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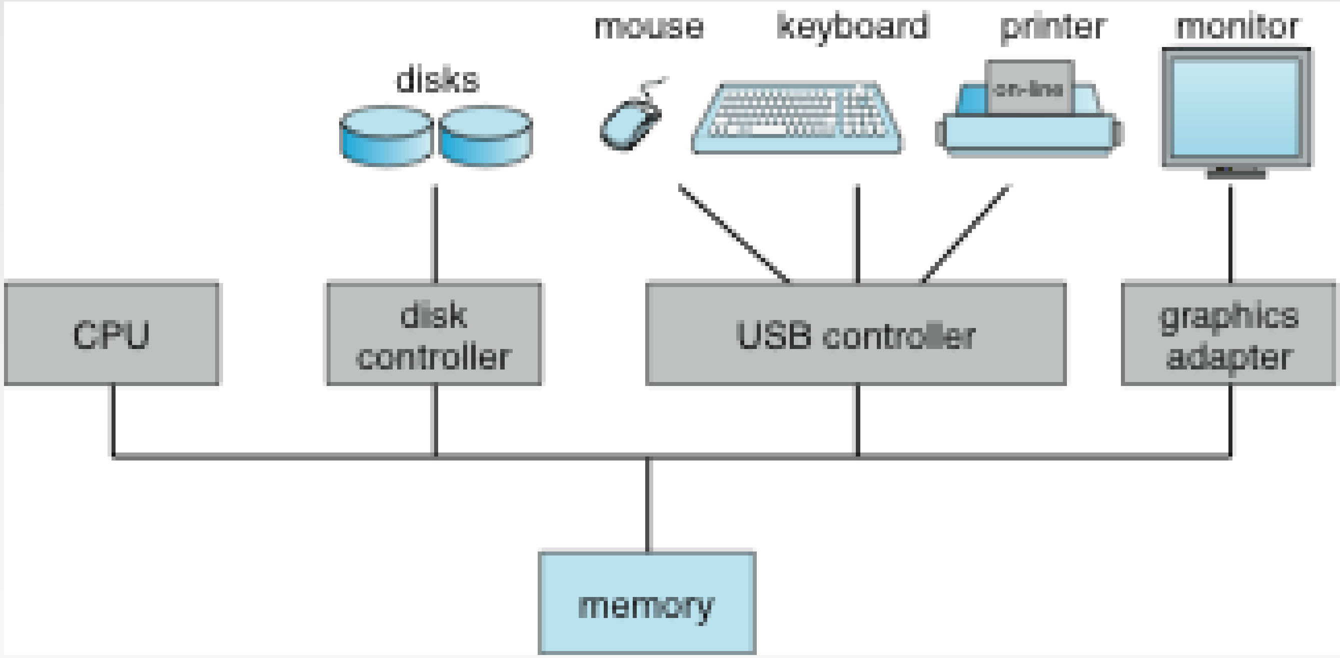
Distributed Databases

These slides are a modified version of the slides of the book "Database System Concepts" (Chapter 20 and 22), 5th Ed., McGraw-Hill, by Silberschatz, Korth and Sudarshan. Original slides are available at www.db-book.com

Database-system architectures

The architecture of a database system is greatly influenced by the underlying computer system on which it run, in particular by such aspects of computer architecture as networking, parallelism and distribution

Centralized Databases



Centralized Database systems are those that run on a single computer system

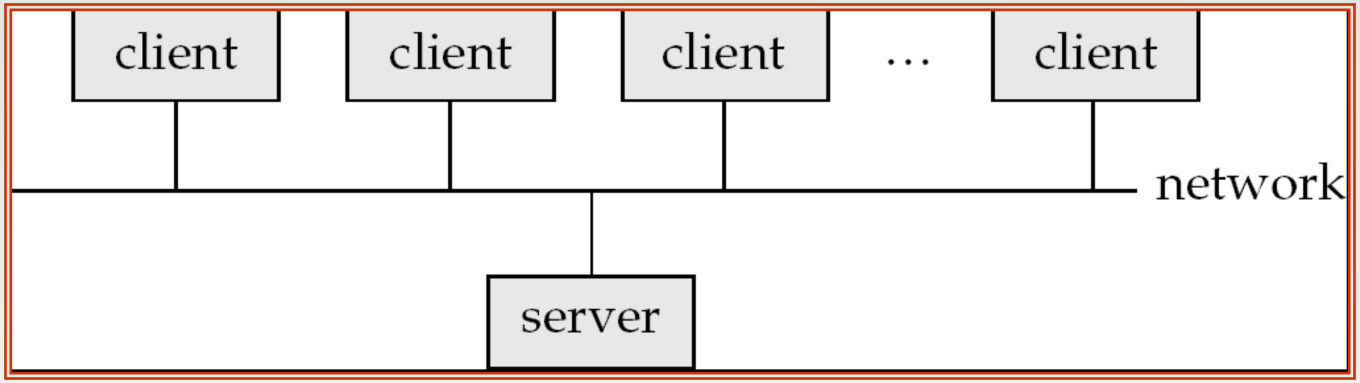
Centralized Systems

- Run on a single computer system and do not interact with other computer systems.
- One to a few CPUs and a number of device controllers that are connected through a common bus that provides access to shared memory.
- Single-user system (e.g., personal computer or workstation): desk-top unit, single user, usually has only one CPU and one or two hard disks; the OS may support only one user.
- Multi-user system: more disks, more memory, multiple CPUs, and a multi-user OS. Serve a large number of users who are connected to the system vie terminals. Often called *server* systems.

Database-systems support the full transactional features that we have studied earlier.

Client-Server Systems

- A centralized system acts as server system.
- Server systems satisfy requests generated at *m* client systems, whose general structure is shown below:



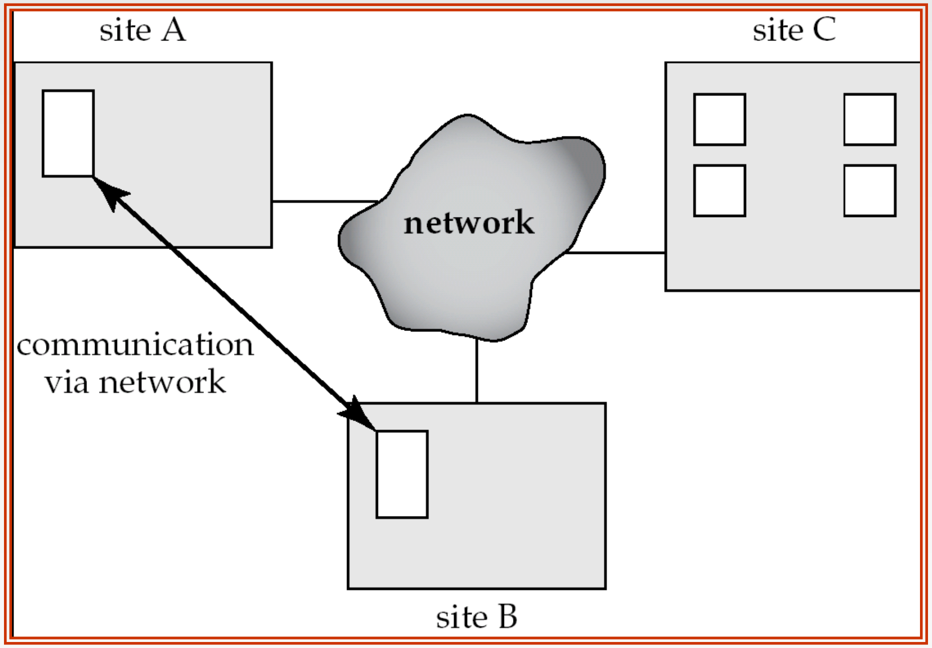
The functionality provided by the database system can be divided into two parts:

