Physical Data Organization and Indexing

Chapter 11

1

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

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Disks

- Capable of storing large quantities of data cheaply
- Non-volatile
- Extremely slow compared with cpu speed
- Performance of DBMS largely a function of the number of disk I/O operations that must be performed

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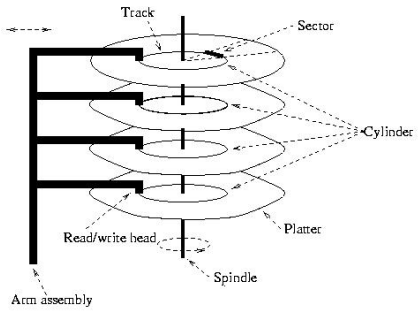
Physical Disk Structure



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Pages and Blocks

- Data files decomposed into *pages*
  - Fixed size piece of contiguous information in the file
  - Unit of exchange between disk and main memory
- Disk divided into page size *blocks* of storage
  - Page can be stored in any block
- Application's request for read item satisfied by:
  - Read page containing item to buffer in DBMS
  - Transfer item from buffer to application
- Application's request to change item satisfied by
  - Read page containing item to buffer in DBMS (if it is not already there)
  - Update item in DBMS (main memory) buffer
  - (Eventually) copy buffer page to page on disk

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I/O Time to Access a Page

- *Seek latency* – time to position heads over cylinder containing page (avg = ~10 - 20 ms)
- *Rotational latency* – additional time for platters to rotate so that start of block containing page is under head (avg = ~5 - 10 ms)
- *Transfer time* – time for platter to rotate over block containing page (depends on size of block)
- *Latency* = seek latency + rotational latency
- Our goal – minimize average latency, reduce number of page transfers

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Reducing Latency

- Store pages containing related information close together on disk
  - *Justification*: If application accesses *x*, it will next access data related to *x* with high probability
- Page size tradeoff:
  - Large page size – data related to *x* stored in same page; hence additional page transfer can be avoided
  - Small page size – reduce transfer time, reduce buffer size in main memory
  - Typical page size – 4096 bytes

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Reducing Number of Page Transfers

- Keep cache of recently accessed pages in main memory
  - *Rationale*: request for page can be satisfied from cache instead of disk
  - Purge pages when cache is full
    - For example, use LRU algorithm
    - Record clean/dirty state of page (clean pages don't have to be written)

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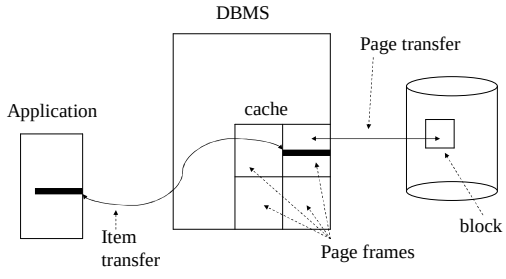
Accessing Data Through Cache



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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

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Transcript Stored as a Heap File

666666	MGT123	F1994	4.0	
123456	CS305	S1996	4.0	page 0
987654	CS305	F1995	2.0	
717171	CS315	S1997	4.0	
666666	EE101	S1998	3.0	page 1
765432	MAT123	S1996	2.0	
515151	EE101	F1995	3.0	
234567	CS305	S1999	4.0	
				page 2
878787	MGT123	S1996	3.0	

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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
- *Deleting a row*:
  - Access path is scan
  - Avg. *F*/2+1 page transfers if row exists
  - *F* page transfers if row does not exist

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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'
```

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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                    -- equality search
WHERE T.StudId = 123456

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

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Sorted File

- Rows are sorted based on some attribute(s)
  - Access path is binary search
  - Equality or range query based on that attribute has cost $log_2 F$ to retrieve page containing first row
  - Successive rows are in same (or successive) page(s) and cache hits are likely
  - By storing all pages on the same track, seek time can be minimized
- Example – Transcript sorted on *StudId* :

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

SELECT T.Course, T.Grade
FROM Transcript T
WHERE T.StudId BETWEEN
      111111 AND 199999
```

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Transcript Stored as a Sorted File

