Database 2

Lecture II

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Summary of Lecture II

- **I**ndexing.
  - Indexes on Sequential Files: Dense Vs. Sparse Indexes.
  - Primary Indexes with Duplicate Keys.
  - Secondary Indexes.
  - Document Indexing.
  - B-Tree Indexes.

Indexing

Indexing is the principal technique used to efficiently answering a given query.

- An Index for a DB is like an Index in a book:
  1. It is smaller that the book;
  2. The words are in sorted order;
  3. If we are looking for a particular topic we first search on the index, find the pages where it is discussed, go to the actual pages in the book.

Example.

`MovieStar(Name,Address,Gender,Birthdate)`

SELECT *
FROM MovieStar
WHERE Name = 'Jim Carrey';

All the blocks for the `MovieStar` relation should be inspected if there is no index on Name.

Index

An *Index* is a data structure that facilitates the query answering process by minimizing the number of disk accesses.

- An index structure is usually defined on a single Attribute of a Relation, called the **S**earch Key;
- An Index takes as input a Search Key value and returns the address of the record(s) (block physical address + offset of the record) holding that value.
- Index structure: Search Key-Pointer pairs

Search Key	Pointer to a data-file record

- The Searck Key values stored in the Index are *Sorted* and a binary search can be done on the Index.
- Only a small part of the records of a relation have to be inspected: Appropriate indexes can speed up query processing passing from minutes to seconds.

Index Structures

Different data structures give rise to different indexes:

1. **Indexes on Sequential Files (Primary Index);**
2. **Secondary Indexes on Unsorted Files;**
3. **B-Trees;**
4. **Hash Tables.**

Evaluating Different Index Structures

No one technique is the best. Each has to evaluated w.r.t. the following criteria:

- **Access Type.** Finding records either with a particular search key, or with the search key falling in a given range.
- **Access Time.** The time it takes to find item(s) using the index in question.
- **Insertion Time.** The time to insert an item in the data file, as well as the time to update the index.
- **Deletion Time.** The time to delete the item from the data file (which include the time to find the item), and the time to update the index.
- **Space Overhead.** Additional space for the index.

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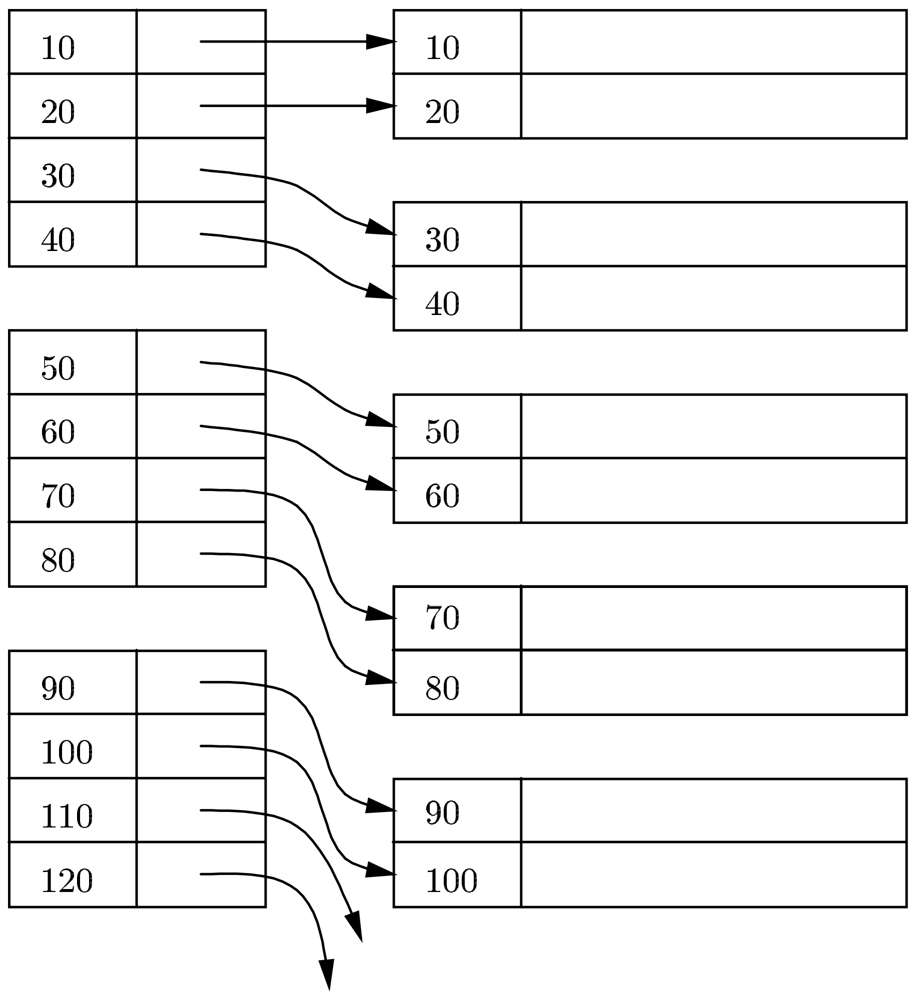
Indexes on Sequential Files

- **I**ndex on Sequential File, also called **P**rimary Index, when the Index is associated to a *Data File* which is in turn *sorted with respect to the search key*.
  1. A Primary Index forces a sequential file organization on the Data File;
  2. Since a Data File can have just one order there can be just one Primary Index for Data File.
- Usually used when the search key is also the primary key of the relation.
- Usually, these indexes fit in main memory.
- Indexes on sequential files can be:
  1. **D**ense: One entry in the index file for every record in the data file;
  2. **S**parse: One entry in the index file for each block of the data file.

Dense Indexes

Every value of the search key has a representative in a **Dense Index**. The index maintains the keys in the same order as in the data file.



Database System Implementation, H. Garcia-Molina, J. Ullman, and J. Widom, Prentice-Hall, 2000.

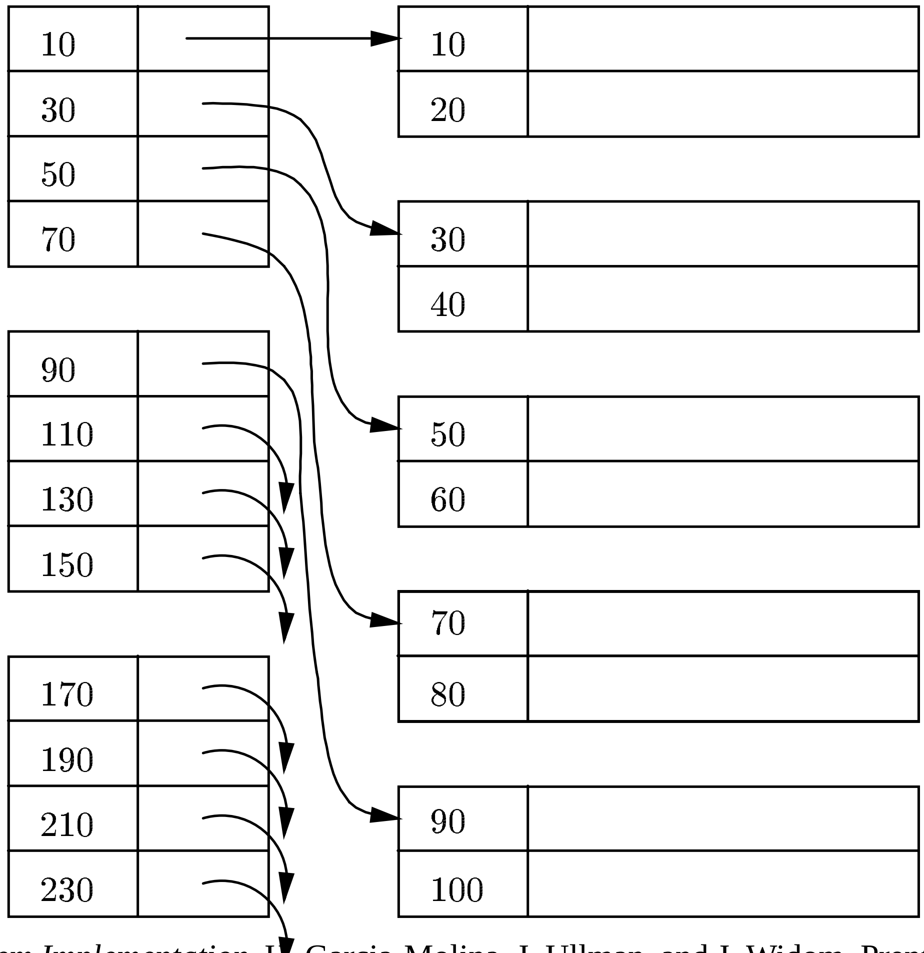
Queries with Dense Indexes

Algorithm for **Lookup**: Searching a data record with a given search key value.

- Given a search key K, the index is scanned and when K is found the associated pointer to the data file record is followed and the record (block containing it) is read in main memory.
- Dense indexes support also *range queries*: The minimum value is located first, if needed, consecutive blocks are loaded in main memory until a search key greater than the maximum value is found.
- Query-answering using dense indexes is *efficient*:
  1. Since the index is usually kept in main memory, just 1 disk I/O has to be performed during lookup;
  2. Since the index is sorted we can use binary search: If there are n search keys then at most $log_2 n$ steps are required to locate a given search key.

Sparse Indexes

- Used when dense indexes are too large: A Sparse Index uses less space at the expense of more time to find a record given a key.
- A sparse index holds **one key-pointer pair per data block**, usually the first record on the data block.



