7. Concurrency Control for Transactions *Part Two*

CSEP 545 Transaction Processing

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Outline

- ✓ 1. A Model for Concurrency Control
- ✓ 2. Serializability Theory
- ✓ 3. Synchronization Requirements for Recoverability
- ✓ 4. Two-Phase Locking
- ✓ 5. Implementing Two-Phase Locking
- 6. Locking Performance
- 7. Multigranularity Locking (revisited)
- 8. Hot Spot Techniques
- 9. Query-Update Techniques
- 10. Phantoms
- 11. B-Trees
- 12. Tree locking

8.6 Locking Performance

- Deadlocks are rare
  - Up to 1% - 2% of transactions deadlock.
- One exception: lock conversions
  - r-lock a record and later upgrade to w-lock
  - e.g., T_i = read(x) … write(x)
  - If two txns do this concurrently, they'll deadlock (both get an r-lock on x before either gets a w-lock).
  - To avoid lock conversion deadlocks, get a w-lock first and down-grade to an r-lock if you don't need to write.
  - Use SQL Update statement or explicit program hints.

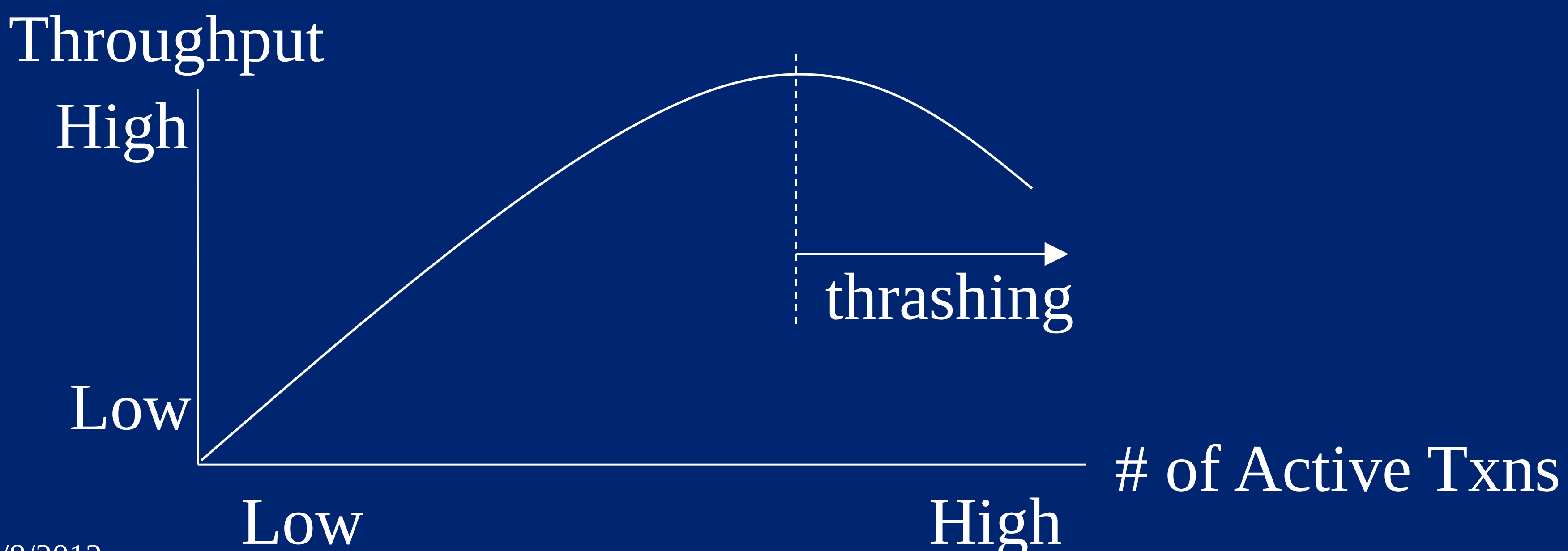
Conversions in MS SQL Server

- Update-lock prevents lock conversion deadlock.
  - Conflicts with other update and write locks, but not with read locks.
  - Since at most one transaction can have an update lock, it can’t lead to a lock conversion deadlock.
  - Only on pages and rows (not tables).
- You get an update lock by using the UPDLOCK hint in the FROM clause

```
Select Foo.A
From Foo (UPDLOCK)
Where Foo.B = 7
```

Blocking and Lock Thrashing

- The locking performance problem is too much delay due to blocking.
  - Little delay until locks are saturated.
  - Then major delay, due to the locking bottleneck.
  - <u>Thrashing</u> - the point where throughput decreases with increasing load.



More on Thrashing

- It's purely a blocking problem
  - It happens even when the abort rate is low.
- As number of transactions increase
  - Each additional transaction is more likely to block.
  - But first, it gathers some locks, increasing the probability others will block (negative feedback).

