Based on slides from Shasha et al, Kifer et al.

INDEXING

Agenda

- Access Path
  - Type of queries
  - Heap vs. indexes
  - Clustered vs. Unclustered
  - Dense vs. Sparse
- Data Structures
  - ISAM
  - B+-Tree
  - Hash
- Tuning

Access Path

- Refers to the algorithm + data structure (*e.g.*, an index) used for retrieving and storing data in a table
- The choice of an access path to use in the execution of an SQL statement has no effect on the semantics of the statement
- This choice can have a major effect on the execution time of the statement

Types of Queries

1. Point Query

   SELECT balance
   FROM accounts
   WHERE number = 1023;

2. Multipoint Query

   SELECT balance
   FROM accounts
   WHERE branchnum = 100;

3. Range Query

   SELECT number
   FROM accounts
   WHERE balance > 10000;

4. Prefix Match Query

   SELECT *
   FROM employees
   WHERE name = „Jensen"
   and firstname = „Carl"
   and age < 30;

Types of Queries

5. Extremal Query

```
SELECT *
FROM accounts
WHERE balance =
  max(select balance from accounts)
```

6. Ordering Query

```
SELECT *
FROM accounts
ORDER BY balance;
```

7. Grouping Query

```
SELECT branchnum, avg(balance)
FROM accounts
GROUP BY branchnum;
```

8. Join Query

```
SELECT distinct branch.adresse
FROM accounts, branch
WHERE
  accounts.branchnum =
                    branch.number
and accounts.balance > 10000;
```

Storage Structure

- Structure of file containing a table
  - Heap file (no index, not integrated)
  - Integrated file containing index and rows (index entries contain rows in this case)
    - ISAM
    - B^+ tree
    - Hash

Heap Files

- Rows appended to end of file as they are inserted
  - Hence the file is unordered
- Deleted rows create gaps in file
  - File must be periodically compacted to recover space

Transcript Stored as a Heap File

page 0

666666	MGT123	F1994	4.0
123456	CS305	S1996	4.0
987654	CS305	F1995	2.0

page 1

717171	CS315	S1997	4.0
666666	EE101	S1998	3.0
765432	MAT123	S1996	2.0
515151	EE101	F1995	3.0

page 2

234567	CS305	S1999	4.0
878787	MGT123	S1996	3.0

Heap File - Performance

- Assume file contains F pages
- *Inserting a row*:
  - Access path is scan
  - Avg. $F/2$ page transfers if row already exists
  - $F+1$ page transfers if row does not already exist

Heap File - Performance

- Query
  - Access path is scan
  - Organization efficient if query returns all rows and order of access is not important

    SELECT * FROM Transcript
  - Organization inefficient if a *few* rows are requested
    - Average *F*/2 pages read to get get a single row

```
SELECT  T.Grade
FROM  Transcript T
WHERE  T.StudId=12345 AND  T.CrsCode = „CS305“
        AND  T.Semester = „S2000“
```

Heap File - Performance

– Organization inefficient when a subset of rows is requested: *F* pages must be read

```
SELECT  T.Course, T.Grade
FROM  Transcript T                          -- point query
WHERE  T.StudId = 123456

SELECT  T.StudId, T.CrsCode
FROM  Transcript T                          -- range query
WHERE  T.Grade BETWEEN 2.0 AND 4.0
```

Index

- Mechanism for efficiently locating row(s) without having to scan entire table
- Based on a *search key:* rows having a particular value for the search key attributes can be quickly located
- Don't confuse candidate key with search key:
  - Candidate key: *set* of attributes; *guarantees* uniqueness
  - Search key: *sequence* of attributes; *does not guarantee* uniqueness –just used for search

Index Structure

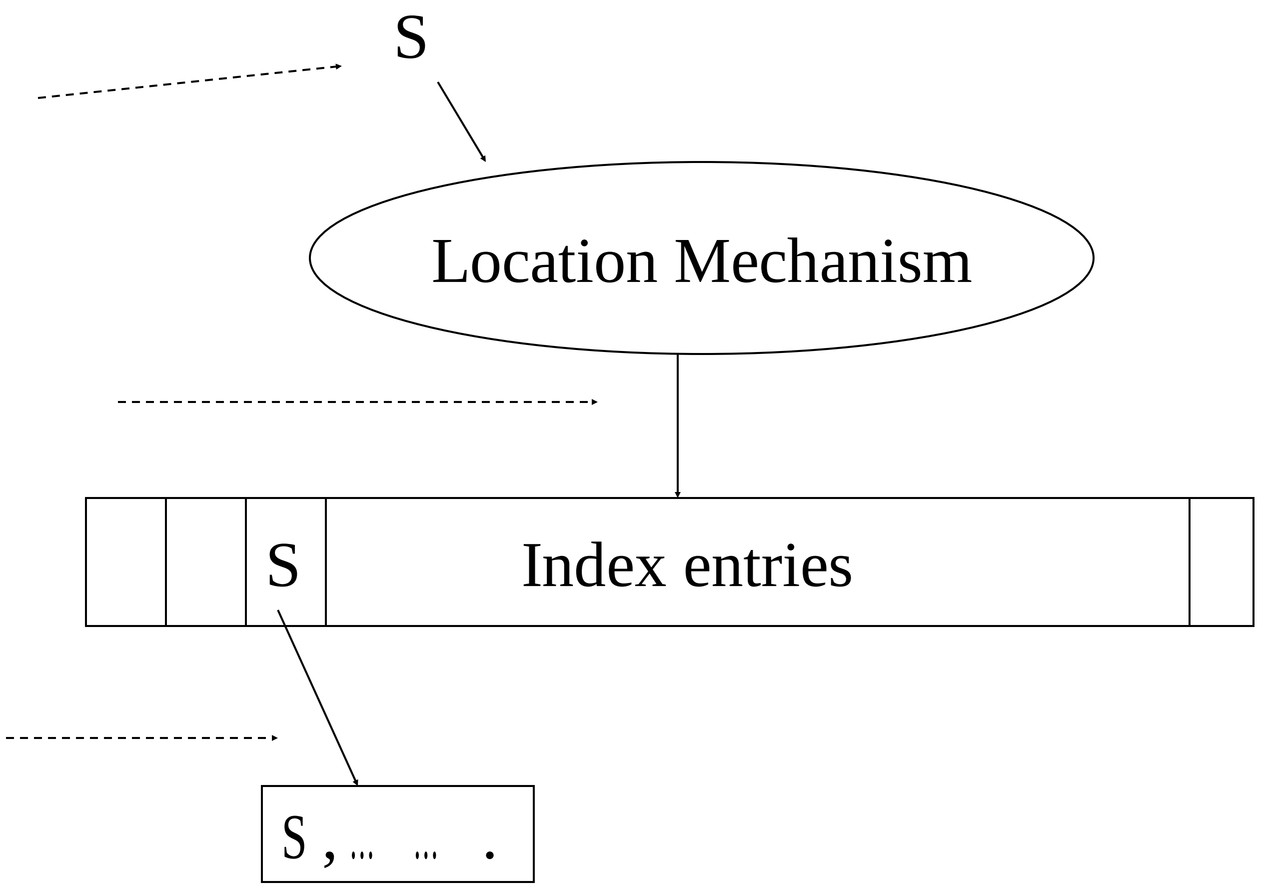
- Contains:
  - *Index entries*
    - Can contain the data tuple itself (index and table are *integrated* in this case); or
    - Search key value and a pointer to a row having that value; table stored separately in this case – *unintegrated* index
  - *Location mechanism*
    - Algorithm + data structure for locating an index entry with a given search key value
  - Index entries are stored in accordance with the search key value
    - Entries with the same search key value are stored together (hash, B-tree)
    - Entries may be sorted on search key value (B-tree)

