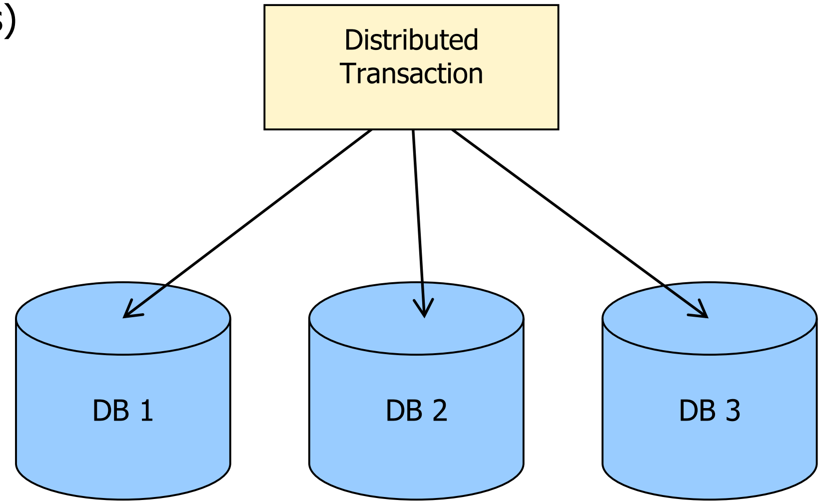
Chapter 6
Distributed Transactions

Commit Protocols
X/OPEN-DTP
Global Serializability

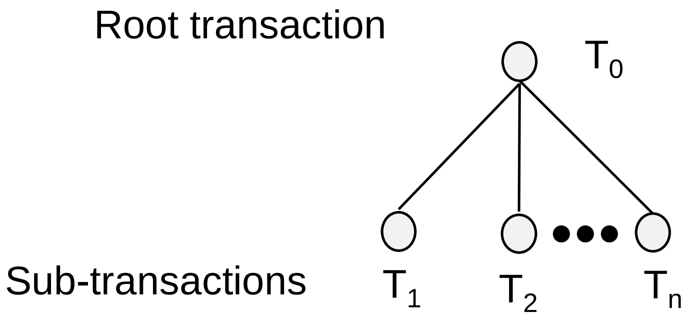
TA-Mgmt in Distributed DBMS

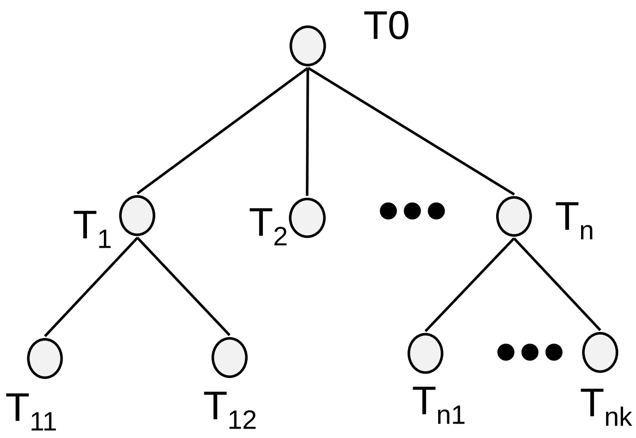
- **ACID properties must be ensured also in the distributed case**
- **Logging and Recovery**
  - global Commit Protocol
  - Robustness w.r.t. to partial failures, esp. Communication failures (network partitions)
- **Synchronization**
  - Global serializability
  - Global dependencies (e.g., global deadlocks)



Transaction Structure

- **Control Structure: Transaction Tree**
  - Represents invocation relations
  - Single-level or multi-level
  - No isolated rollback of sub-transaction: abort of sub-transactions leads to abort of overall transaction



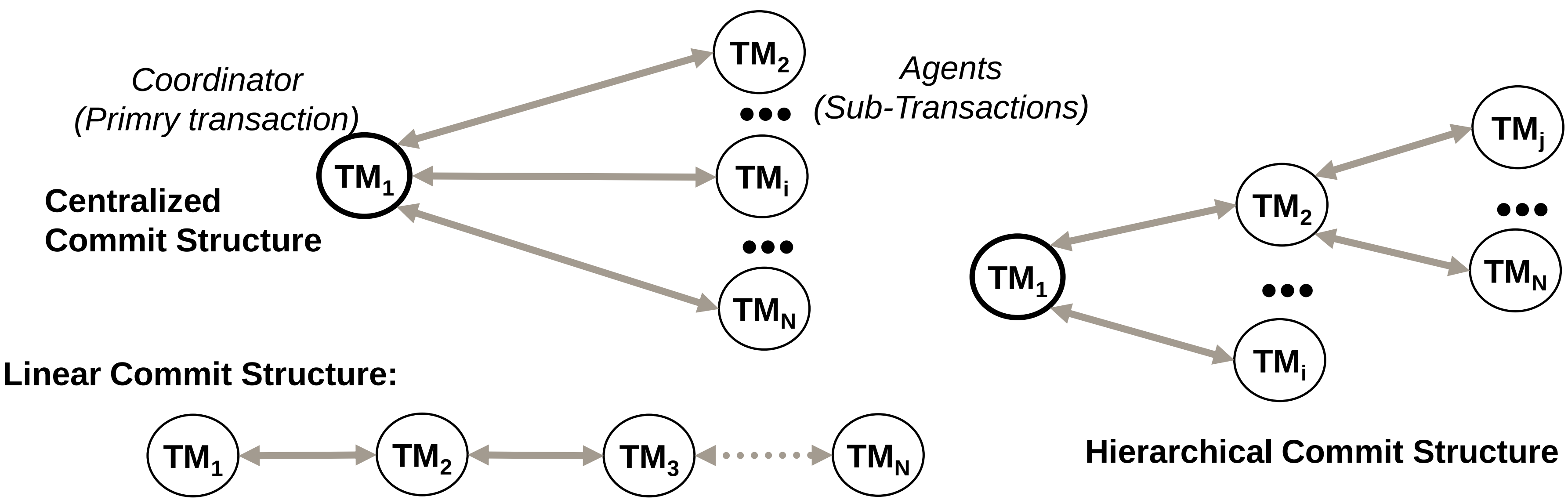


Commit Protocols

- **Ensuring atomicity of distributed transaction by comprehensive Multi-Phase-Commit-Protocol**
- **Requirements**
  - Correctness
  - Low Overhead (#Messages, #Log-Writes)
  - Low extension of response time
  - Robustness against crashes and communication failures
  - Node autonomy: each node has the possibility of an *unilateral abort* as long as possible

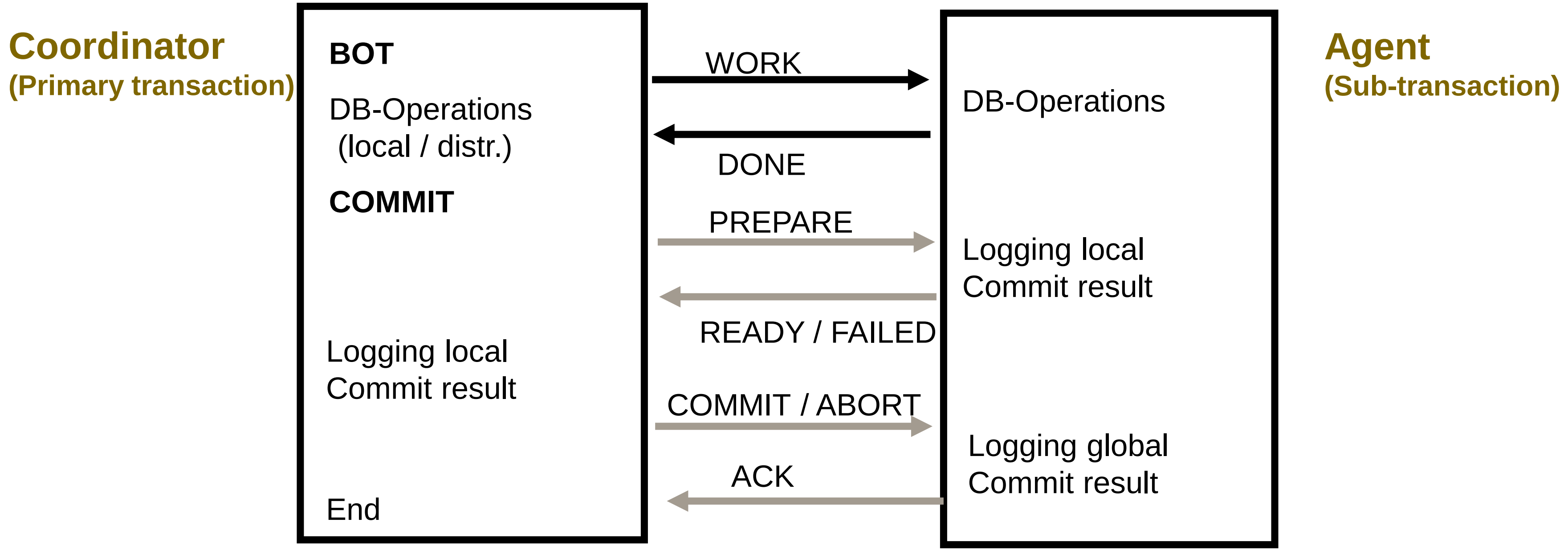
Commit Protocols (2)