- The front end: consists of tools such as SQL user interface, report generation tools, ... Standards such as ODBC and JDBC developed to interface clients with servers

- The back end: manages **access structures, query evaluation and optimization, concurrency control and recovery**

Distributed Databases

- Data spread over multiple machines (also referred to as **sites** or **nodes**). Sites do not share main memory or disks.
- Network interconnects the machines (LAN or WAN)
- Data shared by users on multiple machines
- We differentiate between local transactions (access data only from the site where the transaction was initiated) / global transaction (access data in a site different from the site where the transaction was initiated



General structure
of a distributed system

Distributed Databases

- Homogeneous distributed databases
  - Same software/schema on all sites, data may be partitioned among sites (e.g, banking application: data at different branches)
  - Goal: provide a view of a single database, hiding details of distribution

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

Trade-offs in Distributed Systems

There are several reasons for building distributed database systems

- Sharing data – users at one site able to access the data residing at some other sites.
- Autonomy – each site is able to retain a degree of control over data stored locally.
- Higher system availability through redundancy — data can be replicated at remote sites, and system can function even if a site fails.
- Disadvantage: added complexity required to ensure proper coordination among sites.

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Distributed Databases

Implementation Issues for Distributed Databases

- Atomicity needed for transactions that update data at multiple sites
  - All or nothing
    (updates are executed at all sites or none update is executed)
  - A transaction that commits at one site and abort at another, leads to an inconsistent state.
- Distributed concurrency control (and deadlock detection) required: Transaction managers at sites where the transaction is executed, need to coordinate to implement concurrency control.

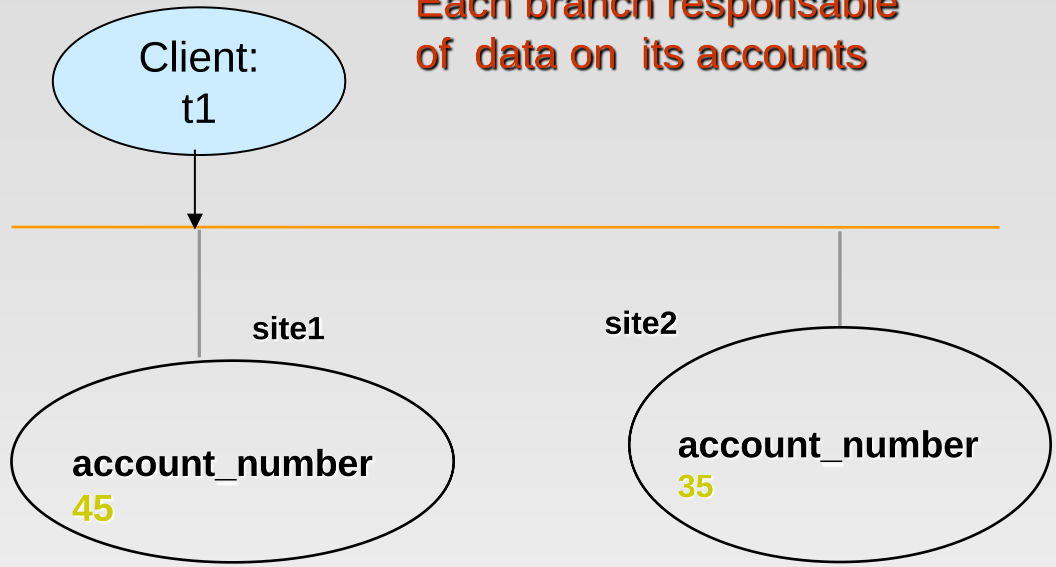
System Failure Modes

- Failures unique to distributed systems:
  - Failure of a site
  - Loss of messages
  - Failure of a communication link
  - **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

Distributed transactions

t1: distributed transaction
(access data at different sites)

Each branch responsable
of data on its accounts



t1: begin transaction

UPDATE account

SET balance=balance + 500.000

WHERE account_number=45;

UPDATE account

SET balance=balance - 500.000

WHERE account_number=35;

commit

end transaction

Account =(account_name, branch_name, balance)
divided into a number of fragments, each of which
consists of accounts belonging to a particular branch

t1

t11: UPDATE account
SET balance=balance + 500.000
WHERE account_number=45;

t12:UPDATE account
SET balance=balance - 500.000
WHERE account number=35;

