Database Technology

Topic 7: Data Structures for Databases

Olaf Hartig

olaf.hartig@liu.se

LINKÖPING UNIVERSITY

Database System

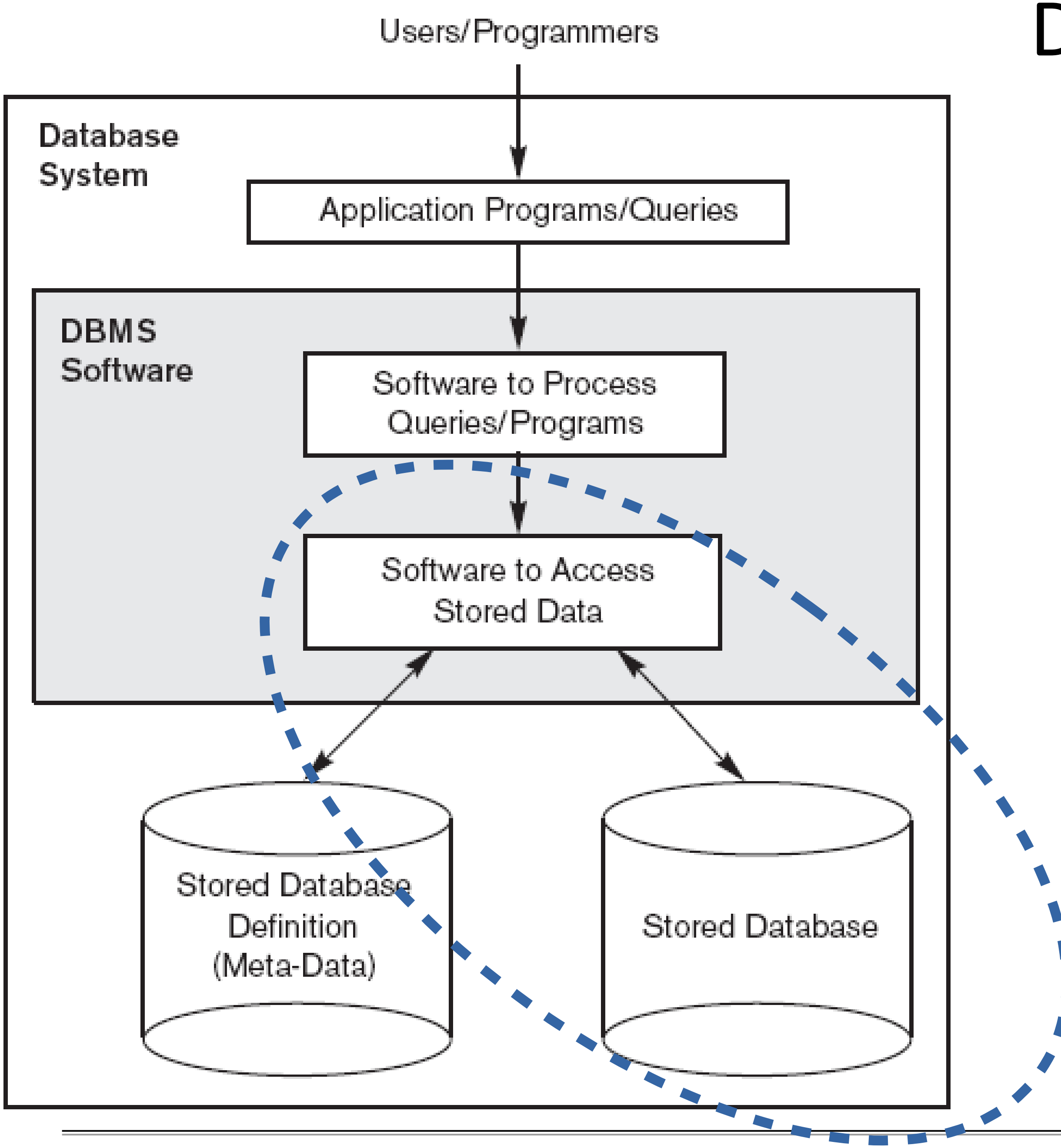
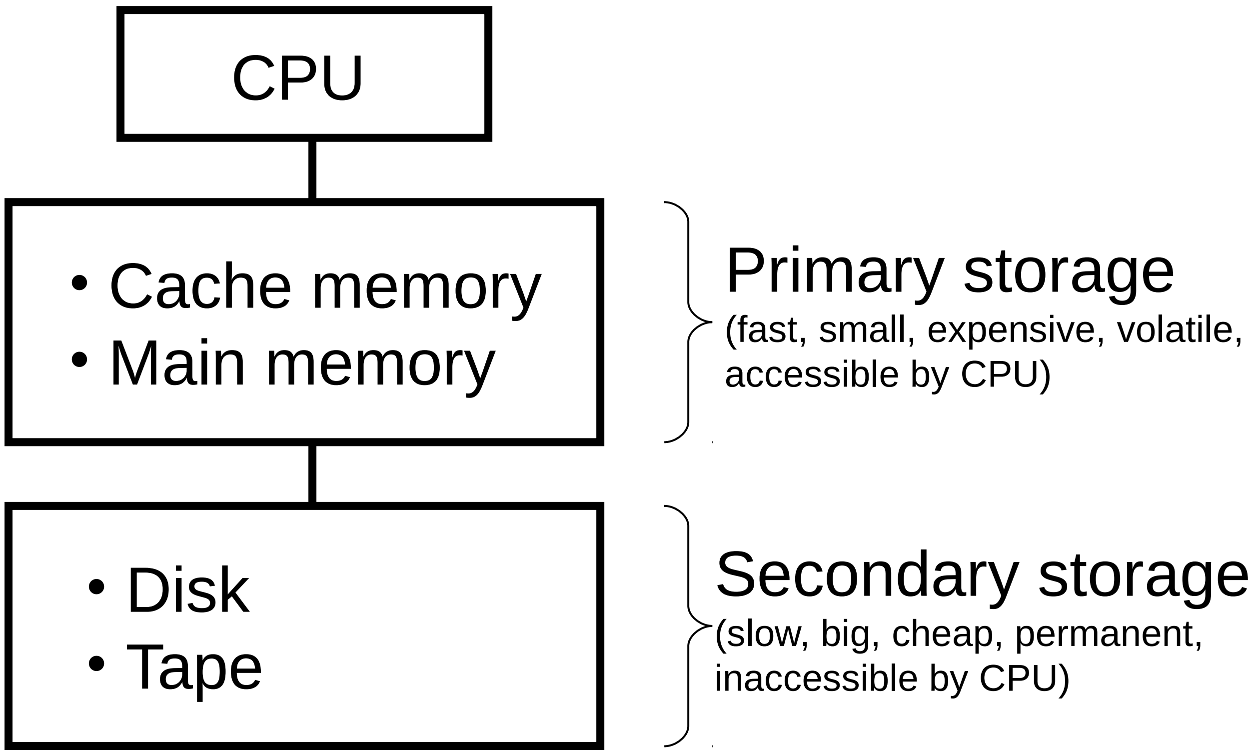


