Concurrent Internal Binary Search Trees

Arunmoezhi Ramachandran
Supervisor - Neeraj Mittal

The University of Texas at Dallas

Overview

Introduction

- CPUs aren't getting faster (memory wall, ILP wall and power wall)
- Shift towards multicore and manycore

Problem

How to keep all the cores **busy**?

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Concurrent computing (a better choice)

Concurrency vs Parallelism

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Parallel Computing

- decades of research done
- Example - Matrix-Matrix Multiplication
- **do** lot of things simultaneously
- cannot be done on a single CPU
- **deterministic** control flow
- is about **speedup**
- **hard** to debug

Concurrent Computing

- Relatively new
- Example - A web crawler, mouse/keyboard
- **deal** lot of things simultaneously
- can be done on a single CPU
- **non-deterministic** control flow
- is about **hiding latency**
- **very hard** to debug

Designing Concurrent Data Structures

- Shared-memory multiprocessors concurrently execute multiple threads
- Threads communicate and synchronize through data structures in shared memory
- Threads can interleave in exponential number of ways
- Concurrent data structure must preserve its properties for all possible interleavings

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fetchAndIncrement: Using locks

```
repeat
    rOld = x;
    rNew = rOld+1;
until (x.compareAndSwap(rOld,rNew));
```

fetchAndIncrement: using atomic instructions

compareAndSwap updates(atomically) the value of x to *rNew* only if the read value of x is equal to *rOld*. Returns *true* if it succeeds in updating the value of x

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  - use locks to resolve contention
  - coarse grained or fine grained locking
  - easier to design
  - weaker progress guarantees (thread owns a lock)
  - are prone to deadlock, priority inversion
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- Non-Blocking Algorithms
  - use atomic (Read-Modify-Write) instructions to resolve contention. E.g. Compare-And-Swap(CAS) instruction
  - lock-free or wait-free
  - stronger progress guarantees (operation owns a lock - helping)
  - deadlock or priority inversion not possible
  - harder to design

Binary Search Tree - Defintion

A *binary search tree* (BST) is a data structure which meets the following requirements:

- it is a binary tree (a node can contain atmost two children)
- each node contains a key k
- left subtree of a node contains keys lesser than k
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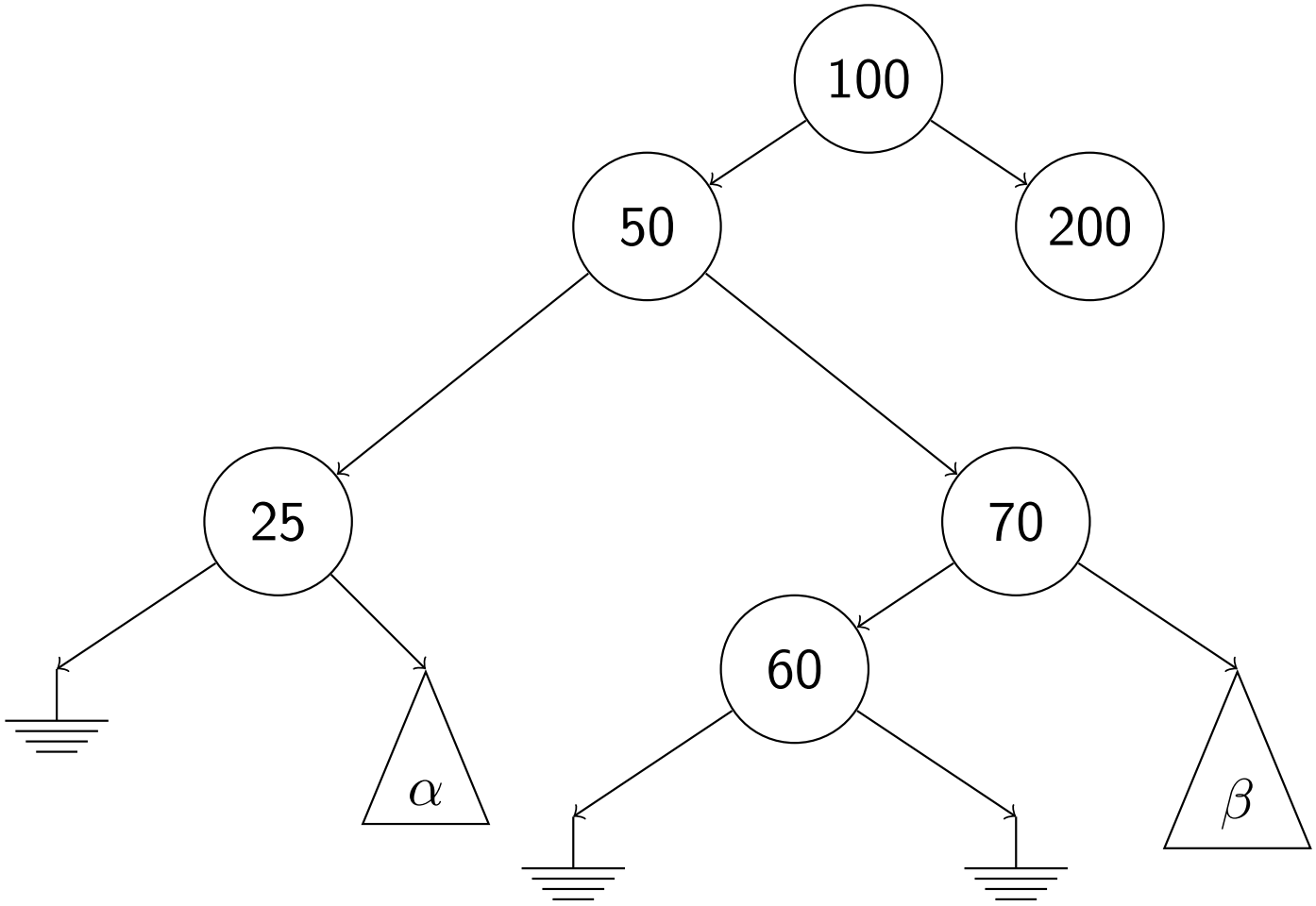
Operations on a BST

- **search(k)** - returns *true* only if key k is present in the tree
- **insert(k)** - inserts k into the tree if it does not already exist
- **delete(k)** - deletes k from the tree if it already exist

BST - Search

search(70**)**



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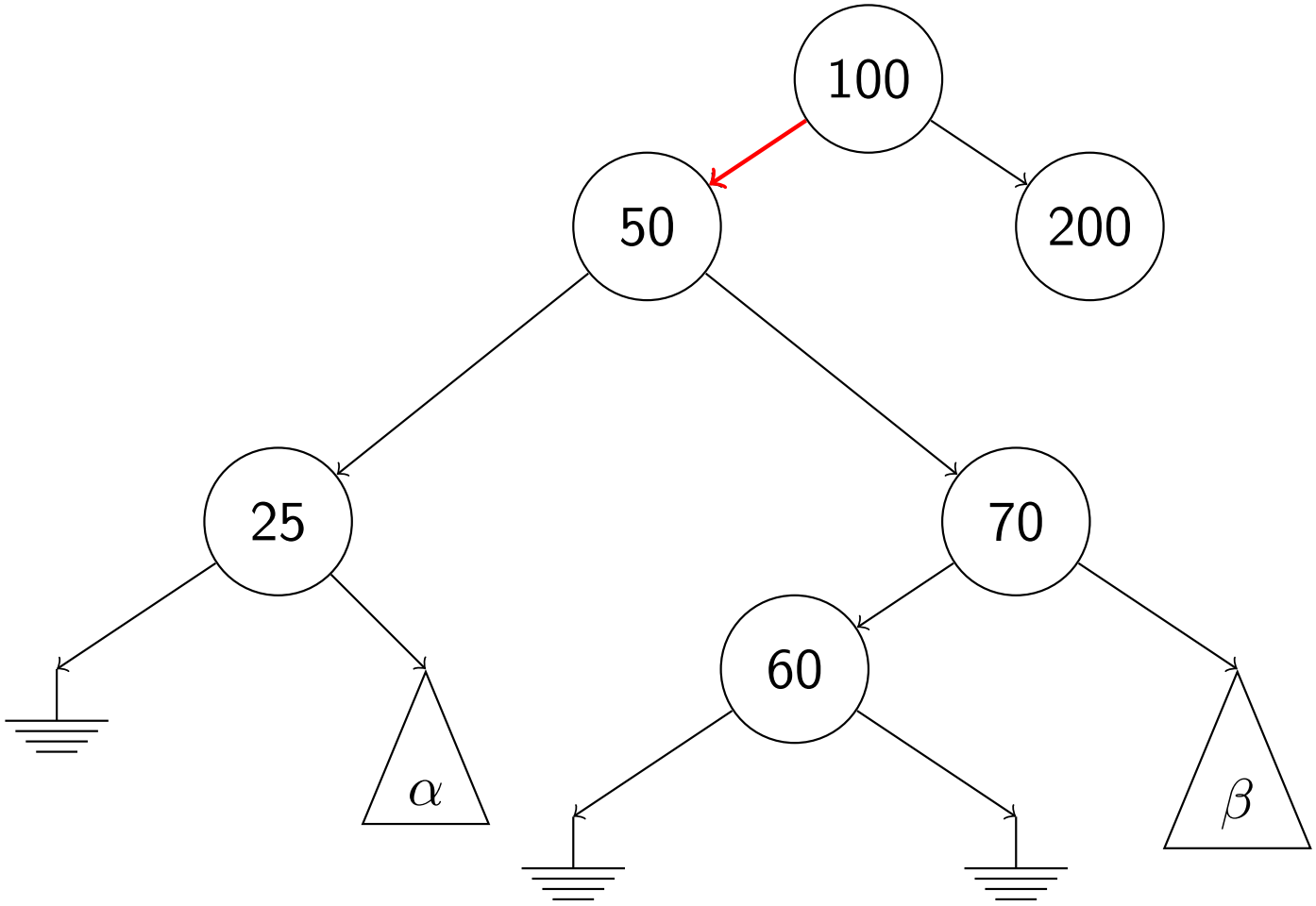

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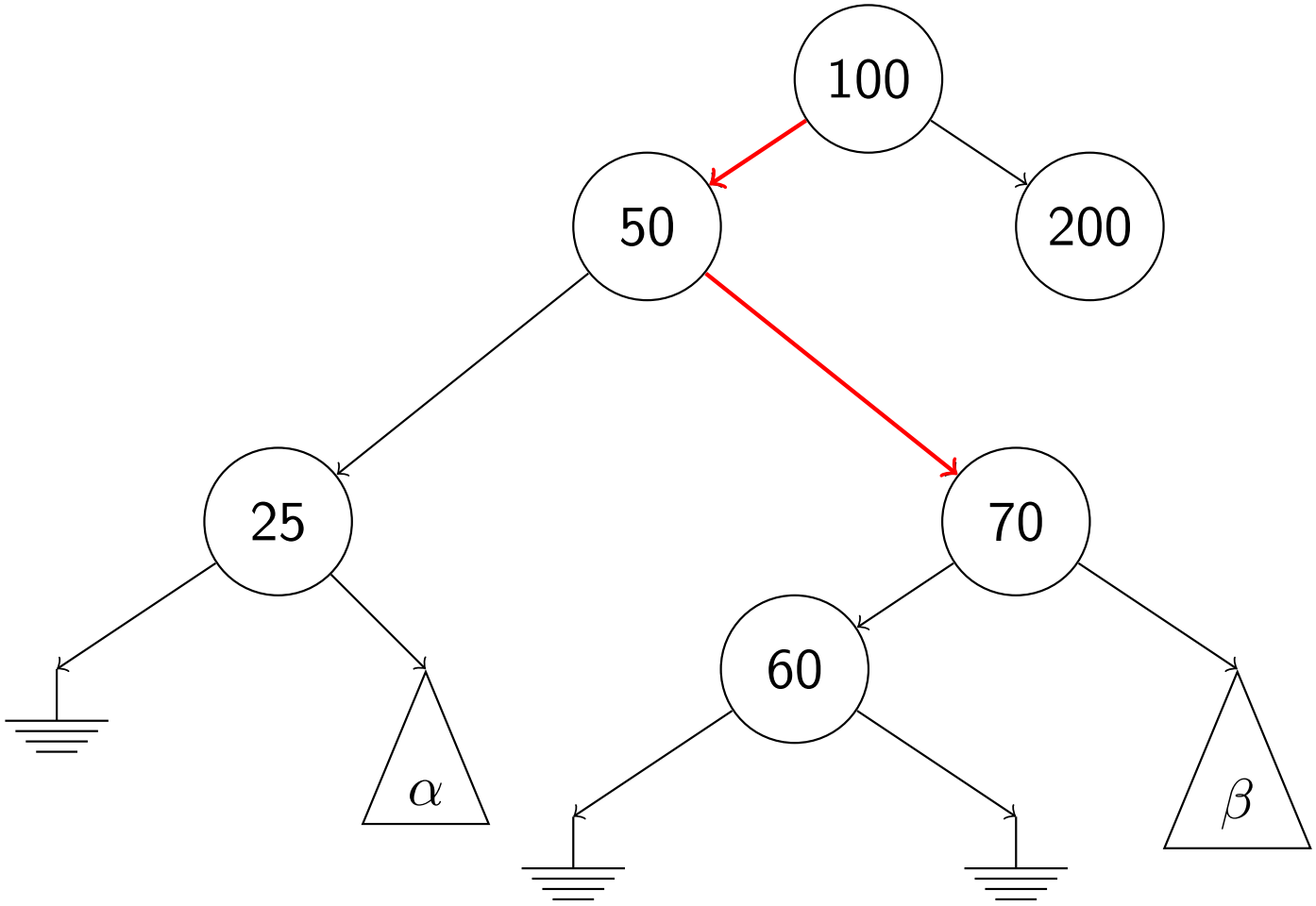

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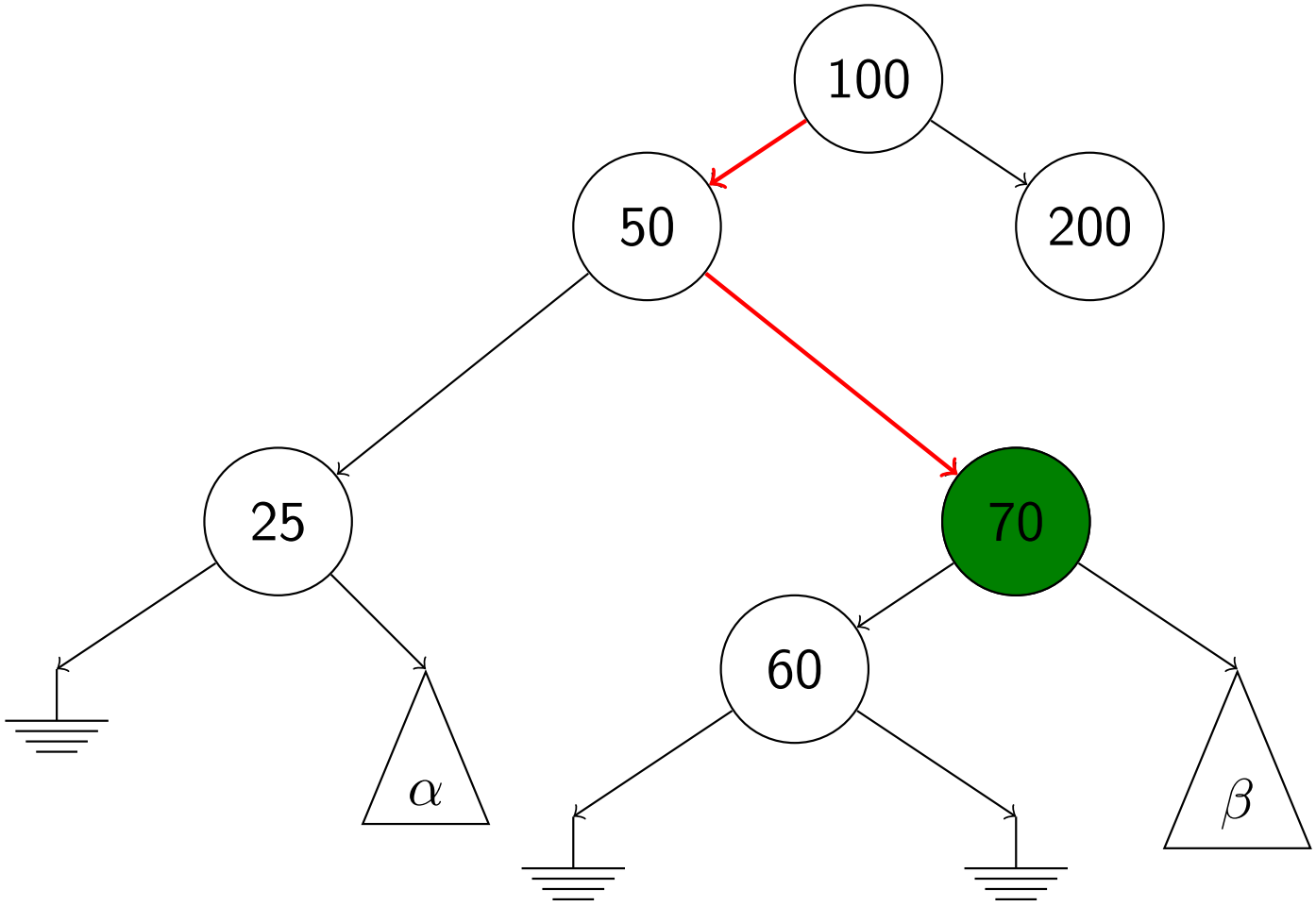

