Carnegie Mellon University

09 Index Concurrency Control

Intro to Database Systems
15-445/15-645
Fall 2020

AP
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Computer Science
Carnegie Mellon University

ADMINISTRIVIA

Homework #2 is due Sunday Oct 4th

Project #2 is now released:

→ Checkpoint #1: Due Sunday Oct 11th

→ Checkpoint #2: Due Sunday Oct 25th

OBSERVATION

We assumed that all the data structures that we have discussed so far are single-threaded.

But we need to allow multiple threads to safely access our data structures to take advantage of additional CPU cores and hide disk I/O stalls.

They Don't Do This!

VOLTDB

redis

H-Store

CONCURRENCY CONTROL

A **concurrency control** protocol is the method that the DBMS uses to ensure "correct" results for concurrent operations on a shared object.

A protocol's correctness criteria can vary:
→ **Logical Correctness:** Can a thread see the data that it is supposed to see?
→ **Physical Correctness:** Is the internal representation of the object sound?

TODAY'S AGENDA

Latches Overview

Hash Table Latching

B+Tree Latching

Leaf Node Scans

Delayed Parent Updates

LOCKS VS. LATCHES

Locks

→ Protects the database's logical contents from other txns.
→ Held for txn duration.
→ Need to be able to rollback changes.

Latches

→ Protects the critical sections of the DBMS's internal data structure from other threads.
→ Held for operation duration.
→ Do not need to be able to rollback changes.

LOCKS VS. LATCHES

	Locks	*Latches*
Separate…	User transactions	Threads
Protect…	Database Contents	In-Memory Data Structures
During…	Entire Transactions	Critical Sections
Modes…	Shared, Exclusive, Update, Intention	Read, Write
Deadlock	Detection & Resolution	Avoidance
…by…	Waits-for, Timeout, Aborts	Coding Discipline
Kept in…	Lock Manager	Protected Data Structure

Source: Goetz Graefe

LOCKS VS. LATCHES

Lecture 17

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LATCH MODES

Read Mode

→ Multiple threads can read the same object at the same time.

→ A thread can acquire the read latch if another thread has it in read mode.

Write Mode

→ Only one thread can access the object.

→ A thread cannot acquire a write latch if another thread holds the latch in any mode.

Compatibility Matrix

	Read	Write
Read	✔	X
Write	X	X

LATCH IMPLEMENTATIONS

Blocking OS Mutex

Test-and-Set Spinlock

Reader-Writer Locks

LATCH IMPLEMENTATIONS

Approach #1: Blocking OS Mutex

→ Simple to use
→ Non-scalable (about 25ns per lock/unlock invocation)
→ Example: **std::mutex**

```
std::mutex m; → pthread_mutex_t
                      ↓
 ⋮                  futex
m.lock();
// Do something special...
m.unlock();
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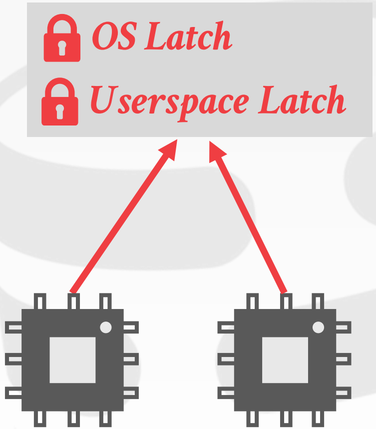

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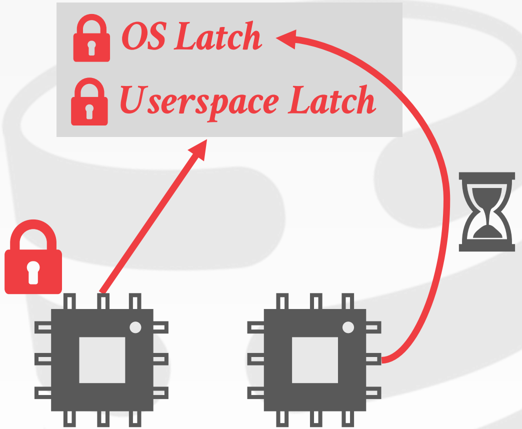

LATCH IMPLEMENTATIONS

Approach #2: Test-and-Set Spin Latch (TAS)

→ Very efficient (single instruction to latch/unlatch)
→ Non-scalable, not cache friendly, not OS friendly.
→ Example: **std::atomic<T>**

std::atomic<bool>

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std::atomic_flag latch;
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while (latch.test_and_set(…)) {
    // Retry? Yield? Abort?
}
```

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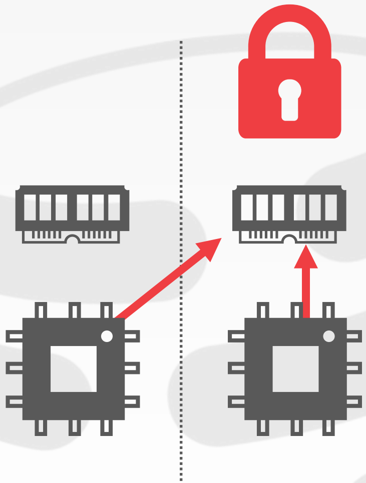

LATC

Approach

→ Very effic
→ Non-scal
→ Example:

By: **Linus Torvalds** (torvalds.delete@this.linux-foundation.org), January 3, 2020 6:05 pm
Room: Moderated Discussions

Beastian (no.email.delete@this.aol.com) on January 3, 2020 11:46 am wrote:
> I'm usually on the other side of these primitives when I write code as a consumer of them,
> but it's very interesting to read about the nuances related to their implementations:

The whole post seems to be just wrong, and is measuring something completely different than what the author thinks and claims it is measuring.

First off, spinlocks can only be used if you actually know you're not being scheduled while using them. But the blog post author seems to be implementing his own spinlocks in user space with no regard for whether the lock user might be scheduled or not. And the code used for the claimed "lock not held" timing is complete garbage.

It basically reads the time before releasing the lock, and then it reads it after acquiring the lock again, and claims that the time difference is the time when no lock was held. Which is just inane and pointless and completely wrong.

That's pure garbage. What happens is that

(a) since you're spinning, you're using CPU time

(b) at a random time, the scheduler will schedule you out

I repeat: **do not use spinlocks in user space, unless you actually know what you're doing**. And be aware that the likelihood that you know what you are doing is basically nil.

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ne slice", and
hen it looks at

related to your
running right now! ... thread that wants that lock that is still being held by the thread that isn't even ... that one already got its

So the code in question is pure garbage. You can't do spinlocks like that. Or rather, you very much can do them like that, and when you do that you are measuring random latencies and getting nonsensical values, because what you are measuring is "I have a lot of busywork, where all the processes are CPU-bound, and I'm measuring random points of how long the scheduler kept the process in place".

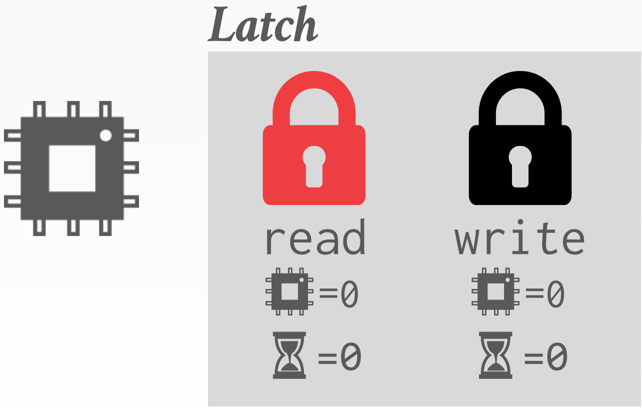
And then you write a blog-post blamings others, not understanding that it's your incorrect code that is garbage, and is giving random garbage values.

```
    // Re
}
```

LATCH IMPLEMENTATIONS

Choice #3: Reader-Writer Locks

→ Allows for concurrent readers.
→ Must manage read/write queues to avoid starvation.
→ Can be implemented on top of spinlocks.



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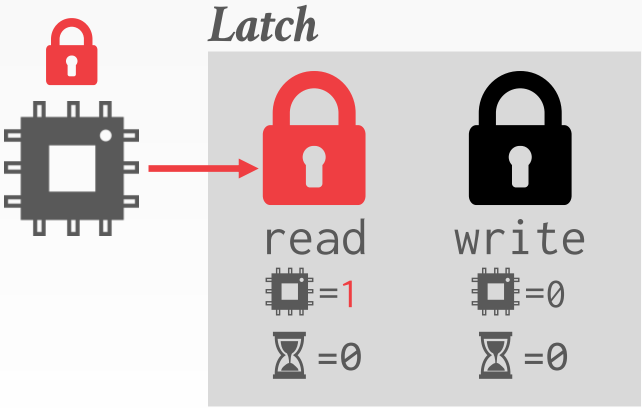

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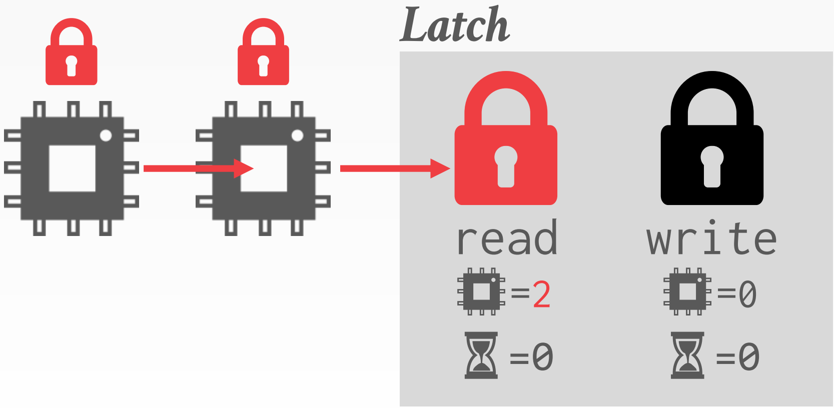

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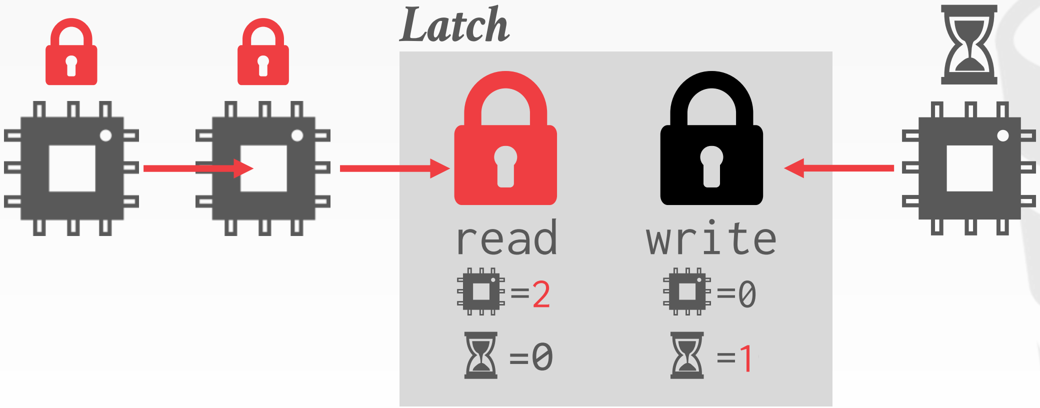

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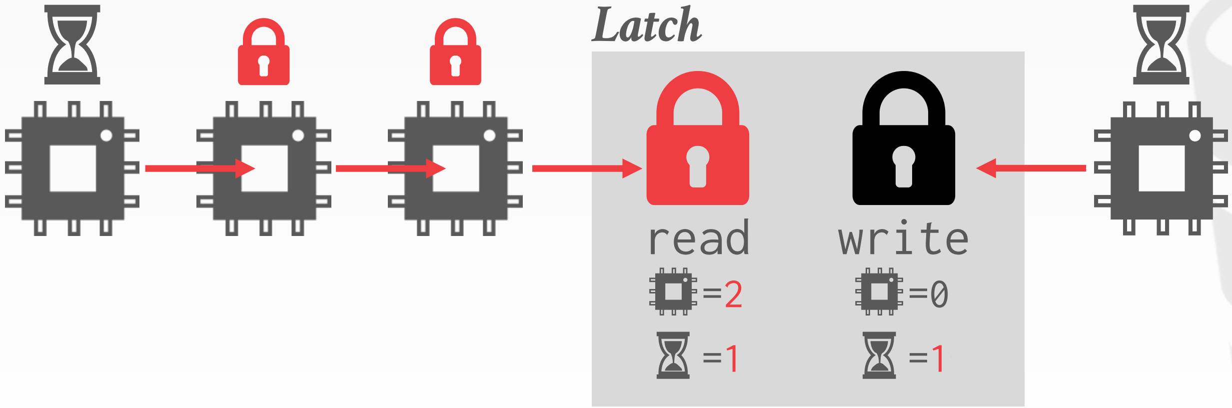


HASH TABLE LATCHING

Easy to support concurrent access due to the limited ways threads access the data structure.

→ All threads move in the same direction and only access a single page/slot at a time.

→ Deadlocks are not possible.

To resize the table, take a global write latch on the entire table (i.e., in the header page).

HASH TABLE LATCHING

Approach #1: Page Latches

→ Each page has its own reader-write latch that protects its entire contents.
→ Threads acquire either a read or write latch before they access a page.

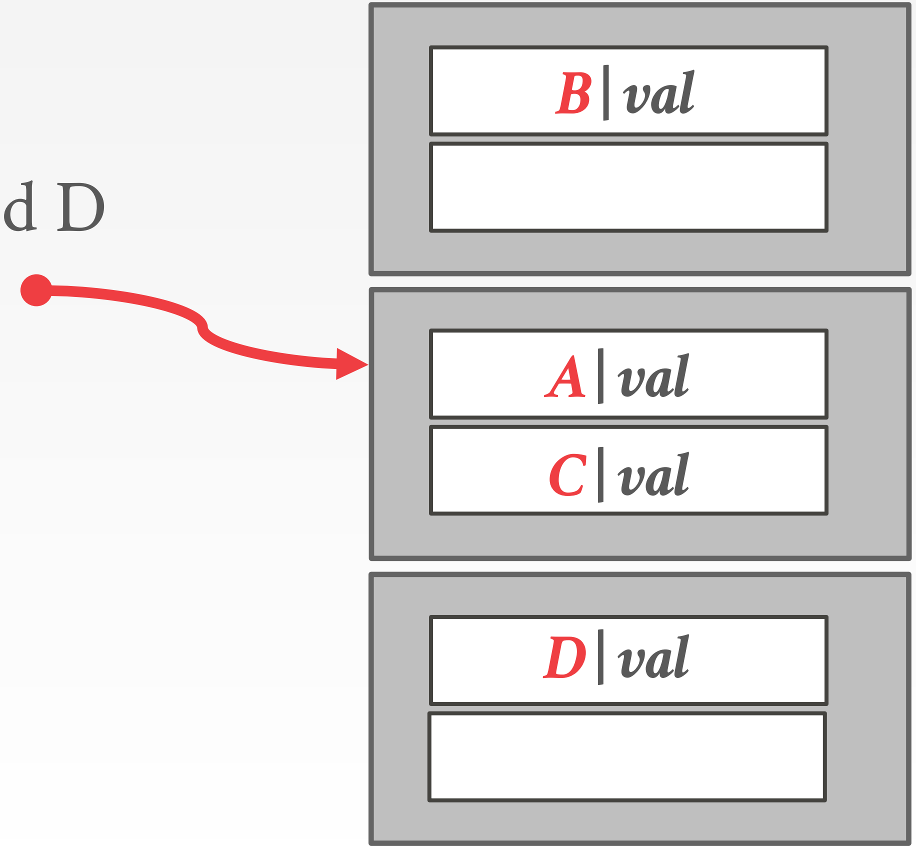
Approach #2: Slot Latches

→ Each slot has its own latch.
→ Can use a single mode latch to reduce meta-data and computational overhead.

HASH TABLE – PAGE LATCHES

T_1: Find D

hash(D)



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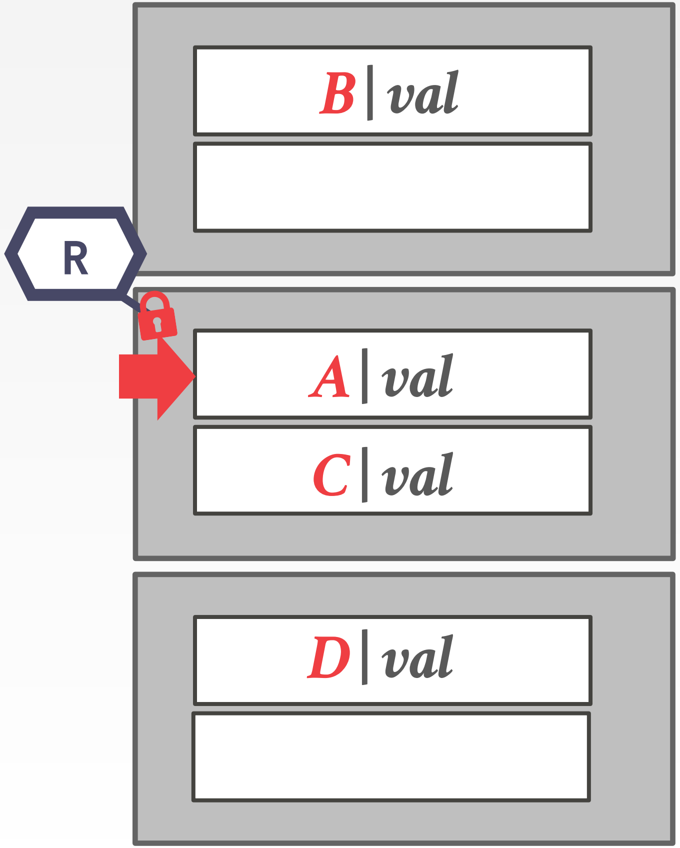

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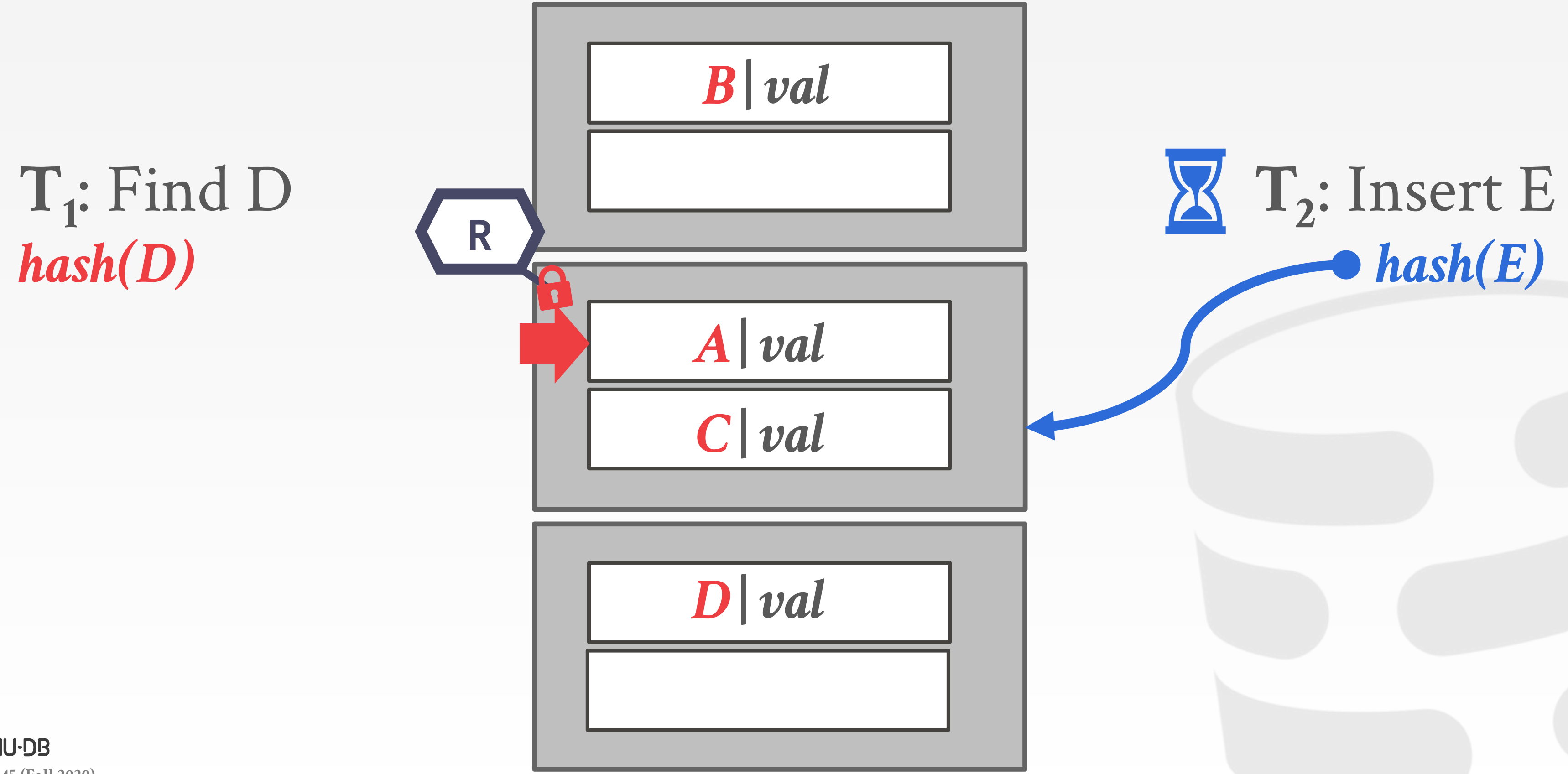

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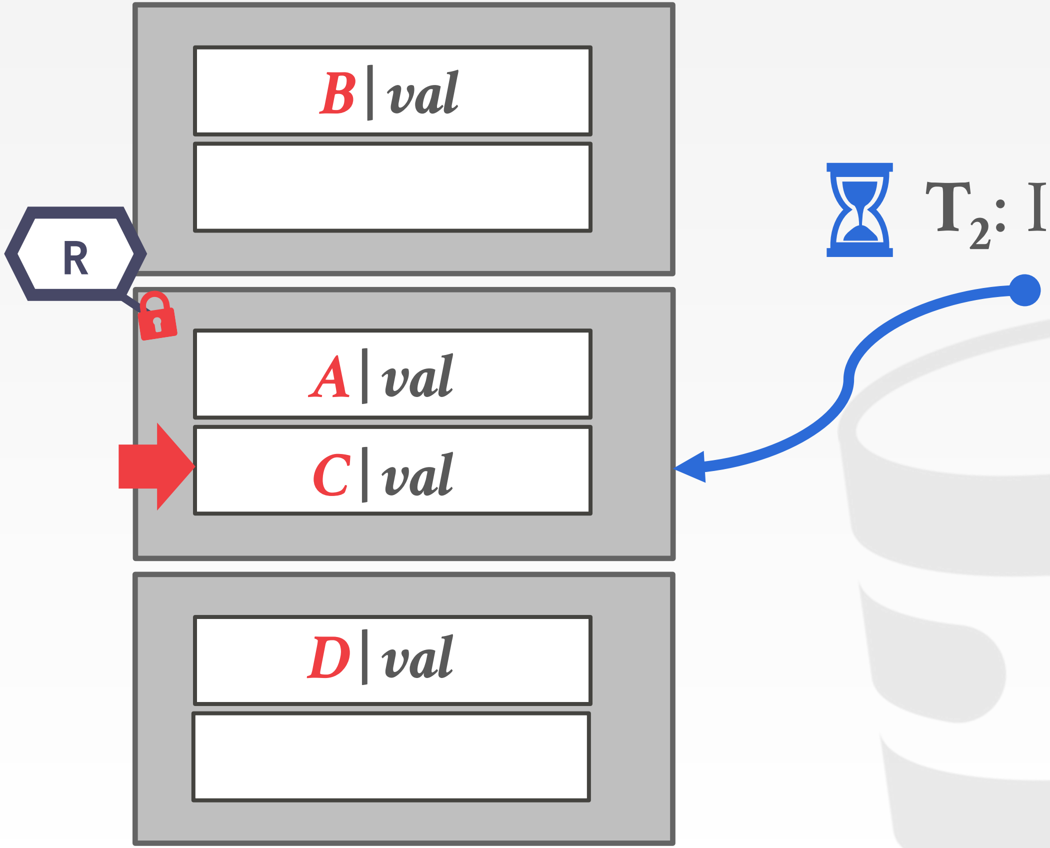
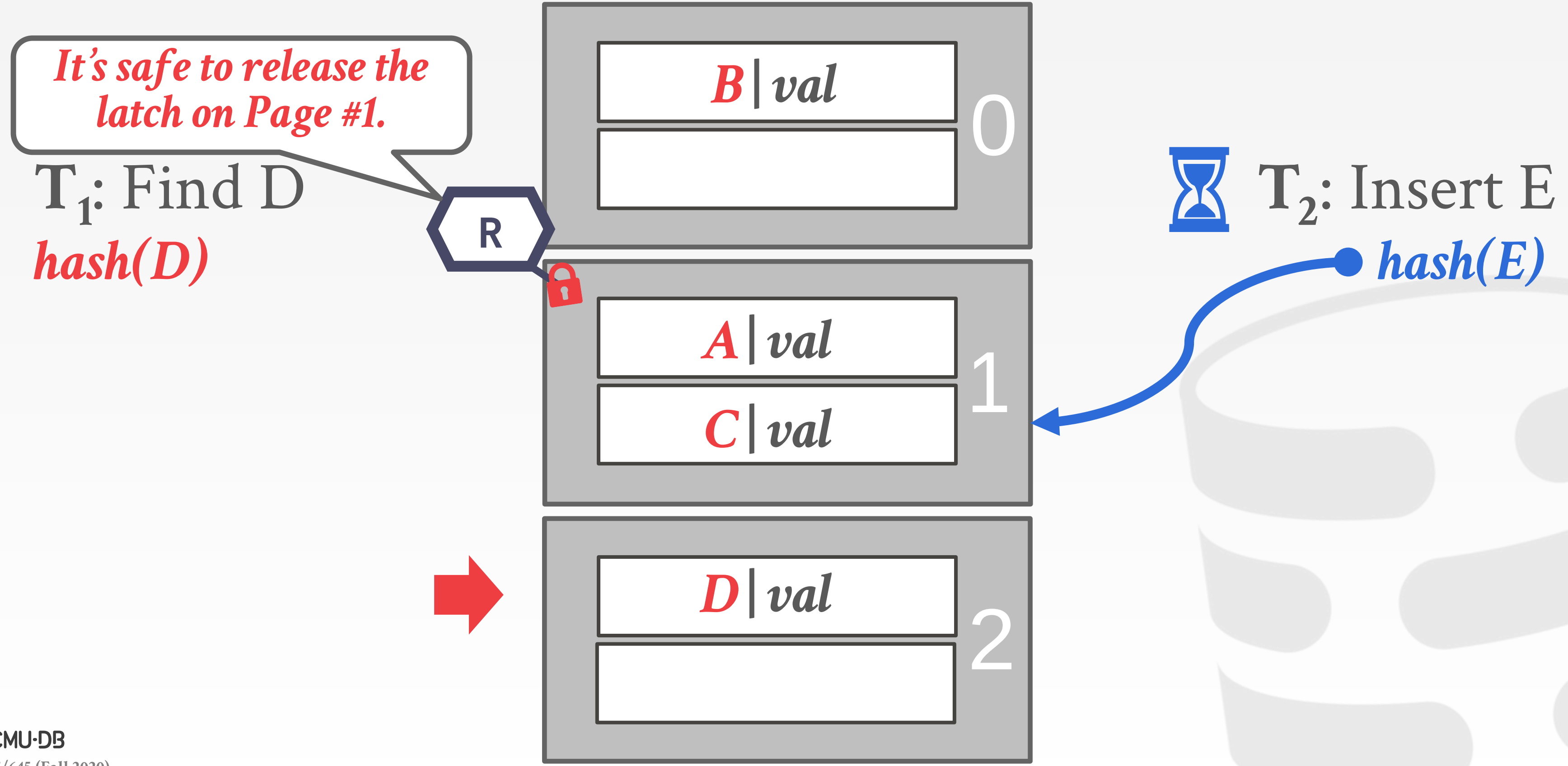


T2: Insert E
hash(E)

HASH TABLE – PAGE LATCHES



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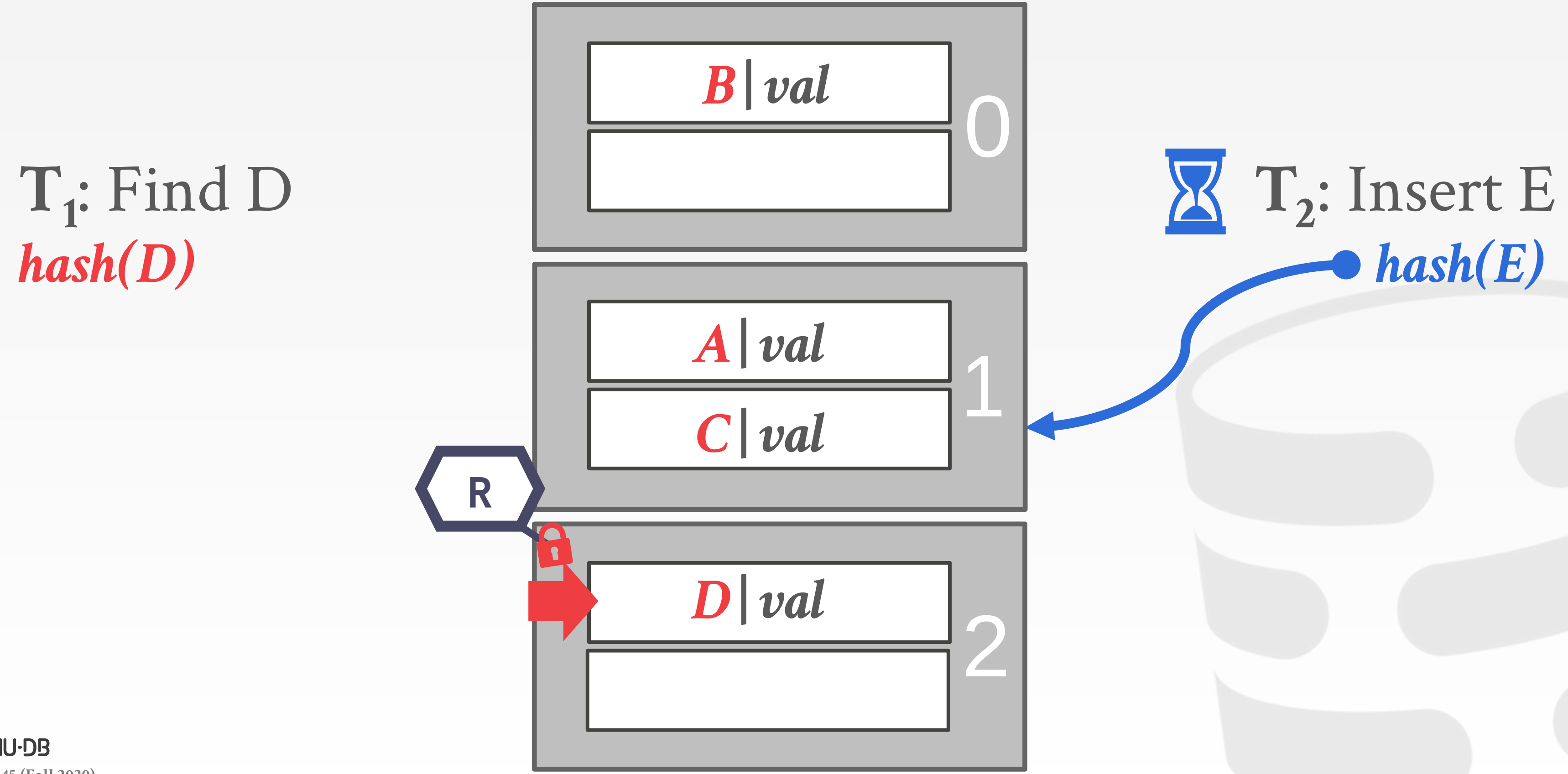

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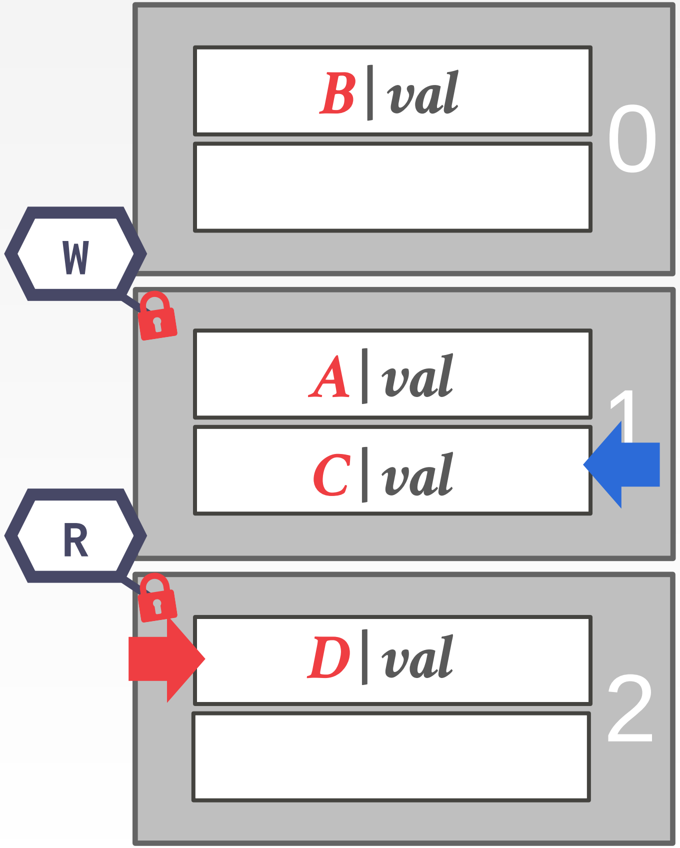

T_2: Insert E
hash(E)

HASH TABLE – PAGE LATCHES

T_1: Find D
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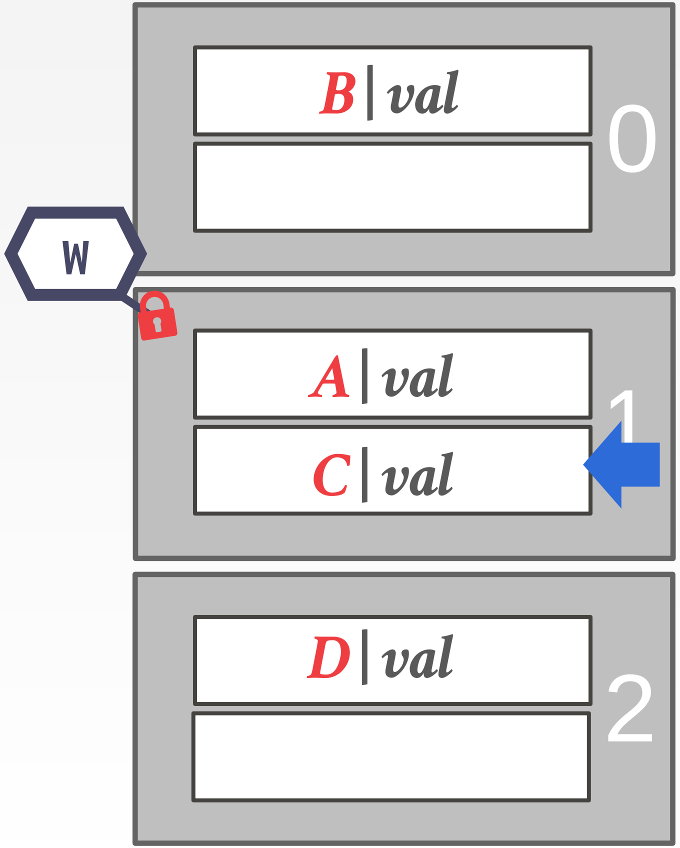
T_2: Insert E
hash(E)



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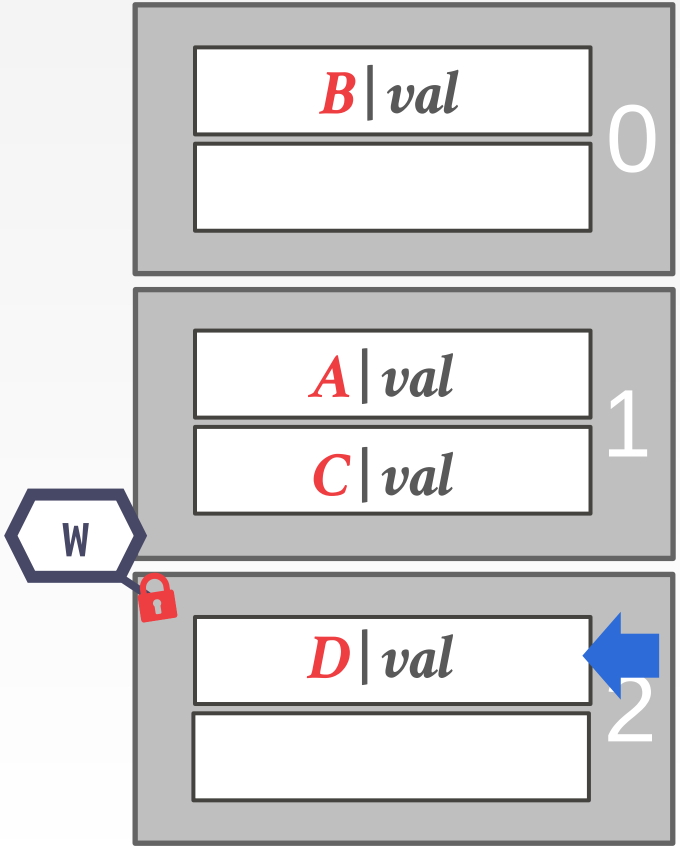

