3: Transaction Model

Page Model

- All operations on data will be eventually mapped into read and write operations on pages.
- To study the concurrent execution of transactions it is sufficient to inspect the interleavings of the resulting page operations.
- Independently whether a page resides in cache memory or resides on disk, read and write are considered as indivisible.

Parallelism as prerequisite for distributed execution

A transaction T is a partial order $<$[1] of actions in OP, $T = (OP, <)$, where OP is a finite set of T's actions RX and WX, where X is a data item.

Moreover, $< \subseteq OP \times OP$ is a partial order on OP which fulfills the following properties:

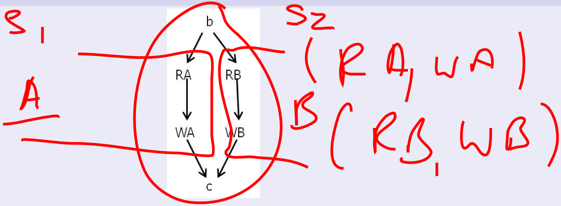
- Each data item is read and written by T at most once.
- If p is a read action and q is a write actions of T and both access the same data item, then $p < q$.

Complete transaction

We call a transaction *complete*, if its first action is begin b and its last action either is commit c or abort a.

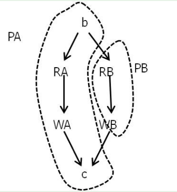
[1] A binary relation is a partial order , if it is reflexive, antisymmetric and transitive.

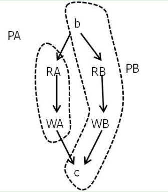
A parallel debit/credit transaction. *b*: BEGIN; *c*: COMMIT.



When transactions are depicted as directed graphs, we omit transitive edges.

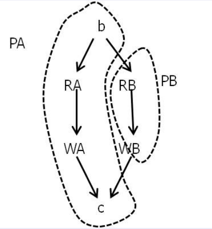
Two parallel debit/credit transactions, each prepared for parallel execution.



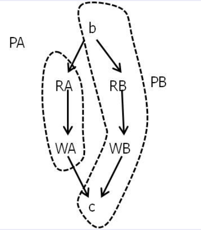


$\Longrightarrow$ Definition of a schedule? Definition of serializability?

Two parallel debit/credit transactions, each prepared for parallel execution.



Transaction T_1



Transaction T_2

Locally observable schedules of the two transactions when executed in parallel by CPU PA and CPU PB.

(i) $$\begin{array}{ll} PA: & R_1A\ W_1A\ R_2A\ W_2A \\ PB: & R_1B\ W_1B\ R_2B\ W_2B \end{array}$$

(ii) $$\begin{array}{ll} PA: & R_1A\ W_1A\ R_2A\ W_2A \\ PB: & R_2B\ W_2B\ R_1B\ W_1B \end{array}$$

On each CPU in both cases the local schedules are serializable - however, globally, in the second case the transactions are not executed in a serializable manner!

Histories and schedules

Let $\mathcal{T} = \{T_1, \ldots, T_n\}$ be a (finite) set of complete transactions, where for each T_i we have $T_i = (OP_i, <_i)$.

A *history* of $\mathcal{T}$ is a pair $S = (OP_S, <_S)$, where

- $OP_S = \cup_{i=1}^{n} OP_i$ and $<_S$ a partial order on OP_S such that $<_S \supseteq \cup_{i=1}^{n} <_i$.
- Let $p, q \in OP_S$, where p and q belong to distinct transactions, however access the same data object. If p or q is a write action, then either $p <_S q$ or $q <_S p$; we say, p and q are in *conflict*; if $p <_S q$ and p and q are in conflict, we write $(p, q) \in conf(S)$.

