Distributed Database Management Systems

Distributed architectures

- Data and computation are distributed over different machines
- Different levels of complexity
  - Depending on the independence level of nodes
- Typical advantages
  - Performance improvement
  - Increased availability
  - Stronger reliability

Distributed architectures

- Client/server
  - Simplest and more widespread
  - Server manages the database
  - Client manages the user interface
- Distributed database system
  - Different DBMS servers on different network nodes
    - autonomous
    - able to cooperate
  - Guaranteeing the ACID properties requires more complex techniques

Distributed architectures

- Data replication
  - A *replica* is a copy of the data stored on a different network node
  - The replication server autonomously manages copy update
  - Simpler architecture than distributed database

Distributed architectures

- Parallel architectures
  - Performance increase is the only objective
  - Different architectures
    - Multiprocessor machines
    - CPU clusters
      - Dedicated network connections
- Data warehouses
  - Servers specialized in *decision support*
  - Perform OLAP (On Line Analytical Processing)
    - different from OLTP (On Line Transaction Processing)

Relevant properties

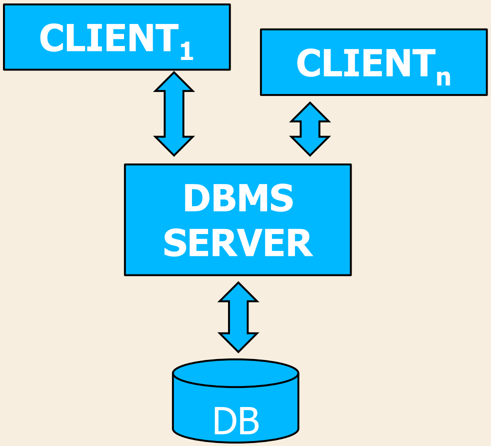
- Portability
  - Capability of moving a program from a system to a different system
  - Guaranteed by the SQL standard
- Interoperability
  - Capability of different DBMS servers to cooperate on a given task
  - Interaction protocols are needed
    - ODBC
    - X-Open-DTP

Database Management Systems

Client/server Architectures

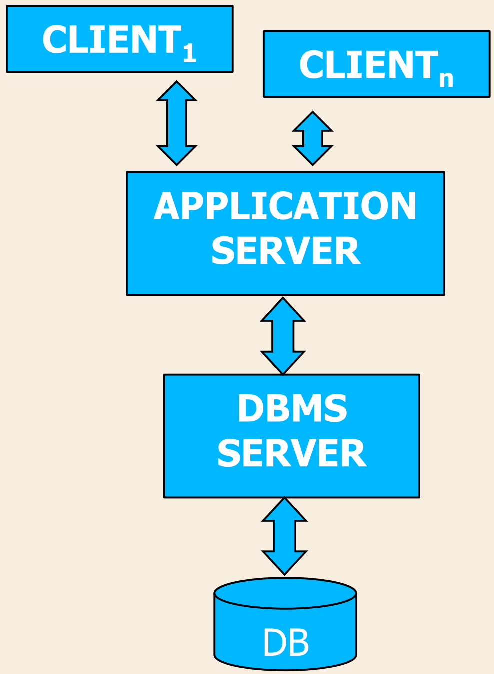
Client/server architectures

- 2-Tier
  - *Thick* clients
    - with some application logic
  - DBMS server
    - provides access to data



Client/server architectures

- 3-Tier
  - *Thin* client
    - browser
  - Application server
    - implements business logic
    - typically also a web server
  - DBMS Server
    - provides access to data



SQL execution

- Compile & Go
  - The query is sent to the server
  - The query is prepared
    - generation of the query plan
  - The query is executed
  - The result is shipped
    - The query plan is not stored on the server
- Effective for one-shot query executions
  - provides flexible execution of dynamic SQL

SQL execution

- Compile & Store
  - The query is sent to the server
  - The query is prepared
    - generation of the query plan
    - the query plan is *stored* for future usage
  - may continue with execution
    - the query is executed
    - the result is shipped
- Efficient for repeated query executions
  - parametric executions of the same query

Distributed Database Systems

Distributed database systems

- Client transactions access more than one DBMS server
  - Different complexity of available distributed services
- *Local autonomy*
  - Each DBMS server manages its local data in an autonomous way
    - e.g., concurrency control, recovery

Distributed database systems

- Functional advantages
  - Appropriate *localization* of data and applications
    - e.g., geographical distribution
- Technological advantages
  - Increased *data availability*
    - Total block probability is reduced
    - Local blocks may be more frequent
  - Enhanced *scalability*
    - Provided by the modularity and flexibility of the architecture

Database Management Systems

Distributed Database Design

Data fragmentation

- Given a relation R, a data fragment is a subset of R in terms of tuples, or schema, or both
- Different criteria to perform fragmentation
  - horizontal
    - subset of tuples
  - vertical
    - subset of schema
  - mixed
    - both horizontal and vertical together

Horizontal fragmentation

- The horizontal fragmentation of a relation R selects a subset of tuples in R with
  - same schema of R
  - obtained by means of σ_p
    - p is the partitioning predicate
- Fragments are *not overlapped*

Example

- The following table is given

  Employee (<u>Emp#</u>, Ename, DeptName, Tax)

- Horizontal fragmentation on attribute DeptName
  - card(DeptName) = N

    $E_1 = \sigma_{DeptName = \text{'Production'}}$ Employee

    …

    $E_N = \sigma_{DeptName = \text{'Marketing'}}$ Employee

- Reconstruction of the original table

  $Employee = E_1 \cup E_2 \cup \ldots \cup E_N$

Vertical fragmentation

- The vertical fragmentation of a relation R selects a subset of schema of R
  - Obtained by means of π_X
    - X is a subset of the schema of R
    - The primary key should be included in X to allow rebuilding R
  - All tuples are included
- Fragments are *overlapping* on the primary key