Avoiding Thrashing

- Good heuristic:
  - If over 30% of active transactions are blocked, then the system is (nearly) thrashing so reduce the number of active transactions.
- Timeout-based deadlock detection mistakes
  - They happen due to long lock delays.
  - So the system is probably close to thrashing.
  - So if deadlock detection rate is too high (over 2%) reduce the number of active transactions.

Interesting Sidelights

- By getting all locks before transaction Start, you can increase throughput at the thrashing point because blocked transactions hold no locks.
  - But it assumes that you get exactly the locks you need and that retries of get-all-locks are cheap.
- Pure restart policy - abort when there's a conflict and restart when the conflict disappears.
  - If aborts are cheap and there's low contention for other resources, then this policy produces higher throughput before thrashing than a blocking policy.
  - But response time is greater than a blocking policy.

How to Reduce Lock Contention

- If each transaction holds a lock *L* for *t* seconds, then the maximum throughput is 1/*t* txns/second

- To increase throughput, reduce *t* (lock holding time)
  – Set the lock later in the transaction's execution (e.g., defer updates till commit time).
  – Reduce transaction execution time (reduce path length, read from disk before setting locks).
  – Split a transaction into smaller transactions.

Reducing Lock Contention (cont'd)

- Reduce number of conflicts
  - Use finer grained locks, e.g., by partitioning tables vertically.

Part#	Price	OnHand	PartName	CatalogPage

Part#	Price	OnHand

Part#	PartName	CatalogPage

  - Use record-level locking (i.e., choose a database system that supports it).

Mathematical Model of Locking

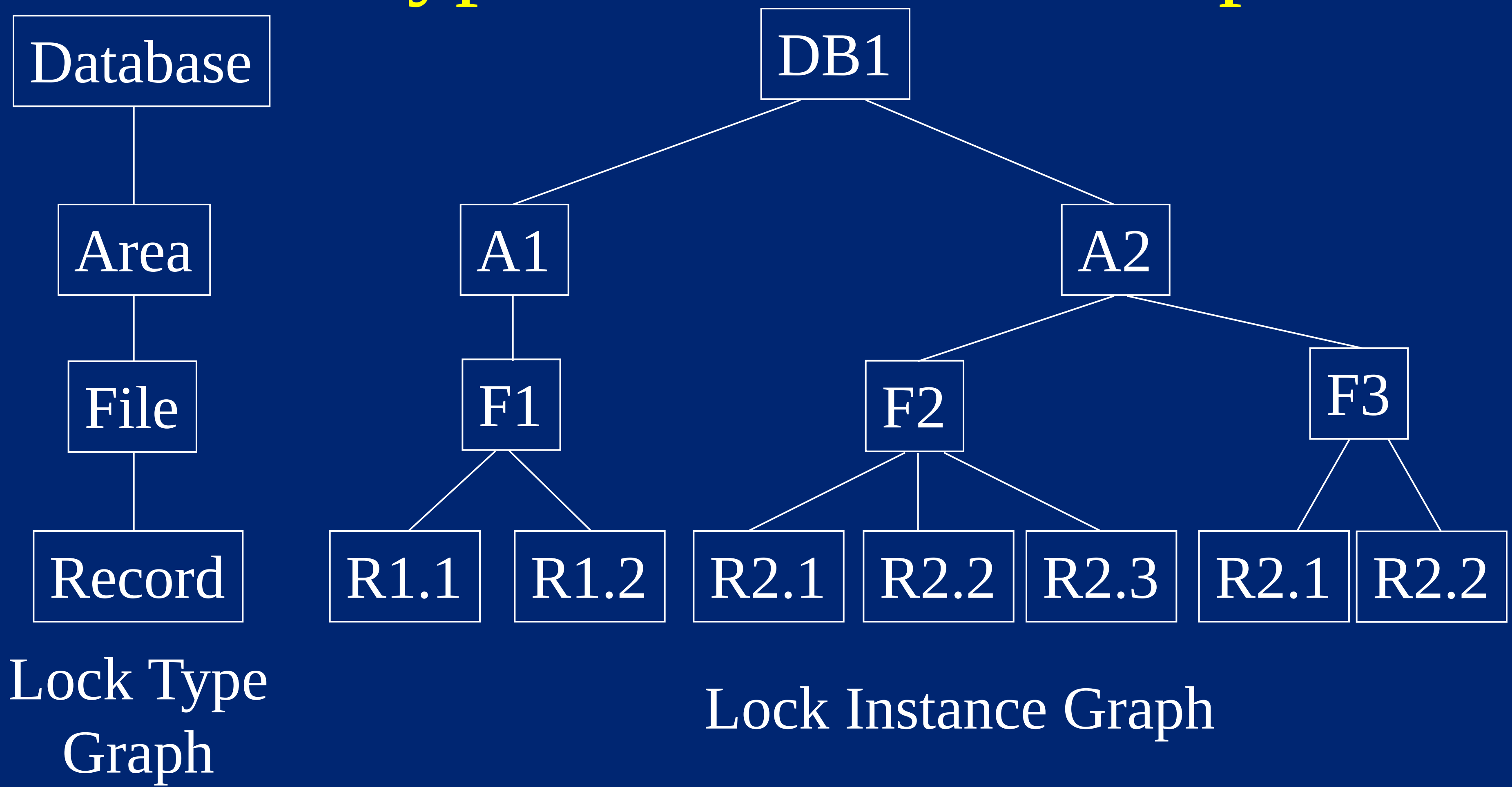
- K locks per transaction
- N transactions
- D lockable data items
- T time between lock requests

