Indexing

CPS 116
Introduction to Database Systems

Announcements (Thu. Nov. 17)

- Project milestone #2 feedback will be emailed to by this weekend
- Homework #4 will be assigned next Tuesday

Basics

- 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*;

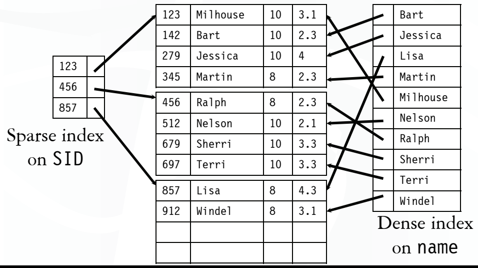
- Other search criteria, e.g.
  - Range search

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

    database indexing Search

Dense and sparse indexes

- ❖ Dense: one index entry for each search key value
- ❖ Sparse: one index entry for each block
  - Records must be clustered according to the search key



123	Milhouse	10	3.1
142	Bart	10	2.3
279	Jessica	10	4
345	Martin	8	2.3
456	Ralph	8	2.3
512	Nelson	10	2.1
679	Sherri	10	3.3
697	Terri	10	3.3
857	Lisa	8	4.3
912	Windel	8	3.1

Dense versus sparse indexes

- ❖ Index size
  - Sparse index is smaller
- ❖ Requirement on records
  - Records must be clustered for sparse index
- ❖ Lookup
  - Sparse index is smaller and may fit in memory
  - Dense index can directly tell if a record exists
- ❖ Update
  - Easier for sparse index

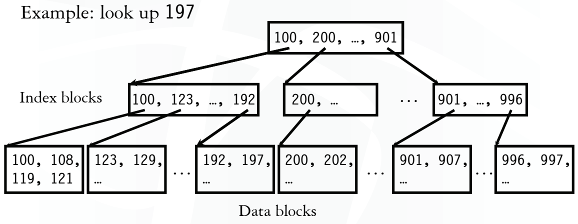
Primary and secondary indexes

- ❖ Primary index
  - Created for the primary key of a table
  - Records are usually clustered according to the primary key
  - Can be sparse
- ❖ Secondary index
  - Usually dense
- ❖ 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 StudentGPAIndex ON Student(GPA);`

ISAM

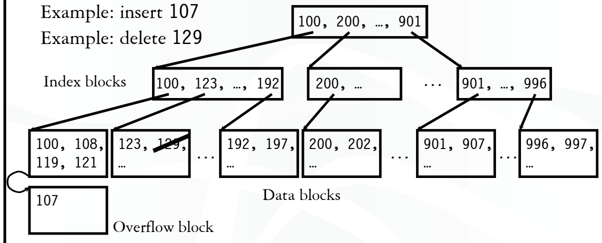
- What if an index is still too big?
  - Put a another (sparse) index on top of that!
  - ☞ISAM (Index Sequential Access Method), more or less

Example: look up 197



Updates with ISAM

Example: insert 107
Example: delete 129

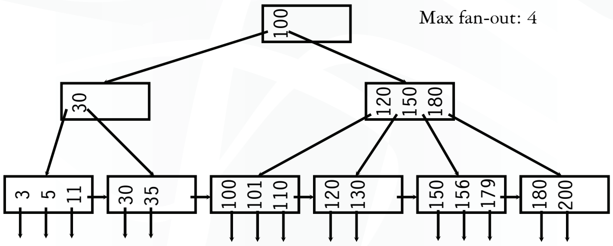


- Overflow chains and empty data blocks degrade performance
  - Worst case: most records go into one long chain

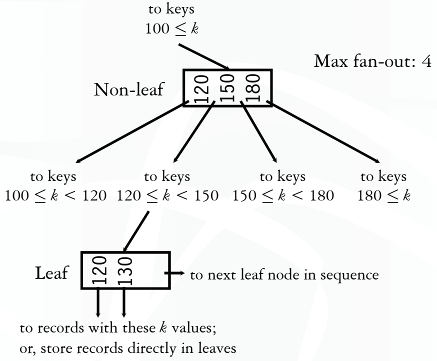
B$^+$-tree

- A hierarchy of 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


to keys
$100 \le k$

Max fan-out: 4

Non-leaf

to keys
$100 \le k < 120$

to keys
$120 \le k < 150$

to keys
$150 \le k < 180$

to keys
$180 \le k$

Leaf

to next leaf node in sequence

to records with these k values;
or, store records directly in leaves

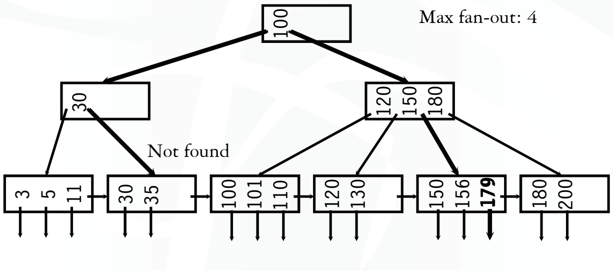
B^+-tree balancing properties

- 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

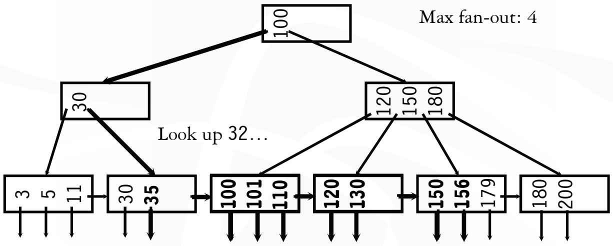
```
SELECT * FROM R WHERE k = 179;
SELECT * FROM R WHERE k = 32;
```