- ***Transaction Manager (TM)*** **at each node (1 Coordinator + N-1 Agents)**
- **Standard: 2-Phase-Commit**
- **Alternatives: 1-Phase-Commit, 3-Phase-Commit**
- **Communication structures: centralized, linear or hierarchical**



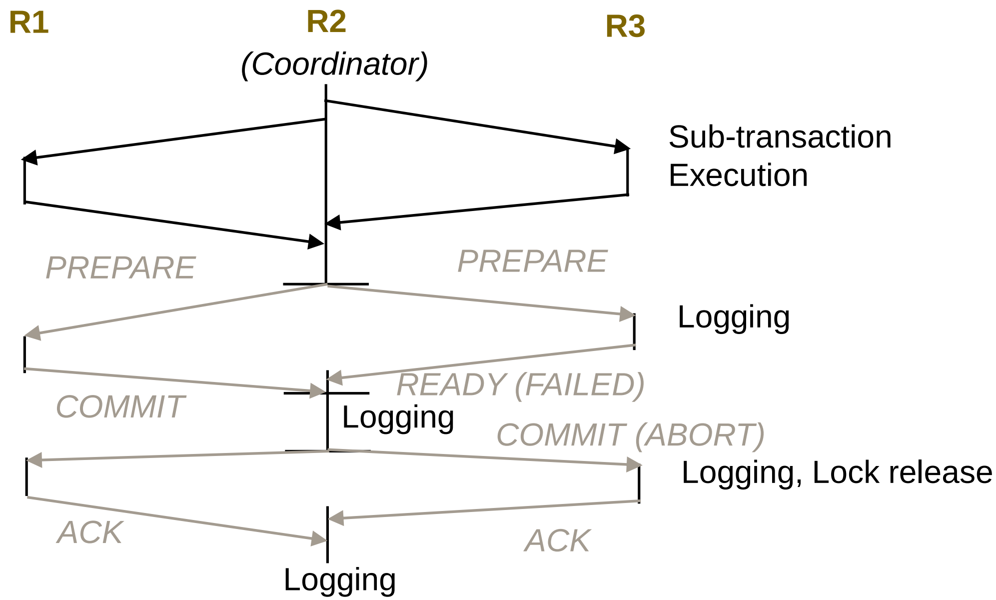
Centralized 2-Phase-Commit (N=2)

- **Overhead**
  - Successful processing: 4 messages, 4 Log-Writes
  - ABORT messages only for sub-transactions which not voted with FAILED
- **Problem Coordinator drop out => Blocking**

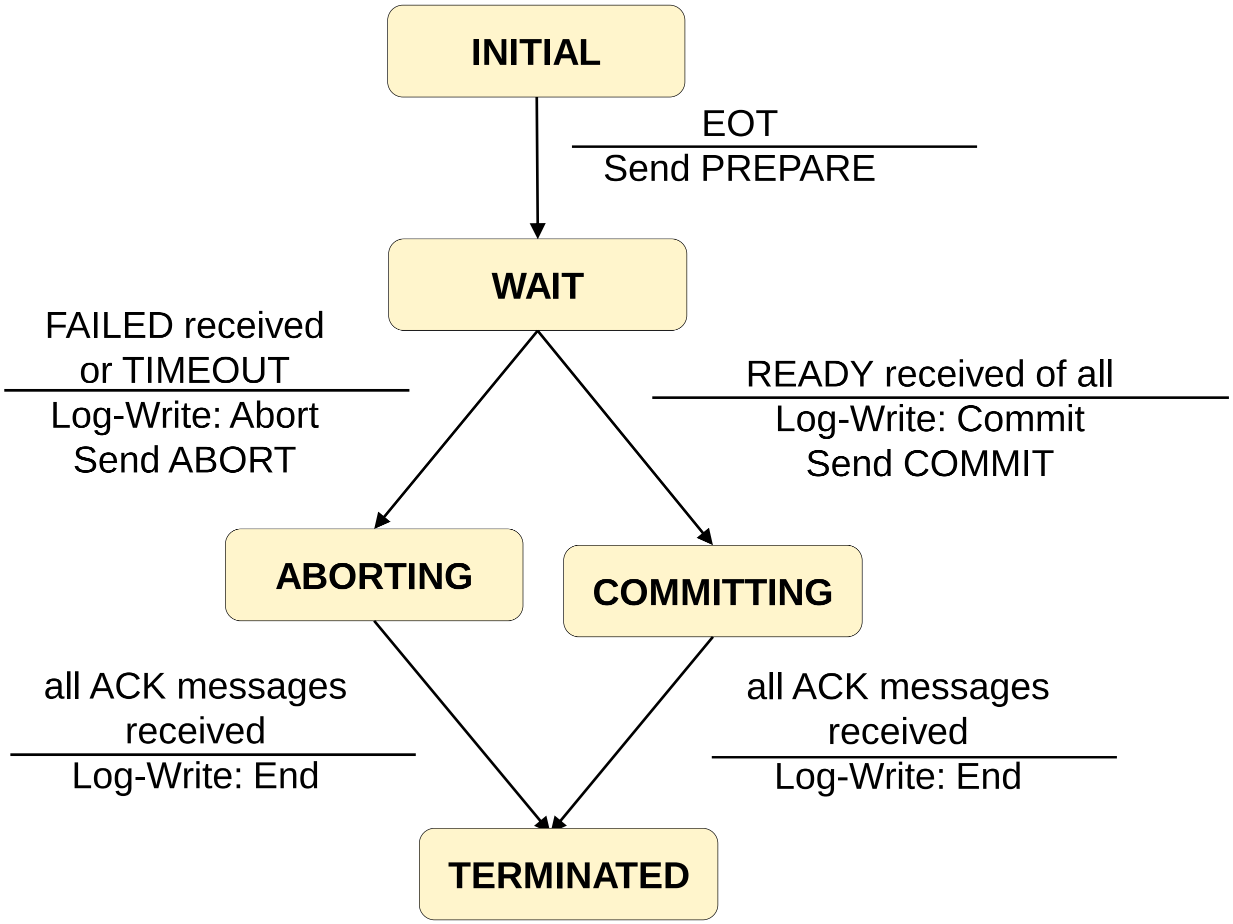


Centralized 2-Phase-Commit (N=3)

- **Basic mechanism:**
  - 4 (N-1)   Messages (N = no of nodes)
  - 2 N   Log-Writes
- **Optimization for read-only sub-transactions (M)**
  - 4 (N-1) - 2M   Messages for M < N, 2 (N-1) for M=N
  - 2 N - M   Log-Writes