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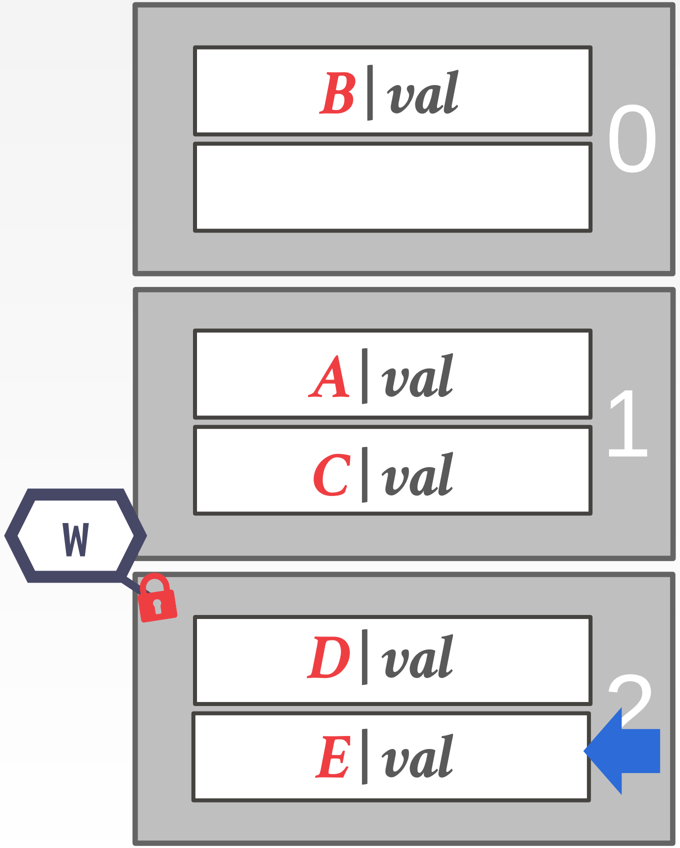
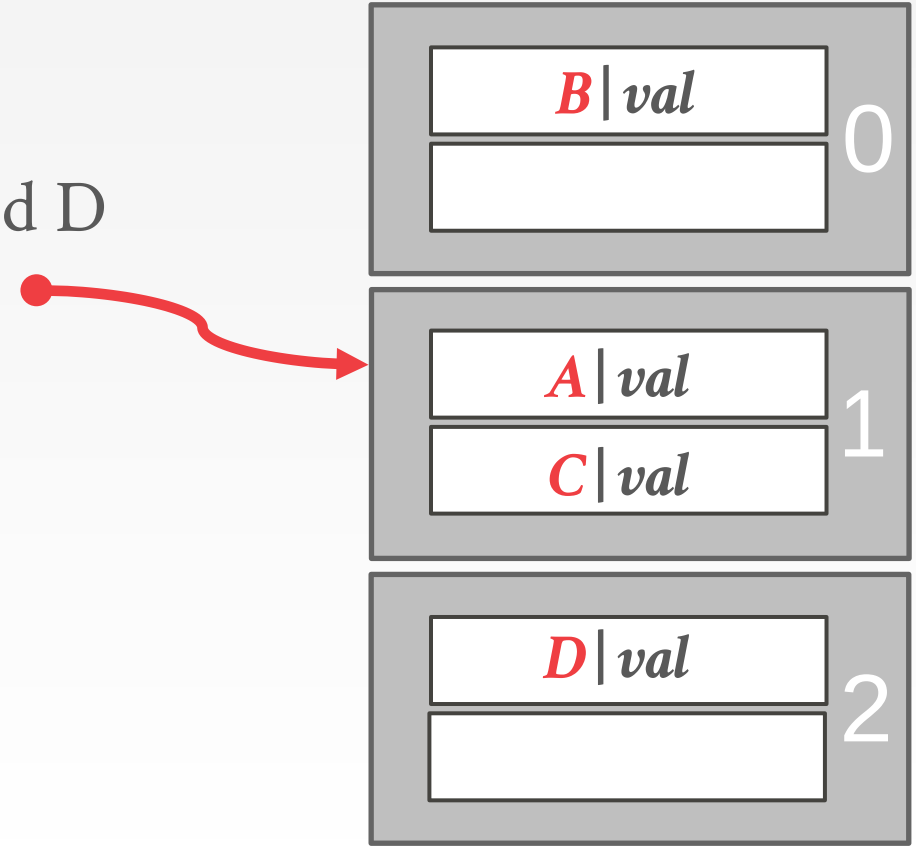


T_2: Insert E
hash(E)

HASH TABLE – SLOT LATCHES

T_1: Find D

hash(D)



T_2: Insert E

hash(E)

HASH TABLE – SLOT LATCHES

T_1: Find D

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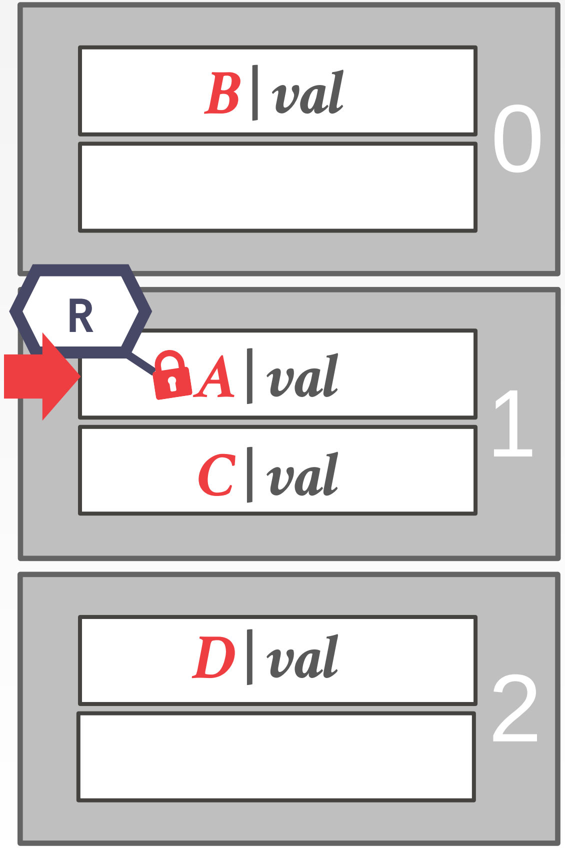

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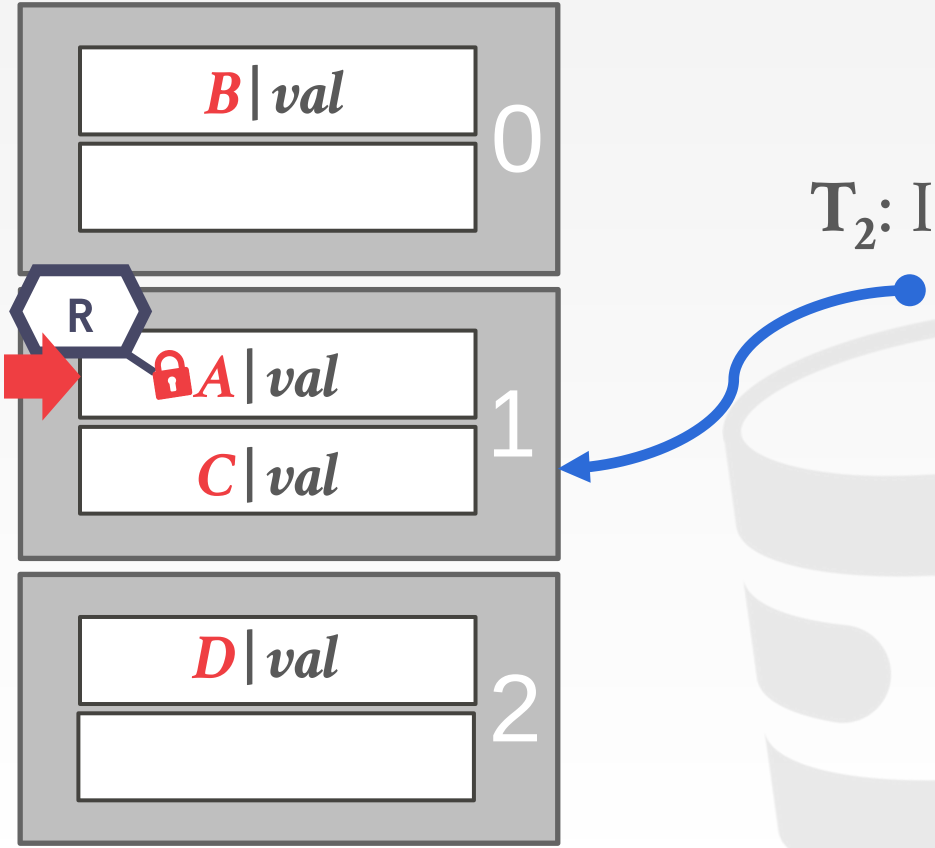
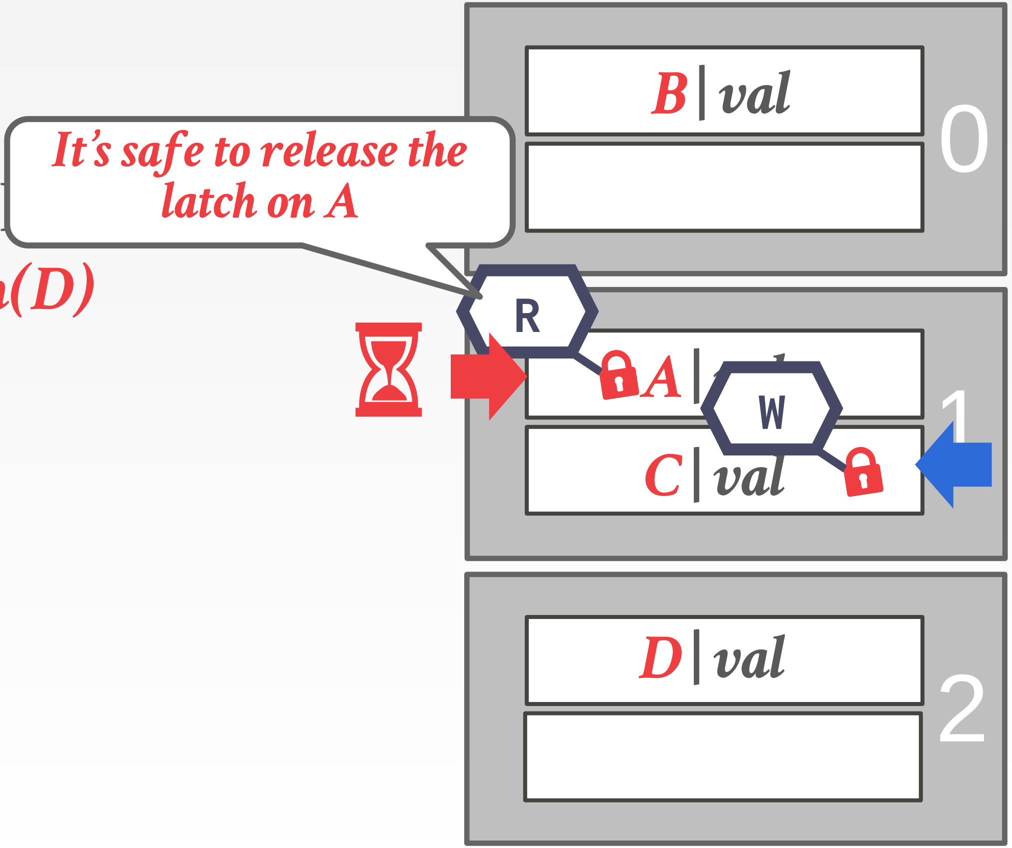


T_2: Insert E
hash(E)

HASH TABLE – SLOT LATCHES

T_1: ...

hash(D)



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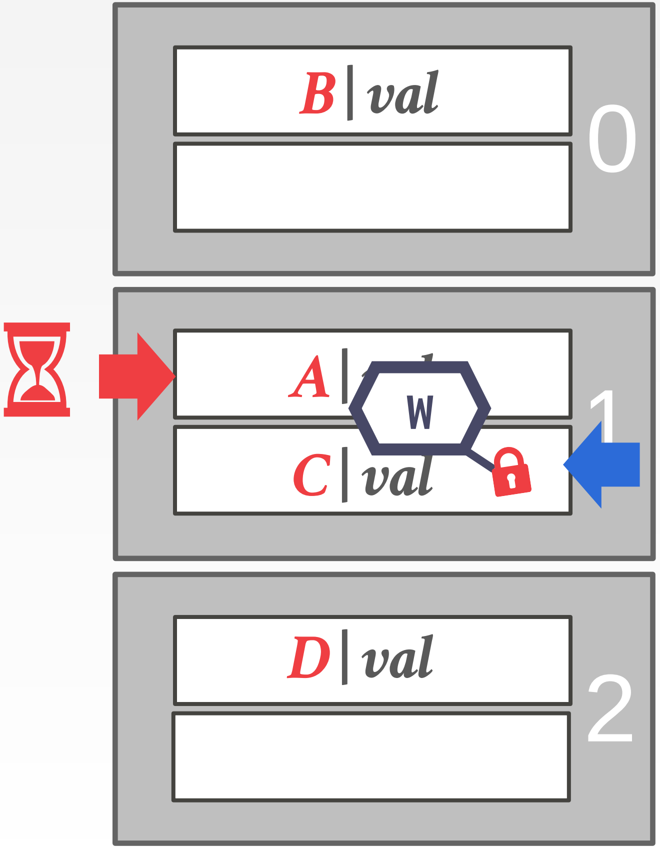

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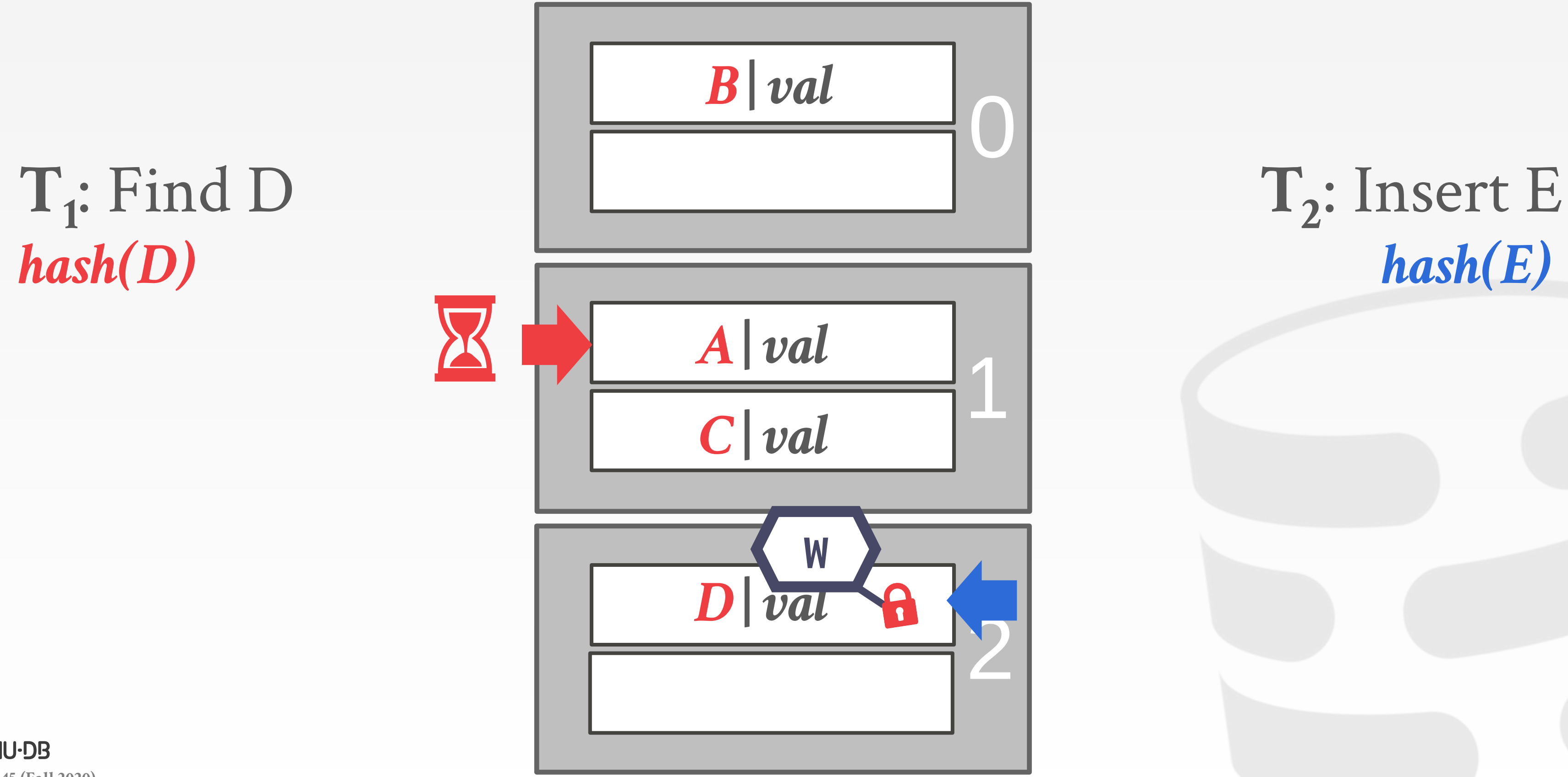

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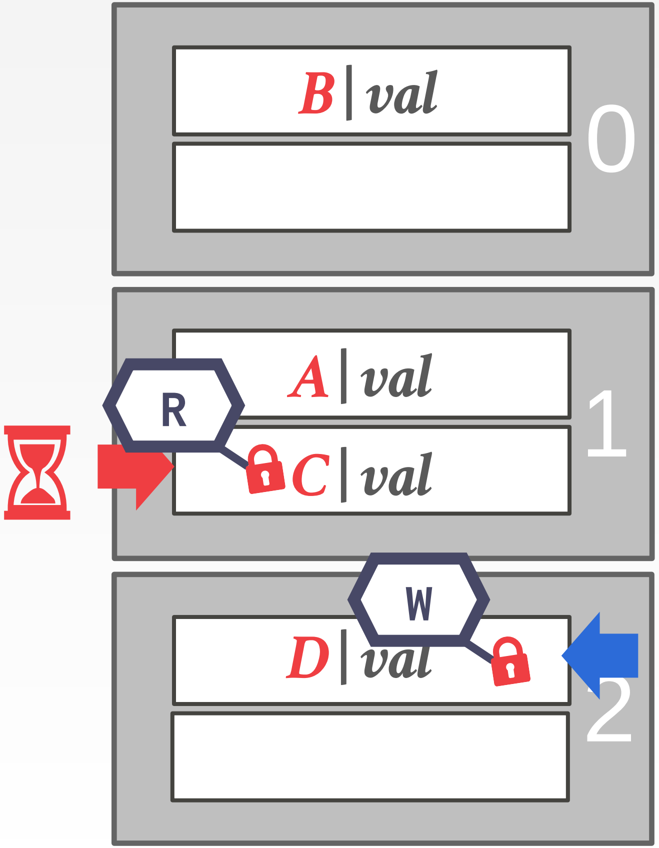

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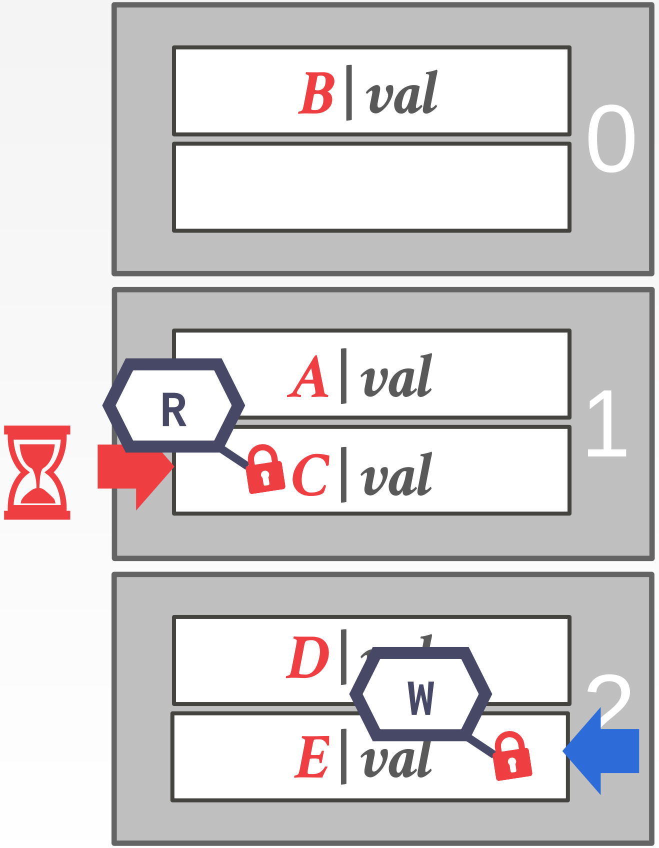

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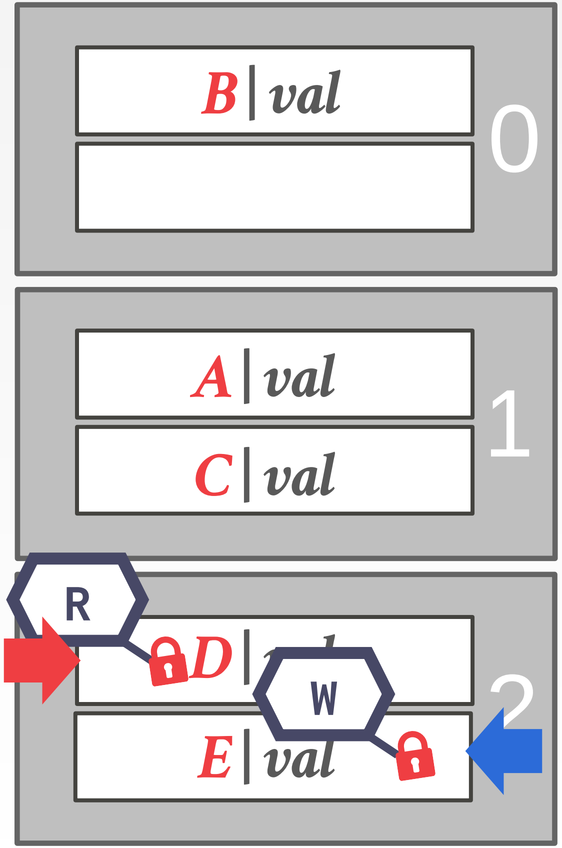


T_2: Insert E
hash(E)

B+TREE CONCURRENCY CONTROL

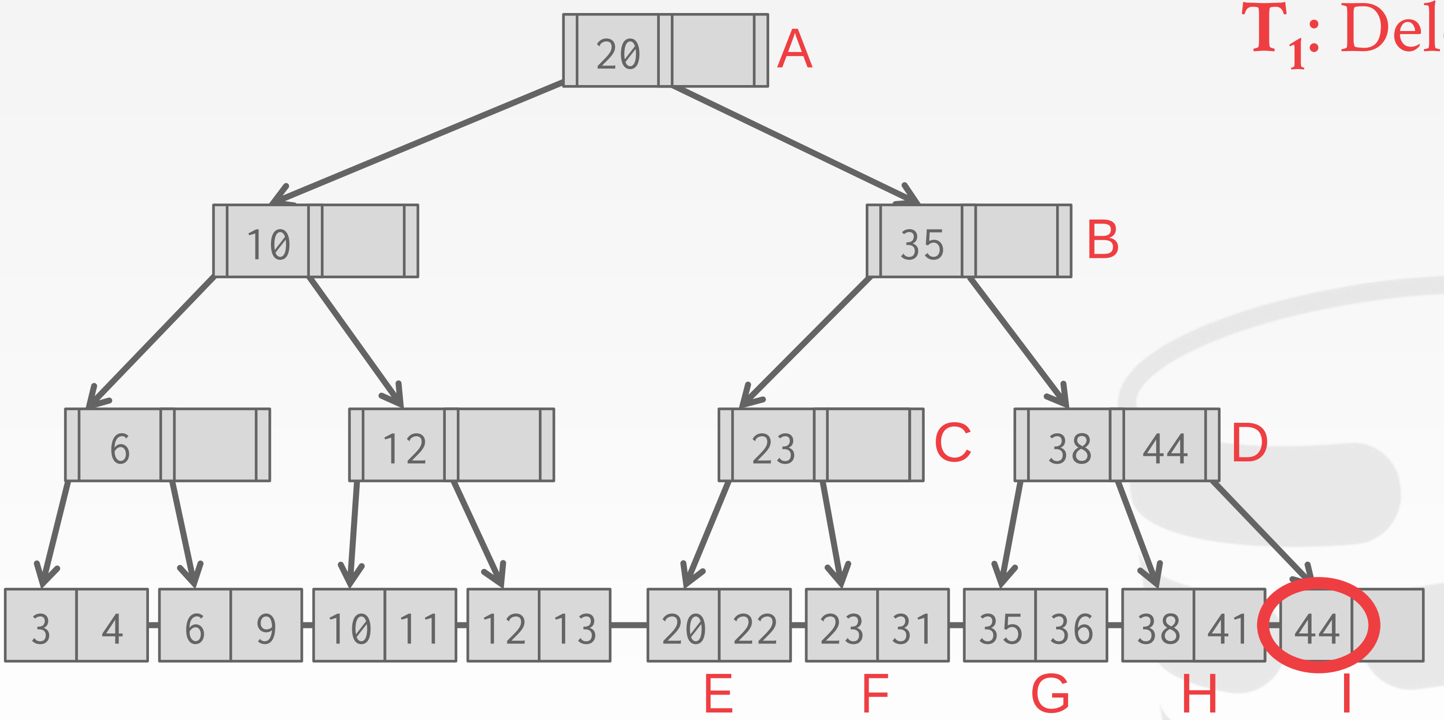
We want to allow multiple threads to read and update a B+Tree at the same time.

We need to protect from two types of problems:

→ Threads trying to modify the contents of a node at the same time.
→ One thread traversing the tree while another thread splits/merges nodes.

B+TREE MULTI-THREADED EXAMPLE

T$_1$: Delete 44



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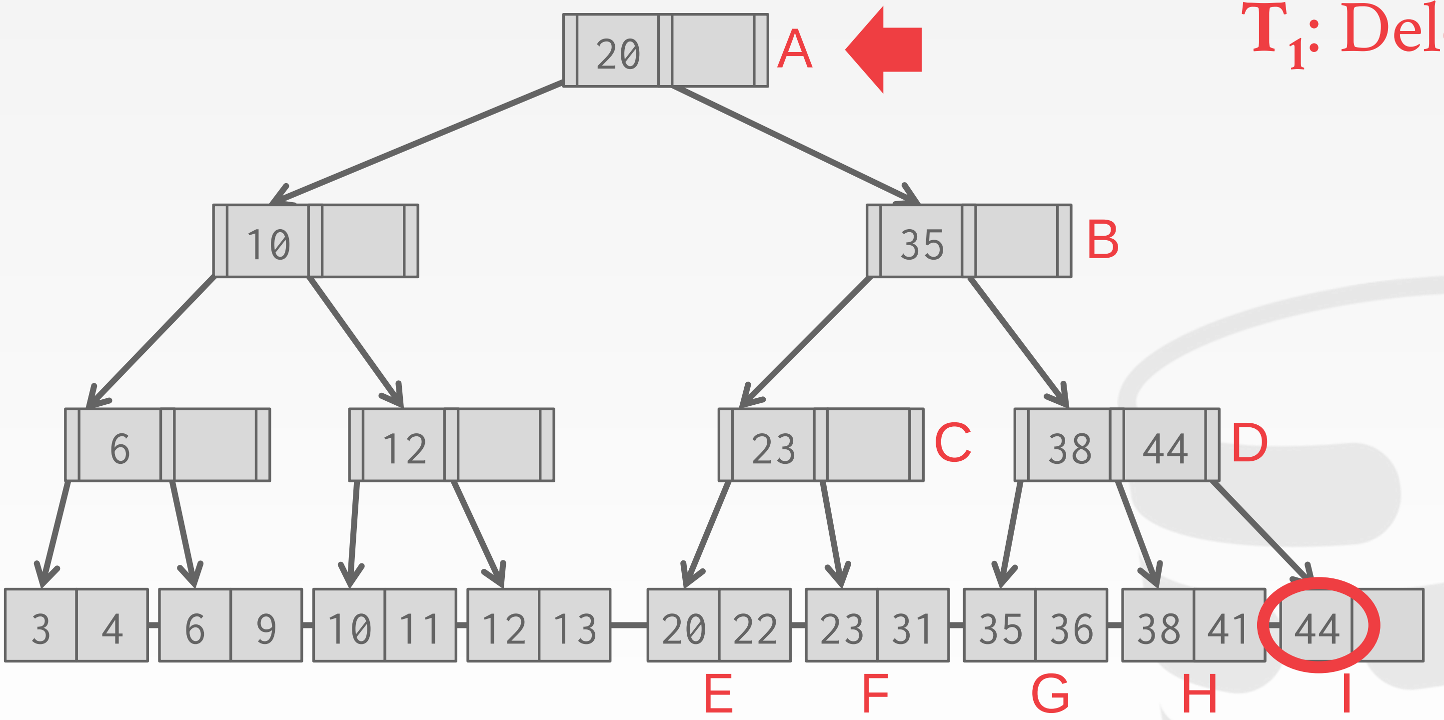

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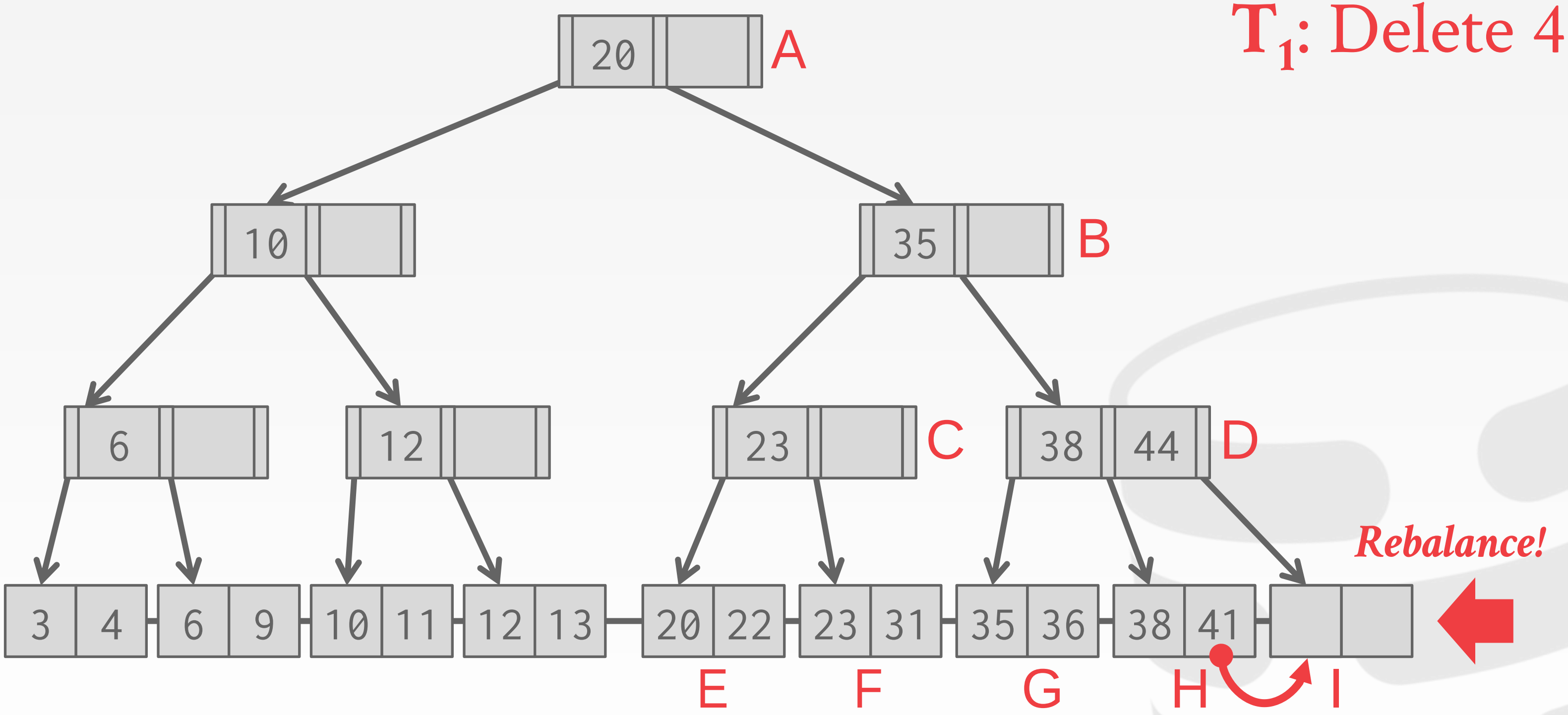

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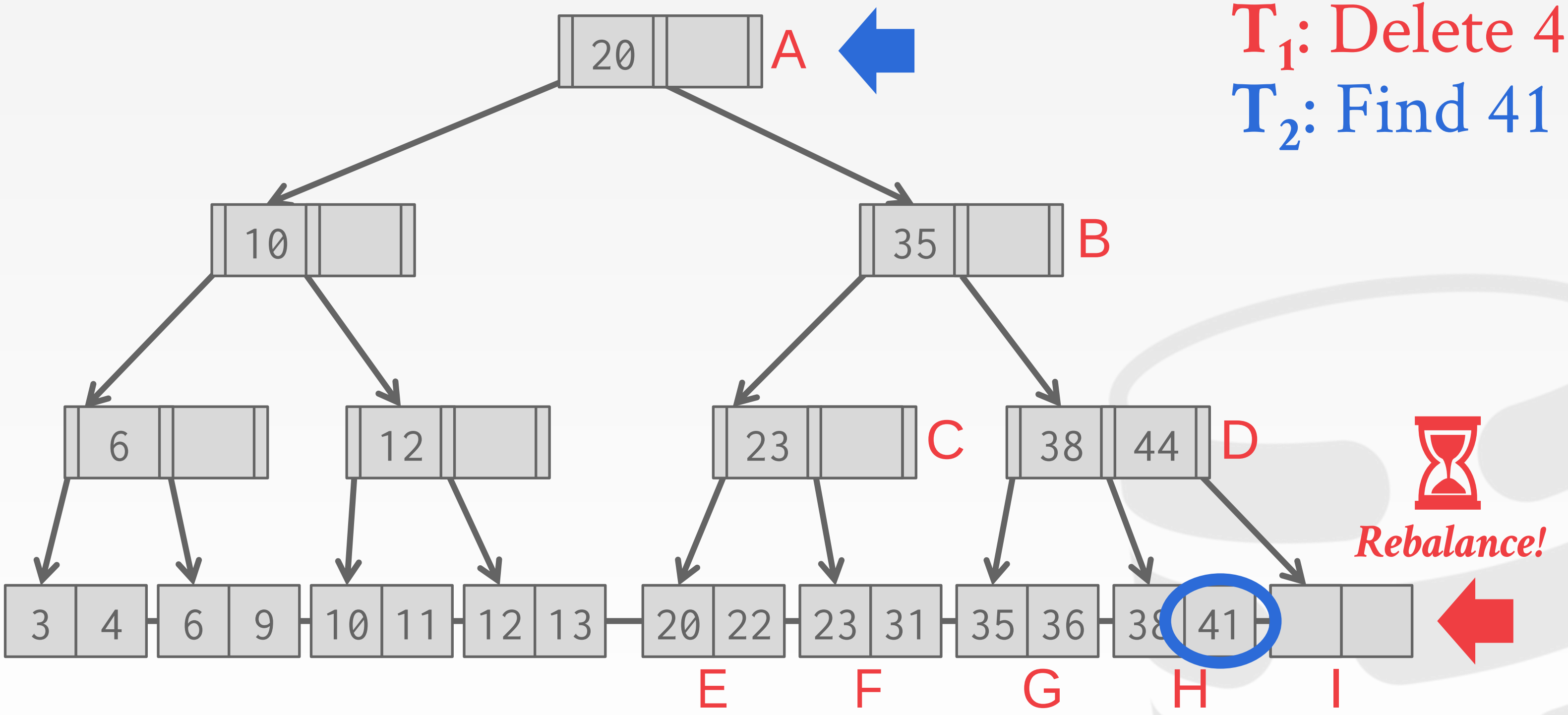

T_1: Delete 44

T_2: Find 41

B+TREE MULTI-THREADED EXAMPLE

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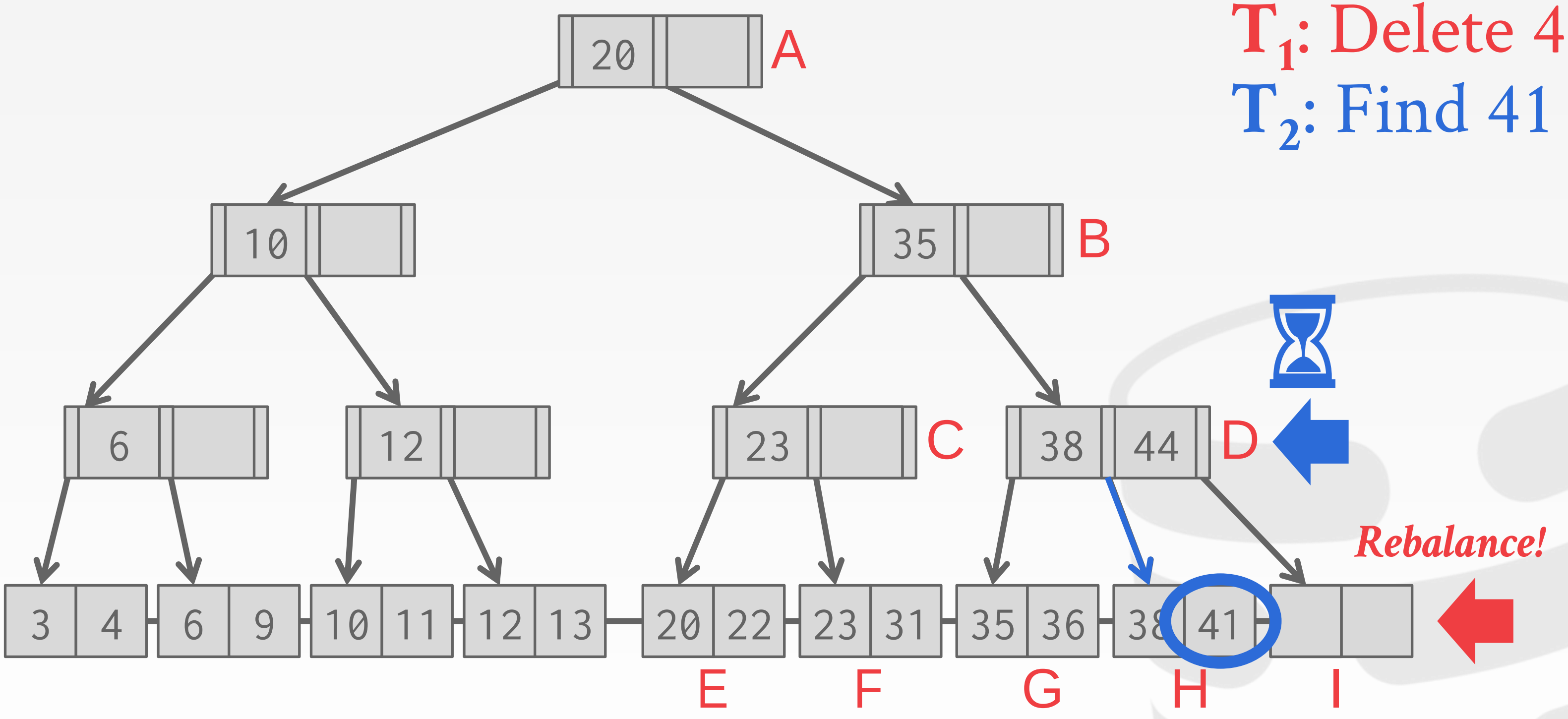
T_2: Find 41



