



Chapter 14: Indexing

Database System Concepts, 7th Ed.

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Chapter 14: Indexing

- Basic Concepts
- Ordered Indices
- B⁺-Tree Index Files
- B-Tree Index Files
- Hashing
- Write-optimized indices
- Spatio-Temporal Indexing



Basic Concepts

- Indexing mechanisms used to speed up access to desired data.
 - E.g., author catalog in library
- **Search Key** - attribute to set of attributes used to look up records in a file.
- An **index file** consists of records (called **index entries**) of the form

search-key	pointer
------------	---------

- Index files are typically much smaller than the original file
- Two basic kinds of indices:
 - **Ordered indices:** search keys are stored in sorted order
 - **Hash indices:** search keys are distributed uniformly across “buckets” using a “hash function”.



Index Evaluation Metrics

- Access types supported efficiently. E.g.,
 - records with a specified value in the attribute
 - or records with an attribute value falling in a specified range of values.
- Access time
- Insertion time
- Deletion time
- Space overhead



Ordered Indices

- In an **ordered index**, index entries are stored sorted on the search key value.
- **Clustering index**: in a sequentially ordered file, the index whose search key specifies the sequential order of the file.
 - Also called **primary index**
 - The search key of a primary index is usually but not necessarily the primary key.
- **Secondary index**: an index whose search key specifies an order different from the sequential order of the file. Also called **nonclustering index**.
- **Index-sequential file**: sequential file ordered on a search key, with a clustering index on the search key.



Dense Index Files

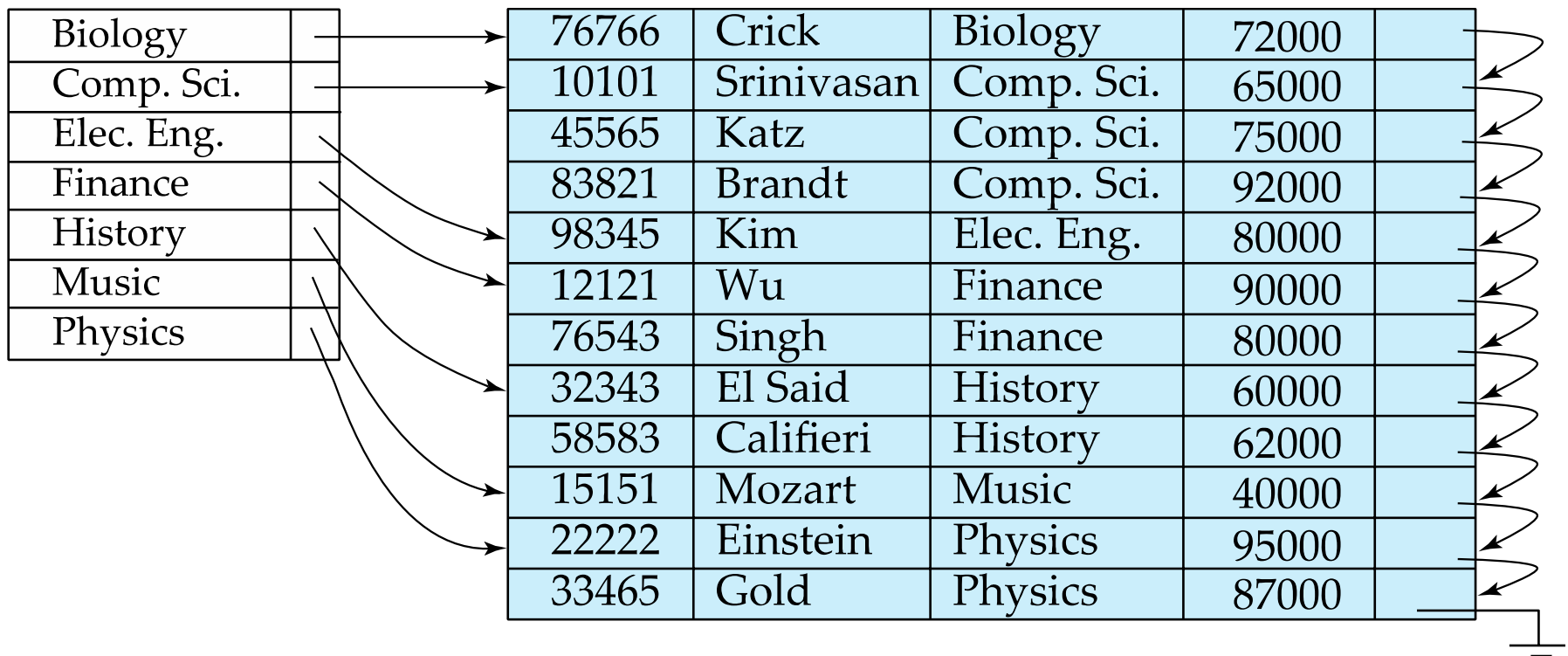
- **Dense index** — Index record appears for every search-key value in the file.
- E.g. index on *ID* attribute of *instructor* relation

10101	→	10101	Srinivasan	Comp. Sci.	65000	↙
12121	→	12121	Wu	Finance	90000	↙
15151	→	15151	Mozart	Music	40000	↙
22222	→	22222	Einstein	Physics	95000	↙
32343	→	32343	El Said	History	60000	↙
33456	→	33456	Gold	Physics	87000	↙
45565	→	45565	Katz	Comp. Sci.	75000	↙
58583	→	58583	Califieri	History	62000	↙
76543	→	76543	Singh	Finance	80000	↙
76766	→	76766	Crick	Biology	72000	↙
83821	→	83821	Brandt	Comp. Sci.	92000	↙
98345	→	98345	Kim	Elec. Eng.	80000	↙



Dense Index Files (Cont.)

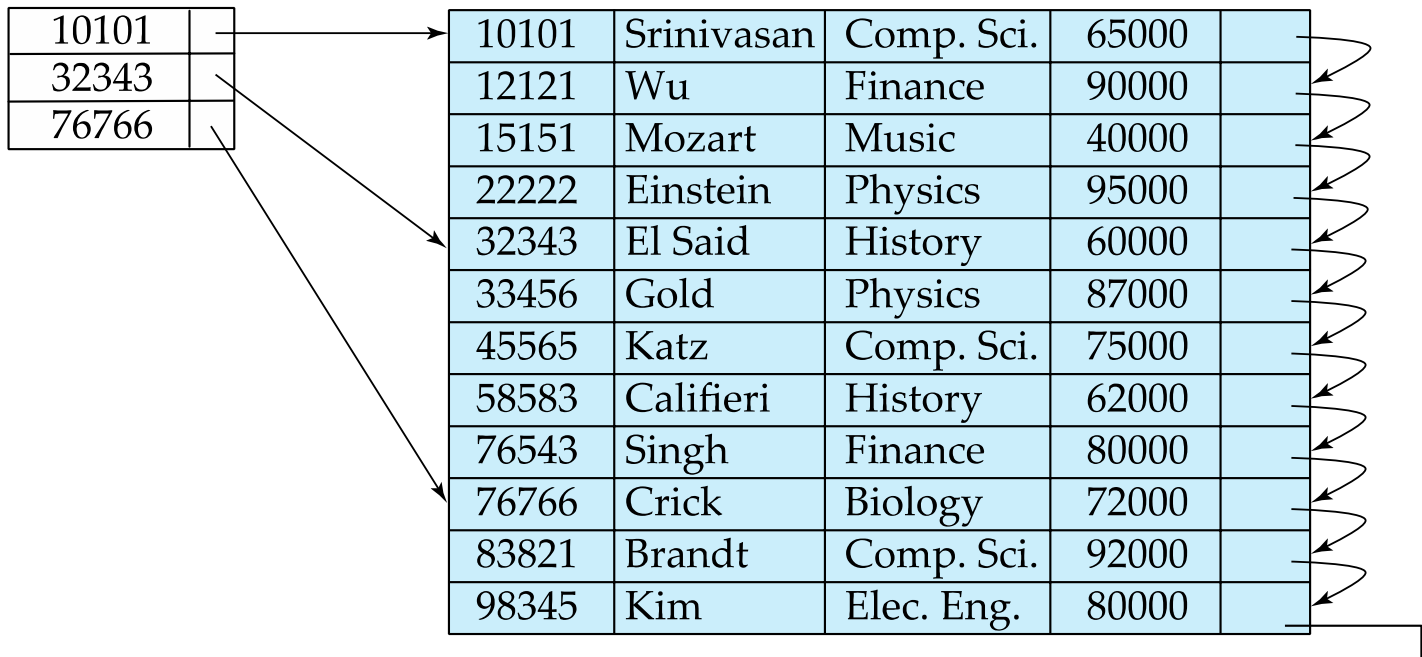
- Dense index on *dept_name*, with *instructor* file sorted on *dept_name*





Sparse Index Files

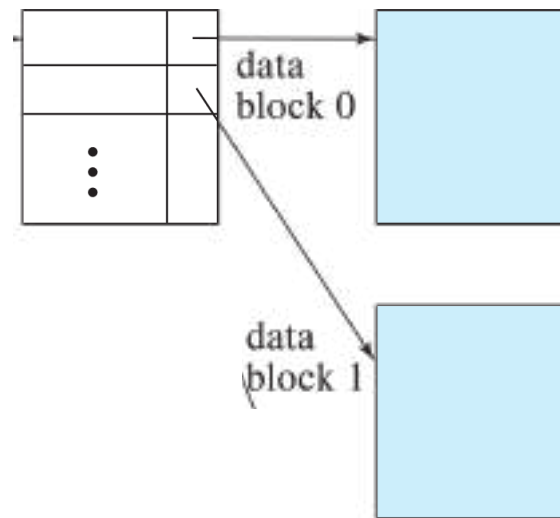
- **Sparse Index:** contains index records for only some search-key values.
 - Applicable when records are sequentially ordered on search-key
- To locate a record with search-key value K we:
 - Find index record with largest search-key value $< K$
 - Search file sequentially starting at the record to which the index record points





Sparse Index Files (Cont.)