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Queries with Sparse Indexes

Algorithm for Lookup.

- Given a search key K:
  1. Search the sparse index for the greatest key $\leq$ to K using binary search;
  2. We retrieve the pointed block to main memory to look for the record with search key K (always using binary search).
- With respect to dense indexes we need to start two different binary searches: the first on the sparse index, and the second on the retrieved data block.
- Still 1 disk I/O for lookup.
- In conclusion, a Sparse Index is more efficient in space at the cost of a worst computing time in Main Memory.

Primary Dense Index: Example

Example of a **Primary Dense Index** with **Search Key**=`Account#`.

A-101	→
A-102	→
A-110	→
A-201	→
A-215	→
A-217	→
A-218	→
A-222	→
A-305	→

Account♯	Branch	Balance
A-101	Downtown	500
A-102	Perryridge	400
A-110	Downtown	600
A-201	Perryridge	900
A-215	Mianus	700
A-217	Brighton	750
A-218	Perryridge	700
A-222	Redwood	700
A-305	Round Hill	350

Primary Sparse Index: Example

Example of a **Primary Sparse Index** with **Search Key**=`Account#`.

A-101	
A-201	
A-218	

Account♯	Branch	Balance
A-101	Downtown	500
A-102	Perryridge	400
A-110	Downtown	600
A-201	Perryridge	900
A-215	Mianus	700
A-217	Brighton	750
A-218	Perryridge	700
A-222	Redwood	700
A-305	Round Hill	350

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  - **P**rimary Indexes with Duplicate Keys.
  - Secondary Indexes.
  - Document Indexing.
  - B-Tree Indexes.

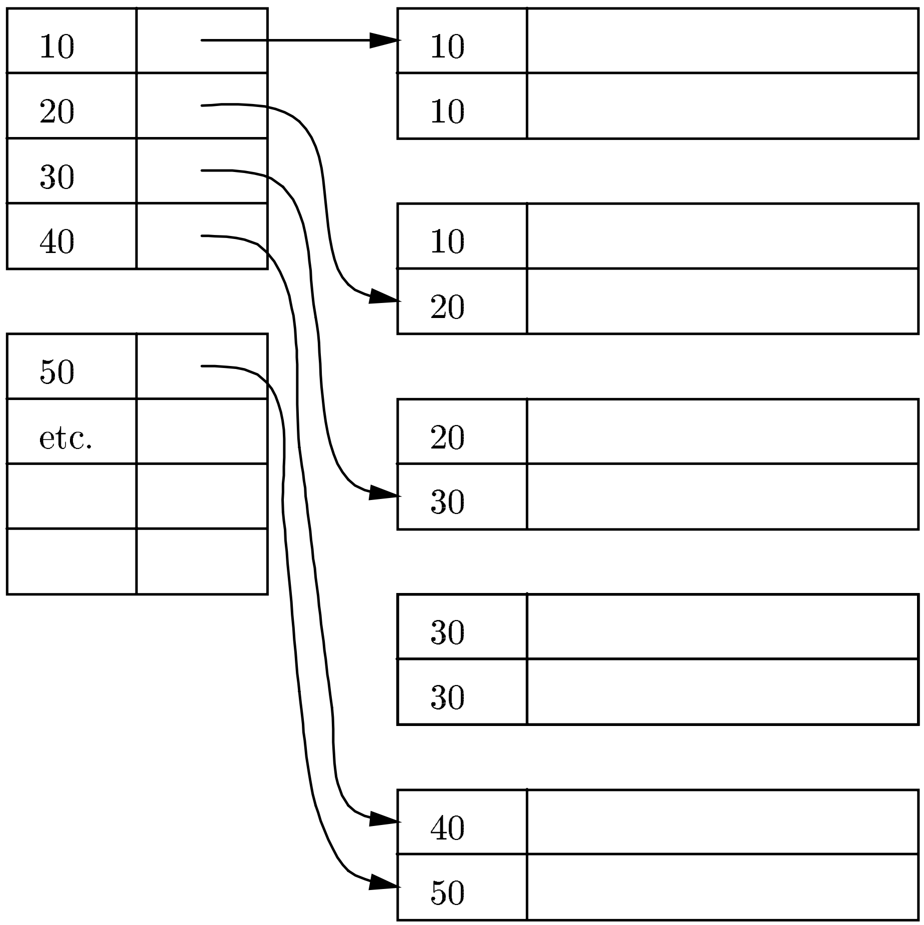
Primary Indexes with Duplicate Keys

- Indexes for **non key attributes**:
  More than one record with the same search key.
- As usual, the data file should be sorted w.r.t the search key to speak of primary indexes.
- Techniques for dense indexes:
  1. One entry for each record in the data file: Duplicate key-pointer pairs (not used);
  2. Just a single entry for each record in the data file with search key K – no duplicate key-pointer pairs: Pointer to the first record with search key K (more efficient).

Dense Index with Duplicate Search Keys

Single Entry Index

Lookup. Find the search key on the index, read the pointed disk block, possibly read successive blocks.



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Primary Dense Index with Duplicates: Example

Example of a **Primary Dense Index with Duplicates** with **Search Key**=`Branch`.

Brighton	
Downtown	
Mianus	
Perryridge	
Redwood	
Round Hill	

`Account♯`	`Branch`	`Balance`
A-217	Brighton	750
A-101	Downtown	500
A-110	Downtown	600
A-215	Mianus	700
A-102	Perryridge	400
A-201	Perryridge	900
A-218	Perryridge	700
A-222	Redwood	700
A-305	Round Hill	350

Analysis of Primary indexes

- **Advantages.**
  Efficient access of tuples with a given search key.
  - Very few blocks should be read (also in case of duplicate keys);
  - **R**ange Queries – looking for search key values in a certain range – are answered efficiently.

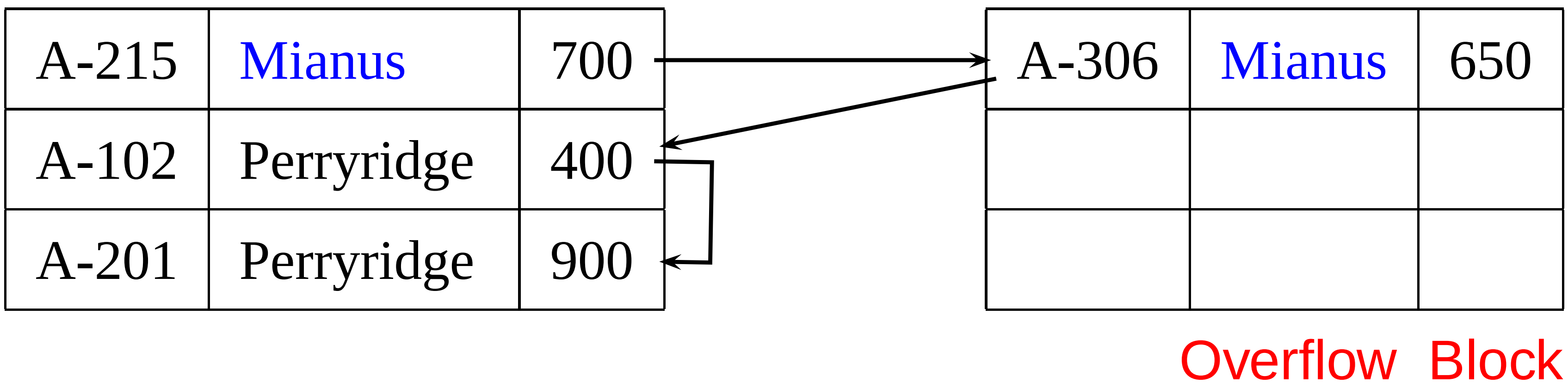
Analysis of Primary indexes (cont.)

- **Disadvantages.**

  Expensive maintenance of the physical records storage to maintain the sorted order.

  - Technique used for insertion based on **O**verflow Blocks.
    1. If there is space in the block insert the new record there in the right place;
    2. Otherwise, insert the new record in an *Overflow Blocks*. In order to maintain the order, records are linked by means of pointers: The pointer in each record points to the next record in search-key order.
  - In general, performance degrades as far as the relation grows. The file is *reorganized* when the system load is low.
  - An optimal solution is to implement primary indexes as *B-Tree* structures (presented soon).

Insertion in Sequential Files: Example



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  - Secondary Indexes.
  - Document Indexing.
  - B-Tree Indexes.

Secondary Indexes

- A *primary index* is an index on a file sorted w.r.t. the search key. Then a primary index *"controls"* the storage of records in the data file.
- Indexes on Sequential files and Hash Tables are examples of primary indexes.
- Since a file can have at most one physical order then it can have at most one primary index.
- Secondary Indexes facilitate query-answering on attributes other than primary keys – or, more generally, on *non-ordering* attributes.
- A file can have *several* secondary indexes.

Secondary indexes do not determine the placement of records in the data file.