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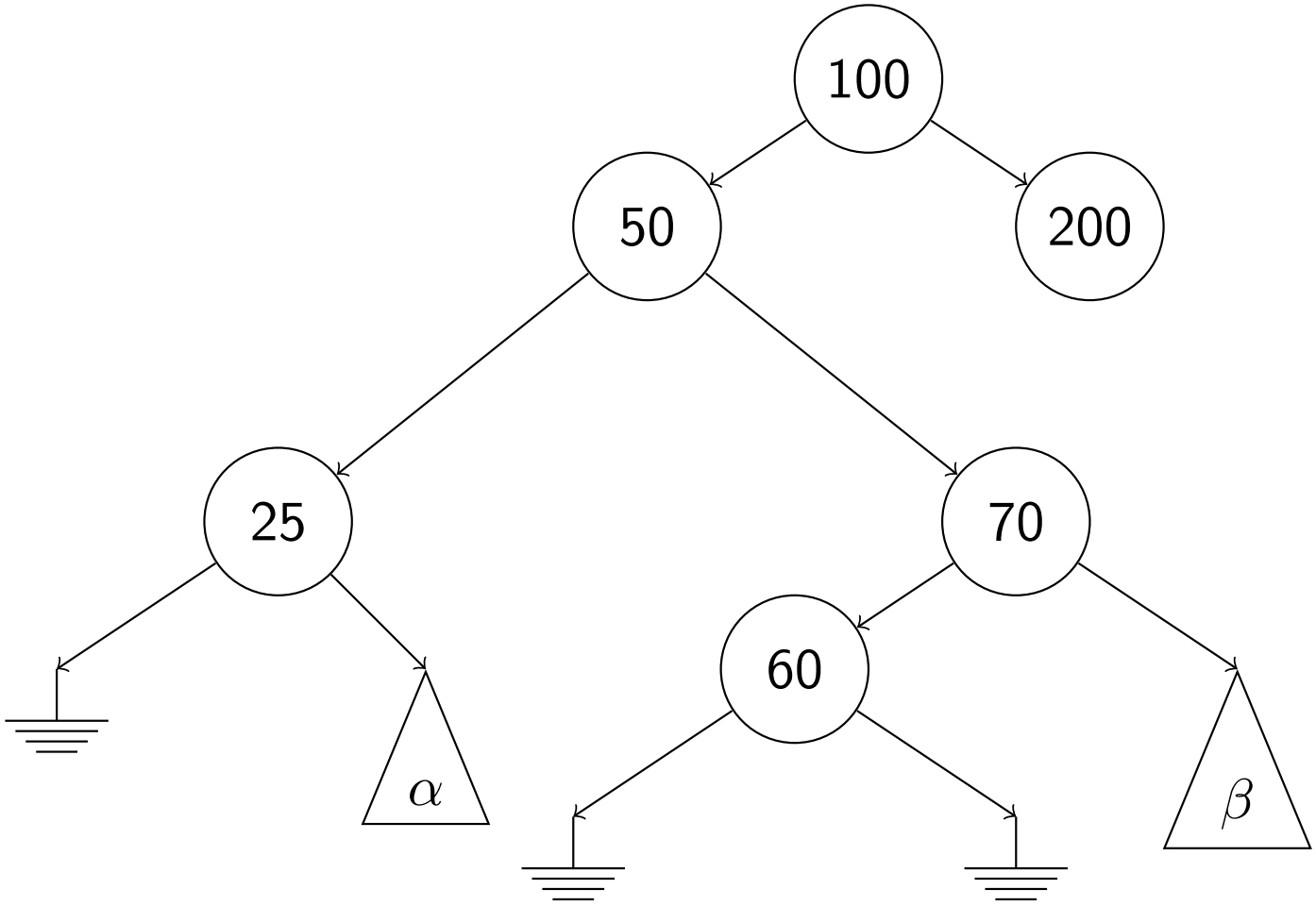

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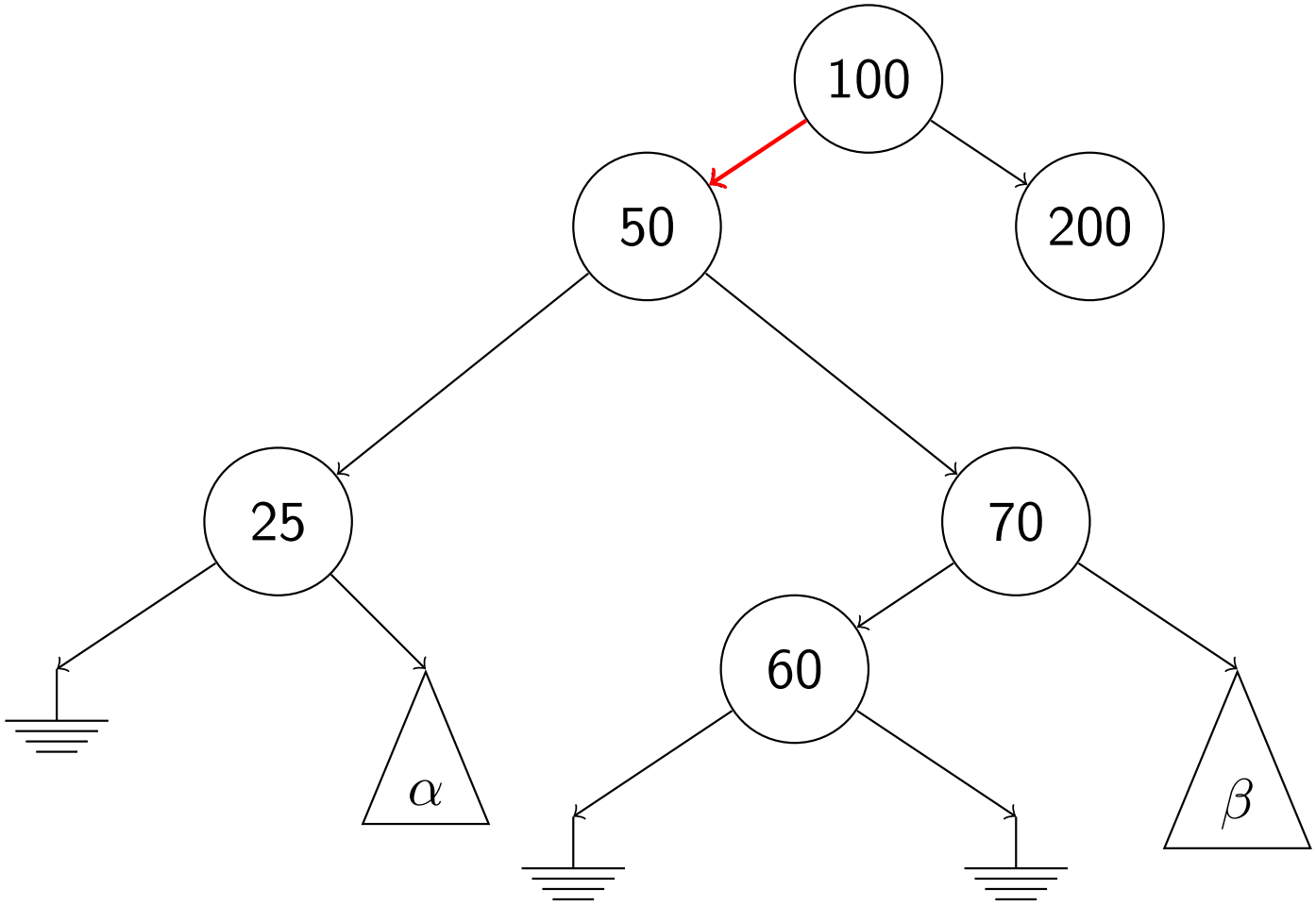

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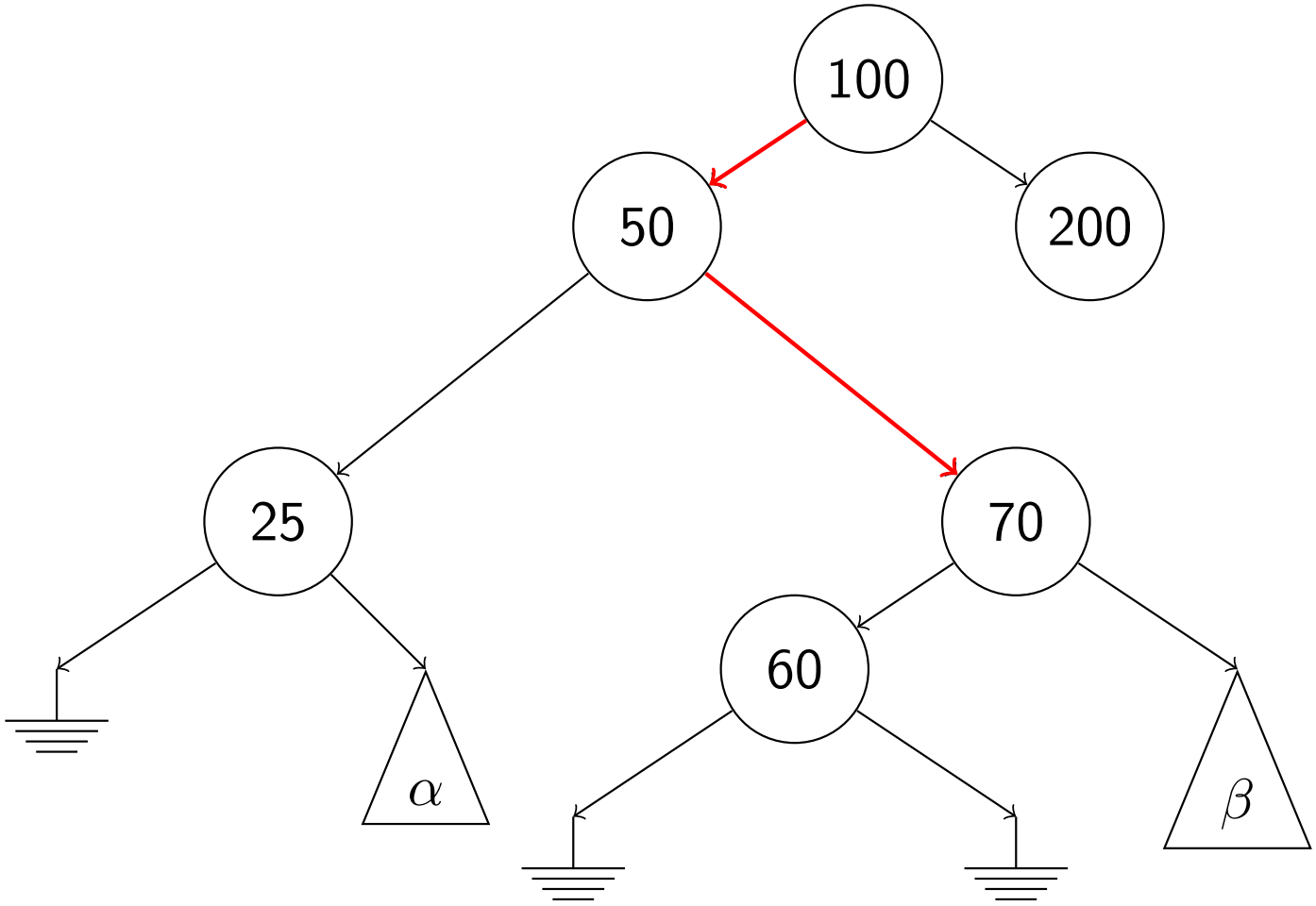

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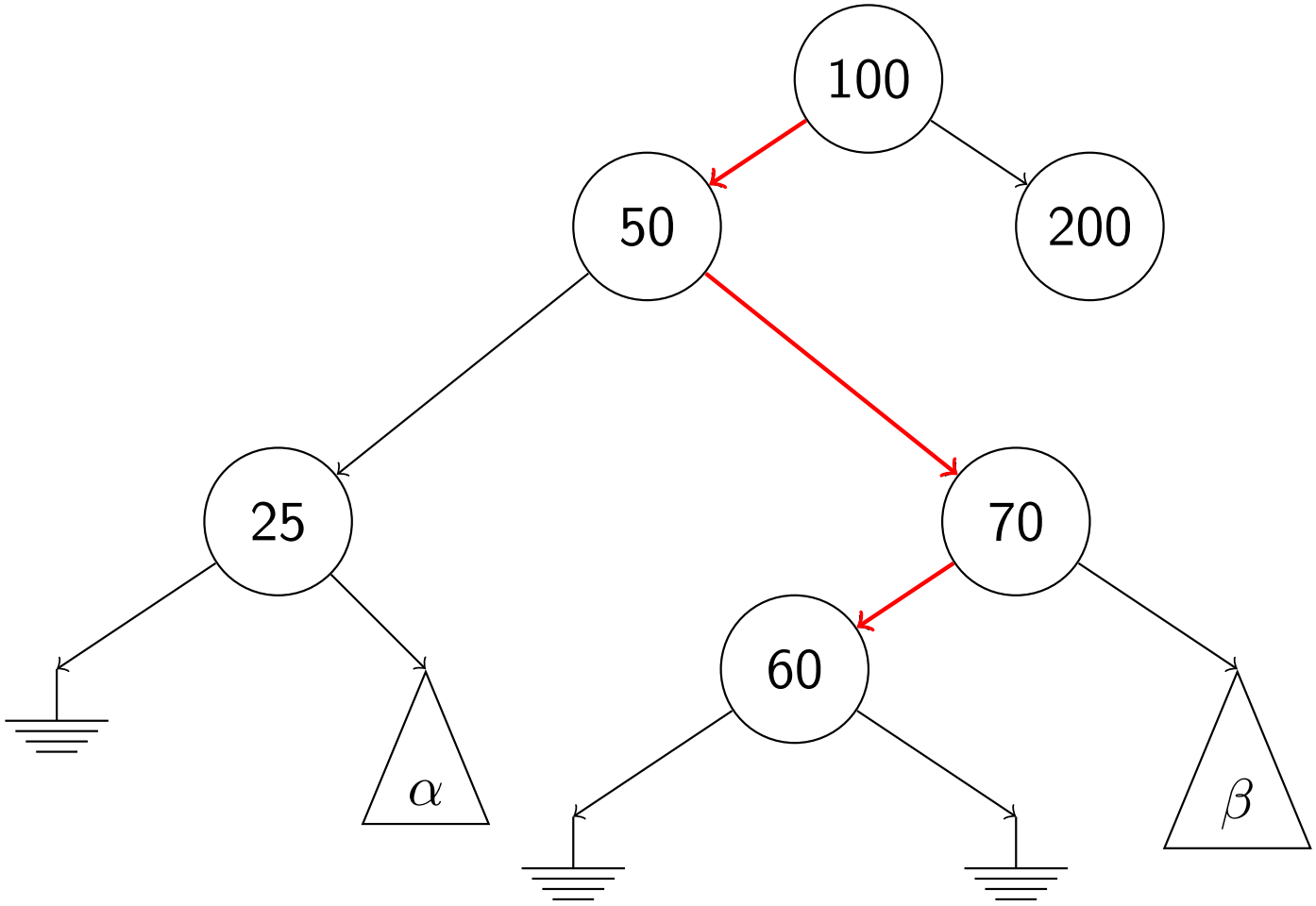