2PC State Transitions: Coordinator

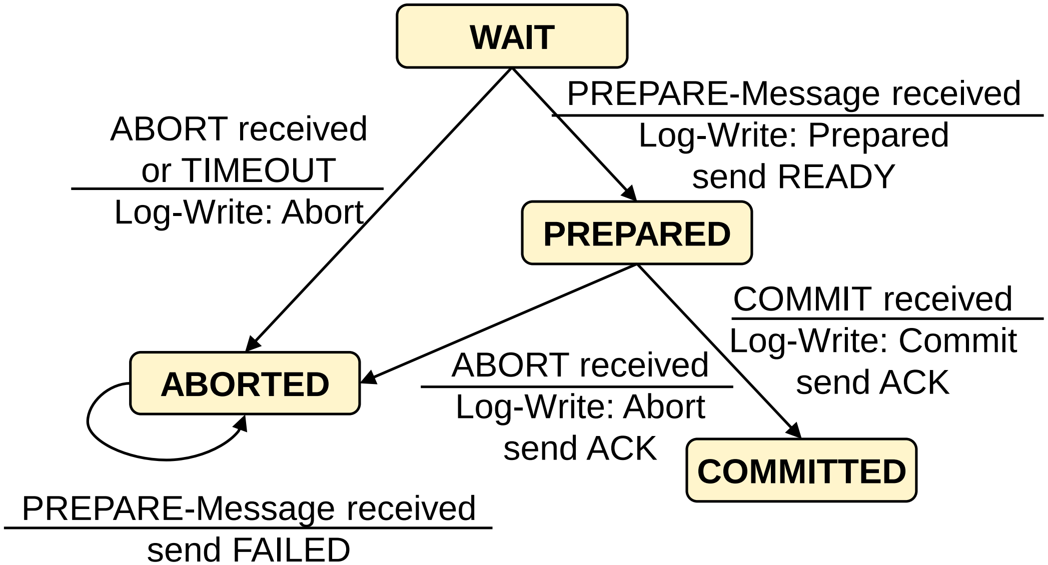


2PC: Failure Management

- **Timeout Conditions Coordinator:**
  - WAIT => Abort Transaction; send ABORT Message
  - ABORTING, COMMITTING => record Agents, which did not send ACK so far
- **Coordinator Drop Out**
  - Log-State TERMINATED:
    - UNDO/REDO-Recovery depending on transaction end
    - No “open�‟ sub-transactions
  - Log-State ABORTING:
    - UNDO-Recovery
    - ABORT-Message to each node, which did not send ACK so far
  - Log-State COMMITTING:
    - REDO-Recovery
    - COMMIT-Message to each node, which did not send ACK so far
  - Otherwise: UNDO-Recovery

2PC: Failure Management (2)

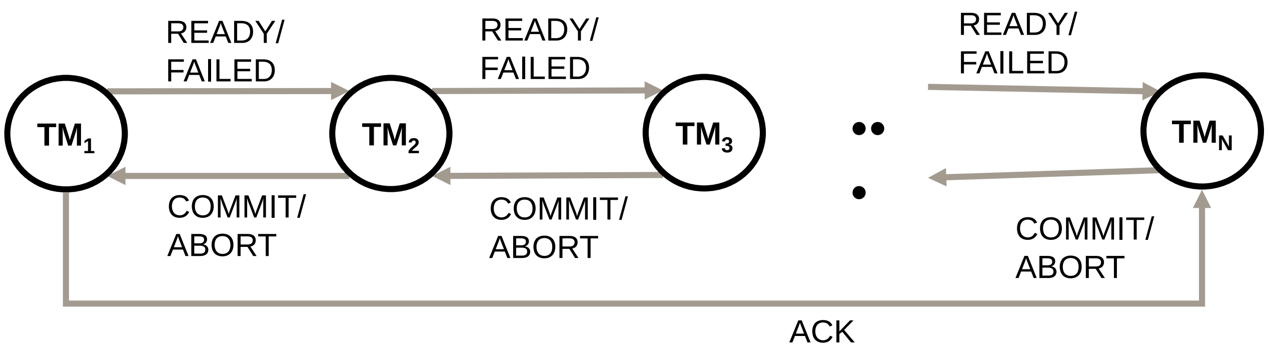
State Transitions Agent



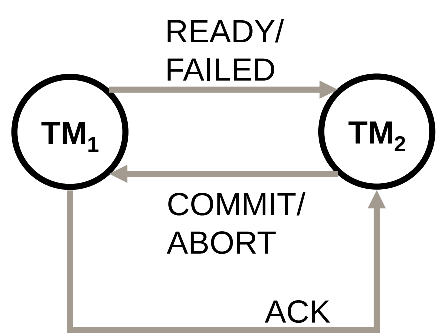
- **Timeout-Conditions for Agents:**
  - WAIT => unilateral ABORT
  - *PREPARED => ask coordinator (or other node) about transaction state/end*
- **Agent Drop Out:**
  - Log-State COMMITTED: REDO-Recovery
  - Log-State ABORTED or no 2PC-Log-Record: UNDO-Recovery
  - *Log-State PREPARED: ask coordinator abort transaction state/end (coordinator keeps information, since no ACK so far)*

Linear 2PC

- Sequential Commit Processing, #Messages: (N-1) + N = 2N-1
- Transfer of Coordination Task to last Agent
  ("Last Agent"-Optimization)

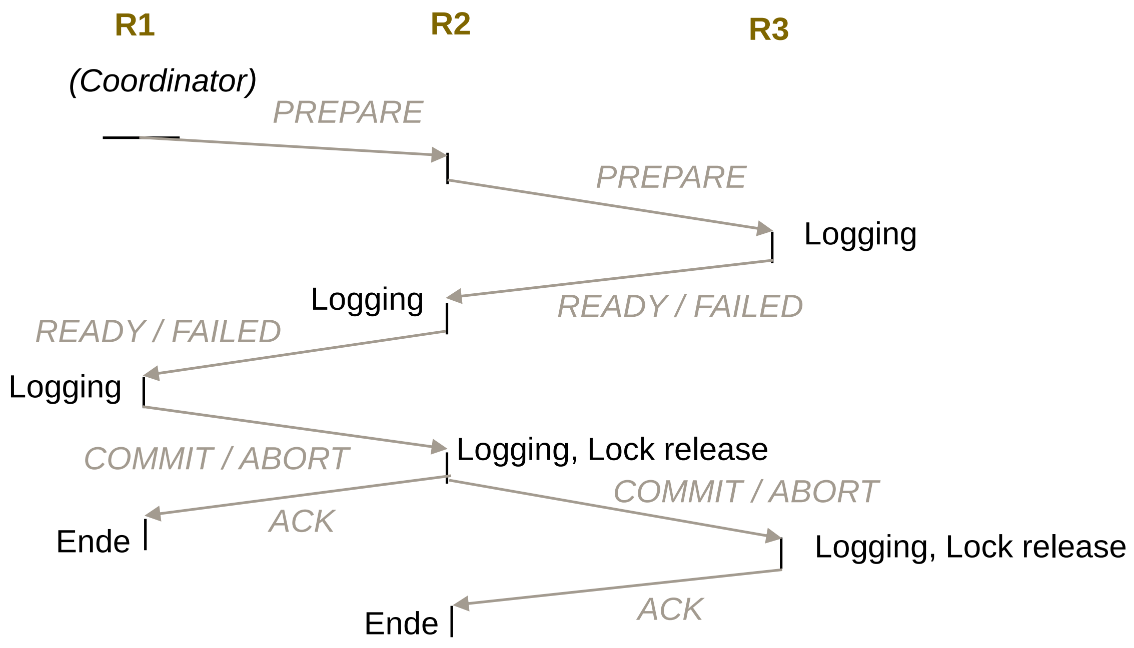


N=2:
3 Messages



Hierarchical 2PC

- **General model with arbitrary nesting**
  - Answering time increases with nesting depth (lower parallelization)



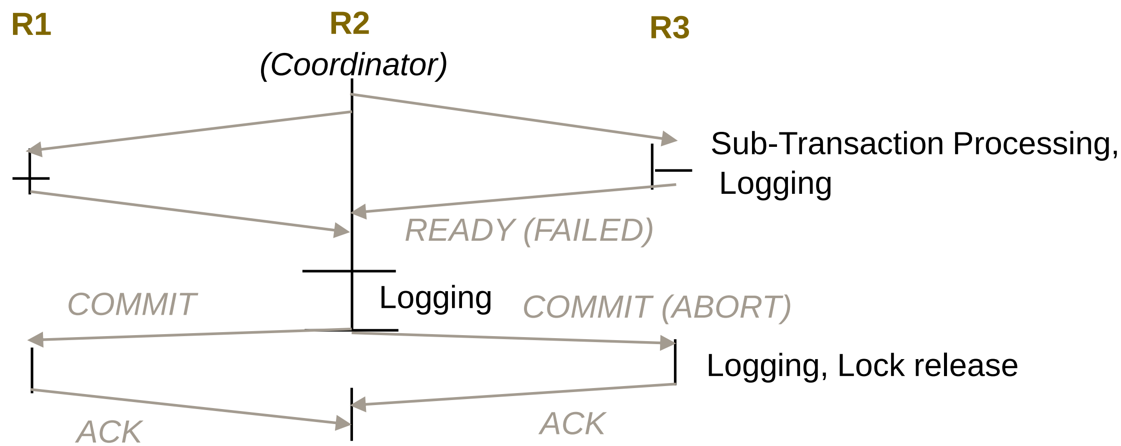
2PC Optimizations (1)

