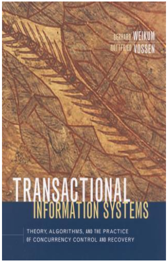
Transactional Information Systems:

Theory, Algorithms, and the Practice of Concurrency Control and Recovery

Gerhard Weikum and Gottfried Vossen



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"Teamwork is essential. It allows you to blame someone else."(Anonymous)

Part II: Concurrency Control

- 3 Concurrency Control: Notions of Correctness for the Page Model
- 4 Concurrency Control Algorithms
- 5 Multiversion Concurrency Control
- 6 Concurrency Control on Objects: Notions of Correctness
- 7 Concurrency Control Algorithms on Objects
- 8 Concurrency Control on Relational Databases
- 9 Concurrency Control on Search Structures
- 10 Implementation and Pragmatic Issues

Chapter 5: Multiversion Concurrency Control

- **5.2 Multiversion Schedules**
- 5.3 Multiversion Serializability
- 5.4 Limiting the Number of Versions
- 5.5 Multiversion Concurrency Control Protocols
- 5.6 Lessons Learned

"A book is a version of the world. If you do not like it, ignore it; or offer your own version in return." (Salmon Rushdie)

Motivation

Example 5.1:

$s = r_1(x)\ w_1(x)\ r_2(x)\ w_2(y)\ r_1(y)\ w_1(z)\ c_1\ c_2$ $\rightarrow \notin$ CSR

but: schedule would be tolerable
if $r_1(y)$ could read the **old version** y_0 of y
to be consistent with $r_1(x)$

$\rightarrow$ s would then be equivalent to serial $s' = t_1\ t_2$

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Approach:

- each w step creates a new version
- each r step can choose which version it wants/needs to read
- versions are transparent to application and transient (i.e., subject to garbage collection)

Multiversion Schedules

Definition 5.1 (Version Function):
Let s be a history with initial transaction t_0 and final transaction t_∞.
A **version function** for s is a function h which associates with each read step of s a previous write step on the same data item, and the identity for writes.

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Definition 5.2 (Multiversion Schedule):
A **multiversion (mv) history** for transactions $T = \{t_1, ..., t_n\}$ is a pair $m=(op(m), <_m)$ where $<_m$ is an order on op(m) and

(1) $op(m) = \cup_{i=1..n}\ h(op(t_i))$ for some version function h,
(2) for all $t \in T$ and all $p, q \in op(t_i)$: $p <_t q \Rightarrow h(p) <_m h(q)$,
(3) if $h(r_j(x)) = w_j(x_i)$, $i \neq j$, then c_i is in m and $c_i <_m c_j$.

A **multiversion (mv) schedule** is a prefix of a multiversion history.

Example 5.2: $r_1(x_0)\ w_1(x_1)\ r_2(x_1)\ w_2(y_2)\ r_1(y_0)\ w_1(z_1)\ c_1\ c_2$ with $h(r_1(y)) = w_0(y_0)$

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Example 5.2: $r_1(x_0)\; w_1(x_1)\; r_2(x_1)\; w_2(y_2)\; r_1(y_0)\; w_1(z_1)\; c_1\; c_2$ with $h(r_1(y)) = w_0(y_0)$

Definition 5.3 (Monoversion Schedule):
A multiversion schedule is a **monoversion schedule** if its version function maps each read to the last preceding write on the same data item.

Example: $r_1(x_0)\; w_1(x_1)\; r_2(x_1)\; w_2(y_2)\; r_1(y_2)\; w_1(z_1)\; c_1\; c_2$

Chapter 5: Multiversion Concurrency Control

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- **5.3 Multiversion Serializability**
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Multiversion View Serializability

Definition 5.4 (Reads-from Relation):
For mv schedule m the reads-from relation of m is
RF(m) = $\{(t_i, x, t_j) \mid r_j(x_i) \in op(m)\}$.

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mv histories m and m' with trans(m)=trans(m') are **view equivalent**,
$m \approx_v m'$, if RF(m) = RF(m').