- Each transaction has K/2 locks on average $\rightarrow$KN/2 in total
- Each lock request has probability KN/2D of conflicting with an existing lock.
- Each transaction requests K locks, so its probability of experiencing a conflict is $K^2N/2D$.
- Probability of a deadlock is proportional to K^4N/D^2
  - Prob(deadlock) / Prop(conflict) = K^2/D
  - if K=10 and D = 10^6, then K^2/D = .0001
- That's why blocking, not deadlocks, is the perf problem.

8.7 Multigranularity Locking (MGL)

- Allow different txns to lock at different granularity
  - Big queries should lock coarse-grained data (e.g. tables).
  - Short transactions lock fine-grained data (e.g. rows).
- Lock manager can't detect these conflicts.
  - Each data item (e.g., table or row) has a different id.
- Multigranularity locking "trick"
  - Exploit the natural hierarchy of data containment.
  - Before locking fine-grained data, set *intention locks* on coarse grained data that contains it.
  - E.g., before setting a read-lock on a row, get an intention-read-lock on the table that contains the row.

MGL Type and Instance Graphs



- Before setting a read lock on R2.3, first set an intention-read lock on DB1, then A2, and then F2.
- Set locks root-to-leaf. Release locks leaf-to-root.

MGL Compatibility Matrix

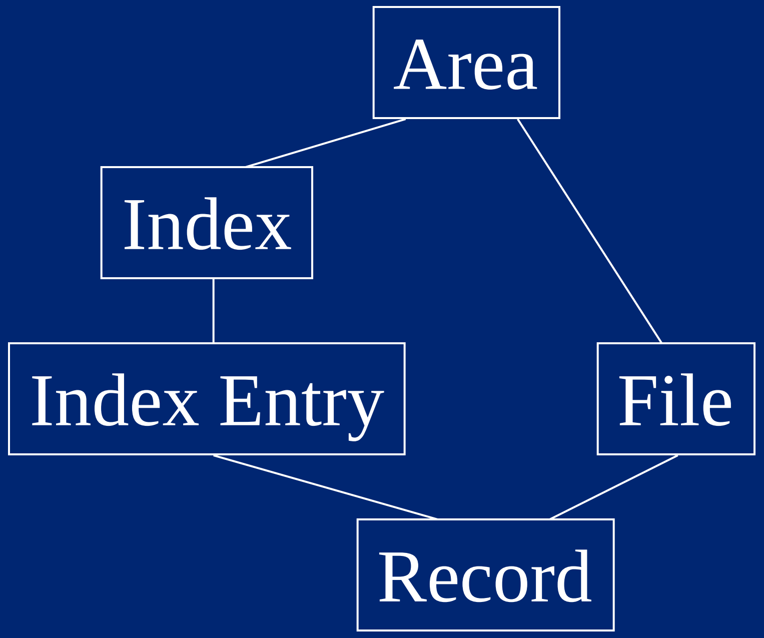
	r	w	ir	iw	riw
r	y	n	y	n	n
w	n	n	n	n	n
ir	y	n	y	y	y
iw	n	n	y	y	n
riw	n	n	y	n	n

riw = read with intent to write, for a scan that updates some of the records it reads

- E.g., ir conflicts with w because ir says there’s a fine-grained r-lock that conflicts with a w-lock on the container
- To r-lock an item, need an r-, ir- or riw-lock on its parent
- To w-lock an item, need a w-, iw- or riw-lock on its parent

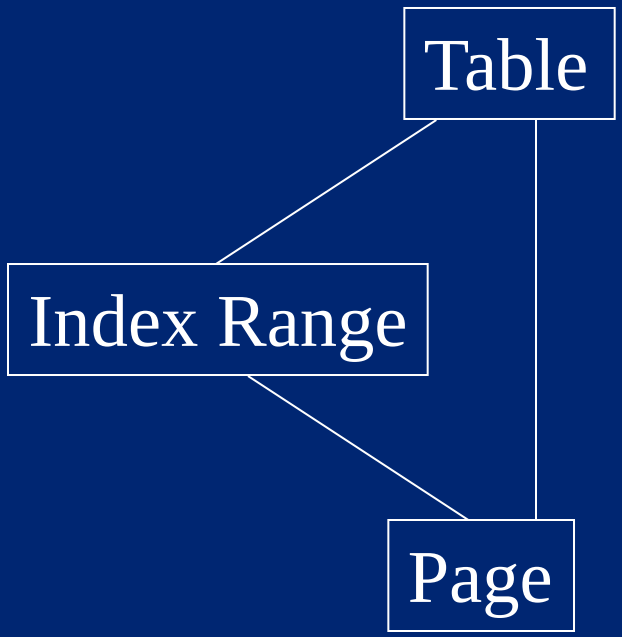
MGL Complexities

- Relational DBMSs use MGL to lock SQL queries, short updates, and scans with updates.
- Use lock escalation - start locking at fine-grain and escalate to coarse grain after n^{th} lock is set.
- The lock type graph is a directed acyclic graph, not a tree, to cope with indices.
- R-lock one path to an item. W-lock all paths to it.