- ***Read-Only Sub-Transactions***
  - Read-Only-Agent answers in phase 1 with READ-ONLY
  - No logging necessary, lock release possible after phase 1
    - However: all other agents need to have their work finished, since locks are released
  - Thus, phase-2-communication not needed for read-only participants

2PC Optimizations (2)

- ***Presumed Abort-Protocol***
  - As soon as coordinator decides abort and has send the corresponding messages to agents, he forgets all transaction data
  - Agents do not reply to abort message (no ack)
  - If coordinator abort message does not reach an agent, this agent asks coordinator about final decision: if then coordinator does not find any information in its log, abort is assumed
  - Advantages
    - Coordinator does not need to write abort record
    - Aborted transactions do not cause ack messages

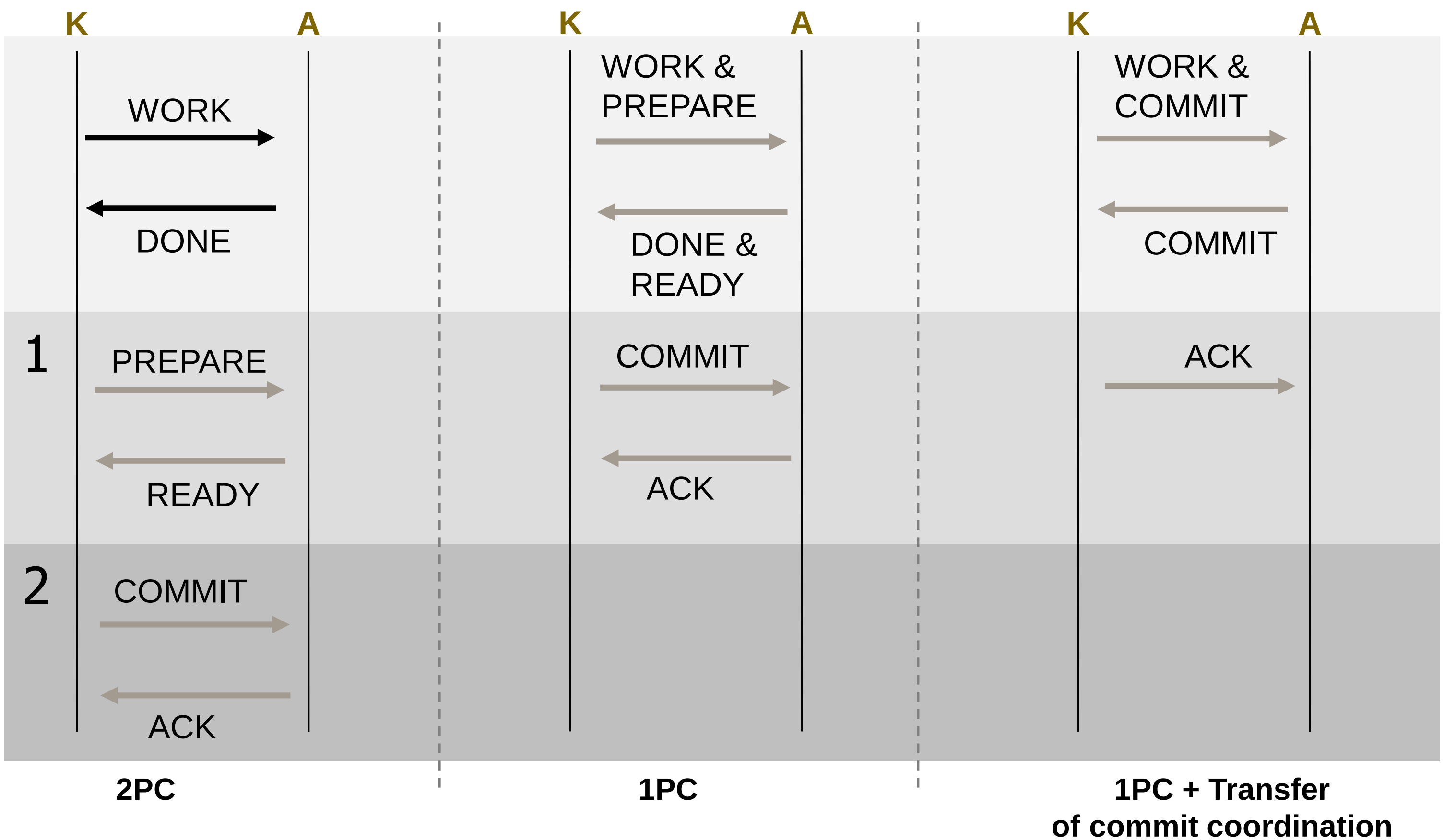
1-Phase-Commit



- **Sub-transactions already save their modifications before they pass back results to primary transaction**
  - After local Commit at coordinator node transaction success is given
- **2 (N-1) Messages**
  - Esp. advantageous for short (distributed) transactions
- **Disadvantages**
  - High dependency from coordinator, early relinquishment of unilateral abort
  - Higher probability of blocking through early prepared

1-Phase-Commit (2)

- For N=2 one more message can be saved by transfer of coordination

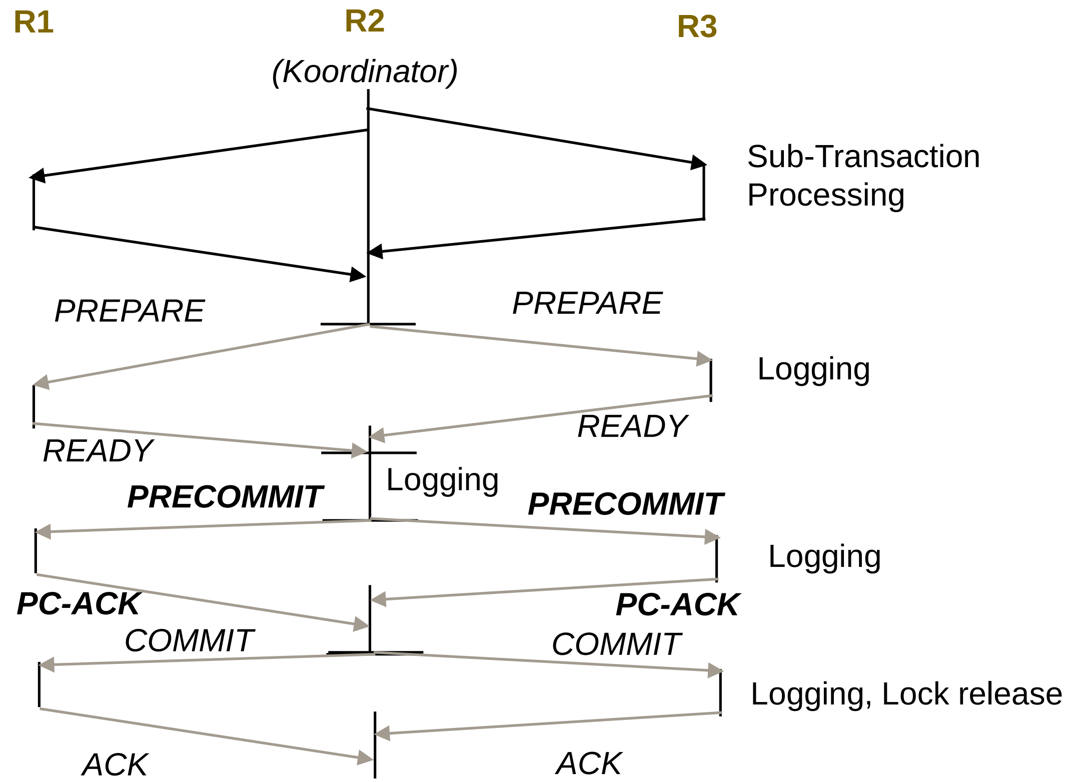


C = Coordinator

A = Agent

3-Phase-Commit

- **Non-blocking Technique**
- **Preconditions:**
  - No network partitions
  - At most K < N nodes fail simultaneously



3-Phase-Commit (2)

- **ABORT Processing like 2PC**
- **New intermediate phase, if sub-transactions finish phase 1 with READY**
  - Coordinator gets to state PRECOMMIT und tells all the sub-transactions about this decision
  - After k receipts (PC-ACK) COMMIT decision is taken
  - Now it is clear that transaction ‚will survive‶, not earlier
- **Coordinator drop out: selection of new coordinator**
  - Requesting transaction state of not finally processed transactions at ‘surviving’ nodes
    - Commit / Abort (or no Information, resp.): notification
    - Precommit at least at one surviving node:
      Commit protocol is continued by new coordinator by sending precommit messages
- **Resolves blocking problem in state Prepared**
  - Negative coordinator decision: no sub-transaction in Precommit
  - Positive coordinator decision: at least 1 node must be in Precommit
  - Even if coordinator in Precommit, abort still possible!

