Endurable Transient Inconsistency in Byte-Addressable Persistent B+-Tree

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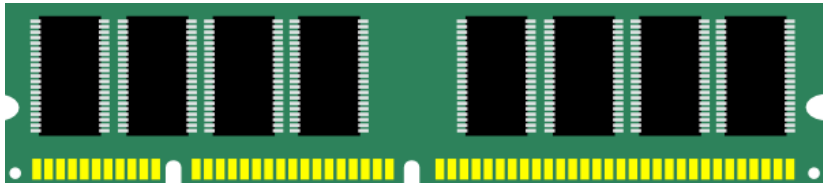
Background – Persistent Memory



Fast but Asymmetric Access Latency

Non-Volatility

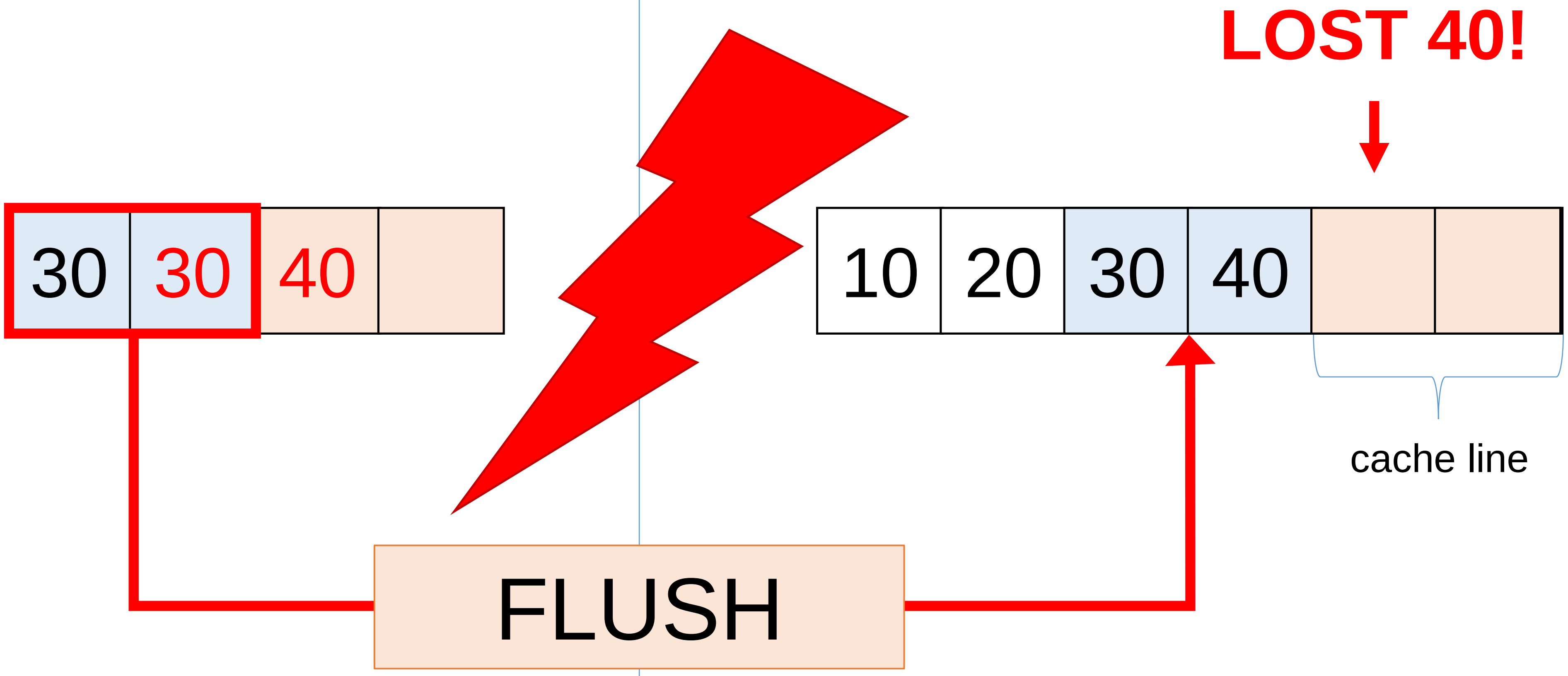
Byte-Addressability

Large Capacity

Background – B+-Tree for Persistent Memory

CPU Caches
(Volatile)

Persistent Memory (Non-Volatile)



LOST 40!

30 30 40

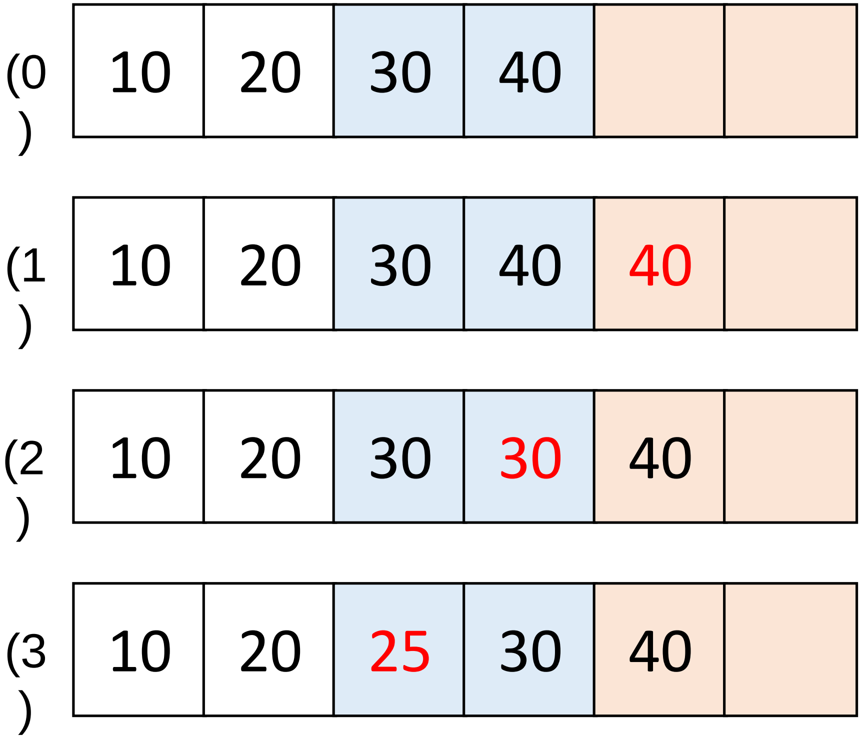
10 20 30 40

cache line

FLUSH

Background – B+-Tree for Persistent Memory

Inserting 25 into a node



(0)	10	20	30	40		
(1)	10	20	30	40	40	
(2)	10	20	30	30	40	
(3)	10	20	25	30	40	

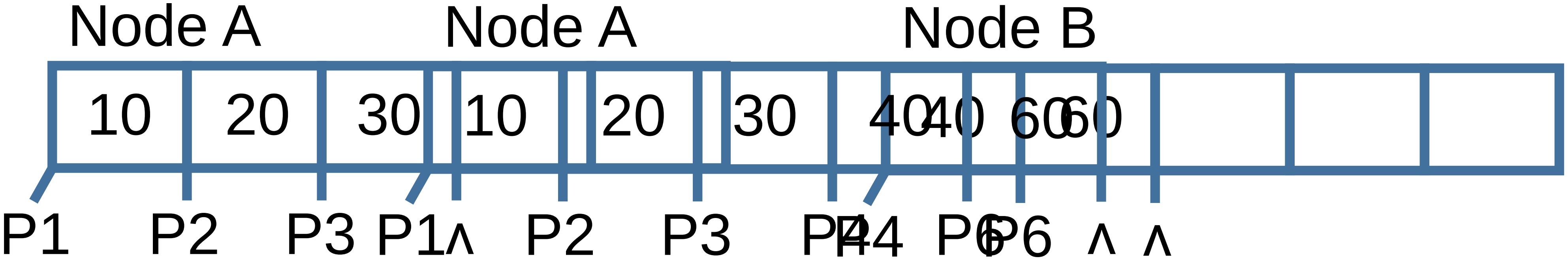
Partially updated tree node is inconsistent

↓

Append-Only Update

Background – B+-Tree for Persistent Memory

Node Split


Node A Node A Node B

10 20 30 10 20 30 40 40 60 60

P1 P2 P3 P1 ∧ P2 P3 P4 P4 P6 P6 ∧ ∧

Logging → Selective Persistence (Internal node in DRAM)

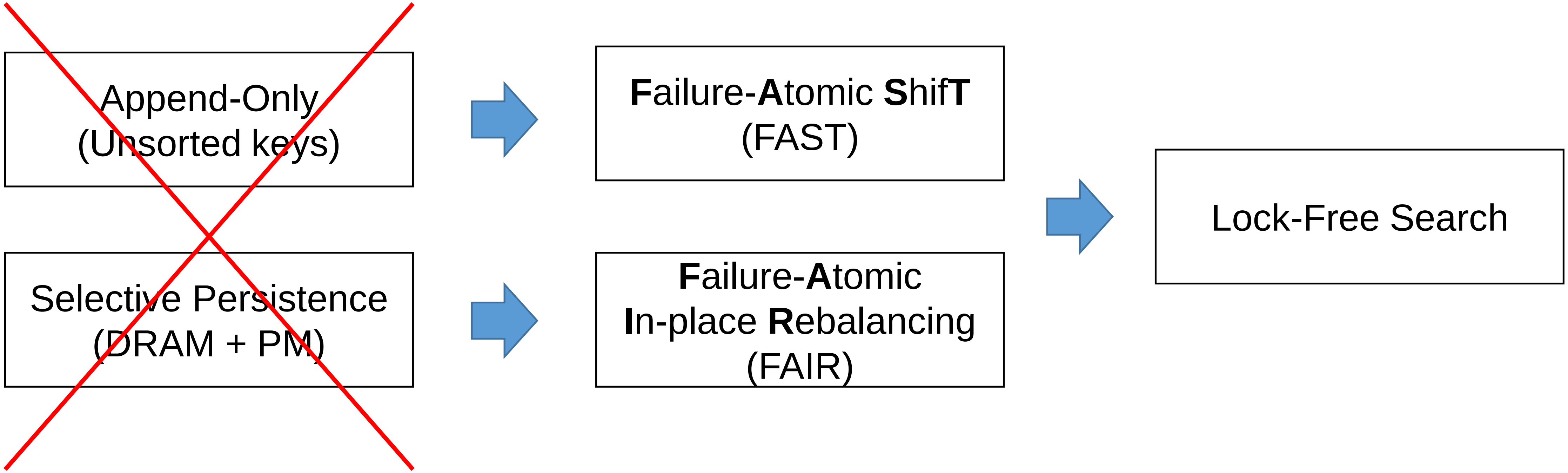
Background – B+-Tree for Persistent Memory

- Append-Only
  - Unsorted keys
- Selective Persistence
  - Internal node → DRAM
  - Internal nodes have to be reconstructed from leaf nodes after failures
  - Logging for leaf nodes

- Previous solutions

NV-Tree [FAST'15]	Append-Only leaf update + Selective Persistence
wB+-Tree [VLDB'15]	Append-Only node update + bitmap/slot array metadata
FP-Tree [SIGMOD'16]	Append-Only leaf update + fingerprints + Selective Persistence

Contributions



~~Append-Only~~
~~(Unsorted keys)~~

~~Selective Persistence~~
~~(DRAM + PM)~~

Failure-**A**tomic **S**hif**T**
(FAST)

Failure-**A**tomic
In-place **R**ebalancing
(FAIR)

Lock-Free Search

Background – Reordering Memory Access

- Modern processors reorder instructions to utilize the memory bandwidth
- Memory ordering in x86 and ARM

	x86	**ARM**
stores-after-stores	Y	N
stores-after-loads	N	N
loads-after-stores	N	N
loads-after-loads	N	N
Inst. w/ dependency	Y	Y

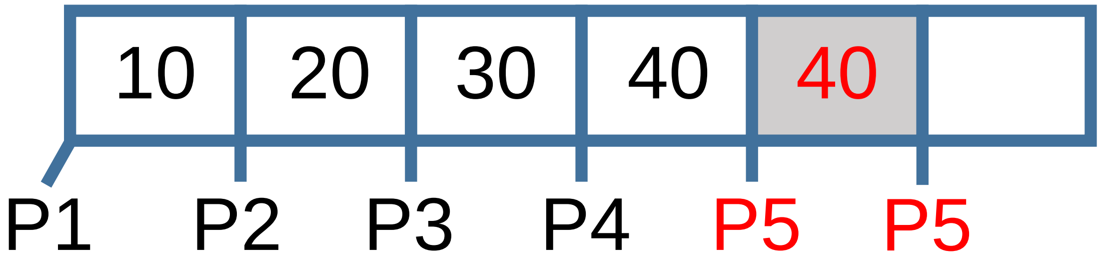
- x86 guarantees **Total Store Ordering (TSO)**
- Dependent instructions are not reordered

Failure-Atomic ShifT (FAST)

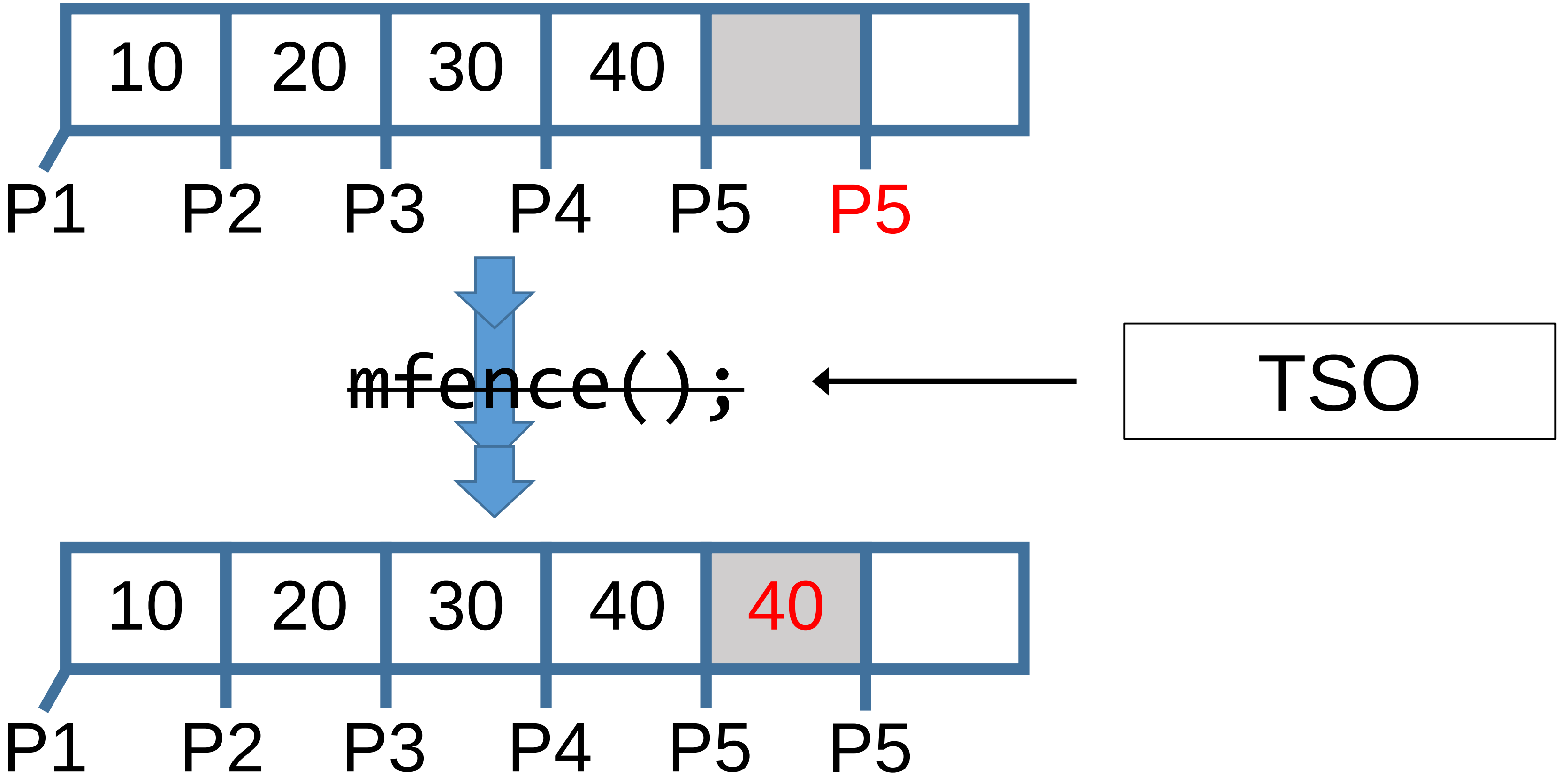
- Pointers in B+-Tree store unique memory addresses
- 8-byte pointer can be atomically updated