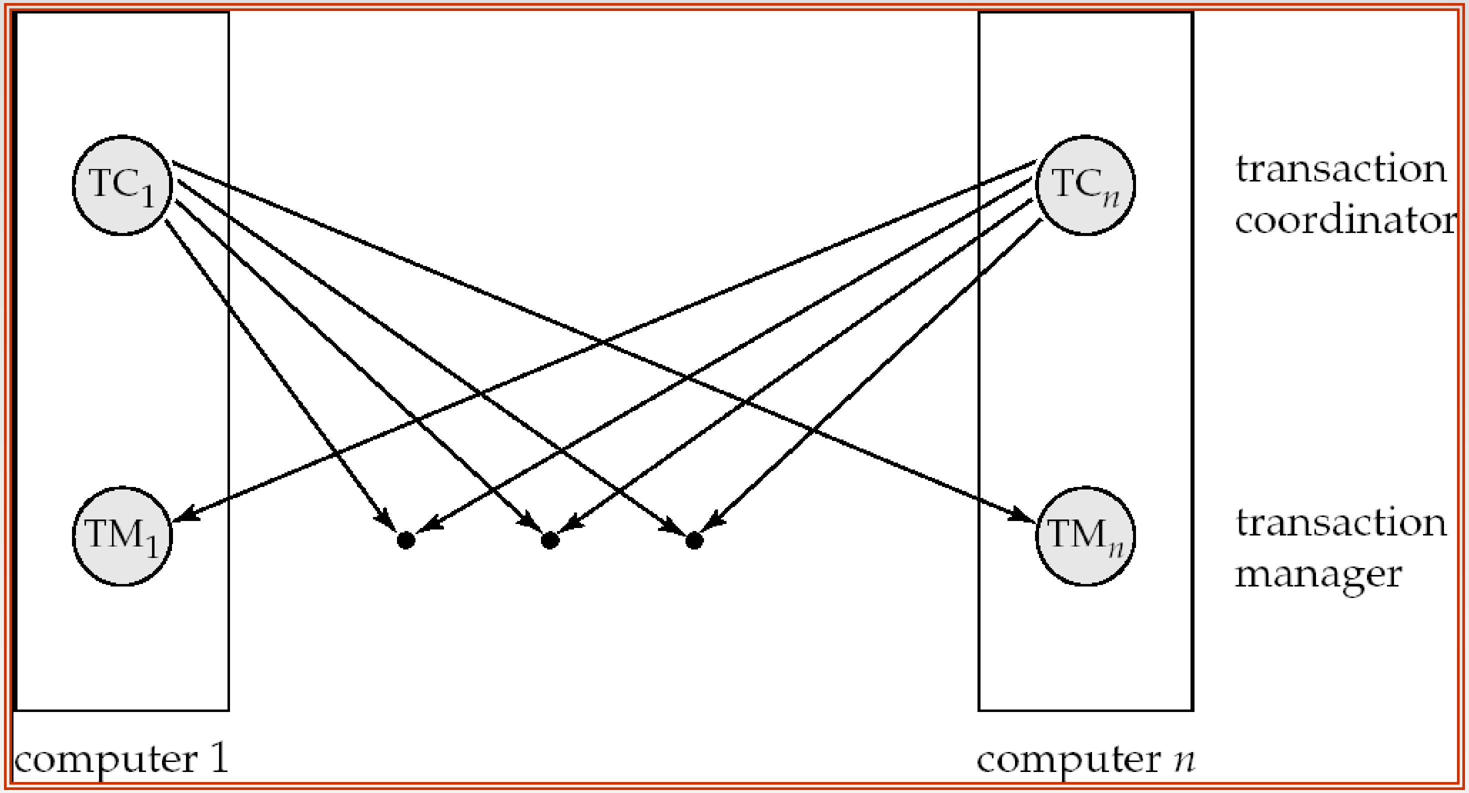
Distributed Transactions

- Each site has a transaction coordinator, which is responsible for:
  - Starting the execution of transactions that originate at the site.
  - Distributing sub-transactions 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”

- 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.

Transaction System Architecture



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.
- The *four-phase commit* (4PC) avoids some drawbacks by replicating the transaction coordinator.

