CS460: Intro to Database Systems

Class 22: Concurrency Control

Instructor: Manos Athanassoulis

https://bu-disc.github.io/CS460/

Concurrency Control

Serializability

Readings: Chapter 17.1

Two phase locking

Lock management and deadlocks

Locking granularity

Tree locking

Phantoms and predicate locking

Review

DBMSs support ACID Transaction semantics

Concurrency control and Crash Recovery are key components

For Isolation property, serial execution of transactions is safe but slow

- Try to find schedules equivalent to serial execution

Formal Properties of Schedules

Serial schedule: Schedule that does not interleave the actions of different transactions

Equivalent schedules: For any database state, the effect of executing the first schedule is identical to the effect of executing the second schedule

Serializable schedule: A schedule that is equivalent to some serial execution of the transactions

Note: If each transaction preserves consistency, every serializable schedule preserves consistency.

Conflicting Operations

We need a formal notion of equivalence that can be implemented efficiently

- Base it on the notion of "conflicting" operations

Definition: Two operations conflict if:

- They are done by different transactions,
- They are done on the same object,
- And at least one of them is a write

Conflict Serializable Schedules

Definition: Two schedules are conflict equivalent iff:

- They involve the same actions of the same transactions, and
- every pair of conflicting actions is ordered the same way

Definition: Schedule S is conflict serializable if:

- S is conflict equivalent to some serial schedule

Note, some “serializable” schedules are NOT conflict serializable

- A price we pay to achieve efficient enforcement

Conflict Serializability – Intuition

A schedule S is conflict serializable if:

– You are able to transform S into a serial schedule by swapping **consecutive non-conflicting** operations of different transactions

Example:

R(A) W(A) R(B) W(B)

R(A) W(A) R(B) W(B)

$\equiv$

R(A) W(A) R(B) W(B)

R(A) W(A) R(B) W(B)

Conflict Serializability (Continued)

Here's another example:

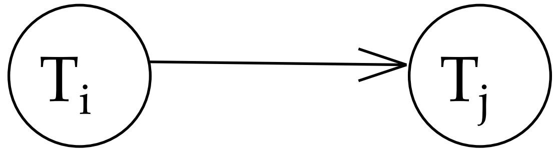
R(A) W(A)

R(A) W(A)

Serializable or not?

NOT!

Dependency Graph



Dependency graph:

- One node per transaction
- Edge from T_i to T_j if:
  - An operation O_i of T_i conflicts with an operation O_j of T_j and
  - O_i appears earlier in the schedule than O_j

Theorem: Schedule is conflict serializable if and only if its dependency graph is acyclic

Example

A schedule that is not conflict serializable:

T1:	R(A), W(A),		R(B), W(B)
T2:		R(A), W(A), R(B), W(B)	

$$\begin{tikzcd} T1 \arrow[r, bend left, "A"] & T2 \arrow[l, bend left, "B"] \end{tikzcd}$$

Dependency graph

The cycle in the graph reveals the problem. The output of T1 depends on T2, and vice-versa

View Serializability

Alternative (weaker) notion of serializability

Schedules S1 and S2 are view equivalent if:

1. If T_i reads initial value of A in S1, then T_i also reads initial value of A in S2
2. If T_i reads value of A written by T_j in S1, then T_i also reads value of A written by T_j in S2
3. If T_i writes final value of A in S1, then T_i also writes final value of A in S2

Basically, allows all conflict serializable schedules
+ "blind writes"

T1:	R(A)		W(A)	
T2:		W(A)		
T3:				W(A)

$\overset{\text{view}}{\equiv}$

T1:	R(A),W(A)		
T2:		W(A)	
T3:			W(A)

Notes on Serializability Definitions

View Serializability allows (slightly) more schedules than **Conflict Serializability**

- Problem: it is difficult to enforce efficiently

Neither definition allows all schedules that you would consider "serializable"

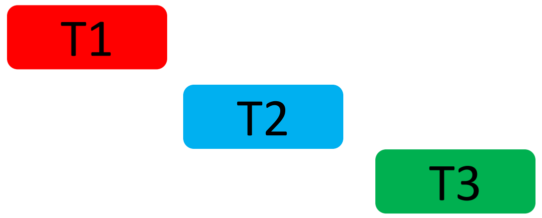
- Because they don't understand the meanings of the operations or the data

In practice, **Conflict Serializability** is used, because it can be enforced *efficiently*

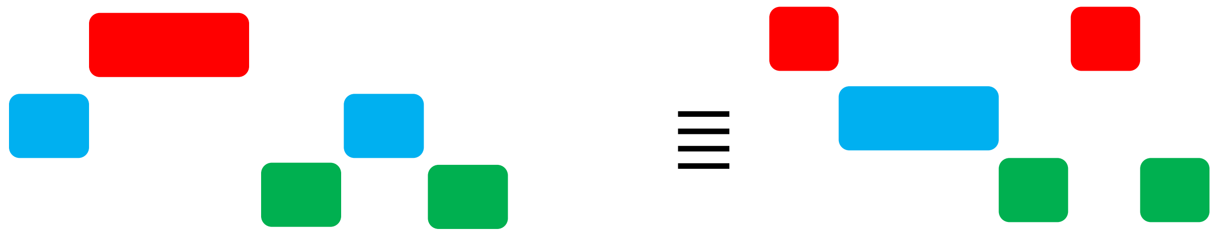
- To allow more concurrency, some special cases do get handled separately, such as travel reservations

Serializability Summary

Serial schedule



Equivalent schedules



conflict equivalent = if all conflicting op's same order

view equivalent = if same view after

easier to enforce!

Conflict Serializable schedule S_a, if S_a conflict equivalent with (some) S_{serial}

View Serializable schedule S_b, if S_b view equivalent with (some) S_{serial}

Concurrency Control

Serializability

Two phase locking

Readings: Chapter 17.1

Lock management and deadlocks

Locking granularity

Tree locking

Phantoms and predicate locking

Two-Phase Locking (2PL)

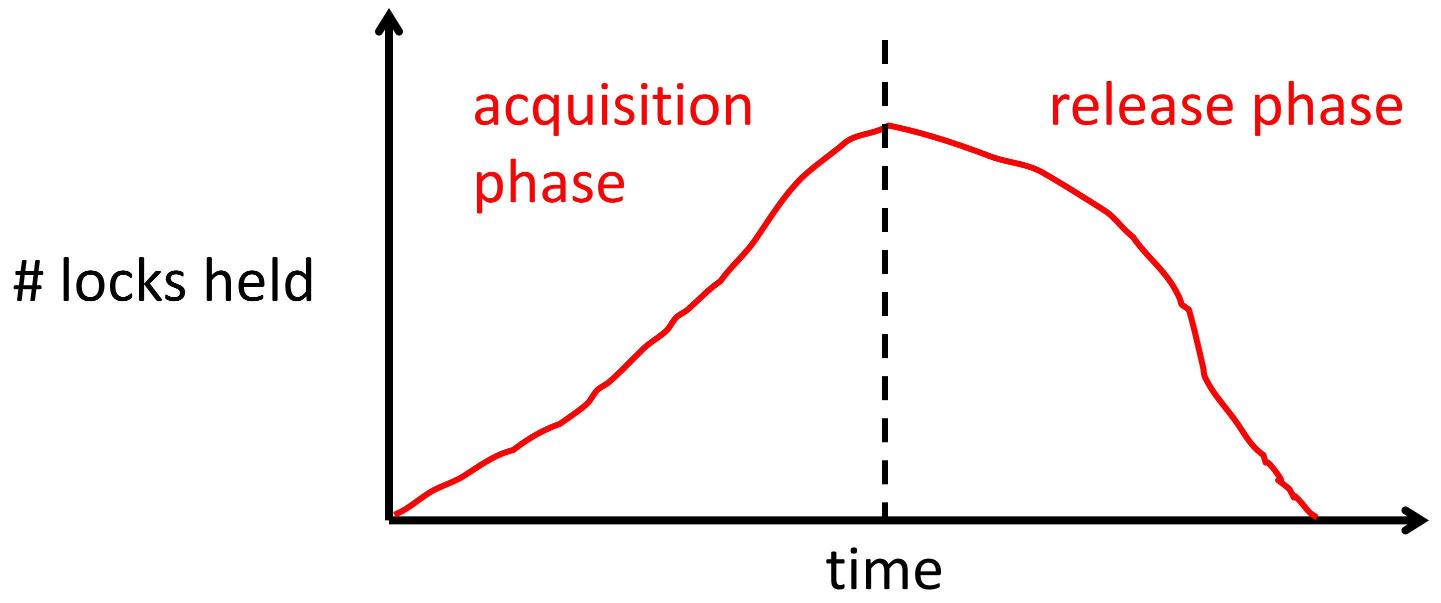
Lock Compatibility Matrix

	S	X
S	√	–
X	–	–

Locking Protocol

- each transaction obtains
  - S (*shared*) lock on object before reading
  - X (*exclusive*) lock on object before writing
- A transaction cannot request additional locks once it releases any locks
- Thus, there is a "growing phase" followed by a "shrinking phase"

Two-Phase Locking (2PL)



2PL on its own is sufficient to guarantee conflict serializability (i.e., schedules whose dependency graph is acyclic), but, it is subject to **Cascading Aborts**

