Indexing and Query Processing

Introduction to Databases

CompSci 316 Fall 2017

DUKE COMPUTER SCIENCE

Announcements (Wed., Mar. 8)

- Homework #3
  - follow piazza posts for updates after each lecture
- Project
  - Comments on milestone-1 tomorrow
  - Keep working on it
- No class next week
  - spring break

Today:

- Finish B+ tree and index
- Start query processing

Index

Recall: What are indexes for?

- Given a value (search key), locate the record(s) with this value, or range search
  - SELECT * FROM R WHERE $A = value$;
  - SELECT * FROM R, S WHERE $R.A = S.B$;
  - SELECT * FROM R WHERE $A > value$;

- Search key $\neq$ key in a relation (unique attributes)
  - "Key" is highly overloaded in databases

- Recap: index structure on whiteboard

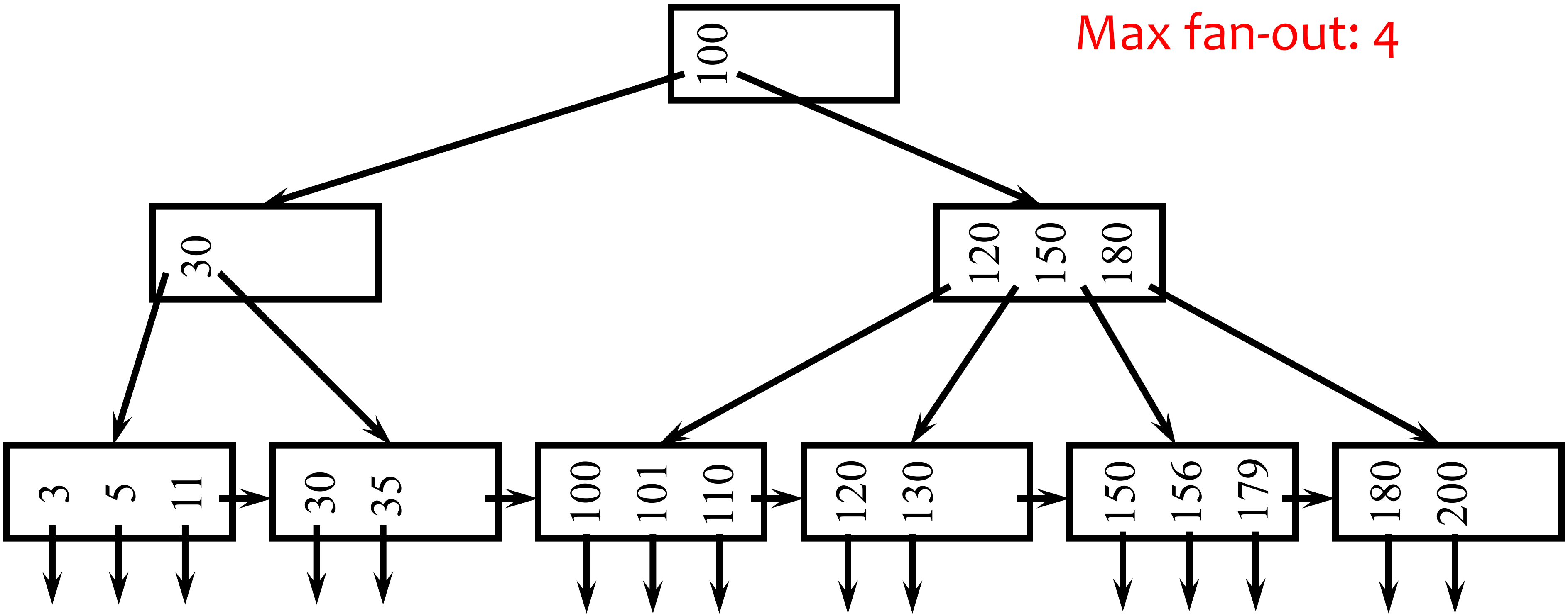
Recall: Index classification

- Dense vs. Sparse
- Clustered vs. unclustered
- Primary vs. Secondary
- Tree-based vs. Hash-based
    - we will only do tree indexes in 316

