# Indexing

CPS 116

Introduction to Database Systems

## Announcements (November 8)

- ❖ Homework #3 sample solution available
- ❖ Project milestone #2 due this Thursday
  - Platform, production dataset, and performance tuning

## 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

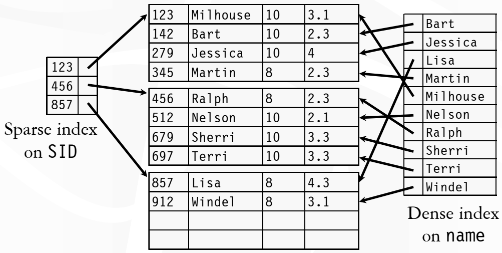
```
SELECT * FROM R WHERE A > value;
```

  - 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 | |
| 456 | |
| 857 | |

Sparse index on SID

| | | | |
|---|---|---|---|
| 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 |
| | | | |
| | | | |

| | |
|---|---|
| | Bart |
| | Jessica |
| | Lisa |
| | Martin |
| | Milhouse |
| | Nelson |
| | Ralph |
| | Sherri |
| | Terri |
| | Windel |

Dense index on name

## 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

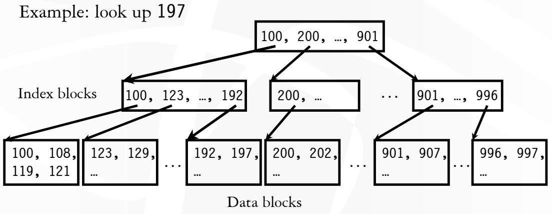
- ❖ Primary index
  - Created for the primary key of a table
  - Records are usually clustered according to the primary key
  - Can be sparse
- ❖ Secondary index
  - Usually dense
- ❖ SQL
  - PRIMARY KEY declaration automatically creates a primary index, UNIQUE key automatically creates a secondary index
  - Additional secondary index can be created on non-key attribute(s)

```
CREATE INDEX StudentGPAIndex ON Student(GPA);
```

# ISAM

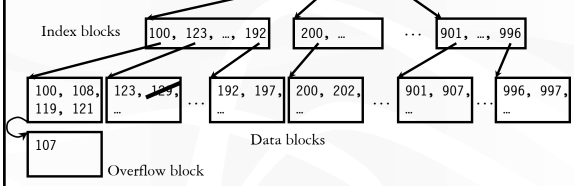
- ❖ What if an index is still too big?
  - ▪ Put a another (sparse) index on top of that!
  - ☞ISAM (Index Sequential Access Method), more or less

Example: look up 197



# Updates with ISAM

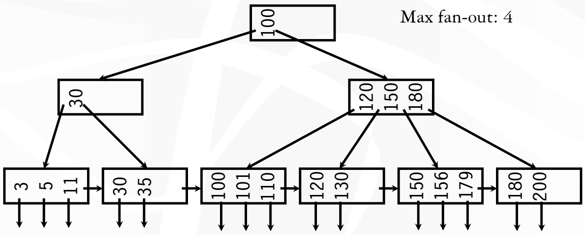
Example: insert 107
Example: delete 129



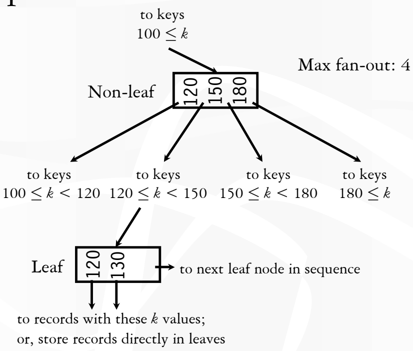
- ❖ Overflow chains and empty data blocks degrade performance
  - ▪ Worst case: most records go into one long chain

