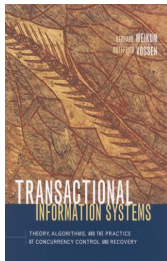


Transactional Information Systems:

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
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- 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

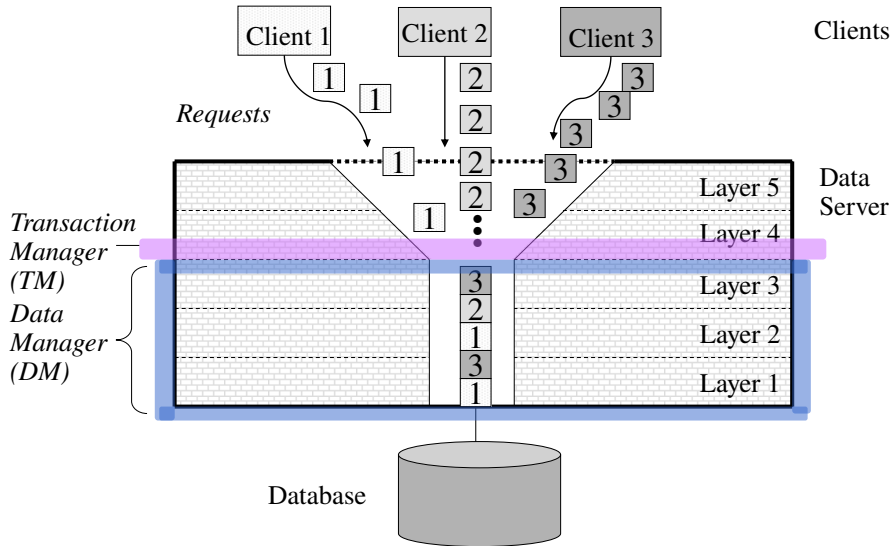
Chapter 4: Concurrency Control Algorithms

- **4.2 General Scheduler Design**

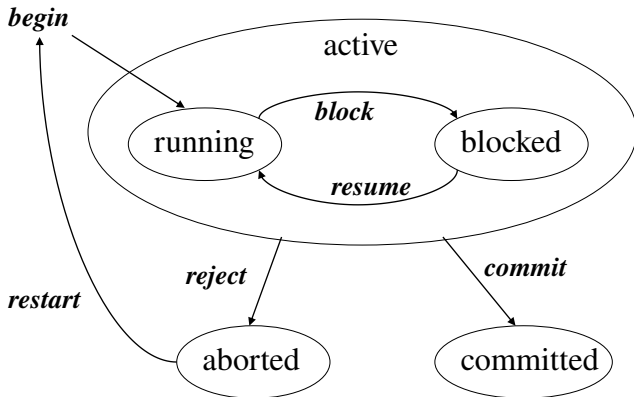
- 4.3 Locking Schedulers
- 4.4 Non-Locking Schedulers
- 4.5 Hybrid Protocols
- 4.6 Lessons Learned

“The optimist believes we live in the best of all possible worlds. The pessimist fears this is true.” (Robert Oppenheimer)

