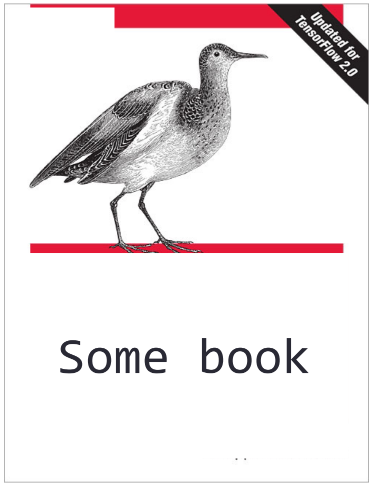
Indexing

CS 4750
Database Systems

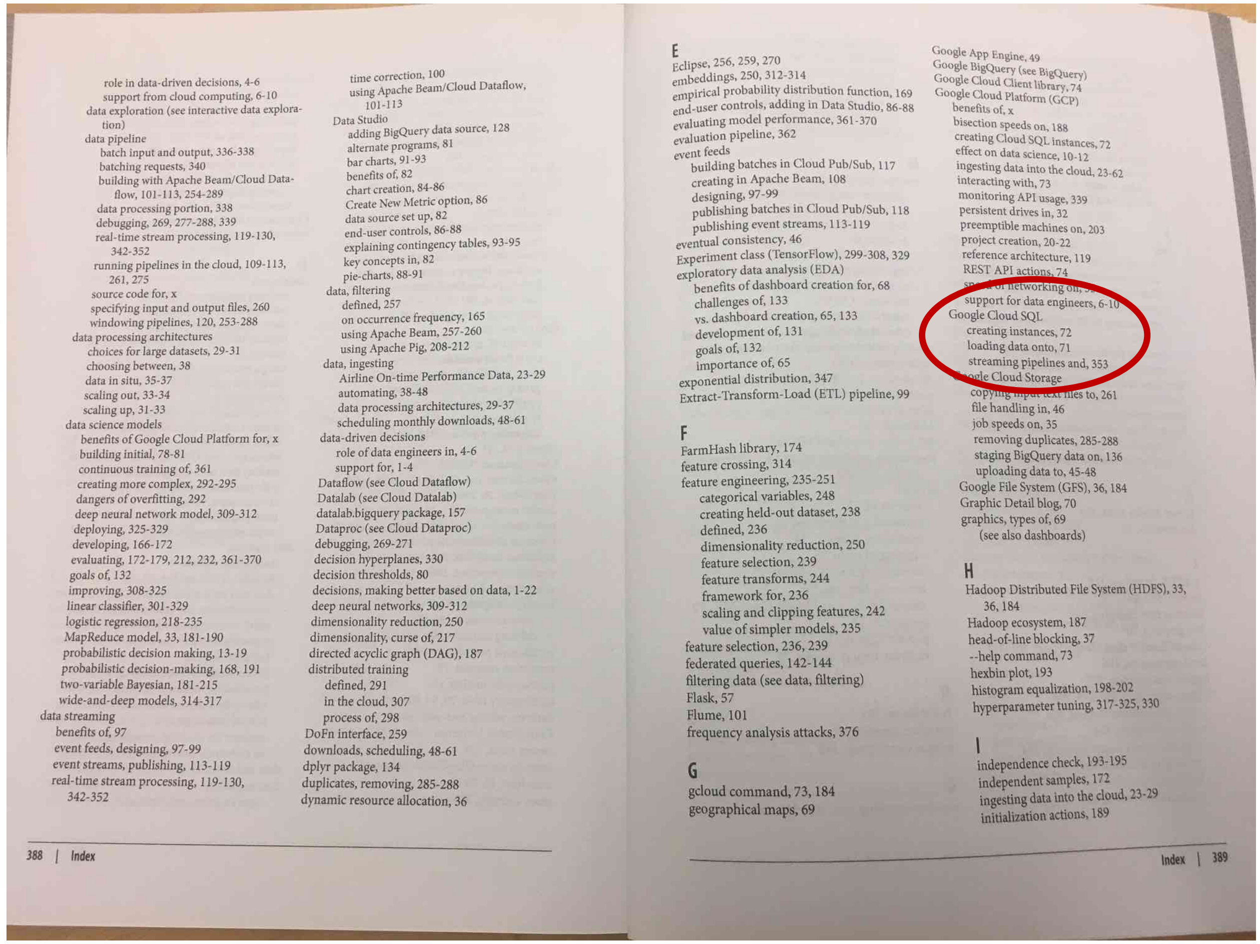
[Silberschatz, Korth, Sudarshan, “Database System Concepts,” Ch.14]
[H. Garcia-Molina, J.D. Ullman, J. Widom, Database Systems: The Complete Book, Ch.14]

Indexing in a Book

Find information about "Google Cloud SQL" from



- Look for the keywords in the index
- Find the pages where the words occur
- Read the pages to find the information



Sorted order

Indexing in Database

Example: Find 2nd year students who have taken < 45 credits

There might be 10,000 tuples in `students` relation.

```
SELECT *
FROM students
WHERE year=2 AND credits < 45;
```

Get all 10,000 tuples and test the condition of the `WHERE` clause on each tuple?

- Find which disk block the corresponding record resides
- Fetch the disk block
- Get the appropriate student records

Is there a way to get only the tuples from 2nd year students and then test each of them to see if the credits match?

Indexing in Database

- Indexing = data structure technique to optimize the performance of a database by minimizing the number of disk accesses required when query is processed
- Basic algorithm to search – linear. However, complex search queries (especially with joins) impacts performance
- Indexing helps improve performance

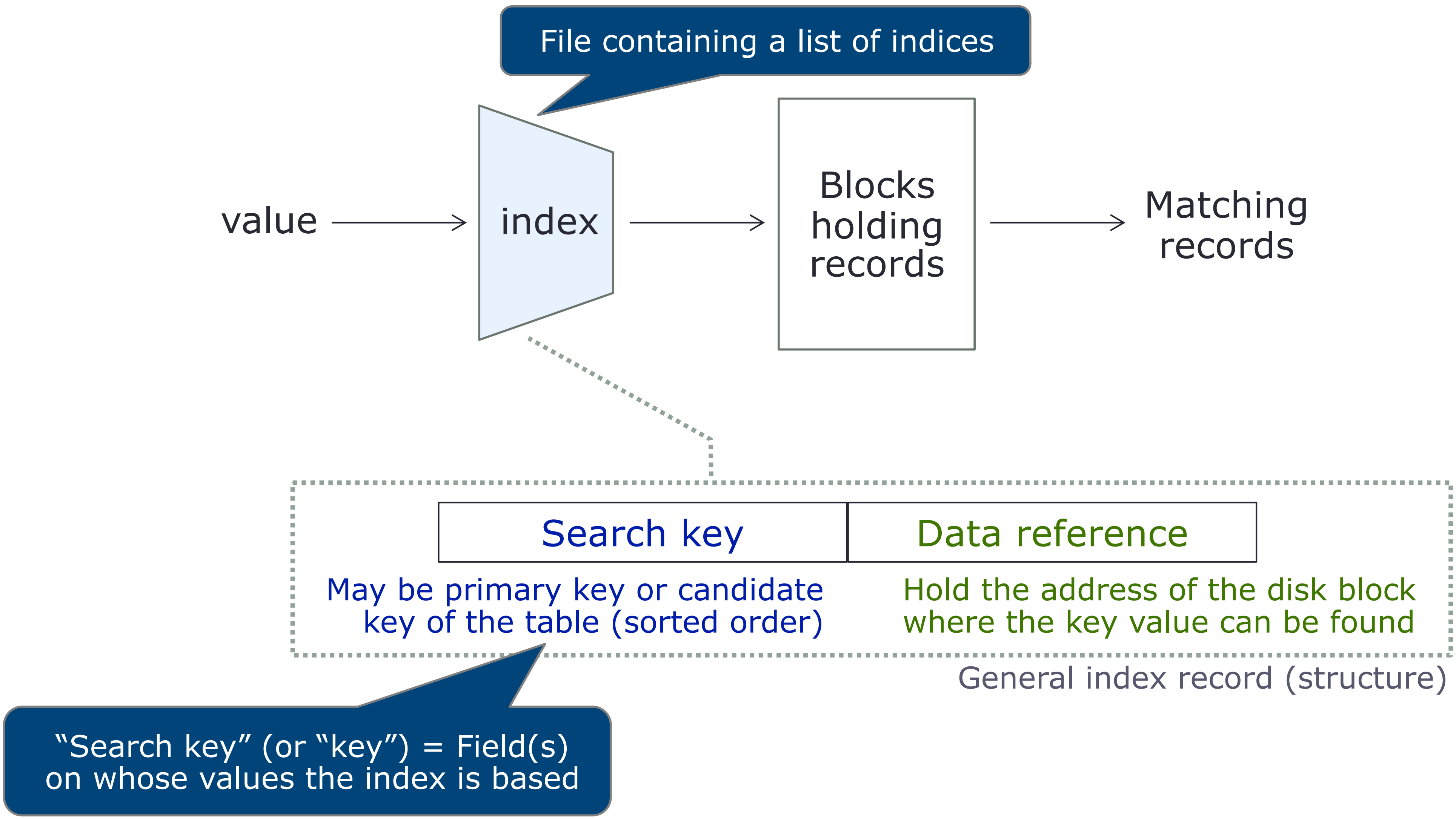
Common structure used by a typical DBMS is B+ tree

