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)
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“As long as one keeps searching, the answers come.”
(Joan Baez)
Example

\[ t_1: \]
Update Persons
Set City = ‘Phoenix’
Where Age ≥ 50
And City = ‘Dallas’
→ modifies record x

\[ t_2: \]
Select * From Persons
Where City = ‘Phoenix’
→ fetches records p, q

Select * From Persons
Where City = ‘Dallas’
→ fetches records d, e

Observations:
• page locking would prevent this phantom-problem execution
• locking the accessed records alone is insufficient
• need appropriate locks on (key, RID) pairs in City index
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Implementation of Index by B+-tree

Search tree interface:
• lookup <index> where <indexed field> = <search key>
• lookup <index> where <indexed field> between <lower bound> and <higher bound>
Simple Insertion into B⁺-tree Index

Adam  Bill  Carl
Dick   Eve
Hank  Jane  Jill  Tom

↓ + Ellen, + Bob

Adam  Bill  Bob  Carl  Dick  Ellen  Eve
Hank  Jane  Jill  Tom
Insertion into $B^+\text{-tree}$ with Leaf Node Split

Leaf Node Split

+ Sue
Insertion into B⁺-tree with Root Node Split

+ Betty

Root Node Split

root node

inner nodes

leaf nodes
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- 9.2 Implementation by B+-trees
- **9.3 Key-Range Locking at the Access Layer**
- 9.4 Techniques for the Page Layer
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Simple Key-Range Locking

ADT interface for search structure:

\[\text{insert (key, RID)}\]
\[\text{delete (key, RID)}\]
\[\text{search (key)}\]
\[\text{range_search (lowkey, highkey)}\]

Protocol:

- insert, delete, and search lock single key
  (insert and delete in compatible modes)
- range_search locks interval \([\text{lowkey}, \text{highkey}]\)
- table scan effectively locks interval \([- \infty, + \infty]\)
+ page locks acquired during subtransactions

→ lock manager needs “key in interval” test
→ range_search “preclaims” lock on entire interval
Incremental Key-Range Locking

refined ADT interface with
range_search(lowkey, highkey) replaced by:

\[
\text{search (lowkey)} \uparrow \text{key} \uparrow \text{page}
\]
\[
\text{next (currentkey, currentpage, highkey)} \uparrow \text{key} \uparrow \text{page}
\]
next  ...

Approach:
operations lock intervals [found-key, next-existing-key)
identified by “found-key” (i.e., only keys that do exist in the index)
+ page locks during subtransactions

Incremental Key-Range (Previous-Key) Locking Protocol:
• search(x) requests read lock on x if x is present,
  or largest key < x if x is not found
• next(currentkey, ...) requests read lock on currentkey
• insert (y, RID) requests write locks on y and largest key < y
• delete (y, RID) requests write locks on y and largest key < y
Example: Incremental Key-Range Locking

range_search (23, 34):
  search (23) ↑ 25 ↑ p
  lock page r, page n, page p
  lock key 22
  unlock pages r, n, p
  next (25, p, 34) ↑ 31 ↑ p
  lock key 25
  next (31, p, 34) ↑ 33 ↑ q
  lock key 31
  next (33, q, 34) ↑ nil ↑ nil
  lock key 33

insert (27, ...):
  lock page r, page n, page p
  lock key 25
  lock key 27
  unlock pages r, n, p
Correctness of Incremental Key-Range Locking

Theorem 9.1:
Previous-key locking generates only conflict-serializable schedules as far as index operations are concerned.

Proof sketch:
• search(x) is in conflict with insert(y, RID) or delete (y, RID) only for x=y
  • for successful search the conflict is detected by locks on x
  • for unsuccessful search the conflict is detected by locks on largest key < x
• range_search (low, high) is in conflict with insert (y, RID) or delete (y, RID) if y falls into [low, high]
  • this conflict is detected because range_search incrementally acquires locks on all keys from low or the largest key < low up to and including the largest key ≤ high, which must include the largest key < y
• insert (x, RID) and insert (y, RID) conflict only for x=y (and only for unique index)

...
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- **9.4 Techniques for the Page Layer**
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Problem Scenario

Problem: search(31) or insert(31) in between stage 1 and stage 2
Solution 1: Lock Coupling (“Crabbing”)

Definition: A tree node is **split-safe** if it has enough free space to accommodate at least one additional routing key and child pointer.

Protocol:
- Search operations need a read lock before accessing a node. Insert operations need a write lock before accessing a node.
- A lock can be granted only if there is no conflict and the requestor holds a lock (in the same mode) on the node’s parent.
- Search operations can release a lock on a node once they have acquired a lock on a child of that node.
- Insert operations can release a lock on a node if:
  - the node is split-safe and
  - they have acquired a lock on a child of that node.