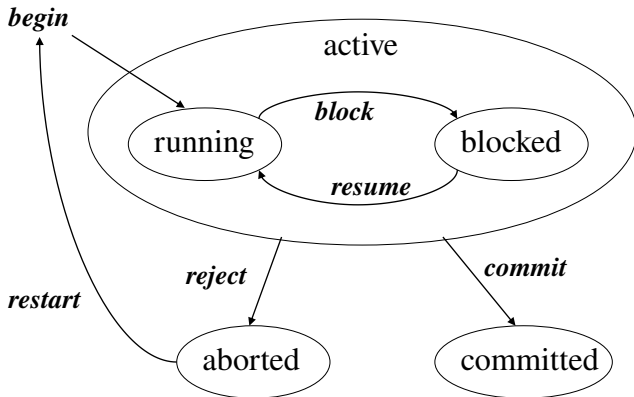
Transaction Scheduler



Scheduler Actions and Transaction States



Scheduler Actions and Transaction States

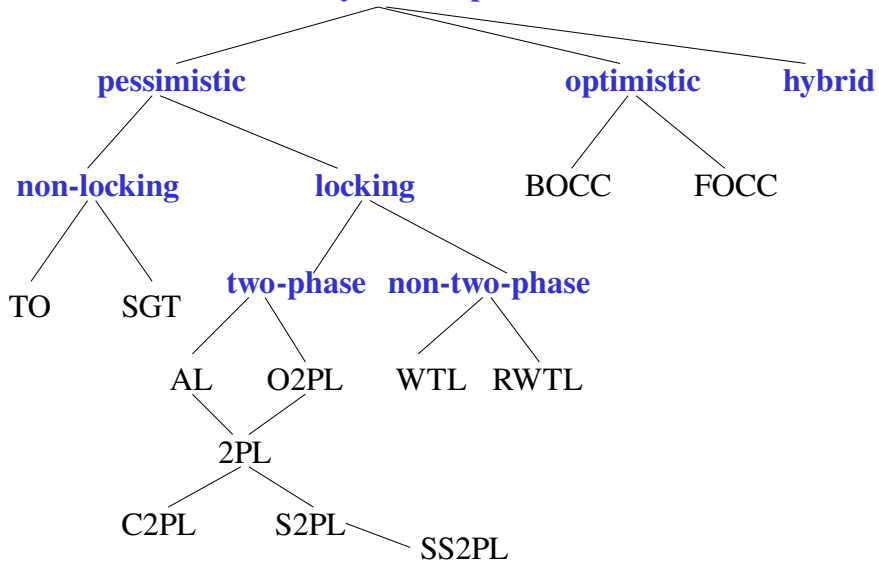


Definition 4.1 (CSR Safety):

For a scheduler S , $\text{Gen}(S)$ denotes the set of all schedules that S can generate. A scheduler is called **CSR safe** if $\text{Gen}(S) \subseteq \text{CSR}$.

Scheduler Classification

concurrency control protocols



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General Locking Rules

For each step the scheduler **requests a lock** on behalf of the step's transaction. Each lock is requested in a specific **mode (read or write)**. If the data item is not yet locked in an **incompatible mode** the lock is granted; otherwise there is a **lock conflict** and the transaction becomes **blocked** (suffers a **lock wait**) until the current lock holder **releases the lock**.

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Compatibility of locks:

		$rl_j(x)$	$wl_j(x)$	lock requestor
lock holder	$rl_i(x)$	+	-	
	$wl_i(x)$	-	-	

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General locking rules:

LR1: Each data operation $o_i(x)$ must be preceded by $ol_i(x)$ and followed by $ou_i(x)$.

LR2: For each x and t_i there is at most one $ol_i(x)$ and at most one $ou_i(x)$.

LR3: No $ol_i(x)$ or $ou_i(x)$ is redundant.

LR4: If x is locked by both t_i and t_j , then these locks are compatible.

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Two-Phase Locking (2PL)

Definition 4.2 (2PL):

A locking protocol is **two-phase (2PL)** if for every output schedule s and every transaction $t_i \in \text{trans}(s)$ no q_l step follows the first ou_i step ($q, o \in \{r, w\}$).

Example 4.4:

$s = w_1(x) r_2(x) w_1(y) w_1(z) r_3(z) c_1 w_2(y) w_3(y) c_2 w_3(z) c_3$

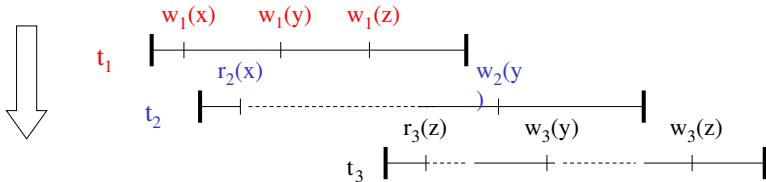
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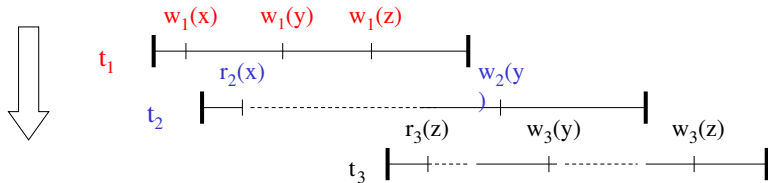
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Correctness and Properties of 2PL

Theorem 4.1:

$\text{Gen}(2\text{PL}) \subset \text{CSR}$ (i.e., 2PL is CSR-safe).

Example 4.5:

$s = w_1(x) r_2(x) c_2 r_3(y) c_3 w_1(y) c_1 \in \text{CSR}$

but $\notin \text{Gen}(2\text{PL})$ for $wu_1(x) < rl_2(x)$ and $ru_3(y) < wl_1(y)$,

$rl_2(x) < r_2(x)$ and $r_3(y) < ru_3(y)$, and $r_2(x) < r_3(y)$

would imply $wu_1(x) < wl_1(y)$ which contradicts the two-phase property.

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Theorem 4.2:

$\text{Gen}(2\text{PL}) \subset \text{OCSR}$

Example:

$w_1(x) r_2(x) r_3(y) r_2(z) w_1(y) c_3 c_1 c_2$

Proof of 2PL Correctness

Let s be the output of a 2PL scheduler, and let G be the conflict graph of CP ($DT(s)$) where DT is the projection onto data and termination operations and CP is the committed projection.