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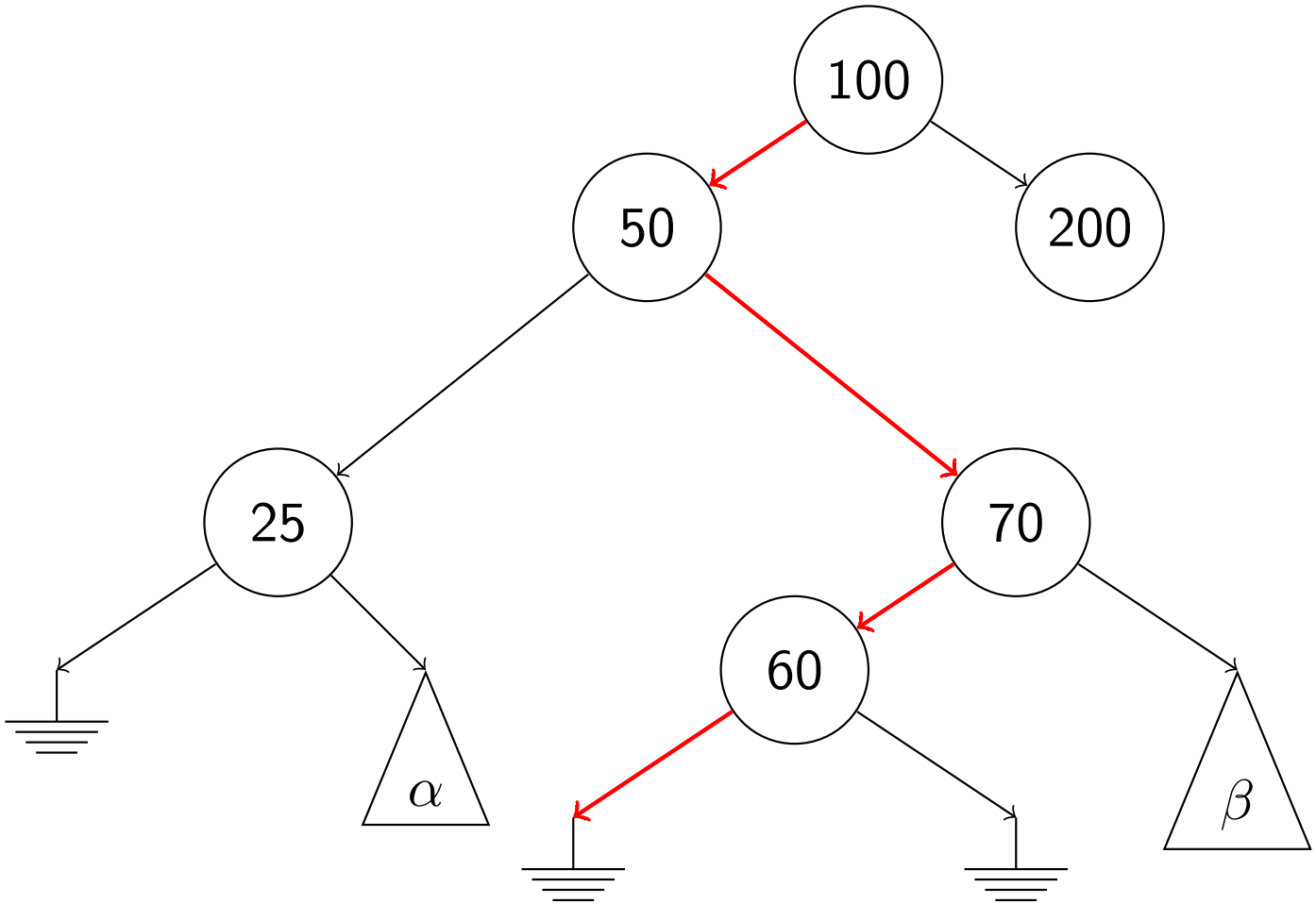

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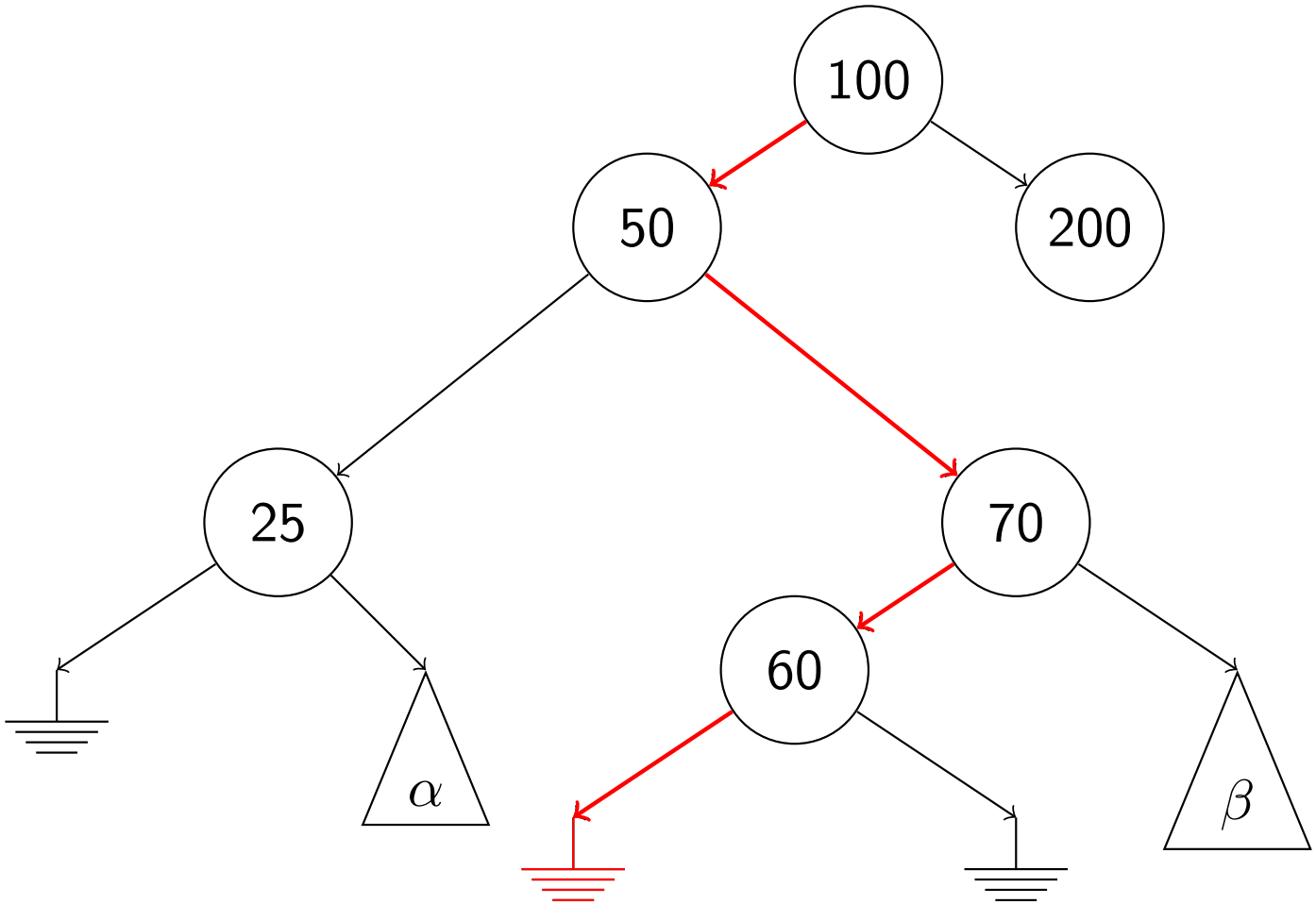

BST - Insert

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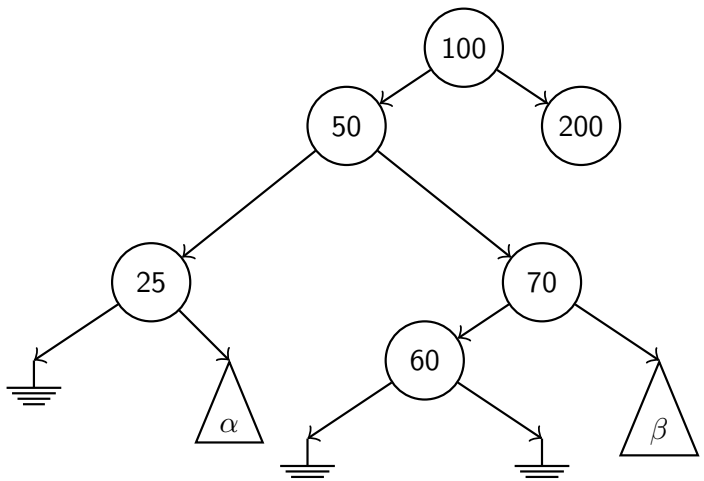

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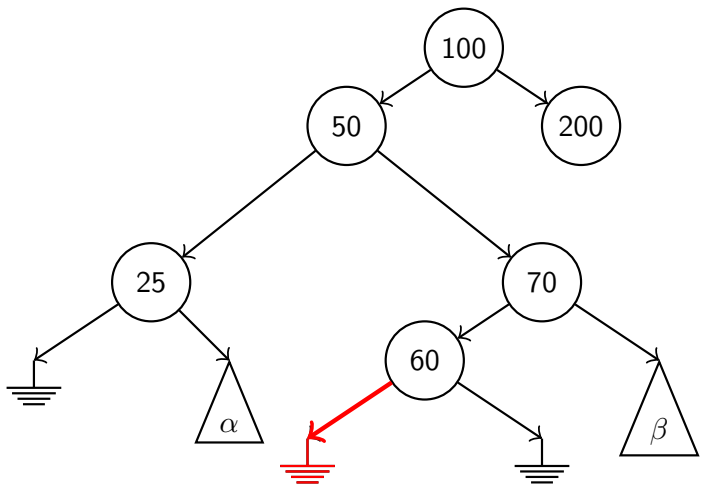

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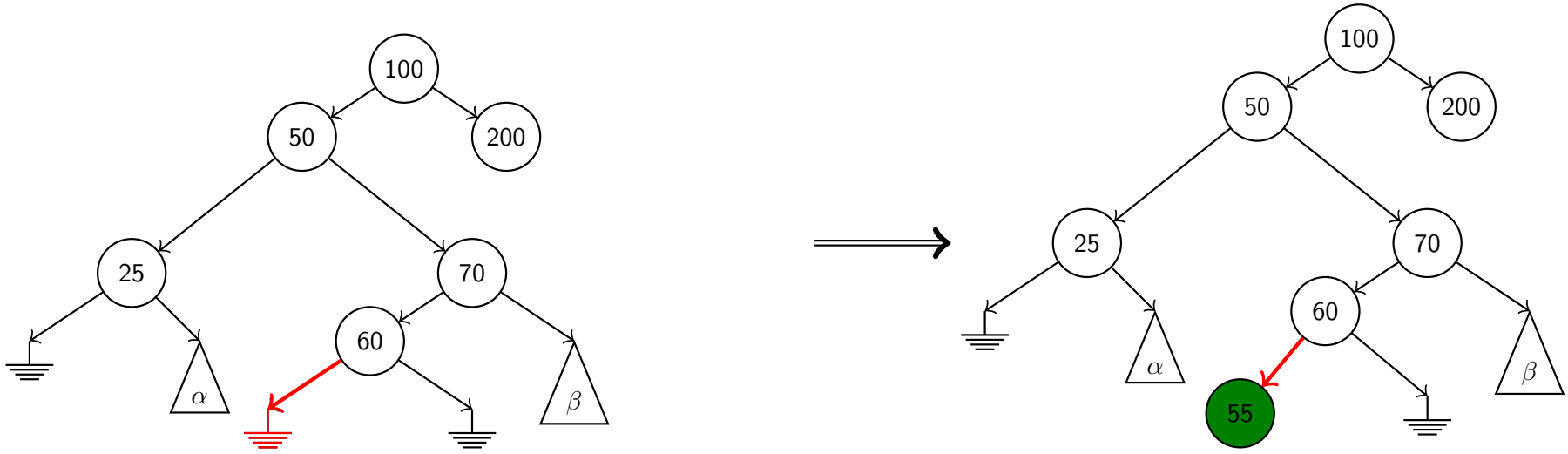
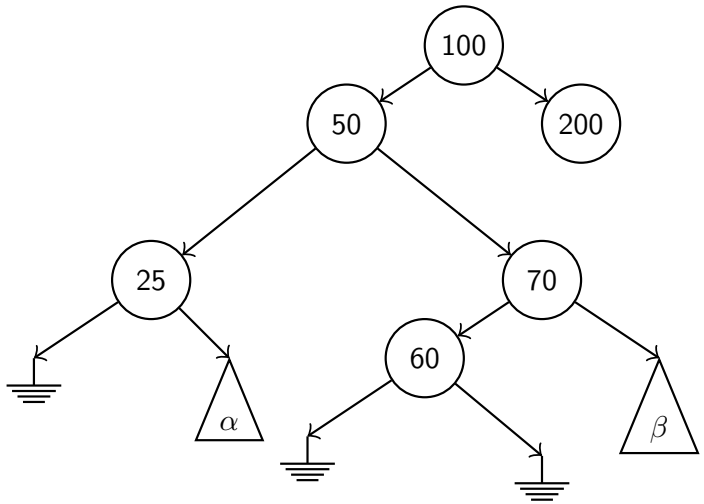


Types of delete

- simple - removing a node which has atmost one child
- complex - removing a node which has exactly two children

BST - Simple Delete

delete(25)



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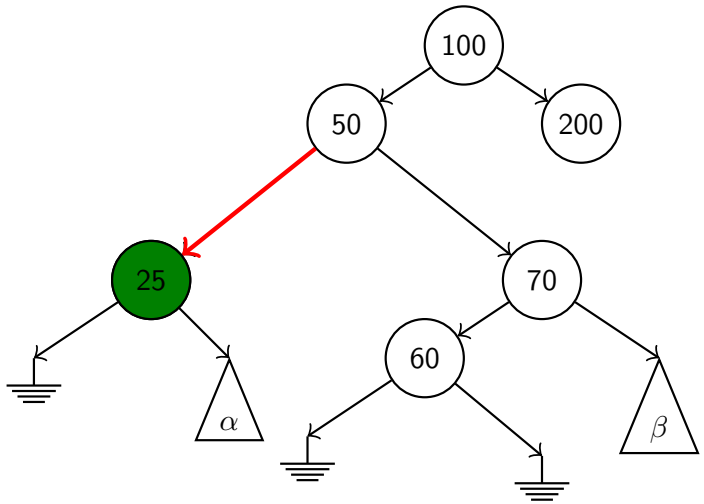

