# 15 Concurrency control

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Lit.: Eickler/ Kemper chap 11.6-11.13, Elmasri /Navathe chap. 20, Garcia-Molina, Ullman, Widom: chap. 18

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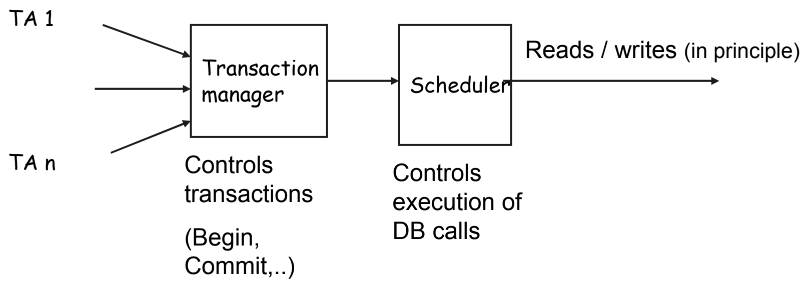
## Concurrency control …and serializability

Wanted:

effective real-time scheduling of operations with guaranteed serializability of the resulting execution sequence.



## Concurrency control

### Concurrency control in DBS

- methods for scheduling the operations of database transactions in a way which guarantees serializability of all transactions ("between system start and shutdown")

- Primary concurrency control methods
  - Locking (most important)
  - Optimistic concurrency control
  - Time stamps
  - Multiversion CC

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## Concurrency control

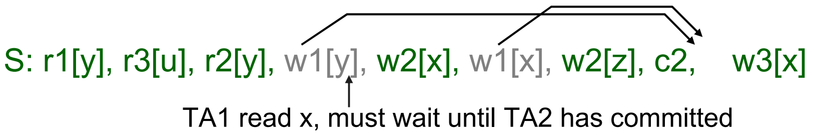
- No explicit locking in application programs  
  - error prone,  
  - responsibility of scheduler (and lock manager)

  In most DBS also explicit locking allowed in addition to implicit locking by scheduler. Use with care!

- Not considered here: transaction independent locking, e.g. writing a page p to disk requires a short term lock on p

## Optimistic vs. pessimistic

- Locking is pessimistic
  - Assumption: during operation op [x] of TA1 a (potentially) conflicting operation op'[x] of TA2 will access the same object x
  - This has to be avoided by locking x before accessing x


S: r1[y], r3[u], r2[y], w1[y], w2[x], w1[x], w2[z], c2, w3[x]

TA1 read x, must wait until TA2 has committed

Note: call sequence and execution sequence different

- An optimistic strategy would be:
  - Perform all operations on a copy of the data. Check at the end – before commit – if there were any conflicts.
  - If no: commit, else abort (rollback) - more or less

---

## 15.2.1 Lock protocols

### Simple object locking

Lock each object before writing / writing,
unlock when operation finished

⇨ schedule will not be serializable (why?)

Example
l1(x) r1(x) ul1(x) l2(x) w2(x) ul2(x) l1(x) w1(x) ul(x)

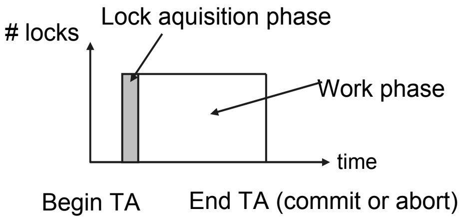
⇨ lost update ⇨ useless

# Lock protocols

- Preclaiming
  - Acquire all locks needed before performing an operation
  - release, if you do not get all of them. Try again.
    *race condition, transaction could starve!*
  - Execute transaction
  - Release locks

Preclaiming serializable?

Why (not) ?



Bad: objects to be processed may not be known in advance.

Not used in DBS.

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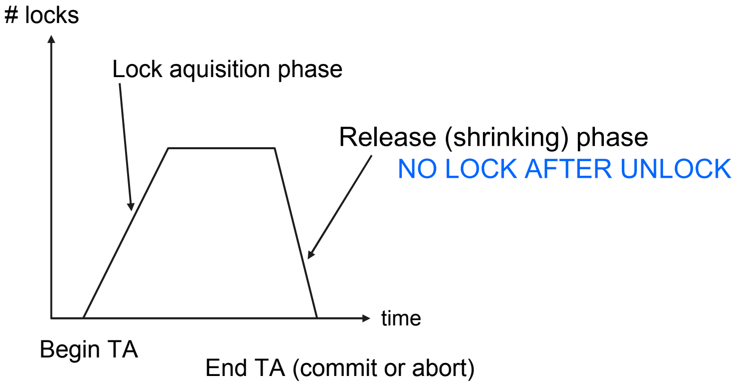
# 12.3 Two phase locking (2PL)

## The 2PL protocol

1. Each object referenced by $TA_i$ has to be locked before usage
2. Existing locks of other TA's will be respected
3. No lock is requested by a $TA_i$ , if a lock has been released by the same transaction $TA_i$
   ("no lock after unlock")
4. Locks are released at least at commit time
5. A requests of a lock by a TA which it already holds, has no effect.

