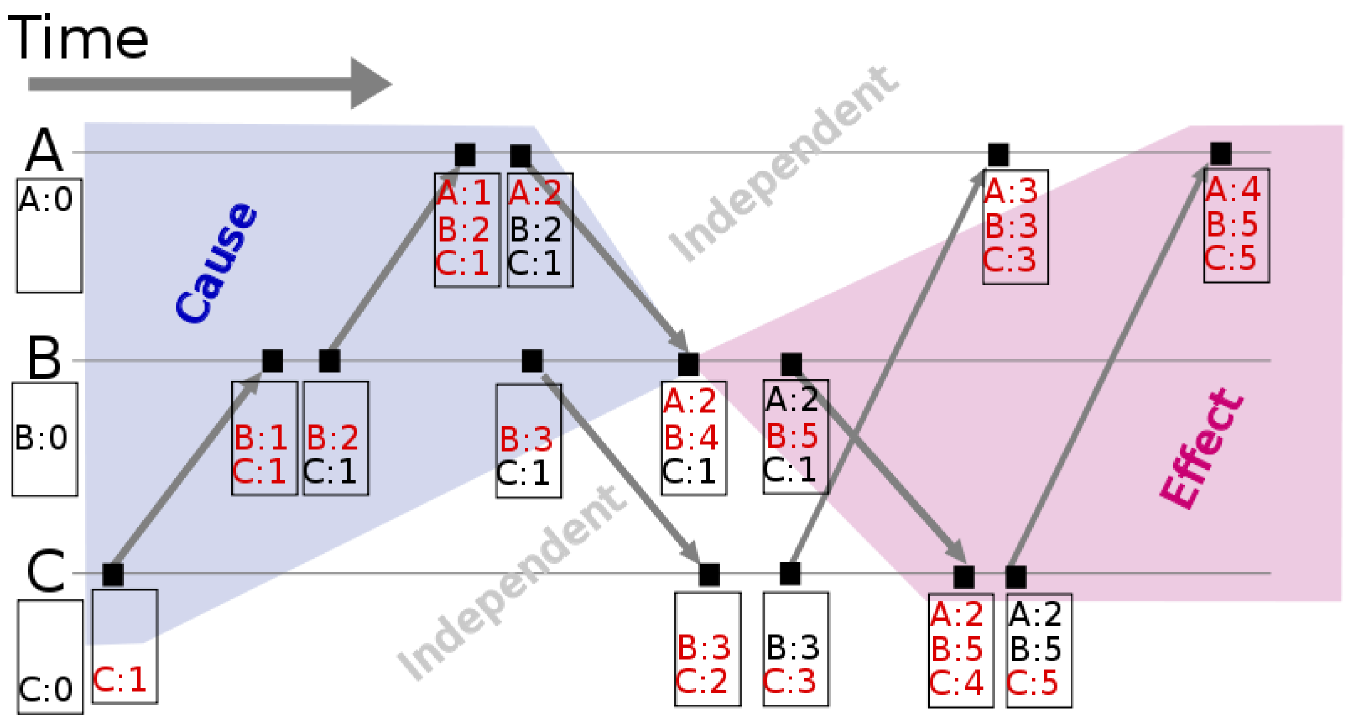
Vector Clock/1

- Replica: each data item is replicated at n sites S_i, $1 \leq i \leq n$
- Data item: d_i is the copy of data item d at site S_i
- Vector clock:
  - each d_i has vector $V_i[j]$, $1 \leq j \leq n$
  - $V_i[j]$: timestamp of data item d at site S_j as known by S_i
  - initialization: $V_i[j] \leftarrow 0$, $1 \leq i, j \leq n$
- Local update at site S_i: $V_i[i] \leftarrow V_i[i] + 1$
- Copy from remote site S_k with vector V_k to S_i:
  - $V_i[i] \leftarrow V_i[i] + 1$
  - for all $1 \leq j \leq n$: $V_i[j] \leftarrow \max(V_i[j], V_k[j])$

Vector Clock/2

- Exchange versions between replica S_i, S_j
  - d_i with vector V_i from site S_i
  - d_j with vector V_j from site S_j
- Conflict detection:
  a. $\exists x, y : V_i[x] < V_j[x] \wedge V_i[y] > V_j[y]$: branching history
  b. otherwise: linear history
- Linear History: d_j is a newer version of d_i
  - the updates of d_j include the updates of d_i
  - reconciliation: keep new version, $d_i \leftarrow d_j$
- Branching history: conflicting updates
  - d_i and d_j have received independent updates in parallel
  - reconciliation: some sort of conflict resolution (e.g. user interaction)

Vector Clock/3 – Example



Source: https://commons.wikimedia.org/wiki/File:Vector_Clock.svg