111111	MGT123	F1994	4.0	
111111	CS305	S1996	4.0	page 0
123456	CS305	F1995	2.0	
123456	CS315	S1997	4.0	
123456	EE101	S1998	3.0	page 1
232323	MAT123	S1996	2.0	
234567	EE101	F1995	3.0	
234567	CS305	S1999	4.0	
				page 2
313131	MGT123	S1996	3.0	

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Maintaining Sorted Order

- **Problem**: After the correct position for an insert has been determined, inserting the row requires (on average) *F*/2 reads and *F*/2 writes (because shifting is necessary to make space)
- **Partial Solution 1**: Leave empty space in each page: *fillfactor*
- **Partial Solution 2**: Use *overflow pages* (*chains*).
  - Disadvantages:
    - Successive pages no longer stored contiguously
    - Overflow chain not sorted, hence cost no longer $log_2 F$

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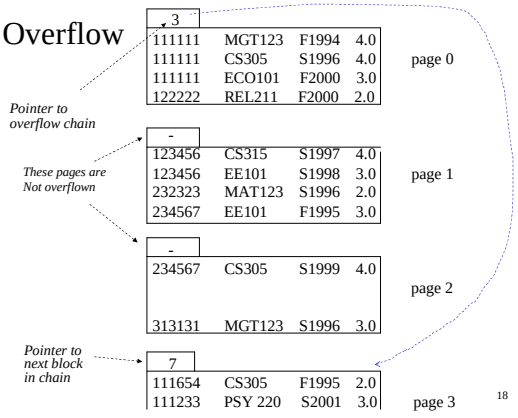
Overflow



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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

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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)

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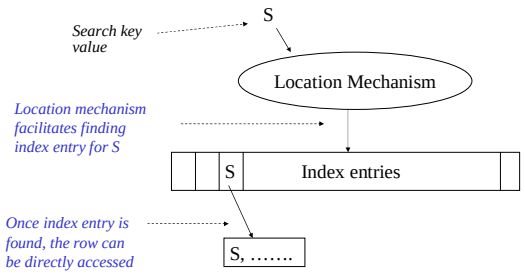
Index Structure



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Storage Structure

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

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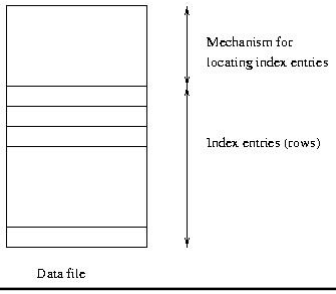
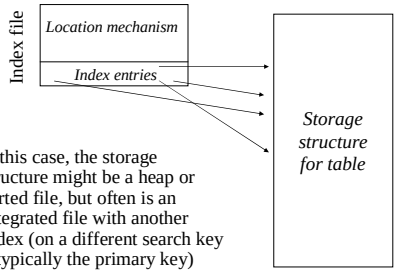
Integrated Storage Structure

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)

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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

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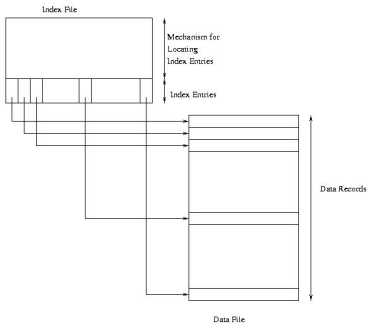
Clustered Secondary Index



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Clustered Index

- *Clustered index*: index entries and rows are ordered in the same way
  - An integrated storage structure is always clustered (since rows and index entries are the same)
  - The particular index structure (eg, hash, tree) dictates how the rows are organized in the storage structure
    - There can be at most one clustered index on a table
  - CREATE TABLE generally creates an integrated, clustered (main) index on primary key

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Unclustered Index

- Unclustered (secondary) index: index entries and rows are not ordered in the same way
- An secondary index might be clustered or unclustered with respect to the storage structure it references
  - It is generally unclustered (since the organization of rows in the storage structure depends on main index)
  - There can be many secondary indices on a table
  - Index created by CREATE INDEX is generally an unclustered, secondary index