Read transactions detect *transient inconsistency* between duplicate pointers

- *transient inconsistency*
    - In-flight state partially updated by a write transaction

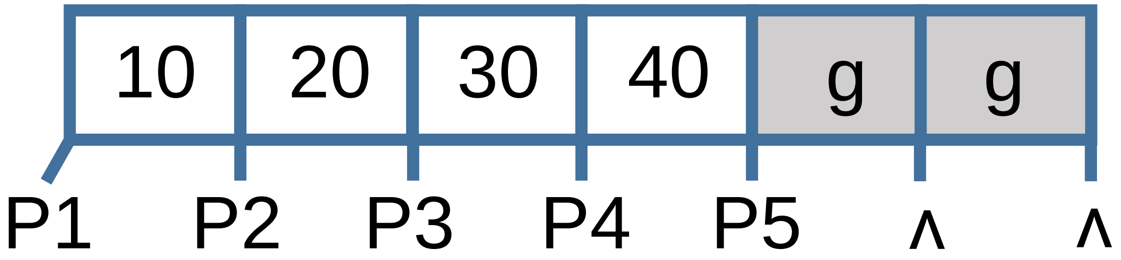


Failure-Atomic ShifT (FAST)



Failure-Atomic ShifT (FAST)

Insert (25, P6) into a node using FAST

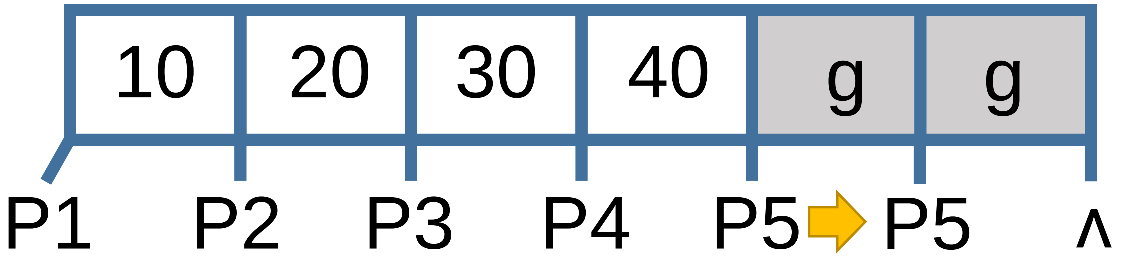


g: Garbage
ʌ: Null

Read transactions can succeed in finding a key even if a system crashes in any step

Failure-Atomic ShifT (FAST)

Insert (25, P6) into a node using FAST



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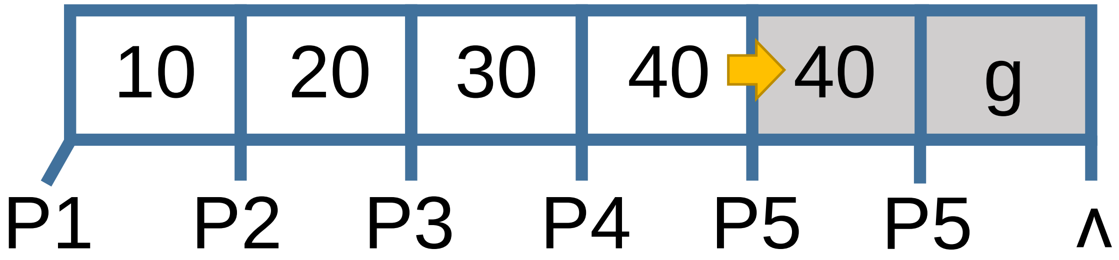

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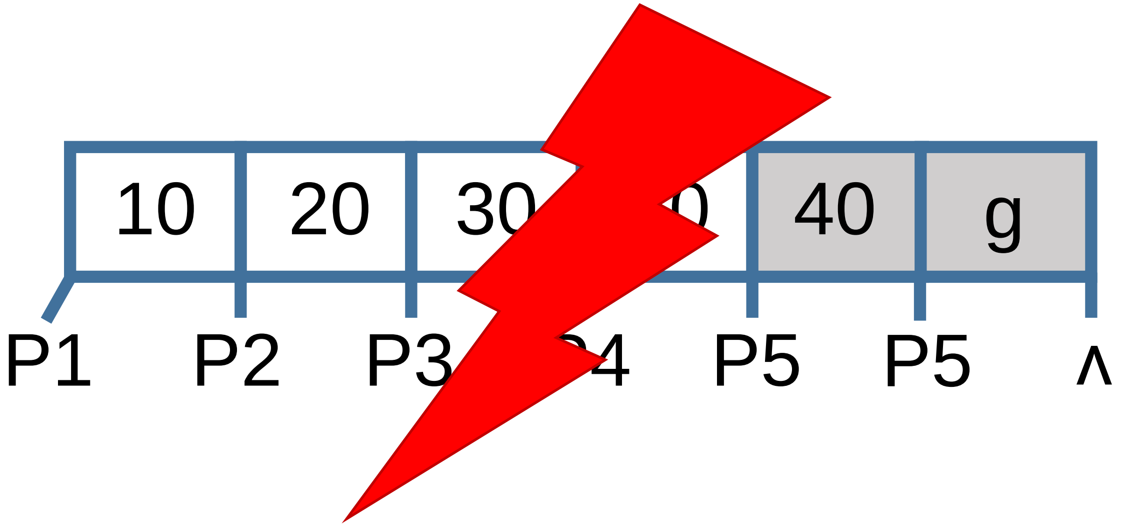
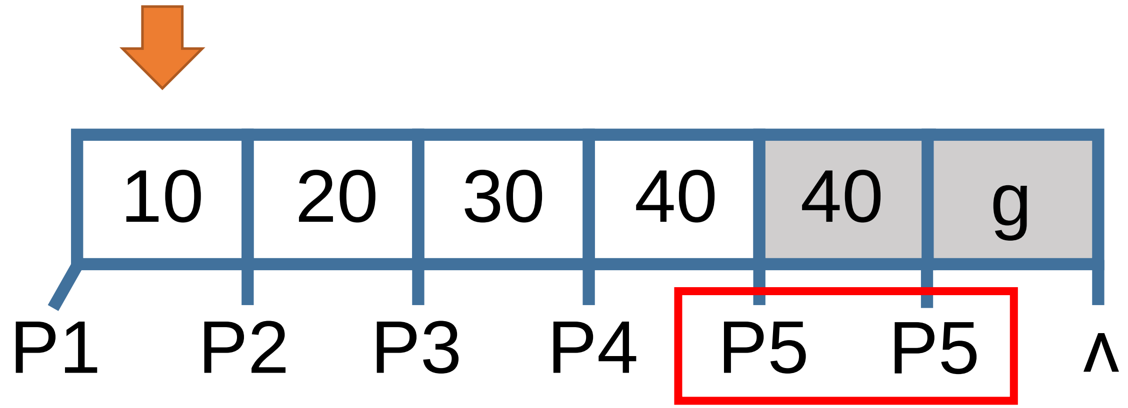


Failure-Atomic ShifT (FAST)

Insert (25, P6) into a node using FAST

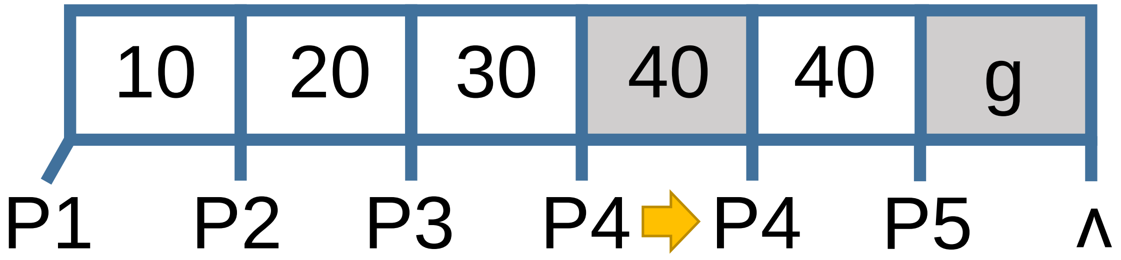
read transaction



Key 40 between duplicate pointers is ignored!

Failure-Atomic ShifT (FAST)

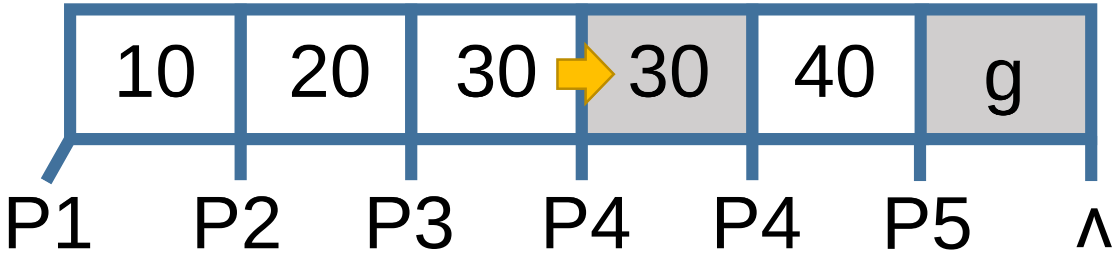
Insert (25, P6) into a node using FAST



Shifting P4 invalidates the left 40

Failure-Atomic ShifT (FAST)

Insert (25, P6) into a node using FAST



Failure-Atomic ShifT (FAST)

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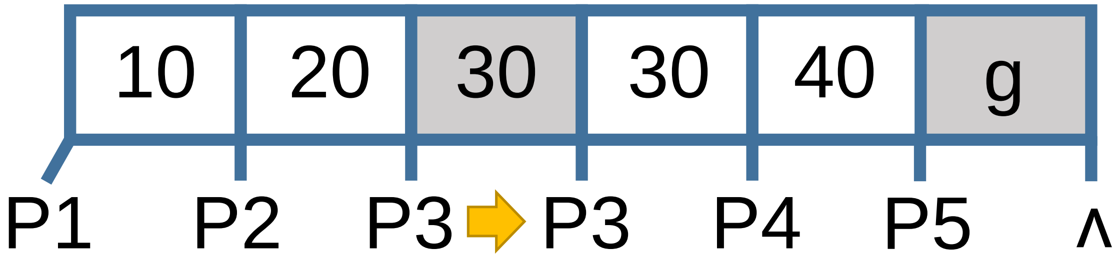
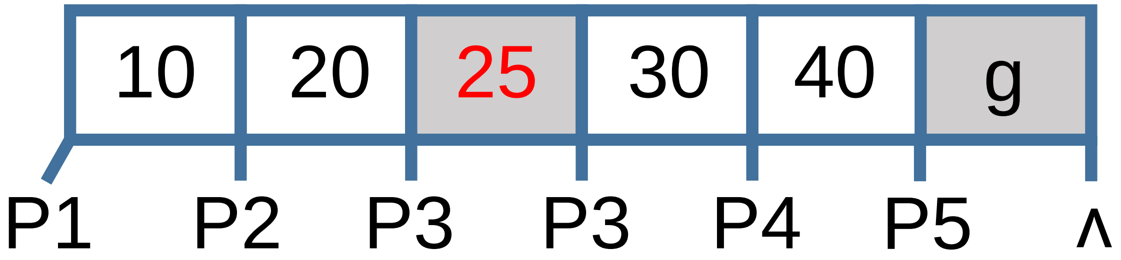


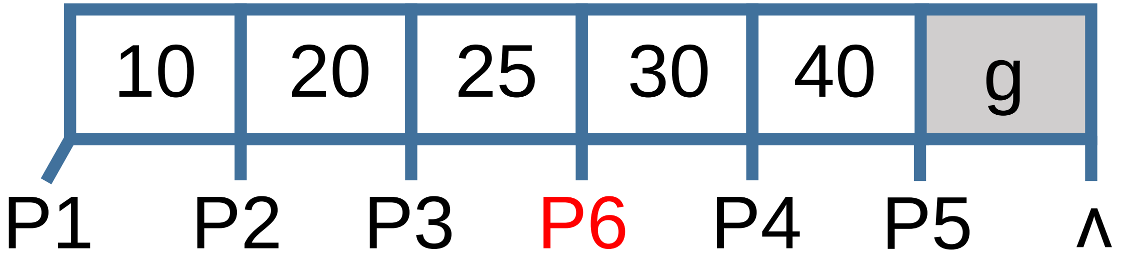
Failure-Atomic ShifT (FAST)

Insert (25, P6) into a node using FAST



Failure-Atomic ShifT (FAST)

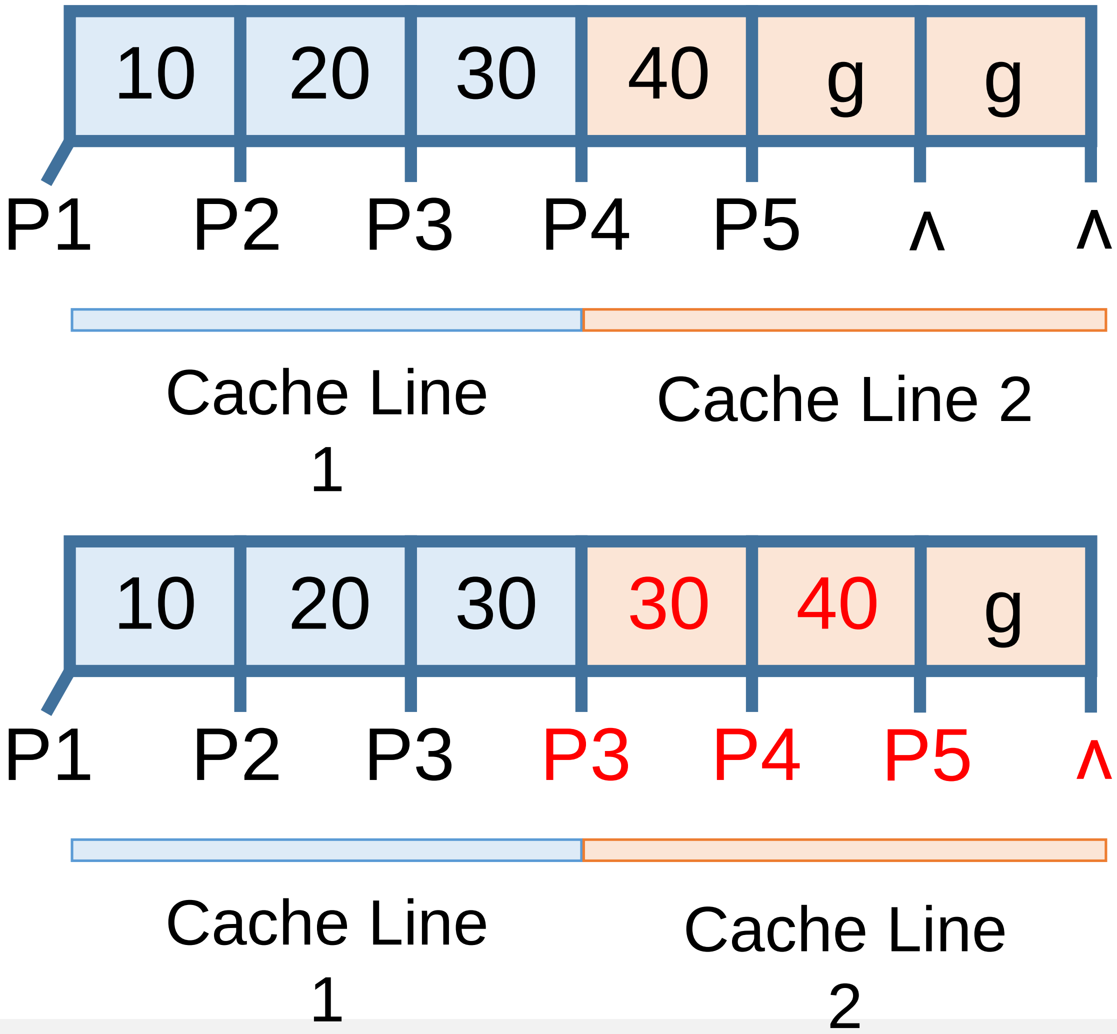
Insert (25, P6) into a node using FAST



Storing P6 validates 25

Failure-Atomic ShifT (FAST)

