# Database Technology

# Topic 8: Data Structures for Databases

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# Database System

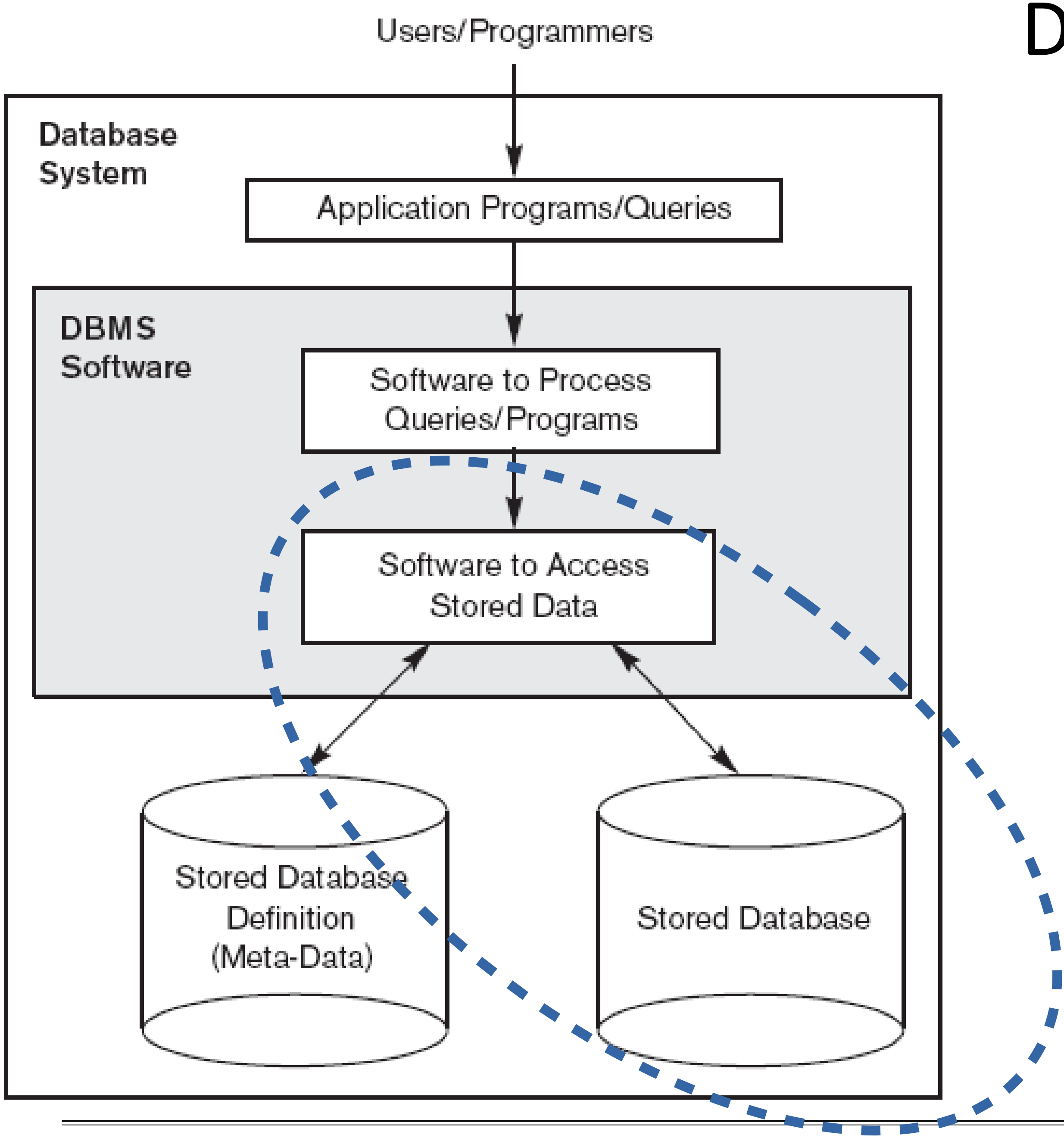
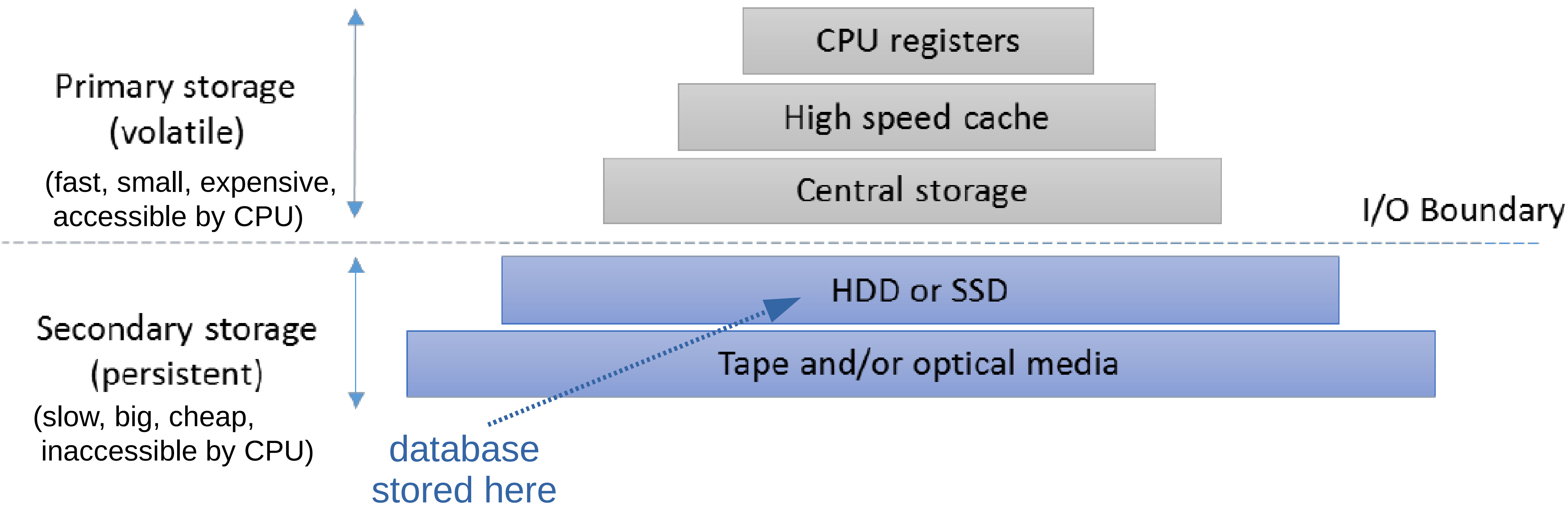



