3. Transaction theory

6 Serializability
3. Transaction theory

6. Serializability

7. View Serializability
3. Transaction theory

6 Serializability

7 View Serializability

8 Conflict Serializability
3. Transaction theory

6. Serializability

7. View Serializability

8. Conflict Serializability

9. Conflict Graph
3. Transaction theory

6. Serializability

7. View Serializability

8. Conflict Serializability

9. Conflict Graph

10. Closure Properties
3. Transaction theory

6. Serializability

7. View Serializability

8. Conflict Serializability

9. Conflict Graph

10. Closure Properties

11. Transaction Abort and Fault Tolerance
Serializability

- Introduction to the topic
- Formalization of schedules
- Serializability concepts
- Comparison of serializability concepts
**Introduction to Serializability**

\[ T_1 : \text{read}(A); \quad A := A - 10; \quad \text{write}(A); \quad \text{read}(B); \]
\[ \quad B := B + 10; \quad \text{write}(B); \]

\[ T_2 : \text{read}(B); \quad B := B - 20; \quad \text{write}(B); \quad \text{read}(C); \]
\[ \quad C := C + 20; \quad \text{write}(C); \]

- Execution alternatives for two transactions:
  - Serial, e.g. \( T_1 \) before \( T_2 \)
  - Interleaved, e.g. alternating steps of \( T_1 \) and \( T_2 \)
## Interleaved execution: Example

<table>
<thead>
<tr>
<th>Execution 1</th>
<th>Execution 2</th>
<th>Execution 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>$T_1$</td>
<td>$T_1$</td>
</tr>
<tr>
<td>$T_2$</td>
<td>$T_2$</td>
<td>$T_2$</td>
</tr>
<tr>
<td>read($A$)</td>
<td>read($A$)</td>
<td>read($A$)</td>
</tr>
<tr>
<td>$A-10$</td>
<td>$A-10$</td>
<td>$A-10$</td>
</tr>
<tr>
<td>write($A$)</td>
<td>write($A$)</td>
<td>write($A$)</td>
</tr>
<tr>
<td>read($B$)</td>
<td>read($B$)</td>
<td>read($B$)</td>
</tr>
<tr>
<td>$B+10$</td>
<td>$B-20$</td>
<td>$B-20$</td>
</tr>
<tr>
<td>write($B$)</td>
<td>write($B$)</td>
<td>write($B$)</td>
</tr>
<tr>
<td>read($B$)</td>
<td>read($B$)</td>
<td>read($B$)</td>
</tr>
<tr>
<td>$B-20$</td>
<td>$B+10$</td>
<td>$B+10$</td>
</tr>
<tr>
<td>write($B$)</td>
<td>write($B$)</td>
<td>write($B$)</td>
</tr>
<tr>
<td>read($C$)</td>
<td>read($C$)</td>
<td>read($C$)</td>
</tr>
<tr>
<td>$C+20$</td>
<td>$C+20$</td>
<td>$C+20$</td>
</tr>
<tr>
<td>write($C$)</td>
<td>write($C$)</td>
<td>write($C$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>write($C$)</td>
</tr>
</tbody>
</table>
## Results of different executions

<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$A + B + C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Value</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>After execution 1</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>After execution 2</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>After execution 3</td>
<td>0</td>
<td>20</td>
<td>30</td>
<td>50</td>
</tr>
</tbody>
</table>
Simplified model

*Lock-Unlock-Model*

\[ T_1 : \text{lock } A; \quad \text{unlock } A; \quad \text{lock } B; \quad \text{unlock } B; \]
\[ T_2 : \quad \text{lock } B; \quad \text{unlock } B; \quad \text{lock } C; \quad \text{unlock } C; \]
## Interleaved Executions with Lock/Unlock: Example

<table>
<thead>
<tr>
<th>Execution 1</th>
<th>Execution 2</th>
<th>Illegal execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>$T_1$</td>
<td>$T_1$</td>
</tr>
<tr>
<td>$T_2$</td>
<td>$T_2$</td>
<td>$T_2$</td>
</tr>
<tr>
<td>lock $A$</td>
<td>lock $A$</td>
<td>lock $A$</td>
</tr>
<tr>
<td>unlock $A$</td>
<td>unlock $A$</td>
<td>unlock $A$</td>
</tr>
<tr>
<td>lock $B$</td>
<td>lock $B$</td>
<td>lock $B$</td>
</tr>
<tr>
<td>unlock $B$</td>
<td>unlock $B$</td>
<td>unlock $B$</td>
</tr>
<tr>
<td>read $C$</td>
<td>lock $C$</td>
<td>unlock $B$</td>
</tr>
<tr>
<td>unlock $B$</td>
<td>unlock $C$</td>
<td>lock $C$</td>
</tr>
<tr>
<td>unlock $C$</td>
<td>unlock $C$</td>
<td>unlock $C$</td>
</tr>
</tbody>
</table>
Serializability