Index Structure

Search key value

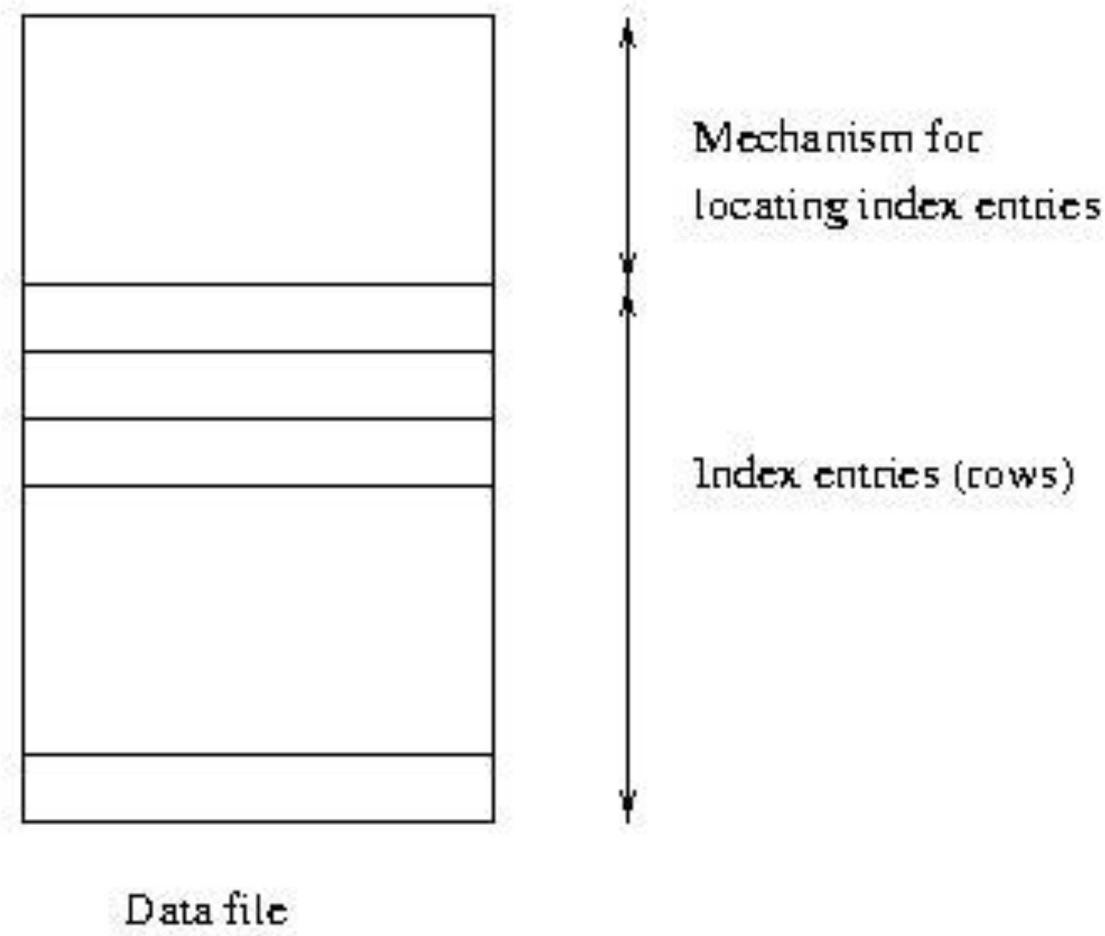
Location mechanism facilitates finding index entry for S

Once index entry is found, the row can be directly accessed

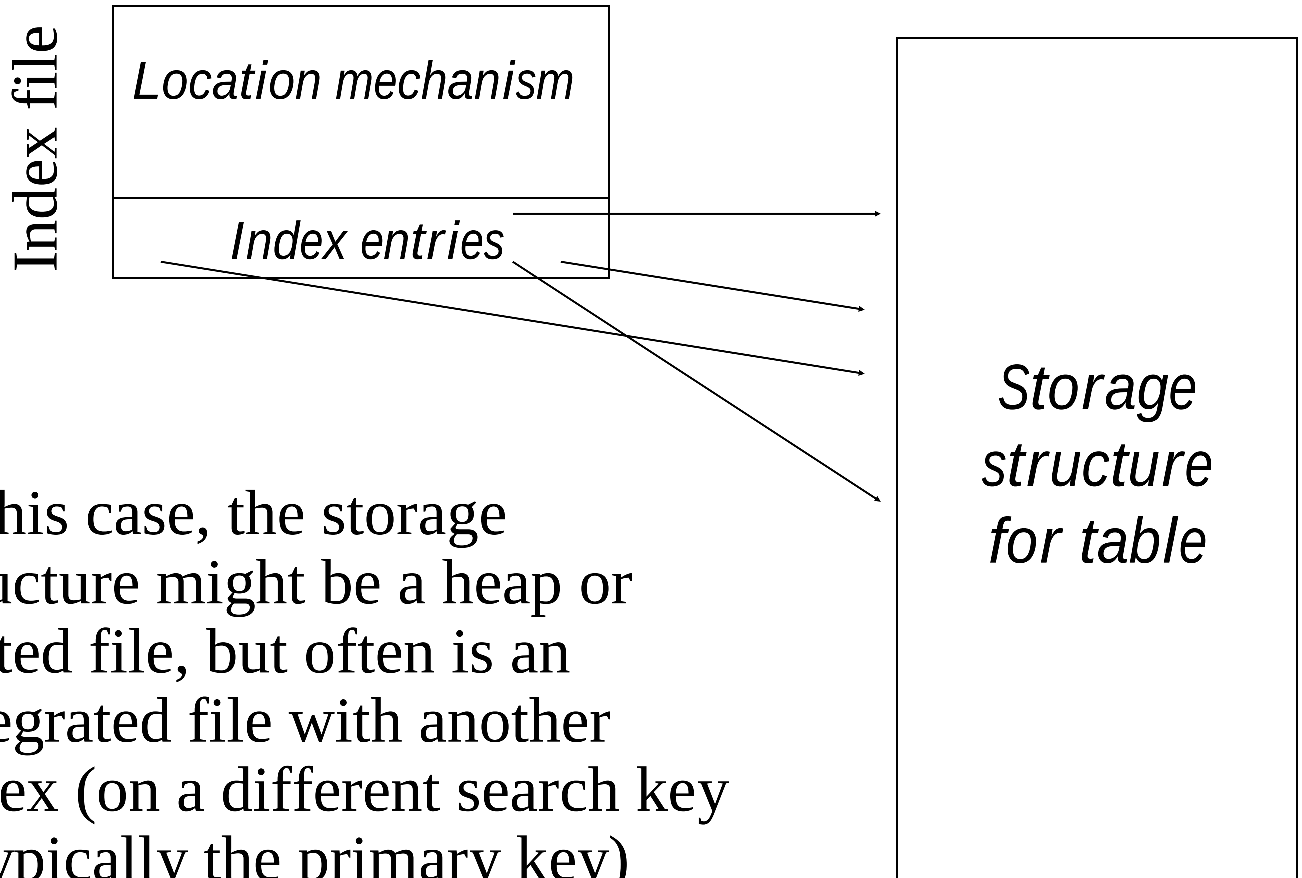


Integrated Storage Structure

Contains table and (main) index



Index File With Separate Storage Structure



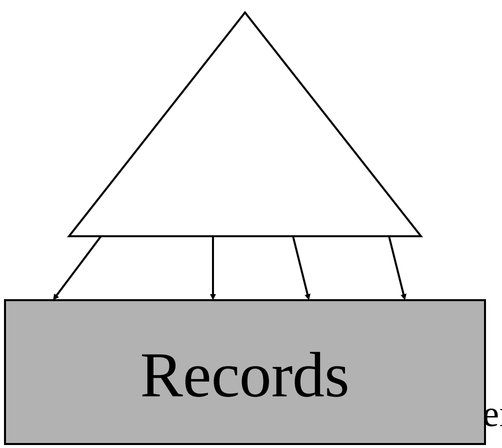
In this case, the storage structure might be a heap or sorted file, but often is an integrated file with another index (on a different search key – typically the primary key)

Indices: The Down Side

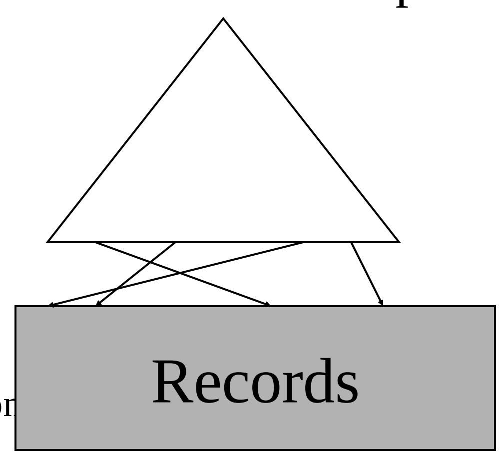
- Additional I/O to access index pages (except if index is small enough to fit in main memory)
- Index must be updated when table is modified.
- SQL-92 does not provide for creation or deletion of indices
  - Index on primary key generally created automatically
  - Vendor specific statements:
    - CREATE INDEX ind ON Transcript (*CrsCode*)
    - DROP INDEX ind

Clustered / Non clustered index

- Clustered index (primary index)
  - A clustered index on attribute X co-locates records whose X values are *near* to one another.



- Non-clustered index (secondary index)
  - A non clustered index does not constrain table organization.
  - There might be several non-clustered indexes per table.