Theorem 9.2: Lock coupling for search and insert operations generates only OCSR schedules.
Example: Lock Coupling

insert (30):

- write lock r
- write lock n
- unlock r
- write lock p
- allocate new page p'
- write lock p'
- split contents of p onto p and p'
- adjust contents of n
- release locks on n, p, p'

search (31):

- read lock r
- request read lock on n
- acquire read lock on n
- release lock on r
- read lock p'
- release lock on n
- return RID for key 31
- release lock on p'
Lock Coupling with Range Searches, Next, and Delete Operations

- the initial search (lowkey) of a range_search (lowkey, highkey) operation applies the locking rules for exact-key search operations
- a next (currentkey, currentpage, highkey) operation needs to acquire a read lock on currentpage, and it can acquire a lock on another leaf node only if it holds a lock on the preceding leaf.

- delete operations do not trigger node merging
- an empty node can be deallocated only when all transactions that were active at the time when the node became empty have terminated ("drain technique")
**Correctness of Extended Lock Coupling**

**Theorem 9.3:**
Lock coupling with next operations generates only OCSR schedules.

**Proof sketch:**
- By Theorems 9.1 and 9.3, schedules with search, insert, delete, and next operations are tree reducible.
- So the remaining problem scenario is of the form:
  ... search\(_i\) (lowkey) ... insert\(_k\) (x, RID\(_1\)) ... next\(_i\) (currentkey\(_1\), ..., highkey) ...
  ... insert\(_l\) (y, RID\(_2\)) ... next\(_i\) (currentkey\(_2\), ..., highkey) ...
  with active transactions \(t_i\), \(t_k\), \(t_l\)
- \(x\) cannot fall into \([\text{lowkey}, \text{currentkey}_1]\) and \(y\) cannot fall into \([\text{lowkey}, \text{currentkey}_2]\) because of previous-key lock conflicts
- So both insert\(_k\) (x, ...) and insert\(_l\) (y, ...) can be commuted to the left of \(t_i\)

**Theorem 9.4:**
(Extended) Lock coupling at the page layer together with incremental key-range locking at the access layer ensure tree reducibility of all 2-level schedules.
Example: Extended Lock Coupling

range_search (24, 35):

search (24)
  read lock r, read lock n, unlock r
  read lock p, unlock n
  read lock key 22, unlock p

next (25, p, 35)
  read lock p
  read lock key 25, unlock p

next (27, p, 35)
  request read lock on p

....

acquire lock on p
request read lock on key 27

acquire lock on key 27
read lock p', unlock p, unlock p'

next (30, p', 35)
  read lock p', read lock key 30, unlock p'

insert (30):

write lock r, write lock n, unlock r

write lock p

write lock key 30, write lock key 27
write lock p' (was missing!)

release locks on p, p', n

commit transaction
Solution 2: Link Technique

Link protocol:
• Search operations need only lock the currently accessed node (no need for holding two page locks simultaneously)
• Upon “not found”, search and next operations proceed to the right sibling node until they have seen a larger key

Solution 3: Giveup Technique

Giveup protocol:
• All operations need only lock the currently accessed node (no need for holding two page locks simultaneously)
• Each node contains a “range field” for its subtree, maintained by splits on a per node basis
• Upon seeing a node with a range field that does not contain the search key, the operation “gives up” and is retried, starting again from the root
Example: Link Technique

insert (30):

write lock r
write lock n
unlock r
write lock p
allocate new page p'
write lock p'
split contents of p onto p and p'
adjust contents of n
release locks on n, p, p'

search (31):

read lock r
release lock on r
read lock n
release lock on n
request read lock on p
acquire lock on p
release lock on p
read lock p'
return RID for key 31
release lock on p'
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Further Optimizations

- Index traversal can use deadlock-free page latching rather than full-fledged locks.
- Insert operations for the same key interval are commutative.
  → insert lock mode compatible with itself, but incompatible with read.
- Insert operations merely need instant-duration lock on previous key.
- Delete operations that leave a “ghost key” for deferred garbage collection need to lock only the deleted key.
- Fewer locks (but possibly less concurrency) by locking (key, RID) pairs or only RIDs.
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Lessons Learned

- Index concurrency control is a perfect example for layered schedules.
- At the access layer, a primitive form of predicate locking is used, namely, key-range locking, and optimized for incremental, low-overhead lock acquisition.
- At the page layer, short-term locks or latches are used to isolate index operations, with protocols ranging from S2PL for subtransactions to lock coupling, link techniques, or give-up protocols.
- Locking rules at the two levels are integrated with each other.