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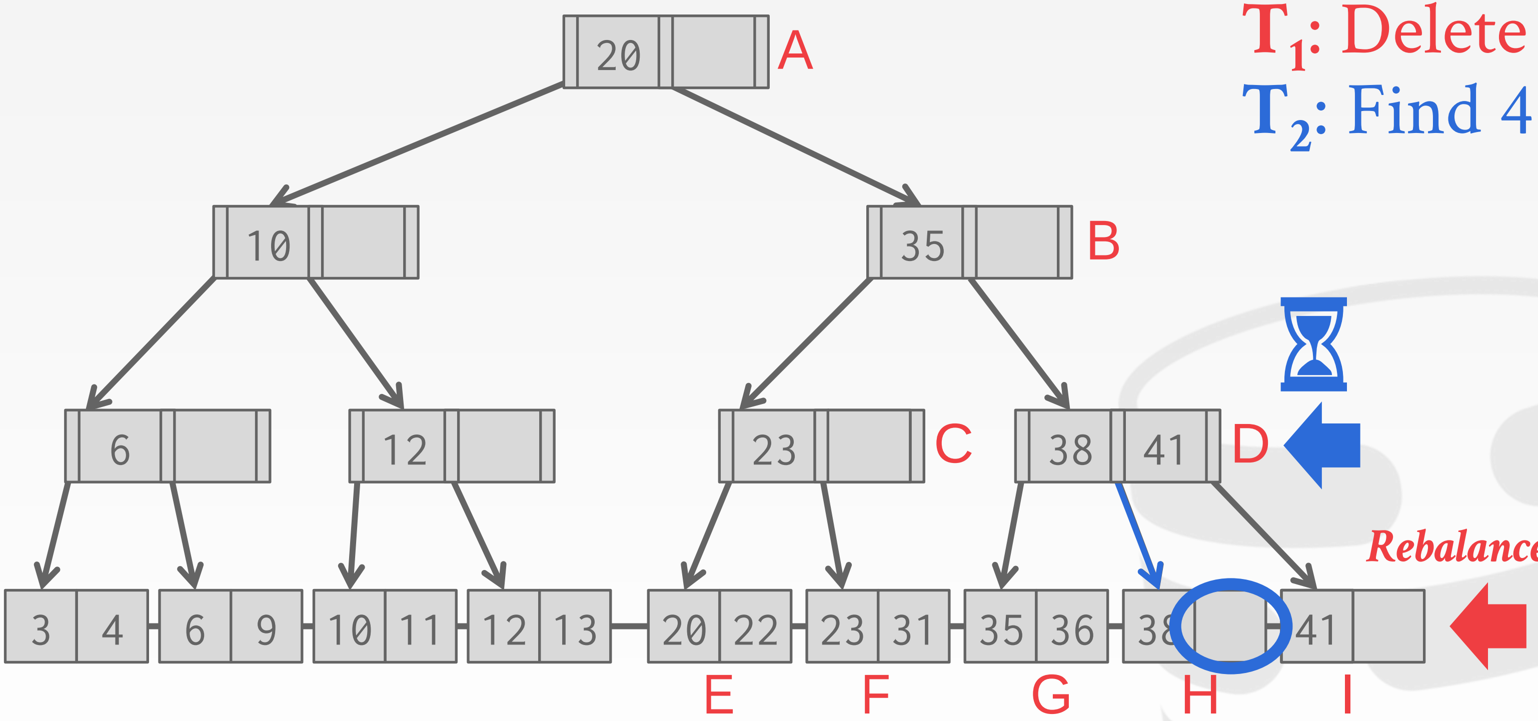
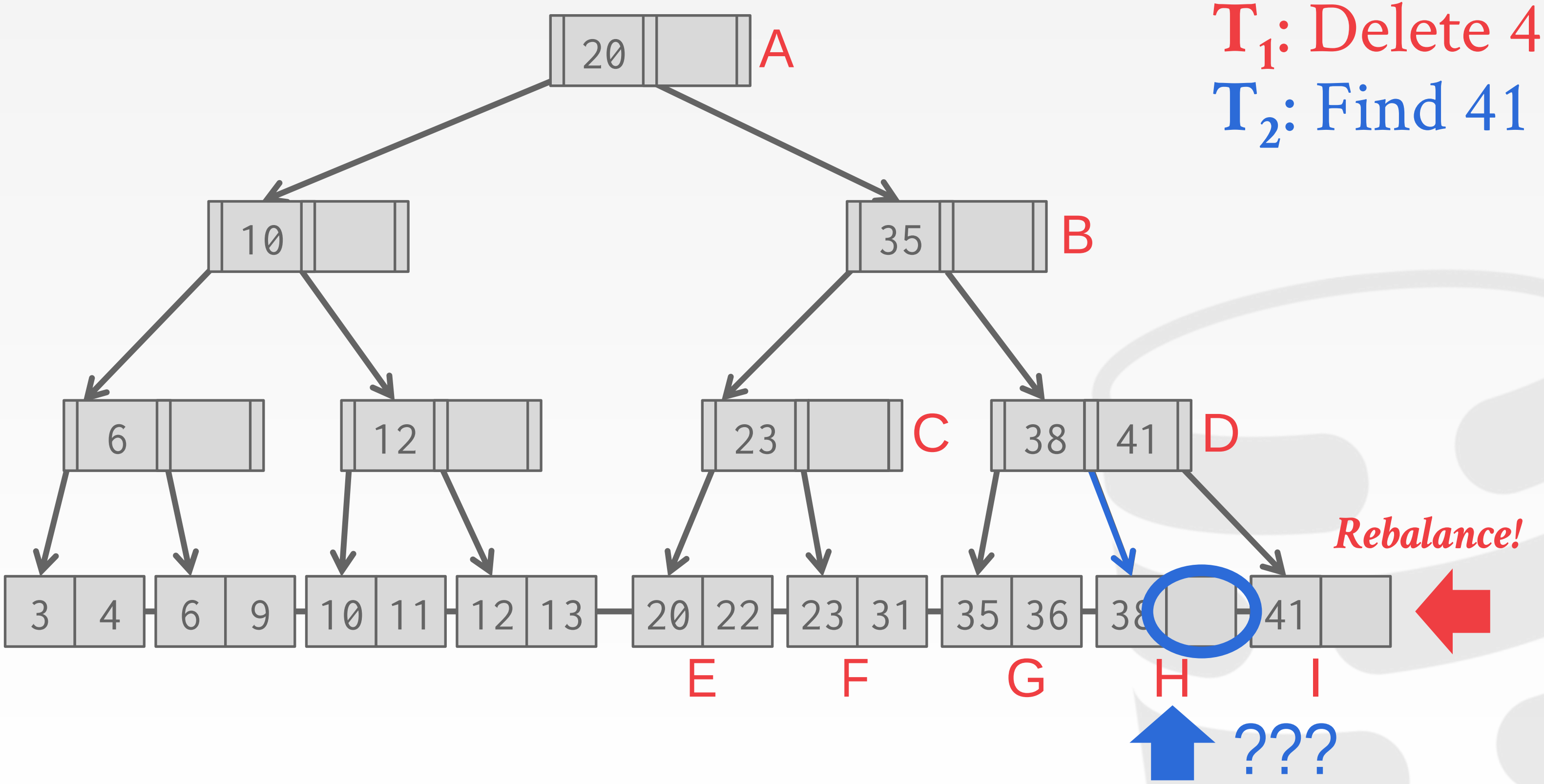
T_2: Find 41



B+TREE MULTI-THREADED EXAMPLE

T_1: Delete 44
T_2: Find 41



LATCH CRABBING/COUPLING

Protocol to allow multiple threads to access/modify B+Tree at the same time.

Basic Idea:

→ Get latch for parent.
→ Get latch for child
→ Release latch for parent if “safe”.

A **safe node** is one that will not split or merge when updated.

→ Not full (on insertion)
→ More than half-full (on deletion)

LATCH CRABBING/COUPLING

Find: Start at root and go down; repeatedly,

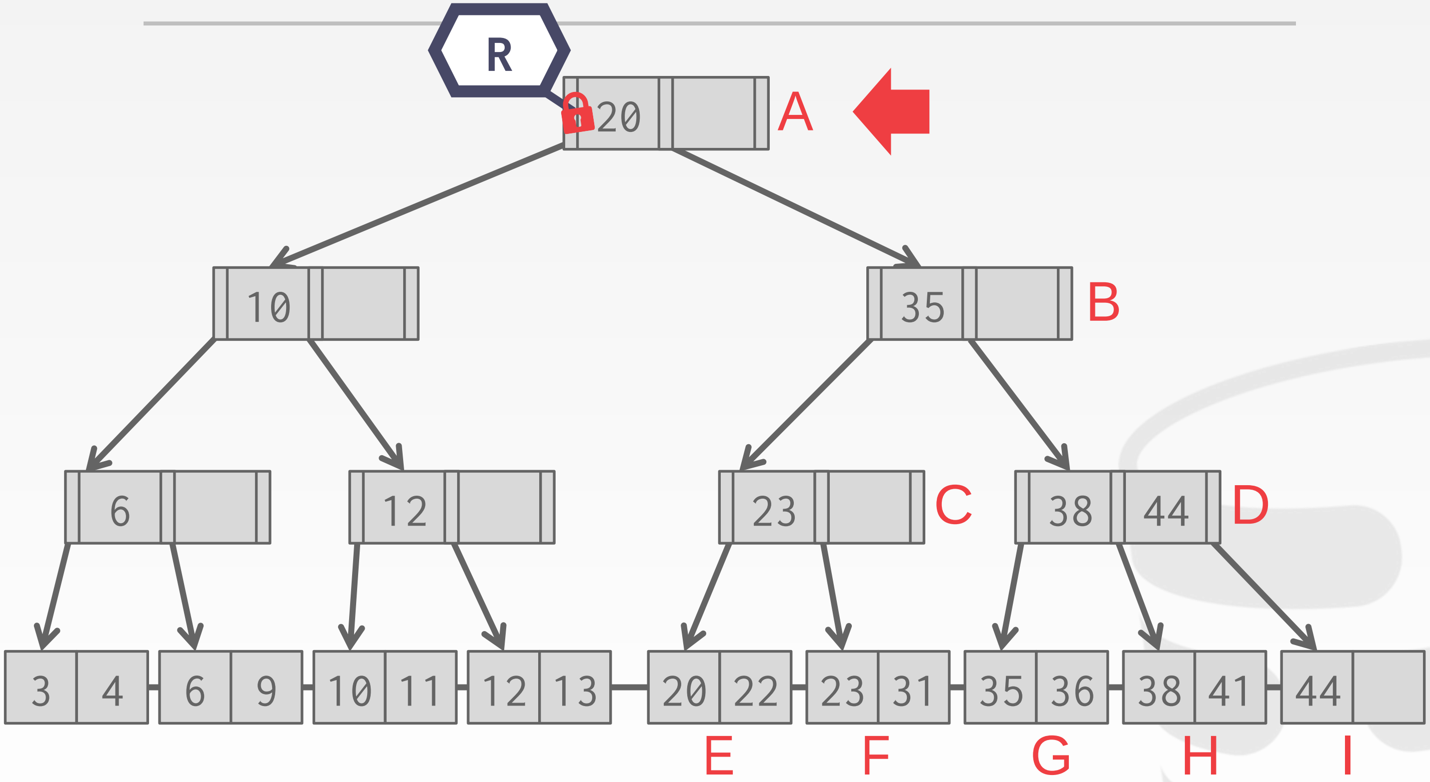
→ Acquire **R** latch on child

→ Then unlatch parent

Insert/Delete: Start at root and go down, obtaining **W** latches as needed. Once child is latched, check if it is safe:

→ If child is safe, release all latches on ancestors.

EXAMPLE #1 – FIND 38



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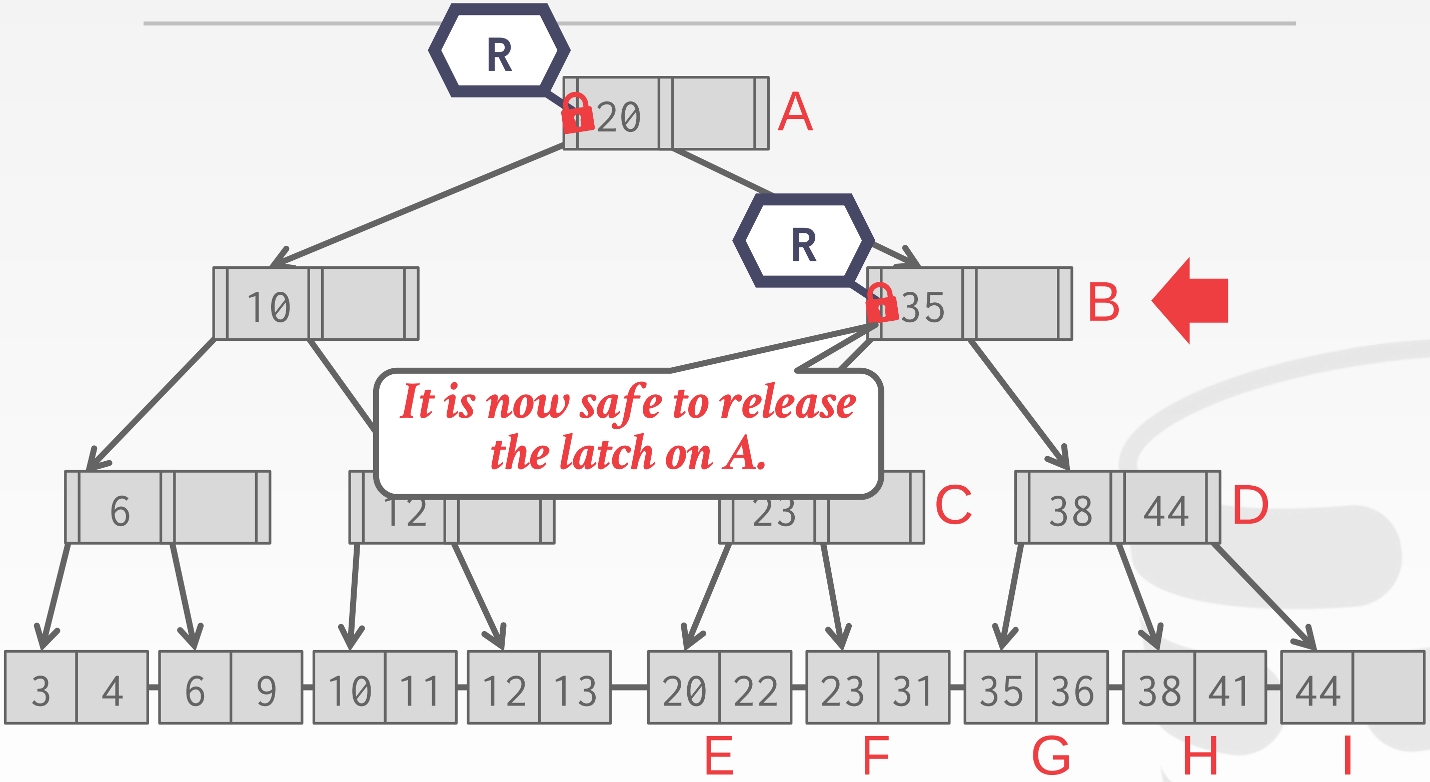

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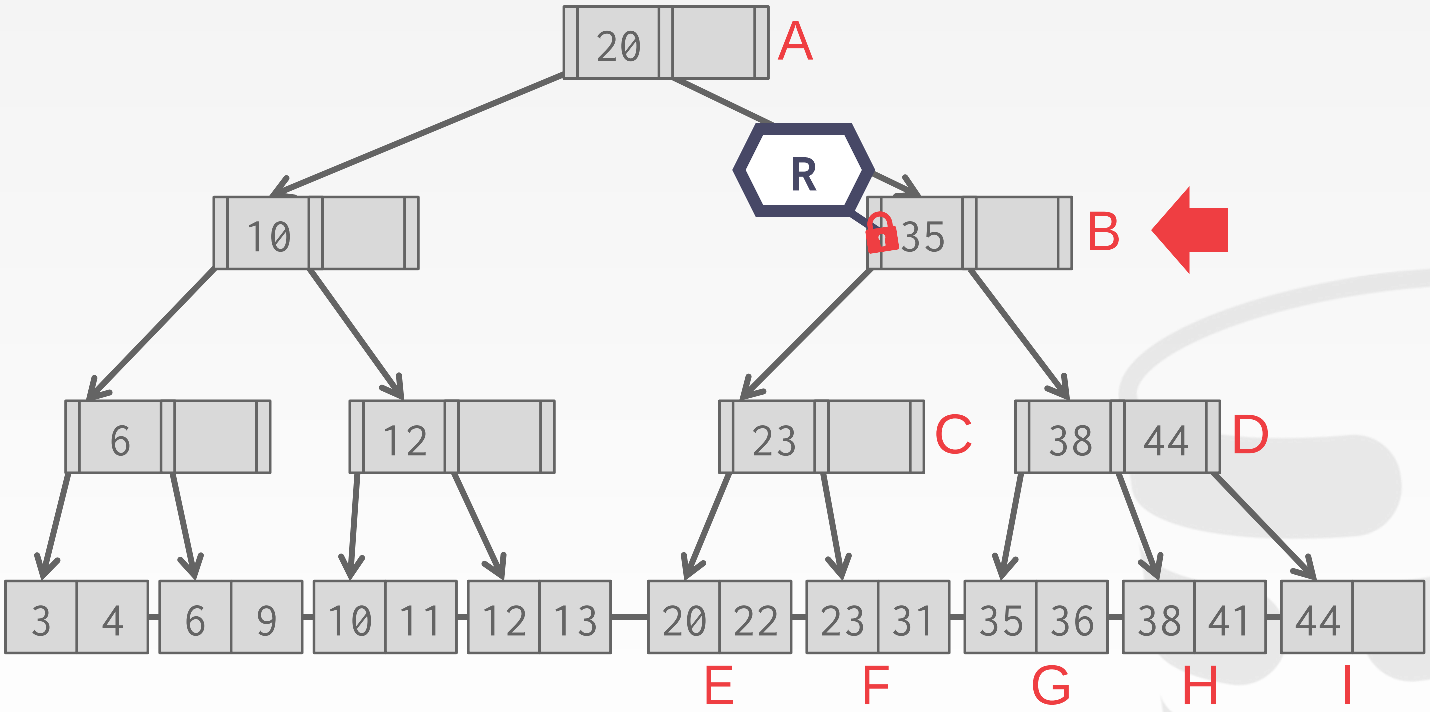

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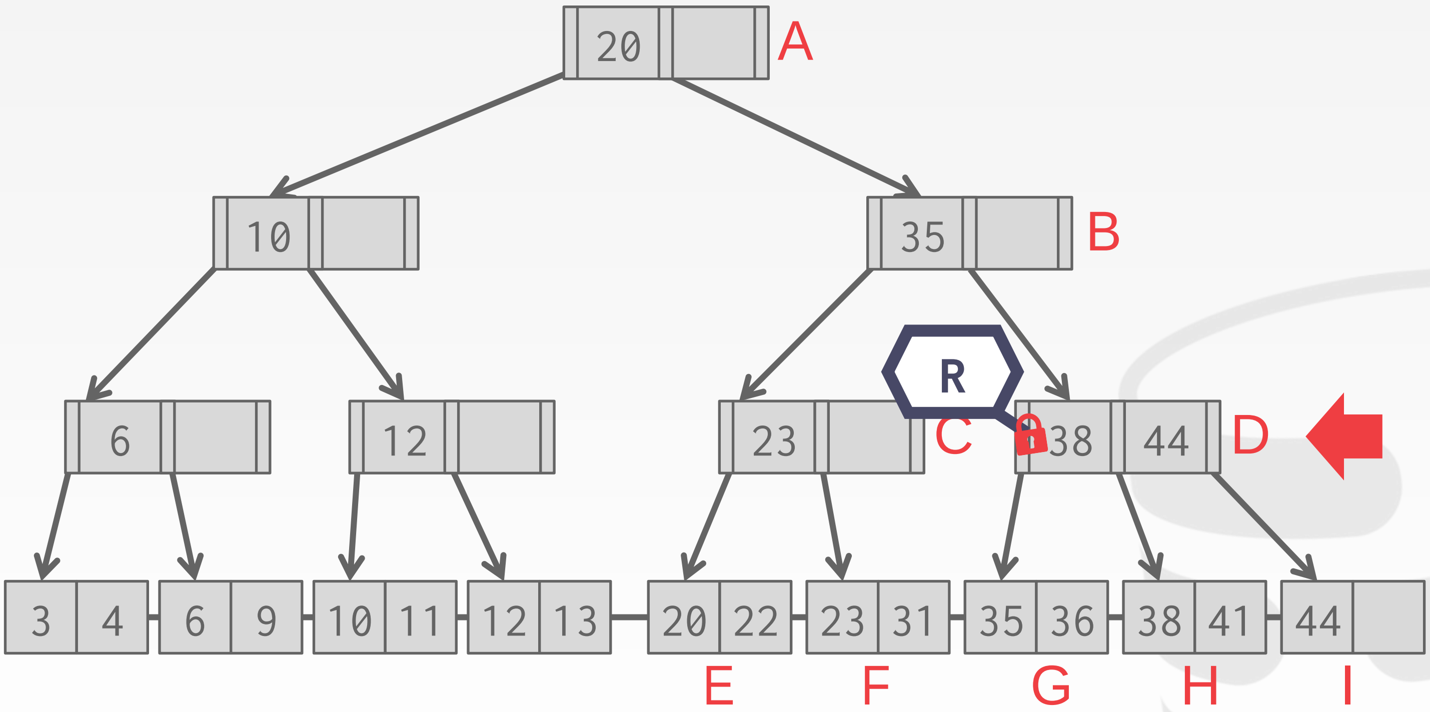

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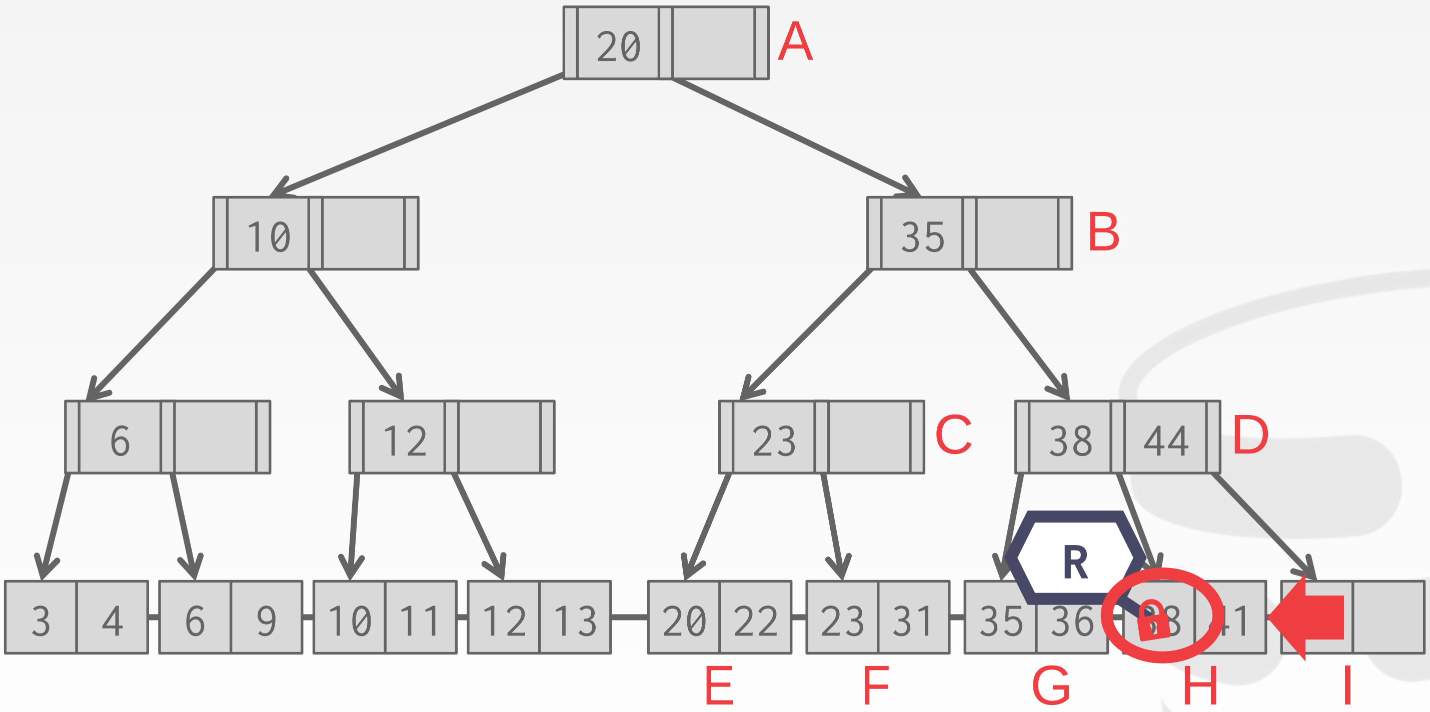

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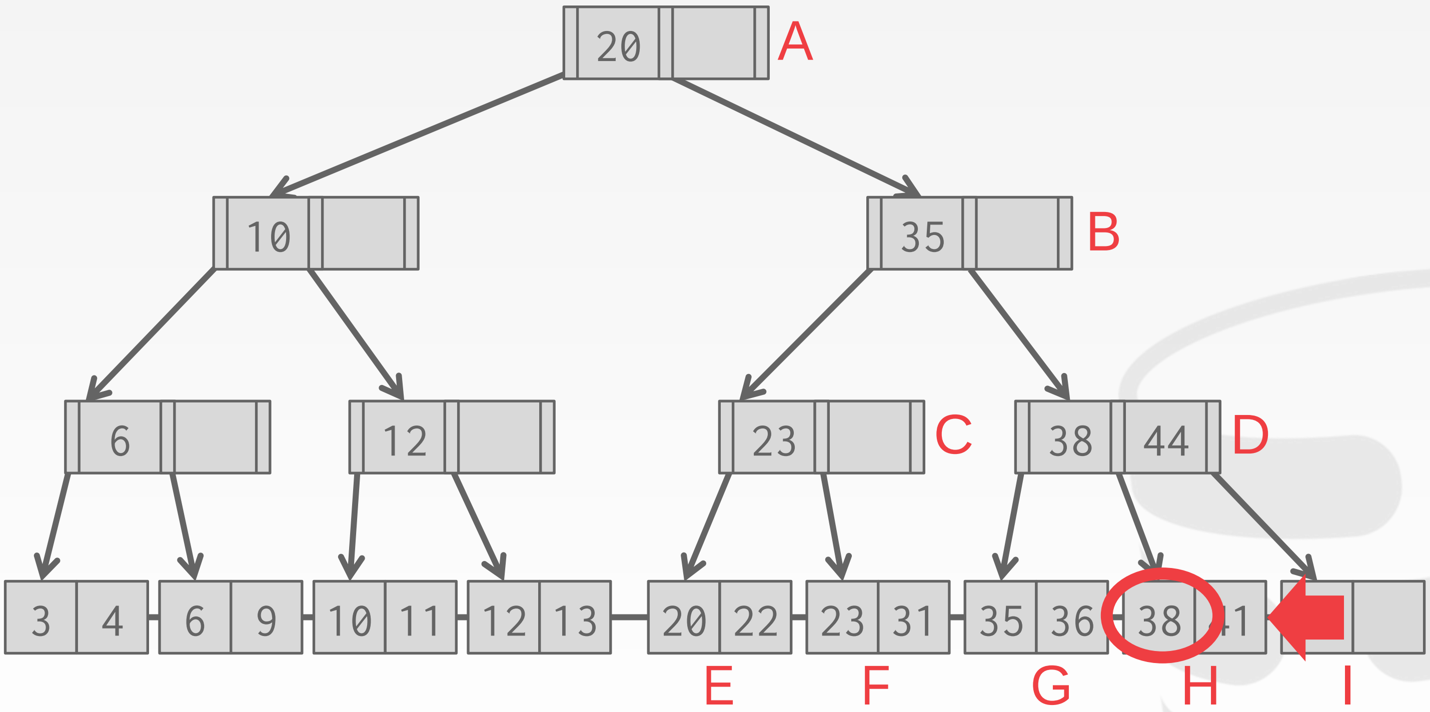
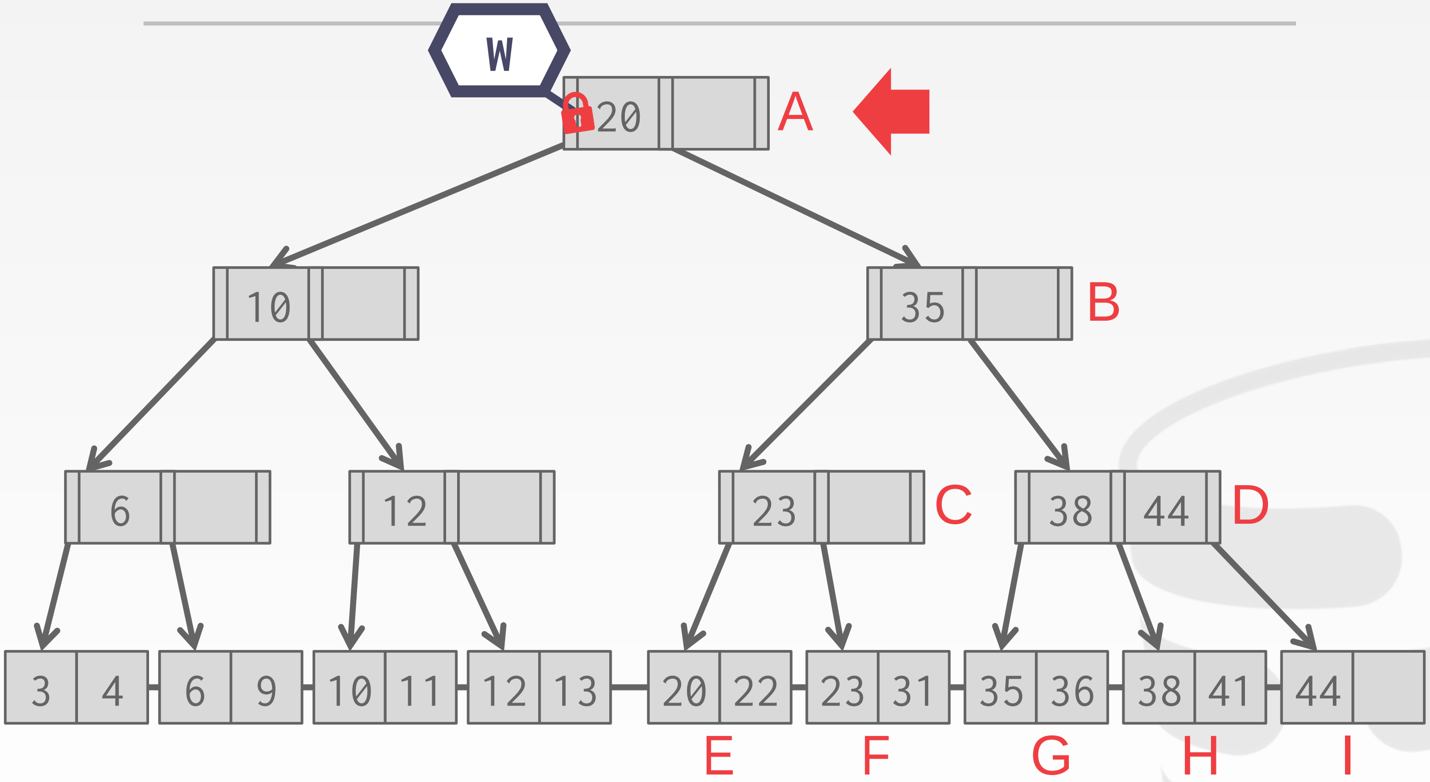


EXAMPLE #2 – DELETE 38



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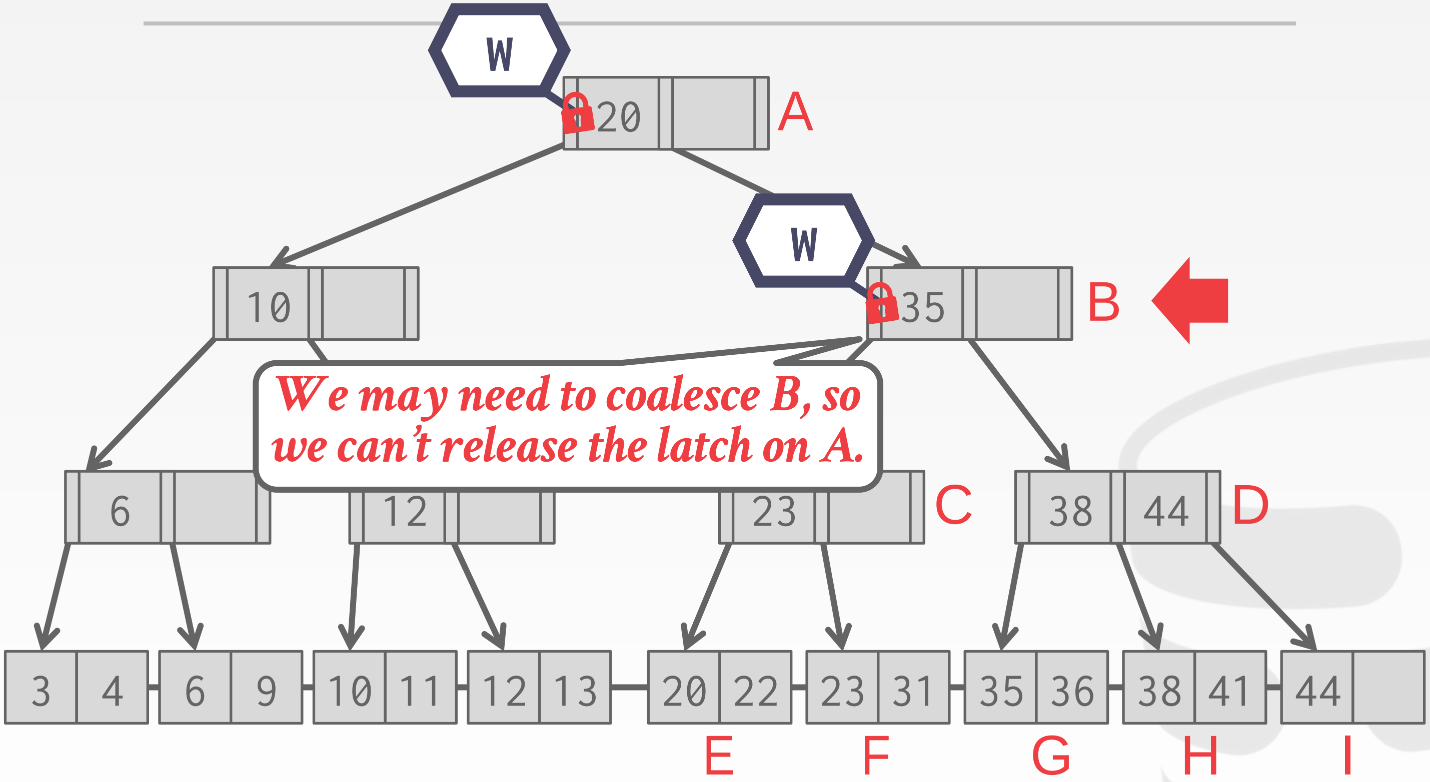

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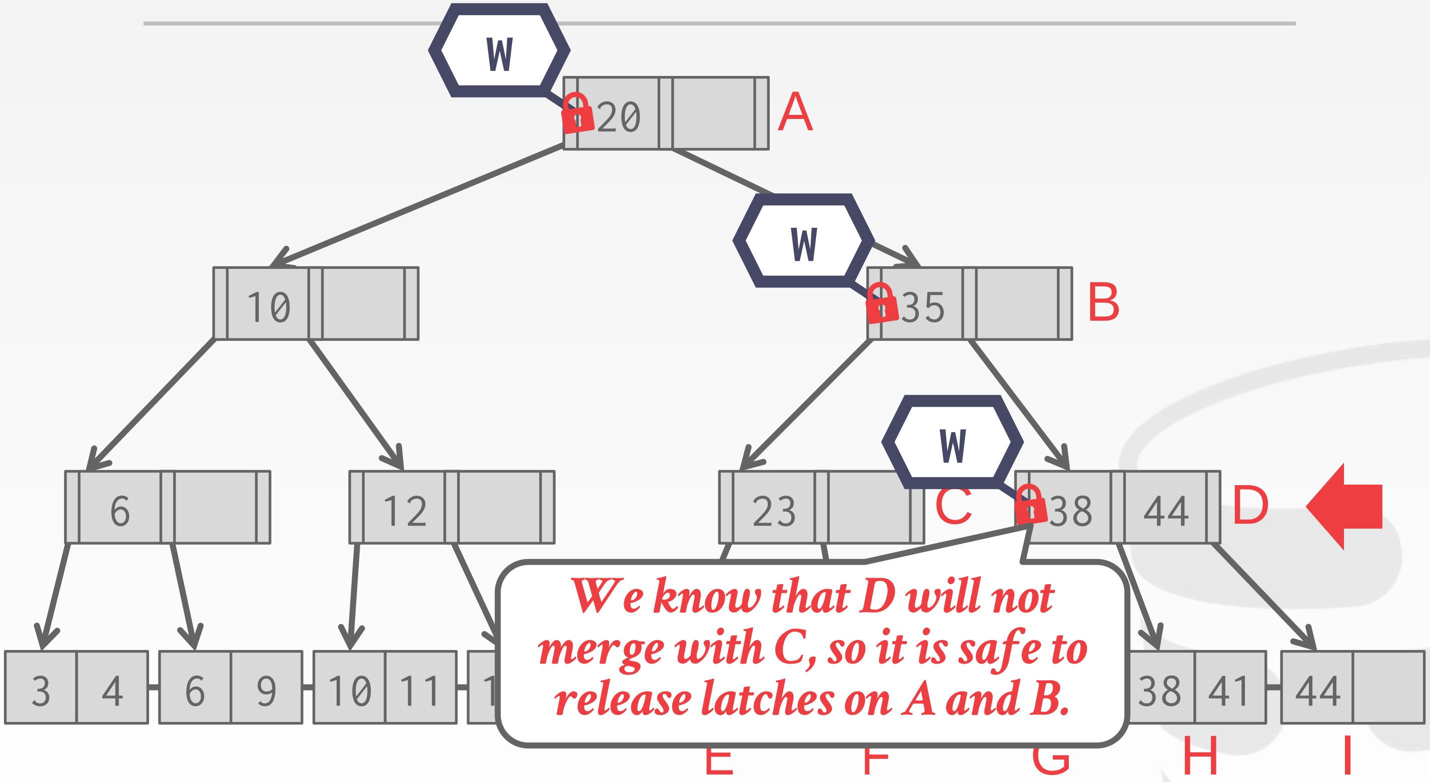