Clustered Index

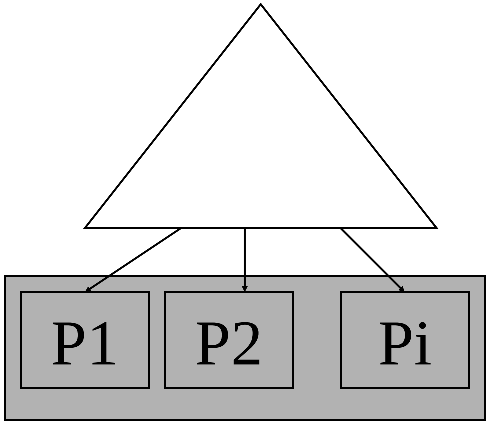
- Good for range searches when a range of search key values is requested
  - Use location mechanism to locate index entry at start of range
    - This locates first row.
  - Subsequent rows are stored in successive locations if index is clustered (not so if unclustered)
  - Minimizes page transfers and maximizes likelihood of cache hits

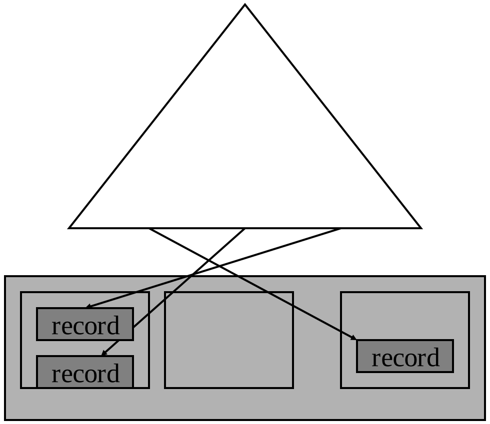
Example – Cost of Range Search

- Data file has 10,000 pages, 100 rows in search range
- Page transfers for table rows (assume 20 rows/page):
  - Heap: 10,000 (entire file must be scanned)
  - File sorted on search key: $\log_2 10000$ + (5 or 6)   19
  - Unclustered index: 100
  - Clustered index: 5 or 6
- Page transfers for index entries (assume 200 entries/page)
  - Heap and sorted: 0
  - Unclustered secondary index: 1 or 2 (all index entries for the rows in the range must be read)
  - Clustered secondary index: 1 (only first entry must be read)

Dense / Sparse Index

- Sparse index
  - Pointers are associated to pages
- Dense index
  - Pointers are associated to records
  - Non clustered indexes are dense





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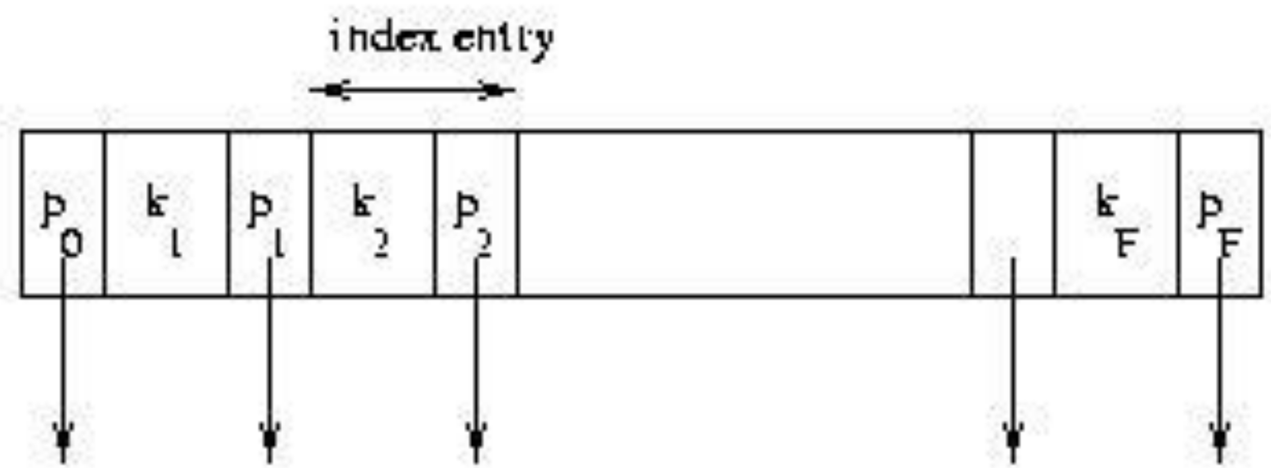
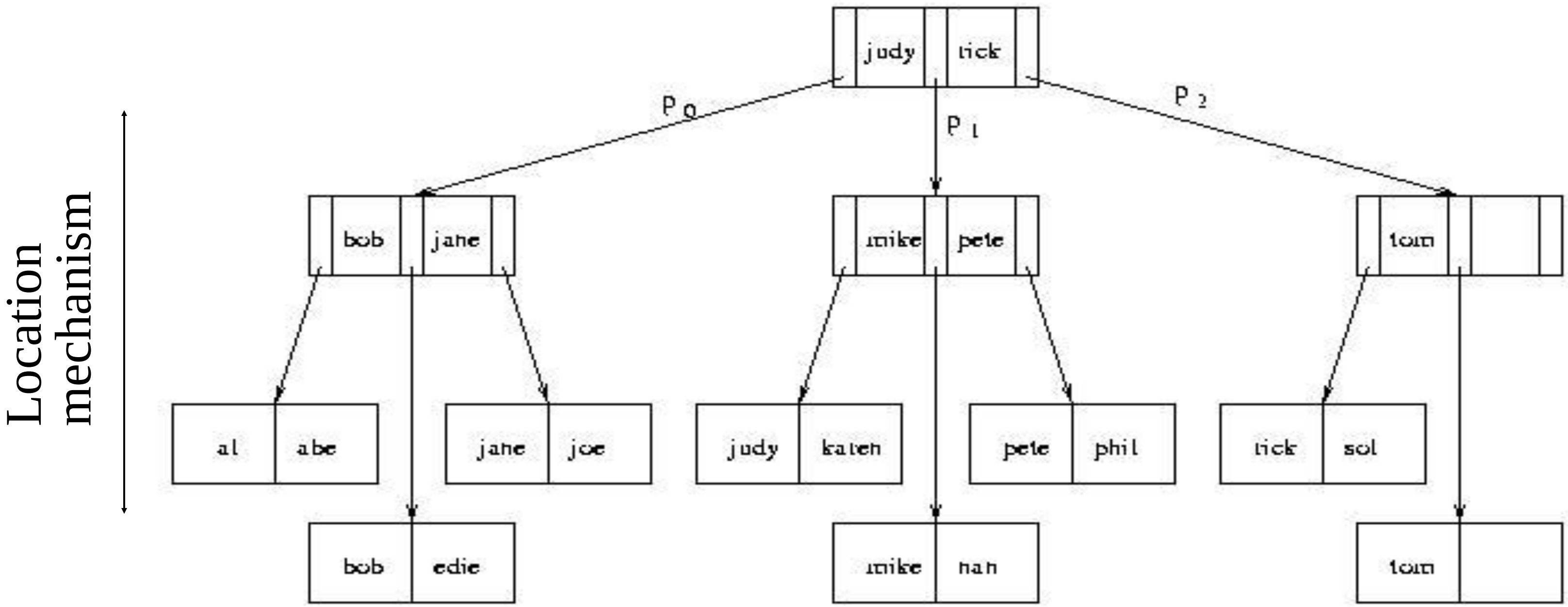
  - B+-Tree
  - Hash
- Tuning

Index Sequential Access Method (ISAM)

- Generally an integrated storage structure
  - Clustered, index entries contain rows
- Separator entry = (k_i , p_i); k_i is a search key value; p_i is a pointer to a lower level page
- k_i separates set of search key values in the two subtrees pointed at by p_{i-1} and p_i.