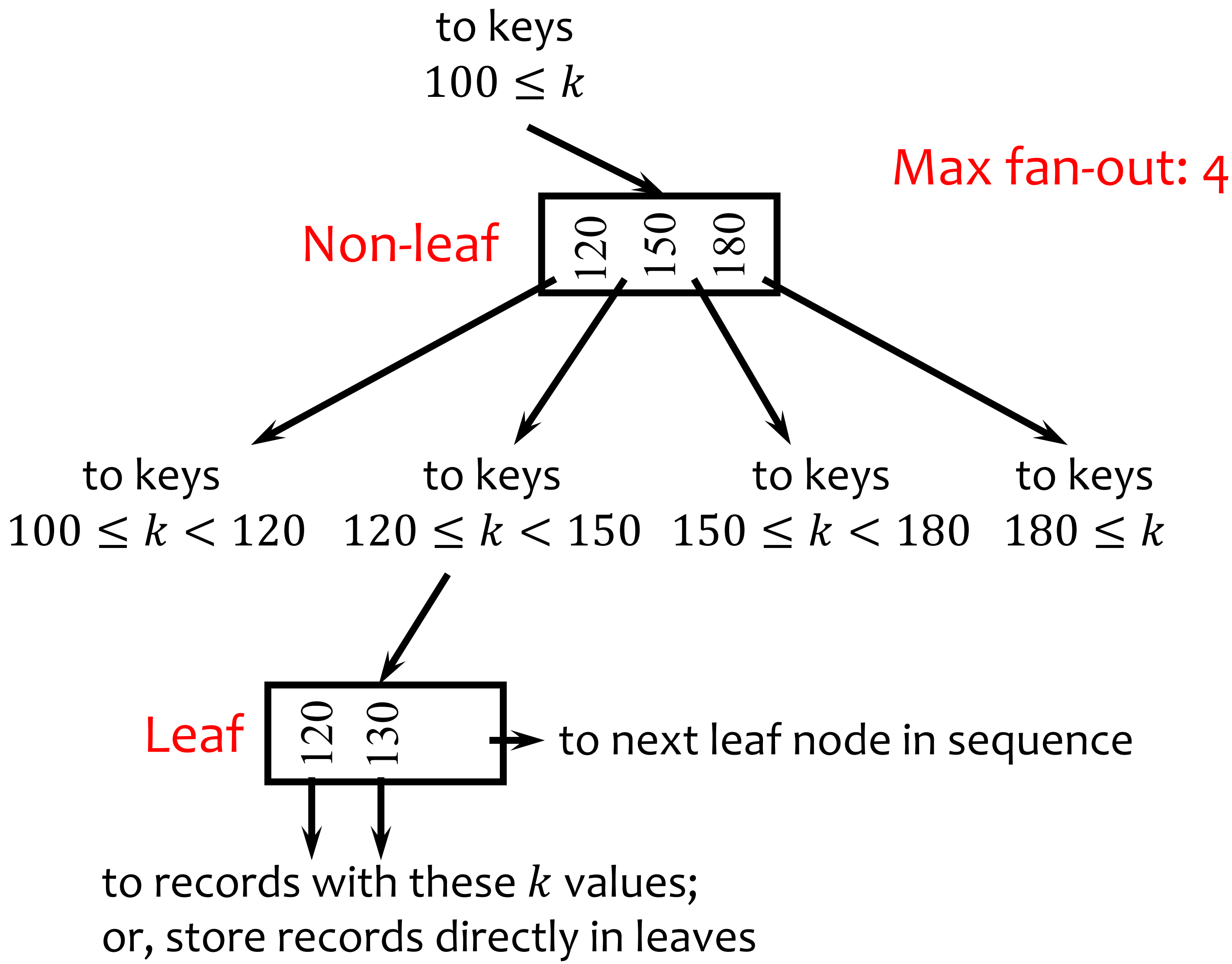
Recall: B⁺-tree

- A hierarchy of nodes with intervals
- Balanced (more or less): good performance guarantee
- Disk-based: one node per block; large fan-out

Max fan-out: 4



Recall: Sample B$^+$-tree nodes



Recall: B$^+$-tree balancing properties

- Height constraint: all leaves at the same lowest level
