Database Tuning

Index Tuning

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Adapted from "Database Tuning" by Dennis Shasha and Philippe Bonnet.

Outline

1. Index Tuning
   - Query Types
   - Index Types
   - Data Structures
   - Composite Indexes
   - Indexes and Joins
   - Index Tuning Examples

Outline

Query Types

- Different indexes are good for different query types.
- We identify categories of queries with different index requirements.

Query Types

- Point query: returns at most one record

```
SELECT name
FROM Employee
WHERE ID = 8478
```

- Multipoint query: returns multiple records based on equality condition

```
SELECT name
FROM Employee
WHERE department = 'IT'
```

- Range query on X returns records with values in interval of X

```
SELECT name
FROM Employee
WHERE salary >= 155000
```

Query Types

- Prefix match query: given an ordered sequence of attributes, the query specifies a condition on a prefix of the attribute sequence
- Example: attribute sequence: lastname, firstname, city
  - The following are prefix match queries:
    - `lastname='Gates'`
    - `lastname='Gates' AND firstname='George'`
    - `lastname='Gates' AND firstname like 'Ge%'`
    - `lastname='Gates' AND firstname='George' AND city='San Diego'`
  - The following are not prefix match queries:
    - `firstname='George'`
    - `lastname LIKE '%ates'`

Query Types

- Extremal query: returns records with max or min values on some attributes

```
SELECT name
FROM Employee
WHERE salary = MAX(SELECT salary FROM Employee)
```

- Ordering query: orders records by some attribute value

```
SELECT *
FROM Employee
ORDER BY salary
```

- Grouping query: partition records into groups; usually a function is applied on each partition

```
SELECT dept, AVG(salary)
FROM Employee
GROUP BY dept
```

Query Types

- Join queries: link two or more tables
- Equality join:

```
SELECT Employee.ssnum
FROM Employee, Student
WHERE Employee.ssnum = Student.ssnum
```

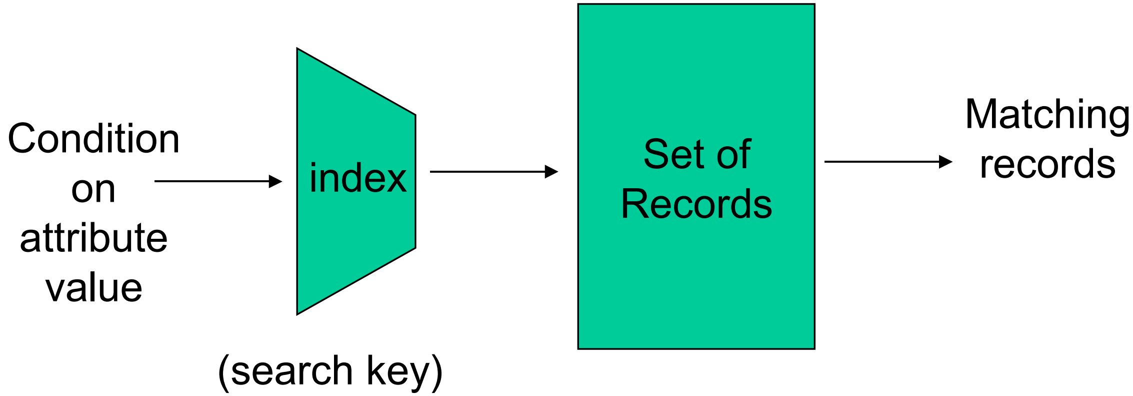
- Join with non-equality condition:

```
SELECT e1.ssnum
FROM Employee e1, Employee e2
WHERE e1.manager = e2.ssnum
AND e1.salary > e2.salary
```

Outline

What is an Index?

- An index is a data structure that supports efficient access to data:



- Index tuning essential to performance!
- Improper index selection can lead to:
  - indexes that are maintained but never used
  - files that are scanned in order to return a single record
  - multitable joins that run for hours or days

Key of an Index

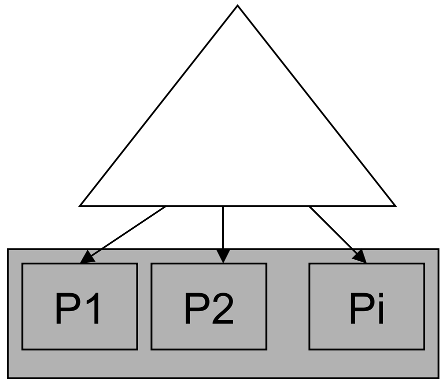
- Search key or simply "key" of an index:
  - single attribute or sequence of attributes
  - values on key attributes used to access records in table
- Sequential Key:
  - value is monotonic with insertion order
  - examples: time stamp, counter
- Non-sequential Key:
  - value unrelated to insertion order
  - examples: social security number, last name
- Note: index key different from key in relational theory
  - relational theory: key attributes have unique values
  - index key: not necessarily unique

Index Characteristics

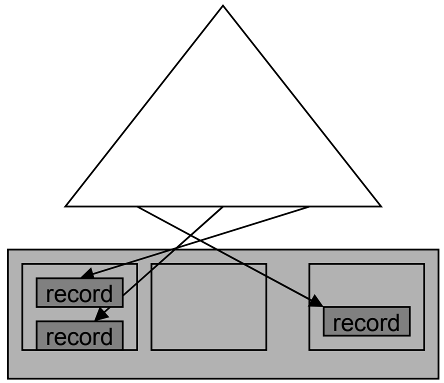
- Indexes can often be viewed as trees (B^+-tree, hash)
  - some nodes are in main memory (e.g., root)
  - nodes deeper down in tree are less likely to be in main memory
- Number of levels: number of nodes in root-leaf path
  - a node is typically a disk block
  - one block read required per level
  - reading a block costs several milliseconds (involves disk seek)
- Fanout: number of children a node can have
  - large fanout means few levels
- Overflow strategy: insert into a full index node n
  - a new node n' must be allocated on disk
  - B^+-tree: split n into n and n', both at same distance from root
  - hash index: n stores pointer to new node n' (overflow chaining)

Sparse vs. Dense

- Sparse index: pointers to disk pages
  - at most one pointer per disk page
  - usually much fewer pointers than records



- Dense index: pointers to individual records
  - one key per record
  - usually more keys than sparse index
  - optimization: store repeating keys only once, followed by pointers



Sparse vs. Dense

- Number of pointers:

  ptrs in dense index = records per page × ptrs in sparse index

- Pro sparse: fewer pointers
  - typically record size is smaller than page size
  - fewer pointers result in fewer levels (and disk accesses)
  - uses less space
- Pro dense:
  - index may "cover" query
  - multiple dense indexes per table possible (vs. only 1 spares index)

Covering Index

- Covering index:
  - answers read-only query within index structure
  - fast: data records are not accessed
- Example 1: dense index on lastname

```
SELECT COUNT(lastname) WHERE lastname='Smith'
```

- Example 2: dense index on `A, B, C` (in that order)
  - covered query:

```
SELECT B, C
FROM R
WHERE A = 5
```

  - covered query, but not prefix:

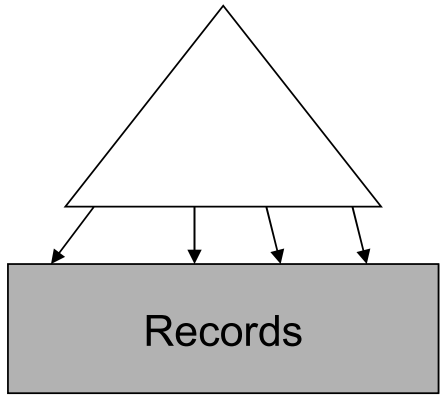
```
SELECT A, C
FROM R
WHERE B = 5
```

  - non-covered query: `D` requires data access

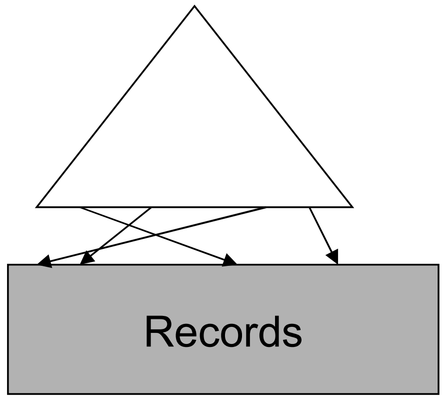
```
SELECT B, D
FROM R
WHERE A = 5
```

Clustering vs. Non-Clustering

- Clustering index on attribute X (also *primary index*)
  - records are grouped by attribute X on disk
  - B^+-tree: records sorted by attribute X
  - only one clustering index per table
  - dense or sparse