Index Sequential Access Method

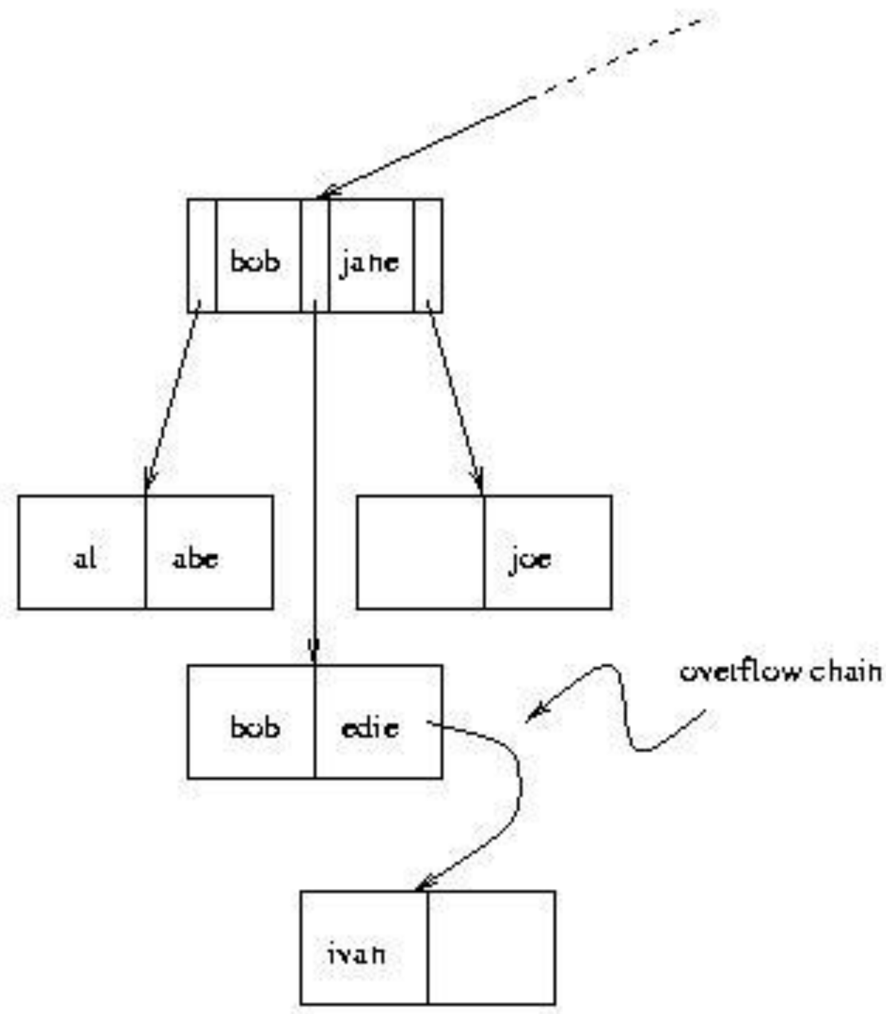


Index Sequential Access Method

- The index is static:
  - Once the separator levels have been constructed, they never change
  - Number and position of leaf pages in file stays fixed
- Good for equality and range searches
  - Leaf pages stored sequentially in file when storage structure is created to support range searches
    - if, in addition, pages are positioned on disk to support a scan, a range search can be very fast (static nature of index makes this possible)
- Supports multiple attribute search keys and partial key searches

Overflow Chains

- Contents of leaf pages change
- Row deletion yields empty slot in leaf page
- Row insertion can result in overflow leaf page and ultimately overflow chain
  - *Chains can be long, unsorted, scattered on disk*
  - *Thus ISAM can be inefficient if table is dynamic*

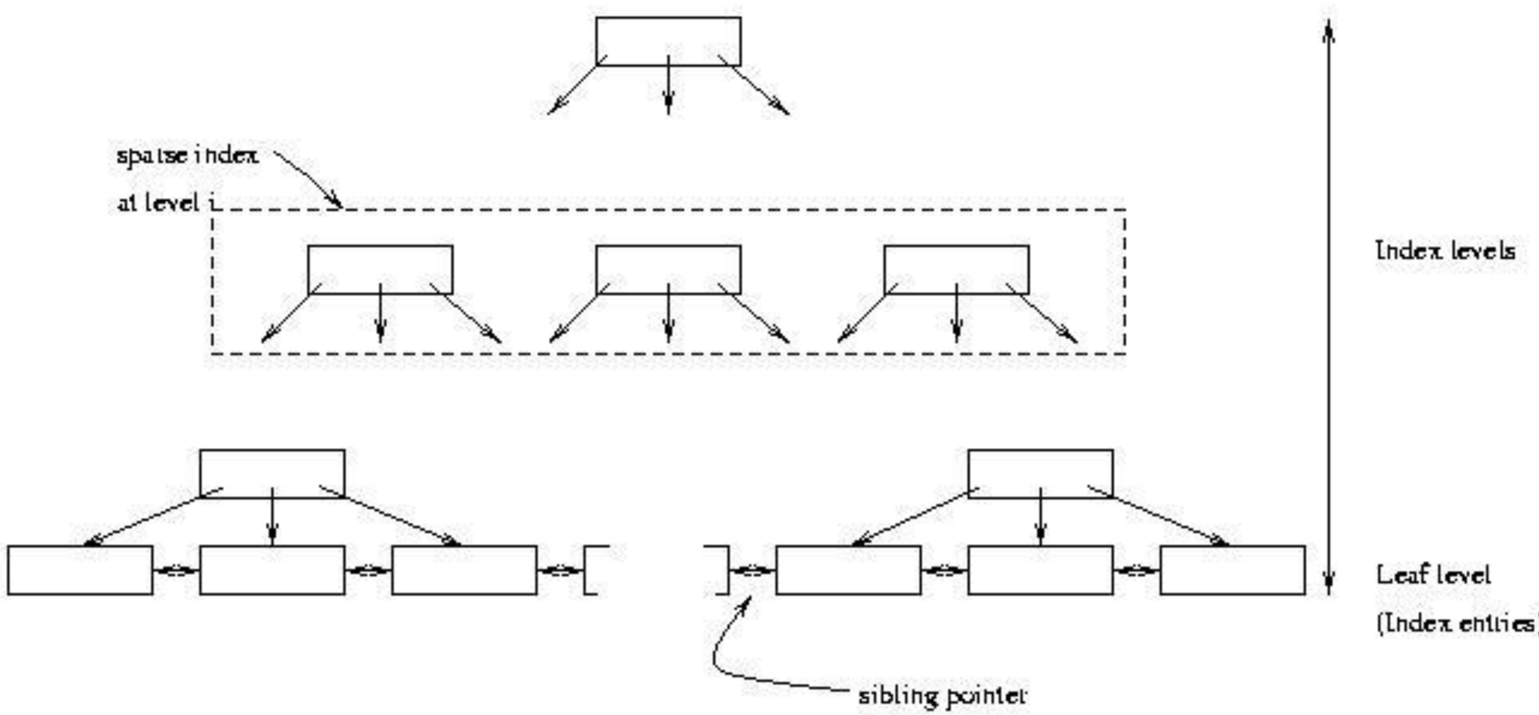


B^+ Tree

- Supports equality and range searches, multiple attribute keys and partial key searches
- Either a secondary index (in a separate file) or the basis for an integrated storage structure

➢ *Responds to dynamic changes in the table*

B^+ Tree Structure



– Leaf level is a (sorted) linked list of index entries

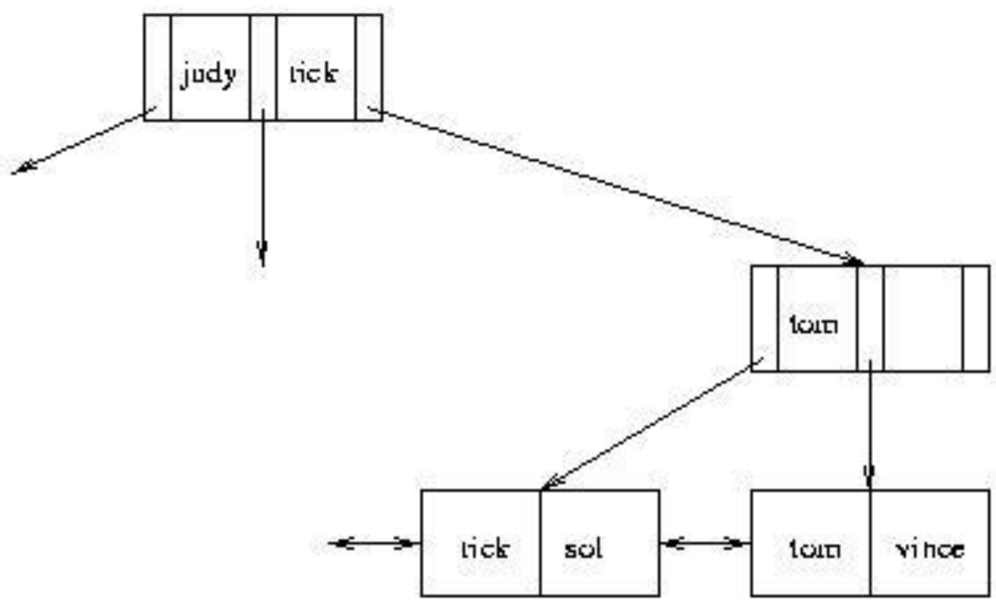
– Sibling pointers support range searches in spite of allocation and deallocation of leaf pages (but leaf pages might not be physically contiguous on disk)

Insertion and Deletion in B$^+$ Tree

- Structure of tree changes to handle row insertion and deletion – *no* overflow chains
- Tree remains *balanced*: all paths from root to index entries have same length
- Algorithm guarantees that the number of separator entries in an index page is between *_/2* and _ (_ is the fanout of a non leaf node)
  - Hence the maximum search cost is $log_{/2} Q + 1$ (with ISAM search cost depends on length of overflow chain)

