Indexing

Introduction to Database Management

CS348 Fall 2022

Announcements (Tue, Nov 1)

- Midterm Exam
  - Fri, Nov 4, 4:30-6:00pm
  - **Cover Lectures 1-6** [instead of Lectures 1-10]
  - Practice questions on Learn
  - Survey for midterm review session

- Assignment 2
  - Grade won't be released before midterm exam, but we will cover solutions related to Lectures 1-6 on the midterm review lecture on Thur, Nov 3.

- Project
  - Milestone 2 due Nov 17 (Thu)

Outline

- Types of indexes
- Index structure
- How to use index

What are indexes for?

- Given a value, locate the record(s) with this value

  SELECT * FROM *R* WHERE *A = value*;

  SELECT * FROM *R*, *S* WHERE *R.A = S.B*;

- Find data by other search criteria, e.g.
  - Range search

    SELECT * FROM *R* WHERE *A > value*;
  - Keyword search

    database indexing | Search

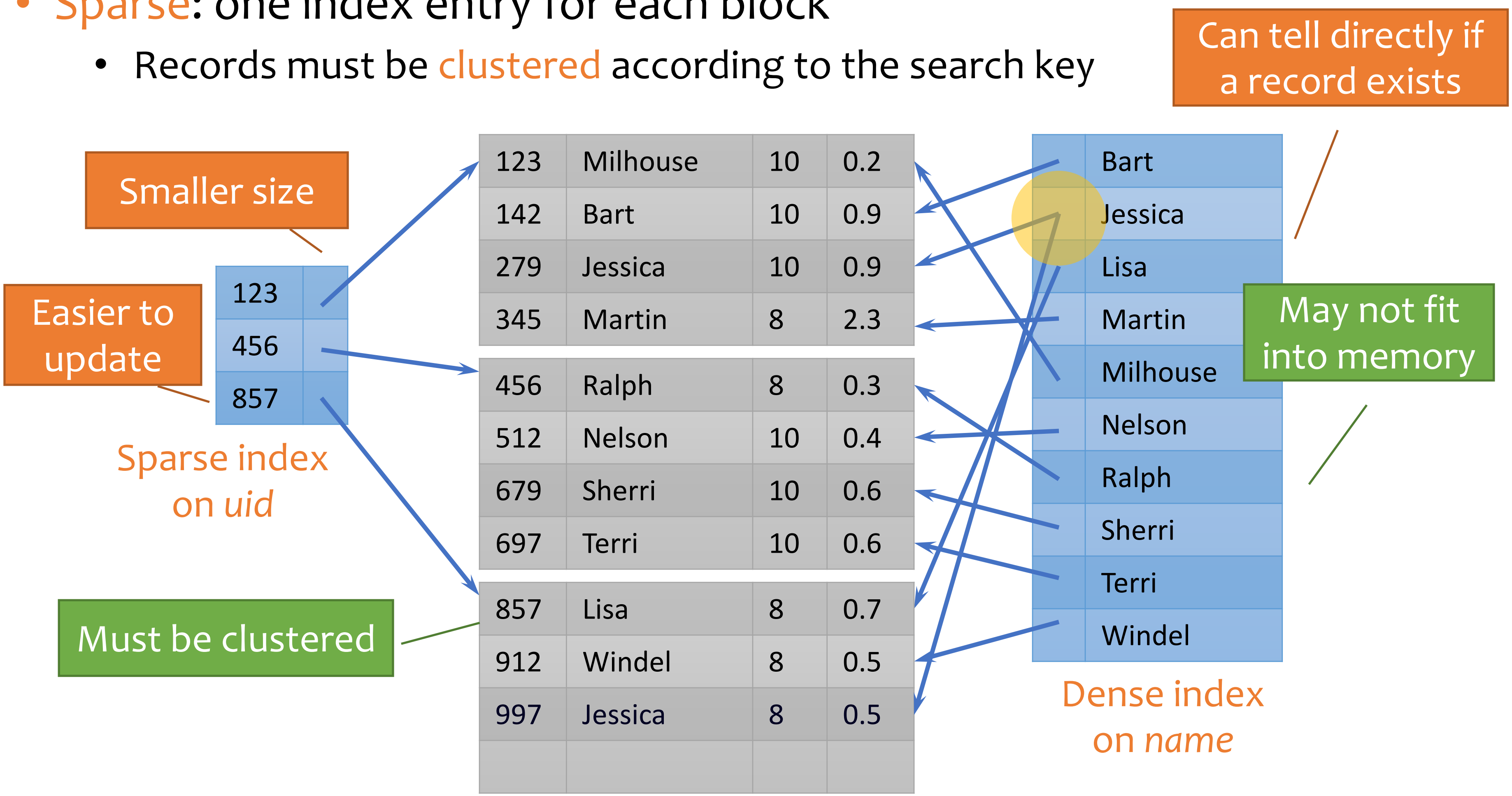
Focus of this lecture

Dense v.s. sparse indexes

- Dense: one index entry for each search key value
  - One entry may "point" to multiple records (e.g., two users named Jessica)
- Sparse: one index entry for each block
  - Records must be clustered according to the search key

Dense v.s. sparse indexes

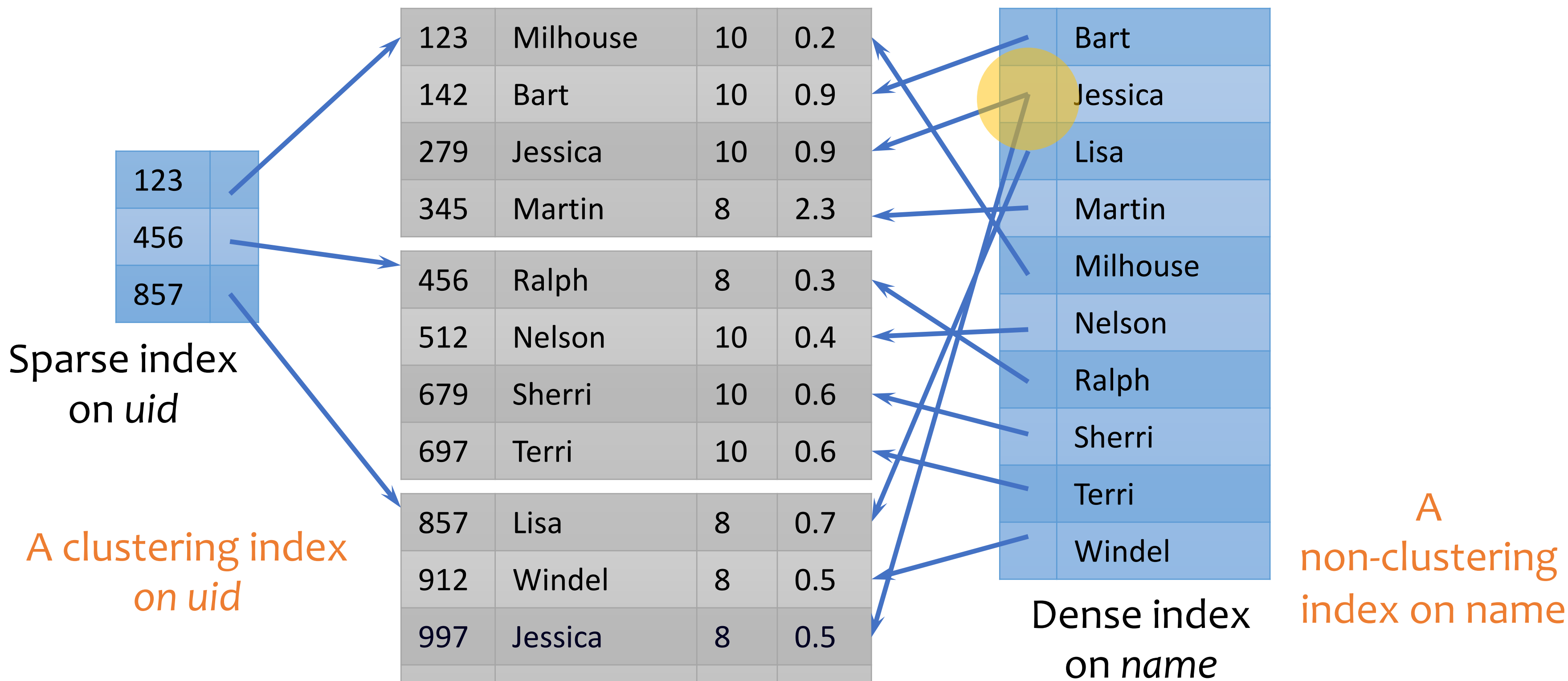
- Dense: one index entry for each search key value
  - One entry may "point" to multiple records (e.g., two users named Jessica)
- Sparse: one index entry for each block
  - Records must be clustered according to the search key



123	Milhouse	10	0.2
142	Bart	10	0.9
279	Jessica	10	0.9
345	Martin	8	2.3
456	Ralph	8	0.3
512	Nelson	10	0.4
679	Sherri	10	0.6
697	Terri	10	0.6
857	Lisa	8	0.7
912	Windel	8	0.5
997	Jessica	8	0.5

Clustering v.s. non-clustering indexes

- An index on attribute A of a relation is a clustering index if tuples in the relation with similar values for A are stored together in the same block.
- Other indices are non-clustering (or secondary) indices.
- Note: A relation may have at most one clustering index, and any number of non-clustering indices.