MS SQL Server

- MS SQL Server can lock at table, page, and row level.
- Uses intention read (“share”) and intention write (“exclusive”) locks at the table and page level.
- Tries to avoid escalation by choosing the “appropriate” granularity when the scan is instantiated.



8.8 Hot Spot Techniques

- If each txn holds a lock for *t* seconds, then the max throughput is 1/*t* txns/second <u>for that lock</u>.
- Hot spot - A data item that's more popular than others, so a large fraction of active txns need it
  - Summary information (total inventory)
  - End-of-file marker in data entry application
  - Counter used for assigning serial numbers
- Hot spots often create a <u>convoy</u> of transactions. The hot spot lock serializes transactions.

Hot Spot Techniques (cont'd)

- Special techniques are needed to reduce *t*
  - Keep the hot data in main memory
  - Delay operations on hot data till commit time
  - Use optimistic methods
  - Batch up operations to hot spot data
  - Partition hot spot data

Delaying Operations Until Commit

- Data manager logs each transaction's updates
- Only applies the updates (and sets locks) after receiving Commit from the transaction
- IBM IMS Fast Path uses this for
  - Data Entry DB
  - Main Storage DB
- Works for write, insert, and delete, but not read

Locking Higher-Level Operations

- Read is often part of a read-write pair, such as Increment(x, n), which adds constant n to x, but doesn't return a value.
- Increment (and Decrement) commute
- So, introduce Increment and Decrement locks

	r	w	inc	dec
r	y	n	n	n
w	n	n	n	n
inc	n	n	y	y
dec	n	n	y	y

- But if Inc and Dec have a threshold (e.g. a quantity of zero), then they conflict (when the threshold is near)

Solving the Threshold Problem
Another IMS Fast Path Technique

- Use a blind Decrement (no threshold) and Verify(x, n), which returns true if $x \geq n$
- Re-execute Verify at commit time
  - If it returns a different value than it did during normal execution, then abort
  - It's like checking that the threshold lock you didn't set during Decrement is still valid.

```
bEnough = Verify(iQuantity, n);
If (bEnough) Decrement(iQuantity, n)
else print ("not enough");
```

Optimistic Concurrency Control

- The Verify trick is optimistic concurrency control
- Main idea
  - Execute operations on shared data without setting locks
  - At commit time, test if there were conflicts on the locks (that you didn't set).
- Often used in client/server systems
  - Client does all updates in cache without shared locks
  - At commit time, try to get locks and perform updates.

Batching

- Transactions add updates to a mini-batch and only periodically apply the mini-batch to shared data.
  – Each process has a private data entry file,
    in addition to a global shared data entry file
  – Each transaction appends to its process' file
  – Periodically append the process' file to the shared file.
- Tricky failure handling
  – Gathering up private files
  – Avoiding holes in serial number order.

Partitioning

- Split up inventory into partitions
- Each transaction only accesses one partition
- Example
  - Each ticket agency has a subset of the tickets
  - If one agency sells out early, it needs a way to get more tickets from other agencies (partitions)

8.9 Query-Update Techniques

- Queries run for a long time and lock a lot of data — a performance nightmare when trying also to run short update transactions.
- There are several good solutions
  - Use a data warehouse
  - Accept weaker consistency guarantees
  - Use multiversion data.
- Solutions trade data quality or timeliness for performance.

Data Warehouse

- A data warehouse contains a snapshot of the DB which is periodically refreshed from the TP DB
- All queries run on the data warehouse
- All update transactions run on the TP DB
- Queries don't get absolutely up-to-date data
- How to refresh the data warehouse?
  - Stop processing transactions and copy the TP DB to the data warehouse. Possibly run queries while refreshing
  - Treat the warehouse as a DB replica and use a replication technique.

Degrees of Isolation

- Serializability = *Degree 3 Isolation*
- Degree 2 Isolation (a.k.a. cursor stability)
  - Data manager holds read-lock(x) only while reading x, but holds write locks till commit (as in 2PL)
  - E.g. when scanning records in a file, each get-next-record releases lock on current record and gets lock on next one
  - read(x) is not "repeatable" within a transaction, e.g., $rl_1[x]\ r_1[x]\ ru_1[x]\ \underline{wl_2[x]\ w_2[x]\ wu_2[x]\ c_2}\ rl_1[x]\ r_1[x]\ ru_1[x]$
  - Degree 2 is commonly used by ISAM file systems
  - Degree 2 is often a DB system's default behavior! And customers seem to accept it!!!