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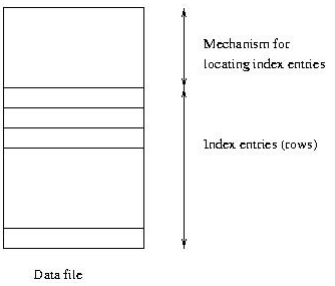
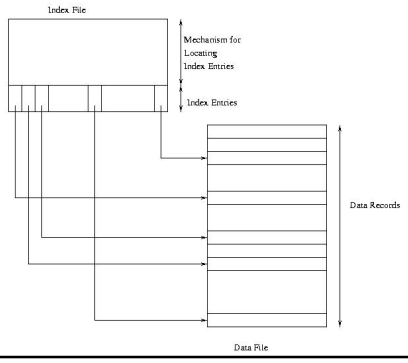
Clustered Main Index

Storage structure contains table and (main) index; rows are contained in index entries



Unclustered Secondary Index



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

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Example – Cost of Range Search

- Data file has 10,000 pages, 100 rows in search range
- Page transfers <u>for table rows</u> (assume 20 rows/page):
  - Heap: 10,000 (entire file must be scanned)
  - File sorted on search key: $\log_2 10000 + (5 \text{ or } 6) \approx 19$
  - Unclustered index: ≤ 100
  - Clustered index: 5 or 6
- Page transfers <u>for index entries</u> (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)

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Sparse vs. Dense Index

- *Dense index*: has index entry for each data record
  - Unclustered index *must* be dense
  - Clustered index need not be dense
- *Sparse index*: has index entry for each page of data file

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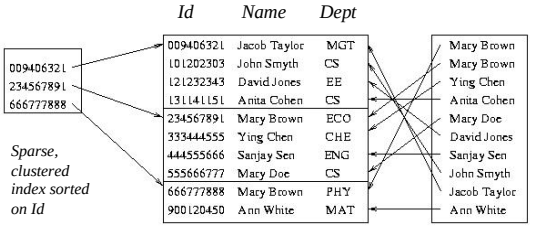
Sparse Vs. Dense Index



Sparse, clustered index sorted on Id

Data file sorted on Id

Dense, unclustered index sorted on Name

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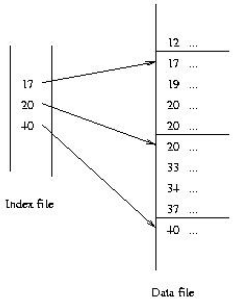
Sparse Index

Search key should be candidate key of data file (else additional measures required)



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′ "

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Locating an Index Entry

- Use binary search (index entries sorted)
  - If Q pages of index entries, then $log_2 Q$ page transfers (which is a big improvement over binary search of the data pages of a F page data file since $F >> Q$)
- Use multilevel index: Sparse index on sorted list of index entries

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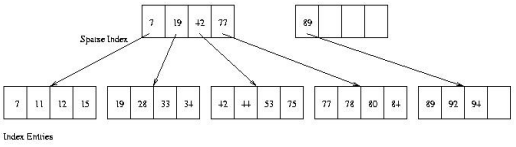
Two-Level Index



– *Separator level* is a sparse index over pages of index entries
– *Leaf level* contains index entries
– Cost of searching the separator level << cost of searching index level since separator level is sparse
– Cost or retrieving row once index entry is found is 0 (if integrated) or 1 (if not)

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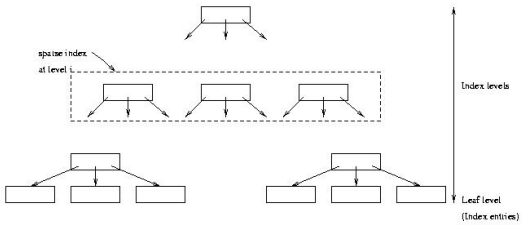
Multilevel Index



– Search cost = number of levels in tree
– If Φ is the fanout of a separator page, cost is $log_\Phi Q + 1$
– Example: if $\Phi = 100$ and $Q = 10{,}000$, cost = 3 (reduced to 2 if root is kept in main memory)

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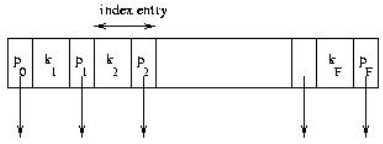
Index Sequential Access Method (ISAM)

- 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.