Example

- The following table is given

  Employee (Emp#, Ename, DeptName, Tax)

- Vertical fragmentation

  $E_1 = \pi_{\text{Emp\#, Ename, DeptName}}$ Employee

  $E_2 = \pi_{\text{Emp\#, Ename, Tax}}$ Employee

- Reconstruction of the original table

  Employee = $E_1 \bowtie E_2$

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Fragmentation properties

- Completeness
  - each information in relation R is contained in at least one fragment R_i
- Correctness
  - the information in R can be rebuilt from its fragments

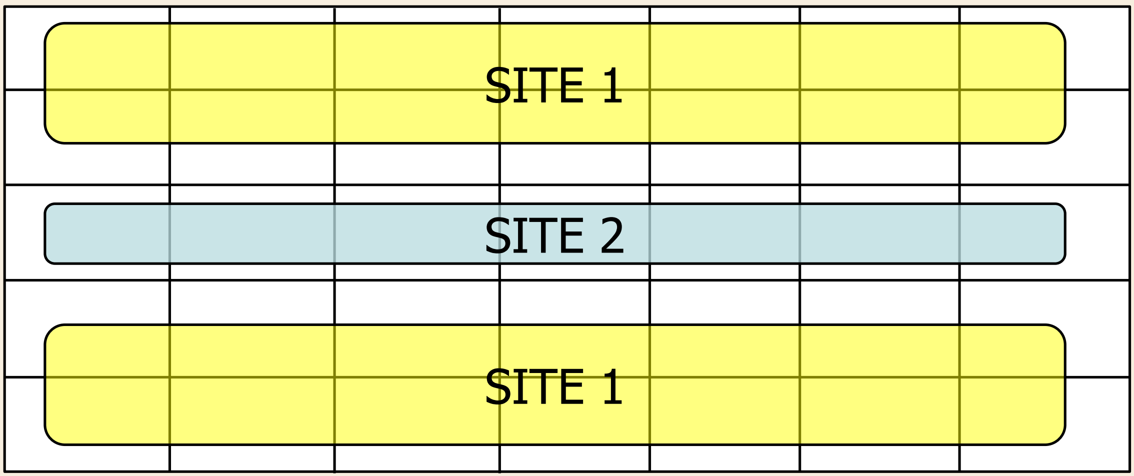
DBMG

Distributed database design

- It is based on *data fragmentation*
  - Data distribution over different servers
- Each fragment of a relation R is usually stored
  - in a different file
  - possibly, on a different server
- Relation *R* does not exist
  - it may be rebuilt from fragments

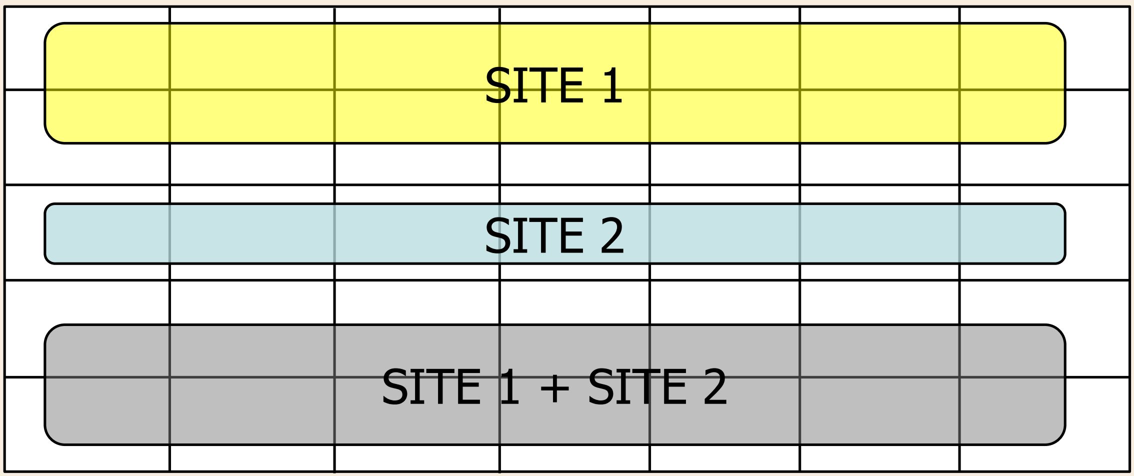
Allocation of fragments

- The *allocation schema* describes how fragments are stored on different server nodes
  - Non redundant mapping if each fragment is stored on one single node



Allocation of fragments

- Redundant mapping if some fragments are replicated on different servers
  - increased data availability
  - complex maintenance
    - copy synchronization is needed



Transparency levels

- *Transparency levels* describe the knowledge of data distribution
- An application should operate differently depending on the transparency level supported by the DBMS
- Transparency levels
  - fragmentation transparency
  - allocation transparency
  - language transparency

Transparency levels

- The following table is given
  - Supplier S (S#, SName, City, Status)
- Horizontal fragmentation on the City attribute
  - domain of city = {Torino, Roma}
- Allocation schema

Horizontal fragment	Allocation schema
$S_1 = \sigma_{city = 'Torino'} S$	S_1@xxx.torino.it
$S_2 = \sigma_{city = 'Roma'} S$	S_2@xxx.roma1.it S_2@xxx.roma2.it

Fragmentation transparency

- Applications know the existence of tables and not of their fragments
  - data distribution is not visible
- Example
  - The programmer only accesses table S
    - not its fragments

```
SELECT SName
FROM S
WHERE S#=:CODE
```

Allocation transparency

- Applications know the existence of fragments, but not their allocation
  - not aware of replication of fragments
  - must enumerate all fragments
- Example

```
SELECT SName
FROM S1
WHERE S# = :CODE
IF (NOT FOUND)
        SELECT SName
        FROM S2
        WHERE S# = :CODE
```