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m is multiversion view serializable if there is a serial monoversion history m'
s.t. $m \approx_v m'$.
MVSR is the class of multiversion view serializable histories.

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Example 5.5:
$m = w_0(x_0)\ w_0(y_0)\ c_0\ r_1(x_0)\ r_1(y_0)\ w_1(x_1)\ w_1(y_1)\ c_1\ r_2(x_0)\ r_2(y_1)\ c_2$ $\quad \notin$ MVSR

Example 5.6:
$m = w_0(x_0)\ w_0(y_0)\ c_0\ w_1(x_1)\ c_1\ r_2(x_1)\ r_3(x_0)\ w_3(x_3)\ c_3\ w_2(y_2)\ c_2$ $\quad \approx_v t_0\ t_3\ t_1\ t_2$

Properties of MVSR

Theorem 5.1: VSR $\subset$ MVSR

Example: $s = r_1(x)\ w_1(x)\ r_2(x)\ w_2(y)\ r_1(y)\ w_1(z)\ c_1\ c_2$

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Theorem 5.1: VSR $\subset$ MVSR

Example: s = $r_1(x)\ w_1(x)\ r_2(x)\ w_2(y)\ r_1(y)\ w_1(z)\ c_1\ c_2$

Theorem 5.2: Deciding if a mv history is in MVSR is NP-complete.

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Theorem 5.2: Deciding if a mv history is in MVSR is NP-complete.

Theorem 5.3:
The conflict graph of an mv schedule m is a directed graph G(m) with transactions as nodes and an edge from t_i to t_j if $r_j(x_i) \in op(m)$.
For all mv schedules m, m': $m \approx_v m' \Rightarrow G(m) = G(m')$.

Example:

$$\left.\begin{array}{l} m = w_1(x_1)\ r_2(x_0)\ w_1(y_1)\ r_2(y_1)\ c_1\ c_2 \\ m' = w_1(x_1)\ w_1(y_1)\ c_1\ r_2(x_1)\ r_2(y_0)\ c_2 \end{array}\right\} \begin{array}{l} G(m) = G(m'), \\ \text{but not } m \approx_v m' \end{array}$$

Testing MVSR

Definition 5.8 (Multiversion Serialization Graph (MVSG)):
A version order for data item x, denoted $<<_x$, is a total order among all versions of x.
A **version order** for mv schedule m is the
union of version orders for items written in m.
The **mv serialization graph** for m and a given version order <<, **MVSG (m, <<),**
is a graph with transactions as nodes and the following edges:

(i) all edges of G(m) are in MVSG(m, <<)
(i.e., for $r_k(x_j)$ in op(m) there is an edge from t_j to t_k)

(ii) for $r_k(x_j)$, $w_i(x_i)$ in op(m): if $x_i << x_j$ then there is an edge from t_i to t_j

(iii) for $r_k(x_j)$, $w_i(x_i)$ in op(m): if $x_j << x_i$ then there is an edge from t_k to t_i

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Theorem 5.4:
m is in MVSR iff there exists a version order << s.t. MVSG(m, <<) is acyclic.

MVSG Example

Examples 5.7 and 5.8:

$m = w_0(x_0)\ w_0(y_0)\ w_0(z_0)\ c_0$
$\mathbf{r_1(x_0)}\ r_2(x_0)\ r_2(z_0)\ r_3(z_0)$
$w_1(y_1)\ \mathbf{w_2(x_2)}\ w_3(y_3)\ w_3(z_3)\ c_1\ c_2\ c_3$
$r_4(x_2)\ r_4(y_3)\ r_4(z_3)\ c_4$

with version order <<:
$x_0 << x_2$
$y_0 << y_1 << y_3$
$z_0 << z_3$

MVSG(m, <<):

$$\begin{tikzcd}
 & t_1 \arrow[d] \arrow[drr] & & \\
t_0 \arrow[ur] \arrow[rrr] \arrow[dr] & & & t_3 \arrow[r] & t_4 \\
 & t_2 \arrow[urr] \arrow[urrr] & & &
\end{tikzcd}$$

MVSG Example

Examples 5.7 and 5.8:

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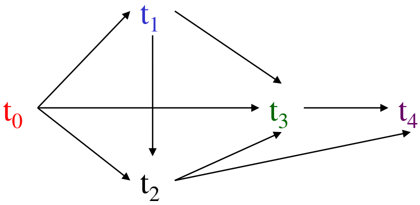
$\quad \mathbf{r_1(x_0)}\ r_2(x_0)\ r_2(z_0)\ r_3(z_0)$
$\quad w_1(y_1)\ \mathbf{w_2(x_2)}\ w_3(y_3)\ w_3(z_3)\ c_1\ c_2\ c_3$
$\quad r_4(x_2)\ r_4(y_3)\ r_4(z_3)\ c_4$

with version order <<:
$x_0 \ll x_2$
$y_0 \ll y_1 \ll y_3$
$z_0 \ll z_3$

MVSG(m, <<):



Notice: Testing whether appropriate << exists for given m is not necessarily polynomial ⇒ NP-completeness result remains

Multiversion Conflict Serializability

Definition 5.9 (Multiversion Conflict):
A **multiversion conflict** in m is a pair $r_i(x_j)$ and $w_k(x_k)$ such that $r_i(x_j) <_m w_k(x_k)$.

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An mv history is **multiversion reducible** if it can be transformed into a serial monoversion history by exchanging the order of adjacent steps other than multiversion conflict pairs.

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Definition 5.11 (Multiversion Conflict Serializability):
An mv history is **multiversion conflict serializable** if there is a serial monoversion history with the same transactions and the same (ordering of) multiversion conflict pairs.
MCSR denotes the class of all multiversion conflict serializable histories.

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For an mv schedule m the **multiversion conflict graph** is a graph with transactions as nodes and an edge from t_i to t_k if there are steps $r_i(x_j)$ and $w_k(x_k)$ such that $r_i(x_j) <_m w_k(x_k)$.

Properties of MCSR

Theorem:
m is in MCSR $\Leftrightarrow$ m is multiversion reducible $\Leftrightarrow$ m's mv conflict graph is acyclic

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Example:

$m = w_0(x_0)\ w_0(y_0)\ w_0(z_0)\ c_0\ \underline{r_2(y_0)}\ r_3(z_0)\ w_3(x_3)\ c_3\ \underline{r_1(x_3)}\ \underline{w_1(y_1)}\ c_1\ \underline{w_2(x_2)}\ c_2$
$\quad r_\infty(x_2)\ r_\infty(y_1)\ r_\infty(z_0)\ c_\infty$

$\rightarrow\ \notin$ MCSR

$\rightarrow\ \in$ MVSR

$m \approx_v t_0\ t_3\ t_2\ t_1\ t_\infty$

Chapter 5: Multiversion Concurrency Control

MVTO Protocol

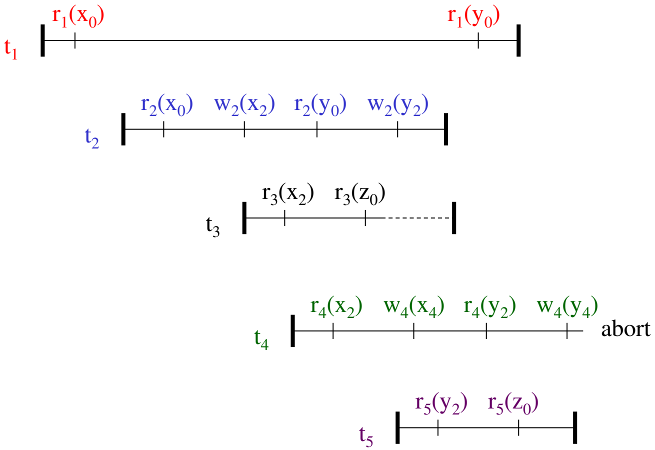
Multiversion timestamp ordering (MVTO):

- each transaction t_i is assigned a unique timestamp $ts(t_i)$
- $r_i(x)$ is mapped to $r_i(x_k)$ where x_k is the version that carries the largest timestamp $\leq ts(t_i)$
- $w_i(x)$ is
  - rejected if there is $r_j(x_k)$ with $ts(t_k) < ts(t_i) < ts(t_j)$
  - mapped into $w_i(x_i)$ otherwise
- c_i is delayed until c_j of all transactions t_j that have written versions read by t_i