Secondary Index: An Example

Let us consider the `MovieStar` relation:

`MovieStar(`<u>`Name`</u>`,Address,Gender,Birthdate)`

and a query involving the non-key `Birthdate` attribute:

SELECT Name, Address
FROM MovieStar
WHERE Birthdate = '1975-01-01';

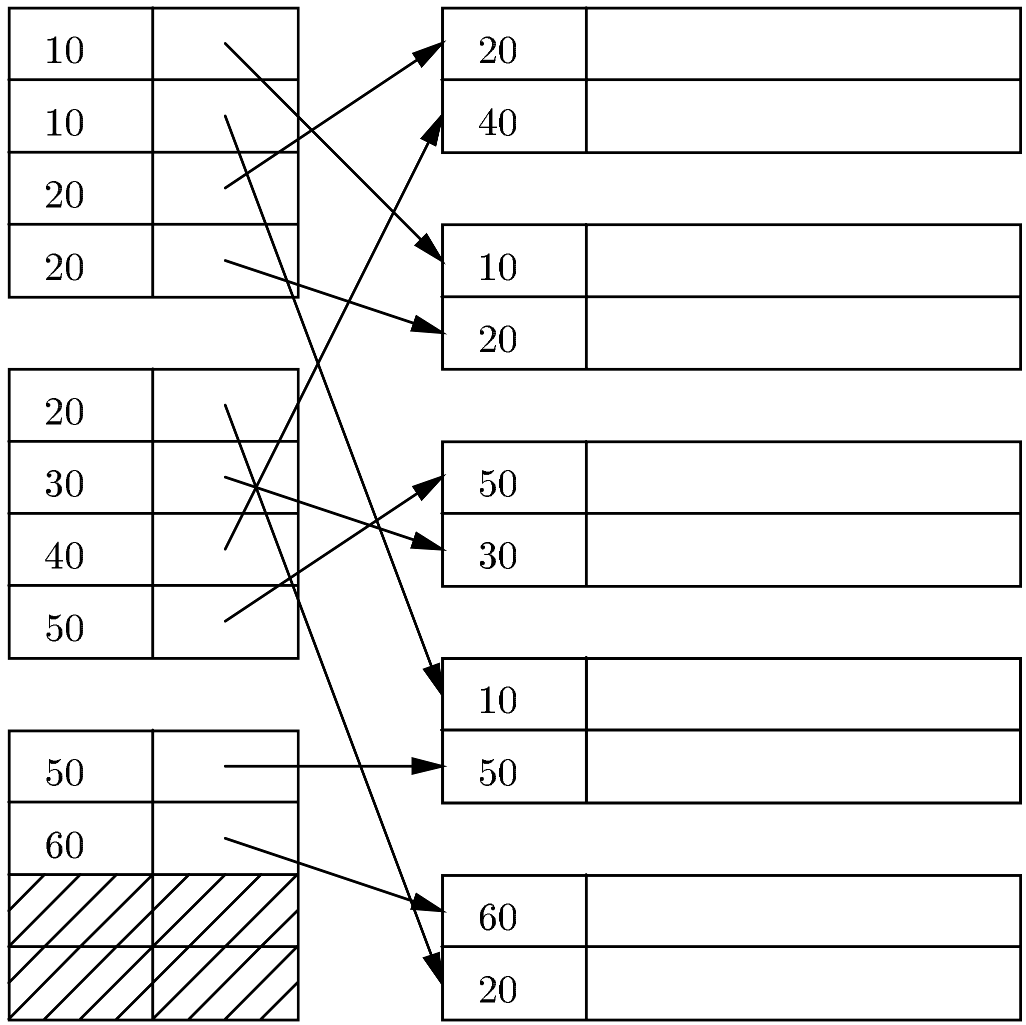
A secondary index on the `MovieStar` relation w.r.t. the `Birthdate` attribute would reduce the answering time.

Structure of Secondary Indexes

- Secondary Indexes are always Dense:
  Sparse secondary indexes make no sense!
- Secondary indexes are sorted w.r.t. the search key $\rightarrow$ Binary search.
- The Data File **IS NOT** sorted w.r.t. the Secondary Index Search Key!
- More than one data block may be needed for a given search key $\rightarrow$ in general more disk I/O to answer queries:
  - Secondary Indexes are less efficient than Primary Indexes.

Secondary Indexes: An Example

The example shows that 3 data blocks (i.e., 3 disk I/O) are needed to retrieve all the tuples with search key $K = 20$ using the Secondary Index.



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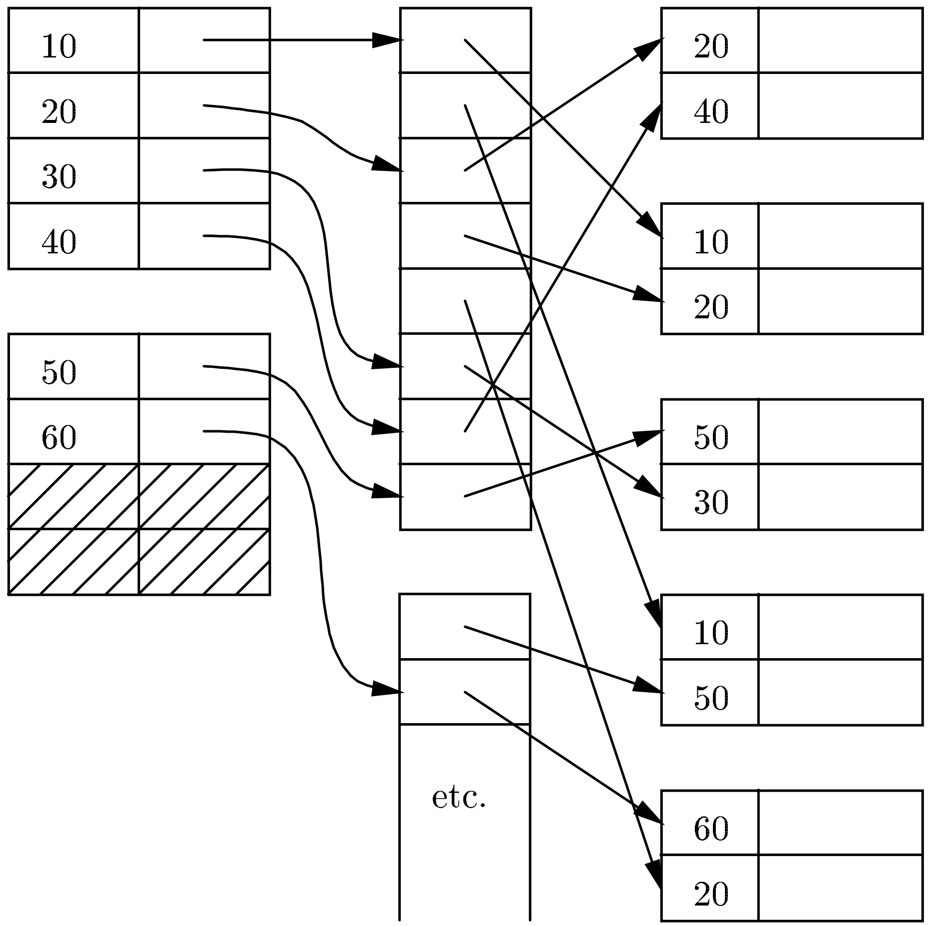
Indirect Buckets

- To avoid repeating keys in secondary index, use a level of indirection, called **Buckets**.

- The index maintains only one key-pointer pair for each search key K: The pointer for K goes to a position in the bucket which contains pointers to records with search key K till the next position pointed by the index.



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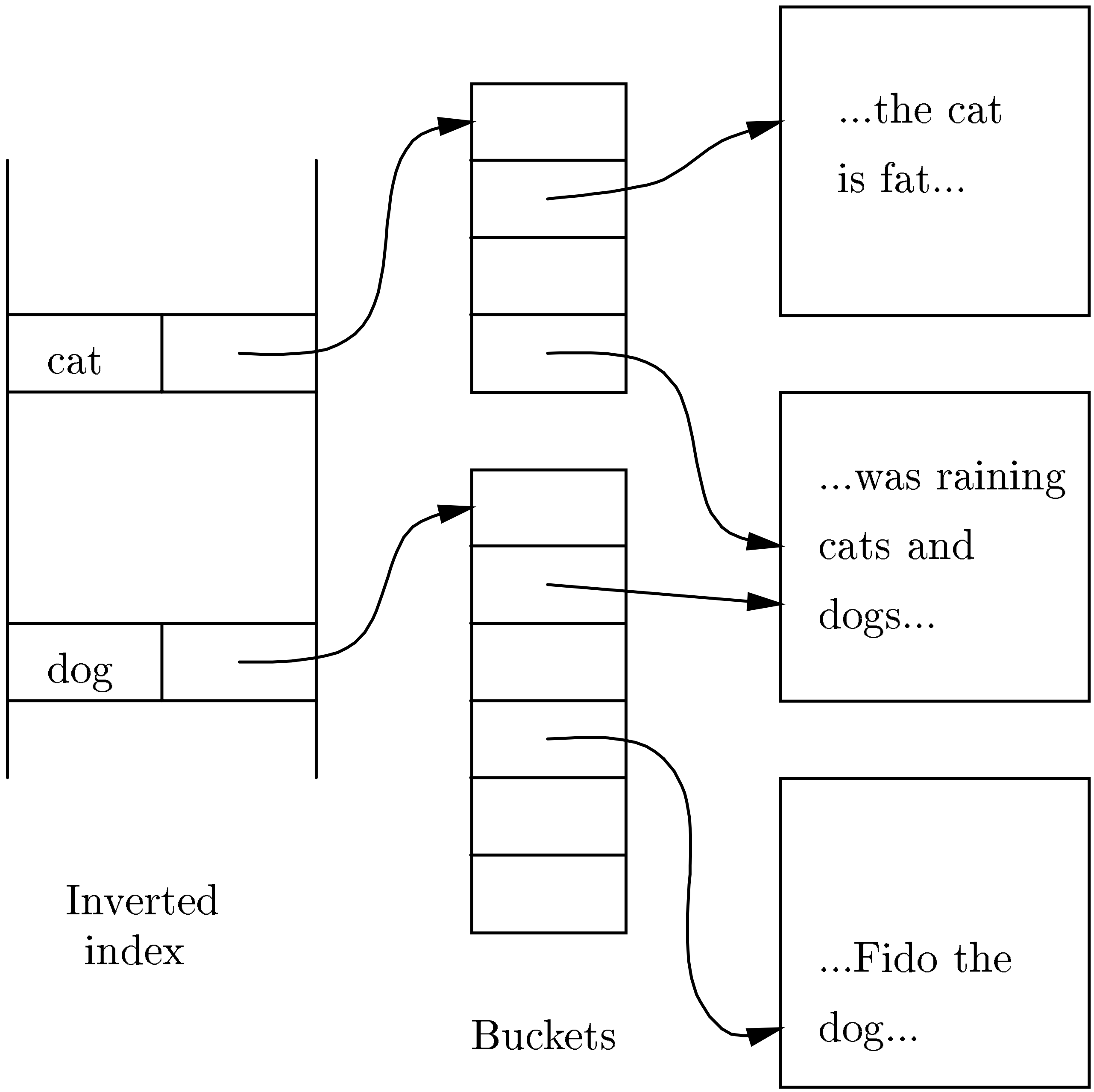
  - **D**ocument Indexing.
  - B-Tree Indexes.