**Figure 1.1**
A simplified database system environment.

# Storage Hierarchy

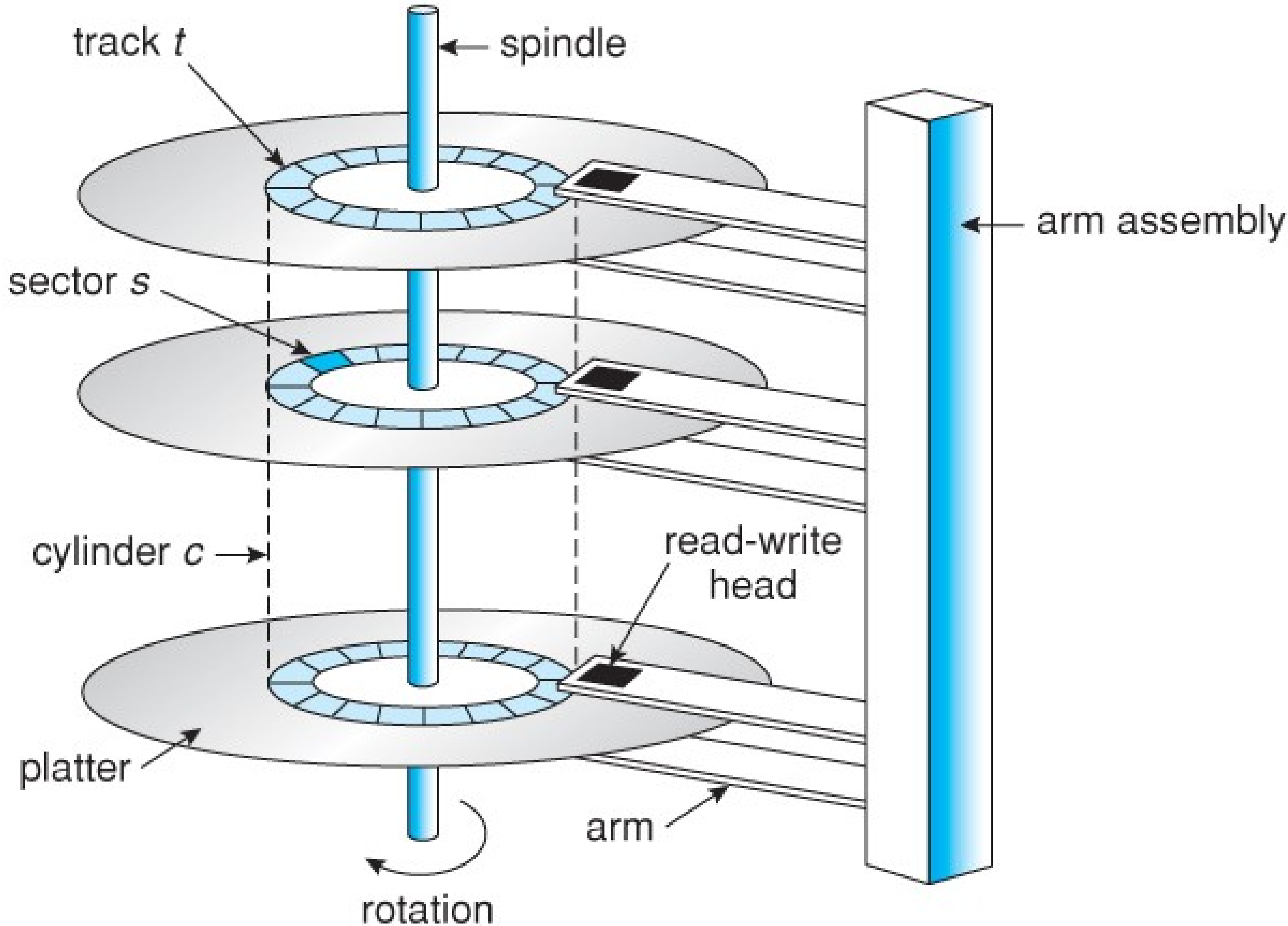
# Storage Hierarchy



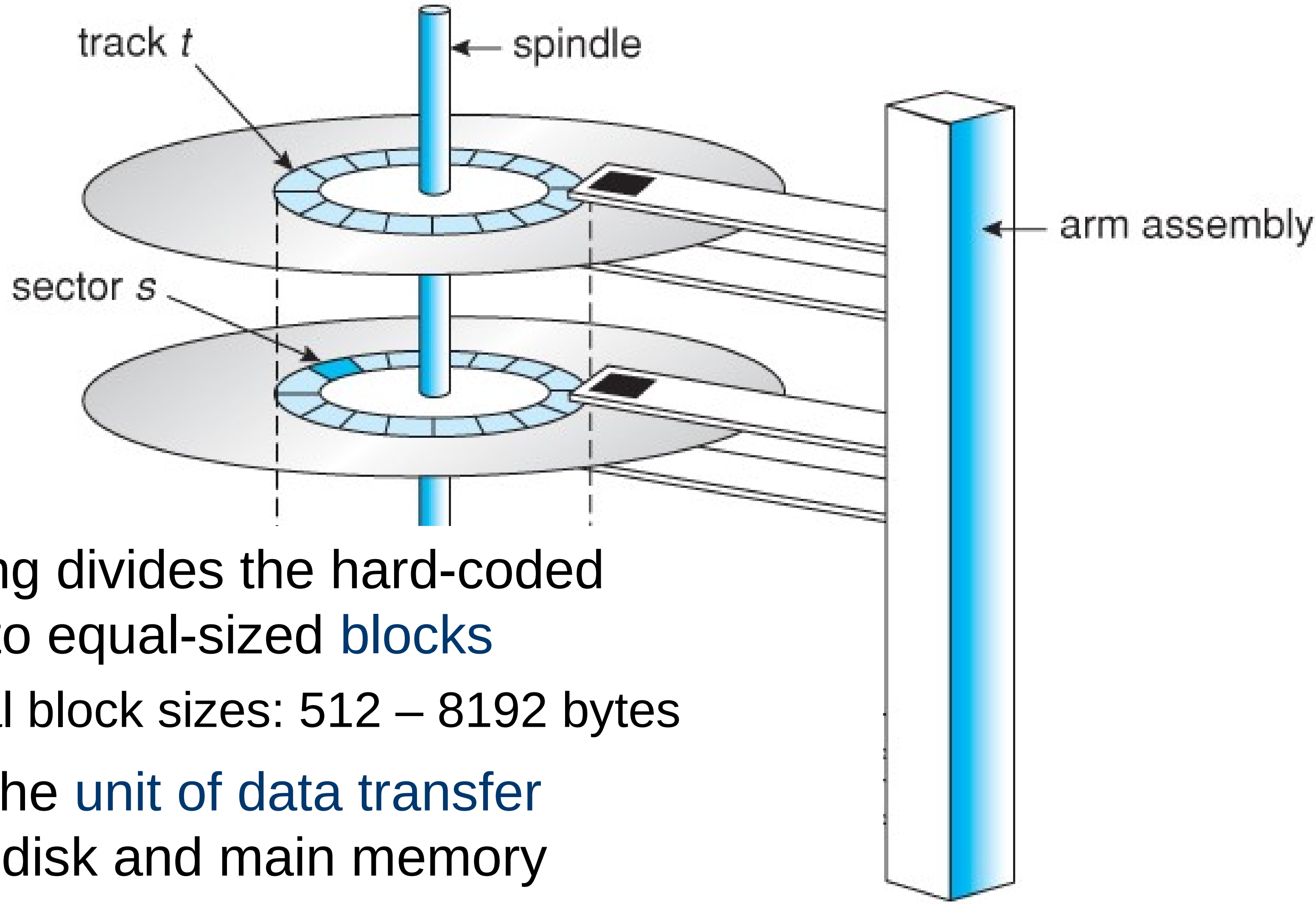

- Reading from / writing to disk is a major bottleneck!
  - CPU instruction: ca. 1 ns ($10^{-9}$ secs)
  - Main memory access: ca. 10 ns ($10^{-8}$ secs)
  - Disk access: ca. 1 ms (1M ns, $10^{-3}$ secs)

Image source: https://www.pdbmbook.com/vault/Chapter%20Physical%20File%20Organization%20and%20Indexing.pdf/access

# Magnetic Hard Disk Drives



# Magnetic Hard Disk Drives



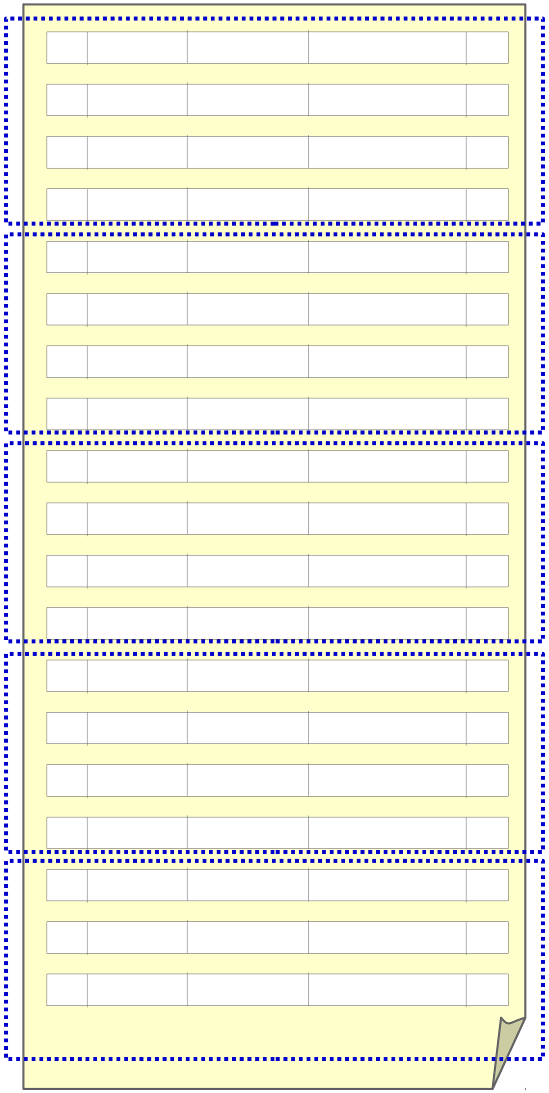

- Formatting divides the hard-coded sector into equal-sized blocks
  - Typical block sizes: 512 – 8192 bytes
- Block is the unit of data transfer between disk and main memory

# Files and Records

- Block is the unit of data transfer between disk and main memory

# Terminology

- Data stored in files
- File is a sequence of records
- Record is a set of field values
- For instance,
  - file = relation
  - record = row
  - field = attribute value



- Block is the unit of data transfer between disk and main memory
  - Records are allocated to file blocks

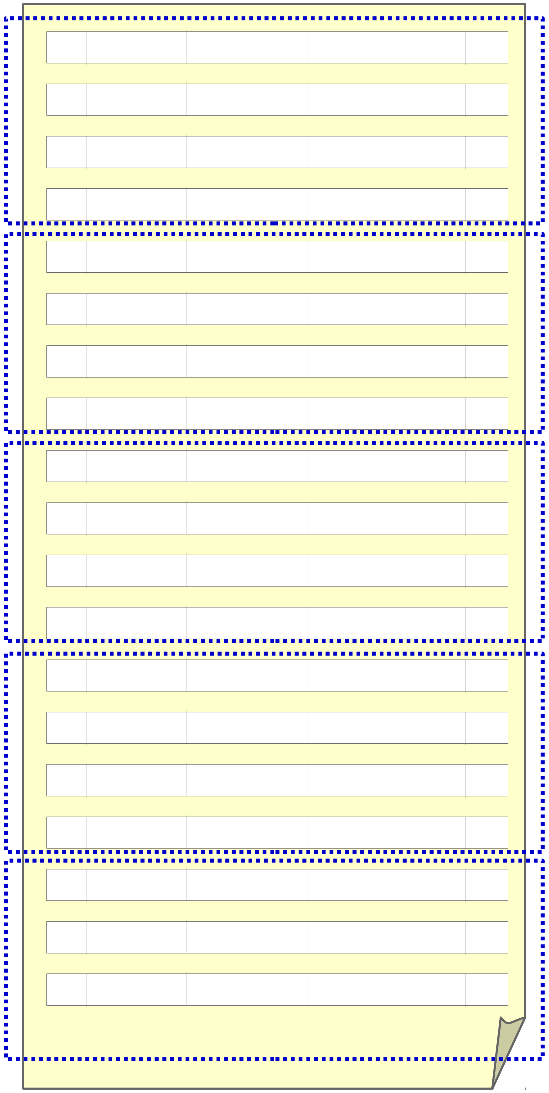
# Blocking Factor

- 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:

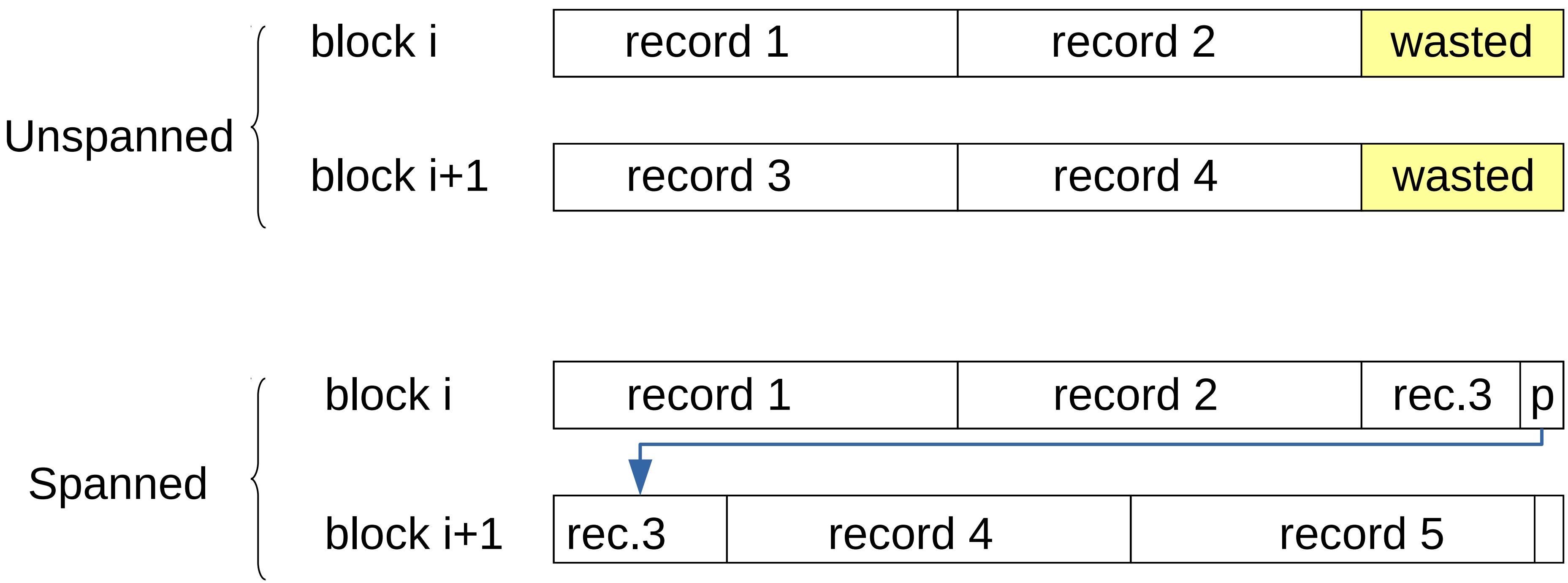
$$bfr = \left\lfloor \frac{B}{R} \right\rfloor$$