Strict 2PL

Problem: Cascading Aborts

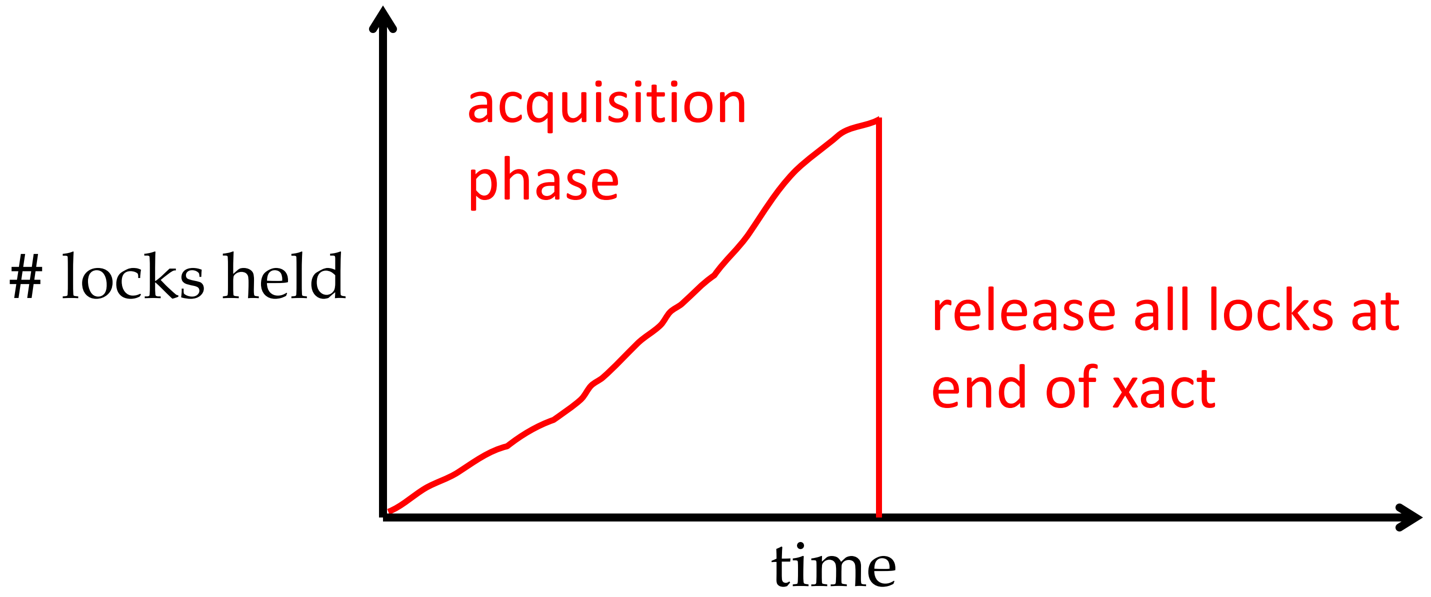
Example: rollback of T1 requires rollback of T2!

```
T1:    R(A), W(A),                        R(B), W(B), Abort
T2:                    R(A), W(A)
```

How to avoid *Cascading Aborts*?

Strict Two-phase Locking (Strict 2PL) Protocol:

- Same as 2PL, except:
- All locks held by a transaction are released only when the transaction completes



Allows only conflict serializable schedules, but it is actually stronger than needed for that purpose

In effect, “shrinking phase” is delayed until

a) Transaction has committed (commit log record on disk), or
b) Decision has been made to abort the transaction (locks can be released after rollback)

Non-2PL, A= 1000, B=2000, Output =?

Lock_X(A)	
Read(A)	Lock_S(A)
A: = A-50	
Write(A)	
Unlock(A)	
	Read(A)
	Unlock(A)
	Lock_S(B)
Lock_X(B)	
	Read(B)
	Unlock(B)
	PRINT(A+B)
Read(B)	
B := B +50	
Write(B)	
Unlock(B)	

what is the problem here?

A+B not executed in *Isolation*

2PL, A= 1000, B=2000, Output =?

Lock_X(A)	
Read(A)	Lock_S(A)
A: = A-50	
Write(A)	
Lock_X(B)	
Unlock(A)	
	Read(A)
	Lock_S(B)
Read(B)	
B := B +50	
Write(B)	
Unlock(B)	Unlock(A)
what if it aborts?	Read(B)
	Unlock(B)
	PRINT(A+B)

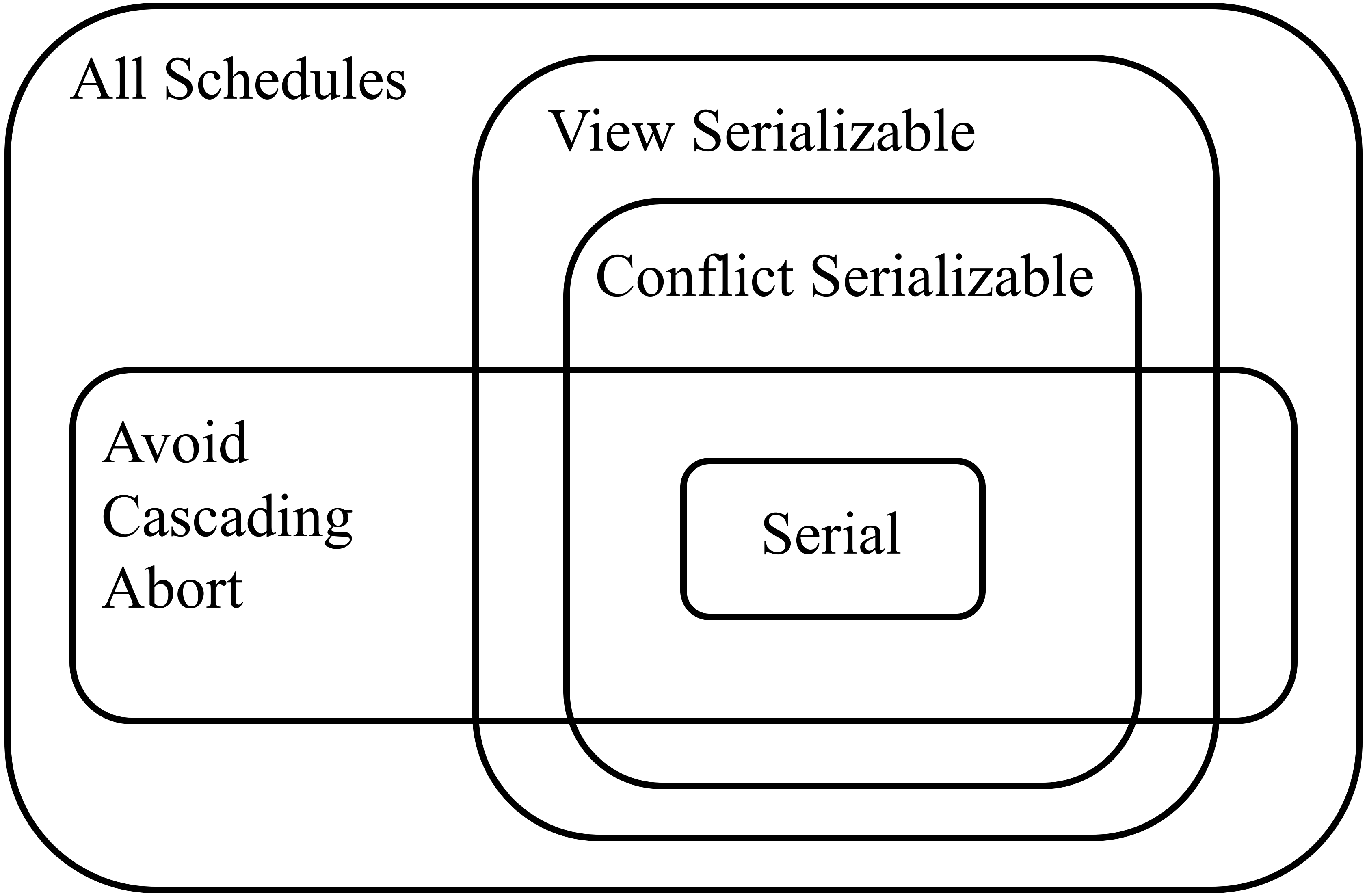
what is the problem here?