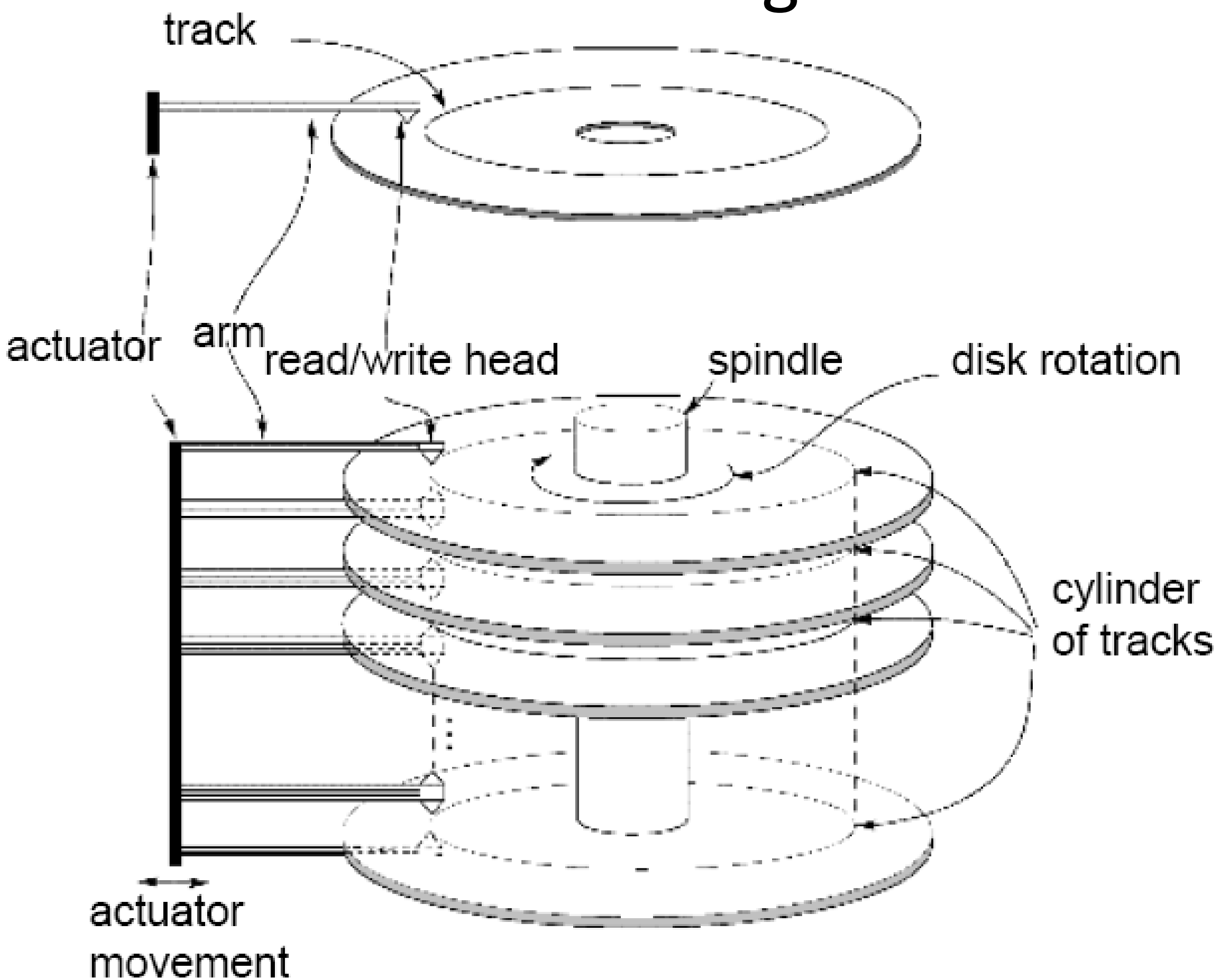
Figure 1.1
A simplified database system environment.

Storage Hierarchy

Traditional Storage Hierarchy



Magnetic Disk



Properties of Using Magnetic Disks

- Formatting divides the hard-coded sector into equal-sized blocks
  - Block is the unit of data transfer between disk and main memory
  - Typical block sizes: 512 – 8192 bytes
- Read/write from/to disk is a major bottleneck!

$$\textit{R/W time} = \underbrace{\underset{\textit{(search track)}}{\textit{seek time}} + \underset{\textit{(search block)}}{\textit{rotational delay}} + \textit{block transfer time}}_{\textit{12–60 ms}}$$

  - CPU instruction: ca. 1 ns (10^{-9} secs)
  - Main memory access: ca. 10 ns (10^{-8} secs)
  - Disk access: ca. 1 ms (1M ns, 10^{-3} secs)

Files and Records

Terminology

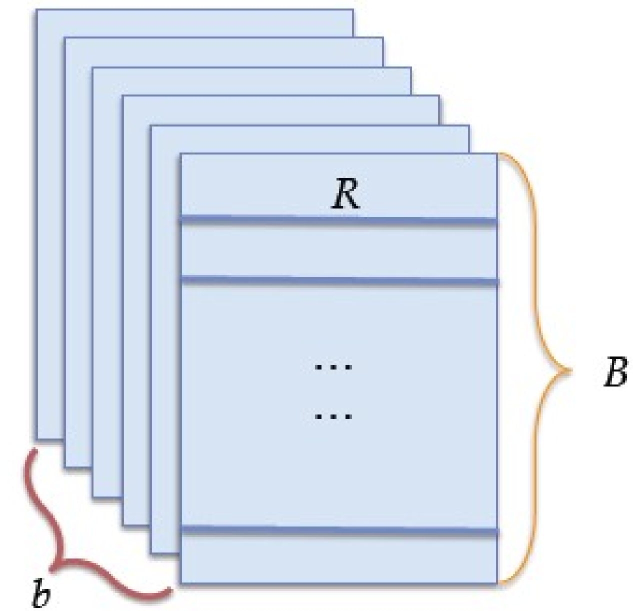
- Data stored in files
- File is a sequence of records
- Records are allocated to file blocks
- Record is a set of field values
- For instance,
  - File = relation
  - Record = row
  - Field = attribute value

Blocking Factor

- Blocking factor (*bfr*) is the number of records per block
- Assume
  - r is the number of records in a file,
  - R is the size of a record, and
  - B is the block size in bytes,

  then:

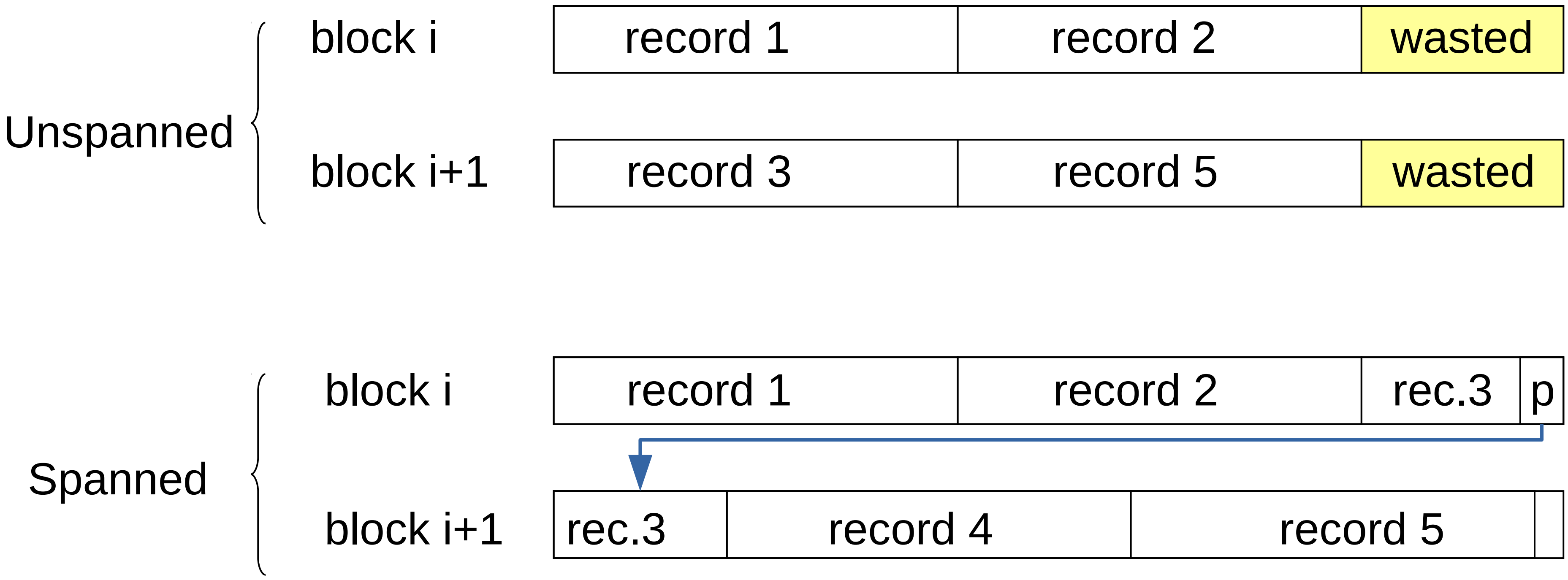
$$bfr = \left\lfloor \frac{B}{R} \right\rfloor$$



- Blocks needed to store the file: $b = \left\lceil \frac{r}{bfr} \right\rceil$
- Space wasted per block = $B - bfr * R$

Spanned Records

… avoid wasting space



Allocating File Blocks on Disk

- **Contiguous allocation:** file blocks allocated consecutively (one after another)
  - Fast sequential access, but expanding is difficult
- **Linked allocation:** each file block contains a pointer to the next one
  - Expanding the file is easy, but reading is slower
- **Linked clusters allocation:** hybrid of the two above
  - i.e., linked clusters of consecutive blocks
- **Indexed allocation:** index blocks contain pointers to the actual file blocks

File Organization

(Organizing Records in Files)

Heap Files

- Records are added to the end of the file
- Adding a record is cheap
- Retrieving, removing, and updating a record is expensive because it implies *linear search*
  - Average case: $\lceil \frac{b}{2} \rceil$ block accesses
  - Worst case: b block accesses