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

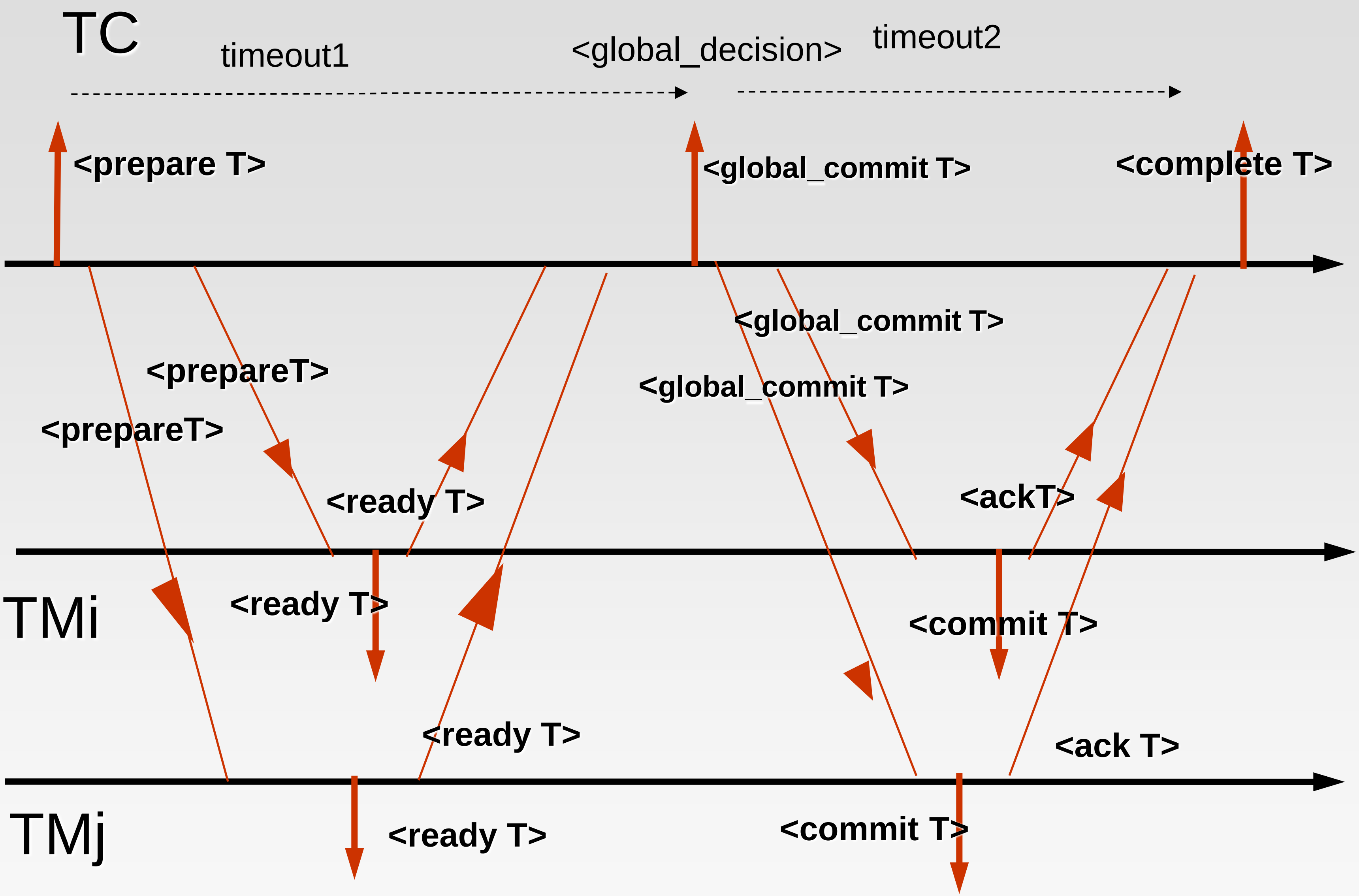
Phase 1: Obtaining a Decision

- 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

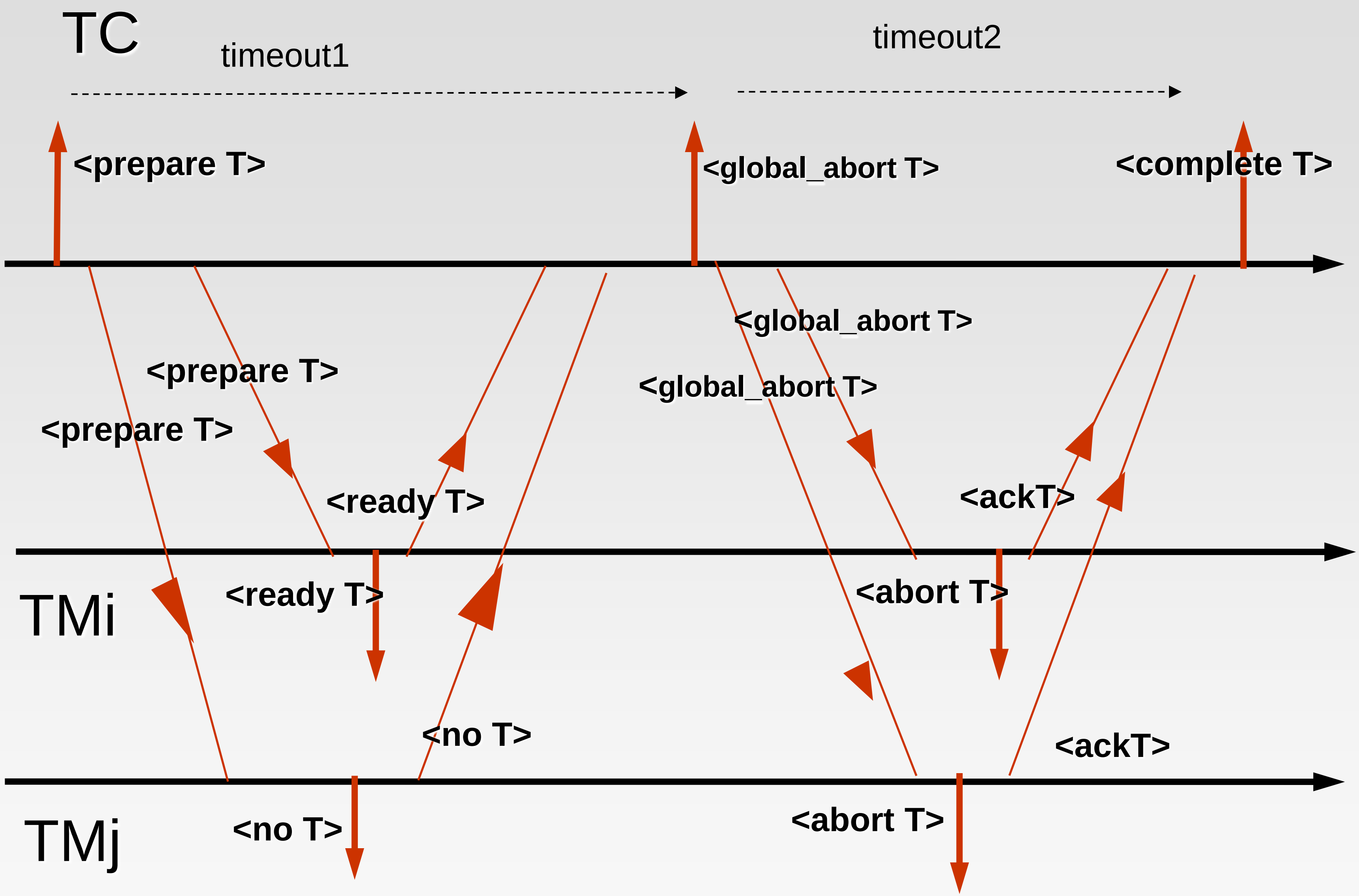
Phase 2: Recording the Decision

- *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.

Two-phase commit: commit of a transaction



Two-phase commit: abort of a transaction



Two-phase commit

- A site at which T executed can unconditionally abort T any time before it sends the message <ready T> to the coordinator
- The <ready T> message is a promise by a site to follow the coordinator's decision to commit T or abort T
- Time-out at the end of the first phase: the coordinator can decide abort of the transaction.
- Time-out at the end of the second phase: the coordinator re-sends the global decision.
- The acknowledgement message <ack T> at the end of the second phase, is optional

Handling of Failures - Site Failure

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

- Log contains <**commit** *T*> record: site executes **redo** (*T*)
- Log contains <**abort** *T*> record: site executes **undo** (*T*)
- Log contains <**ready** *T*> record: site must consult *the coordinator* to determine the fate of *T*.
  - If *T* committed, **redo** (*T*)
  - If *T* aborted, **undo** (*T*)
- The log contains no control records concerning *T*
  S_i failed before responding to the **prepare** *T* message
- since the failure of S_i precludes the sending of such a response *the coordinator* must abort *T*
  - S_i must execute **undo** (*T*)

Handling of Failures- Coordinator Failure

When coordinator C_i recovers, it examines its log:

- Log contains < **prepare** T> record:
  T is aborted or the prepare message is re-sent
- Log contains <global_decision> record: global decision is re-sent

- **Blocking problem** : active sites may have to wait for failed coordinator to recover.

  If a site has a <**ready** *T*> record in its logs, but no additional control records (such as <**abort** *T*> of <**commit** *T*>), the site must wait for C_i to recover, to find decision.

- A participant can't assume the role of the coordinator to terminate the transaction

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

Three-phase commit

- Pre-commit phase is added.

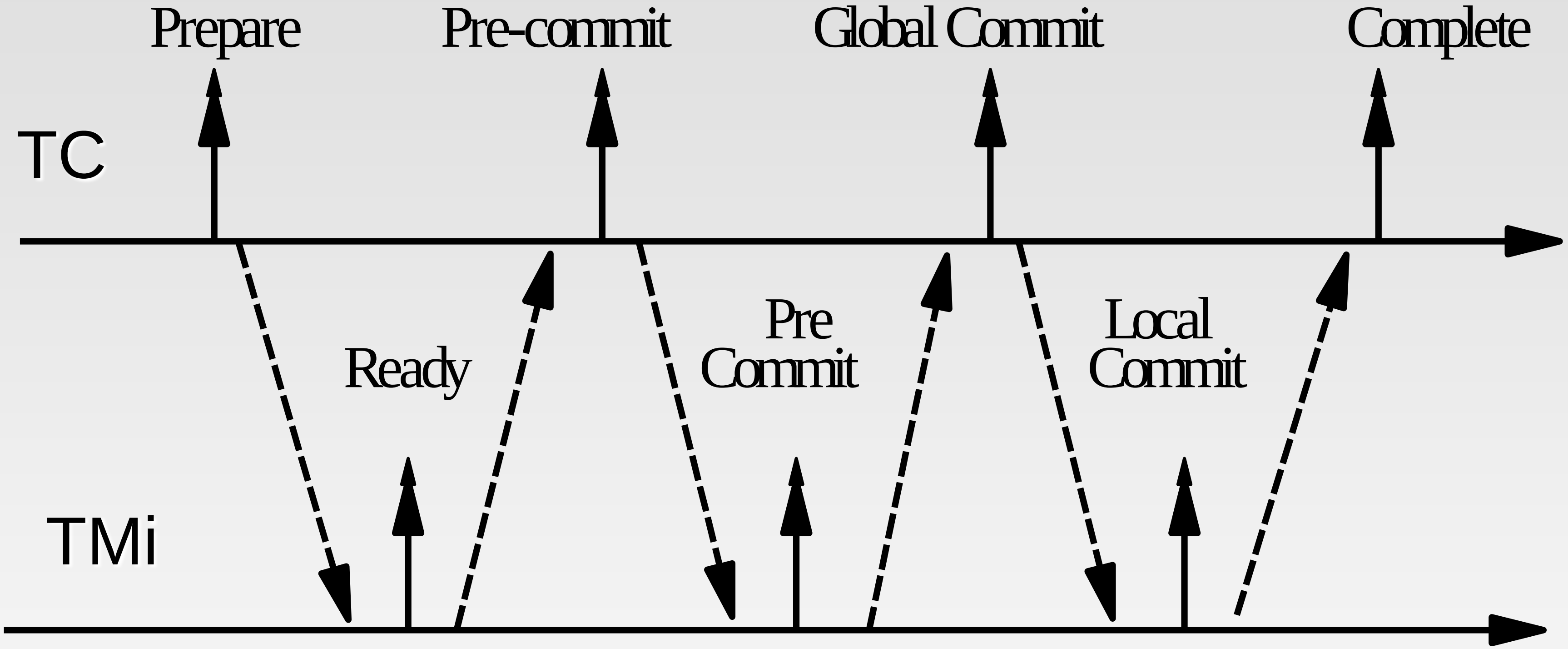
- Assume a permanent crash of the coordinator.
  A site can substitute the coordinator to terminate the transaction.