Language transparency

- The programmer should select both the fragment and its allocation
  - No SQL dialects are used
- This is the format in which higher level queries are transformed by a distributed DBMS
- Example

```
SELECT SName
FROM S1@xxx.torino.it
WHERE S# = :CODE
IF (NOT FOUND)
        SELECT SName
        FROM S2@xxx.roma1.it
        WHERE S# = :CODE
```

Selection of a specific replica of S_2

Transaction classification

Transaction classification

- The client requests the execution of a transaction to a given DBMS server
  - the DBMS server is in charge of redistributing it
- Classes define different complexity levels in the interaction among DBMS servers
  - They are based on the type of SQL instruction which the transaction is allowed to contain

Transaction classification

- Remote request
  - Read only request
    - only select statement
  - Single remote server
- Remote transaction
  - Any SQL command
  - Single remote server

Transaction classification

- Distributed transaction
  - Any SQL command
  - Each SQL statement is addressed to one single server
  - Global atomicity is needed
    - 2 phase commit protocol
- Distributed request
  - Each SQL command may refer to data on different servers
  - Distributed optimization is needed
  - Fragmentation transparency is in this class only

Example

- The following table is given
  - Account (Acc#, Name, Balance)
- Fragments and allocation schema

Horizontal fragmentation	Allocation schema
$A_1 = \sigma_{acc\# < 10000}$ Account	Node 1
$A_2 = \sigma_{acc\# >= 10000}$ Account	Node 2

Example

- Money transfer transaction

```
BoT       (Beginning of transaction)
UPDATE Account
SET Balance = Balance - 100
WHERE Acc# = 3000

UPDATE Account
SET Balance = Balance + 100
WHERE Acc# = 13000
EoT       (End of transaction)
```

Example

- What is the class of the transaction?
  - Distributed request because Account is not explicitly partitioned
- If instead the update instructions reference explicitly A_1 and A_2
  - Distributed transaction
- If both update instructions reference only A_1
  - e.g., second update with WHERE Acc#=9000
  - Remote transaction

Database Management Systems

Distributed DBMS Technology

DBMG

ACID properties

- Atomicity
  - It requires distributed techniques
    - 2 phase commit
- Consistency
  - Constraints are currently enforced only locally
- Isolation
  - It requires strict 2PL and 2 Phase Commit
- Durability
  - It requires the extension of local procedures to manage atomicity in presence of failure

Other issues

- *Distributed query optimization* is performed by the DBMS receiving the query execution request
  - It partitions the query in subqueries, each addressed to a single DBMS
  - It selects the execution strategy
    - order of operations and execution technique
    - order of operations on different nodes
      - transmission cost may become relevant
    - (optionally) selection of the appropriate replica
  - It coordinates operations on different nodes and information exchange

Atomicity

- All nodes (i.e., DBMS servers) participating to a distributed transaction must implement the *same decision* (commit or rollback)
  - Coordinated by *2 phase commit* protocol
- Failure causes
  - Node failure
  - Network failure which causes lost messages
    - Acknowledgement of messages (ack)
    - Usage of timeout
  - Network partitioning in separate subnetworks

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2 Phase Commit protocol

- Objective
  - Coordination of the conclusion of a distributed transaction
- Parallel with a wedding
  - Priest celebrating the wedding
    - Coordinates the agreement
  - Couple to be married
    - Participate to the agreement

2 Phase Commit protocol

- Distributed transaction
  - One coordinator
    - *Transaction Manager* (TM)
  - Several DBMS servers which take part to the transaction
    - *Resource Managers* (RM)
- Any participant may take the role of TM
  - Also the client requesting the transaction execution

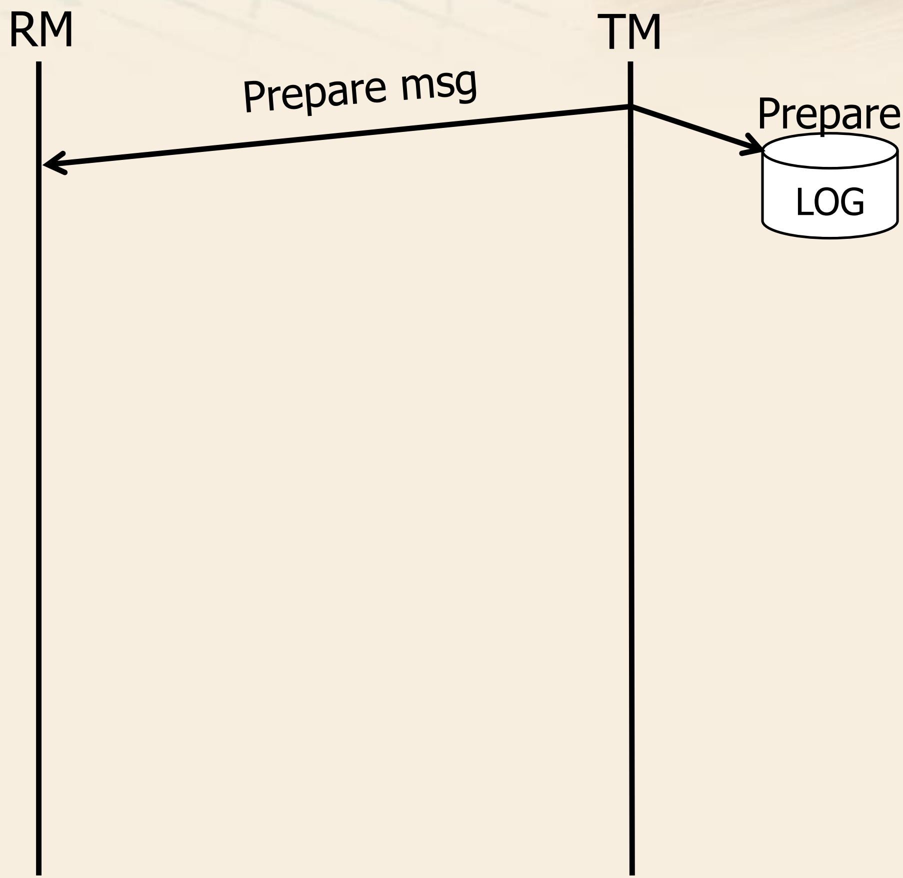
New log records

- TM and RM have *separate private* logs
- Records in the TM log
  - *Prepare*
    - it contains the identity of all RMs participating to the transaction (Node ID + Process ID)
  - *Global commit/abort*
    - final decision on the transaction outcome
  - *Complete*
    - written at the end of the protocol