An interleaved execution of a set of transactions is called **serializable**, if the result of the interleaved execution is identical with the result of a (randomly chosen) serial execution of the same set of transactions.
The concept of schedules
The Read-Write Model

- **Transaction** $T$ is a finite sequence of operations (steps) $p_i$ of the form $r(x_k)$ or $w(x_k)$:

  \[ T = p_1 p_2 p_3 \cdots p_n \]  with \( p_i \in \{ r(x_k), w(x_k) \} \)

- A complete transaction $T$ has as last step either an Abort $a$ or a Commit $c$:

  \[ T = p_1 \cdots p_n a \]  or  

  \[ T = p_1 \cdots p_n c. \]
Interleaved transactions

**SHUFFLE**($T$): set of all possible interleaved executions of the steps of all transactions $T_i$ in the set $T$

- All steps of the transaction $T_i$ are included only once
- The relative order of the steps of a transaction is preserved

\[
T_1 := r_1(x)w_1(x)
\]
\[
T_2 := r_2(x)r_2(y)w_2(y)
\]

\[
\text{SHUFFLE}(T) = \{ r_1(x)w_1(x)r_2(x)r_2(y)w_2(y), \\
r_2(x)r_1(x)w_1(x)r_2(y)w_2(y), \\
... \}
\]
Schedule

A complete schedule is a SHUFFLE-Element of a set of complete transactions.

A schedule is a prefix of a complete schedule.

\[ r_1(x)r_2(x)w_1(x)\overline{r_2(y)a_1w_2(y)c_2} \]

a schedule

\[ \overline{a \text{ complete} \text{ schedule}} \]
Serial schedule

- A **serial schedule** \( s \) for \( T \) is a complete schedule of the following form:

\[
s := T_{\rho(1)} \cdots T_{\rho(n)}
\]

for a permutation \( \rho \) of \( \{1, \ldots, n\} \)

- Resulting serial schedules for two transactions:

\( T_1 := r_1(x)w_1(x)c_1 \) and \( T_2 := r_2(x)w_2(x)c_2 \):

\[
\begin{align*}
S_1 & := r_1(x)w_1(x)c_1 \underbrace{r_2(x)w_2(x)c_2}_{T_2} \\
S_2 & := r_2(x)w_2(x)c_2 \underbrace{r_1(x)w_1(x)c_1}_{T_1}
\end{align*}
\]
Correctness criteria

A schedule $s$ is **correct**, if its effect (the result of the execution of the schedule) is equivalent to the effect of a (randomly chosen) serial schedule $s'$ regarding the same set of transactions ($s \approx s'$).

If a schedule $s$ is equivalent to a serial schedule $s'$, then $s$ is **serializable** (to $s'$).

- Open: How to define "being equivalent"?
View serializability

- Idea: Effect of a transaction only depends on what values were seen by the transaction.
- It reads the value that was written last
- Special treatment necessary for the initialization and for the final result of a schedule
View serializability: Preparations

- Artificial additional transactions:
  1. *Initial transaction* $T_0$: initially writes all involved objects
  2. *Terminal transaction* $T_\infty$: reads all involved objects in the end
Reads-from-relation

If $\rightarrow_s$ is the relation "temporally before in the schedule $s$", then "$r_j(x)$ reads $x$ from $T_i$" if and only if:

- $w_i(x) \rightarrow_s r_j(x)$ and
- $\forall k (w_i(x) \rightarrow_s w_k(x) \land w_k(x) \rightarrow_s r_j(x))$.