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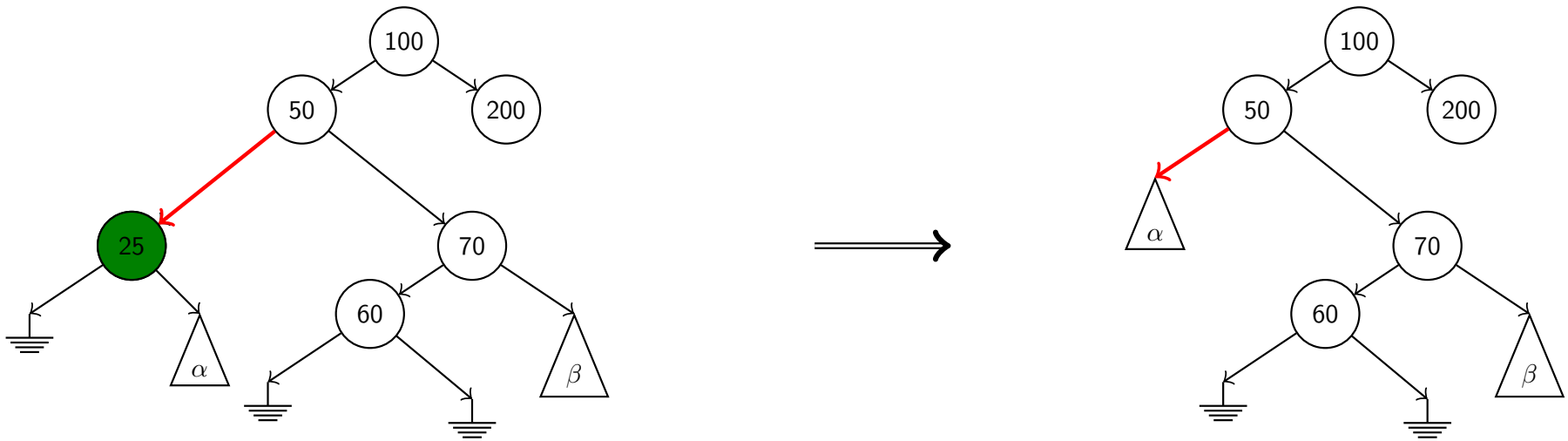
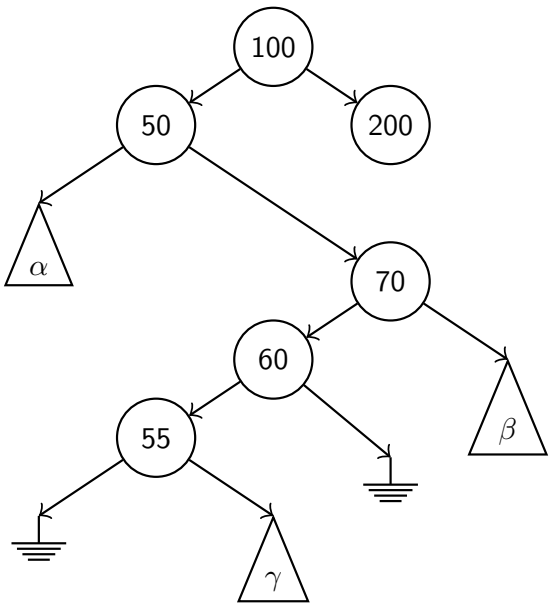


BST - Complex Delete

delete(50)



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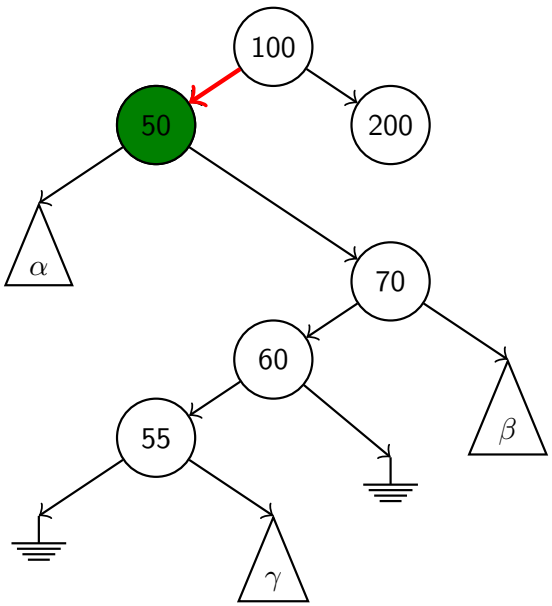

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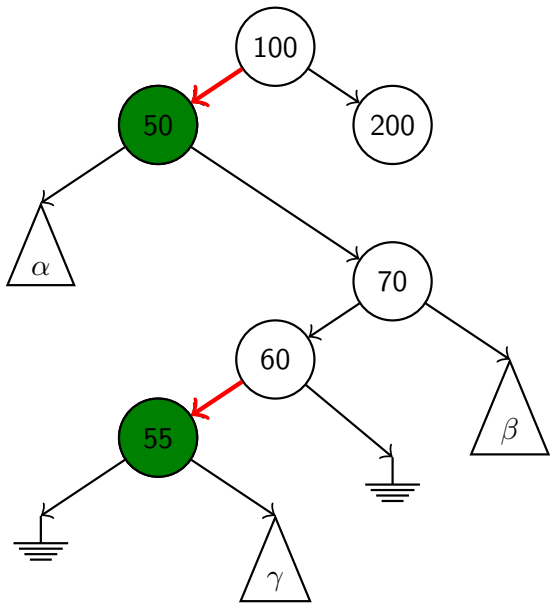

find successor

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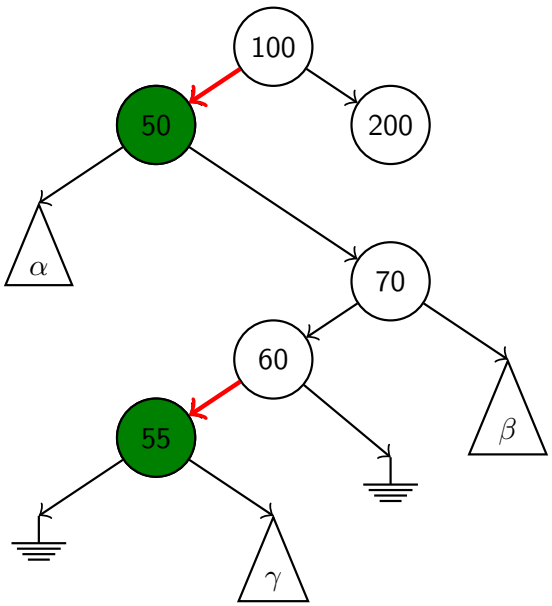

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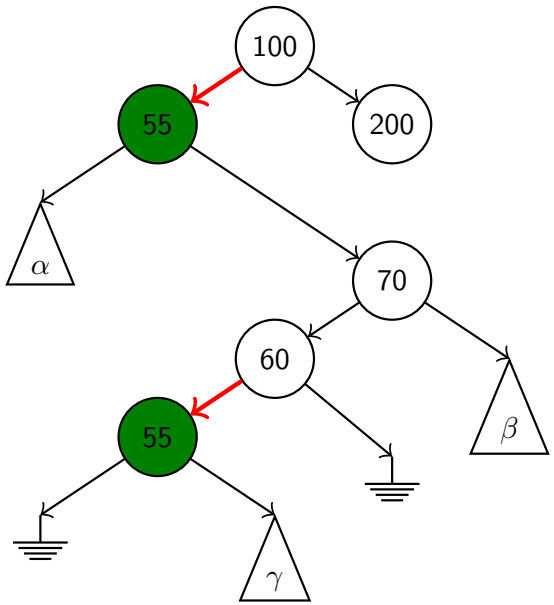

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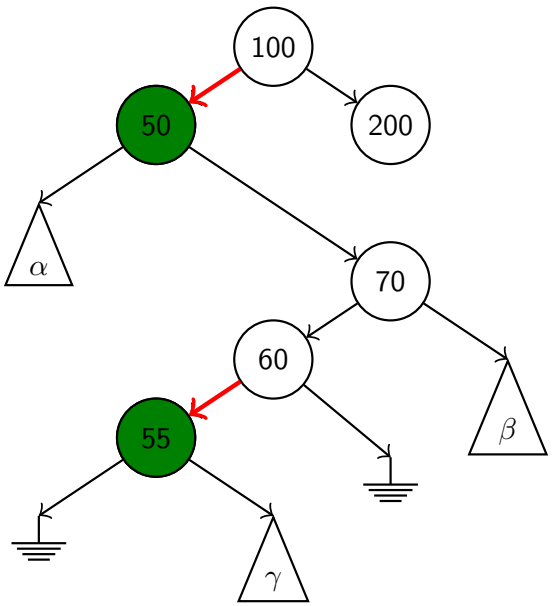

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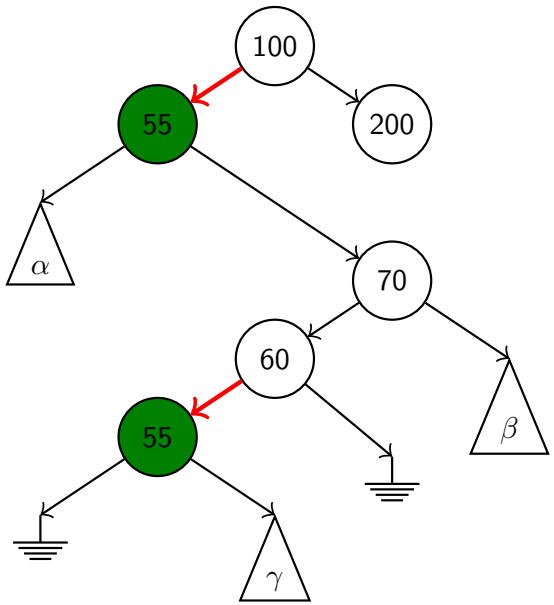

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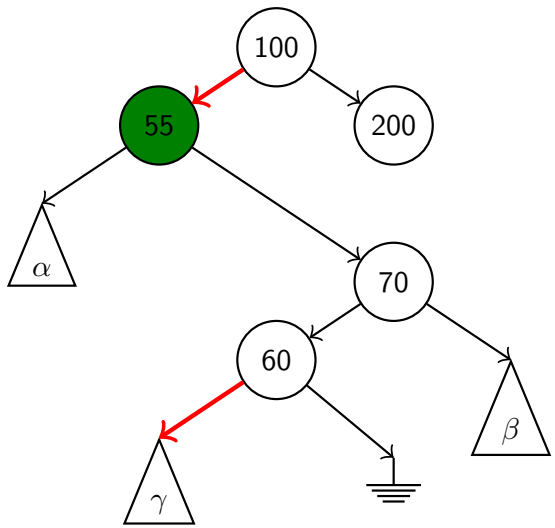

remove successor

Related Works

#	Algorithm Type	Works At	BST Type	Authors
1	lock free	node level	external	Ellen et.al[PODC'10]
2	lock free	node level	internal	Howley & Jones[SPAA'12]
3	lock free	edge level	external	Natarajan &Mittal[PPoPP'14]
4	lock based	node level	internal	Arbel & Attiya[PODC'14]
5	lock based	node level	internal	Drachsler et.al[PPoPP'14]

Lock Based BST[PPoPP'15 Poster]

Contributions

- combine edge-based locking with internal representation of BST
- optimistic tree traversal

Lock Based BST[PPoPP'15 Poster]

- common workloads have more searches than updates
  - design is optimized for searches
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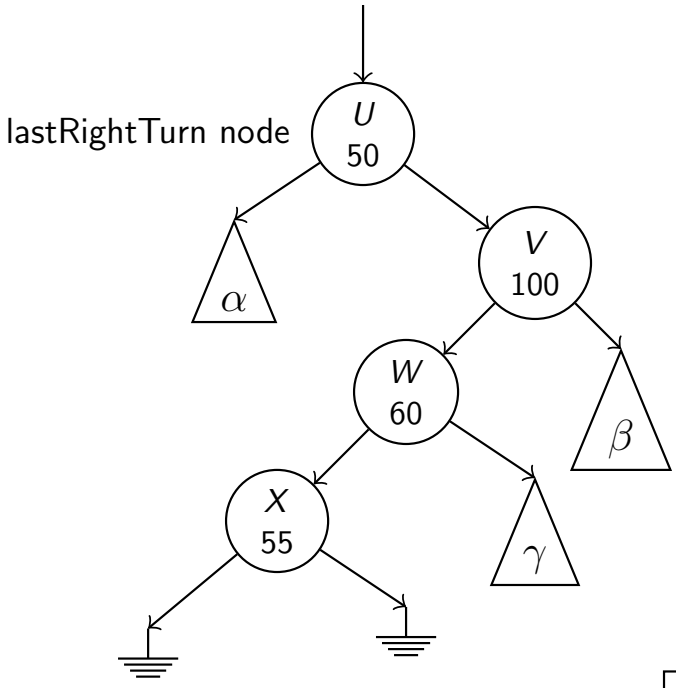
- Any real life workload will have more inserts than deletes
  - insert operations do not obtain any locks
  - performs only one atomic operation
- removal of a node in a concurrent BST is challenging
  - delete operations uses locks
  - locks can be obtained on nodes or edges
  - locking edges instead of nodes increases concurrency

Lock Based BST - Challenges in search



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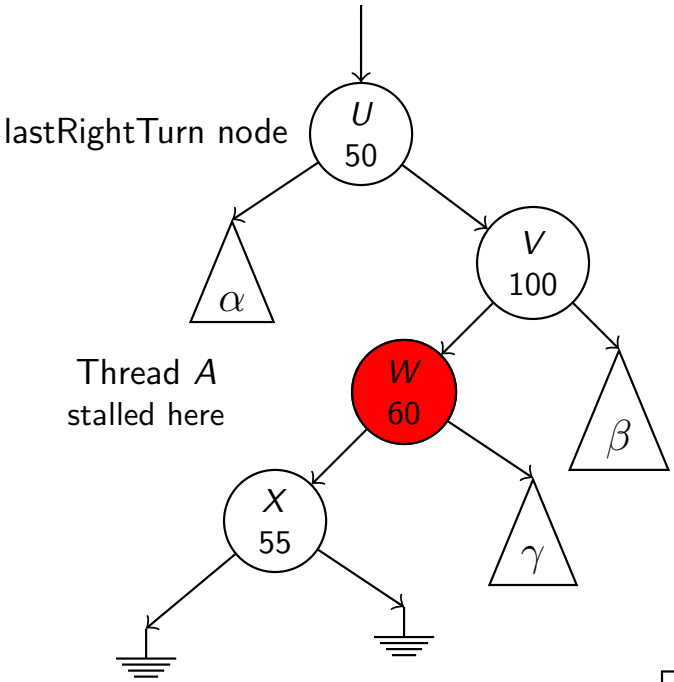

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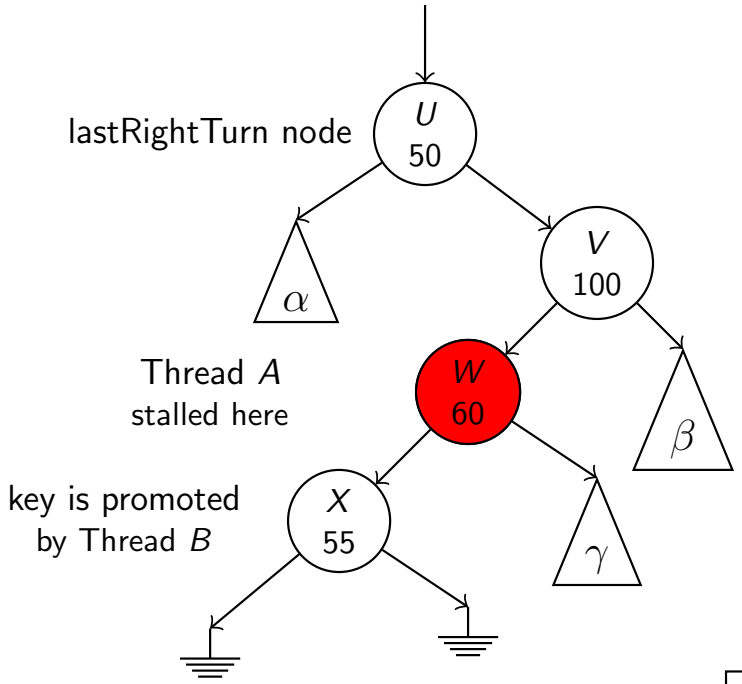