- 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: $\left\lceil \frac{b}{2} \right\rceil$ block accesses*
  - Worst case: $b$ block accesses
- Record removal also implies waste of space
  - Periodic reorganization

*recall, $b$ is the number of blocks of the file

# 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)

*recall, $b$ is the number of blocks of the file

# Hash Files

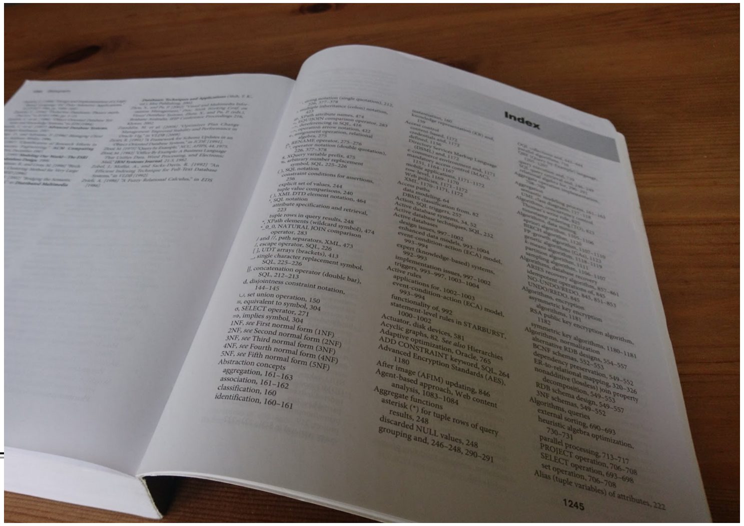
- File is logically split into "buckets"
  - Bucket: one or several contiguous disk blocks
  - Table converts bucket number into address of block
- Choose a field of the records to be the *hash field*
- Given a record, which bucket does it belong to?
  - apply hash function $h$ to the value $x$ that the record has in its hash field
  - resulting hash value $h(x)$ is the number of the bucket into which the record goes
- Cheapest random retrieval (when searching for equality)
- Ordered record retrieval is expensive

# Indexes

(Secondary Access Methods)

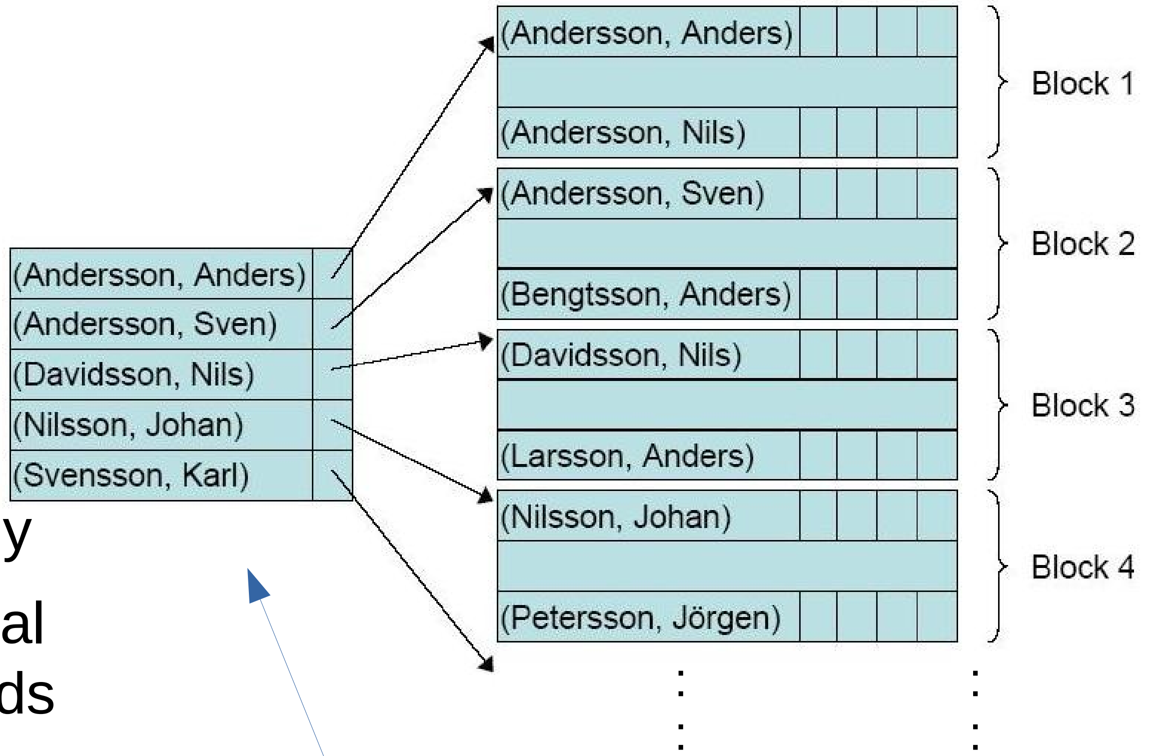
# Motivation

- File organization (heap, sorted, hash) determines primary method to access data in a file
  - e.g., sequential search, binary search, hash-based
- However, this may not be fast enough
- Solution: index files
  - introduce secondary access methods
  - goal: speed up access under specific conditions
  - there exist various types of index structures
- 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

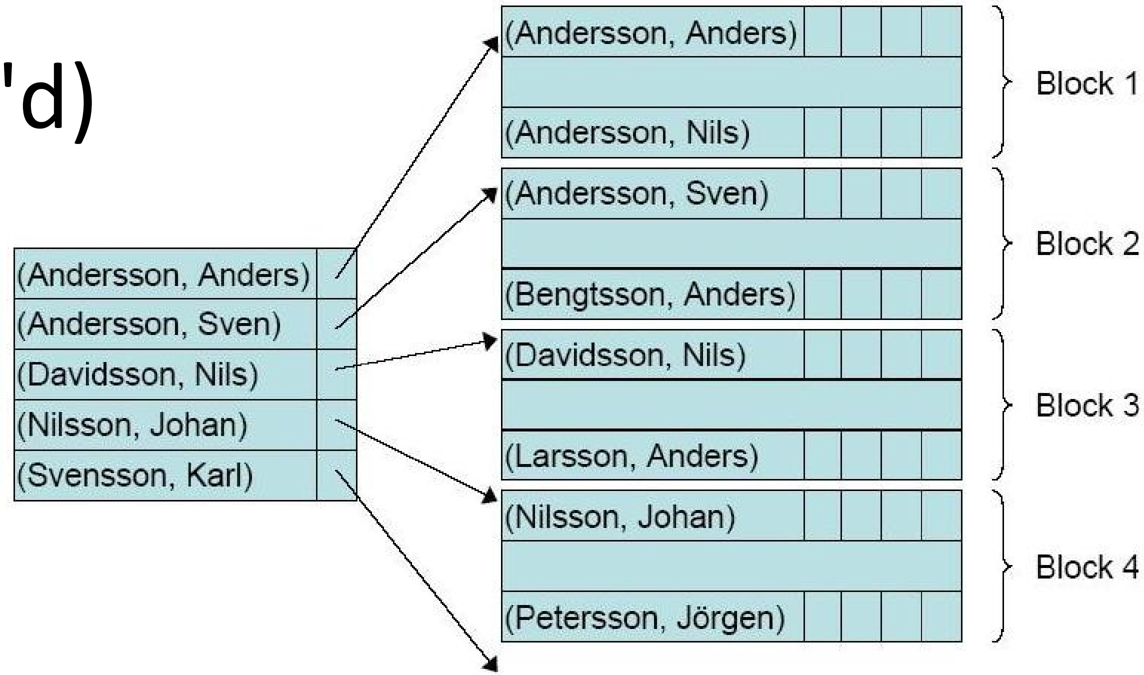



- Assumptions:
  - Data file is sorted
  - Ordering field *F* is a key
- Primary index: an additional *sorted file* whose records contain two fields:
  - *V* - one of the values of *F*
  - *P* - pointer to a disk block of the data file
- One index record (*V*,*P*) per data block such that the first data record in the data block pointed to by *P* has *V* as the value of the ordering key *F*