- Non-clustering index on attribute X (also *secondary index*)
  - no constraint on table organization
  - more than one index per table
  - always dense



Clustering Indexes

- Can be sparse:
  - fewer pointers than non-clustering index (always dense!)
- Good for multi-point queries:
  - equality access on non-unique attribute
  - all result records are on consecutive pages
  - example: look up last name in phone book
- Good for range, prefix, ordering queries:
  - works if clustering index is implemented as B^+-tree
  - prefix example: look up all last names starting with 'St' in phone book
  - result records are on consecutive pages
- Good for equality join:
  - fast also for join on non-key attributes
  - index on one table: indexed nested-loop
  - index on both tables: merge-join
- Overflow pages reduce efficiency:
  - if disk page is full, overflowing records go to overflow pages
  - overflow pages require additional disk accesses

Equality Join with Clustering Index

- Example query:

```
SELECT Employee.ssnum, Student.course
FROM Employee, Student
WHERE Employee.firstname = Student.firstname
```

- Index on Emplyee.firstname: use index nested loop join
  - for each student look up employees with same first name
  - all matching employees are on consecutive pages
- Index on both firstname attributes: use merge join
  - read both tables in sorted order and merge (B^+-tree)
  - each page read exactly once
  - works also for hash indexes with same hash function

Clustering Index and Overflow Pages

- Why overflow pages?
  - clustering index stores records on consecutive disk pages
  - insertion between two consecutive pages not possible
  - if disk page is full, overflowing records go to overflow pages
- Additional disk access for overflow page: reduced speed
- Overflow pages can result from:
  - inserts
  - updates that change key value
  - updates that increase record size (e.g., replace NULL by string)
- Reorganize index:
  - invoke special tool
  - or simply drop and re-create index

Overflow Strategies

- Tune free space in disk pages:
  - Oracle, DB2: `pctfree` (0 is full), SQLServer: `fillfactor` (100 is full)
  - free space in page is used for new or growing records
  - little free space: space efficient, reads are faster
  - much free space: reduced risk of overflows
- Overflow strategies:
  - split: split full page into two half-full pages and link new page e.g., $A \rightarrow B \rightarrow C$, splitting B results in $A \rightarrow B' \rightarrow B'' \rightarrow C$ (SQLServer)
  - chaining: full page has pointer to overflow page (Oracle)
  - append: overflowing records of all pages are appended at the end of the table (DB2)

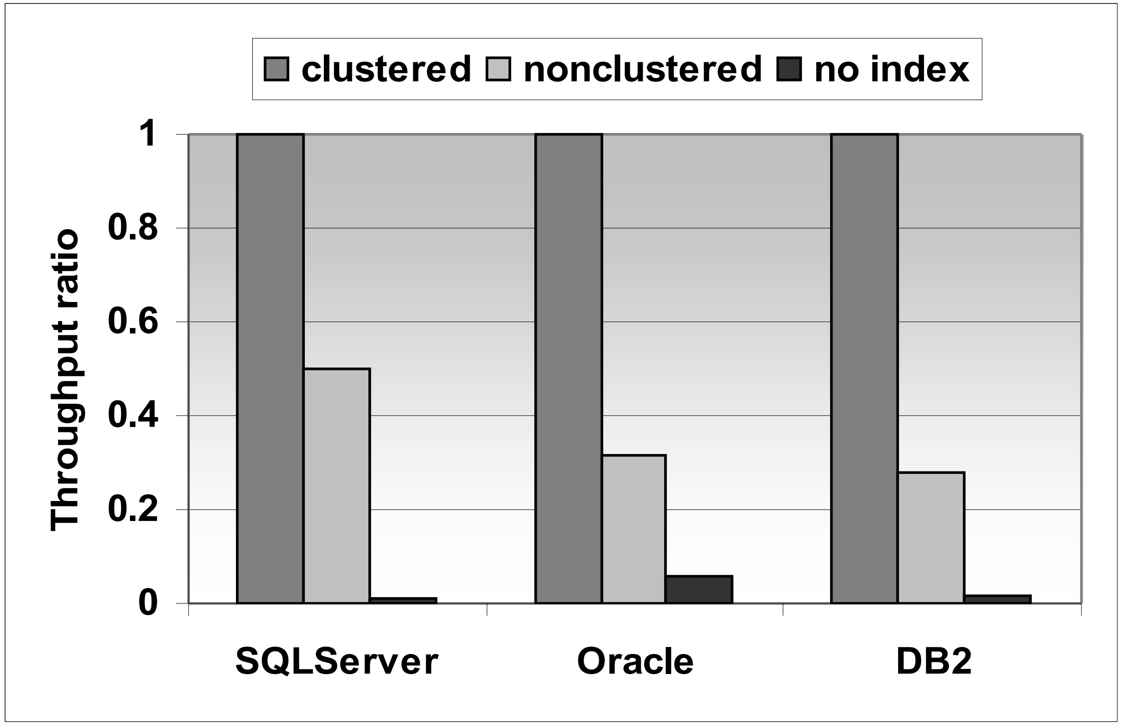
Non-Clustering Index

- Always useful for point queries.
- Particularly good if index covers query.
- Critical tables: covering index on all relevant attribute combinations
- Multi-point query (not covered): good for strongly selective queries (=small result size)
  - $\#r$: number of records returned by query
  - $\#p$: number of disk pages in table
  - the $\#r$ records are uniformly distributed over all pages
  - thus query will read $\min(\#r, \#p)$ disk pages
- Index may slow down weakly selective multi-point query:
  - scan is by factor 2–10 faster than accessing all pages with index
  - thus $\#r$ should be significantly smaller than $\#p$

Non-Clustering Index and Multi-point Queries – Example

- Example 1:
  - records size: $50B$
  - page size: $4kB$
  - attribute A takes 20 different values (evenly distributed among records)
  - does non-clustering index on A help?
- Evaluation:
  - $\#r = n/20$ (n is the total number of records)
  - $\#p = n/80$ (80 records per page)
  - $n/20 > n/80$ thus index does not help
- Example 2: as above, but record size is $2kB$
- Evaluation:
  - $\#r = n/20$ (n is the total number of records)
  - $\#p = n/2$ (2 records per page)
  - $n/20 << n/2$ thus index might be useful

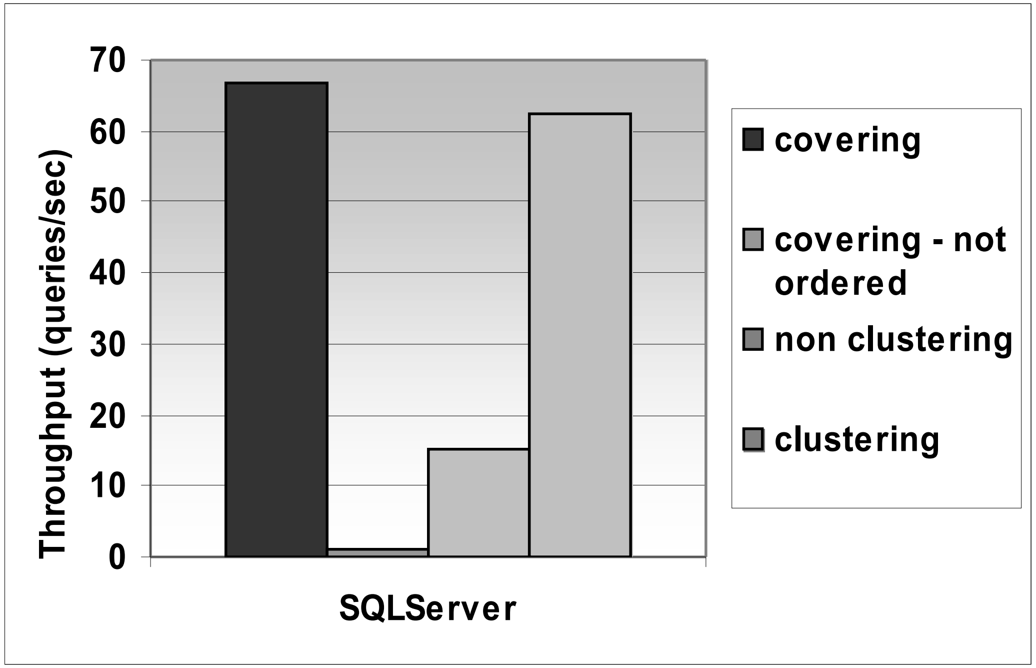
Clustering vs. Non-Clustering Index



- multi-point query with selectivity 100/1M records (0.01%)
- clustering index much faster than non-clustering index
- full table scan (no index) orders of magnitude slower than index