# B$^+$-tree

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



# Sample B$^+$-tree nodes



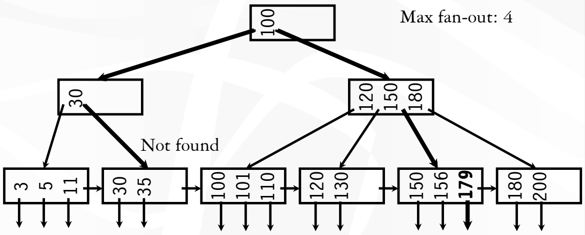
# B$^+$-tree balancing properties

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

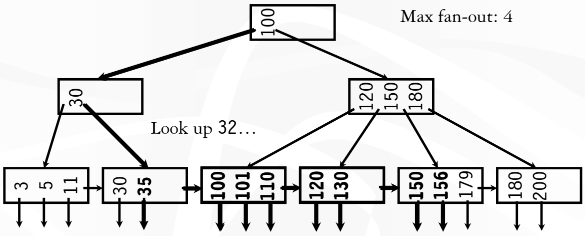
# Lookups

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



# Range query

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



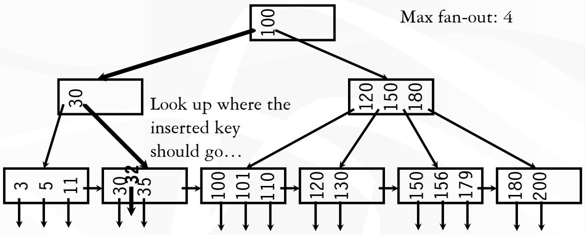
Max fan-out: 4

Look up 32…

And follow next-leaf pointers

# Insertion

- Insert a record with search key value 32



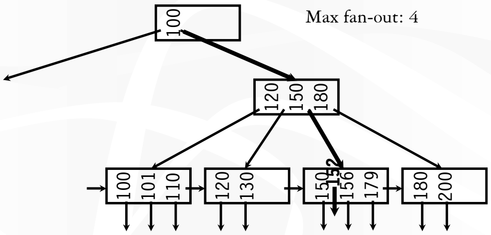
Max fan-out: 4

Look up where the inserted key should go…

And insert it right there

# Another insertion example

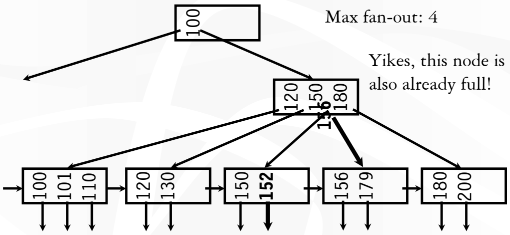
- Insert a record with search key value 152



Max fan-out: 4

Oops, node is already full!

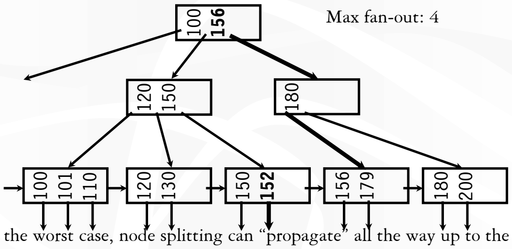
# Node splitting



Max fan-out: 4

Yikes, this node is also already full!

# More node splitting

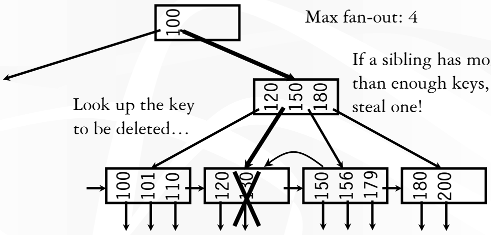


Max fan-out: 4

- 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

# Deletion

- Delete a record with search key value 130



Max fan-out: 4

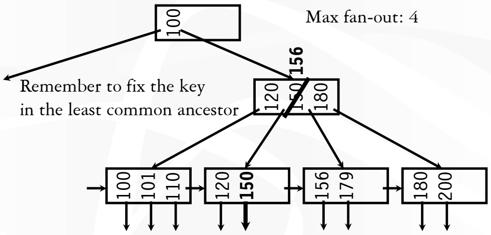
If a sibling has more than enough keys, steal one!

Look up the key to be deleted…

And delete it

Oops, node is too empty!

## Stealing from a sibling

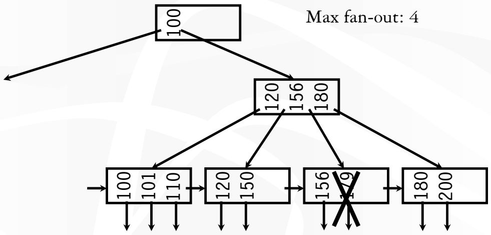


Max fan-out: 4

Remember to fix the key
in the least common ancestor

## Another deletion example

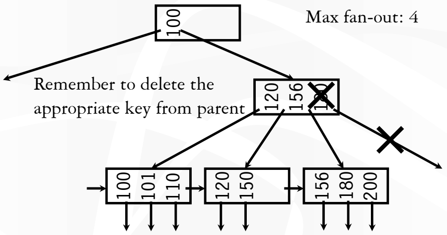
- ❖ Delete a record with search key value 179



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

## $B^+$-tree versus ISAM

- ISAM is more static; $B^+$-tree is more dynamic
- ISAM is 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 indexs: R-trees and variants, GiST, etc.
- Hashing-based indexes: extensible hashing, linear hashing, etc.
- Text indexes: inverted-list index, suffix arrays, etc.
- Other tricks: bitmap index, bit-sliced index, etc.