Primary and secondary indexes

- Primary index
  - Created for the primary key of a table
  - Records are usually clustered by the primary key
  - Clustering index → sparse
- Secondary index
  - Non-clustering index, usually dense (to find each search key value, since records are not clustered by this search key)
- SQL
  - PRIMARY KEY declaration automatically creates a primary index, UNIQUE key automatically creates a secondary index
  - Additional secondary index can be created on non-key attribute(s):
    CREATE INDEX UserPopIndex ON User(pop);

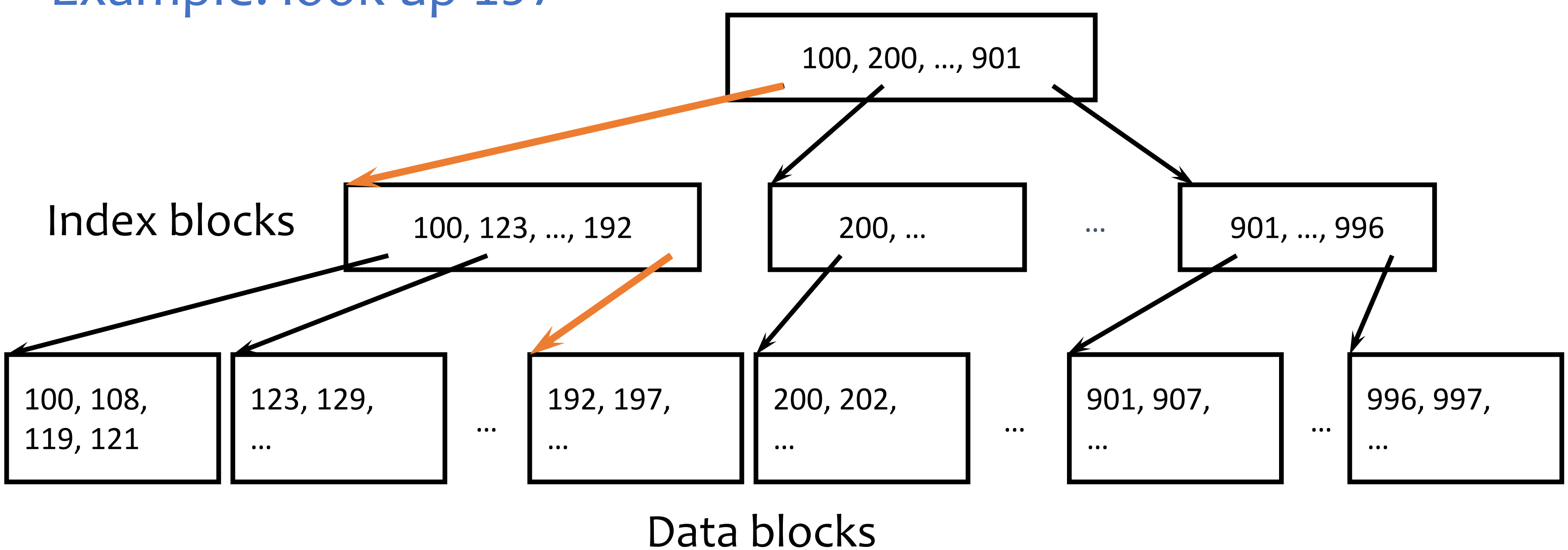
Outline

- Types of indexes
  - Sparse v.s. dense
  - Clustering v.s. non-clustering
  - Primary v.s. secondary
- Index structure
- How to use index

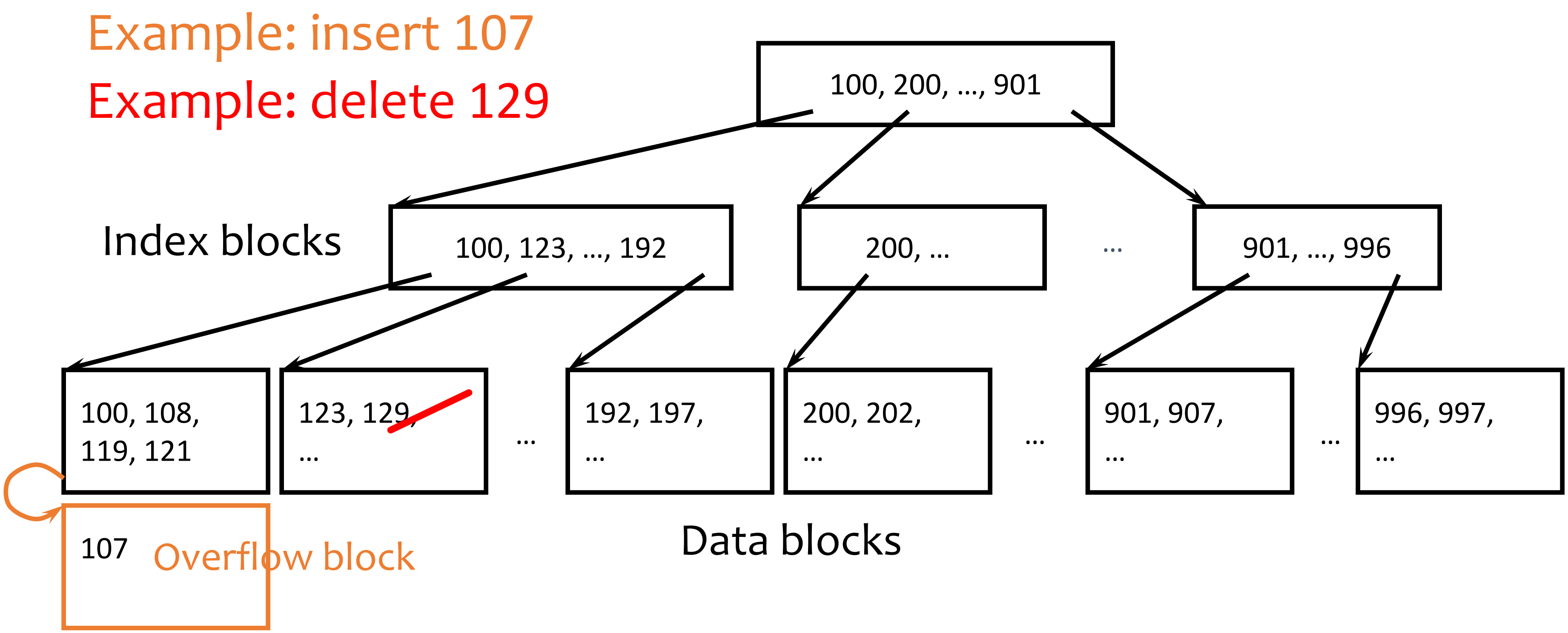
ISAM

- What if an index is still too big?
  - Put a another (sparse) index on top of that!
  - ☞ ISAM (Index Sequential Access Method), more or less