- It is necessary to call `clflush` at the boundary of cache line



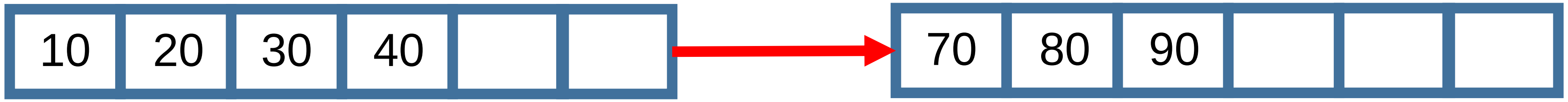
```
mfence()
clflush( Cache Line 2 )
mfence()
```

Failure-Atomic In-place Rebalancing (FAIR)

- Let's avoid expensive logging

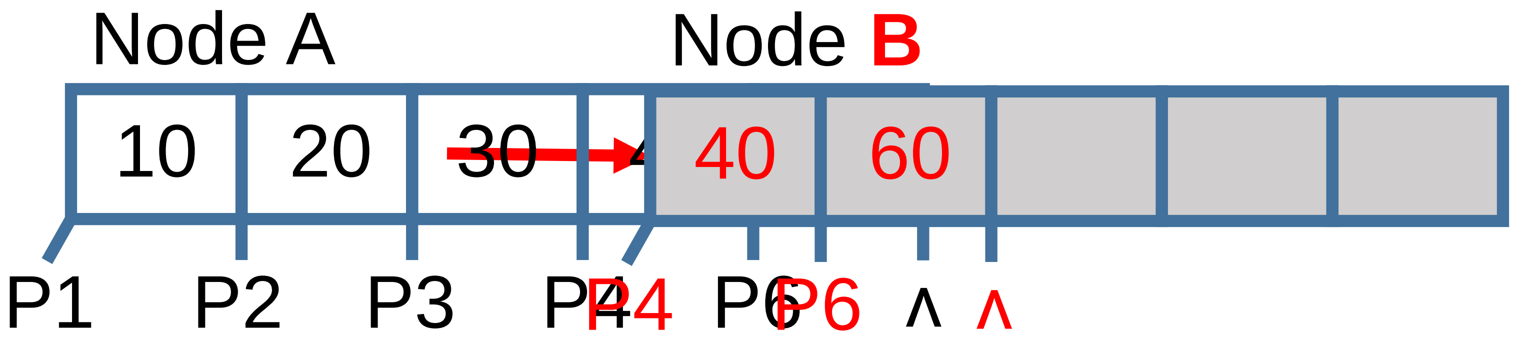
by making read transactions
be aware of rebalancing operations

- B^{link}-Tree



Failure-Atomic In-place Rebalancing (FAIR)

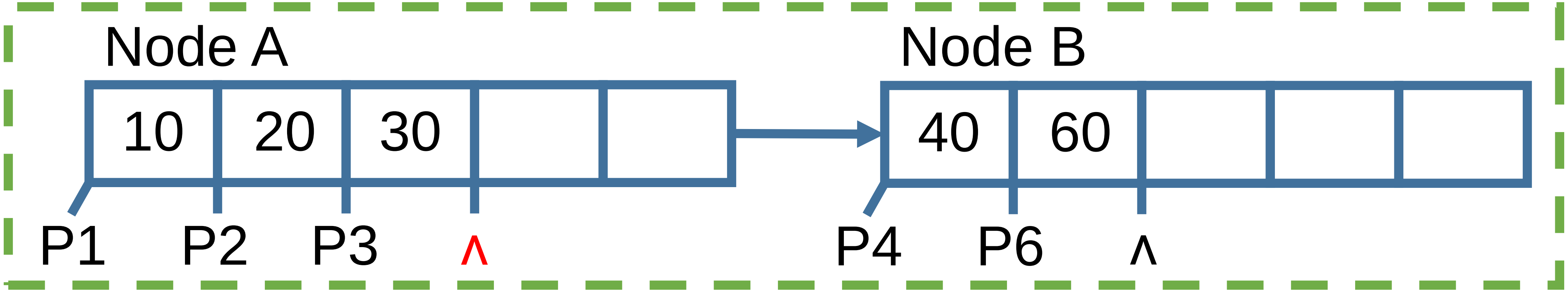
FAIR split a node



A read transaction can detect transient inconsistency if keys are out of order

Failure-Atomic In-place Rebalancing (FAIR)

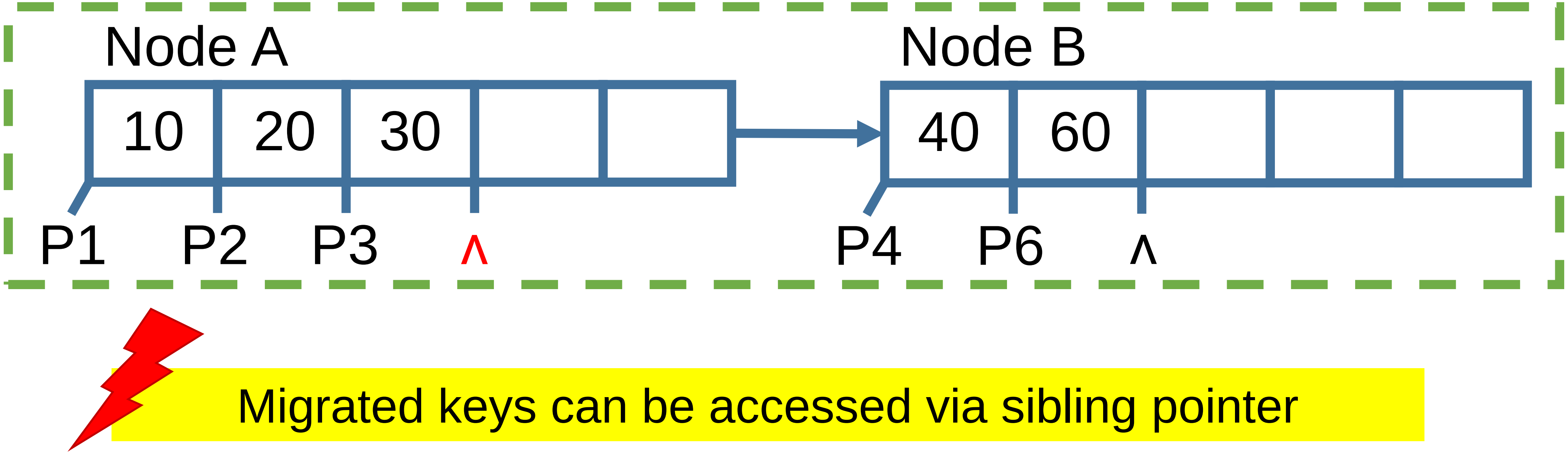
FAIR split a node



Setting NULL pointer validates Node B.
Node A and Node B are virtually a single node

Failure-Atomic In-place Rebalancing (FAIR)

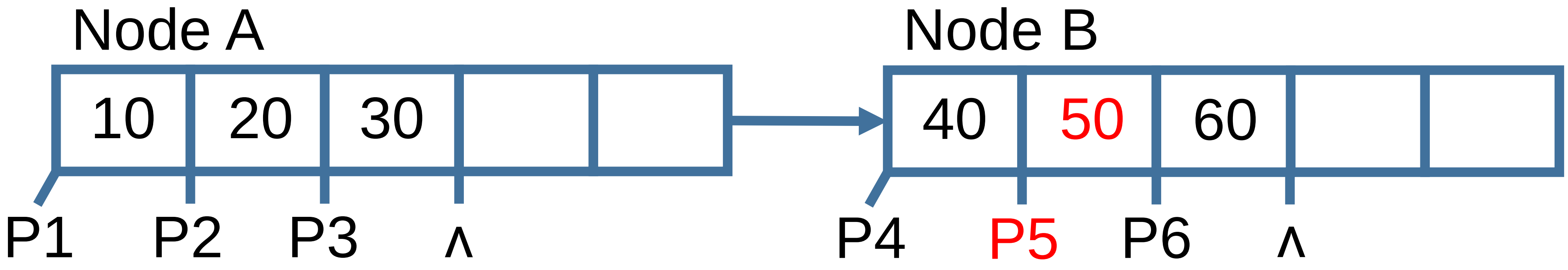
FAIR split a node



Migrated keys can be accessed via sibling pointer

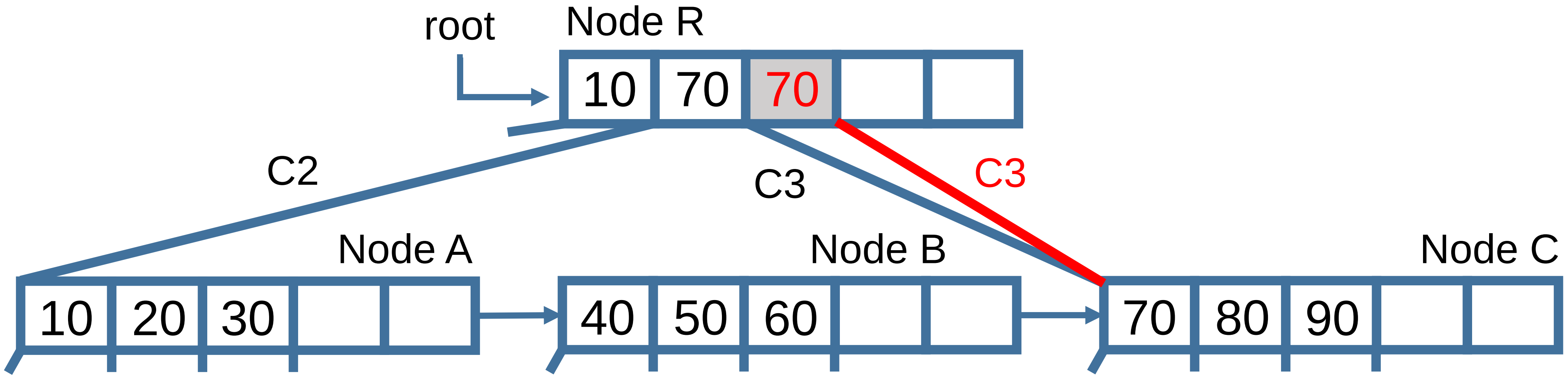
Failure-Atomic In-place Rebalancing (FAIR)

FAIR split a node



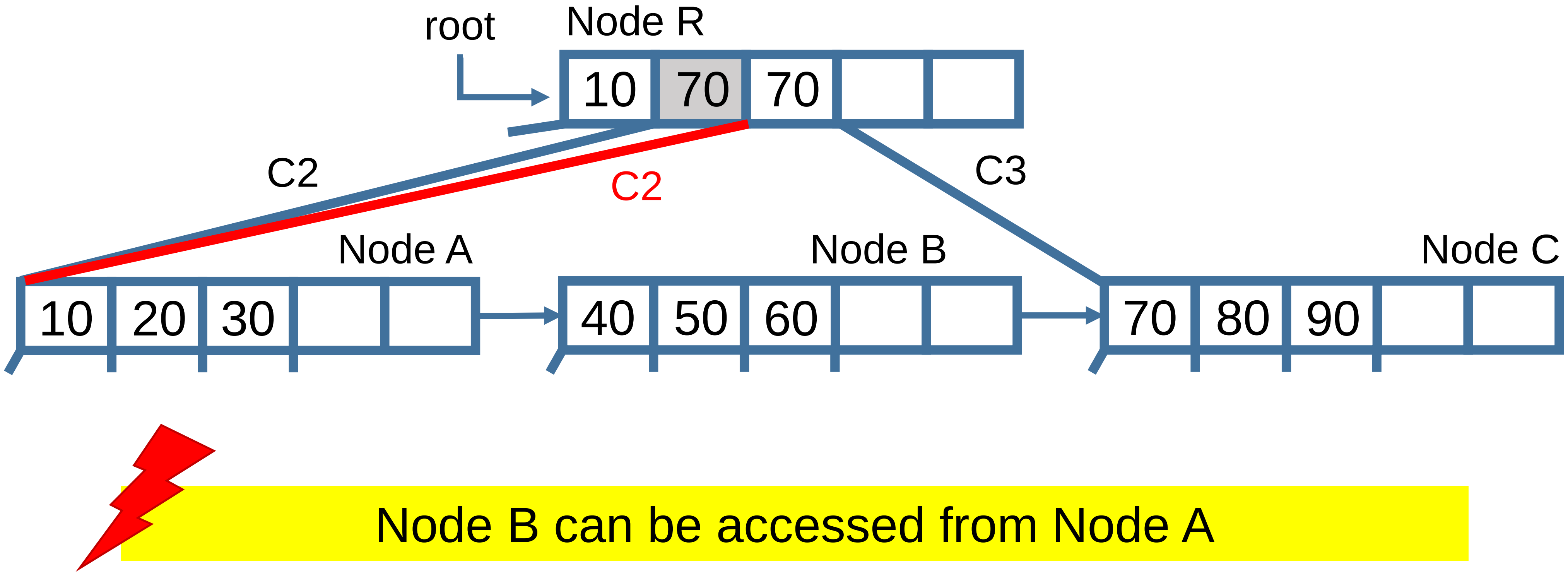
Failure-Atomic In-place Rebalancing (FAIR)

Insert a key into the parent node using FAST after FAIR split



Failure-Atomic In-place Rebalancing (FAIR)

Insert a key into the parent node using FAST after FAIR split

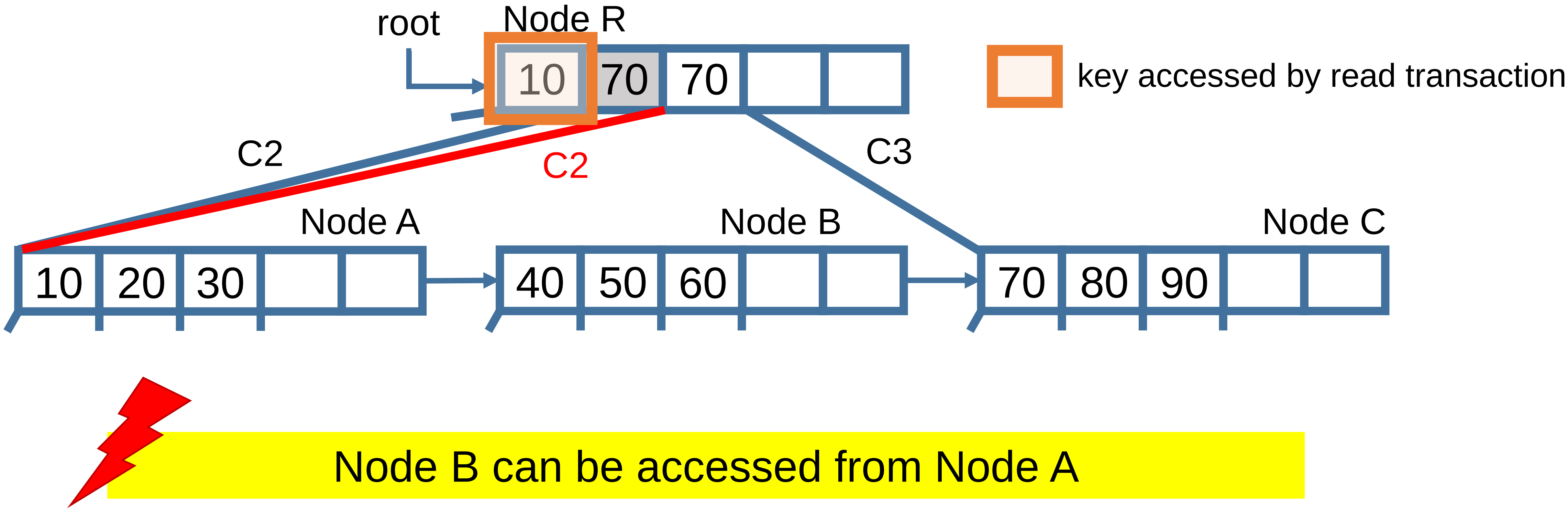


Node B can be accessed from Node A

Failure-Atomic In-place Rebalancing (FAIR)