The following holds (Lemma 4.2):

- (i) If (t_i, t_j) is an edge in G , then $pu_i(x) < ql_j(x)$ for some x with conflicting p, q .
- (ii) If (t_1, t_2, \dots, t_n) is a path in G , then $pu_1(x) < ql_n(y)$ for some x, y .
- (iii) G is acyclic.

This can be shown as follows:

- (i) By locking rules LR1 through LR4.
- (ii) By induction on n .
- (iii) Assume G has a cycle of the form $(t_1, t_2, \dots, t_n, t_1)$.
By (ii), $pu_1(x) < ql_1(y)$ for some x, y ,
which contradicts the two-phase property.

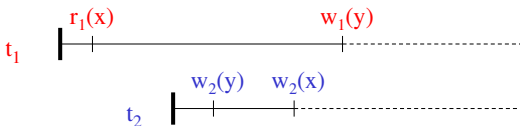
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Deadlock Detection

Deadlocks are caused by cyclic lock waits
(e.g., in conjunction with lock conversions).

Example:



Deadlock detection:

- (i) Maintain dynamic **waits-for graph (WFG)** with active transactions as nodes and an edge from t_i to t_j if t_j waits for a lock held by t_i .
- (ii) Test WFG for cycles
 - continuously (i.e., upon each lock wait) or
 - periodically.

Deadlock Resolution

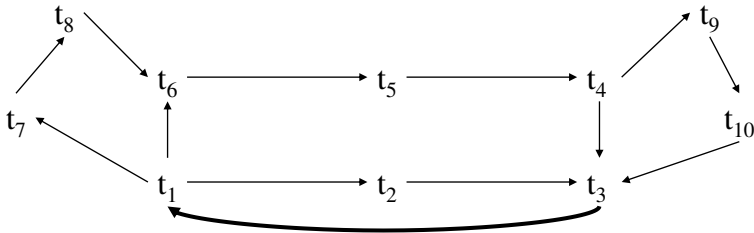
Choose a transaction on a WFG cycle as a **deadlock victim** and abort this transaction, and repeat until no more cycles.

Possible victim selection strategies:

1. Last blocked
2. Random
3. Youngest
4. Minimum locks
5. Minimum work
6. Most cycles
7. Most edges

Illustration of Victim Selection Strategies

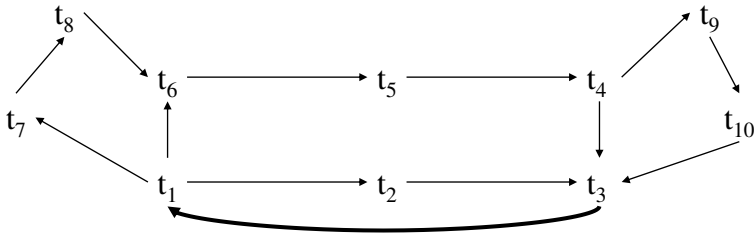
Example WFG:



Most-cycles strategy would select t_1 (or t_3) to break all 5 cycles.

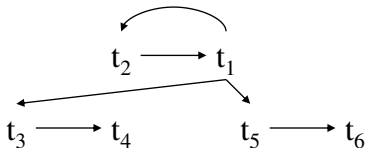
Illustration of Victim Selection Strategies

Example WFG:



Most-cycles strategy would select t_1 (or t_3) to break all 5 cycles.

Example WFG:



Most-edges strategy would select t_1 to remove 4 edges.

Deadlock Prevention

Restrict lock waits to ensure **acyclic WFG** at all times.

Reasonable deadlock prevention strategies:

1. **Wait-die:**

upon t_i blocked by t_j :

if t_i started before t_j then wait else abort t_i

2. **Wound-wait:**

upon t_i blocked by t_j :

if t_i started before t_j then abort t_j else wait

3. **Immediate restart:**

upon t_i blocked by t_j : abort t_i

4. **Running priority:**

upon t_i blocked by t_j :

if t_j is itself blocked then abort t_j else wait

5. **Timeout:**

abort waiting transaction when a timer expires

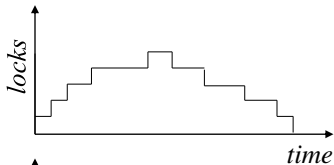
Abort entails later restart.

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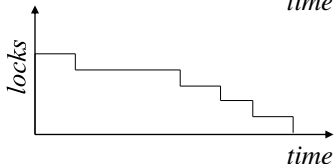
Variants of 2PL

general 2PL



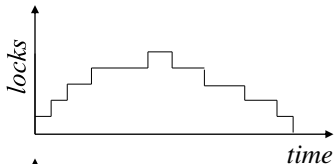
Definition 4.3 (Conservative 2PL):

Under **static or conservative 2PL (C2PL)** each transaction acquires all its locks before the first data operation (**preclaiming**).