Cascade Abort

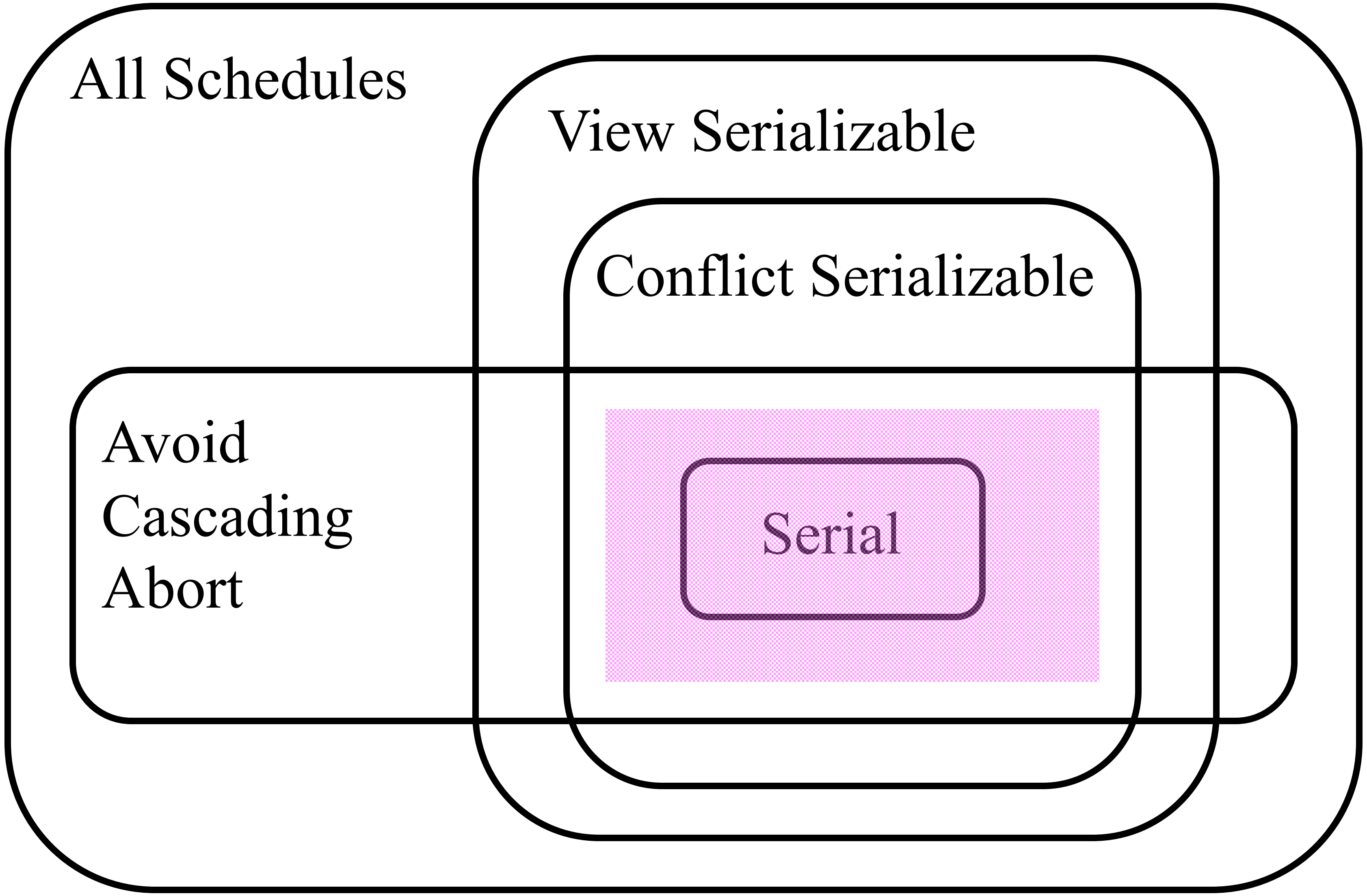
Strict 2PL, A= 1000, B=2000, Output =?

Lock_X(A)	
Read(A)	Lock_S(A)
A: = A-50	
Write(A)	
Lock_X(B)	
Read(B)	
B := B +50	
Write(B)	
Unlock(A)	
Unlock(B)	
	Read(A)
	Lock_S(B)
	Read(B)
	PRINT(A+B)
	Unlock(A)
	Unlock(B)

Venn Diagram for Schedules



Q: Which schedules does Strict 2PL allow?



Two phase locking: Summary

Locks implement the notions of conflict directly

2PL has:

- Growing phase where locks are acquired and no lock is released
- Shrinking phase where locks are released and no lock is acquired

Strict 2PL requires all locks to be released at once, when transaction ends

Concurrency Control

Serializability

Two phase locking

Lock management and deadlocks

Readings: Chapter 17.2-17.4

Locking granularity

Tree locking

Phantoms and predicate locking

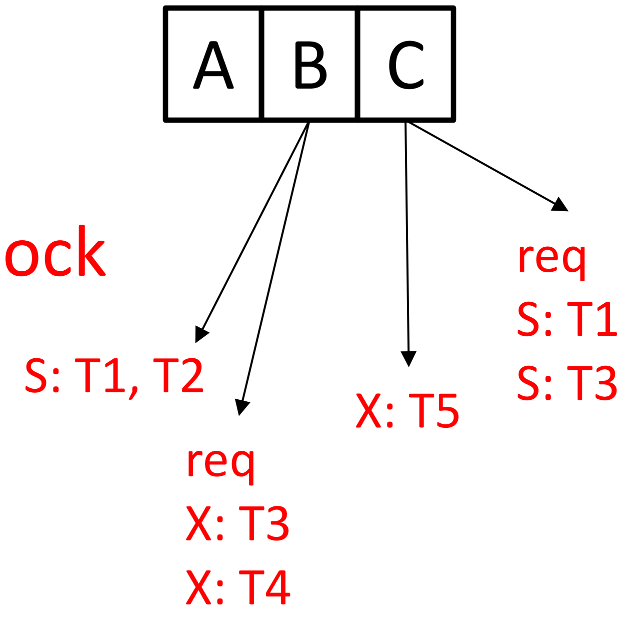
Lock Management

Lock and unlock requests handled by the Lock Manager

Lock Manager contains an entry for each currently held lock

Lock table entry:

- Pointer to list of transactions currently holding the lock
- Type of lock held (shared or exclusive)
- Pointer to queue of lock requests



Lock Management, continued

Basic operation: when lock request arrives see if any other transaction holds a conflicting lock

- **If not**, create an entry and grant the lock
- **Else**, put the requestor on the wait queue

Lock upgrade: transaction that holds a shared lock can be upgraded to hold an exclusive lock

Two-phase locking is simple enough, right?

Example: Output = ?

Lock_X(A)	
	Lock_S(B)
	Read(B)
	Lock_S(A)
Read(A)	
A: = A-50	
Write(A)	
Lock_X(B)	

what is the problem here?

Deadlock

Deadlocks

Deadlock: Cycle of transactions waiting for locks to be released by each other

Two ways of dealing with deadlocks:

- Deadlock prevention
- Deadlock detection

Many systems just "punt" and use Timeouts

- What are the dangers with this approach?

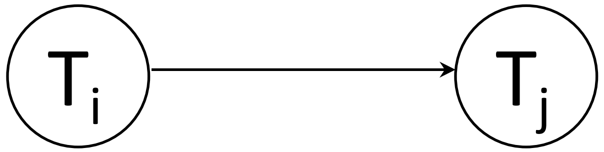
forward progress

Deadlock Detection

Create a waits-for graph:

- Nodes are transactions
- Edge from T_i to T_j if T_i is waiting for T_j to release a lock

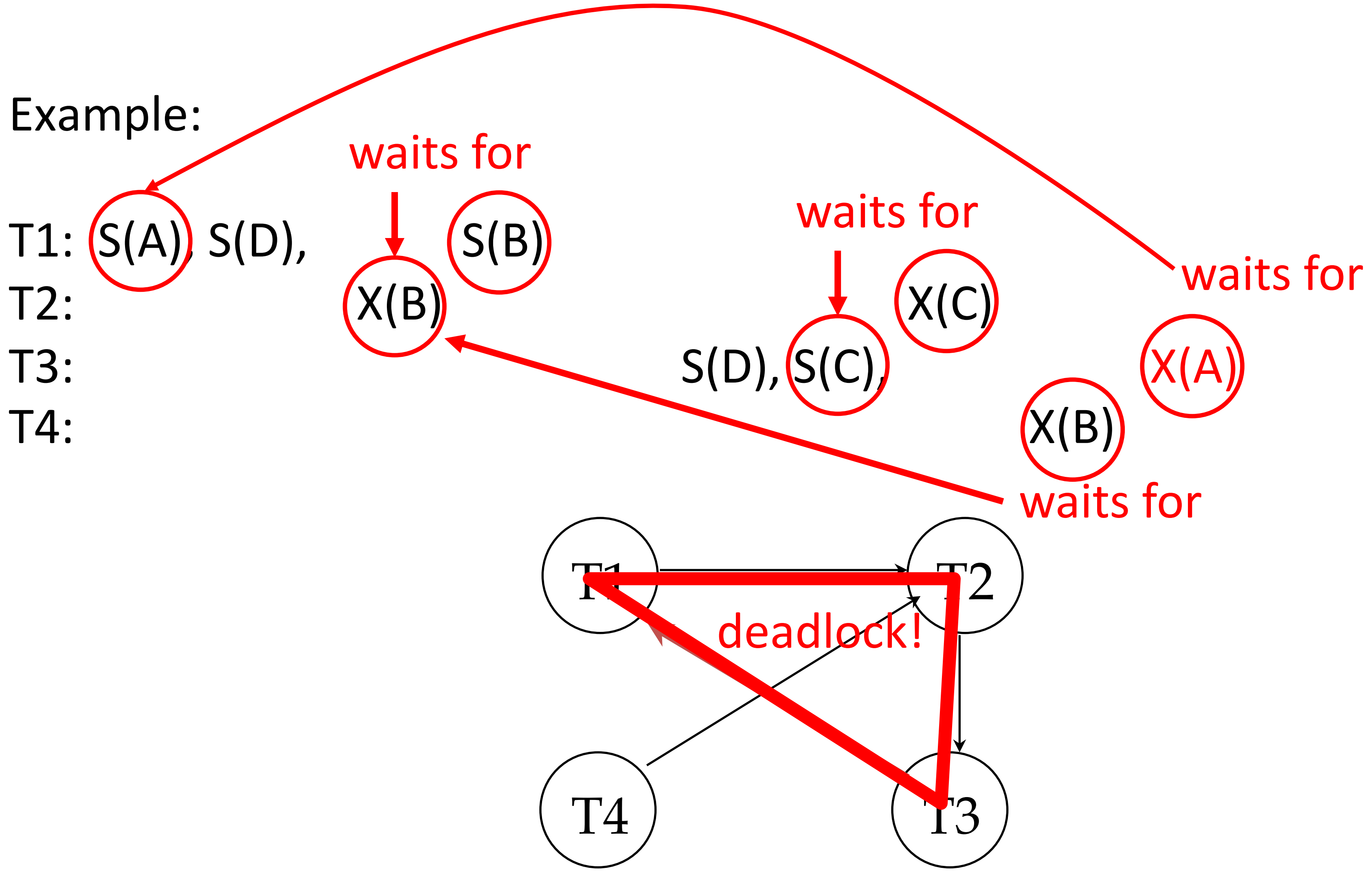
Periodically check for cycles in waits-for graph



T_i waits T_j to release a lock

Important!! This is different than dependency graph!