Example: look up 197



Updates with ISAM

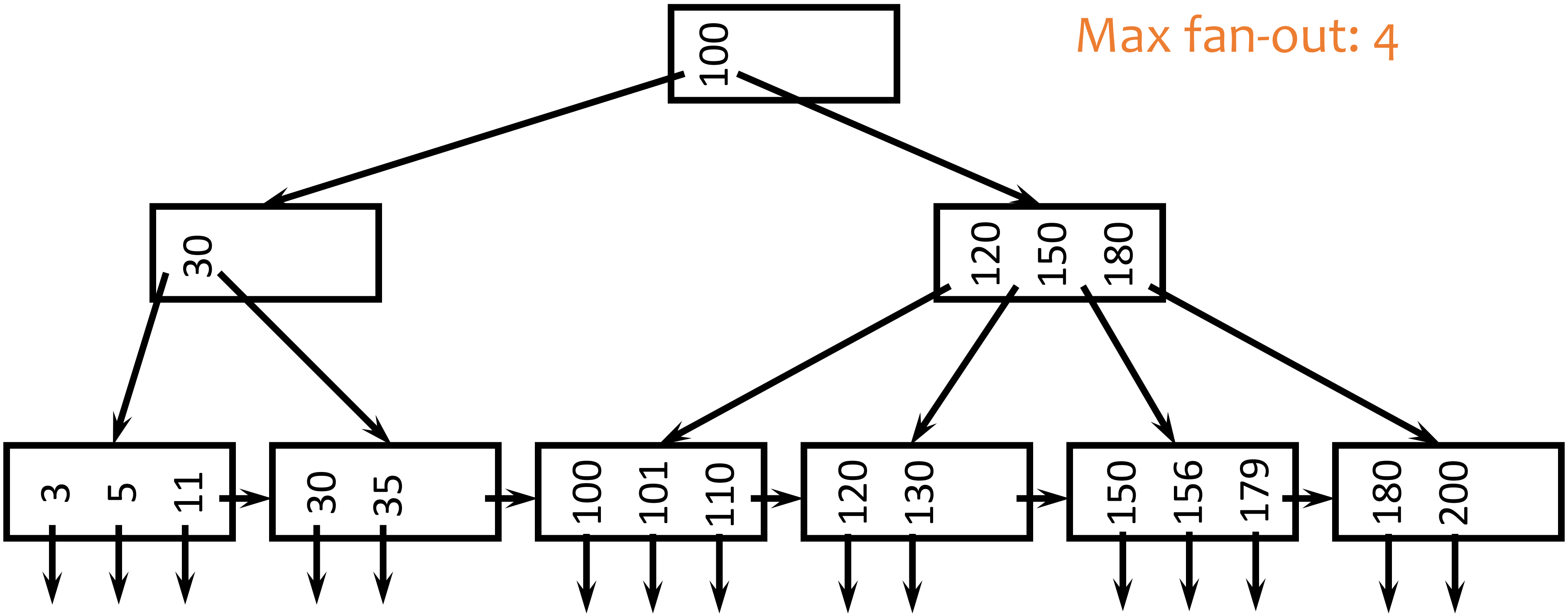


- Overflow chains and empty data blocks degrade performance
  - Worst case: most records go into one long chain, so lookups require scanning all data!