Max fan-out: 4

Not found

Range query

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



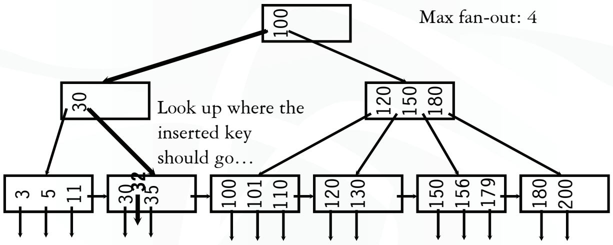
Max fan-out: 4

Look up 32…

And follow next-leaf pointers

Insertion

- Insert a record with search key value 32



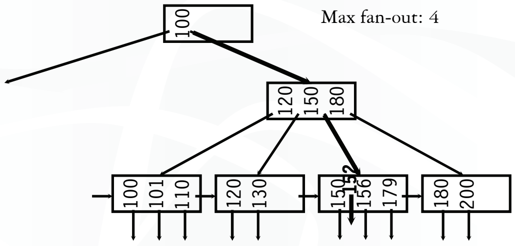
Max fan-out: 4

Look up where the inserted key should go…

And insert it right there

Another insertion example

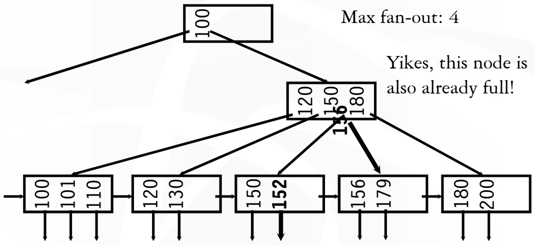
- Insert a record with search key value 152



Max fan-out: 4

Oops, node is already full!

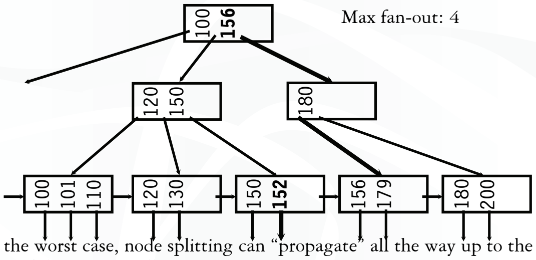
Node splitting



Max fan-out: 4

Yikes, this node is also already full!

More node splitting



Max fan-out: 4

- 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

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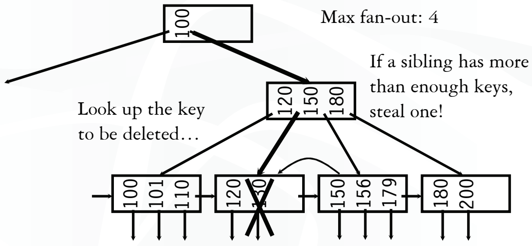
Deletion

- Delete a record with search key value 130



Max fan-out: 4

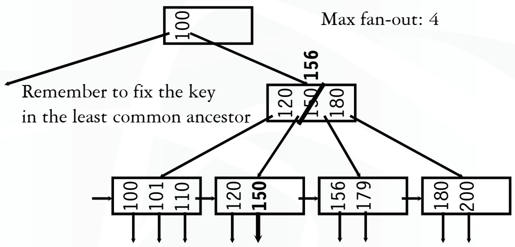
If a sibling has more than enough keys, steal one!

Look up the key to be deleted…

And delete it

Oops, node is too empty!

Stealing from a sibling

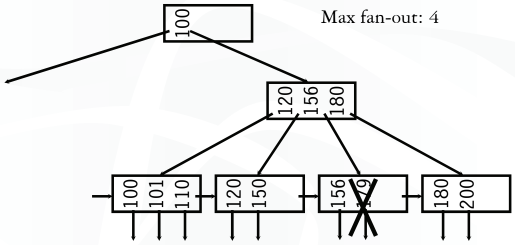


Max fan-out: 4

Remember to fix the key
in the least common ancestor

Another deletion example

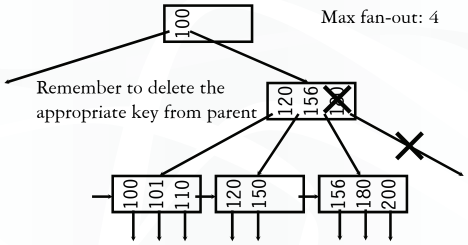
- Delete a record with search key value 179



Max fan-out: 4

Cannot steal from siblings
Then coalesce (merge) with a sibling!

Coalescing



Max fan-out: 4

Remember to delete the
appropriate key from parent

- 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 (should be very rare if f is large)
  - Minus one if we cache the root in memory
- How big is h?
  - Roughly $\log_{\text{fan-out}} N$, 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

B$^+$-tree in practice

- Complex reorganization for deletion often is not implemented (e.g., Oracle, Informix)
  - 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 >= 100000;
```

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

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?

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

- Other tree-based indexes: R-trees and variants, GiST, etc.
  - How about binary tree?
- Hashing-based indexes: extensible hashing, linear hashing, etc.
- Text indexes: inverted-list index, suffix arrays, etc.
- Other tricks: bitmap index, bit-sliced index, etc.