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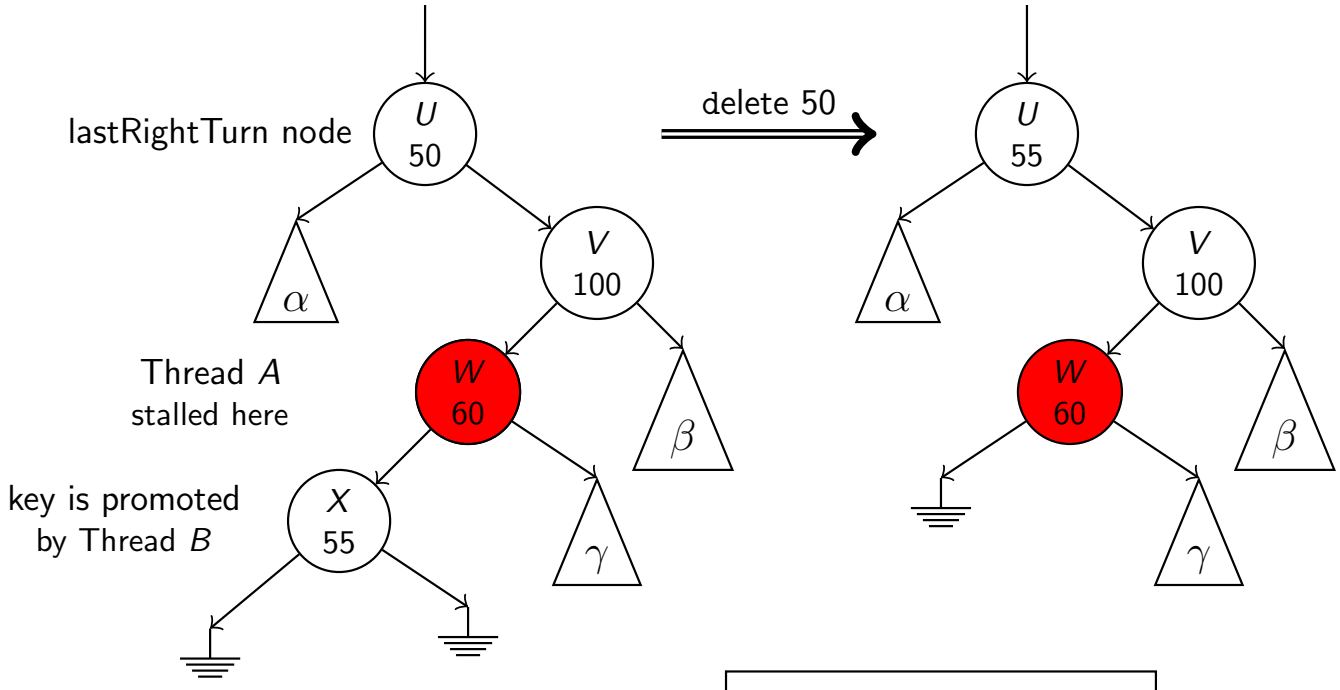

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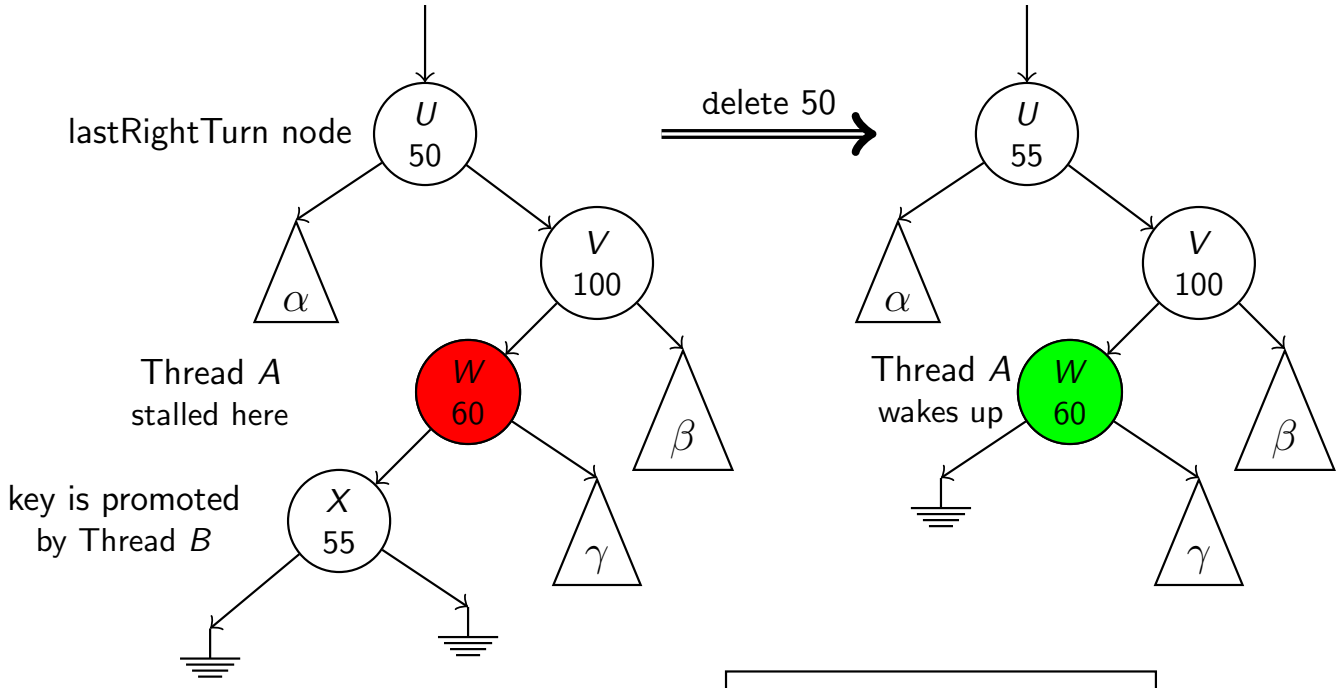

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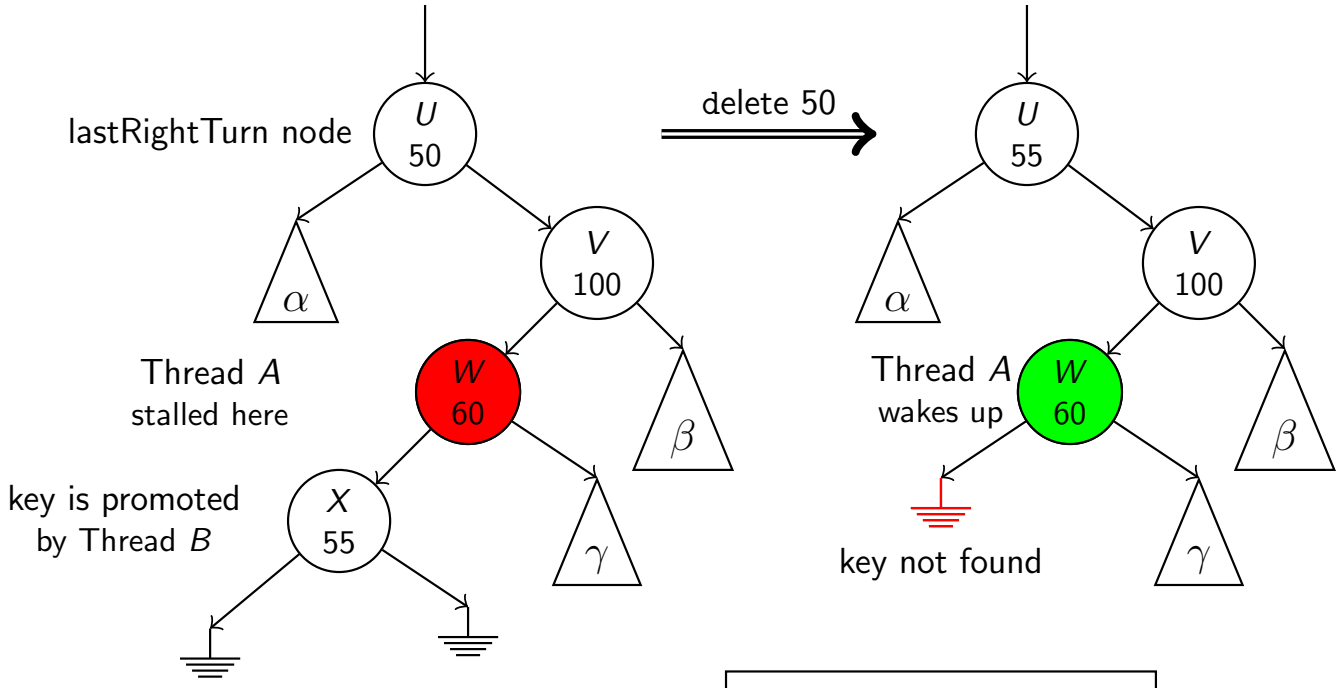

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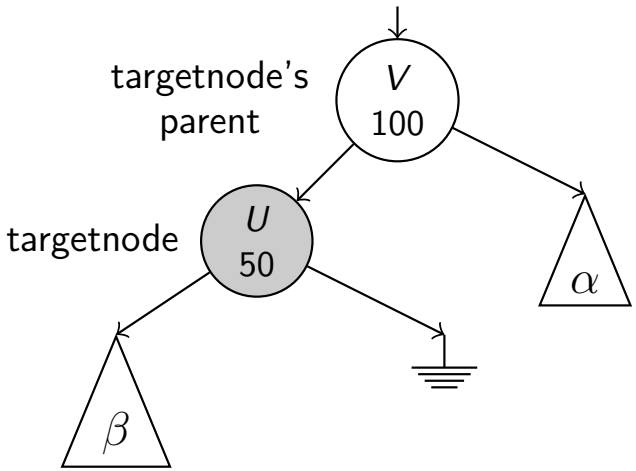
Keep track of last right turn node and its key. If search terminates at a NULL node, check if the current key in the last right turn node has changed. If yes restart the operation from root.

Lock Based BST - Delete

pseudocode for delete

```
locate the node to delete;
if simple delete then
    lock the edge ⟨parent,node⟩;
    lock the children edges;
    make the parent point to the non-null child using a simple write
    instruction;
    release all locks;
else // complex delete
    lock the edge ⟨node,rightChild⟩;
    find the successor;
    lock the edge ⟨successorParent,successor⟩;
    lock the children edges of successor;
    promote key;
    remove successor by a making successorParent point to non-null child of
    successor;
    release all locks;
end
```

Lock Based BST - Simple Delete



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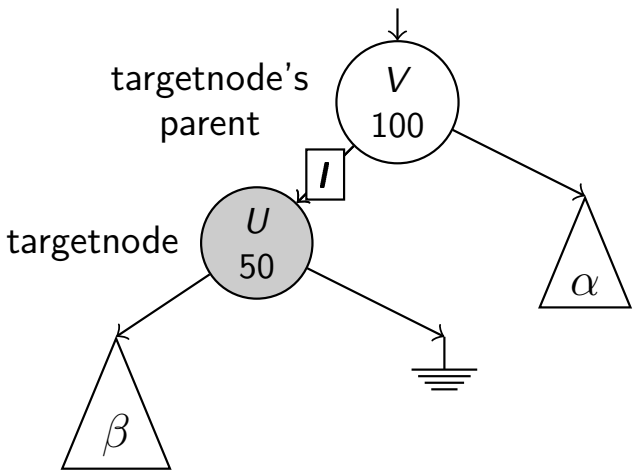

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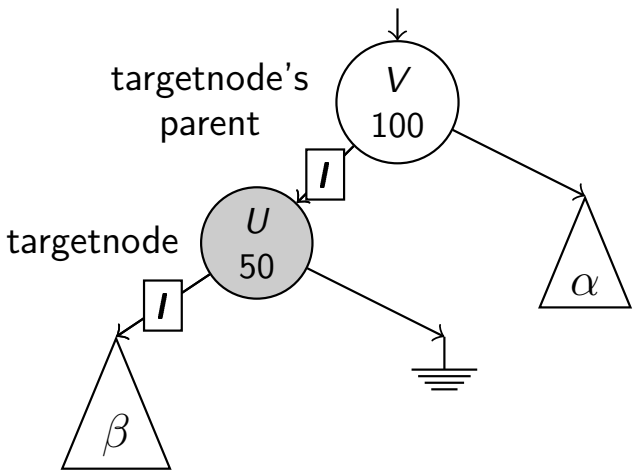

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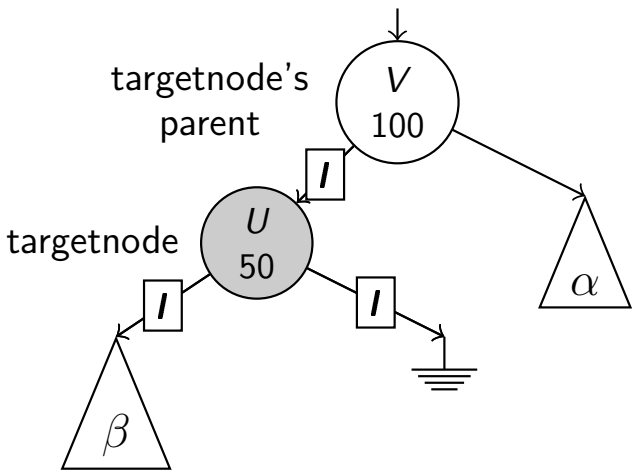

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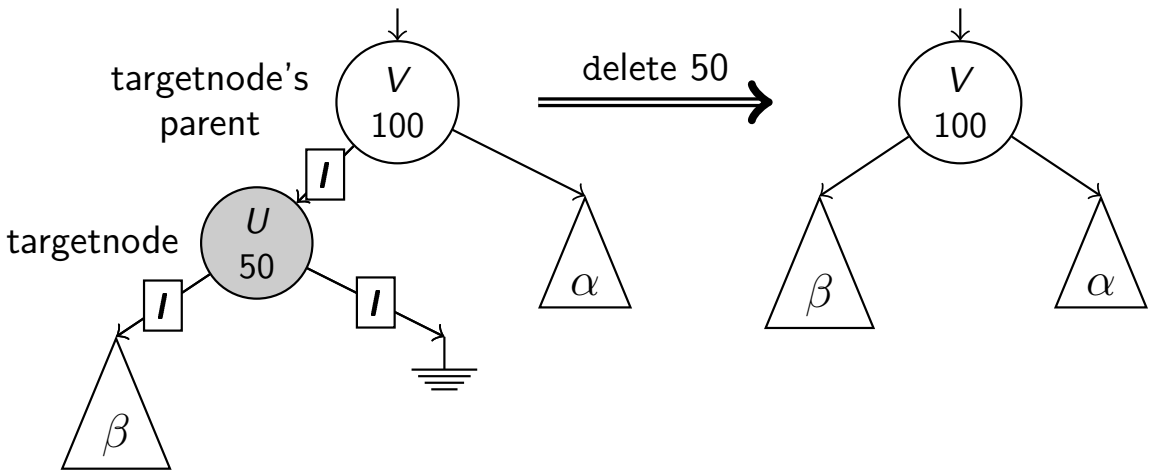