…

# Concurrency control2PL



- Locked objects may be read / written already in lock aquisition phase

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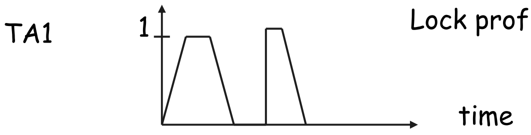
# Concurrency control2PL

- Why no lock after unlock?
- Example:

lock1(x), r1[x], x=x*10, ulock1(x)
lock2(x), r1[x], x:=x+1, w2[x] ulock2(x)
lock1(x), w1(x), ulock1(x)

results in a lost update



Lock profil of TA1 is NOT 2PL

⇒ Rule 3 is essential

# Concurrency control 2PL

## 2-Phase locking theorem

If all transactions follow the 2-phase locking protocol, the resulting schedule is serializable

- Proof sketch:
  - Suppose a resulting schedule is not serializable. when using 2PL ⇒ conflict graph contains a cycle ⇒ there are transactions TA1 and TA2 with conflict pairs (p,q) and (q', p'), p, p' atomic operations of TA1, q,q' of TA2, p,q access the same object x, and q', p' an object y (assuming a cycle of length 1, induction for the general case)

→

---

# Concurrency control 2PL

Let e.g. (p,q) = (r1[x], w2[x]),
(q', p') = (w2[y], w1[y])

Analyze all of the possible execution sequences:

p, q, q', p
p, q', q, p'
q', p, q, p'
q', p, p', q
q', p', p, q

T2: Lock y, T1: Lock x, T2: Lock x, T1: Lock y

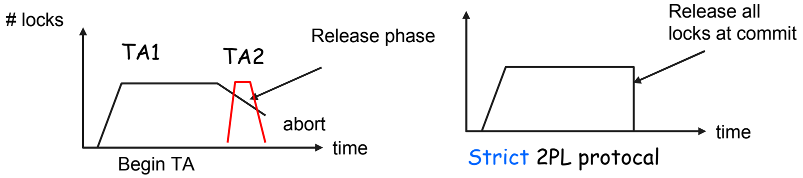
T1 must have released lock on x and acquired one on y (or T2 must have acquired after release)
Violates 2-phase rule! Contradiction to assumption that all follow TAs use 2PL protocol

Same holds for the other possible sequences ⇒ Theorem

Note: serializability does not imply 2PL, i.e. there are serializable schedules which do not result from a 2PL scheduler

## 15.2.3 Strict concurrency protocols

Locking protocol is strict if locks are released at commit / abort.



- A different transaction TA2 could have used an object x which was unlocked by TA1 in the release phase
  - no problem, if TA1 commits
  - if TA1 aborts, TA2 has used a wrong state of x TA2 has to be aborted by the system
- May happen recursively: cascading abort, bad ...
- Strict 2PL: Release all locks at commit point.

---

## 15.2.4 Lock conflicts and deadlocks

- Lock conflict
  - Two or more processes request an exclusive lock for the same object
- Deadlock
  - Locking: threat of deadlock
    - No preemption
    - No lock release in case of lock conflicts

⇨ Two-Phase locking may cause deadlocks

$L_i[x]$ = Transaction i requests lock on x

$U_i[x]$ = Transaction i releases lock on x

Lock sequence: $L_1[x]$ , $L_2[y]$, ..., $L_1[y]$, $L_2[x]$ causes deadlock

How to deal with deadlocks? --> see below

## 15.2.5 Lock modes

- Primary goal
  - no harmful effects (lost update, ...)
- Secondary goal
  - Degree of parallelism should be as high as possible, even when locking is used
  - Low deadlock probability, if any

- Ways to increase parallelism
  - Compatible locks (read versus write semantics)
  - Different lock granularity
  - Application semantics
  - No locks, optimistic cc

---

## Lock modes

### Lock modes and lock compatibility

RX – model: read (R) and eXclusive(X) locks

(or: write locks)

holder

requester

|   | R | X |
|---|---|---|
| R | + | - |
| X | - | - |

R-lock same as
Shared (S) lock

Lock compatibility matrix

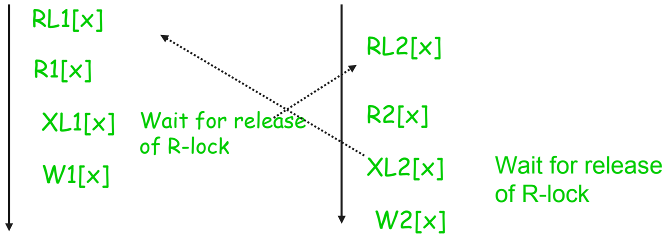
- Lock compatibility in the RX model:
  - Objects locked in R-mode may be locked in R- mode by other transactions(+)
  - Objects locked in X-mode may not be locked by any other transaction in any mode.
    Lock conflict: requesting TA has to wait

