AALBORG UNIVERSITY

# Main-Memory Operation Buffering for Efficient R-Tree Update

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joint work with

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presented at VLDB 2007, Vienna

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# Outline

- Motivation
- Contributions
- Related work
- Assumptions
- Updates in R-trees
- The $R^R$-tree
  - Structure and algorithms
  - Results of performance studies
- Conclusions

# Motivation

- A typical pervasive computing scenario
  - Sampling of continuous processes via large numbers of sensors
  - Maintenance of an up-to-date current state of the processes
  - Query processing against the current state
- Example: moving objects
  - The current positions of moving objects
  - Large populations of objects are anticipated (mobile phone users)
  - Updates are very frequent.
    - E.g., 600,000 objects, each issuing an update every minute yields 10,000 updates per second.
- Indexing is essential to efficient query processing.
- The index must be stored on disk, at least in part.
- Existing indices do not  support massive update loads.

# Contributions

- The paper proposes a new main-memory buffering technique for R-tree-type indices.

- Index maintenance and querying algorithms are provided.
- Analysis
  - An accurate analytical cost model is provided.
  - An empirical I/O performance study is conducted.
- Properties
  - Assumes that index updates need not be written to disk immediately
  - Supports normal index operations, including instantaneous queries
  - Supports disk-based index storage
  - Works with any amount of main memory
  - Exploits all available main memory
  - Supports more frequent index updates than possible so far

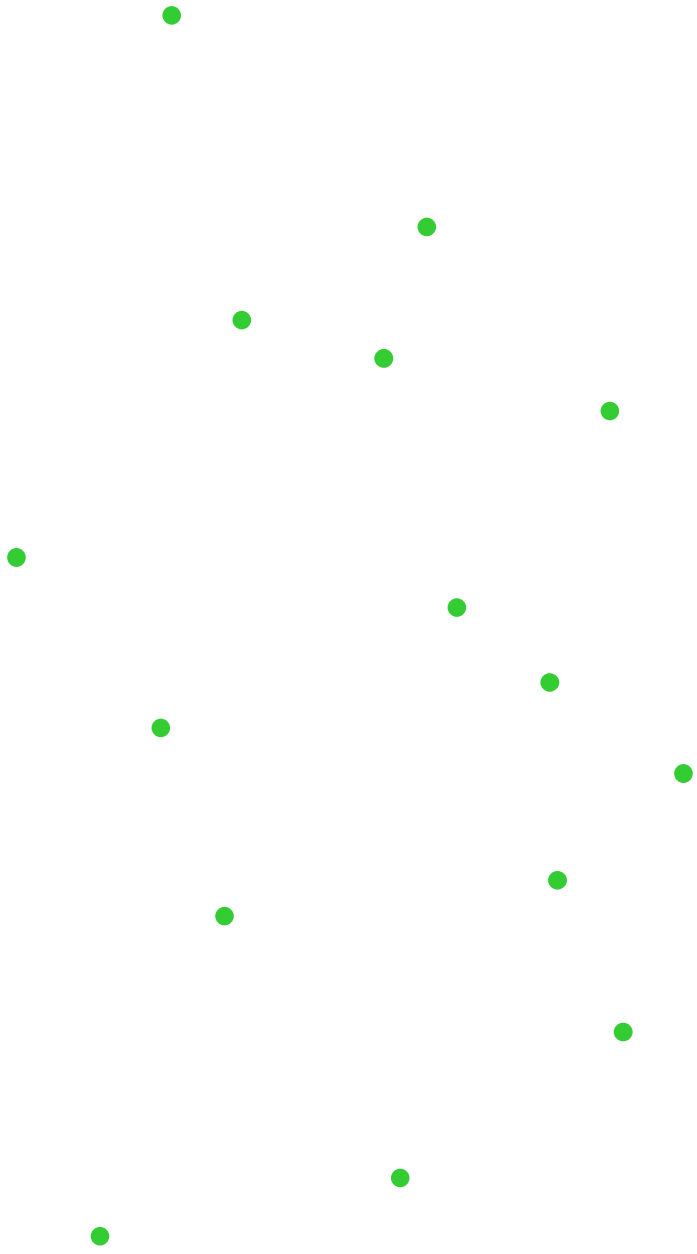
# Existing Solutions

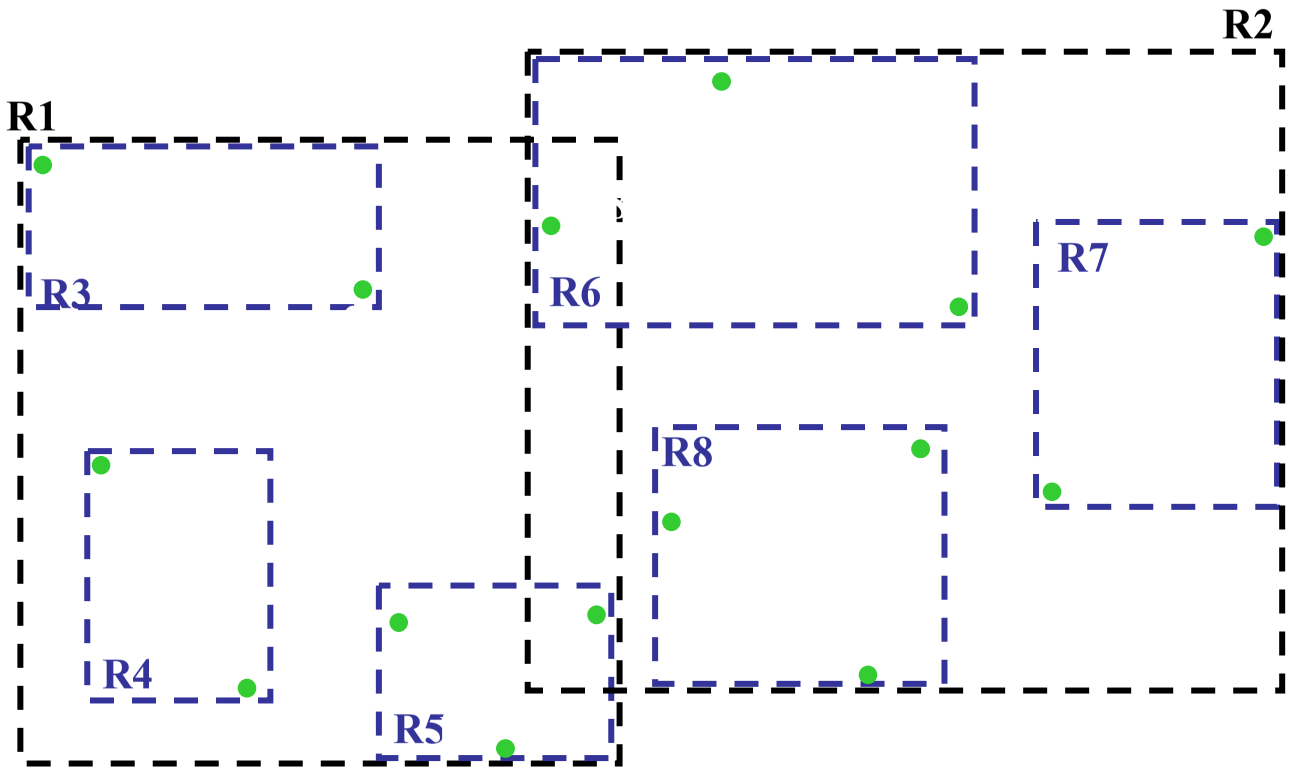
- Write-back LRU buffer
  - We compare with this.
- Modeling of data by functions of time
  - Orthogonal to this paper's proposal
- Bottom-up update techniques with direct leaf-level access
  - We need better performance.
- Buffer-tree-based solutions [e.g., Arge et al., 2002]
  - Complex; do not support instantaneous queries
- LGU [Lin and Su, 2005]
  - Complex; *requires* large amount of main-memory (relative to the data set size)
- The RUM-tree [Xiong and Aref, 2006]
  - We compare with this.
- LUGrid [Xiong et al., 2006]
  - The same persistency assumptions
- Various buffering techniques for B-trees
  - We build on these
  - Partial and selective buffer emptying not explored

# Assumptions

- The current state is a set of (id, key) pairs
  - For moving objects, key = (x, y)
- Each object sends a sequence of updates
  - *Update* (id, old_key, new_key)
    - Delete (id, old_key) + Insert (id, new_key)
- Softer persistency requirements
  - Not all of the index has to be committed on disk in-between operations
  - After a system crash
    - Wait (one minute) while the index is being populated
    - Alternatively, rebuild the index from the base data