DB2 UDB V7.1, Oracle 8.1, SQL Server 7 on Windows 2000

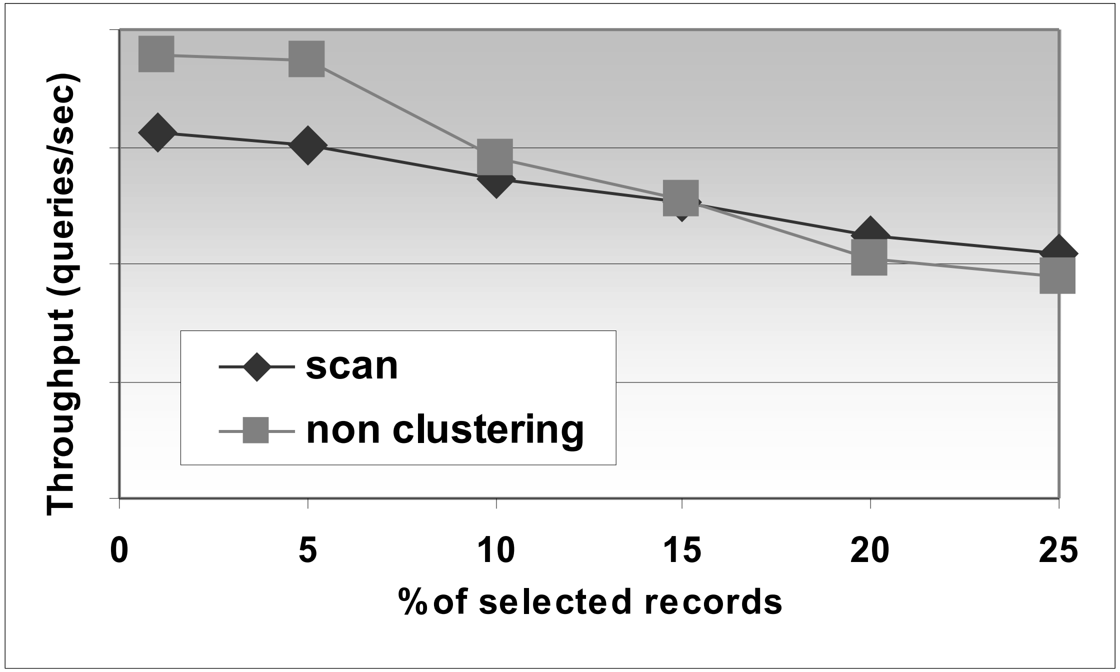
Covering vs. Non-Covering Index



- prefix match query on sequence of attributes
- covering: index covers query, query condition on prefix
- covering, not ordered: index covers query, but condition not prefix
- non-clustering: non-covering index, query condition on prefix
- clustering: sparse index, query condition on prefix

SQL Server 7 on Windows 2000

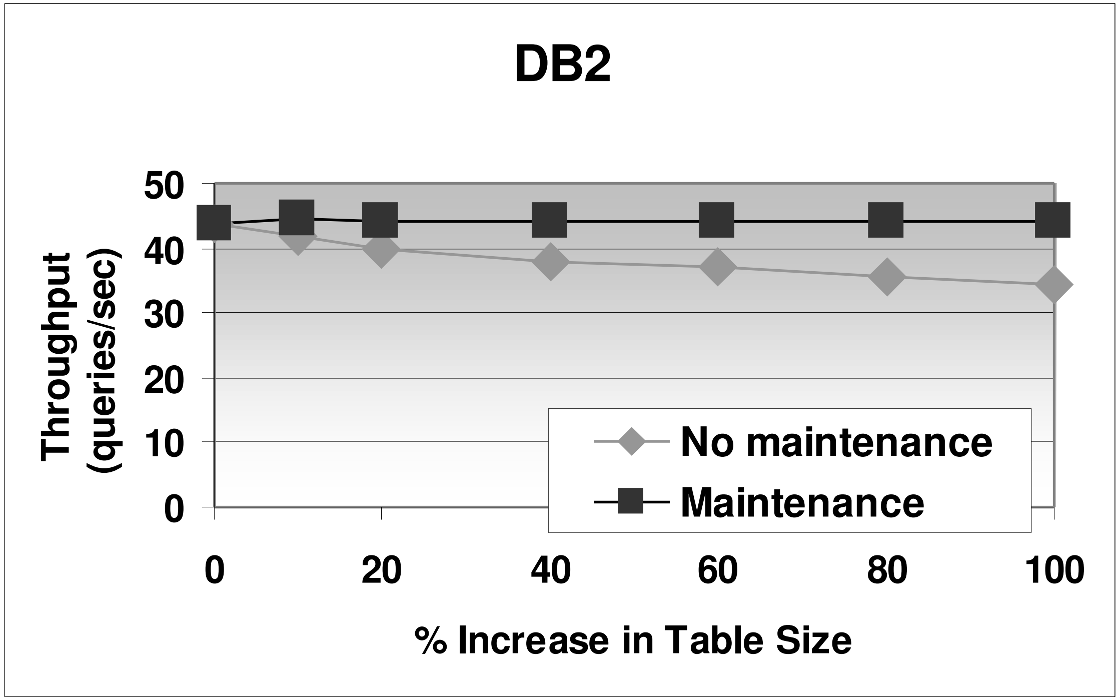
Non-Clustering vs. Table Scan



- query: range query
- non clustering: non-clustering non-covering index
- scan: no index, i.e., table scan required
- index is faster if less than 15% of the records are selected

DB2 UDB V7.1 Windows 2000

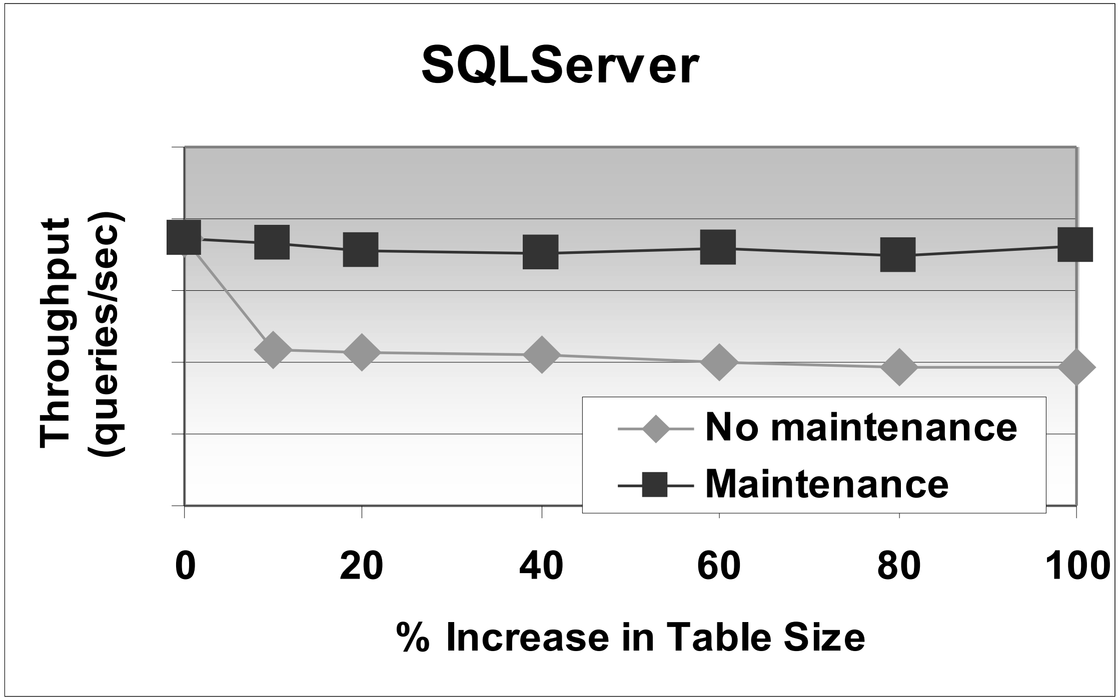
Index Maintenance - DB2



- query: batch of 100 multi-point queries, `pctfree`=0 (data pages full)
- performance degrades with insertion
- overflow records simply appended
- query traverses index and then scans all overflow records
- reorganization helps