Handling Insertions - Example

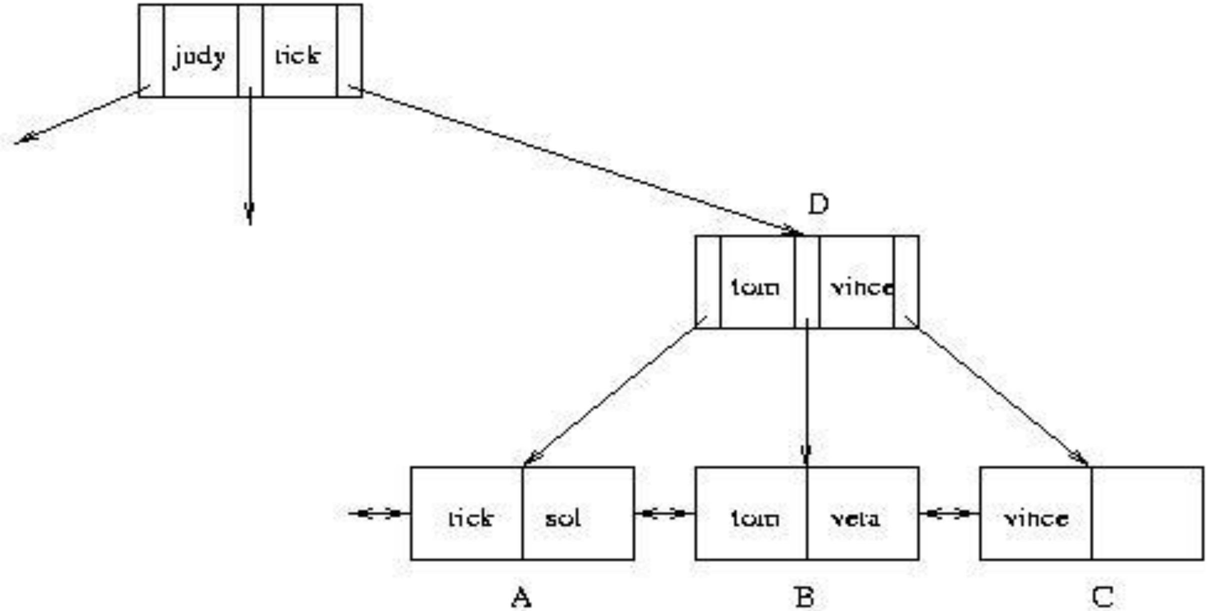
- Insert "vince"



Handling Insertions (cont'd)

– Insert "vera": Since there is no room in leaf page:

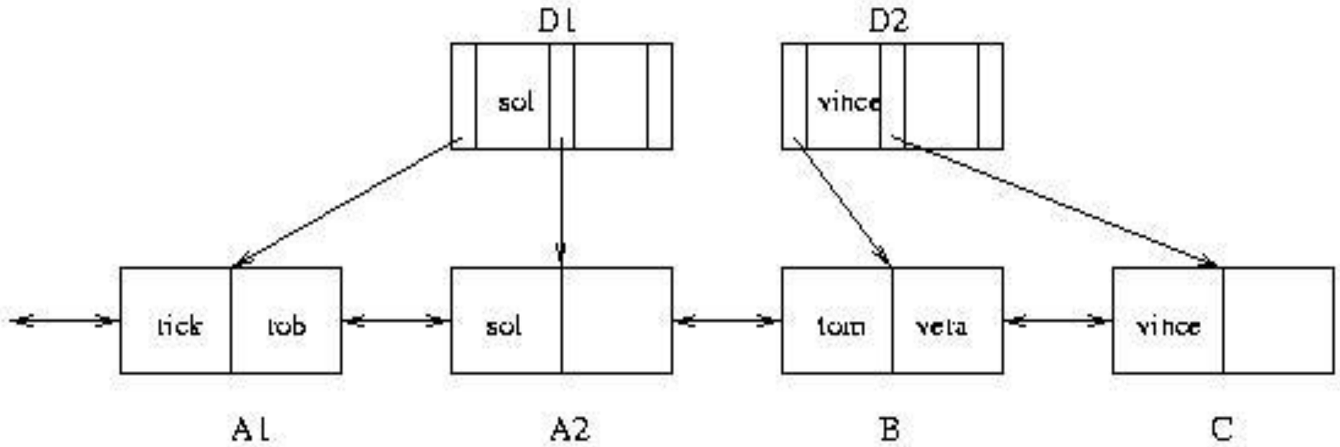
1. Create new leaf page, C
2. Split index entries between B and C (but maintain sorted order)
3. Add separator entry at parent level



Handling Insertions (con"t)

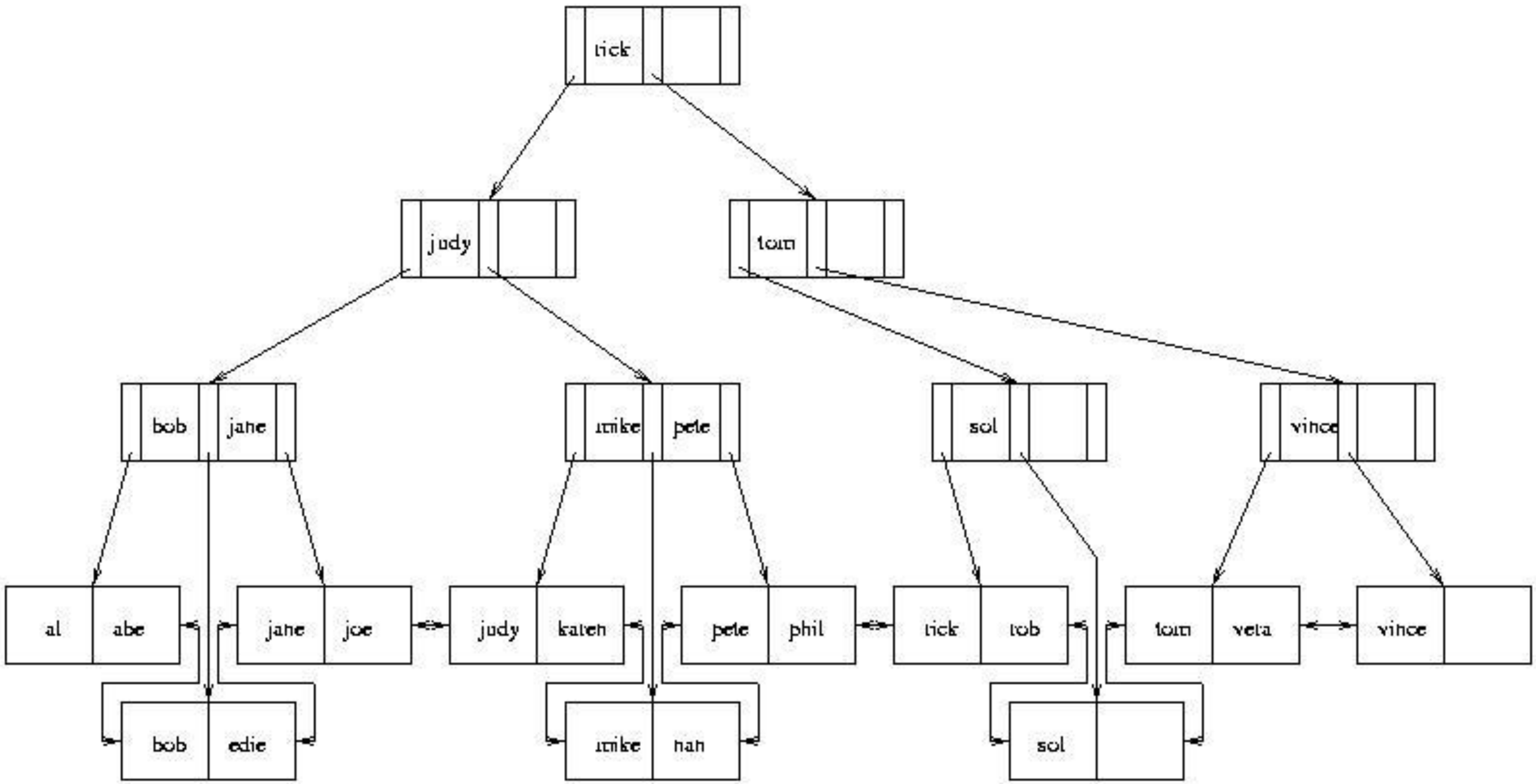
– Insert "rob". Since there is no room in leaf page A:

1. Split A into A1 and A2 and divide index entries between the two (but maintain sorted order)
2. Split D into D1 and D2 to make room for additional pointer
3. Three separators are needed: "sol", "tom" and "vince"



Handling Insertions (cont‟d)

- When splitting a separator page, push a separator up
- Repeat process at next level
- Height of tree increases by one



Handling Deletions

- Deletion can cause page to have fewer than */2* entries
  - Entries can be redistributed over adjacent pages to maintain minimum occupancy requirement
  - Ultimately, adjacent pages must be merged, and if merge propagates up the tree, height might be reduced
  - See book
- In practice, tables generally grow, and merge algorithm is often not implemented
  - *Reconstruct tree to compact it*

Index Locks, Predicate Locks, and Key-Range Locking

- If a WHERE clause refers to a predicate name = mary and if there is an index on name, then an index lock on the index entries for name = mary is like a predicate lock on that predicate
- If a WHERE clause refers to a predicate such as 50000< salary < 70000 and if there is an index on salary, then a key-range index lock can be used to get the equivalent of a predicate lock on the predicate 50000<salary<70000