- The participant site decides:

  <**global_abort** T> if the last record in the log is <**ready** *T*>

  <**global_commit** T> the last record in the log is <**precommit** *T*>

Three-phase commit



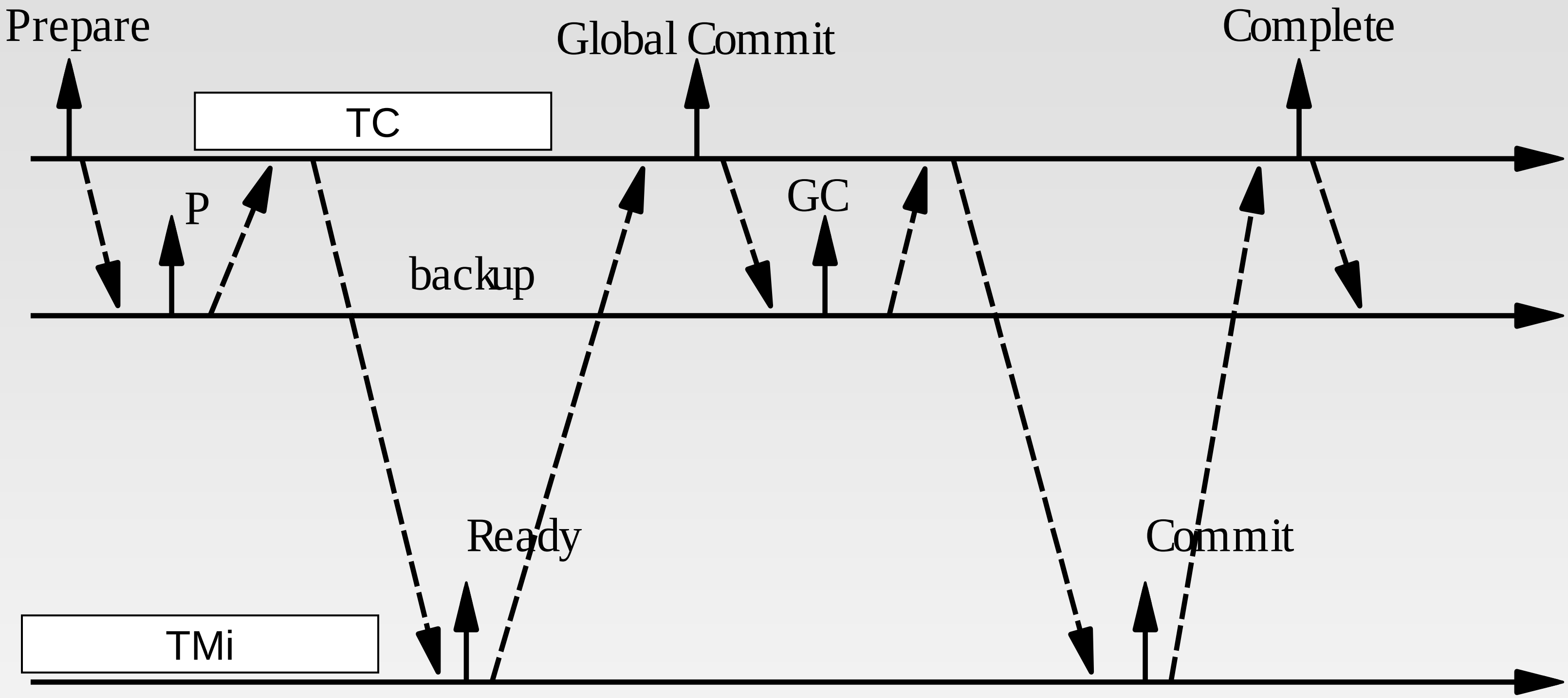
Four-phase commit

- Coordinator backup is created at a different site
  the backup maintains enough information to assume the role of coordinator if the actual coordinator crashes and does not recover.

- The coordinator informs the backup of the actions taken.

- If the coordinator crashes, the backup assume the role of coordinator:
  1) Another backup is started.
  2) The two-phase commit protocol is completed.

Four-phase commit



Atomicity property

- We assume that each site participates in the execution of a commit protocol to ensure global transaction automicity.

Concurrency Control

- Modify concurrency control schemes for use in distributed environment.

Given a distributed transaction ti, we use the following notation:

tij: sub-transaction of ti executed at site j

rij(x): ti executes *read(x)* at site j

wij(x): ti executes *write(x)* at site j

Distributed transactions

t1:

t11 [read(x) write(x)]

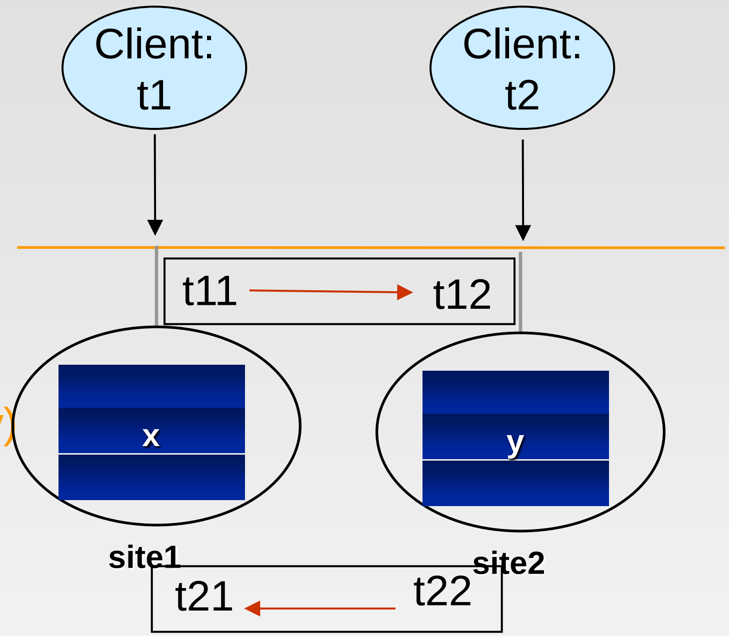
t12 [read(y) write(y)]

t2:

t22 [read(y) write(y)]

t21 [read(x) write(x)]

S= t11 t22 t21 t12



S= r11(x) w11(x) r22(y)w22(y) r21(x) w21(x) r12(y) w12(y)

NOT GLOBALLY SERIALIZABLE

LOCK RELEASED AFTER THE TWO-PHASE COMMIT PROTOCOL

t1: lock_X(x) ok

t2: lock_X(y) ok

t2: lock_X(x) wait for t1 DEADLOCK

t1: lock_X(y) wait for t2

Locking protocol

- (strict) rigorous 2PL

all locks are held till abort/commit

(Two-phase commit protocol)

lock_X(record 45) site1

…..