New log records

- New records in the RM log
  - *Ready*
    - The RM is willing to perform commit of the transaction
    - The decision *cannot be changed* afterwards
    - The node has to be in a reliable state
      - WAL and commit precedence rules are enforced
      - Resources are locked
    - After this point the RM *loses its autonomy* for the current transaction

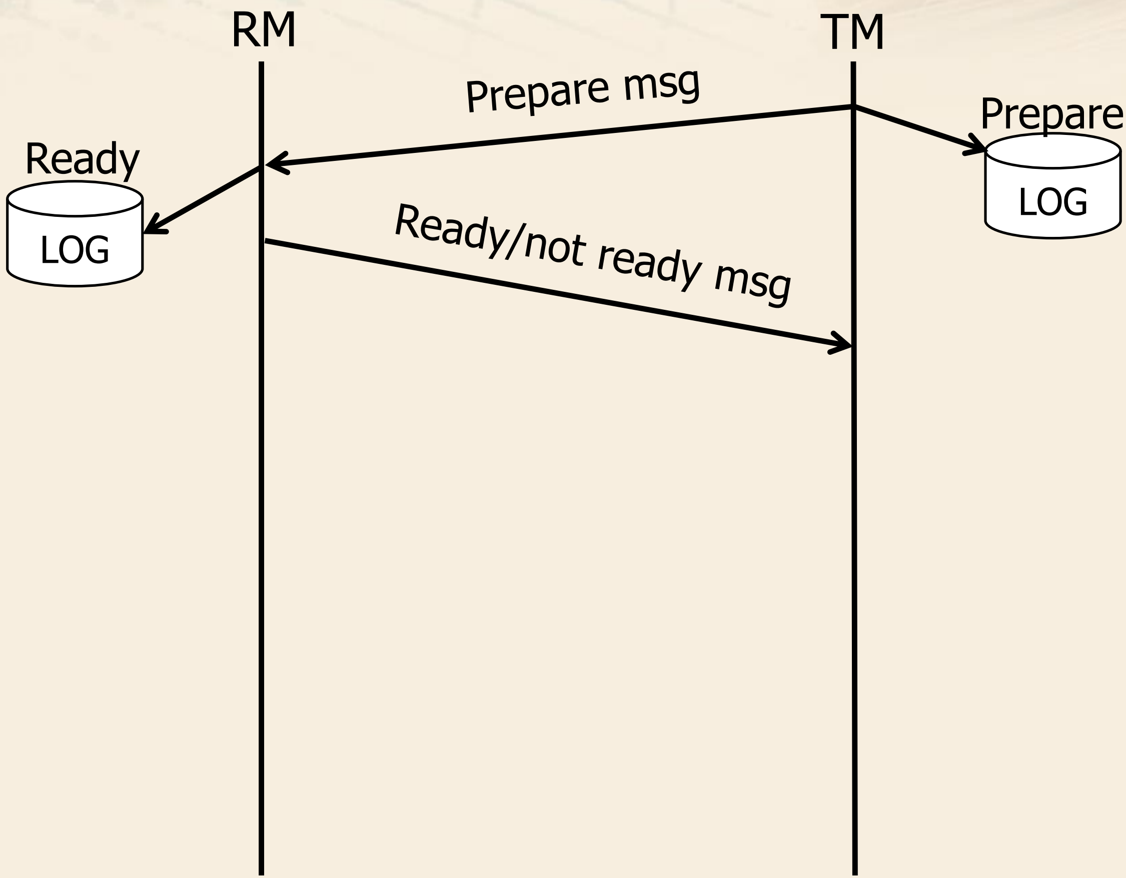
2 Phase Commit protocol



Phase I

1. The TM
   - Writes the prepare record in the log
   - Sends the prepare message to all RM (participants)
   - Sets a timeout, defining maximum waiting time for RM answer