DB2 UDB V7.1 on Windows 2000

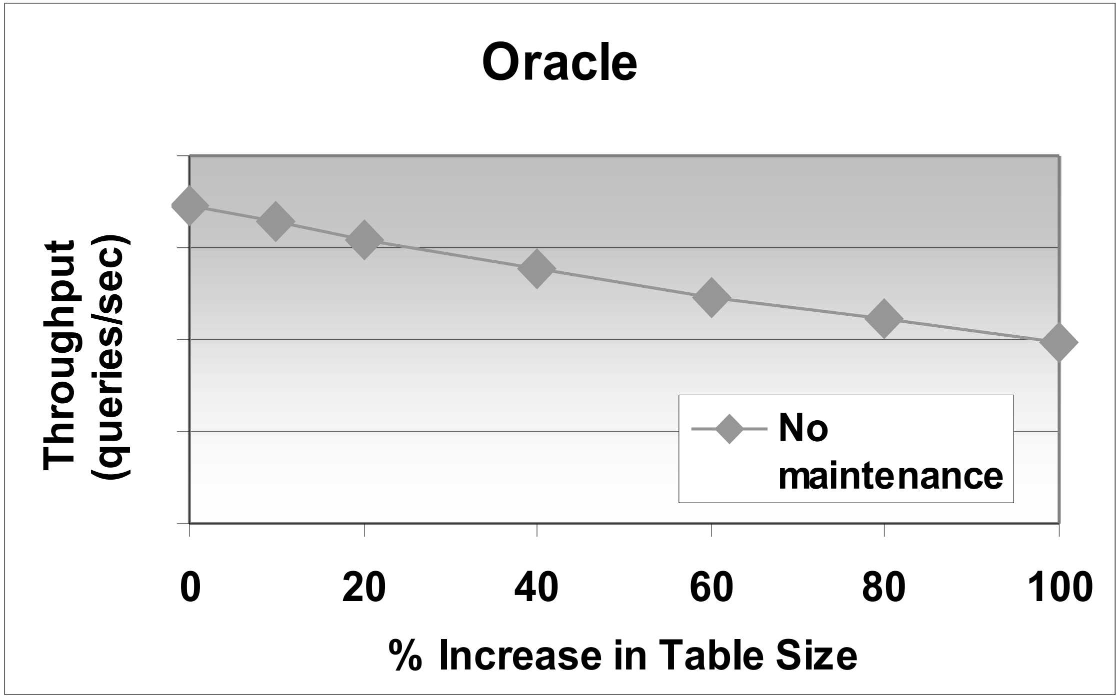
Index Maintenance - SQL Server



- `fillfactor=100` (data pages full)
- performance degrades with insertion
- overflow chain maintained for overflowing page
- extra disk access
- reorganization helps

SQL Server 7 on Windows 2000

Index Maintenance - Oracle



- pctfree $= 0$ (data pages full), performance degrades with insertion
- all indexes in Oracle are non-clustering
- recreating index does not reorganize table
- index-organized table (IOT) is clustered by primary key
- maintenance: export and re-import IOT (ALTER TABLE MOVE)

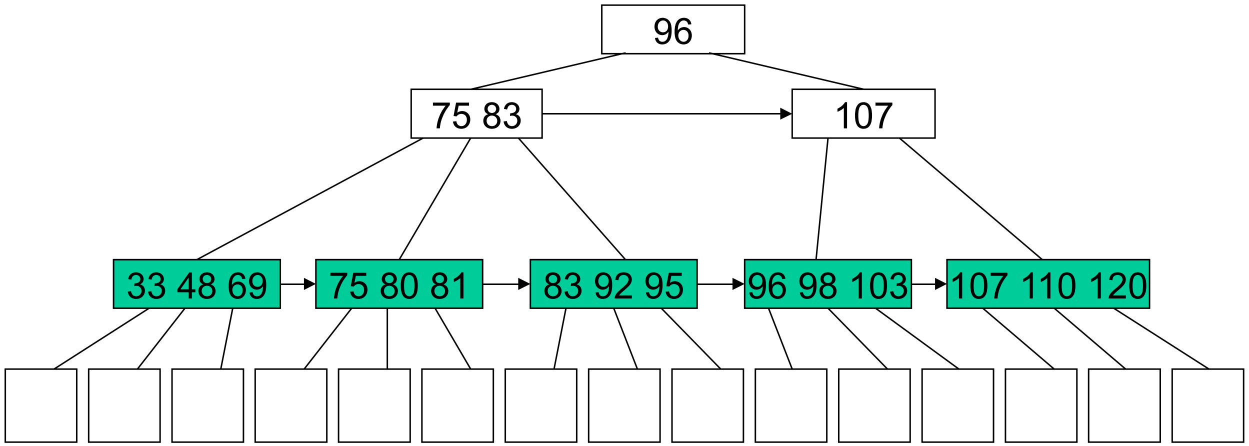
Oracle 8i EE on Windows 2000

Outline

Index Data Structures

- Indexes can be implemented with different data structures.
- We discuss:
  - B^+-tree index
  - hash index
  - bitmap index (briefly)
- Not discussed here:
  - dynamic hash indexes: number of buckets modified dynamically
  - R-tree: index for spatial data (points, lines, shapes)
  - quadtree: recursively partition a 2D plane into four quadrants
  - octree: quadtree version for three dimensional data
  - main memory indexes: T-tree, 2-3 tree, binary search tree

B^+-Tree



- balanced tree of key-pointer pairs
- keys are sorted by value
- nodes are at least half full
- access records for key: traverse tree from root to leaf

Key Length and Fanout

- Key length is relevant in B^+-trees: short keys are good!
  - fanout is maximum number of key-pointer pairs that fit in node
  - long keys result in small fanout
  - small fanout results in more levels

Key Length and Fanout – Example

- Store $40M$ key-pointer pairs in leaf pages (page: $4kB$, pointer: $4B$)
  - $6B$ key: fanout 400 $\Rightarrow$ 3 block reads per accesses

level	nodes	key-pointer pairs
1	1	400
2	400	160,000
3	160,000	64,000,000

  - $96B$ key: fanout 40 $\Rightarrow$ 5 block reads per accesses

level	nodes	key-pointer pairs
1	1	40
2	40	1,600
3	1,600	64,000
4	64,000	2,560,000
5	2,560,000	102,400,000

  - $6B$ key almost twice as fast as $96B$ key!

Estimate Number of Levels

- Page utilization:
  - examples assumes 100% utilization
  - typical utilization is 69% (if half-full nodes are merged)
- Number of levels:

$$\text{fanout} = \left\lfloor \frac{\text{node size}}{\text{key-pointer size}} \right\rfloor$$

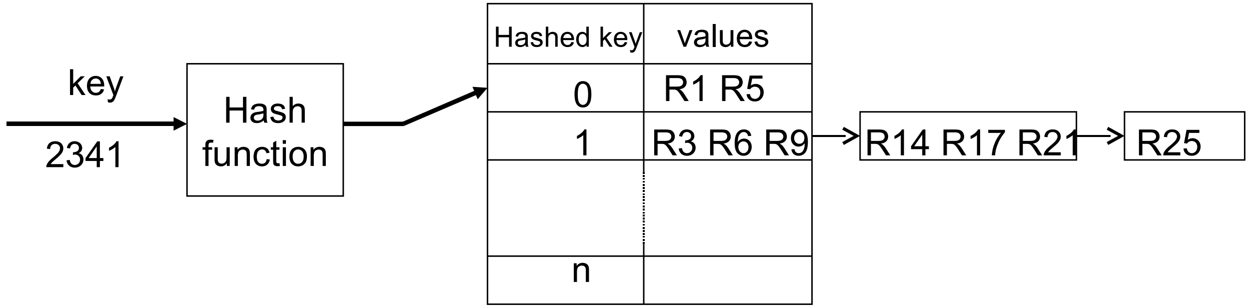
$$\text{number of levels} = \lceil \log_{\text{fanout} \times \text{utilization}}(\text{leaf key-pointer pairs}) \rceil$$

- Previous example with utilization = 69%:
  - $6B$ key: fanout $= 400$, levels $= \lceil 3.11 \rceil = 4$
  - $96B$ key: fanout $= 40$, levels $= \lceil 5.28 \rceil = 6$

Key Compression

- Key compression: produce smaller keys
  - reduces number of levels
  - adds some CPU cost (ca. 30% per access)
- Key compression is useful if
  - keys are long, for example, string keys
  - data is static (few updates)
  - CPU time is not an issue
- Prefix compression: very popular
  - non-leaf nodes only store prefix of key
  - prefix is long enough to distinguish neighbors
  - example: Cagliari, Casoria, Catanzaro → Cag, Cas, Cat

Hash Index



- Hash function:
  - maps keys to integers in range $[0..n]$ (hash values)
  - pseudo-randomizing: most keys are uniformly distributed over range
  - similar keys usually have very different hash values!
  - database chooses good hash function for you
- Hash index:
  - hash function is "root node" of index tree
  - hash value is a bucket number
  - bucket either contains records for search key
    or pointer to overflow chain with records
- Key length:
  - size of hash structure independent of key length
  - key length slightly increases CPU time for hash function