- Fan-out constraint: all nodes at least half full (except root)

	Max # pointers	Max # keys	Min # active pointers	Min # keys
Non-leaf	f	$f-1$	$\lceil f/2 \rceil$	$\lceil f/2 \rceil - 1$
Root	f	$f-1$	2	1
Leaf	f	$f-1$	$\lfloor f/2 \rfloor$	$\lfloor f/2 \rfloor$

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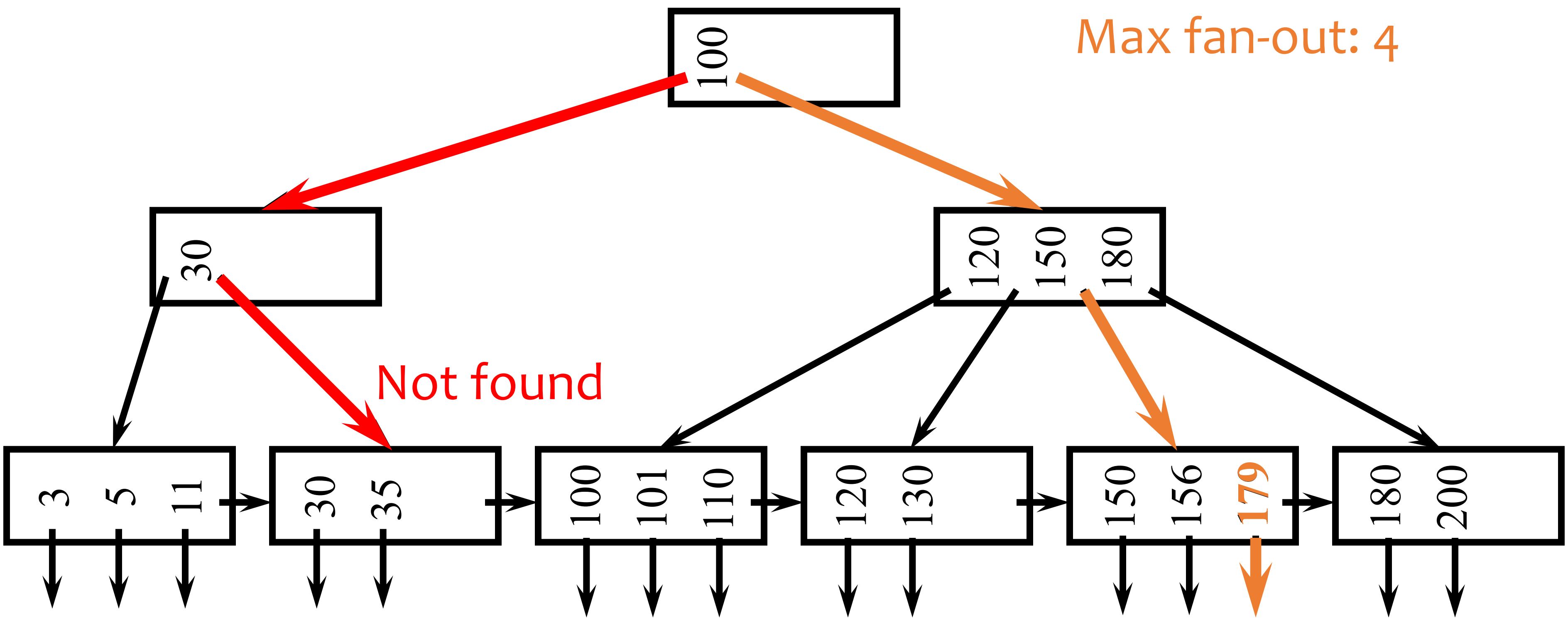
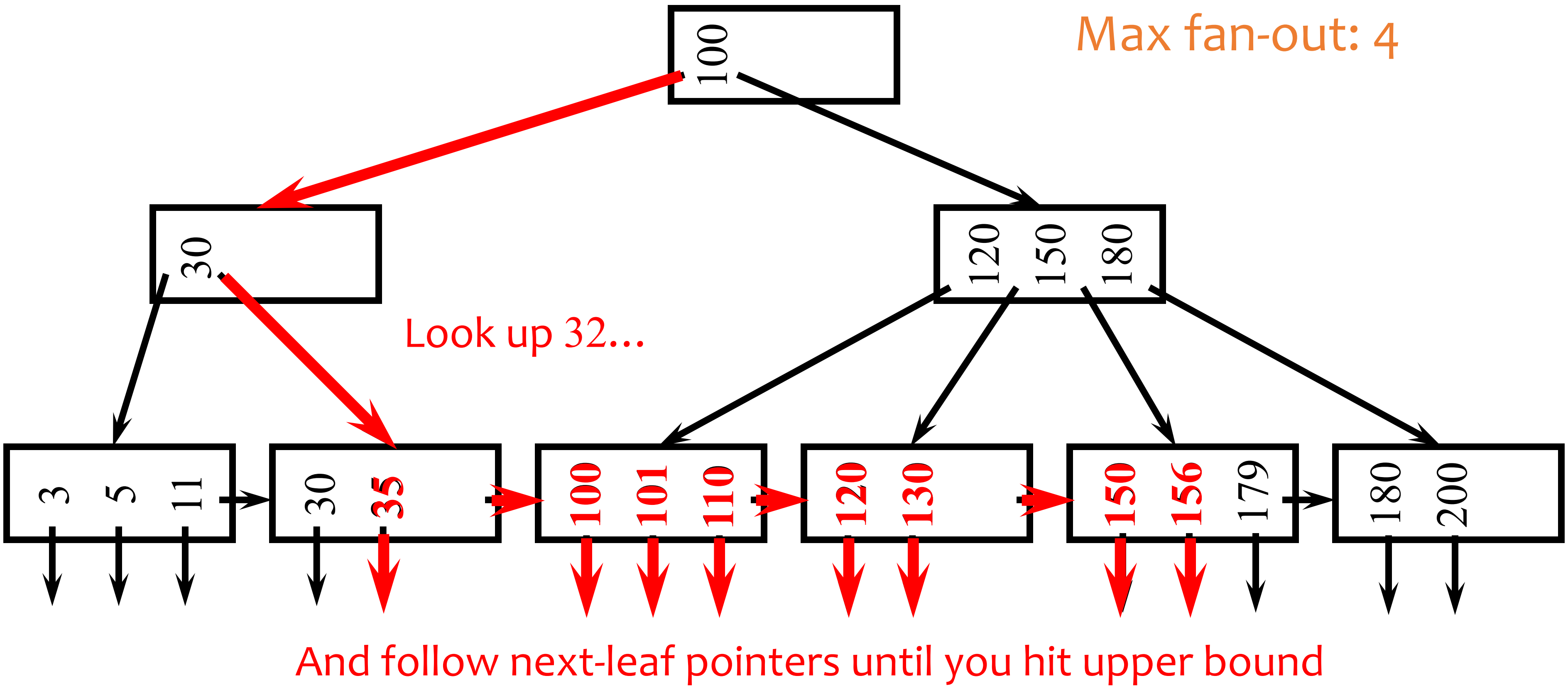
Lookups