sorted file with all the records
- sorted by name, and
- name is a key

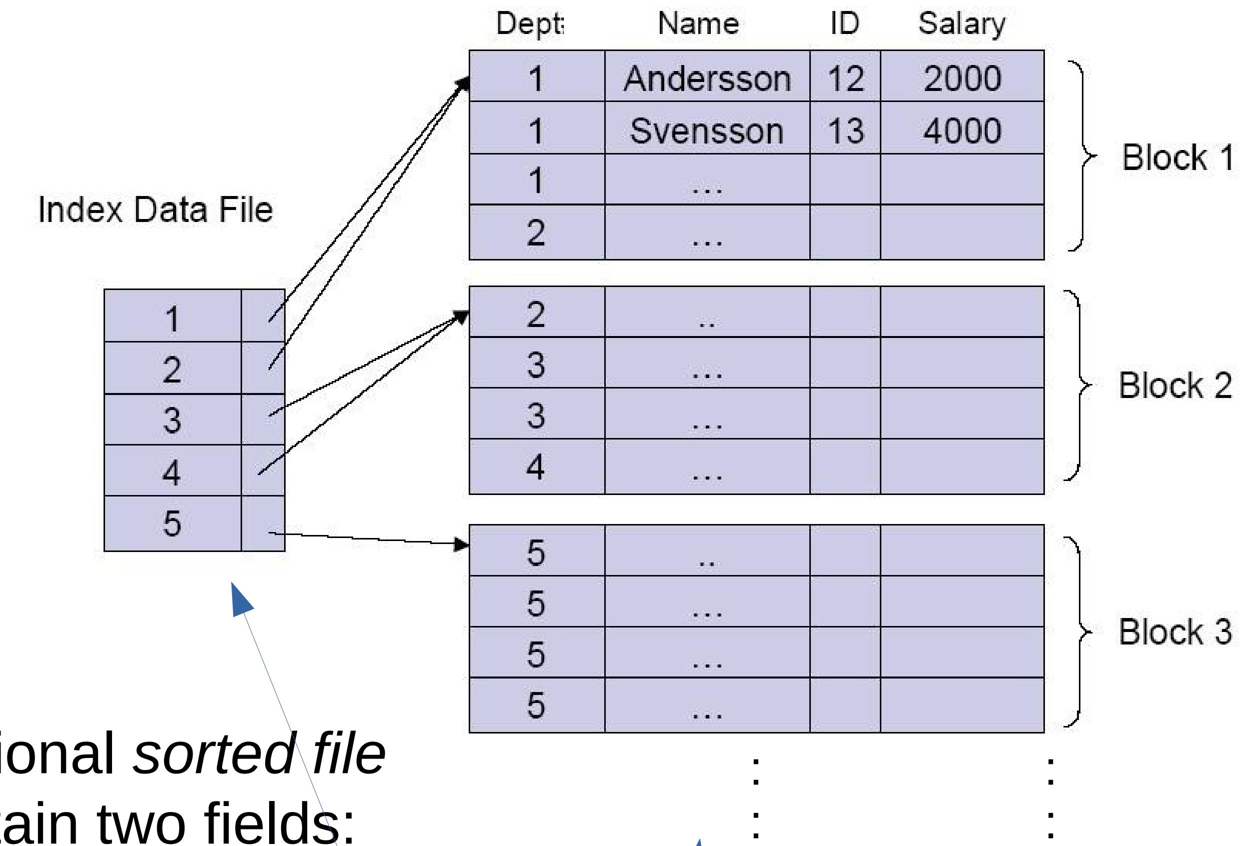
index file (sorted) with one record per block in the data file

# 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?
  - Index file is much smaller than the data file because:
    - (a) Number of index records << number of data records
    - (b) Index records smaller than data records (i.e., higher blocking factor for the index file than for the data file)
  - Much smaller file → binary search converges must faster!
- There is a cost of maintaining the index!

# Clustering Index

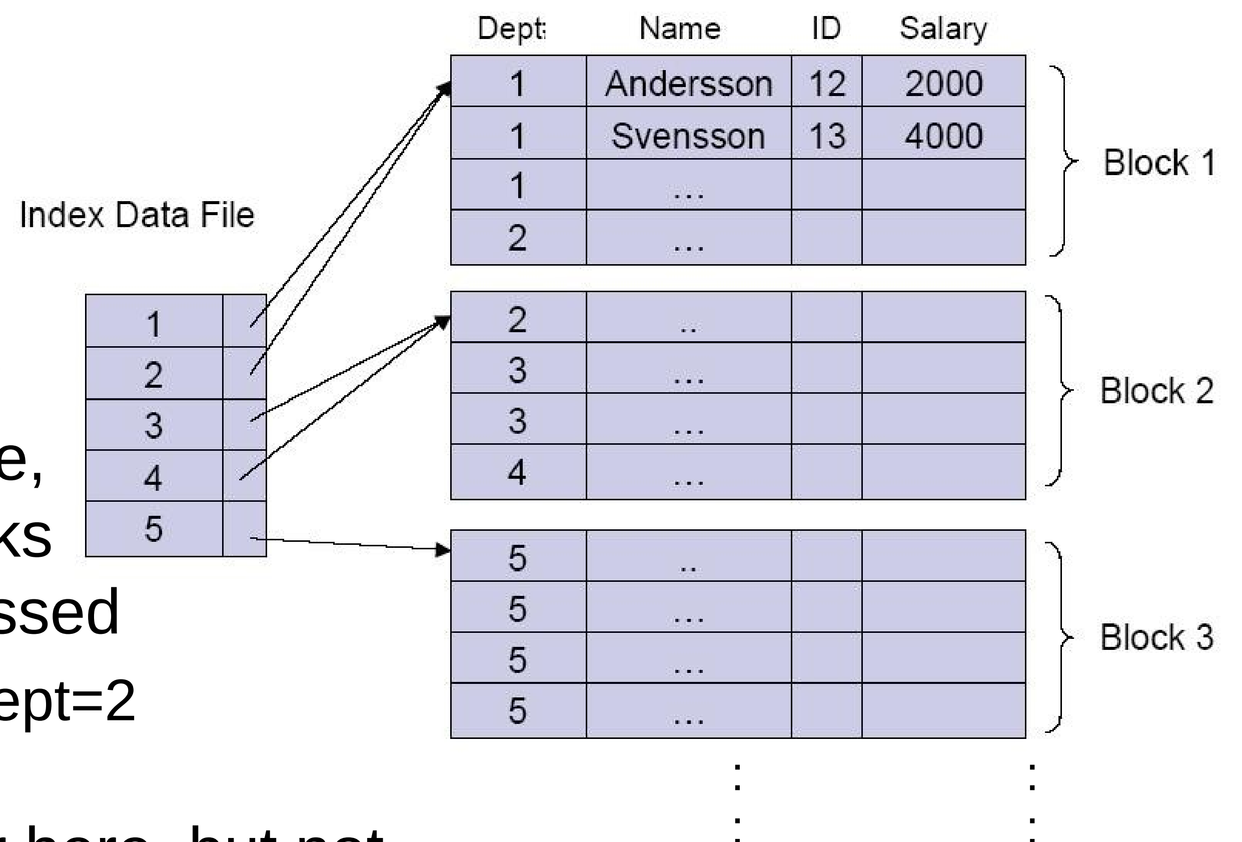



- Assumptions:
  - Data file is sorted
  - Ordering field *F* is **not** a key (hence, we cannot assume distinct values)
- Clustering index: additional *sorted file* whose records contain two fields:
  - *V* - one of the values of *F*
  - *P* - pointer to a disk block of the data file
- One index record (*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

sorted file with all the records
- sorted by Dept
- Dept is *not a key*

index file (sorted) with one record per possible Dept value

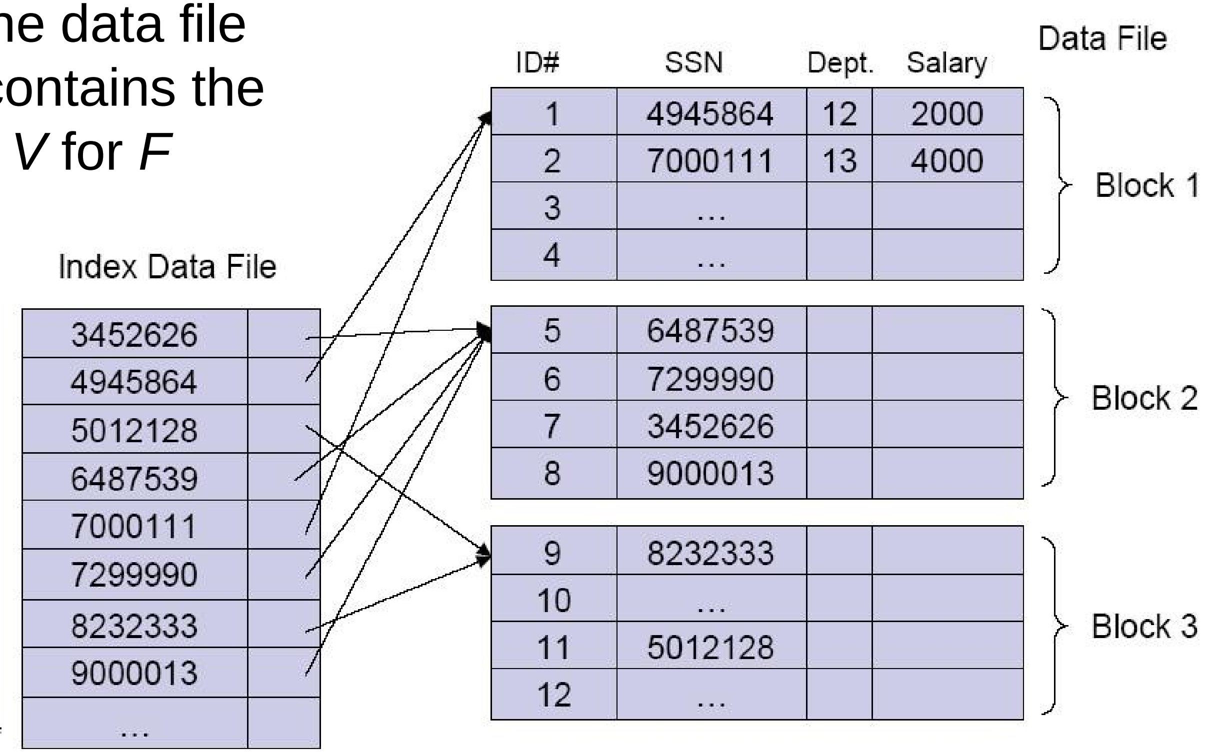
# Clustering Index




- Attention: after binary search in the index file, multiple data file blocks may need to be accessed
  - see, for instance, Dept=2
- Index file also smaller here, but not as much as for a primary index
  - number of index records ≤ number of data records
  - at least, index records smaller than data records (like in a primary index)