# Reduce deadlock threat

Deadlocks caused by typical read / write sequences

TA1: read account_record x; incr(x.balance); write account_record

TA2: read account_record x; incr(x.balance); write account_record



RL1[x]

R1[x]

XL1[x] Wait for release of R-lock

W1[x]

RL2[x]

R2[x]

XL2[x] Wait for release of R-lock

W2[x]

RL[x] Read lock

XL[x] Write lock

- ⇨ Read-Update-Exclusive Model (RUX)

---

# Lock modes: RUX

## RUX Lock protocol

– Transactions which read and subsequently update an object y request a U-lock, upgrade to X-lock before write

– Read locks cannot be upgraded

– U-locks incompatible with U-locks

⇒ deadlock-thread avoided

– U / R-lock compatibility asymmetric, why?

holder

requester

| | R | U | X |
|---|---|---|---|
| R | + | - | - |
| U | + | - | - |
| X | - | - | - |

How does DBS know, that update is intended?

# Lock modes

## Hierarchical locking

– One single lock granularity (e.g. records) insufficient, large overhead when many rows have to be locked

– Most DBS have at least two lock granularities:
row locks and table locks

Issue: $TA_i$ wants to lock table R

- some rows of R locked by different transactions

⇨ different lock conflict as before: $TA_i$ is waiting for release of all record locks

- No other TA should be able to lock a record, otherwise $TA_i$ could starve

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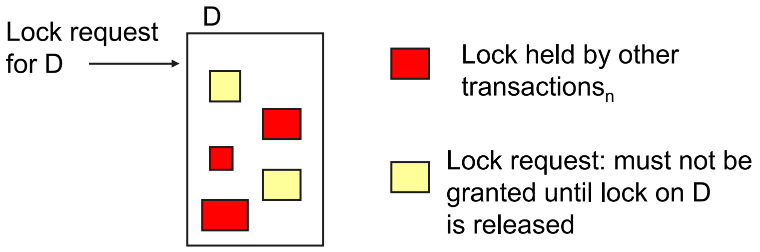
# Concurrency control

## Locks of different granularity



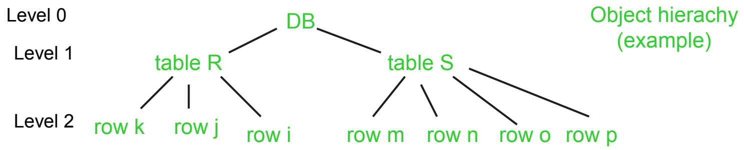
🟥 Lock held by other transactions$_n$

🟨 Lock request: must not be granted until lock on D is released

Efficient implementation of this type of situation??

# Lock modes: Hierarchical locking

## Intention locks



- Feature of intention locks for hierarchical locking:
for each lock mode, there is an intention lock, e.g. for RX-lock modes: IR and IX

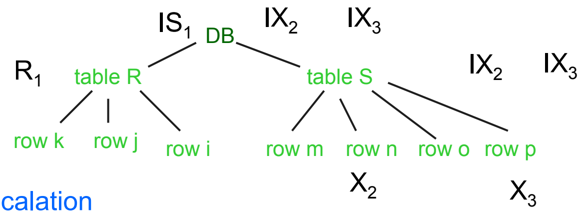
- Semantics:
A TA holds a IM-lock on an object D on level i, if and only if it holds an M-lock on an object D' on level j > i subordinate to D

---

# Concurrency controlLock modes

## Hierarchical locking

- An object O on level i contains all objects x on level i+1
- Locks of O lock all subordinate objects x
- If a subordinate object x (level i+1) is locked, this is indicated by an intention lock on level i



### Lock escalation

If too many objects x on level i+1 are locked by a transaction, it may be converted into one lock on level i

# Lock modes

## Hierarchical locking (cont)

- Advantage: one lookup is sufficient to check if a lock on higher level (say on a table) can be granted
- Protocol: if a TA wants to lock an object on level i in mode <M> ( X or R), lock all objects on higher level (on the path to root) in I<M> – mode
- Easy to check, if the locks on all subordinate objects are released: implement I<M>-lock as a counter

holder

requester

| | IR | IX | R | X |
|---|---|---|---|---|
| IR | + | + | + | - |
| IX | + | + | - | - |
| R | + | - | + | - |
| X | - | - | - | - |

Compatibility matrix

How to combine
with U-lock mode?

# 15.2.6 Deadlock detection, resolution, avoidance

## Deadlocks

... can happen with 2PL protocol (see above)

- Release of a lock could break rule 4

XL1[x] , XL2[y], XL1[y] -> TA1: WAIT for XU2[y] , XL2[x] -> TA2: WAIT for XU1[x]

- Note: deadlocks very different from lock conflicts:

.... XL1[x] , XL2[y], XL1[y] -> TA1: WAIT for XU2[y] XL2[z], w2[y], w2[z], XU2[y],...