Deadlock Detection (Continued)



Deadlock Prevention

Assign priorities based on timestamps

Say T_i wants a lock that T_j holds

Two policies are possible:

Wait-Die: If T_i has higher priority, T_i waits for T_j;
otherwise T_i **aborts**

Wound-wait: If T_i has higher priority, T_j aborts;
otherwise T_i **waits**

the trx that wants a (held) lock:

high priority : waits
low priority : aborts

high priority : kills the other
low priority : wait

Why do these schemes guarantee no deadlocks?

Important detail: If a transaction re-starts, make sure it gets its original timestamp. -- Why?

to avoid starvation!

Deadlocks: summary

The lock manager keeps track of the locks issued

Deadlock is a cycle of transactions waiting for locks to be released to each other

Deadlocks may arise and can be:

- Prevented, e.g. using timestamps
- Detected, e.g. using waits-for graphs

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Class 23: Concurrency Control (cont’d)

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Concurrency Control

Serializability

Two phase locking

Lock management and deadlocks

Quick Recap

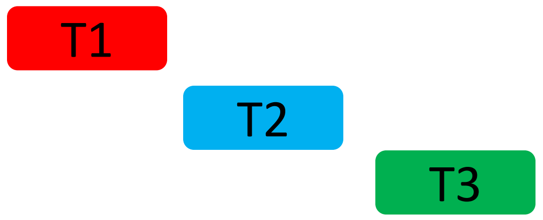
Locking granularity

Tree locking

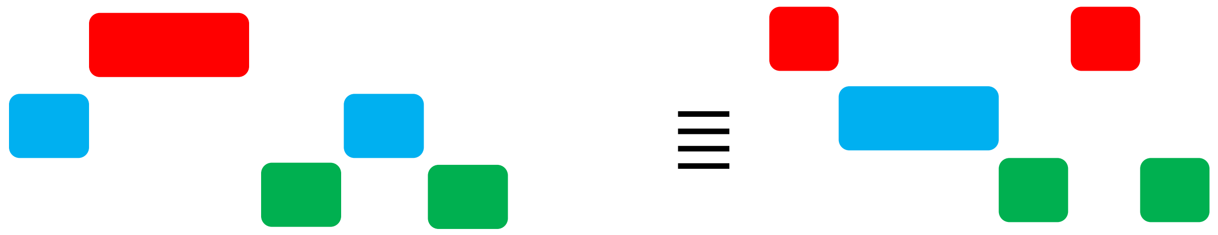
Phantoms and predicate locking

Serializability Summary

Serial schedule



Equivalent schedules



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Conflict Serializable schedule S_a, if S_a conflict equivalent with (some) S_{serial}

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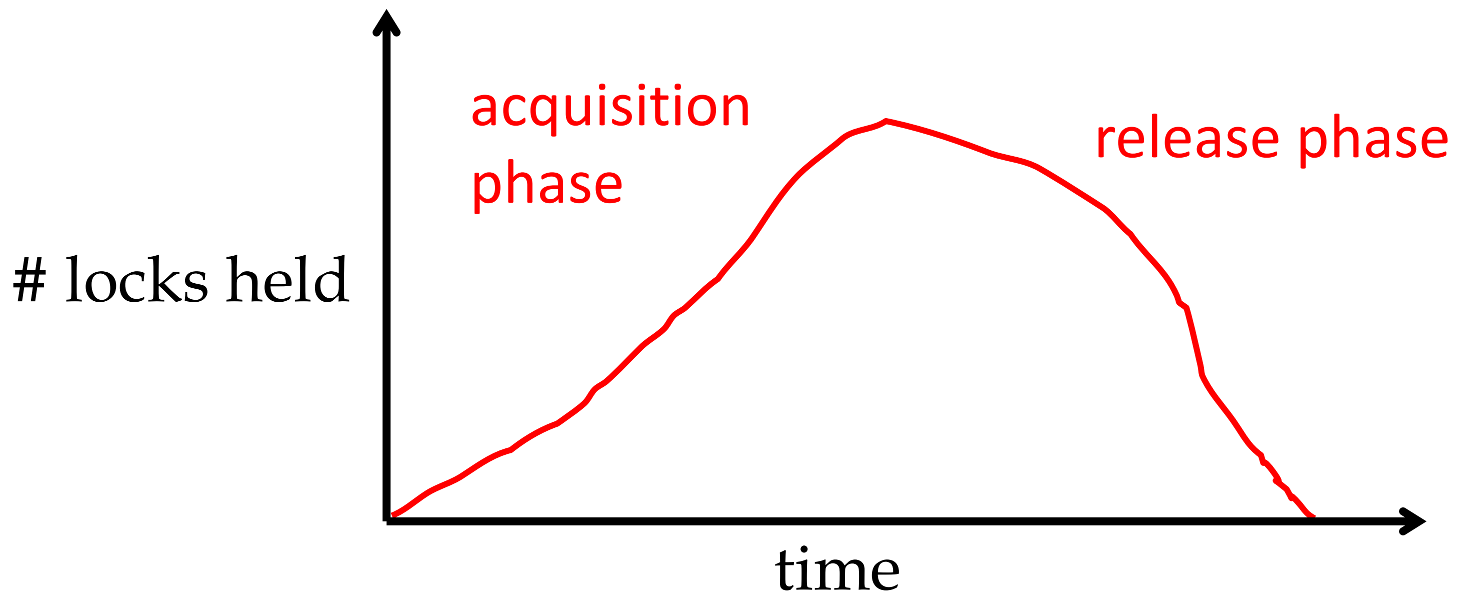
From previous class!

Reminder: Two-Phase Locking (2PL)

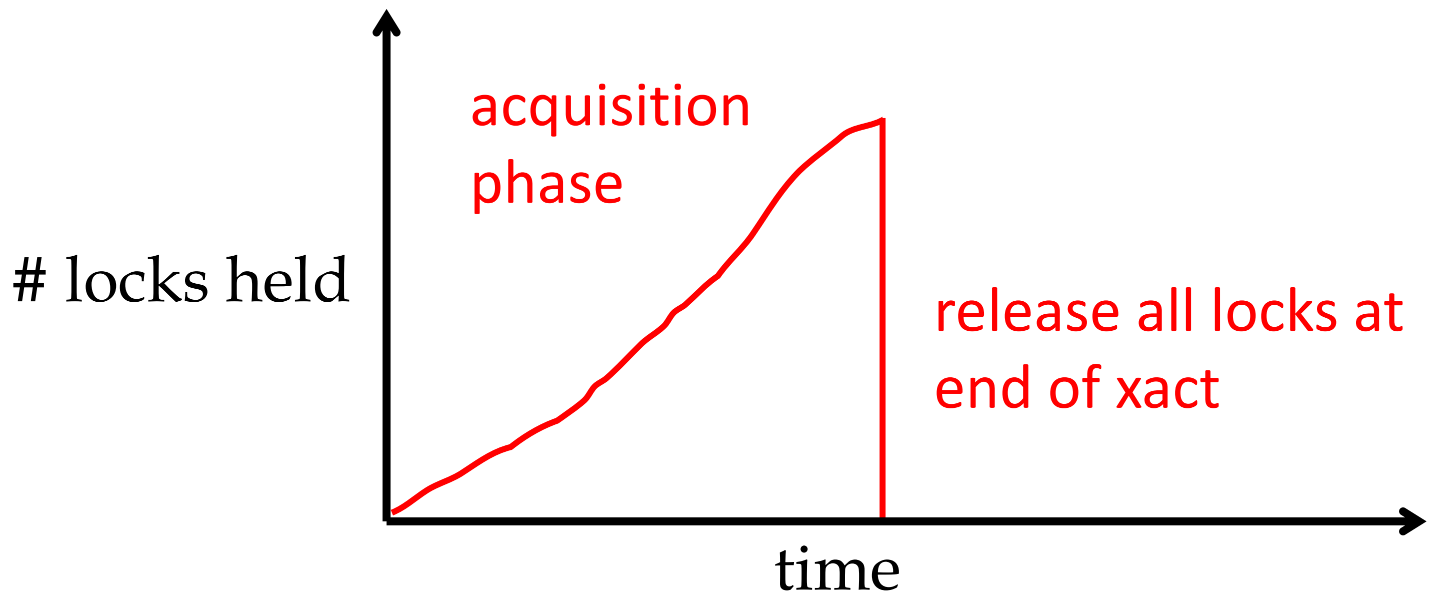


Lock Compatibility Matrix

	S	X
S	√	–
X	–	–

From previous class!