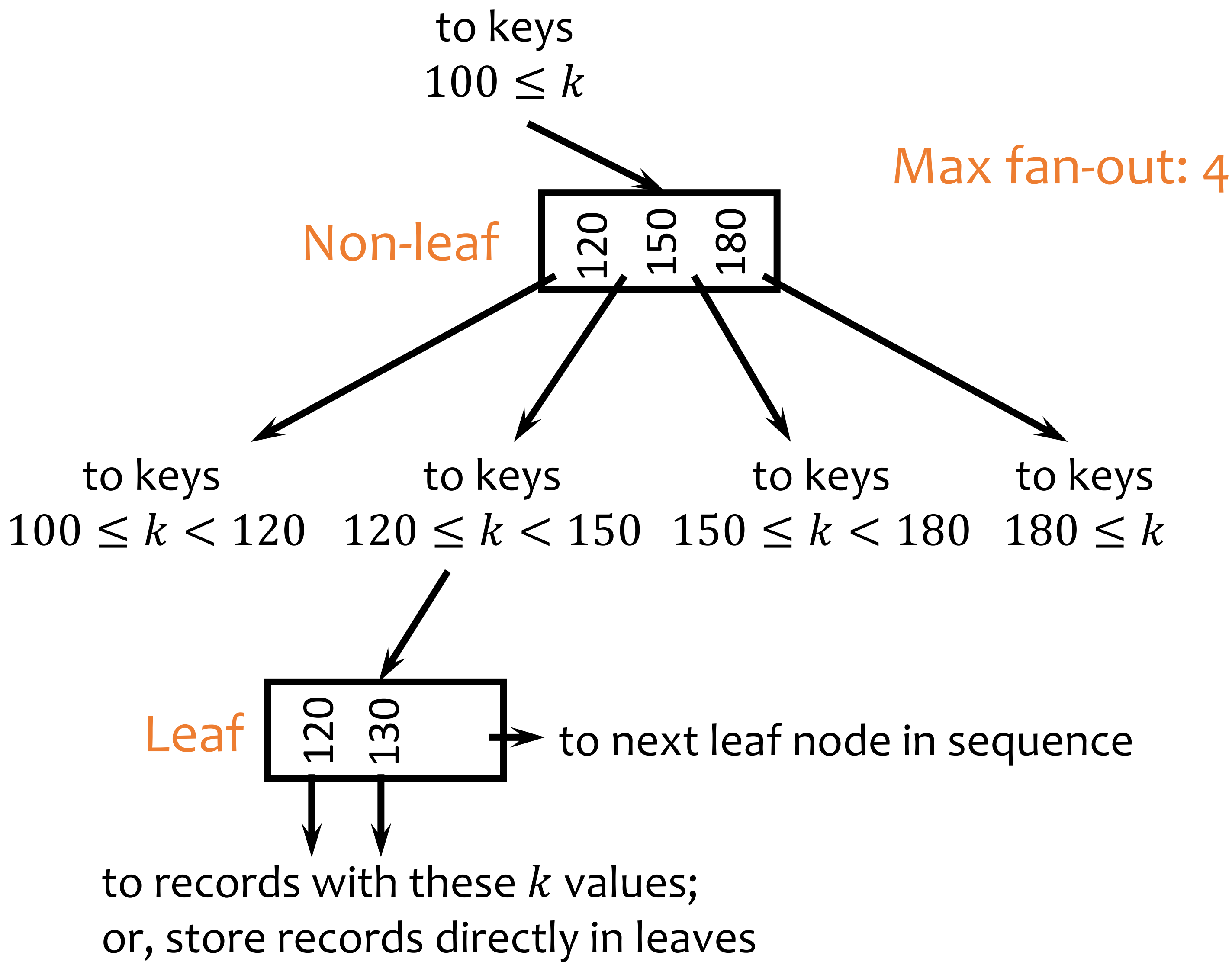
B+-tree

- 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



Sample B+-tree nodes



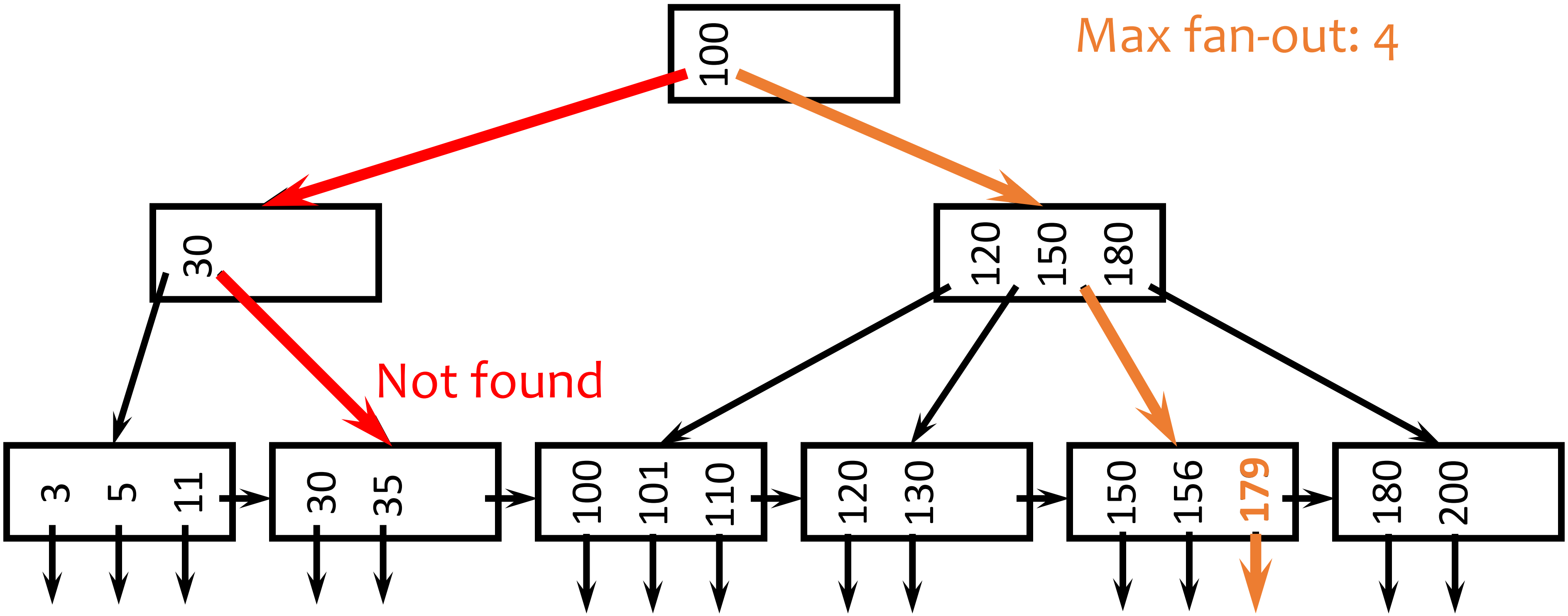
B+-tree balancing properties

- 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	$f-1$	$\lfloor f/2 \rfloor$	$\lfloor f/2 \rfloor$