Insert a key into the parent node using FAST after FAIR split

- Searching the key 50 from the root after a system crash



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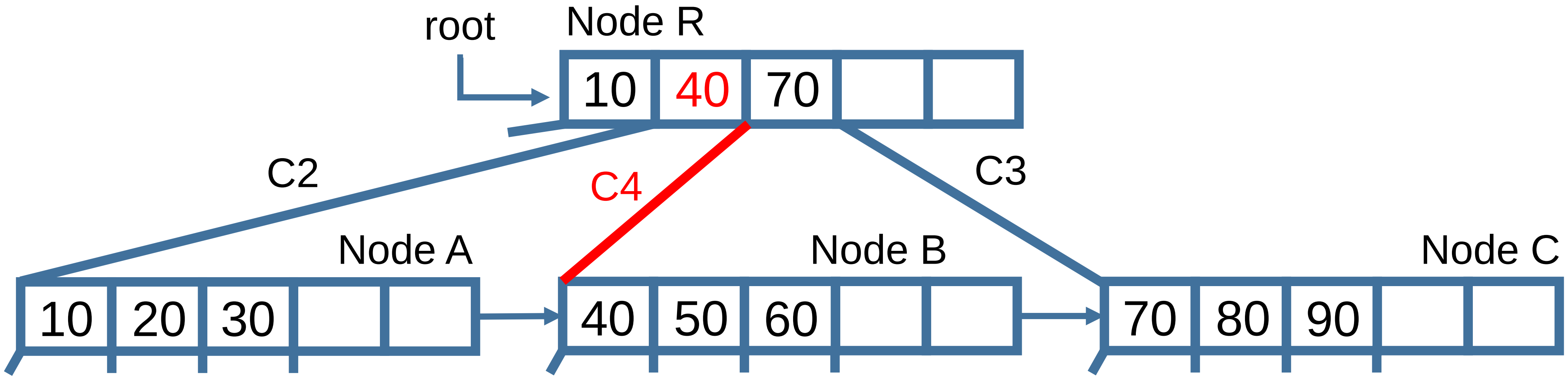
Insert a key into the parent node using FAST after FAIR split



FAST inserting makes Node B visible atomically

Lock-Free Search

Read transactions can tolerate any inconsistency caused by write transactions

↓

Read transactions can access the transient inconsistent tree node being modified by a write transaction

↓

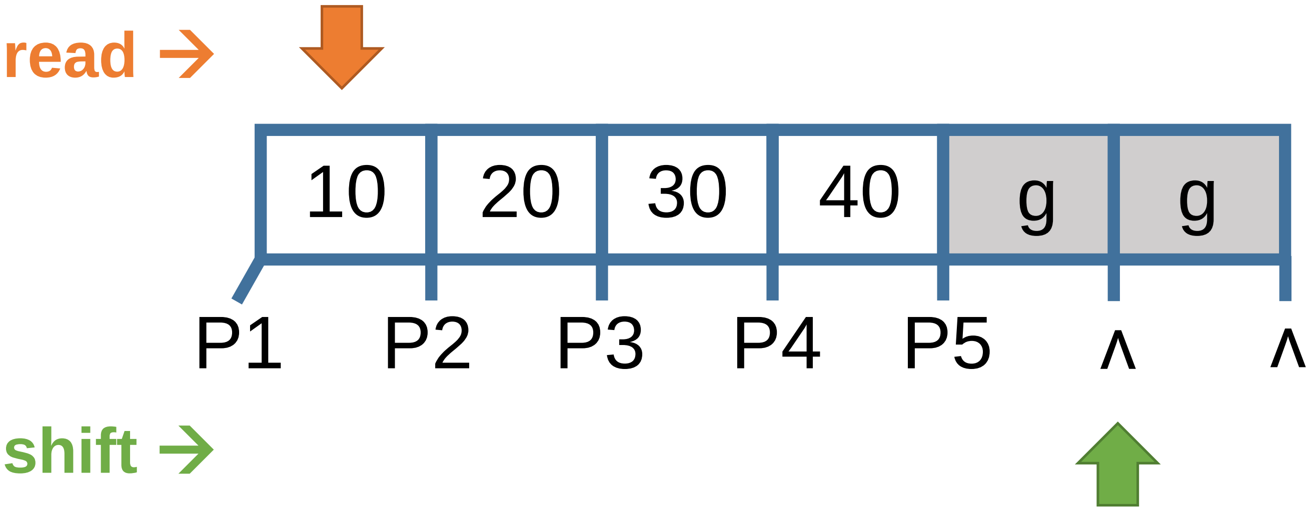
Lock-Free Search

Lock-Free Search

[Example 1] Searching 30 while inserting (15, P6)

⬇ Read transaction

⬆ Write transaction



Lock-Free Search

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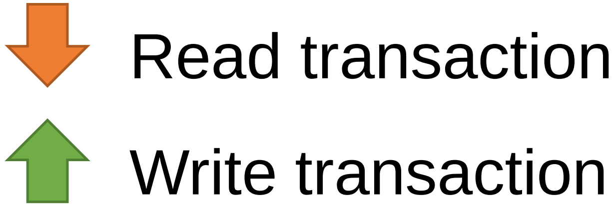

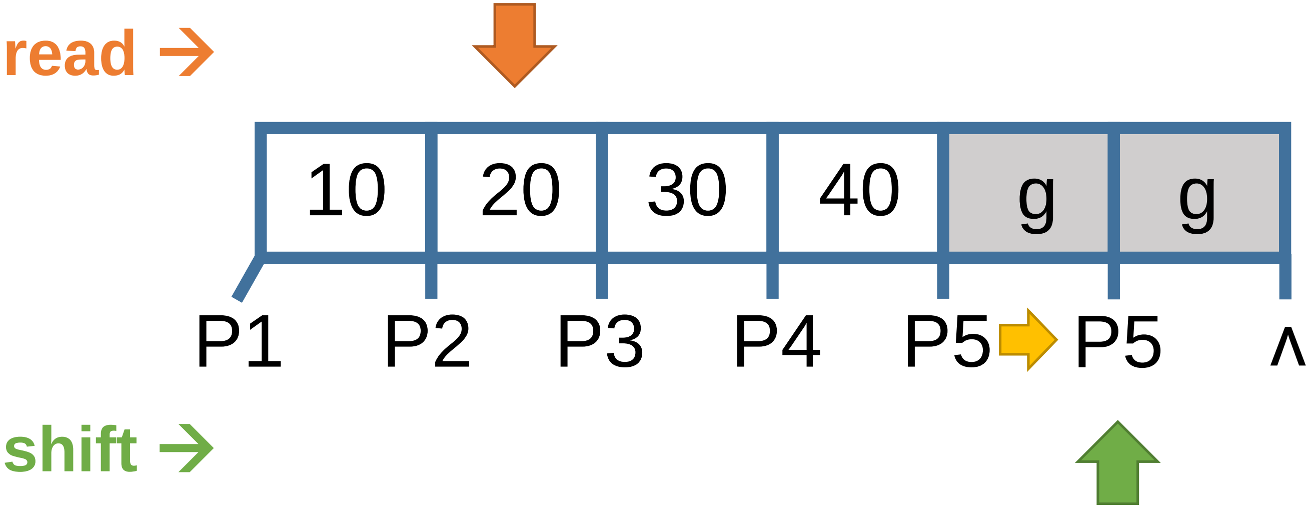

Lock-Free Search

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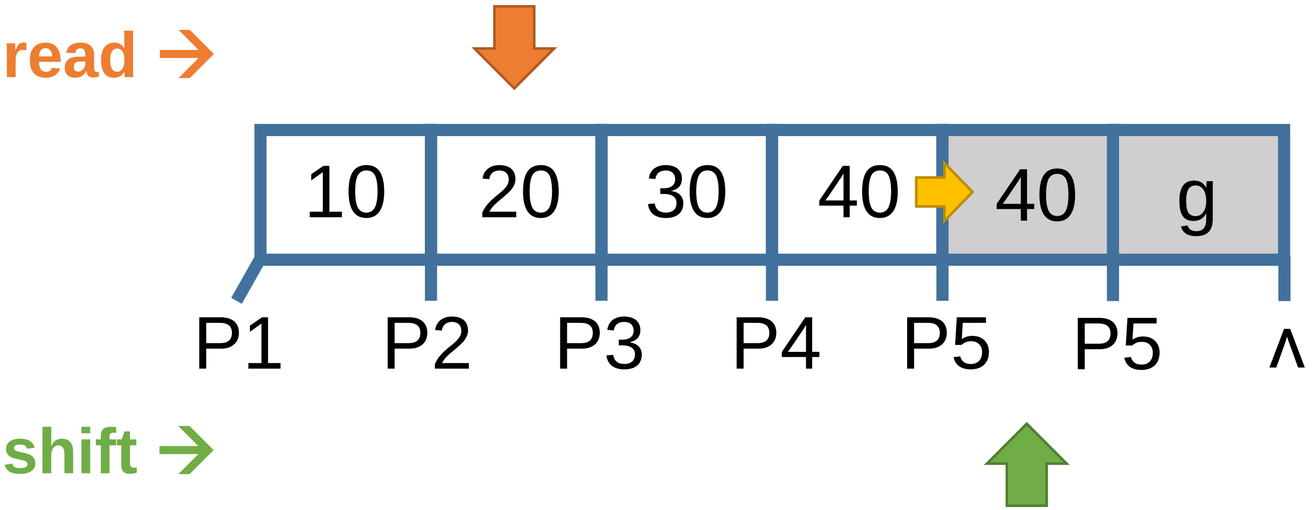
↓ Read transaction

↑ Write transaction



Lock-Free Search

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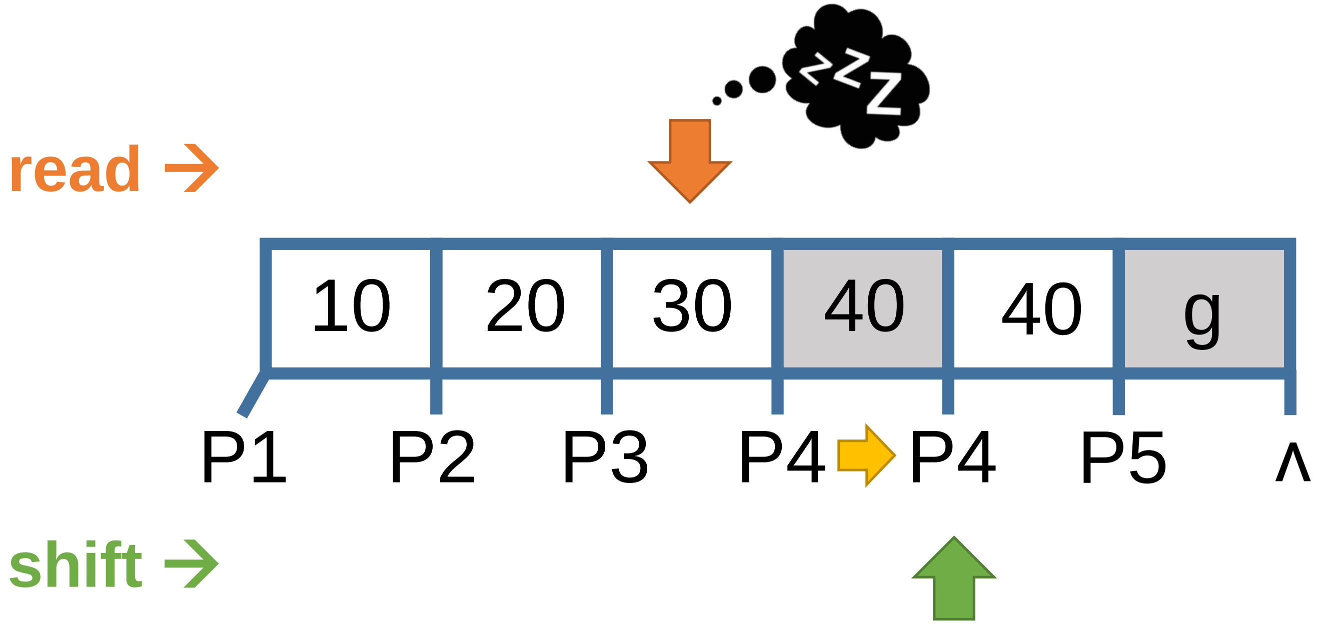


read →

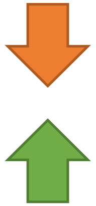
10	20	30	40	40	g

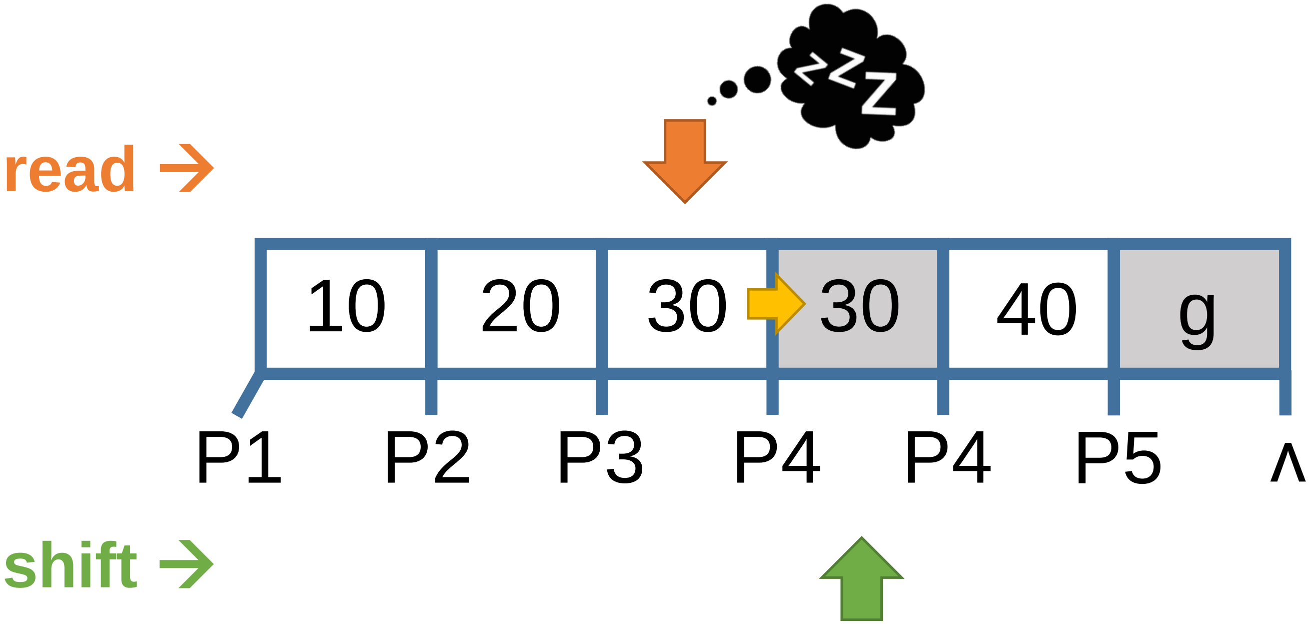
P1 P2 P3 P4 ⇨ P4 P5 ∧

shift →

Lock-Free Search

[Example 1] Searching 30 while inserting (15, P6)