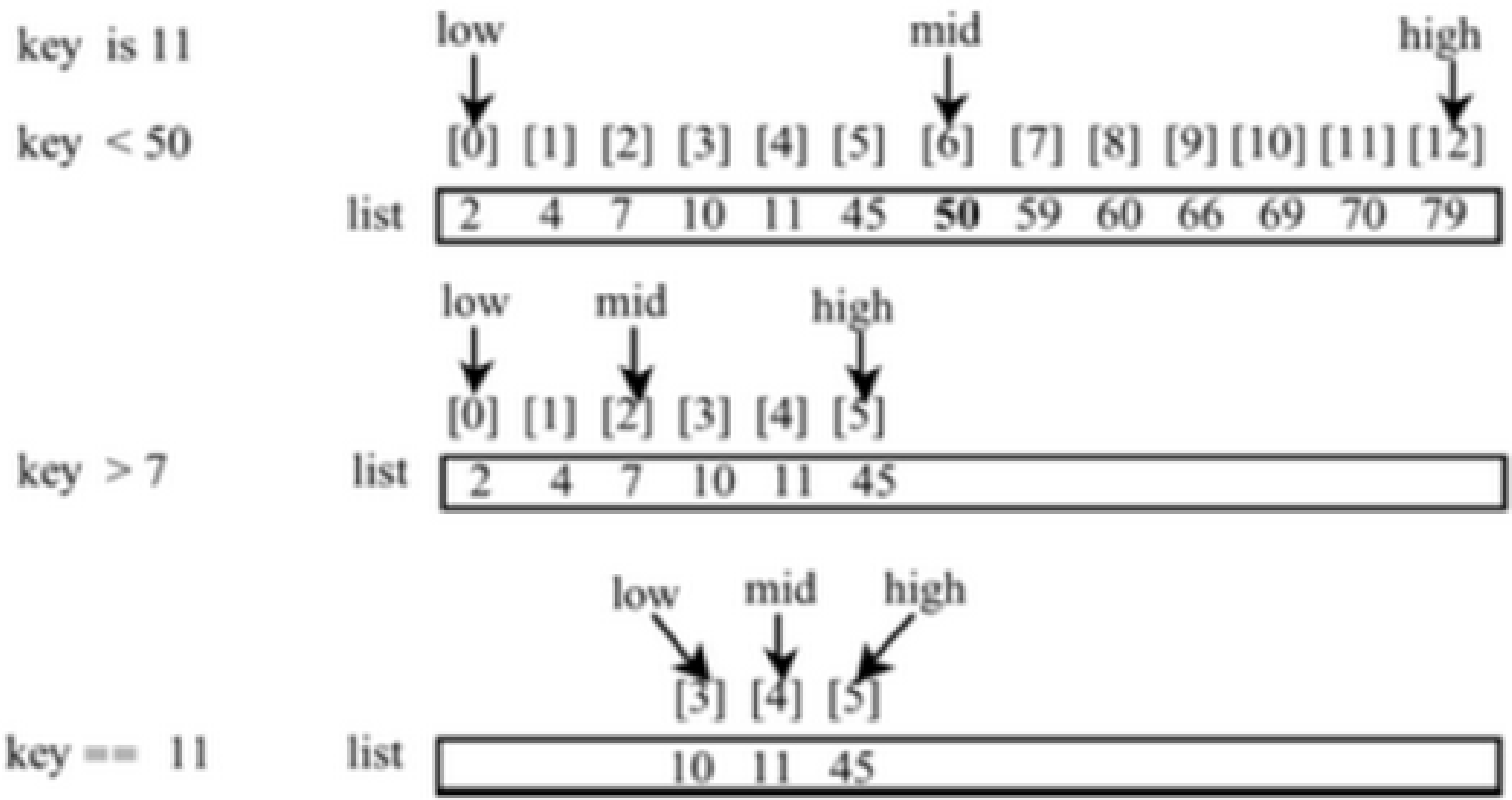
(recall, b is the number of blocks of the file)

- Record removal also implies waste of space
  - Periodic reorganization

Sorted Files

- Records ordered according to some field
- Ordered record retrieval is cheap (i.e., on the ordering field, otherwise expensive)
  - All the records: access the blocks sequentially
  - Next record: probably in the same block
  - Random record: *binary search*; hence, $\lceil \log_2 b \rceil$ block accesses in the worst case
- Adding a record is expensive, but removing is less expensive (deletion markers and periodic reorganization)

Binary Search



Internal Hashing

- Choose a field of the records to be the *hash field*
- Applying hash function h to the value x of the hash field returns the position of the record in the file
  - e.g., $h(x) = x \bmod r$

    (recall, r is the number of records in the file)
- Collision: different field values hash to same position
- Solutions to deal with collisions (*collision resolution*):
  - Check subsequent positions until one is empty
  - Use a second hash function
  - Put the record in an overflow area and link it

External Hashing

- Hashing for disk files
- Applying hash function to the value of the hash field returns a bucket number (instead of a position)
  - Bucket: one or several contiguous disk blocks
  - Table converts bucket number into address of block
- Collisions are typically resolved via overflow area
- Cheapest random retrieval (when searching for equality)
- Ordered record retrieval is expensive

Indexes

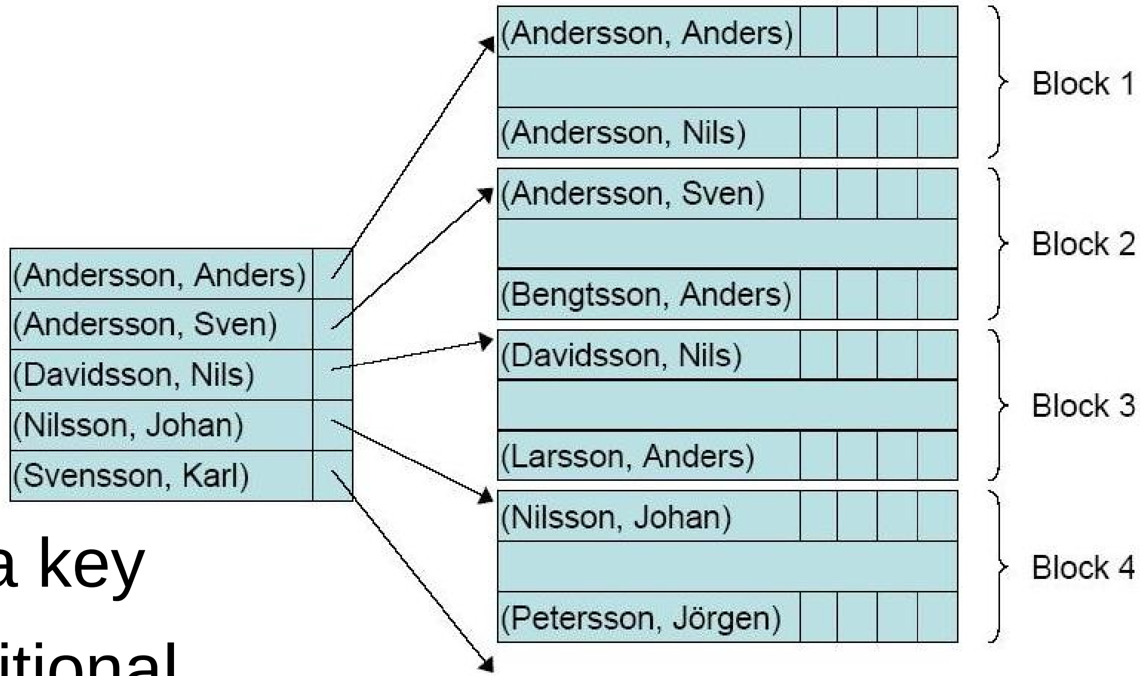
(Secondary Access Methods)

Overview

- Seen so far: file organization
  - Analogous to organization of books into chapters, sections, etc.
  - Determines primary method to access data in a file
    - e.g., sequential search, binary search
- Now: index structures
  - Allow for secondary access methods
  - Analogous to the index of a book
  - Goal: speed up access under specific conditions
  - Outline:
    1) Single-level ordered indexes (primary, secondary, and clustering indexes)
    2) Multilevel indexes
    3) Dynamic multilevel indexes (B+-trees)