Correctness of MVTO (i.e., Gen(MVTO) $\subseteq$ MVSR):

$$x_i << x_j \Leftrightarrow ts(t_i) < ts(t_j)$$

MVTO Example



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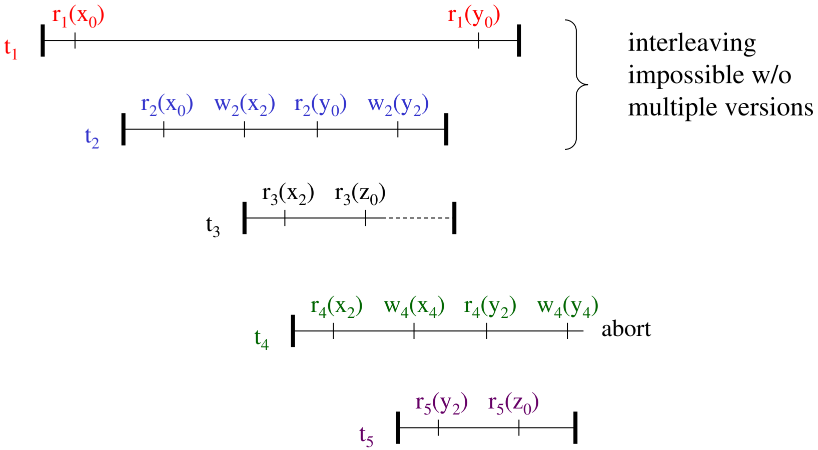

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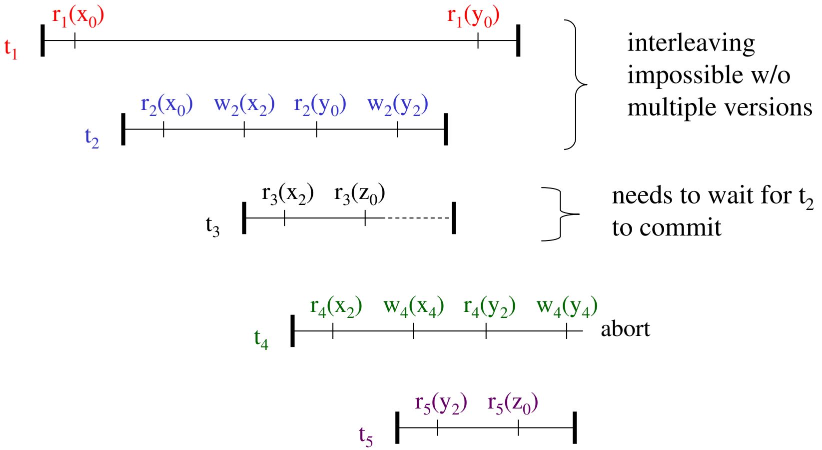
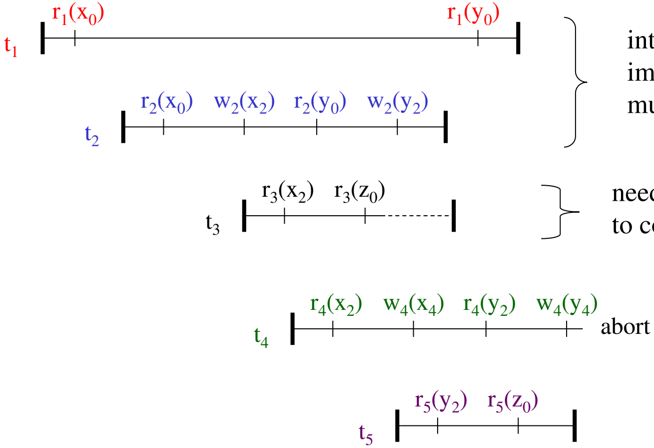


MVTO Example



interleaving impossible w/o multiple versions

needs to wait for t_2 to commit

since last write is too late (in the presence of t_5)