- SELECT * FROM R WHERE $k = 179$;
- SELECT * FROM R WHERE $k = 32$;



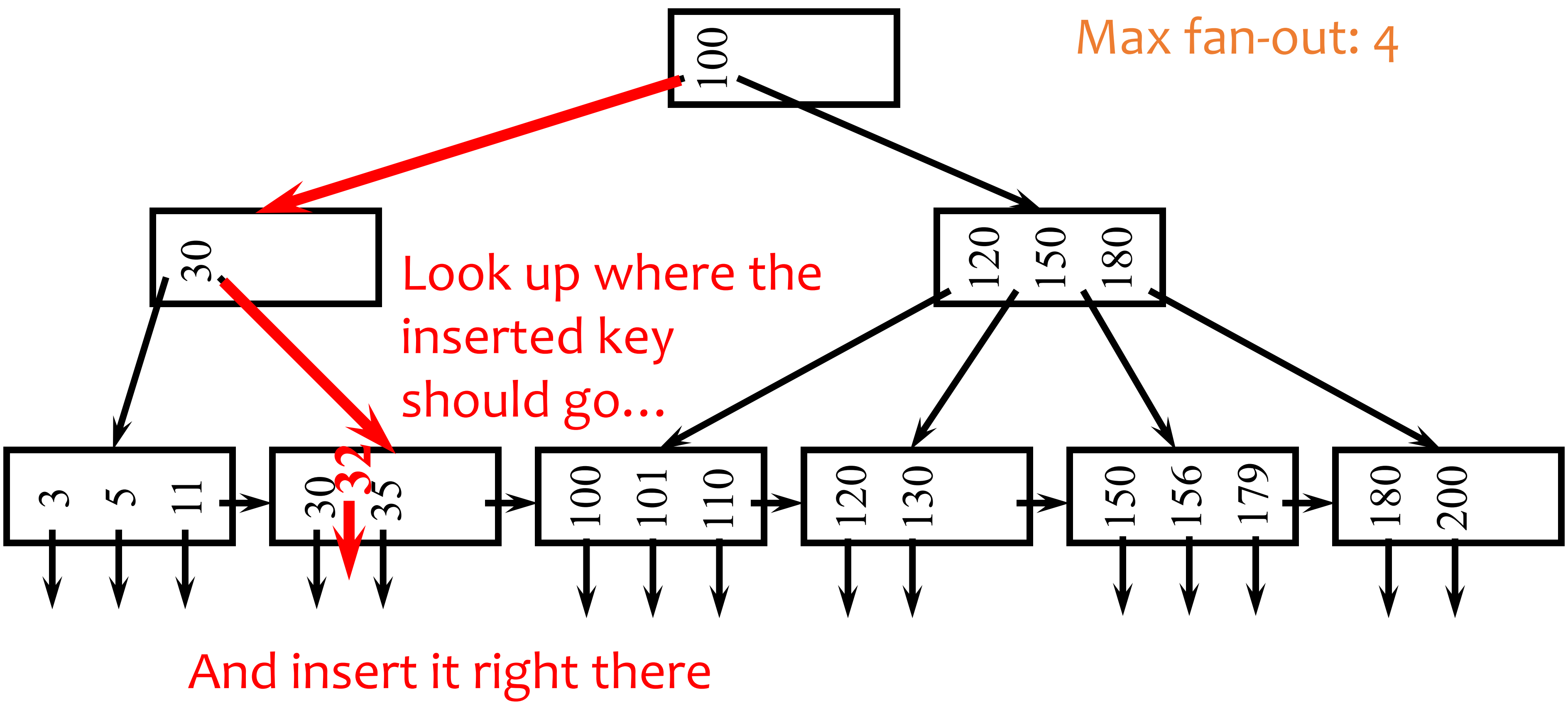
Range query

- SELECT * FROM R WHERE $k > 32$ AND $k < 179$;