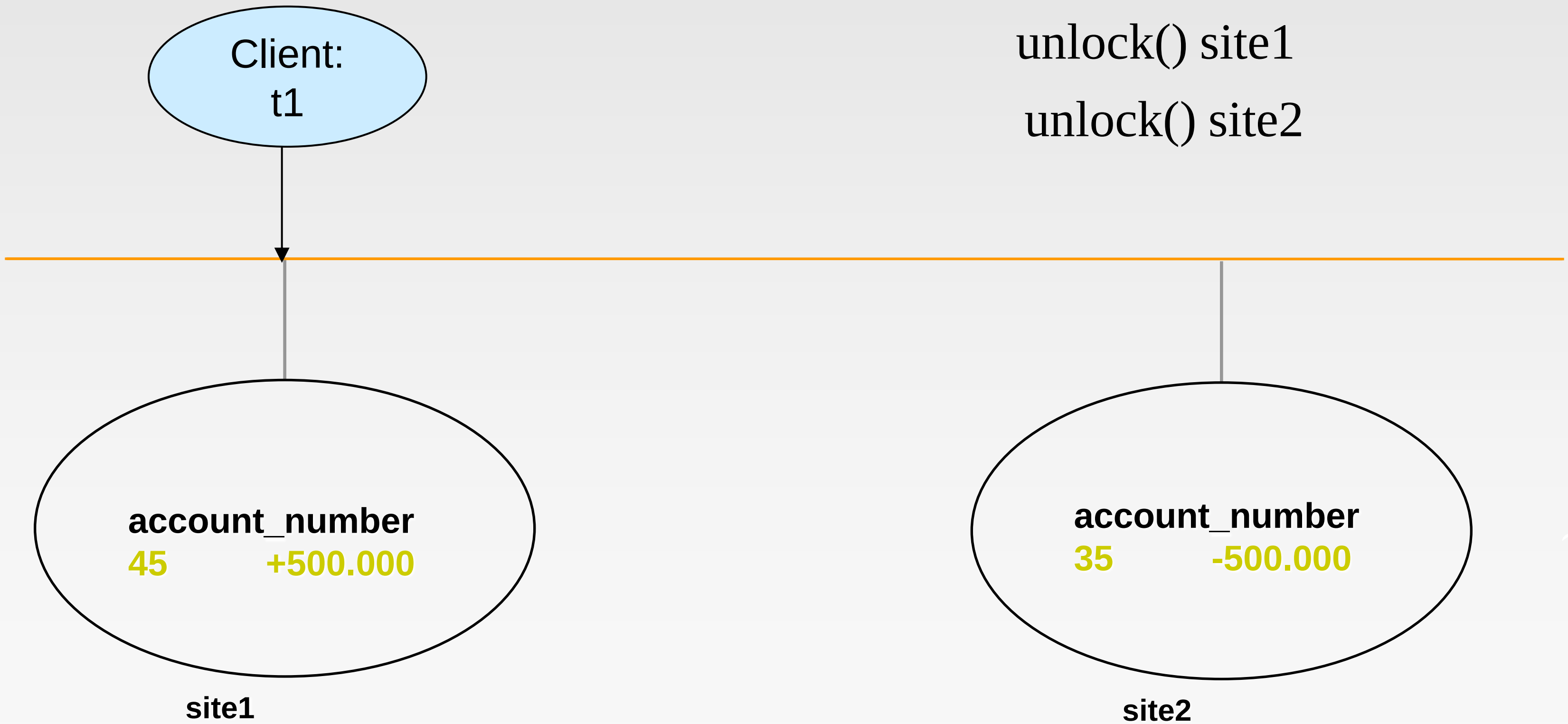
lock_X(record 35) site2

…..

< Two-phase commit protocol>

unlock() site1

unlock() site2

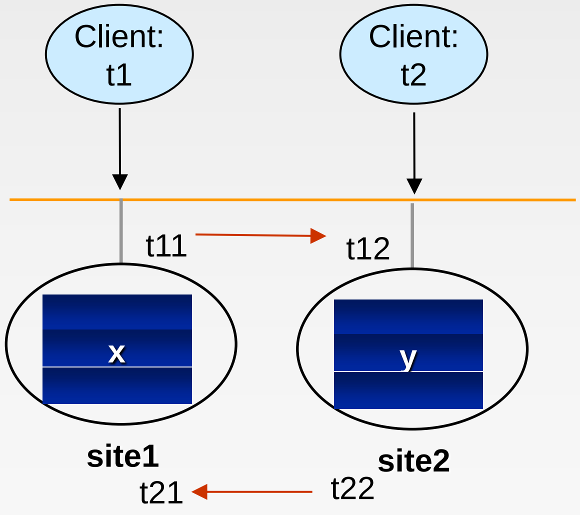


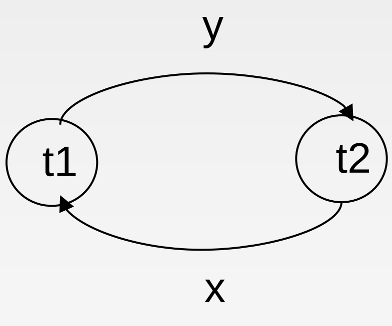
Single-Lock-Manager Approach

- 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.)

- 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.

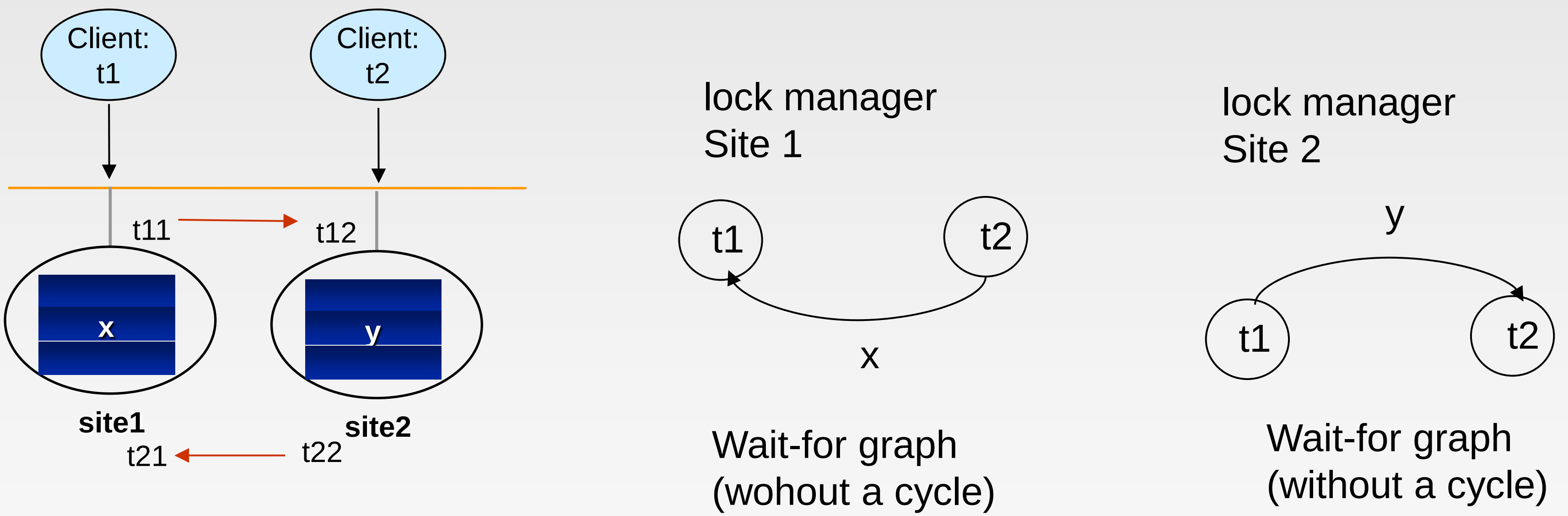




Wait-for graph
(cycle)