Degrees of Isolation (cont’d)

- Could run queries Degree 2 and updaters Degree 3
  – Updaters are still serializable w.r.t. each other
- Degree 1 - no read locks; hold write locks to commit
- Unfortunately, SQL concurrency control standards have been stated in terms of “repeatable reads” and “cursor stability” instead of serializability, leading to much confusion.

ANSI SQL Isolation Levels

- Uncommitted Read - Degree 1
- Committed Read - Degree 2
- Repeatable Read - Uses read locks and write locks, but allows "phantoms"
- Serializable - Degree 3

MS SQL Server

- Lock hints in SQL FROM clause
  - All the ANSI isolation levels, plus …
  - UPDLOCK - use update locks instead of read locks
  - READPAST - ignore locked rows (if running read committed)
  - PAGLOCK - use page lock when the system would otherwise use a table lock
  - TABLOCK - shared table lock till end of command or transaction
  - TABLOCKX - exclusive table lock till end of command or transaction

Multiversion Data

- Assume record granularity locking.
- Each write operation creates a new version instead of overwriting existing value.
- So each logical record has a sequence of versions.
- Tag each record with transaction id of the transaction that wrote that version.

Tid	Previous	E#	Name	Other fields
123	null	1	Bill	
175	123	1	Bill	
134	null	2	Sue	
199	134	2	Sue	
227	null	27	Steve	

Multiversion Data (cont'd)

- Execute update transactions using ordinary 2PL
- Execute queries in *snapshot mode*
  - System keeps a commit list of tids of all committed txns
  - When a query starts executing, it reads the commit list
  - When a query reads x, it reads the latest version of x written by a transaction on its commit list
  - Thus, it reads the database state that existed when it started running

Commit List Management

- Maintain and periodically recompute a tid T-Oldest, such that
  - Every active txn's tid is greater than T-Oldest
  - Every new tid is greater than T-Oldest
  - For every committed transaction with tid ≤ T-Oldest, its versions are committed
  - For every aborted transaction with tid ≤ T-Oldest, its versions are wiped out
- Queries don't need to know tids ≤ T-Oldest
  - So only maintain the commit list for tids > T-Oldest

Multiversion Garbage Collection

- Can delete an old version of x if no query will ever read it
  - There's a later version of x whose tid $\leq$ T-Oldest (or is on every active query's commit list)
- Originally used in Prime Computer's CODASYL DB system and Oracle's Rdb/VMS

Oracle Multiversion Concurrency Control

- Data page contains latest version of each record, which points to older version in rollback segment.
- Read-committed query reads data as of its start time.
- Read-only isolation reads data as of transaction start time.
- "Serializable" txn reads data as of the txn's start time.
  - So update transactions don't set read locks
  - Checks that updated records were not modified after txn start time
  - If that check fails, Oracle returns an error.
  - If there isn't enough history for Oracle to perform the check, Oracle returns an error. (You can control the history area's size.)
  - What if T_1 and T_2 modify each other's readset concurrently?

Oracle Concurrency Control (cont'd)

$r_1[x]\ r_1[y]\ r_2[x]\ r_2[y]\ w_1[x']\ c_1\ w_2[y']\ c_2$

- The result is not serializable!
- In any SR execution, one transaction would have read the other's output
- Oracle's isolation level is called "snapshot isolation"

8.10 Phantoms

- Problems when using 2PL with inserts and deletes

Accounts

Acct#	Location	Balance
1	Seattle	400
2	Tacoma	200
3	Tacoma	300

Assets

Location	Total
Seattle	400
Tacoma	500

The phantom record

T_1: Read Accounts 1, 2, and 3
T_2: Insert Accounts[4, Tacoma, 100]
T_2: Read Assets(Tacoma), returns 500
T_2: Write Assets(Tacoma, 600)
T_1: Read Assets(Tacoma), returns 600
T_1: Commit

The Phantom Phantom Problem

- It looks like T_1 should lock record 4, which isn't there!
- Which of T_1's operations determined that there were only 3 records?
  - Read end-of-file?
  - Read record counter?
  - SQL Select operation?
- This operation conflicts with T_2's Insert Accounts[4,Tacoma,100]
- Therefore, Insert Accounts[4,Tacoma,100] shouldn't run until after T_1 commits

Avoiding Phantoms - Predicate Locks

- Suppose a query reads all records satisfying predicate P. For example,
  - Select * From Accounts Where Location = “Tacoma”
  - Normally would hash each record id to an integer lock id
  - And lock control structures. Too coarse grained.
- Ideally, set a read lock on P
  - which conflicts with a write lock Q if some record can satisfy (P and Q)
- For arbitrary predicates, this is too slow to check
  - Not within a few hundred instructions, anyway