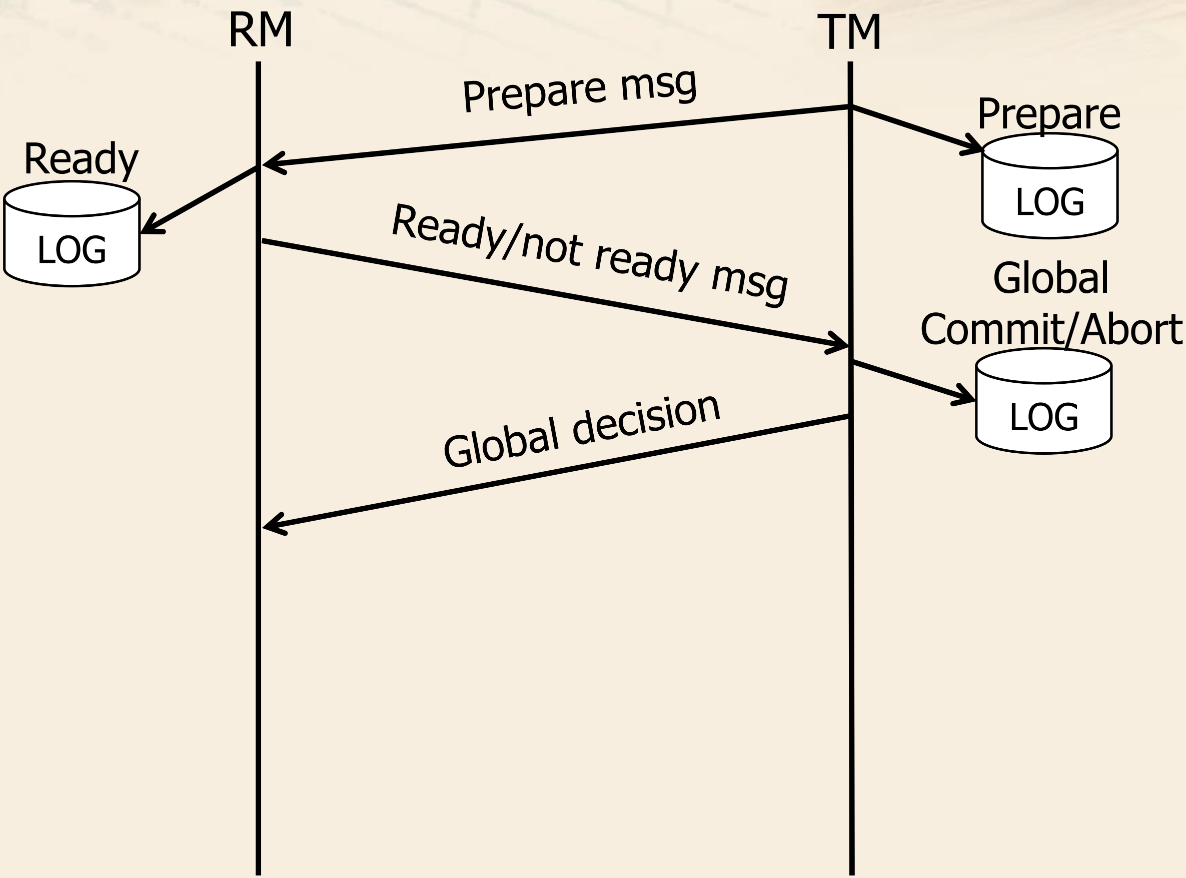
2 Phase Commit protocol



Phase I

2. The RMs
   - Wait for the prepare message
   - When they receive it
     - If they are in a reliable state
       - Write the ready record in the log
       - Send the ready message to the TM
     - If they are not in a reliable state
       - Send a not ready message to the TM
       - Terminate the protocol
       - Perform local rollback
     - If the RM crashed
       - No answer is sent

2 Phase Commit protocol



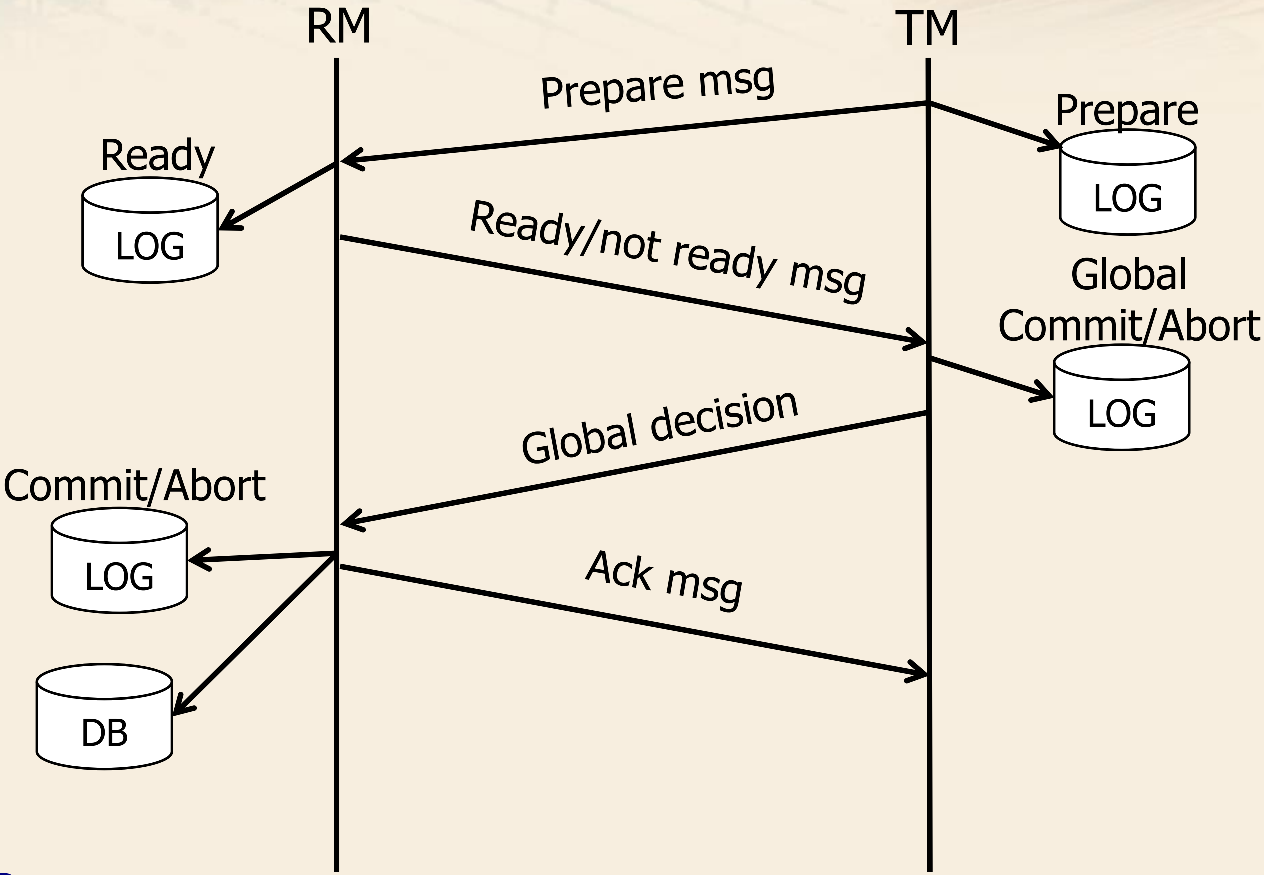
Phase I

3. The TM
   - Collects all incoming messages from the RMs
   - If it receives ready from *all* RMs
     - The commit global decision record is written in the log
   - If it receives one or more not ready or the timeout expires
     - The abort global decision record is written in the log