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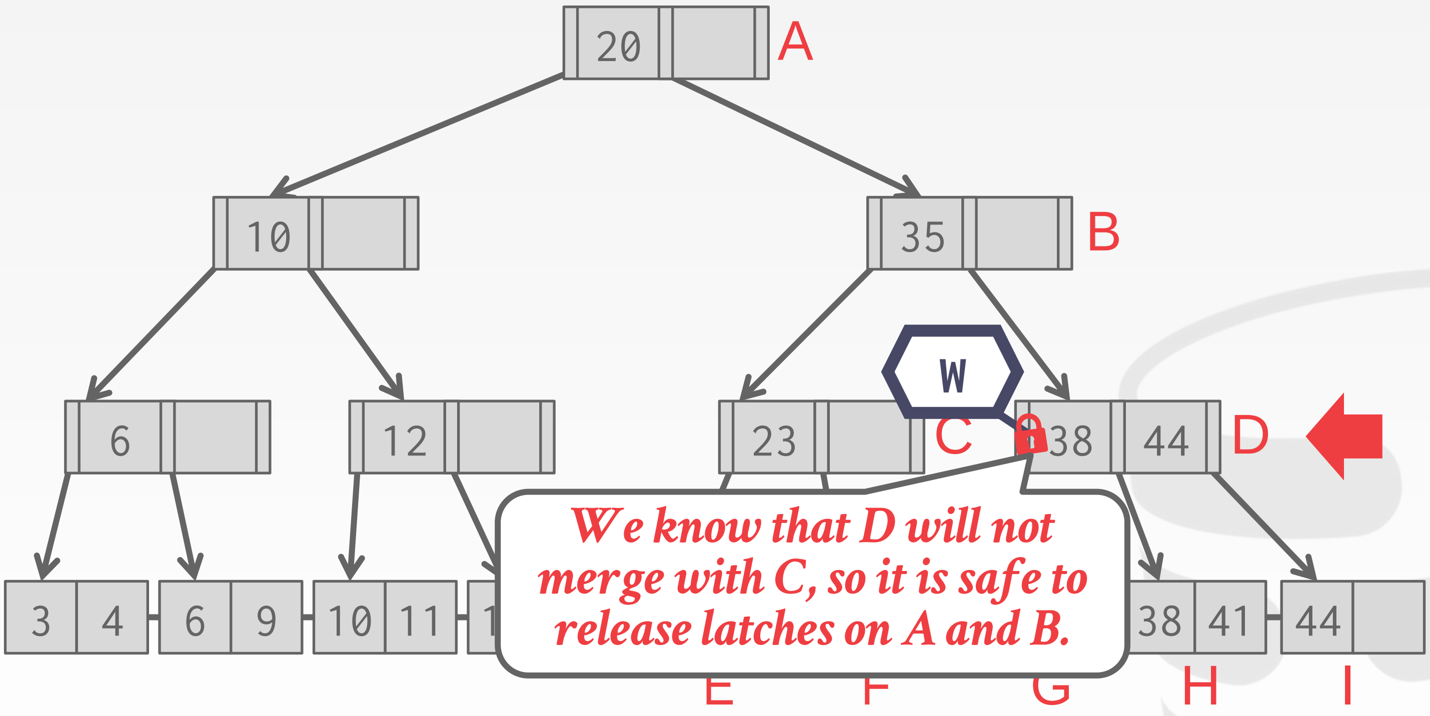
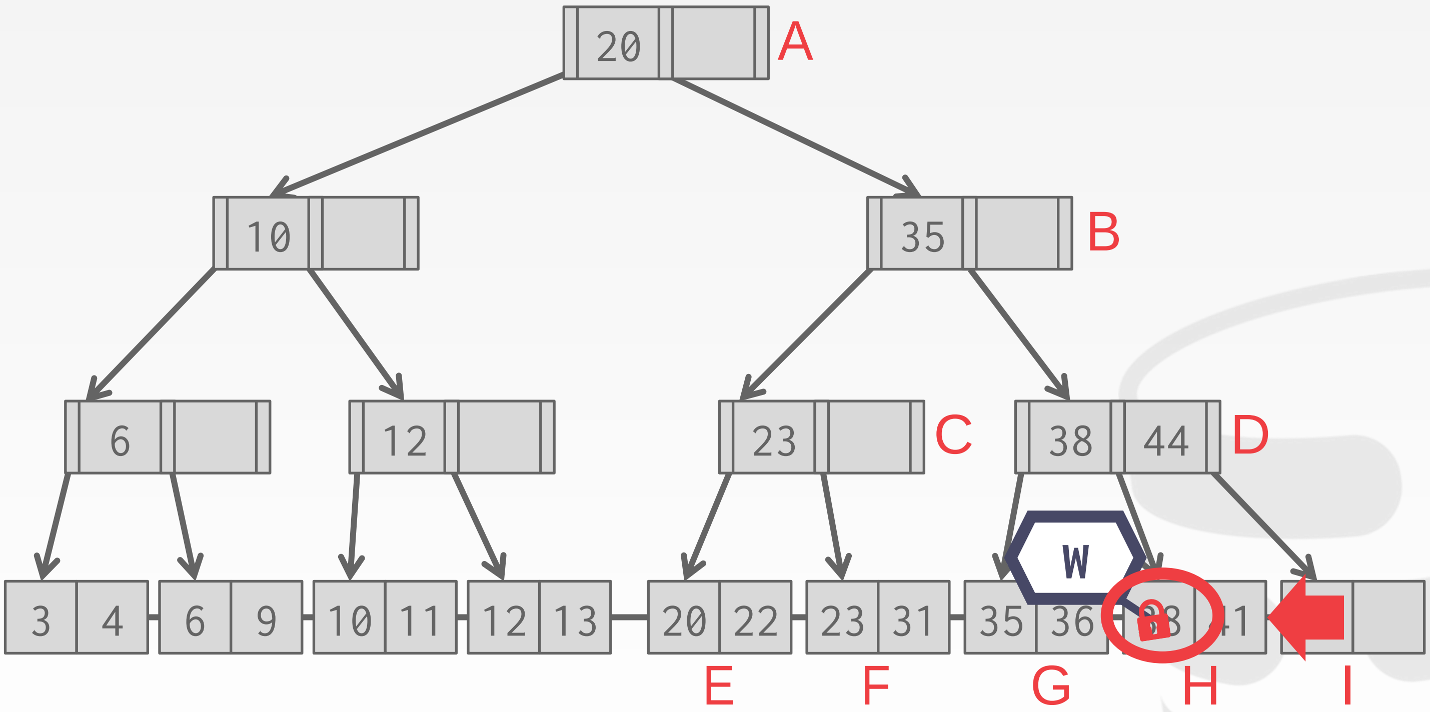
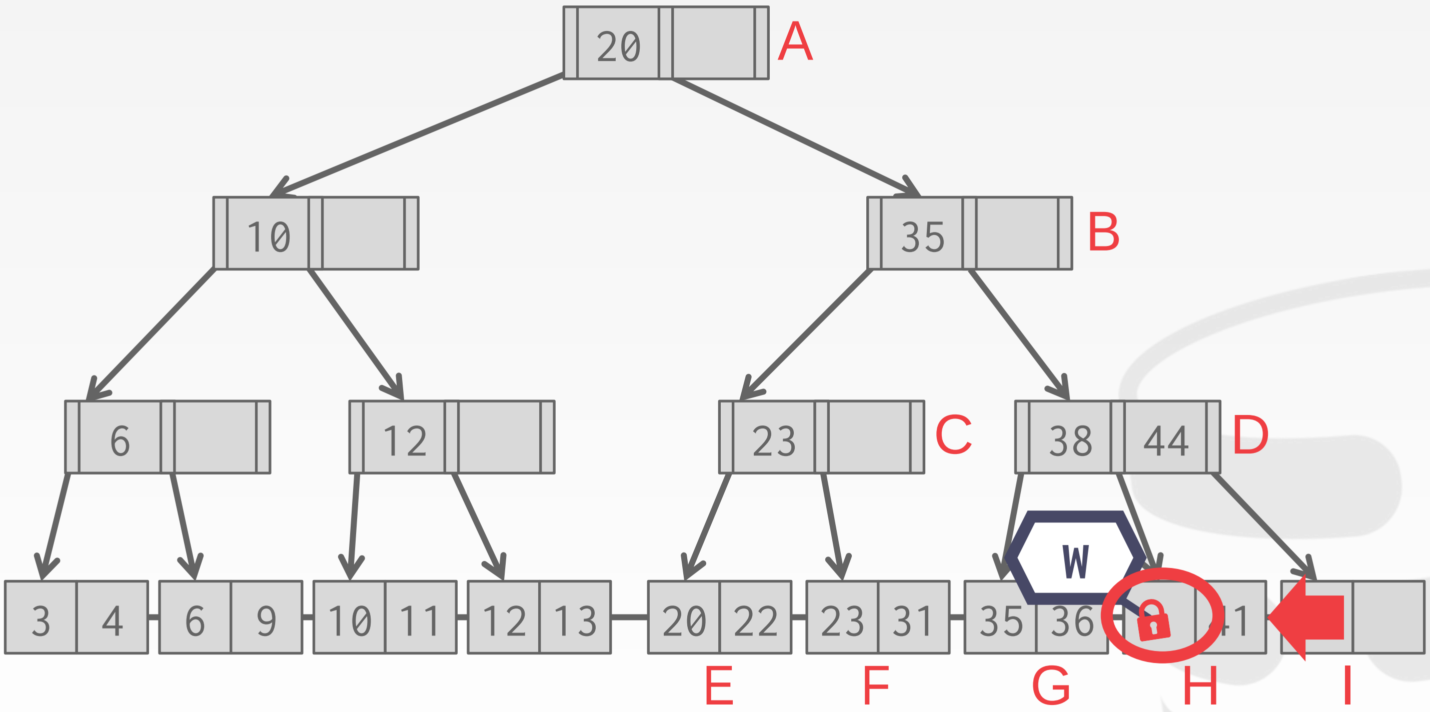