Precision Locks

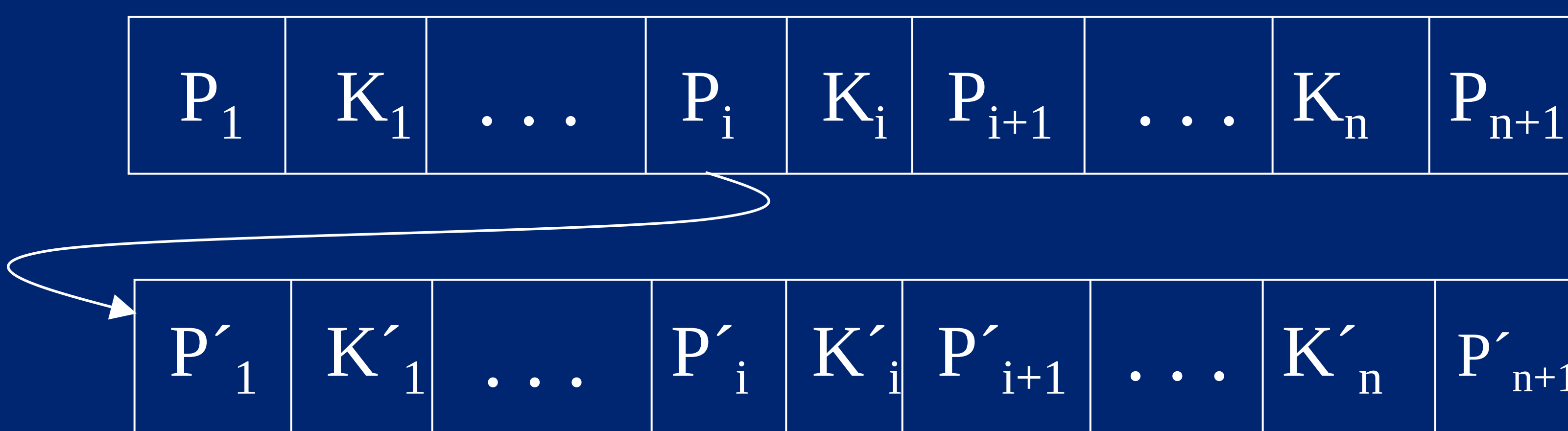
- Suppose update operations are on single records
- Maintain a list of predicate Read-locks
- Insert, Delete, & Update write-lock the record and check for conflict with all predicate locks
- Query sets a read lock on the predicate and check for conflict with all record locks
- Cheaper than predicate satisfiability, but still too expensive for practical implementation.

8.11 B-Trees

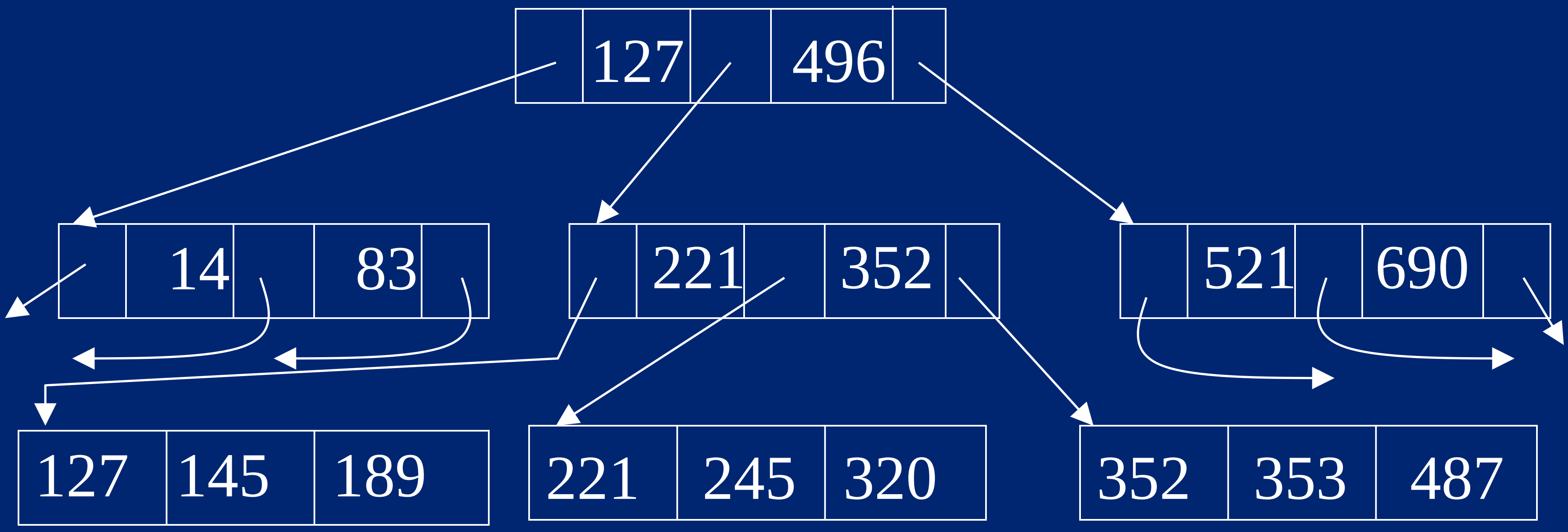
- An *index* maps field values to record ids.
  - Record id = [page-id, offset-within-page]
  - Most common DB index structures: hashing and B-trees
  - DB index structures are *page-oriented*
- Hashing uses a function $H:V \rightarrow B$, from field values to block numbers.
  - V = social security numbers. B = {1 .. 1000}
    H(v) = v mod 1000
  - If a page overflows, then use an extra overflow page
  - At 90% load on pages, 1.2 block accesses per request!
  - BUT, doesn't help for key range access ($10 < v < 75$)