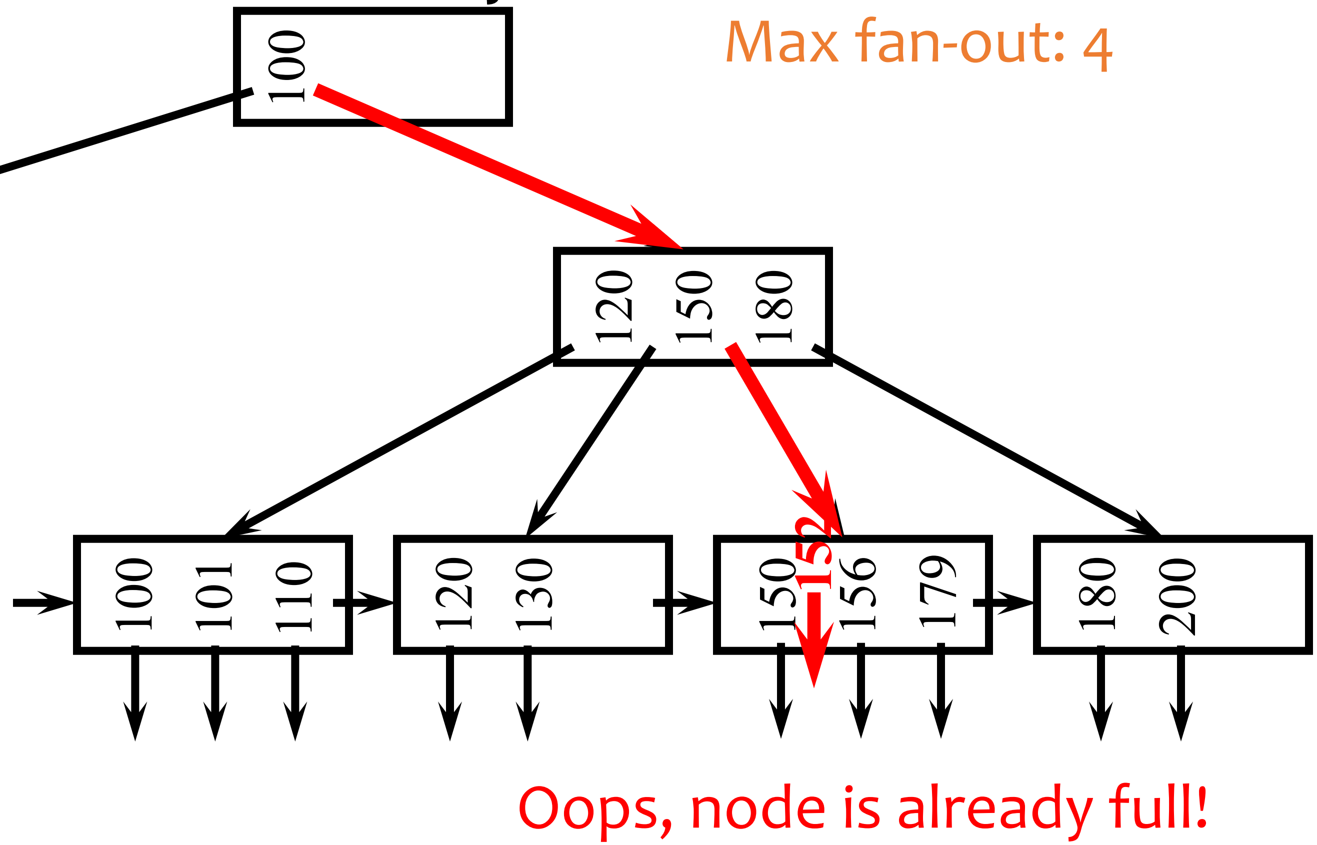
Insertion

- Insert a record with search key value 32

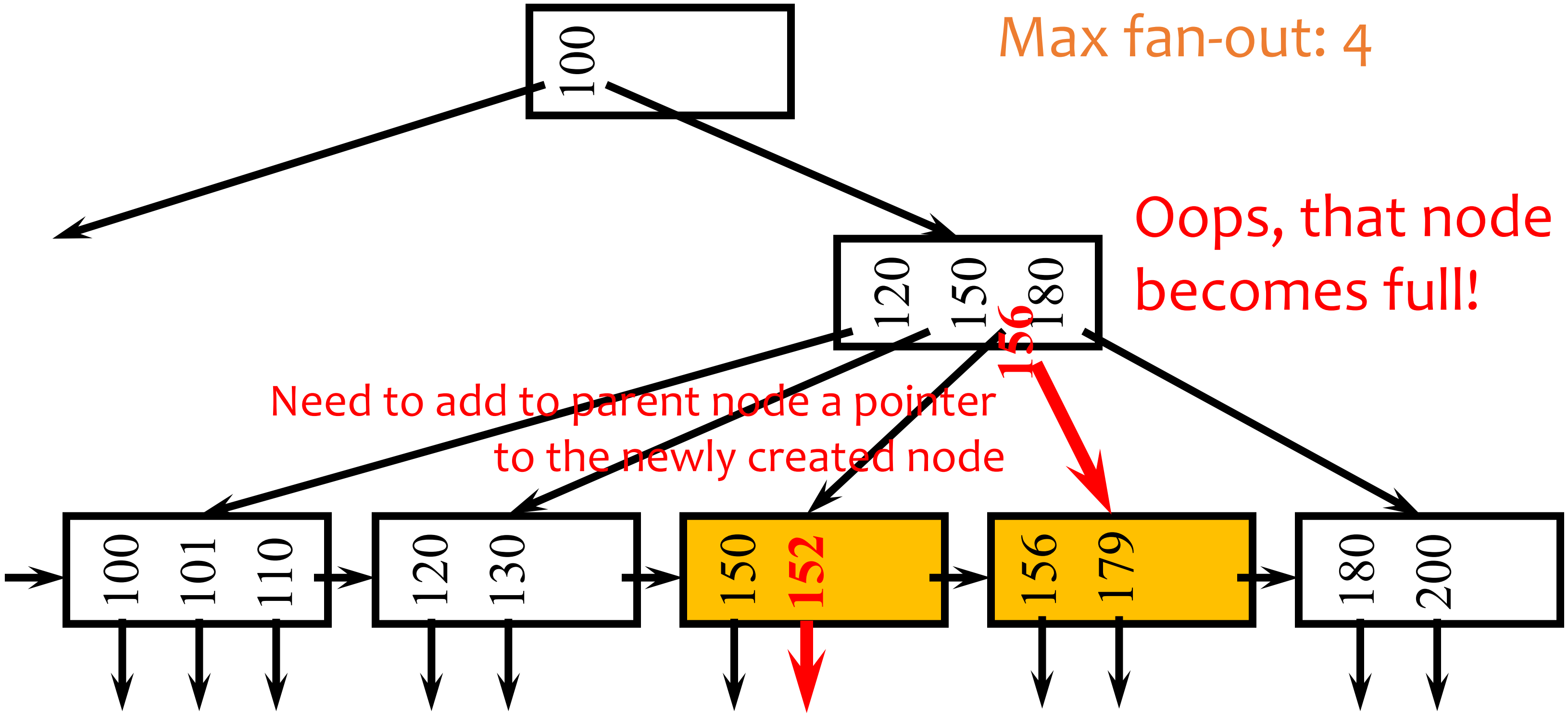


Another insertion example

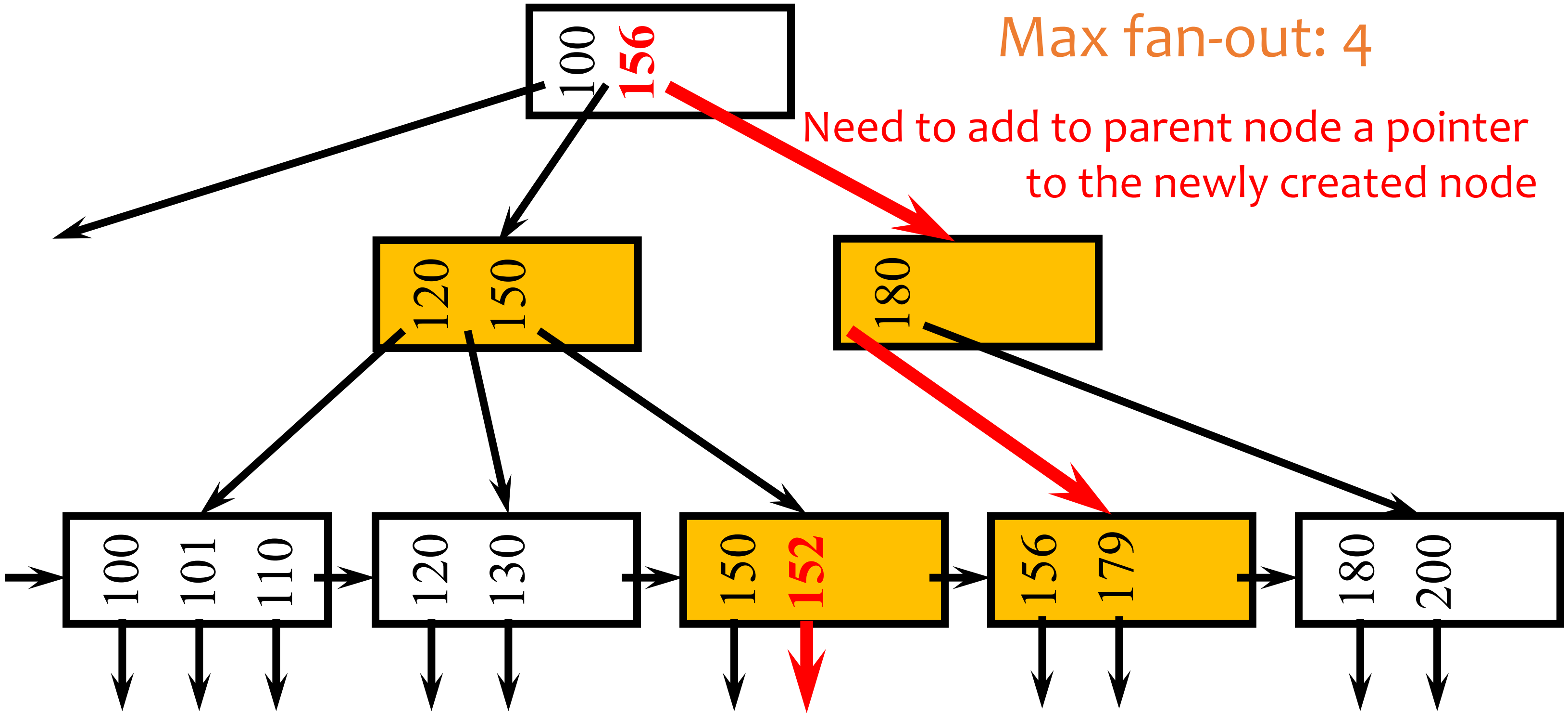
- Insert a record with search key value 152