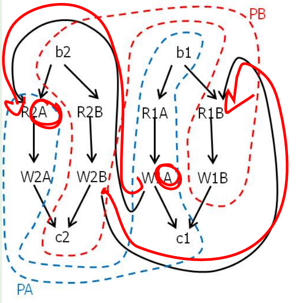
A *schedule* of $\mathcal{T}$ is a prefix of a history.[2]

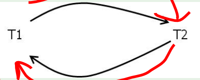
Conflict graph

The conflict graph of a schedule S is given as $G(S) = (V, E)$, where V is the set of transactions in S and the set of edges E is given by the conflicts in S: $T_i \to T_j \in E$, iff there are conflicting actions $p \in OP_i$, $q \in OP_j$ and $p <_S q$.

[2]A partial order $L' = (A', <')$ is a prefix of a partial order $L = (A, <)$, if $A' \subseteq A$, $<' \subseteq <$, for all $a, b \in A'$: $a <' b$ if $a < b$, and for all $p \in A, q \in A'$: $p < q \Rightarrow p <' q$.

A schedule/history of the two parallel debit/credit transactions.





The schedule is not serializable as its conflict graph is cyclic.

Serializability

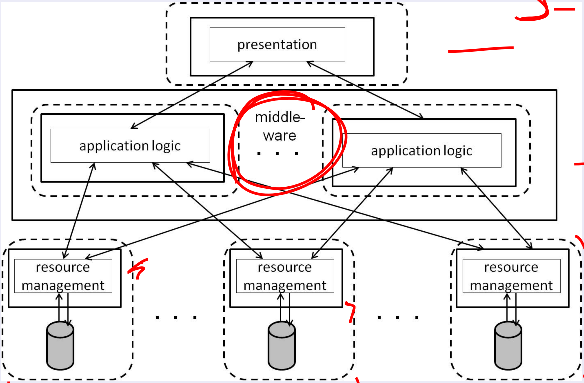
- A schedule $S = (OP_S, <_S)$ is *serial*, if for any two transactions T_1, T_2 appearing in S, $<_S$ orders all actions of T_1 before all actions of T_2, or vice versa.
- A schedule is called (conflict-)serializable,[3] if there exists a (conflict-)equivalent serial schedule over the same set of transactions.
- A schedule $S = (OP_S, <_S)$ is serializable, iff its conflict graph is acyclic.

[3] We consider only conflict-serializability and therefore talk about serializability in the sequel, for short.

4. Distributed Concurrency Control

General reference architecture.

3-tier



heterogeneous homogeneous

Federated system

4.1: Preliminaries

S_1 S_2

$D = D_1 \cup D_2$

$D_1 = \{A - K\}$ $D_2 = \{L - Z\}$

B

Sites and subtransactions

- Let be given a fixed number of sites across which the data is distributed. The server at site i, $1 \leq i \leq n$ is responsible for a (finite) set D_i of data items. The corresponding global database is given as $D = \cup_{i=1}^{n} D_i$.
- Data items are not replicated; thus $D_i \cap D_j = \emptyset$, $i \neq j$.
- Let $\mathcal{T} = \{T_1, \ldots, T_m\}$ be a set of transactions, where $T_i = (OP_i, <_i)$, $1 \leq i \leq m$.
- Transaction T_i is called *global*, if its actions are running at more than one server; otherwise it is called *local*.
- The part of a transaction T_i being executed at a certain site j is called *subtransaction* and is denoted by T_{ij}.

T_{11} T_{12} T_2

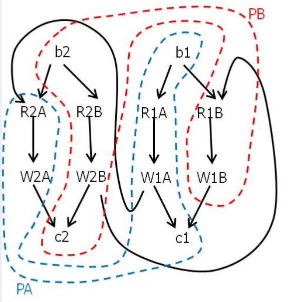
Local and global schedules

We are interested in deciding whether or not the execution of a set of transactions is serializable, or not.

- At the local sites we can observe an evolving sequence of the respective transactions' actions.
- We would like to decide whether or not all these locally observable sequences imply a (globally) serializable schedule.
- However, on the global level we cannot observe an evolving sequence, as there does not exist a notion of global physical time.