Reads-from-relation $RF(s)$ for a schedule $s$:

$$RF(s) := \{ (T_i, x, T_j) \mid r_j(x) \text{ reads } x \text{ from } T_i \}$$
View equivalence

Two schedules $s$ and $s'$ are **view equivalent**, if:

1. $op(s) = op(s')$
   
   $op(s)$: the set of all steps occurring in $s$ including $a$ and $c$ (Sets must be identical for both schedules)

2. $RF(s) = RF(s')$

   Schedules $s$ and $s'$ have the same ”Reads-from-relation”
View equivalence: Example I

Given two complete schedules $s_1$ and $s_2$ consisting of two transactions $T_1$ and $T_2$ with:

$$s_1 := r_1(x)r_2(y)w_1(y)w_2(y)c_1c_2$$

$$s_2 := r_1(x)w_1(y)r_2(y)w_2(y)c_2c_1$$
View equivalence: Example II

- For calculating the reads-from-relations \( RF(s_1) \) and \( RF(s_2) \), \( s_1 \) and \( s_2 \) are expanded by the initial transaction \( T_0 \) and the terminal transaction \( T_\infty \) in the following way:

\[
\begin{align*}
  s_1 & := w_0(x)w_0(y)c_0 r_1(x)r_2(y)w_1(y)w_2(y)c_1 c_2 r_\infty(x), r_\infty(y)c_\infty \\
  s_2 & := w_0(x)w_0(y)c_0 r_1(x)w_1(y)r_2(y)w_2(y)c_2 c_1 r_\infty(x), r_\infty(y)c_\infty
\end{align*}
\]
View equivalence: Example III

- Resulting *reads-from-relations*:
  
  \[ RF(s_1) := \{(T_0, x, T_1), (T_0, y, T_2), (T_0, x, T_\infty), (T_2, y, T_\infty)\} \]
  
  \[ RF(s_2) := \{(T_0, x, T_1), (T_1, y, T_2), (T_0, x, T_\infty), (T_2, y, T_\infty)\} \]

- View equivalence of \( s_1 \) and \( s_2 \): Comparison of *reads-from-relations*

- Since \( RF(s_1) \neq RF(s_2) \), \( s_1 \) and \( s_2 \) are *not* view equivalent
A schedule $s$ is **view serializable**, only if $s$ is view equivalent to a serial schedule.

- Set of all view serializable schedules: $\text{VSR}$ (view serializability)
- For $n$ transactions, there exist $n!$ serial schedules
- Problems:
  - Exponential complexity for testing
  - Testing requires complete schedules (blind writes and transaction aborts)
View Serializability: Example

- Obviously, schedule $s_2$ is view serializable, because $s_2$ is serial.
- Possible serial schedules $s'$ and $s''$ for $s_1$:
  - $s' = T_1 T_2 = r_1(x)w_1(y)c_1 r_2(y)w_2(y)c_2$
    
    $RF(s') := \{(T_0, x, T_1), (T_1, y, T_2), (T_0, x, T_\infty), (T_2, y, T_\infty)\}$
    
    $\rightarrow RF(s') \neq RF(s_1)$
  - $s'' = T_2 T_1 = r_2(y)w_2(y)c_2 r_1(x)w_1(y)c_1$
    
    $RF(s'') := \{(T_0, y, T_2), (T_0, x, T_1), (T_0, x, T_\infty), (T_1, y, T_\infty)\}$
    
    $\rightarrow RF(s'') \neq RF(s_1)$

$RF(s') \neq RF(s_1)$ and $RF(s'') \neq RF(s_1)$: Schedule $s_1$ is not serializable!
Conflict Serializability

- Idea: Only the relative order of operations and not the actually read value is of importance in conflict situations.
- It is not necessary to know which transaction has most recently written a value, only whether the value has been written before or after a transaction.
## Conflicts

<table>
<thead>
<tr>
<th>$T_1$</th>
<th>$T_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>read $A$</td>
<td>read $A$</td>
</tr>
</tbody>
</table>

*order independent*

<table>
<thead>
<tr>
<th>$T_1$</th>
<th>$T_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>read $A$</td>
<td>write $A$</td>
</tr>
</tbody>
</table>

*order dependent*

<table>
<thead>
<tr>
<th>$T_1$</th>
<th>$T_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>write $A$</td>
<td>write $A$</td>
</tr>
</tbody>
</table>

*order dependent*
Conflict Serializability

- Conflict relation $C$ of $s$:
  \[ C(s) := \{ (p, q) \mid p, q \text{ are in conflict and } p \rightarrow_s q \} \]

- Conflict matrix:

<table>
<thead>
<tr>
<th></th>
<th>$r_i(x)$</th>
<th>$w_i(x)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_j(x)$</td>
<td>$\sqrt{}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$w_j(x)$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>
Adjusted conflict relation

- \( \text{conf}(s) \) is an "adjusted" conflict relation, which includes no aborted transactions
  \[
  \text{conf}(s) := C(s) - \{ (p, q) \mid (p \in t' \lor q \in t') \land t' \in \text{aborted}(s) \}
  \]
- \( \text{aborted}(s) \): Set of aborted transactions in schedule \( s \)
Adjusted conflict relation: Example