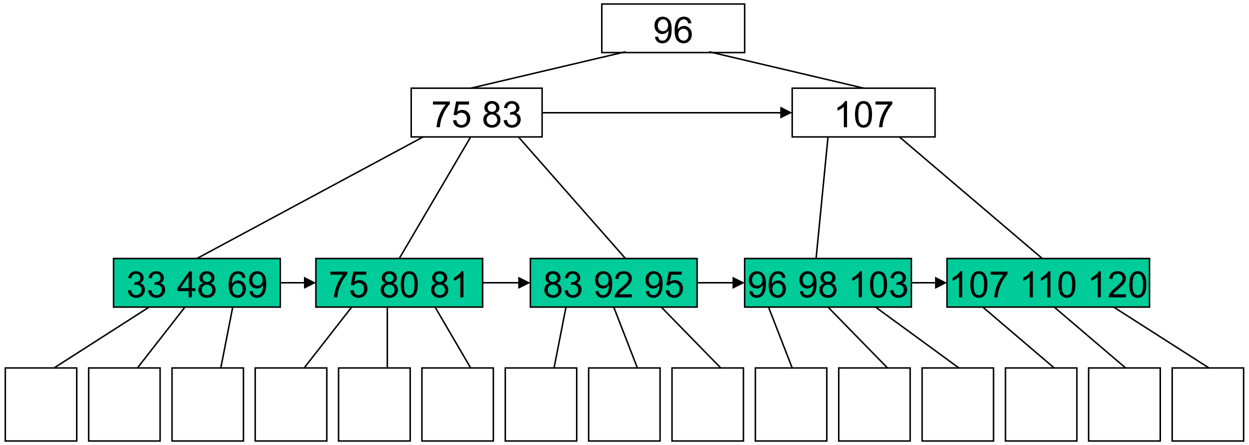
Overflow Chains

- Hash index without overflows: single disk access
- If bucket is full: overflow chain
  - each overflow page requires additional disk access
  - under-utilize hash space to avoid chains!
  - empirical utilization value: 50%
- Hash index with many overflows: reorganize
  - use special reorganize function
  - or simply drop and add index

Bitmap Index

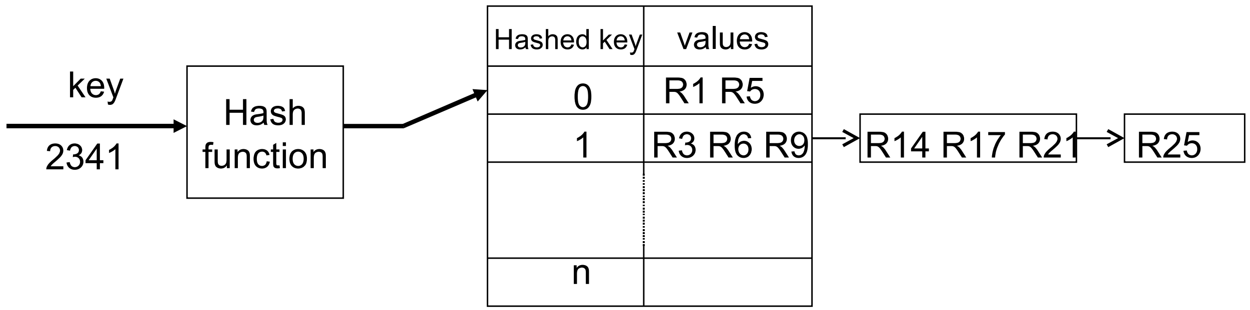
- Index for data warehouses
- One bit vector per attribute value (e.g., two for gender)
  - length of each bit vector is number of records
  - bit *i* for vector "male" is set if key value in row *i* is "male"
- Works best if
  - query predicates are on many attributes
  - the individual predicates have weak selectivity (e.g., male/female)
  - all predicates together have strong selectivity (i.e., return few tuples)
- Example: "Find females who have brown hair, blue eyes, wear glasses, are between 50 and 60, work in computer industry, and live in Bolzano"

Which Queries Are Supported?



- B^+-tree index supports
  - point: traverse tree once to find page
  - multi-point: traverse tree once to find page(s)
  - range: traverse tree once to find one interval endpoint and follow pointers between index nodes
  - prefix: traverse tree once to find prefix and follow pointers between index nodes
  - extremal: traverse tree always to left/right (MIN/MAX)
  - ordering: keys ordered by their value
  - grouping: ordered keys save sorting

Which Queries Are Supported?

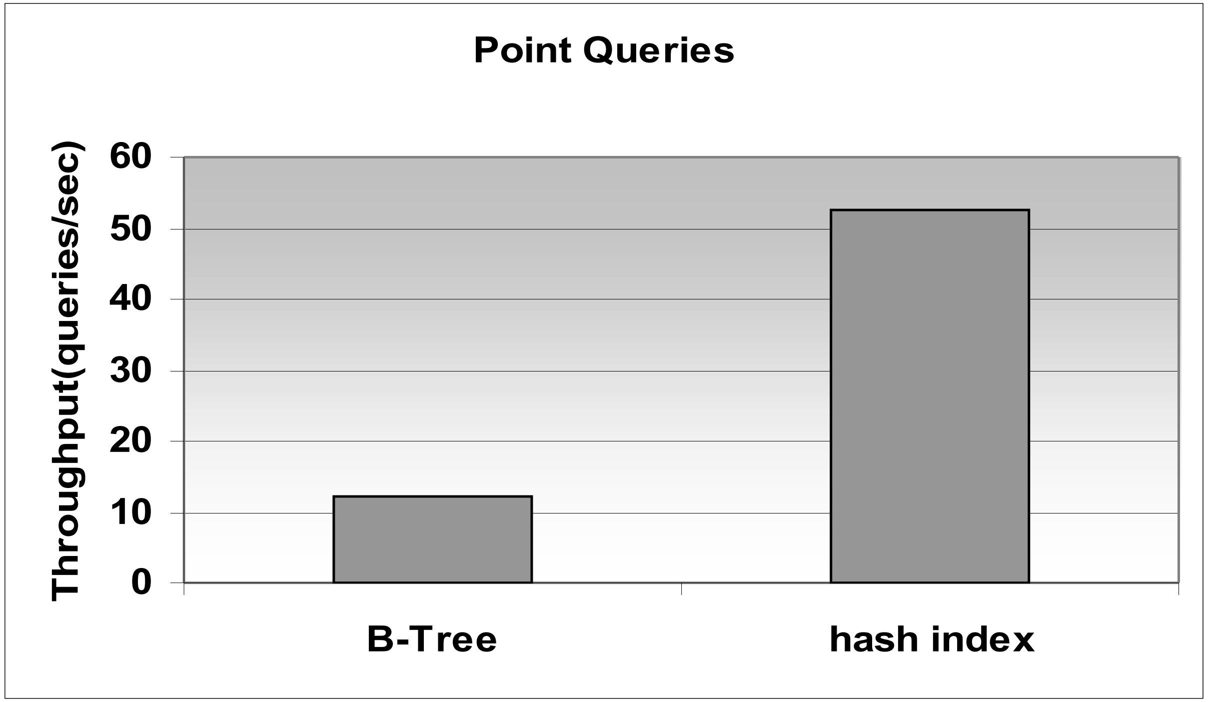


- Hash index supports
  - point: single disk access!
  - multi-point: single disk access to first record
  - grouping: grouped records have same hash value
- Hash index is useless for
  - range, prefix, extremal, ordering
  - similar key values have dissimilar hash values
  - thus similar keys are in different pages

Experimental Setup

- `Employee(ssnum, name, hundreds ...)`
- 1,000,000 records
- `ssnum` is a key (point query)
- `hundreds` has the same value for 100 employees (multipoint query)
- point query: index on `ssnum`
- multipoint and range query: index on `hundreds`
- B^+-tree and hash indexes are clustered
- bitmap index is never clustered