Phase II

1. The TM
   - Sends the global decision to the RMs
   - Sets a timeout for the RM answers

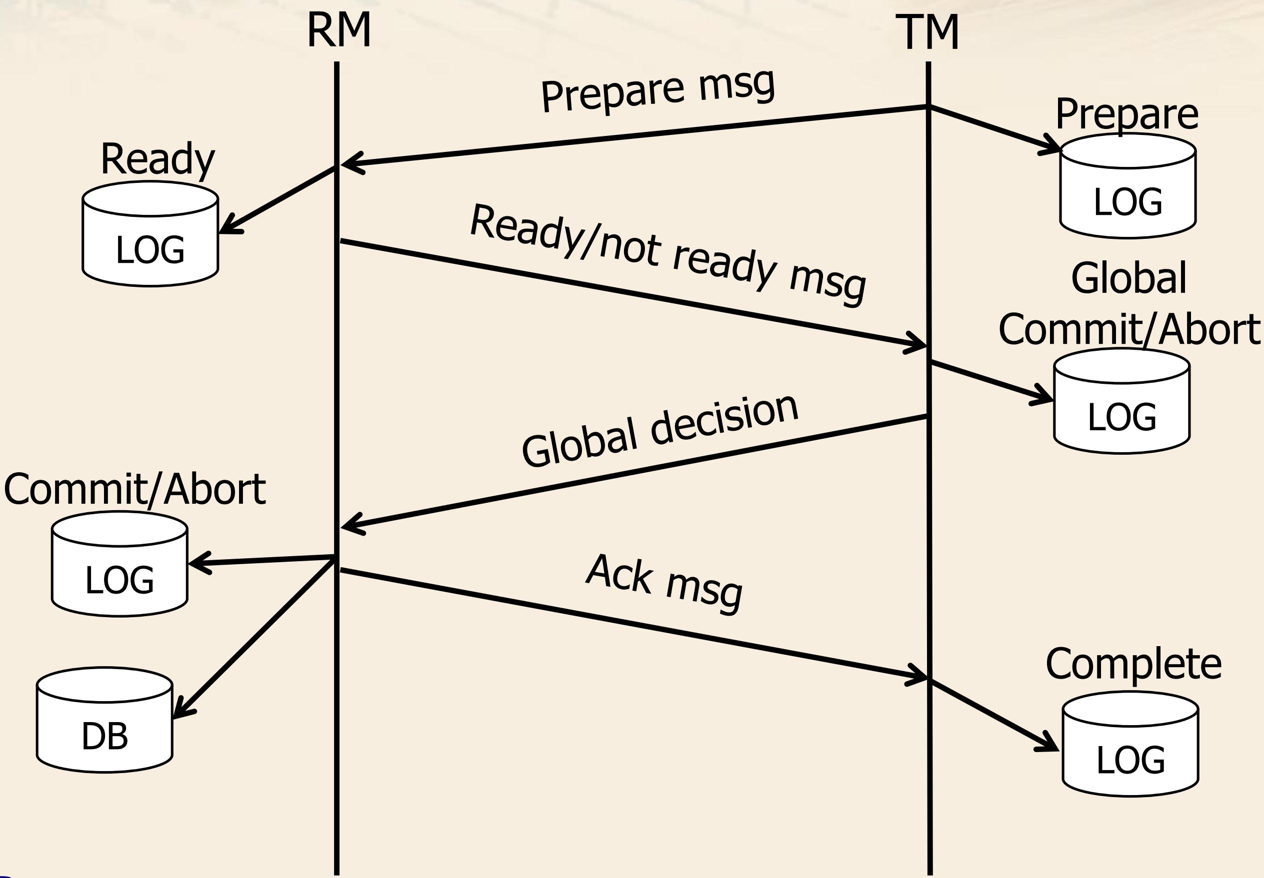
2 Phase Commit protocol



Phase II

2. The RM
   - Waits for the global decision
   - When it receives it
     - The commit/abort record is written in the log
     - The database is updated
     - An ACK message is sent to the TM