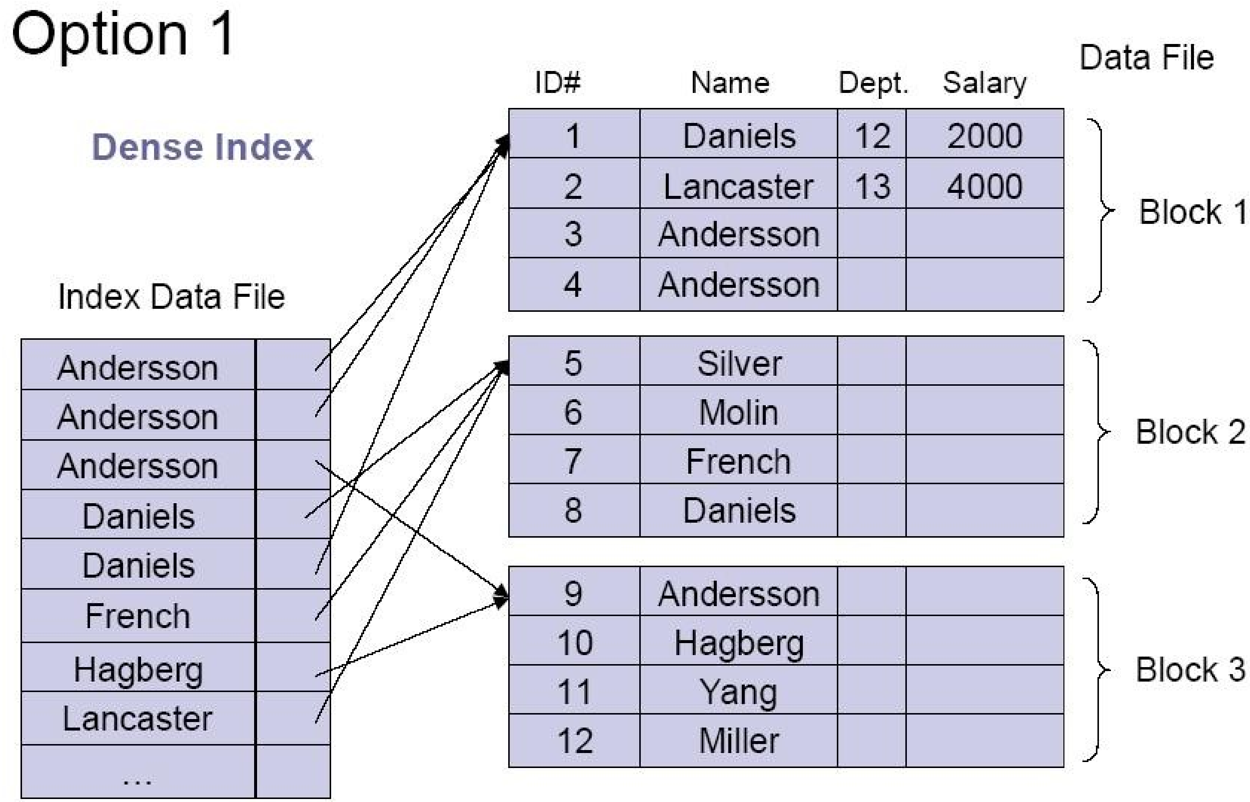
# Secondary Indexes on Key Field

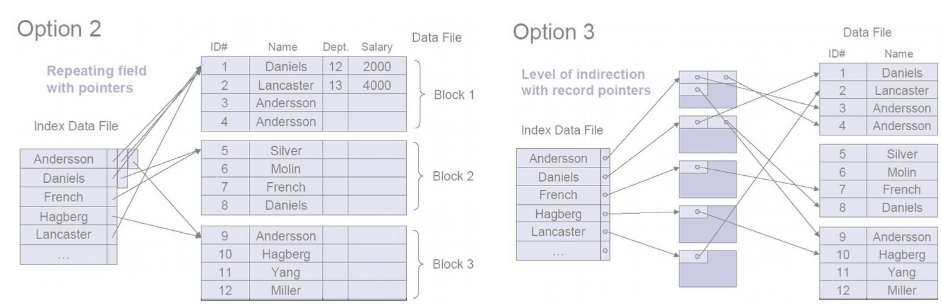
- Index on a *non*-ordering *key* field *F*
  - Data file may be sorted or not
- Secondary index: additional *sorted* file
  whose records contain two fields:
  *V* - one of the values of *F*
  *P* - pointer to the data file block that contains the record with *V* for *F*
- One index record per data record
- Searching based on a value of *F* can now be done with a binary search in the index