Node splitting



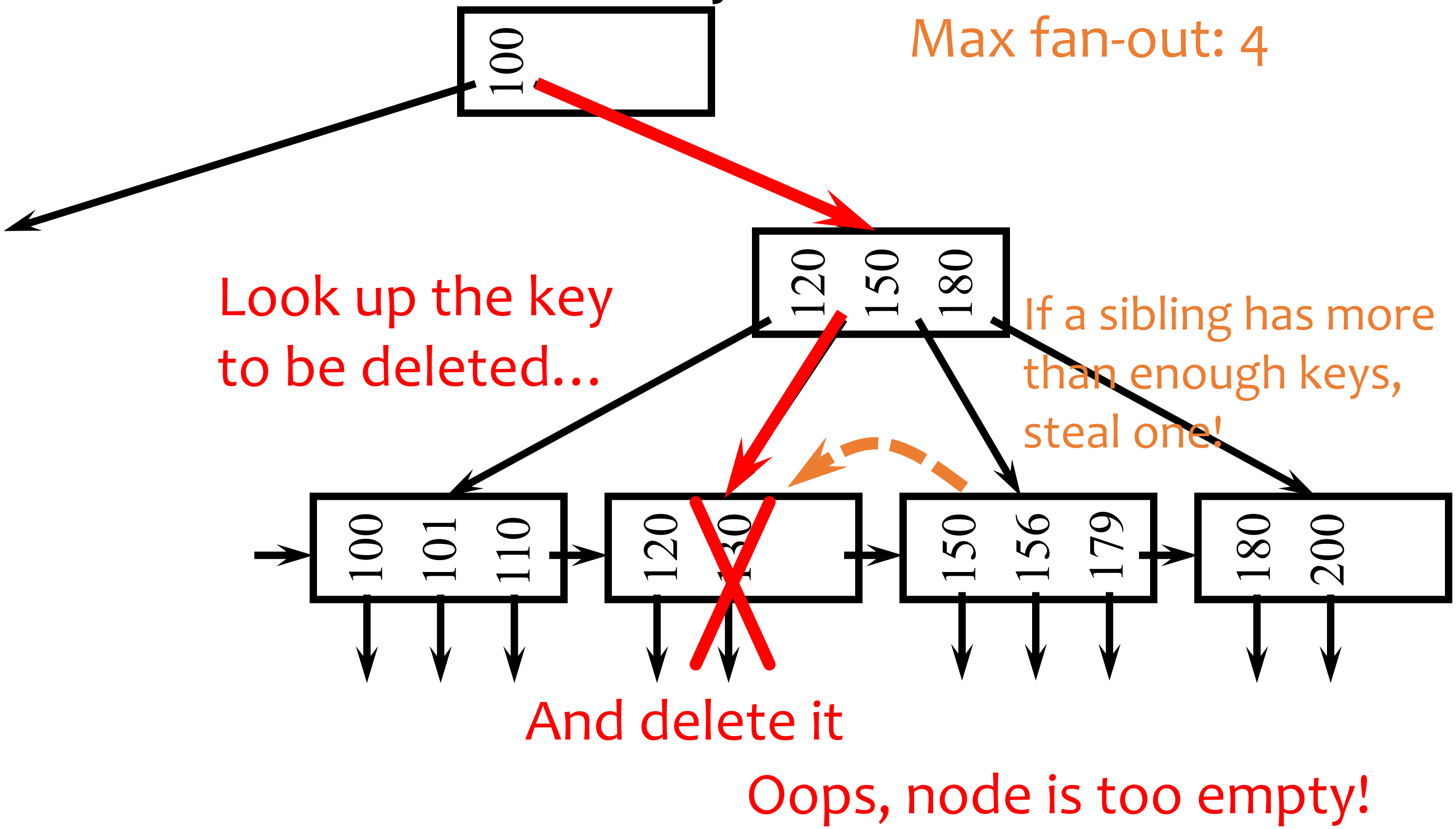
More node splitting



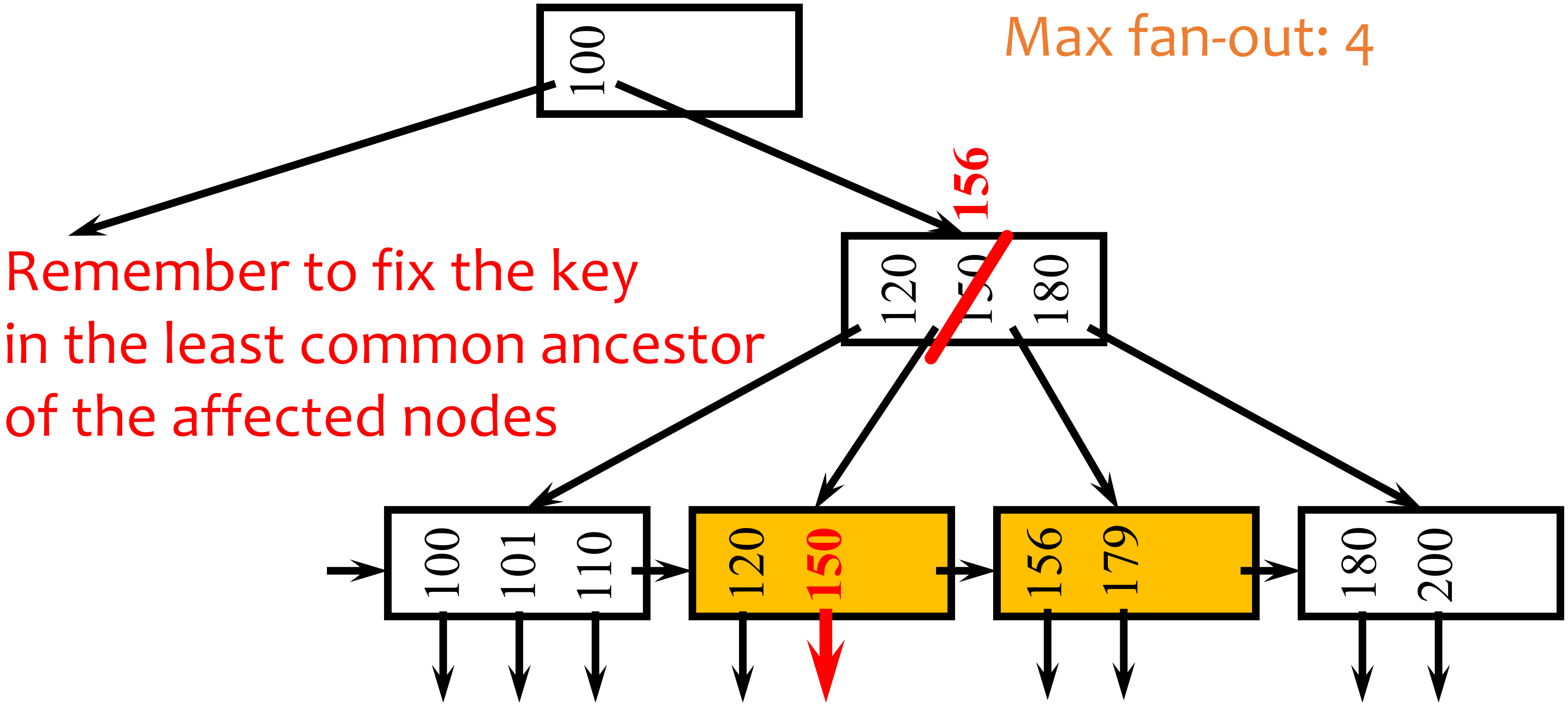
- In the worst case, node splitting can "propagate" all the way up to the root of the tree (not illustrated here)
  - Splitting the root introduces a new root of fan-out 2 and causes the tree to grow "up" by one level