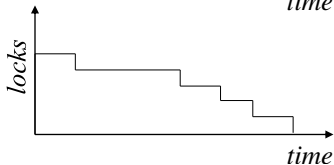
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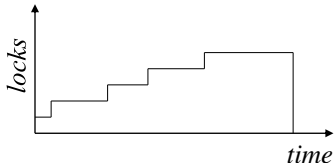
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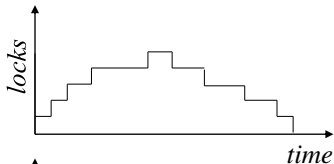
Definition 4.4 (Strict 2PL):

Under **strict 2PL (S2PL)** each transaction holds all its write locks until the transaction terminates.



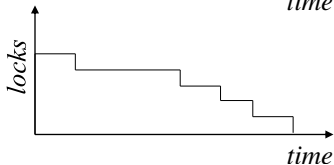
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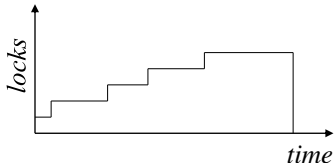
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Under **strict 2PL (S2PL)** each transaction holds all its write locks until the transaction terminates.



Definition 4.5 (Strong 2PL):

Under **strong 2PL (SS2PL)** each transaction holds all its locks (i.e., both r and w) until the transaction terminates.

Properties of S2PL and SS2PL

Theorem 4.3:

$$\text{Gen}(\text{SS2PL}) \subset \text{Gen}(\text{S2PL}) \subset \text{Gen}(\text{2PL})$$

Theorem 4.4:

$$\text{Gen}(\text{SS2PL}) \subset \text{COCSR}$$

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Ordered Sharing of Locks

Motivation:

Example 4.6:

$s_1 = w_1(x) r_2(x) r_3(y) c_3 w_1(y) c_1 w_2(z) c_2 \in \text{COCSR}$, but
 $\notin \text{Gen}(2\text{PL})$

Observation:

the schedule were feasible if **write locks could be shared**
s.t. the order of lock acquisitions dictates the order of data operations

Notation:

$pl_i(x) \rightarrow ql_j(x)$ (with $i \neq j$) for $pl_i(x) <_s ql_j(x) \wedge p_i(x) <_s q_j(x)$

Example reconsidered with ordered sharing of locks:

$wl_1(x) w_1(x) rl_2(x) r_2(x) rl_3(y) r_3(y) ru_3(y) c_3$

$wl_1(y) w_1(y) wu_1(x) wu_1(y) c_1 wl_2(z) w_2(z) ru_2(x) wu_2(z) c_2$

Lock Compatibility Tables With Ordered Sharing

LT_1	$rl_i(x)$	$wl_i(x)$
$rl_i(x)$	+	-
$wl_i(x)$	-	-

LT_2	$rl_j(x)$	$wl_j(x)$
$rl_i(x)$	+	→
$wl_i(x)$	-	-

LT_3	$rl_j(x)$	$wl_j(x)$
$rl_i(x)$	+	-
$wl_i(x)$	→	-

LT_4	$rl_j(x)$	$wl_j(x)$
$rl_i(x)$	+	-
$wl_i(x)$	-	→

LT_5	$rl_j(x)$	$wl_j(x)$
$rl_i(x)$	+	→
$wl_i(x)$	→	-

LT_6	$rl_j(x)$	$wl_j(x)$
$rl_i(x)$	+	-
$wl_i(x)$	→	→

LT_7	$rl_j(x)$	$wl_j(x)$
$rl_i(x)$	+	→
$wl_i(x)$	-	→

LT_8	$rl_j(x)$	$wl_j(x)$
$rl_i(x)$	+	→
$wl_i(x)$	→	→

Additional Locking Rules for O2PL

OS1 (lock acquisition):

Assuming that $pl_i(x) \rightarrow ql_j(x)$ is permitted,
if $pl_i(x) <_s ql_j(x)$ then $p_i(x) <_s q_j(x)$ must hold.

Example:

$wl_1(x) w_1(x) wl_2(x) w_2(x) wl_2(y) w_2(y) wu_2(x) wu_2(y) c_2$
 $wl_1(y) w_1(y) wu_1(x) wu_1(y) c_1$

Satisfies OS1,
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Satisfies OS1,
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OS2 (lock release):

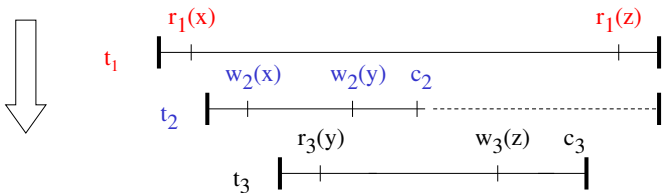
If $pl_i(x) \rightarrow ql_j(x)$ and t_i has not yet released any lock, then
 t_j is **order-dependent** on t_i . If such t_i exists, then t_j is **on hold**.
While a transaction is on hold, it must not release any locks.