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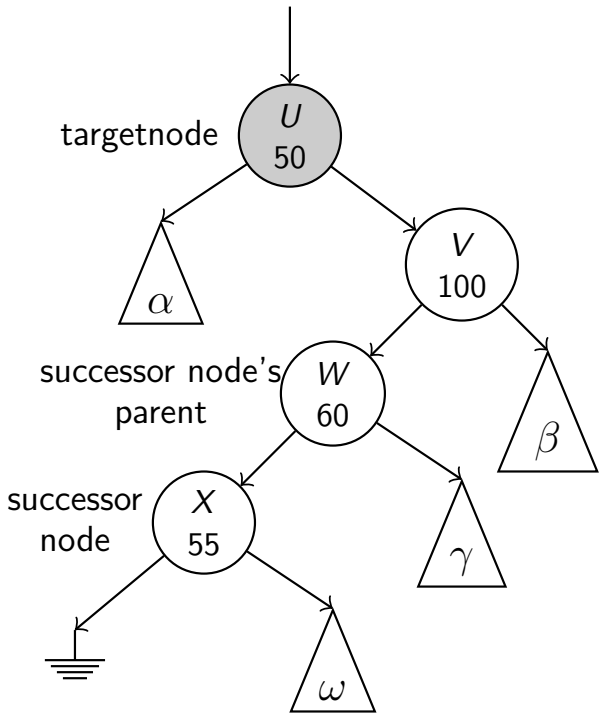

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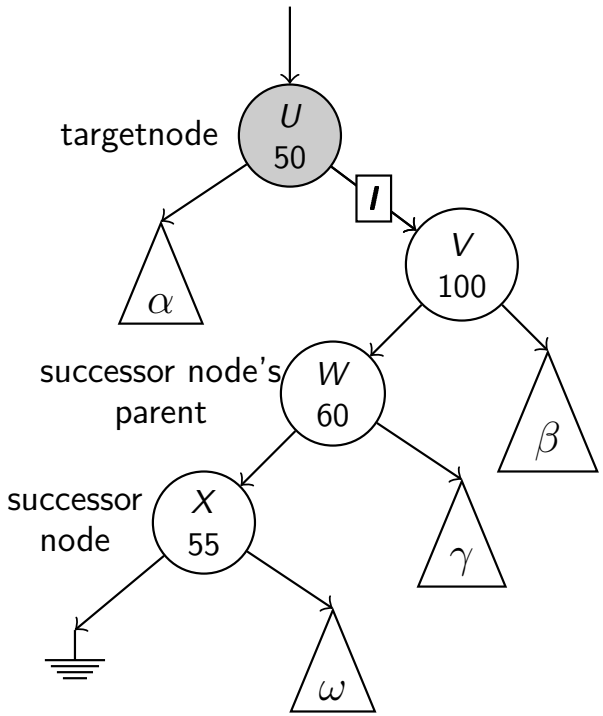

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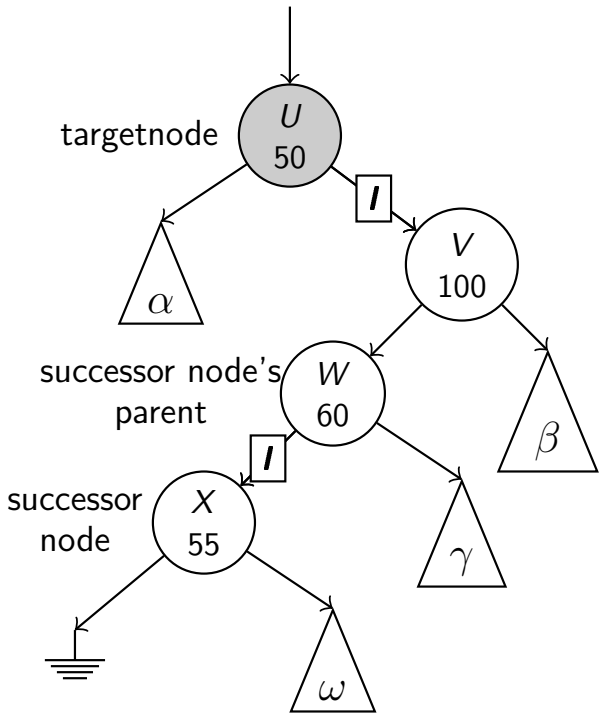

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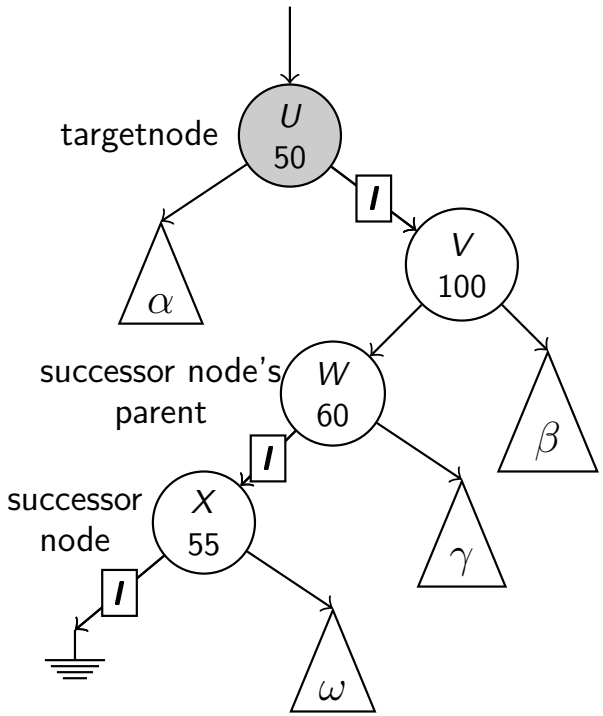

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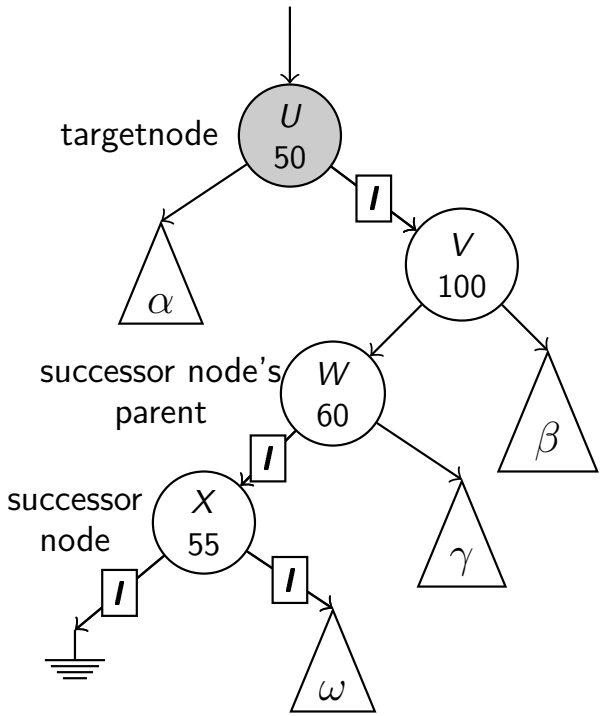

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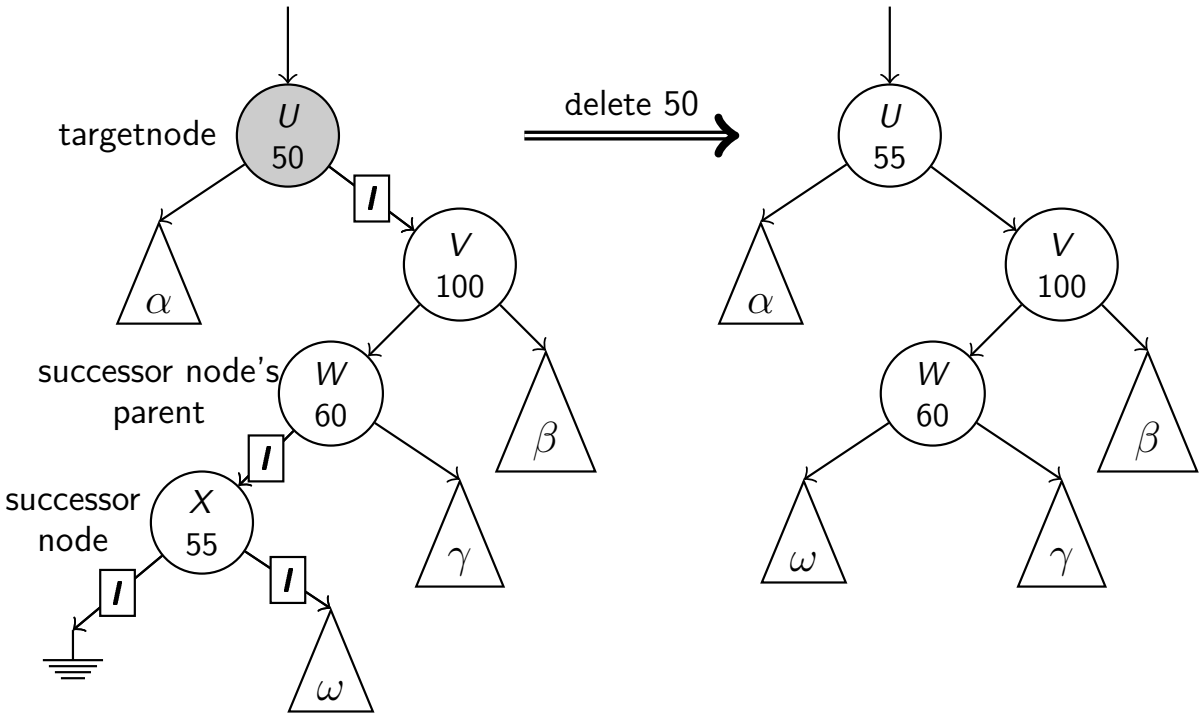
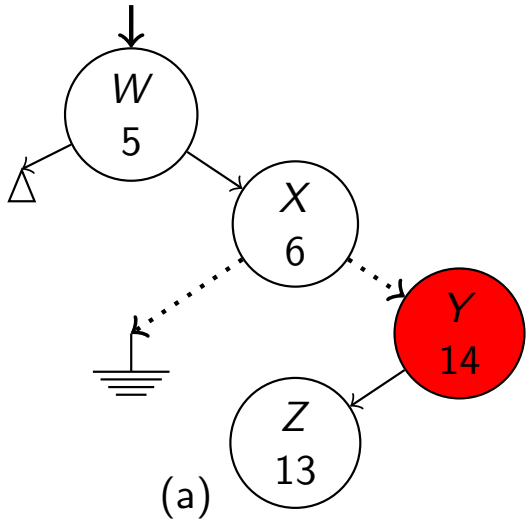


Lock Based BST - More challenges in search

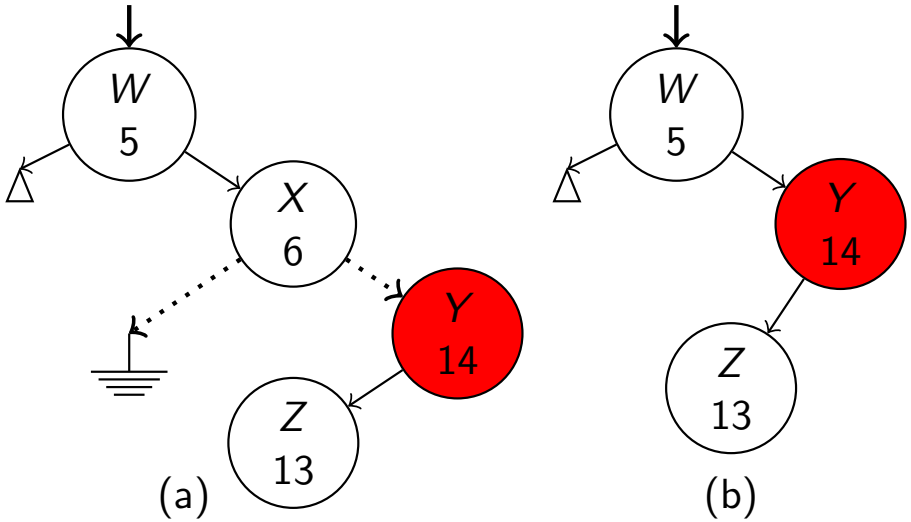
A scenario in which the last right turn node is removed



- Search(13) gets stalled at Y in (a). Its last right turn node is X

Lock Based BST - More challenges in search

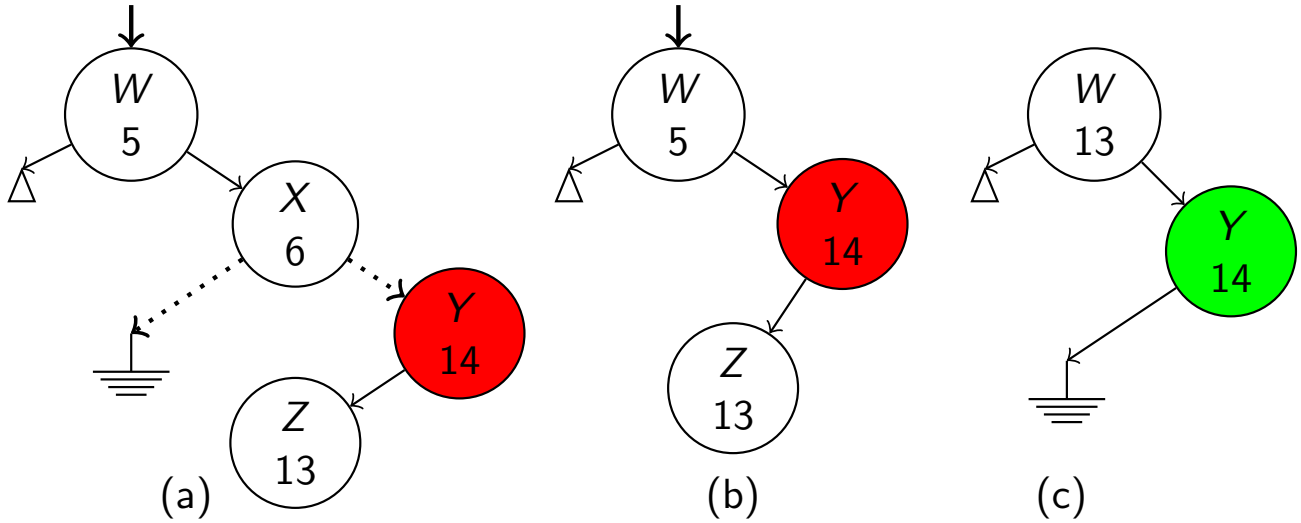
A scenario in which the last right turn node is removed



- Delete(6) removes X from the tree in (b). The key stored in X is still 6

Lock Based BST - More challenges in search

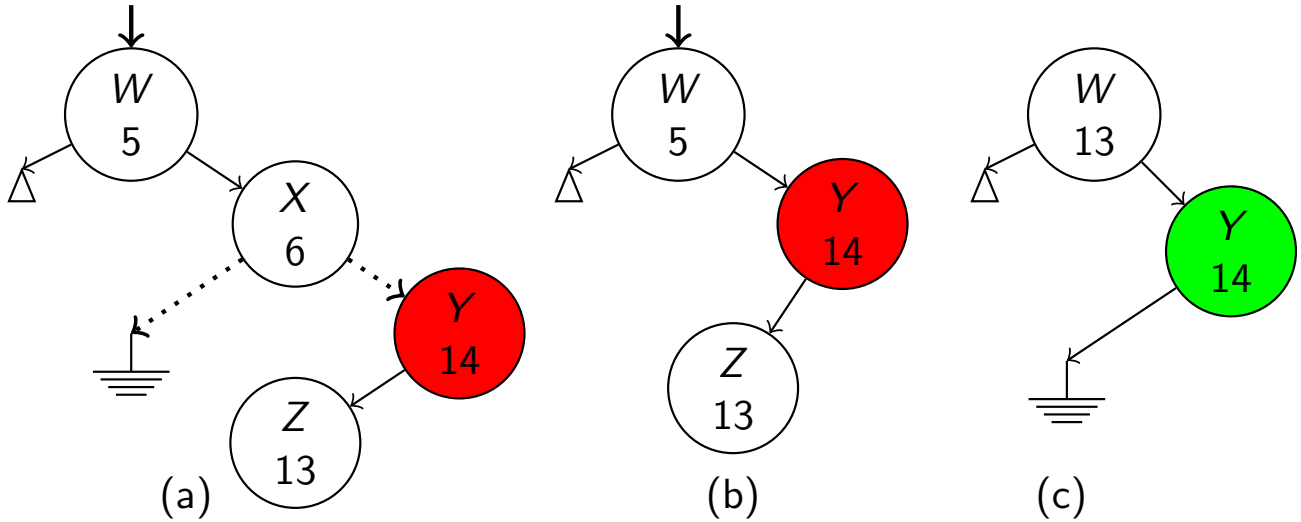
A scenario in which the last right turn node is removed