# Background: R-trees

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R2
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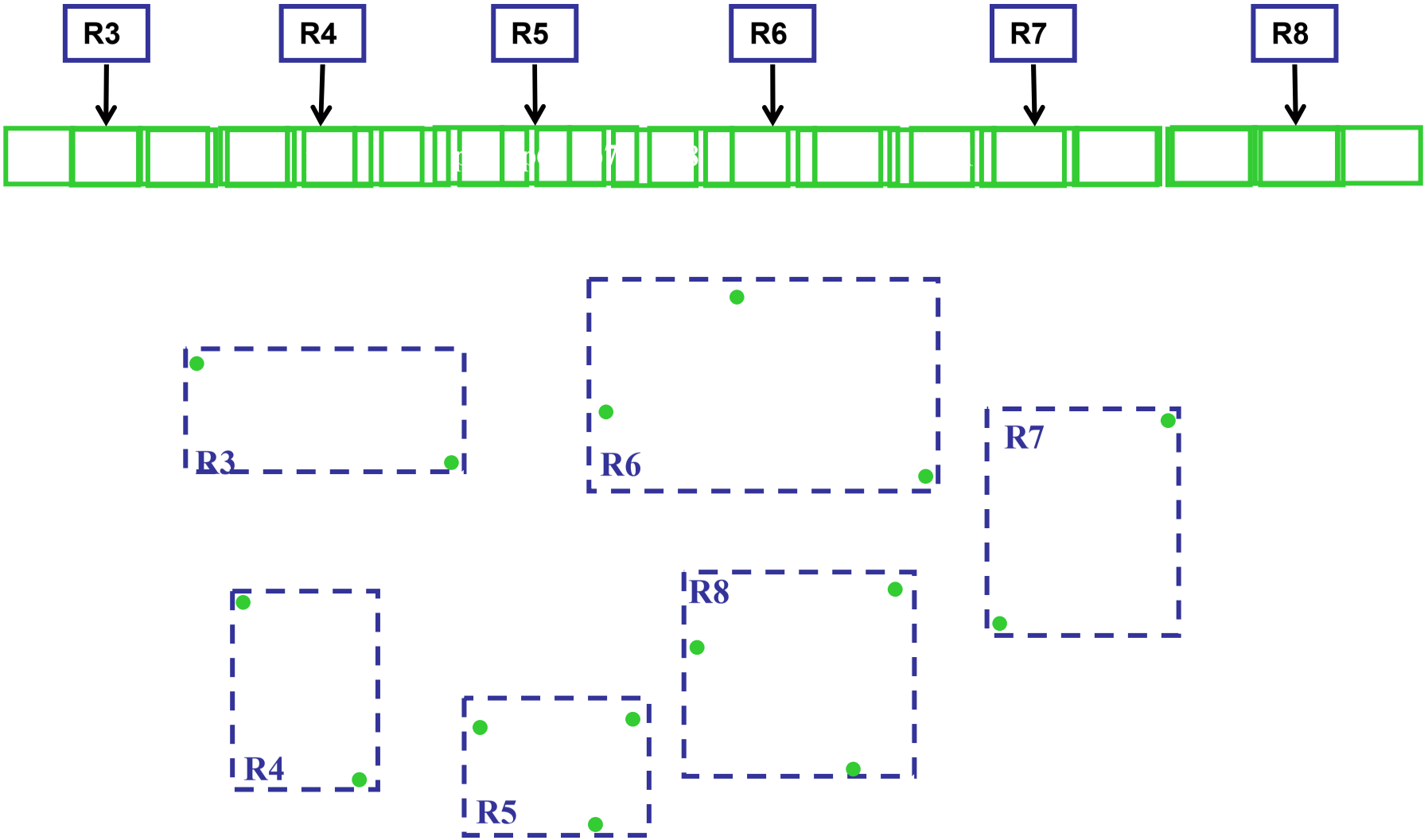
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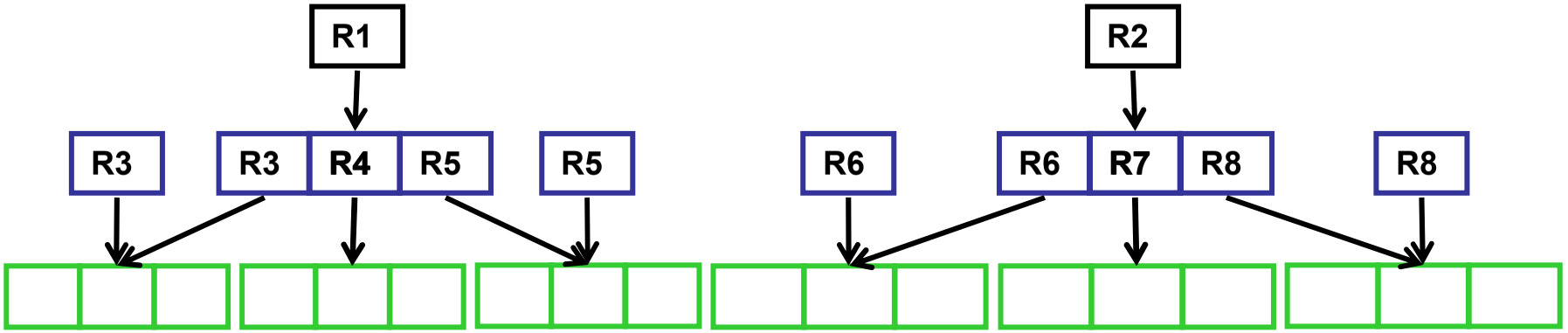
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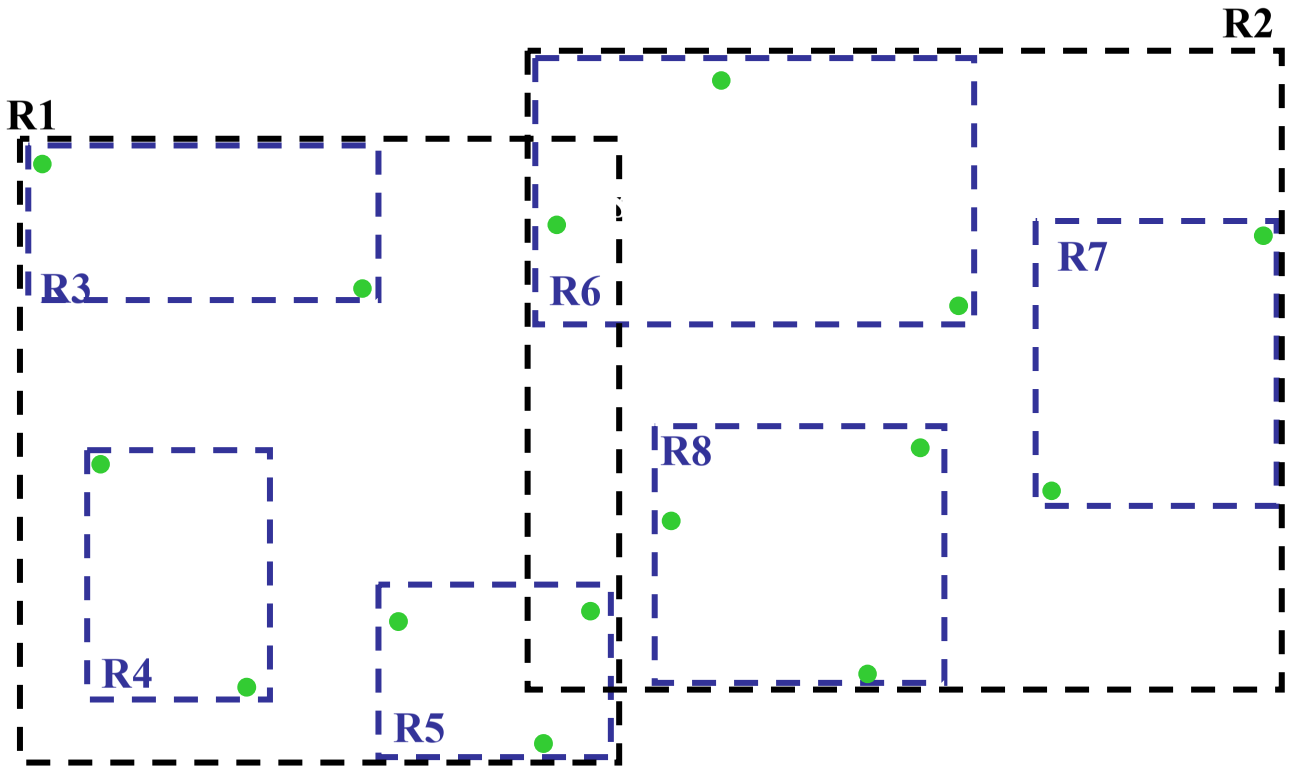
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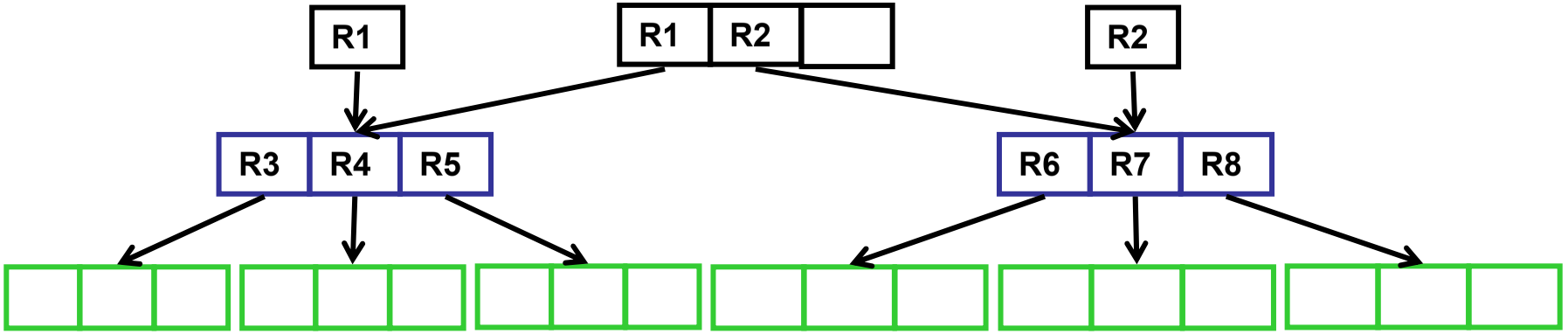
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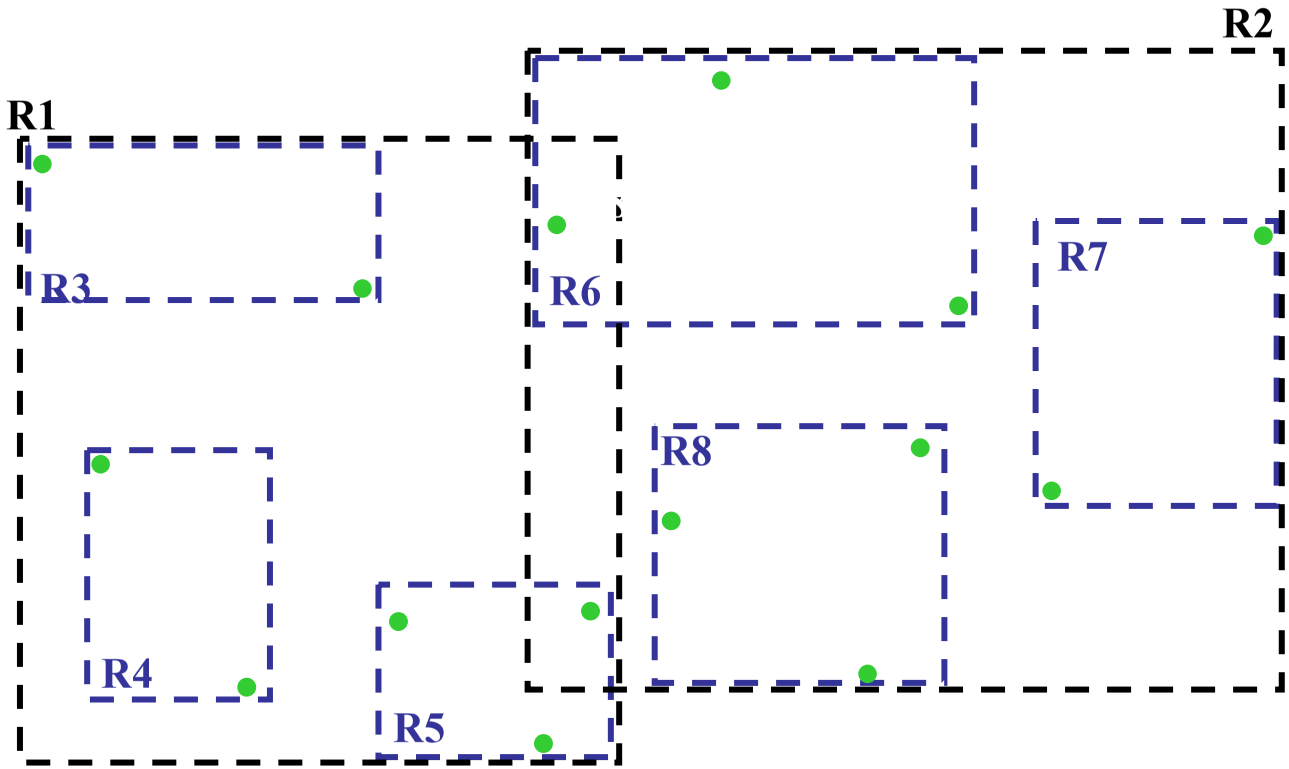
R2
R1
R3
R6
R7
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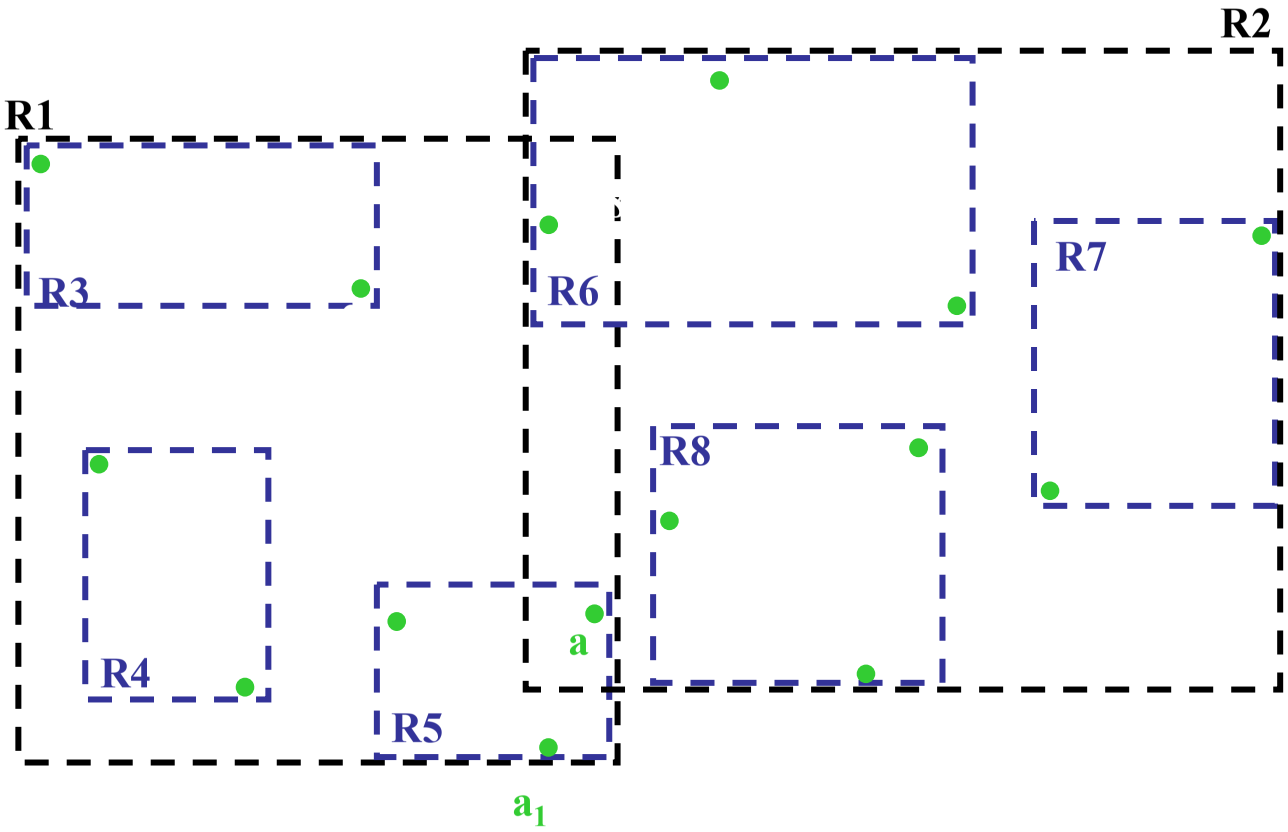
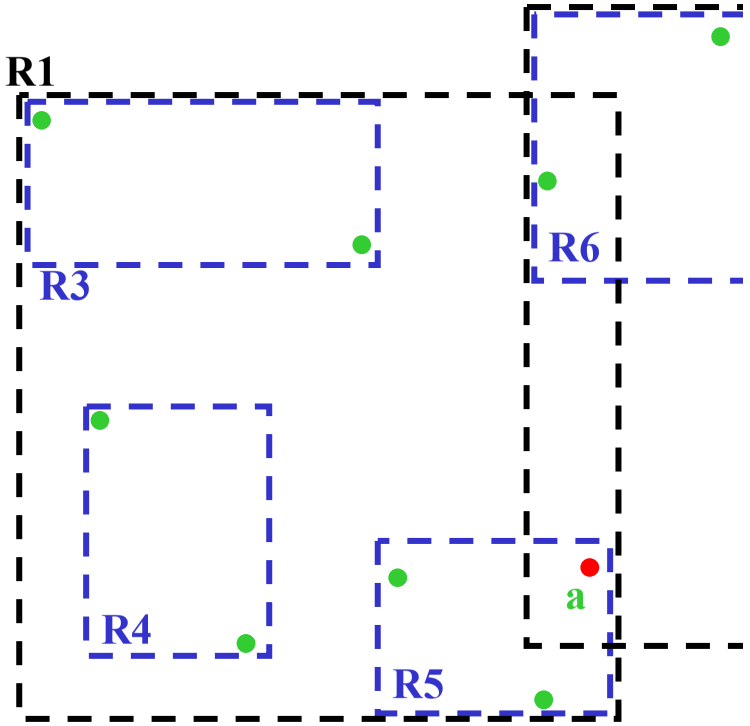
R4
R5