O2PL: locking with rules LR1 - LR4, two-phase property,
rules OS1 - OS2, and lock table LT_8

O2PL Example

Example 4.7:

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



$$rl_1(x) r_1(x) wl_2(x) w_2(x) rl_3(y) r_3(y) wl_2(y) w_2(y) \\ wl_3(z) w_3(z) ru_3(y) wu_3(z) c_3 rl_1(z) r_1(z) ru_1(x) ru_1(z) wu_2(x) wu_2(y) c_2 c_1$$

Correctness and Properties of O2PL

Theorem 4.5:

Let LT_i denote the locking protocol with ordered sharing according to lock compatibility table LT_i .

For each i , $1 \leq i \leq 8$, $\text{Gen}(LT_i) \subseteq \text{CSR}$.

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Theorem 4.7:

$\text{OCSR} \subseteq \text{Gen}(\text{O2PL})$

Corollary 4.1:

$\text{Gen}(\text{O2PL}) = \text{OCSR}$

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Altruistic Locking (AL)

Motivation:

Example 4.8: concurrent executions of

$t_1 = w_1(a) w_1(b) w_1(c) w_1(d) w_1(e) w_1(f) w_1(g)$

$t_2 = r_2(a) r_2(b)$

$t_3 = r_3(c) r_3(e)$

Observations:

- t_2 and t_3 access subsets of the data items accessed by t_1
- t_1 knows when it is “finished” with a data item
- t_1 could “pass over” locks on specific data items to transactions that access only data items that t_1 is finished with (such transactions are “in the wake” of t_1)

Notation:

$d_i(x)$ for t_i **donating** its lock on x to other transactions

Example with donation of locks:

$wl_1(a) w_1(a) d_1(a) rl_2(a) r_2(a) wl_1(b) w_1(b) d_1(b) rl_2(b) r_2(b) wl_1(c) w_1(c) \dots$
 $\dots ru_2(a) ru_2(b) \dots wu_1(a) wu_1(b) wu_1(c) \dots$

Additional Locking Rules for AL

- AL1:** Once t_i has donated a lock on x , it can no longer access x .
- AL2:** After t_i has donated a lock x , t_i must eventually unlock x .
- AL3:** t_i and t_j can simultaneously hold conflicting locks only if t_i has donated its lock on x .

Additional Locking Rules for AL

AL1: Once t_i has donated a lock on x , it can no longer access x .

AL2: After t_i has donated a lock x , t_i must eventually unlock x .

AL3: t_i and t_j can simultaneously hold conflicting locks only if t_i has donated its lock on x .

Definition 4.27:

- (i) $p_j(x)$ is **in the wake** of t_i ($i \neq j$) in s if $d_i(x) <_s p_j(x) <_s ou_i(x)$.
- (ii) t_j is in the wake of t_i if some operation of t_j is in the wake of t_i .
 t_j is **completely in the wake** of t_i if all its operations are in the wake of t_i .
- (iii) t_j is **indebted** to t_i in s if there are steps $o_i(x)$, $d_i(x)$, $p_j(x)$ s.t.
 $p_j(x)$ is in the wake of t_i and ($p_j(x)$ and $o_i(x)$ are in conflict or there is $q_k(x)$ conflicting with both $p_j(x)$ and $o_i(x)$ and $o_i(x) <_s q_k(x) <_s p_j(x)$).

Additional Locking Rules for AL

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AL4: When t_j is indebted to t_i ,
 t_j must remain completely in the wake of t_i .

AL: locking with rules LR1 - LR4, two-phase property, donations, and rules AL1 - AL4 .

AL Example

Example:

$rl_1(a) r_1(a) d_1(a) wl_3(a) w_3(a) wu_3(a) c_3$

$rl_2(a) r_2(a) wl_2(b) ru_2(a) w_2(b) wu_2(b) c_2 rl_1(b) r_1(b) ru_1(a) ru_1(b) c_1$

→ disallowed by AL (even \notin CSR)

Example corrected using rules AL1 - AL4:

$rl_1(a) r_1(a) d_1(a) wl_3(a) w_3(a) wu_3(a) c_3$

$rl_2(a) r_2(a) rl_1(b) r_1(b) ru_1(a) ru_1(b) c_1 wl_2(b) ru_2(a) w_2(b) wu_2(b) c_2$

→ admitted by AL (t_2 stays completely in the wake of t_1)

Correctness and Properties of AL

Theorem 4.8:

$\text{Gen}(2\text{PL}) \subset \text{Gen}(\text{AL})$.