Example

Schedule:



Observed local schedules:

Site 1 (PA) : $R_1A\ W_1A\ R_2A\ W_2A$
Site 2 (PB) : $R_2B\ W_2B\ R_1B\ W_1B$

Can schedules be represented as action sequences, as well?

… yes, we call them *global schedules*.

From now on local and global schedules are sequences of actions!

Let $\mathcal{T} = \{T_1, \ldots, T_m\}$ be a set of transactions being executed at n sites. Let $S_1, \ldots, S_n$ be the corresponding local schedules.

A *global schedule* of $\mathcal{T}$ with respect to $S_1, \ldots, S_n$ is any sequence S of the actions of the transactions in $\mathcal{T}$, such that its projection onto the local sites equals the corresponding local schedules $S_1, \ldots, S_n$.

Example

A   B

Consider local schedules $S_1 = R_1A\ W_2A$ and $S_2 = W_1B\ R_2B$.

Global schedules: $S : R_1A\ W_1B\ W_2A\ R_2B$
$S' : R_1A\ W_1B\ R_2B\ W_2A$

$S[S_1] = R_1AW_2A$ ✓
$S[S_2] = W_1BR_2B$ ✓

Not a global schedule: $S'' : R_1A\ R_2B\ W_1B\ W_2A$

$S'[S_1] = R_1AW_2A$ ✓
$S'[S_2] = W_1BR_2B$ ✓

$S''[S_1] = R_1AW_2A$ ✓
$S''[S_2] = R_2BW_1B$ ↯

Examples where there does not exist a serializable global schedule

- $T_1 = R_1A\ W_1B$, $T_2 = R_2C\ W_2A$ are global transactions and $T_3 = R_3B\ W_3C$ is a local transaction.

A / B C

S_1 :	R_1A	W_2A			
S_2 :	R_3B	W_1B	R_2C	W_3C	

$T_1 \to T_2$

$T_2 \to T_3 \to T_1$

Note, in S_2 subtransactions T_{12} and T_{22} have no conficiting actions!

S1 S2 S1 S2

- $T_1 = RA\ RD$ und $T_2 = RB\ RC$ are global transactions, while $T_3 = RA\ RB\ WA\ WB$ and $T_4 = RD\ WD\ RC\ WC$ are local transactions.

A B / C D

S_1 :	R_1A	R_3A	R_3B	W_3A	W_3B	R_2B
S_2 :	R_4D	W_4D	R_1D	R_2C	R_4C	W_4C

$T_1 \to T_3 \to T_2 \to T_4 \to T_1$

Note, both global transactions are only reading and, in particular, disjoint data sets!

In both examples the local schedules are serializable, however no serializable global schedule exists.

Serializability of global schedules

- As we do not have replication of data items, whenever there is a conflict in a global schedule, the same conflict must be part of exactly one local schedule.
- Consequently, the conflict graph of a global schedule is given as the union of the conflict graphs of the respective local schedules.
- In particular, given a set of local schedules, either all or none corresponding global schedule is serializable.

Examples

- $S_1 :\quad R_1 A \quad W_1 A \quad R_2 A \quad W_2 A$
  $S_2 :\quad R_2 B \quad W_2 B \quad R_1 B \quad W_1 B$

- $S_1 :\quad R_1 A \quad W_2 A$
  $S_2 :\quad R_3 B \quad W_1 B \quad R_2 C \quad W_3 C$

- $S_1 :\quad R_1 A \quad R_3 A \quad R_3 B \quad W_3 A \quad W_3 B \quad R_2 B$
  $S_2 :\quad R_4 D \quad W_4 D \quad R_1 D \quad R_2 C \quad R_4 C \quad W_4 C$

MapReduce

Types of federation

- *homogeneous* federation:

  Same services and protocols at all servers. Characterized by *distribution transparency*: the federation is perceived by the outside world as if it were not distributed at all.