Messages Overhead

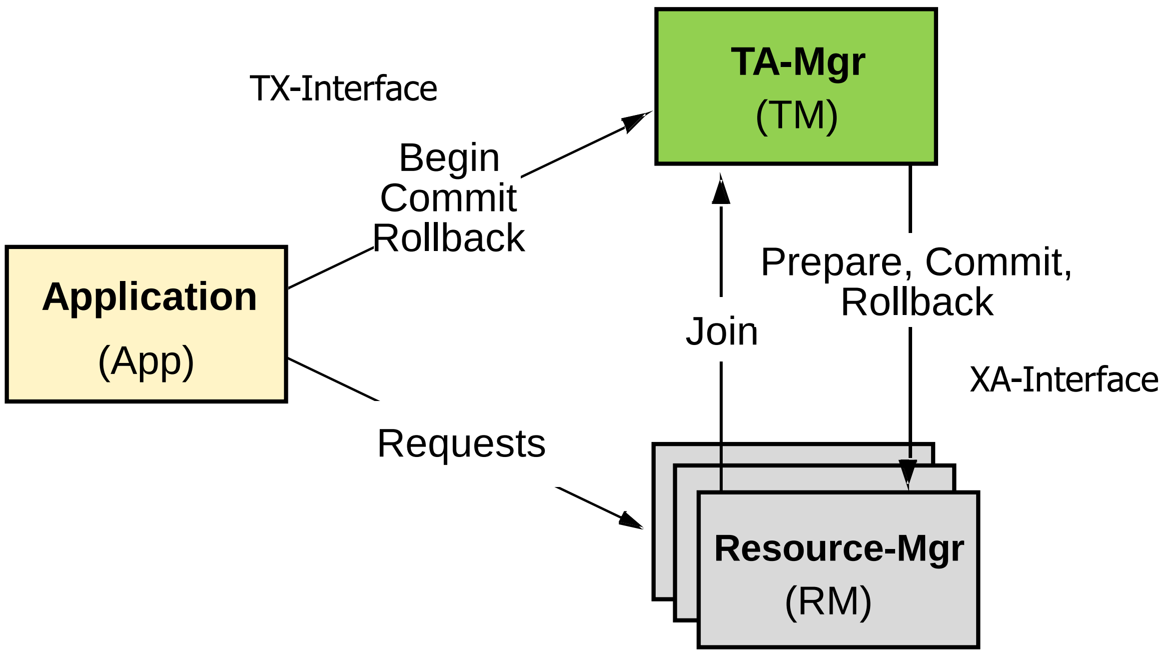
N: #Nodes

M: #Read-Only Sub-Transactions

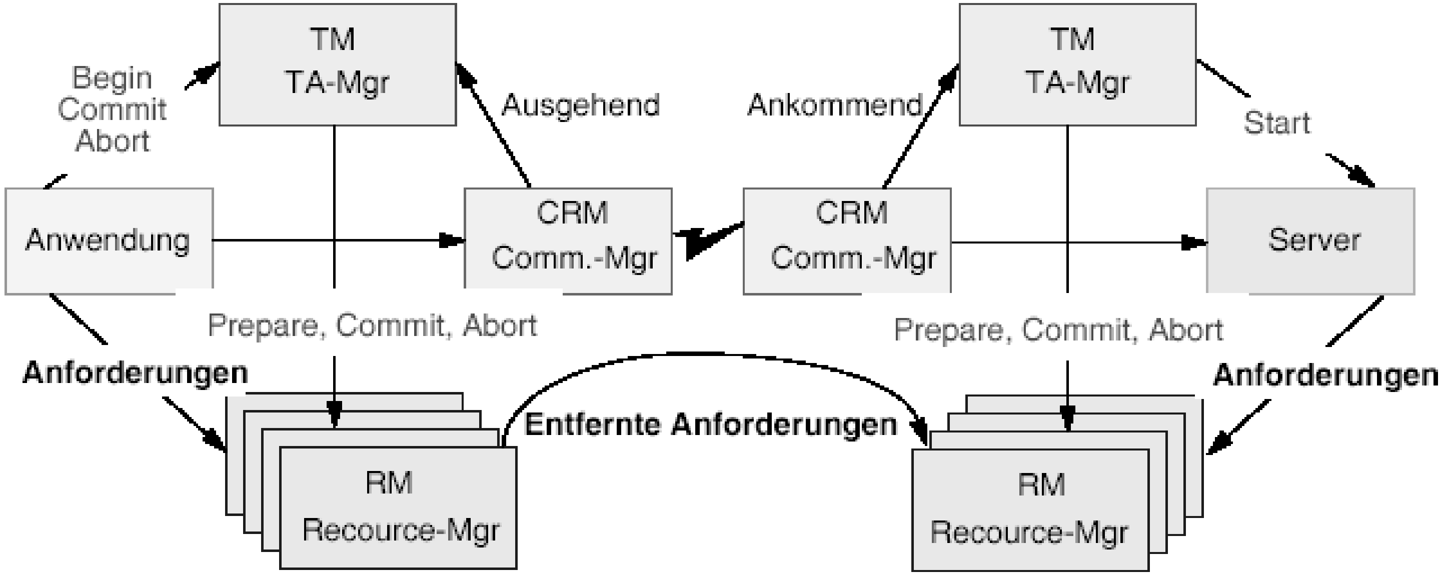
	General	Example 1 (N=2, M=0)	Example 2 (N=10, M=5)
1-Phase-Commit	2*(N-1)	2	18
Linear 2PC	2*N-1	3	19
centralized/hierarchical 2PC	4*(N-1)-2M	4	26
3-Phase-Commit	6*(N-1)-4M	6	34

TA-Mgmt in Open Systems

- **X/OPEN DTP**
  - Independent TA-Mgr
  - Resource Manager
    - recoverable
    - XA-compliant



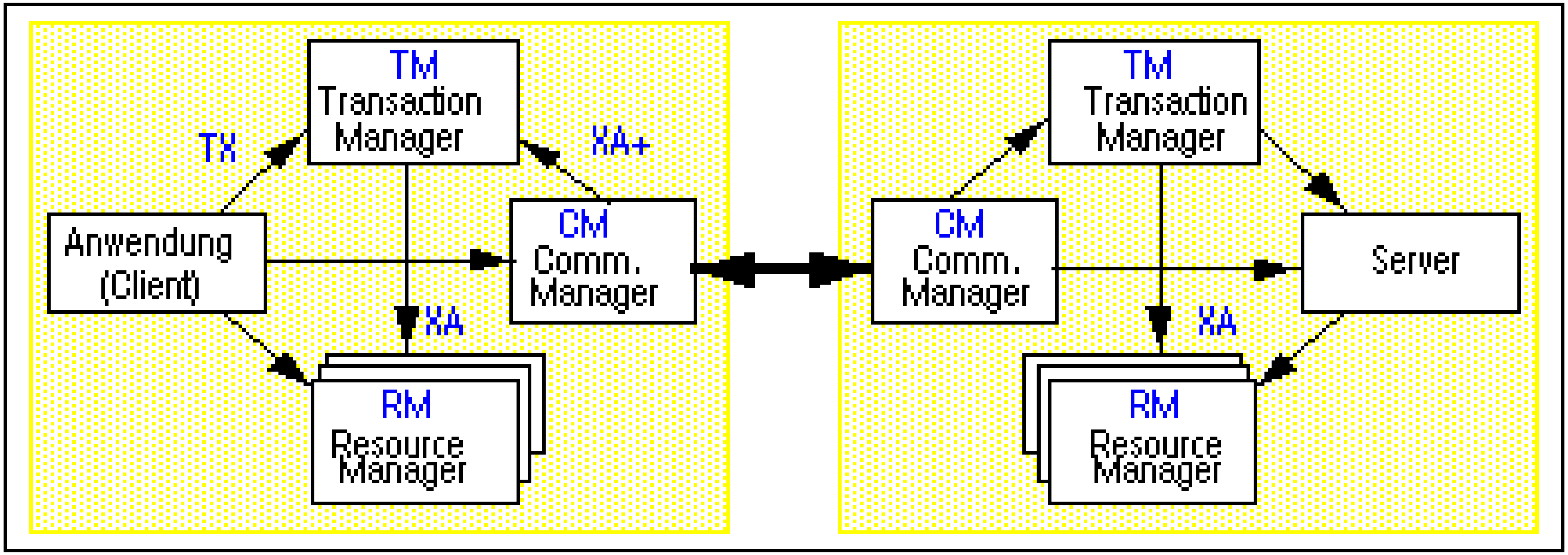
TA-Mgmt in Open Systems (2)