Theorem 4.9:

$\text{Gen}(\text{AL}) \subset \text{CSR}$

Example:

$s = r_1(x) r_2(z) r_3(z) w_2(x) c_2 w_3(y) c_3 r_1(y) r_1(z) c_1$

$\rightarrow \in \text{CSR}$,
but $\notin \text{Gen}(\text{AL})$

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 - 4.3.1 Introduction
 - 4.3.2 Two-Phase Locking (2PL)
 - 4.3.3 Deadlock Handling
 - 4.3.4 Variants of 2PL
 - 4.3.5 Ordered Sharing of Locks (O2PL)
 - 4.3.6 Altruistic Locking (AL)
 - **4.3.7 Non-Two-Phase Locking (WTL, RWTL)**
 - 4.3.8 Geometry of Locking
- 4.4 Non-Locking Schedulers
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- 4.6 Lessons Learned

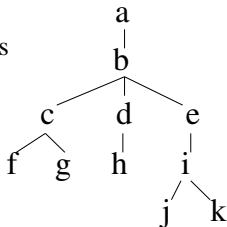
(Write-only) Tree Locking

Motivating example:

concurrent executions of transactions with access patterns that comply with organizing data items into a virtual tree

$t_1 = w_1(a) w_1(b) w_1(d) w_1(e) w_1(i) w_1(k)$

$t_2 = w_2(a) w_2(b) w_2(c) w_2(d) w_2(h)$



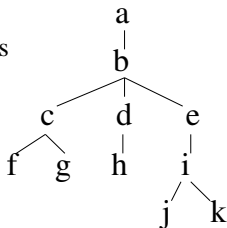
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$t_2 = w_2(a) w_2(b) w_2(c) w_2(d) w_2(h)$



Definition (Write-only Tree Locking (WTL)):

Under the **write-only tree locking protocol (WTL)** lock requests and releases must obey LR1 - LR4 and the following additional rules:

WTL1: A lock on a node x other than the tree root can be acquired only if the transaction already holds a lock on the parent of x .

WTL2: After a $wu_i(x)$ no further $wl_i(x)$ is allowed (on the same x).

Example:

$wl_1(a) w_1(a) wl_1(b) wu_1(a) w_1(b) wl_2(a) w_2(a) wl_1(d) w_1(d) wu_1(d) wl_1(e) wu_1(b) w_1(e) wl_2(b) wu_2(a) w_2(b) \dots$

Correctness and Properties of WTL

Lemma 4.6:

If t_i locks x before t_j does in schedule s , then for each successor v of x that is locked by both t_i and t_j the following holds: $wl_i(v) <_s wu_i(v) <_s wl_j(v)$.

Theorem 4.10:

$\text{Gen}(\text{WTL}) \subseteq \text{CSR}$.

Theorem 4.11:

WTL is deadlock-free.

Comment: WTL is applicable even if a transaction's access patterns are not tree-compliant, but then locks must still be obtained along all relevant paths in the tree using the WTL rules.

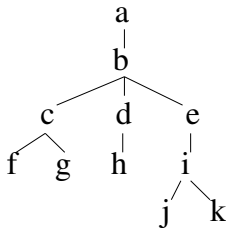
Read-Write Tree Locking

Problem: t_i locks root before t_j does,
but t_j passes t_i within a “read zone”

Example:

$rl_1(a)$ $rl_1(b)$ $r_1(a)$ $r_1(b)$ $wl_1(a)$ **$w_1(a)$** $wl_1(b)$ $ul_1(a)$ $rl_2(a)$ **$r_2(a)$**
 $w_1(b)$ $rl_1(e)$ $ul_1(b)$ $rl_2(b)$ $r_2(b)$ $ul_2(a)$ $rl_2(e)$ $rl_2(i)$ $ul_2(b)$ $r_2(e)$ $r_1(e)$
 $r_2(i)$ $wl_2(i)$ **$w_2(i)$** $wl_2(k)$ $ul_2(e)$ $ul_2(i)$ $rl_1(i)$ $ul_1(e)$ **$r_1(i)$** ...

→ appears to follow TL rules
but \notin CSR



Solution: formalize “read zone”
and enforce two-phase property on “read zones”

Locking Rules of RWTL

For transaction t with read set $RS(t)$ and write set $WS(t)$

let C_1, \dots, C_m be the connected components of $RS(t)$.

A **pitfall** of t is a set of the form

$C_i \cup \{x \in WS(t) \mid x \text{ is a child or parent of some } y \in C_i\}$.

Definition (read-write tree locking (RWTL)):

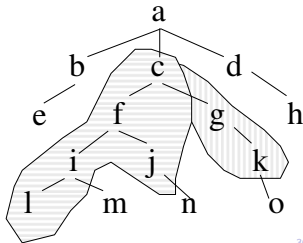
Under the **read-write tree locking protocol (RWTL)** lock requests and releases

Must obey LR1 - LR4, WTL1, WTL2, and the two-phase property within each pitfall.

Example:

t with $RS(t)=\{f, i, g\}$ and $WS(t)=\{c, l, j, k, o\}$

has pitfalls $pf_1=\{c, f, i, l, j\}$ and $pf_2=\{g, c, k\}$.