# Secondary Indexes on Non-Key

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

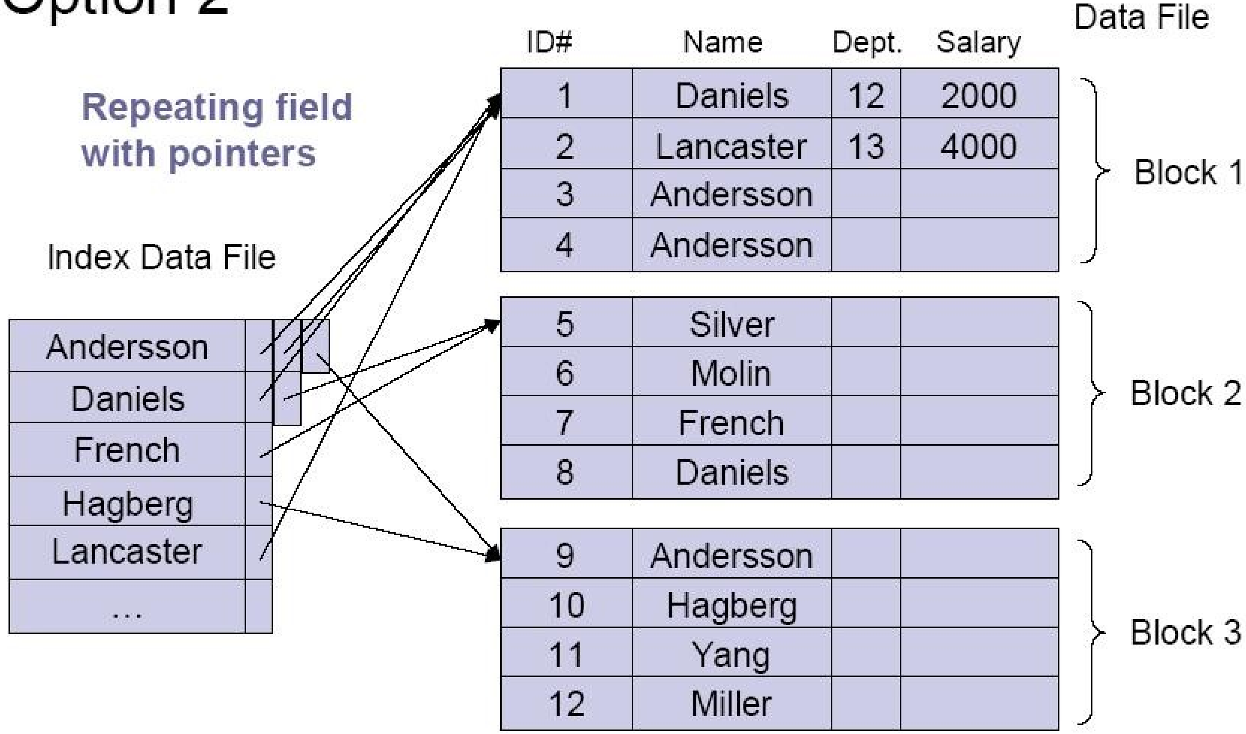


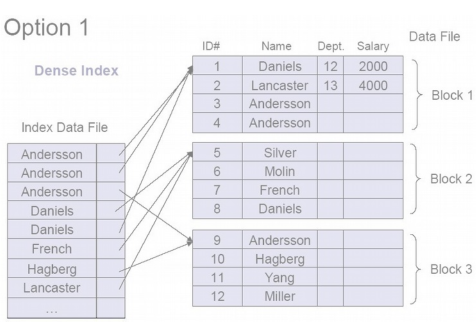



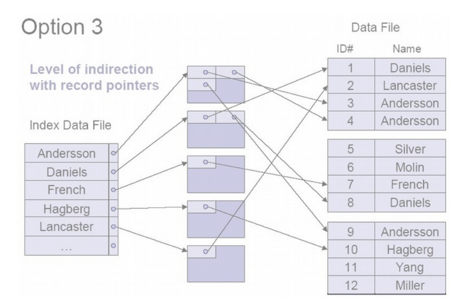
# Secondary Indexes on Non-Key

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

Option 2

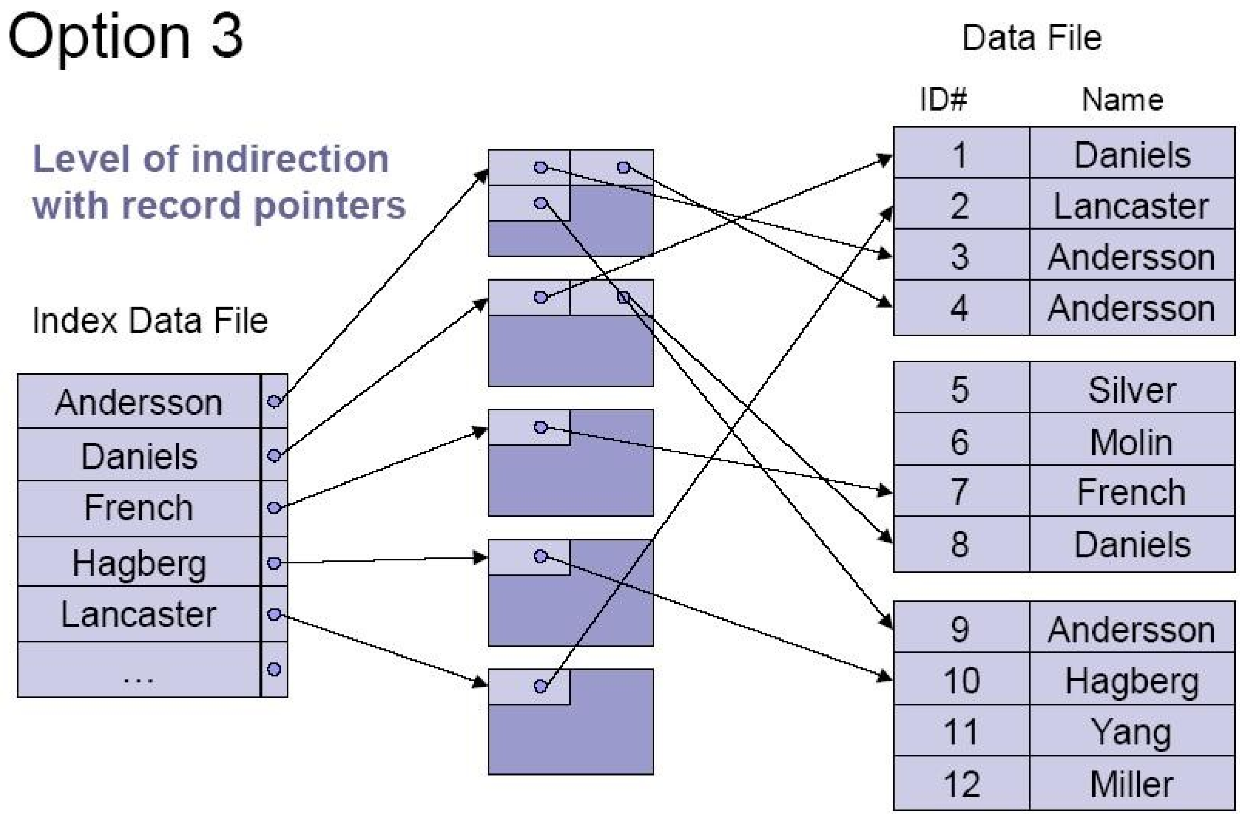


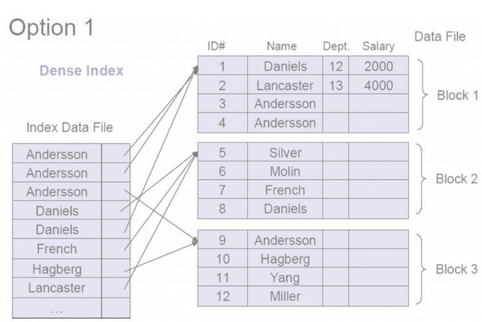



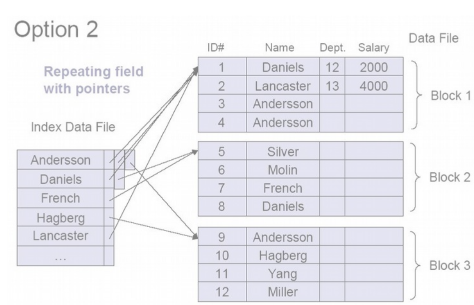



# Secondary Indexes on Non-Key

- Index on a *non*-ordering *non*-key field
- also called *inverted file*



# Summary of Single-Level Indexes

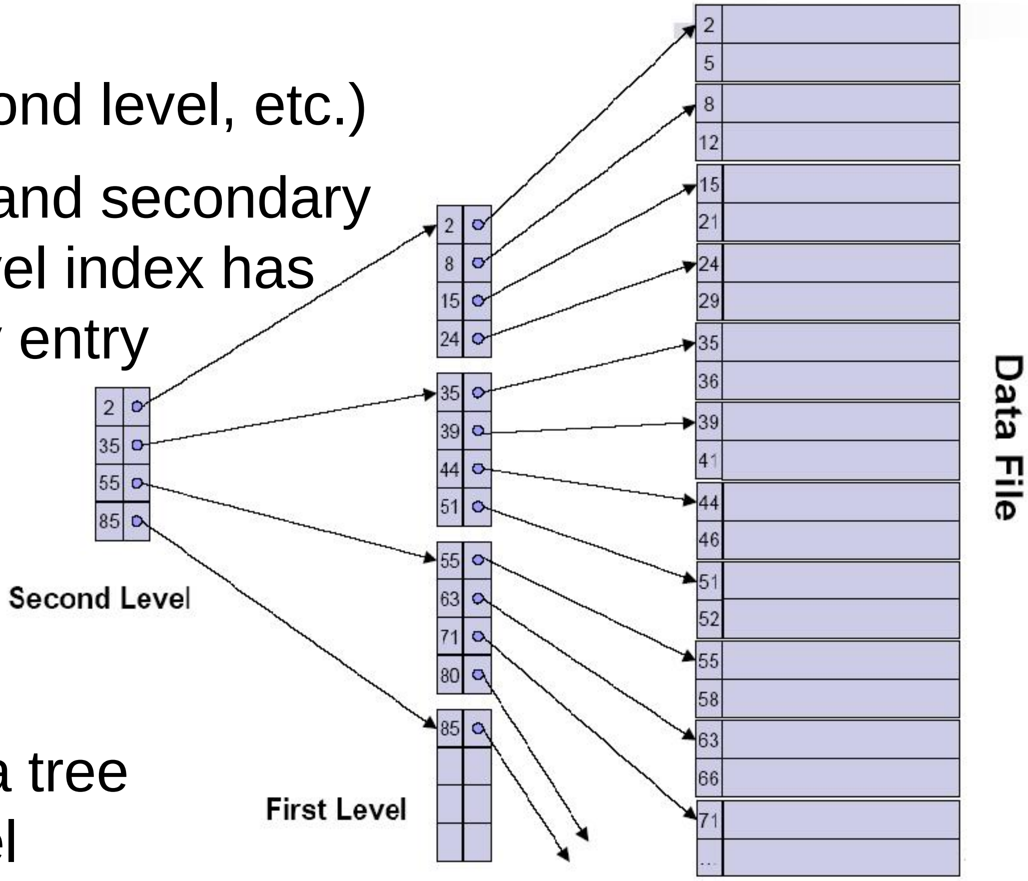
| | **Index field used for sorting the data records** | **Index field *not* used for sorting the data records** |
|---|---|---|
| **Index field is a key** | Primary index | Secondary index (key) |
| **Index field is not a key** | Clustering index | Secondary index (non-key) |

| **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 records 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 highest level fits into a single block
- Such a full multilevel index is a tree
  - single block of highest level is the root node in this tree
- How many block accesses to retrieve a random record?
  - number of index levels + 1



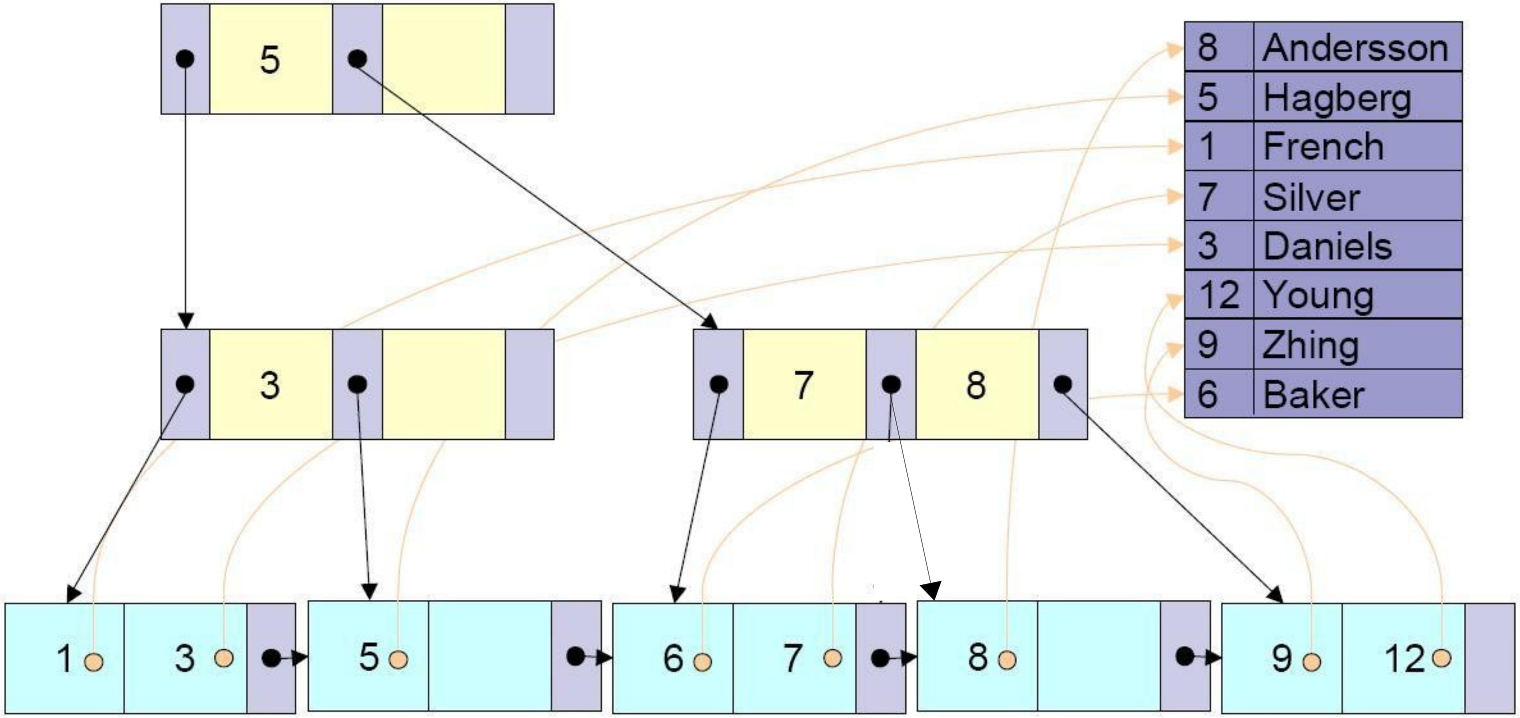
# Multilevel Indexes (cont'd)

- 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)

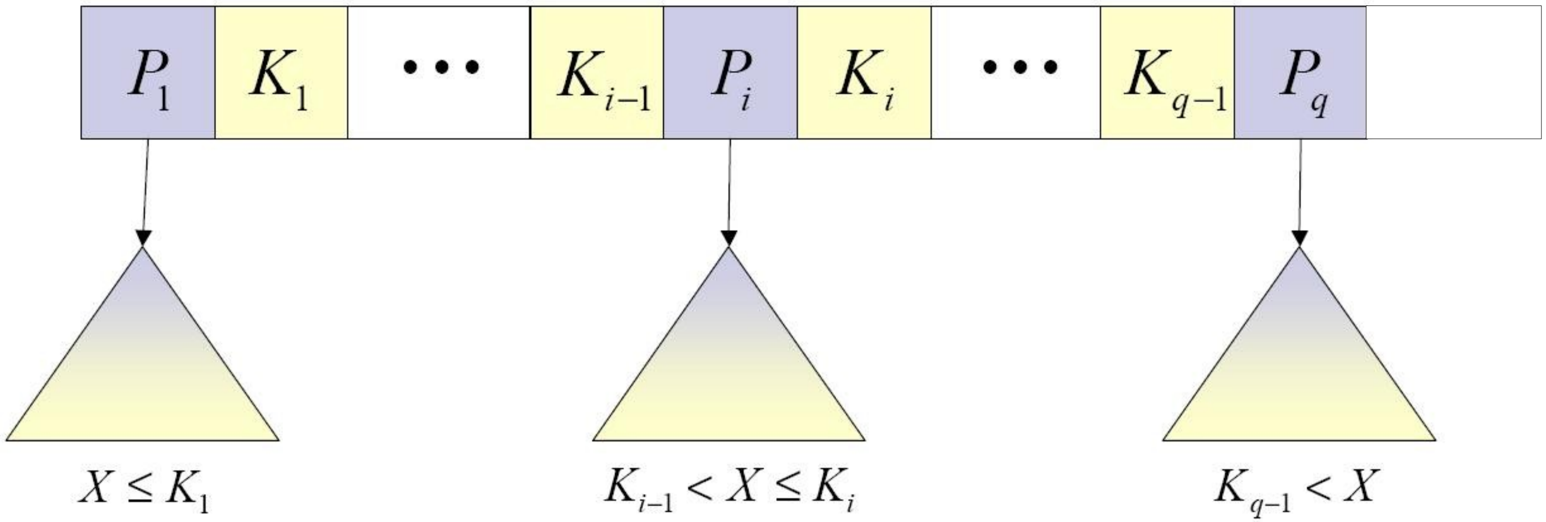
# $B^+$-Trees

Dynamic Multilevel Indexes

# Example B+-Tree



# Internal Nodes of a B+-Tree




- $q \leq p$ (where $p$ is the order of the B+-tree)
- Every $K_i$ is an index value, every $P_i$ is a tree pointer
- Within each node: $K_1 < K_2 < \ldots < K_{q-1}$
- For every value $X$ in the $P_i$ subtree: $K_{i-1} < X \leq K_i$
- Each internal node (except the root) must be at least half full
  - i.e., there must be at least $\left\lceil \frac{p}{2} \right\rceil$ tree pointers