TA-Ablauf

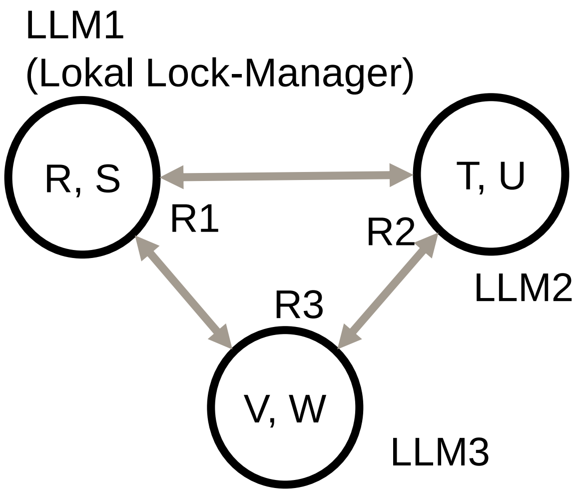
- AW startet TA, die vom lokalen TA-Mgr verwaltet wird
- Wenn die AW oder der RM, der für die AW eine Anforderung bearbeitet, eine entfernte Anforderung durchführen, informieren die CRMs an jedem Knoten ihre lokalen TA-Mgr über die ankommende oder ausgehende TA
- TA-Mgr verwalten an jedem Knoten jeweils die TA-Arbeit am betreffenden Knoten
- Wenn die AW COMMIT oder ROLLBACK durchführt oder scheitert, kooperieren alle beteiligten TA-Mgr, um ein atomares und dauerhaftes Commit zu erzielen.

TA-Mgmt in Open Systems (3)



Concurrency Control in Distributed DBS

- **Centralized locking techniques unacceptable**
  - Decrease of node autonomy
  - High communication overhead
- **Distributed locking techniques**
  - Each node manages locks for local data
  - Lock requests do not require messages
  - Locks release within commit protocol
  - Most relevant approach
- **Timestamp ordering**
  - Transactions get unique timestamp at BOT
  - Data accesses in timestamp order
  - No deadlocks, however many aborts
- **Optimistic concurrency control**
  - Validation at transaction end
  - Many aborts and starvation of transactions



Homogeneous Federations (1)

- **Homogeneous Federation**
  - Data distributed on n *Sites*
  - $D = \bigcup_{i=1}^{n} D_i$, $1 \leq i \leq n$
  - No replication
  - global TA only
- **Definition *Global History***
  - Given: federation with n *Sites*.
    $T = \{t_1, ..., t_m\}$ set of (global) TA.
    $s_1, ..., s_n$ local histories
  - A Global History for T and $s_1, ..., s_n$ is a History s for T, so that:
    $\prod_i(s) = s_i$ for all i, $1 \leq i \leq n$.

Homogeneous Federations (2)

- **Sub-Transaction**
  - Projection of a (global) Transaction on *Site* i
- **Example**
  - Given: Federation with 2 *Sites,* D1 ={x} und D2={y}
  - $s_1 = r_1(x)\ w_2(x)$ and $s_2 = w_1(y)\ r_2(y)$ local schedules
  - $s = r_1(x)\ w_1(y)\ w_2(x)\ c_1\ r_2(y)\ c_2$ global history
  - $\prod_1(s) = s_1$ and $\prod_2(s) = s_2$ (without considering commit operations)
  - Alternative notation for global Histories:

Server 1:	$r_1(x)$		$w_2(x)$	
Server 2:		$w_1(y)$		$r_2(y)$

Homogeneous Federations (3)

- **Definition *Conflict Serializability***
  - A global (local) History s is *globally (locally) conflict serializable*, if there is a conflict-equivalent serial history over the global (local) (sub-) transactions
- **Example**
  - History s

    Server 1: $r_1(x)$ $w_2(x)$

    Server 2: $r_2(y)$ $w_1(y)$
  - Scheduler at *Site* 1: $t_1 < t_2$
  - Scheduler at *Site* 2: $t_2 < t_1$
  - Conflict graph would be cyclic, s not conflict serializable

Homogeneous Federations (4)

- **Theorem**
  - Let s be global History with local Histories $s_1, ..., s_n$ over a set T of Transactions, so that each s_i, $1 \leq i \leq n$, conflict serializable. Then it is true:
    - s globally conflict serializable, if and only if there is a total order „<" on T, which is consistent with the local serialization orders of the Transactions, i.e.,
    - $(\forall\ t, t' \in T, t \neq t')\ t < t' \Rightarrow$
      $(\forall\ s_i, 1 \leq i \leq n, t, t' \in trans(s_i))\ (s_i' \text{ serial}, s_i \approx_c s_i')\ t <_{s_i'} t'$

Homogeneous Federations (5)

- **Exploitation of 2PL**
  - Local exploitation of 2PL: Problem
    - global decision, when locks can be released
  - Solution 1: *Primary Site 2PL*
    - Locks are managed only at *Primary Site*
      - Drawback: *Primary Site* as bottleneck
  - Solution 2: *Distributed 2PL (D2PL)*
    - Managing states of all local schedules at all sites
      - Drawback: high communication overhead
    - Before entering unlock-phase local server asks all others
      - Drawback: Overhead still (too) high

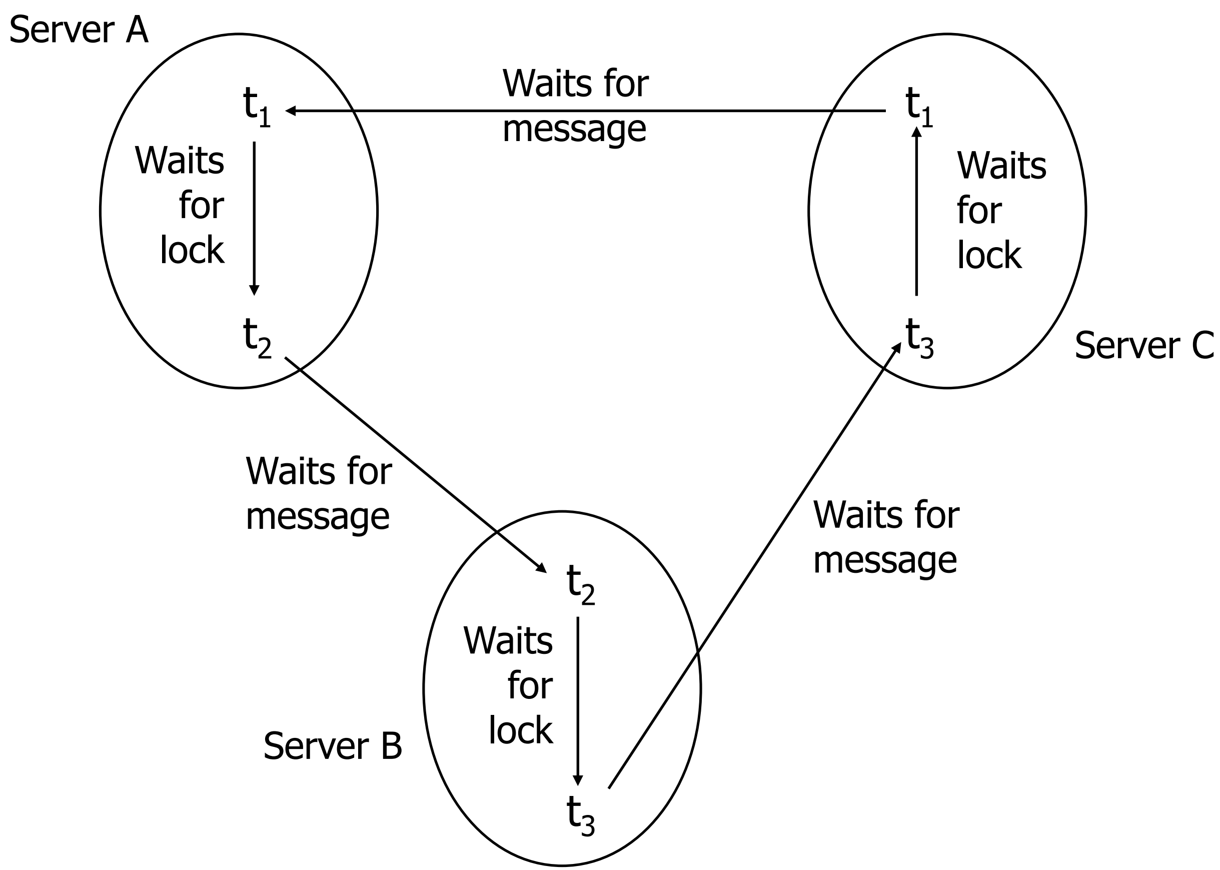
Homogeneous Federations (6)