Correctness and Generalization of RWTL

Theorem 4.12:

Gen (RWTL) \subseteq CSR.

RWTL can be generalized for a DAG organization of data items into a **DAG locking** protocol with the following additional rule:
 t_i is allowed to lock data item x only if holds locks on a majority of the predecessors of x .

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 - **4.4.1 Timestamp Ordering**
 - 4.4.2 Serialization-Graph Testing
 - 4.4.3 Optimistic Protocols
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(Basic) Timestamp Ordering

Timestamp ordering rule (TO rule):

Each transaction t_i is assigned a **unique timestamp** $ts(t_i)$

(e.g., the time of t_i 's beginning).

If $p_i(x)$ and $q_j(x)$ are in conflict, then the following must hold:

$p_i(x) <_s q_j(x)$ iff $ts(t_i) < ts(t_j)$ for every schedule s .

Theorem 4.15:

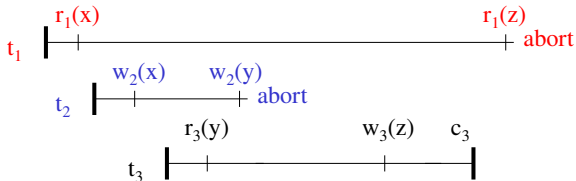
Gen (TO) \subseteq CSR.

Basic timestamp ordering protocol (BTO):

- For each data item x maintain $\max\text{-r}(x) = \max\{ts(t_j) \mid r_j(x) \text{ has been scheduled}\}$ and $\max\text{-w}(x) = \max\{ts(t_j) \mid w_j(x) \text{ has been scheduled}\}$.
- Operation $p_i(x)$ is compared to $\max\text{-q}(x)$ for each conflicting q :
 - if $ts(t_i) < \max\text{-q}(x)$ for some q then abort t_i
 - else schedule $p_i(x)$ for execution and set $\max\text{-p}(x)$ to $ts(t_i)$

BTO Example

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



$r_1(x) w_2(x) r_3(y) a_2 w_3(z) c_3 a_1$

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Serialization Graph Testing (SGT)

SGT protocol:

- For $p_i(x)$ create a new node in the graph if it is the first operation of t_i
- Insert edges (t_j, t_i) for each $q_j(x) <_s p_i(x)$ that is in conflict with $p_i(x)$ ($i \neq j$).
- If the graph has become cyclic then abort t_i (and remove it from the graph) else schedule $p_i(x)$ for execution.

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Theorem 4.16:

Gen (SGT) = CSR.

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- If the graph has become cyclic then abort t_i (and remove it from the graph) else schedule $p_i(x)$ for execution.

Theorem 4.16:

Gen (SGT) = CSR.

Node deletion rule:

A node t_i in the graph (and its incident edges) can be removed when t_i is terminated and is a source node (i.e., has no incoming edges).

Example:

$r_1(x)$ $w_2(x)$ $w_2(y)$ c_2 $r_1(y)$ c_1

removing node t_2 at the time of c_2

would make it impossible to detect the cycle.

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Optimistic Protocols

Motivation: conflicts are infrequent

Approach:

divide each transaction t into three phases:

read phase:

execute transaction with writes into **private workspace**

validation phase (certifier):

upon t 's commit request

test if schedule remains CSR if t is committed now

based on t 's read set $RS(t)$ and write set $WS(t)$

write phase:

upon successful validation

transfer the workspace contents into the database

(deferred writes)

otherwise abort t (i.e., discard workspace)

Backward-oriented Optimistic CC (BOCC)

Execute a transaction's validation and write phase together as a **critical section**: while t_i being in the **val-write phase**, no other t_k can enter its val-write phase

BOCC validation of t_j :

compare t_j to all previously committed t_i

accept t_j if one of the following holds

- t_i has ended before t_j has started, or
- $RS(t_j) \cap WS(t_i) = \emptyset$ and t_i has validated before t_j

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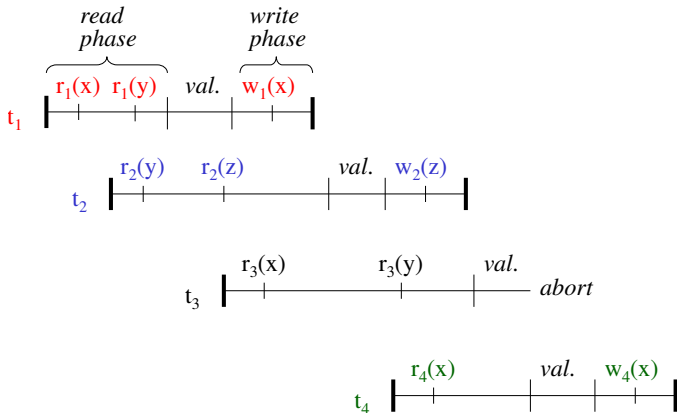
Theorem 4.46:

Gen (BOCC) \subset CSR.