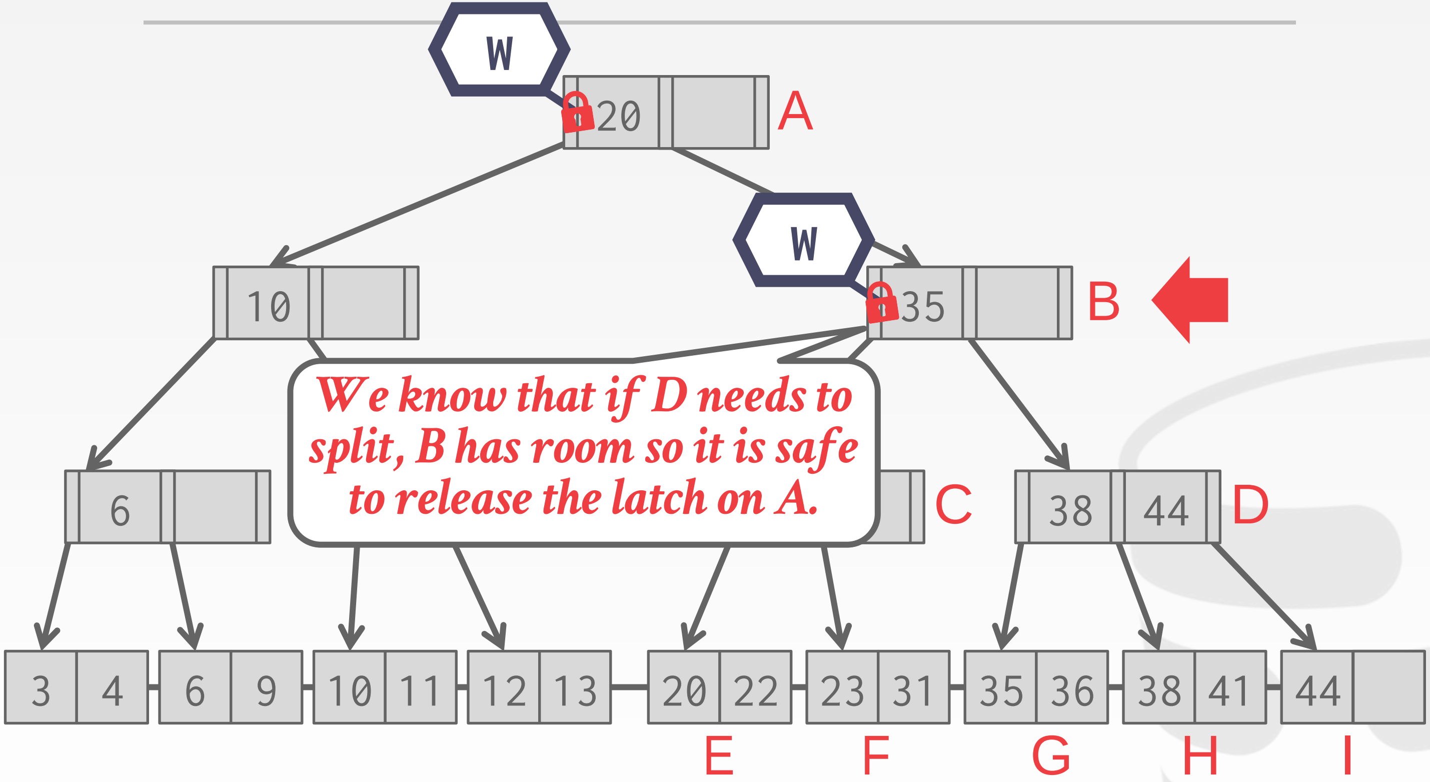
EXAMPLE #2 – DELETE 38



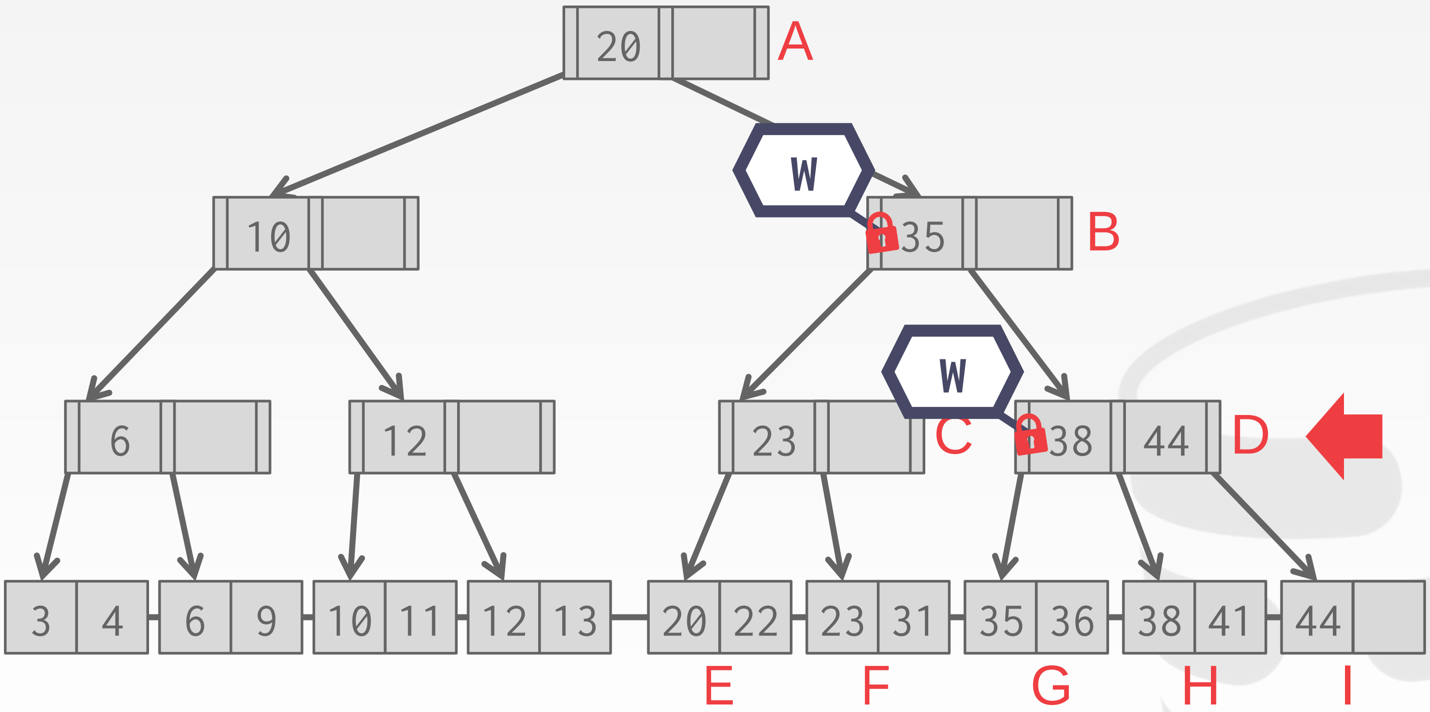
EXAMPLE #2 – DELETE 38



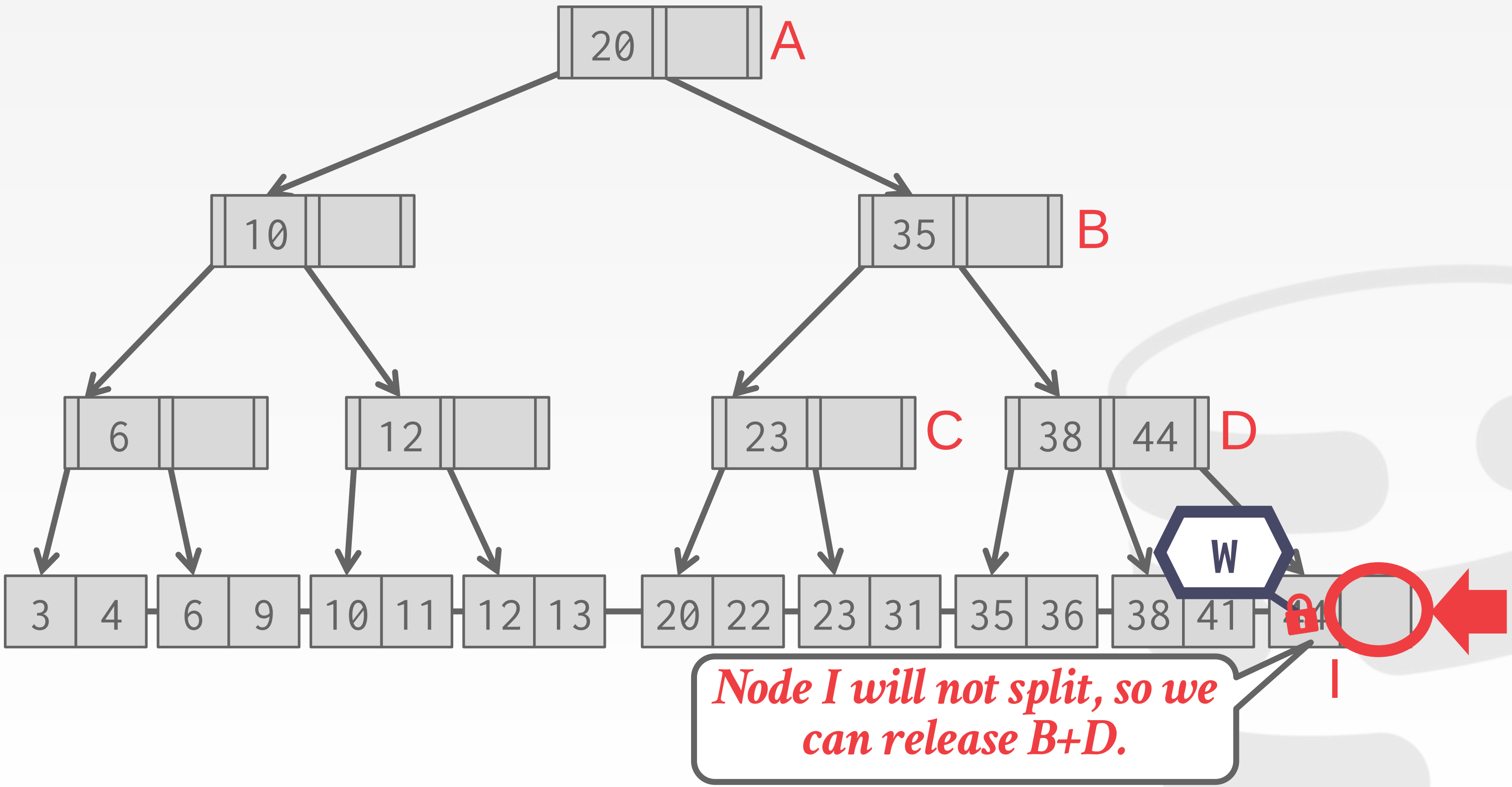
EXAMPLE #3 – INSERT 45



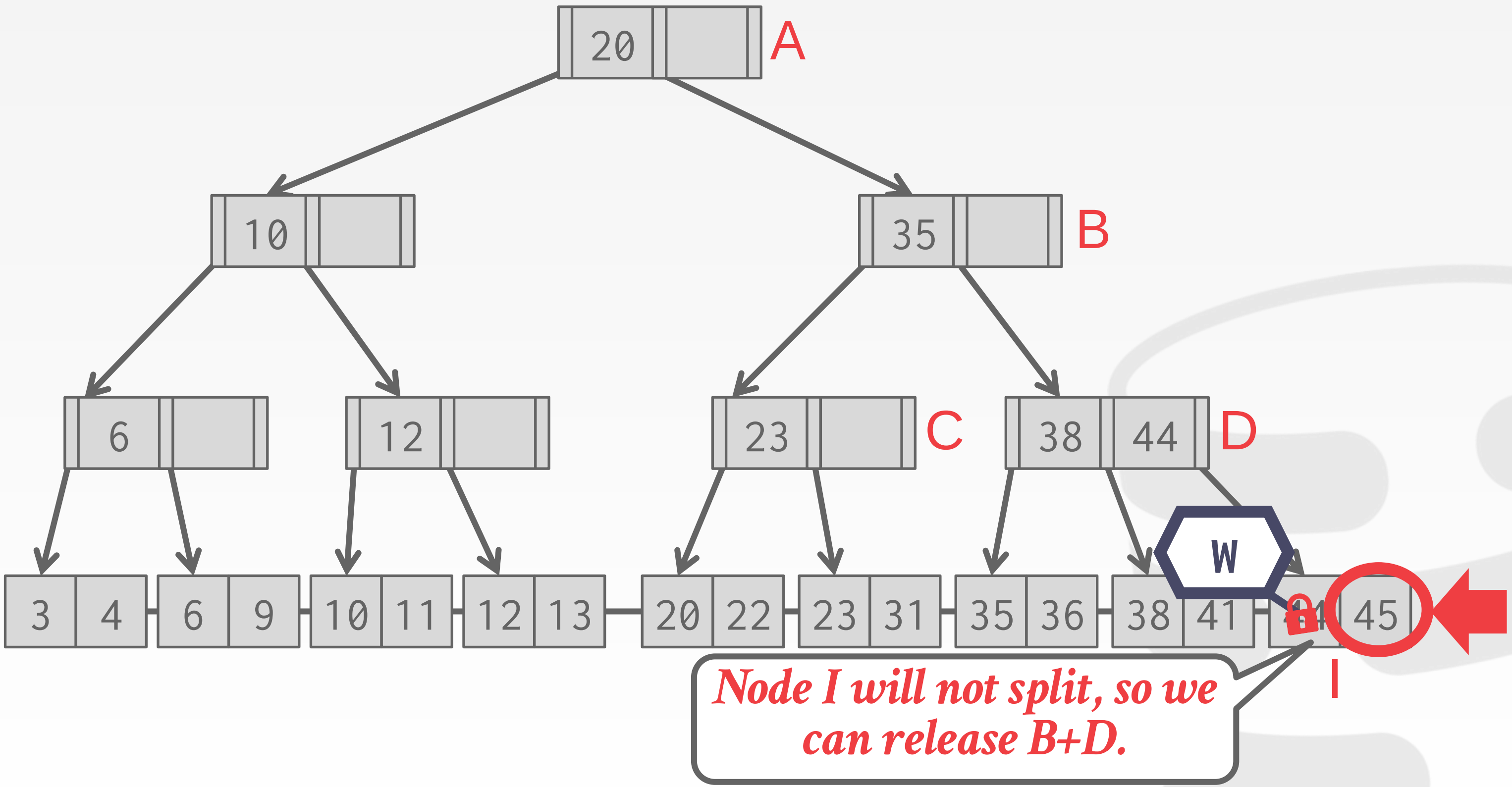
EXAMPLE #3 – INSERT 45



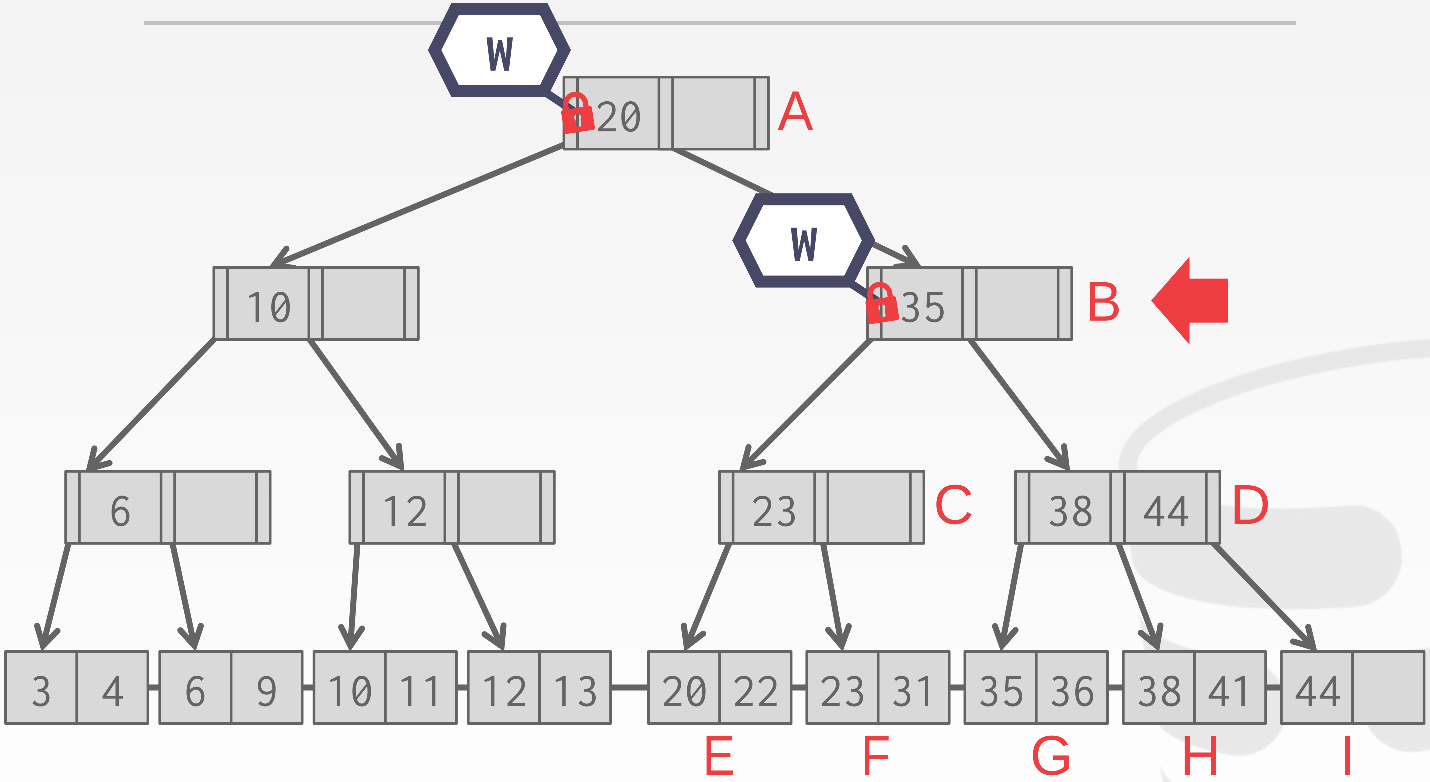
EXAMPLE #3 – INSERT 45



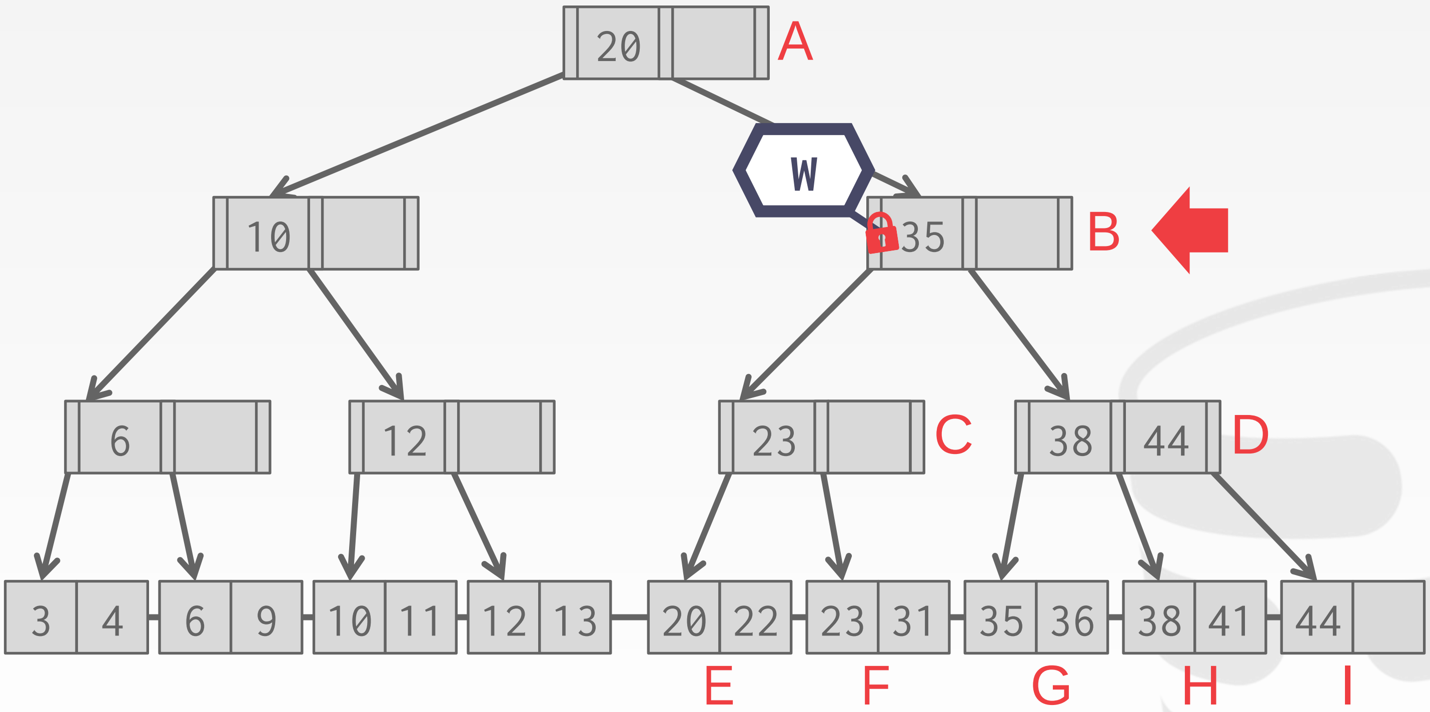
EXAMPLE #3 – INSERT 45



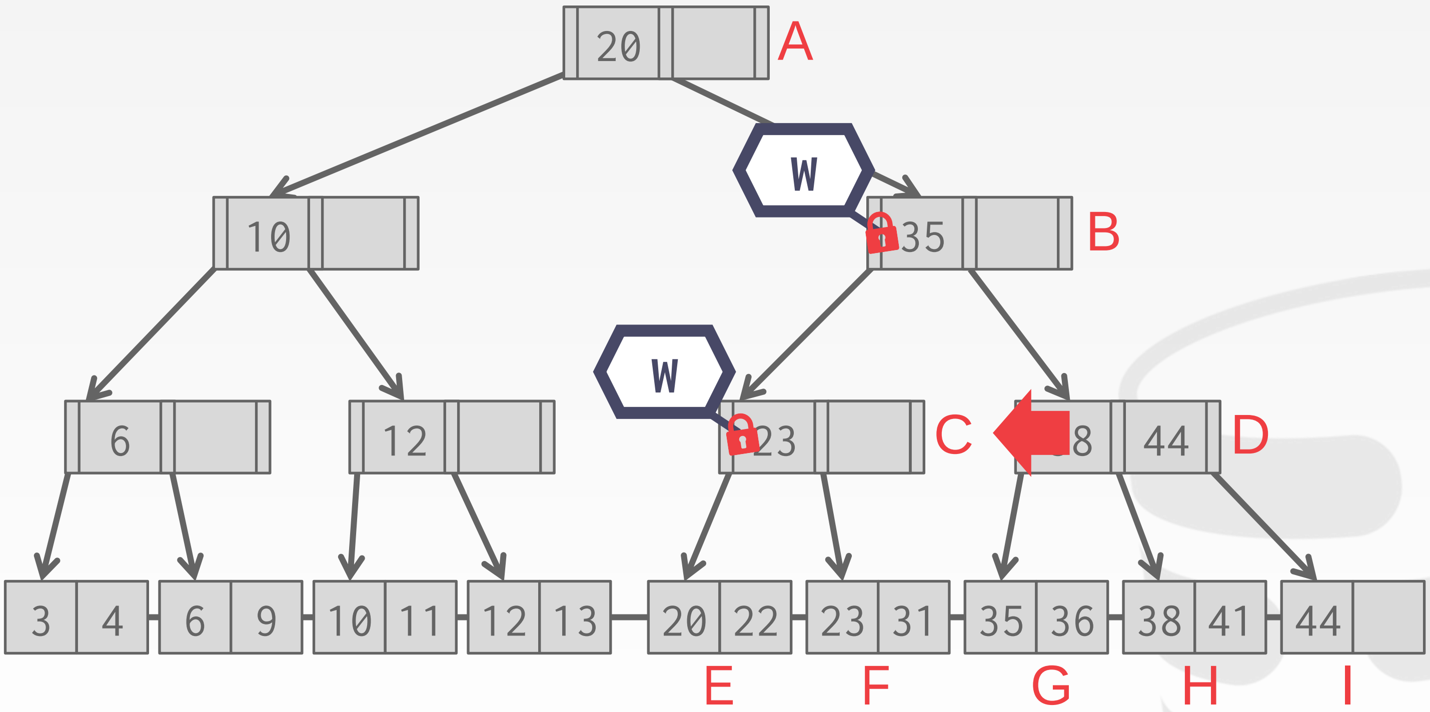
EXAMPLE #4 – INSERT 25



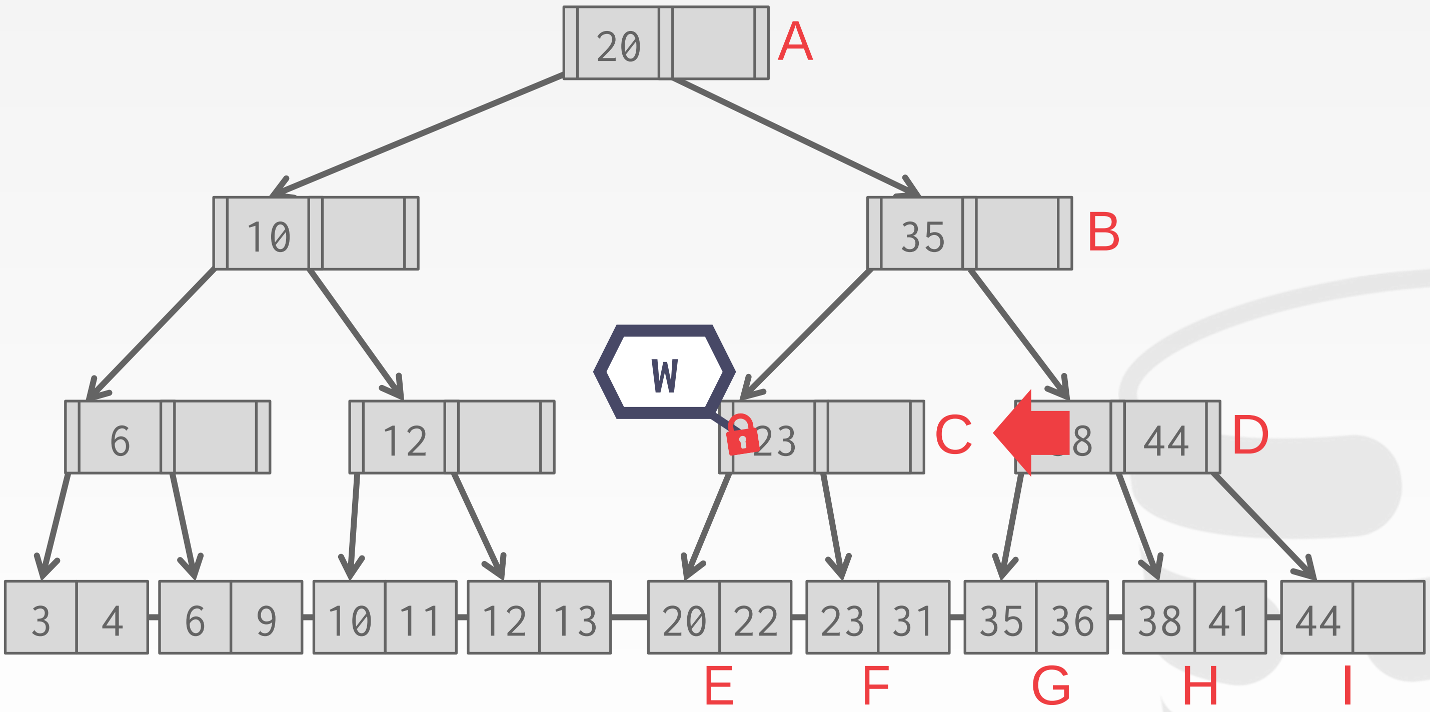
EXAMPLE #4 – INSERT 25



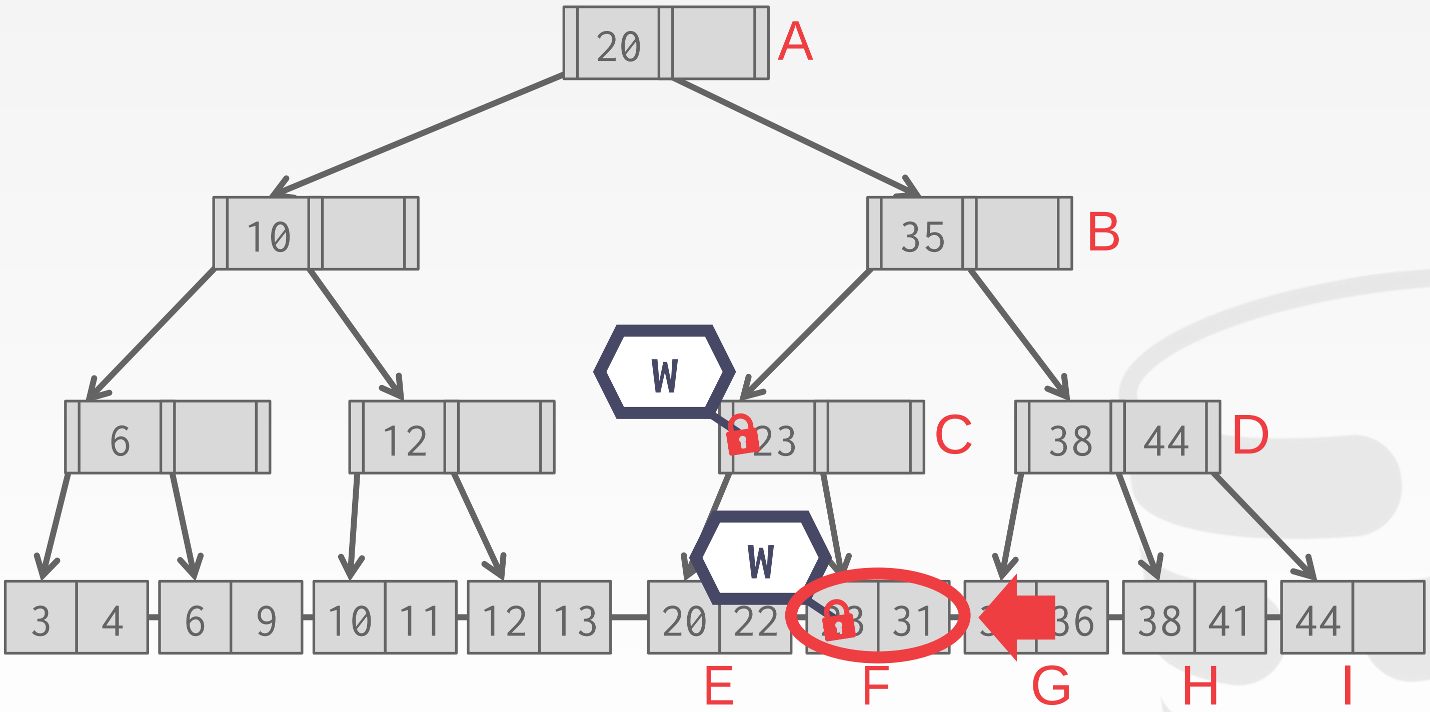
EXAMPLE #4 – INSERT 25



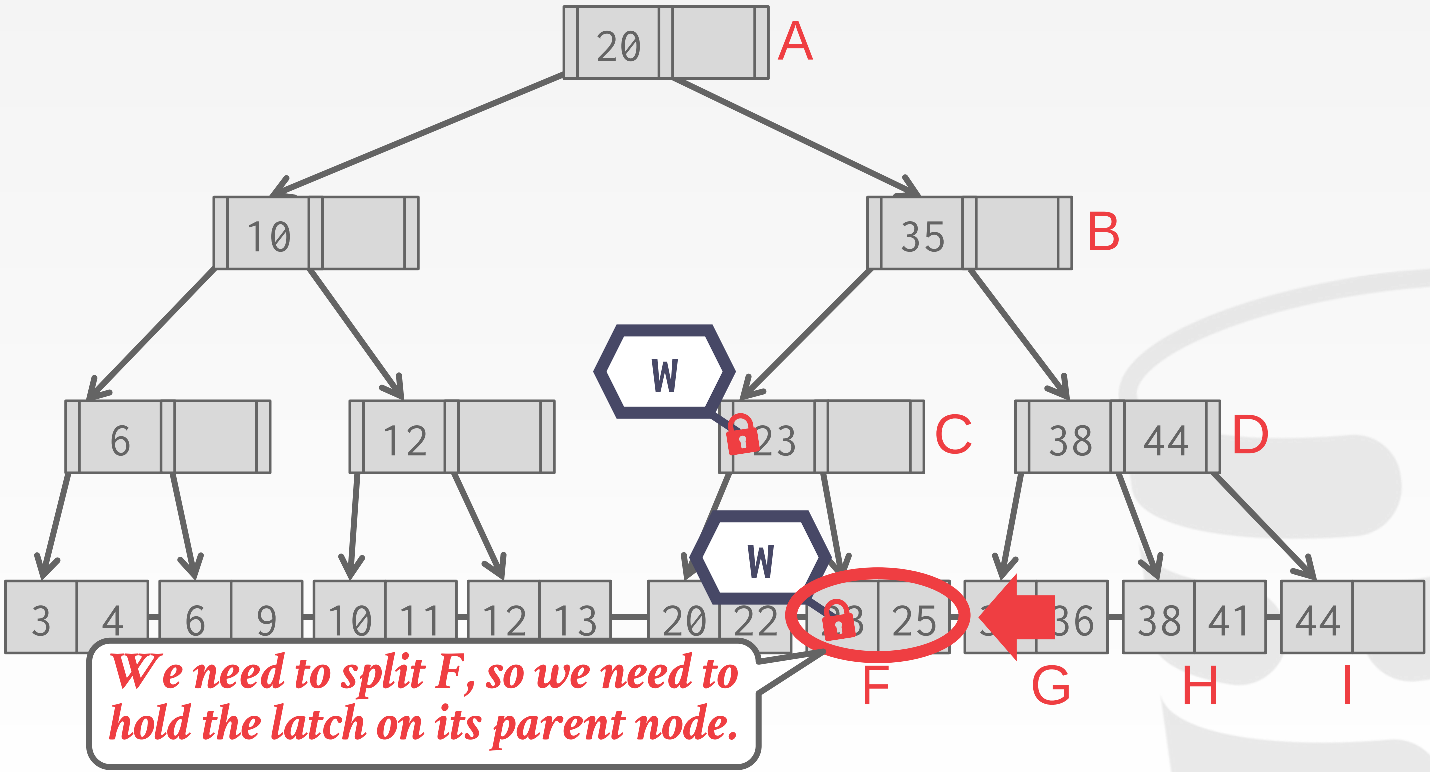
EXAMPLE #4 – INSERT 25



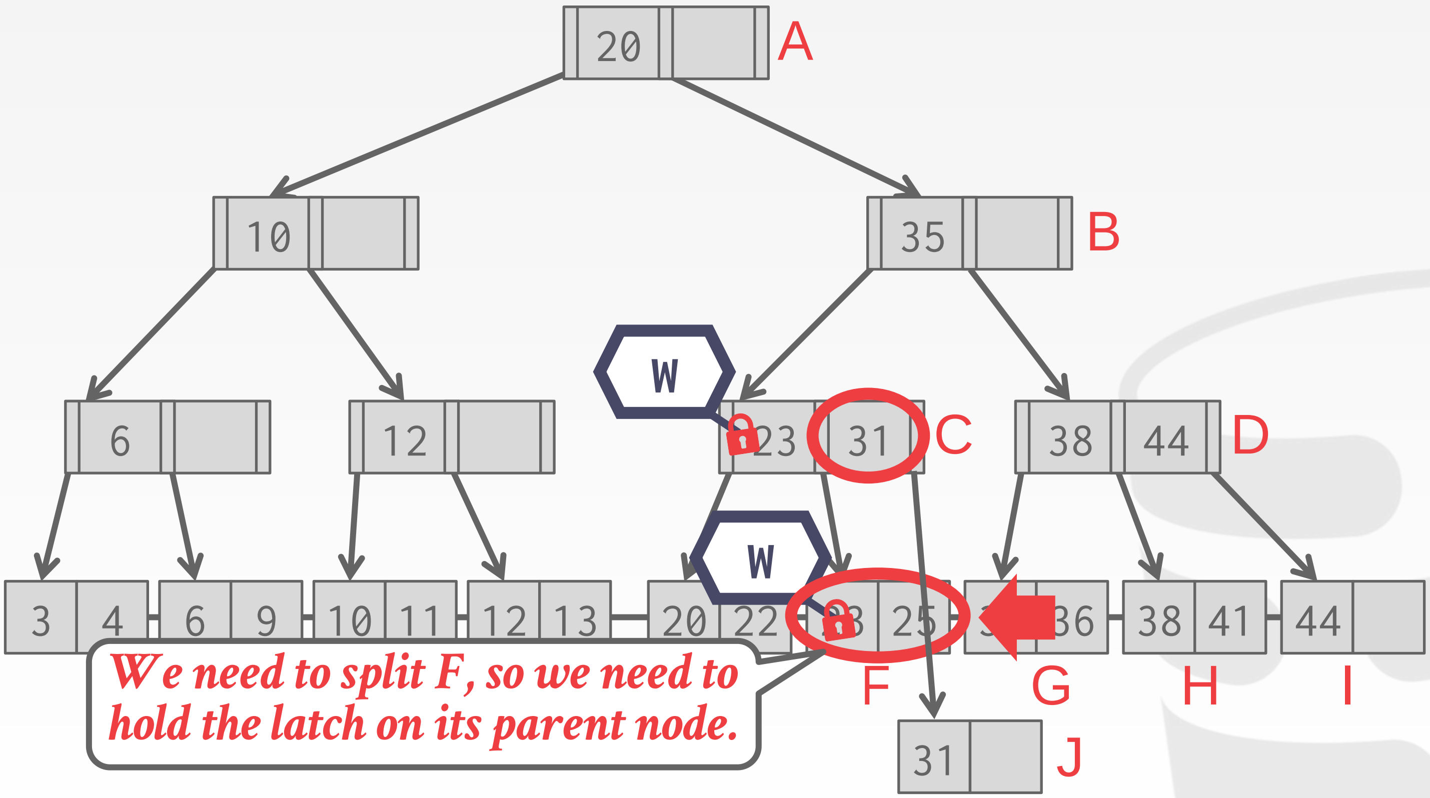
EXAMPLE #4 – INSERT 25



EXAMPLE #4 – INSERT 25



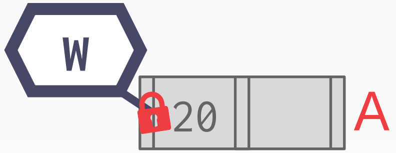
EXAMPLE #4 – INSERT 25



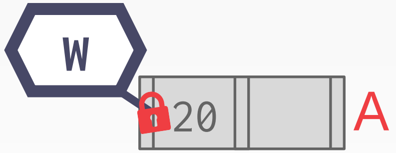
OBSERVATION

What was the first step that all the update examples did on the B+Tree?

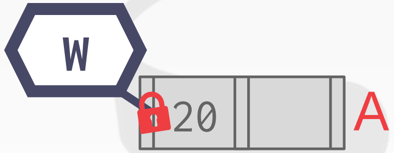
Delete 38



Insert 45



Insert 25



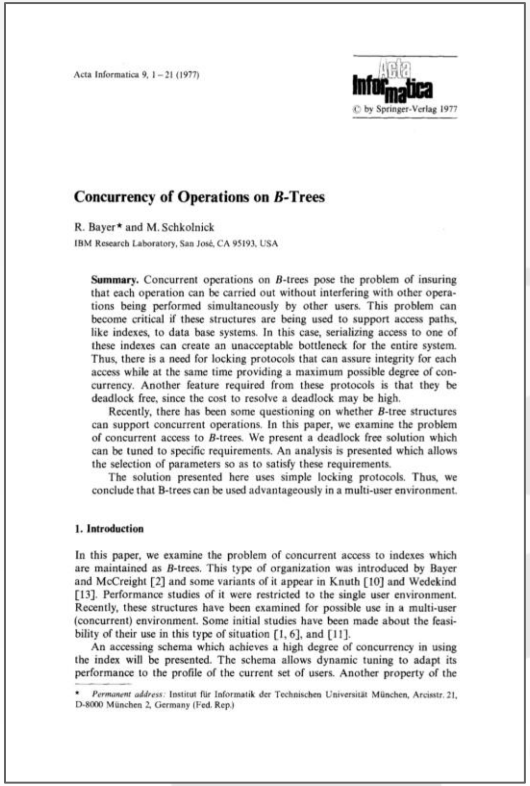
Taking a write latch on the root every time becomes a bottleneck with higher concurrency.

BETTER LATCHING ALGORITHM

Most modifications to a B+Tree will not require a split or merge.

Instead of assuming that there will be a split/merge, optimistically traverse the tree using read latches.

If you guess wrong, repeat traversal with the pessimistic algorithm.



Acta Informatica 9, 1 – 21 (1977)

Acta Informatica
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Concurrency of Operations on *B*-Trees

R. Bayer* and M. Schkolnick
IBM Research Laboratory, San José, CA 95193, USA

Summary. Concurrent operations on *B*-trees pose the problem of insuring that each operation can be carried out without interfering with other operations being performed simultaneously by other users. This problem can become critical if these structures are being used to support access paths, like indexes, to data base systems. In this case, serializing access to one of these indexes can create an unacceptable bottleneck for the entire system. Thus, there is a need for locking protocols that can assure integrity for each access while at the same time providing a maximum possible degree of concurrency. Another feature required from these protocols is that they be deadlock free, since the cost to resolve a deadlock may be high.

Recently, there has been some questioning on whether *B*-tree structures can support concurrent operations. In this paper, we examine the problem of concurrent access to *B*-trees. We present a deadlock free solution which can be tuned to specific requirements. An analysis is presented which allows the selection of parameters so as to satisfy these requirements.

The solution presented here uses simple locking protocols. Thus, we conclude that B-trees can be used advantageously in a multi-user environment.

1. Introduction

In this paper, we examine the problem of concurrent access to indexes which are maintained as *B*-trees. This type of organization was introduced by Bayer and McCreight [2] and some variants of it appear in Knuth [10] and Wedekind [13]. Performance studies of it were restricted to the single user environment. Recently, these structures have been examined for possible use in a multi-user (concurrent) environment. Some initial studies have been made about the feasibility of their use in this type of situation [1, 6], and [11].

An accessing schema which achieves a high degree of concurrency in using the index will be presented. The schema allows dynamic tuning to adapt its performance to the profile of the current set of users. Another property of the

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BETTER LATCHING ALGORITHM

Search: Same as before.

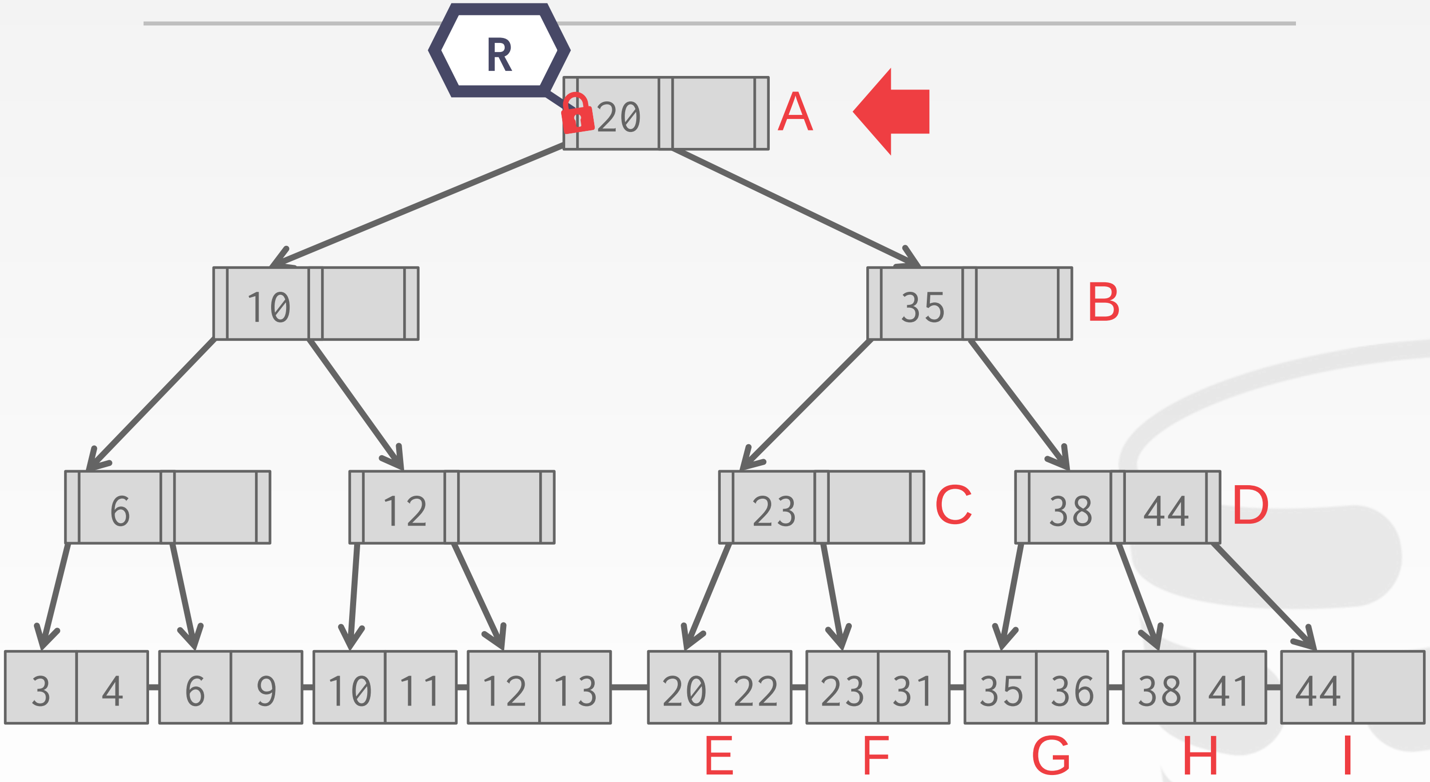
Insert/Delete:

→ Set latches as if for search, get to leaf, and set **W** latch on leaf.

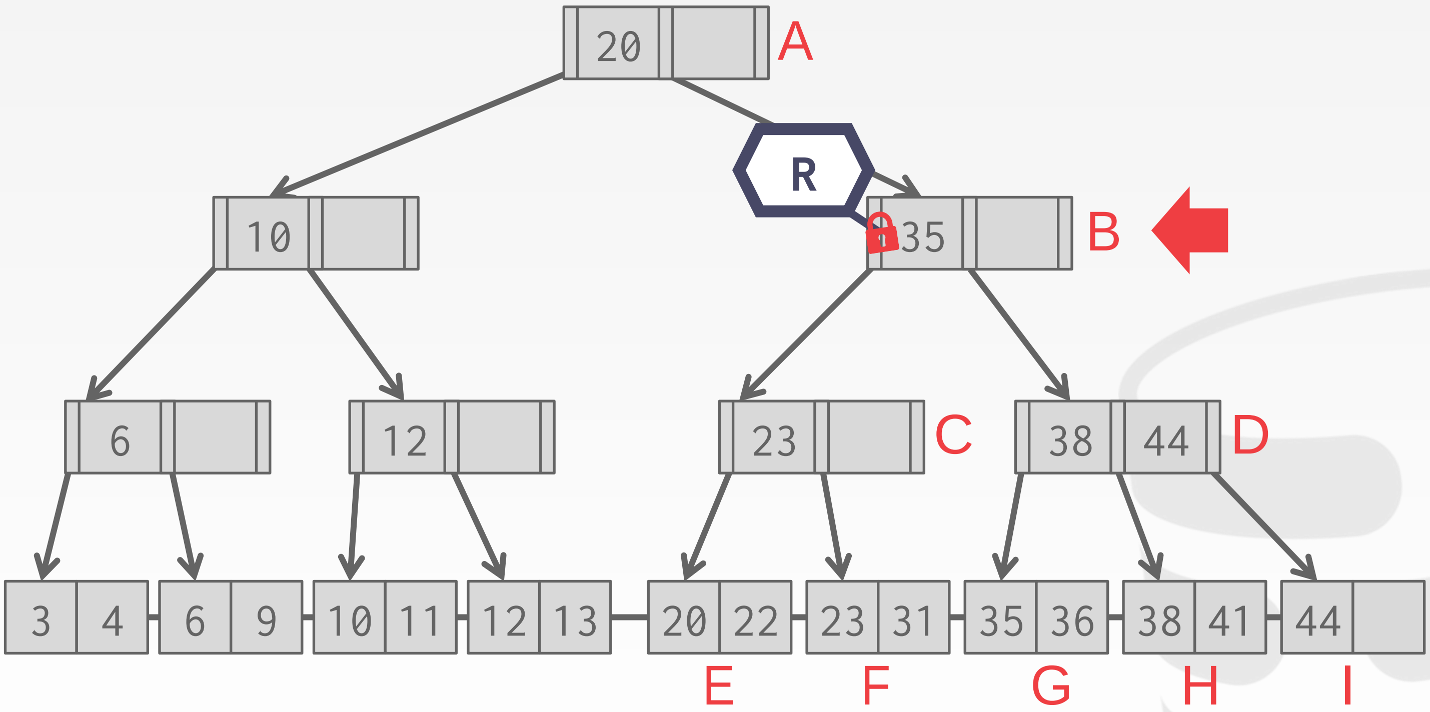
→ If leaf is not safe, release all latches, and restart thread using previous insert/delete protocol with write latches.

This approach optimistically assumes that only leaf node will be modified; if not, **R** latches set on the first pass to leaf are wasteful.

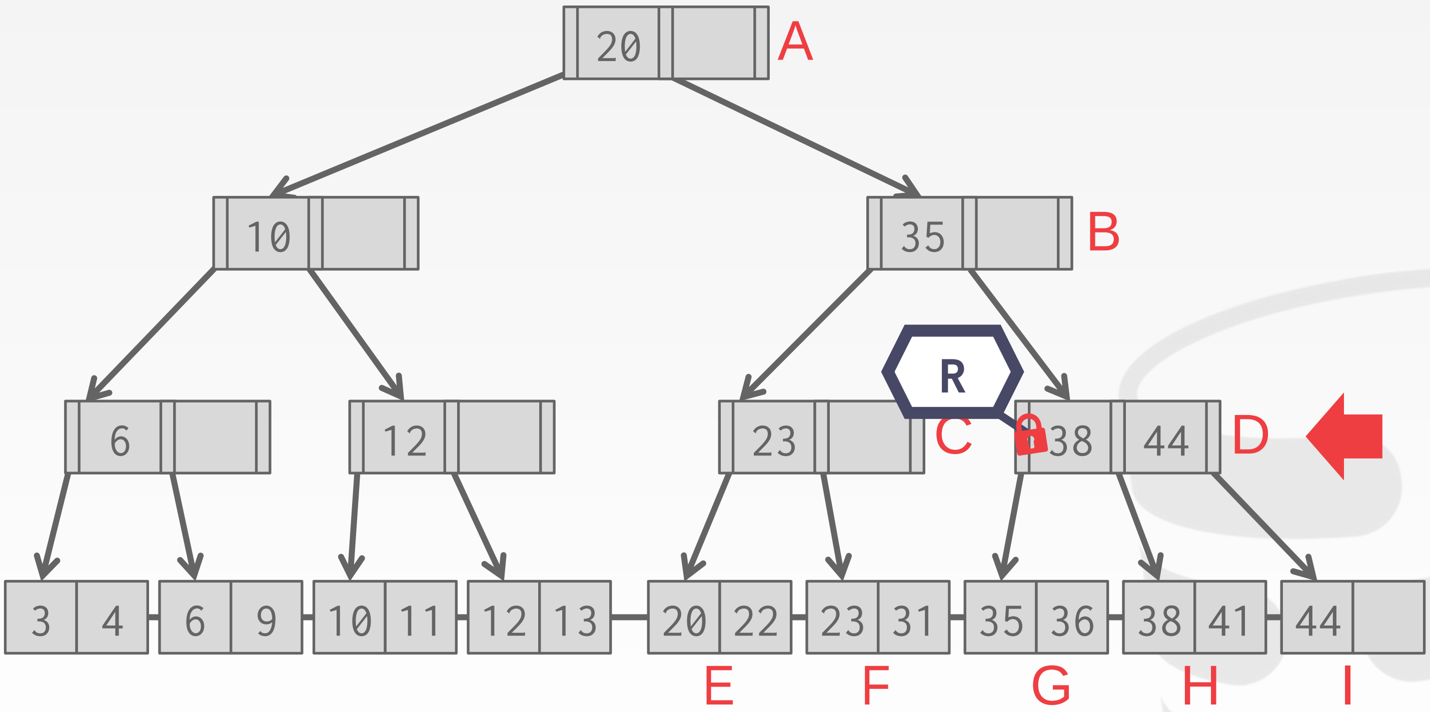
EXAMPLE #2 – DELETE 38



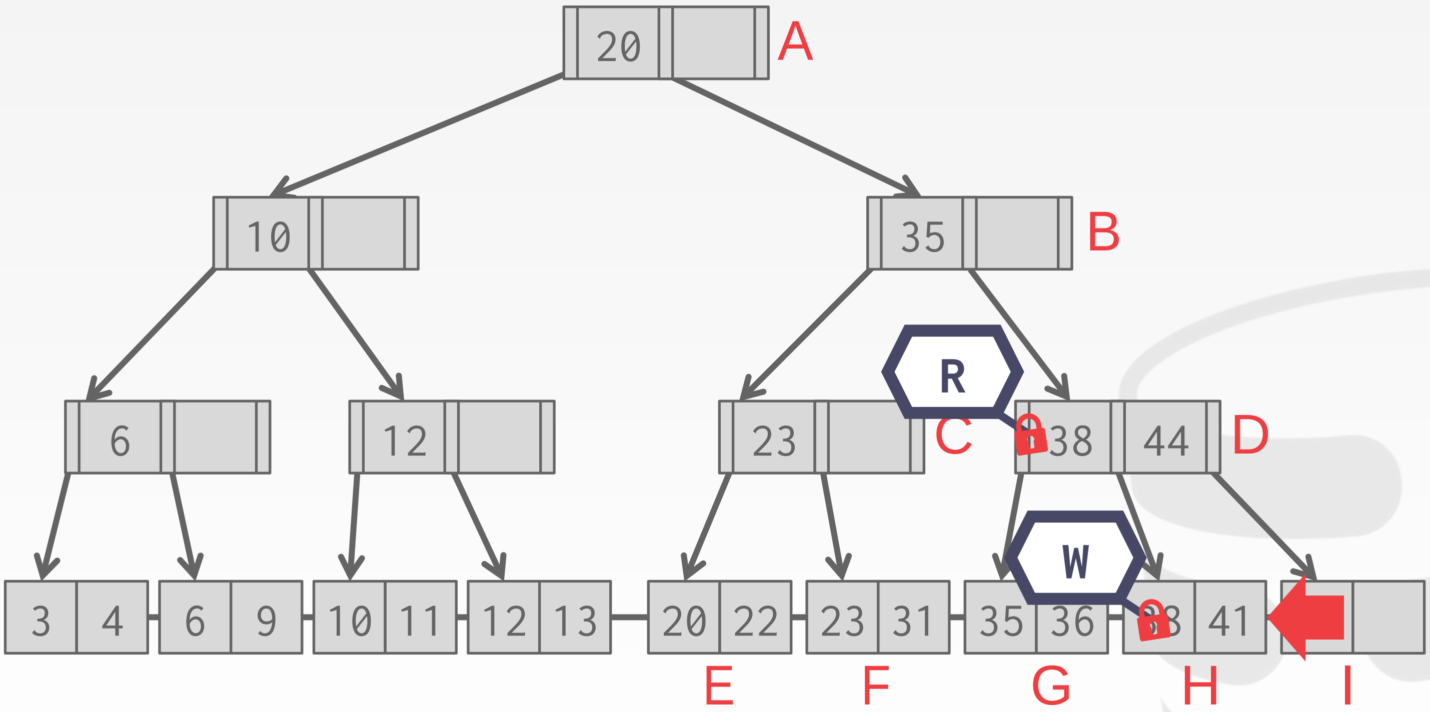
EXAMPLE #2 – DELETE 38



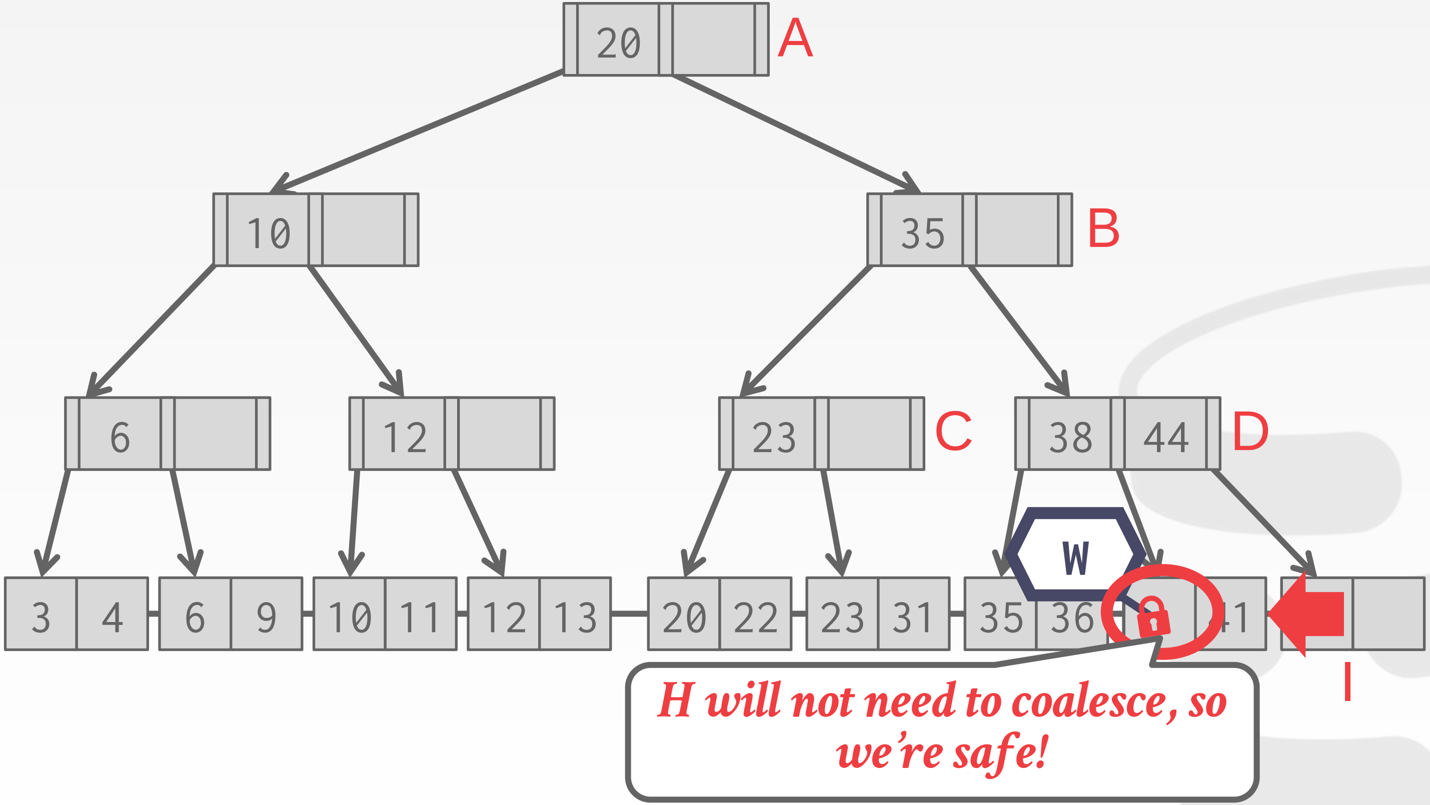
EXAMPLE #2 – DELETE 38



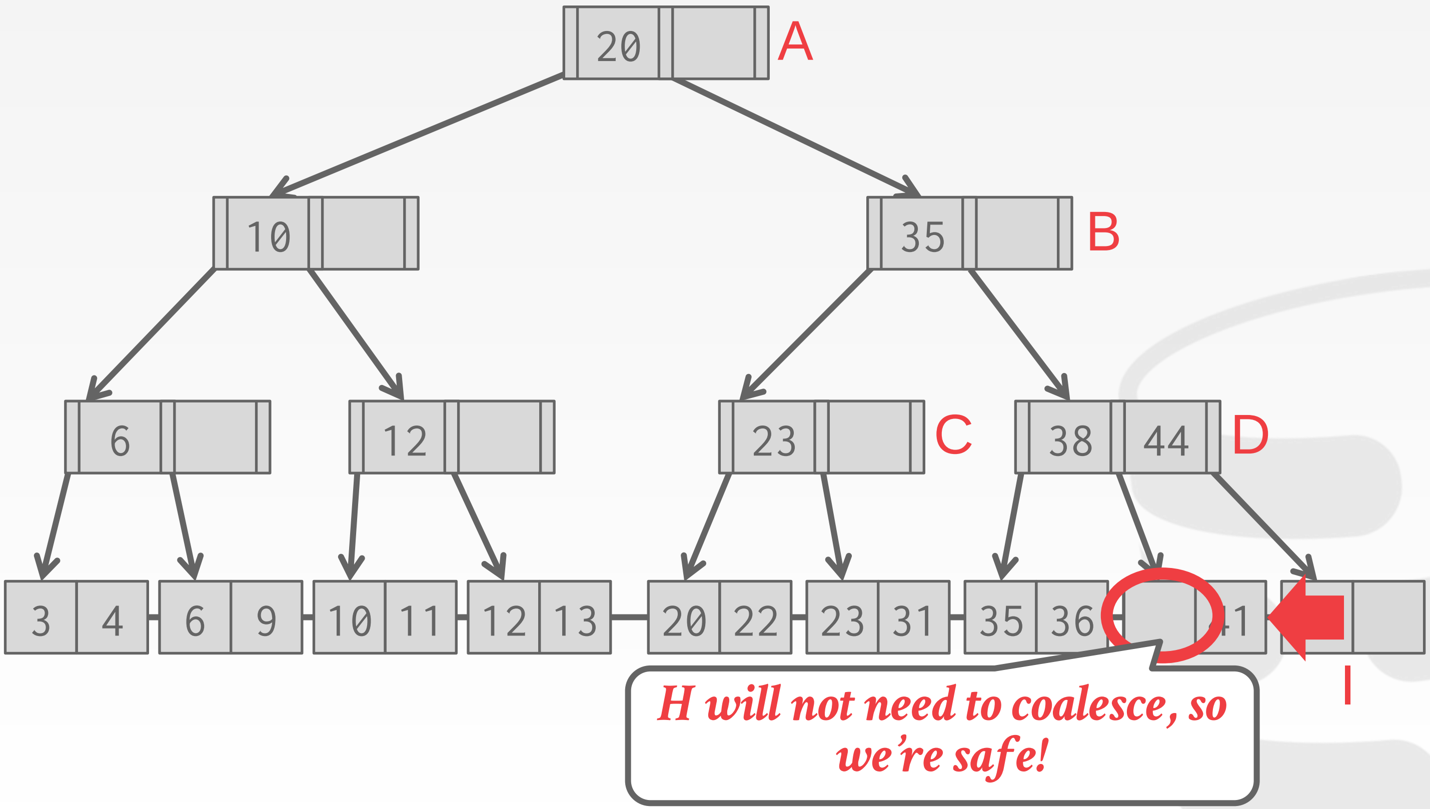
EXAMPLE #2 – DELETE 38



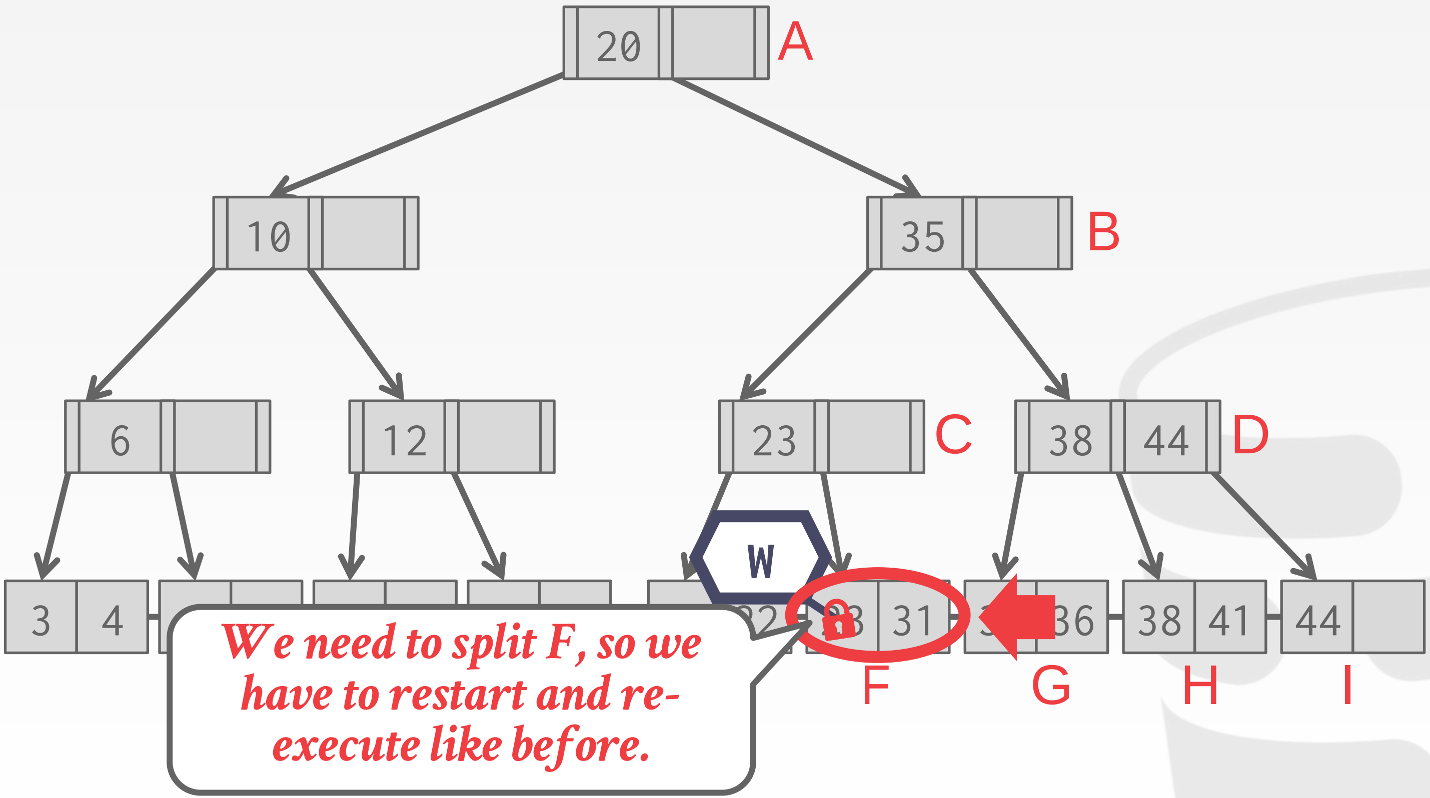
EXAMPLE #2 – DELETE 38



EXAMPLE #2 – DELETE 38



EXAMPLE #4 – INSERT 25



OBSERVATION

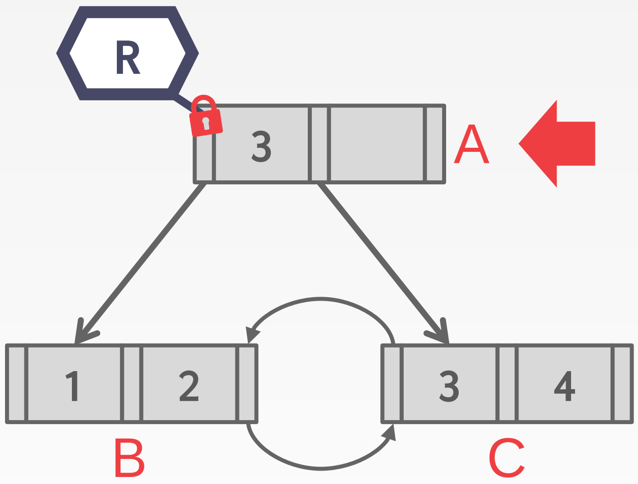
The threads in all the examples so far have acquired latches in a "top-down" manner.