- **Exploitation of 2PL (contd.)**
  - Remark
    - If all local servers apply SS2PL, then the resulting global history is not only conflict serializable but also strict
- **Also available**

  (Weikum, Vossen: Transactional Information Systems, pp. 680)
  - Distributed TO
  - Distributed SGT
  - Distributed optimistic protocols

Distributed Deadlock Detection (1)

- **Example of a distributed deadlocks**



Distributed Deadlock Detection (2)

- **Solution 1: *Centralized Detection***
  - Exploiting (kind of) *centralized Monitor*
    - Collecting and analyzing ‚Wait-for-Information' of local servers
    - After deadlock detection selection of ‚victim' by appropriate communication with local servers (taking rollback costs into account)
  - Drawback
    - Bottleneck
    - (Communication-) Overhead
  - Adequacy
    - Only in the case of fast and highly available communication connections
    - Not for communication over the Internet

Distributed Deadlock Detection (3)

- **Solution 1: *Centralized Detection (contd.)***
  - Further Problem: *False Deadlocks*
    - Immediately after cycle is closed by last edge, one of the corresponding TAs is locally aborted
    - Monitor does not notice and aborts second TA
    - Does not happen, if all local schedulers use 2PL and there are no spontaneous aborts (‚TA-suicide‘)
  - Timeouts can be used

Distributed Deadlock Detection (4)

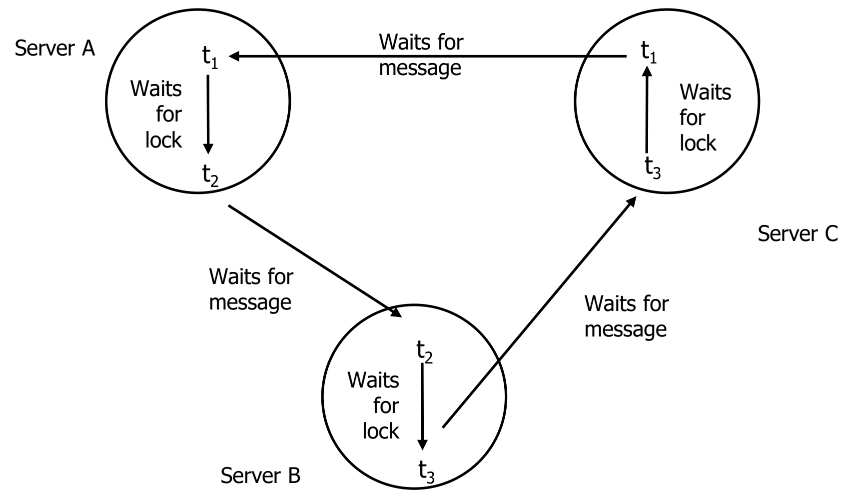
- **Solution 2: *Decentralized Approaches***
  - *Edge chasing*
  - *Path pushing*
- ***Edge chasing***
  - Blocked TA sends *Probe*-Message with own TA-ID to blocking TA
  - Each TA, which gets *Probe*-Message, sends it further to blocking TA
  - If a TA gets a message containing own TA-ID, deadlock is detected
  - Solution van be own abort

Distributed Deadlock Detection (5)

- ***Path pushing***
  - Idea: circulating paths instead of single TA-IDs
  - Algorithm
    1. Each server, which has a *waits-for path* from t_i to t_j, with t_i has an incoming and t_j an outgoing *waits-for message*, sends this path along the outgoing edge, providing that identifier of t_i is smaller than the one of t_j.
    2. After receipt of a path the server concatenates this path with its local paths and passes result further again.
       If there is a cycle among n servers, at least one of them detects the cycle in at most n steps.

Distributed Deadlock Detection (6)

- ***Path pushing (contd.)***
  - Example (slide 28)



Server A

$t_1 \longrightarrow t_2$

Server B

$t_2 \longrightarrow t_3$

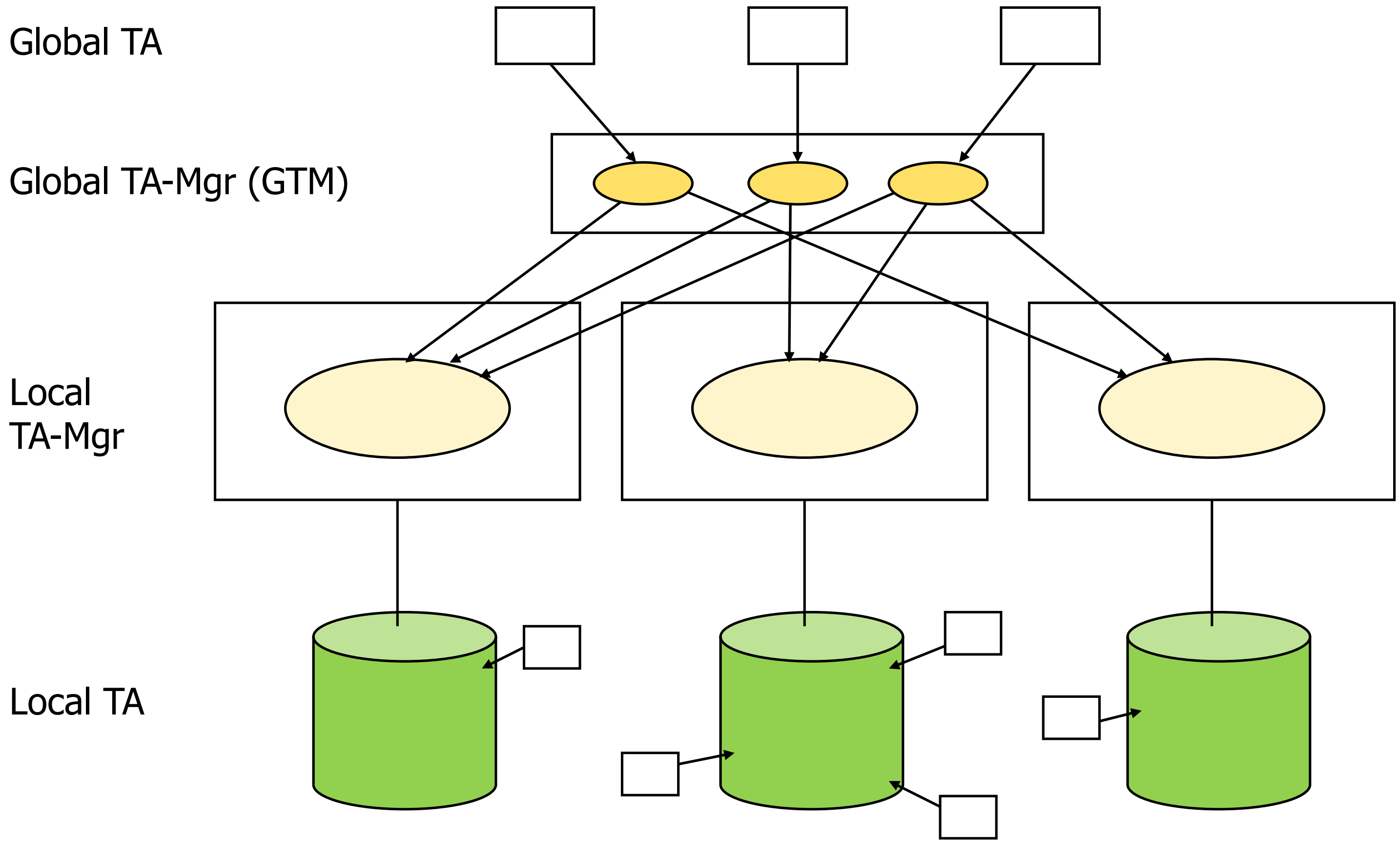
$t_1 \longrightarrow t_2 \longrightarrow t_3$