2 Phase Commit protocol



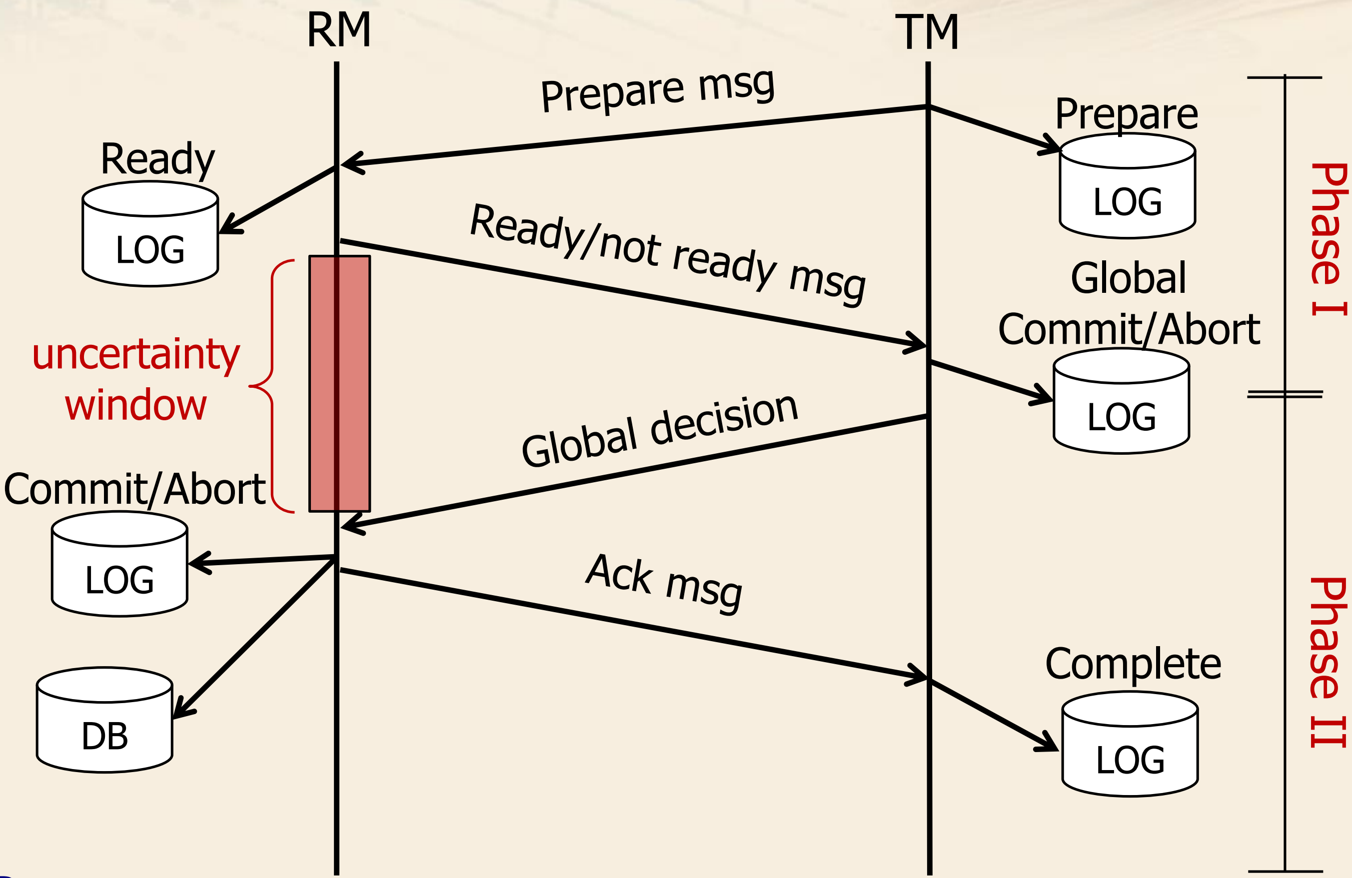
Phase II

3. The TM
   - Collects the ACK messages from the RMs
   - If *all* ACK messages are received
     - The complete record is written in the log
   - If the timeout expires and some ACK messages are missing
     - A new timeout is set
     - The global decision is resent to the RMs which did not answer

   until all answers are received

DBMG

2 Phase Commit protocol



Uncertainty window

- Each RM is affected by an *uncertainty window*
  - Start after ready msg is sent
  - End upon receipt of global decision
- Local resources in the RM are locked during the uncertainty window
  - It should be small

Failure of a participant (RM)

- The warm restart procedure is modified with a new case
  - If the last record in the log for transaction T is "ready", then T does not know the global decision of its TM
- Recovery
  - READY list
    - new list collecting the IDs of all transactions in ready state
  - For all transactions in the ready list, the global decision is asked to the TM at restart
    - Remote recovery request

Failure of the coordinator (TM)

- Messages that can be lost
  - Prepare (outgoing) } I Phase
  - Ready (incoming) } I Phase
  - Global decision (outgoing) } II Phase
- Recovery
  - If the last record in the TM log is prepare
    - The global abort decision is written in the log and sent to all participants
    - Alternative: redo phase I (not implemented)
  - If the last record in the TM log is the global decision
    - Repeat phase II

Network failures

- Any network problem in phase I causes global abort
  - The prepare or the ready msg are not received
- Any network problem in phase II causes the repetition of phase II
  - The global decision or the ACK are not received

X-Open-DTP

X-Open-DTP

- Protocol for the coordination of distributed transactions
- It guarantees interoperability of distributed transactions on *heterogeneous* DBMSs
  - i.e., different DBMS products
- Based on
  - One client
  - One TM
  - Several RMs

Interfaces

- X-Open-DTP defines interfaces for the communication
  - between client and TM
    - TM interface
  - between TM and RM
    - XA interface
- DBMS servers provide the XA interface
- Specialized products implement the TM and provide the TM interface
  - E.g., BEA tuxedo

Standard features

- RMs are passive and only answer to remote procedure invocations from the TM
- The control of the protocol is embedded in the TM
- The protocol implements two optimizations of 2 Phase Commit
  - Presumed abort
  - Read only
- Heuristic decision to allow controlled transaction evolution in presence of failures

Presumed abort

- The TM, when no information is available in the log, answers abort to a remote recovery request by a RM
  - Reduces the number of synchronous log writes
    - prepare, global abort, complete are not synchronous
  - Synchronous writes are still needed
    - global commit in TM log
    - ready, commit in RM log

Read only

- Exploited by a RM that did not modify its database during the transaction
- The RM
  - answers read only to the prepare request
  - does not write the log
  - locally terminates the protocol
- The TM will ignore the RM in phase II of the protocol