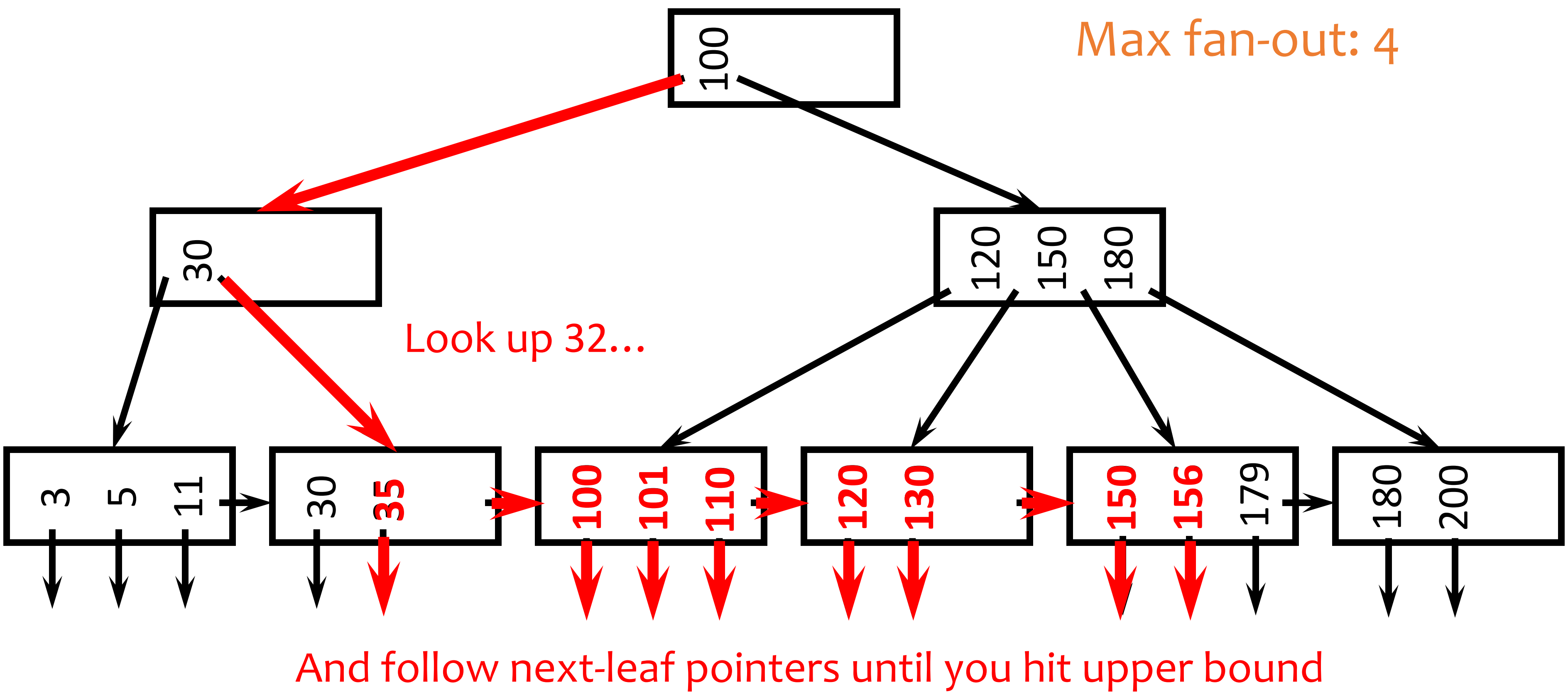
Lookups

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



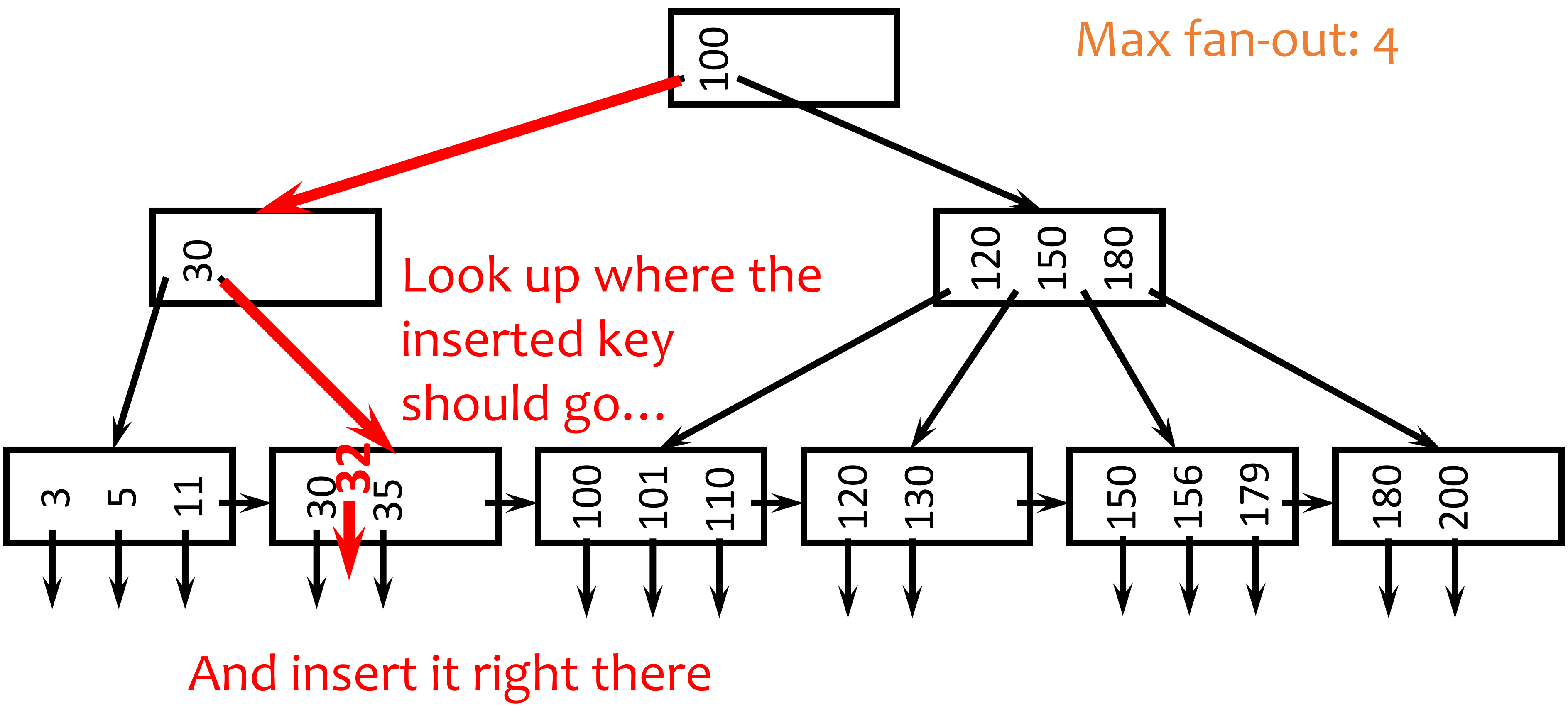
Range query

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