The key for the index can be any attribute or set of attributes and need not be the key for the relation on which the index is built.

Rule of thumb: Create an index on the attribute that is used frequently in the search

Indexing in Database

- An index takes a value for some field(s) and finds records with the matching value quickly



Selection of Indexes

- An index on an attribute may speed up the execution of those queries in which a value, or range of values, is specified for that attribute, and may speed up joins involving that attribute.

- On the other hand, every index built for one or more attributes of some relation makes insertions, deletions, and updates to that relation more complex and time-consuming.

Database designers must analyze the trade-off

Which Indexing Technique to Use

Aspects that must be considered:

- Access types
  - Finding records with a specified attribute value (search key), or
  - Finding records with attribute value based on a specified range
- Access time
  - Time needed to find a particular data item or set of data items
- Insertion time
  - Time to find the place to insert + time to insert a new data item + time to update the index structure
- Deletion time
  - Time to find the data item to be deleted + time to delete the data + time to update the index structure
- Space overhead
  - Space occupied by an index structure (vs. performance)

Types of File Organization Mechanism

Sequential file organization (or Ordered index)

- Indices based on sorted ordering of the values
- Generally fast
- Basic / traditional structure that most DBs use

Hash file organization (or Hash index)

- Indices based on a uniform distribution of values across a range of buckets
- Hash function determines a value assigned to a bucket

Example: Sequential File

Instructor

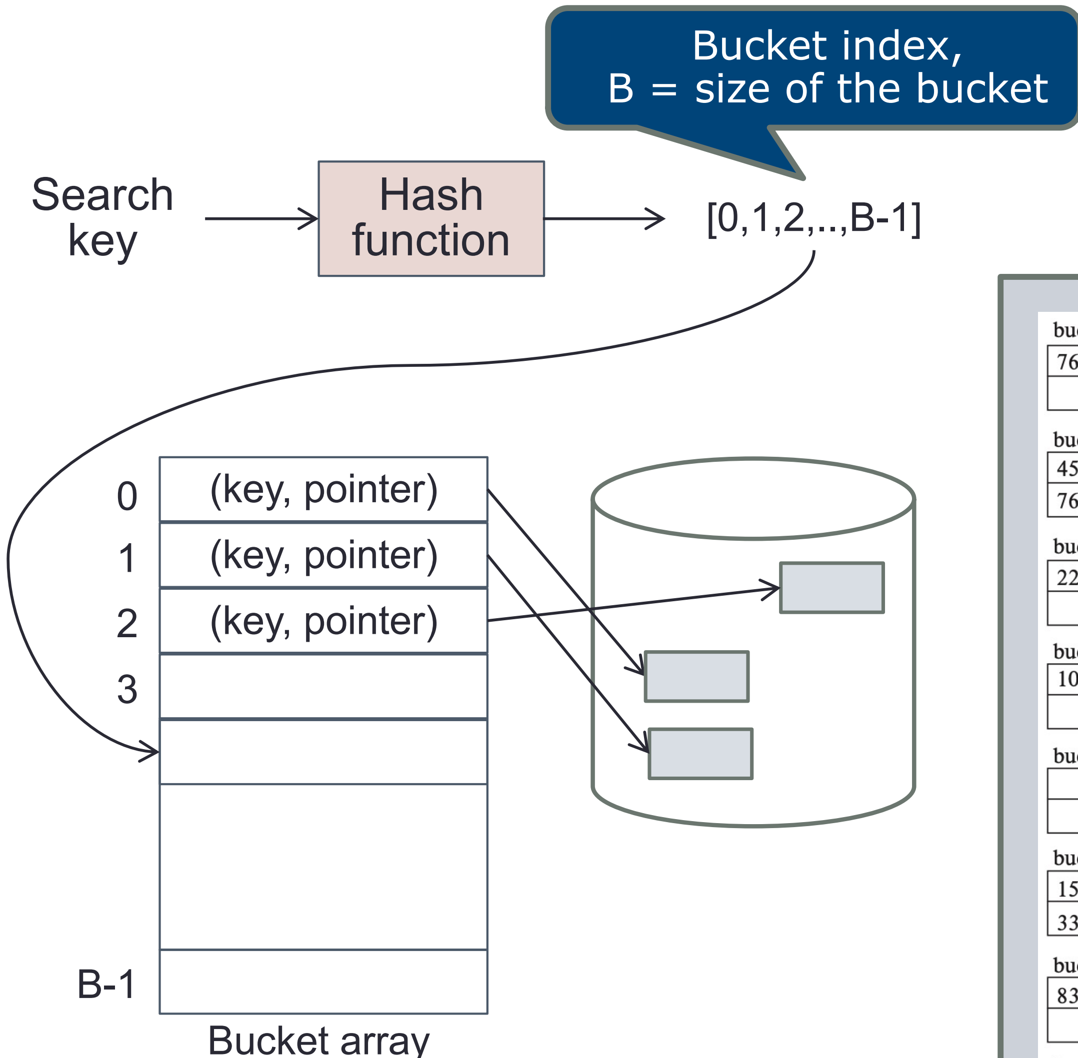
10101	Srinivasan	Comp. Sci.	65000	
12121	Wu	Finance	90000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
32343	El Said	History	60000	
33456	Gold	Physics	87000	
45565	Katz	Comp. Sci.	75000	
58583	Califieri	History	62000	
76543	Singh	Finance	80000	
76766	Crick	Biology	72000	
83821	Brandt	Comp.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