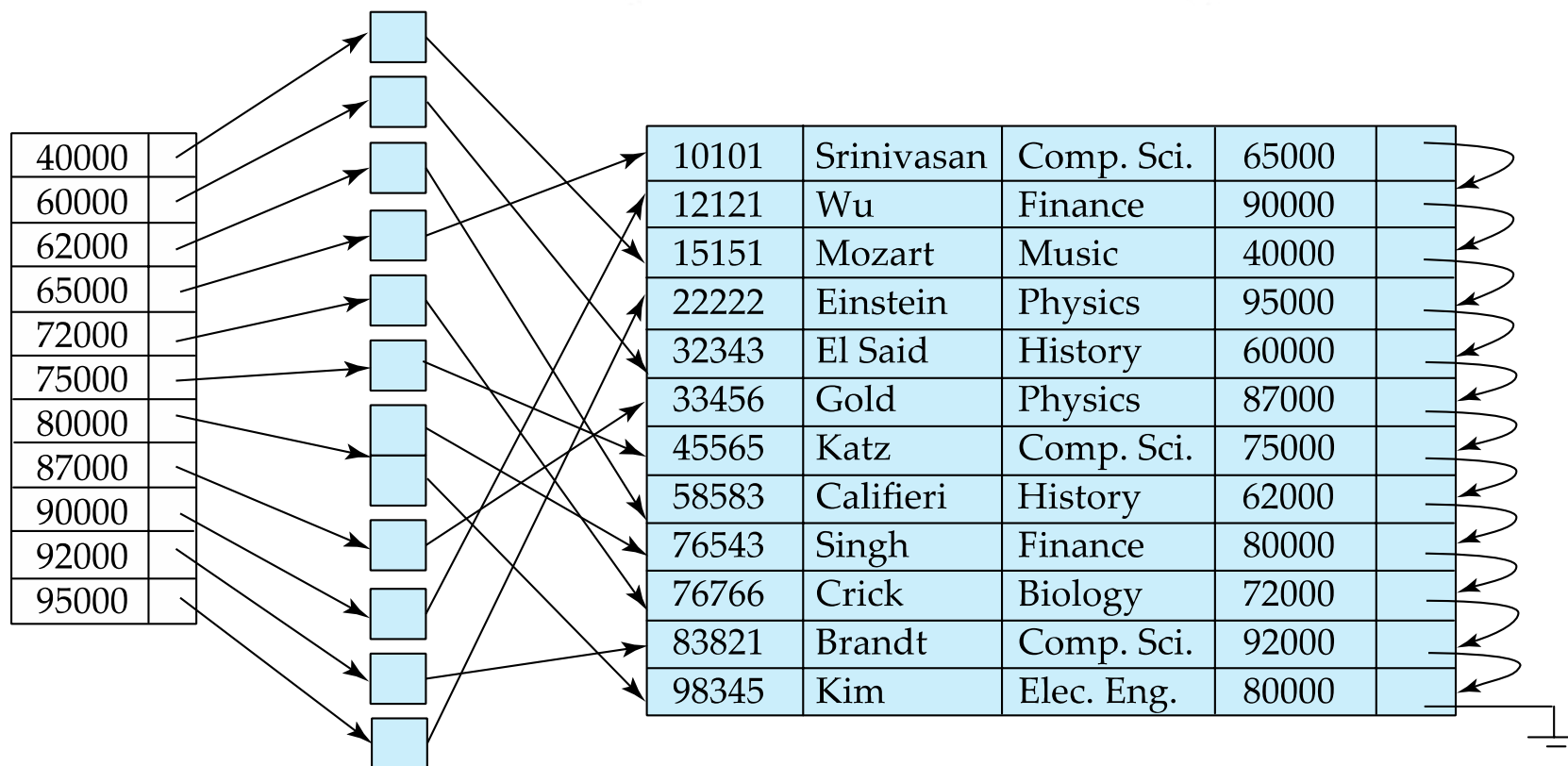
- Compared to dense indices:
 - Less space and less maintenance overhead for insertions and deletions.
 - Generally slower than dense index for locating records.
- **Good tradeoff:**
 - for clustered index: sparse index with an index entry for every block in file, corresponding to least search-key value in the block.



- For unclustered index: sparse index on top of dense index (multilevel index)



Secondary Indices Example



Secondary index on *salary* field of *instructor*

- Index record points to a bucket that contains pointers to all the actual records with that particular search-key value.
- Secondary indices have to be dense

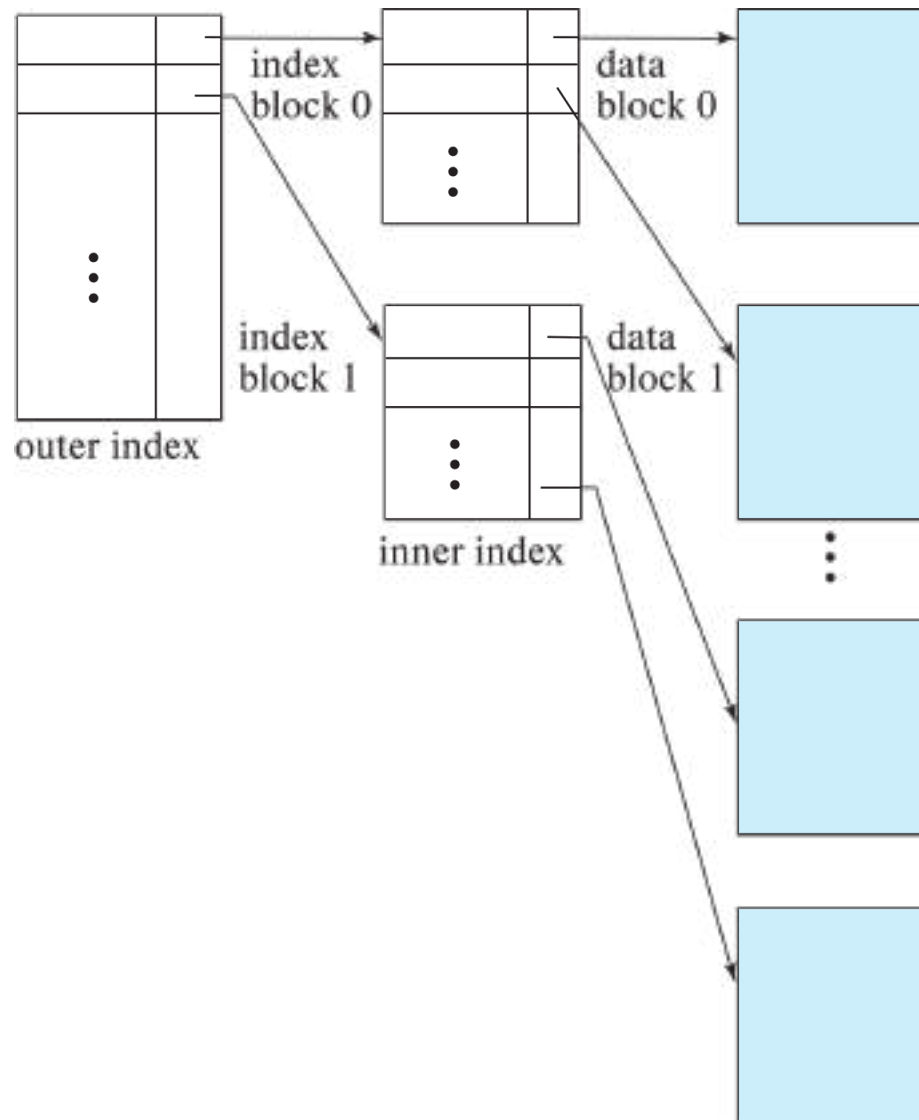


Multilevel Index

- If index does not fit in memory, access becomes expensive.
- Solution: treat index kept on disk as a sequential file and construct a sparse index on it.
 - outer index – a sparse index of the basic index
 - inner index – the basic index file
- If even outer index is too large to fit in main memory, yet another level of index can be created, and so on.
- Indices at all levels must be updated on insertion or deletion from the file.



Multilevel Index (Cont.)