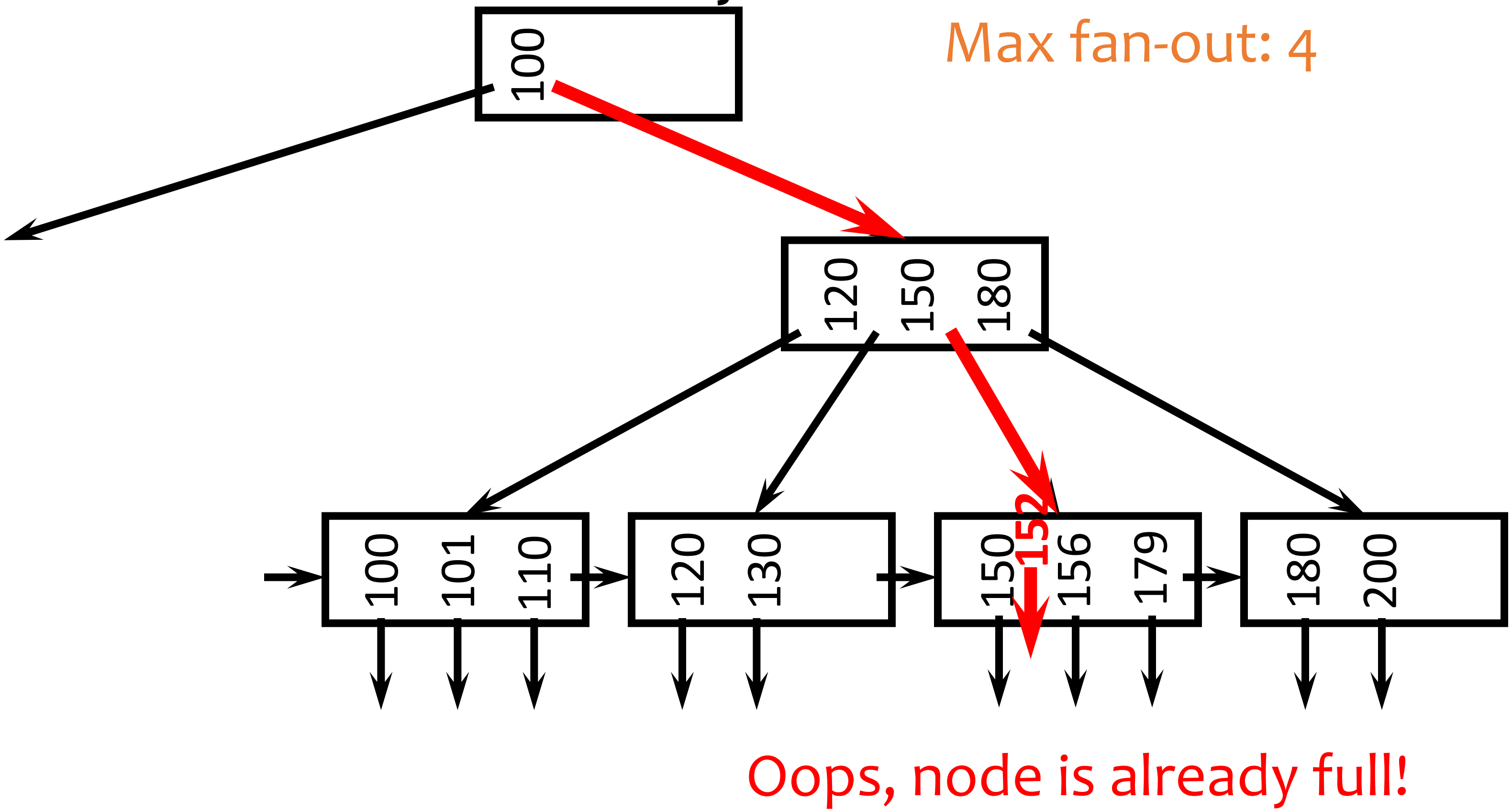
Insertion

- Insert a record with search key value 32

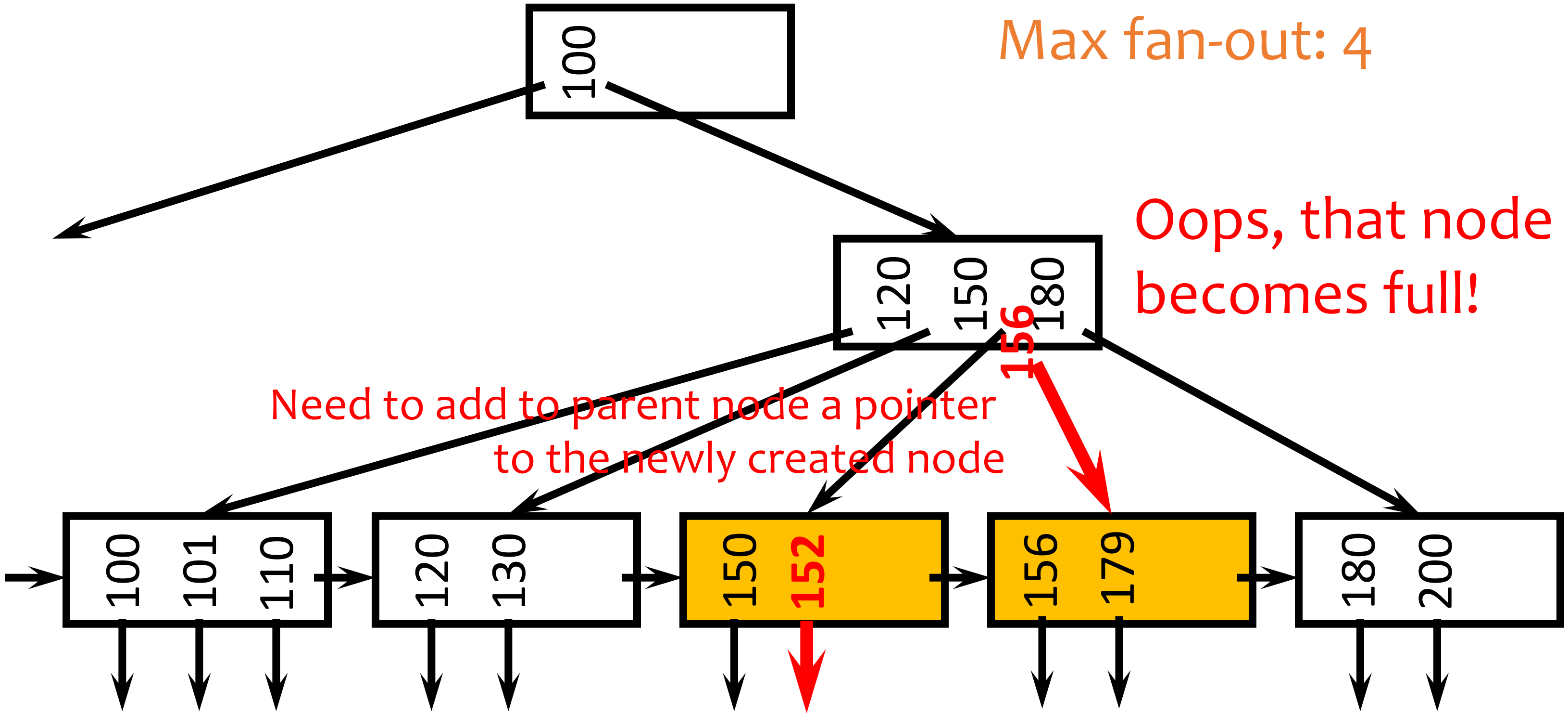


Another insertion example

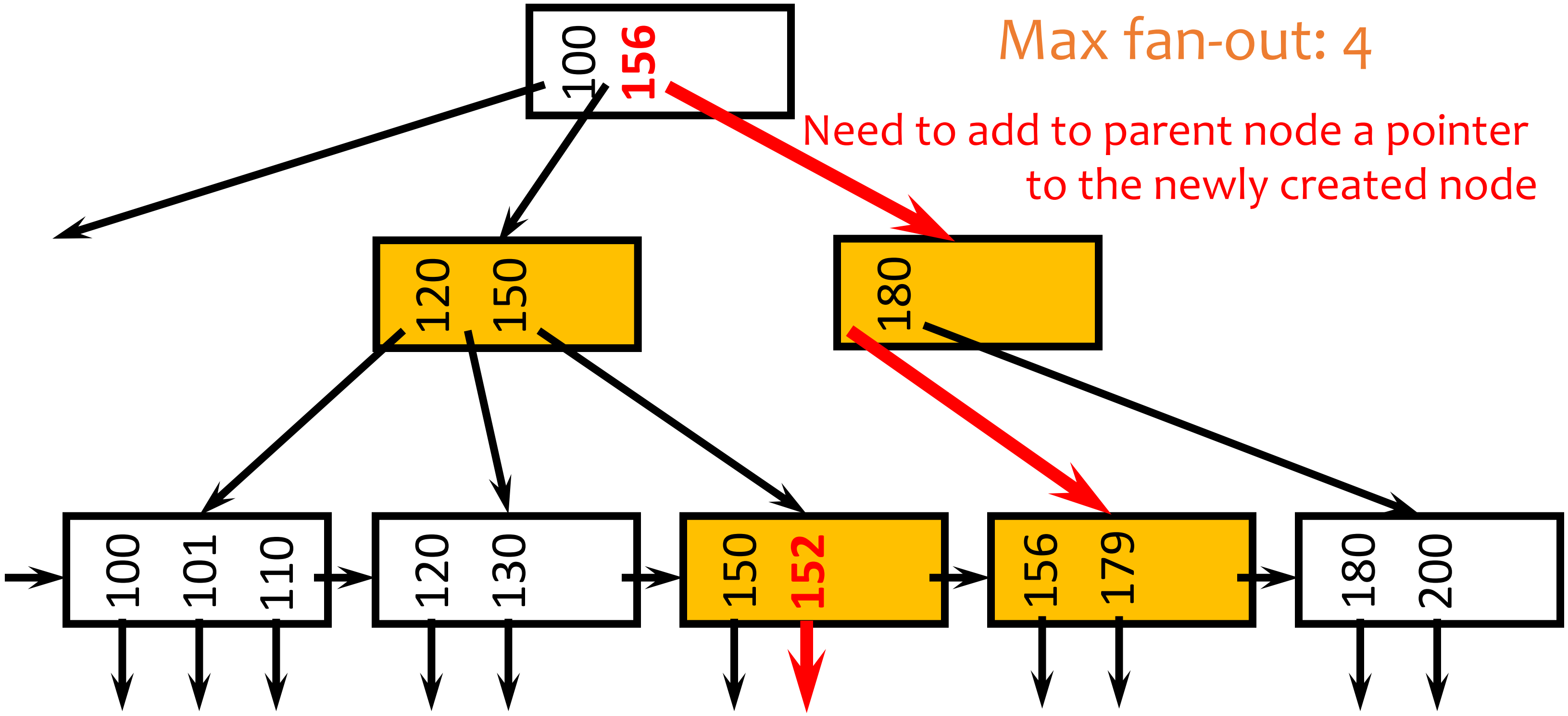
- Insert a record with search key value 152