# Update operations in R-trees

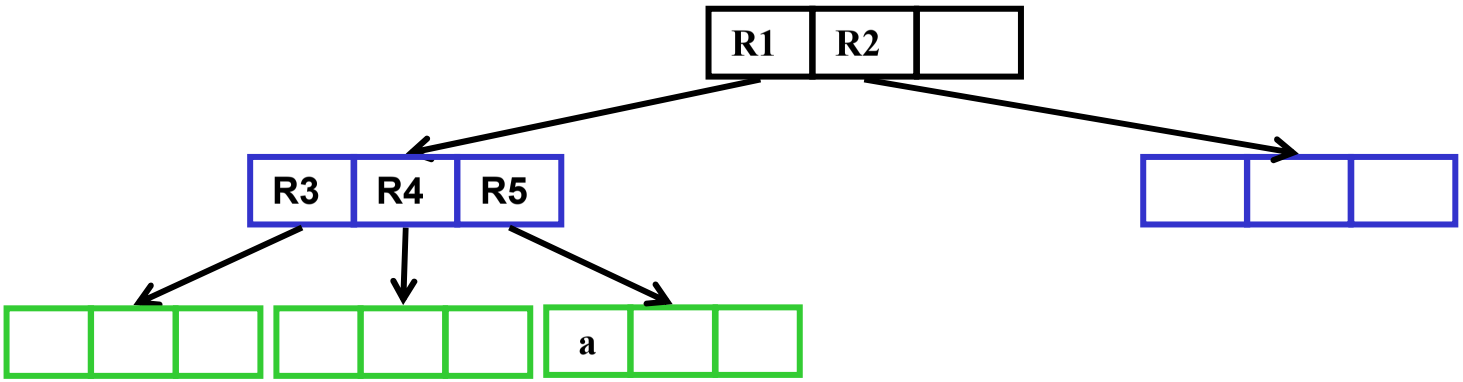
# Operations: $a^-$ $a_1{}^+$



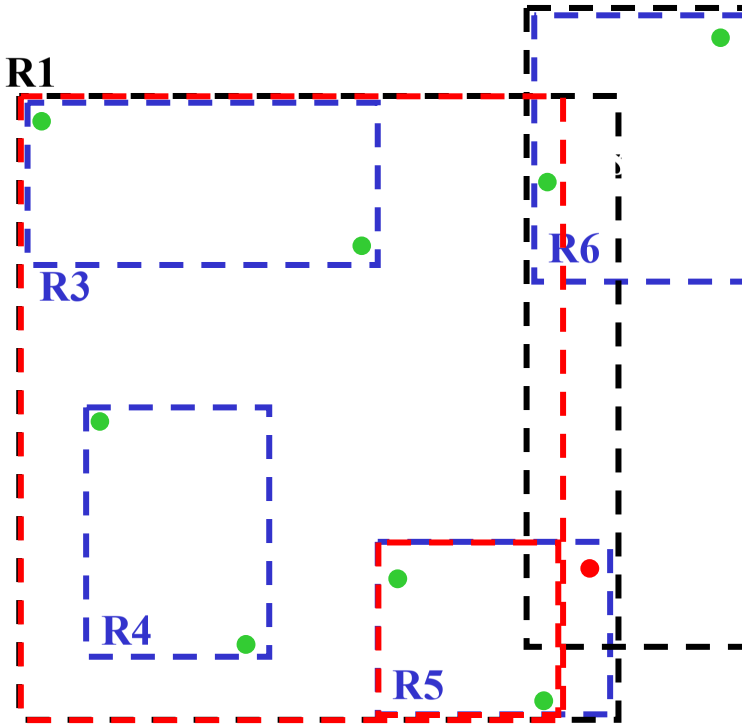
# Operations: $a^-$



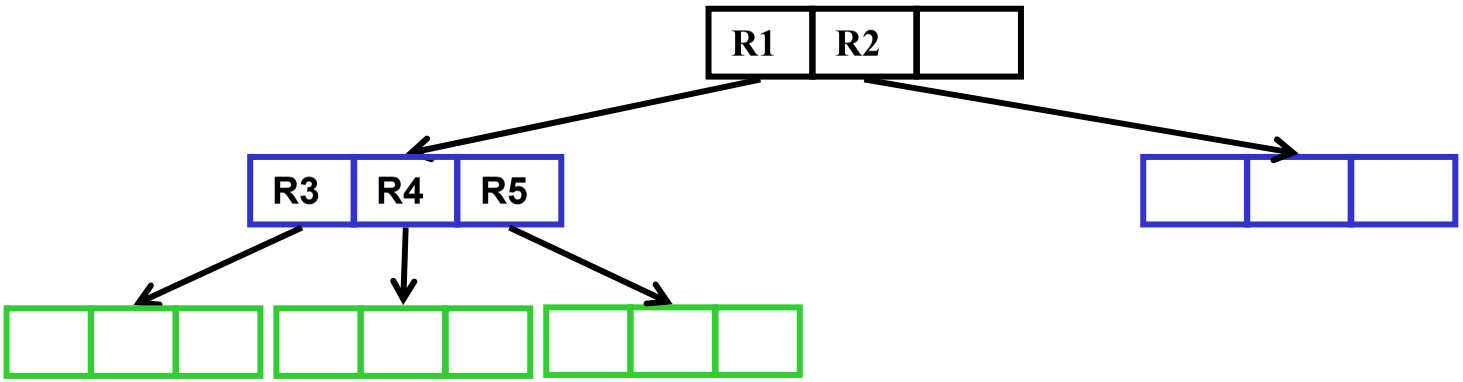

- **R-tree deletion, 1st step**:
  - Find the object – several partial paths may be followed
  - Remove the object from the leaf node



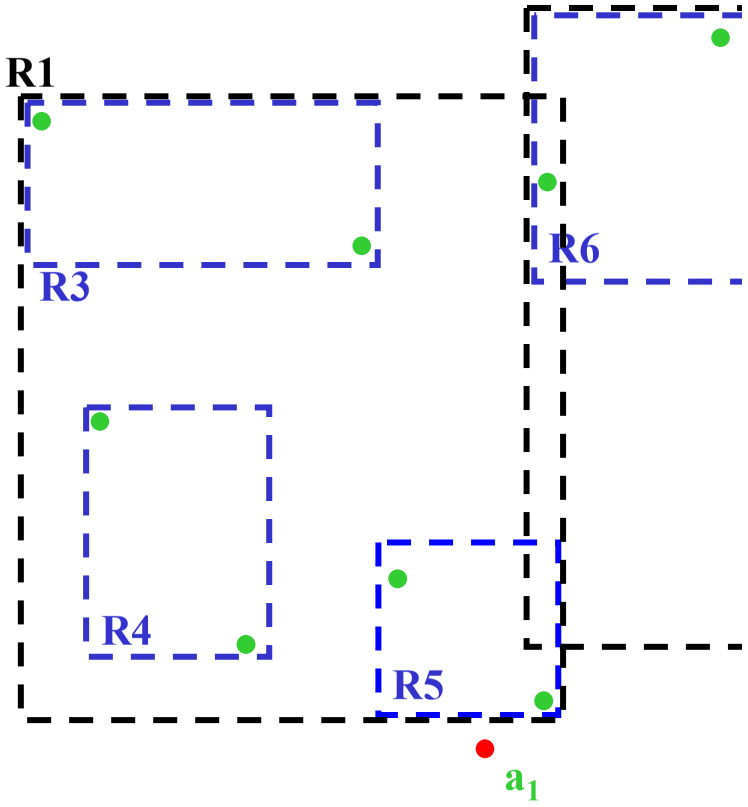
# Operations: $a^-$



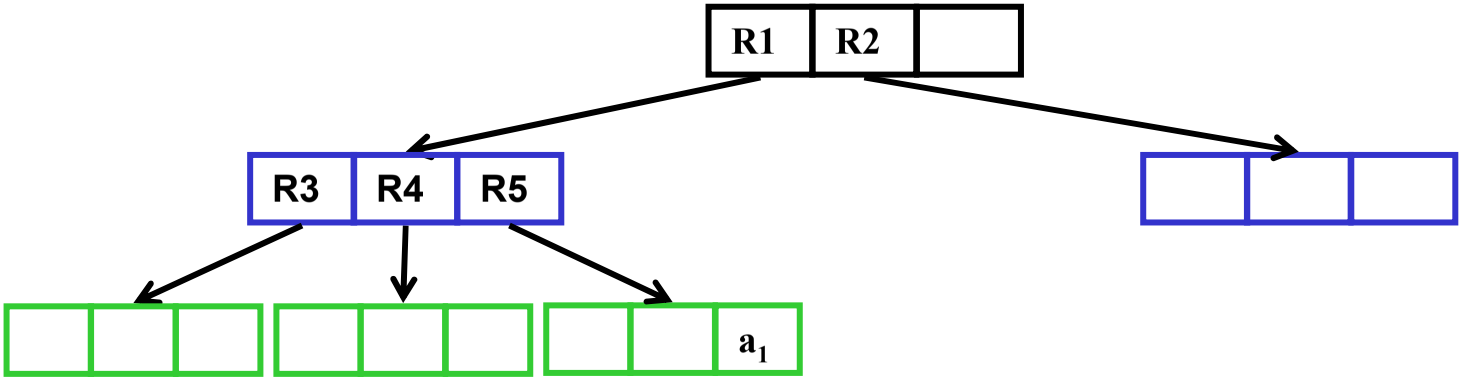

- **R-tree deletion, 2nd step**:
  - Traverse up the tree and update bounding rectangles