Key-Range Locking

- Instead of locking index pages, index entries at the leaf level are locked
  - Each such lock is interpreted as a lock on a range
- Suppose the domain of an attribute is A … Z and suppose at some time the entries in the index are

  C G P R X

- A lock on G is interpreted as a lock on the half-open interval

  [G P)

  - Which includes G but not P

Key-Range Locking (cont)

- Recall the index entries are: C G P R X
- Two special cases
  - A lock on X locks everything greater than X
  - A new lock must be provided for [A C)
- Then for example to lock the interval H < K < Q, we would lock G and P

Key-Range Locking (cont)

- Recall the index entries are: C G P R X
- To insert a new key, J, in the index
  - Lock G thus locking the interval [G P)
  - Insert J thus splitting the interval into [G J) [J P)
  - Lock J thus locking [J P)
  - Release the lock on G
- If a SELECT statement had a lock on G as part of a key-range, then the first step of the insert protocol could not be done
  - Thus phantoms are prevented and the key-range lock is equivalent to a predicate lock

Locking a B-Tree Index

- Many operations need to access an index structure concurrently
  - This would be a bottleneck if conventional two-phase locking mechanisms were used
- Because we understand the semantics of the index, we can develop a more efficient locking algorithm
  - The goal is to maintain isolation amount different operations that are concurrently accessing the index
  - The short term locks on the index structure are called latches
    - The long term locks on leaf entries we have been discussing are still obtained

Locking a B-Tree Index (cont)

- Read Locks
  - Obtain a read lock on the root, and work your way down the tree locking each entry as it is reached
  - When a new entry is locked, the lock on the previous entry (its parent) can be released
    - This operation will never revisit the parent
    - No write operation of a concurrent transaction can pass this operation as it goes down the tree
    - Called lock coupling or crabbing

Locking a B-Tree Index (cont)

- Write Locks
  - Obtain a write lock on the root, and work your way down the tree locking each entry as it is reached
  - When a new entry, n, is locked, if that entry is not full, the locks on all its parents can be released
    - An insert operation might have to go back up the tree, revisiting and perhaps splitting some nodes
    - Even if that occurs, because n is not full, it will not have to split n and therefore will not have to go further up the tree
    - Thus it can release locks further up in the tree.

Hash Index

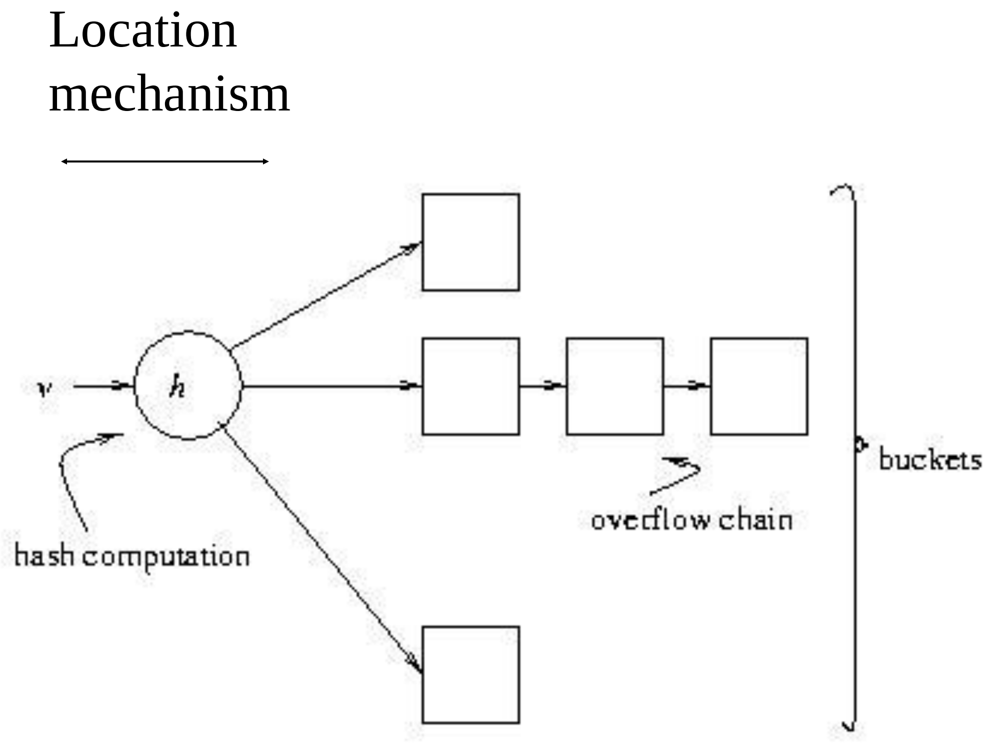
- Index entries partitioned into *buckets* in accordance with a *hash function*, *h(v)*, where *v* ranges over search key values
  - Each bucket is identified by an address, *a*
  - Bucket at address *a* contains all index entries with search key *v* such that *h(v) = a*
- Each bucket is stored in a page (with possible overflow chain)
- If index entries contain rows, set of buckets forms an integrated storage structure; else set of buckets forms an (unclustered) secondary index

Equality Search with Hash Index

Given *v*:

1. Compute *h(v)*
2. Fetch bucket at *h(v)*
3. Search bucket

Cost = number of pages in bucket (cheaper than B^+ tree, if no overflow chains)



Hash Indices – Problems

- Does not support range search
  - Since adjacent elements in range might hash to different buckets, there is no efficient way to scan buckets to locate all search key values v between v_1 and v_2
- Although it supports multi-attribute keys, it does not support partial key search
  - Entire value of v must be provided to h
- Dynamically growing files produce overflow chains, which negate the efficiency of the algorithm

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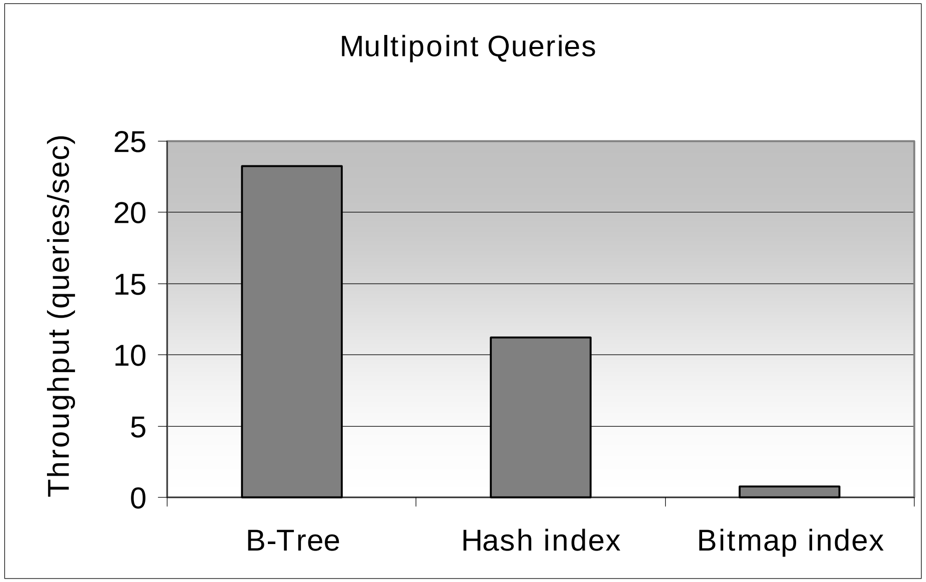
Index Tuning Knobs

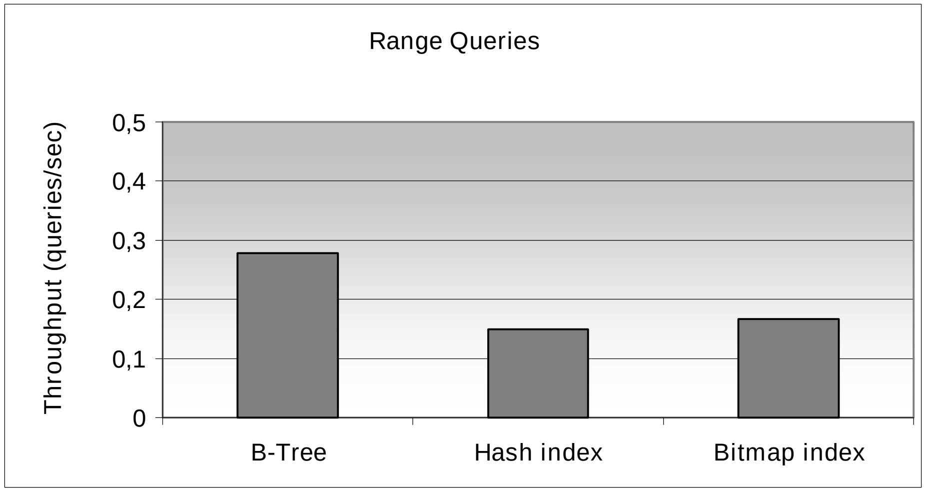
- Index data structure
- Search key
- Size of key
- Clustered/Non-clustered/No index
- Covering
- Maintenance