→ A thread can only acquire a latch from a node that is below its current node.
→ If the desired latch is unavailable, the thread must wait until it becomes available.

But what if we want to move from one leaf node to another leaf node?

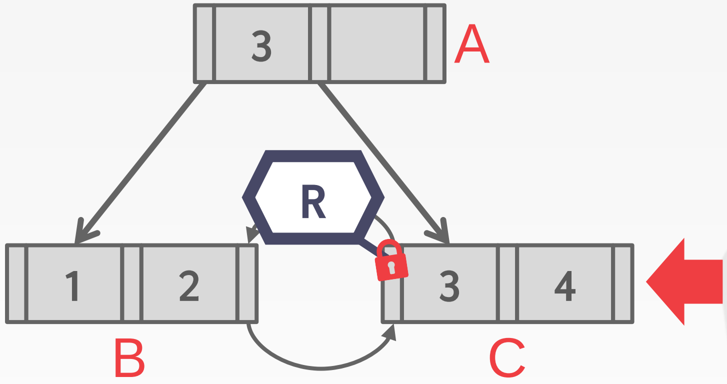
LEAF NODE SCAN EXAMPLE #1

T_1: Find Keys < 4



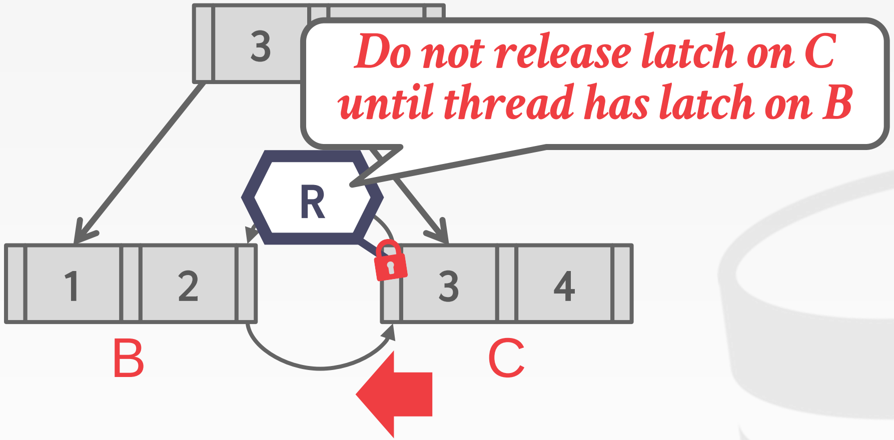
LEAF NODE SCAN EXAMPLE #1

T_1: Find Keys < 4



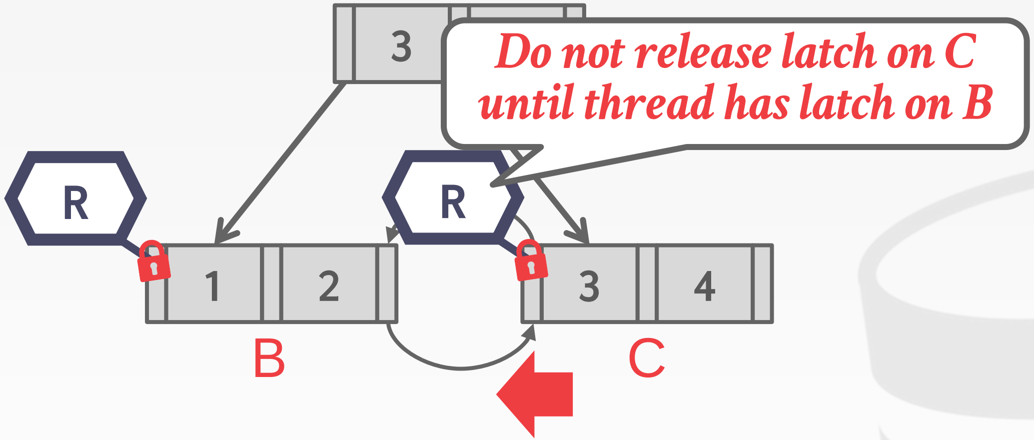
LEAF NODE SCAN EXAMPLE #1

T_1: Find Keys < 4



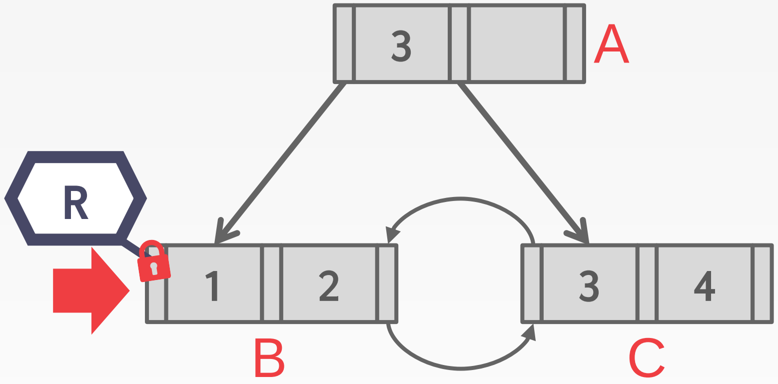
LEAF NODE SCAN EXAMPLE #1

T_1: Find Keys < 4



LEAF NODE SCAN EXAMPLE #1

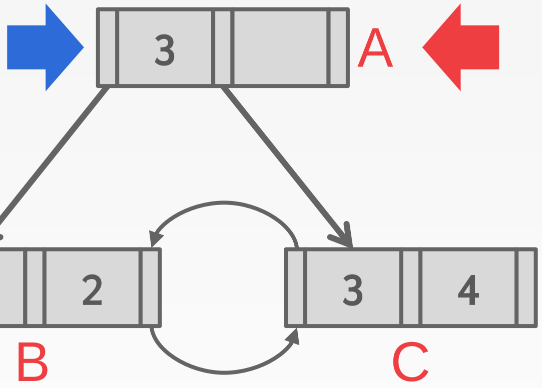
T_1: Find Keys < 4



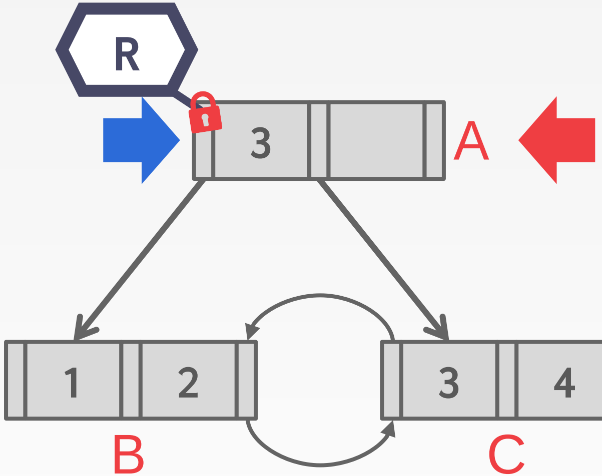
LEAF NODE SCAN EXAMPLE #2

T_1: Find Keys < 4

T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #2



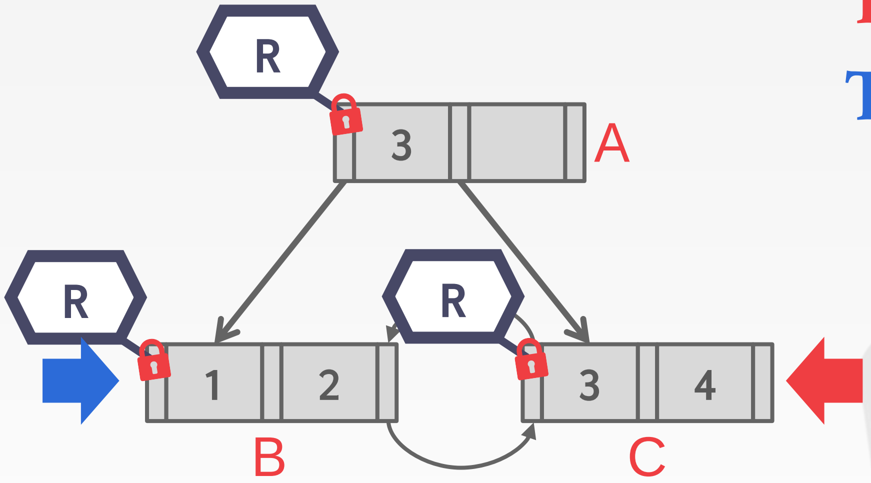
T_1: Find Keys < 4

T_2: Find Keys > 1

LEAF NODE SCAN EXAMPLE #2

T_1: Find Keys < 4

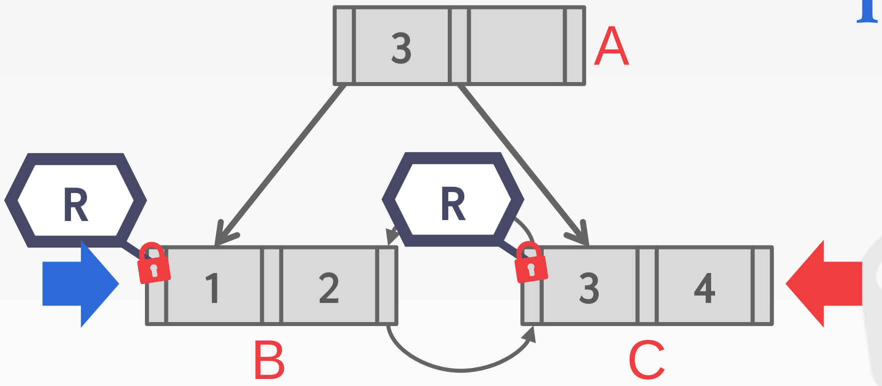
T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #2

T_1: Find Keys < 4

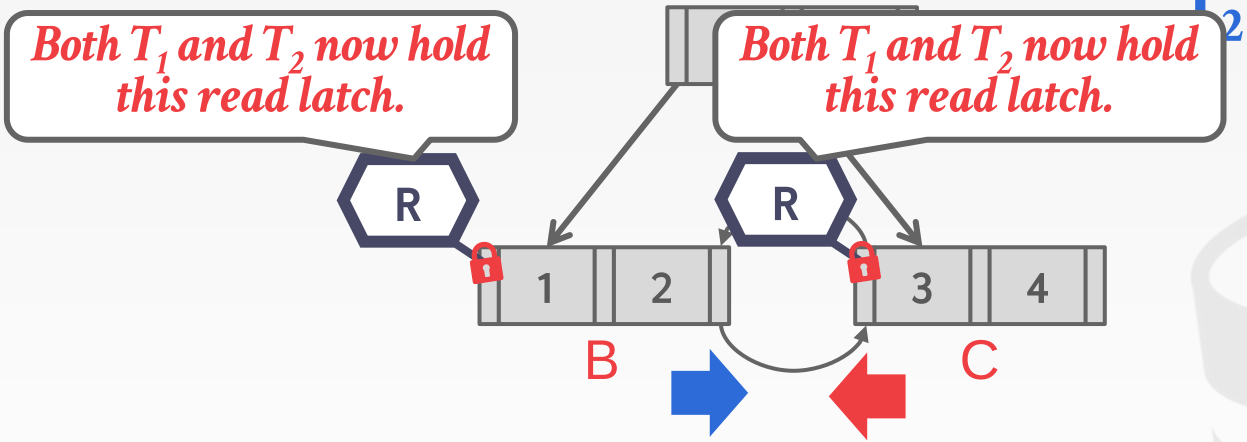
T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #2

T_1: Find Keys < 4

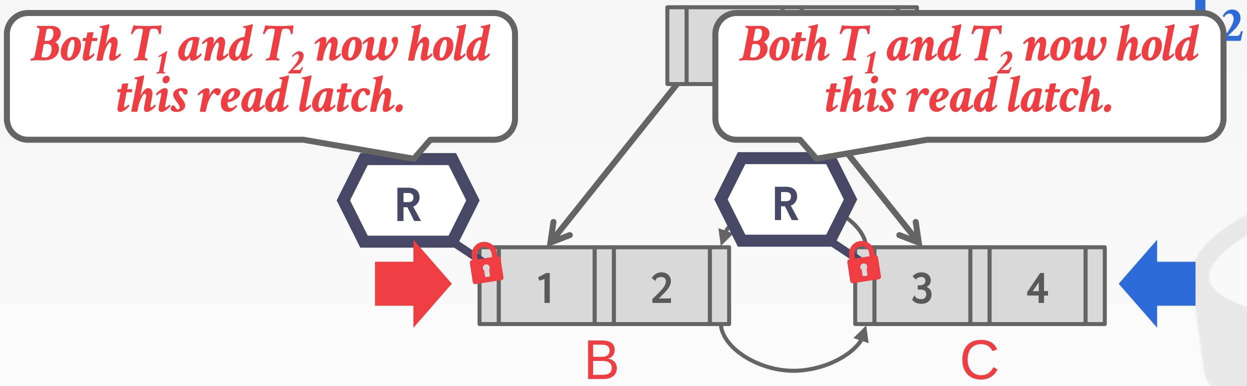
T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #2

T_1: Find Keys < 4

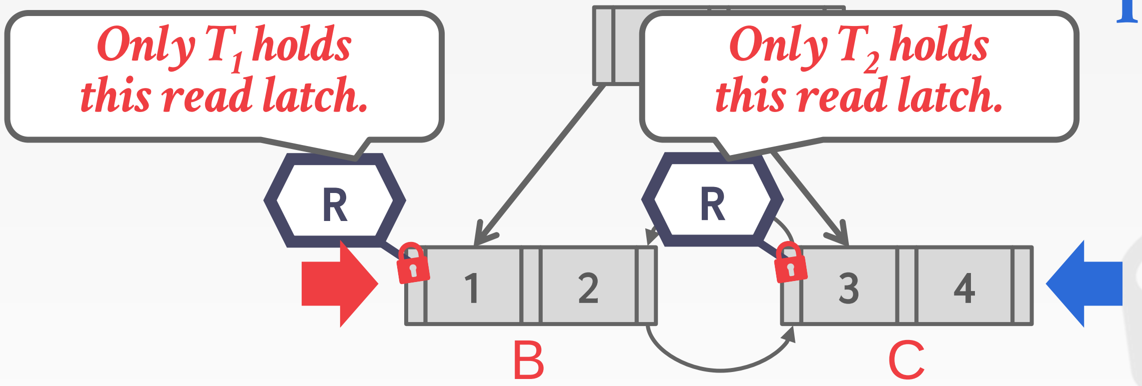
T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #2

T_1: Find Keys < 4

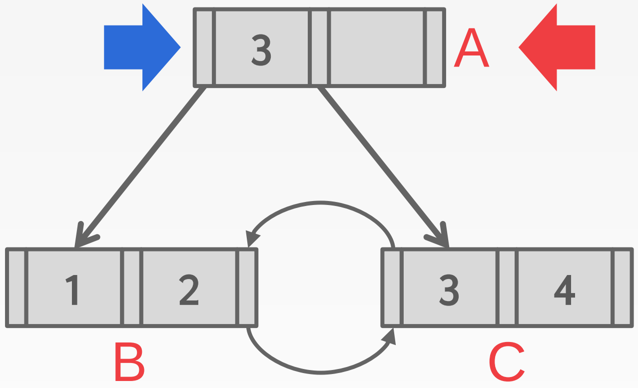
T_2: Find Keys > 1



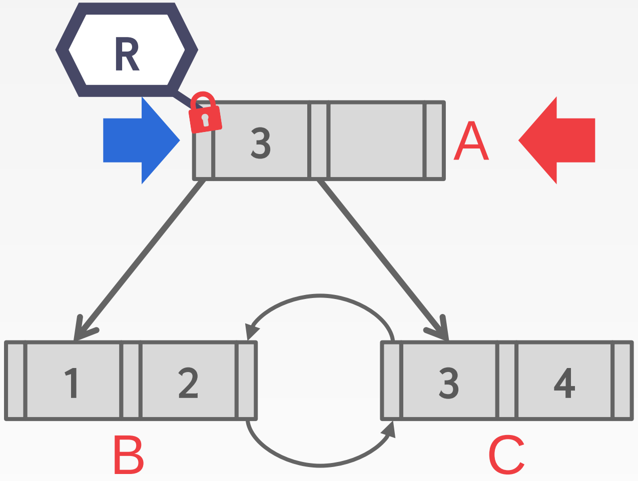
LEAF NODE SCAN EXAMPLE #3

T_1: Delete 4

T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #3

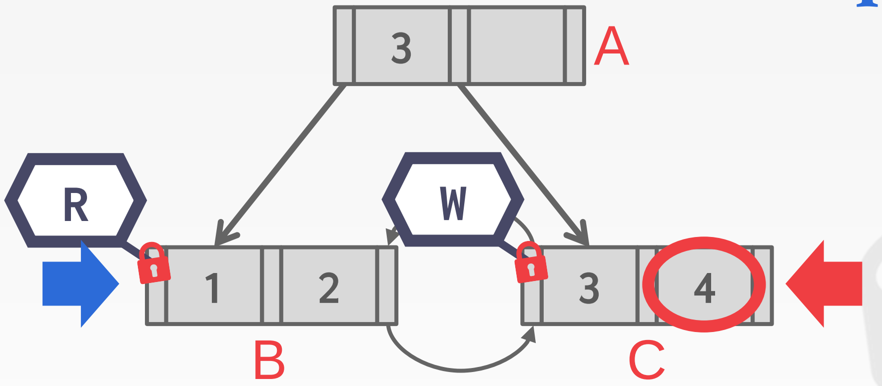


T_1: Delete 4

T_2: Find Keys > 1

LEAF NODE SCAN EXAMPLE #3

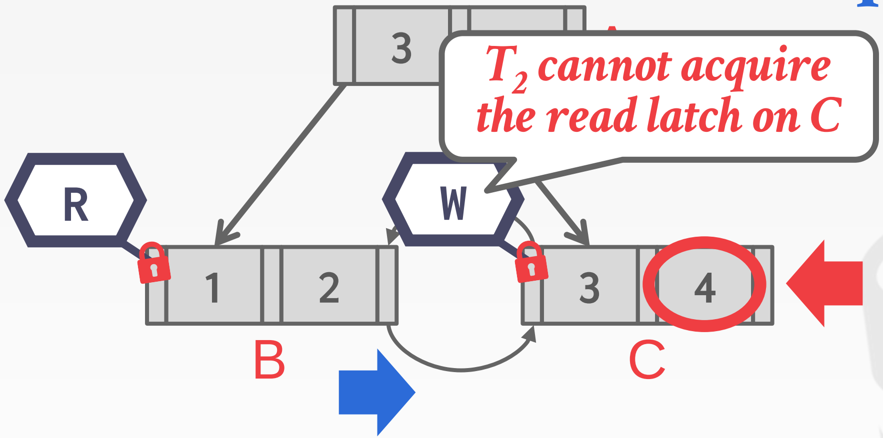
T_1: Delete 4
T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #3

T_1: Delete 4

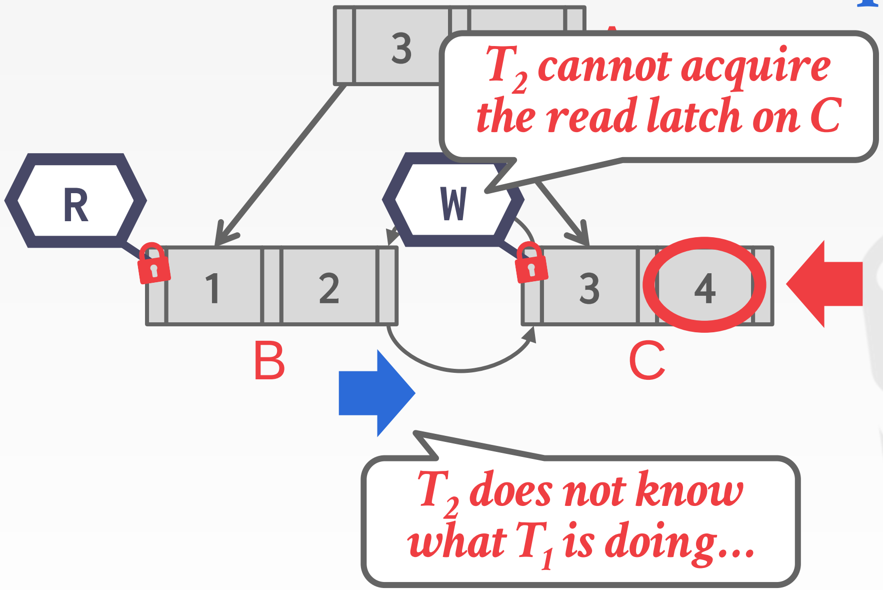
T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #3

T_1: Delete 4

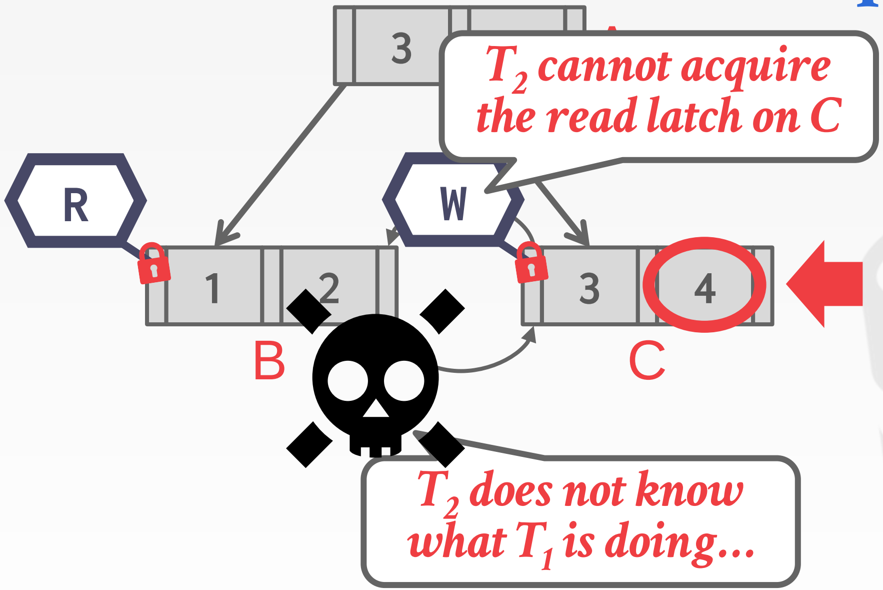
T_2: Find Keys > 1



LEAF NODE SCAN EXAMPLE #3

T_1: Delete 4

T_2: Find Keys > 1



LEAF NODE SCANS

Latches do not support deadlock detection or avoidance. The only way we can deal with this problem is through coding discipline.

The leaf node sibling latch acquisition protocol must support a "no-wait" mode.

The DBMS's data structures must cope with failed latch acquisitions.

DELAYED PARENT UPDATES

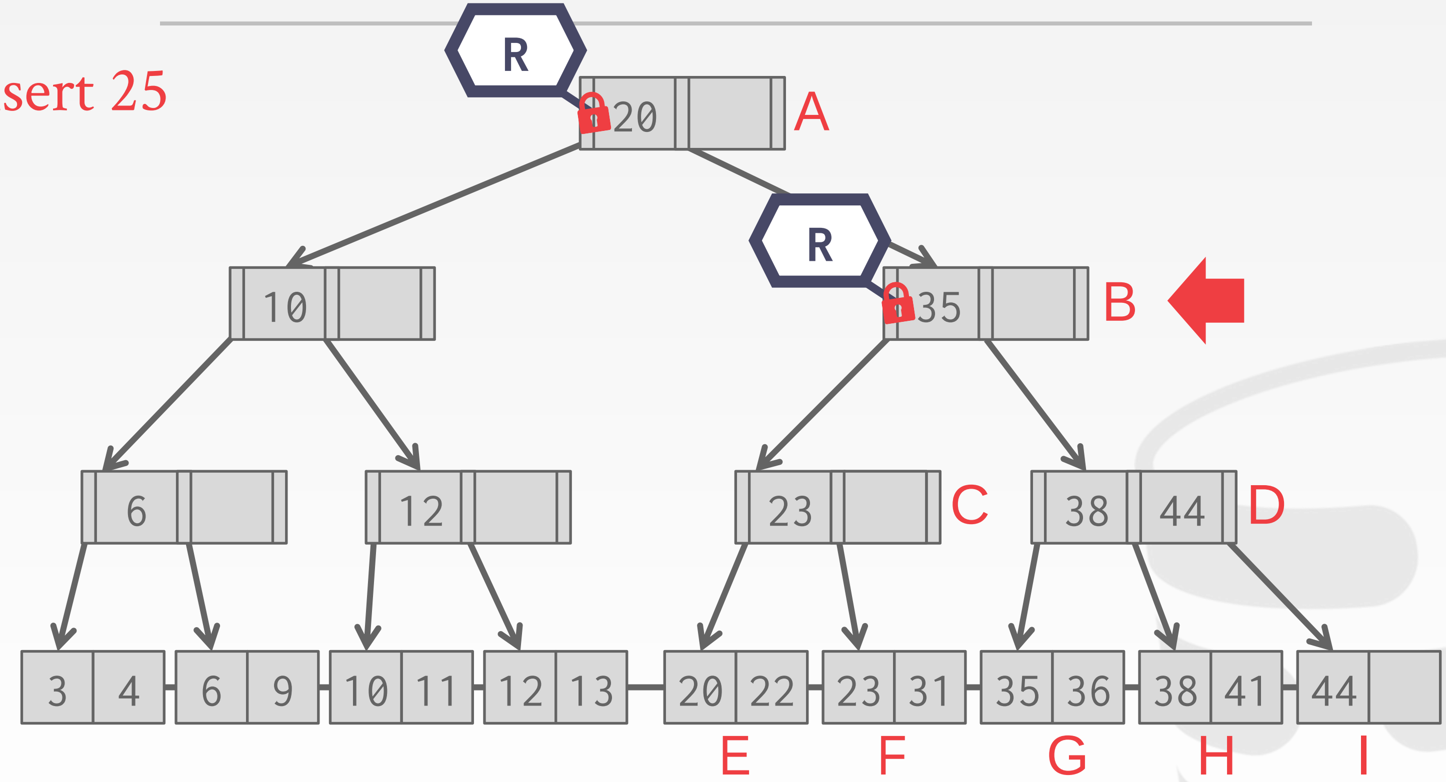
Every time a leaf node overflows, we must update at least three nodes.

→ The leaf node being split.
→ The new leaf node being created.
→ The parent node.

B^{link}-Tree Optimization: When a leaf node overflows, delay updating its parent node.