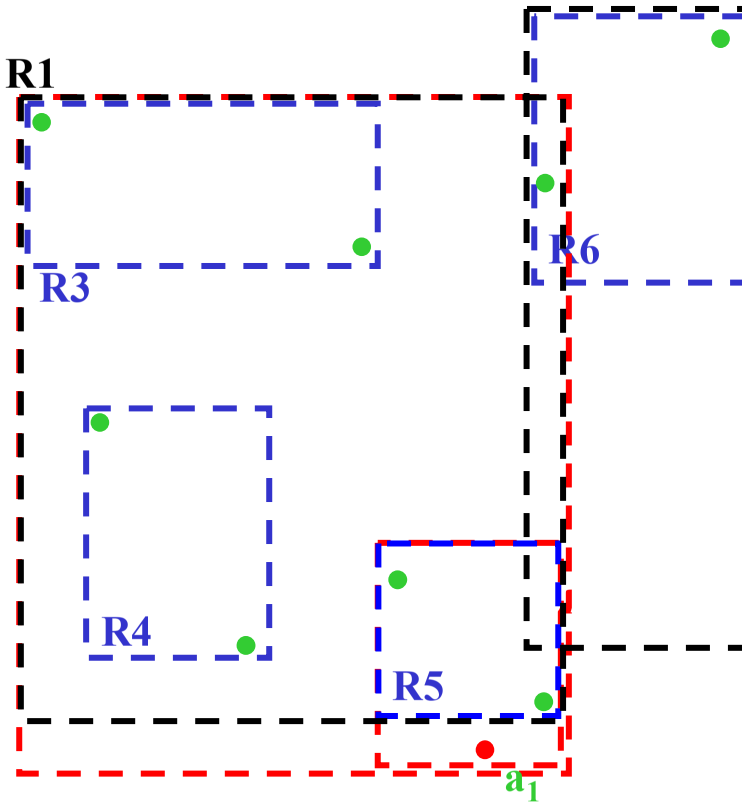
# Operations: $a^-$ $a_1^+$



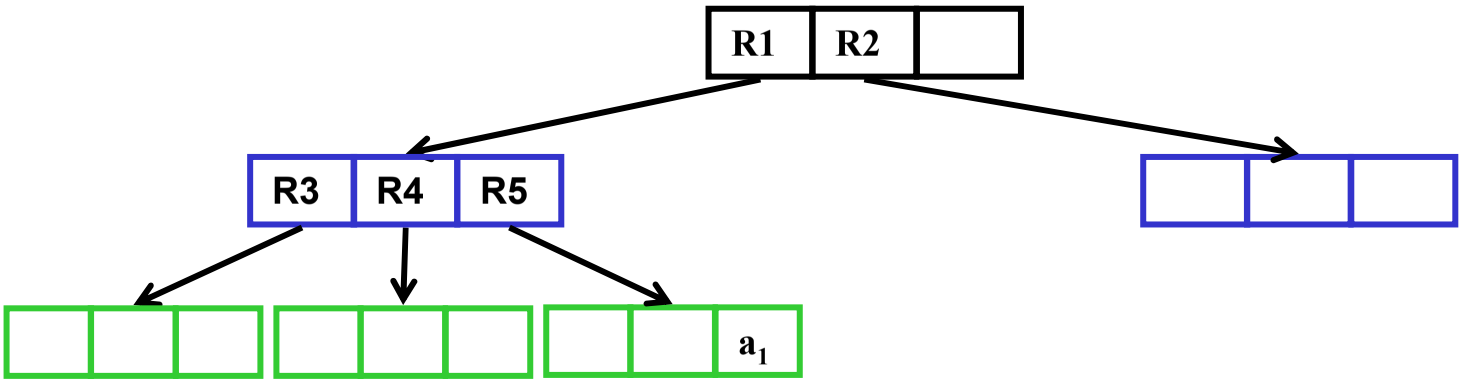

- **R-tree insertion, 1st step**:
  - Use R-tree insertion heuristics to find a path to a leaf
  - Insert *a1* to the leaf node.



# Operations: $a^-$ $a_1^+$

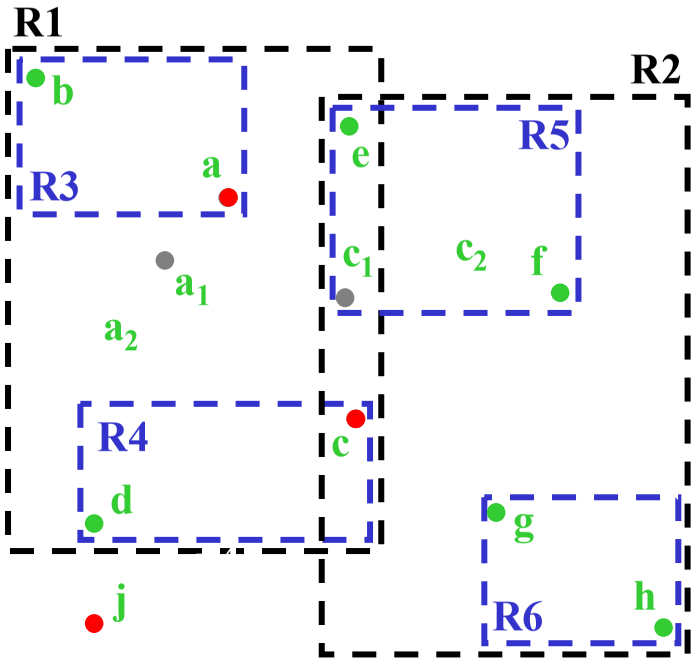



- **R-tree insertion, 2nd step**:
  - Traverse up the tree and update bounding rectangles (and possibly split nodes)
- In total: 4 traversals for an update.

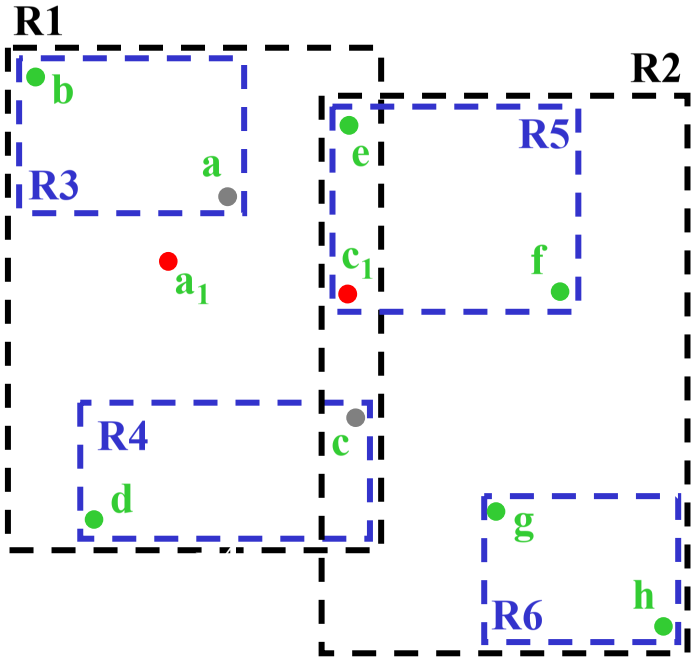


# Update operations in $R^R$-trees

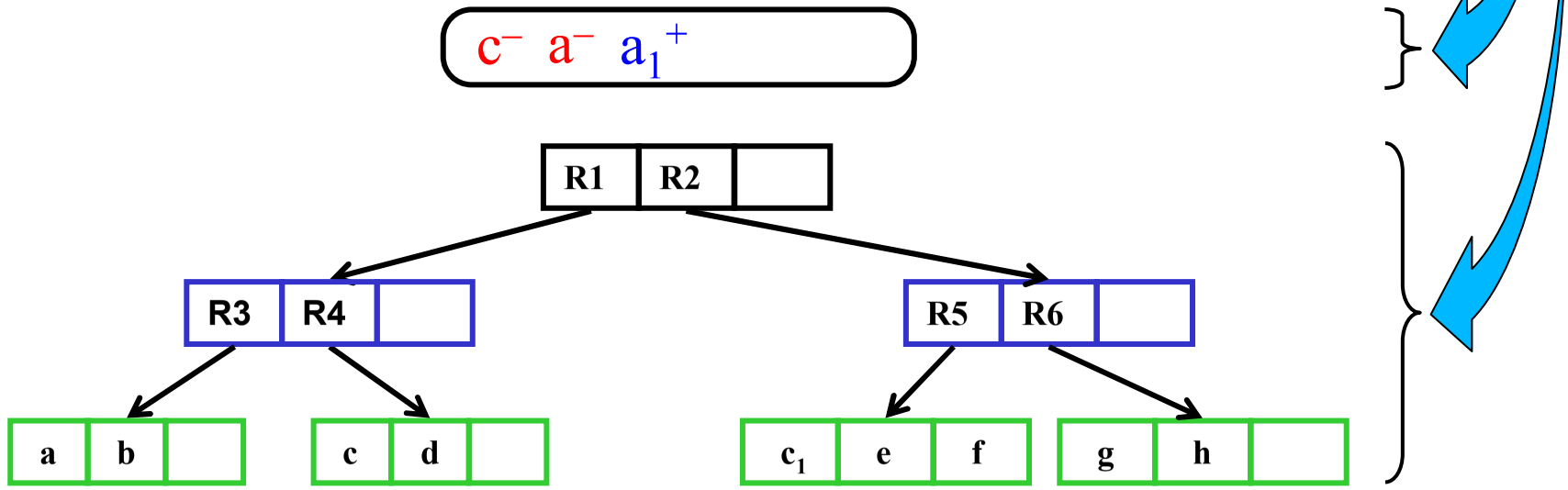
Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$ $a_1^-$ $a_2^+$ $c_1^-$ $c_2^+$ $j^+$



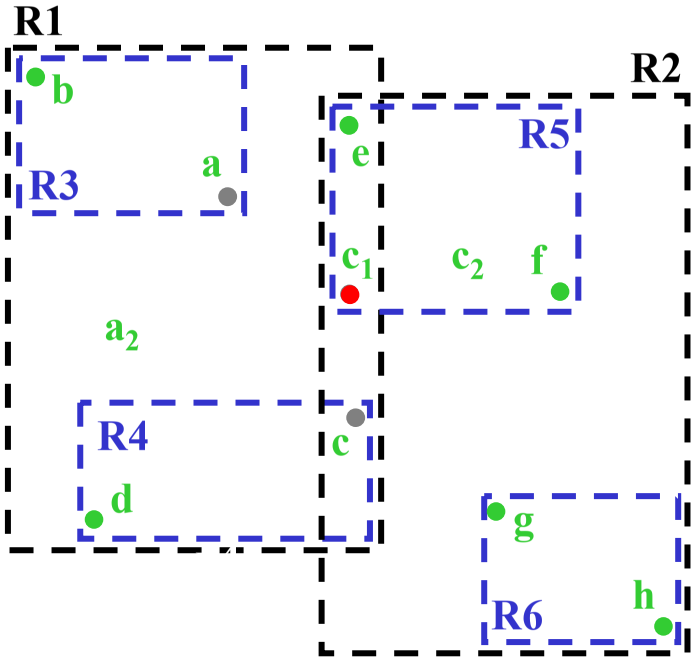
Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$