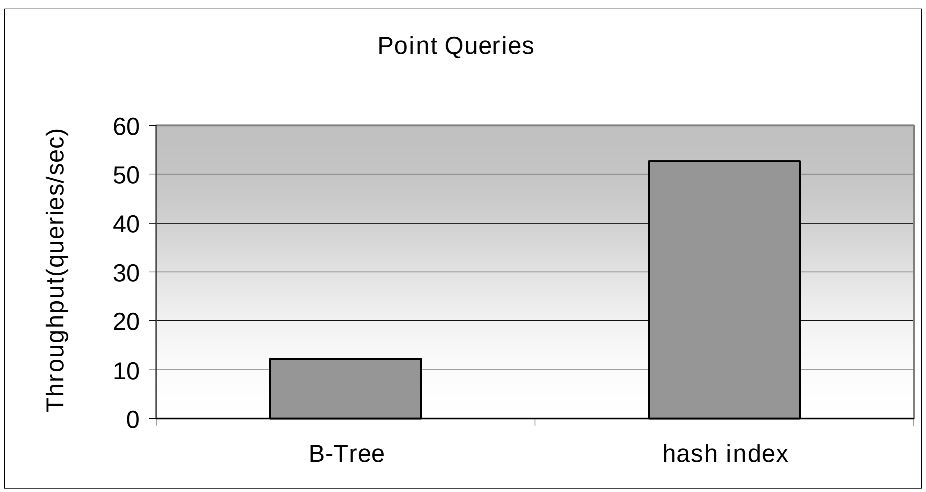
Multipoint query: B-Tree, Hash Tree



- There is an overflow chain in a hash index
- In a clustered B-Tree index records are on contiguous pages.

B-Tree, Hash Tree





- Hash indexes don“t help when evaluating range queries
- Hash index outperforms B-tree on point queries

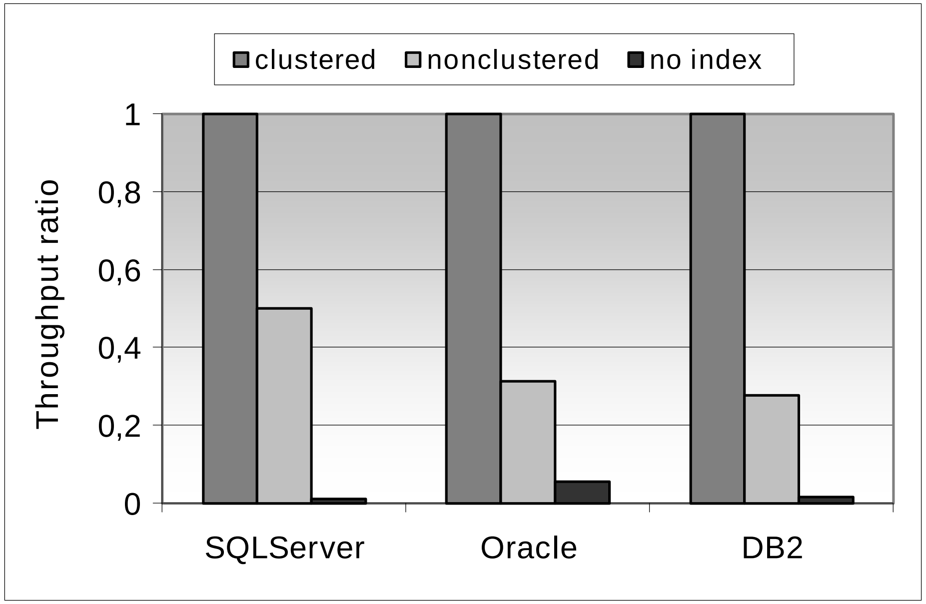
Key Compression

- Use key compression
  - If you are using a B-tree
  - Compressing the key will reduce the number of levels in the tree
  - The system is not CPU-bound
  - Updates are relatively rare

Clustered Index

- Because there is only one clustered index per table, it might be a good idea to replicate a table in order to use a clustered index on two different attributes
  - Yellow and white pages in a paper telephone book
  - Low insertion/update rate

Clustered Index



- Multipoint query that returns 100 records out of 1000000.
- Cold buffer
- Clustered index is twice as fast as non-clustered index and orders of magnitude faster than a scan.

Non-Clustered Index

<u>Benefits of non-clustered indexes</u>

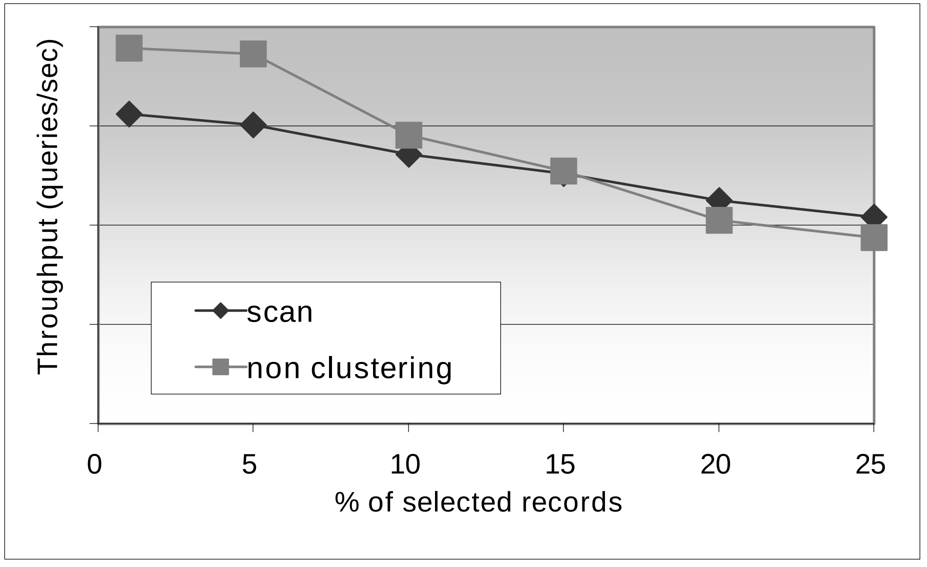
1. A dense index can eliminate the need to access the underlying table through covering.
   - It might be worth creating several indexes to increase the likelihood that the optimizer can find a covering index

2. A non-clustered index is good if each query retrieves significantly fewer records than there are pages in the table.
   - Point queries
   - Multipoint queries:

*number of distinct key values > c * number of records per page*

Where c is the number of pages retrieved in each prefetch

Scan Can Sometimes Win



- IBM DB2 v7.1 on Windows 2000
- Range Query
- If a query retrieves 10% of the records or more, scanning is often better than using a non-clustering non-covering index. Crossover > 10% when records are large or table is fragmented on disk – scan cost increases.

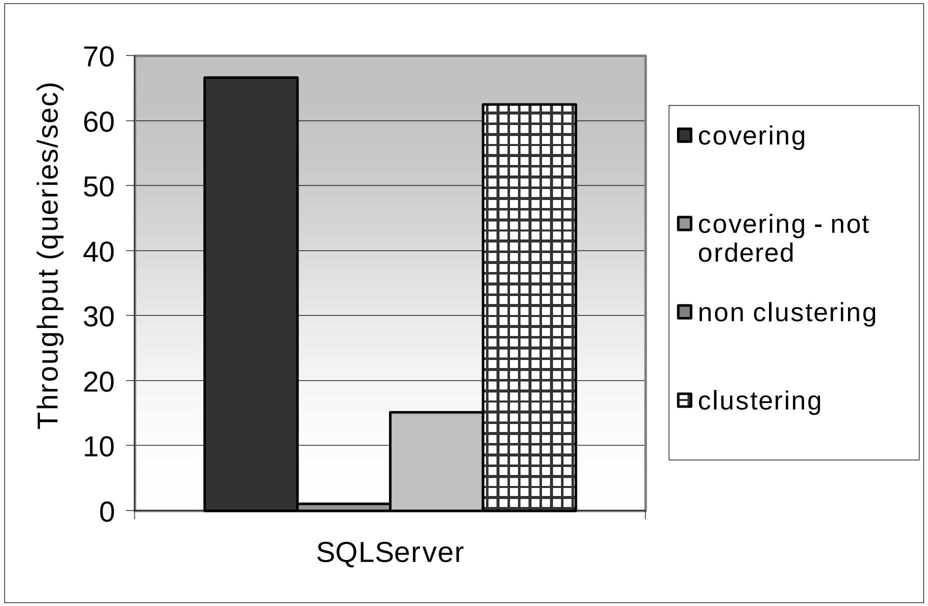
Multiple Attribute Search Key

- CREATE INDEX Inx ON Tbl (A*tt1*, A*tt2*)
- Search key is a *sequence* of attributes; index entries are lexically ordered
- Supports finer granularity equality search:
  - "Find row with value (A1, A2)"
- Supports range search (tree index only):
  - "Find rows with values between (A1, A2) and (A1 , A2)"
- Supports partial key searches (tree index only):
  - Find rows with values of A*tt1* between A1 and A1
  - But not "Find rows with values of A*tt2* between A2 and A2 "