- *heterogenous* federation:

  Servers are autonomous and independent of each other; no uniformity of services and protocols across the federation.

Interface to recovery

Every global transactions runs the 2-phase-commit protocol. By that protocol the subtransactions of a global transaction synchronize such that either all subtransactions commit, or none of them, i.e. all abort. Details are given in Chapter 5.

4.2: Homogeneous Concurrency Control

Serializability by distributed 2-Phase Locking (2PL)

A transactions entry into the unlock-phase has to be synchronized among all sites the transaction is being executed.

Primary Site 2PL:

- One site is selected at which lock maintenance is performed exclusively.
- This site thus has global knowledge and enforcing the 2PL rule for global and local transactions is possible.
- The lock manager simply has to refuse any further locking of a subtransaction T_{ij} whenever a subtransaction T_{ik} has started unlocking already.
- Much communication is resulting which may create a bottleneck at the primary site.

T_{11} T_{12}

Example

S_1 : L_1A R_1A W_1A u_1A L_2A R_2A W_2A u_2A

u_2B

S_2 : L_2B R_2B W_2B R_1B W_1B

L_1B

Distributed 2PL:

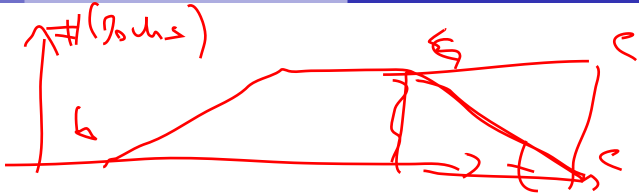
- When a server wants to start unlocking data items on behalf of a transaction, it communicates with all other servers regarding the lock point of the other respective subtransaction.
- The server has to receive a *locking completed*-message from each of these servers.
- This implies extra communication between servers.

Example

S_1 : $R_1 A$ $W_1 A$ $U_1 A$ $R_2 A$ $W_2 A$ $U_2 A$

S_2 : $R_2 B$ $W_2 B$ $L_1 B$ $R_1 B$ $W_1 B$ $U_1 B$

$U_2 B$



Distributed Strong 2PL:

- Every subtransaction of a global transaction and every local transaction holds locks until commit.
- Then by the 2-phase-commit protocol the 2PL-rule is enforced as a side-effect.

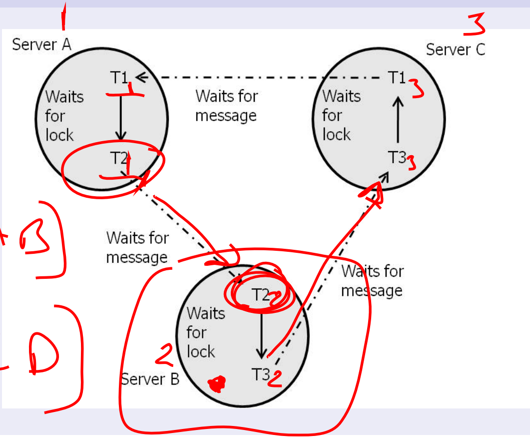
Applying strong 2PL the global 2PL-property is self-guaranteed without any explicit measures!

Locking protocols are prone to deadlocks!

Global deadlock

T_{21} [A B]

T_{22} [C D]



Global deadlock detection is difficult. Detection strategies:

- *Centralized detection*: Each site maintains its local wait-for graph. One distinguished site is selected to which all local wait-for graphs are send periodically. The selected site computes the union of all local wait-for graphs and checks for deadlocks.
- *Time-out based detection*: Whenever during a wait a *time-out* occurs, the respective transaction decides for a deadlock and aborts itself.
- *Edge chasing*: Whenever a transaction T waits for a transaction T', it sends its identification to T'. Whenever a transaction T' receives such a message, it sends the identification of such T to all transctions it is waiting for. If a transaction recieves its own identification, it decides for a deadlock and it aborts itself.
- *Path pushing:*

  (i) Each server that has a waits-for path from transaction t_i to transaction t_j such that T_i has an incoming waits-for-message edge and T_j has an outgoing waits-for-message edge sends that path to the server along the outgoing edge.