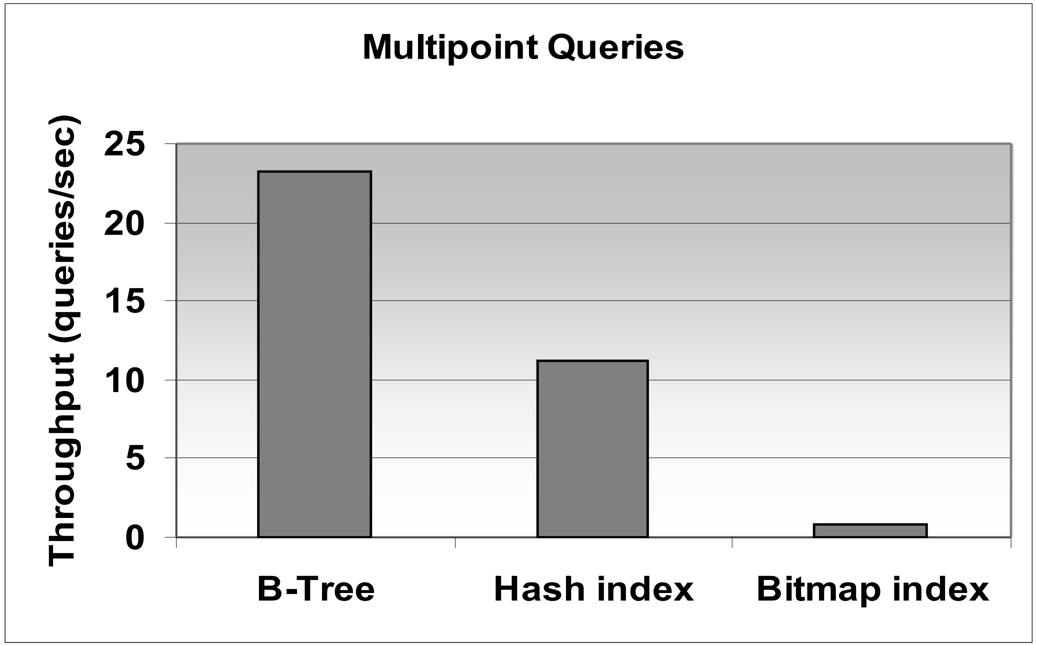
Experiment: Point Query



Oracle 8i Enterprise Edition on Windows 2000.

- B^+-tree: search in $B+$-tree requires additional disk accesses
- Hash index: bucket address is computed without disk access; search key is unique, i.e., bucket overflows are less likely

Experiment: Multi-point Query



- Setup: 100 records returned by each query
- B^+-tree: efficient since records are on consecutive pages
- Hash index: all relevant records in one bucket, but bucket contains also other records; in this experiment, the bucket was too small and an overflow chain was created
- Bitmap index: traverses entire bitmap to fetch a few records

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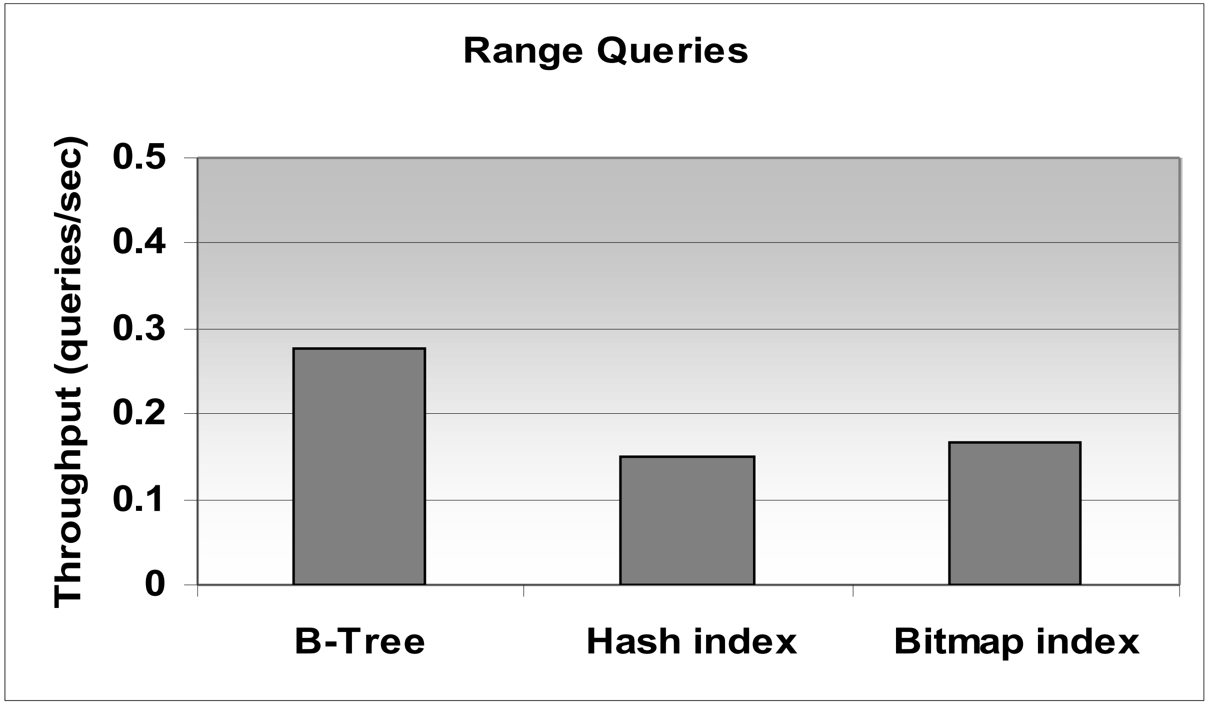
Experiment: Range Query



- B^+-tree: efficient since records are on consecutive pages
- Hash index, bitmap index: do not help

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Outline

Composite Indexes

- Index on more than one attribute (also "concatenated index")
- Example: `Person(ssnum,lastname,firstname,age,address,...)`
  - composite index on `(lastname,firstname)`
  - phone books are organized like that!
- Index can be dense or sparse.
- Dense index on (A, B, C)
  - one pointer is stored per record
  - all pointers to records with the same A value are stored together
  - within one A value, pointers to same B value stored together
  - within one A and B value, pointers to same C value stored together

Composite Indexes – Efficient for Prefix Queries

- Example: composite index on `(lastname,firstname)`

  ```
  SELECT * FROM Person
  WHERE lastname='Gates' and firstname LIKE 'Ge%'
  ```
- Composite index more efficient than two single-attribute indexes:
  - many records may satisfy `firstname LIKE 'Ge%'`
  - condition on `lastname` and `firstname` together has stronger selectivity
  - two-index solution: results for indexes on `lastname` and `firstname` must be intersected
- Dense composite indexes can cover prefix query.

Composite Indexes – Skip Scan in Oracle

- Typically composite index on `(lastname,firstname)` not useful for

```
SELECT lastname FROM Person
WHERE firstname='George'
```

- Problem: Index covers query, but condition is not a prefix.
- Solution: Index skip scan (implemented in Oracle)
  - composite index on (A, B)
  - scan each A value until you find required B values
  - then jump to start of next A value
  - partial index scan instead of full table scan!
  - especially useful if A can take few values (e.g., male/female)

Composite Indexes – Multicolumn Uniqueness

- Example: `Order(supplier, part, quantity)`
  - supplier is not unique
  - part is not unique
  - but `(supplier,part)` is unique
- Efficient way to ensure uniqueness:
  - create unique, composite index on `(supplier,part)`
  - `CREATE UNIQUE INDEX s_p ON Order(supplier,part)`

Composite Indexes – Attribute Order Matters

- Put attribute with more constraints first.
- Example: Geographical Queries
  - table: `City(name,longitude,latitude,population)`

```
SELECT name FROM city
WHERE population >= 10000 AND latitude = 22
      AND longitude >= 5  AND longitude <= 15
```

- Efficient: clustered composite index on `(latitude,longitude)`
  - pointers to all result records are packed together
- Inefficient: clustered composite index on `(longitude, latitude)`
  - each longitude 5 to 15 has some pointers to latitude 22 records
- General geographical queries should use a multi-dimensional index (for example, an R-tree)

Disadvantages of Composite Indexes

- Large key size:
  - B^+ tree will have many layers
  - key compression can help
  - hash index: large keys no problem, but no range and prefix queries supported
- Expensive updates:
  - in general, index must be updated when key attribute is updated
  - composite index has many key attributes
  - update required if any of the attributes is updated

Outline

1. Index Tuning
   - Query Types
   - Index Types
   - Data Structures
   - Composite Indexes
   - Indexes and Joins
   - Index Tuning Examples

Join Strategies – Running Example

- Relations: R and S
  - disk block size: $4kB$
  - R: $n_r = 5000$ records, $b_r = 100$ disk blocks, $0.4MB$
  - S: $n_s = 10000$ records, $b_s = 400$ disk blocks, $1.6MB$
- Running Example: $R \bowtie S$
  - R is called the outer relation
  - S is called the inner relation

Example from *Silberschatz, Korth, Sudarashan. Database System Concepts. McGraw-Hill.*