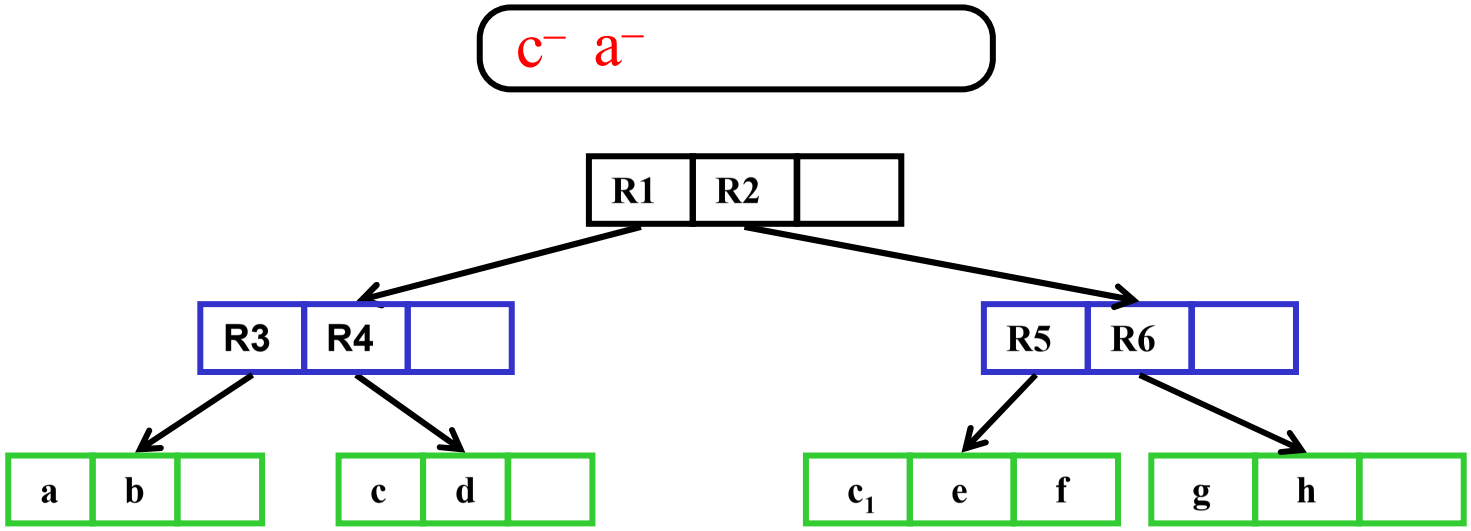

- **Structure of the $R^R$-tree:**
  - A regular disk-based R-tree
  - Main-memory *operations buffer,* storing at most $C_{max}$ pending insertions and deletions.
  - The operations buffer is an R-tree, with a *deletion flag* in leaf entries.



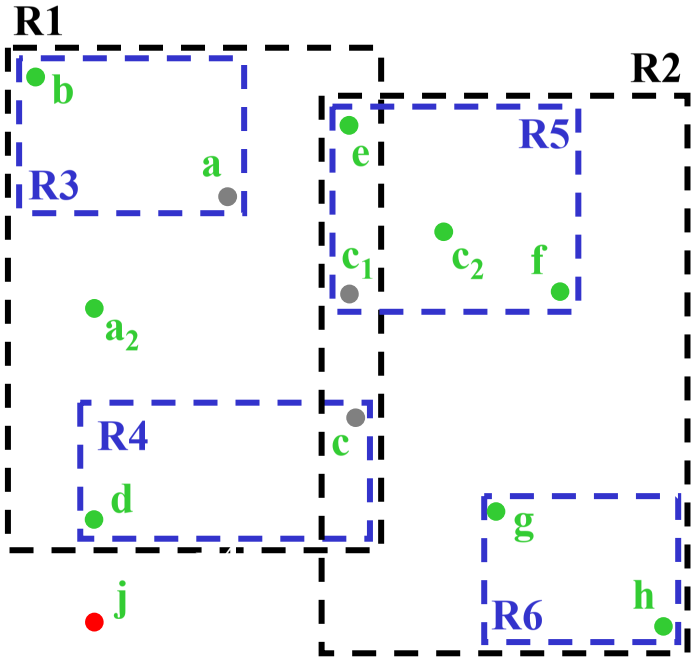
# Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$ $a_1^-$



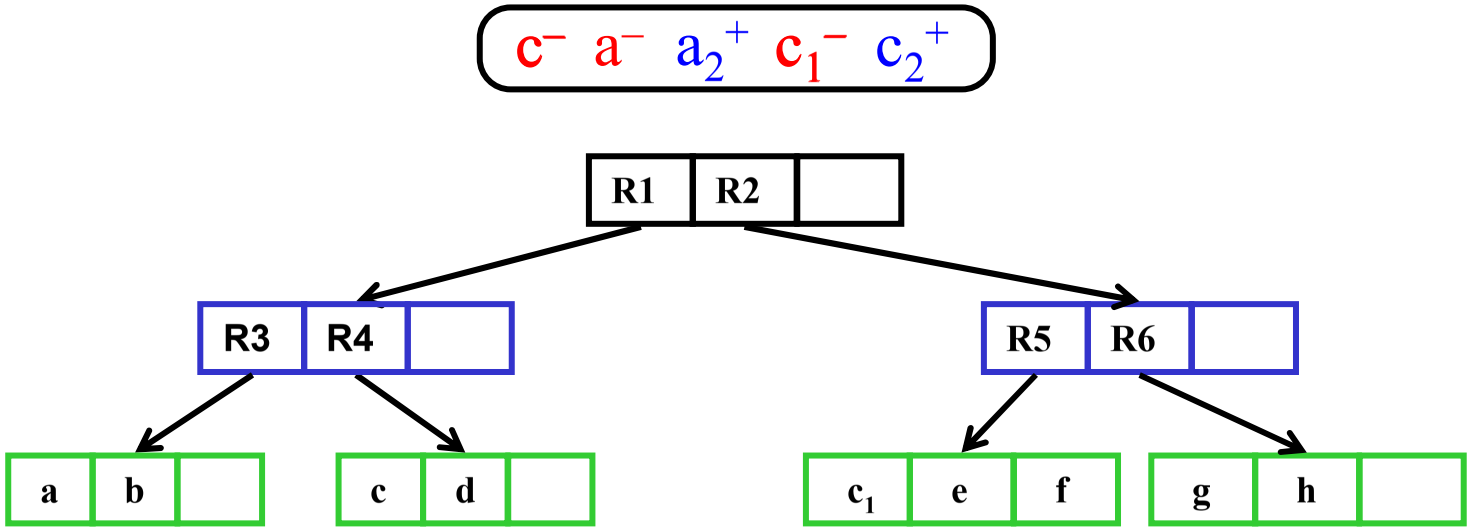

- **Insertions and deletions**
  - Insertions and deletions are put into operations buffer, if it is not full
  - Incoming deletion *annihilates* the matching insertion in the buffer (and vice versa).



Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$ $a_1^-$ $a_2^+$ $c_1^-$ $c_2^+$ $j^+$




- **Partial buffer emptying**
  - Regular R-tree heuristics are used to direct insertions.
  - Copies of deletions are directed into the subtrees that overlap them.
  - Operations go down the tree in groups, sharing the I/O.



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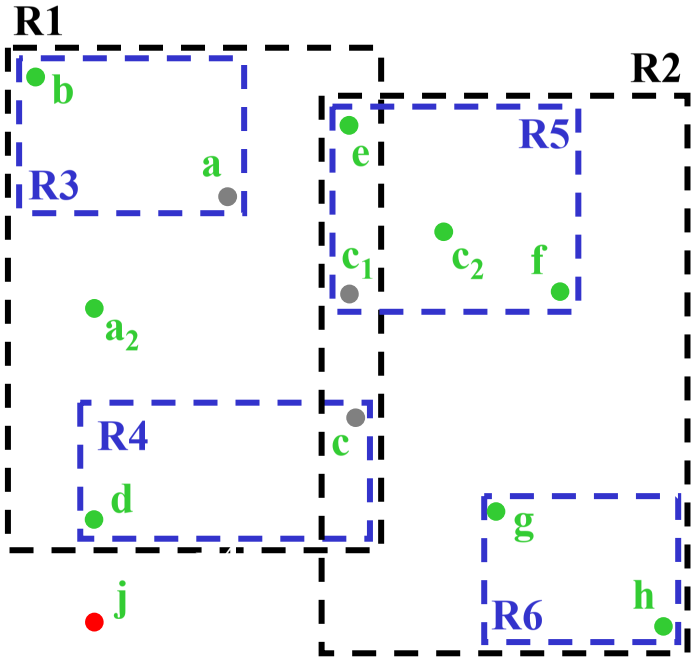
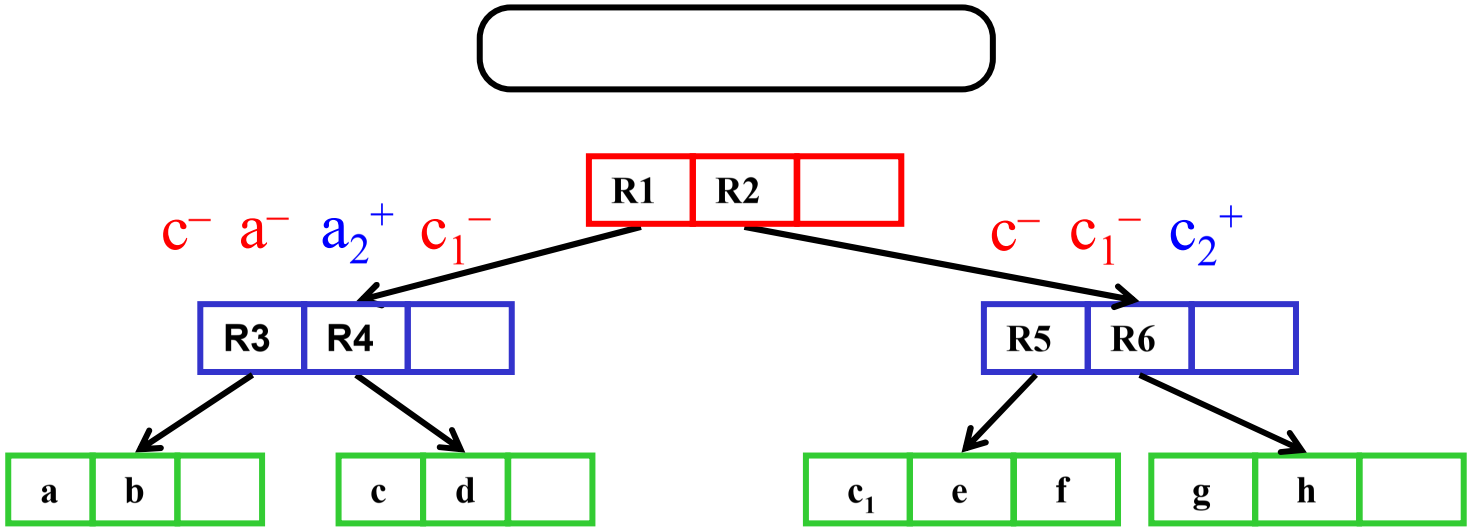
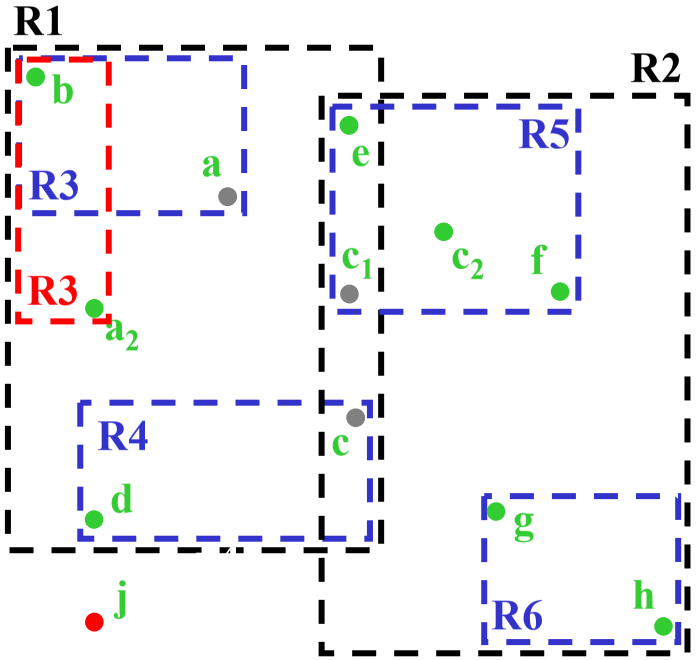