Node splitting



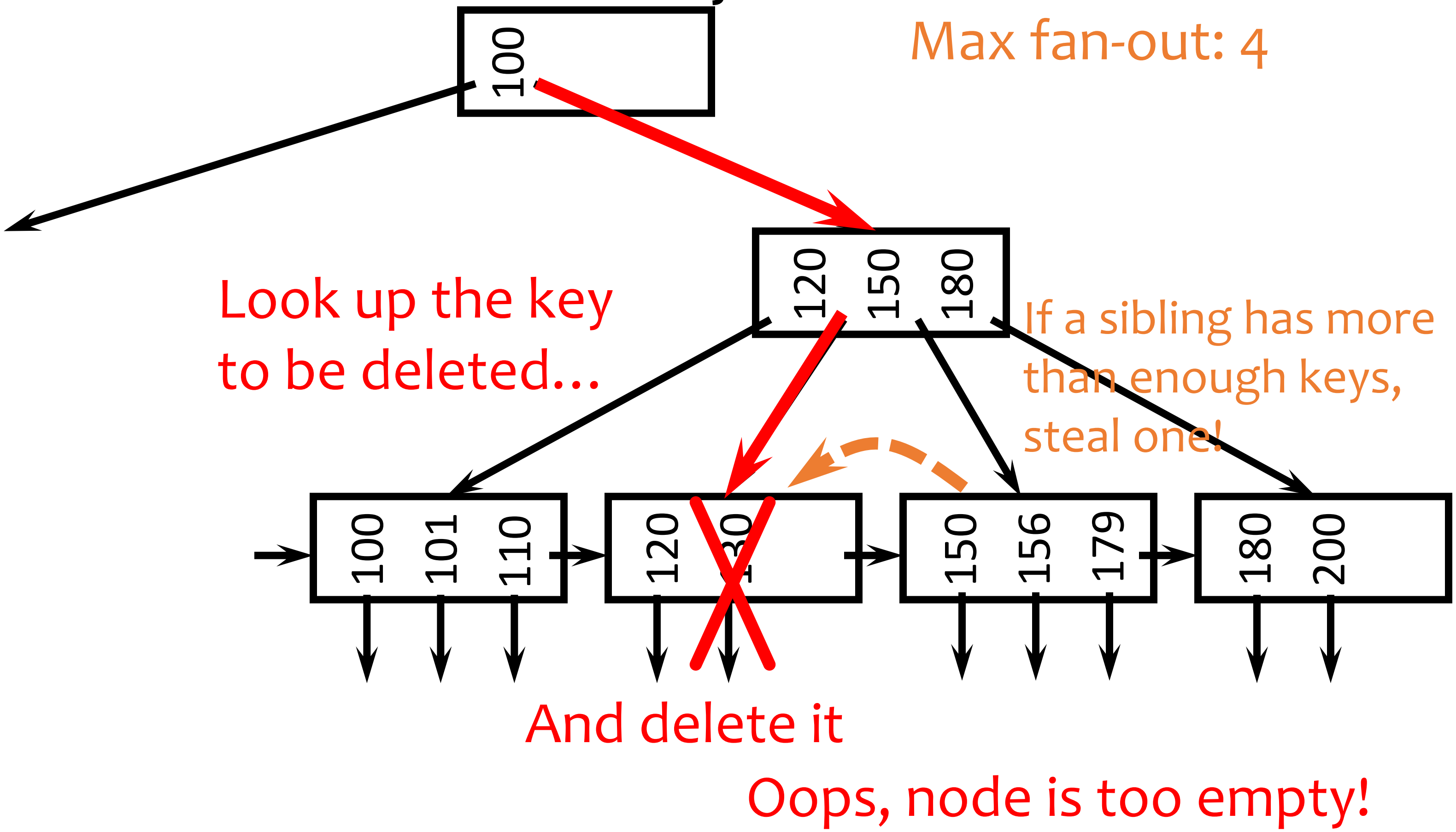
More node splitting



- 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

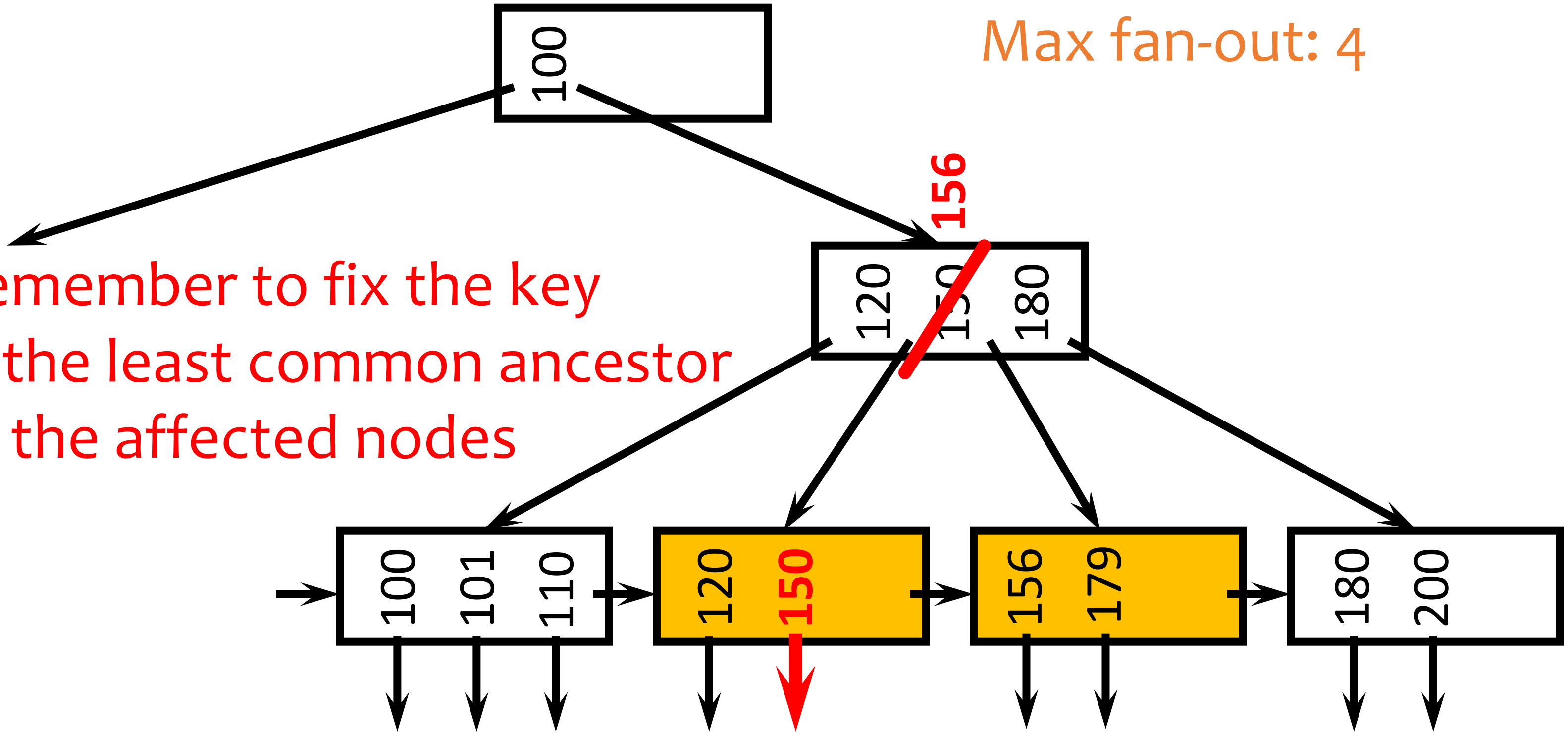
Deletion

- Delete a record with search key value 130



Stealing from a sibling

Max fan-out: 4

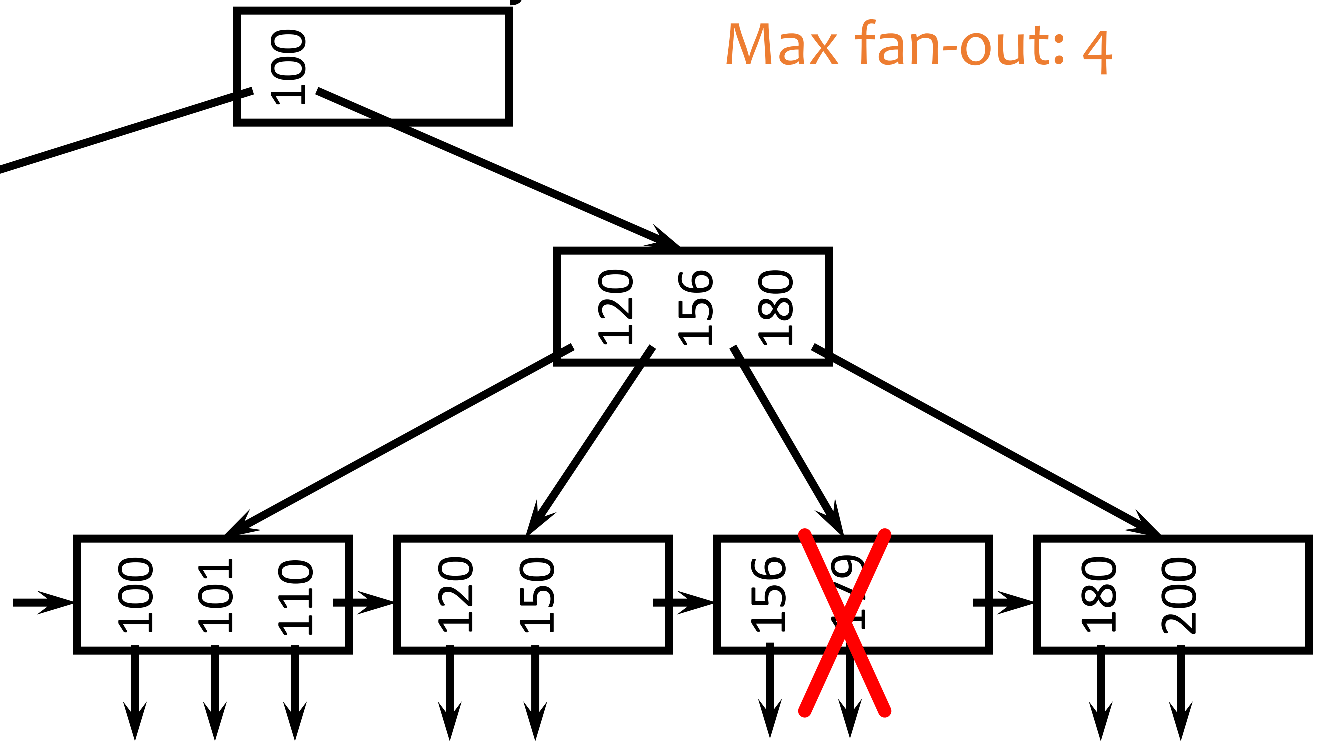


Remember to fix the key
in the least common ancestor
of the affected nodes

Another deletion example

- Delete a record with search key value 179

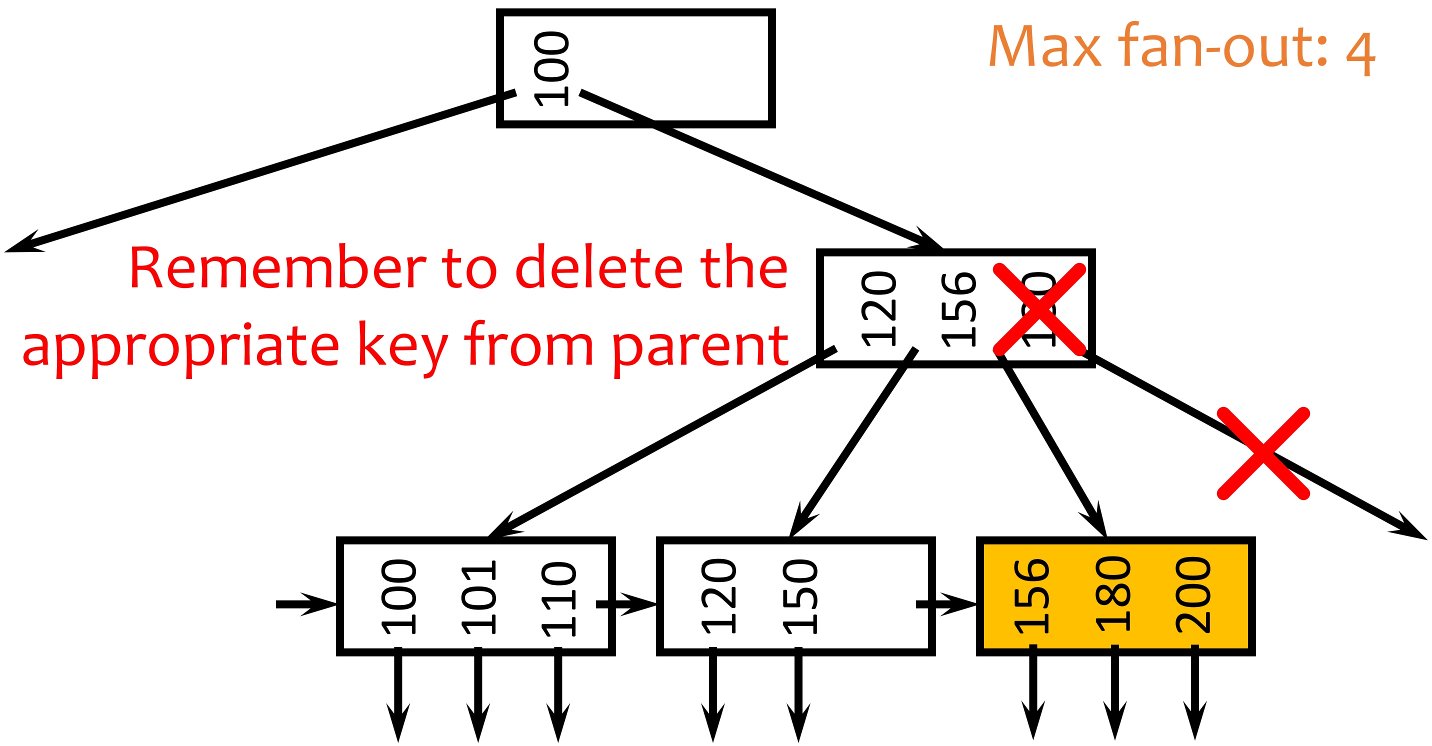
Max fan-out: 4



Cannot steal from siblings

Then coalesce (merge) with a sibling!

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 of B+-tree

- 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
  - 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

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
  - $h(key)\ mod\ f$: which pointer/block to which data entry with key belongs

The Halloween Problem

- Story from the early days of System R…

```
UPDATE Payroll
SET salary = salary * 1.1
WHERE salary >= 100000;
```

  - There is a B$^+$-tree index on *Payroll*(*salary*)
  - The update never stopped (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

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

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!

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

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

vs.

- Hashing-based indexes: extensible hashing, linear hashing, etc.
- Text indexes: inverted-list index, suffix arrays, etc.
- Other tricks: bitmap index, bit-sliced index, etc.

Outline

- Types of indexes:
  - Dense v.s. sparse
  - Clustering v.s. non-clustering
  - Primary v.s. secondary
- Indexing structure
  - ISAM
  - B+-tree
- How to use index

Multi-attribute indices

- Index on several attributes of the same relation.
  - CREATE INDEX NameIndex ON User(LastName,FirstName);

tuples (or tuple pointers) are organized first by Lastname. Tuples with a common surname are then organized by Firstname.

- This index would be *useful* for these queries:
  - **select * from** User **where** Lastname = 'Smith'
  - **select * from** User **where** Lastname = 'Smith' and Firstname='John'
- This index would be not *useful* at all for this query:
  - **select * from** User **where** Firstname='John'

Index-only plan

- For example:
  - select count(*) from User where pop > '0.8' and firstname = 'Bob';
  - non-clustering index on (firstname, pop)

- A (non-clustered) index contains all the columns needed to answer the query without having to access the tuples in the base relation.
  - Avoid one disk I/O per tuple
  - The index is much smaller than the base relation

Physical design guidelines for indices

1. Don’t index unless the performance increase outweighs the update overhead
2. Attributes mentioned in WHERE clauses are candidates for index search keys
3. Multi-attribute search keys should be considered when
   - a WHERE clause contains several conditions; or
   - it enables index-only plans

Physical design guidelines for indices

1. Don’t index unless the performance increase outweighs the update overhead
2. Attributes mentioned in WHERE clauses are candidates for index search keys
3. Multi-attribute search keys should be considered when
4. Choose indexes that benefit as many queries as possible
5. Each relation can have at most one clustering scheme; therefore choose it wisely
    - Target important queries that would benefit the most
        - Range queries benefit the most from clustering
    - A multi-attribute index that enables an index-only plan does not benefit from being clustered

Case study

- User(<u>uid</u>, name, age, pop)
- Group(<u>gid</u>, name, date)
- Member(<u>uid, gid</u>)

- Common queries
  1. List the name, pop of users in a particular age range
  2. List the uid, age, pop of users with a particular name
  3. List the average pop of each age
  4. List all the group info, ordered by their starting date
  5. List the average pop of a particular group given the group name