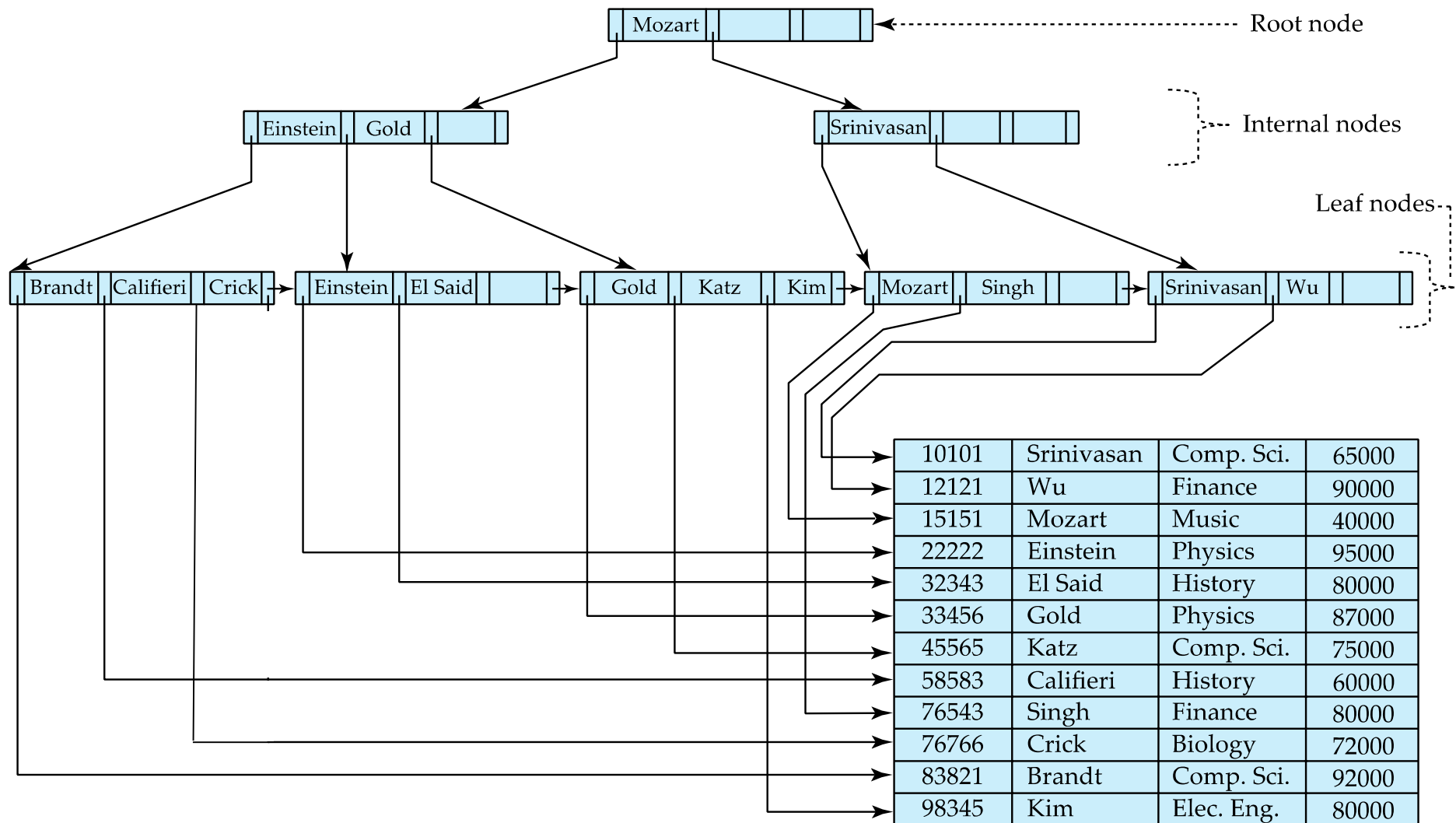
Indices on Multiple Keys

- **Composite search key**

- e.g. index on *instructor* relation on attributes (*name*, *ID*)
- Values are sorted lexicographically
 - E.g. (John, 12121) < (John, 13514) and (John, 13514) < (Peter, 11223)
- Can query on just *name*, or on (*name*, *ID*)



Example of B⁺-Tree





B⁺-Tree Index Files (Cont.)

A B⁺-tree is a rooted tree satisfying the following properties:

- All paths from root to leaf are of the same length
- Each node that is not a root or a leaf has between $\lceil n/2 \rceil$ and n children.
- A leaf node has between $\lceil (n-1)/2 \rceil$ and $n-1$ values
- Special cases:
 - If the root is not a leaf, it has at least 2 children.
 - If the root is a leaf (that is, there are no other nodes in the tree), it can have between 0 and $(n-1)$ values.



B⁺-Tree Node Structure

- Typical node

P_1	K_1	P_2	\dots	P_{n-1}	K_{n-1}	P_n
-------	-------	-------	---------	-----------	-----------	-------

- K_i are the search-key values
- P_i are pointers to children (for non-leaf nodes) or pointers to records or buckets of records (for leaf nodes).

- The search-keys in a node are ordered

$$K_1 < K_2 < K_3 < \dots < K_{n-1}$$

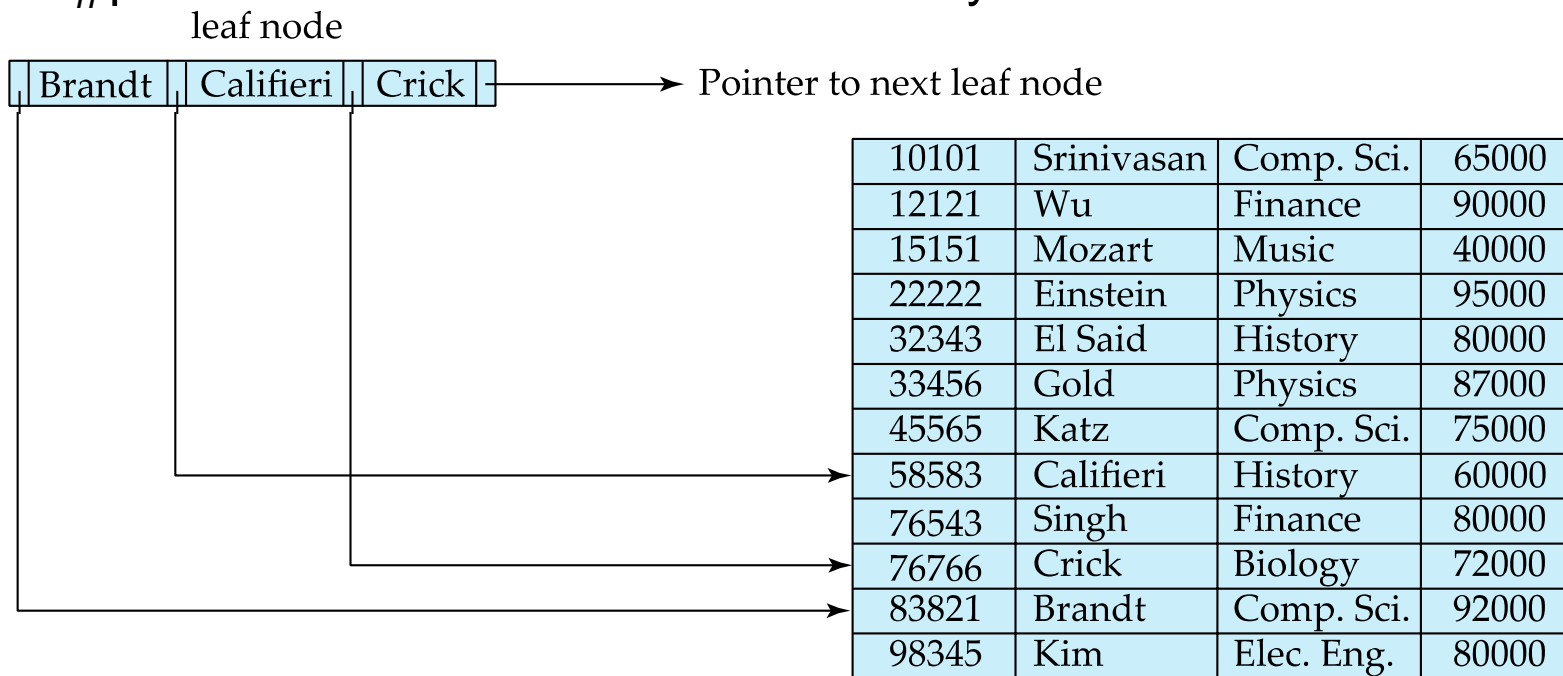
(Initially assume no duplicate keys, address duplicates later)



Leaf Nodes in B⁺-Trees

Properties of a leaf node:

- For $i = 1, 2, \dots, n-1$, pointer P_i points to a file record with search-key value K_i ,
- If L_i, L_j are leaf nodes and $i < j$, L_i 's search-key values are less than or equal to L_j 's search-key values
- P_n points to next leaf node in search-key order





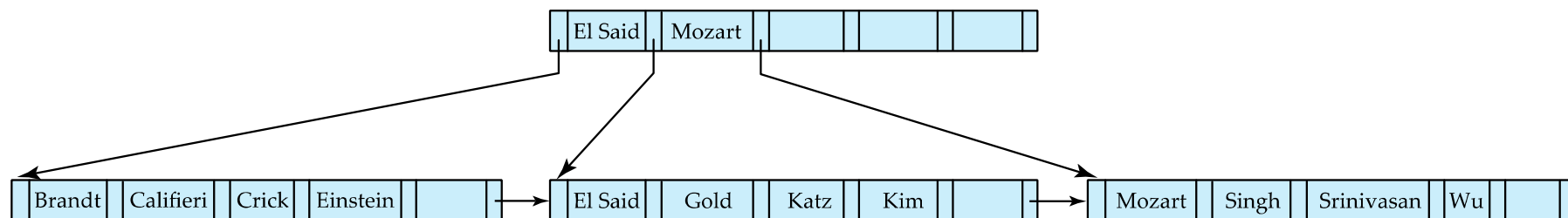
Non-Leaf Nodes in B⁺-Trees

- Non leaf nodes form a multi-level sparse index on the leaf nodes. For a non-leaf node with m pointers:
 - All the search-keys in the subtree to which P_1 points are less than K_1
 - For $2 \leq i \leq n - 1$, all the search-keys in the subtree to which P_i points have values greater than or equal to K_{i-1} and less than K_i
 - All the search-keys in the subtree to which P_n points have values greater than or equal to K_{n-1}

P_1	K_1	P_2	...	P_{n-1}	K_{n-1}	P_n
-------	-------	-------	-----	-----------	-----------	-------



Example of B⁺-tree



B⁺-tree for *instructor* file ($n = 6$)

- Leaf nodes must have between 3 and 5 values ($\lceil (n-1)/2 \rceil$ and $n-1$, with $n = 6$).
- Non-leaf nodes other than root must have between 3 and 6 children ($\lceil n/2 \rceil$ and n with $n = 6$).
- Root must have at least 2 children.