Single-Level Ordered Indexes

Primary Index

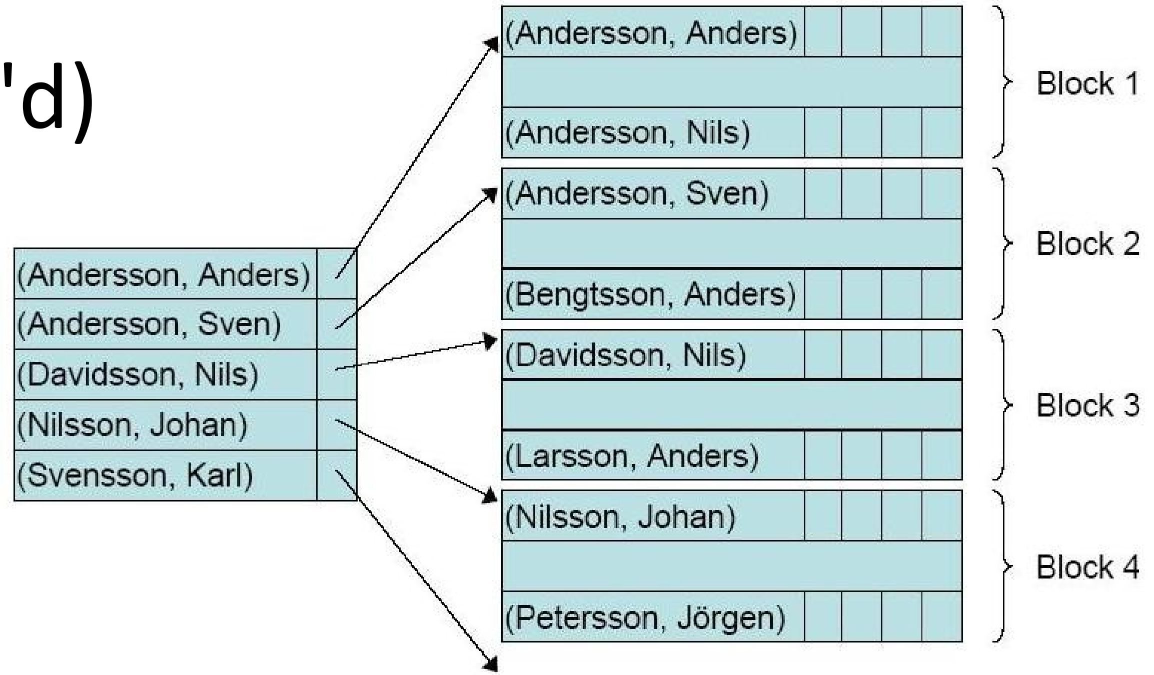


- Assumptions:
  - Data file is sorted
  - Ordering field *F* is a key
- Primary index: an additional *sorted file* whose records contain two fields:

  V - one of the values of *F*

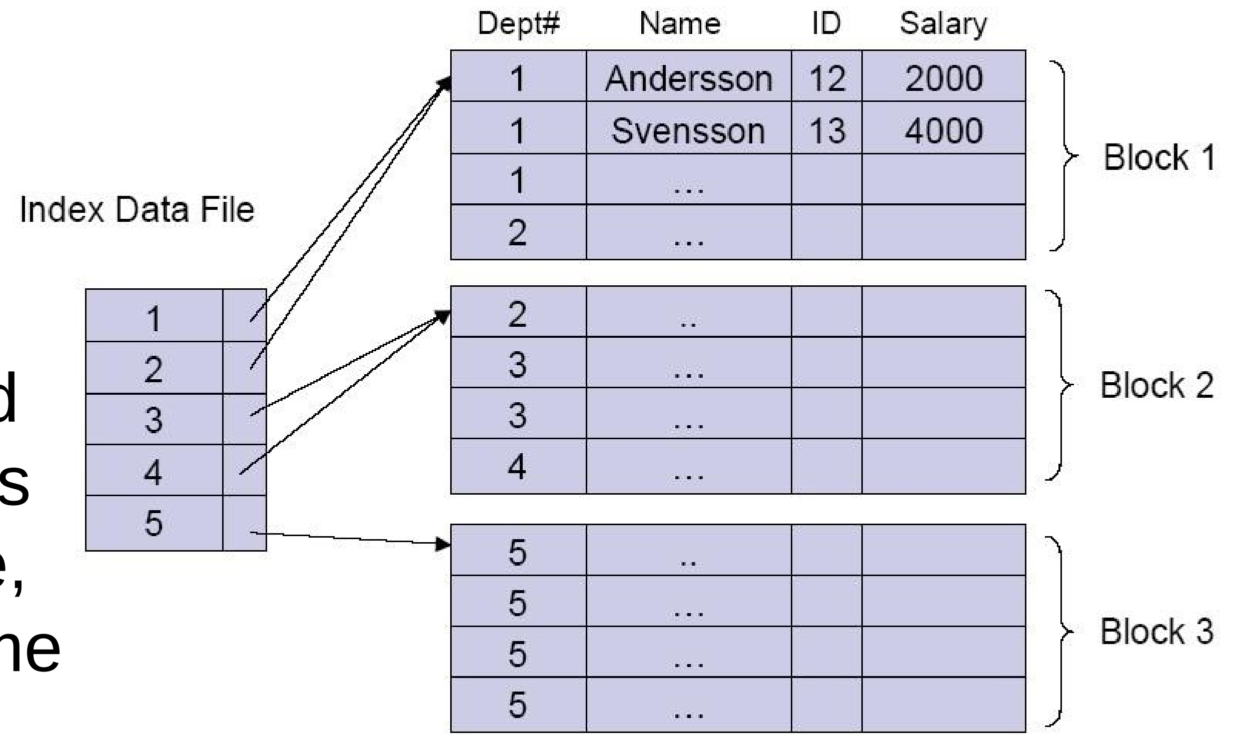
  P - pointer to a disk block of the data file
- One index record (*V*,*P*) per data block such that the first data record in the data block pointed to by *P* has *V* as the value of the ordering key *F*

Primary Index (cont'd)



- Why is it faster to access a random record via a binary search in the index than in the data file?
  - Number of index records << number of data records
  - Index records smaller than data records (i.e., higher blocking factor for the index file than for the data file)
- What is the cost of maintaining a primary index? (if the order of the data records changes)

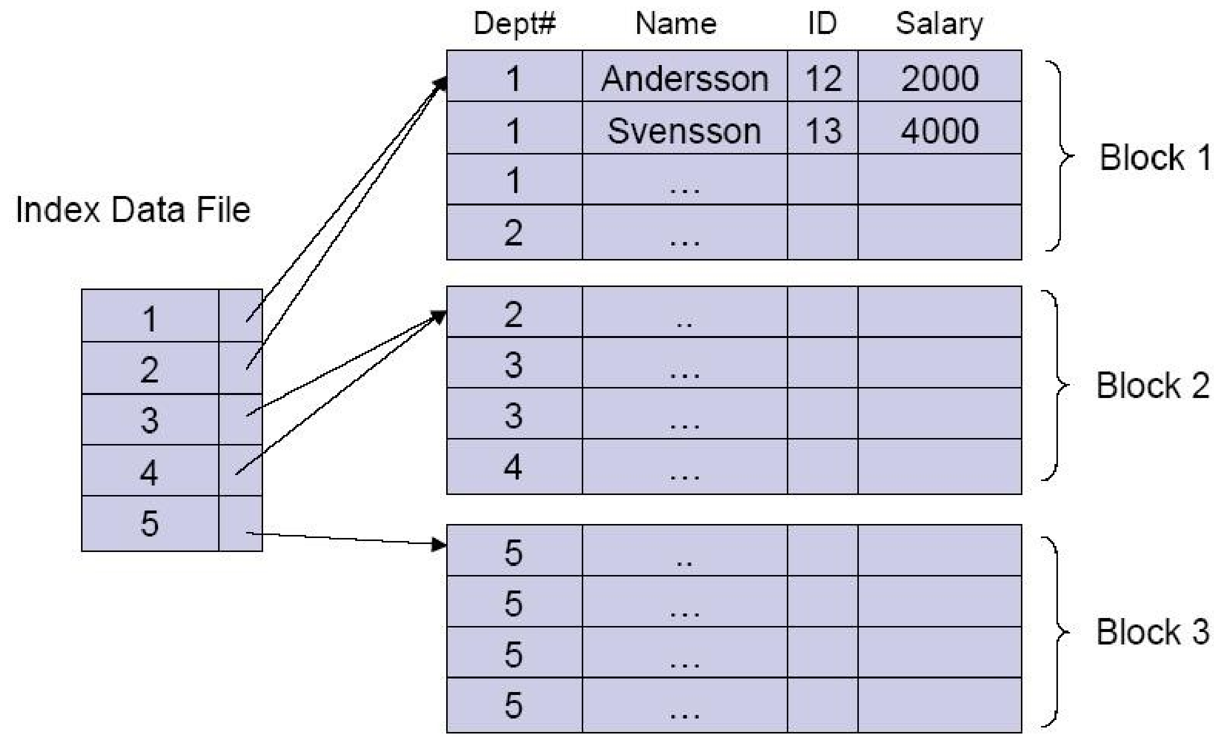
Clustering Index



- Assumptions:
  - Data file is sorted
  - Ordering field *F* is **not** a key (hence, we cannot assume distinct values)
- Clustering index: additional *sorted file* whose records contain two fields:
  V - one of the values of *F*
  P - pointer to a disk block of the data file
- One index record (*V*,*P*) for each distinct value *V* of the ordering field *F* such that *P* points to the first data block in which *V* appears