Lock-Free Search

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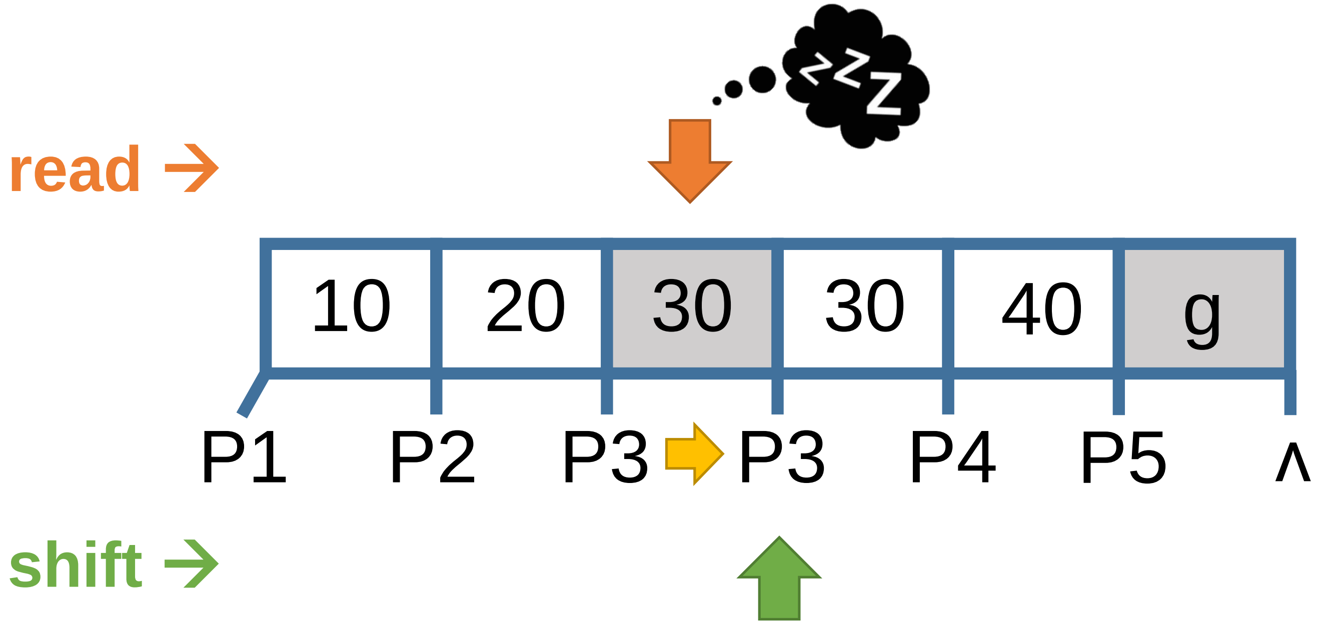

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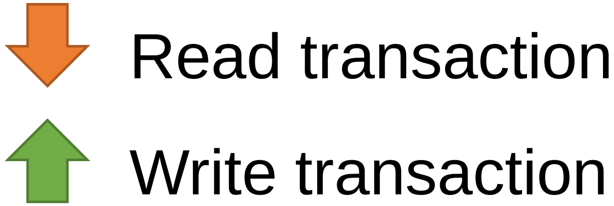

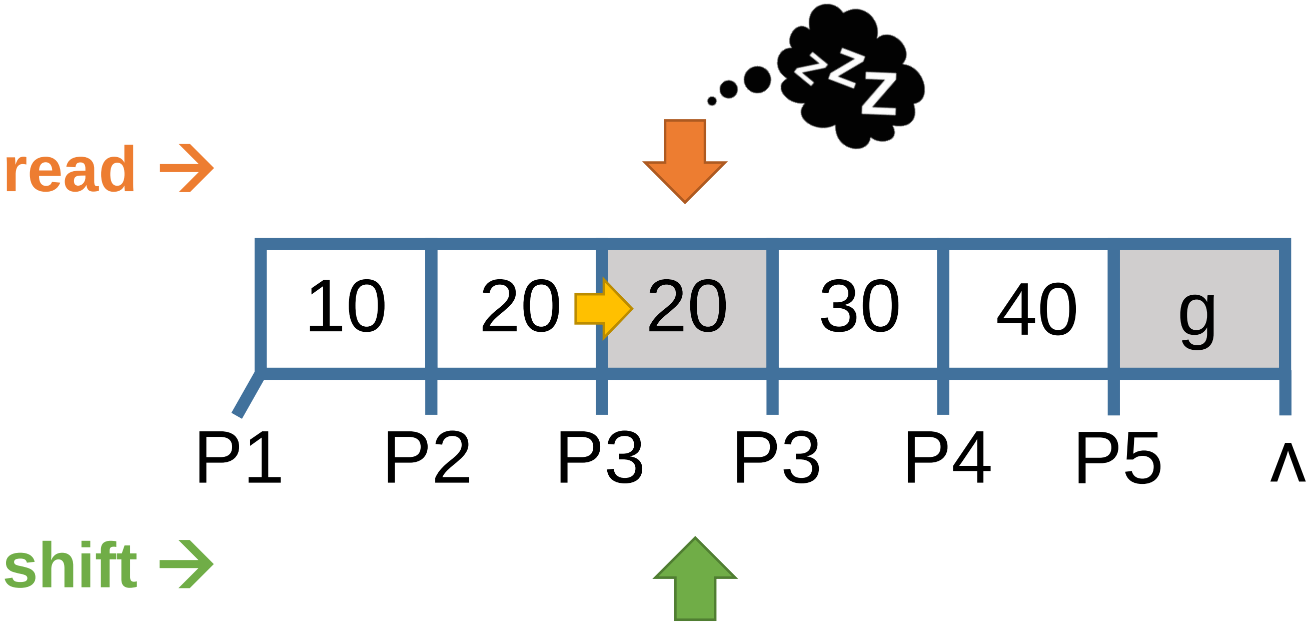

Lock-Free Search

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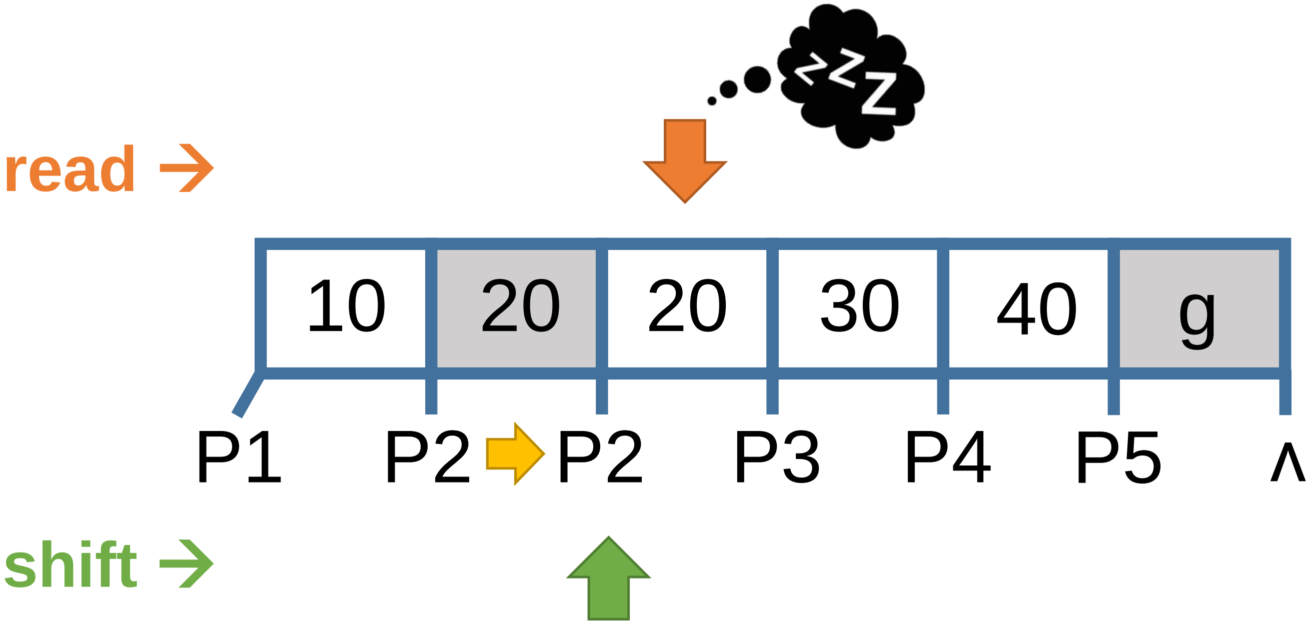

Lock-Free Search

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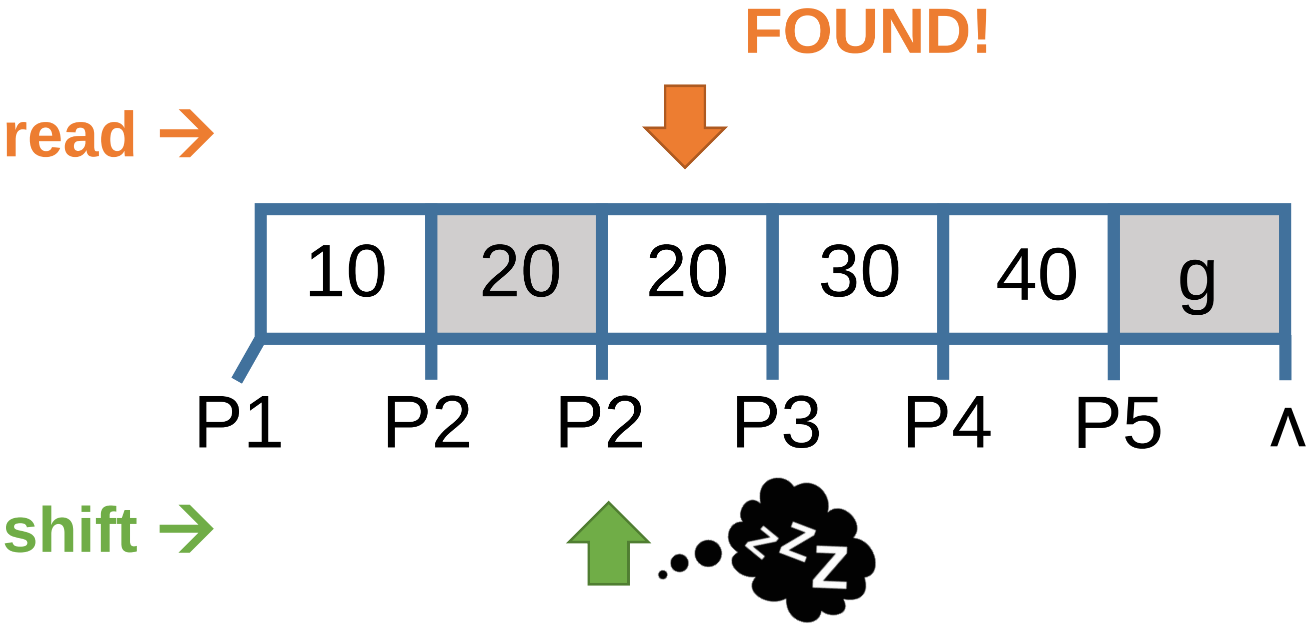
⬆ Write transaction



FOUND!

read →

10	20	20	30	40	g

P1 P2 P2 P3 P4 P5 ∧

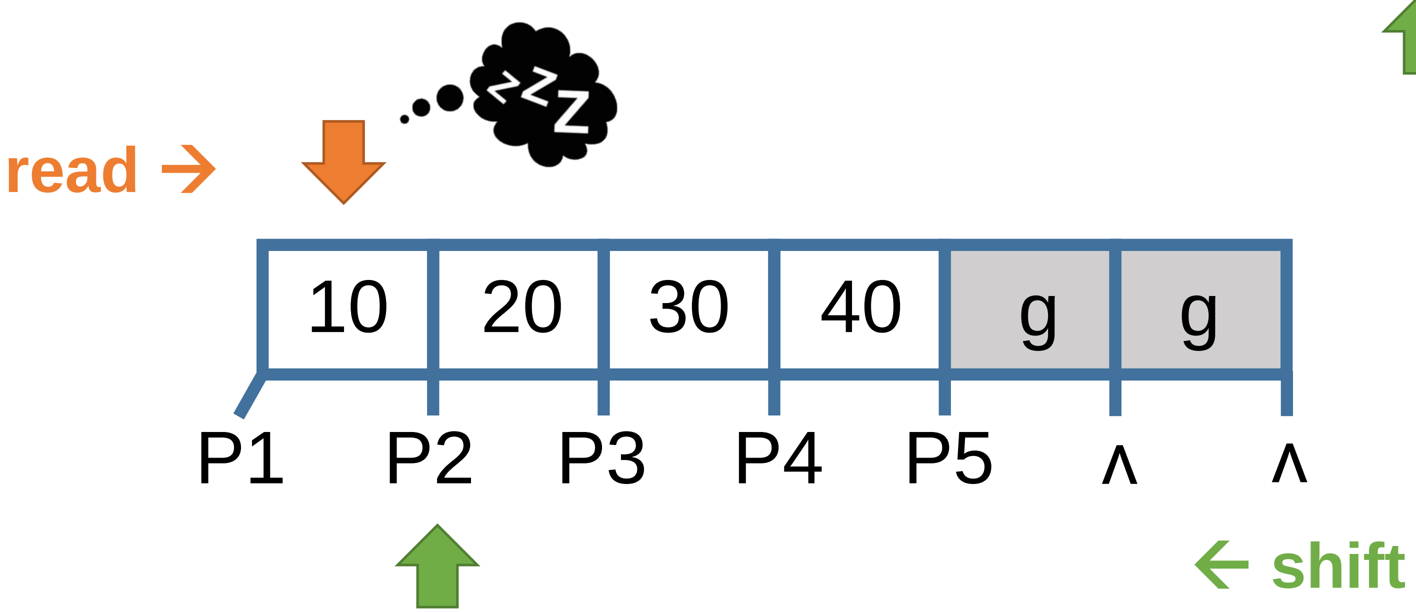
shift →

Lock-Free Search

[Example 2] Searching 30 while deleting (20, P2)

⬇ Read transaction

⬆ Write transaction

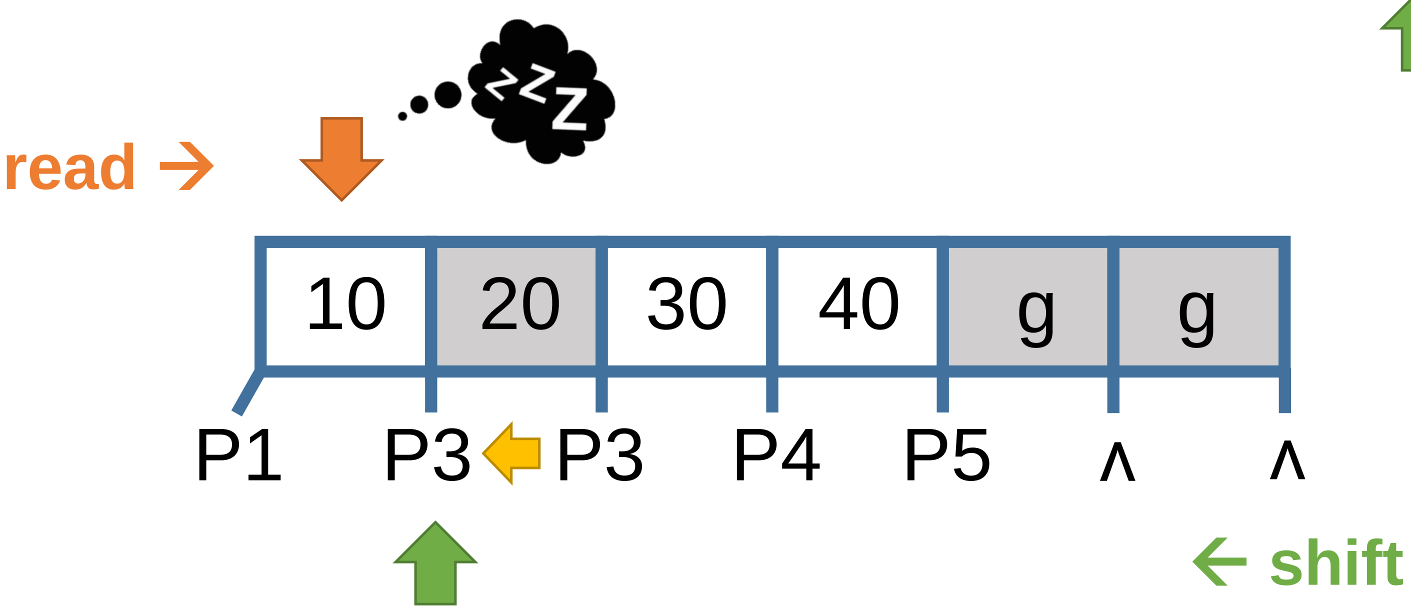


Lock-Free Search

[Example 2] Searching 30 while deleting (20, P2)