Observations about B⁺-trees

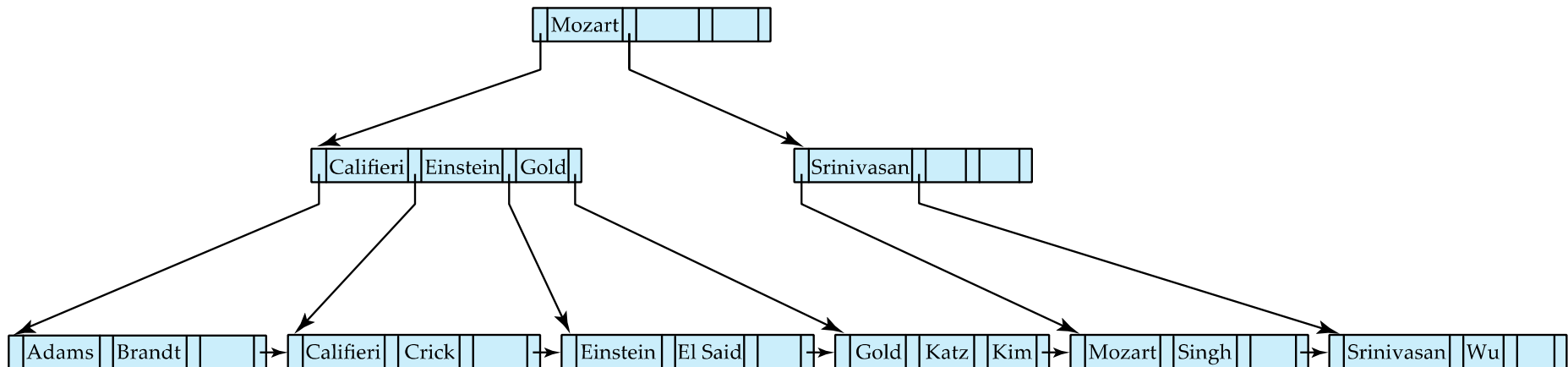
- Since the inter-node connections are done by pointers, “logically” close blocks need not be “physically” close.
- The non-leaf levels of the B⁺-tree form a hierarchy of sparse indices.
- The B⁺-tree contains a relatively small number of levels
 - Level below root has at least $2 * \lceil n/2 \rceil$ values
 - Next level has at least $2 * \lceil n/2 \rceil * \lceil n/2 \rceil$ values
 - .. etc.
- If there are K search-key values in the file, the tree height is no more than $\lceil \log_{\lceil n/2 \rceil}(K) \rceil$
- thus searches can be conducted efficiently.
- Insertions and deletions to the main file can be handled efficiently, as the index can be restructured in logarithmic time (as we shall see).



Queries on B⁺-Trees

function *find*(*v*)

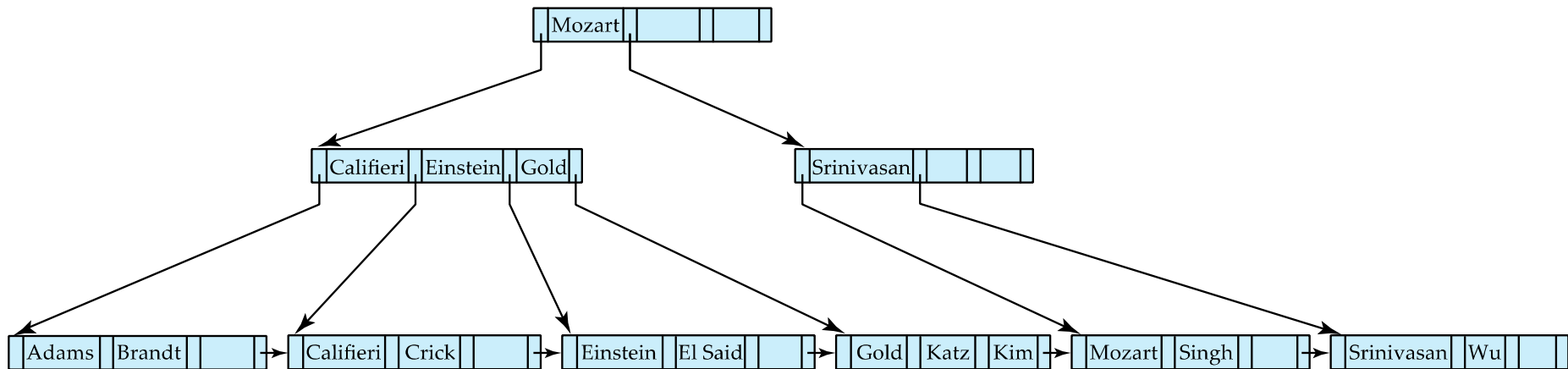
1. *C* = *root*
2. **while** (*C* is not a leaf node)
 1. Let *i* be least number s.t. $V \leq K_i$.
 2. **if** there is no such number *i* *then*
 3. Set *C* = *last non-null pointer in C*
 4. **else if** ($v = C.K_i$) Set *C* = *P_{i+1}*
 5. **else set** *C* = *C.P_i*
3. **if** for some *i*, $K_i = V$ **then** return *C.P_i*
4. **else** return null /* no record with search-key value *v* exists. */





Queries on B⁺-Trees (Cont.)

- **Range queries** find all records with search key values in a given range
 - See book for details of **function** *findRange(lb, ub)* which returns set of all such records
 - Real implementations usually provide an iterator interface to fetch matching records one at a time, using a *next()* function





Queries on B⁺-Trees (Cont.)

- If there are K search-key values in the file, the height of the tree is no more than $\lceil \log_{\lceil n/2 \rceil}(K) \rceil$.
- A node is generally the same size as a disk block, typically 4 kilobytes
 - and n is typically around 100 (40 bytes per index entry).
- With 1 million search key values and $n = 100$
 - at most $\log_{50}(1,000,000) = 4$ nodes are accessed in a lookup traversal from root to leaf.
- Contrast this with a balanced binary tree with 1 million search key values — around 20 nodes are accessed in a lookup
 - above difference is significant since every node access may need a disk I/O, costing around 20 milliseconds



Non-Unique Keys

- If a search key a_i is not unique, create instead an index on a composite key (a_i, A_p) , which is unique
 - A_p could be a primary key, record ID, or any other attribute that guarantees uniqueness
- Search for $a_i = v$ can be implemented by a range search on composite key, with range $(v, -\infty)$ to $(v, +\infty)$
- But more I/O operations are needed to fetch the actual records
 - If the index is clustering, all accesses are sequential
 - If the index is non-clustering, each record access may need an I/O operation



Updates on B⁺-Trees: Insertion

Assume record already added to the file. Let

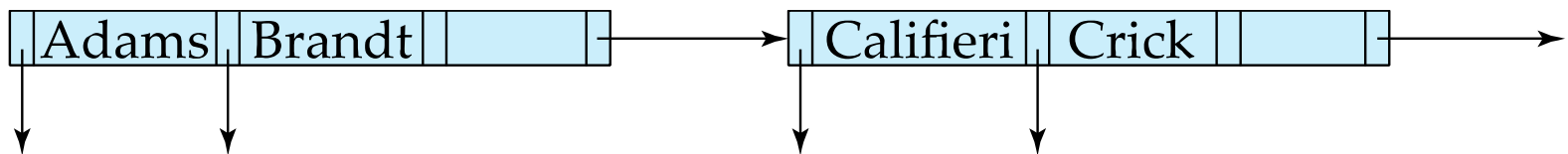
- | pr be pointer to the record, and let
- | v be the search key value of the record

1. Find the leaf node in which the search-key value would appear
 1. If there is room in the leaf node, insert (v, pr) pair in the leaf node
 2. Otherwise, split the node (along with the new (v, pr) entry) as discussed in the next slide, and propagate updates to parent nodes.



Updates on B⁺-Trees: Insertion (Cont.)

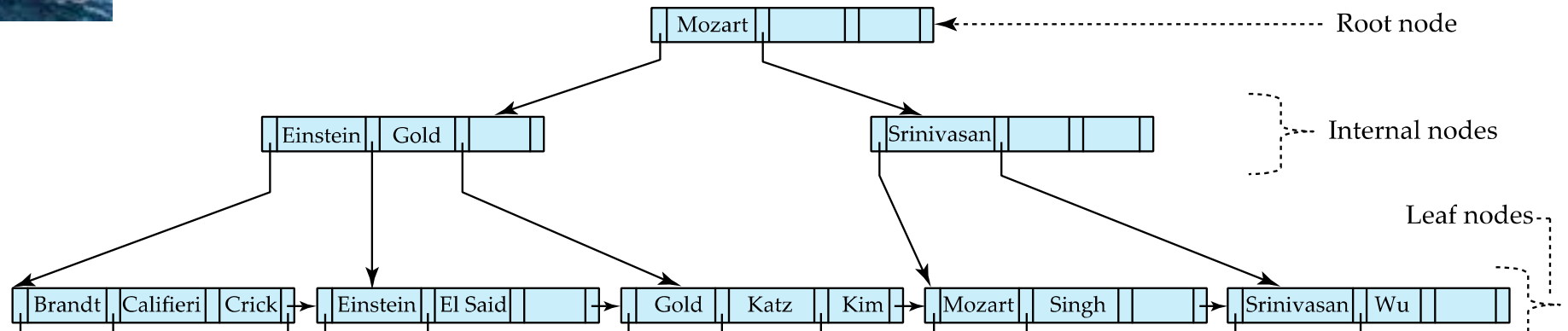
- Splitting a leaf node:
 - take the n (search-key value, pointer) pairs (including the one being inserted) in sorted order. Place the first $\lceil n/2 \rceil$ in the original node, and the rest in a new node.
 - let the new node be p , and let k be the least key value in p . Insert (k, p) in the parent of the node being split.
 - If the parent is full, split it and **propagate** the split further up.
- Splitting of nodes proceeds upwards till a node that is not full is found.
 - In the worst case the root node may be split increasing the height of the tree by 1.