  (ii) Upon receiving a path the server concatenats this with the local paths that already exist, and forwards the result along its outgoing edges again. If there exists a cycle among k servers, at least one of them will detect the cycle in at most k rounds.

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Serializabilty by assigning timestamps to transactions

- Global and local transactions are timestamped; all subtransactions of a transaction obtain the same timestamp.
- Timestamps must be system-wide unique and based on synchronized clocks.
- To be system-wide unique, timestamps are values of local clocks concatenated with the site ID.

Time Stamp Protocol TS

- To each transaction T it is assigned a unique timestamp $Z(T)$ when it is started.
- A transaction T must not write an object which has been read by any T' where $Z(T') > Z(T)$.
- A transaction T must not write an object which has been written by any T' where $Z(T') > Z(T)$.
- A transaction T must not read an object which has been written by any T' where $Z(T') > Z(T)$.

The TS-protocol guarantees serializability of schedules.

Let S be a global schedule of a set of transactions $\mathcal{T} = \{T_1, \ldots, T_n\}$, which all apply TS.

Assume, S is not serializable, i.e. the conflict graph $G(S)$ is cyclic, where w.l.o.g. $T_1 \rightarrow T_2 \rightarrow \cdots \rightarrow T_k \rightarrow T_1$.

- Each edge $T \rightarrow T'$ implies T and T' have conflicting actions, where the action of T precedes the one of T'.
- Because of TS we know $Z(T) < Z(T')$. This implies the following:

$$Z(T_1) < Z(T_2) < \ldots < Z(T_n) < Z(T_1),$$

a contradiction. Therefore S is serializable.

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4.3: Heterogeneous Concurrency Control

Local and global transaction managers

- Each server runs its own *local* transaction manager which guarantees local serializability, i.e. the serializable execution of its local transactions and subtransactions.
- To guarantee global serializability a *global* transaction manager controls the execution of the global transactions. This could either be based on ordering the commit of the transaction, or by introducing artificial data objects called *tickets* which have to be accessed by the subtransactions.

Global serializability through local guarantees: rigorous local schedules

Rigorous schedules

A local schedule $S = (OP_S, <_S)$ of a set of complete transactions is *rigorous* if for all involved transactions (local and subtransactions) T_i, T_j there holds:

> Let $p_j \in OP_j$, $q_i \in OP_i$, $i \neq j$ such that $(p_j, q_i) \in conf(S)$. Then either $a_j <_S q_i$ or $c_j <_S q_i$.

Commit-deferred transaction

A global transaction T is *commit-deferred* if its commit action is sent by the global transaction manager to the local sites of T only *after* the local executions of all subtransactions of T at that sites have been acknowledged.

Commit-deferment is achieved as a side-effect of the 2-phase-commit protocol.

Examples

Consider two servers where $D_1 = \{A, B\}$ and $D_2 = \{C, D\}$. We have the following transactions:

$$\text{global}: \quad T_1 = WA\ WD \qquad \text{local}: \quad T_3 = RA\ RB$$
$$T_2 = WC\ WB \qquad T_4 = RC\ RD$$

$W_1A < R_3A$ $R_3B <$

We have the following local schedules:

AB	S_1 :	W_1A	c_1	R_3A	R_3B	c_3	W_2B	c_2
CD	S_2 :	W_2C	c_2	R_4C	R_4D	c_4	W_1D	c_1

Even though the local schedules are serializable, the two global transactions are not executed in a serializable manner. The local schedules are rigorous, however not commit-deferred.

Lemma

A local schedule is serializable, whenever it is rigorous.

Sketch of proof: Assume the contrary. Then there exists a history which has a cyclic conflict graph, though rigorousness holds. As a commit is the final action of a transaction, rigorousness makes such a cycle impossible.