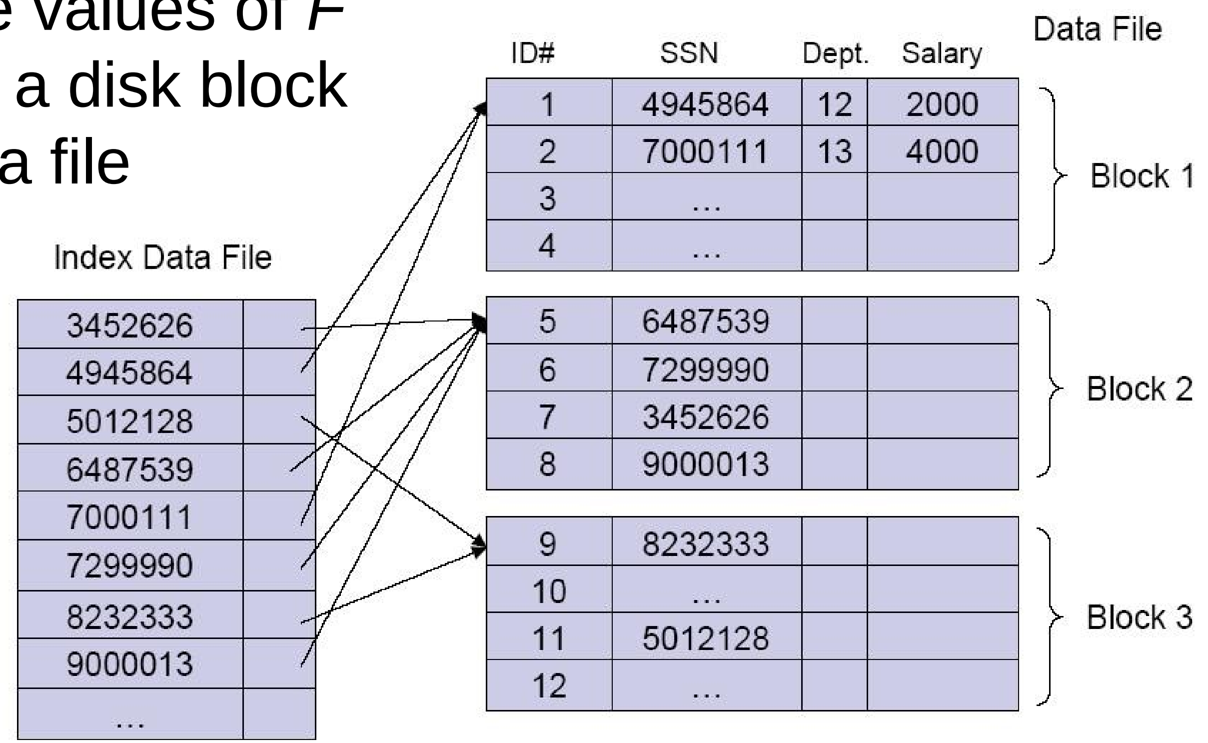
Clustering Index

- Efficiency gain?
- Maintenance cost?



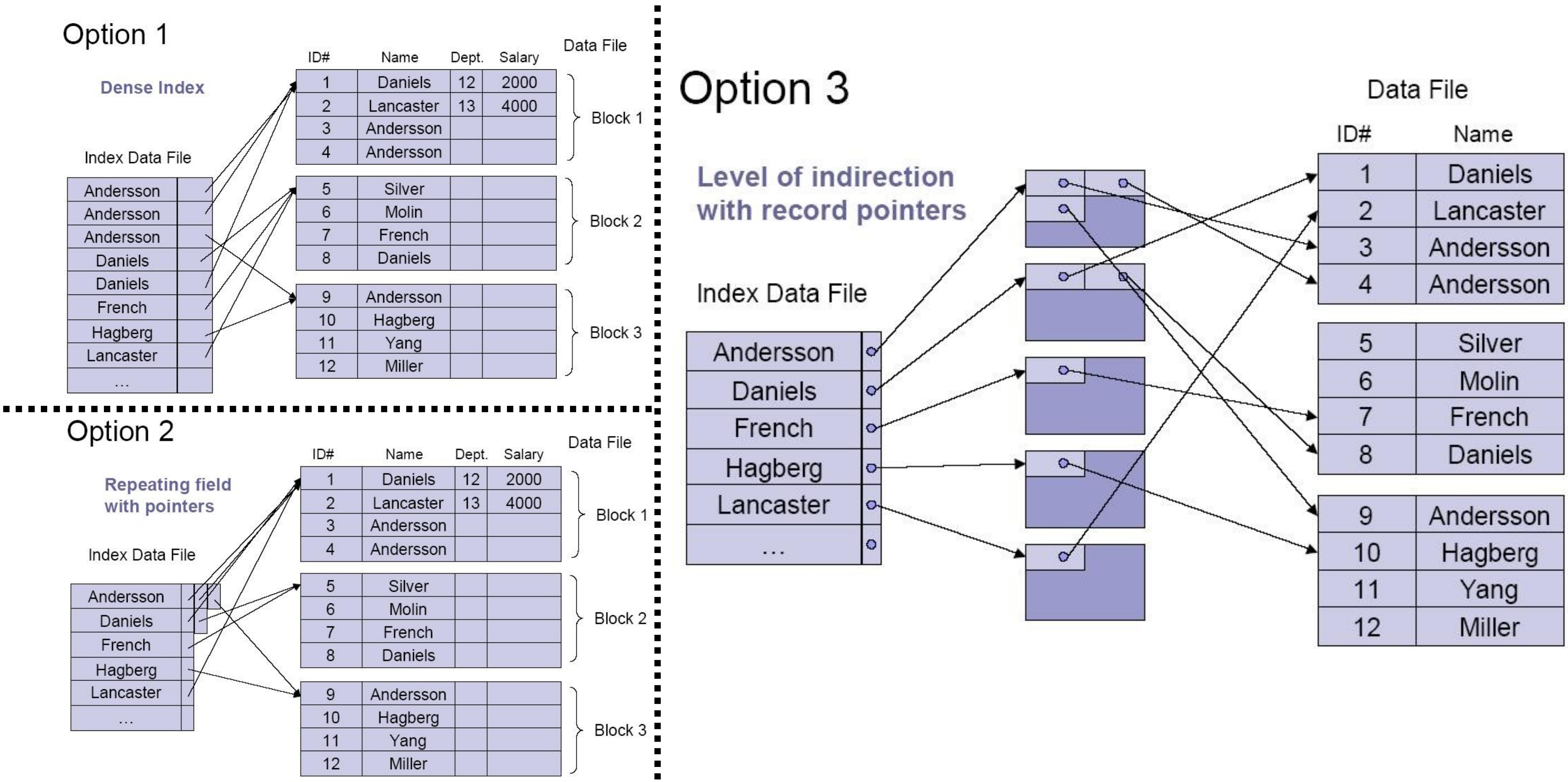
Secondary Indexes on Key Field

- Index on a *non*-ordering *key* field *F*
  - Data file may be sorted or not
- Secondary index: additional *sorted* file whose records contain two fields:
  - *V* - one of the values of *F*
  - *P* - pointer to a disk block of the data file
- One index record per data record



Secondary Indexes on Non-Key

- Index on a *non*-ordering *non*-key field



Summary of Single-Level Indexes

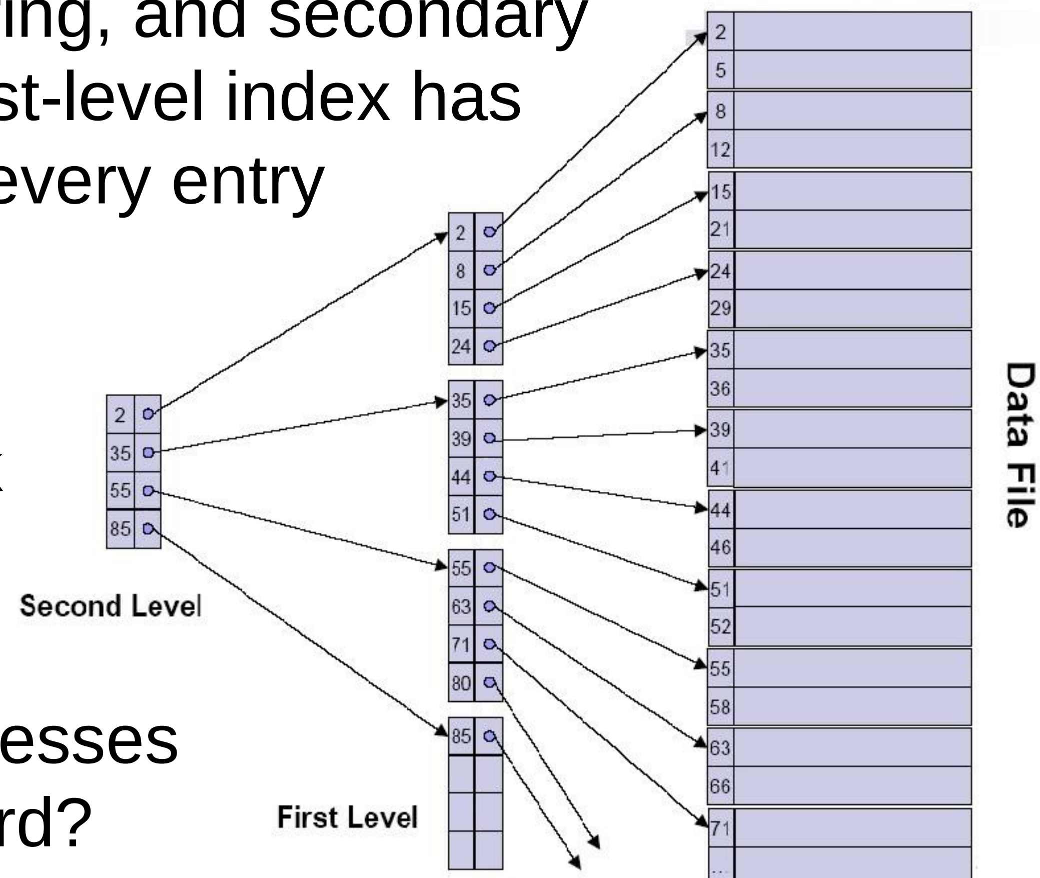
	Index field used for ordering the data file	**Index field *not* used for ordering the data file**
Index field is key	Primary index	Secondary index (key)
Index field is not key	Clustering index	Secondary index (non-key)