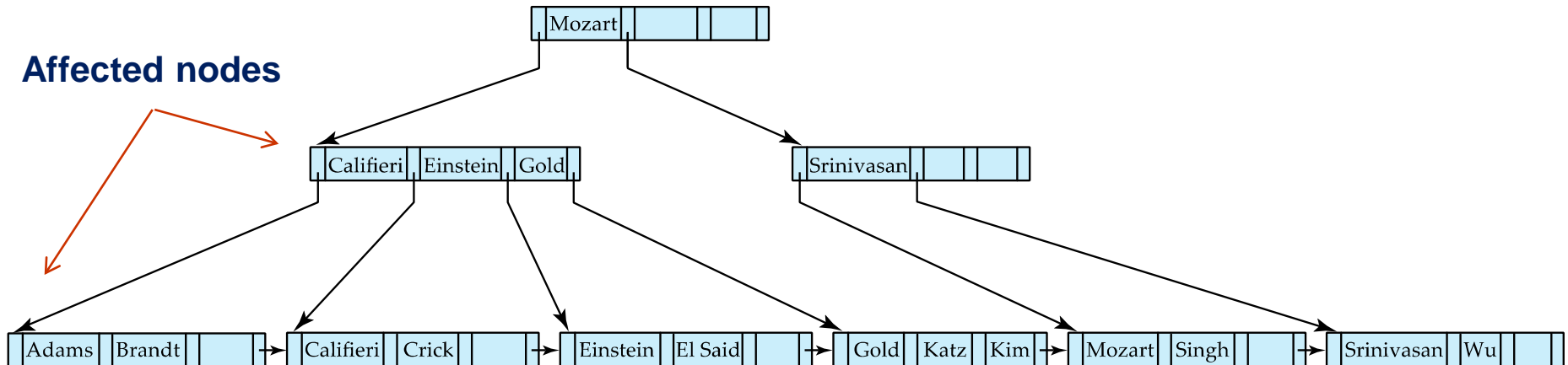
Result of splitting node containing Brandt, Califieri and Crick on inserting Adams
Next step: insert entry with (Califieri, pointer-to-new-node) into parent



B⁺-Tree Insertion



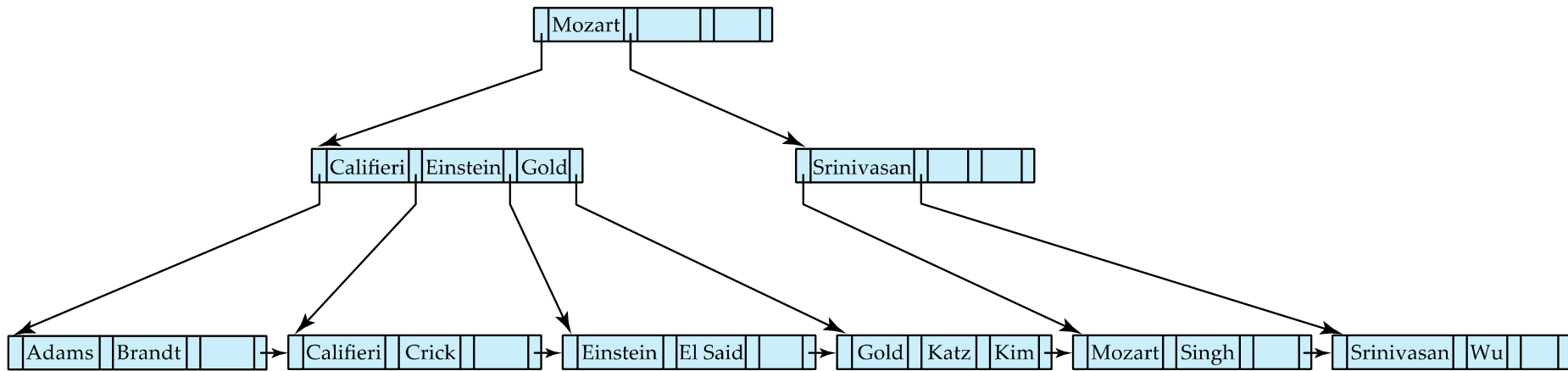
Affected nodes



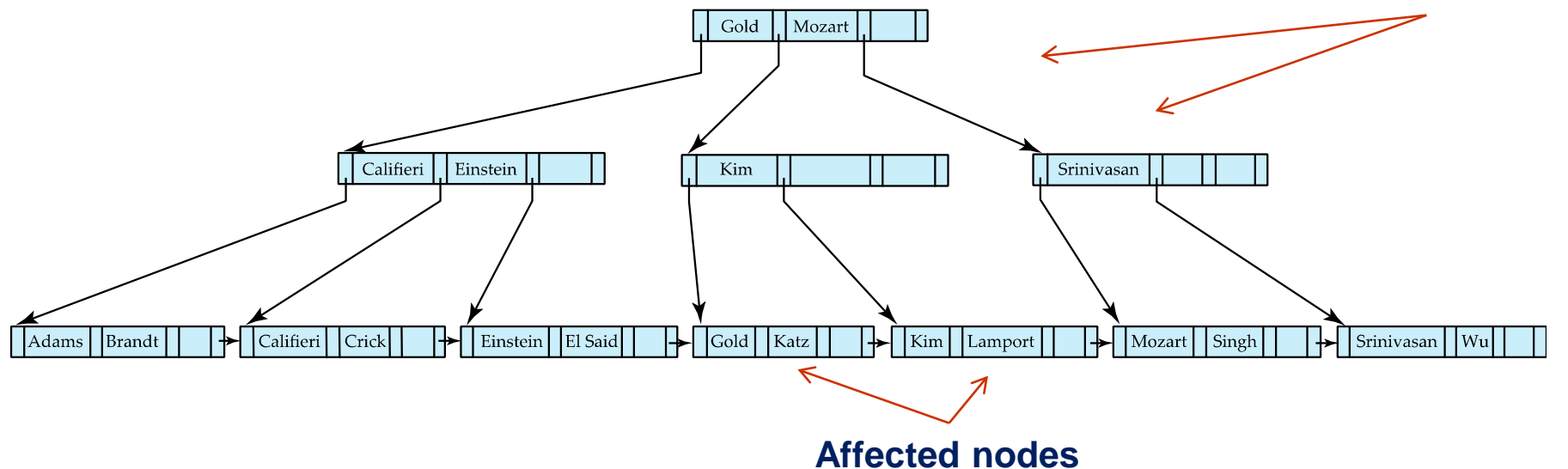
B⁺-Tree before and after insertion of “Adams”



B⁺-Tree Insertion



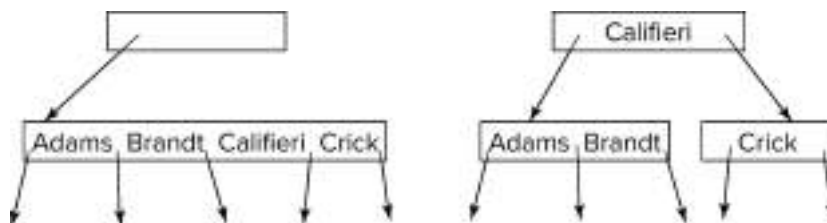
B⁺-Tree before and after insertion of “Lamport”





Insertion in B⁺-Trees (Cont.)

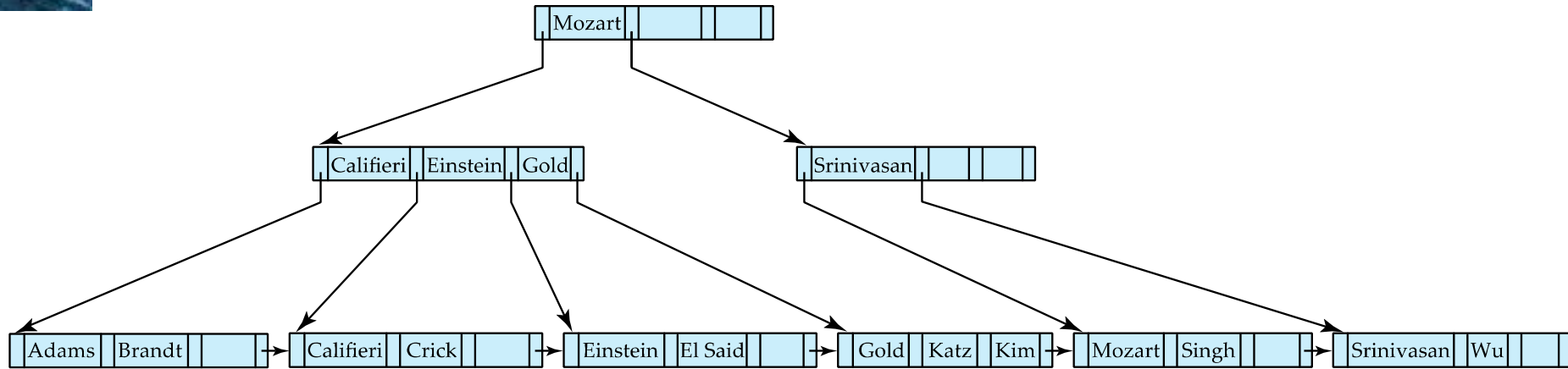
- Splitting a non-leaf node: when inserting (k,p) into an already full internal node N
 - Copy N to an in-memory area M with space for $n+1$ pointers and n keys
 - Insert (k,p) into M
 - Copy $P_1, K_1, \dots, K_{\lceil n/2 \rceil - 1}, P_{\lceil n/2 \rceil}$ from M back into node N
 - Copy $P_{\lceil n/2 \rceil + 1}, K_{\lceil n/2 \rceil + 1}, \dots, K_n, P_{n+1}$ from M into newly allocated node N'
 - Insert $(K_{\lceil n/2 \rceil}, N')$ into parent N
- Example