Deletion

- Delete a record with search key value 130

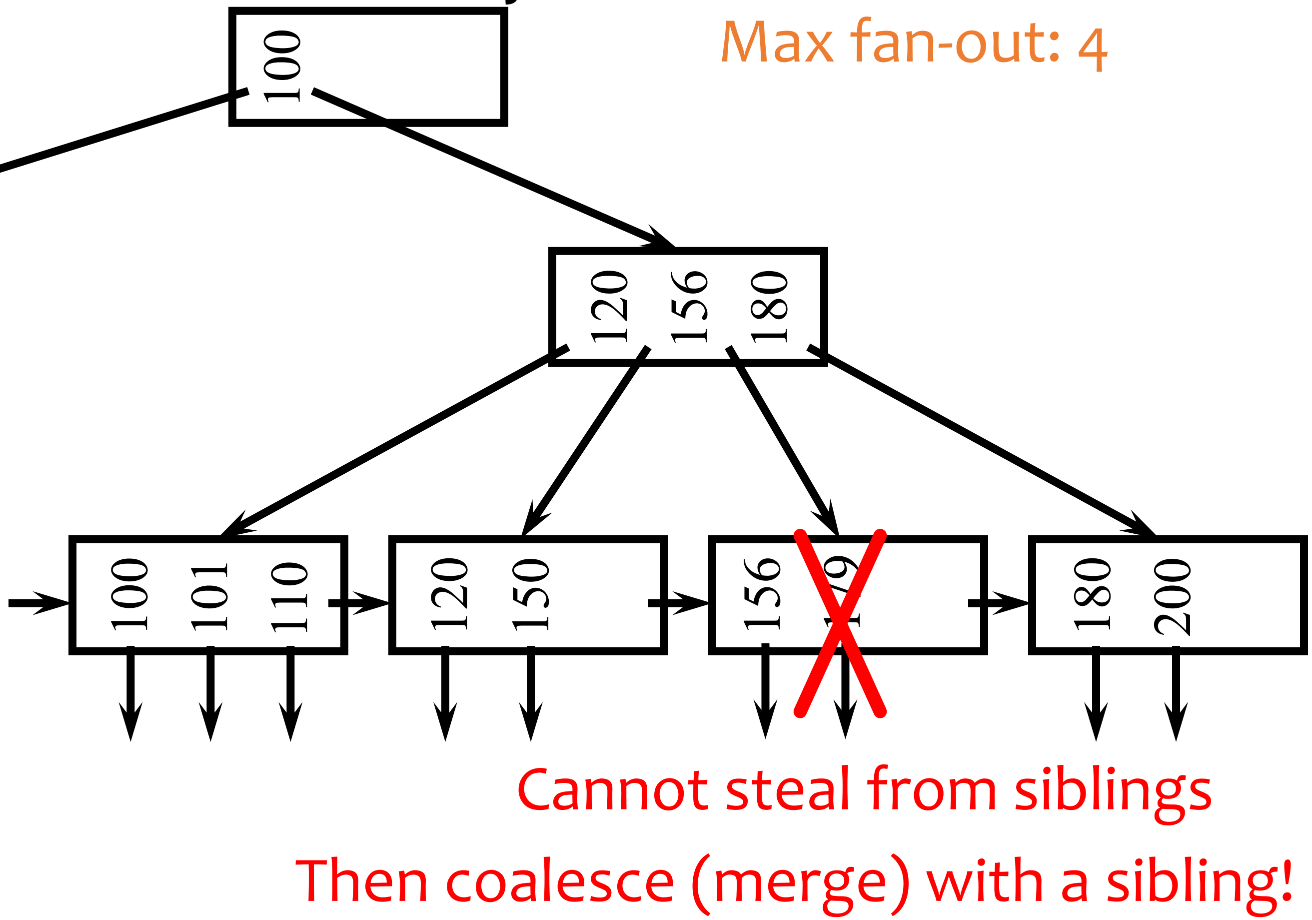


Stealing from a sibling

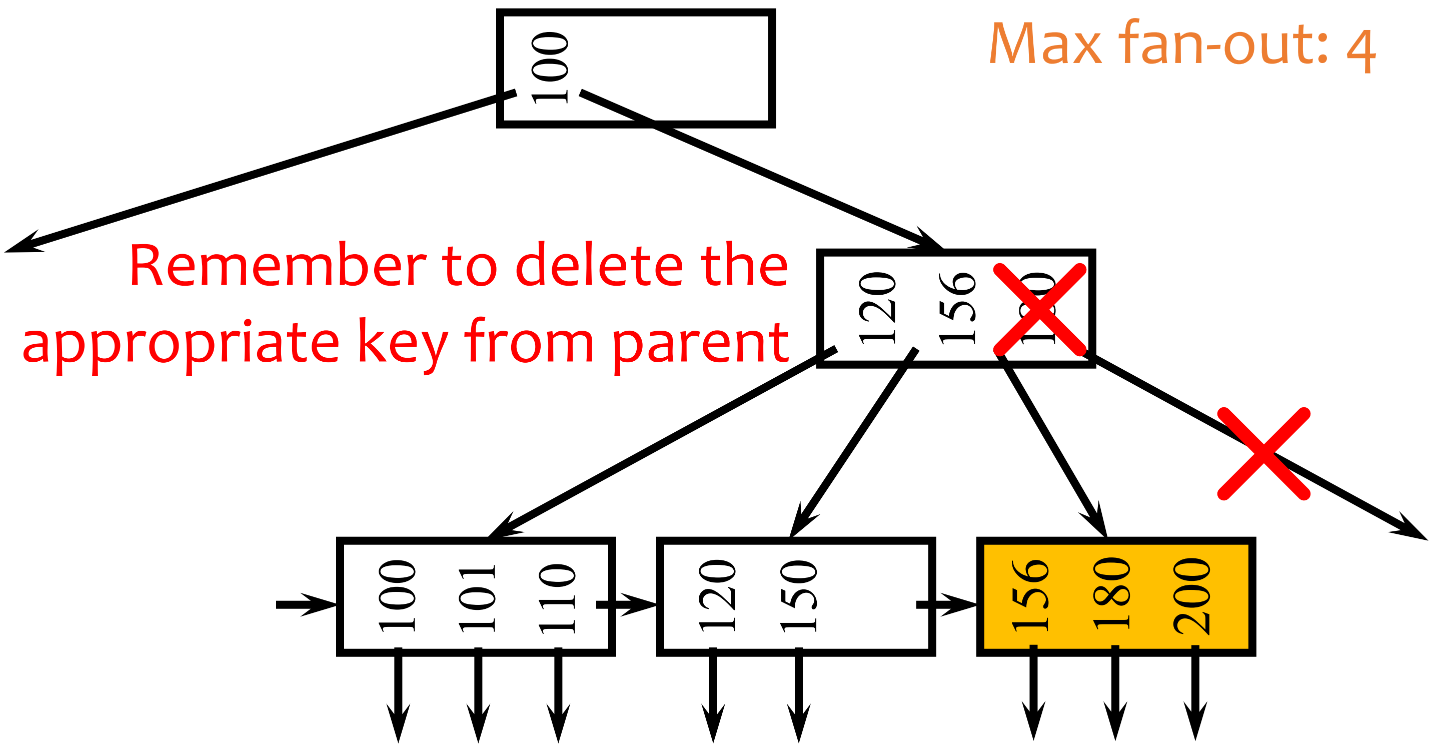


Another deletion example

- Delete a record with search key value 179



Coalescing



- Deletion can "propagate" all the way up to the root of the tree (not illustrated here)
  - When the root becomes empty, the tree "shrinks" by one level

Performance analysis

- How many I/O's are required for each operation?
  - h, the height of the tree (more or less)
  - Plus one or two to manipulate actual records
  - Plus $O(h)$ for reorganization (rare if f is large)
  - Minus one if we cache the root in memory
- How big is h?
  - Roughly $\log_{\text{fanout}} N$, where N is the number of records
  - B+-tree properties guarantee that fan-out is least $f/2$ for all non-root nodes
  - Fan-out is typically large (in hundreds)—many keys and pointers can fit into one block
  - A 4-level B+-tree is enough for "typical" tables (next slide)

Typicall B+ Trees in Practice

- Typical max entries: 200.
  - Typical fill-factor: 67%
  - average fanout F = 133
- Typical capacities:
  - Height 4: 133^4 = 312,900,700 records
  - Height 3: 133^3 = 2,352,637 records
- Can often hold top levels in buffer pool:
  - Level 1 = 1 page = 8 Kbytes
  - Level 2 = 133 pages = 1 Mbyte
  - Level 3 = 17,689 pages = 133 MBytes

B^+-tree in practice

- Complex reorganization for deletion often is not implemented (e.g., Oracle)
  - Leave nodes less than half full and periodically reorganize
- Most commercial DBMS use B^+-tree instead of hashing-based indexes because B^+-tree handles range queries

The Halloween Problem

- Story from the early days of System R…

```
UPDATE Payroll
SET salary = salary * 1.1
WHERE salary <= 25000;
```

  - There is a B$^+$-tree index on *Payroll*(*salary*)
  - The update never stopped until all employees earned 25k (why?)

- Solutions?
  - Scan index in reverse, or
  - Before update, scan index to create a "to-do" list, or
  - During update, maintain a "done" list, or
  - Tag every row with transaction/statement id

https://en.wikipedia.org/wiki/Halloween_Problem

B^+-tree versus ISAM

- ISAM is more static; B^+-tree is more dynamic
- ISAM can be more compact (at least initially)
    - Fewer levels and I/O's than B^+-tree
- Overtime, ISAM may not be balanced
    - Cannot provide guaranteed performance as B^+-tree does
    - Due to "skew"