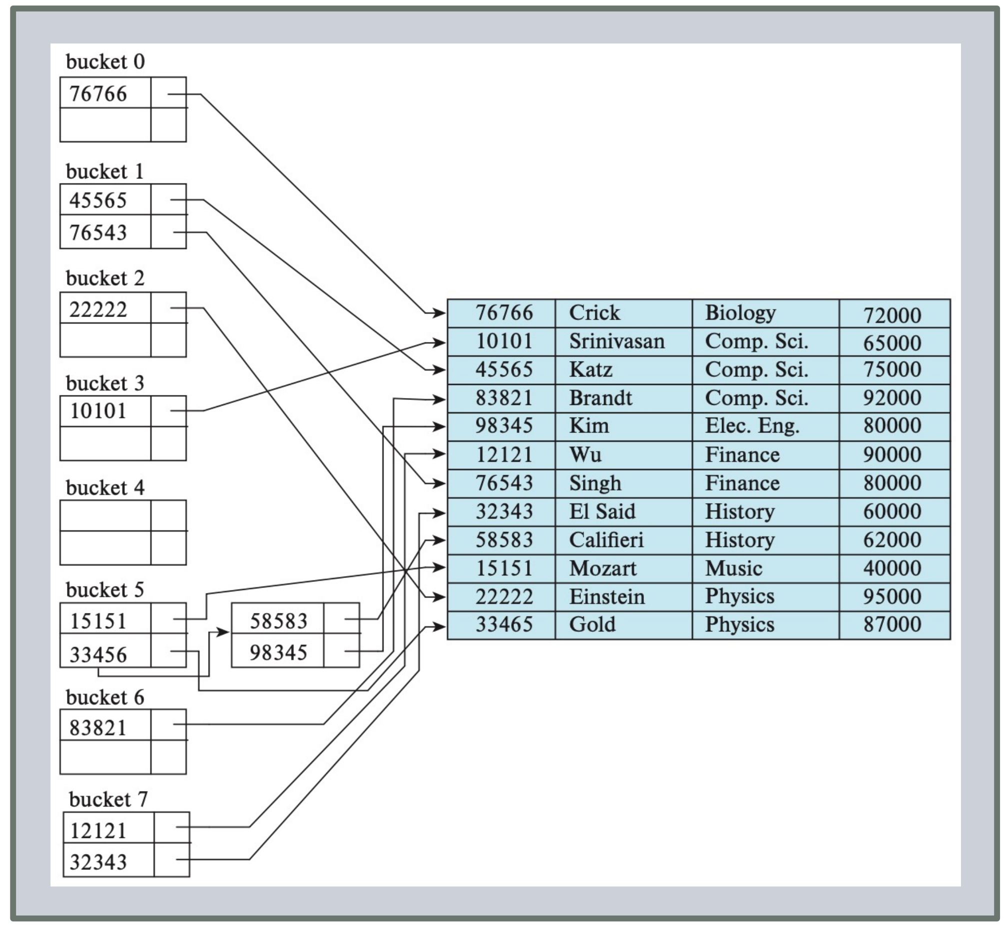
Instructor records

- The records are stored in sorted order of instructor's ID (used as a search key)
- Search key defines the sequential order of the file

[Ref: Figure 11.1, Silberschatz, Korth, Sudarshan, "Database System Concepts," 6th Ed., page 477]

Example: Hash File





[Ref: based in part on Figure 24.6, Silberschatz, Korth, Sudarshan, "Database System Concepts," 7th Ed., page 1191]

Ordered Index Structures

A file may have several indices, on different search keys

- **Primary index (or clustered index)**
  - Search key defines the sequential order of the file
  - Search key of a clustering index is often the primary key (but not necessarily so)

- **Secondary index (or unclustered index)**
  - Search key specifies an order different from the sequential order of the file
  - Use an extra-level of indirection to implement a secondary index, containing pointers to all the records

Example: Primary Index

Search key defines the sequential order of the file

Fast but can result in unnecessary indices and big space needed

10101
12121
15151
22222
32343
33456
45565
58583
76543
76766
83821
98345

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

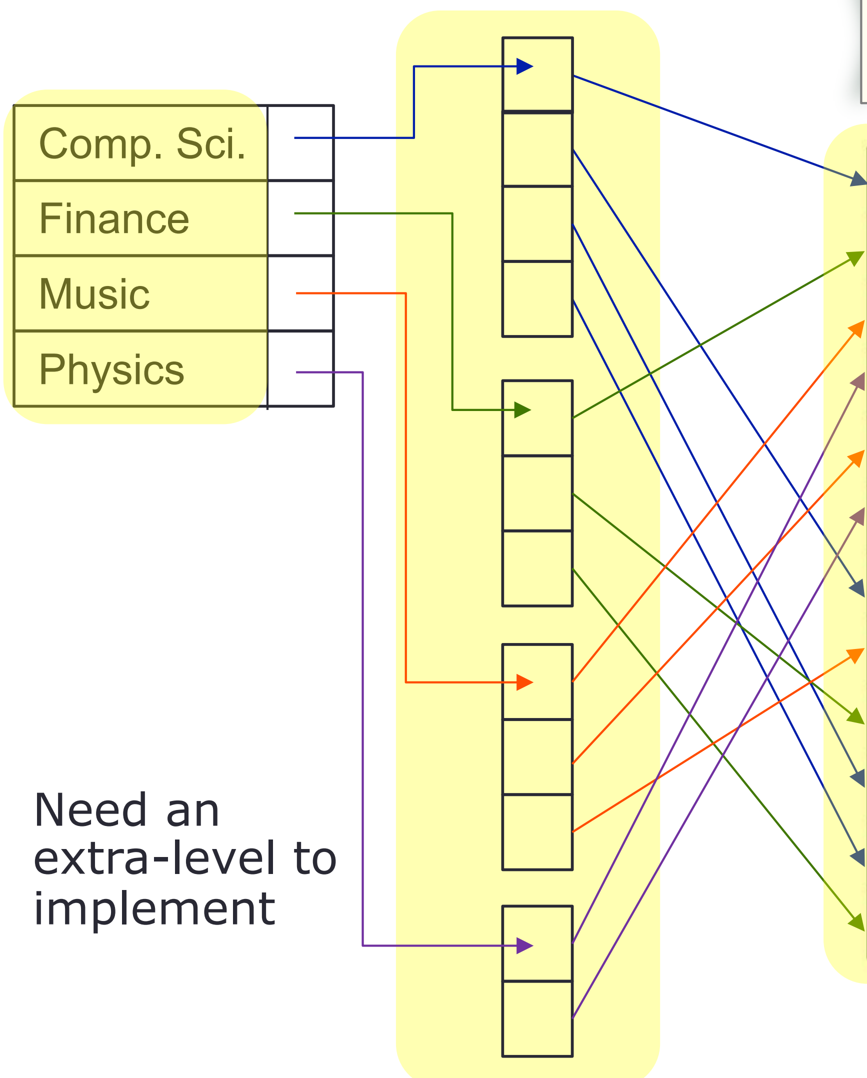
Instructor

[Ref: Figure 11.2, Silberschatz, Korth, Sudarshan, "Database System Concepts," 6th Ed., page 478]

Example: Secondary Index

Search key specifies an order different from the sequential order of the file

Improve performance of queries on non-primary keys but impose overhead



Need an extra-level to implement

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

Instructor

[based in part on Figure 11.6, Silberschatz, Korth, Sudarshan, "Database System Concepts," 6th Ed., page 484]

Ordered Index

- Created on the basis of the key of the table
- Ordered file with fixed, two fields

Search key	Data reference
May be primary key or candidate key of the table (sorted order)	Hold the address of the disk block where the key value can be found

- Unique to each record (i.e., 1:1 mapping)
- Since primary keys are stored in sorted order, the performance of the search operation is quite efficient
- Two types:
  - Dense index
  - Sparse index

Dense Index

- A record is created for every search key value
- Need more space to store index records
- Example: a search key is a primary key