Covering Index - defined

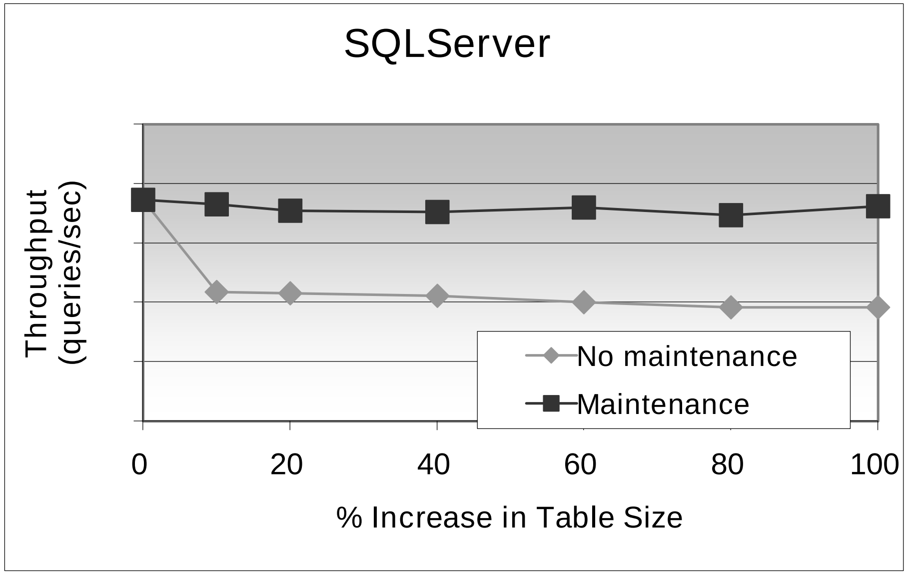
- Select name from employee where department = "marketing"
- Good covering index would be on (department, name)
- Index on (name, department) less useful.
- Index on department alone moderately useful.

Covering Index - impact



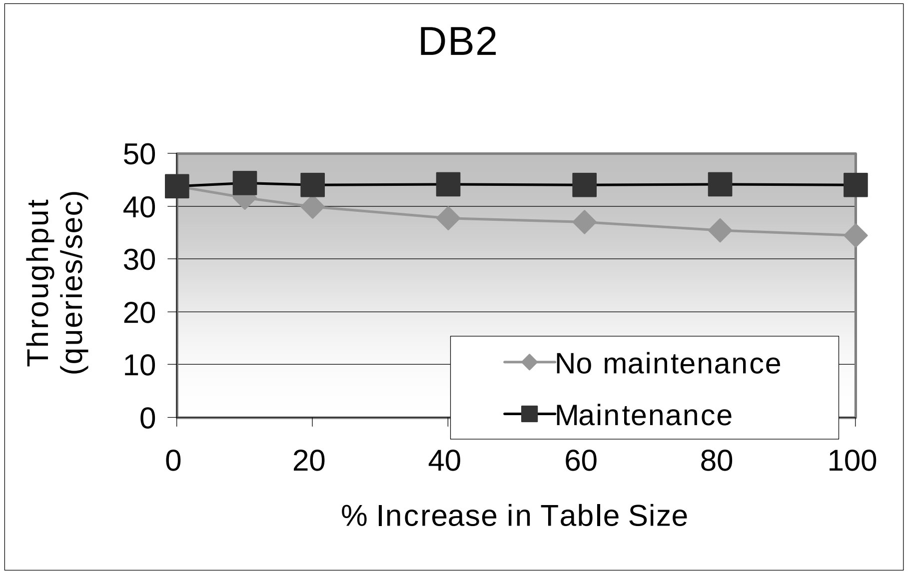
- Covering index performs better than clustering index when first attributes of index are in the where clause and last attributes in the select.
- When attributes are not in order then performance is much worse.

Index "Face Lifts"



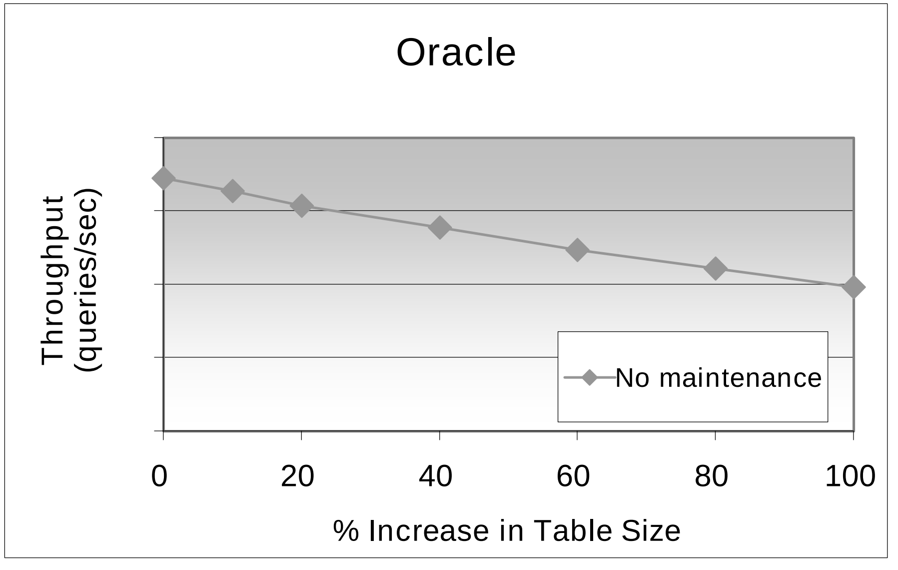
- Index is created with fillfactor = 100.
- Insertions cause page splits and extra I/O for each query
- Maintenance consists in dropping and recreating the index
- With maintenance performance is constant while performance degrades significantly if no maintenance is performed.

Index "Face Lifts"



- Index is created with pctfree = 0
- Insertions cause records to be appended at the end of the table
- Each query thus traverses the index structure and scans the tail of the table.
- Performances degrade slowly when no maintenance is performed.

Index “Face lifts”

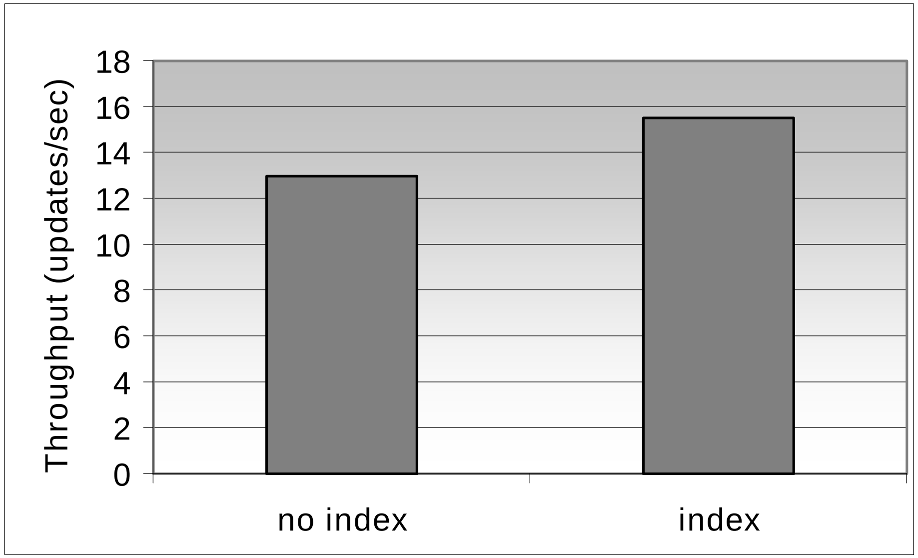


- In Oracle, clustered index are approximated by an index defined on a clustered table
- No automatic physical reorganization
- Index defined with pctfree = 0
- Overflow pages cause performance degradation

Index on Small Tables

- Tuning manuals suggest to avoid indexes on small tables
  - If all data from a relation fits in one page then an index page adds an I/O
  - If each record fits in a page then an index helps performance

Index on Small Tables



- Small table: 100 records
- Two concurrent processes perform updates (each process works for 10ms before it commits)
- No index: the table is scanned for each update. No concurrent updates.
- A clustered index allow to take advantage of row locking.

Summary

1. Use a hash index for point queries only. Use a B-tree if multipoint queries or range queries are used
2. Use clustering
   - if your queries need all or most of the fields of each records returned
   - if multipoint or range queries are asked
3. Use a dense index to cover critical queries
4. Don't use an index if the time lost when inserting and updating overwhelms the time saved when querying