Document Retrieval and Inverted Indexes

Problem: Given a set of text documents we need to retrieve that ones where a particular word(s) occurs.

- Given the success of the Web this has become an urgent database problem.
- A document is thought as a tuple in the relation `Doc(ID,cat,dog,...)`, with one attribute for each possible word.
- Each attribute has a Boolean value, eg, the value of `cat` is `TRUE` if and only if the word *cat* appears in the document.
- An **I**nverted Index is a form of secondary index with indirect bucket containing – as search keys – all the attribute names of the `Doc` relation.
- Pointers are stored in a bucket file and consider only the `TRUE` occurrences of a search key.

Inverted Indexes: An Example



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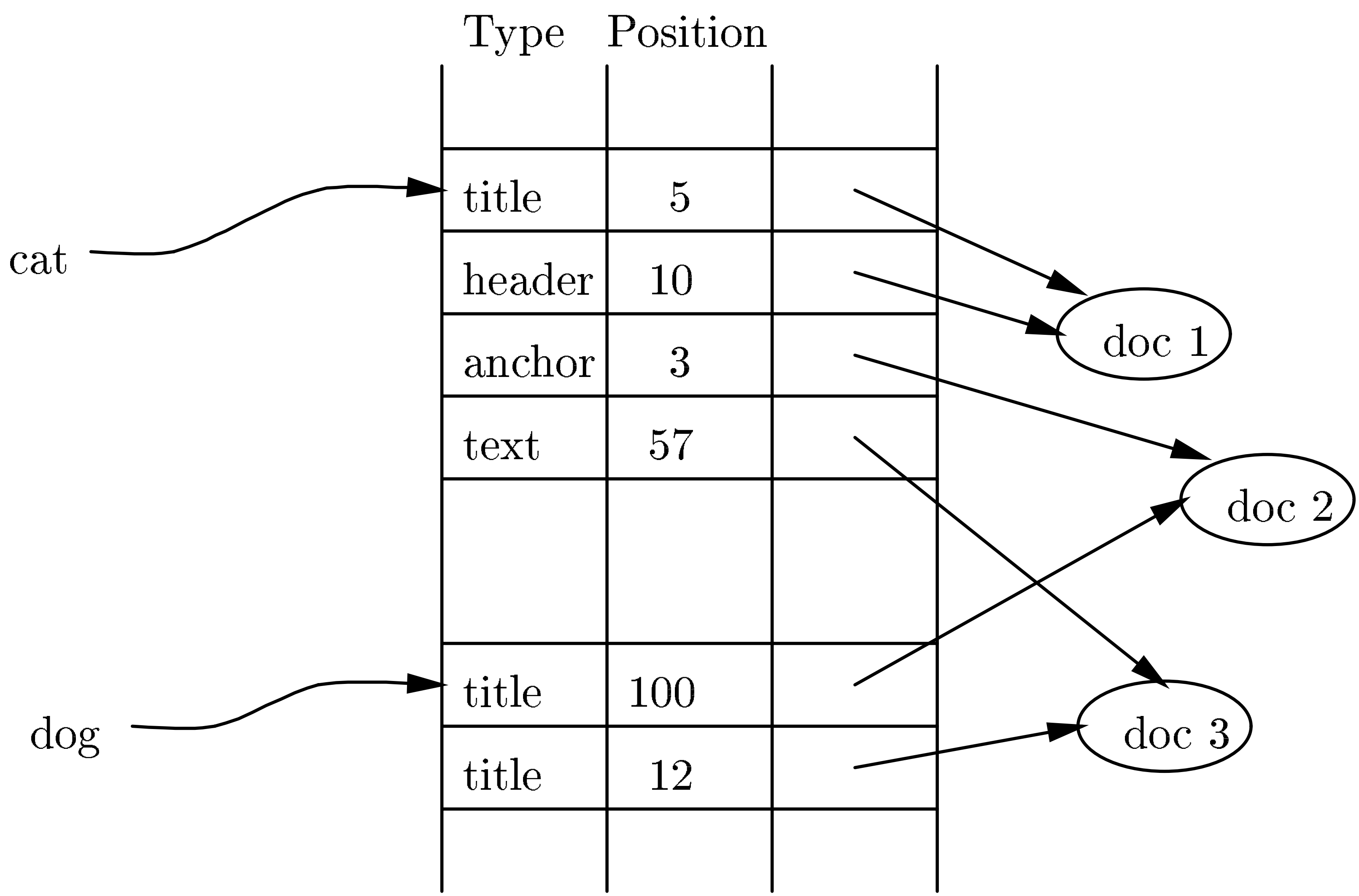
Additional Information in Buckets

Buckets can be extended to include “Type” (e.g., specify whether the word appears in the title, abstract or body), “Position” of word, etc.



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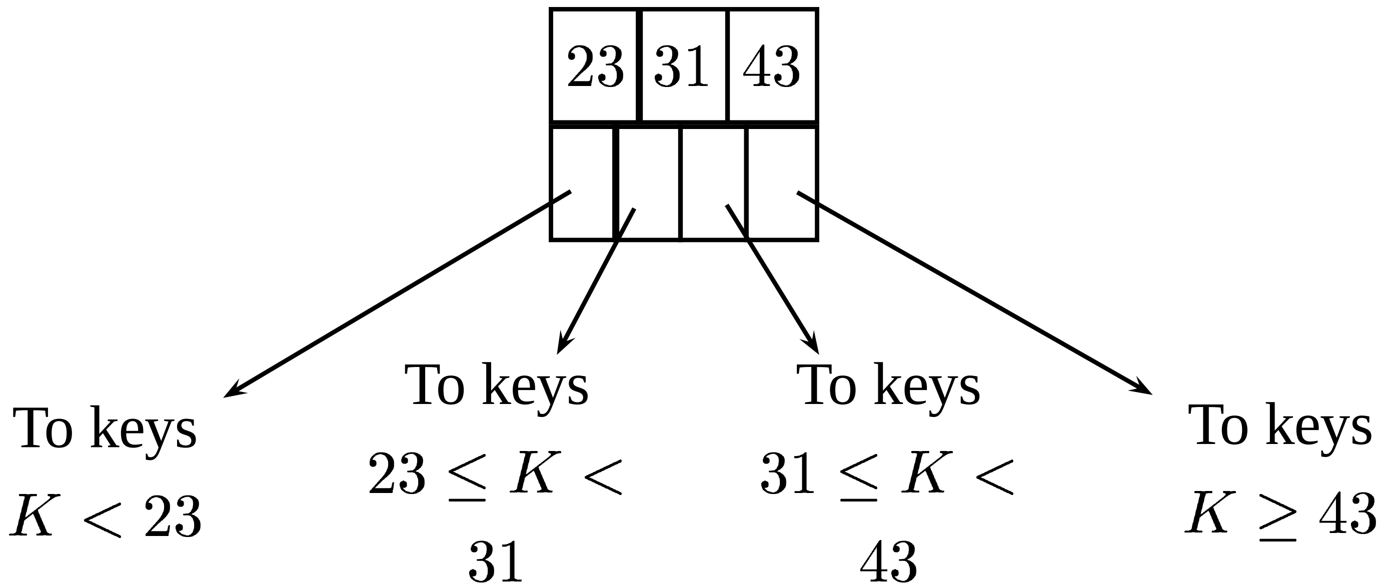
  - **B-**Tree Indexes.

B-Trees

- A B-Tree is a multilevel index with a *Tree* structure;
- When used as primary index (i.e., on a sorted file) maintains efficiency against insertion and deletion of records avoiding file reorganization (the main disadvantage of index on sequential file);
- Also used to index very-large relations when single-level indexes don't fit in main memory;
- Commercial systems (DB2, ORACLE) implement indexes with B-Trees;
- In the following we will present the structure of so called B^+-*Tree* – the **B** stands for **Balanced Tree**.