Distributed Lock Manager

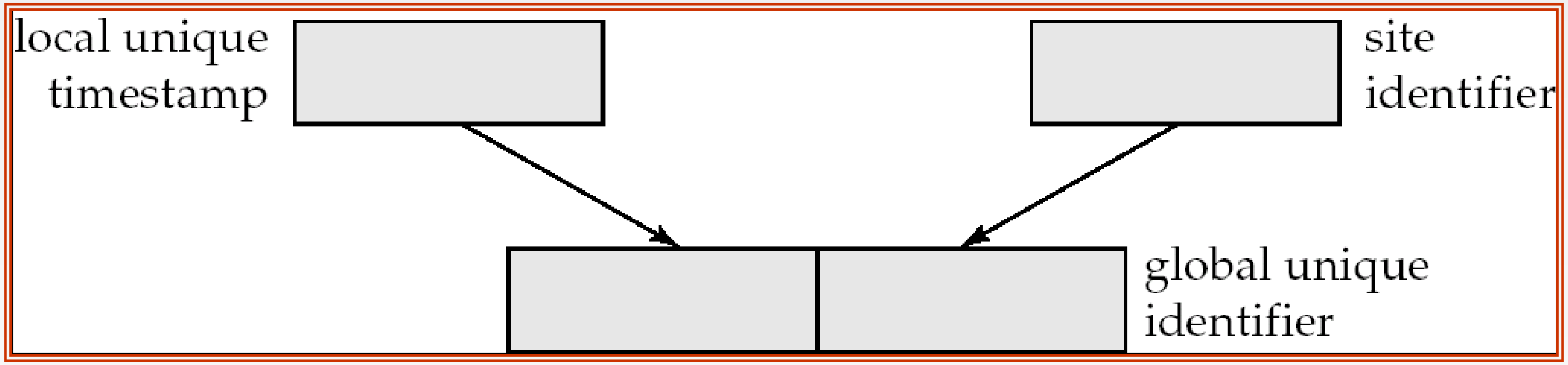
- In this approach, functionality of locking is implemented by lock managers at each site
  - Lock managers control access to local data items
- Advantage: work is distributed and can be made robust to failures
- Disadvantage: deadlock detection is more complicated
  - Lock managers cooperate for deadlock detection



deadlock which cannot be detected locally at either site

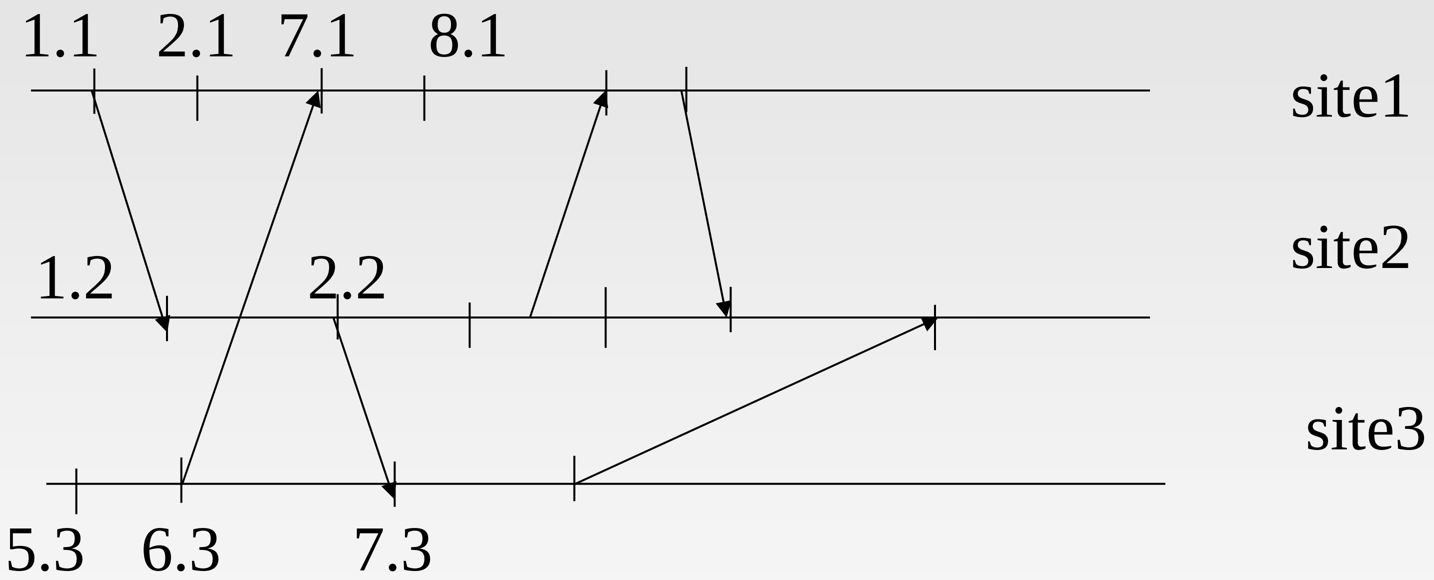
Timestamping

- 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.



Lamport algoritm to assign timestamps

Timestamp: local_timestamp.site_identifier
(integer)



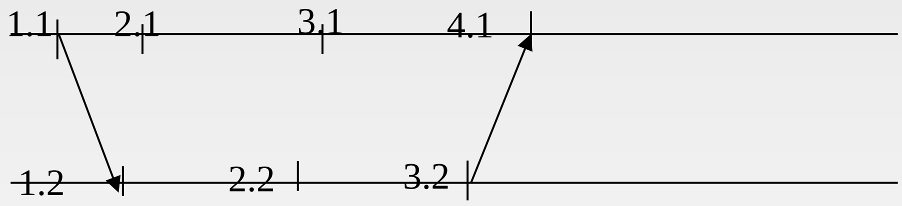
Timestamping (Cont.)

- Transaction initiated at a site are assigned timestamps in sequence

  site1:   1.1   2.1   3.1 ……

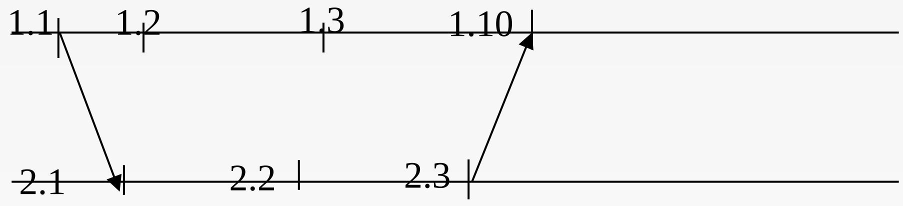
  site2:   1.2   2.2   3.2 ……

When a transaction moves from site i to site j, the timestamp assigned to the transaction at site j must be greater than the last timestamp already assigned to transactions at j and the current timestamp of the transaction



The order of concatenation (local timestamp, site identifier) is important!

If we have (site identifier, local timestamp):



Distributed Lock Manager: Handling deadlock

Deadlock detection locally at each site is not sufficient

Centralized Approach

- A global wait-for graph is constructed and maintained in a *single* site (the deadlock-detection coordinator)
- 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.