Type of index	**Number of index entries**
Primary	Number of blocks in data file
Clustering	Number of distinct index field values
Secondary (key)	Number of record in data file
Secondary (non-key)	Number of records or number of distinct index field values

Multilevel Indexes

Multilevel Indexes

- Index on index (first level, second level, etc.)
- Works for primary, clustering, and secondary indexes as long as the first-level index has a distinct index value for every entry
- How many levels?
  - Until the last level fits into a single disk block
- How many disk block accesses to retrieve a random record?
  - Number of index levels + 1



Multilevel Indexes (cont'd)

- When using a (static) multilevel index, record insertion, deletion, and update may be expensive because all the index levels are *sorted* files

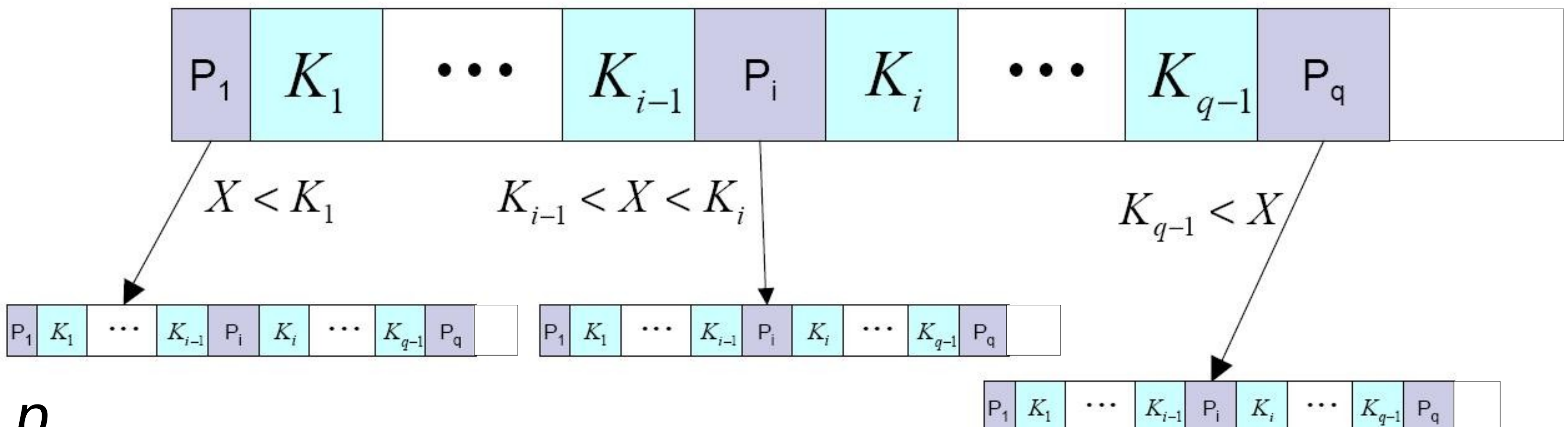
- Solutions:
  - Overflow area + periodic reorganization
  - Dynamic multilevel indexes that leave some space in index blocks for new entries (e.g., B-trees and B+-trees)

Dynamic Multilevel Indexes

(B-Trees and B+-Trees)

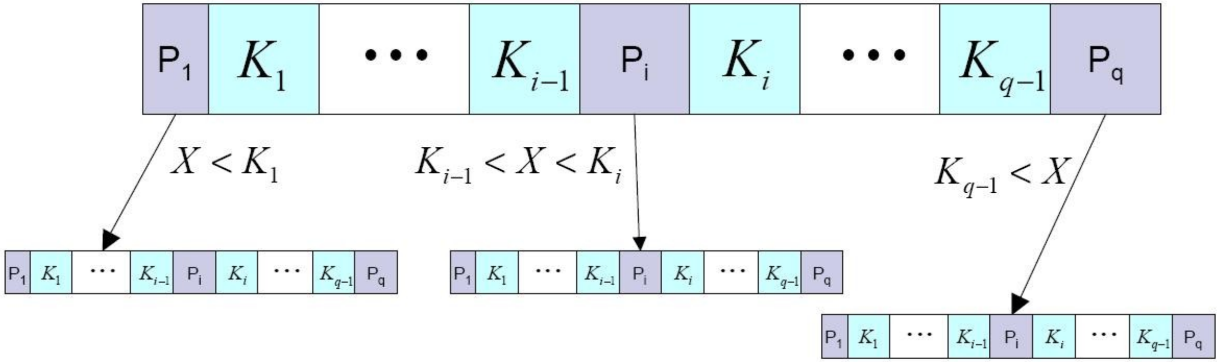
Search Trees

- Used to guide the search for a record
  - Generalization of binary search
- Nodes of a search tree of order *p* look like:



  - $q \leq p$
  - Every K_i is a key value
  - Every $\mathrm{P_i}$ is a tree pointer to a subtree (or a null pointer)
  - Within each node: $K_1 < K_2 < \ldots < K_{q-1}$
  - For every value X in the subtree: $K_{i-1} < X < K_i$

B-Trees



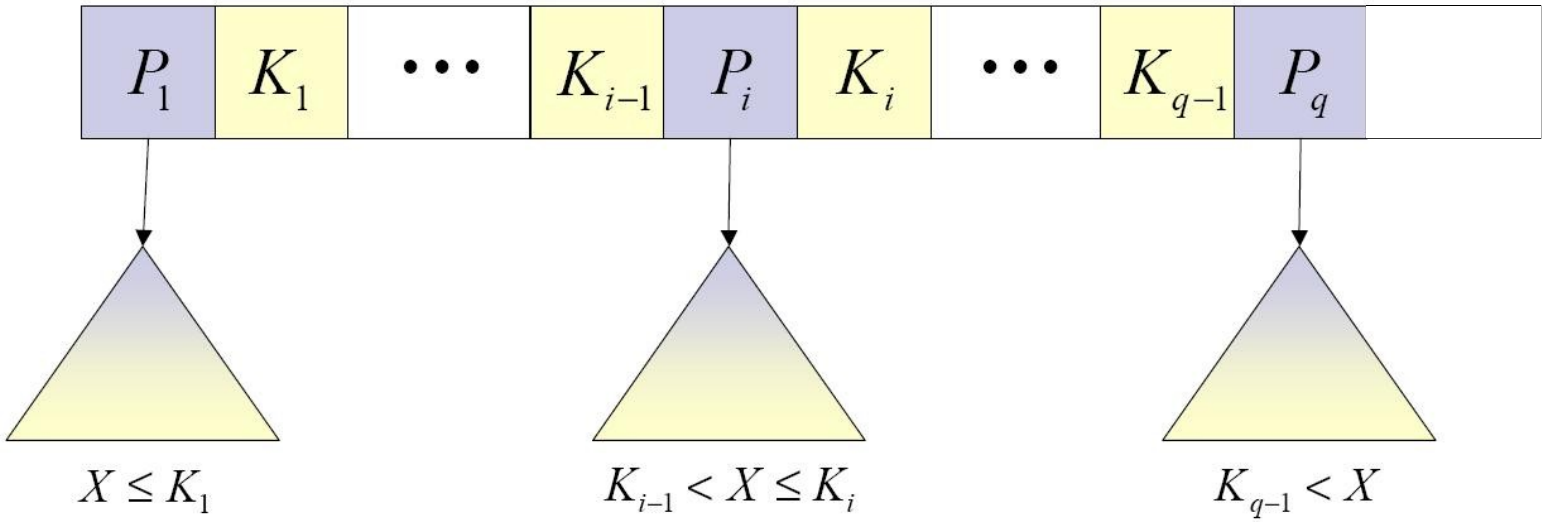
- B-tree is a variant of a *balanced* search tree
  - Balanced: all leaf nodes are at the same level (Why is this good?)