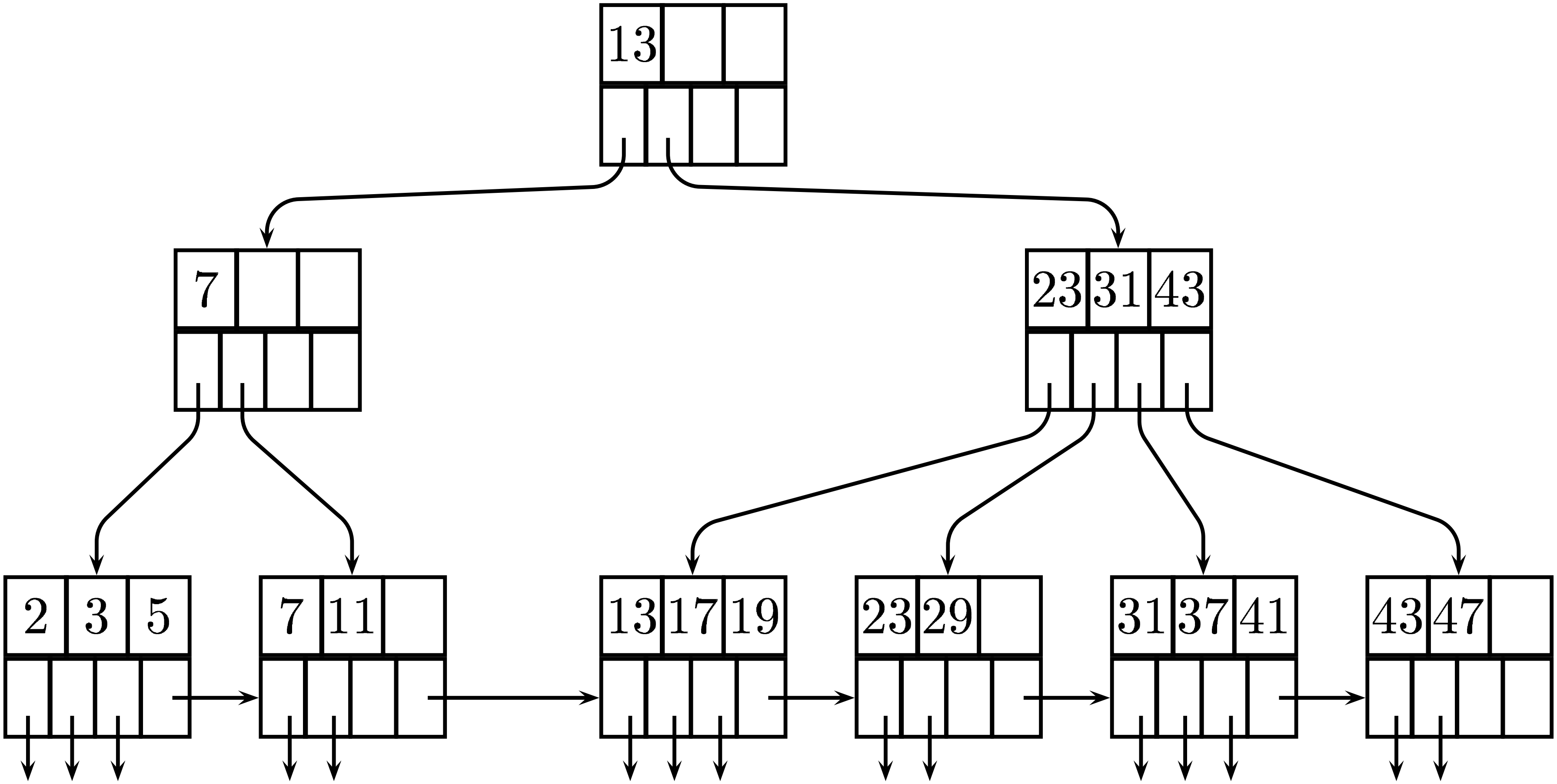
B-Trees (cont.)

- B-tree is usually a 3 levels tree: the root, an intermediate level, the leaves.
- All the leaves are at the same level $\rightarrow$ *Balanced Tree*.
- The size of each node of the B-tree is equal to a disk block. All nodes have the same format: **n keys** and $\mathbf{n}+1$ **pointers** $\rightarrow$ n key-pointer pairs plus 1 extra pointer.



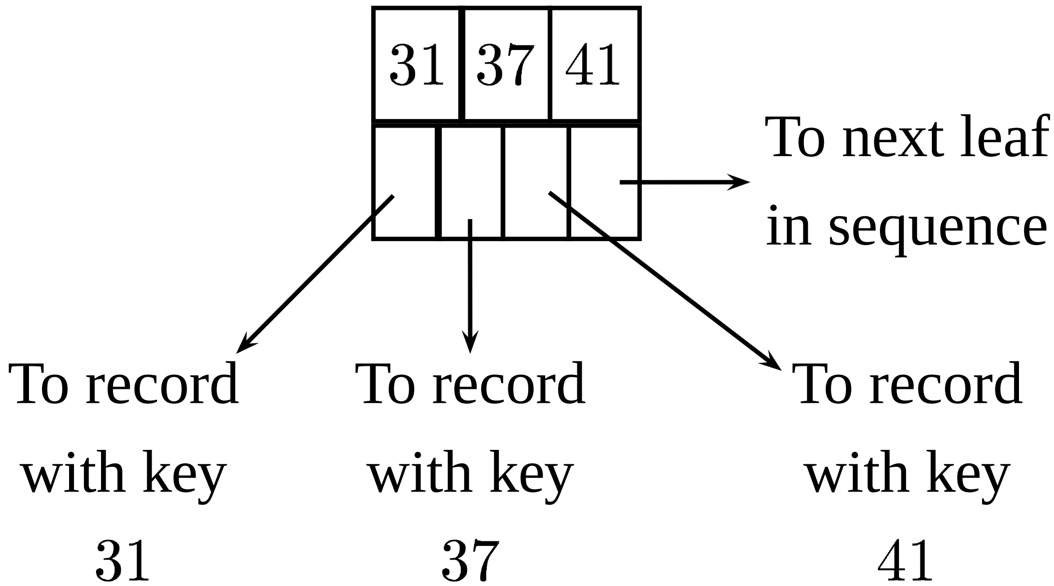
Example. Let a block be 4096 bytes, a search key be an integer of 4 bytes, and a pointer be 8 bytes. If there is no additional header in the block then n is the largest integer s.t. $4n + 8(n+1) \leq 4096 \;\; \rightarrow n = 340$.

B-Tree: An Example



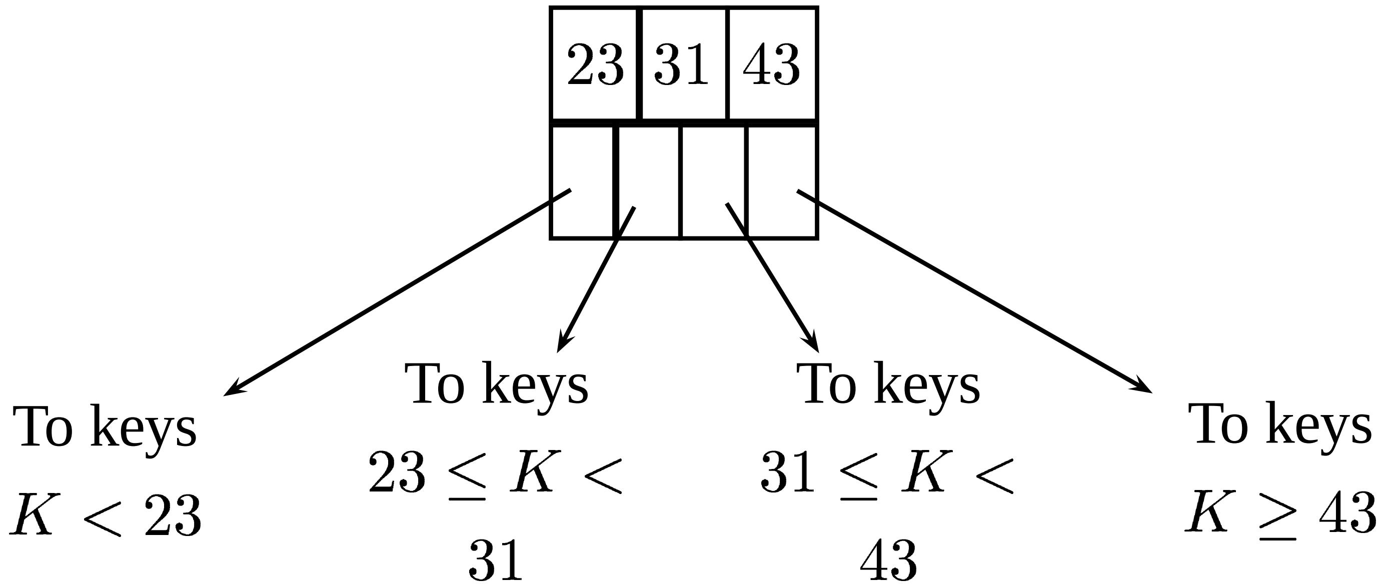
- Data file where search-keys are all the prime numbers from 2 to 47.
- All the keys appear once (in case of a dense index), and in sorted order at the leaves.
- A pointer points to either a file record (in case of a primary index structure) or to a bucket of pointers (in case of a secondary index structure).

Leaves



- One pointer to next leaf—used to chain leaf nodes in search-key order for efficient sequential processing;
- At least $\left\lfloor \frac{n+1}{2} \right\rfloor$ (round down) key-pointer pairs pointing to either records of the data file (as shown in the Figure) or to a bucket of pointers.

Interior Nodes



- All $n + 1$ pointers can be used to point to B-tree nodes of the inferior level;
- At least $\lceil \frac{n+1}{2} \rceil$ (round up) pointers must be used, and one more pointer than key is used.
  - **Exception:** the root may have only 2 children, then one key and two pointers, regardless of how large n is.