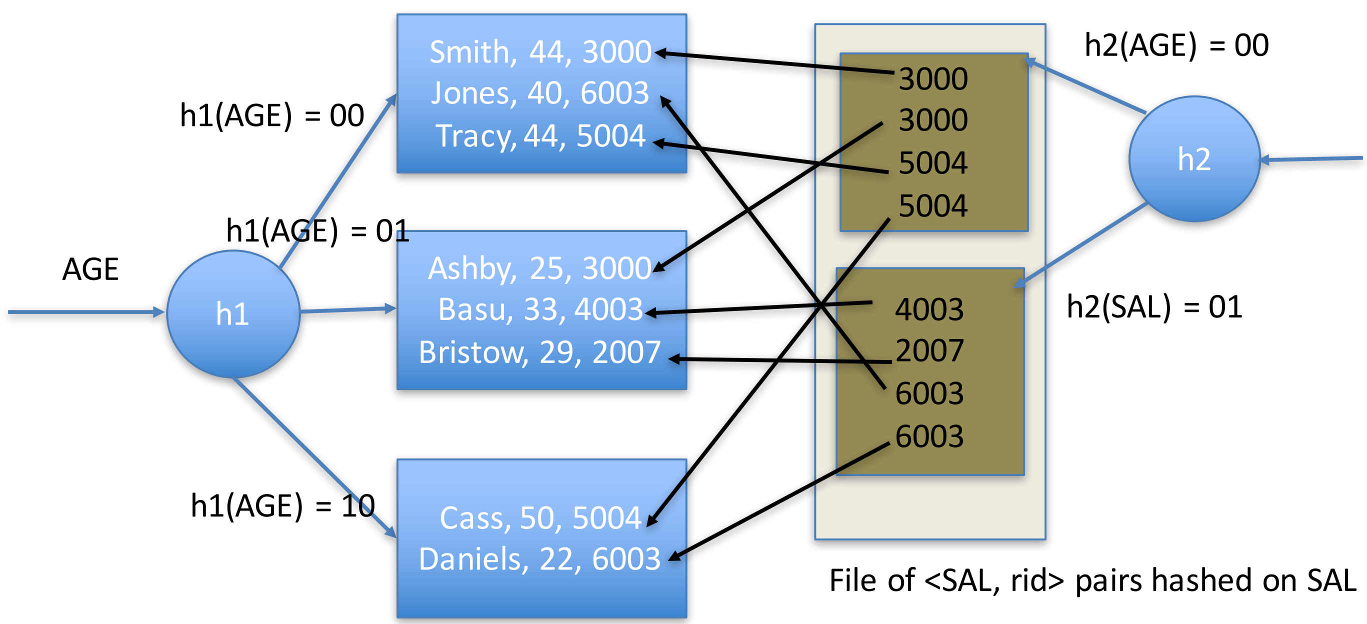
B^+-tree versus B-tree

- B-tree: why not store records (or record pointers) in non-leaf nodes?
  - These records can be accessed with fewer I/O's
- Problems?
  - Storing more data in a node decreases fan-out and increases h
  - Records in leaves require more I/O's to access
  - Vast majority of the records live in leaves!

B+ tree vs. Hash-based indexes

- Extensible hashing, linear hashing, etc.
- Can only handle "=" in join or selection
  - Cannot handle range predicates >, ≥, <, ≤

Index organized file hashed on AGE, with Auxiliary index on SAL



Employee File hashed on AGE

File of <SAL, rid> pairs hashed on SAL

Beyond ISAM, B-, and B$^+$-trees, and hash

- Other tree-based indexes: R-trees and variants, GiST, etc.
  - How about binary tree?

vs.

- Text indexes: inverted-list index, suffix arrays, etc.
- Other tricks: bitmap index, bit-sliced index, etc.

Query Processing

Overview

- Many different ways of processing the same query
  - Scan? Sort? Hash? Use an index?
  - All have different performance characteristics and/or make different assumptions about data
- Best choice depends on the situation
  - Implement all alternatives
  - Let the query optimizer choose at run-time

Notation

- Relations: R, S
- Tuples: r, s
- Number of tuples: $|R|, |S|$
- Number of disk blocks: $B(R), B(S)$
- Number of memory blocks available: M
- Cost metric
  - Number of I/O's
  - Memory requirement
- We do not count the cost of final write to disk

- Do not try to memorize the formulas for cost estimation!
  - understand the logic
  - recall the diagram of disk and memory on whiteboard

Scanning-based algorithms

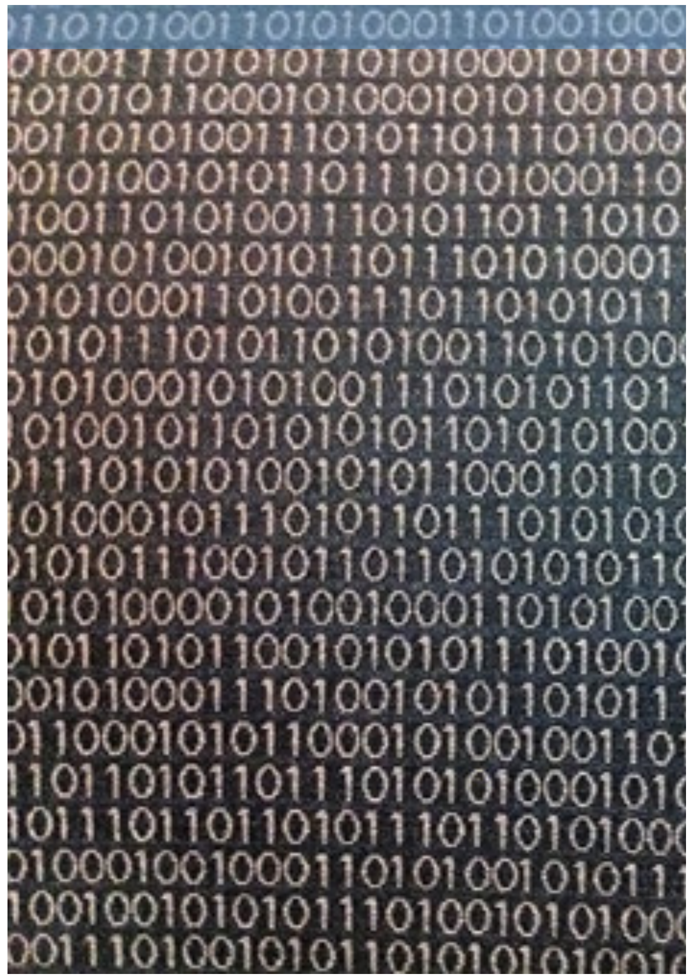


Table scan

- Scan table *R* and process the query
  - Selection over *R*
  - Projection of *R* without duplicate elimination
- I/O's: $B(R)$
  - Trick for selection: stop early if it is a lookup by key
- Memory requirement: 2
- Not counting the cost of writing the result out
  - Same for any algorithm!
  - Maybe not needed—results may be pipelined into another operator

Nested-loop join

$R \bowtie_p S$

- For each block of R, and for each r in the block:
  For each block of S, and for each s in the block:
  Output rs if p evaluates to true over r and s
  - R is called the outer table; S is called the inner table
  - I/O's: $B(R) + |R| \cdot B(S)$
  - Memory requirement: 3

Improvement: block-based nested-loop join

- For each block of R, for each block of S:
  For each r in the R block, for each s in the S block: …
  - I/O's: $B(R) + B(R) \cdot B(S)$
  - Memory requirement: same as before

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