B-Tree Structure

- Index node is a sequence of [pointer, key] pairs
- $K_1 < K_2 < \ldots < K_{n-1} < K_n$
- P_1 points to a node containing keys $< K_1$
- P_i points to a node containing keys in range $[K_{i-1}, K_i)$
- P_{n+1} points to a node containing keys $> K_n$
- So, $K'_1 < K'_2 < \ldots < K'_{n-1} < K'_n$



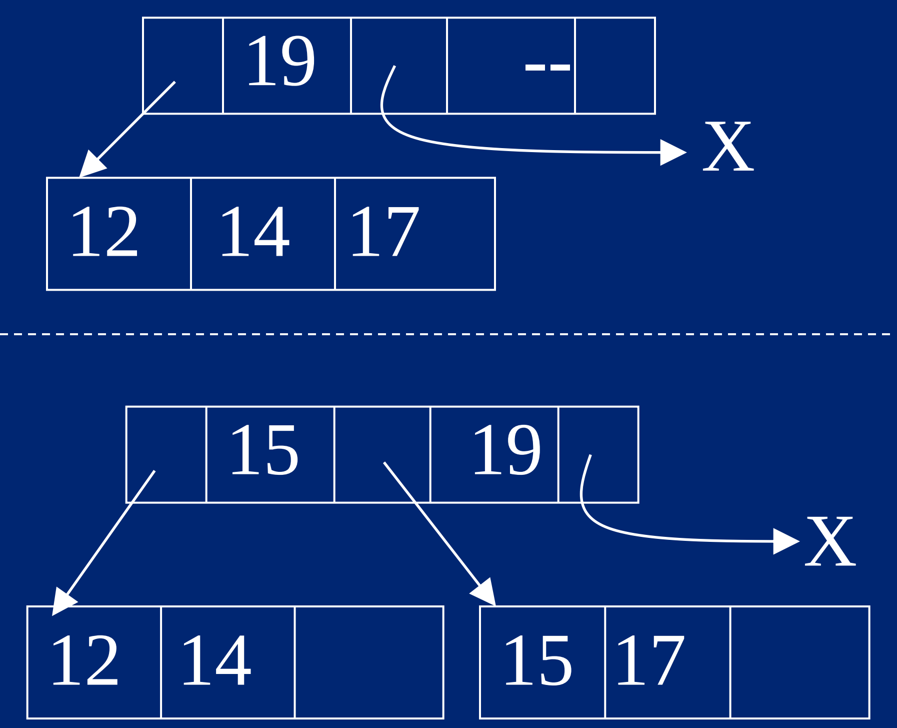
Example n=3



- Notice that leaves are sorted by key, left-to-right
- Search for value v by following path from the root
- If key = 8 bytes, ptr = 2 bytes, page = 4K, then n = 409
- So 3-level index has up to 68M leaves (409^3)
- At 20 records per leaf, that's 136M records

Insertion

- To insert key v, search for the leaf where v should appear
- If there's space on the leave, insert the record
- If no, split the leaf in half, and split the key range in its parent to point to the two leaves



To insert key 15

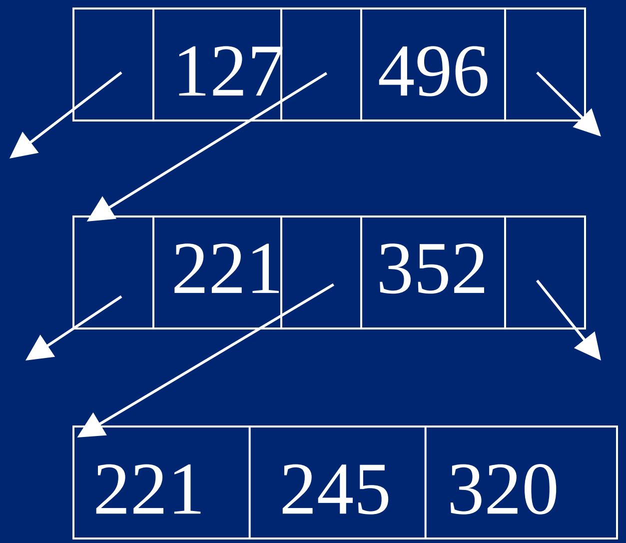
- split the leaf
- split the parent's range [0, 19) to [0, 15) and [15, 19)
- if the parent was full, you'd split that too (not shown here)
- this automatically keeps the tree balanced