- Additional constraints:
  - In addition to a tree pointer P_i, each key value K_i is associated with a data pointer Pr_i to the record with value K_i
  - Each internal node must have at least $\lceil \frac{p}{2} \rceil$ tree pointers (i.e., is at least half full)

B+-Trees

- Variation of B-trees, most commonly used
- In contrast to a B-tree, in a B+tree the leaf nodes are different from the internal nodes; that is:
  - Internal nodes have key values and tree pointers only (no data pointers)
  - Leaves have key values and data pointers
  - Usually, each leaf node additionally has a pointer to the next leaf to allow for ordered access (much like a linked list)
- Every key value is present in one of the leaves
- Of course, B+-trees are balanced

Internal Nodes of a B+-Tree



- $q \leq p$ (where p is the order of the B+-tree)
- Every K_i is a key value, every P_i is a tree pointer
- Within each node: $K_1 < K_2 < \dots < K_{q-1}$
- For every value X in the subtree: $K_{i-1} < X \leq K_i$
- Every internal node (except the root) has at least $\lceil \frac{p}{2} \rceil$ tree pointers

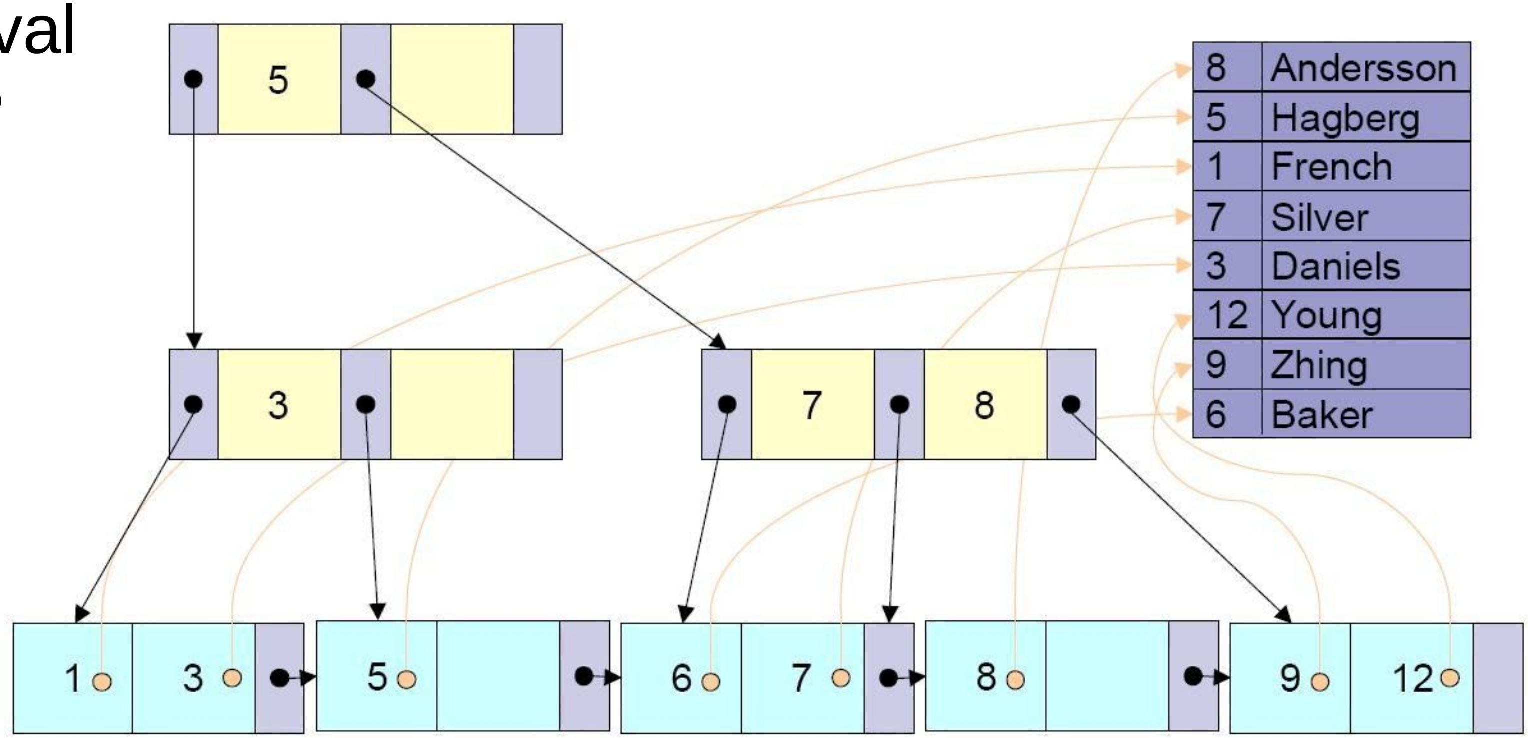
Leaf Nodes of a B+-Tree

K_1	Pr_1	…	K_i	Pr_i	…	K_q	Pr_q	P

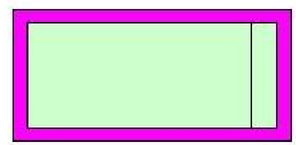
- $q \leq p$ (where p is the order for leaf nodes of the B+-tree)
- Every K_i is a key value
- Every Pr_i is a data pointer to the record with key value K_i
- P is a pointer to the next leaf node
- Within each node: $K_1 < K_2 < \ldots < K_q$
- Every leaf node has at least $\lceil \frac{p}{2} \rceil$ key values

Retrieval of Records in a B+-Tree

- Very fast retrieval of a random record, at worst: $\left\lceil \log_{\lceil \frac{p}{2} \rceil} N \right\rceil + 1$
  - p is the order of the internal nodes
  - N is the number of leaf nodes
- How would the retrieval proceed?