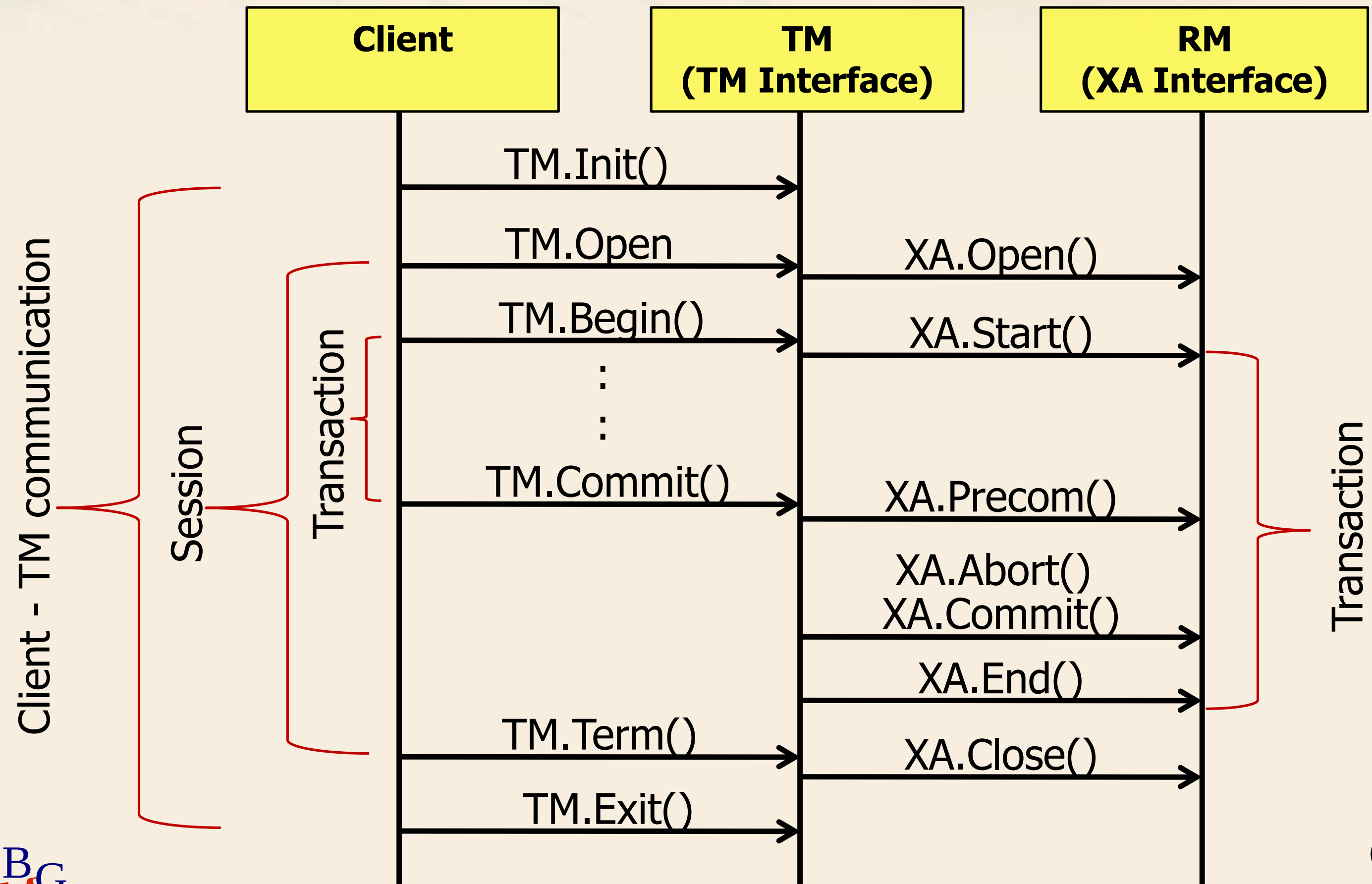
Heuristic decision

- Allows transaction evolution in presence of TM failures
  - During the uncertainty window, a RM may be blocked because of a TM failure
    - Locked resources are blocked until TM recovery
- The blocked transaction evolves locally under operator control
  - Transaction end is forced by the operator
    - Typically rollback, rarely commit
      - Heuristic decision, because actual transaction outcome is not known
    - Blocked resources are released

Heuristic decision

- During TM recovery, decisions are compared to the actual TM decisions
  - If TM decision and RM heuristic decision are different, atomicity is lost
  - The protocol guarantees that the inconsistency is notified to the client process
- Resolving inconsistencies caused by a heuristic decision is up to user applications

Protocol interaction



Parallel DBMS

Parallelism

- Parallel computation increases DBMS efficiency
- Queries can be effectively parallelized
  - Examples
    - large table scan performed in parallel on different portions of data
      - data is fragmented on different disks
    - group by on a large dataset
      - partitioned on different processors
      - group by result merged
- Different technological solutions are available
  - Multiprocessor systems
  - Computer clusters

Inter-query parallelism

- Different queries are scheduled on different processors
- Used in OLTP systems
- Appropriate for workloads characterized by
  - simple, short transactions
  - high transaction load
    - 100-1000 tps
- Load balancing on the pool of available processing units

Intra-query parallelism

- Subparts of the same query are executed on different processors
- Used in OLAP systems
- Appropriate for workloads characterized by
  - complex queries
  - reduced query load
- Complex queries are partitioned in subqueries
  - each subquery performs one or more operations on a subset of data
    - group by and join are easily parallelizable
    - pipelining operations is possible

DBMS benchmarks

DBMS benchmarks

- Benchmarks describe the conditions in which performance is measured for a system
- DBMS benchmarks are standardized by the TPC (Transaction Processing Council)
- Each benchmark is characterized by
  - Transaction load
    - distribution of arrival time of transactions
  - Database size and content
    - randomized data generation
  - Transaction code
  - Techniques to measure and certify performance

Types of benchmarks

- TPC C
  - Order entry transactions
  - It simulates the behavior of an OLTP system
  - New evolution is TPC E
- TPC H
  - Decision support (OLAP)
  - It is a mix of complex queries
  - Also TPC-DI and TPC-DS
- TPCx-HS
  - Big data management
  - Assessment of implementation of Hadoop clusters