Find instructor with ID "58583"

A primary index that is dense on a primary-key, ordered table is redundant (requiring unnecessary spaces)

10101	
12121	
15151	
22222	
32343	
33456	
45565	
58583	
76543	
76766	
83821	
98345	

Instructor

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

Instructor file is sorted by instructor's *ID* (every search key valued)

Point to the real record on the disk

[Ref: Figure 11.2, Silberschatz, Korth, Sudarshan, "Database System Concepts," 6th Ed., page 478]

Dense Index

- Support range queries
- Example: a search key is not a primary key

Find a history instructor with ID "58583"

Pointer points to the first data record with the search-value.
The rest of the records are sorted on the same search key

Biology	
Comp. Sci.	
Elec. Eng.	
Finance	
History	
Music	
Physics	

76766	Crick	Biology	72000	
10101	Srinivasan	Comp. Sci.	65000	
45565	Katz	Comp. Sci.	75000	
83821	Brandt	Comp. Sci.	92000	
98345	Kim	Elec. Eng.	80000	
12121	Wu	Finance	90000	
76543	Singh	Finance	80000	
32343	El Said	History	60000	
58583	Califieri	History	62000	
15151	Mozart	Music	40000	
22222	Einstein	Physics	95000	
33465	Gold	Physics	87000	

Instructor

Instructor file is sorted on the search key *dept-name*

Follow the pointer directly to the first record, then follow the pointer in that record to locate the next record in search key order until the desired record is found

[Ref: Figure 11.4, Silberschatz, Korth, Sudarshan, "Database System Concepts," 6th Ed., page 480]

Dense Index: Lookup

- Given a search key *K*, the index is scanned
  - When *K* is found, the associated pointer to the data file recorded is followed and the block containing the record is read in main memory
- When dense indexes are used for non-primary key, the minimum value is located first
  - Consecutive blocks are loaded in main memory until a search key greater than the maximum value is found
- The index is usually kept in main memory. Thus one disk I/O has to be performed during lookup
- Since the index is sorted, a binary search can be used.
  - If there are n search keys, at most $log_2 n$ steps are required to locate a given search key
- Query-answering using dense indices is efficient

Sparse Index

- Used when dense indices are too large
- One key-pointer pair per data block
- Can be used only if the relation is stored in sorted order of the search key

Find instructor with ID "22222"

10101	
32343	
76766	

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

Instructor

Start with search-key value less than or equal to the desired search value, then linear search

[Ref: Figure 11.3, Silberschatz, Korth, Sudarshan, "Database System Concepts," 6th Ed., page 479]

Sparse Index: Lookup

- Given a search key *K*,
  - Search the sparse index for the greatest key ≤ *K*, using binary search
  - Retrieve the pointed block to main memory to look for the record with search key *K* (linear search vs. binary search)

- The index is usually kept in main memory. Thus one disk I/O has to be performed during lookup

- Efficient in space but may require more computation time due two binary searches
  - Search on the sparse index
  - Search on the retrieved data block

Dense Index vs. Sparse Index

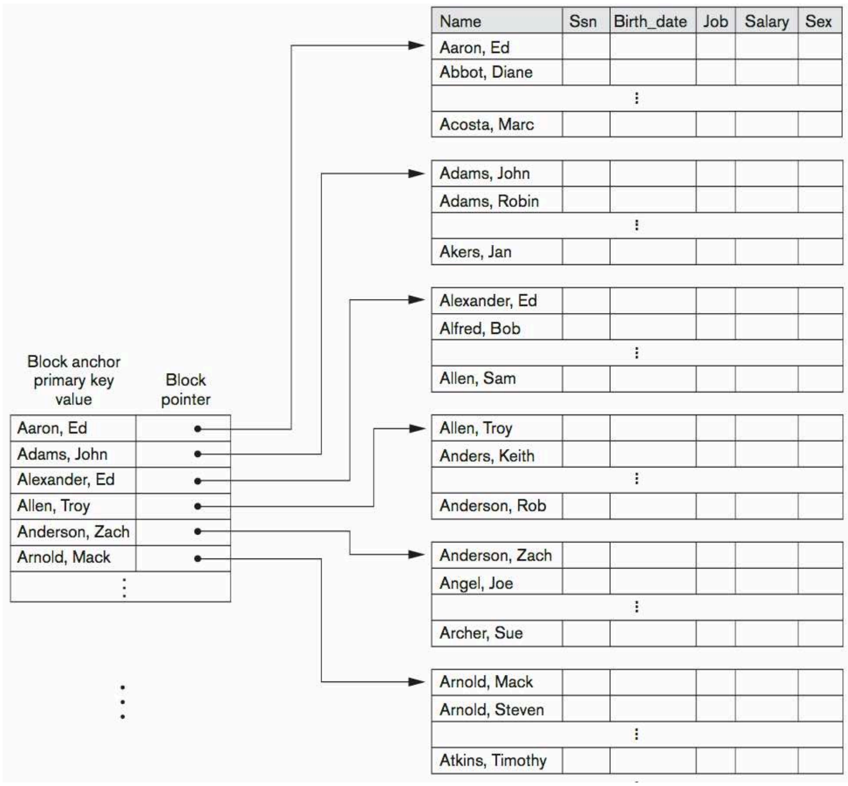
- A primary index that is dense on an ordered table is redundant
- Thus, a primary index on an ordered table is always sparse

- Dense indices are faster in general

- Sparse indices require less space and impose less maintenance for insertions and deletions

- Try to have a sparse index with one entry per block

Try to keep index size small



[Ref: Figure 18.1, Elmasri Navathe, "Fundamentals of Database Systems," 6th Ed., page 634]

More Info on Indexing

- When a primary key is created for a table, a table is ordered based on the primary key
- At least one sparse index is created on that record to reduce search time
- If a column (or some columns) is declared as unique, a secondary index is created
- Every index introduces more data and more overhead (especially when doing insert, delete, or update)

Can we create (or add) indices to just any table (or DB)? – **No!**

Read-heavy DBs – **can index a lot** (if space allows)
Write-heavy DBs – **index sparingly** (take a balanced approach)
Write-ONLY DBs – **one or no index**