Reminder: Strict Two-Phase Locking (Strict-2PL)



Lock Compatibility Matrix

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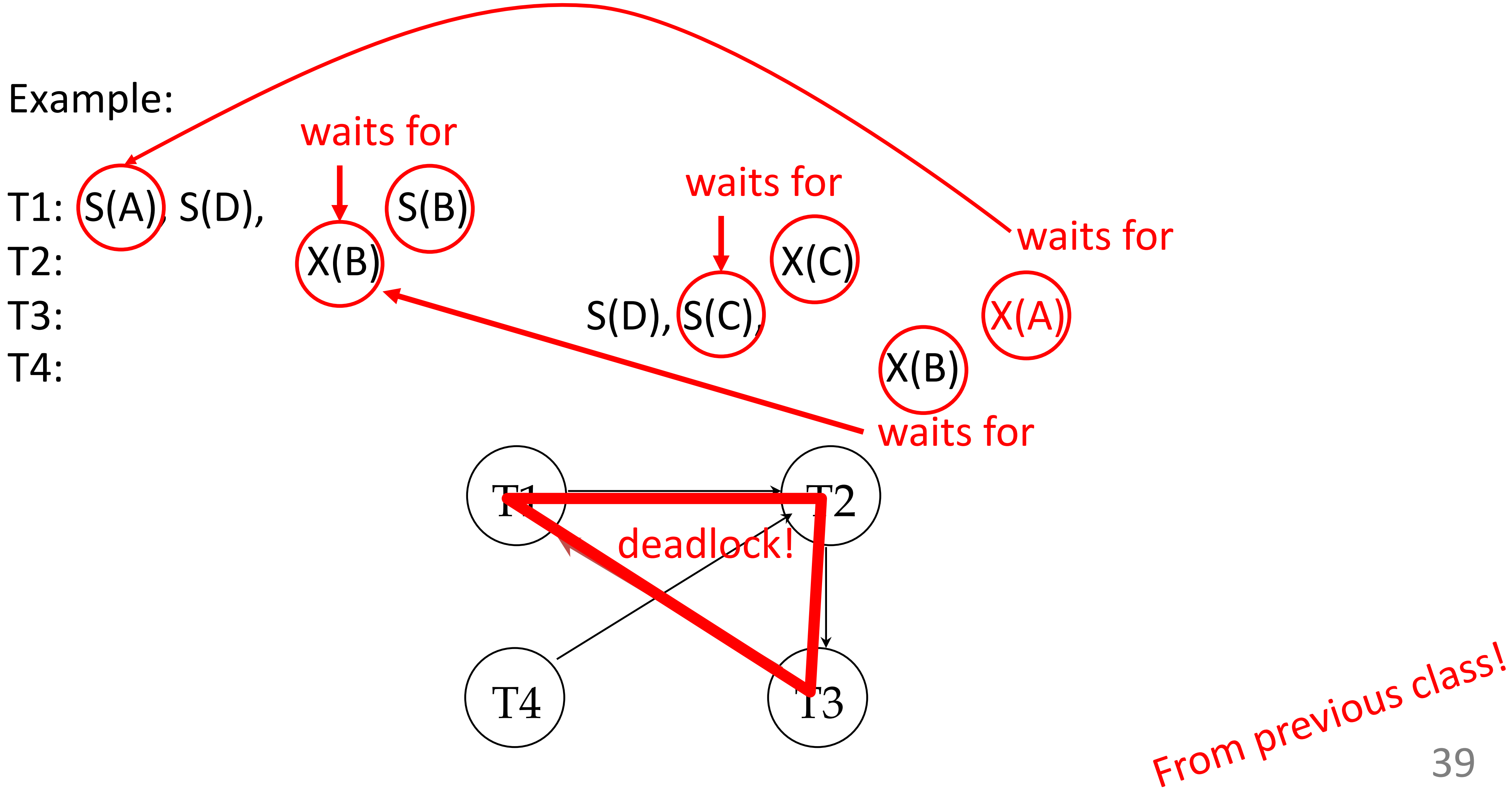
S	√	–
X	–	–

From previous class!

Reminder: Deadlock Detection (waits-for-graph)



Reminder: Deadlock Prevention

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Say Ti wants a lock that Tj holds

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Locking granularity

Readings: Chapter 17.5.2

Tree locking

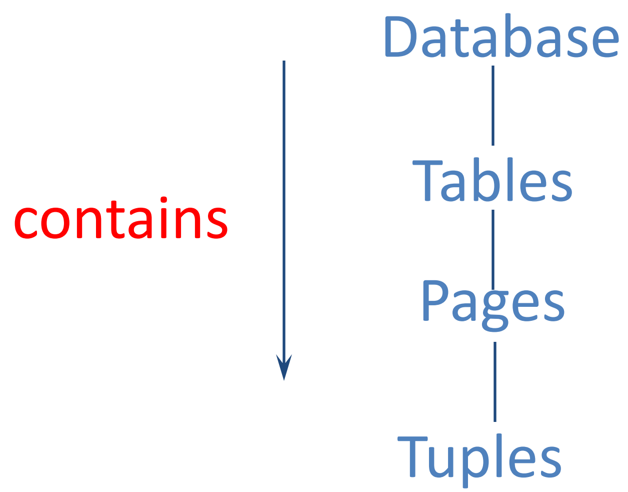
Phantoms and predicate locking

Multiple-Granularity Locks

Hard to decide what granularity to lock (tuples vs. pages vs. tables)

Shouldn’t have to make same decision for all transactions!

Data “containers” are nested:



what if T1 has a lock on a page,
and T2 on a tuple of this page?
how to correctly protect the data?

Solution: New Lock Modes, Protocol

Allow transaction to lock at each level, but with a special protocol using new “intention” locks:

Still need S and X locks, but before locking an item, transaction must have proper intension locks on all its ancestors in the granularity hierarchy

Database
|
Tables
|
Pages
|
Tuples

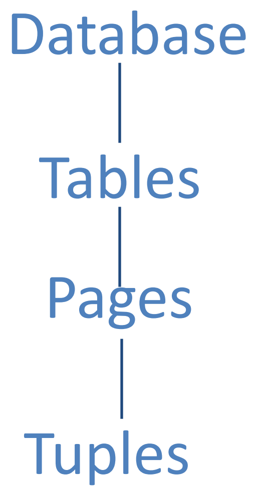
IS – Intent to get S lock(s) at finer granularity

IX – Intent to get X lock(s) at finer granularity

SIX mode: Like S & IX at the same time.

Why is it useful?

Multiple Granularity Lock Protocol



Each transaction starts from the root of the hierarchy

To get S or IS lock on a node, must hold IS or IX on parent node

- What if transaction holds SIX on parent? S on parent?

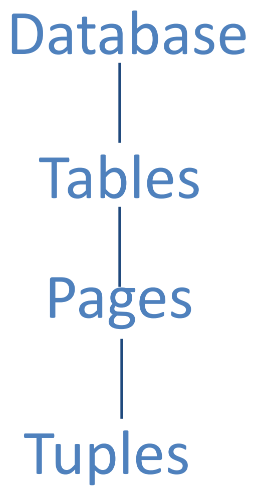
To get X or IX or SIX on a node, must hold IX or SIX on parent node

Must release locks in bottom-up order and must follow 2PL

Protocol is equivalent to directly setting locks at the leaf levels of the hierarchy.

Lock Compatibility Matrix

	IS	IX	SIX	S	X
IS	√	√	√	√	-
IX	√	√	-	-	-
SIX	√	-	-	-	-
S	√	-	-	√	-
X	-	-	-	-	-



IS – Intent to get S lock(s) at finer granularity

IX – Intent to get X lock(s) at finer granularity

SIX mode: S & IX at the same time

Examples – 2 level hierarchy

T1 scans R, and updates a few tuples:

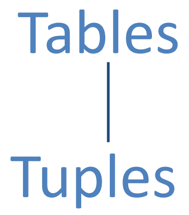
- T1 gets an SIX lock on R, then get X lock on tuples that are updated

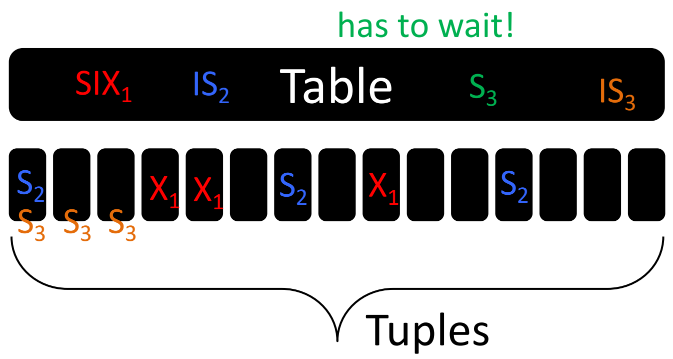
T2 uses an index to read only part of R:

- T2 gets an IS lock on R, and repeatedly gets an S lock on tuples of R

T3 reads all of R:

- T3 gets an S lock on R
- OR, T3 could behave like T2
- We can use lock escalation to decide
- Lock escalation dynamically asks for coarser-grained locks when too many low level locks acquired





	IS	IX	SIX	S	X
IS	√	√	√	√	
IX	√	√			
SIX	√				
S	√			√	
X					

Multiple granularity locking: Summary

Allows flexibility for each transaction to choose locking granularity independently