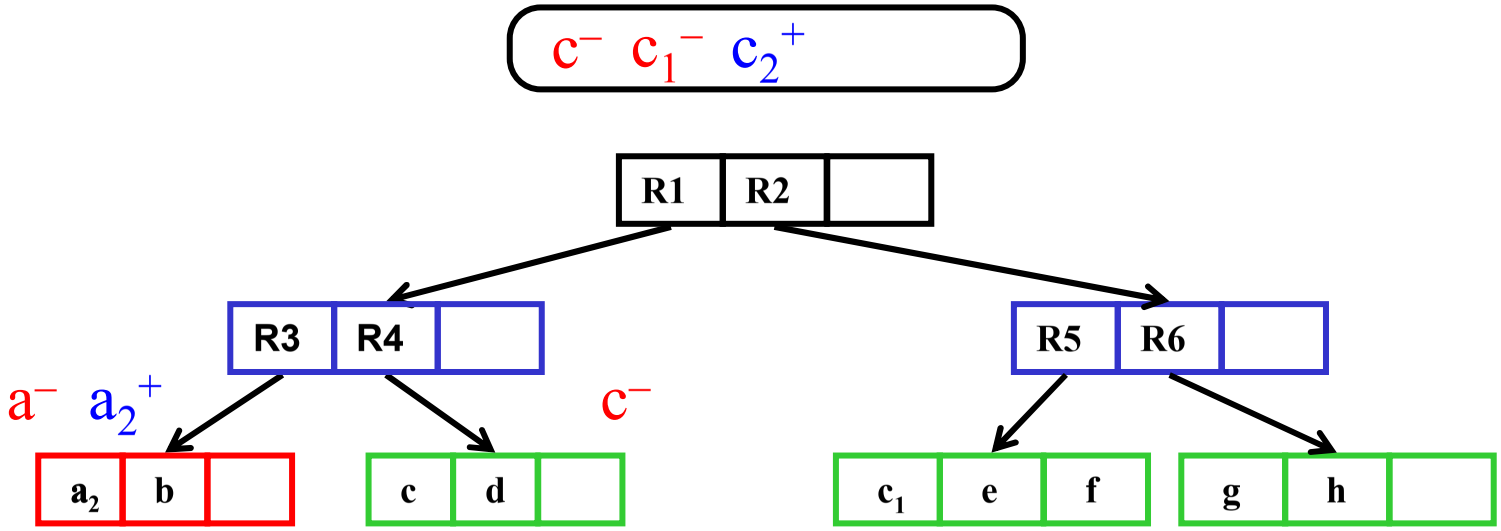

- **Partial buffer emptying**
  - Regular R-tree heuristics are used to direct insertions.
  - Copies of deletions are directed into the subtrees that overlap them.
  - Operations go down the tree in groups, sharing the I/O.
    - We avoid small groups – *at the root level*, all groups are put back to the buffer, except for the largest one.



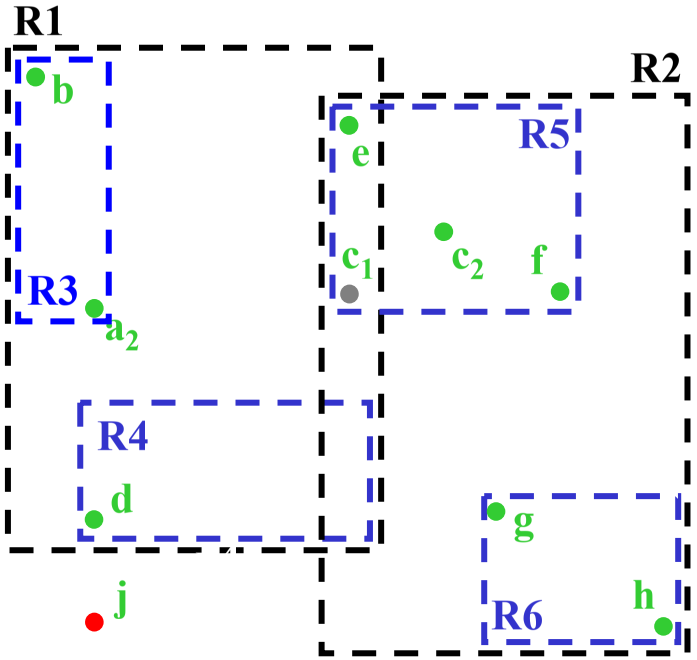
Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$ $a_1^-$ $a_2^+$ $c_1^-$ $c_2^+$ $j^+$



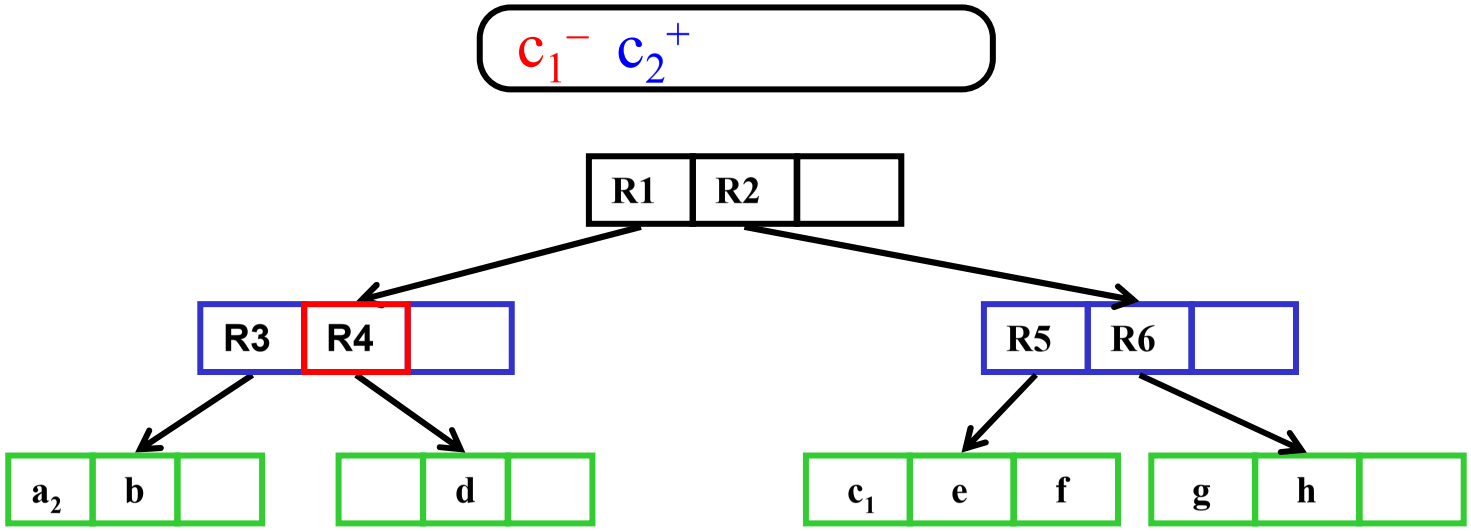

- **Partial buffer emptying**
  - When operations reach leaves they are performed.
  - A parent is written only when all its children are updated.
  - When a deletion is successfully performed, a corresponding entry from the buffer is removed.



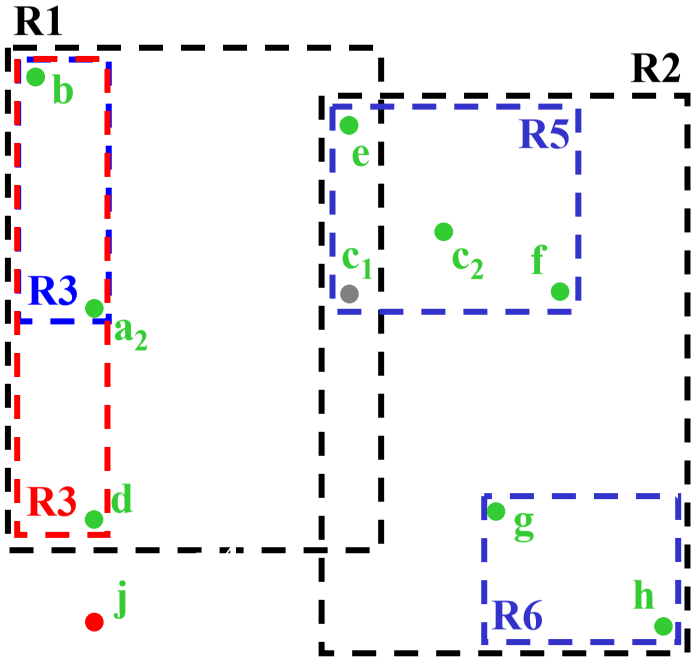
Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$ $a_1^-$ $a_2^+$ $c_1^-$ $c_2^+$ $j^+$




- **Bulk restructuring of the tree**
  - A child subtree may become
    - like *R4* – with an underfull subtree root: *merge with a sibling (single-entry non-leaf root is removed)*



Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$ $a_1^-$ $a_2^+$ $c_1^-$ $c_2^+$ $j^+$

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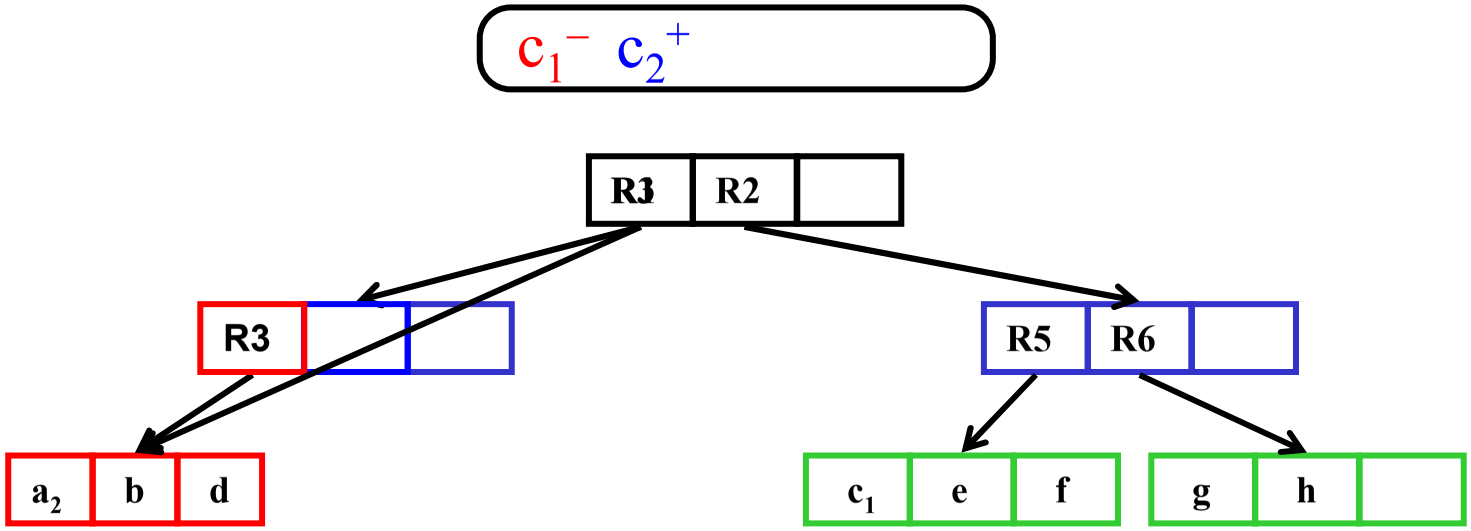