↓ Read transaction

↑ Write transaction

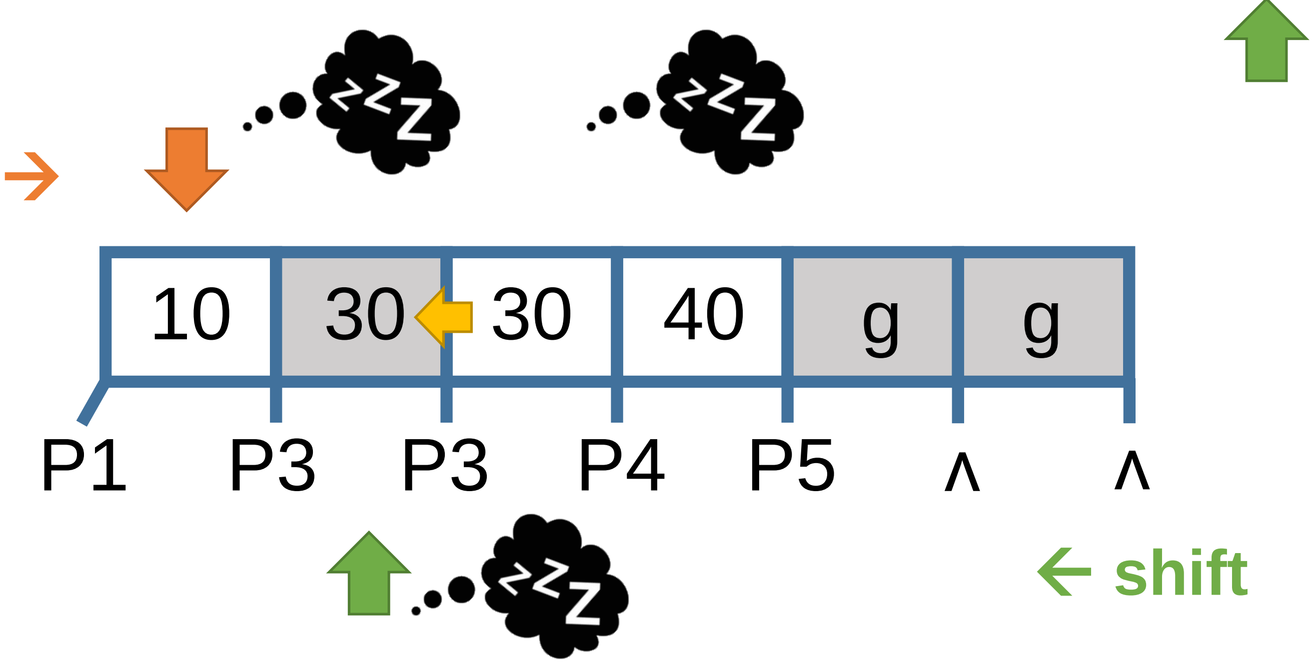


Lock-Free Search

[Example 2] Searching 30 while deleting (20, P2)

⬇ Read transaction

⬆ Write transaction

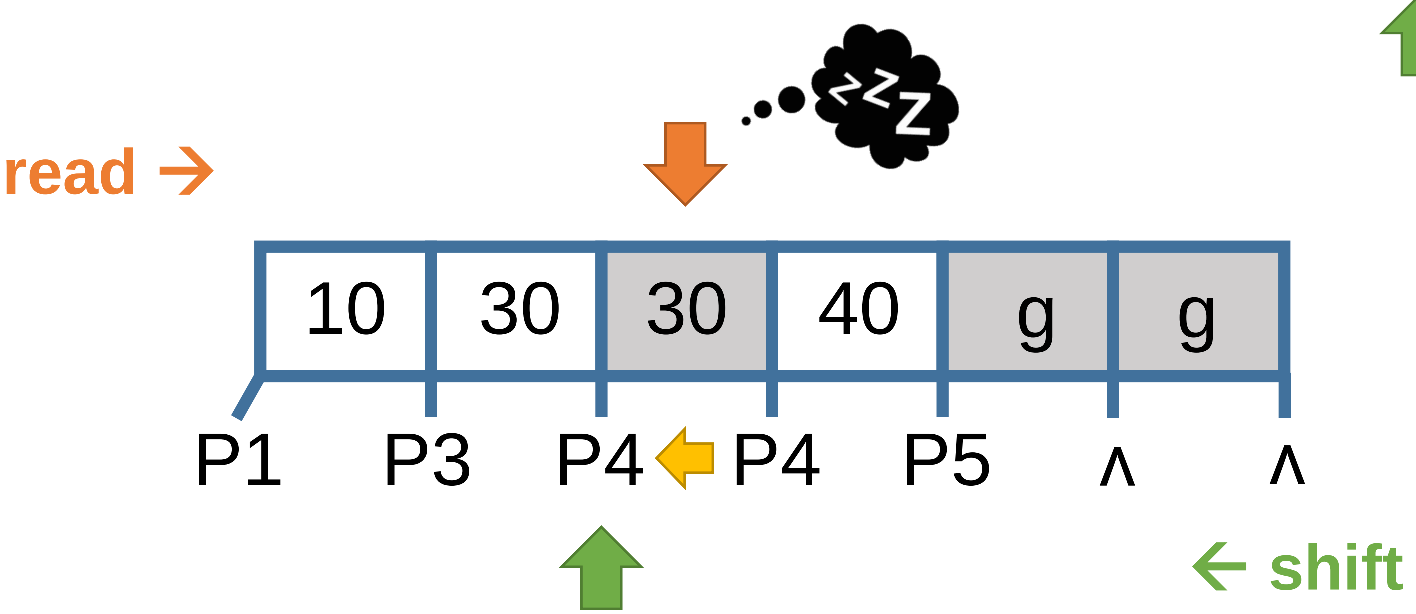


Lock-Free Search

[Example 2] Searching 30 while deleting (20, P2)

⬇ Read transaction

⬆ Write transaction



Lock-Free Search

[Example 2] Searching 30 while deleting (20, P2)

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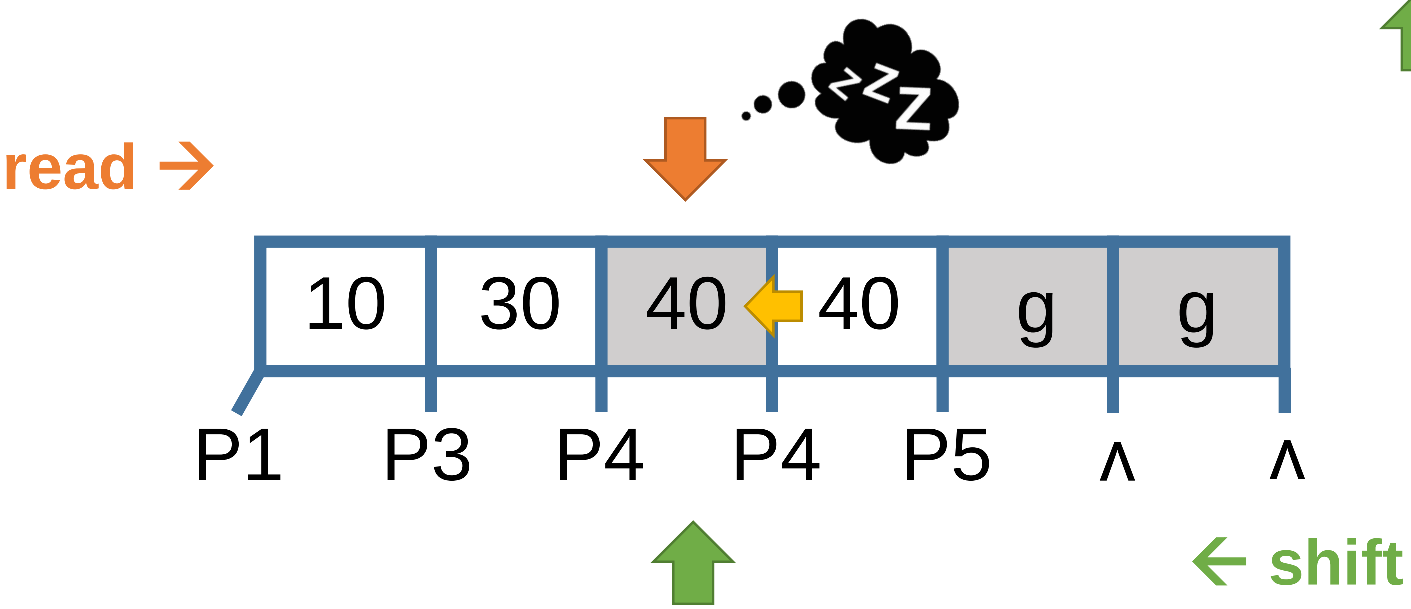
↑ Write transaction



Lock-Free Search

[Example 2] Searching 30 while deleting (20, P2)

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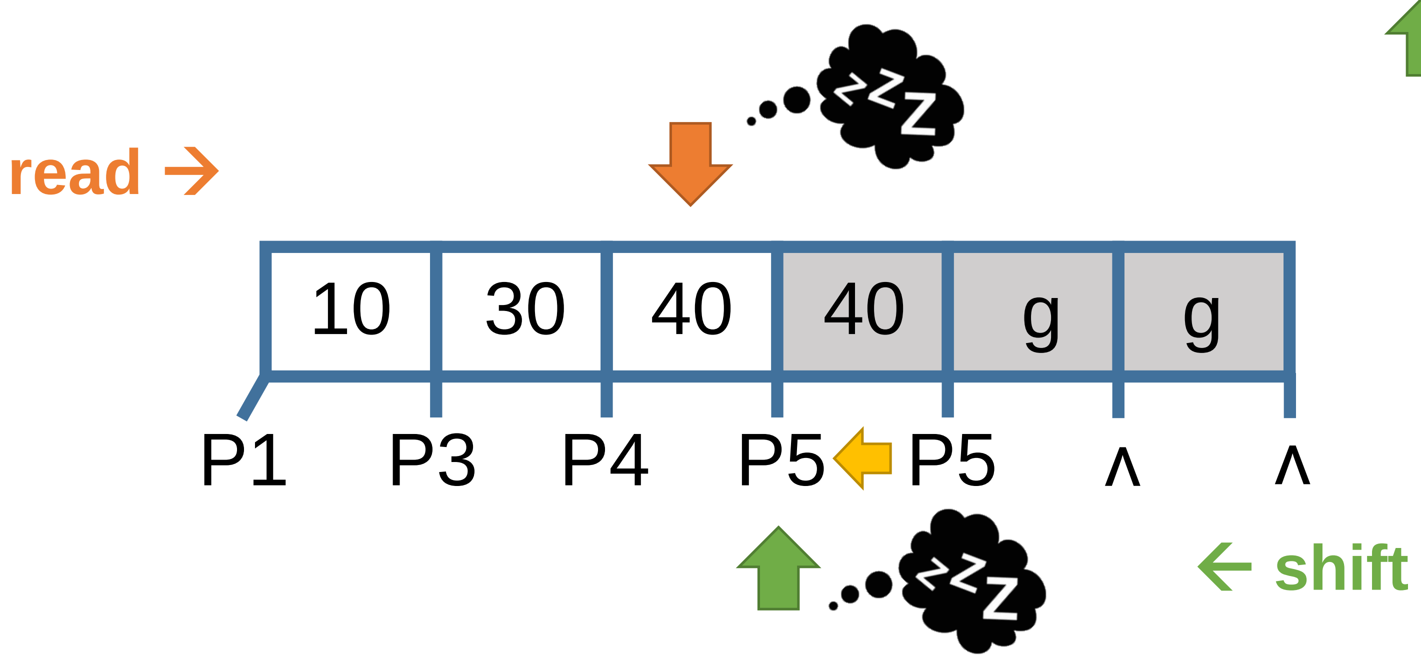


read →

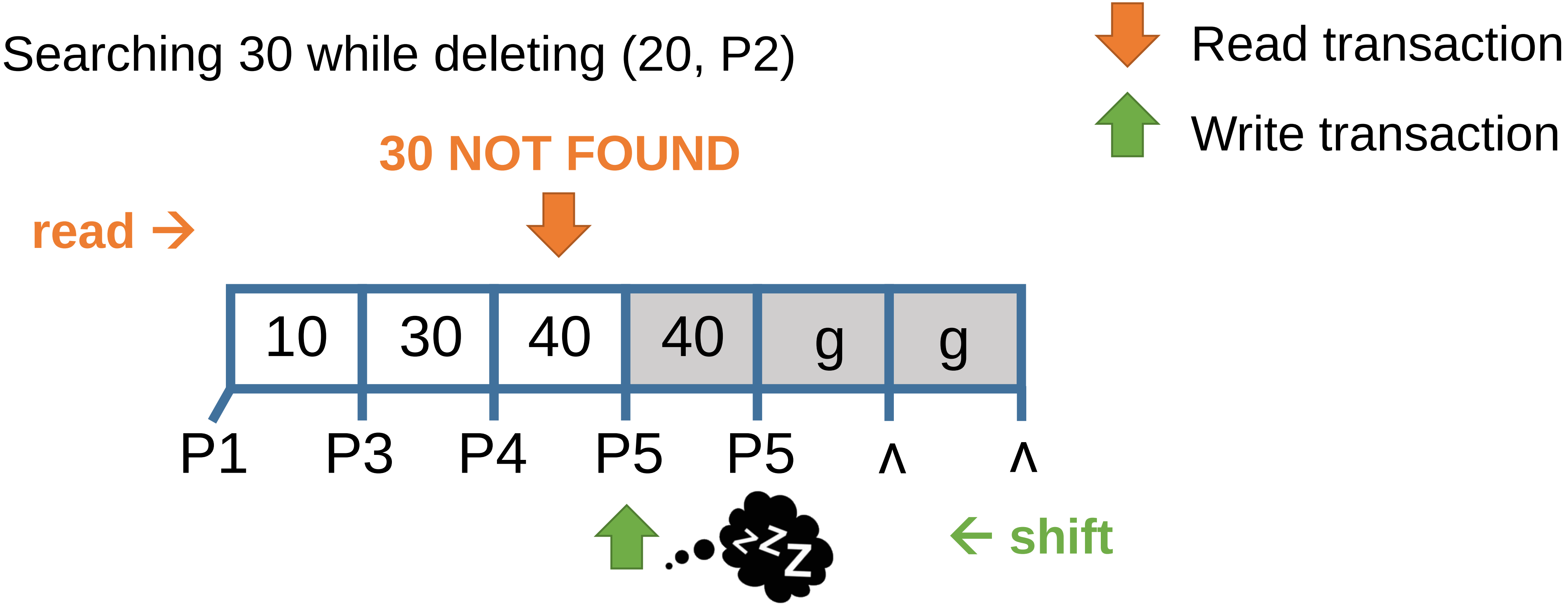
10	30	40	40	g	g

P1 P3 P4 P5 ⬅ P5 ∧ ∧

← shift

Lock-Free Search

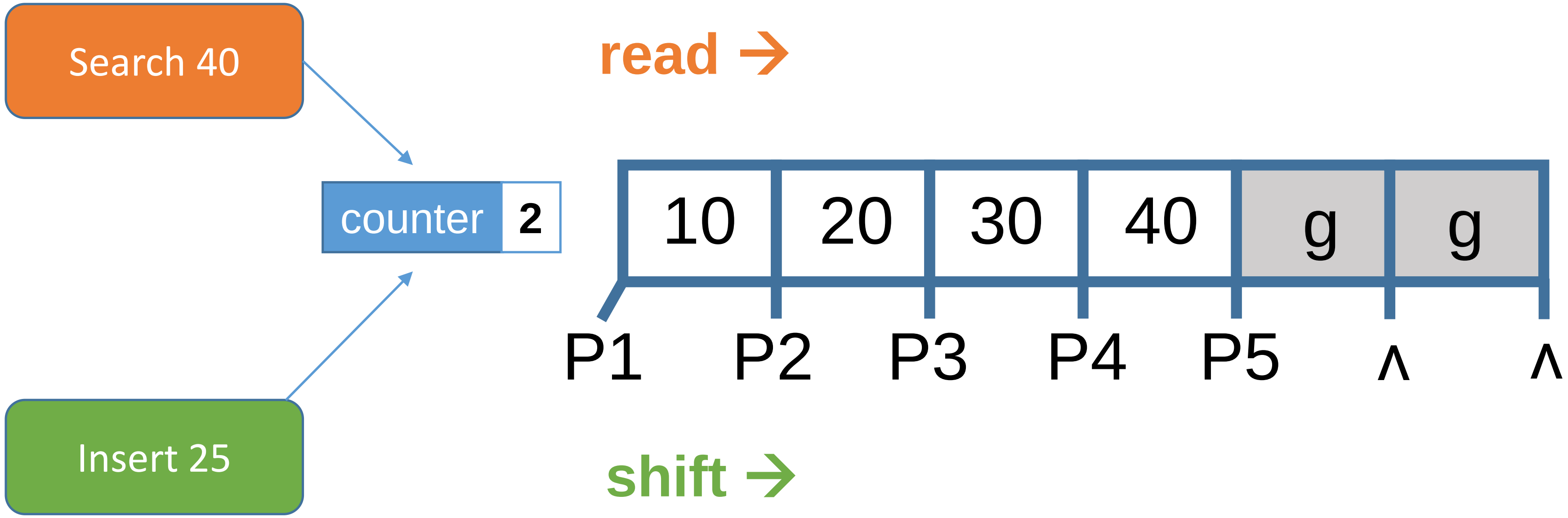
[Example 2] Searching 30 while deleting (20, P2)