B-Trees as Indexes

B-Trees are useful for various types of indexes:

1. The search key is a primary or candidate key (i.e., no duplicates) of the data file and the B-Tree is a dense index with a key-pointer pair in a leaf for every record in the data file. The data file may or may not be sorted by primary key (primary or secondary index).

2. The search key is not a key (i.e., *duplicate values*) and the data file is *sorted* by this attribute. The B-Tree is a dense primary index with no duplicate key-pointer pairs: just a single entry for each record in the data file with search key K, and pointers to the first record with search key K.

3. The data file is *sorted* by search-key, and the B-Tree is a sparse primary index with a key-pointer pair for each data block of the data file.

4. The search key is not a key (i.e., *duplicate values*) and the data file is **NOT** *sorted*. The B-Tree is a secondary index with indirect bucket: No duplicate key-pointer pairs, just a single entry for each record in the data file with a given search key, and pointers to a bucket of pointers.

Lookup in B-trees

Problem: Given a B-tree (dense) index, find a record with search key K.

Recursive search, starting at the root and ending at a leaf:

1. If we are at a leaf then if K is among the keys of the leaf follow the associated pointer to the data file, else fail.

2. If we are at an interior node (included the root) with keys $K_1, K_2, \ldots, K_n$, then if $K < K_1$ then go to the first child, if $K_1 \leq K < K_2$ then go to the second child, and so on.

Note: B-Trees are useful for queries in which a range of values are asked for: *Range Queries*.

B-Tree Updates

Insertion and **D**eletion are more complicated that lookup. It may be necessary to either:

1. Split a node that becomes too large as the result of an insertion;
2. Merge nodes (i.e., combine nodes) if a node becomes too small as the result of a deletion.

B-Tree Insertion

Algorithm for inserting a new search key in a B-Tree.

1. Start a search for the key being inserted. If there is room for another key-pointer at the reached leaf, insert there;
2. If there is no room in the leaf, **split** the leaf in two and divide the keys between the two new nodes (each node is at least half full);
3. The splitting of nodes implies that a new key-pointer pair has to be inserted at the level above. If necessary the parent node will be split and we proceed recursively up the tree (including the root).

B-Tree Insertion: Splitting Leaves

Let N be a leaf whose capacity is n keys, and we need to insert the $(n+1)$ key-pointer pair.

1. Create a new sibling node M, to the right of N;
2. The first $\lceil \frac{n+1}{2} \rceil$ key-pointer pairs remain with N, while the other move to M.
3. The first key of the new node M is also inserted at the parent node.

Note: At least $\lfloor \frac{n+1}{2} \rfloor$ key-pointer pairs for both of the splitted nodes.

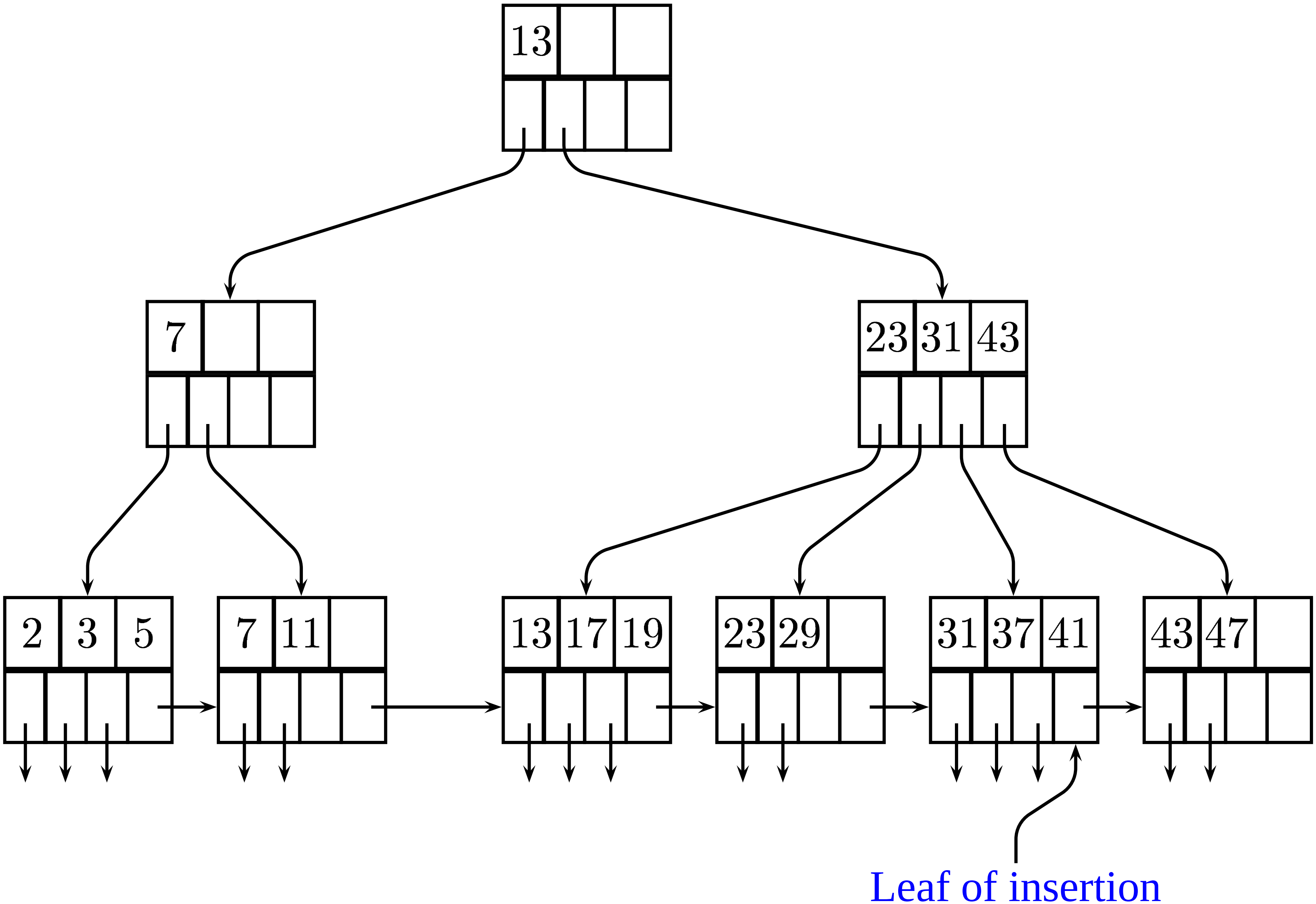
B-Tree Insertion: Splitting Interior Nodes

Let N be an interior node whose capacity is n keys and $(n+1)$ pointers, and N has been assigned the new pointer $(n+2)$ because of a node splitting at the inferior level.

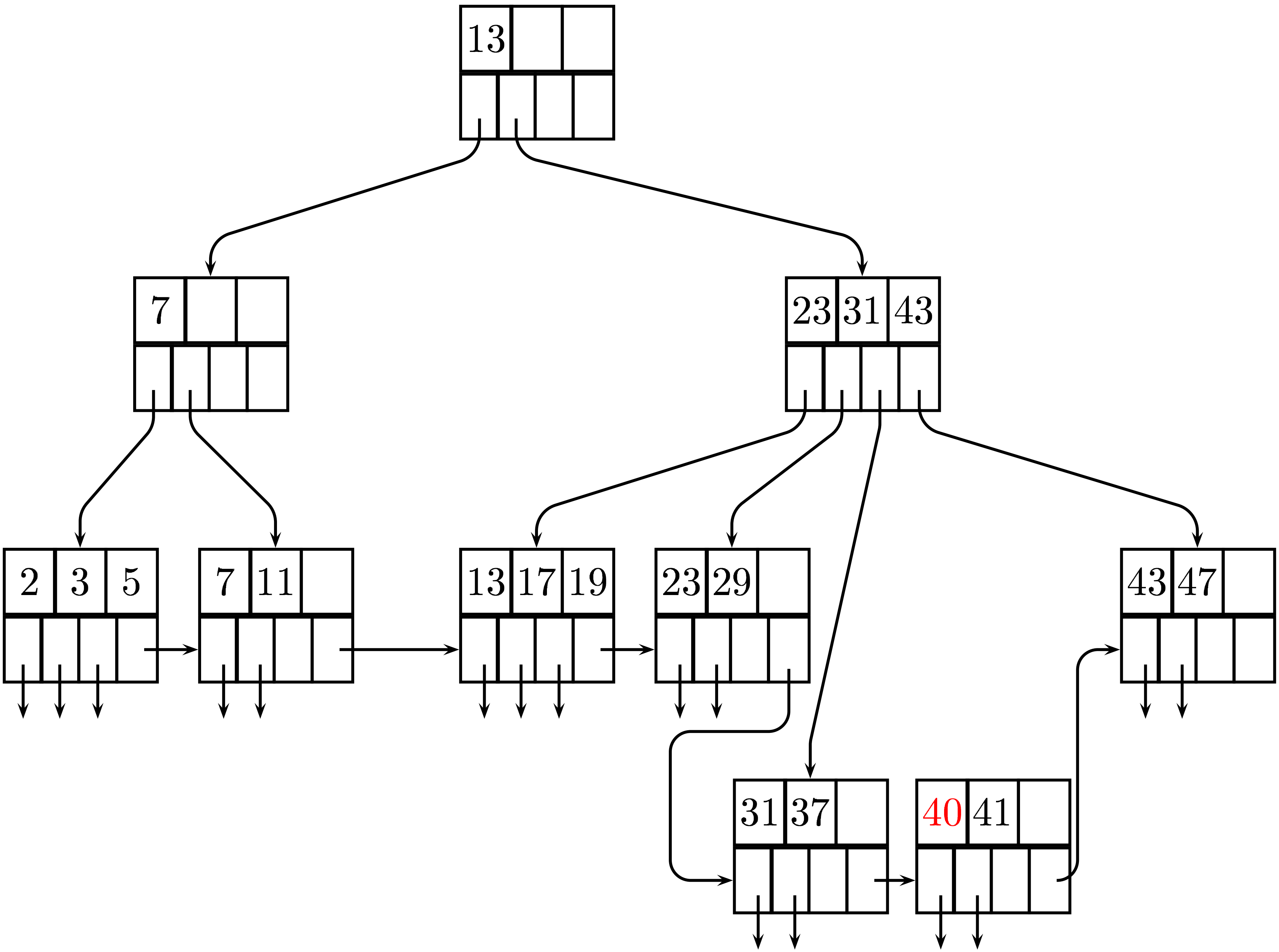
1. Create a new sibling node M, to the right of N;
2. Leave at N the first $\lceil \frac{n+2}{2} \rceil$ pointers, and move the other to M;
3. The first $\lceil \frac{n}{2} \rceil$ keys stay with N, while the last $\lfloor \frac{n}{2} \rfloor$ keys move to M. Since there are $(n+1)$ keys there is one key in the middle (say it K_l) that doesn't go with neither N nor M, but:
   - K_l is reachable via the first of M's children;
   - K_l is used by the common parent of N and M to distinguish the search between those two nodes.