Distributed deadlock detection algorithm (IBM DB2)

- A transaction is divided into sub-transactions executing at different sites
- Sub-transactions are executed synchronously

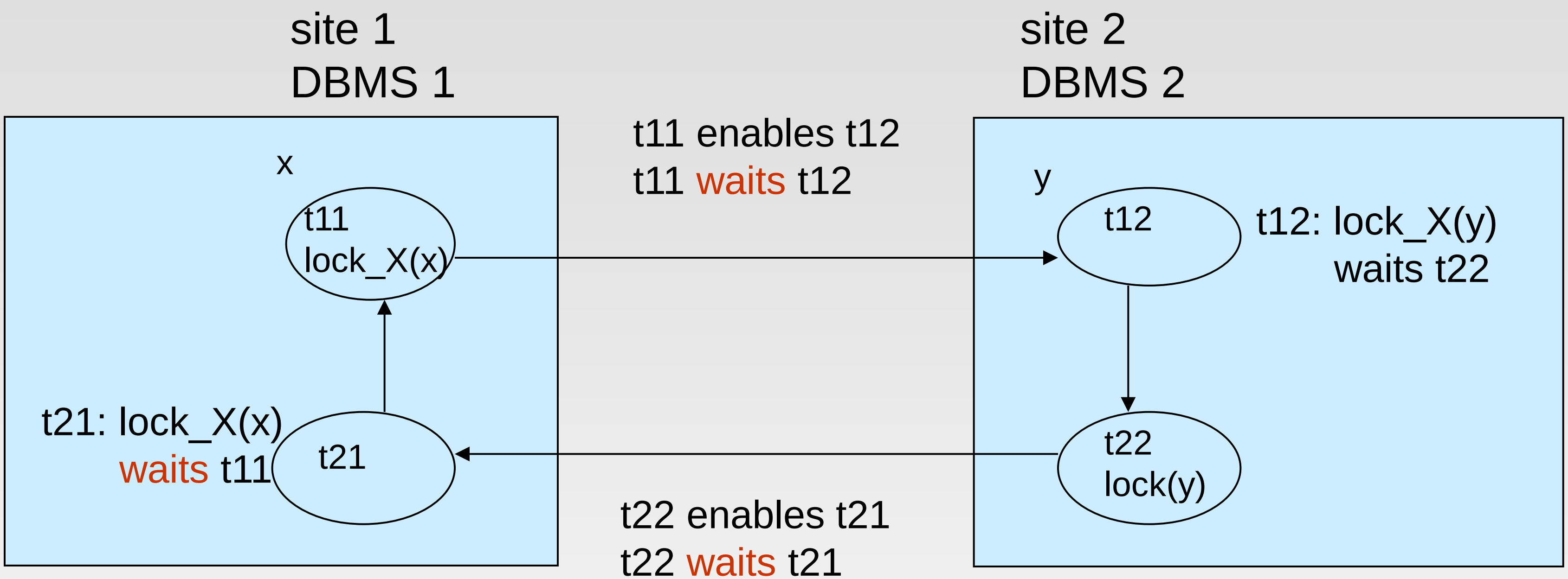
  t11 enables t12

  t11 waits for the completion of t12

Waiting conditions:

1) A sub-transaction of t waits for another sub-stransaction of t executed at a different site
2) A sub-transaction of t waits for a sub-transaction of t' on a shared data item x

Distributed deadlock detection algorithm (IBM DB2)



t1: r11(x) w11(x) r12(y) w12(y)

t2: r22(y)w22(y) r21(x) w21(x)

S = r11(x) w11(x) r22(y)w22(y) r21(x) w21(x) r12(y) w12(y)

Distributed deadlock detection algorithm (IBM DB2)

- Wait-for sequences

  Ein -> ti -> tj -> Eout

Example:

DBMS1: E2 -> t21 -> t11 -> E2
DBMS2: E1 -> t12 -> t22 -> E1

- Build the wait-for graph locally to a site

Distributed deadlock detection algorithm

Each site periodically runs the algorithm:

Phase 1

- update the wait-for graph locally with received "wait-for sequences"

Phase 2

- check the wait-for graph locally: if a deadlock arises, rollback a selected transaction. Abort of the transaction at all sites

Phase 3

- "wait-for sequences" are computed and sent to other sites

The same deadlock can be deteced at multiple sites.
Different transactions can be chosen for the rollback at sites.

Distributed deadlock detection algorithm

RULE:

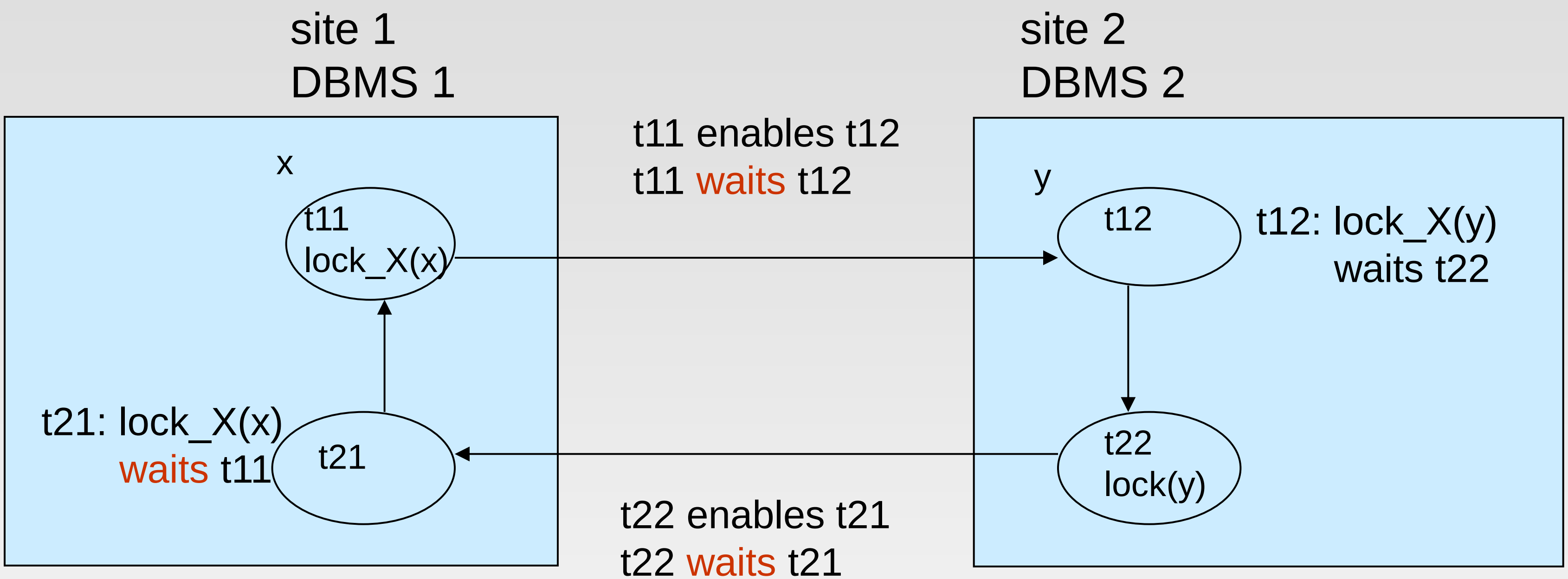
Ein -> ti -> tj -> Eout

- a wait-for sequence is sent iff :

  i > j, with i and j the transaction identifiers

- Sequences are sent forward, i.e., to the DBMS where transaction tj is executed

Example



Phase 1
DBMS1: wait-for graph t2 -> t1
DBMS2: wait-for graph t1 -> t2

Phase2
DBMS1: -
DBMS2: -

Example

Phase 3

DBMS1: E2 -> t21 -> t11 -> E2 ⇒ E2 -> t2 -> t1 -> E2

2>1

sent to DBMS2

DBMS2: E1 -> t12 -> t22 -> E1 ⇒ E1 -> t1 -> t2 -> E1

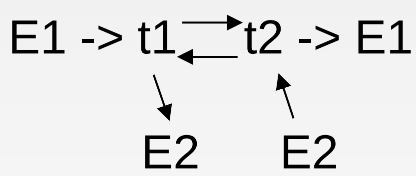
1> 2

not sent

Phase1:

DBMS1: -

DBMS2 receives the sequence and updates the wait-for graph:



Phase 2

Site 1: -

Site2: deadlock detected. Abort of a transaction

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.