The read transaction cannot find the key 30 due to shift operation

Lock-Free Search

- Direction flag:
  - Even Number
    - Insertion shifts to the right.
    - Search must scan from Left to Right
  - Odd Number
    - Deletion shifts to the left.
    - Search must scan from Right to Left



Search 40

read →

counter 2

10	20	30	40	g	g

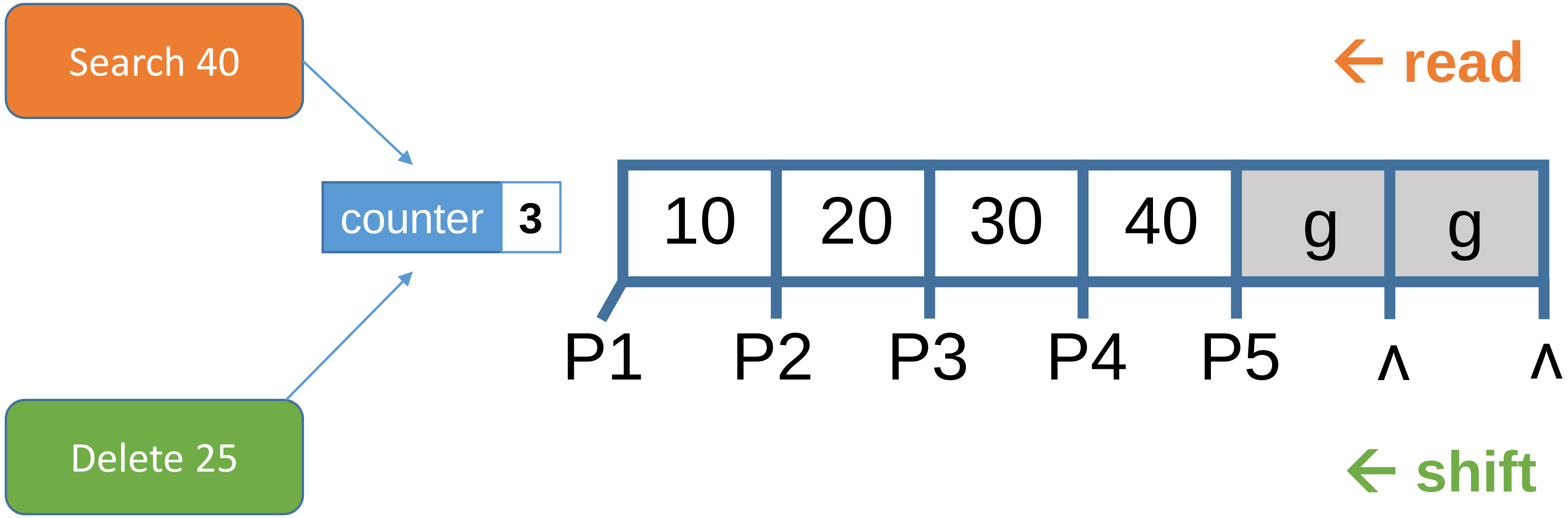
P1 P2 P3 P4 P5 ∧ ∧

shift →

Insert 25

Lock-Free Search

- Direction flag:
  - Even Number
    - Insertion shifts to the right.
    - Search must scan from Left to Right
  - Odd Number
    - Deletion shifts to the left.
    - Search must scan from Right to Left



Lock-Free Search

- Direction flag:
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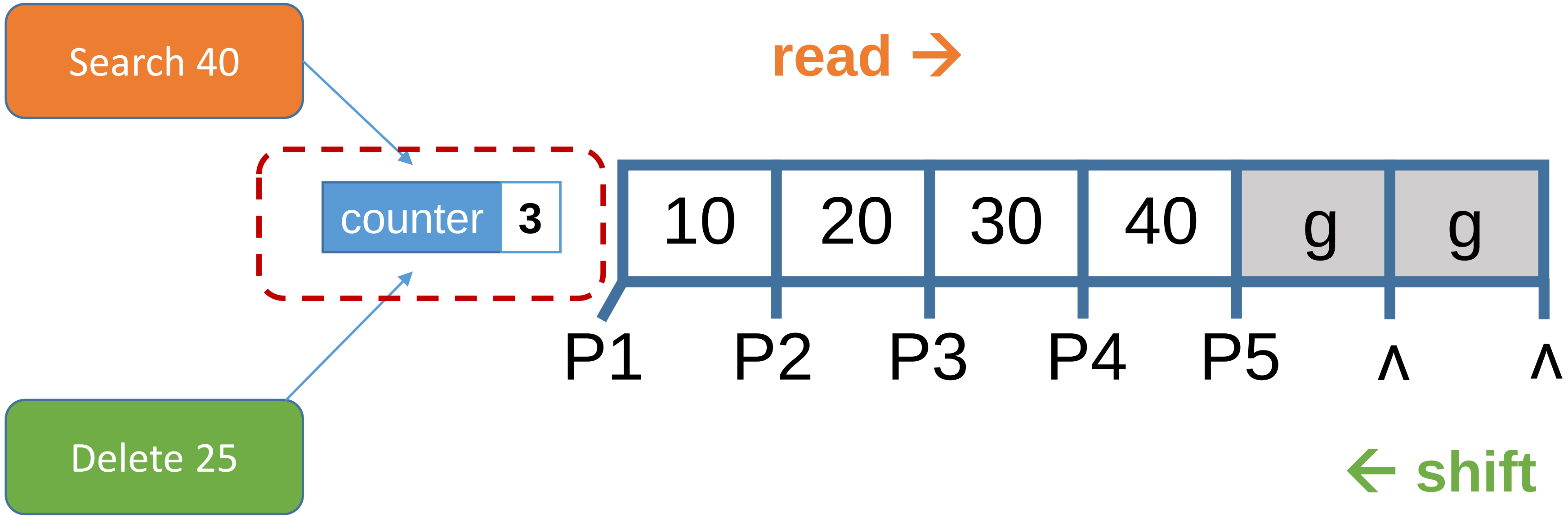


The read transaction has to check the counter once again to make sure the counter has not changed. Otherwise, search the node again.

Lock-Free Search Consistency Model

Transaction A

```
BEGIN
INSERT 10
SUSPENDED
```

```
WAKE UP
```

ABORT

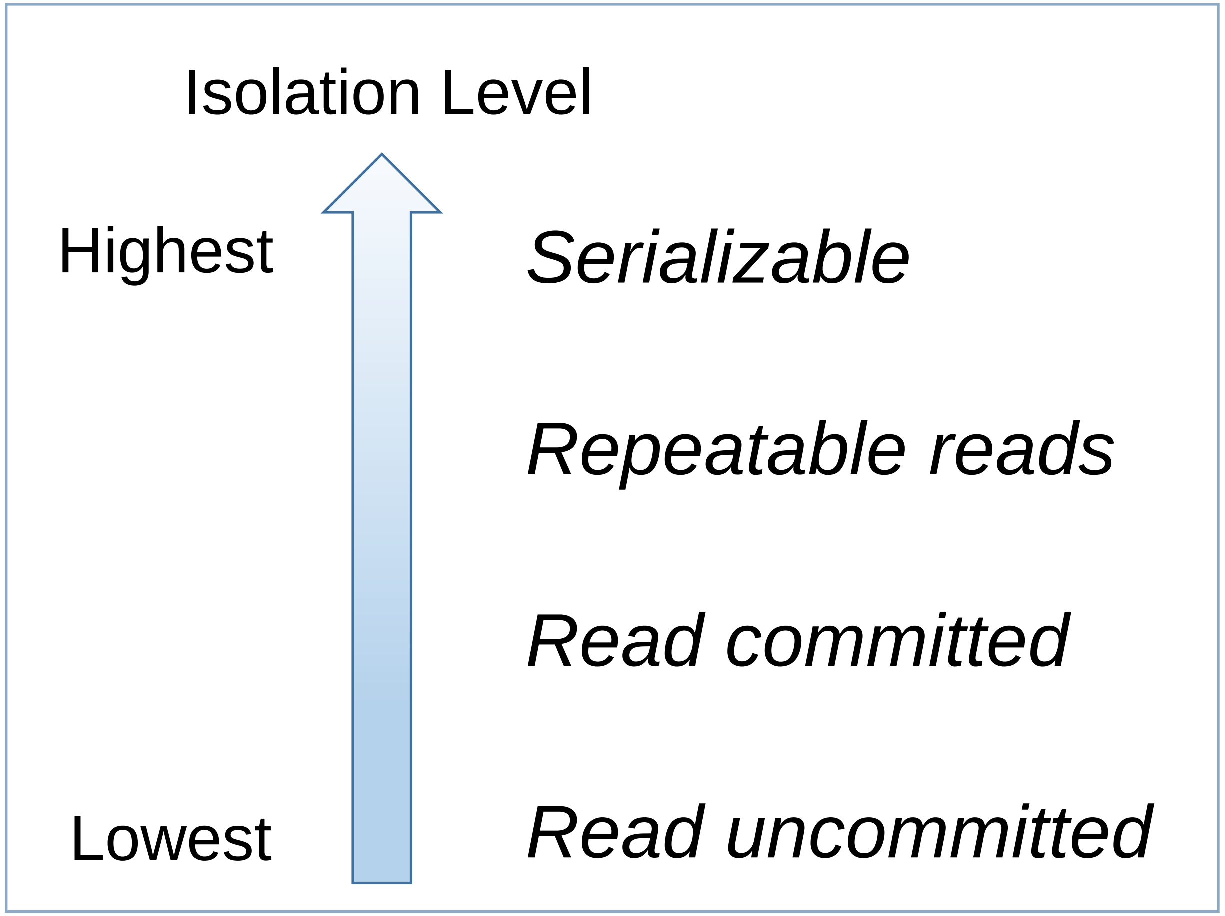
Transaction B

```
BEGIN
SEARCH 10(FOUND)
COMMIT
```