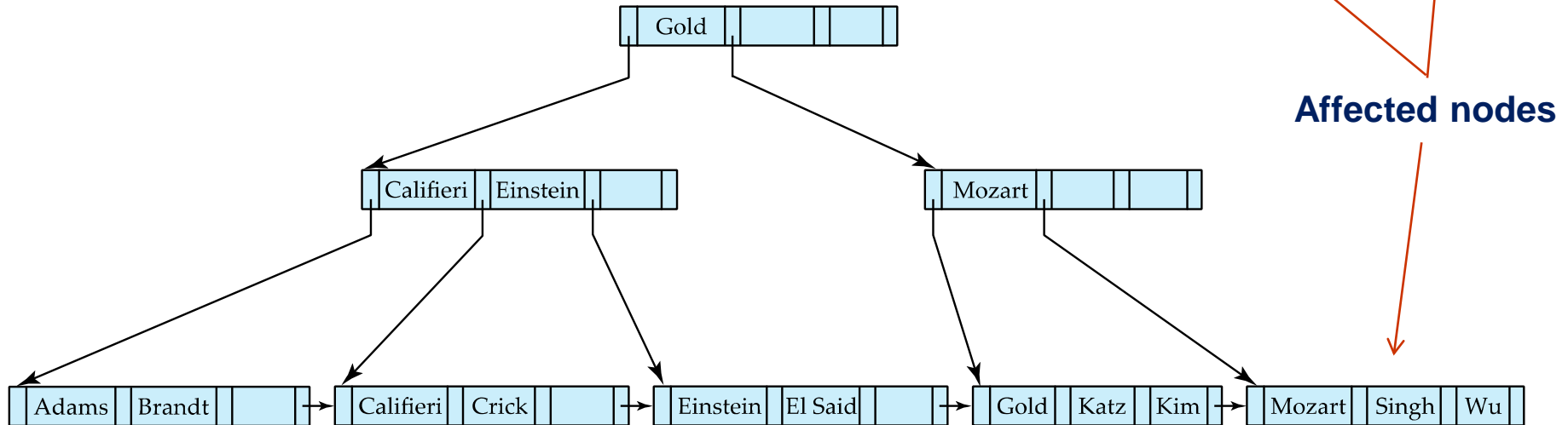
- **Read pseudocode in book!**



Examples of B⁺-Tree Deletion



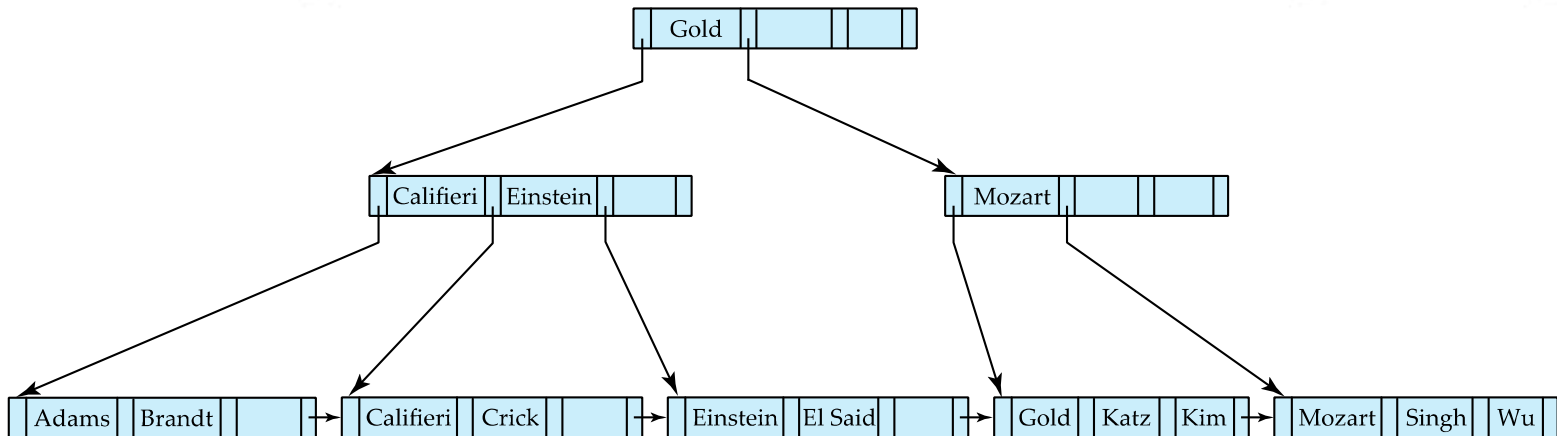
Before and after deleting “Srinivasan”



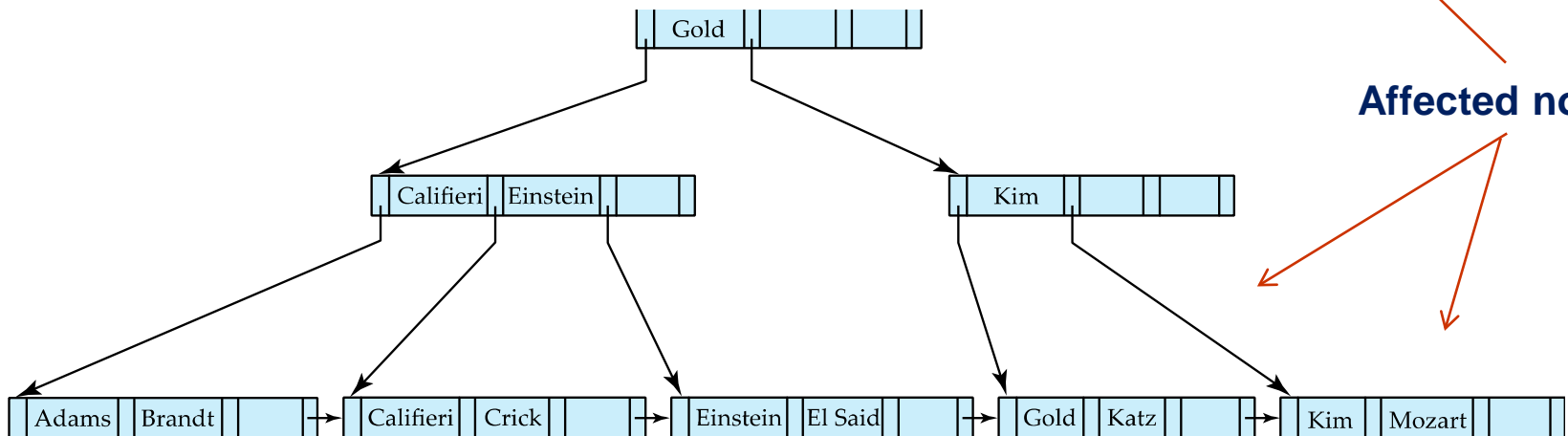
- Deleting “Srinivasan” causes **merging** of under-full leaves



Examples of B+-Tree Deletion (Cont.)



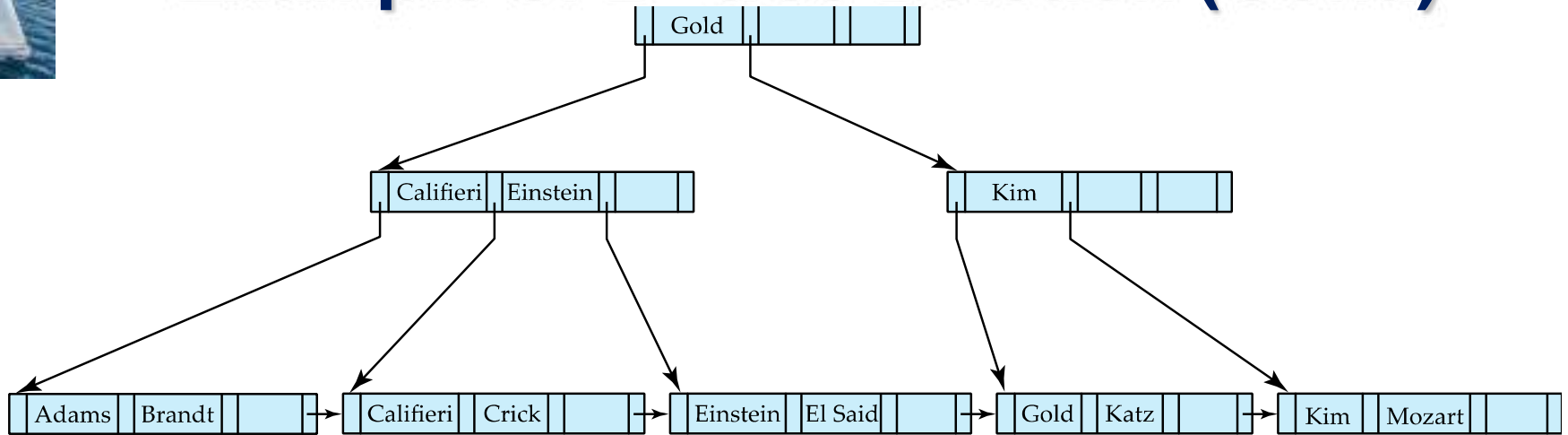
Before and after deleting “Singh” and “Wu”