Join Strategies – Naive Nested Loop

- Naive nested loop join
  - take each record of R (outer relation) and search through all records of S (inner relation) for matches
  - for each record of R, S is scanned
- Example: Naive nested loop join
  - worst case: buffer can hold only one block of each relation
  - R is scanned once, S is scanned n_r times
  - in total $n_r b_s + b_r = 2,000,100$ blocks must be read ($= 8GB$)!
  - note: worst case different if S is outer relation
  - best case: both relations fit into main memory
  - $b_s + b_r = 500$ block reads

Join Strategies – Block Nested Loop

- Block nested loop join
  - compare all rows of each block of R to all records in S
  - for each block of R, S is scanned
- Example: (continued)
  - worst case: buffer can hold only one block of each relation
  - R is scanned once, S is scanned b_r times
  - in total $b_r b_s + b_r = 40,100$ blocks must be read $(= 160MB)$
  - best case: $b_s + b_r = 500$ block reads

Join Strategies – Indexed Nested Loop

- Indexed nested loop join
  - take each row of R and look up matches in S using index
  - runtime is $O(|R| \times \log|S|)$ (vs. $O(|R| \times |S|)$ of naive nested loop)
  - efficient if index covers join (no data access in S)
  - efficient if R has less records than S has pages: not all pages of S must be read (e.g., foreign key join from small to large table)
- Example: (continued)
  - B^+-tree index on S has 4 layers, thus max. $c = 5$ disk accesses per record of S
  - in total $b_r + n_r c = 25,100$ blocks must be read $(= 100MB)$

Join Strategies – Merge Join

- Merge join (two clustered indexes)
  - scan R and S in sorted order and merge
  - each block of R and S is read once
- No index on R and/or S
  - if no index: sort and store relation with $b(2\lceil log_{M-1}(b/M)\rceil + 1) + b$ block transfers (M: free memory blocks)
  - if non-clustered index present: index scan possible
- Example: (continued)
  - best case: clustered indexes on R and S ($M = 2$ enough)
  - $b_r + b_s = 500$ blocks must be read ($2MB$)
  - worst case: no indexes, only $M = 3$ memory blocks
  - sort and store R (1400 blocks) and S (7200 blocks) first: join with 9100 ($36MB$) block transfers in total
  - case $M = 25$ memory blocks: 2500 block transfers ($10MB$)

Join Strategies – Hash Join

- Hash join (equality, no index):
  - hash both tables into buckets using the same hash function
  - join pairs of corresponding buckets in main memory
  - R is called probe input, S is called build input
- Joining buckets in main memory:
  - build hash index on one bucket from S (with new hash function)
  - probe hash index with all tuples in corresponding bucket of R
  - build bucket must fit main memory, probe bucket needs not
- Example: (continued)
  - assume that each probe bucket fits in main memory
  - R and S are scanned to compute buckets, buckets are written to disk, then buckets are read pairwise
  - in total $3(b_r + b_s) = 1500$ blocks are read/written ($6MB$)
  - default in SQLServer and DB2 UDB when no index present

Distinct Values and Join Selectivity

- Join selectivity:
  - number of retrieved pairs divided by cardinality of cross product ($|R \bowtie S| / |R \times S|$)
  - selectivity is low if join result is small
- Distinct values refer to join attributes of one table
- Performance decreases with number of distinct join values
  - few distinct values in both tables usually means many matching records
  - many matching records: join result is large, join slow
  - hash join: large buckets (build bucket does not fit main memory)
  - index join: matching records on multiple disk pages
  - merge join: matching records do not fit in memory at the same time

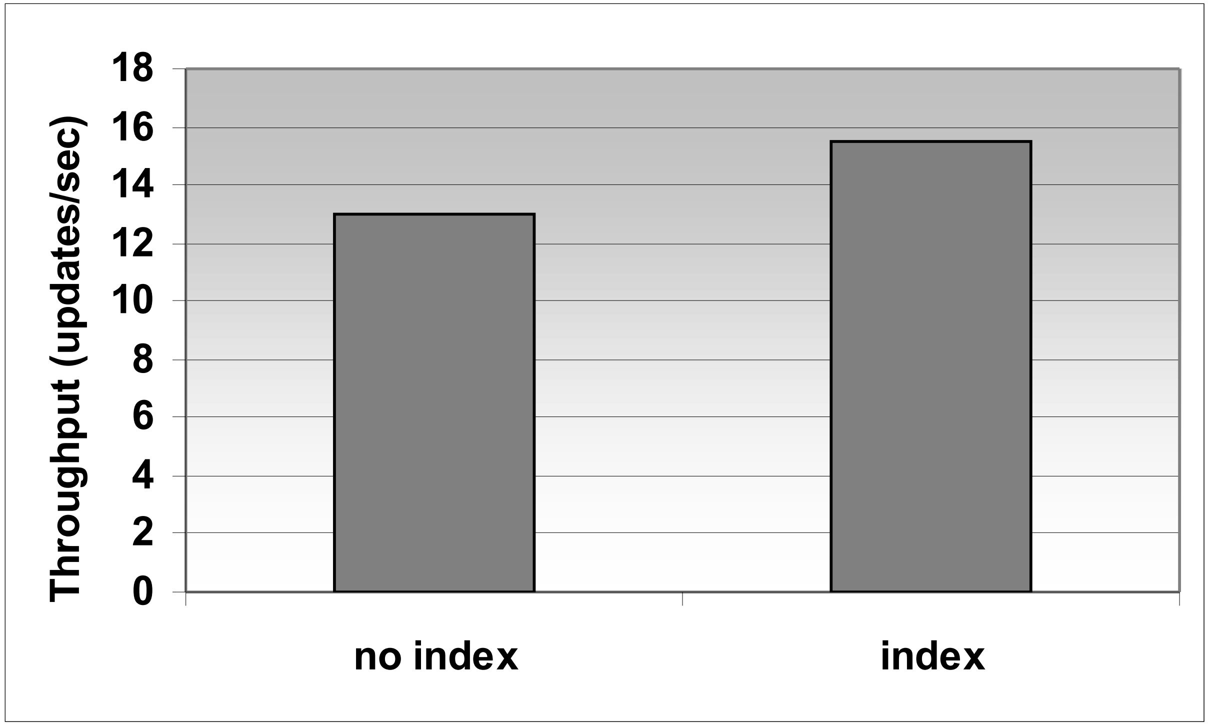
Foreign Keys

- Foreign key: attribute $R.A$ stores key of other table, $S.B$
- Foreign key constraints: $R.A$ must be subset of $S.B$
  - insert in R checks whether foreign key exists in S
  - deletion in S checks whether there is a record with that key in R
- Index makes checking foreign key constraints efficient:
  - index on $R.A$ speeds up deletion from S
  - index on $S.B$ speeds up insertion into R
  - some systems may create index on $R.A$ and/or $S.B$ by default
- Foreign key join:
  - each record of one table matches at most one record of the other table
  - most frequent join in practice
  - both hash and index nested loop join work well

Indexes on Small Tables

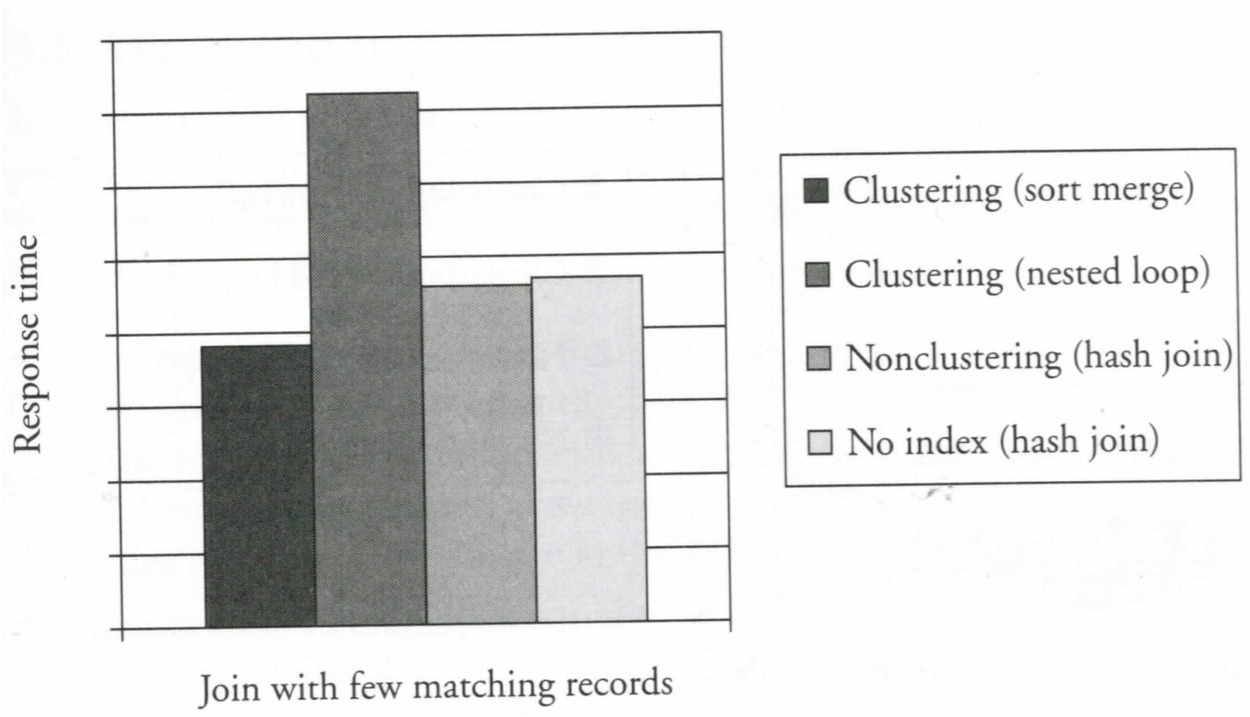
- Read query on small records:
  - tables may fit on a single track on disk
  - read query requires only one seek
  - index not useful: seeks at least one index page and one table page
- Table with large records (∼page size):
  - each record occupies a whole page
  - for example, 200 records occupy 200 pages
  - index useful for point queries (read 3 pages vs. 200)
- Many inserts and deletions:
  - index must be reorganized (locking!)
  - lock conflicts near root since index is small
- Update of single records:
  - without index table must be scanned
  - scanned records are locked
  - scan (an thus lock contention) can be avoided with index