Introduces hierarchy of objects

Introduces intention locks

Concurrency Control

Serializability

Two phase locking

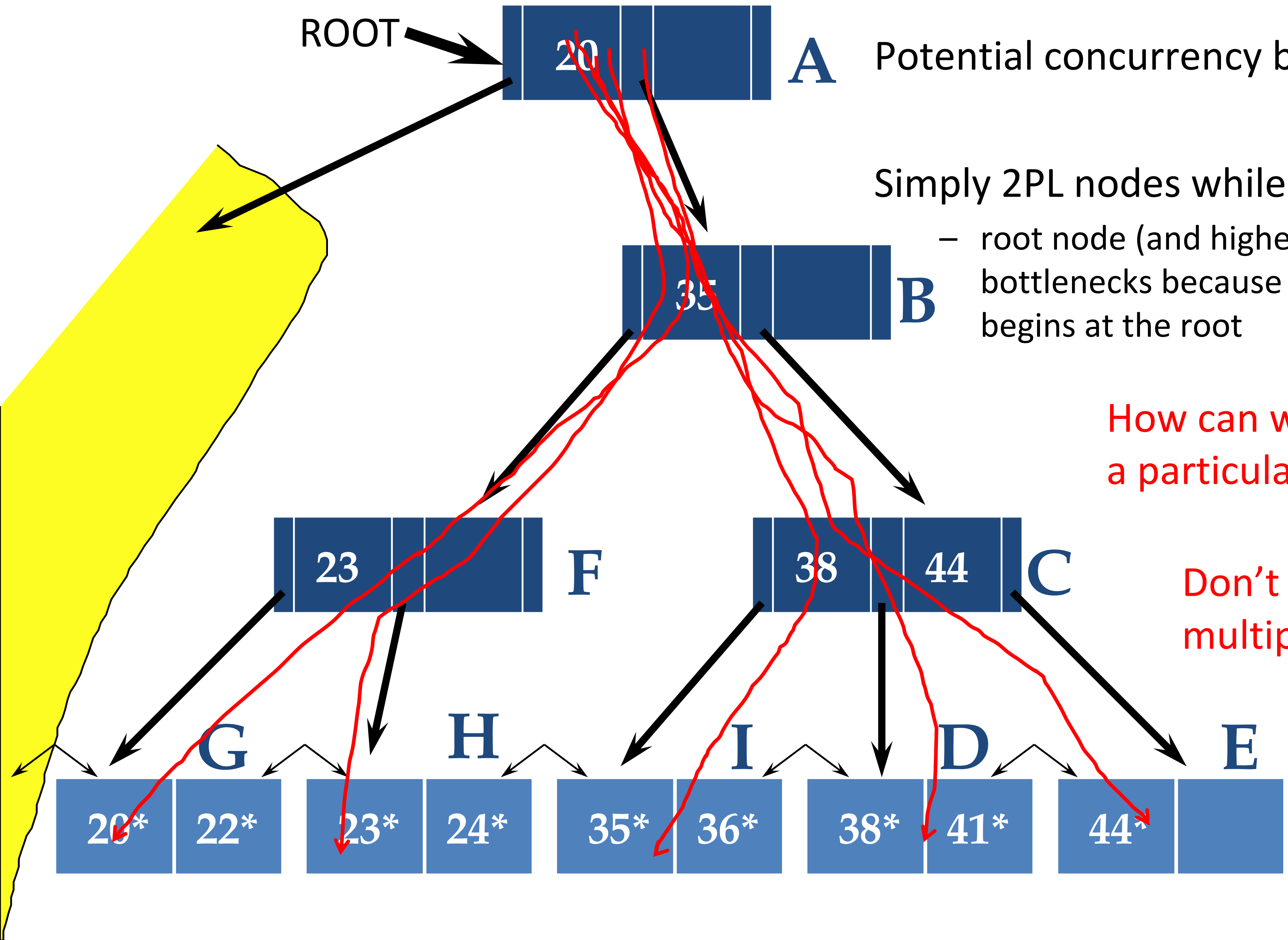
Lock management and deadlocks

Locking granularity

Tree locking

Readings: Chapter 17.5.2

Phantoms and predicate locking



Potential concurrency bottleneck:

Simply 2PL nodes while traversing:

– root node (and higher level nodes) become bottlenecks because every tree access begins at the root

How can we efficiently lock a particular leaf node?

Don't confuse this with multiple granularity locking!!

Two Useful Observations

1. In a B+Tree, higher levels of the tree only direct searches for leaf pages
2. For inserts, a node on a path from root to modified leaf must be locked (in X mode, of course), only if a split can propagate up to it from the modified leaf (Similar point holds w.r.t. deletes)

We can exploit these observations to design efficient locking protocols that guarantee serializability *even though they violate 2PL*

A Simple Tree Locking Algorithm: “crabbing”

Search: Start at root and go down; repeatedly, S lock child then unlock parent

Insert/Delete: Start at root and go down, obtaining X locks as needed. Once child is locked, check if it is safe:

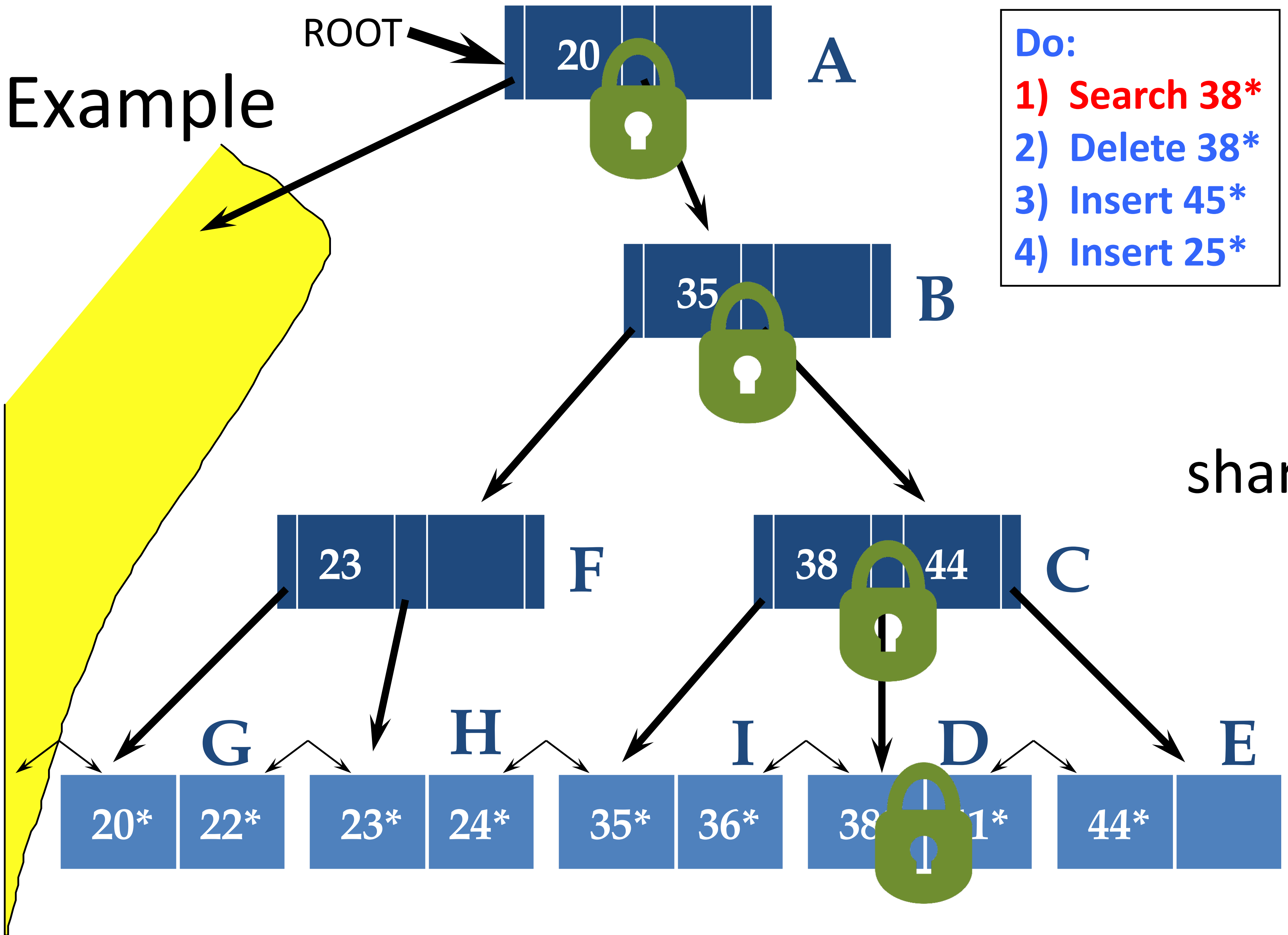
- If child is safe, release all locks on ancestors

Safe node: Node such that changes will not propagate up beyond this node.

-- When?