Lock conflict, y is locked by TA2, TA1 waits for unlock

Lock conflict resolved by XUnlock2[x], TA1 proceeds

Not schedules, but call sequences
including lock / unlock operations by the scheduler

# Deadlock

## Detection and resolving deadlocks

- Cycle check in Wait-for-graph
  - Waiting of TA1 for release of lock on x by TA2 is indicated by an arc from TA1 to TA2 labeled "x"
  - Cycles indicate deadlock
  - In a distributed environment, deadlocks may involve different systems. How to detect cycles?
  - One of the waiting transaction ("victim") is rolled back
  - Which one??
- Timeout
  - If TA has been waiting longer than the time limit, it is aborted.
  - Efficient but may roll back innocent victims (deadlock does not exist)

Oracle: WF-graph in central DB, timeout in distributed

---

# Deadlock avoidance

## Avoiding deadlocks

- Deadlocks only occur, if no preemption
- Force preemption by the lock manager
- TA t is preempted ⇨ forced to rollback
- Preemption ⇨ no deadlocks, but living transactions may be killed

- Wait/Die - Wound/Wait : Basic idea
  - Solve lock conflicts by rollback of one of the conflicting transactions….
  - …. but not always
  - Rollback dependent on the relative age of the transactions
  - Time stamp for each transaction

# Deadlock avoidance

- Wound/Wait – Wait / Die methods
  - Each transaction $Ta_i$ has an initial timestamp $TS(TA_i)$
  - If $TA_2$ requests a lock on x and there is a lock conflict with $TA_1$, one of them may be aborted

TA2 requests lock which TA1 holds:

– WOUND / WAIT

if ts(TA1) < ts(TA2) then TA2.WAIT else TA1.ABORT

Abort lock holding TA if younger than requesting, else wait

– WAIT / DIE

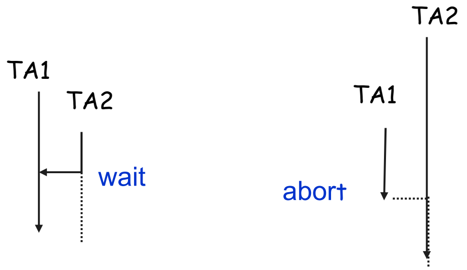
if ts(TA1) < ts(TA2) then TA2.ABORT else TA2.WAIT

Abort requesting TA if younger, else wait

---

# Deadlock avoidance

Wound / Wait



Younger TA may wait for older TA

olderTA preempts younger TA

`If TS(TA1) < TS(TA2) then TA2.wait else TA1.abort`

# Deadlock avoidance

## Wait / Die

older TA
waits for
younger one

**If TS(TA1) < TS(TA2) then TA2.abort else TA2.wait**

No deadlocks! Why?

Aborted transaction restarts with old timestamp
in order to avoid starvation

---

# 15.3 Non-locking protocols (more or less)

Arrows from
TA2-ops to
conflicting TA1-ops

- 15.3.1 Multiversion CC:

  r1[x] w1[x] r2[x] w2[y] r1[y] w1[z] c1 w2[a] c2

  not serializable.

  If r1[y] had arrived at the scheduler before
  w2[y] the schedule would have been serializable.
- Main idea of multiversion concurrency control : Reads should see a consistent (and committed) state, which might be older than the current object state.
- Necessary: Different version of an object
- Read and write locks compatible (!)
- In the example: TA2 must not write its version of y
  before TA1 has released lock on y
- Particular important in practice: 2 versions

# Multiversion concurrency

## Lock based MVCC ("MV2PL")

- Read locks always granted,
  write lock if object not write locked
  =>
  two versions: consistent one and writable private copy
- When TA wants to write modified copy of x into DB it has to wait until all readers of x have released read lock
- write is delayed to ensure consistent read using a certify lock

|   | R | W | C |
|---|---|---|---|
| R | + | + | - |
| W | + | - | - |
| C | - | - | - |

C = Certify

---

# Multiversion concurrency

- Two-version-2PL MVCC
  - has only one uncommitted version, one consistent ("current") version because writes are incompatible
  - Readers benefit, not writers
  - may be generalized to more than one uncommittted
  - is most important in practice

Scheduler:
rl (x) : set read lock immediately on consistent version of x
wl(x) : if not write locked, set write lock on x to produce a new uncommitted version
cl (x) : if neither read-locked nor write-locked cl(x) is granted and x will be written as the new consistent version by the TA

Correctness? Deadlocks? Read locks needed?