- Given schedule \( s \):
  \[
s = r_1(x)w_1(x)r_2(x)r_3(y)w_2(y)c_2a_1c_3
  \]

- Conflict relation for \( s \):
  \[
  C(s) := \{(w_1(x), r_2(x)), (r_3(y), w_2(y))\}
  \]

- Removing aborted transaction \( T_1 \) from \( s \):
  \[
  \text{conf}(s) := \{(r_3(y), w_2(y))\}
  \]
Conflict equivalence

Two schedules $s$ and $s'$ are **conflict equivalent** ($s \approx_c s'$) if:

1. $\text{op}(s) = \text{op}(s')$
2. $\text{conf}(s) = \text{conf}(s')$
Conflict serializability

A schedule $s$ is conflict serializable, if and only if $s$ is conflict equivalent to a serial schedule.

Class of all conflict serializable schedules: $\text{CSR}$ (conflict serializability)
Conflict serializability: Example I

- Given two schedules $s$ and $s'$:
  
  $s = r_1(x)r_1(y)w_2(x)w_1(y)r_2(z)w_1(x)w_2(y)$
  
  $s' = r_1(y)r_1(x)w_1(y)w_2(x)w_1(x)r_2(z)w_2(y)$

- Question:
  Are schedules $s$ and $s'$ conflict equivalent?

- Step 1:
  $\text{op}(s) = \text{op}(s')$ applies, since all database operations occurring in $s$ occur in $s'$ as well; also applies vice versa
Conflict serializability: Example II

Step 2: Adjusted conflict relations

\[
\text{conf}(s) = \{(r_1(x), w_2(x)), (w_2(x), w_1(x)), (r_1(y), w_2(y)), (w_1(y), w_2(y))\}
\]

\[
\text{conf}(s') = \{(r_1(x), w_2(x)), (w_2(x), w_1(x)), (r_1(y), w_2(y)), (w_1(y), w_2(y))\}
\]

\[
\text{conf}(s) = \text{conf}(s') \text{ applies; so the conflict relations are equal and therefore } s \text{ and } s' \text{ are conflict equivalent}
\]
Conflict serializability: Example III

- Test for conflict serializability by comparison with serial schedules
- Given schedule \( s \):

\[
s = r_1(x)r_1(y)w_2(x)w_1(y)r_2(z)w_1(x)w_2(y)
\]
Conflict serializability: Example IV

- Adjusted conflict relation for $s$:

\[
\text{conf}(s) = \{(r_1(x), w_2(x)), (w_2(x), w_1(x)), (r_1(y), w_2(y)), (w_1(y), w_2(y))\}
\]

- Possible serial schedule $s_1$:

\[
s_1 = T_1 T_2 = r_1(x) r_1(y) w_1(y) w_1(x) c_1 w_2(x) r_2(z) w_2(y) c_2
\]

- Conflict relation of $s_1$ is *not* equal to the conflict relation of $s$:

\[
\text{conf}(s_1) = \{(r_1(x), w_2(x)), (w_1(x), w_2(x)), (r_1(y), w_2(y)), (w_1(y), w_2(y))\}
\]
Conflict serializability: Example V

- Possible serial schedule $s_2$ as a candidate:

$$s_2 = T_2 T_1 = w_2(x) r_2(z) w_2(y) c_2 r_1(x) r_1(y) w_1(y) w_1(x) c_1$$

- Conflict relation of $s_2$ is not equal to the conflict relation of $s$:

$$\text{conf}(s_2) = \{(w_2(x), r_1(x)), (w_2(y), r_1(y)), (w_2(y), w_1(y)), (w_2(x), w_1(x))\}$$

- Therefore: $s \notin \text{CSR}$, which means that schedule $s$ is not conflict serializable
Conflict serializability: Example VI

Schedule:

\[ s_3 = r_1(x)r_2(x)w_2(y)c_2w_1(x)c_1 \]

is obviously conflict serializable, since only one conflict occurs.
Graph-based Test

- Conflict graph $G(s) = (V, E)$ for schedule $s$:
  1. Set of vertices $V$ includes all transactions occurring in $s$
  2. Set of edges $E$ includes all directed edges between two conflicting transactions:
     $$(t, t') \in E \iff t \neq t' \land \exists p \in t(\exists q \in t') \text{ with } (p, q) \in \text{conf}(s)$$