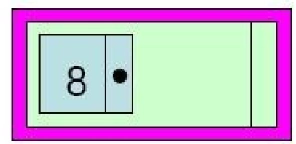


B+-Tree Insertion



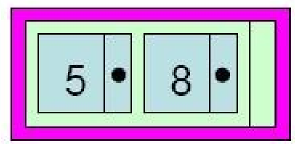
Insert: 8

B+-Tree Insertion



Insert: 5

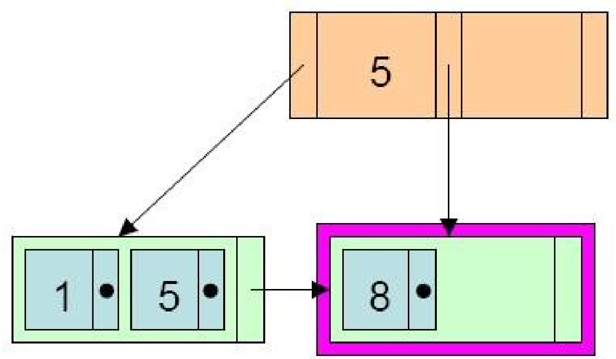
B+-Tree Insertion



Overflow – create a new level

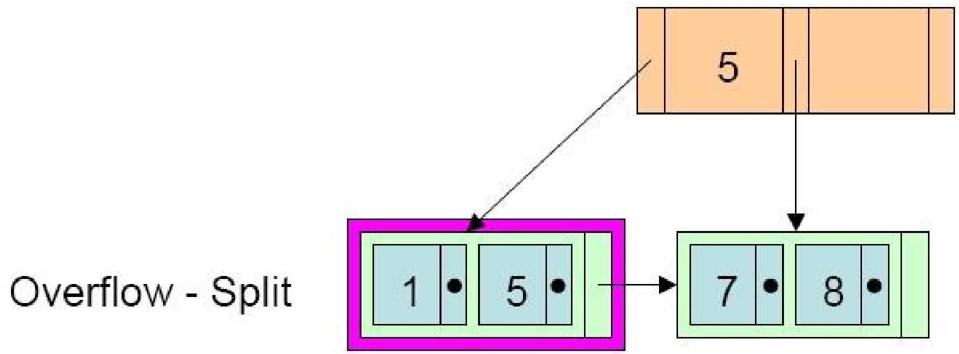
Insert: 1

B+-Tree Insertion



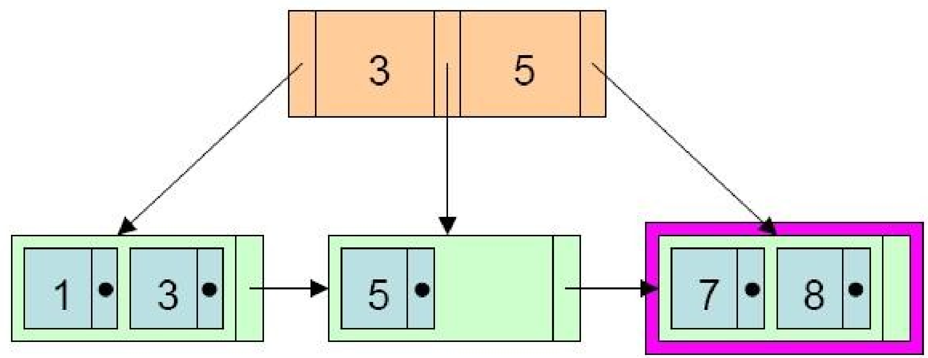
Insert: 7

B+-Tree Insertion



Insert: 3

B+-Tree Insertion

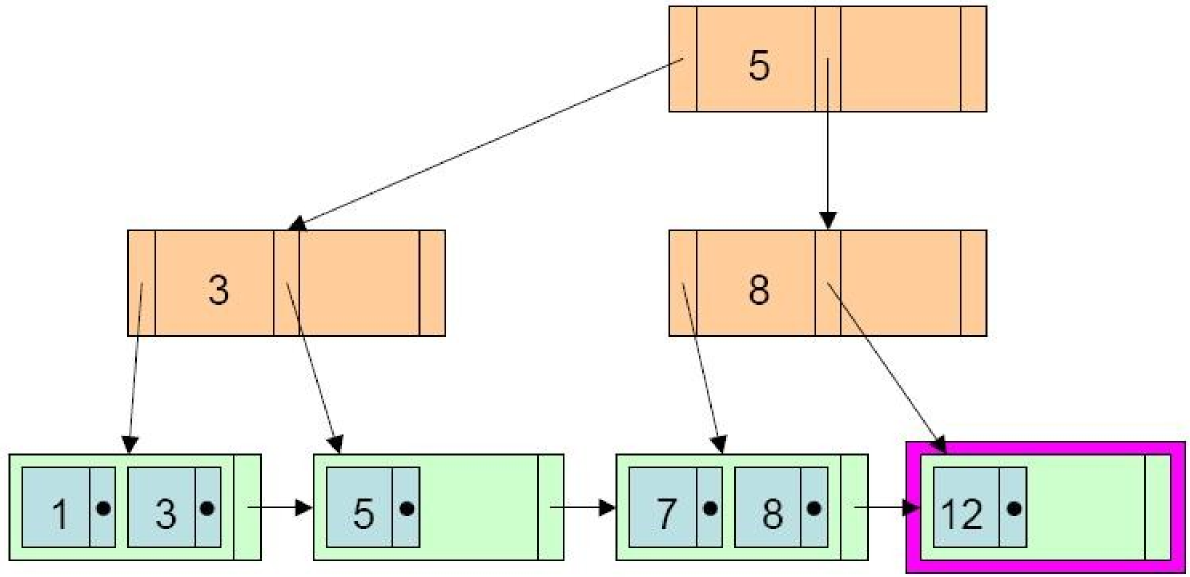


Overflow - Split

Propagates a new level

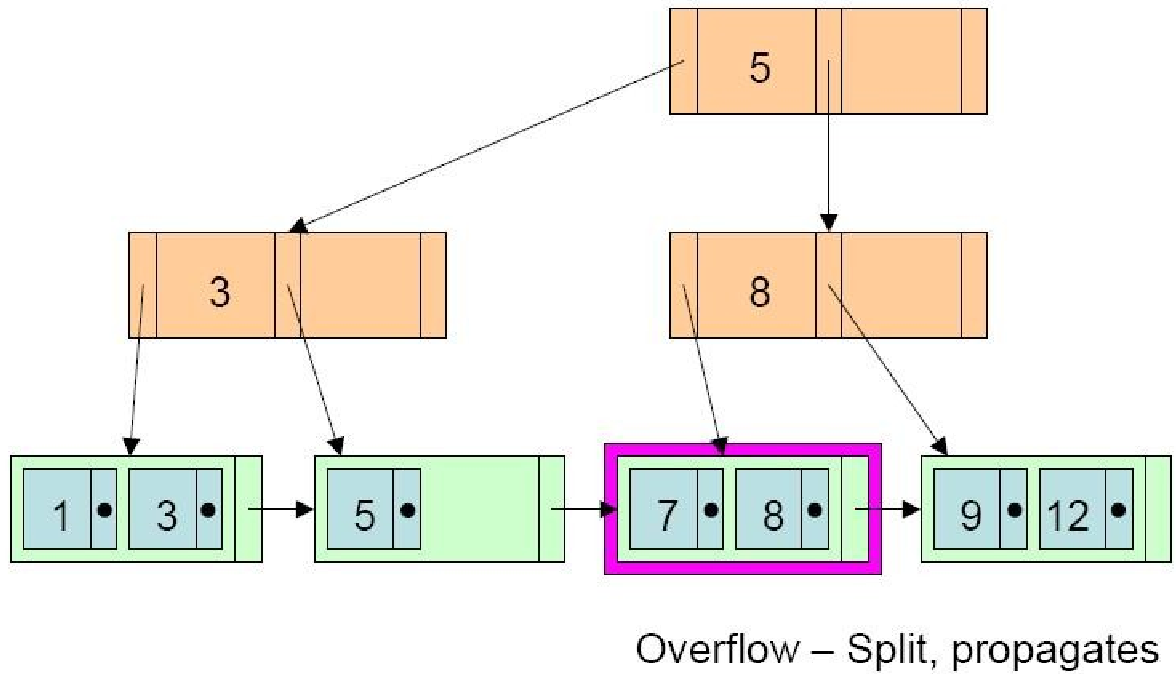
Insert: 12

B+-Tree Insertion



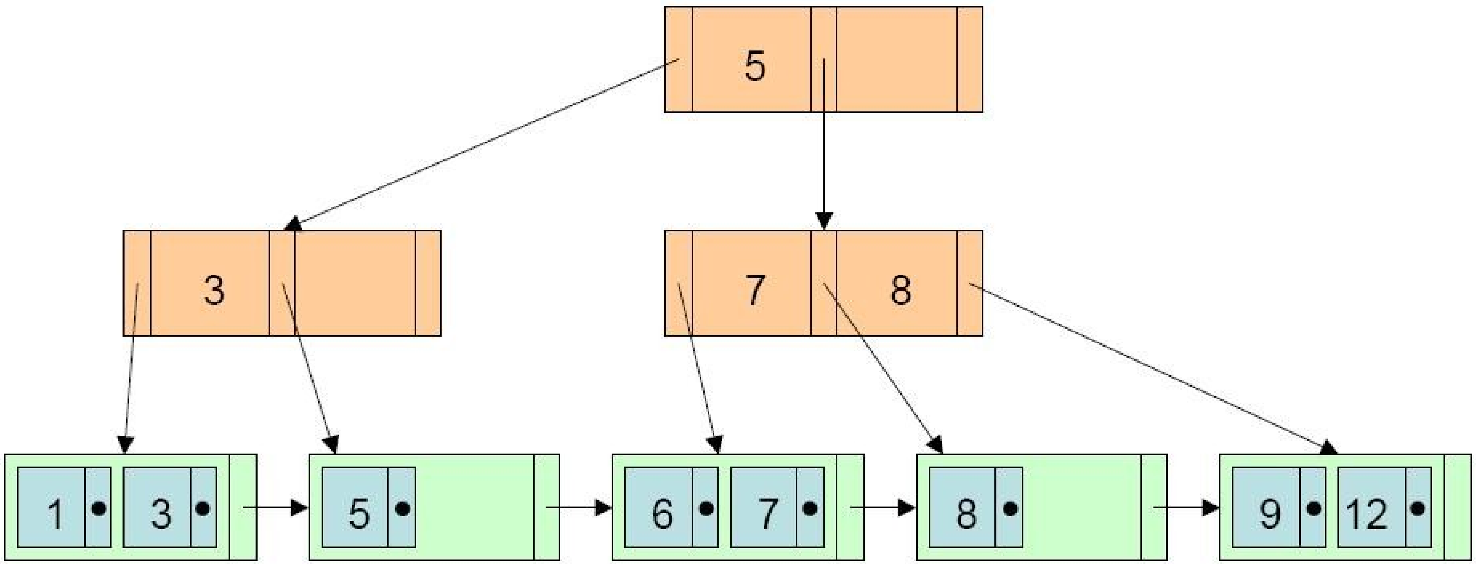
Insert: 9

B+-Tree Insertion



Insert: 6

B+-Tree Insertion



Resulting B+-tree

Summary

Summary

- Storage hierarchy
  - Accessing disk is major bottleneck
- Organizing records in files
  - Heap files, sorted files, hash files
- Indexes
  - Additional sorted files that provide efficient secondary access methods
- Primary, secondary, and clustering indexes
- Multilevel indexes
  - Retrieval requires reading fewer blocks
- Dynamic multilevel indexes
  - Leave some space in index blocks for new entries
  - B-tree and B+-tree