Proof:

Assume that $G(s)$ is acyclic. Adding a newly validated transaction can insert only edges into the new node, but no outgoing edges (i.e., the new node is last in the serialization order).

BOCC Example



Forward-oriented Optimistic CC (FOCC)

Execute a transaction's val -write phase as a **strong critical section**:
while t_i being in the **val-write phase**, no other t_k can perform any steps.

FOCC validation of t_j :

compare t_j to all concurrently active t_i (which must be in their read phase)

accept t_j if $WS(t_j) \cap RS^*(t_i) = \emptyset$ where $RS^*(t_i)$ is the current read set of t_i

Forward-oriented Optimistic CC (FOCC)

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while t_j being in the **val-write phase**, no other t_k can perform any steps.

FOCC validation of t_j :

compare t_j to all concurrently active t_i (which must be in their read phase)
accept t_j if $WS(t_j) \cap RS^*(t_i) = \emptyset$ where $RS^*(t_i)$ is the current read set of t_i

Remarks:

- FOCC is much more flexible than BOCC:
upon unsuccessful validation of t_j it has three options:
 - abort t_j
 - abort one of the active t_i for which $RS^*(t_i)$ and $WS(t_j)$ intersect
 - wait and retry the validation of t_j later
(after the commit of the intersecting t_i)
- Read-only transactions do not need to validate at all.

Correctness of FOCC

Theorem 4.18:

Gen (FOCC) \subset CSR.

Proof:

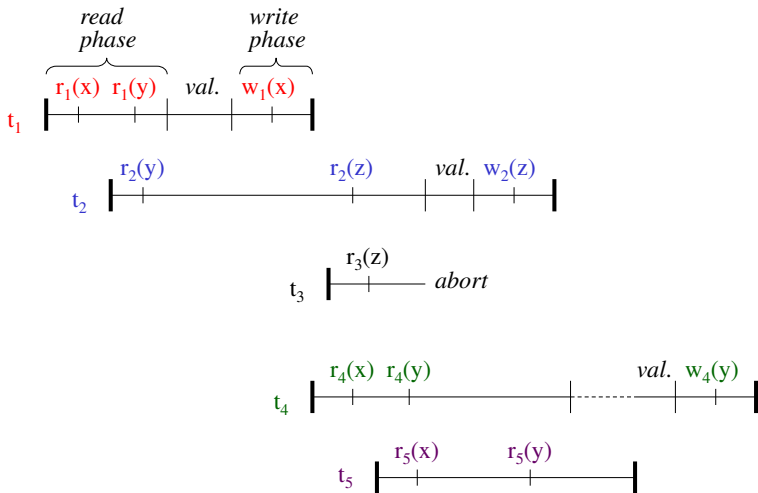
Assume that $G(s)$ has been acyclic and that validating t_j would create a cycle.

So t_j would have to have an outgoing edge to an already committed t_k .

However, for all previously committed t_k the following holds:

- If t_k was committed before t_j started, then no edge (t_j, t_k) is possible.
- If t_j was in its read phase when t_k validated, then $WS(t_k)$ must be disjoint with $RS^*(t_j)$ and all later reads of t_j and all writes of t_j must follow t_k (because of the strong critical section); so neither a wr nor a ww/rw edge (t_j, t_k) is possible.

FOCC Example



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Hybrid Protocols

Idea: Combine different protocols, each handling different types of conflicts (rw/wr vs. ww) or data partitions

Caveat: The combination must guarantee that the **union** of the underlying “local” conflict graphs is acyclic.

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Example 4.15:

use SS2PL for rw/wr synchronization and TO or TWR for ww with **TWR (Thomas' write rule)** as follows:

for $w_j(x)$: if $ts(t_j) > \max\text{-w}(x)$ then execute $w_j(x)$ else do nothing

$s_1 = w_1(x) r_2(y) w_2(x) w_2(y) c_2 w_1(y) c_1$

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

} both accepted by SS2PL/TWR
with $ts(t_1) < ts(t_2)$,
but s_2 is not CSR

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} both accepted by SS2PL/TWR
with $ts(t_1) < ts(t_2)$,
but s_2 is not CSR

Problem with s_2 : needs synch among the two “local” serialization orders

Solution: assign timestamps such that the serialization orders

of SS2PL and TWR are in line

$\rightarrow ts(i) < ts(j) \Leftrightarrow c_i < c_j$

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Lessons Learned

- S2PL is the most versatile and robust protocol and widely used in practice
- Knowledge about specifically restricted access patterns facilitates non-two-phase locking protocols (e.g., TL, AL)
- O2PL and SGT are more powerful but have more overhead
- FOCC can be attractive for specific workloads
- Hybrid protocols are conceivable but non-trivial