Dirty reads problem

The ordering of Transaction A and Transaction B cannot be determined

Lock-Free Search Consistency Model



Isolation Level

Highest

Lowest

Serializable

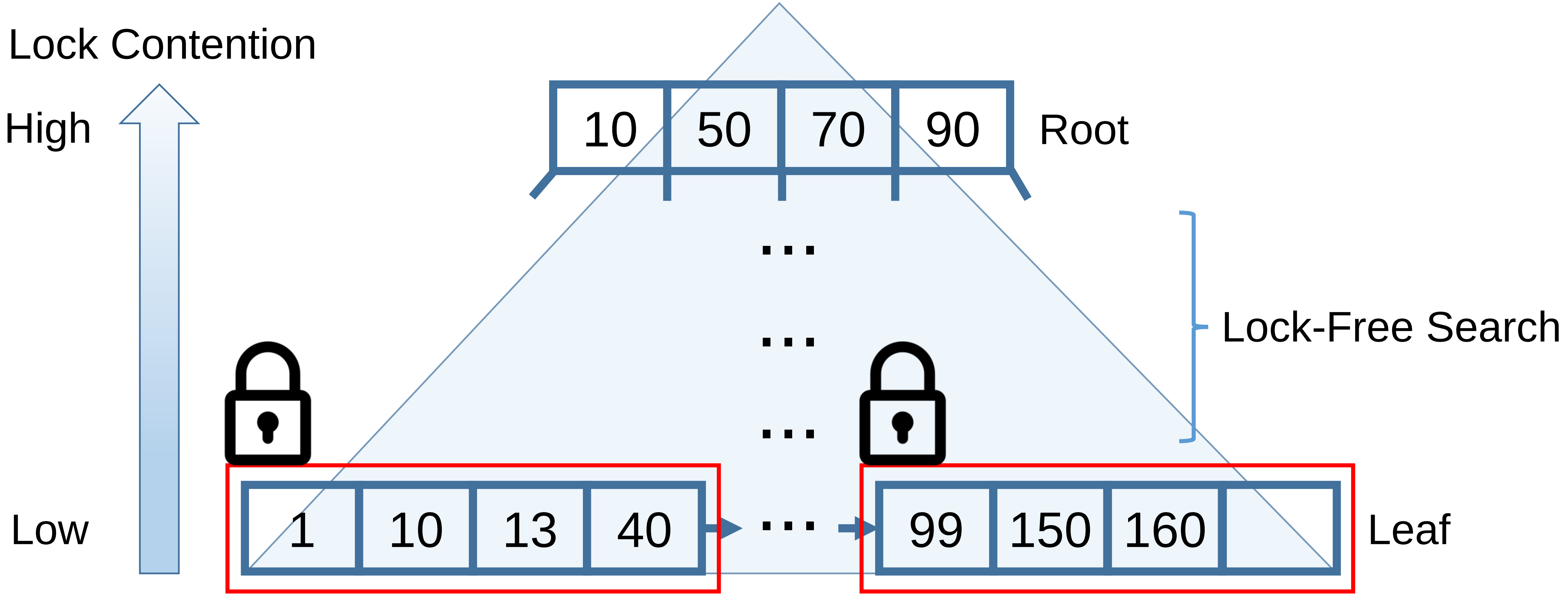
Repeatable reads

Read committed

Read uncommitted

Our Lock-Free Search supports low isolation level

Lock-Free Search Consistency Model

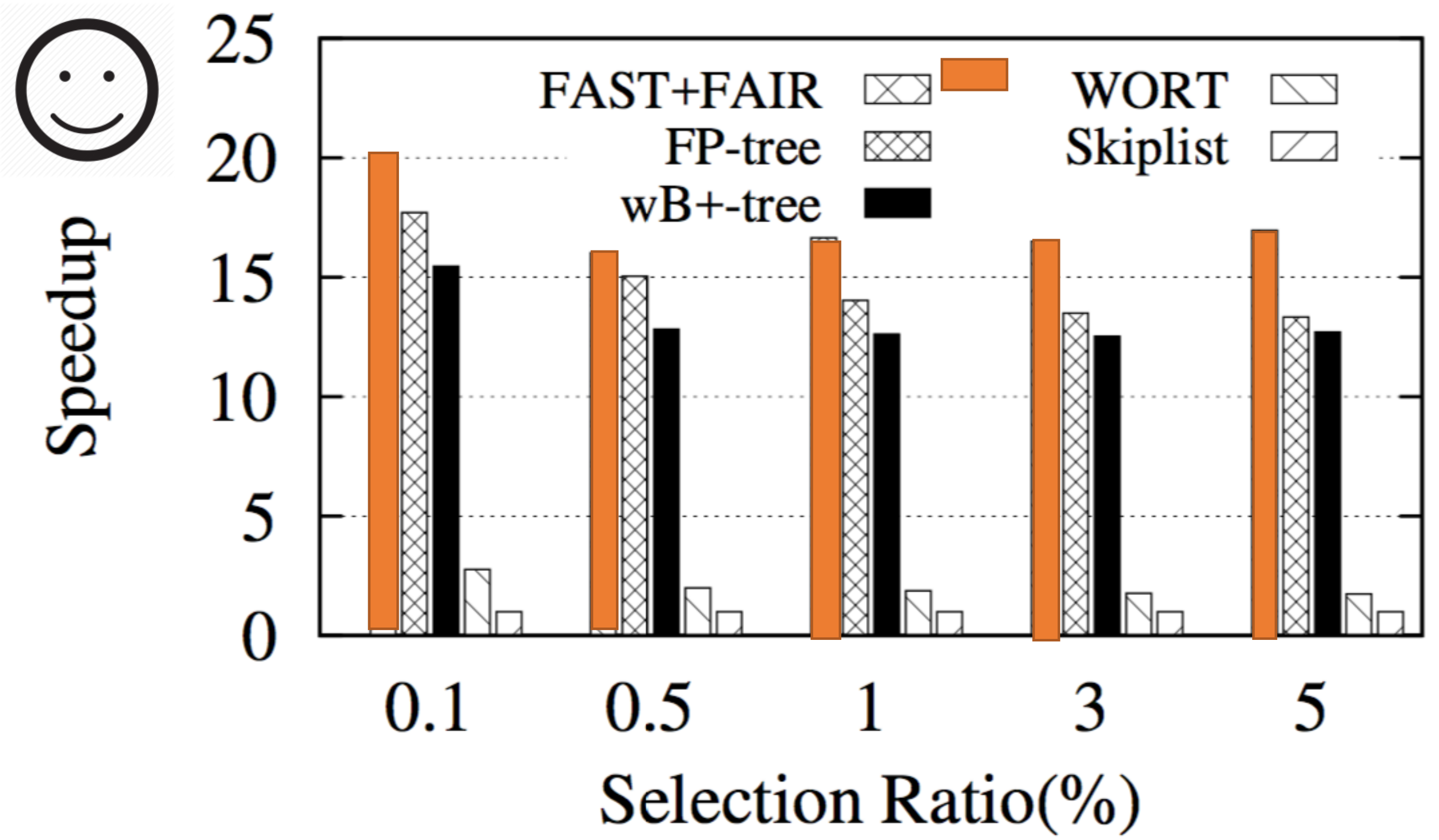


For higher isolation level, read lock is necessary for leaf nodes

Experimental Environments

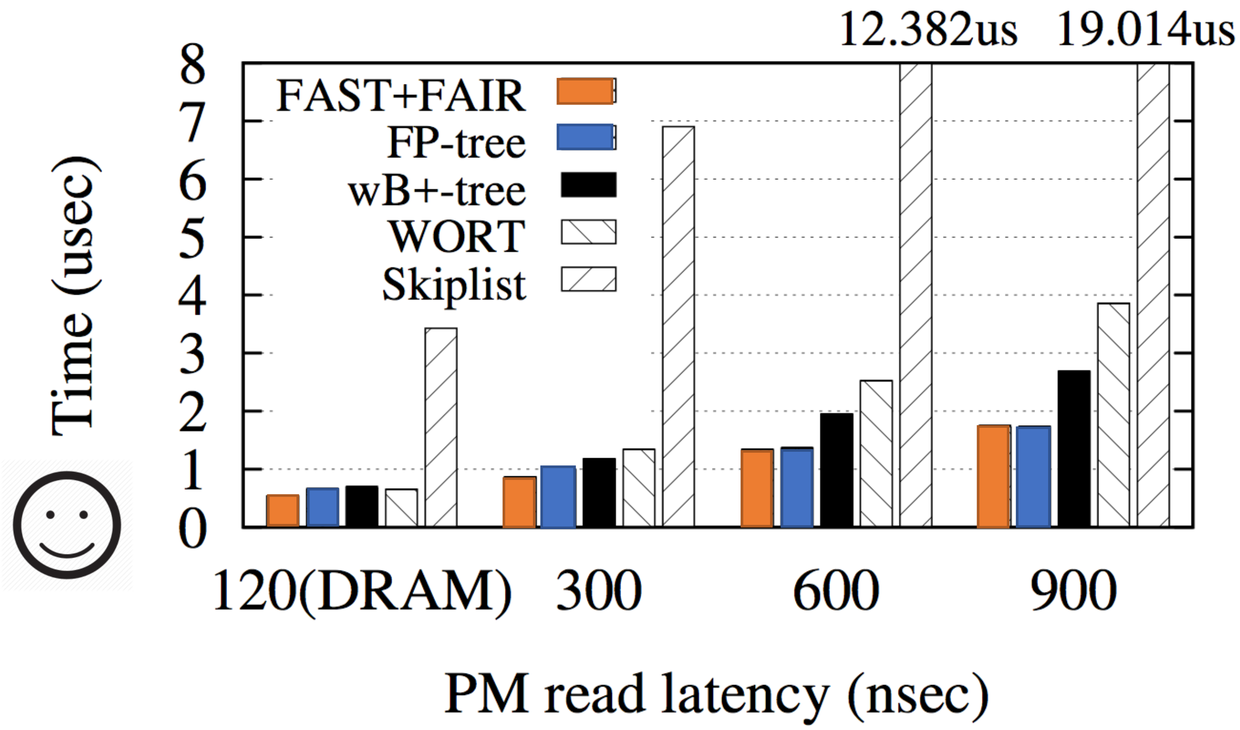
- Xeon Haswell-Ex E7-4809 v3 processors
  - 2.0 GHz, 16 vCPUs with hyper-threading enabled, and 20 MB L3 cache
  - Total Store Ordering (TSO) is guaranteed
- g++ 4.8.2 with -O3
- PM latency
  - Read latency
    - A DRAM-based PM latency emulator, Quartz
  - Write latency
    - Injecting delay

Range Query Performance Improvement over Skiplist



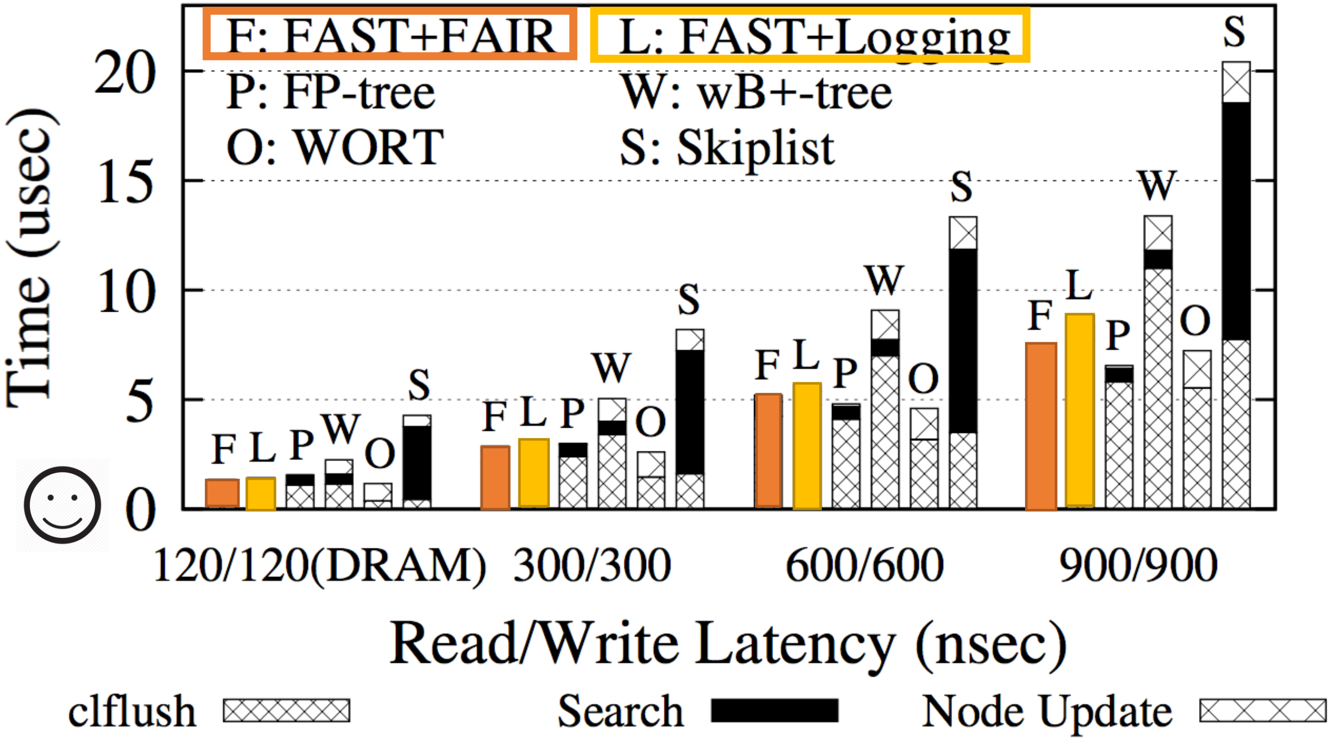
- Sorted keys, cache locality, and memory level parallelism
  → up to 20X speed up

Exact Match Query Performance with varying PM Latencies



FAST+FAIR→ FP-Tree → wB+-Tree → WORT → Skiplist

Breakdown of Time spent for Insertion

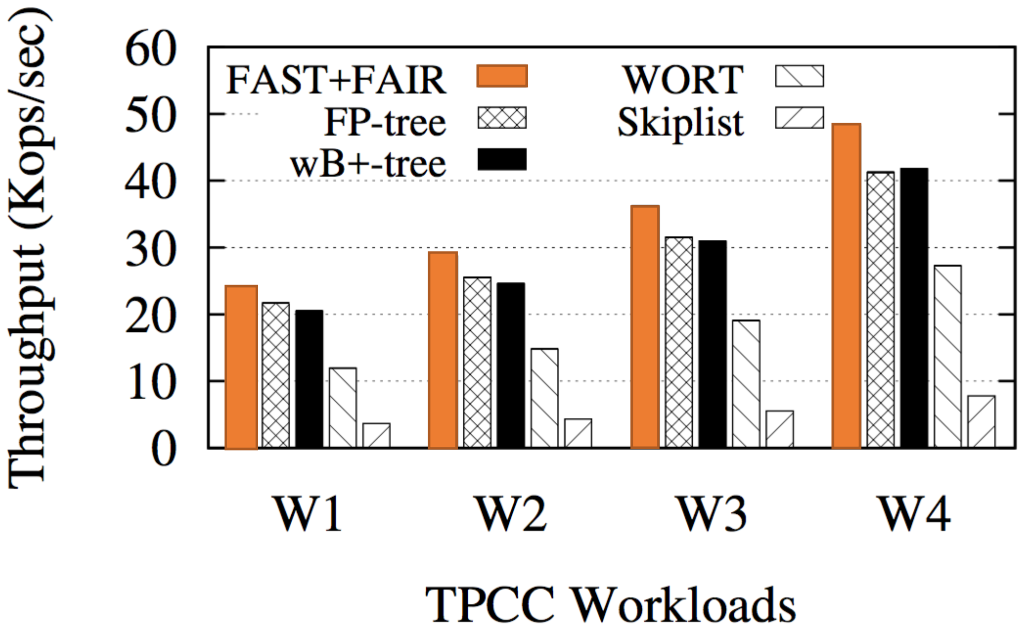


- clflush: I/O time
- Search: Tree traversal time
- Node Update: Computation time

WORT, FAST+FAIR, FP-Tree → FAST+Logging → wB+-Tree → Skiplist

- *FAST+Logging* uses logging instead of *FAIR* when splitting a node

TPC-C Benchmark



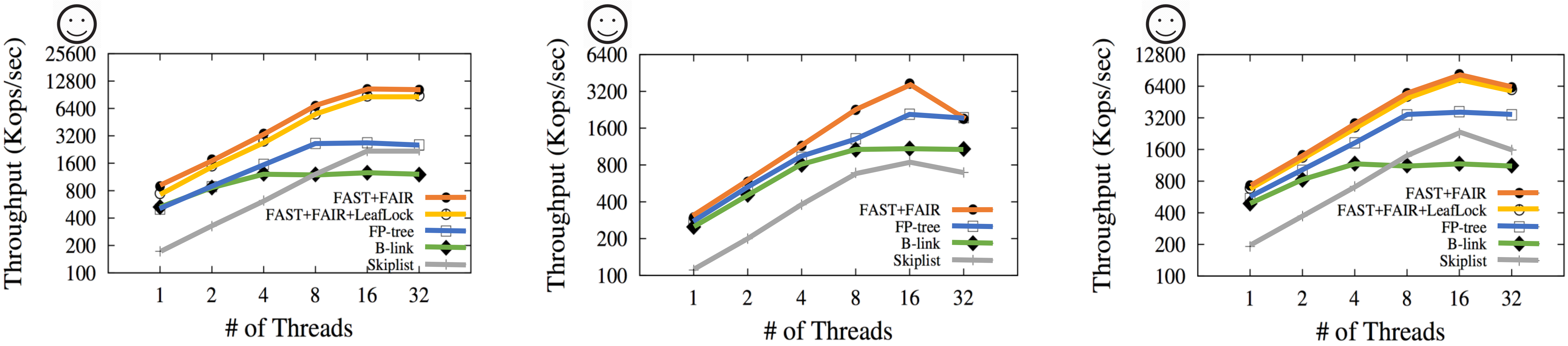
	New Order	Payment	Order Status	Delivery	Stock Level
W1	34%	43%	5%	4%	14%
W2	27%	43%	15%	4%	11%
W3	20%	43%	25%	4%	8%
W4	13%	43%	35%	4%	5%

Specification of TPCC workloads

More Range Queries

- FAST+FAIR consistently outperforms other indexes because of its good insertion performance and superior range query performance

Lock-Free Search with concurrent threads



(a) 50M Search

(b) 50M Insertion

(c) 200M Search / 50M Insertion / 12.5M Deletion

- Lock-free search with FAST+FAIR shows high scalability and performance
- FAST+FAIR+LeafLock shows comparable scalability and provides high concurrency level

Conclusion

- We designed a byte addressable persistent B+-Tree that
  - stores keys in order
  - avoids expensive logging

- FAST and FAIR always transform B+-Trees into consistent/transient inconsistent B+-Trees

- Lock-Free search
  - By tolerating transient inconsistency

Thank you

Endurable Transient Inconsistency in Byte-Addressable Persistent B+-Tree

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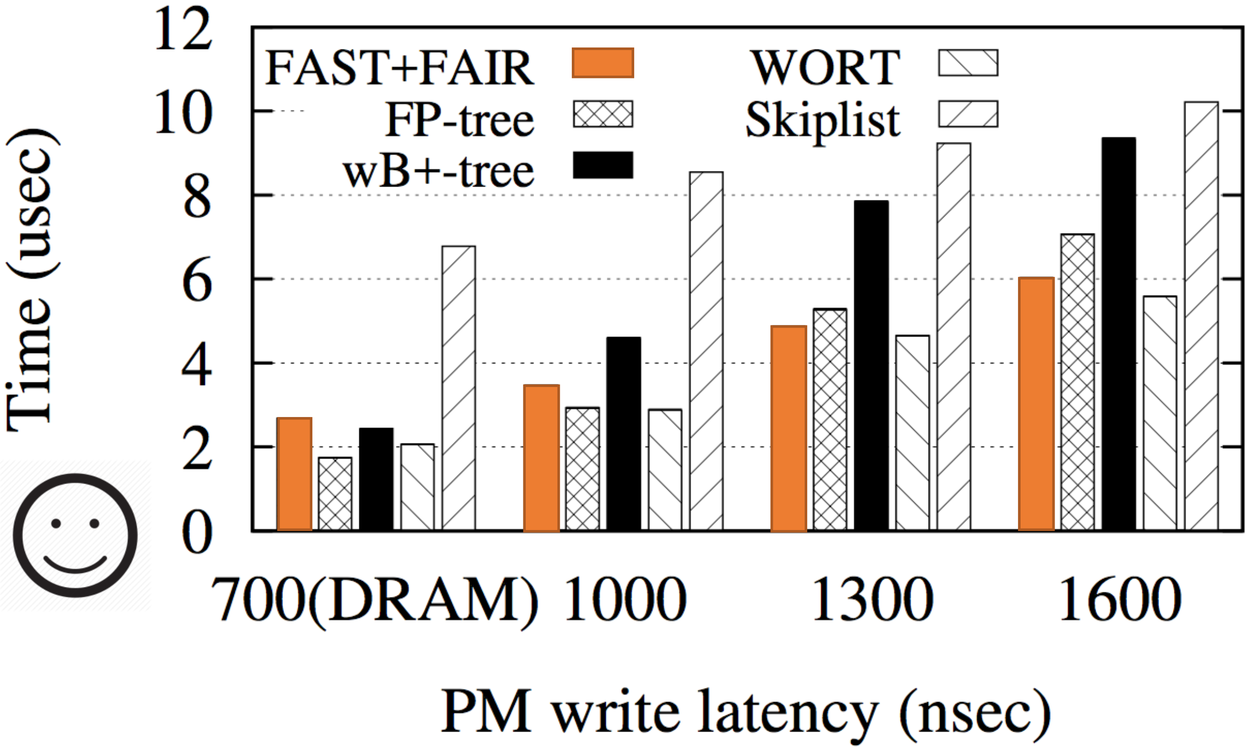
Insertion for Non-TSO with varying write latency



- To guarantee the order of instructions, the *dmb* instruction is used for FAST+FAIR
- Although there is an overhead by *dmb*, FAST+FAIR is less affected by latency