Theorem

Let S be a global history for local histories $S_1, \ldots, S_n$. If S_i rigorous, $1 \leq i \leq n$ and all global transactions are commit-deferred, then S is globally serializable.

Sketch of proof: Assume the contrary. Then there exists a history which has a cyclic conflict graph, though rigorousness and commit-deferment hold. As rigorousness guarantees local serializability, such a cycle must involve at least two sites. As a commit is the final action of a transaction, commit-deferment makes such a cycle impossible.

Because of the 2-phase-commit protocol, under rigorousness global serializability practically comes for free!

Global serializability through explicit measures: tickets

Ticket-based concurrency control

- Each server guarantees serializable local schedules in a way unknown for the global transactions.
- Each server maintains a special counter as database object, which is called *ticket*. Each subtransaction of a global transaction being executed at that server increments (reads and writes) the ticket (*take-a-ticket*-Operation). Doing so we introduce explicit conflicts between global transactions running at the same server.
- The global transaction manager guarantees that the order in which the tickets are accessed by the subtransactions will imply a linear order on the global transactions.

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Applying ticketing by examples

By I_j we denote the ticket at server j.

- Let $T_1 = R_1A\ R_1D$ and $T_2 = R_2B\ R_2C$ be global transactions and let $T_3 = R_3A\ R_3B\ W_3A\ W_3B$ and $T_4 = R_4D\ W_4D\ R_4C\ W_4C$ be local transactions.

  $$S_1: \quad R_1(I_1)\ W_1(I_1)\ R_1A\ R_3A\ R_3B\ W_3A\ W_3B\ R_2(I_1)\ W_2(I_1)\ R_2B$$
  $$S_2: \quad R_4D\ W_4D\ R_1(I_2)\ W_1(I_2)\ R_1D\ R_2(I_2)\ W_2(I_2)\ R_2C\ R_4C\ W_4C$$

  Not serializable - could be detected at server 2.

- Let $T_1 = R_1A\ W_1B$ and $T_2 = R_2B\ W_2A$ be global transactions.

  $$S_1: \quad R_1(I_1)\ W_1(I_1)\ R_1A\ R_2(I_1)\ W_2(I_1)\ W_2A$$
  $$S_2: \quad R_2(I_2)\ W_2(I_2)\ R_2B\ R_1(I_2)\ W_1(I_2)\ W_1B$$

  Not serializable, could not be detected neither at server 1 nor at server 2, however the order of take-a-ticket operations does not imply a linear order on the global transactions.

Applying ticketing by examples

By I_j we denote the ticket at server j.

- Let $T_1 = R_1A\ R_1D$ and $T_2 = R_2B\ R_2C$ be global transactions and let $T_3 = R_3A\ R_3B\ W_3A\ W_3B$ and $T_4 = R_4D\ W_4D\ R_4C\ W_4C$ be local transactions.

  $S_1: \quad R_1(I_1)\ W_1(I_1)\ R_1A\ R_3A\ R_3B\ W_3A\ W_3B\ R_2(I_1)\ W_2(I_1)\ R_2B$

  $S_2: \quad R_4D\ W_4D\ R_1(I_2)\ W_1(I_2)\ R_1D\ R_2(I_2)\ W_2(I_2)\ R_2C\ R_4C\ W_4C$

  Not serializable - could be detected at server 2.

- Let $T_1 = R_1A\ W_1B$ and $T_2 = R_2B\ W_2A$ be global transactions.

  $S_1: \quad R_1(I_1)\ W_1(I_1)\ R_1A\ R_2(I_1)\ W_2(I_1)\ W_2A$

  $S_2: \quad R_2(I_2)\ W_2(I_2)\ R_2B\ R_1(I_2)\ W_1(I_2)\ W_1B$

  Not serializable, could not be detected neither at server 1 nor at server 2, however the order of take-a-ticket operations does not imply a linear order on the global transactions.

T_1 T_2