Chronological sequence of three transactions

<table>
<thead>
<tr>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r(y)$</td>
<td></td>
<td>$r(u)$</td>
</tr>
<tr>
<td>$w(y)$</td>
<td>$r(y)$</td>
<td></td>
</tr>
<tr>
<td>$w(x)$</td>
<td></td>
<td>$w(x)$</td>
</tr>
<tr>
<td>$w(x)$</td>
<td></td>
<td>$w(z)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$w(x)$</td>
</tr>
</tbody>
</table>

$s = r_1(y)r_3(u)r_2(y)w_1(y)w_1(x)w_2(x)w_2(z)w_3(x)$
Conflict graph

\[ G(s): \]

- **T₁**
- **T₂**
- **T₃**

The conflict graph shows the relationships between transactions T₁, T₂, and T₃.
Properties of conflict graph $G(s)$

1. If $s$ is a serial schedule, the given conflict graph is an acyclic graph.

2. For every acyclic graph $G(s)$, a serial schedule $s'$ can be constructed in order to make $s$ conflict serializable to $s'$ (Test e.g. by topological sorting).

3. If a graph contains cycles, the respective schedule is not conflict serializable.
Topological Sorting

- (Recursive) iteration through the graph can detect the absence of cycles
  - Each node is visited once
  - processing status per node and time stamp for entering and leaving is noted
  - repeated reentry on arbitrary unprocessed nodes
- Topological sorting can be done in the same run
  - Times of leaving provides the order
- sorted sequence defines a conflict-equivalent serial schedule
- see example of Saake/Sattler: Algorithmen und Datenstrukturen (the absent-minded professor ...)

Topological Sorting: Input

- panties
- trousers
- belt
- tie
- jacket
- socks
- watch
- shoes

Thomas Leich, Gunter Saake
Transaction Management
Last updated: 17.10.2018
Topological Sorting: Result

- panties
  - trousers
    - belt
  - 11/16
  - 12/15
- shirt
  - tie
    - jacket
  - 6/7
  - 2/5
  - 3/4
- socks
  - shoes
    - watch
      - 17/18
      - 13/14
Topological Sorting: Alternative result

- panties
  - 17/18
  - trousers
    - 9/12
      - belt
        - 1/4
      - shirt
        - 5/8
        - 6/7
        - tie
          - 2/3
        - jacket
          - 2/3
  - 15/16
    - socks
      - 10/11
      - watch
        - 13/14

Conflict Graphs and Serializability

For every schedule $s$ applies:

$$G(s) \text{ acyclical} \iff s \in \text{CSR}$$
Problems during run-time

- Verification of serializability properties during run-time
  - Only incomplete schedules available during run-time $\rightsquigarrow$
    Observation of incomplete schedules is necessary
  - Transactions that have not performed a commit yet can still be aborted anytime

- How does this affect the accuracy of the verification?
Closure Properties

1. **Prefix Closure**
   If property $E$ applies to a schedule $s$, $E$ also applies to any prefix of $s$. If $E$ is fulfilled at the end of a schedule, $E$ must not have been violated before.

2. **Commit Closure**
   If $E$ applies to $s$, $E$ also applies to $CP(s)$ ("committed projection"). If $E$ applies to a set of transactions, it still applies if some of them are aborted.

3. **Prefix-commit Closure (PCC)**
   Prefix-commit closure is the conjunction.
Closure Properties

- **VSR**-Schedules are not *prefix-commit closed*
  - not prefix closed: blind writes can repair
  - not commit closed: last writes can be changed by Abort

- **CSR**-Schedules are *prefix-commit closed*
  - prefix closed: cycles in the graph remain cycles
  - commit closed: Aborts can not generate any cycles
CSR vs VSR: Example I

Does \( \text{CSR} \subset \text{VSR} \) or \( \text{VSR} \subset \text{CSR} \)?

Given: schedule \( s \):

\[
s = r_1(y) r_3(w) \underbrace{r_2(y) w_1(y)}_{T_2 \rightarrow T_1} \underbrace{w_1(x) w_2(x)}_{T_1 \rightarrow T_2} w_2(z) w_3(x) c_2 c_1 c_3
\]
CSR vs VSR: Example II

Schedule $s$ is not conflict serializable, since conflict graph $G(s)$ contains a cycle.
**CSR vs VSR: Example III**

Is $s$ view serializable?