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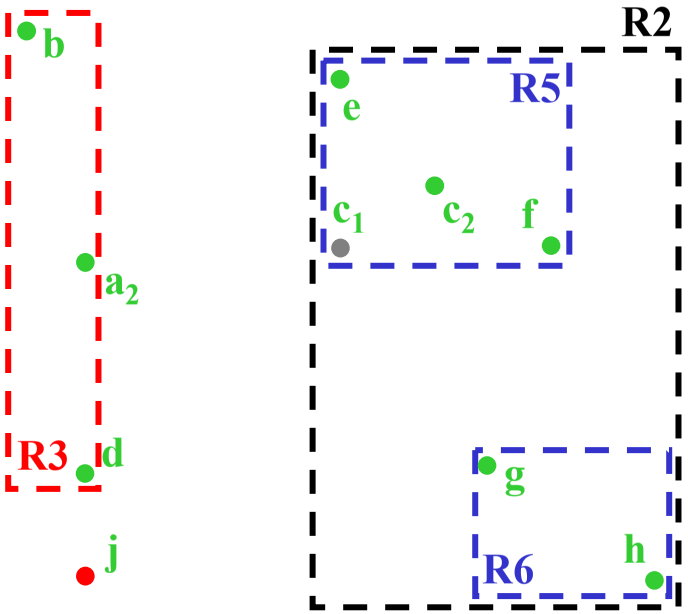


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  - A child subtree may become
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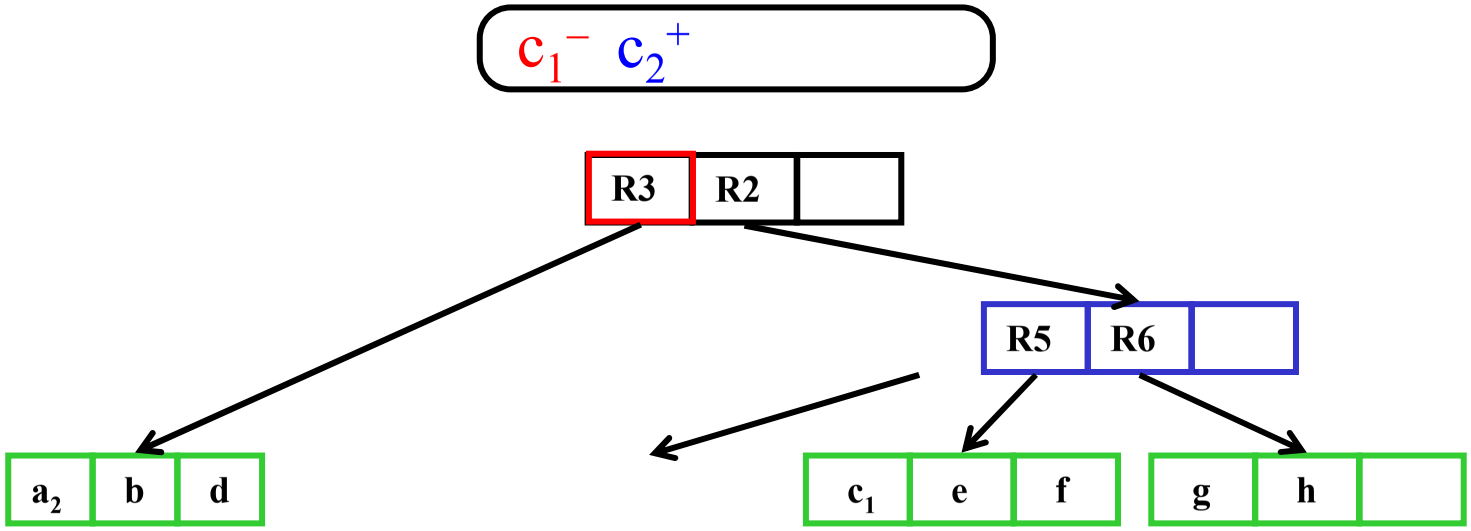
    - like *R3* – of a smaller height: *traverse down the tree using R-tree heuristics and insert at the right level.*



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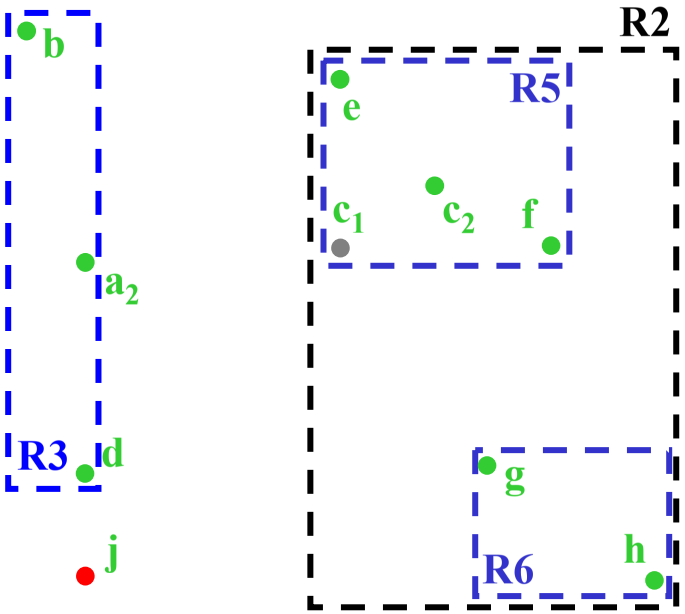


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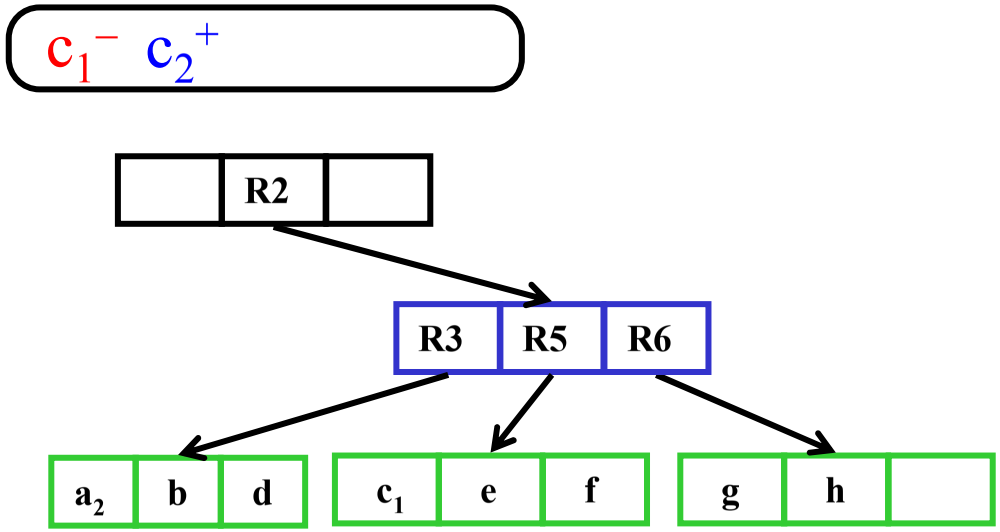
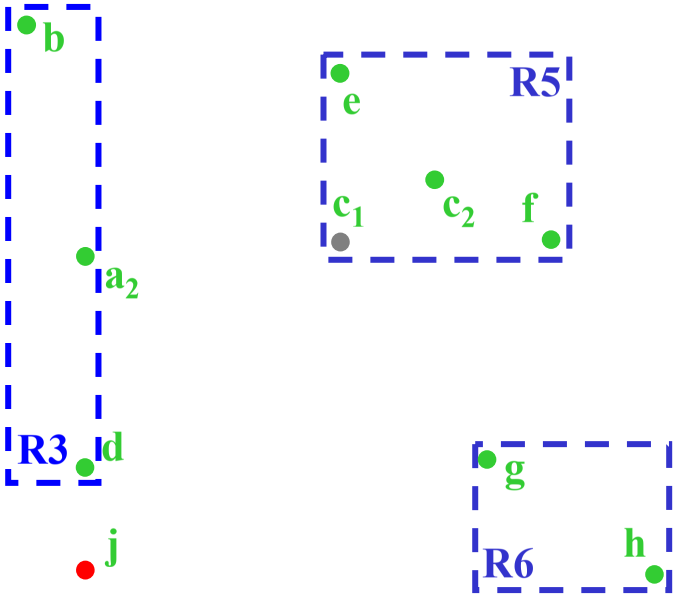
    - like *R3* – of a smaller height: *traverse down the tree using R-tree heuristics and insert at the right level*.
    - of a smaller height and with an underfull subtree root: *merge with a sibling at the right level*

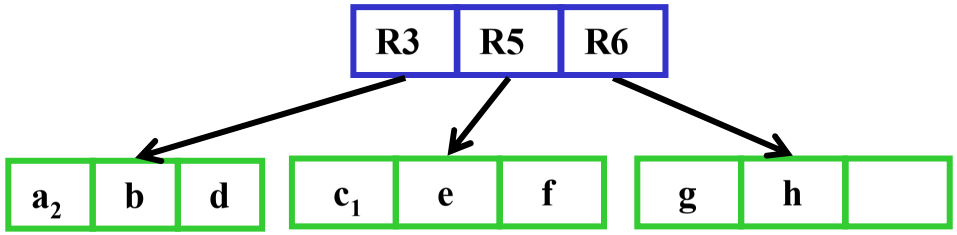


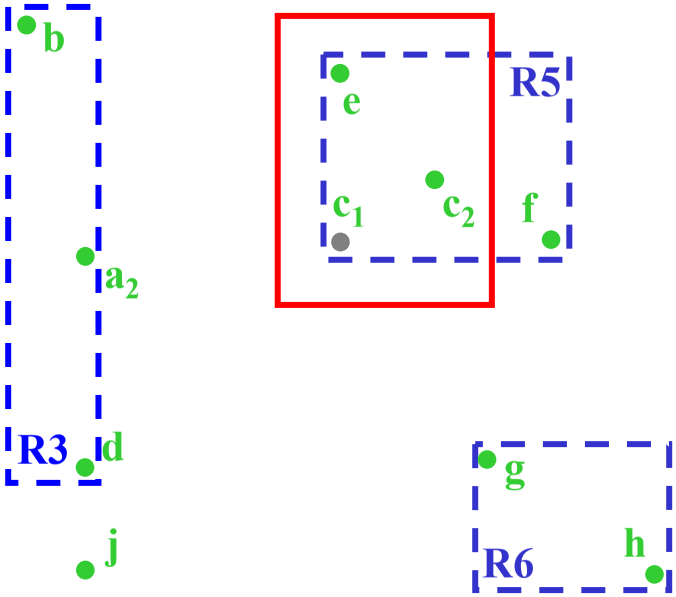
Operations: $c^-$ $c_1^+$ $a^-$ $a_1^+$ $a_1^-$ $a_2^+$ $c_1^-$ $c_2^+$ $j^+$




- **Bulk restructuring of the tree**
  - Overfull node may need to be split multiple times
- Finally put $j^+$ into the buffer!