Multiversion 2PL (MV2PL) Protocol

General approach:

- use write locking to ensure that
  at each time there is at most one uncommitted version
- for t_i that is not yet issuing its final step:
  - $r_i(x)$ is mapped to "current version" (i.e., the most recent committed version)
    or an uncommitted version
  - $w_i(x)$ is executed only if x is not write-locked, otherwise it is blocked
- t_i's final step is delayed until after the commit of:
  - all t_j that have read from a current version of a data item that t_i has written
  - all t_j from which t_i has read

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Example 5.9:

for input schedule

$$s = r_1(x)\ w_1(x)\ r_2(x)\ w_2(y)\ r_1(y)\ w_2(x)\ c_2\ w_1(y)\ c_1$$

MV2PL produces the output schedule

$$r_1(x_0)\ w_1(x_1)\ r_2(x_1)\ w_2(y_2)\ r_1(y_0)\ w_1(y_1)\ c_1\ w_2(x_2)\ c_2$$

Specialization: 2V2PL Protocol

2-Version (before/after image) 2PL:

- request **write lock $wl_i(x)$** for writing a new uncommitted version and ensuring that at most one such version exists at any time
- request **read lock $rl_i(x)$** for reading the current version (i.e., most recent committed version)
- request **certify lock $cl_i(x)$** for final step of t_i on all data items in t_i's write set

lock holder \ lock requestor	$rl_j(x)$	$wl_j(x)$	$cl_j(x)$
$rl_i(x)$	+	+	–
$wl_i(x)$	+	–	–
$cl_i(x)$	–	–	–

Correctness of 2V2PL (i.e., Gen(2V2PL) $\subseteq$ MVSR):

$$x_i \ll x_j \Leftrightarrow f_i < f_j \text{ (for final ``certify'' steps of } t_i, t_j)$$

2V2PL Example

Example 5.10:

s = $r_1(x)$ $w_2(y)$ $r_1(y)$ $w_1(x)$ c_1 $r_3(y)$ $r_3(z)$ $w_3(z)$ $w_2(x)$ c_2 $w_4(z)$ c_4 c_3

2V2PL Example

Example 5.10:

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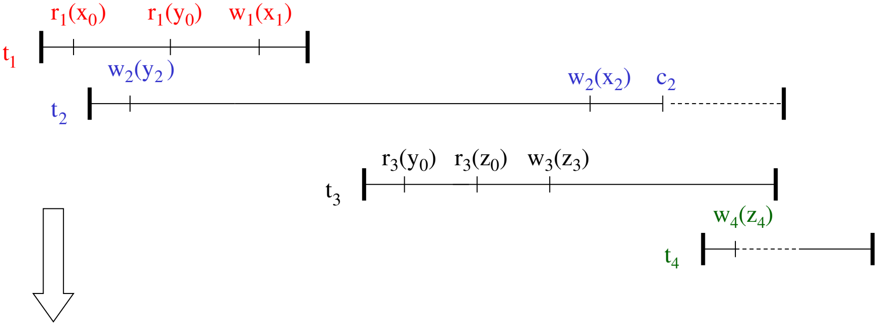

2V2PL Example

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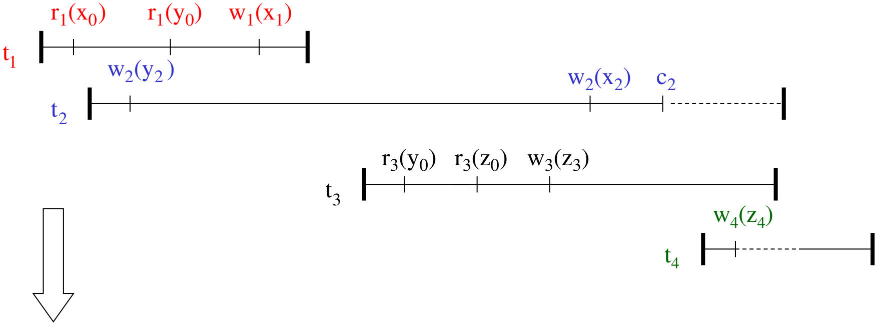