# MVCC for Read only Transactions

- Read-only transactions always read the last consistent state
- Last consistent state for Read only TA R: last committed value(s) before R starts
- Idea:
  - – Each TA has a timestamp ("begin TA")
  - – Update transactions with TS t makes a new version of updated data x,y,.. at commit, version of x,y,.. is t
  - – Read TA with timestamp t' read only those values the version t of which is less than t'
- Update TA use conventional 2PL protocol with S and X locks

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# MVCC / Read Only TAs: Example

call sequence: TA1, TA4 and TA5 are RO

R1(x) r2(x)w2(x)r3(x)r2(y)R4(z)w2(y)c2R4(x)c4w3(x)R5(z)c3R1(y)c1R5(x)c5

R1(x0)_________________________________________R1(y0)c1

r2(x0)w2(x0)__r2(y0)____w2(y)c2

r3(x).......blocked..........r3(x2)__w3(x3)c3

R4(z0)____ R4(x0)c4

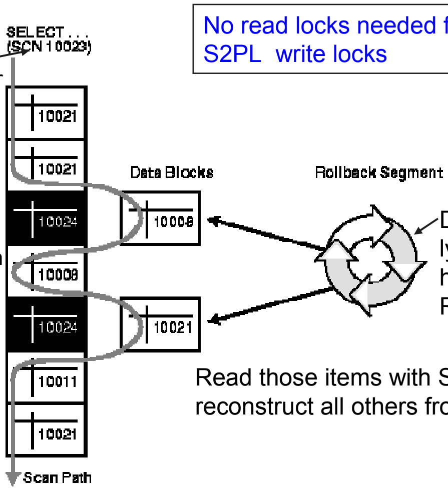
R5(z0)_________R5(x2)c5

R1(y0): there exists a newer version y2, but RO_TA1 is older
R5(x2): reads x2 since TA3 which produces x3, commits after TA 5 begins
R4(x0): same with TA2, which produces x2
TA3 has been blocked, since TA2 holds lock on x, r3(x2) after TA2 commited

## MVCC: How to implement versions

- Read Only Multiple version CC (used in Oracle)

No read locks needed for consistent read, S2PL write locks



"system change number 10023"
-> statement SCN

... or transaction commit time for transaction level read consistency

Data have to be temporarily stored anyway: System has to be prepared for Rollback"

Read those items with SCN' < SCN of statement reconstruct all others from log records

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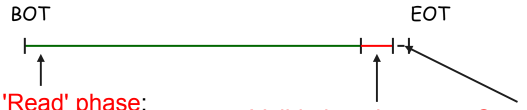
# Optimistic CC

## 15.3.2 Optimistic concurrency control

- Locks are expensive
- Few conflicts ⇨ retrospective check for conflicts cheaper
- Basis idea: all transactions work on copies, check for conflicts before write into DB
- if conflict: abort else commit



**'Read' phase**:
All data used are
copied to private
workspace and used
by the application

**Validation phase**:
any conflicts?
if yes: resolve

**Commit phase:**
write all (changed)
data into DB

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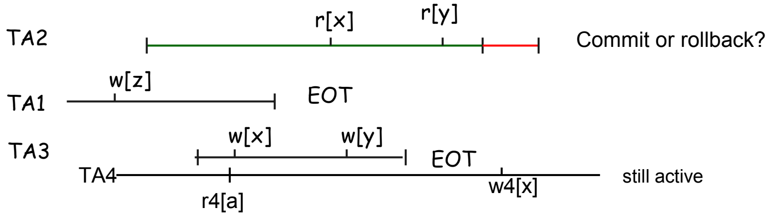
# Optimistic CC: BOCC

## Backward oriented concurreny control (BOCC)



- ReadSet R(T) = data, transaction T has read in read phase
- WriteSet W (T) = data (copies!), T has changed in read phase

Assumption: $W(T) \subseteq R(T)$ - necessary?

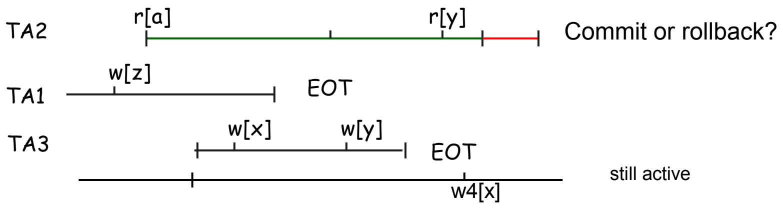
Example above: $x,y \in R(T2)$, $x,y \in W(T3)$, $z \in W(T1)$

Conflict? Let $x \in R(T)$ . T wants to validate.
If a different TA read x, but did not commit ⇨ no problem
If a different TA committed after BOT(T): DB state of x max be different from x at BOT(T) ⇨ conflict

# Optimistic CC: BOCC

BOCC_validate(T) :

if for all transactions T' which committed after BOT(T) :
$R(T) \cap W(T') = \emptyset$ then T.commit // successful validation
else T.abort



Shown: when they are needed! Consequence: More aborts than necessary :

$R(TA2) \cap W(TA3) \,!= \emptyset$ . No abort when locking, not even a lock conflict.

Validation: what happens, if more than one TA validates?