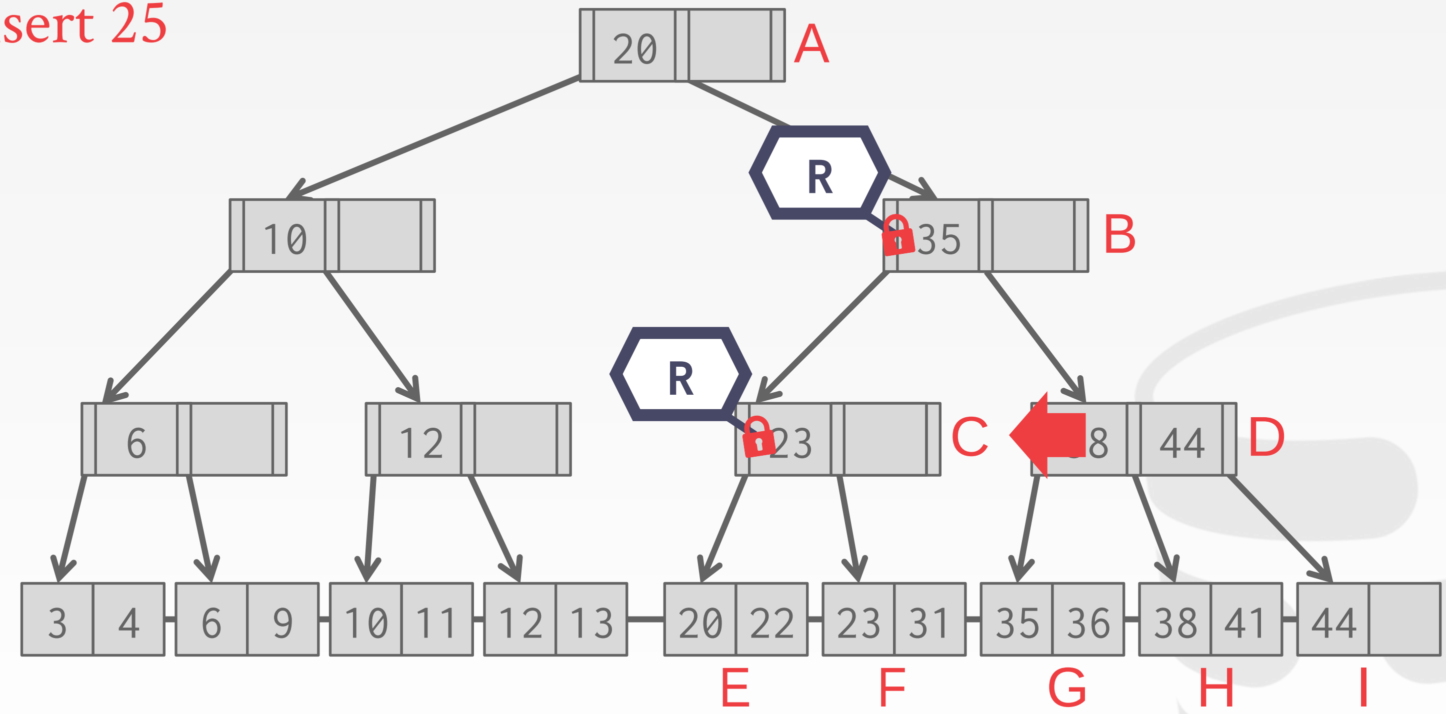
EXAMPLE #4 – INSERT 25

T_1: Insert 25



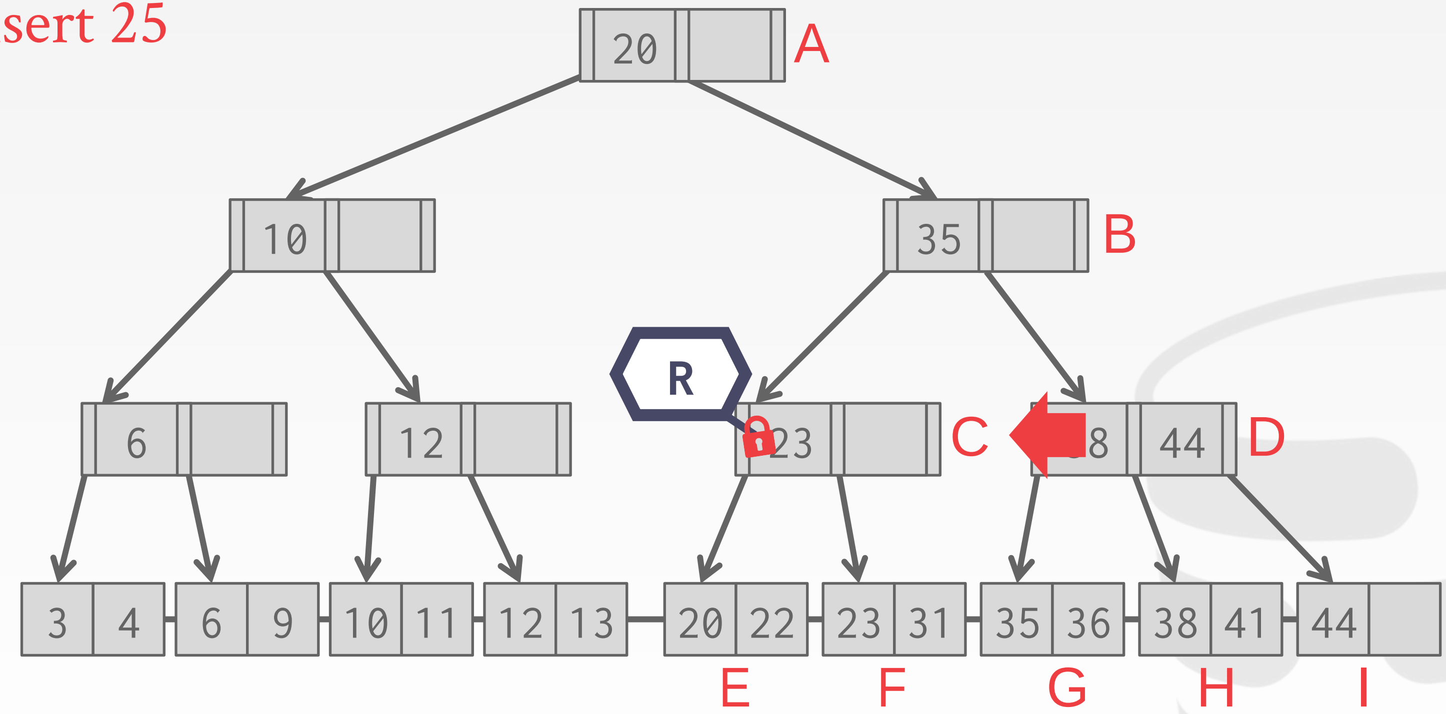
EXAMPLE #4 – INSERT 25

T_1: Insert 25



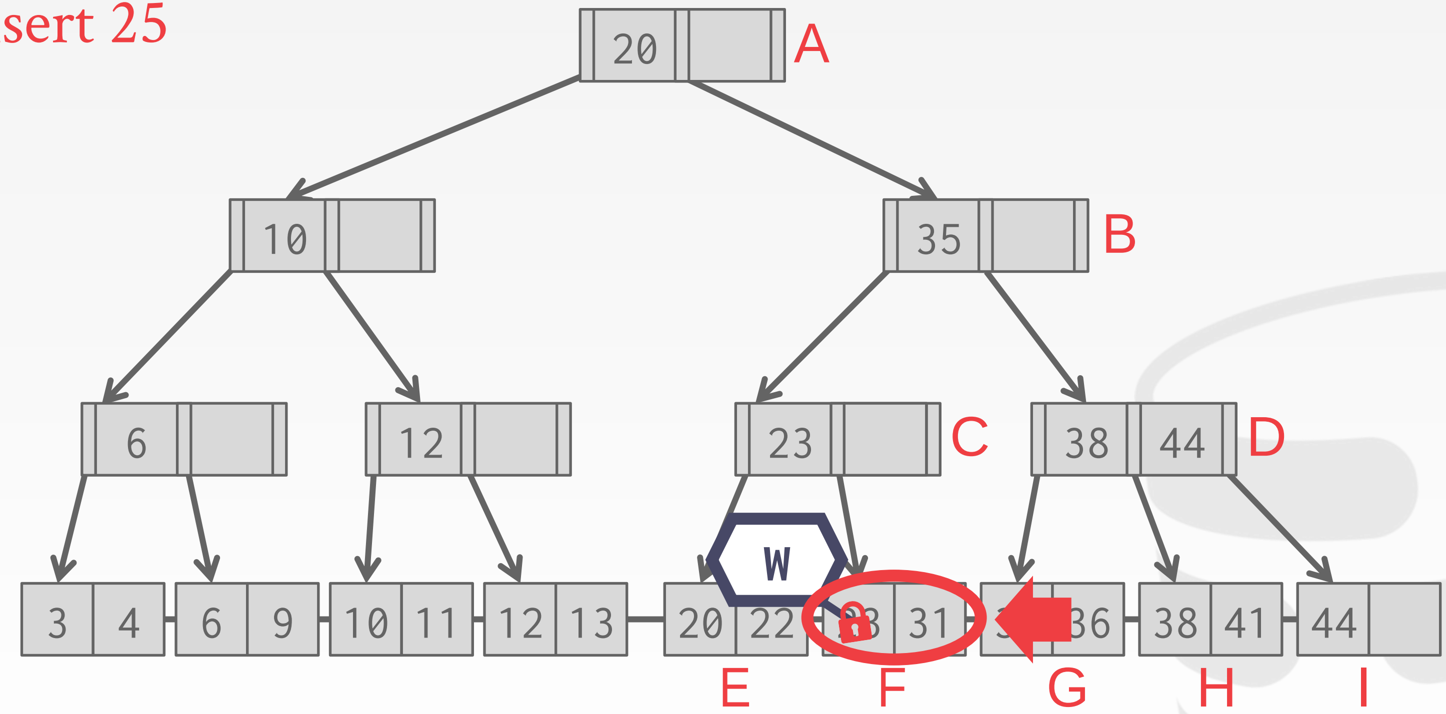
EXAMPLE #4 – INSERT 25

T_1: Insert 25



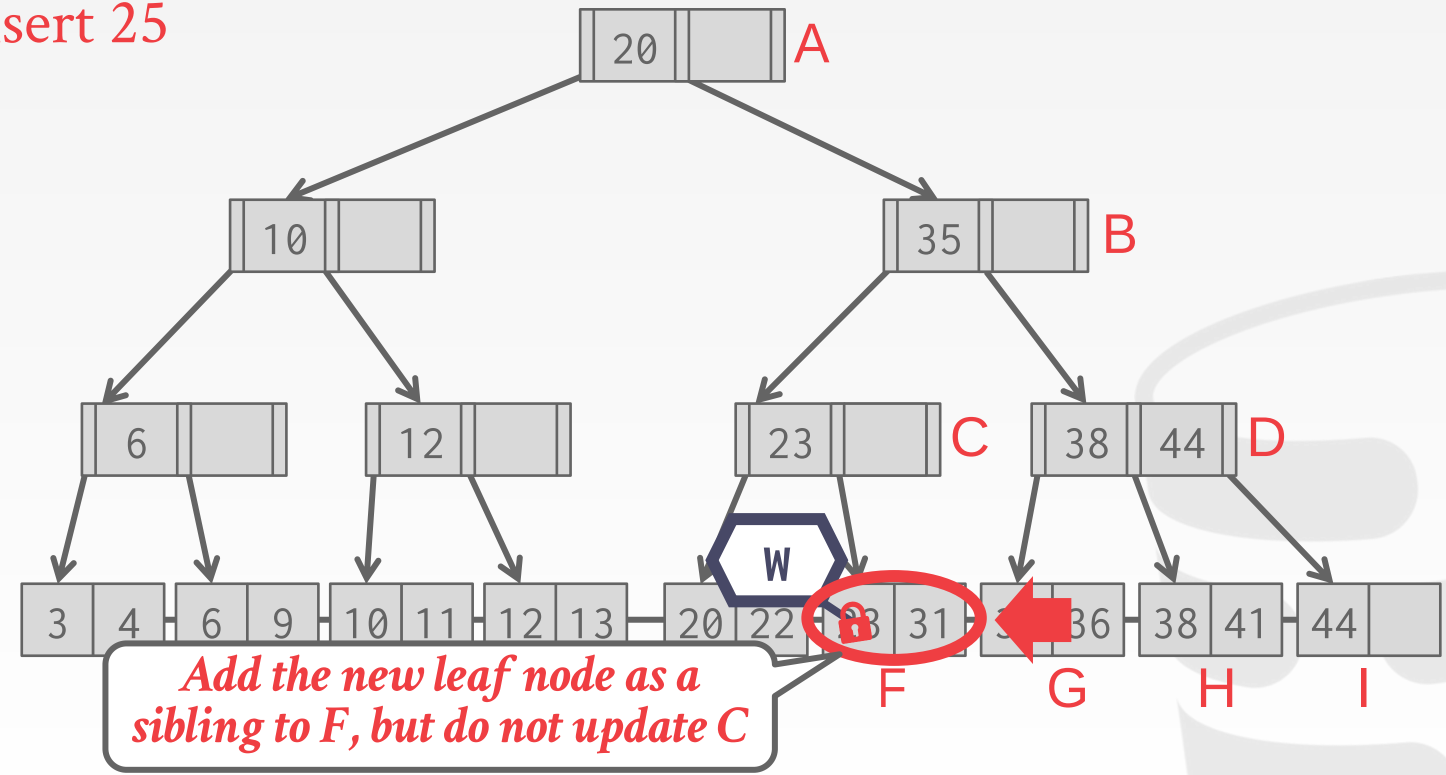
EXAMPLE #4 – INSERT 25

T_1: Insert 25



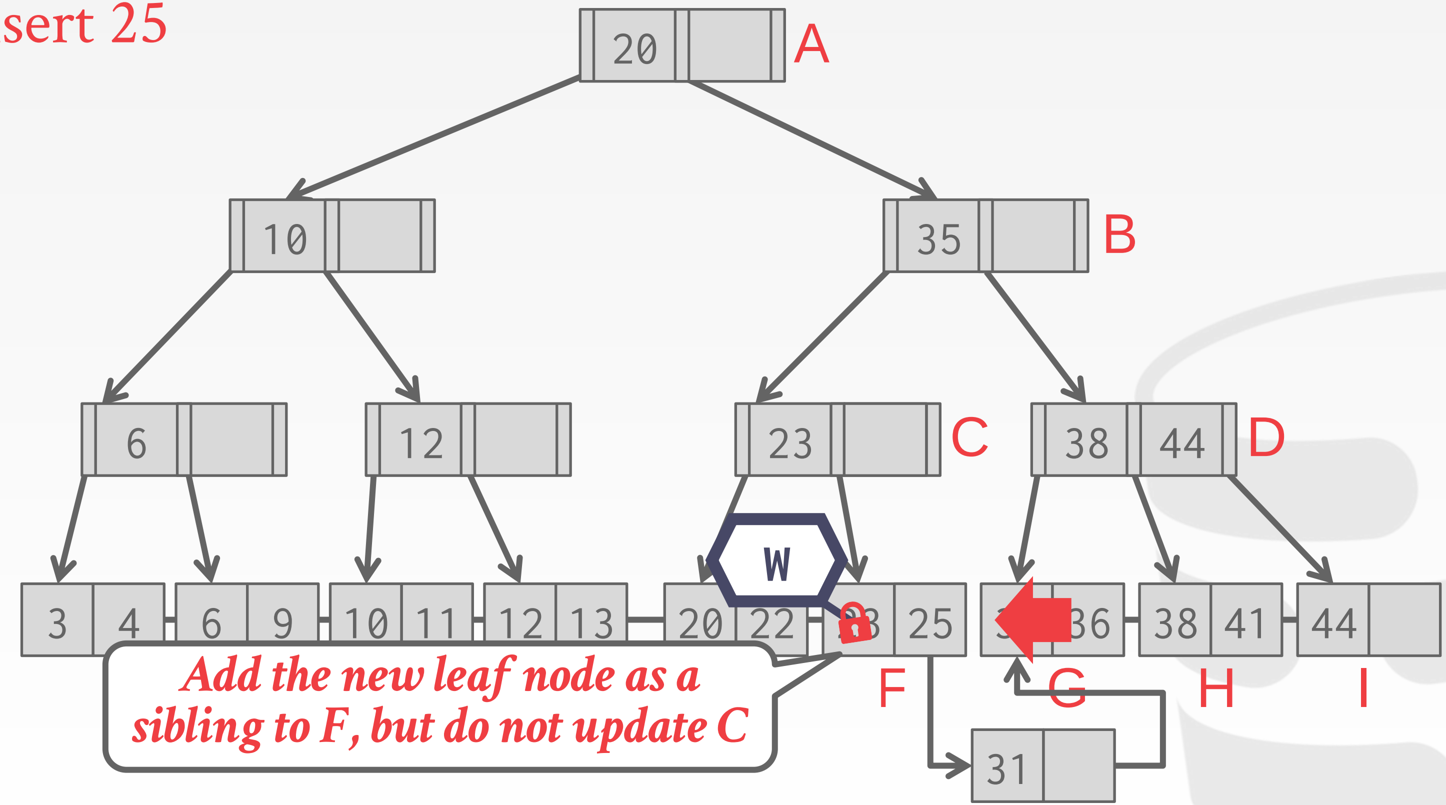
EXAMPLE #4 – INSERT 25

T_1: Insert 25



EXAMPLE #4 – INSERT 25

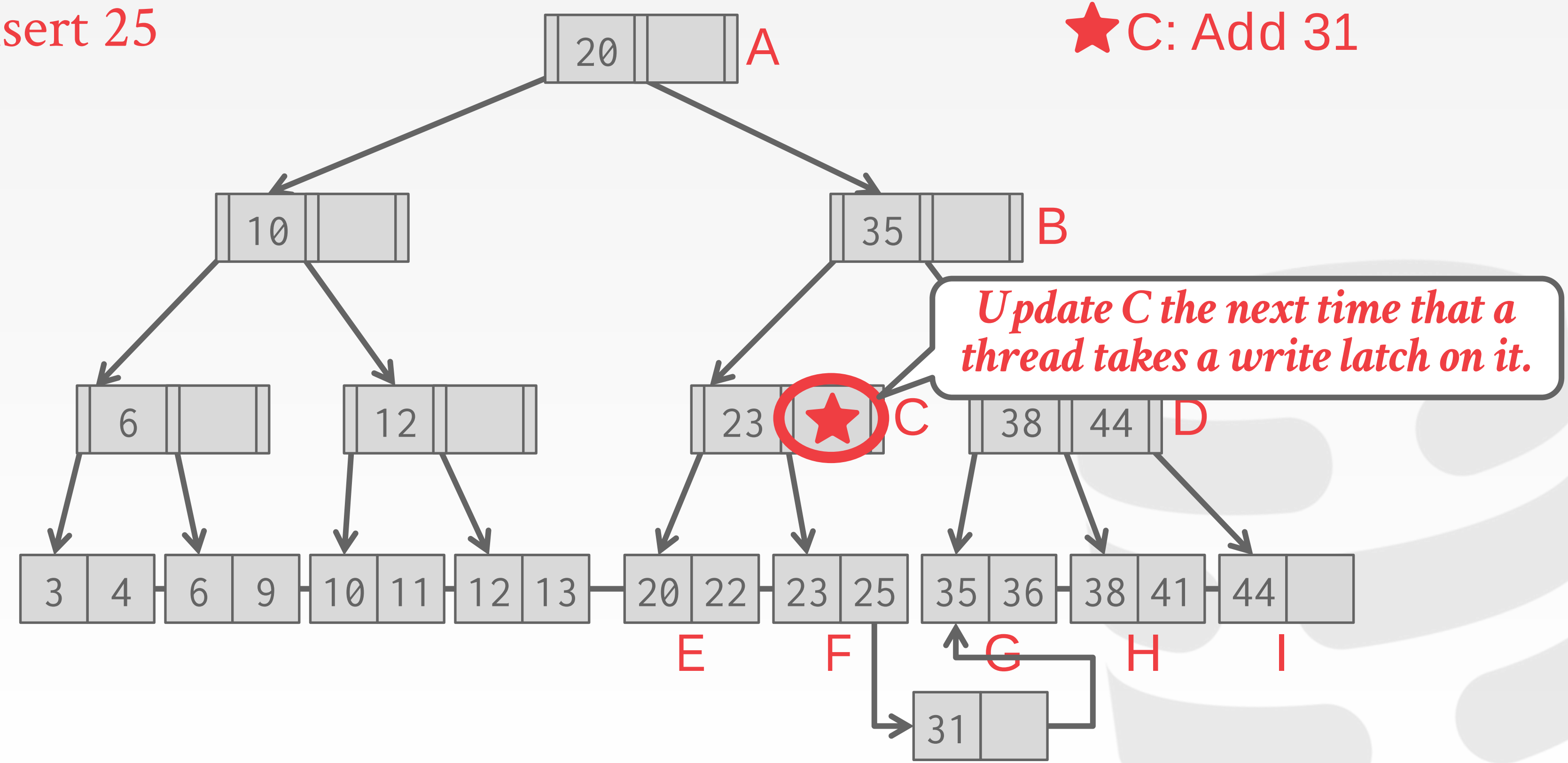
T_1: Insert 25



EXAMPLE #4 – INSERT 25

T_1: Insert 25

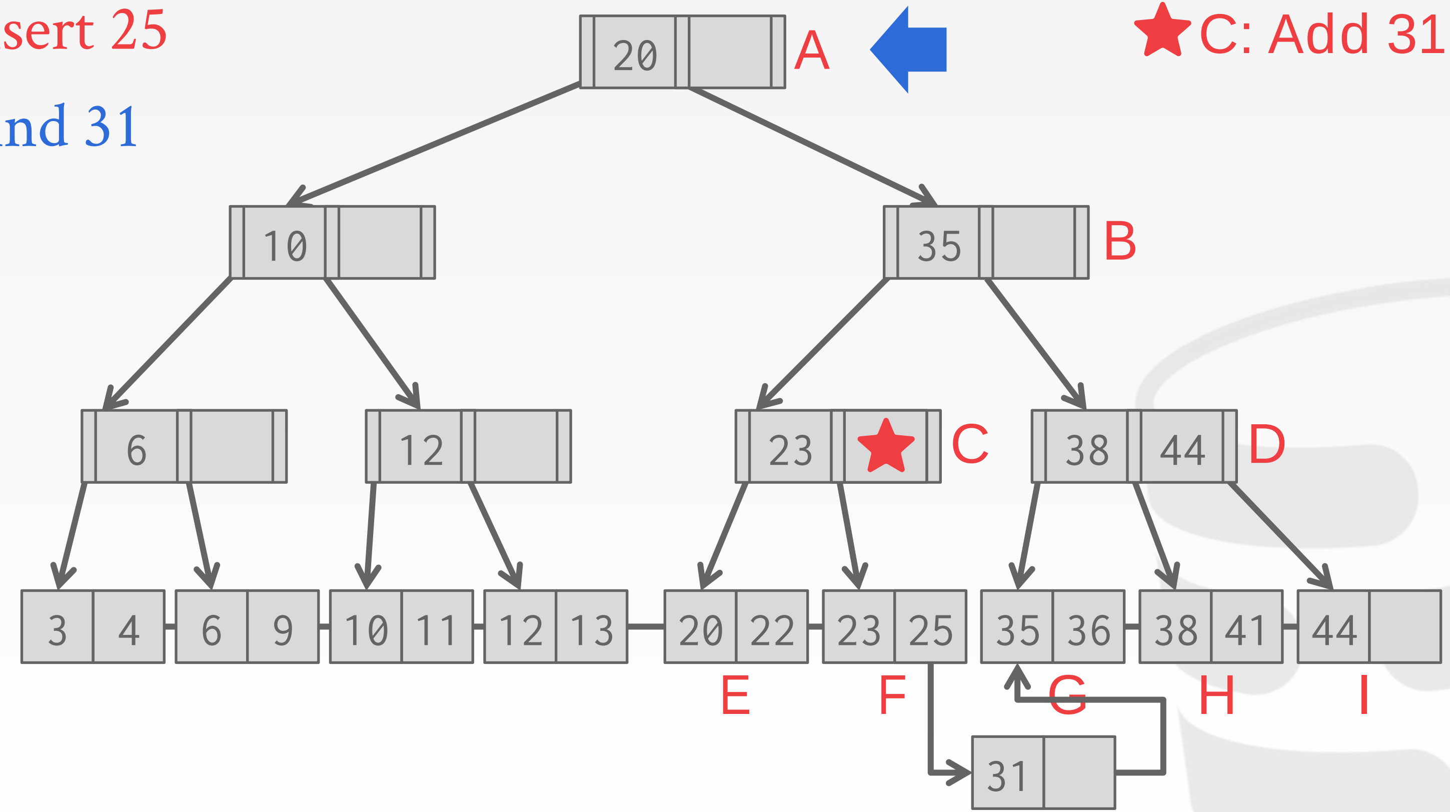
★C: Add 31



EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

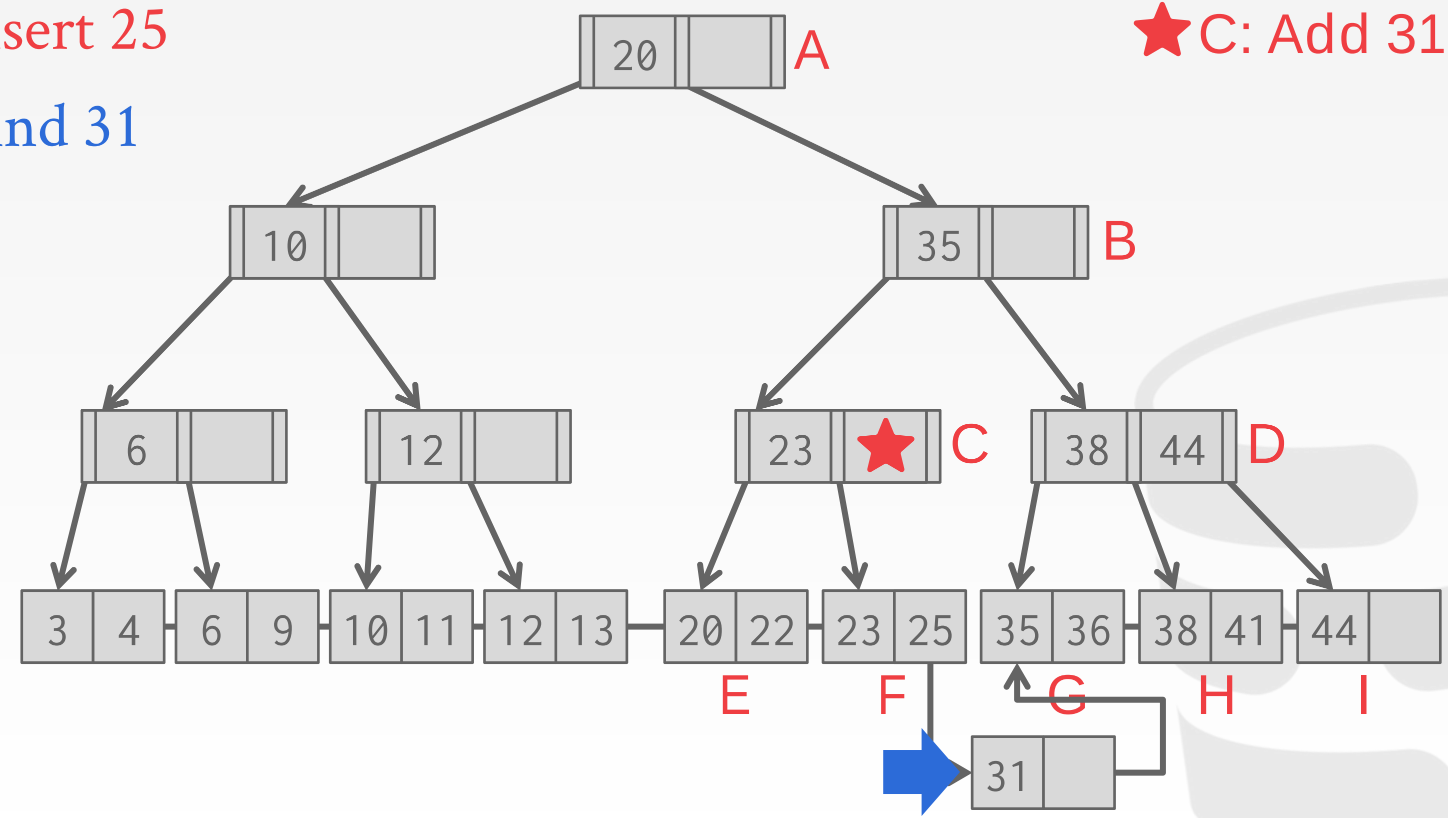


EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

★C: Add 31

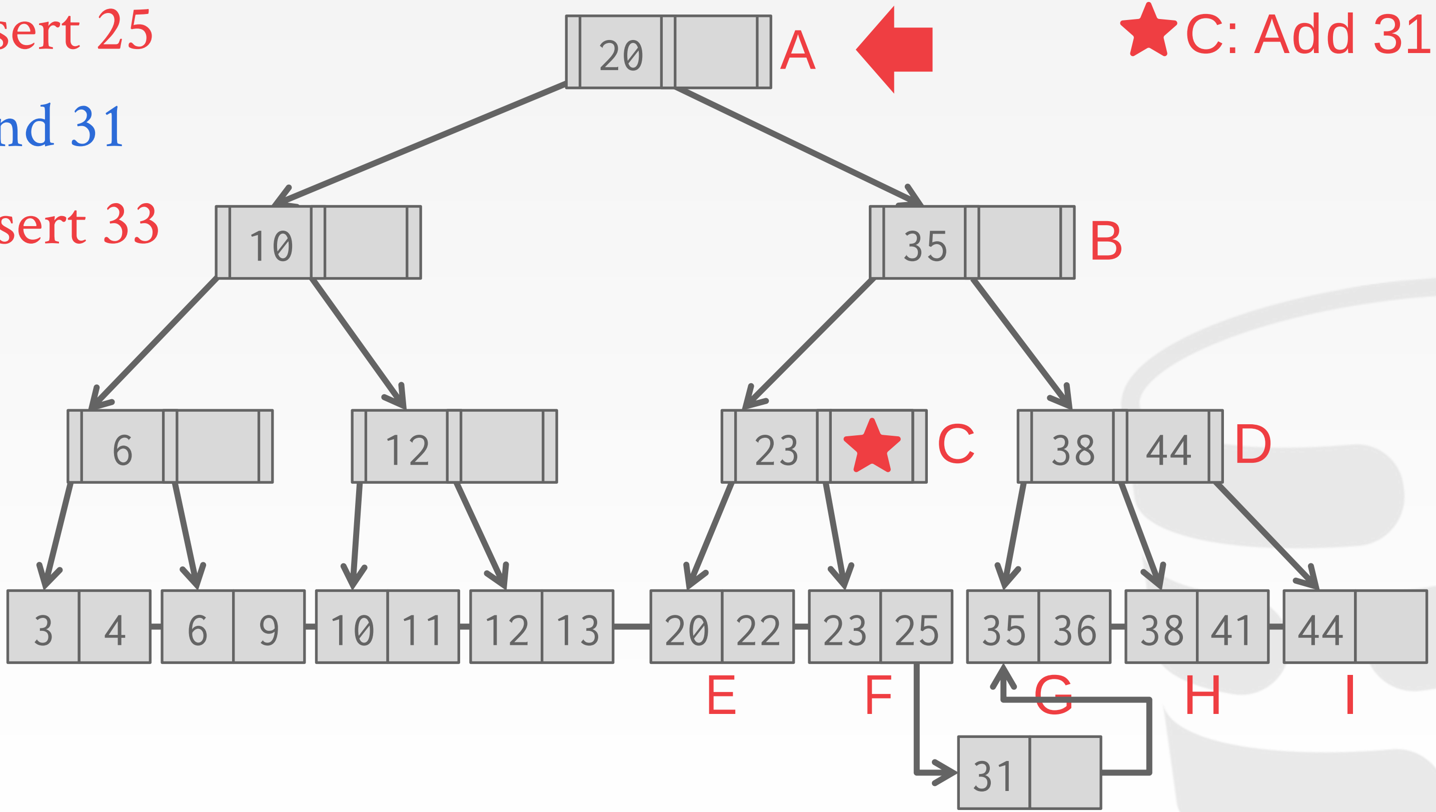


EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

T_3: Insert 33

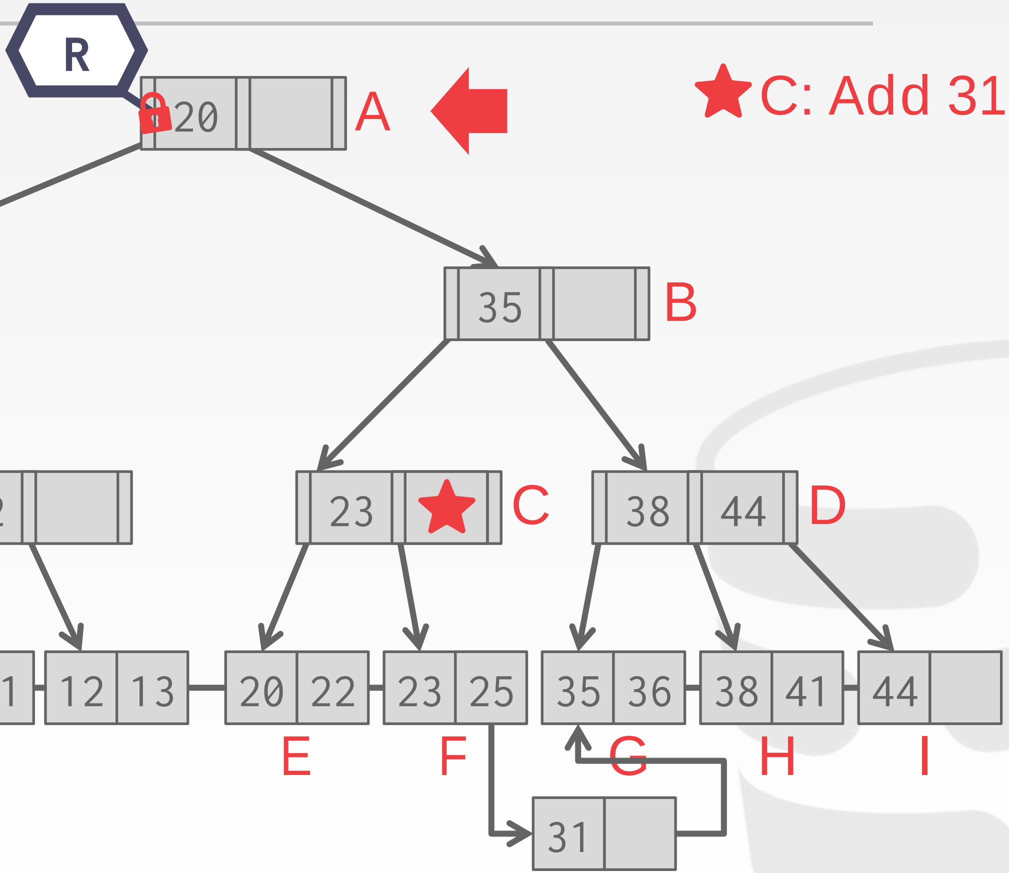


EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

T_3: Insert 33



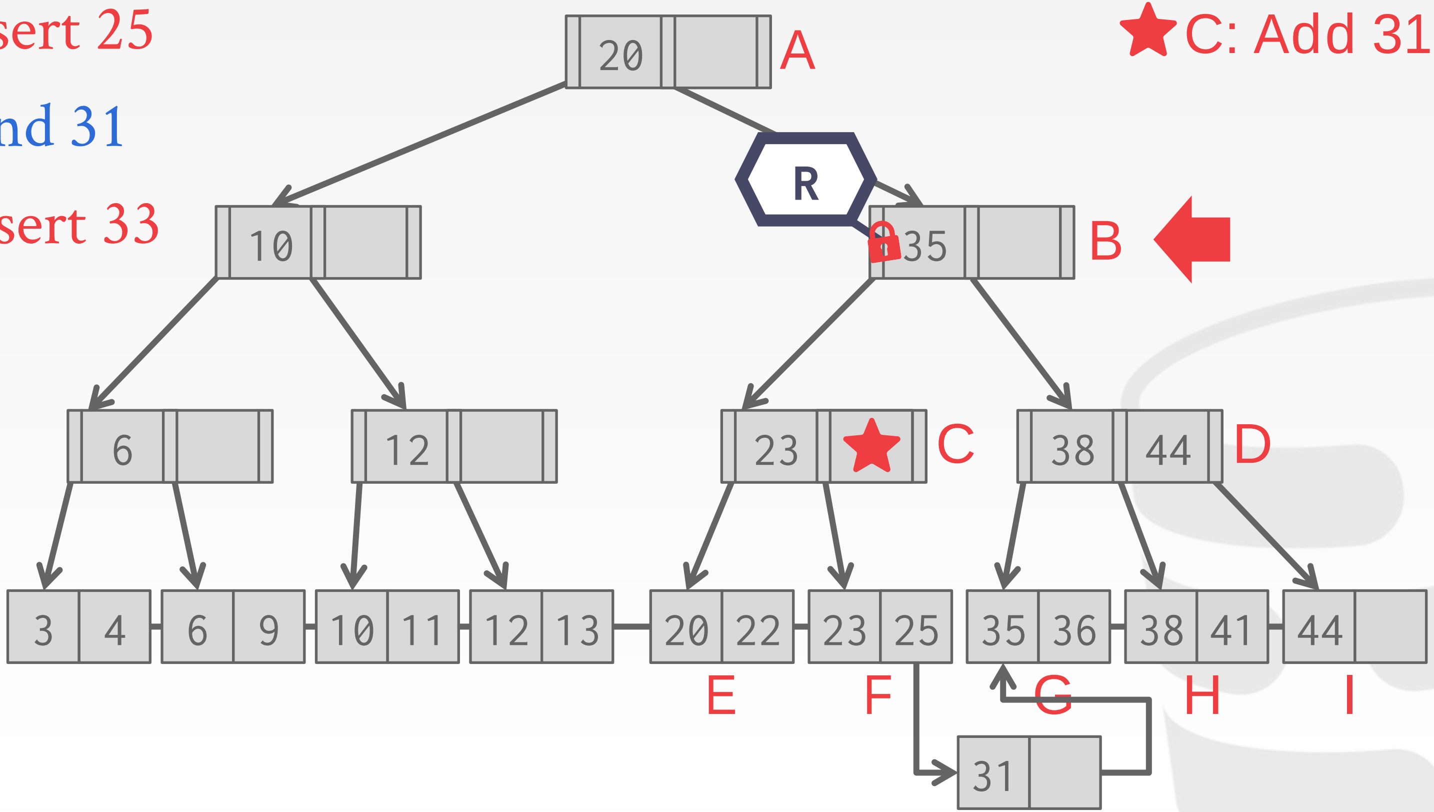
EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

T_3: Insert 33

★C: Add 31



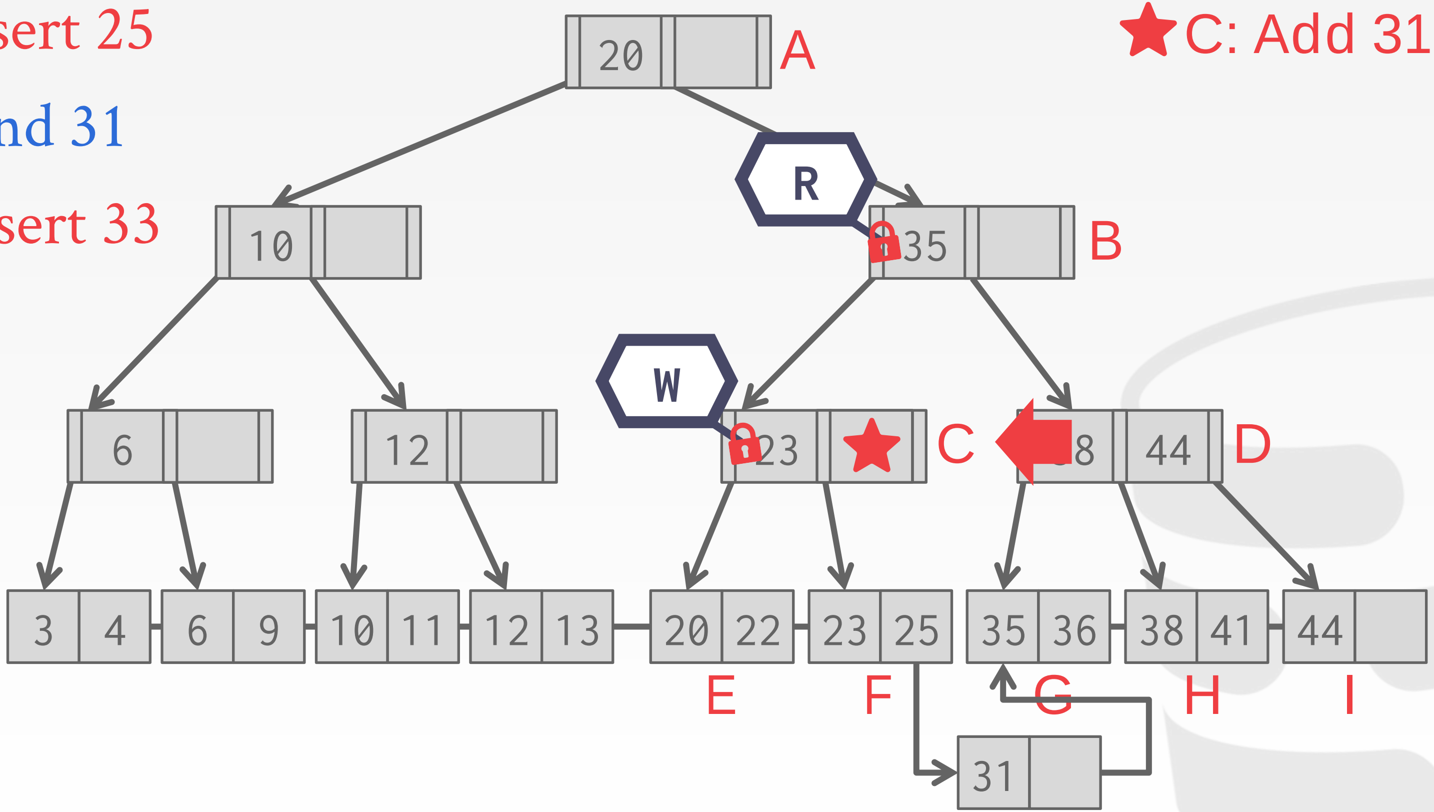
EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

T_3: Insert 33

★C: Add 31



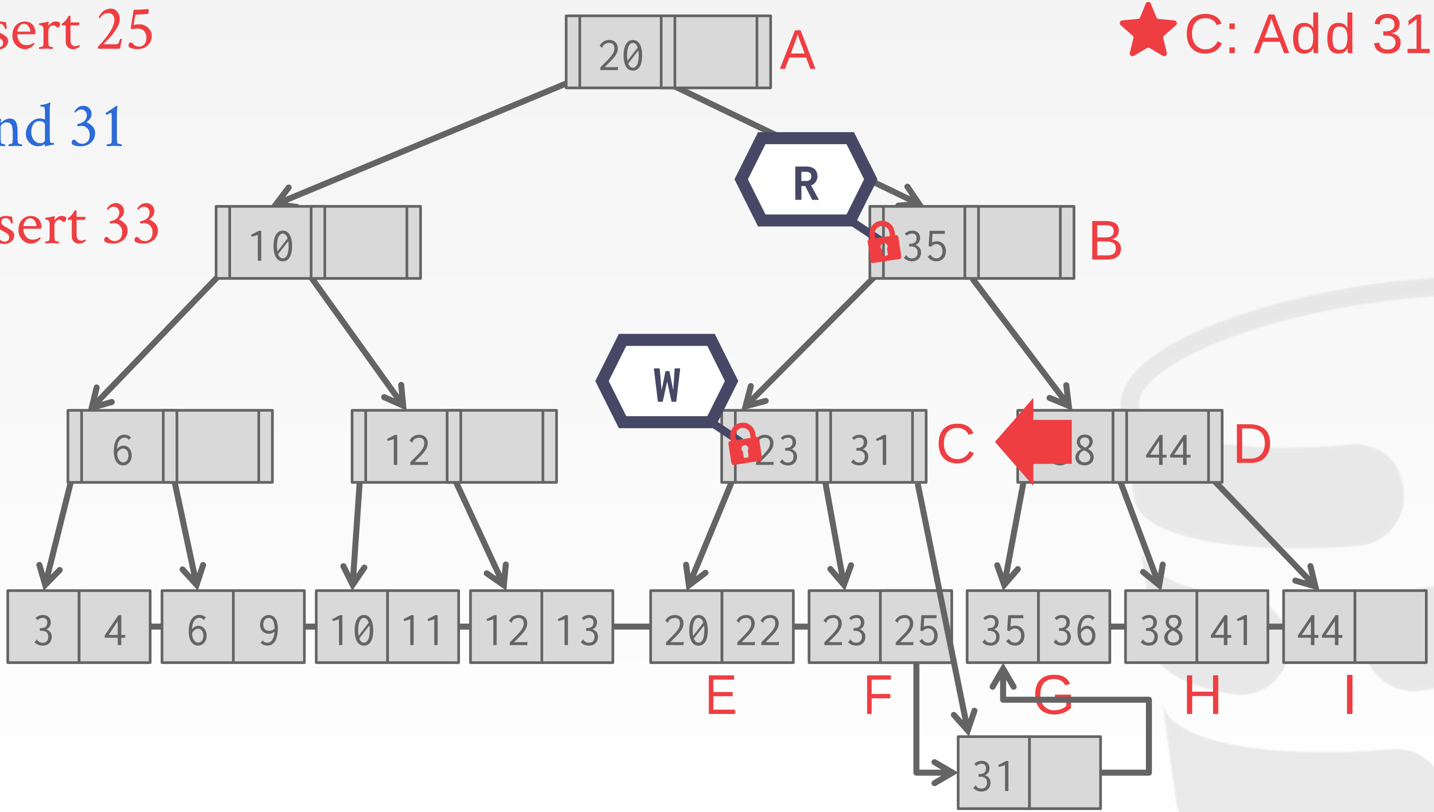
EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

T_3: Insert 33

★C: Add 31



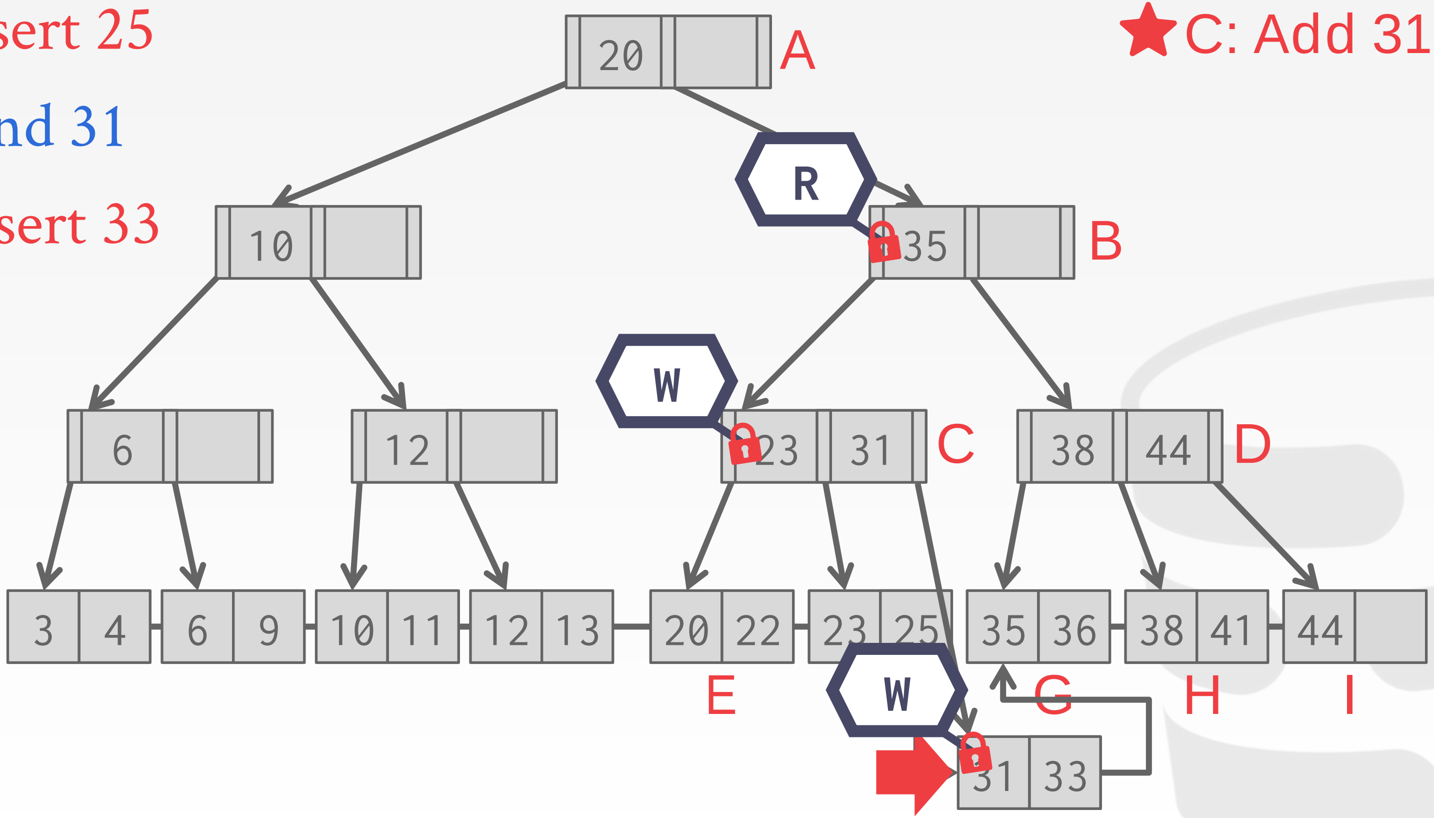
EXAMPLE #4 – INSERT 25

T_1: Insert 25

T_2: Find 31

T_3: Insert 33

★C: Add 31



VERSIONED LATCH COUPLING

Optimistic crabbing scheme where writers are not blocked on readers.