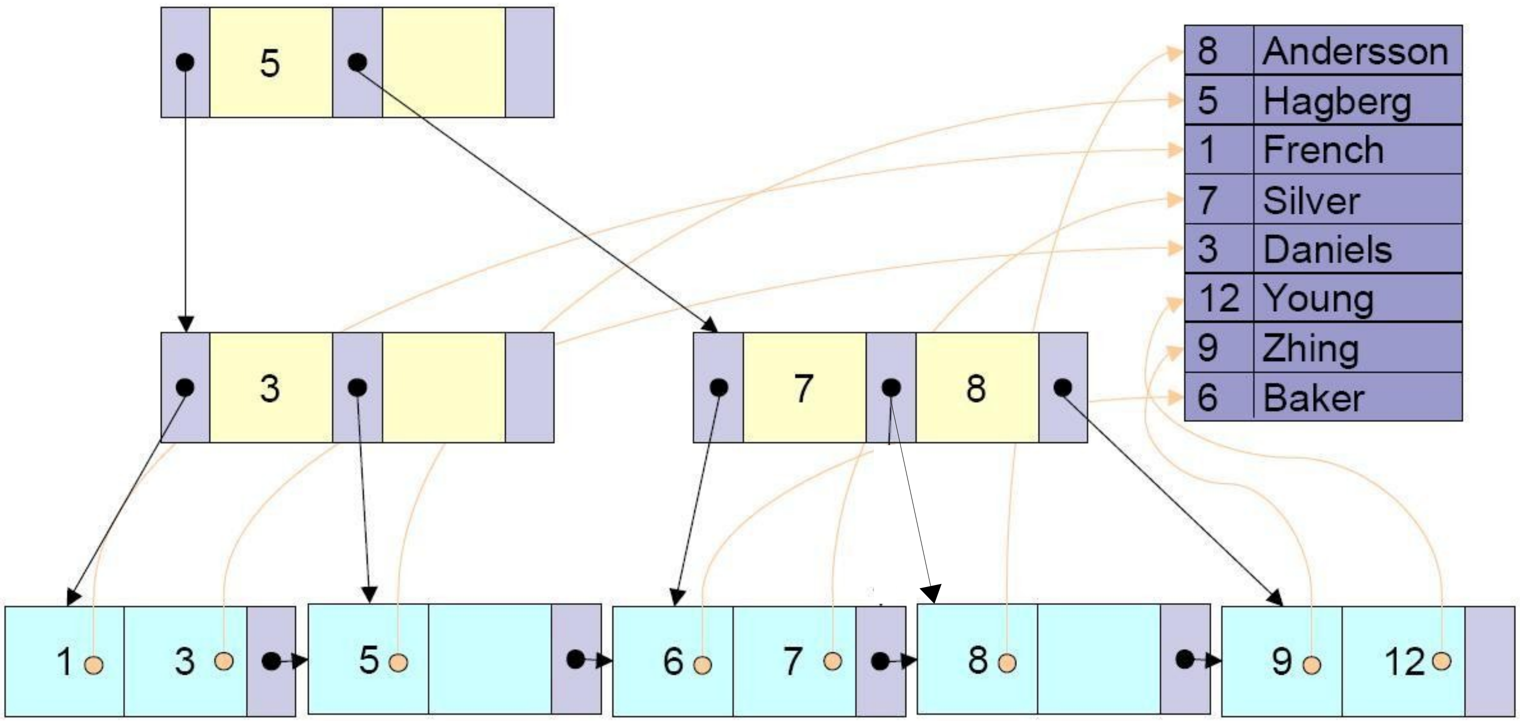
# Leaf Nodes of a B+-Tree

| $K_1$ | $Pr_1$ | … | $K_i$ | $Pr_i$ | … | $K_q$ | $Pr_q$ | $P_{\text{next}}$ |
|---|---|---|---|---|---|---|---|---|

- $q \leq p$ (where $p$ is the order for leaf nodes of the B+-tree)
- Every $K_i$ is an index value
- Every $Pr_i$ is a data pointer to the data file block that contains the record with index value $K_i$
- $P_{\text{next}}$ is a pointer to the next leaf node
- Within each node: $K_1 < K_2 < \ldots < K_q$
- Every leaf node must be at least half full
  - i.e., at least $\left\lceil \frac{p}{2} \right\rceil$ index values in each leaf node

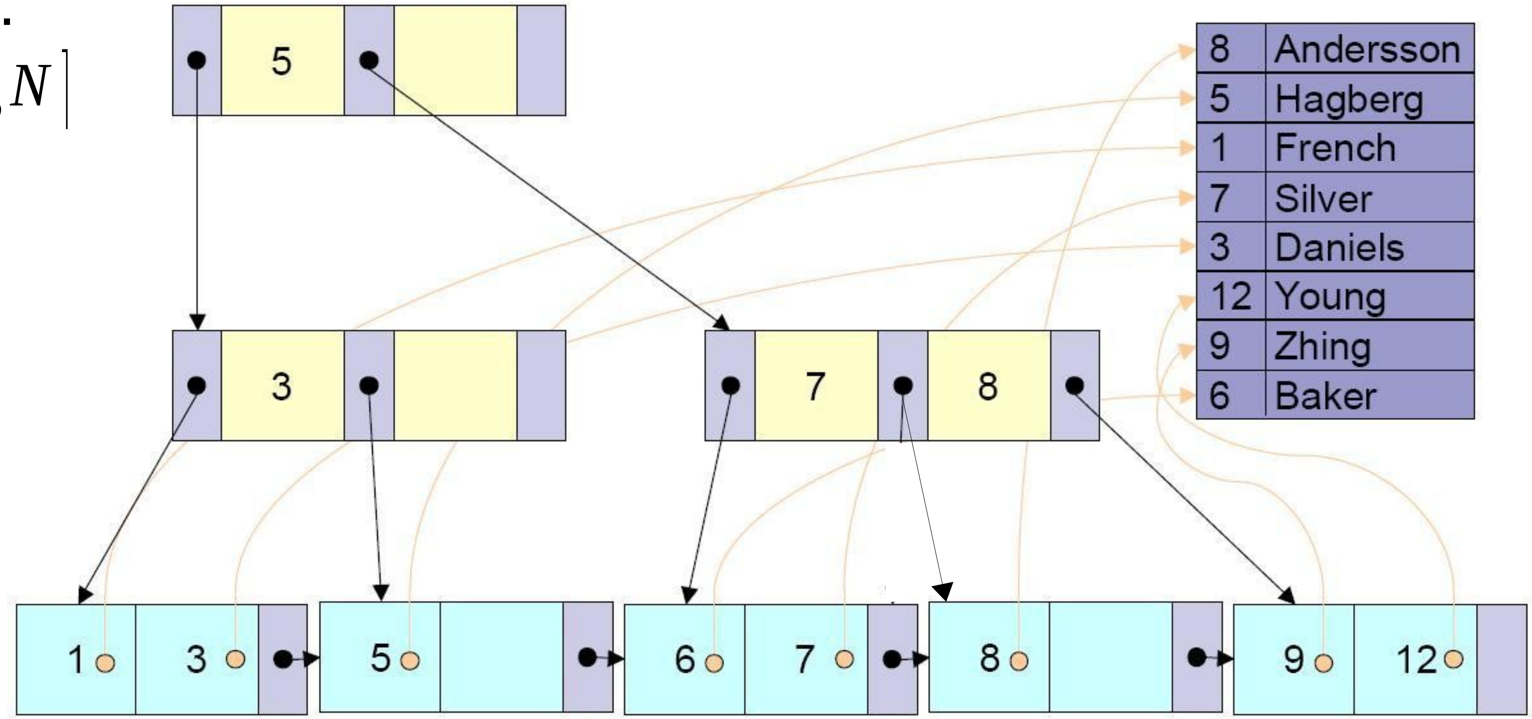
# Retrieval of Records in a B+-Tree

- Very fast retrieval of a random record
- Number of block accesses: depth of tree + 1

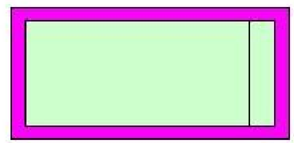


# Depth of a B+-Tree

- Given that internal nodes must have at least $\left\lceil \frac{p}{2} \right\rceil$ children,
- For a depth of $d$, the number $N$ of leaf nodes is at least $\left\lceil \frac{p}{2} \right\rceil^{d}$
- Hence, in the worst case, $d$ is at most $\left\lceil \log_{\left\lceil \frac{p}{2} \right\rceil} N \right\rceil$
- Best case:
  $\left\lceil \log_{p} N \right\rceil$