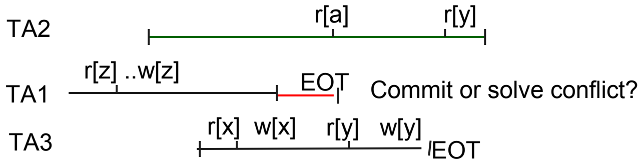
---

# Optimistic CC: FOCC

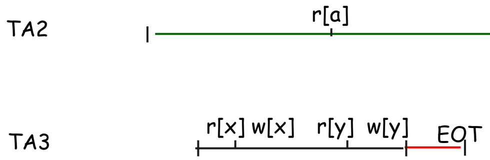
Forward oriented optimistic Concurrency control (FOCC)

- Forward looking validation phase:

  if there is a running transaction T' which read data written by the validating transaction T then solve the conflict (e.g. kill T'), else commit



# Concurrency: Optimistic CC



Commit or solve conflict?

```
FOCC_validate(T) :  if for all running transactions (T')
                      $R(T') \cap W(T) = \emptyset$
                    then T.commit    // successful validation
                    else solve_conflict ( T, T')
```

R(T'): Read set of T' at validation time of T  (current read set)

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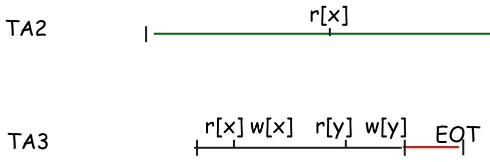
# Concurrency control Optimistic CC

- Validation of read only transactions T:
  FOCC guarantees successful validation !
- FOCC  has greater flexibility
  Validating TA may decide on victims!



solve conflict:
abort TA3 or TA2

- Issues for both approaches:
  fast validation – only one TA can validate at a time.
  Fast and atomic commit processing,
- Useful in situation with few expected conflicts

# Implementation of Read / Write sets

- Possible implementation of Read / Write sets: attach to each object x timestamp ts(x) of last write.
- Validating TA (T) checks if ts(x) changed since BOT(T)
- Important detail: timestamp of data item on disk? Access many disk records to validate? Expensive!
- "Records on disk are older than or equal to the records in buffer"

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# Optimistic CC & Locking

- Combining locks with optimism
  - Example: high traffic reservation system
  - typical TA: check "seats_avail >0 ?" //seats_avail is hot spot
    if yes, do this and that;
    write seats_avail-1
  - seats_avail is a hot spot object
  - Not the state per se is important but the predicate "seats_avail >0 ?"
  - Optimism: if pred is true at BOT then it will be true with high probability at EOT
  - But if not: abort

# Optimistic CC & Locking

- Additional operations Verify and Modify:

```
Verify P : check predicate  P  ("seats_avail >0"?)
              //like read phase
 put "seats_avail-1" into to_do list
 rest of TA
 EOT:
 Modify : for all  operations on to_do list
            { lock; verify once more;
              if 'false' rollback else write updates;}
             unlock all;
```

- Short locks, more parallelism
- If only decrement / increment operations: concurrent writing possible without producing inconsistencies
- Enhancement: Escrow locks – system guarantees that predicate still holds. Only ordered sets and inc / dec operations

---

# 15.3. 3 Time stamp ordering

## Time stamp ordering

Basic idea:

- assign timestamp when transaction starts
- if ts(t1) < ts(t2) … < ts(tn), then scheduler has to produce history equivalent to t1,t2,t3,t4, ... tn

Timestamp ordering rule:

If pi[x] and qj[x] are conflicting operations,
then pi[x] is executed before qj[x] (pi[x] < qj[x])
iff ts(ti) < ts(tj)

## Timestamp ordering

- TO concurrency control guarantees conflict-serializable schedules:

If not: cycle in conflict graph
cycle of length 2: ts(t1) < ts(t2) $\wedge$ ts(t2) < ts(t1)
#
induction over length of cycle => #

=> No cycle in conflict graph ✓

---

## TO Scheduler

- Basic principle:

  Abort transaction if its operation is "too late“
  Remember timestamp of last write of x: maxW[x]
  and last read maxR[x]

| | |
|---|---|
| Transaction i: | ti with timestamp ts(ti) |
| Operations: | ri(x) / wi(x) - ti wants to read / write x |
| Scheduler state: | maxR[x] / maxW[x]<br>timestamp of youngest TA<br>which read x / has written x |

# TO Scheduler: read

Read: TA ti with timestamp ts(ti) wants to read x : ri(x)

maxW[x] > ts(ti):

there is a younger TA wich has written x

⇨ contradicts timestamp ordering:
ti reads too late

⇨ abort TA ti , restart ti

maxW[x] < ts(ti) ⇨ maxR[x] = ts(ti), go ahead

Example: ------|------|----------- >

wj(x) ri(x) ts(ti) < ts(tj)

What would happen in a locking scheduler?