Multi-Level Indices

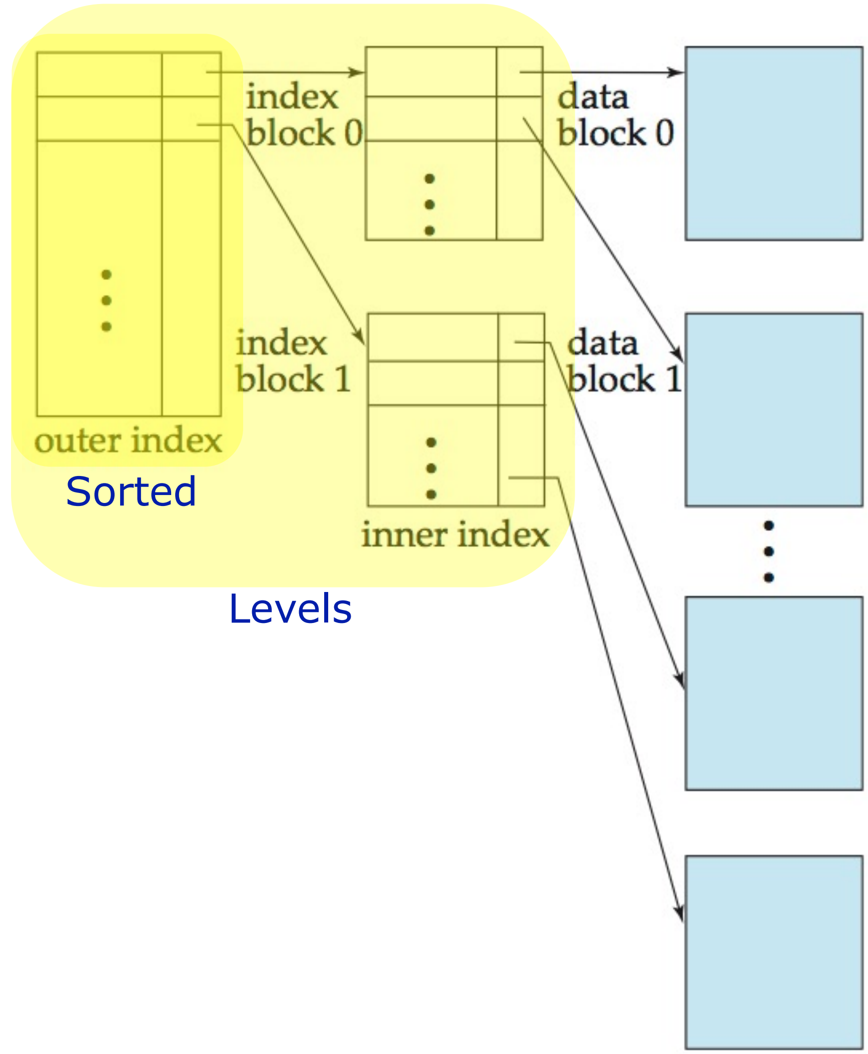
- If an index is small enough to be kept entirely in main memory, the search time to find an entry is low

- If index is too large to be kept in main memory, index blocks must be fetched from disk when required. One search results in several disk-block reads
  - If no overflow blocks in the index → use binary search
  - If overflow blocks → use sequential search

- Solution:
  - Use a sparse index on the index

Example: Two-Level Sparse Index

- Use binary search on outer index
- Scan index block until the correct record is found
- Scan block pointed to for desired record
- For very large files, add additional level of indexing to improve search performance
- Must update indices at all levels when perform insertion or deletion



[Ref: Figure 11.5, Silberschatz, Korth, Sudarshan, "Database System Concepts," 6th Ed., page 481]

Updating Indices

All associated indices must be updated when a record is inserted into or deleted from a file

Insertion:

- Find a place to insert
- For dense index:
  - Insert search key value if not present
- For sparse index:
  - No change unless a new block is created
  - If the first search key value appears in the new block, insert the search key value into the index

Deletion:

- Find the record
- If it is the last record, delete that search key value from index
- For dense index:
  - Delete the search key value
- For sparse index:
  - Delete the search key value
  - Replace the key value’s entry index with the next search key value if not already present

How to Implement: Use B+ Trees

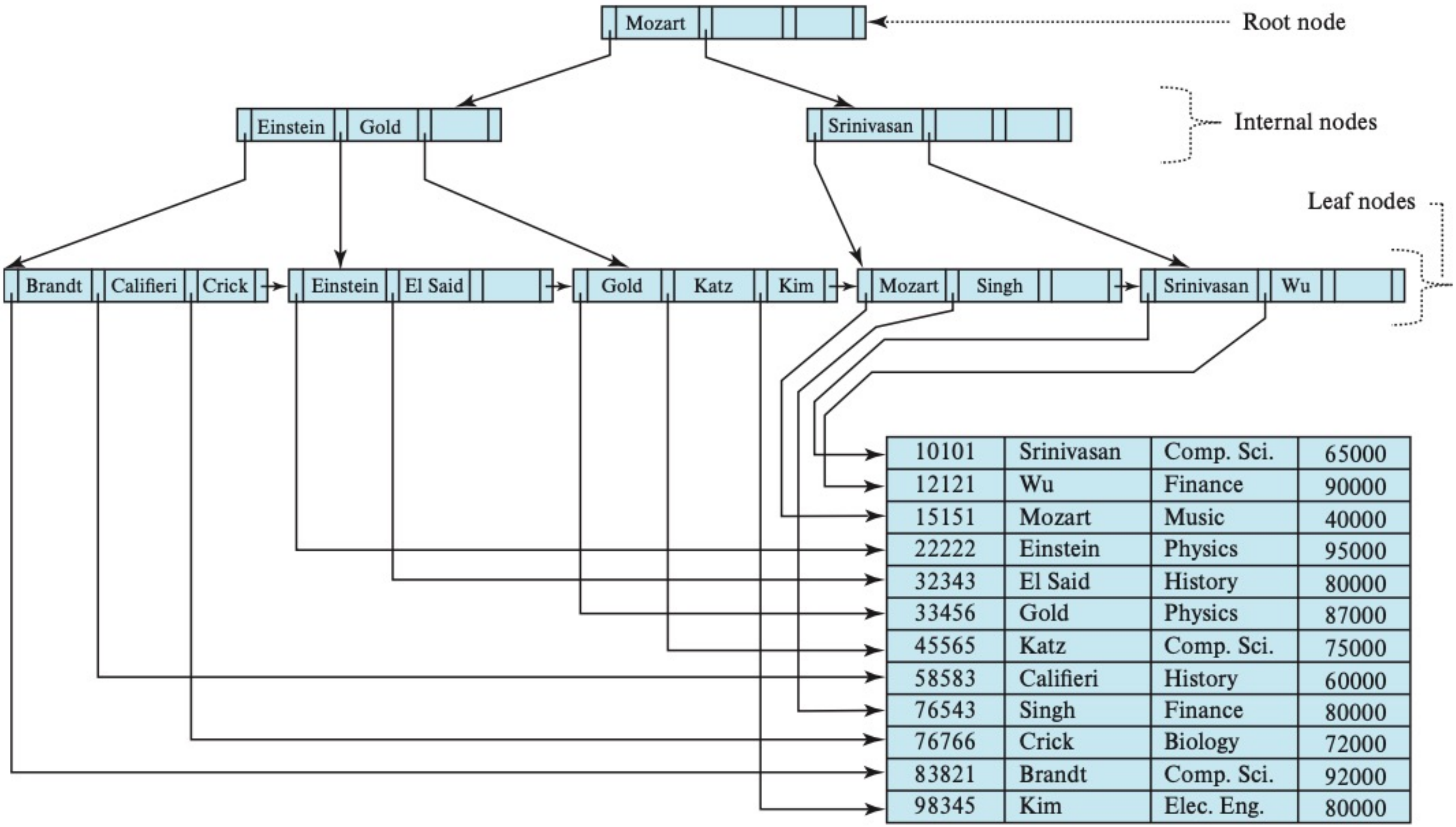
- As the database grows (and the index file grows), performance degrades. Reorganization is costly
- Solution: use B+ tree to maintain indices

Balance sorted tree, allowing fast search and maintenance without overflow pages

B+ Tree

- A tree-like file structure
  - Links nodes with pointers
  - Has exactly one root, bounded by leaves
  - Has unique path from root to each leaf; all paths are equal length
  - Store keys only at leaves, references in other/internal nodes
  - Guides key search via the reference values, from root to leaves
- Balance – same length on every path from root to leaves
- Extensible – number of pointers (n) at any given node