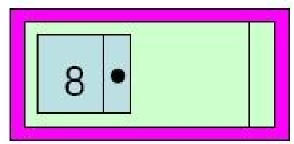


# B+-Tree Insertion



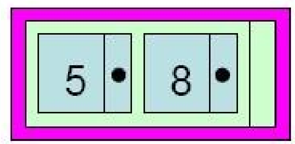
Insert: 8

# B+-Tree Insertion




Insert: 5

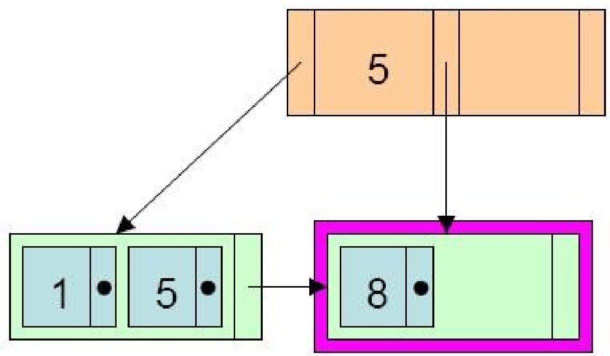
# $B^+$-Tree Insertion




Overflow – create a new level

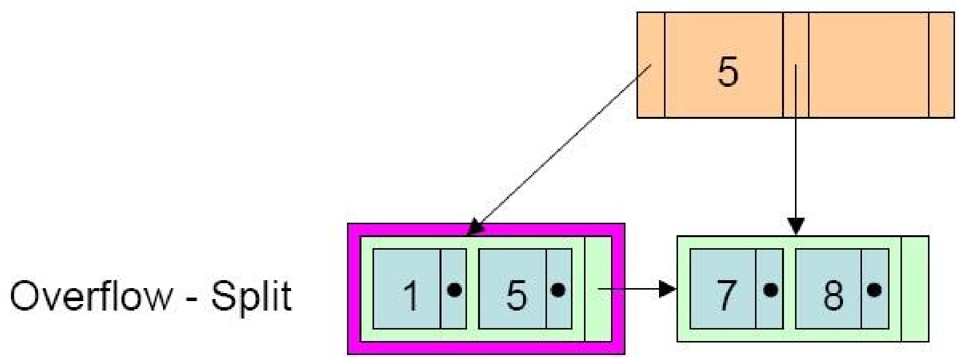
Insert: 1

# B+-Tree Insertion



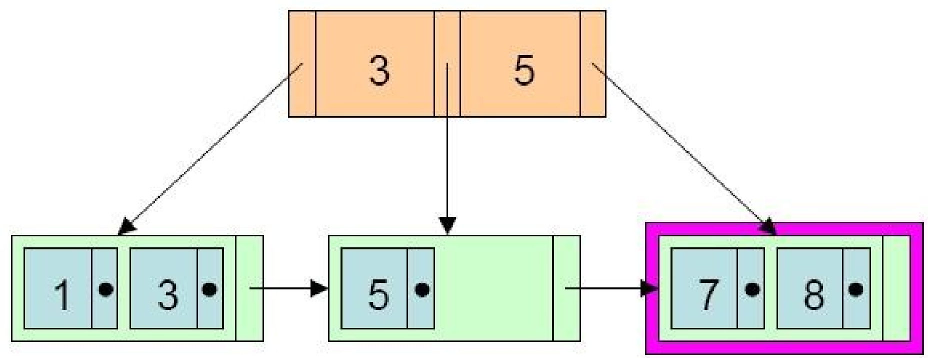

Insert: 7

# B+-Tree Insertion




Insert: 3

# B+-Tree Insertion

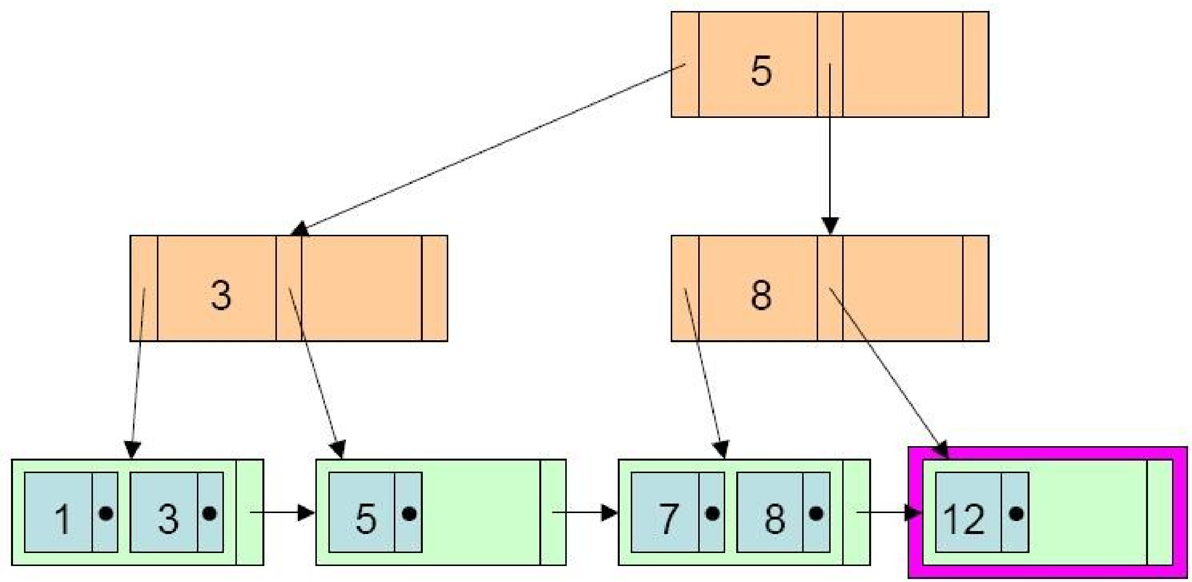



Overflow - Split

Propagates a new level

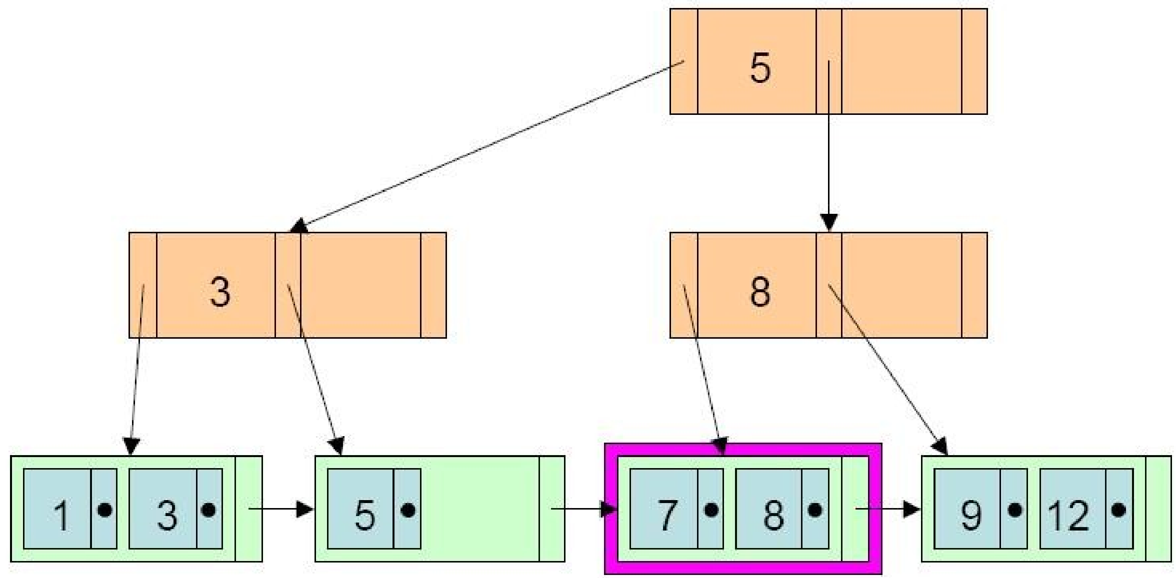
Insert: 12

# B⁺-Tree Insertion




Insert: 9

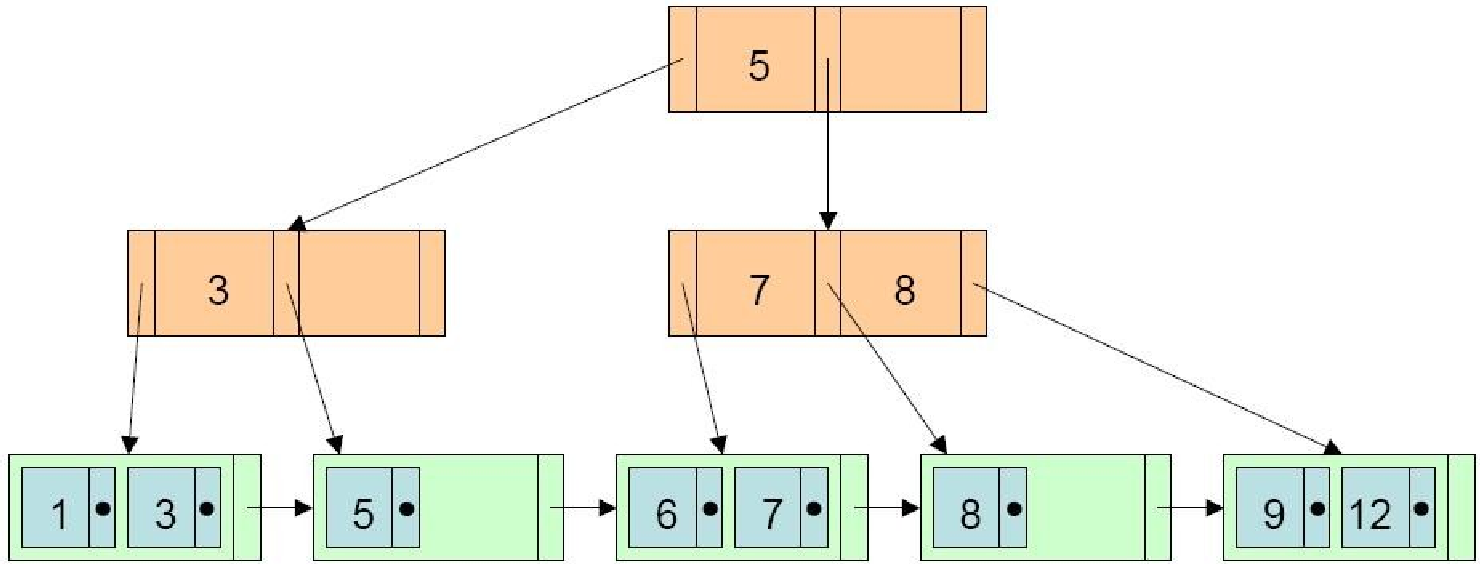
# B$^+$-Tree Insertion




Overflow – Split, propagates

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

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