$rl_1(x)$ $r_1(x_0)$ $wl_2(y)$ $w_2(y_2)$ $rl_1(y)$ $r_1(y_0)$ $wl_1(x)$ $w_1(x_1)$ $cl_1(x)$ u_1 c_1
$rl_3(y)$ $r_3(y_0)$ $rl_3(z)$ $r_3(z_0)$ $wl_2(x)$ $cl_2(x)$ $wl_3(y)$ $w_3(z_3)$ $cl_3(y)$ u_3 c_3
$cl_2(y)$ u_2 c_2 $wl_4(z)$ $w_4(z_4)$ $cl_4(z)$ u_4 c_4

Multiversion Serialization Graph Testing (MVSGT)

Idea:

build version order and MVSG simultaneously (and incrementally)

Protocol rules:

- $r_i(x)$ is mapped to $r_i(x_j)$ such that
  - there is no path $t_j \rightarrow \ldots \rightarrow t_k \rightarrow \ldots \rightarrow t_i$ with previous $w_k(x_k)$ (eliminate "too old" transactions)
  - there is no path $t_i \rightarrow \ldots \rightarrow t_j$ (eliminate "too young" transactions)

  abort t_i if no such t_j exists
- upon $w_i(x_i)$
  add edges $t_j \rightarrow t_i$ for all t_j with previous $r_j(x_k)$
  abort t_i when detecting cycle
- upon $r_i(x_j)$
  add edge $t_j \rightarrow t_i$ and
  edges $t_k \rightarrow t_j$ or $t_i \rightarrow t_k$ for all t_k with previous $w_k(x_k)$

ROMV Protocol

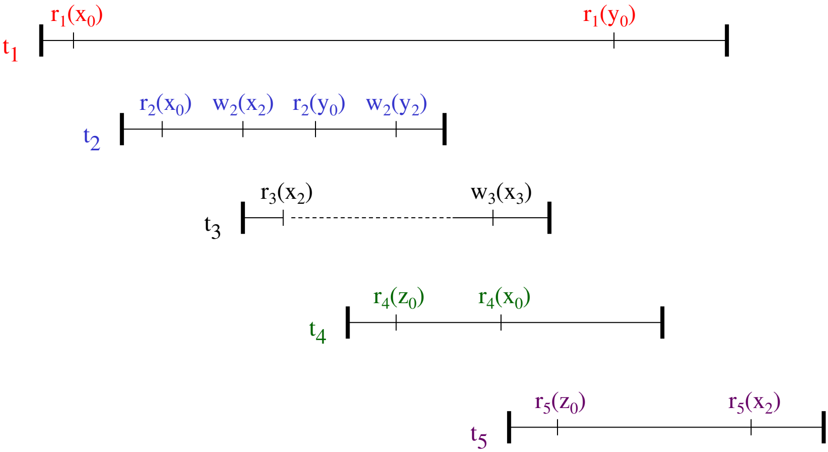
Read-only Multiversion Protocol (ROMV):

- each update transactions uses 2PL on both its read and write set but each write creates a new version and timestamps it with the transaction's commit time
- each read-only transaction t_i is timestamped with its begin time
- $r_i(x)$ is mapped to $r_i(x_k)$ where x_k is the version that carries the largest timestamp $\leq ts(t_i)$ (i.e., the most recent committed version as of the begin of t_i)

Correctness of ROMV (i.e., Gen(ROMV) $\subseteq$ MVSR):

$$x_i << x_j \;\Leftrightarrow\; c_i < c_j$$

ROMV Example



Chapter 5: Multiversion Concurrency Control

Lessons Learned

- Transient and transparent versioning adds a degree of freedom to concurrency control protocols, making MVSR considerably more powerful than VSR
- The most striking benefit is for long read transactions that execute concurrently with writers.
- This specific benefit is achieved with relatively simple protocols like ROMV.

Summary

- Concurrency control in the page model allows for many approaches, yet locking dominates
- Non-locking algorithms may be used in special situations
- Multiple versions can help making concurrency control more flexible