---

# TO Scheduler: write

Write: TA ti with timestamp ts(ti) wants to write x : wi(x)

maxW[x] > ts(ti) ∨ maxR[x] > ts(ti) :

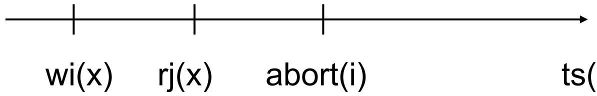
/* but x has been *written or read by younger transaction*:

⇨ contradicts timestamp ordering

⇨ abort TA ti

otherwise: ⇨ schedule wi(x) for execution

Why abort ?

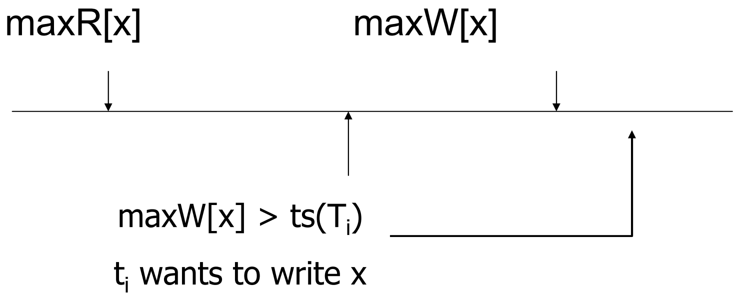


ts(ti) < ts(tj)

Dirty read! Solution: scheduler delays rj until TA committed
TA: the TA which was the last writer.

## Thomas Write Rule

- Idea: younger write overwrites older write without changing effect of timestamp ordering



Rules for Writer T with timestamp ts(T):

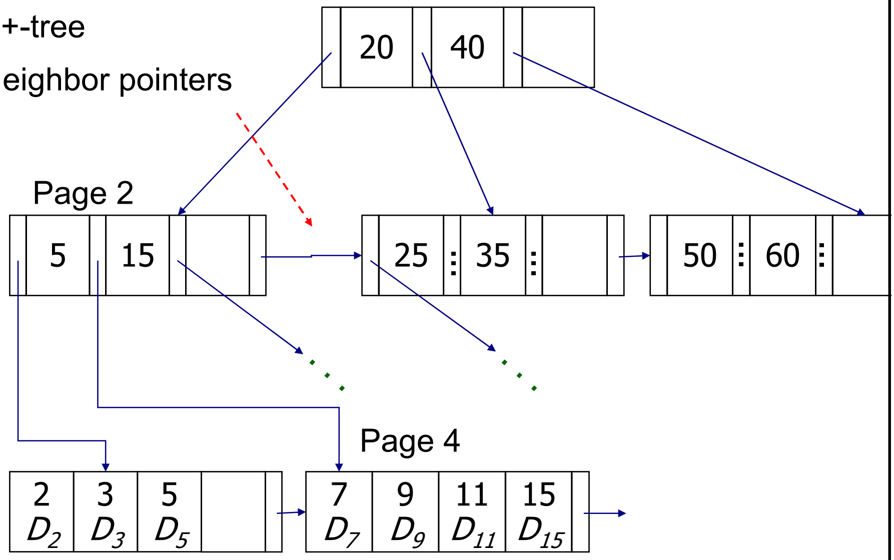
1. maxR[x] > ts(T)   abort T
2. maxW[x] > ts(T)  skip write // Thomas write rule
3. otherwise write(x), maxW[x] = TS(T)

---

## 15.4. Synchronization of Indexstructures

B+-tree

Neighbor pointers



cf Kemper / Eickler

## Synchronisation of index structures

- Basic idea:
  - Index structures are redundant, no reason to put them into transactional brackets
  - Concurrent operation on B+-tree: short page locks

Sufficient??

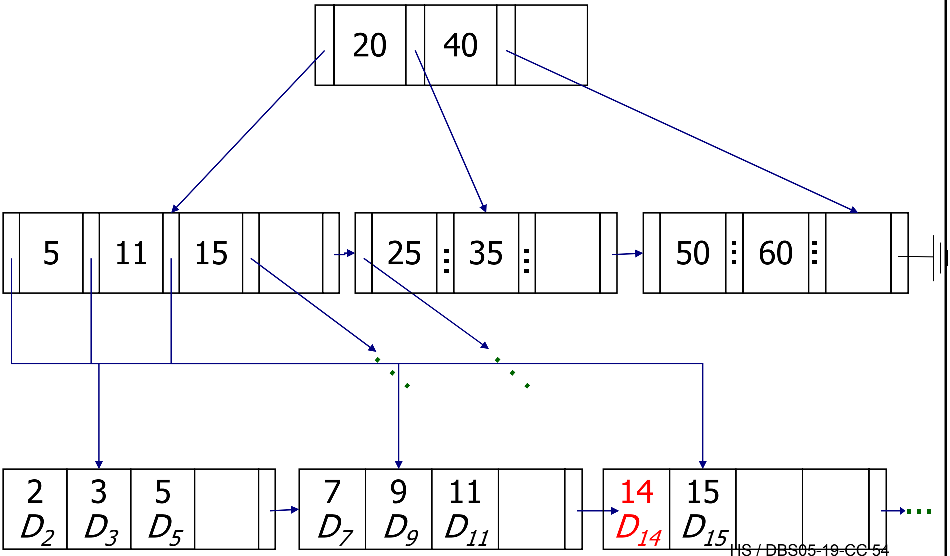
Scenario: TA1 searches for rec 15
has processed page 2 and found pointer to p4