B-Tree Observations

- Delete algorithm merges adjacent nodes < 50% full, but rarely used in practice
- Root and most level-1 nodes are cached, to reduce disk accesses
- In a primary (clustered) index, leaves contain records
- In a secondary (non-clustered) index, leaves contain [key, record id] pairs or [key, primary-key] pairs.
- Use key prefix for long (string) key values
  - Drop prefix and add to suffix as you move down the tree

Key Range Locks

- Lock on B-tree key range is a cheap predicate lock

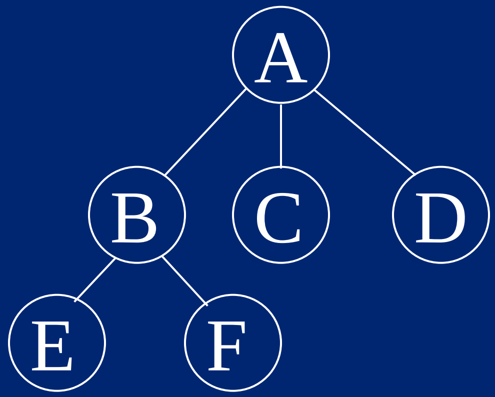


- Select Dept Where ((Budget > 250)
  and (Budget < 350))
- Lock key range [221, 352) record
- Only useful when query is on an indexed field

- Commonly used with multi-granularity locking
  - Insert/delete locks record and intention-write locks range
  - MGL tree defines a fixed set of predicates, and thereby avoids predicate satisfiability

8.12 Tree Locking

- Can beat 2PL by exploiting root-to-leaf access in a tree
- If searching for a leaf, after setting a lock on a node, release the lock on its parent

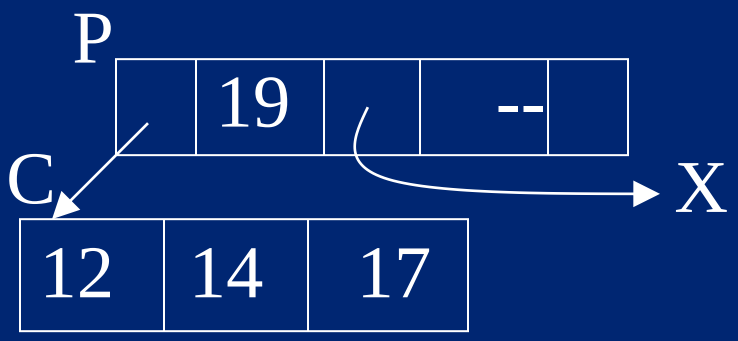


wl(A) wl(B) wu(A) wl(E) wu(B)

- The lock order on the root serializes access to other nodes

B-tree Locking

- Root lock on a B-tree is a bottleneck
- Use tree locking to relieve it
- Problem: node splits

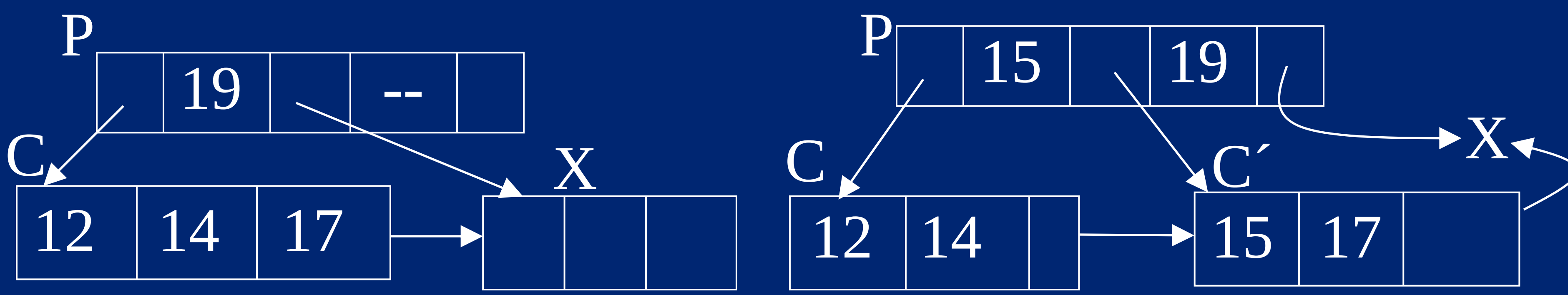


If you unlock P before splitting C, then you have to back up and lock P again, which breaks the tree locking protocol.

- So, don’t unlock a node till you’re sure its child won’t split (i.e. has space for an insert)
- Implies different locking rules for different ops (search vs. insert/update)

B-link Optimization

- B-link tree - Each node has a side pointer to the next
- After searching a node, you can release its lock before locking its child
  - $r_1[P]\ r_2[P]\ r_2[C]\ w_2[C]\ w_2[C']\ w_2[P]\ r_1[C]\ r_1[C']$



- Searching has the same behavior as if it locked the child before releasing the parent … and ran later (after the insert)