Every node now has a version number (counter).

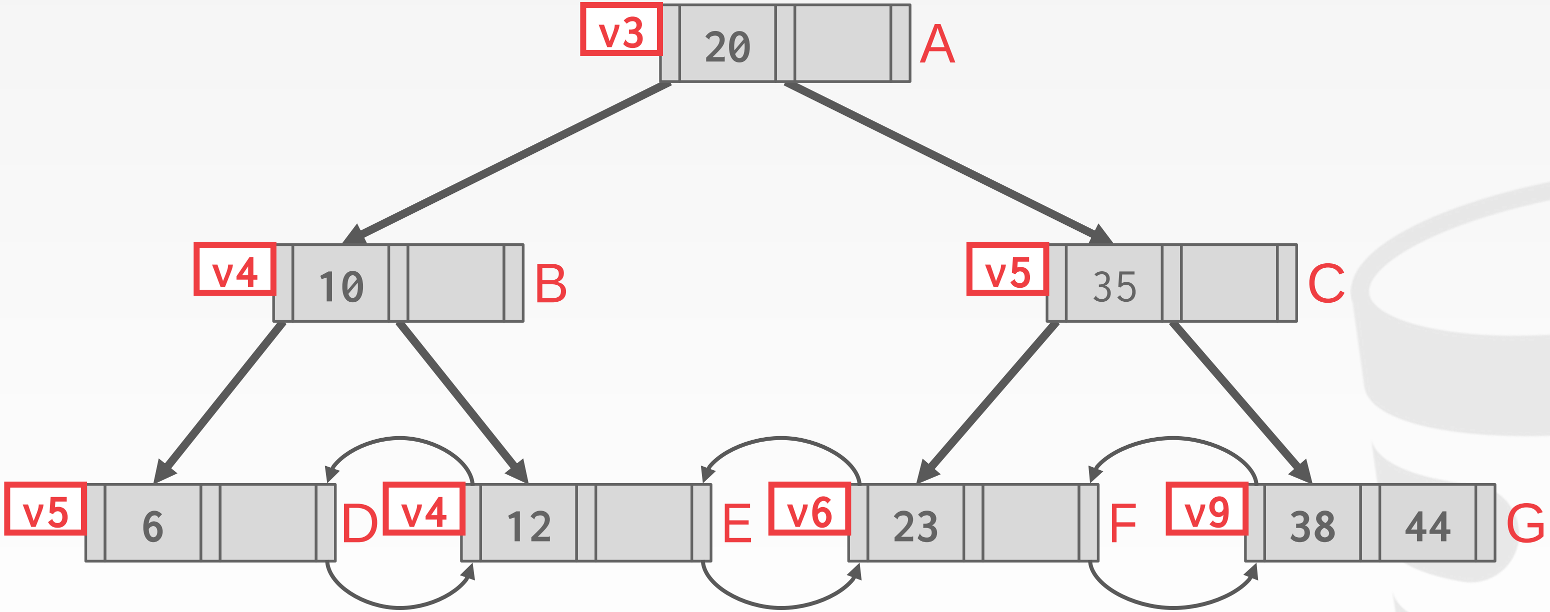
→ Writers increment counter when they acquire latch.
→ Readers proceed if a node's latch is available but then do not acquire it.
→ It then checks whether the latch's counter has changed from when it checked the latch.

Relies on epoch GC to ensure pointers are valid.

THE ART OF PRACTICAL SYNCHRONIZATION
DAMON 2016

VERSIONED LATCHES: SEARCH 44

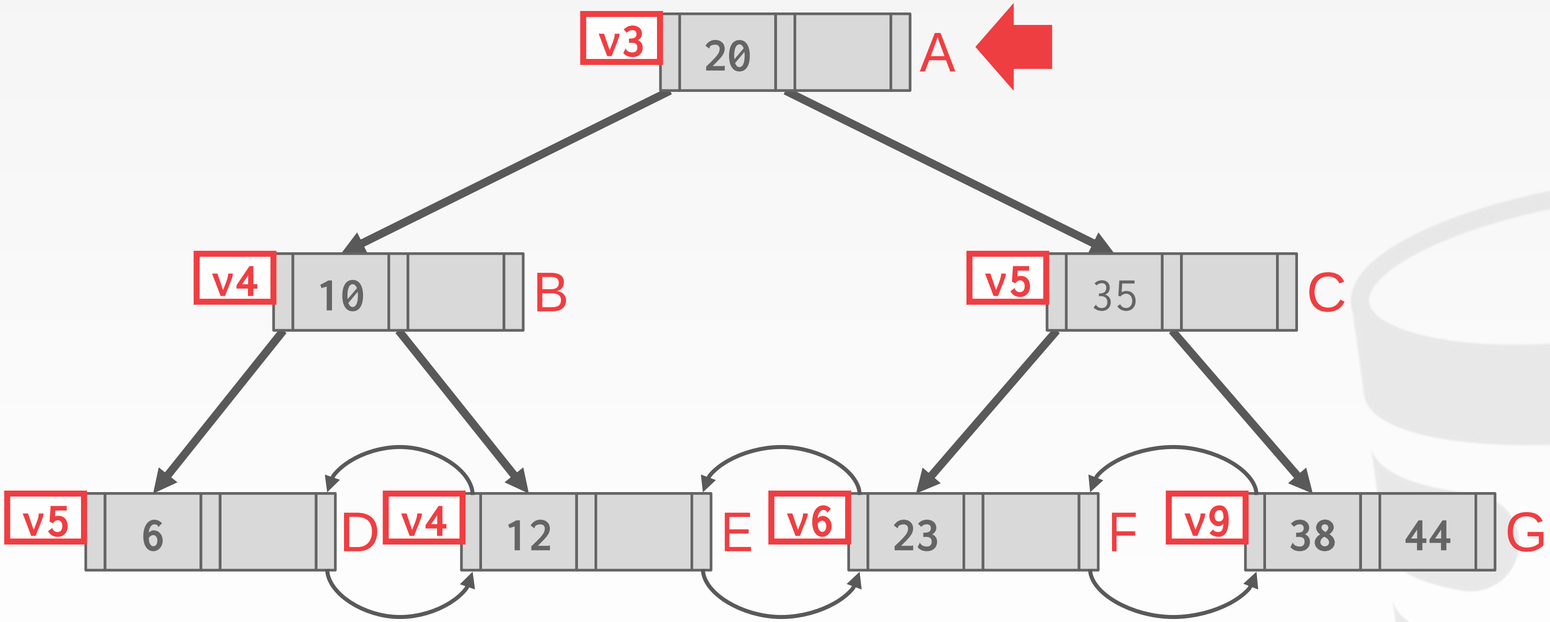
T_1: Find 44



VERSIONED LATCHES: SEARCH 44

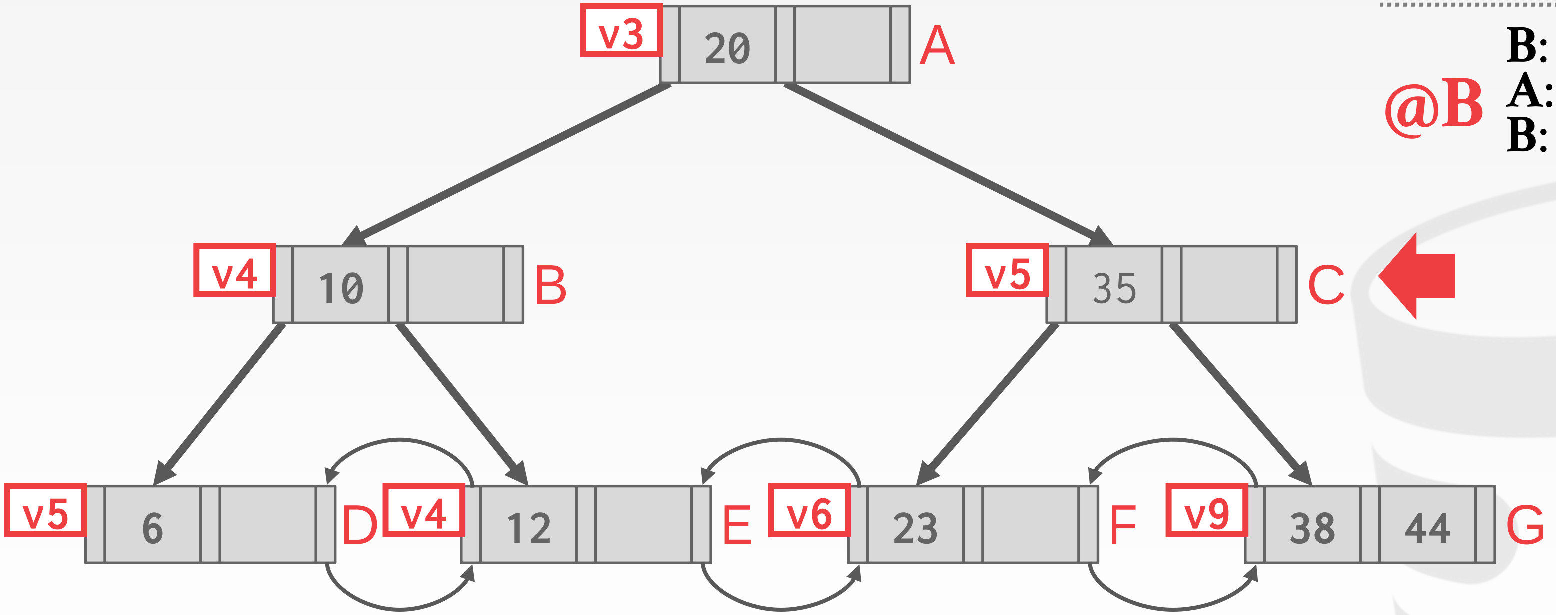
T_1: Find 44

@A
A: Read v3
A: Examine Node



VERSIONED LATCHES: SEARCH 44

T_1: Find 44

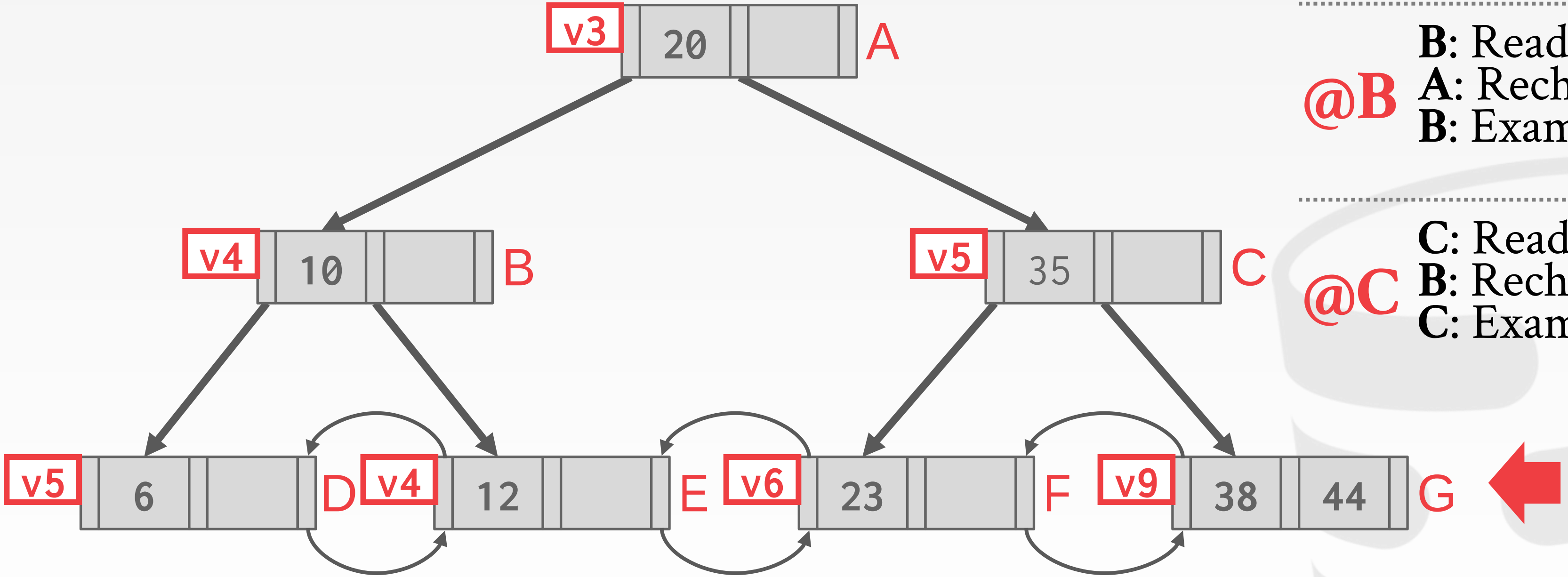


@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

VERSIONED LATCHES: SEARCH 44

T_1: Find 44



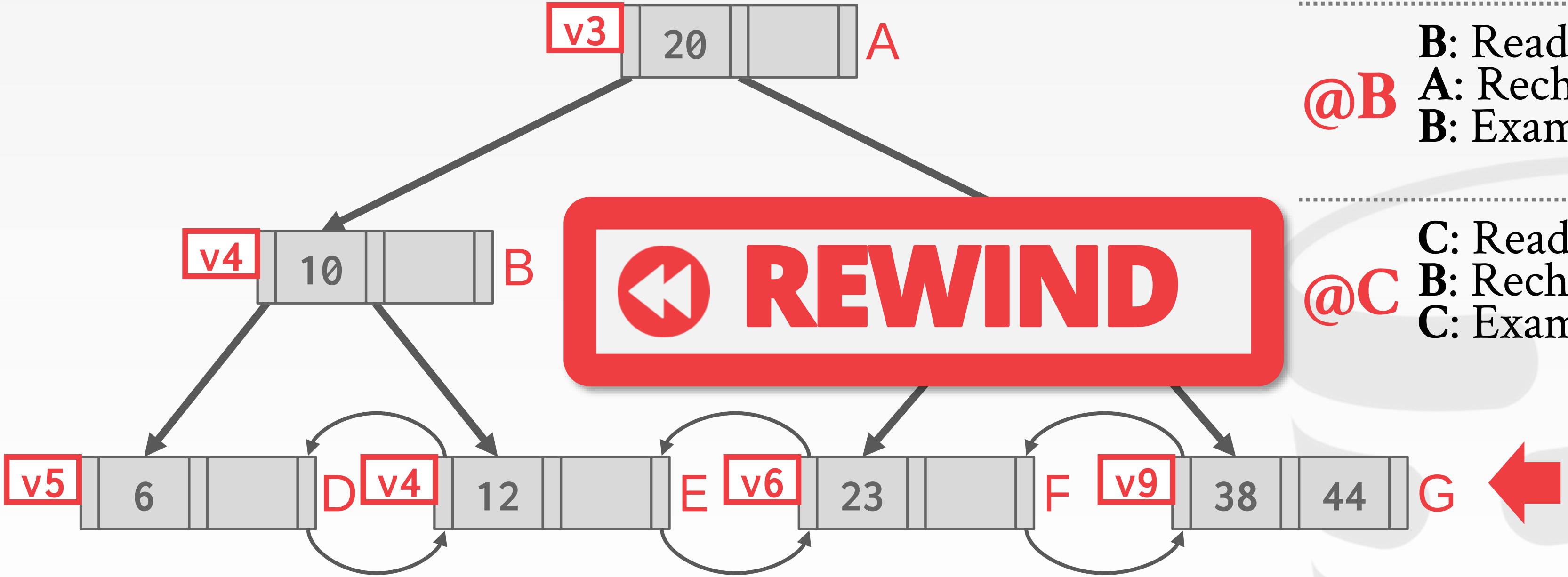
@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

@C
C: Read v9
B: Recheck v5
C: Examine Node

VERSIONED LATCHES: SEARCH 44

T_1: Find 44



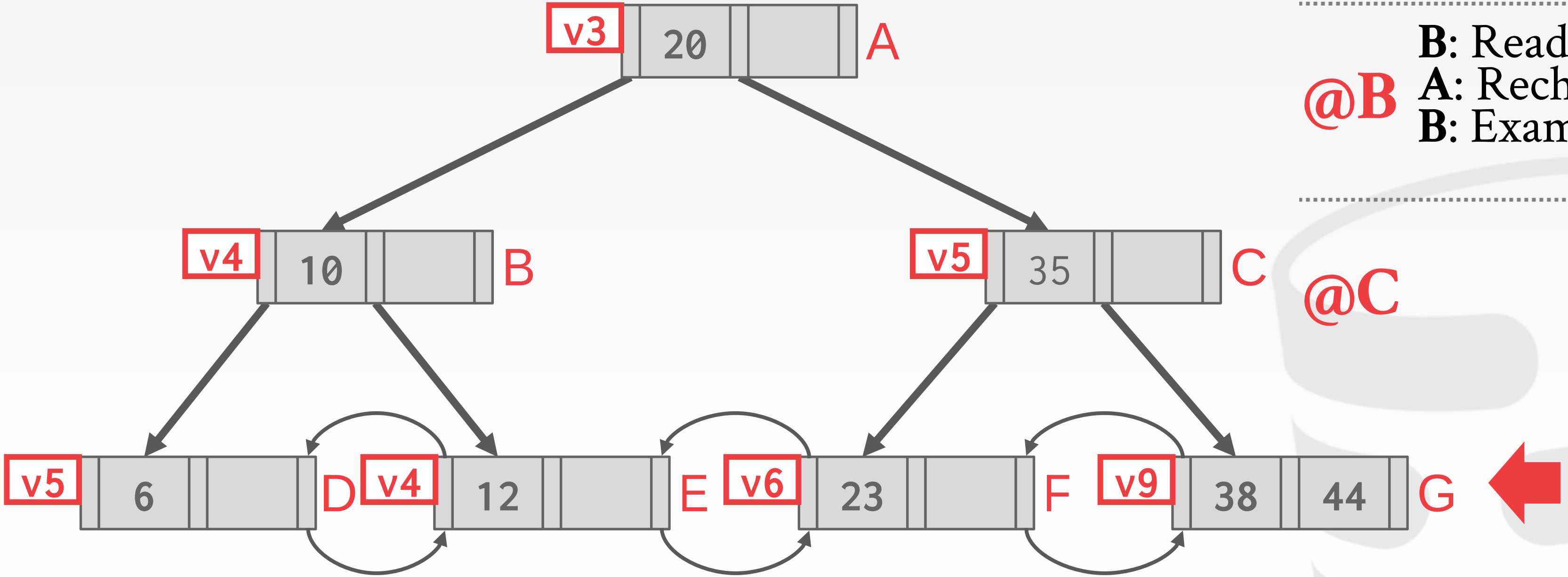
@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

@C
C: Read v9
B: Recheck v5
C: Examine Node

VERSIONED LATCHES: SEARCH 44

T_1: Find 44



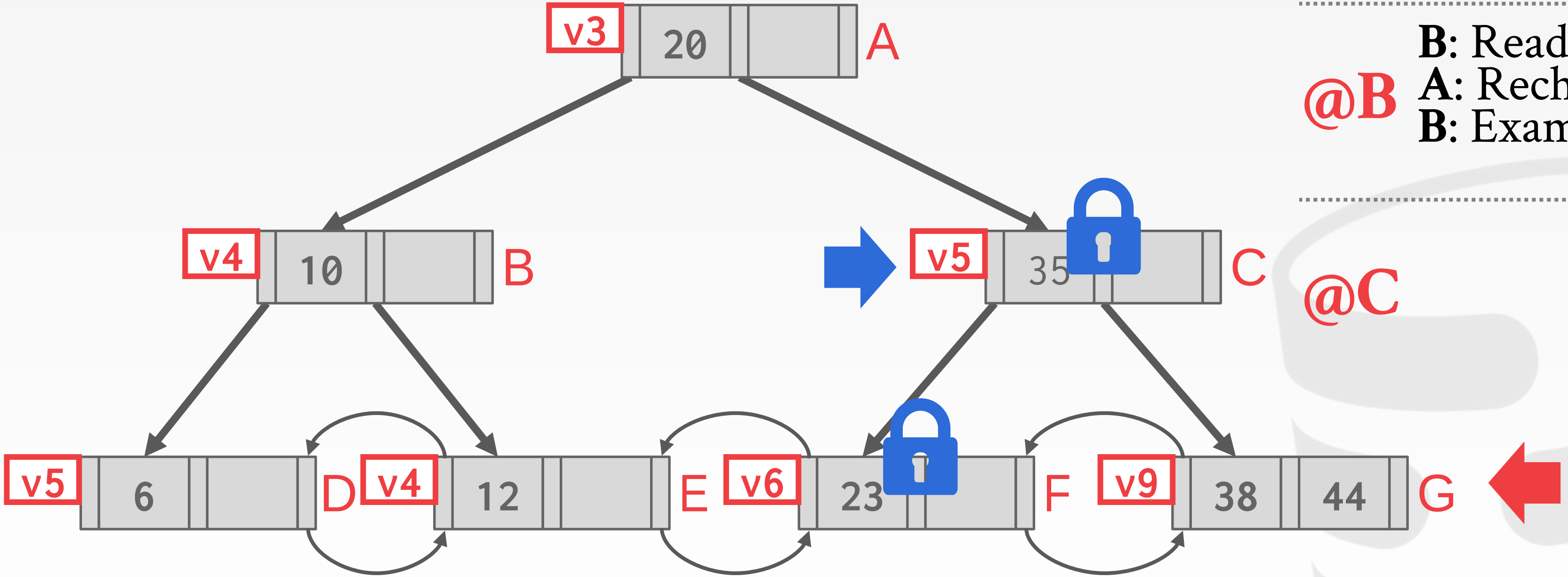
@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

@C

VERSIONED LATCHES: SEARCH 44

T_1: Find 44



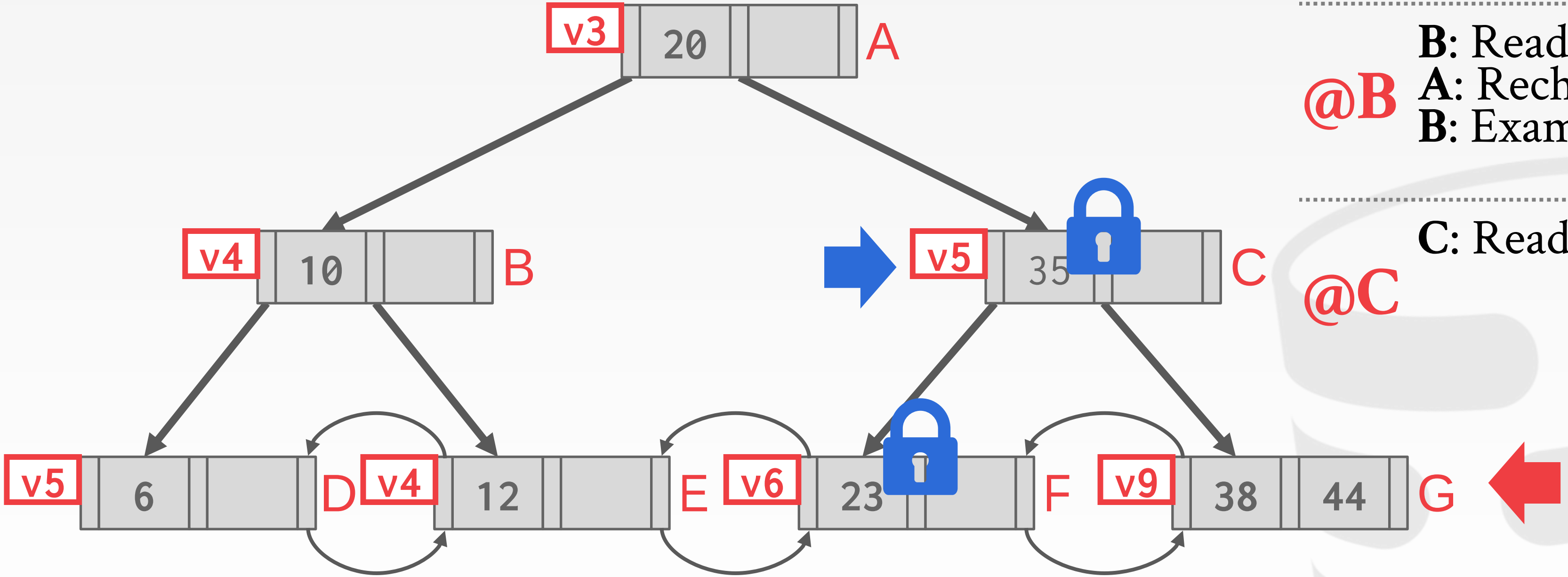
@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

@C

VERSIONED LATCHES: SEARCH 44

T$_1$: Find 44



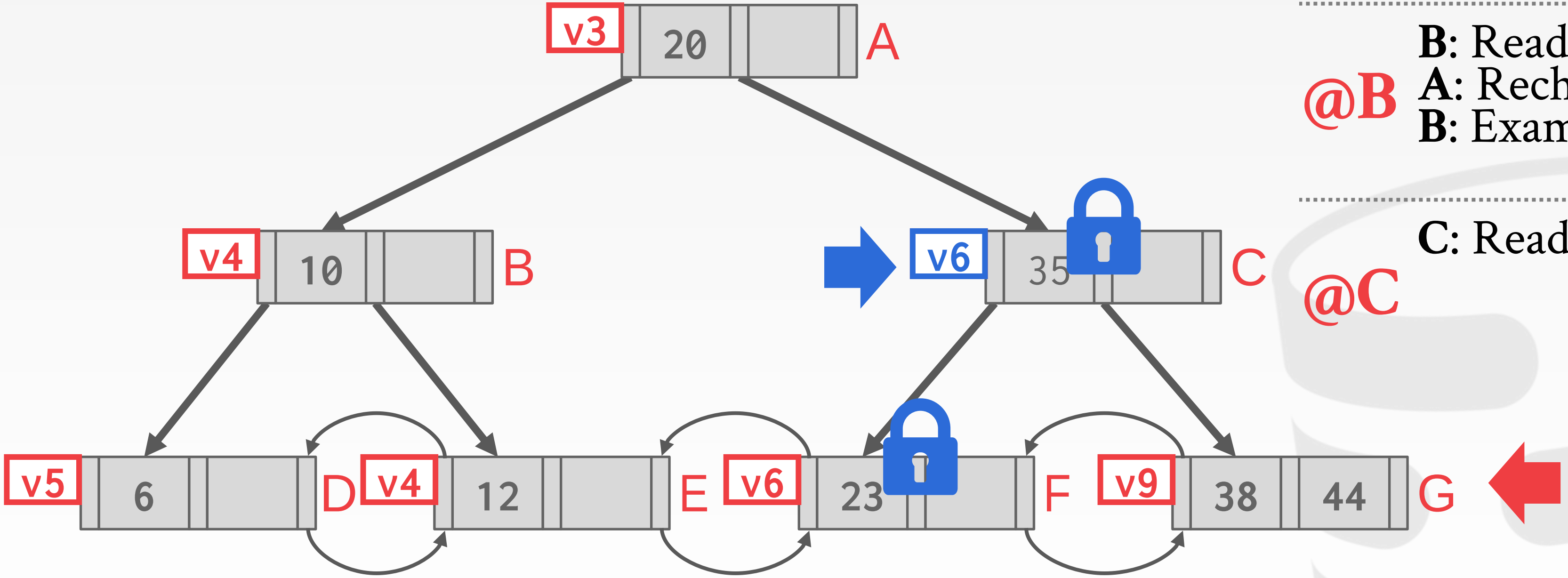
@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

@C
C: Read v9

VERSIONED LATCHES: SEARCH 44

T_1: Find 44



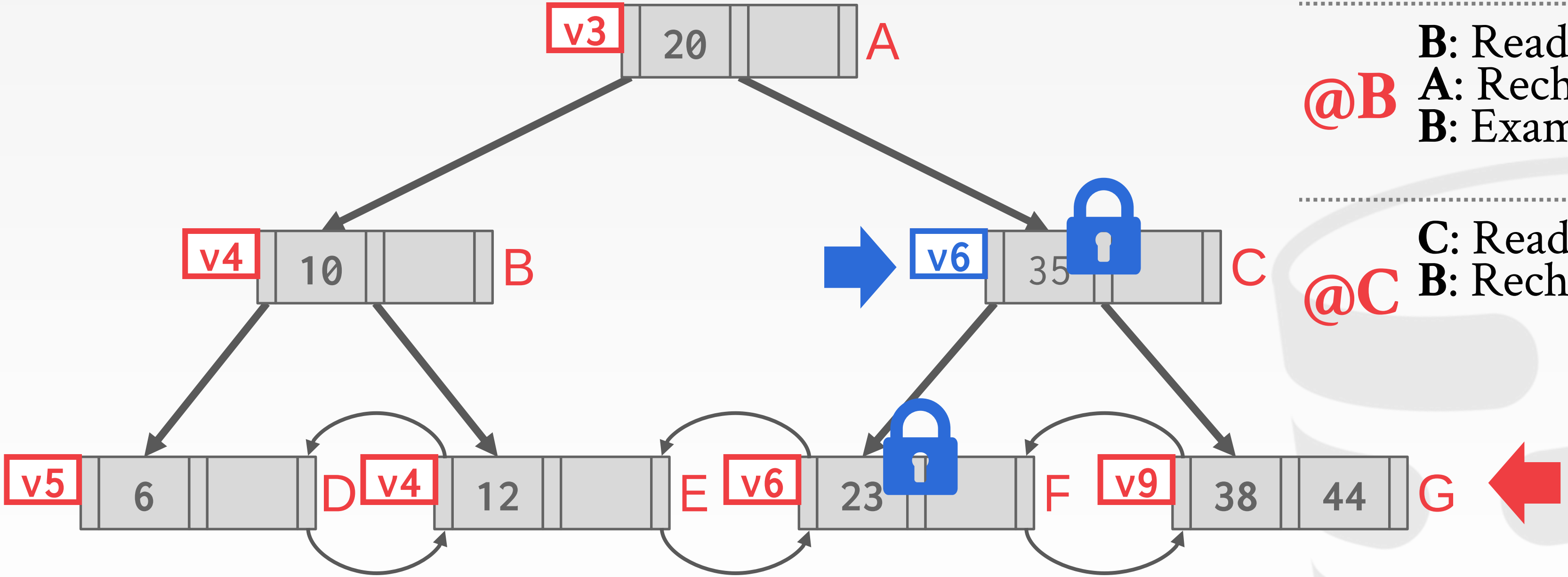
@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

@C
C: Read v9

VERSIONED LATCHES: SEARCH 44

T_1: Find 44



@A
A: Read v3
A: Examine Node

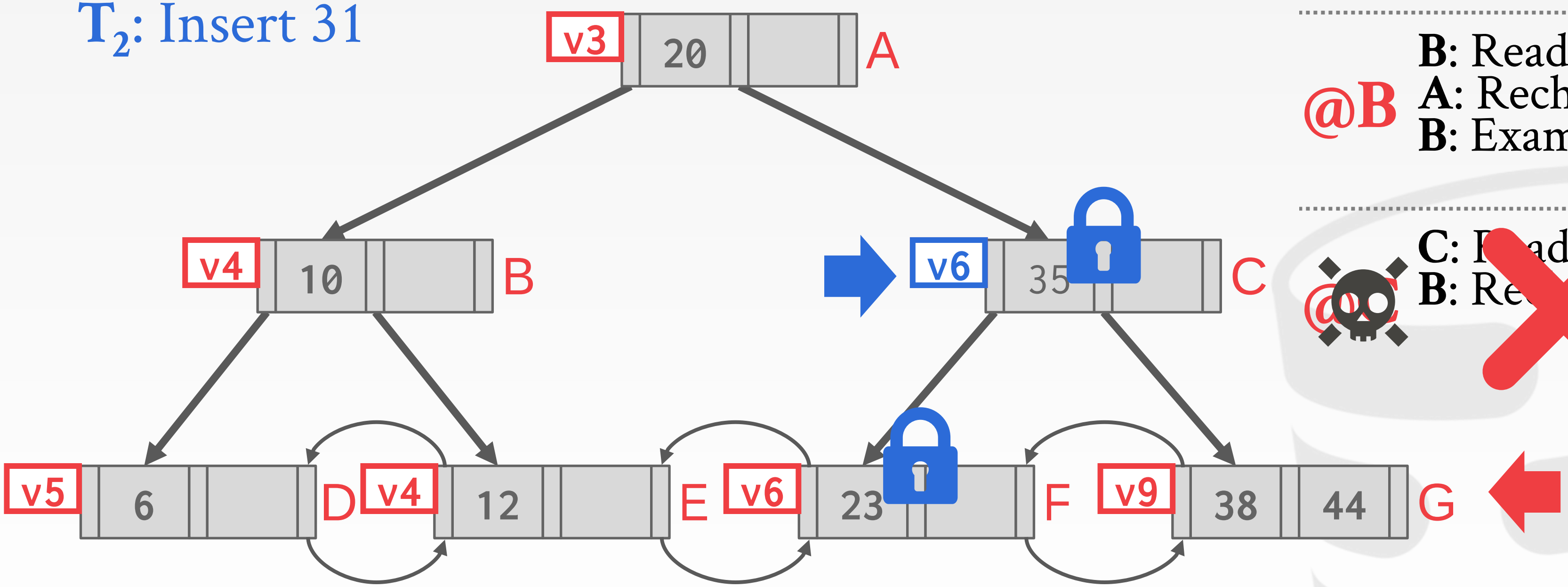
@B
B: Read v5
A: Recheck v3
B: Examine Node

@C
C: Read v9
B: Recheck v5

VERSIONED LATCHES: SEARCH 44

T_1: Find 44

T_2: Insert 31



@A
A: Read v3
A: Examine Node

@B
B: Read v5
A: Recheck v3
B: Examine Node

@[illegible]
C: [illegible]ad [illegible]
B: Re[illegible]ck v5

CONCLUSION

Making a data structure thread-safe is notoriously difficult in practice.

We focused on B+Trees but the same high-level techniques are applicable to other data structures.

NEXT CLASS

We are finally going to discuss how to execute some queries…

PROJECT #2

You will build a thread-safe B+tree.

→ Page Layout
→ Data Structure
→ STL Iterator
→ Latch Crabbing

We define the API for you. You need to provide the method implementations.

https://15445.courses.cs.cmu.edu/fall2020/project2/

CHECKPOINT #1

Due Date: October 11th @ 11:59pm
Total Project Grade: 40%

Page Layouts

→ How each node will store its key/values in a page.
→ You only need to support unique keys.

Data Structure (Find + Insert)

→ Support point queries (single key).
→ Support inserts with node splitting.
→ Does not need to be thread-safe.

CHECKPOINT #2

Due Date: October 25th @ 11:59pm
Total Project Grade: 60%

Data Structure (Deletion)

→ Support removal of keys with sibling stealing + merging.

Index Iterator

→ Create a STL iterator for range scans.

Concurrent Index

→ Implement latch crabbing/coupling.

DEVELOPMENT HINTS

Follow the textbook semantics and algorithms.

Set the page size to be small (e.g., 512B) when you first start so that you can see more splits/merges.

Make sure that you protect the internal B+Tree **root_page_id** member.

THINGS TO NOTE

Do **not** change any other files in the system.

Make sure you pull the latest changes from the main BusTub repo.

Post your questions on Piazza or come to TA office hours.

PLAGIARISM WARNING

Your project implementation must be your own work.

→ You may **not** copy source code from other groups or the web.

→ Do **not** publish your implementation on Github.

Plagiarism will **not** be tolerated.
See CMU's Policy on Academic Integrity for additional information.

COMPARE-AND-SWAP

Atomic instruction that compares contents of a memory location **M** to a given value **V**

→ If values are equal, installs new given value **V'** in **M**

→ Otherwise operation fails

M

20

```
__sync_bool_compare_and_swap(&M, 20, 30)
```

Address (&M) · *Compare Value* (20) · *New Value* (30)

COMPARE-AND-SWAP

Atomic instruction that compares contents of a memory location **M** to a given value **V**

→ If values are equal, installs new given value **V'** in **M**

→ Otherwise operation fails