- Delete(5) results in 13 moving up the tree from Z to W in (c). When search(13) wakes up, it will miss 13 as the key in the last right turn node has not changed

Lock Based BST - More challenges in search

A scenario in which the last right turn node is removed



- In the first traversal search(13) saw the node X
- In the second traversal there are two cases
  - case1, search(13) did not find X - save the traversal and restart
  - case2, search(13) did find X - use the results of previous traversal

Lock Free BST[ICDCN'15]

Contributions

- combine edge-based locking with internal representation of BST
- optimistic tree traversal

Lock Free BST[ICDCN'15]

Contributions

- combine edge-based locking with internal representation of BST
- optimistic tree traversal
- lock-free algorithm

Lock Free BST[ICDCN'15]

- search and inserts are same as in lock Based BST
- to maintain lock-free property, if an insert or delete operation fails, it helps a pending delete operation(if needed)

pseudocode for delete

```
locate the node to delete;
flag the children edges for deletion;
if simple delete then
    make the parent point to the non-null child atomically;
else // complex delete
    find the successor;
    flag the children edges of successor for promotion;
    promote key;
    remove successor by a simple delete;
    replace node with a fresh copy;
end
```

Lock Free BST - Simple Delete

- flag is owned by an operation
- if a thread which installed the flag is stalled, other threads can help complete the operation

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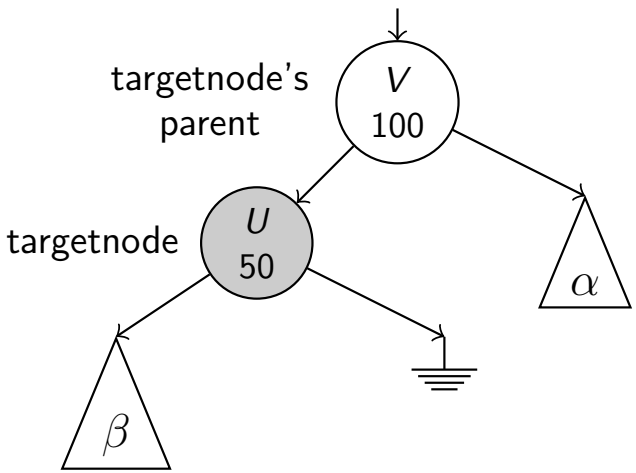

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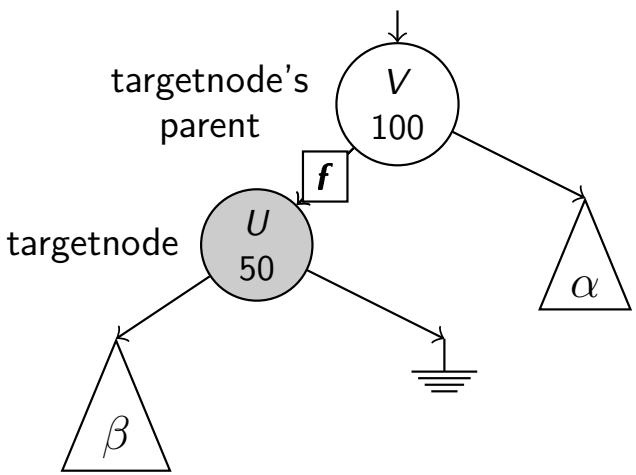

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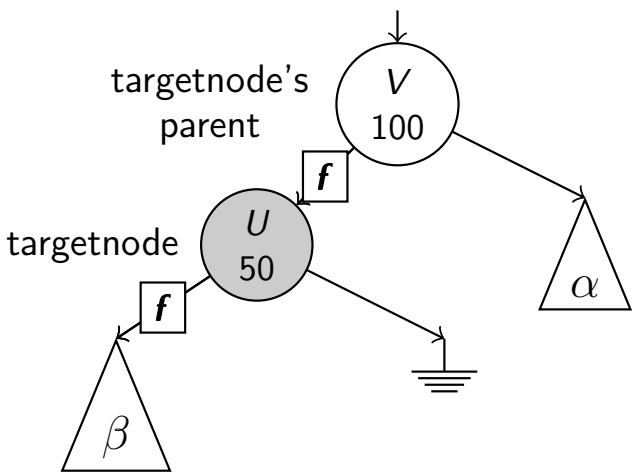

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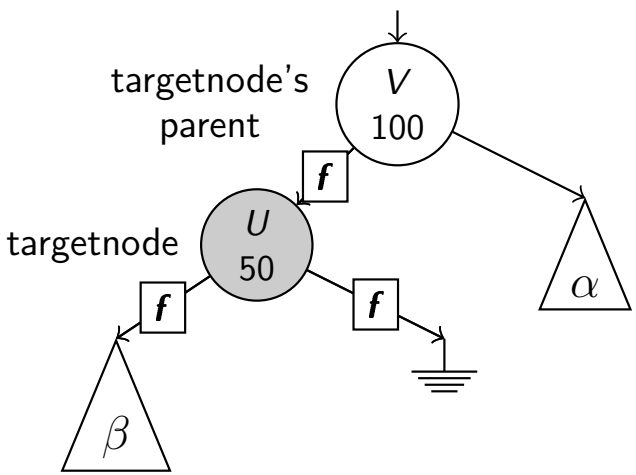

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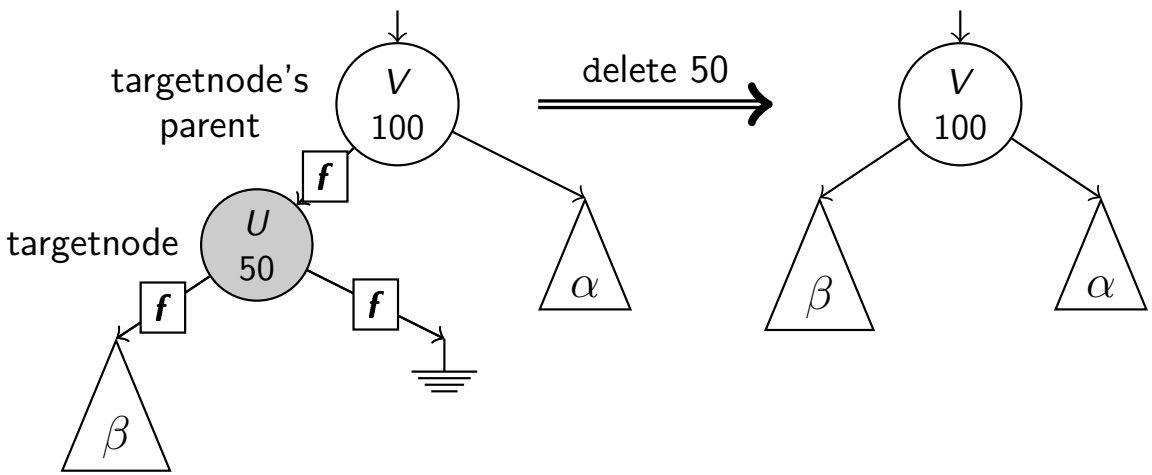

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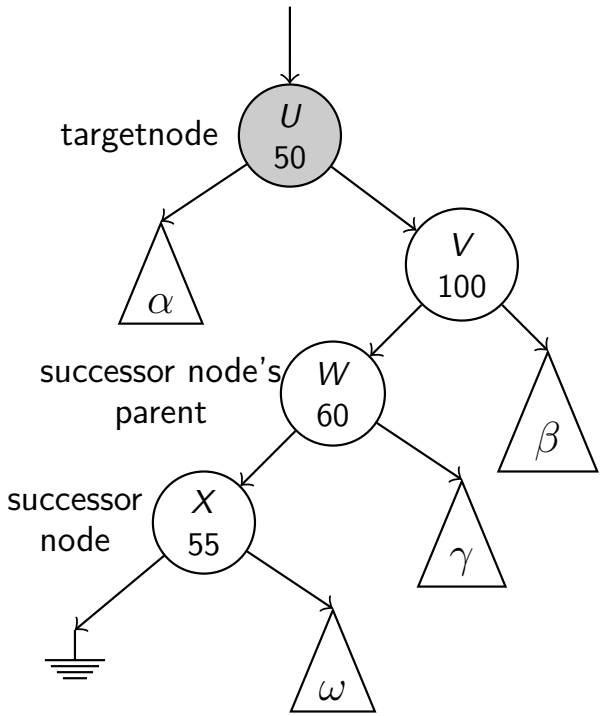

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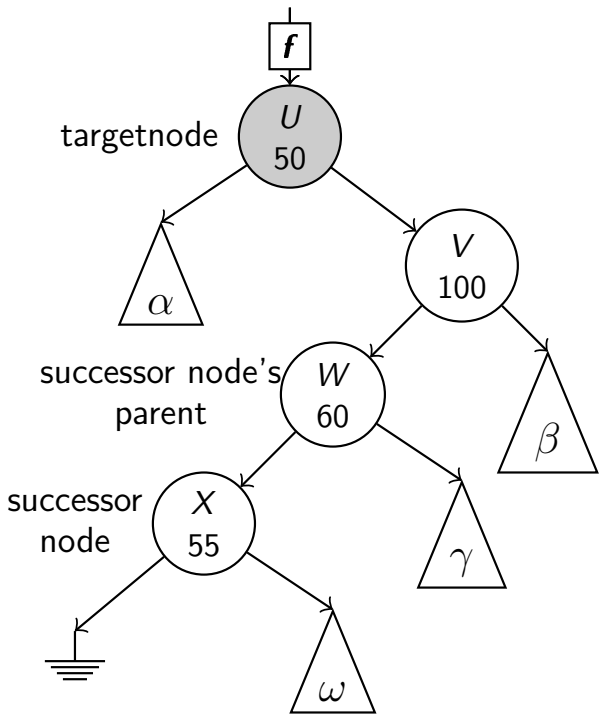

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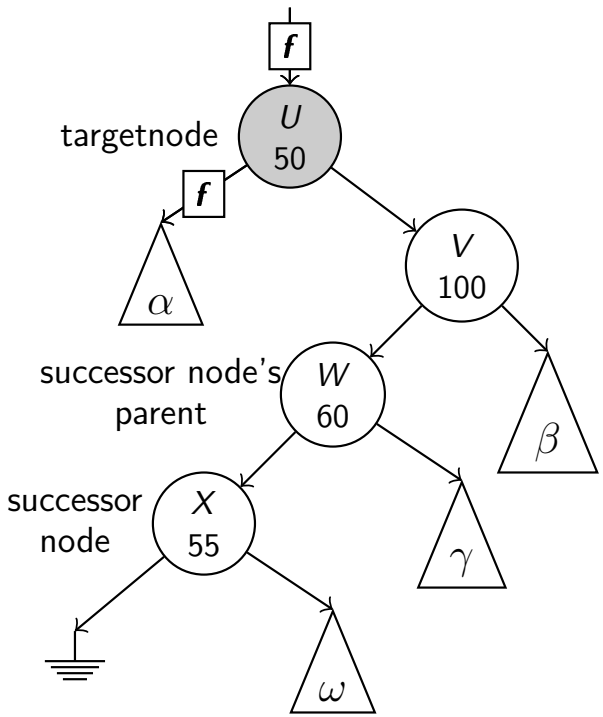

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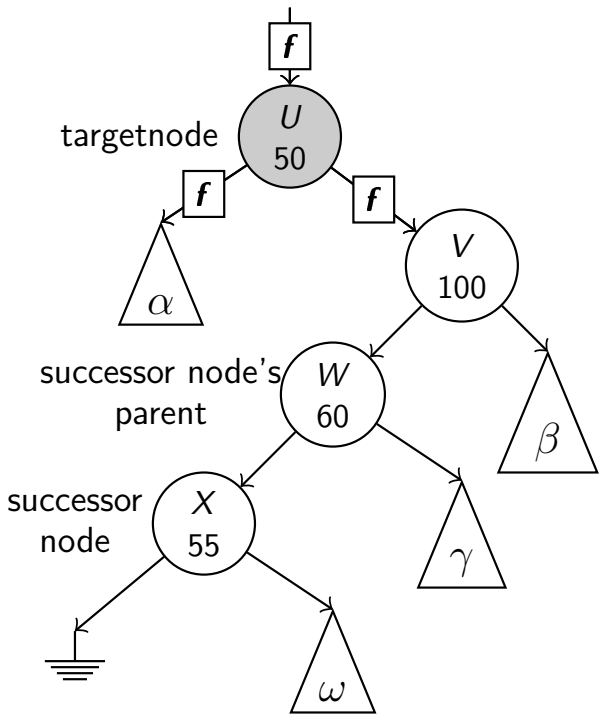

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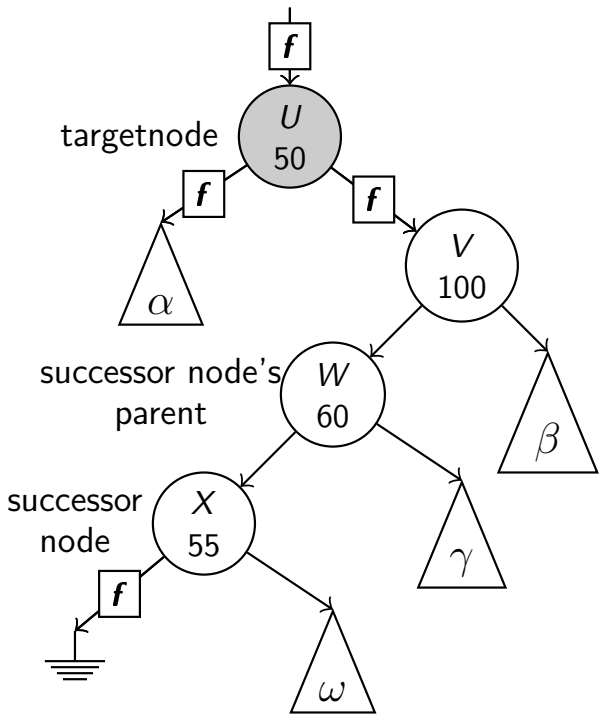

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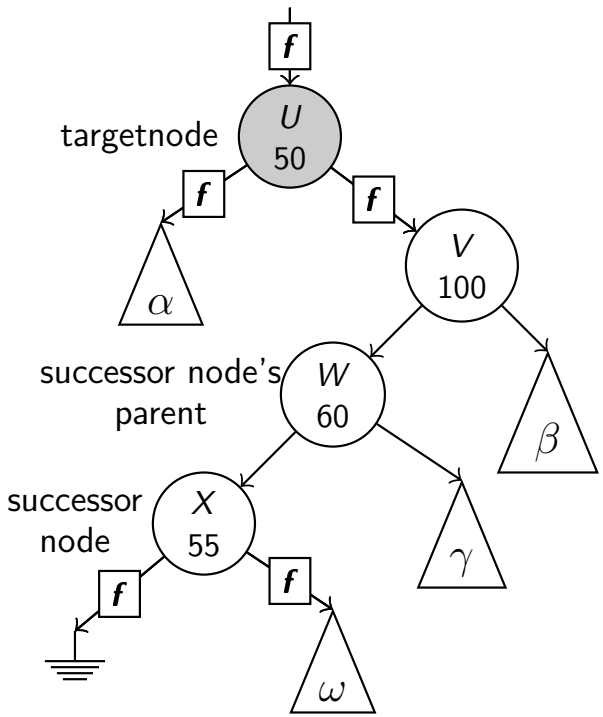