Example: B+ Tree



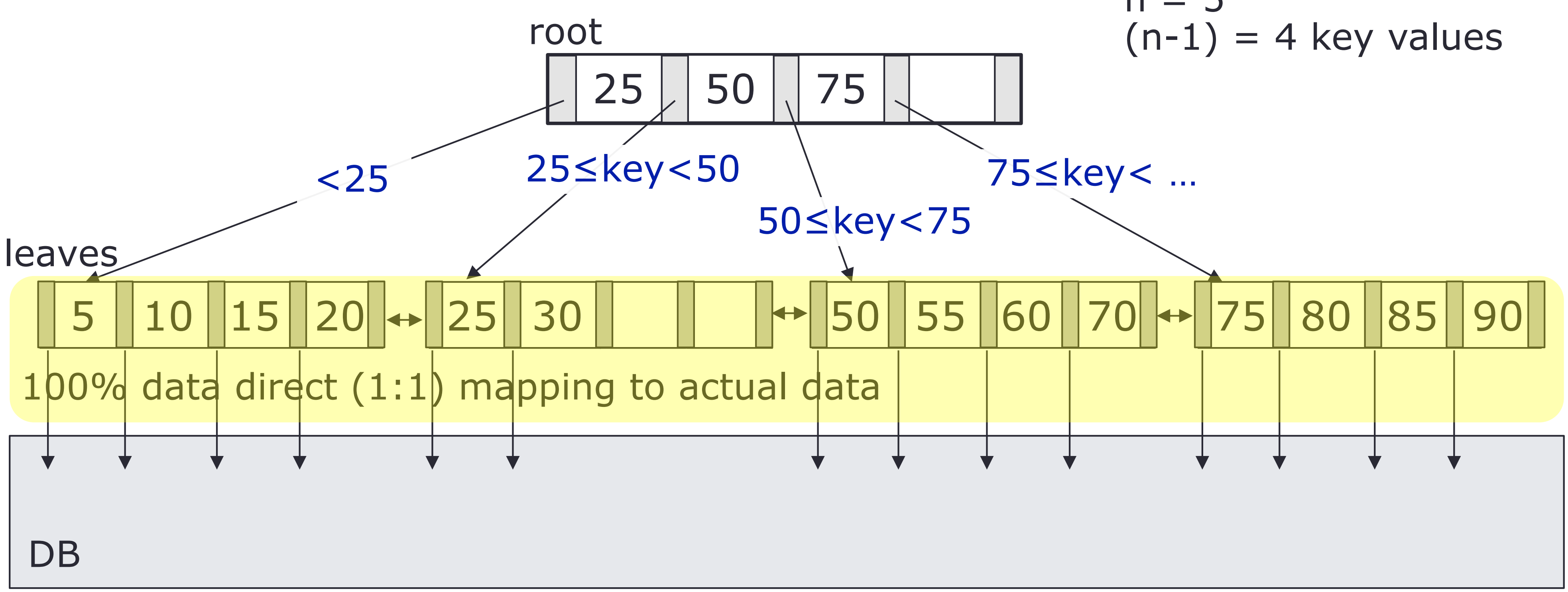
10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	80000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
58583	Califieri	History	60000
76543	Singh	Finance	80000
76766	Crick	Biology	72000
83821	Brandt	Comp. Sci.	92000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

[Ref: Figure 14.9, Silberschatz, Korth, Sudarshan, "Database System Concepts," 7th Ed., page 636]

B+ Tree: Node

- Nodes: root, internal node, or leaf node
- Each node is exactly one disk page ("page" and "node" are used interchangeably)
- Contain **n** pointers and **(n-1)** key values

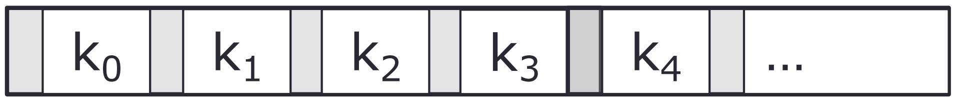
n = 5
(n-1) = 4 key values



B+ Tree: Leaf Node

- Each entry consists of a key value and a pointer to the storage location of data matching the key

- Leaf nodes are organized into a linked list pages, chaining the leaf nodes



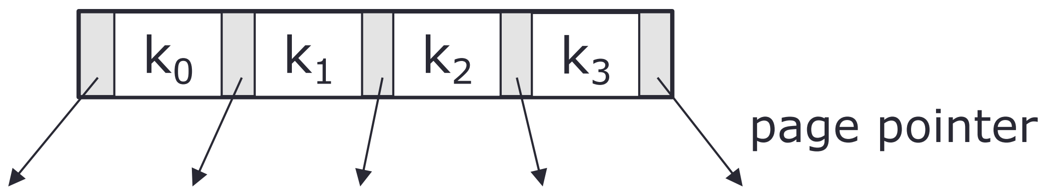
- For a B+ tree with **n** pointers
  - A leaf node holds $\left\lceil \frac{(n-1)}{2} \right\rceil \leq$ key values $\leq$ **(n-1)**

- Example:
  - If n=4, each leaf contains at least $\left\lceil \frac{(4-1)}{2} \right\rceil$ = 2 key values and at most (4-1) = 3 key values

[Ref: Silberschatz, Korth, Sudarshan, "Database System Concepts," 7th Ed., page 635, constraints on leaf nodes]

B+ Tree: Internal Node

- Nonleaf nodes: a multilevel (sparse) index
- Each entry consists of a reference value (key) and a pointer to the leaf nodes



- For a B+ tree with **n** pointers
  - An internal node holds $\left\lceil \frac{n}{2} \right\rceil \leq$ pointers $\leq$ **n**
    (thus, hold up to **(n-1)** key values)
- Example:
  - If n=4, each internal node contains at least $\left\lceil \frac{4}{2} \right\rceil$ = 2 pointers and at most = 4 pointers

[Ref: Silberschatz, Korth, Sudarshan, "Database System Concepts," 7th Ed., page 635, constraints on nonleaf nodes]

B+ Tree: Root Node

- A root node consists of one or more reference values (keys) and pointers to the leaf nodes (or internal nodes)

- For a B+ tree with **n** pointers
  - A root node holds **1** ≤ key values ≤ **(n-1)**
  - Must have at least two pointers if the root points to internal nodes
  - Must have at least one entry if the root is the only node in the tree

- Example:
  - If n=4, a root node can hold fewer than $\left\lceil \frac{4}{2} \right\rceil = 2$ pointers
  - It must hold at least 2 pointers (unless the tree consists of only one node)

[Ref: Silberschatz, Korth, Sudarshan, "Database System Concepts," 7th Ed., page 636, constraints on root nodes]

B+ Tree: # Indices

- For a **n-order** B+ tree with a height of **h**
  - The maximum number of records indexed is $\mathbf{r_{max} = n^{h} - n^{(h-1)}}$
  - The minimum number of records indexed is $\mathbf{r_{min} = 2\left\lceil \frac{n}{2} \right\rceil^{(h-1)}}$

Low n vs. High n

- Small value for n -- Tall and thin B+ tree
  - Advantage: Good consistent performance
    - Equal depth of tree → constant lookup time
  - Disadvantage: High overhead when insert/delete
    - Need to reorganize up and down the tree

- Large value for n -- Short and wide B+ tree
  - Advantage: Low overhead
  - Disadvantage: Performance varies

Read-heavy DB → consistent time → low n

Read/Write-mix DB → less overhead → high n

Advantages and Disadvantages

Index-sequential files:

Disadvantage:

- Performance degrades as sequential file grows because many overflow blocks are created
- Periodic reorganization of entire file is required

B+ Tree indices are alternatives to index sequential files

B+ Tree index file:

B+ Trees are used extensively in all DBMS

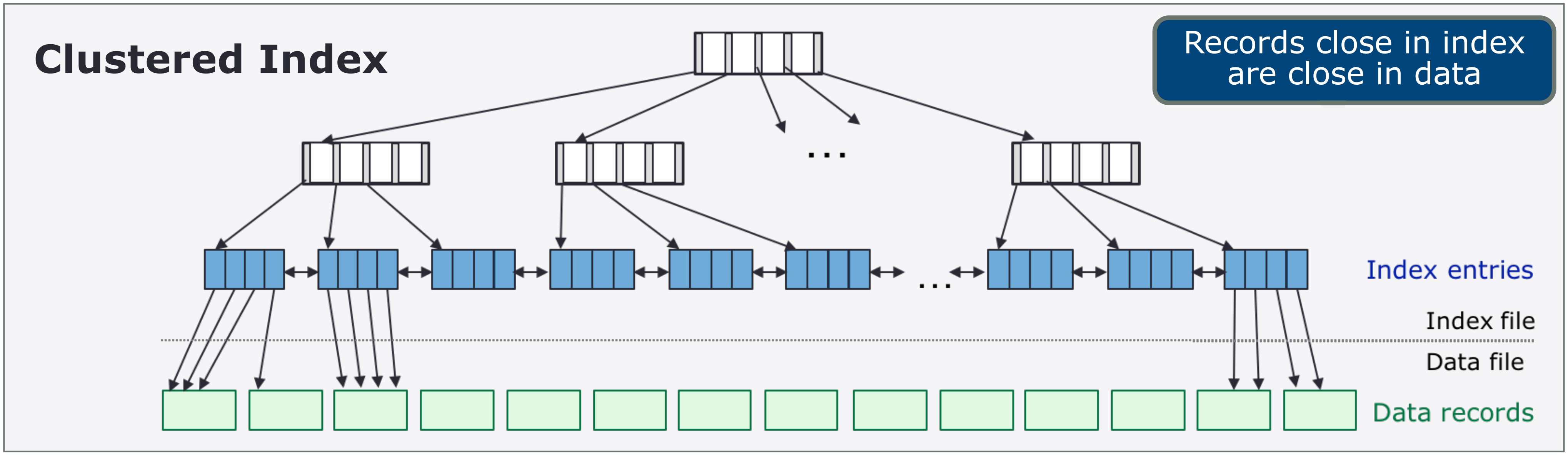
Advantage:

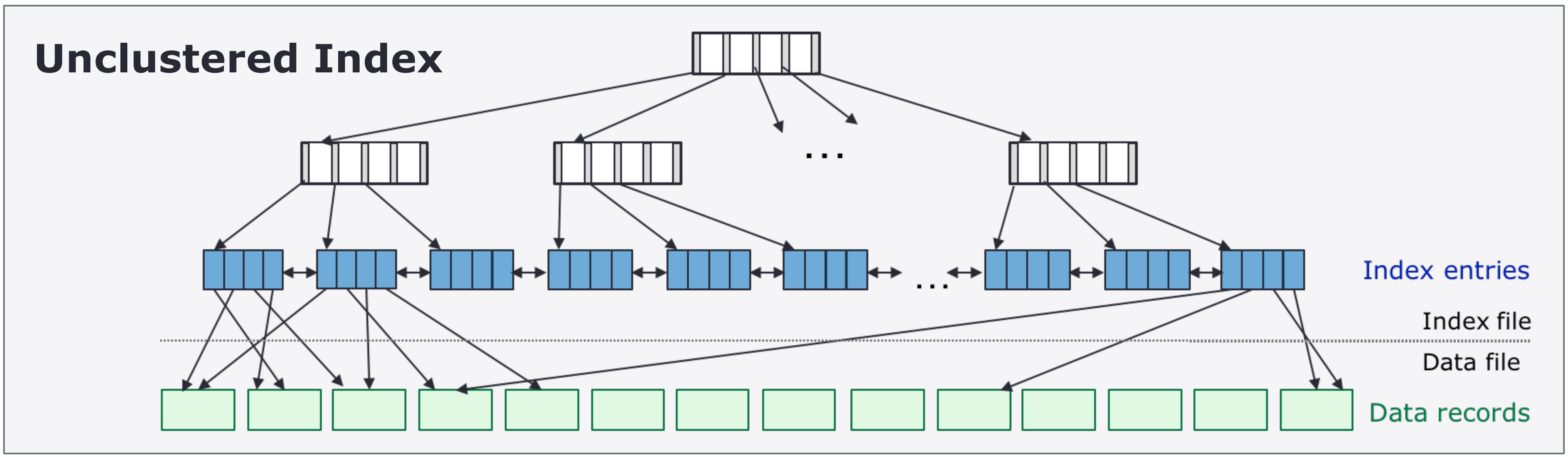
- Automatically recognize itself with small, local changes (when insert or delete data)
- Range queries on indexed attributes are fast

Disadvantage:

- Extra insertion deletion overhead, space overhead revisit

Clustered vs. Unclustered Index



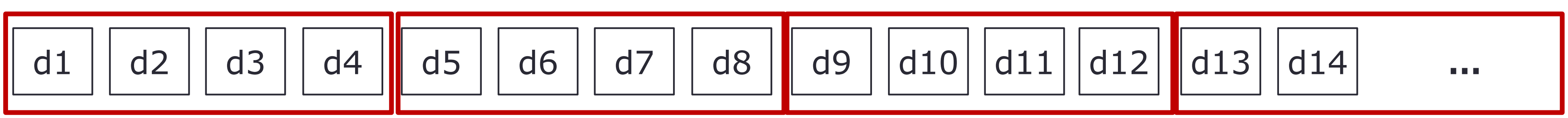


Cost of Disk I/O Operations

Assume a disk block holds 4 tuples of a relation. To find tuples associated with key values 40 – 85