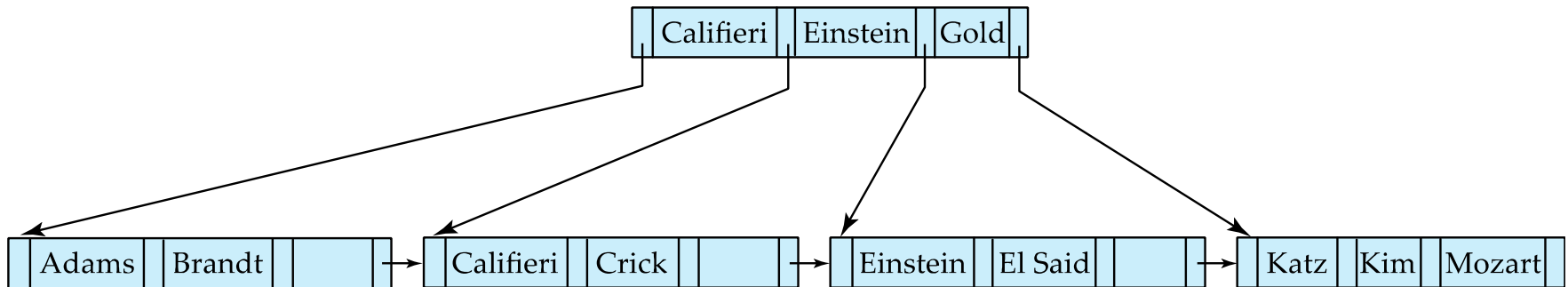
- Leaf containing Singh and Wu became underfull, and **borrowed a value** Kim from its left sibling
- Search-key value in the parent changes as a result



Example of B⁺-tree Deletion (Cont.)



Before and after deletion of "Gold"



- Node with Gold and Katz became underfull, and was merged with its sibling
- Parent node becomes underfull, and is merged with its sibling
 - Value separating two nodes (at the parent) is pulled down when merging
- Root node then has only one child, and is deleted



Updates on B⁺-Trees: Deletion

Assume record already deleted from file. Let V be the search key value of the record, and Pr be the pointer to the record.

- Remove (Pr, V) from the leaf node
- If the node has too few entries due to the removal, and the entries in the node and a sibling fit into a single node, then ***merge siblings***:
 - Insert all the search-key values in the two nodes into a single node (the one on the left), and delete the other node.
 - Delete the pair (K_{i-1}, P_i) , where P_i is the pointer to the deleted node, from its parent, recursively using the above procedure.



Updates on B⁺-Trees: Deletion

- Otherwise, if the node has too few entries due to the removal, but the entries in the node and a sibling do not fit into a single node, then **redistribute pointers**:
 - Redistribute the pointers between the node and a sibling such that both have more than the minimum number of entries.
 - Update the corresponding search-key value in the parent of the node.
- The node deletions may cascade upwards till a node which has $\lceil n/2 \rceil$ or more pointers is found.
- If the root node has only one pointer after deletion, it is deleted and the sole child becomes the root.



Complexity of Updates

- Cost (in terms of number of I/O operations) of insertion and deletion of a single entry proportional to height of the tree
 - With K entries and maximum fanout of n , worst case complexity of insert/delete of an entry is $O(\log_{\lceil n/2 \rceil}(K))$
- In practice, number of I/O operations is less:
 - Internal nodes tend to be in buffer
 - Splits/merges are rare, most insert/delete operations only affect a leaf node
- Average node occupancy depends on insertion order
 - 2/3rds with random, $\frac{1}{2}$ with insertion in sorted order



Non-Unique Search Keys

- Alternatives to scheme described earlier
 - Buckets on separate block (bad idea)
 - List of tuple pointers with each key
 - Extra code to handle long lists
 - Deletion of a tuple can be expensive if there are many duplicates on search key (why?)
 - Worst case complexity may be linear!
 - Low space overhead, no extra cost for queries
 - Make search key unique by adding a record-identifier
 - Extra storage overhead for keys
 - Simpler code for insertion/deletion
 - Widely used

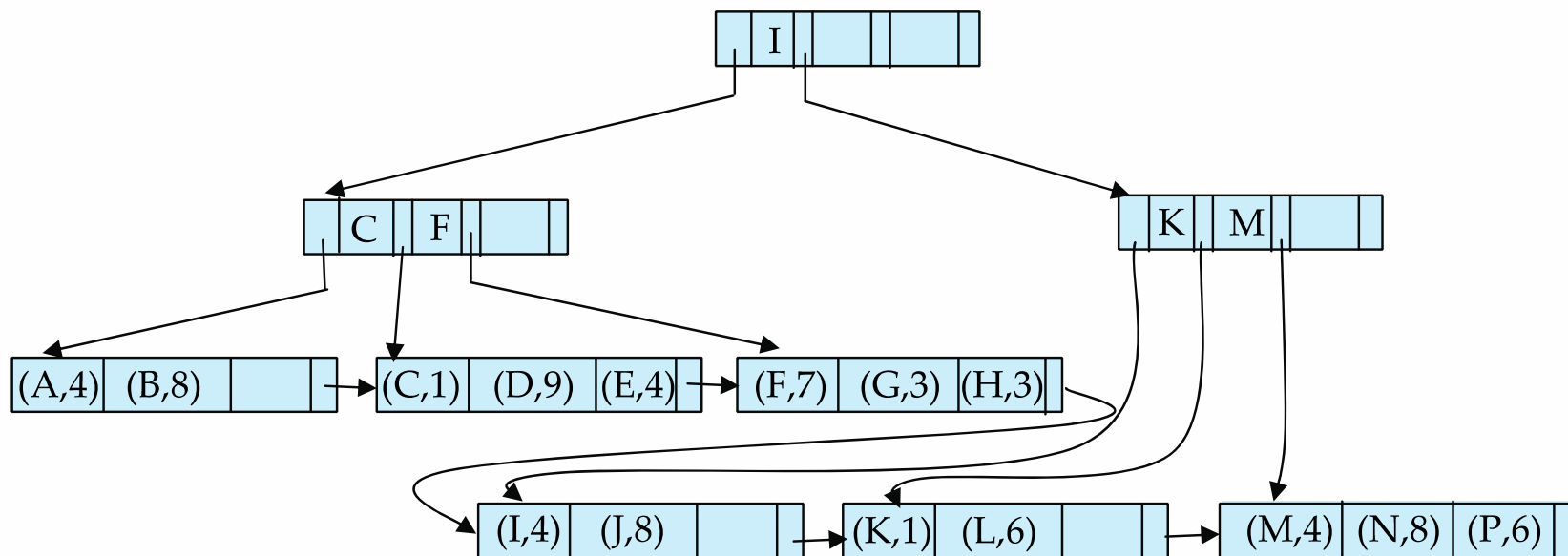


B⁺-Tree File Organization

- B⁺-Tree File Organization:
 - leaf nodes in a B⁺-tree file organization store records, instead of pointers
 - Helps keep data records clustered even when there are insertions/deletions/updates
- Leaf nodes are still required to be half full
 - Since records are larger than pointers, the maximum number of records that can be stored in a leaf node is less than the number of pointers in a nonleaf node.
- Insertion and deletion are handled in the same way as insertion and deletion of entries in a B⁺-tree index.



B⁺-Tree File Organization (Cont.)



Example of B⁺-tree File Organization

- Good space utilization important since records use more space than pointers.
- To improve space utilization, involve more sibling nodes in redistribution during splits and merges
 - Involving 2 siblings in redistribution (to avoid split / merge where possible) results in each node having at least $\lfloor 2n/3 \rfloor$ entries



Other Issues in Indexing

- **Record relocation and secondary indices**
 - If a record moves, all secondary indices that store record pointers have to be updated
 - Node splits in B⁺-tree file organizations become very expensive
 - *Solution:* use search key of B⁺-tree file organization instead of record pointer in secondary index
 - Add record-id if B⁺-tree file organization search key is non-unique
 - Extra traversal of file organization to locate record
 - Higher cost for queries, but node splits are cheap



Indexing Strings

- Variable length strings as keys
 - Variable fanout
 - Use space utilization as criterion for splitting, not number of pointers
- **Prefix compression**
 - Key values at internal nodes can be prefixes of full key
 - Keep enough characters to distinguish entries in the subtrees separated by the key value
 - E.g. “Silas” and “Silberschatz” can be separated by “Silb”
 - Keys in leaf node can be compressed by sharing common prefixes