- Pick a set of clustered/unclustered indexes for these set of queries (without worrying too much about storage and update cost)

Attention! This case study is newly added to this lecture, and hence it has no previous video recording. Try to slowly go through the slides and understand them well.

Case study

- User(<u>uid</u>, name, age, pop)
- Group(<u>gid</u>, name, date)
- Member(<u>uid, gid</u>)

A clustered index on User(age)

A unclustered index on User(name)

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Case study

- User(uid, name, age, pop)
- Group(gid, name, date)
- Member(uid, gid)

A unclustered index on User(age, pop) → index-only plan

A clustered index on User(age)

A unclustered index on User(name)

- Common q

1. List the name, pop users in a particular age range
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A clustered index on Group(date)

Case study

- User(uid, name, age, pop)
- Group(gid, name, date)
- Member(uid, gid)

- Common q

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2. List the uid, age, pop f users with a particular name
3. List the average pop of each age
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5. List the average pop of a particular group given the group name

A unclustered index on User(age, pop) → index-only plan

A clustered index on User(age)

A unclustered index on User(name)

A clustered index on Group(date)

A join between User(uid, …,pop), Member(uid,gid), Group(gid, name)

(i) Search gid by a particular name → Clustered/Unclustered index on Group(name)?

(ii) Search uid by a particular gid → Clustered/Unclustered index on Member(gid)?

(iii) Search pop by a particular uid → Clustered/Unclustered index on User(uid)?

Unclustered, as we already have a clustered index on Group(date)

If many other queries require a clustered index on Group(name), we may reconsider!

Case study

- User(uid, name, age, pop)
- Group(gid, name, date)
- Member(uid, gid)

- Common q[ueries]
  1. List the name, pop [of] users in a particular age range
  2. List the uid, age, pop [o]f users with a particular name
  3. List the average pop of each age
  4. List all the group info, ordered by their starting date
  5. List the average pop of a particular group given the group name

A unclustered index on User(age, pop)
→ index-only plan

A clustered index on User(age)

A unclustered index on User(name)

A clustered index on Group(date)

A join between User(uid, … ,pop) , Member(uid,gid), Group(gid, name)

(i) Search gid by a particular name
→ Unclustered index on Group(name)

(ii) Search uid by a particular gid
→ Clustered/Unclustered index on Member(gid)?

(iii) Search pop by a particular uid
→ Clustered/Unclustered index on User(uid)?

Clustered -> all records of the same gid are clustered

Or clustered index on Member(gid,uid)

Case study

- User(<u>uid</u>, name, age, pop)
- Group(<u>gid</u>, name, date)
- Member(<u>uid, gid</u>)

- Common q
  1. List the name, pop users in a particular age range
  2. List the uid, age, pop of users with a particular name
  3. List the average pop of each age
  4. List all the group info, ordered by their starting date
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A unclustered index on User(age, pop) → index-only plan

A clustered index on User(age)

A unclustered index on User(name)

A clustered index on Group(date)

A join between User(uid, … ,pop) , Member(uid,gid), Group(gid, name)

(i) Search gid by a particular name
→ Unclustered index on Group(name)

(ii) Search uid by a particular gid
→ Clustered index on Member(gid)?

(iii) Search pop by a particular uid
→ Clustered/Unclustered index on User(uid)?

Or unclustered index on User(uid, pop) → index-only plan, if without worrying about storage/update cost

Unclustered, as we already have a clustered index on User(age)

Summary

- Types of indexes:
  - Dense v.s. sparse
  - Clustering v.s. non-clustering
  - Primary v.s. secondary
- Indexing structure
  - ISAM
  - B+-tree
- How to use index
  - Use multi-attribute indices
  - Index-only plan
  - General guideline