Without an index, need sequential scanning

Estimated cost = # blocks scanned



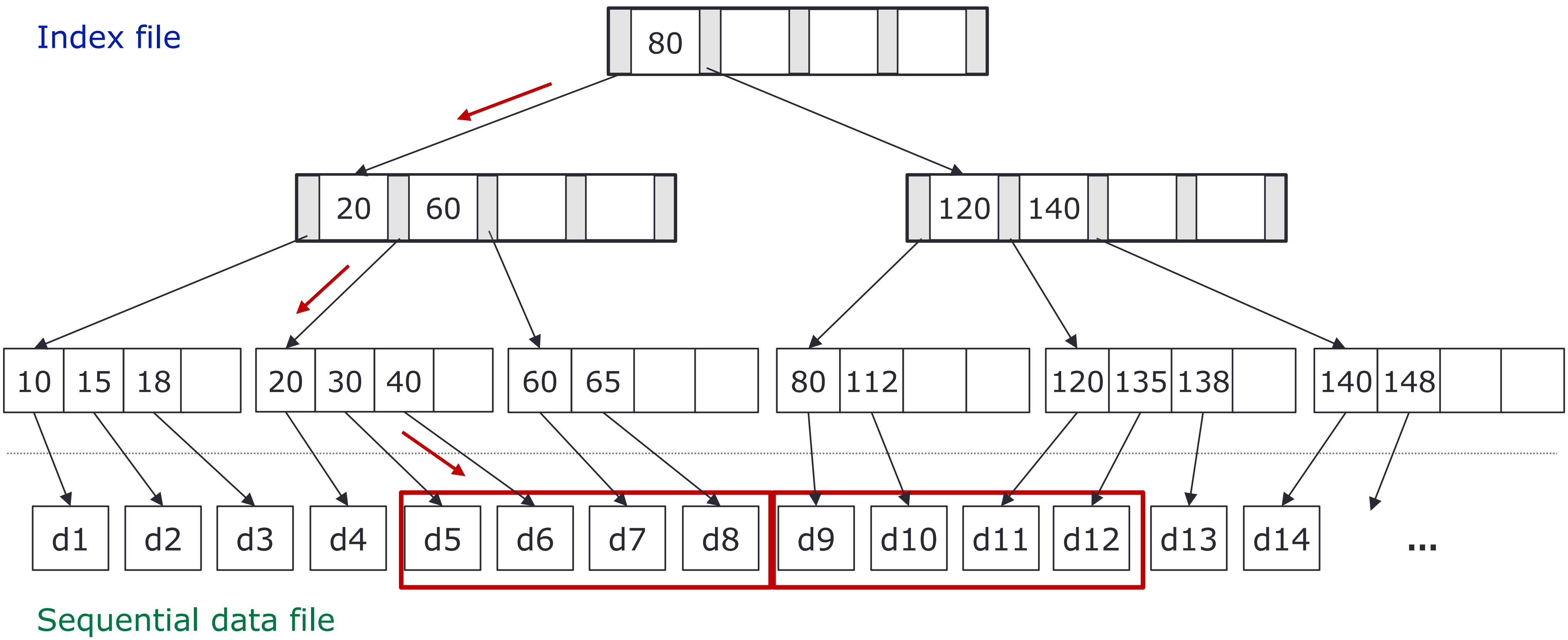
Sequential data file

Cost of Disk I/O Operations

Assume a disk block holds 4 tuples of a relation. To find tuples associated with key values 40 – 85

Use clustered index, index and data are **sorted the same way**

Estimated cost = selectivity estimate x #blocks



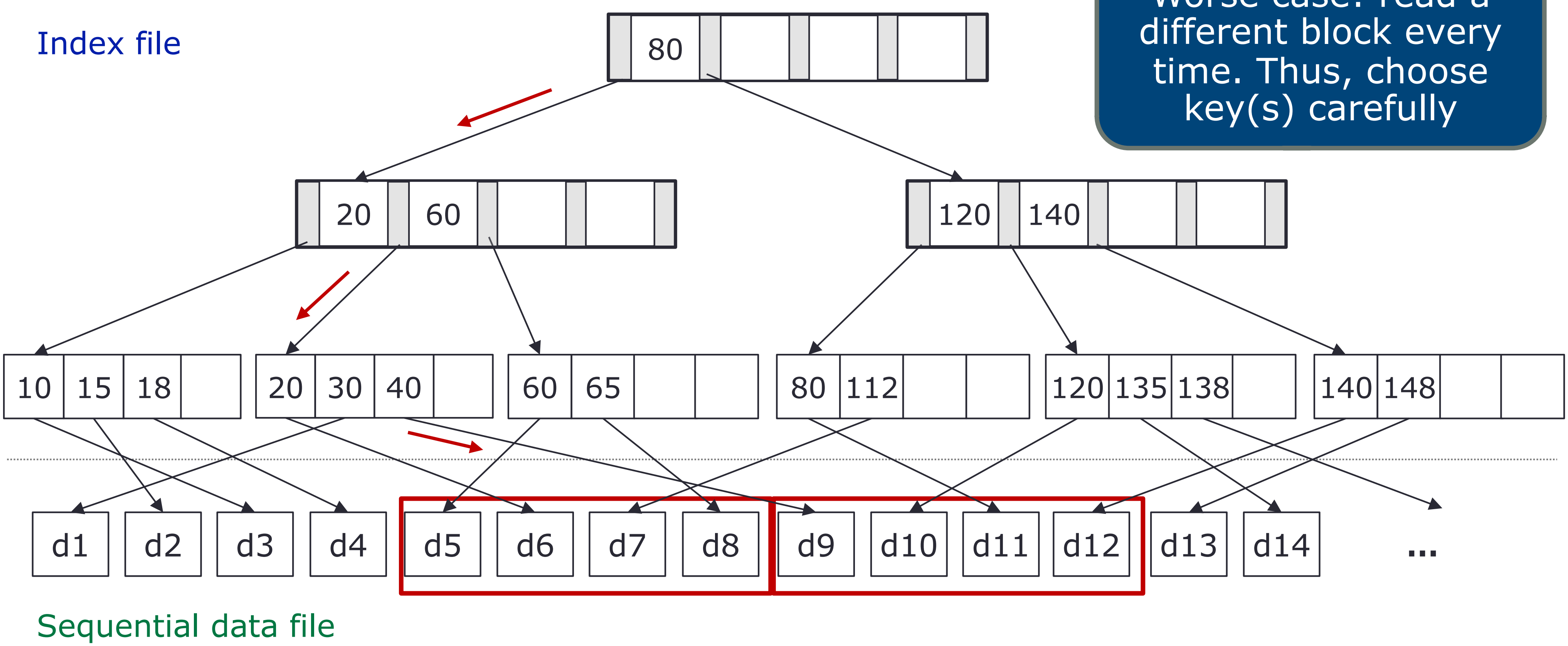
Cost of Disk I/O Operations

Assume a disk block holds 4 tuples of a relation. To find tuples associated with key values 40 – 85

Use unclustered index, index and data are sorted differently

Estimated cost = selectivity estimate x #tuples

Worse case: read a different block every time. Thus, choose key(s) carefully



Another Scenario

Supposed we know the following

#blocks = 100
#tuples = 10000

Using an unclustered index in the wrong scenario can lead to low performance

X = Selectivity estimate (~proportion of tuples matching the selection) of a given query = 0.1

No index (full sequential scan)

Cost = #blocks
= 100

Unclustered index

Cost = X * #tuples
= 0.1 * 10000
= 1000

Full sequential scan is a better option when

- Selectivity is high (many tuples match the selection), or
- Ratio between #tuples:#blocks is high

Create Indices in SQL

```
CREATE INDEX index_name ON table_name(column)
```

Unclusted by default

Order specifies precedence in sorting

```
CREATE INDEX index_name ON table_name(column1, column2)
```

Reorders data on disk
(fails if another clustered index exists)

```
CREATE CLUSTERED INDEX index_name ON table_name(column1, column2)
```

Leveraging Indices

```
students(ID, credits, age, …)
enroll(ID, course, section, semester, year, …)
```

What indices could we make on `students`?

```
Expecting 1000 executions/day
SELECT *
FROM   students, enroll
WHERE  students.ID = enroll.ID
```

IDs are unique.
Unclustered index would do fine.

```
Expecting 1000 executions/day
SELECT *
FROM   students
WHERE  credits > 100
```

This range query would benefit from a clustered index on credits

Only one can exists

```
Expecting 10 executions/day
SELECT *
FROM   students
WHERE  age > 21
```

This range query would benefit from a clustered index on age

Leveraging Indices (2)

```
students(ID, credits, age, …)
enroll(ID, course, section, sem
```

Things to consider:

- Size of the expected result
- Execution time

Without more info, default to clustering on the index that will be used more (thus, clustered index on credits)

```
Expecting 1000 executions/day
SELECT *
FROM   students, enroll
WHERE  students.ID = enroll.ID
```

```
Expecting 1000 executions/day
SELECT *
FROM   students
WHERE  credits > 100
```

This range query would benefit from a clustered index on credits

Only one can exists

```
Expecting 10 executions/day
SELECT *
FROM   students
WHERE  age > 21
```

This range query would benefit from a clustered index on age

Wrap-Up

- The existence of an index on an attribute
  - May speed up the execution of the queries (in which a values or a range of values is specified for that attributes), and
  - May speed up joins involving that attribute.
- Every index built for one or more attributes of some relation makes insertions / deletions / updates to that relation more complex and time consuming.
- When creating indices, transactions that will be executed must be taken into account.

Read-heavy DBs – **can index a lot** (if space allows)

Write-heavy DBs – **index sparingly** (take a balanced approach)

Write-only DBs – **one or no index**

Create indices to match expected query workload