- Determining of the reads-from-relation $RF$

  $$RF(s) = \{(T_0, y, T_1), (T_0, w, T_3), (T_0, y, T_2), (T_3, x, T_\infty), (T_1, y, T_\infty), (T_2, z, T_\infty), (T_0, w, T_\infty)\}$$

- Serial schedule $s' = T_2 \ T_1 \ T_3$:

  $$s' = r_2(y)w_2(x)w_2(z)c_2r_1(y)w_1(y)w_1(x)c_1r_3(w)w_3(x)c_3$$

- Reads-from-relation for schedule $s'$:

  $$RF(s') = \{(T_0, y, T_1), (T_0, w, T_3), (T_0, y, T_2), (T_3, x, T_\infty), (T_1, y, T_\infty), (T_2, z, T_\infty), (T_0, w, T_\infty)\}$$
CSR vs VSR: Example IV

- $RF(s) = RF(s')$ applies, therefore, schedule $s$ is view serializable.
- Therefore: Conflict serializability is more restrictive than view serializability.

\[ \neg (CSR \supset VSR) \]

- Generally:
  \[ CSR \subset VSR \]

- Cause: blind writes can repair violations caused by conflicts.
Fault Tolerance

In terms of fault tolerance, the following schedule $s$ is not acceptable:

$$s = r_1(x)w_1(x)r_2(x)a_1w_2(x)c_2$$

...though it is serializable in VSR and CSR!
Recoverability RC

- $s$ is *recoverable*, if the following condition is fulfilled:

\[
(T_i \text{ reads from } T_j \text{ in } s) \land (c_i \in s) \Rightarrow (c_j \rightarrow_s c_i)
\]
Recoverability: Example

\[ s_1 = w_1(x)w_1(y)r_2(u)w_2(x)r_2(y)w_2(y)c_2 w_1(z)c_1 \]

In \( s_1 \), \( T_2 \) reads data object \( y \) from \( T_1 \) but \( c_2 \) comes before \( c_1 \) \( \rightsquigarrow \) \( s_1 \) is not recoverable

\[ s_2 = w_1(x)w_1(y)r_2(u)w_2(x)r_2(y)w_2(y)w_1(z)c_1 c_2 \]

\( s_2 \) is recoverable

But: Problems when aborting \( T_1 \) instead of \( c_1 \) (dirty read)!
Avoiding cascading aborts

Schedule $s$ avoids cascading aborts ACA, if the following condition is fulfilled:

$$
(T_i \text{ reads } x \text{ from } T_j \text{ in } s) \Rightarrow (c_j \rightarrow_s r_i(x))
$$

$\Rightarrow$ A transaction may only read data that has last been written by an already committed transaction.
Avoiding cascading aborts: Example

- Schedule $s_2$ from the last example does not belong into the class ACA.
- However, $s_3$ avoids cascading aborts:

  $$s_3 = w_1(x)w_1(y)r_2(u)w_2(x)w_1(z)c_1r_2(y)w_2(y)c_2$$

- Therefore: $s_3 \in \text{ACA}$
## Problems with Before-Images

<table>
<thead>
<tr>
<th>DB Content</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 1$ (initial value)</td>
<td>$w_1(x \leftarrow 2) \ [ BF_{x,T_1} = 1 ]$</td>
</tr>
<tr>
<td>$x = 2$</td>
<td>$w_2(x \leftarrow 3) \ [ BF_{x,T_2} = 2 ]$</td>
</tr>
<tr>
<td>$x = 3$</td>
<td>$a_1$ rollback of $w_1(x \leftarrow 2)$ with $BF_x := 1$. Overwriting of $T_2$ has to be maintained</td>
</tr>
<tr>
<td>$x = 3$</td>
<td>$a_2$ rollback of $w_2(x \leftarrow 3)$ with $BF_x := ??$</td>
</tr>
</tbody>
</table>
Strictness ST

Schedule $s$ is **strict**, if the following applies:

\[
(w_j(x) \rightarrow_s p_i(x) \land j \neq i) \Rightarrow \\
(a_j \rightarrow_s p_i(x) \lor c_j \rightarrow_s p_i(x), (p \in \{r, w\}))
\]

\[\Rightarrow \text{ No } "\text{written}\text{" object of an incomplete transaction may be read or overwritten.}\]
Strictness: Example

- $s_3 \notin ST$
- $s_4$ is strict, therefore $s_4 \in ST$:

$$s_4 = w_1(x)w_1(y)r_2(u)w_1(z)c_1w_2(x)r_2(y)w_2(y)c_2$$
Relation between the concepts

- VSR
- CSR
- RC
- ACA
- ST
- serial

Often using strict locking protocols
Acceptable using cascading repair