Update Queries on a Small Tables



- Index avoids tables scan and thus lock contention.

Experiment – Join with Few Matching Records



- non-clustered index is ignored, hash join used instead

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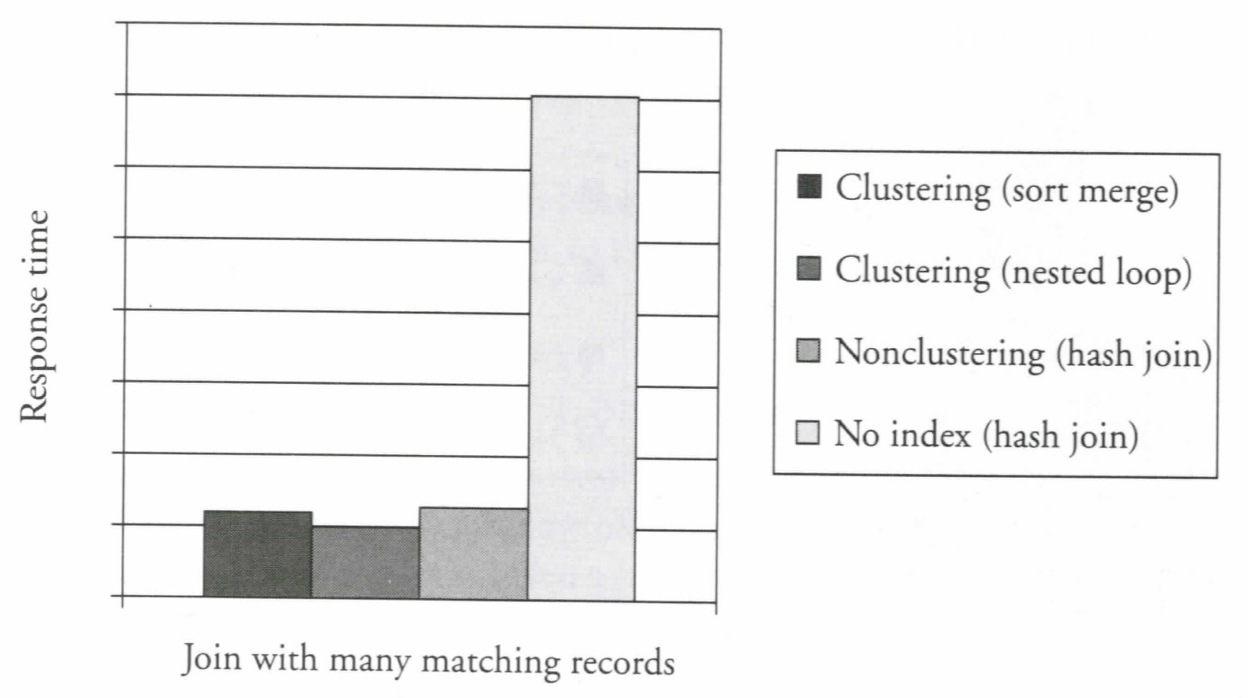
Experiment – Join with Many Matching Records



- all joins slow since output size is large
- hash join (no index) slow because buckets are very large

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Outline

Index Tuning Examples

- The examples use the following tables:
  - `Employee(ssnum,name,dept,manager,salary)`
  - `Student(ssnum,name,course,grade,stipend,evaluation)`

Exercise 1 – Query for Student by Name

- Student was created with non-clustering index on name.
- Query:

```
SELECT *
FROM Student
WHERE name='Bayer'
```

- Problem: Query does not use index on name.

Exercise 2 – Query for Salary I

- Non-clustering index on `salary`.
- Catalog statistics are up-to-date.
- Query:

```
SELECT *
FROM Employee
WHERE salary/12 = 4000
```

- Problem: Query is too slow.

Exercise 3 – Query for Salary II

- Non-clustering index on `salary`.
- Catalog statistics are up-to-date.
- Query:

```
SELECT *
FROM Employee
WHERE salary = 48000
```

- Problem: Query still does not use index. What could be the reason?

Exercise 4 – Clustering Index and Overflows

- Clustering index on `Student.ssnum`
- Page size: $2kB$
- Record size in `Student` table: $1KB$ (`evaluation` is a long text)
- Problem: Overflow when new evaluations are added.

Exercise 5 – Non-clustering Index I

- `Employee` table:
  - 30 employee records per page
  - each employee belongs to one of 50 departments (`dept`)
  - the departments are of similar size
- Query:

```
SELECT ssnum
FROM Employee
WHERE dept = 'IT'
```

- Problem: Does a non-clustering index on `Employee.dept` help?

Exercise 6 – Non-clustering Index II

- `Employee` table:
  - 30 employee records per page
  - each employee belongs to one of 5000 departments (`dept`)
  - the departments are of similar size
- Query:

```
SELECT ssnum
FROM Employee
WHERE dept = 'IT'
```

- Problem: Does a non-clustering index on `Employee.dept` help?

Exercise 7 – Statistical Analysis

- Auditors run a statistical analysis on a copy of `Employee`.
- Queries:
  - count employees with a certain salary (frequent)
  - find employees with maximum or minimum salary within a particular department (frequent)
  - find an employee by its social security number (rare)
- Problem: Which indexes to create?

Exercise 8 – Algebraic Expressions

- Student stipends are monthly, employee salaries are yearly.
- Query: Which employee is paid as much as which student?
- There are two options to write the query:

```
SELECT *                       SELECT *
FROM Employee, Student         FROM Employee, Student
WHERE salary = 12*stipend      WHERE salary/12 = stipend
```

- Index on a table with an algebraic expression not used.
- Problem: Which query is better?

Exercise 9 – Purchasing Department

- Purchasing department maintains table `Onorder(supplier,part,quantity,price)`.
- The table is heavily used during the opening hours, but not over night.
- Queries:
  - Q1: add a record, all fields specified (very frequent)
  - Q2: delete a record, `supplier` and `part` specified (very frequent)
  - Q3: find total quantity of a given part on order (frequent)
  - Q4: find the total value on order to a given supplier (rare)
- Problem: Which indexes should be used?

Exercise 10 – Point Query Too Slow

- `Employee` has a clustering B^+-tree index on `ssnum`.
- Queries:
  - retrieve employee by social security number (`ssnum`)
  - update employee with a specific social security number
- Problem: Throughput is still not enough.

Exercise 11 – Historical Immigrants Database

- Digitalized database of US immigrants between 1800 and 1900:
  - 17M records
  - each record has approx. 200 fields
    e.g., last name, first name, city of origin, ship taken, etc.
- Queries retrieve immigrants:
  - by last name and at least one other attribute
  - second attribute is often first name (most frequent) or year
- Problem: Efficiently serve 2M descendants of the immigrants. . .

Exercise 12 – Flight Reservation System

- An airline manages 1000 flights and uses the tables:
  - `Flight(flightID, seatID, passanger-name)`
  - `Totals(flightID, number-of-passangers)`
- Query: Each reservation
  - adds a record to `Flight`
  - increments `Totals.number-of-passangers`
- Queries are separate transactions.
- Problem: Lock contention on `Totals`.