- Insertions: Node is not full
- Deletions: Node is not half-empty

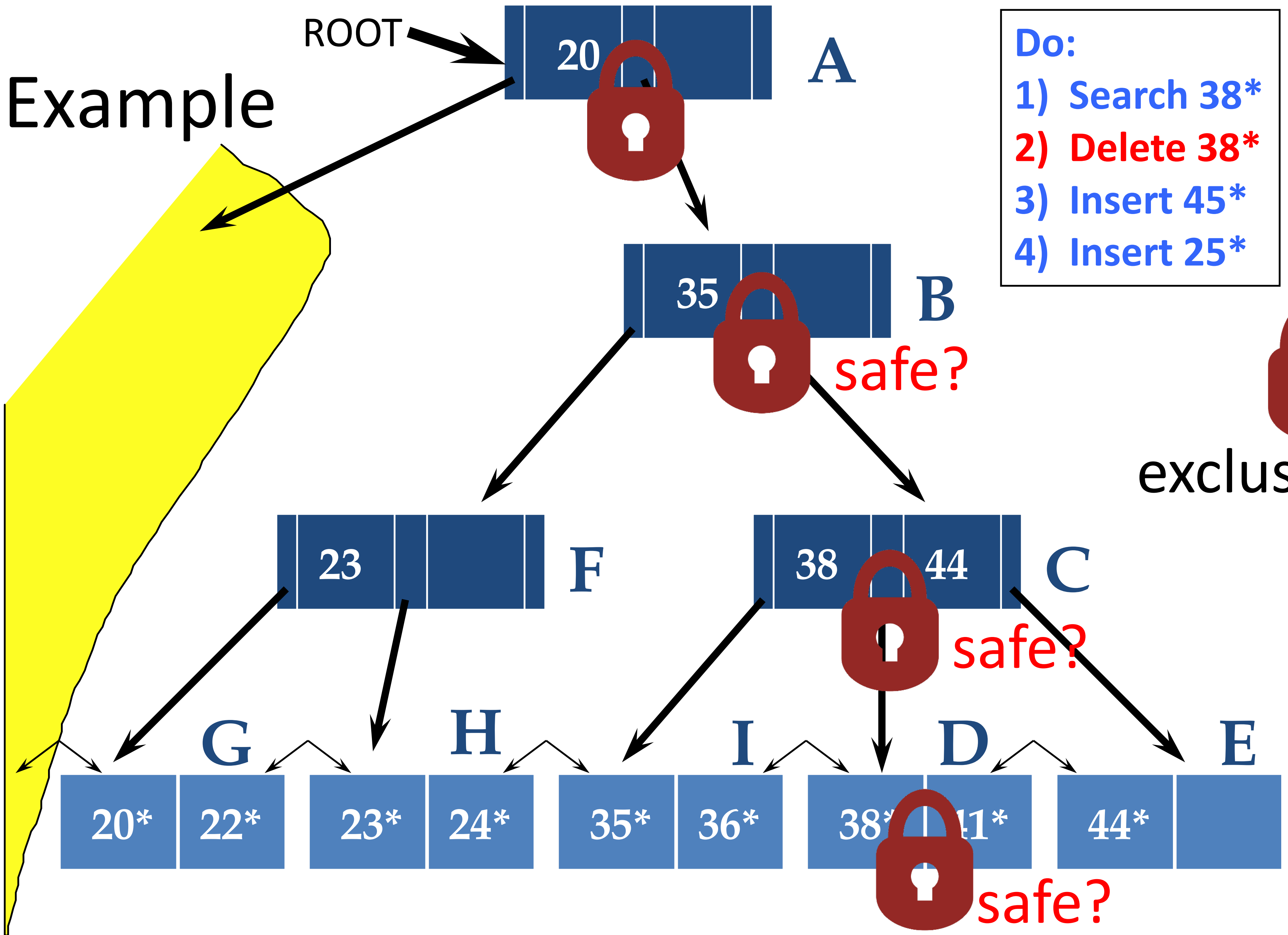
Example



Do:
1) Search 38*
2) Delete 38*
3) Insert 45*
4) Insert 25*

shared lock

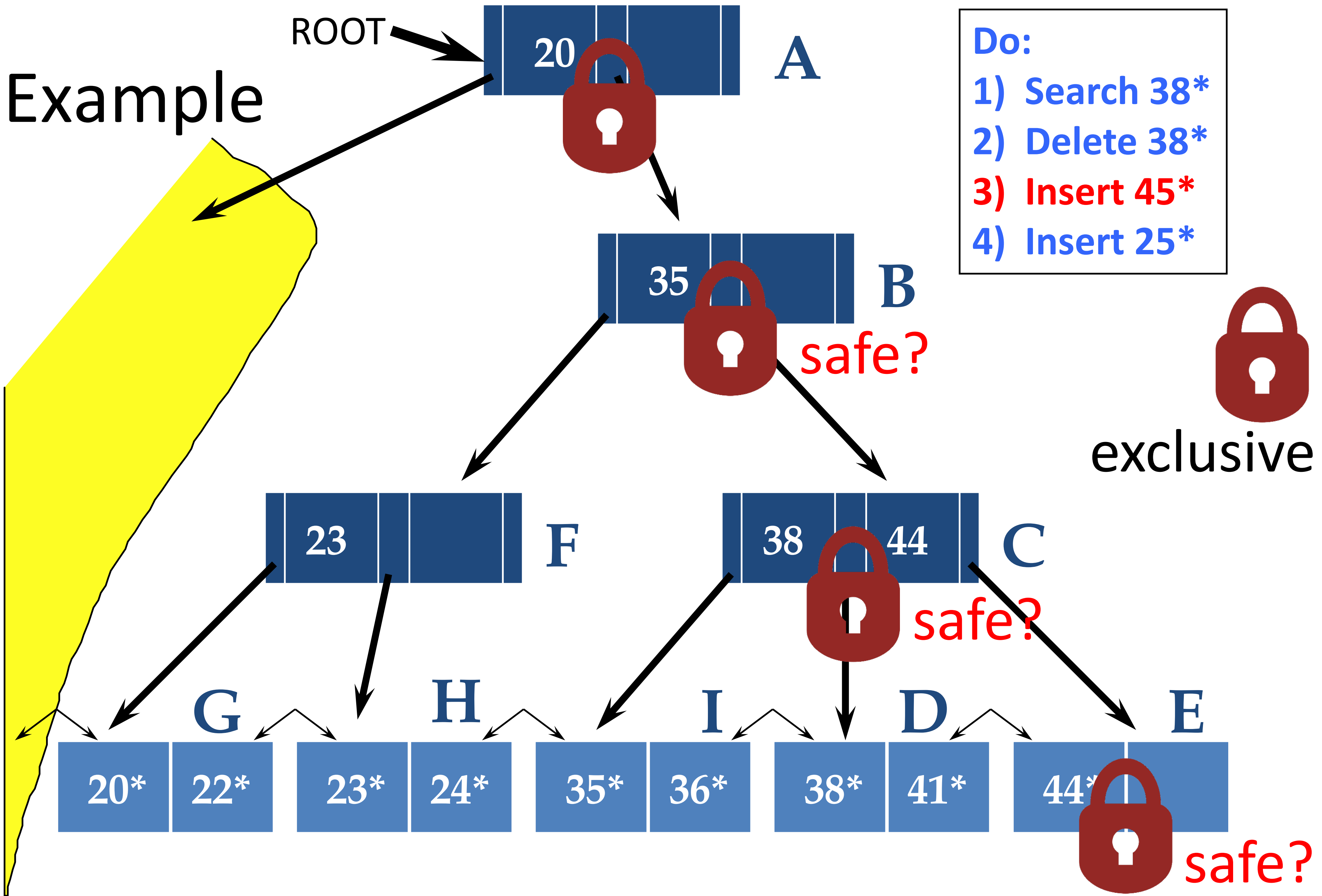
Example



Do:
1) Search 38*
2) Delete 38*
3) Insert 45*
4) Insert 25*

exclusive lock

Example



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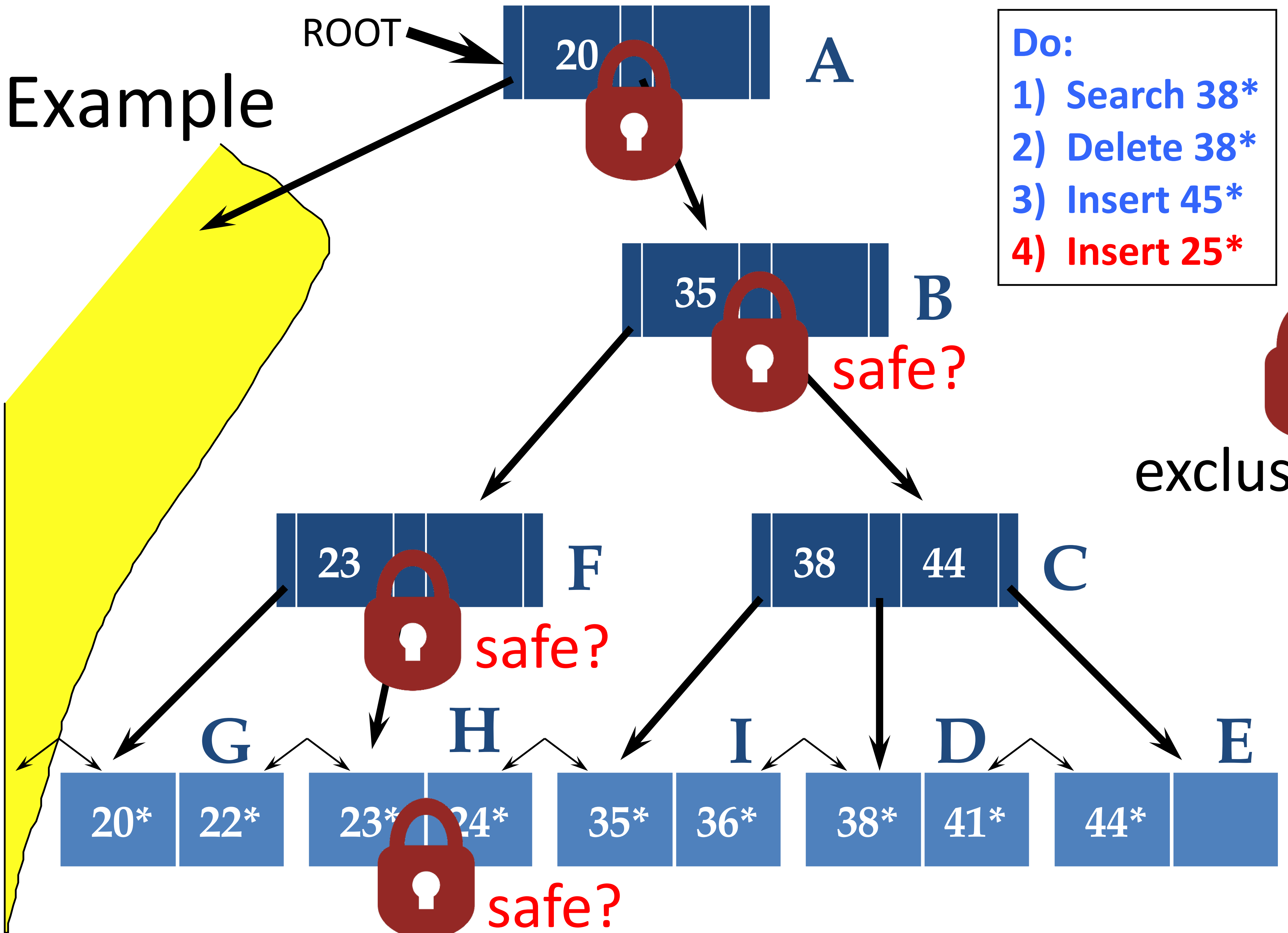