Server C

- Server C knows $t_3 \longrightarrow t_1$
  and detects global Deadlock

Heterogeneous Federations (1)

- **Illustration**



Heterogeneous Federations (2)

- **Histories in heterogeneous Federations**
  - Example
    - $D_1 = \{a, b\}, D_2 = \{c, d, e\}$
    - $D \;\; = \{a, b, c, d, e\}$
    - local TAs: $t_1 = r(a)\ w(b), t_2 = w(d)\ r(e)$
    - global TAs: $t_3 = w(a)\ r(d), t_4 = w(b)\ r(c)\ w(e)$
    - local Histories:

      $s_1 = r_1(a)\ w_3(a)\ c_3\ w_1(b)\ c_1\ w_4(b)\ c_4$

      $s_2 = r_4(c)\ w_2(d)\ r_3(d)\ c_3\ r_2(e)\ c_2\ w_4(e)\ c_4$

Heterogeneous Federations (3)

- **Histories in heterogeneous Federations (contd.)**
  - Definition ***Global History*** *(revisited)*
    - Considered heterogeneous Federation is supposed to have n *Sites*
    - $T_1, ..., T_n$ local TA at *Sites* 1, ..., n
    - T set of global TA
    - $s_1, ..., s_n$ local Histories with
      $T_i \subseteq trans(s_i)$ and $T \cap trans(s_i) \neq \emptyset$ for $1 \leq i \leq n$.
    - A (*heterogeneous) global History* (for $s_1, ..., s_n$) is a History s for $\bigcup_{i=1}^{n} T_i \cup T$, so that local projection equals local history, i.e. $\Pi_i(s) = s_i$ for all i, $1 \leq i \leq n$.

Heterogeneous Federations (4)

- **Histories in heterogeneous Federations (contd.)**
  - Example
    - $D_1 = \{a\}$, $D_2 = \{b, c\}$
    - global TAs: $t_1 = r(a)\ w(b)$, $t_2 = w(a)\ r(c)$
    - local TA: $t_3 = r(b)\ w(c)$
    - Assumption: GTM decides to process t_1 first
    - Resulting local Histories:
      Server 1: $s_1 = r_1(a) \quad w_2(a)$
      Server 2: $s_2 = \quad r_3(b)\ w_1(b) \quad r_2(c) \quad w_3(c)$
    - note: both global TAs are processed serially at both Sites
    - Global History: $s = r_1(a)\ r_3(b)\ w_1(b)\ c_1\ w_2(a)\ r_2(c)\ c_2\ w_3(c)\ c_3$
    - Obviously $s_1, s_2 \in$ CSR, but $s_1 \approx_c t_1\ t_2$ and $s_2 \approx_c t_2\ t_3\ t_1$
    - Thus, conflict graph of s cyclic,
      processing order as chosen by GTM not acceptable

Heterogeneous Federations (5)

- **Histories in heterogeneous Federations (contd.)**
  - Example (contd.)
    - Reasons
      - Direct Conflict between global Transactions in s_1
      - *indirect Conflict* in s_2, since
        - global TA t_2 in direct Conflict with local TA t_3 and
        - local TA t_3 in direct Conflict with global TA t_1
  - Indirect Conflicts can also occur, if there are no direct conflicts between global TA

(Weikum, Vossen: Transactional Information Systems, p. 693)

Heterogeneous Federations (6)

- **Global Serializability**
  - Definition ***Direct and Indirect Conflicts***
    - s_i local History and t and t‘ Transactions of trans(s_i), $t \neq t$‘

1. t and t‘ are in Direct Conflict in s_i if
   $(\exists\ p \in t)\ (\exists\ q \in t')\ (p, q) \in conf(s_i)$ (cf. Chapter 3)
2. t and t‘ in Indirect Conflict in s_i, if there is a sequence $t_1, \ldots, t_r$ of Transactions in trans(s_i), so that t in s_i in direct Conflict with t_1, t_j in s_i in direct Conflict with t_{j+1}, $1 \leq j \leq r-1$ and t_r in s_i in direct Conflict with t‘
3. t and t‘ are in s_i in Conflict, if they are in s_i in direct or indirect Conflict

Heterogeneous Federations (7)

- **Global Serializability**
  - Definition ***Global Conflict Graph***
    - Let s be global History for local Histories $s_1, \dots s_n$
    - Let $G(s_i)$ be Conflict Graph of s_i, $1 \leq i \leq n$, which considers direct as well as indirect Conflicts
    - The *Global Conflict Graph* of s is defined as the Union of all $G(s_i)$, $1 \leq i \leq n$, i.e.
      $G(s) := \bigcup_{i=1}^{n} G(s_i)$
  - **(Multidatabase Serializability) Theorem**
    - Given local Histories $s_1, \dots s_n$,
      with each $G(s_i)$, $1 \leq i \leq n$, acyclic (i.e., $s_i \in CSR$)
    - s global History for s_i, $1 \leq i \leq n$
    - then: s is globally conflict serializable if and only if G(s) acyclic

Heterogeneous Federations (8)

- **Global Serializability through local Guaranties**
  - Exploitation of Commitment Ordering (cf. Chapter 3)
    - One of several possibilities
      (see Weikum, Vossen: Transactional Information Systems, pp. 698, for more)
    - Theorem
      - s global History for $s_1, \dots s_n$
      - If $s_i \in$ COCSR, $1 \leq i \leq n$, and all global TA process their Commits strictly sequentially, then s globally serializable

Heterogeneous Federations (9)

- **Global Serializability through local Guaranties (contd.)**
  - Exploitation of Commitment Ordering (contd.)
    - Example
      - $s_1 = r_1(a)\ c_1\ w_3(a)\ w_3(b)\ c_3\ r_2(b)\ c_2$
      - $s_2 = w_4(c)\ r_1(c)\ r_2(d)\ r_4(e)\ c_1\ c_2\ [w_4(d)\ c_4]$
      - t_1, t_2 global; t_3, t_4 local
      - note: Commit-Operations ordered equally in both Histories
      - Assume s_2 processed until squared bracket
      - note, global TAs concurrently at *Site* 2

Heterogeneous Federations (10)

- **Global Serializability through local Guaranties (contd.)**
  - Exploitation of Commitment Ordering (contd.)
    - Example (contd.)
      - If Server 2 realizes COCSR, then s_2 cannot be continued, because the indirect conflict between t_2 and t_1, which would be caused by $t_{4,}$ would require that TA process their Commit operations in the order given by that conflict; but this is not possible any more
      - A COCSR-Scheduler would abort t_4!
- **Global Serializability without local Guaranties, e.g. by:** ***Ticket-Based CC***

(see Weikum, Vossen: Transactional Information Systems, pp. 698)

Conclusion

- **ACID Properties for Distributed Transactions**
- **Synchronization**
  - Ensuring global Serializability
  - Distributed locking techniques preferred (less communication overhead, fewer rollbacks than timestamp and optimistic techniques)
- **Global Deadlock Management**
  - Simplest Solution: Timeout
  - Deadlock Detection (e.g. Wound/Wait) avoids Communication, but results in unnecessary rollbacks
  - Distributed Deadlock Detection: high Overhead, but fewer rollbacks
- **Distributed Commit Protocols**
  - Atomicity and Durability of distributed modifications
  - Standard: hierarchical 2PC
  - Variants with better performance/availability (1PC, 3PC ...)
  - Comparably high overhead
- **XOPEN/DTP (2PC) and local ACID generally do not ensure global Serializability!**