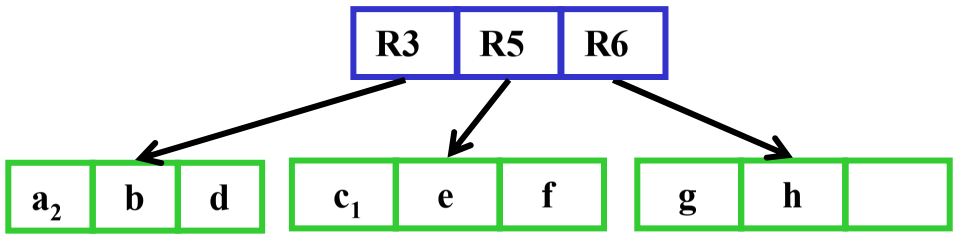
$c_1^-$ $c_2^+$






- **Querying**
  - First query the disk R-tree
  - Next, query the operations buffer
  - Finally, add the results and annihilate matching entries
  - Result: e $c_2$

$c_1^-$ $c_2^+$ $j^+$

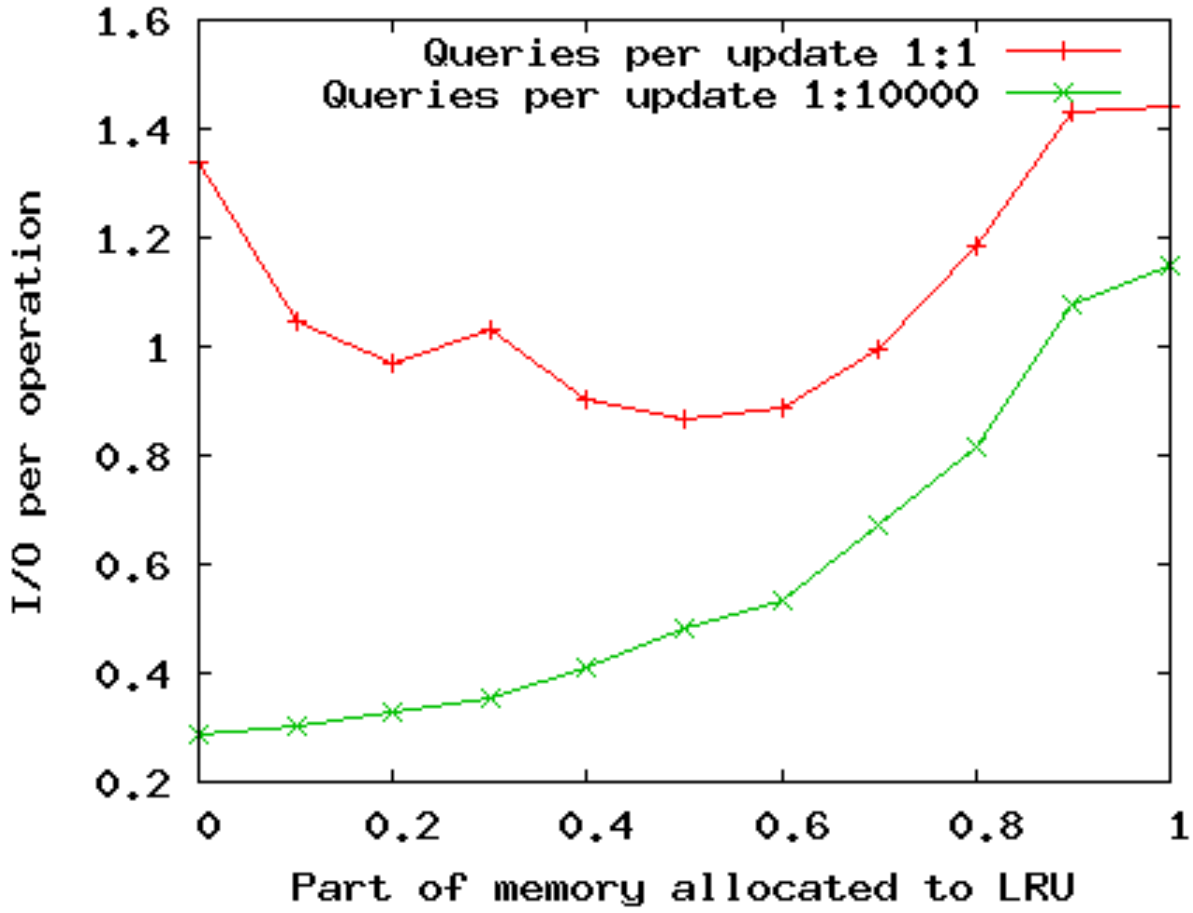


# Empirical study: setup

- Setting
  - Simulation of 100,000 cars in a road network
  - Updates occur whenever they travel 200 meters
- Comparisons
  - The $R^R$-tree (with the *largest-group* BufferEmpty strategy)
  - The RUM-tree (R-tree with update memos) with a write-back LRU cache
  - The R-tree with a write-back LRU cache
- Each structure is given exactly the same amount of main-memory

# Empirical study

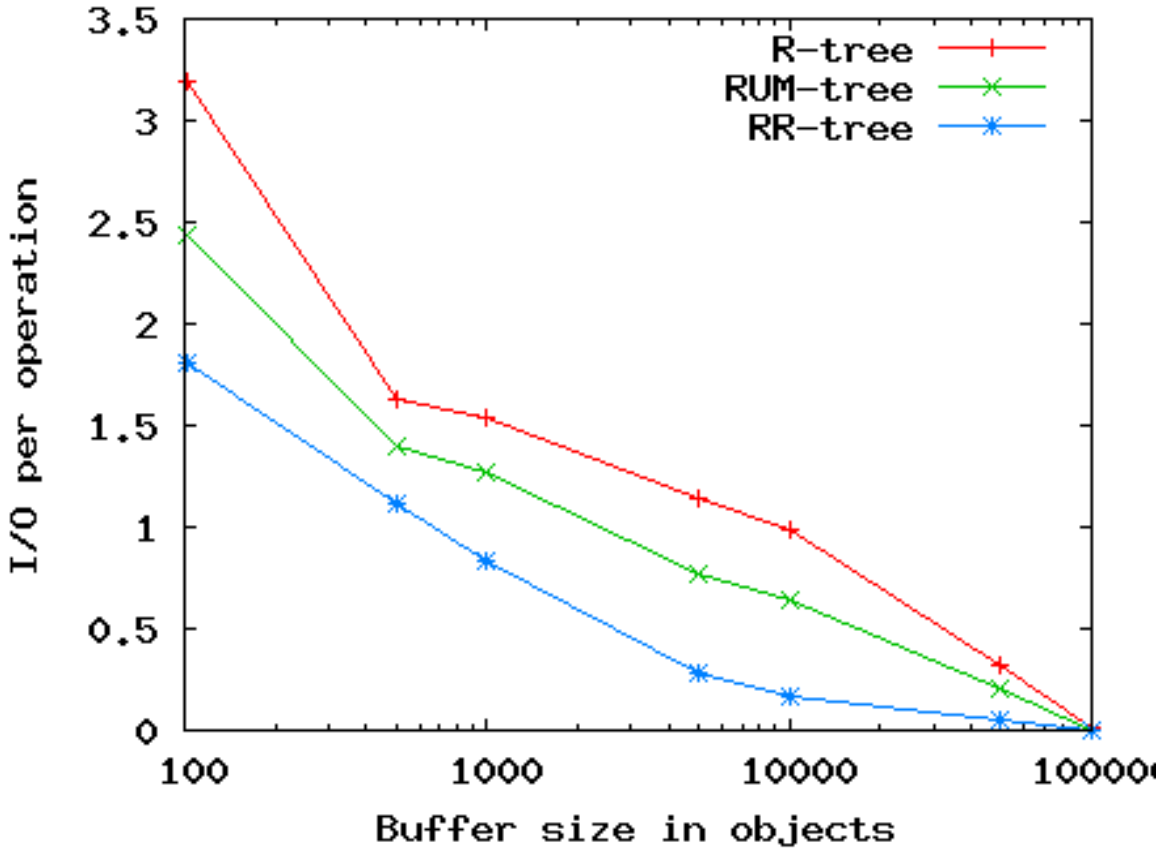
- How much main memory should be used for LRU buffering?




- For dynamic workloads, no LRU buffering should be used.

# Empirical study

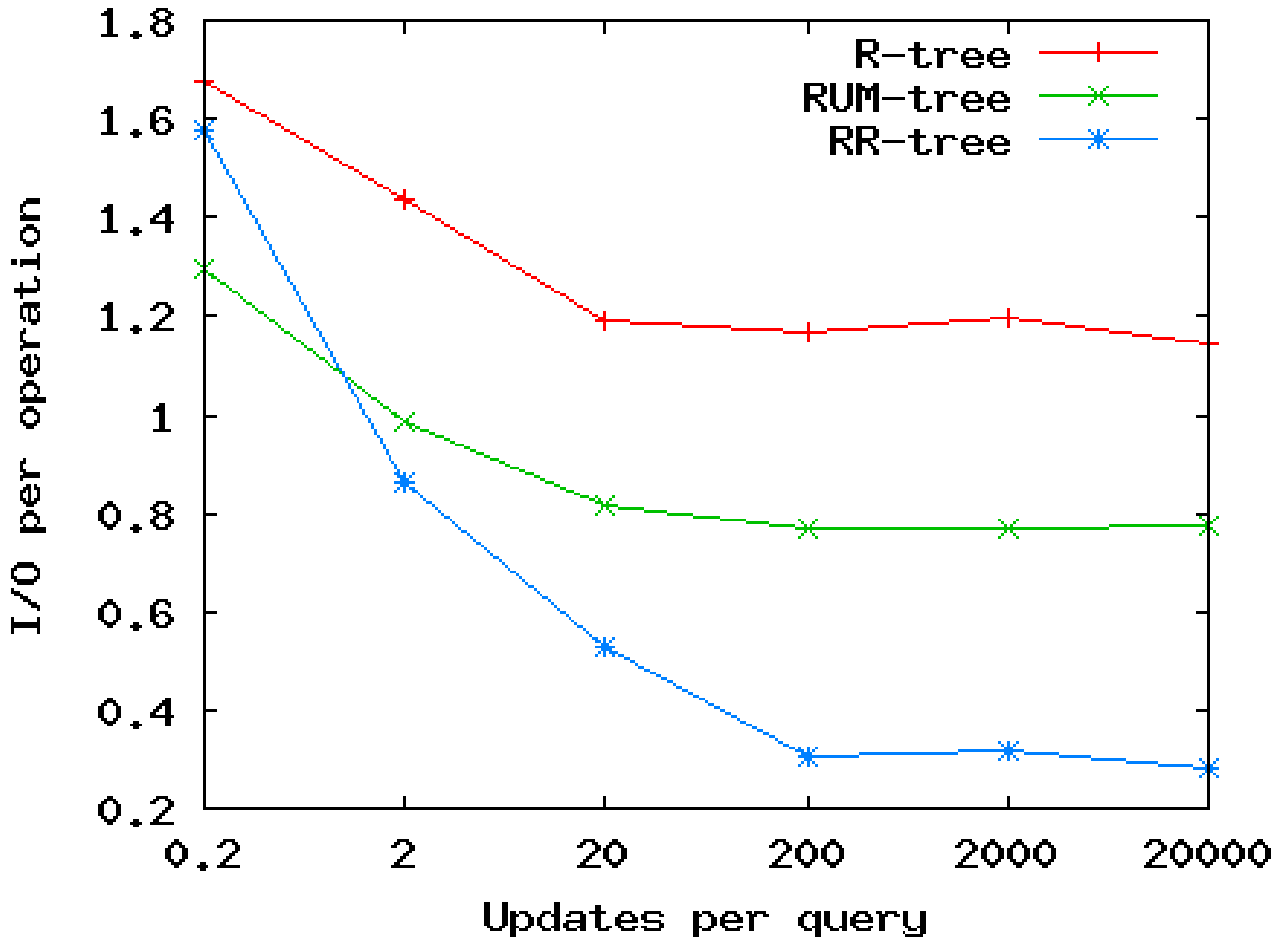
- How do the structures benefit from different amounts of main memory?




- Ex: memory is 10% of data set size: $R^R$-tree is more than 4 times faster than the RUM-tree and 7 times faster than the R-tree

# Empirical study

- How do the structures perform for varying ratios of updates and queries?



# Summary

- Presented a new main-memory buffering technique for R-tree type indices
- The general idea is to speed up updates by allowing these to share I/O.
- Uses partial buffer emptying
- Empirical studies show that the proposal improves on existing proposals.
- See the paper for the analytical study

- Future work
  - Application to other types of indices
  - Better main-memory indexing
  - Exploring the query performance/update performance trade-off
  - New recovery techniques