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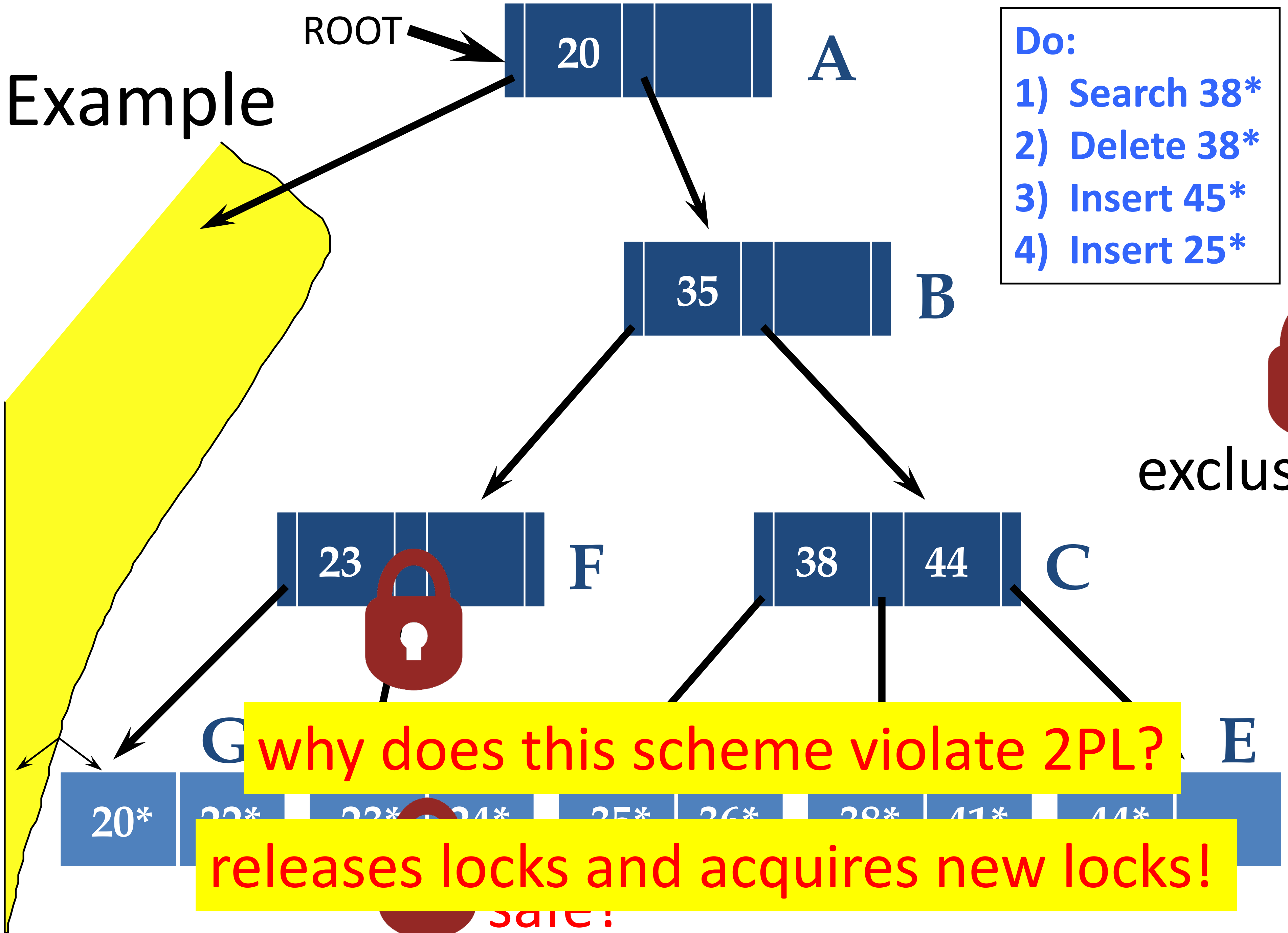
exclusive lock

Example



Do:
1) Search 38*
2) Delete 38*
3) Insert 45*
4) Insert 25*

exclusive lock

why does this scheme violate 2PL?

releases locks and acquires new locks!

Concurrency Control

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Readings: Chapter 17.5.1

Dynamic Databases – The “Phantom” Problem

If we relax the assumption that the DB is a fixed collection of objects, even Strict 2PL (on individual items) will not ensure serializability:

Consider T1 – “Find oldest sailor”

- T1 locks all records, and finds oldest sailor (say, *age* = 71)
- Next, T2 inserts a new sailor; *age* = 96 and commits
- T1 (within the same transaction) checks for the oldest sailor again and finds sailor aged 96!

The sailor with age 96 is a “phantom tuple” from T1’s point of view:

“first it’s not there then it is”

No serial execution of T1 and T2 could result to this!

The “Phantom” Problem – ex. 2

Consider T3 – “Find oldest sailor for each rating”

- T3 locks all pages containing sailor records with *rating* = 1, and finds oldest sailor (say, *age* = 71)
- Next, T4 inserts a new sailor; *rating* = 1, *age* = 96
- T4 also deletes oldest sailor with rating = 2 (and, say, *age* = 80), and commits
- T3 now locks all pages containing sailor records with *rating* = 2, and finds oldest (say, *age* = 63)

T3 saw only part of T4’s effects!

No serial execution where T3’s result could happen!

The Problem

T1 and T3 implicitly assumed that they had locked the set of all sailor records satisfying a predicate

- Assumption only holds if no sailor records are added while they are executing!
- Need some mechanism to enforce this assumption (Index locking and predicate locking)

Examples show that conflict serializability on reads and writes of individual items guarantees serializability only if the set of objects is fixed!

Predicate Locking

Predicate locking:

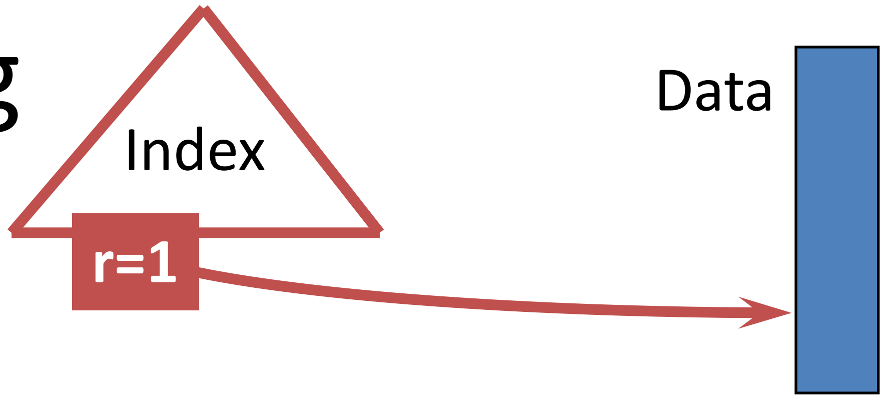
Grant lock on all records that satisfy some logical predicate, e.g., *age > 2*salary*

Index locking is a special case of predicate locking for which an index supports efficient implementation of the predicate lock

– What is the predicate in the sailor example?

In general, predicate locking has a lot of locking overhead

Index Locking



If there is a dense index on the *rating* field using Alternative (2), T3 should lock the index page containing the data entries with *rating* = 1

- If there are no records with *rating* = 1, T3 must lock the index page where such a data entry *would* be, if it existed!

If there is no suitable index, T3 must obtain:

1. A lock on every page in the table file

   → prevent a record's rating from being changed to 1

AND

2. The lock for the file itself

   → prevent records with *rating* = 1 from being added or deleted

Transaction Support in SQL-92

SERIALIZABLE

No phantoms, all reads repeatable, no “dirty” (uncommited) reads

REPEATABLE READS

phantoms may happen

READ COMMITTED

phantoms and unrepeatable reads may happen

READ UNCOMMITTED

all of them may happen

Phantom problem: Summary

If database objects can be added/removed, need to guard against Phantom Problem

Must lock logical sets of records

Efficient solution: index locking