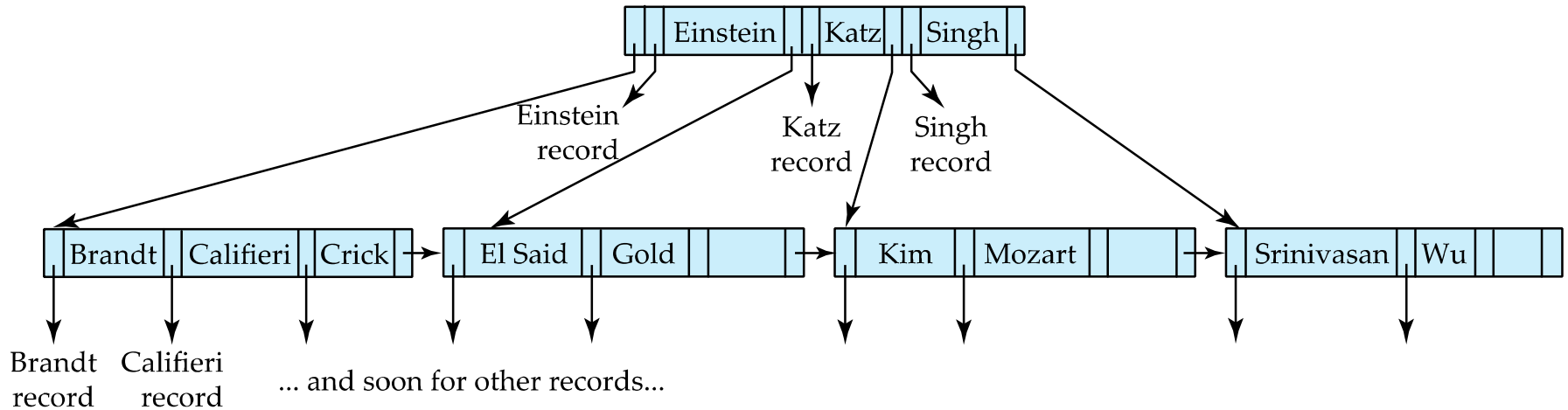


Bulk Loading and Bottom-Up Build

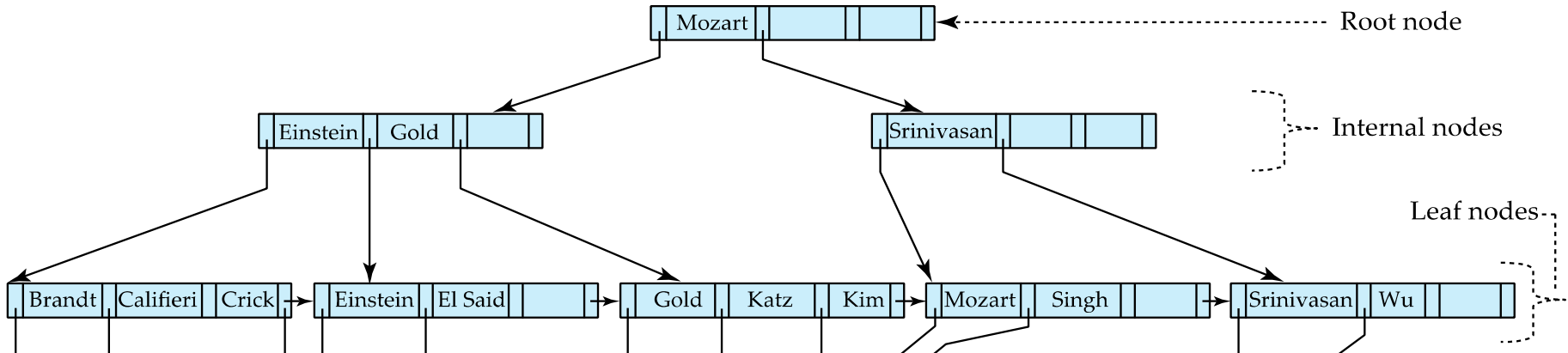
- Inserting entries one-at-a-time into a B⁺-tree requires ≥ 1 IO per entry
 - assuming leaf level does not fit in memory
 - can be very inefficient for loading a large number of entries at a time (**bulk loading**)
- Efficient alternative 1:
 - sort entries first (using efficient external-memory sort algorithms discussed later in Section 12.4)
 - insert in sorted order
 - insertion will go to existing page (or cause a split)
 - much improved IO performance, but most leaf nodes half full
- Efficient alternative 2: **Bottom-up B⁺-tree construction**
 - As before sort entries
 - And then create tree layer-by-layer, starting with leaf level
 - details as an exercise
 - Implemented as part of bulk-load utility by most database systems



B-Tree Index File Example



B-tree (above) and B+-tree (below) on same data





Indexing on Flash

- Random I/O cost much lower on flash
 - 20 to 100 microseconds for read/write
- Writes are not in-place, and (eventually) require a more expensive erase
- Optimum page size therefore much smaller
- Bulk-loading still useful since it minimizes page erases
- Write-optimized tree structures (discussed later) have been adapted to minimize page writes for flash-optimized search trees



Indexing in Main Memory

- Random access in memory
 - Much cheaper than on disk/flash
 - But still expensive compared to cache read
 - Data structures that make best use of cache preferable
 - Binary search for a key value within a large B⁺-tree node results in many cache misses
- B⁺- trees with small nodes that fit in cache line are preferable to reduce cache misses
- Key idea: use large node size to optimize disk access, but structure data within a node using a tree with small node size, instead of using an array.



Hashing

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Static Hashing

- A **bucket** is a unit of storage containing one or more entries (a bucket is typically a disk block).
 - we obtain the bucket of an entry from its search-key value using a **hash function**
- Hash function h is a function from the set of all search-key values K to the set of all bucket addresses B .
- Hash function is used to locate entries for access, insertion as well as deletion.
- Entries with different search-key values may be mapped to the same bucket; thus entire bucket has to be searched sequentially to locate an entry.
- In a **hash index**, buckets store entries with pointers to records
- In a **hash file-organization** buckets store records



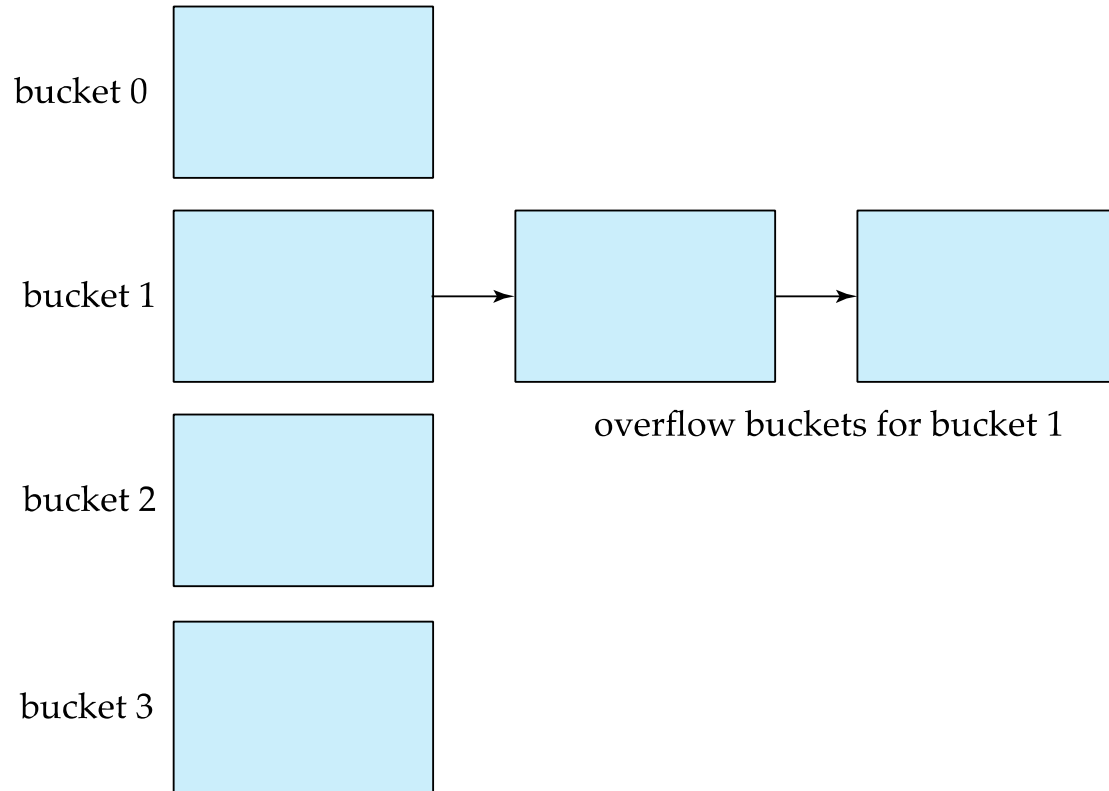
Handling of Bucket Overflows

- Bucket overflow can occur because of
 - Insufficient buckets
 - Skew in distribution of records. This can occur due to two reasons:
 - multiple records have same search-key value
 - chosen hash function produces non-uniform distribution of key values
- Although the probability of bucket overflow can be reduced, it cannot be eliminated; it is handled by using **overflow buckets**.



Handling of Bucket Overflows (Cont.)

- **Overflow chaining** – the overflow buckets of a given bucket are chained together in a linked list.
- Above scheme is called **closed addressing** (also called **closed hashing** or **open hashing** depending on the book you use)
 - An alternative, called **open addressing** (also called **open hashing** or **closed hashing** depending on the book you use) which does not use overflow buckets, is not suitable for database applications.





Example of Hash File Organization

bucket 0

bucket 1

15151	Mozart	Music	40000

bucket 2

32343	El Said	History	80000
58583	Califieri	History	60000

bucket 3

22222	Einstein	Physics	95000
33456	Gold	Physics	87000
98345	Kim	Elec. Eng.	80000

bucket 4

12121	Wu	Finance	90000
76543	Singh	Finance	80000

bucket 5

76766	Crick	Biology	72000

bucket 6

10101	Srinivasan	Comp. Sci.	65000
45565	Katz	Comp. Sci.	75000
83821	Brandt	Comp. Sci.	92000

bucket 7

Hash file organization of *instructor* file, using *dept_name* as key.



Deficiencies of Static Hashing

- In static hashing, function h maps search-key values to a fixed set of B of bucket addresses. Databases grow or shrink with time.
 - If initial number of buckets is too small, and file grows, performance will degrade due to too much overflows.
 - If space is allocated for anticipated growth, a significant amount of space will be wasted initially (and buckets will be underfull).
 - If database shrinks, again space will be wasted.
- One solution: periodic re-organization of the file with a new hash function
 - Expensive, disrupts normal operations
- Better solution: allow the number of buckets to be modified dynamically.