Note: At least $\lceil \frac{n+1}{2} \rceil$ pointers for both of the splitted nodes.

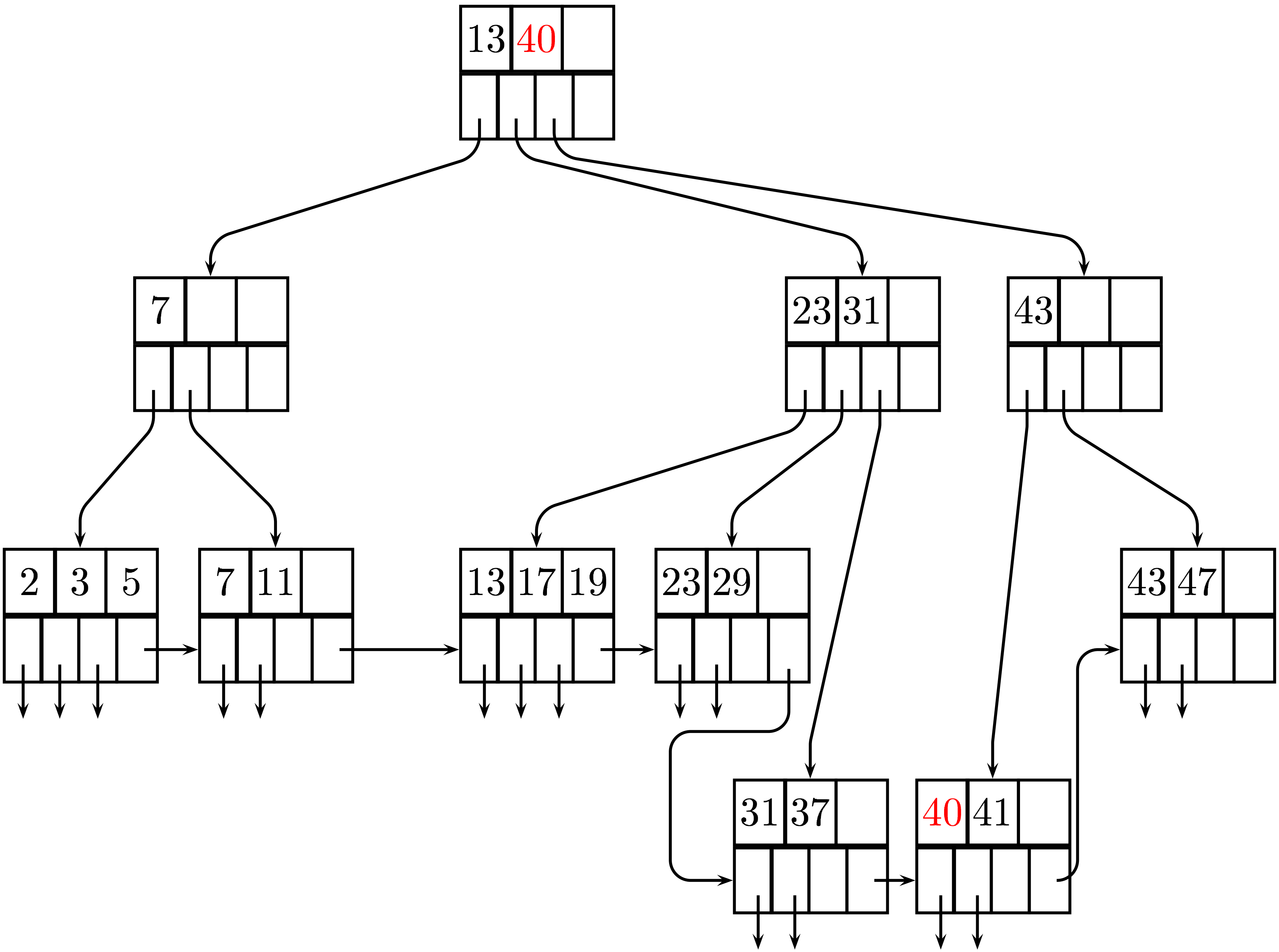
Example: B-Tree Insertion of the key 40



Example: Splitting the Leaf for Inserting Key 40



Example: Splitting Interior Nodes

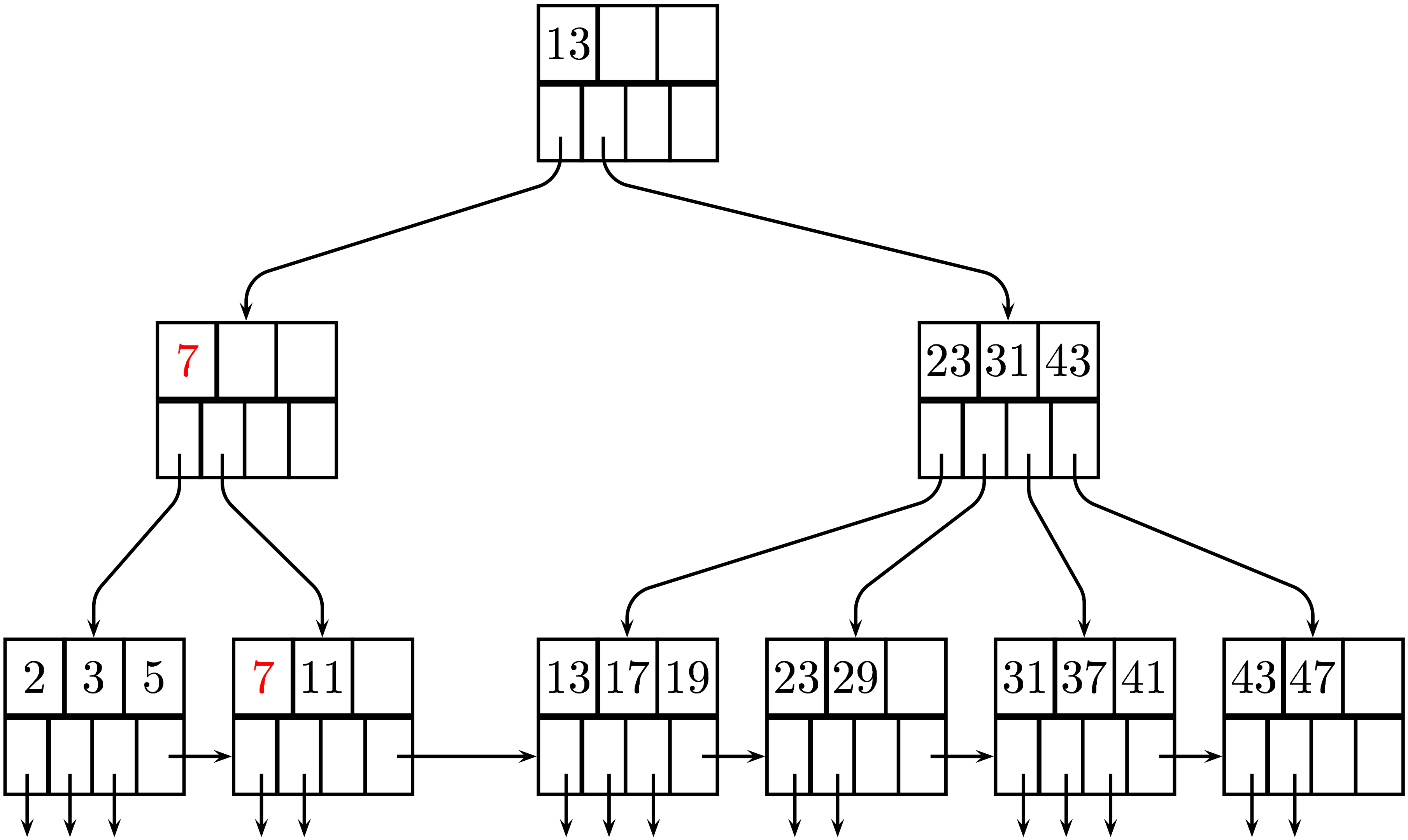


B-Tree Deletion

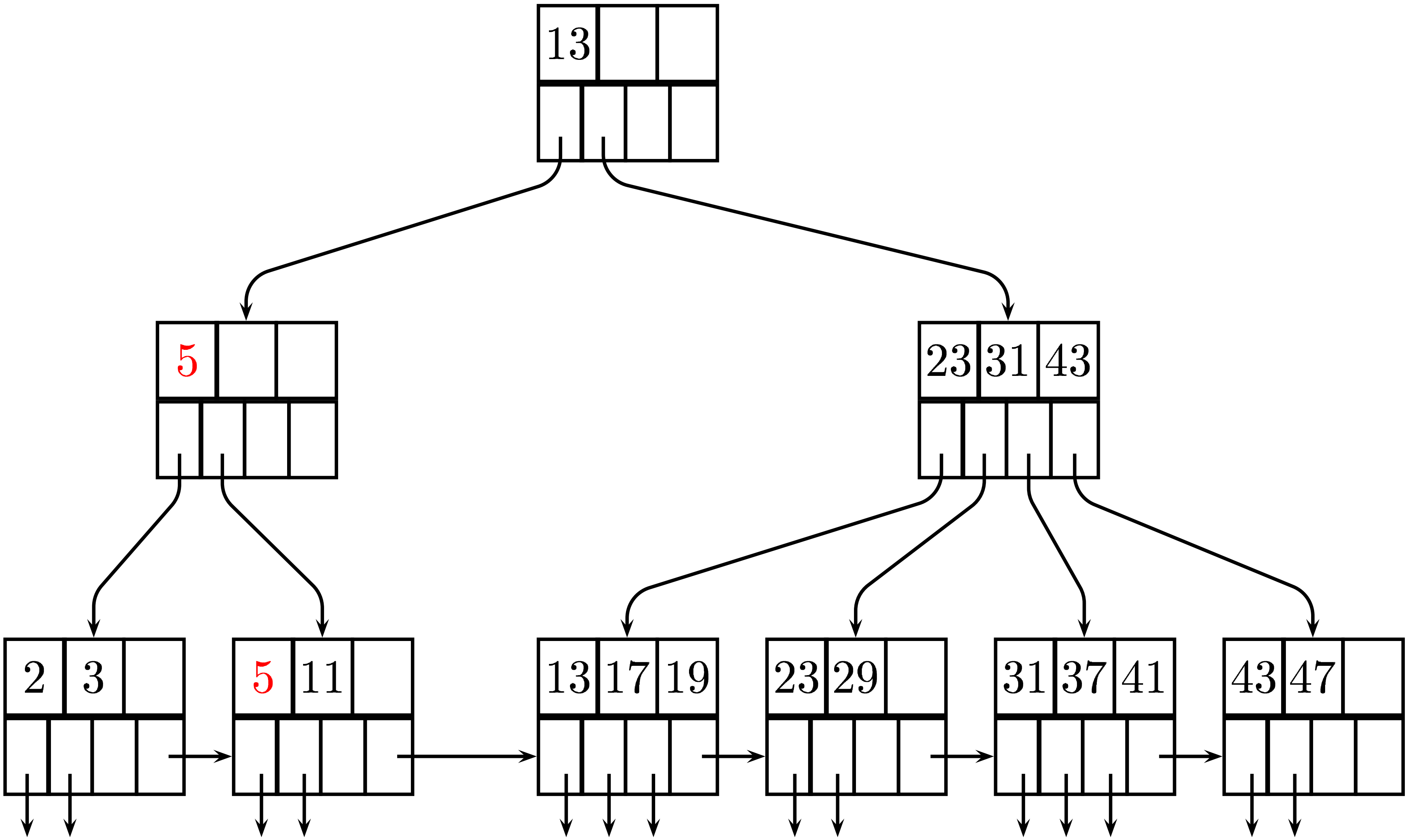
Algorithm for deleting a search key in a B-Tree.

1. Start a search for the key being deleted;
2. Delete the record from the data file and the key-pointer pair from the leaf of the B-tree;
3. If the lower limit of keys and pointers on a leaf is violated then two cases are possible:
   (a) Look for an adjacent sibling that is above lower limit and "steal" a key-pointer pair from that leaf, keeping the order of keys intact. Make sure keys for the parent are adjusted to reflect the new situation.
   (b) Hard case: no adjacent sibling can provide an extra key. Then there must be two adjacent siblings leaves, one at minimum, one below minimum capacity. Just enough to **merge** nodes deleting one of them. Keys at the parent should be adjusted, and then delete a key and a pointer. If the parent is below the minimum capacity then we recursively apply the deletion algorithm at the parent.

Example: B-Tree Deletion of the Key 7



Example: B-Tree Deletion of the Key 7 (cont.)