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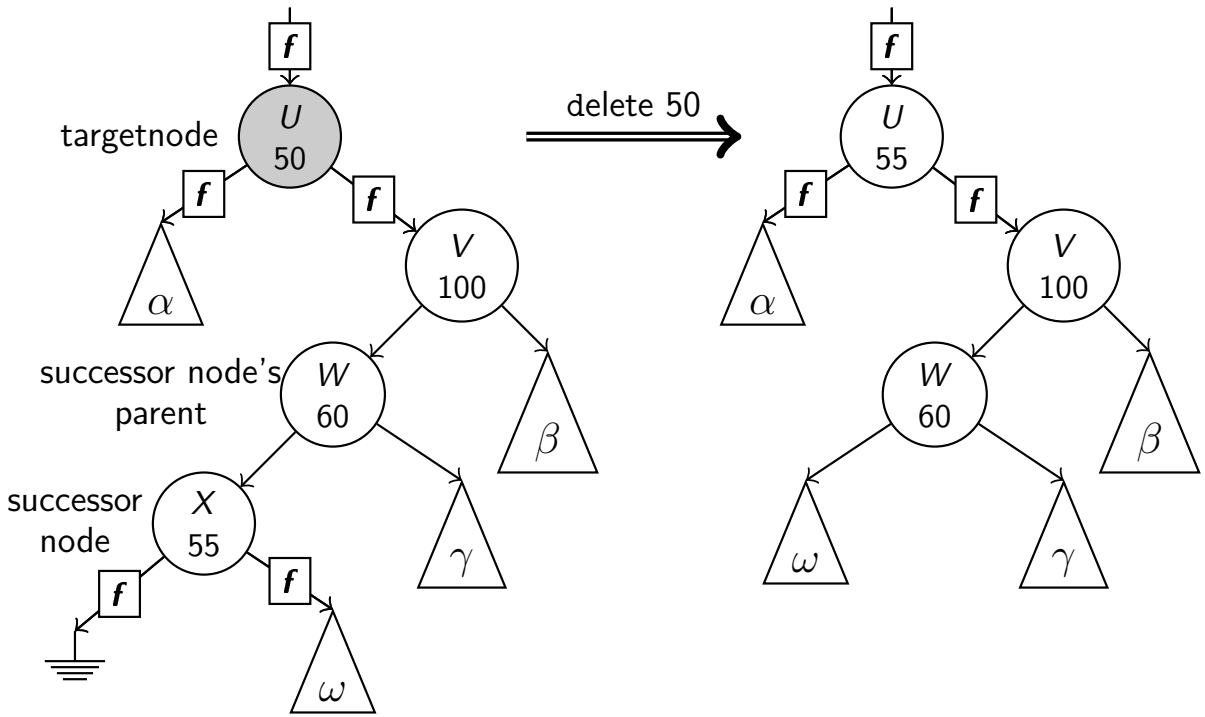

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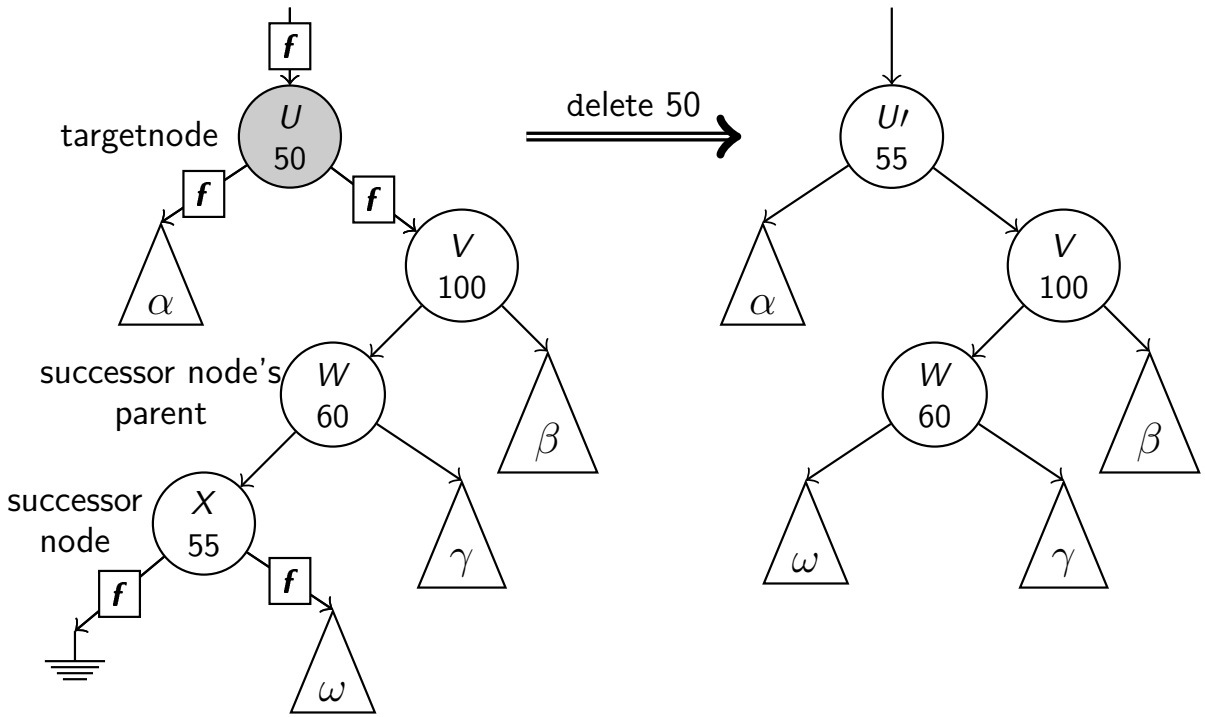


Experimental Setup

To compare the performance of various concurrent BSTs we considered the following parameters:

- Maximum Tree Size
  - key space size varied from 2^{13} (8Ki) to 2^{24} (16Mi).
- Relative Distribution of Operations
  - Read-Dominated (90% search, 9% insert and 1% delete)
  - Mixed (70% search, 20% insert and 10% delete)
  - Write-Dominated (0% search, 50% insert and 50% delete)
- Maximum degree of Contention
  - number of threads that can concurrently operate on the tree
  - we collected data for 32 threads

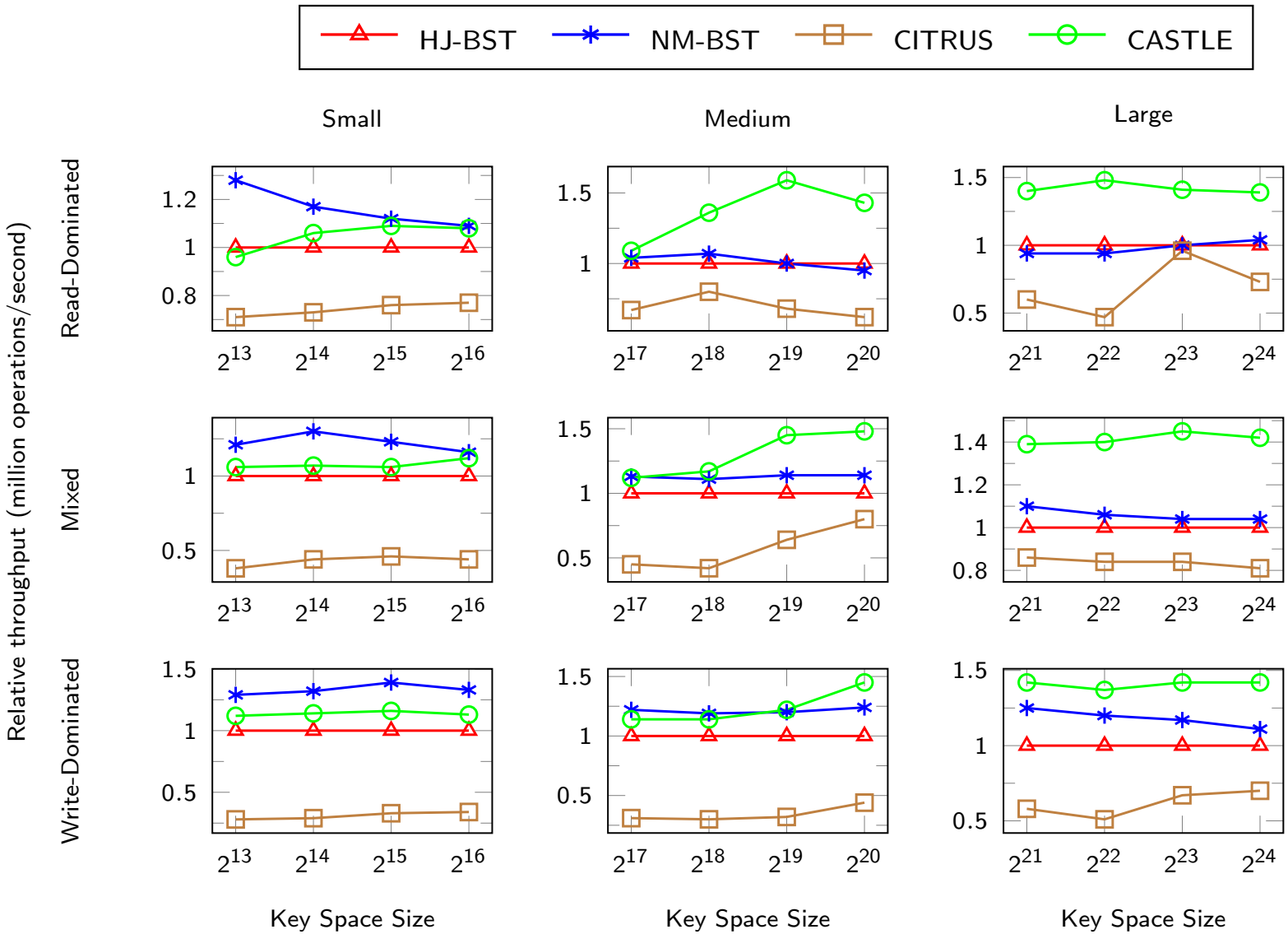
Experimental Setup

- Throughput computed as millions of operations per second (MOPS)
- each trial was run for 10 seconds
- Average over 3 trials
- *pre-populated* the tree to 50% of its maximum size to capture steady state behaviour
- beginning of each run consisted of a "warm-up" phase whose numbers were excluded in the computed statistics to avoid initial caching effects
- The machine we used is a Dell PowerEdge R820 server with 4 Intel E5-4650 @ 2.70GHz 8-core processors (32 cores in total) and 1TB of DDR3 memory with HT disabled. 256KB L2 and 20MB shared L3

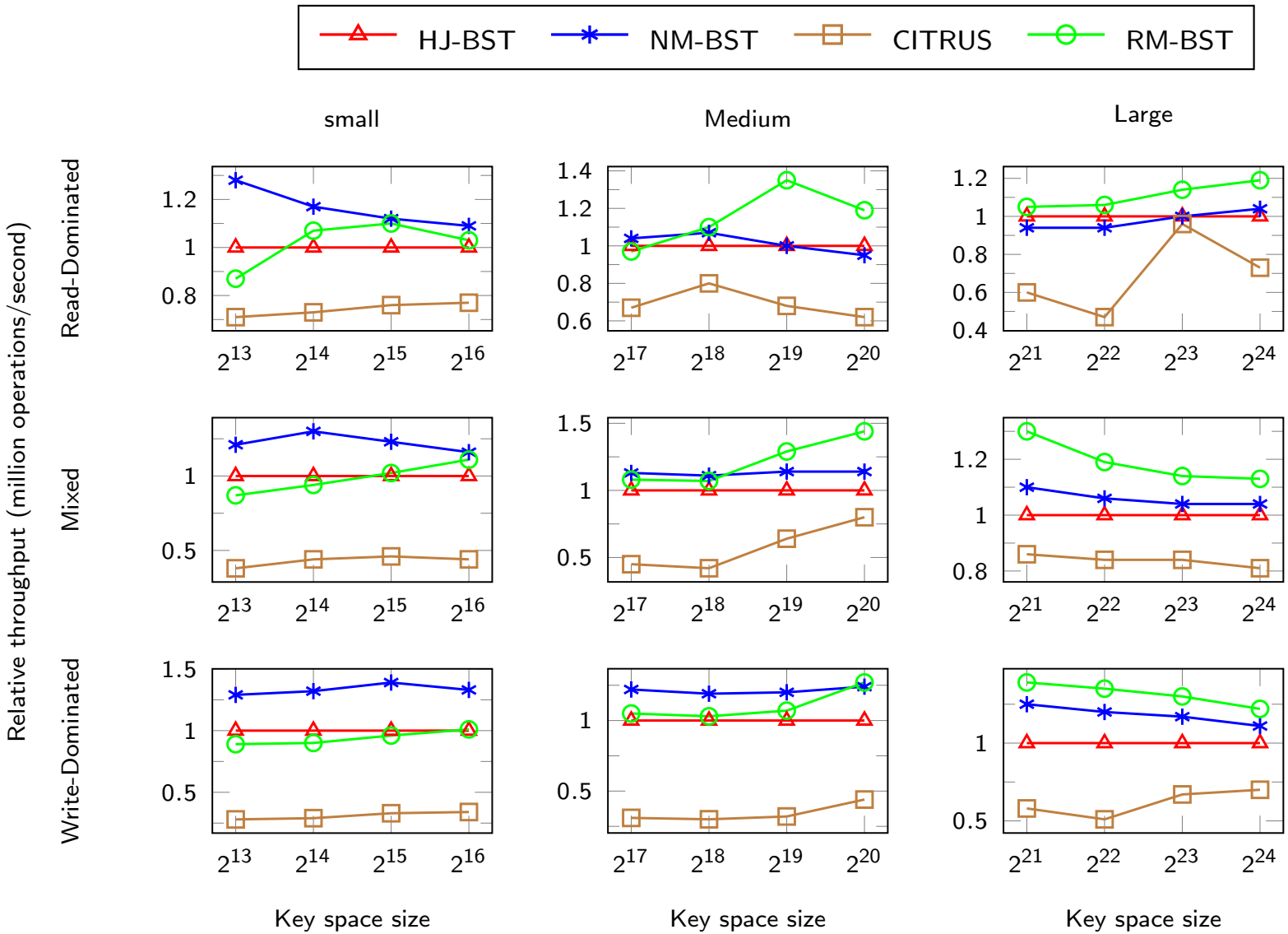
Other Concurrent BSTs

- a lock-free internal BST by Howley and Jones[SPAA'12], denoted by HJ-BST
- a lock-free external BST by Natarajan and Mittal[PPoPP'14], denoted by NM-BST
- RCU-based internal BST by Arbel and Attiya[PODC'14], denoted by CITRUS

Lock Based BST



Lock Free BST



Results Summary

Comparison of different lock-free algorithms in the absence of contention

Algorithm	**Number of Objects Allocated**		**Number of Atomic Instructions Executed**	
	Insert	**Delete**	**Insert**	**Delete**
HJ-BST	2	simple : 1 complex: 1	3	simple : 4 complex: 9
NM-BST	2	0	1	3
CASTLE (Lock Based BST)	1	simple : 0 complex: 0	1	simple : 3 complex: 4
RM-BST (Lock Free BST)	1	simple : 0 complex: 1	1	simple : 4 complex: 7

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- speedup is calculated over the second best algorithm

	Speedup	
Workload	**Lock Based BST**	**Lock Free BST**
Read-Dominated	59%	35%
Mixed	39%	26%
Write-Dominated	28%	13%

Future Work

- do local recovery upon failures
- develop concurrent K-ary BST which can improve spatial locality
- work on other data structures like tries

Future Work - Local Recovery

- currently upon failure, an operation restarts from the root
- Ellen et.al[PODC'14] have shown that local recovery can be done for external BST
- Local recovery on an internal BST is hard due to key movements
- We are currently working on extending our algorithms to enable local recovery

Future Work - K-ary BST

- ideas from Lock Based BST can be extended to external K-ary BST
- updates are relatively easier to handle as they obtain locks
- inserts might result in node splits
- searches are hard if we need to maintain their lock-free property

Future Work - Tries

- Tries are extensively used in text processing
- Tree like structure. So our ideas *can possibly* be applied