TA2 inserts rec 14: page split!
⇨ TA1 will not find rec 15

Solution: TA1 find rec in a right neighbor

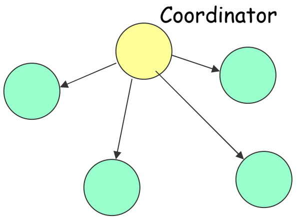
---

## Synchronization of Indexstructures



# 15.5 Distributed Transactions  Intermezzo

- Configuration



•Different resource managers involved in the transaction
e.g: database systems, mail server, file system, message queues,...

•Asynchronous and independent

•One transaction coordinator
can be a resource manager or not

•One or more participants

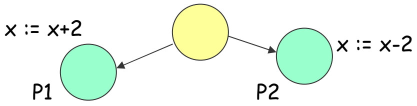
Examples: Transfer of money/shares / ... from Bank A to B
ECommerce systems
All kinds of processing in decentralized systems

Frequently used in multi-tier architectures: middle tier accesses different databases.

---

# Distributed Transactions   Intermezzo

- Problems
  - No problem ... if all systems work reliable
  - Deadlock? Difficult to detect: use optimistic locking
  - Obvious inconsistencies, if one participant commits, another crashes:



Coordinator: COMMIT

P1 commits

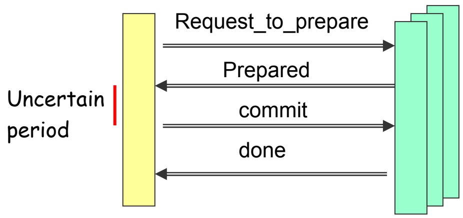
P2 crashes, undo??
Introduces global inconsistency

•Assumptions

- Each resource manager has a transactional recovery system (log operations, commit, rollback)
- There is exactly one commit coordinator, which issues commit for a transaction exactly once
- A transaction has stopped processing at each site before commit is issued

# Distributed Transactions

- The Two Phase Commit protocol (2PC)



1. Coordinator asks for preparing commit of a transaction
2. If (all participants answer 'prepared')
3. Coordinator asks for commit

   else asks for abort
4. Participants send 'done'

- After prepare phase: participants are ready to commit or to abort; they still hold locks
- If one of the participants does not reply or is not able to commit for some reason, the global transaction has to be aborted.
- Problem: if coordinator is unavailable after the prepare phase, resources may be locked for a long time

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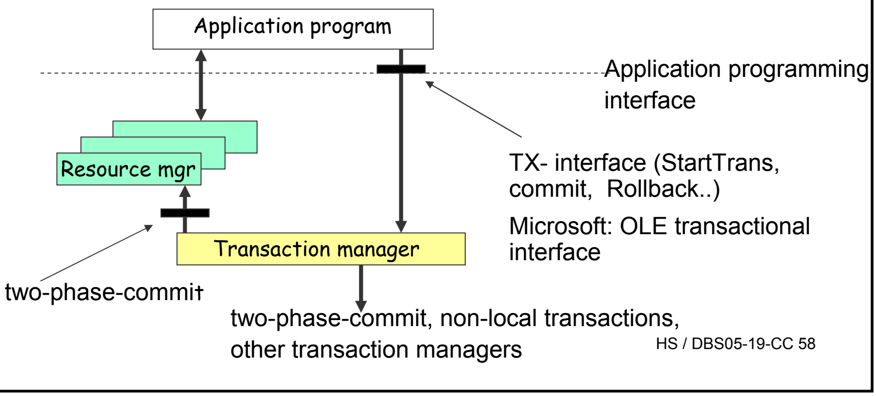
# Distributed Transactions

Transaction managers: the X/Open transaction model

- Independent systems which coordinate transactions involving multiple resource managers as a service for application programs



Application programming interface

TX- interface (StartTrans, commit, Rollback..)

Microsoft: OLE transactional interface

two-phase-commit

two-phase-commit, non-local transactions, other transaction managers

# Summary: Transactions and concurrency

- Transactions: Very import concept
- Model for consistent, isolated execution of TAs
- Scheduler has to decide on interleaving of operations
- Serializability: correctness criterion
- Implementation of serializability:
  - 2-phase-locking
  - hierarchical locks
  - variation in order to avoid deadlocks : wound / wait, wait / die
  - optimistic concurrency control
  - multiversion cc