Efficiency of B-Trees

- B-Trees allow lookup, insertion and deletion of records of very large relations using few disk I/O.

- When the capacity n of B-Tree nodes is reasonably large ($n > 10$) splitting and merging of nodes is rare.

- 3 levels are typical: let a block be 4096 bytes, a search key be an integer of 4 bytes, and a pointer be 8 bytes $\rightarrow n = 340$. Suppose that a node is occupied midway between the minimum (170) and the maximum, then each node has 255 pointers $\rightarrow$ Root $+255$ children $+255^2 = 65025$ leaves $\rightarrow$ $65025 * 255 = 255^3 = 16.6$million pointers to data file records.

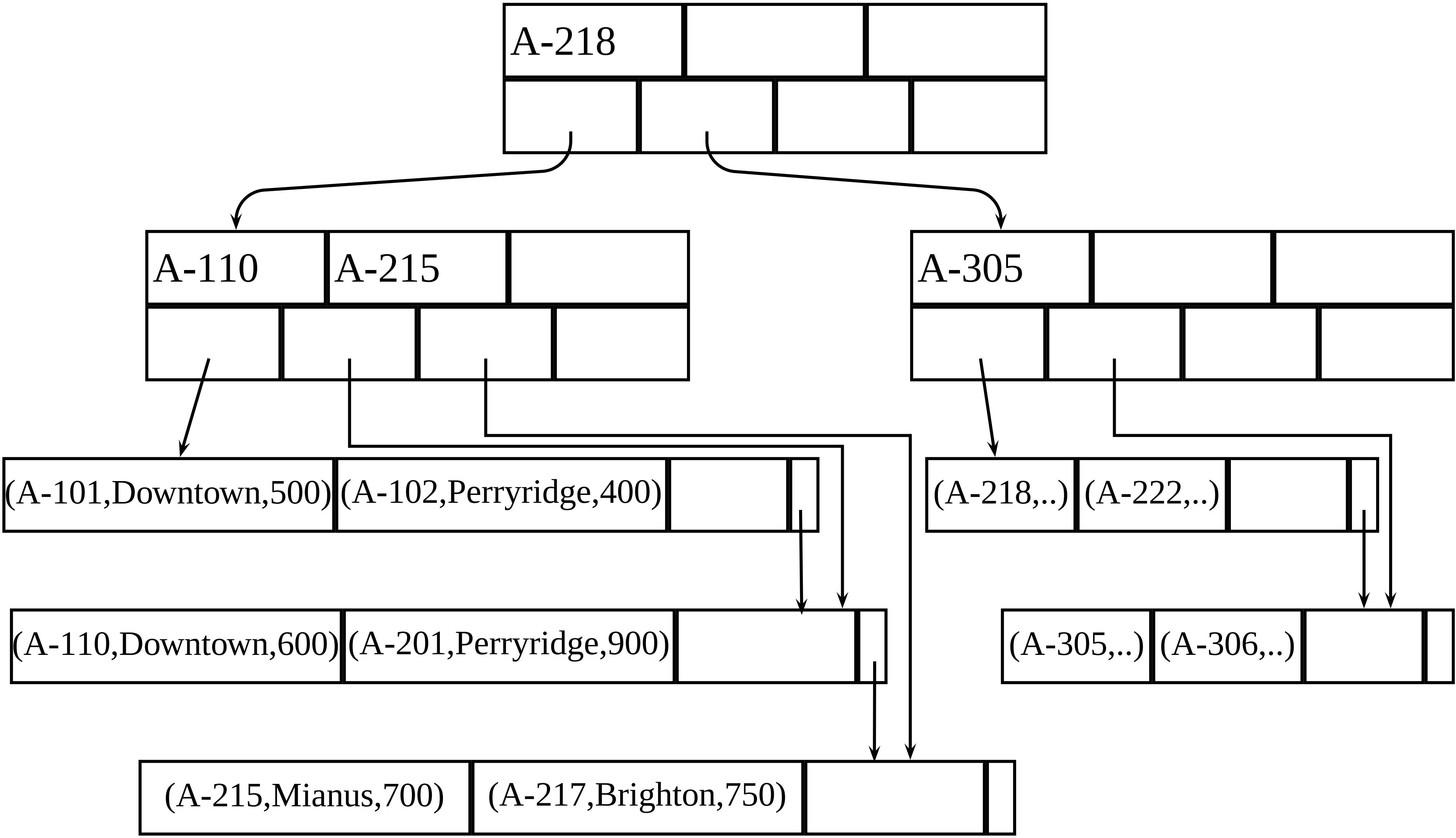
- If the root is kept in main memory lookup requires 2 disk I/O for traversing the tree and 1 disk I/O for accessing the record, if also second level in main memory a single disk I/O is sufficient for traversing the tree.

Efficiency of B-Trees (cont.)

B-Tree maintains its efficiency against relation updates.

- A relation is physically stored into a B-Tree.
- The actual records are stored in the leaf level of the B-Tree.
- Insertion and deletion can cause either node splitting or merging – i.e., no need for overflow blocks.

Efficiency of B-Trees: Relation Storage Example



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