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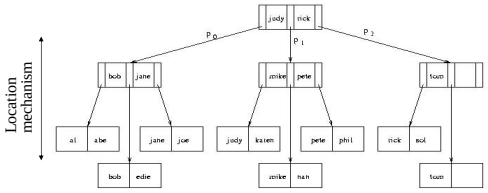
Index Sequential Access Method



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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

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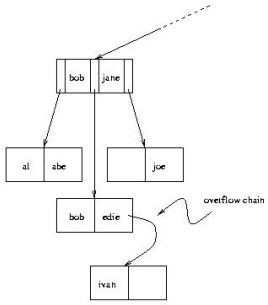
Overflow Chains

- 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*



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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

Ø *Responds to dynamic changes in the table*

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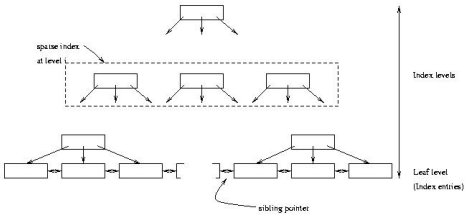
B^+ Tree Structure



– 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)

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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 $\Phi/2$ and Φ
  – Hence the maximum search cost is $log_{\Phi/2}Q + 1$ (with ISAM search cost depends on length of overflow chain)

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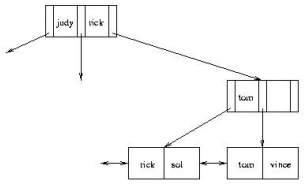
Handling Insertions - Example

- Insert "vince"



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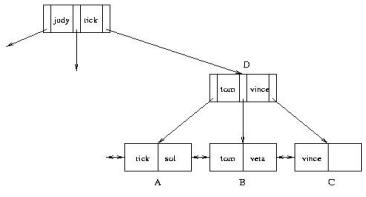
Handling Insertions (cont'd)

– 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



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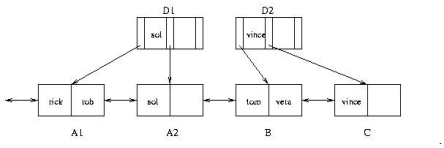
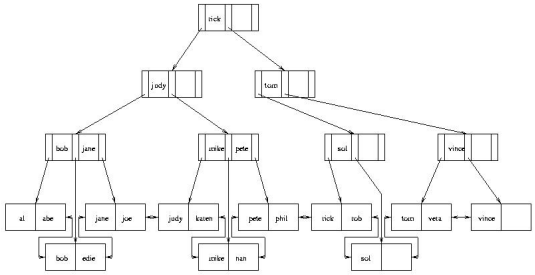
Handling Insertions (con't)

– 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 $\Phi/2$ 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*

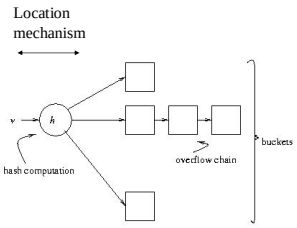
Hash Index

- 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)



Choosing a Hash Function

- Goal of *h*: map search key values randomly
  - Occupancy of each bucket roughly same for an average instance of indexed table
- Example: $h(v) = (c_1 * v + c_2) \bmod M$
  - *M* must be large enough to minimize the occurrence of overflow chains
  - *M* must not be so large that bucket occupancy is small and too much space is wasted

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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Extendable Hashing

- Eliminates overflow chains by splitting a bucket when it overflows
- Range of hash function has to be extended to accommodate additional buckets
- **Example:** family of hash functions based on h:
  - $h_k(v) = h(v) \mod 2^k$ (use the last k bits of $h(v)$)
  - At any given time a unique hash, h_k, is used depending on the number of times buckets have been split

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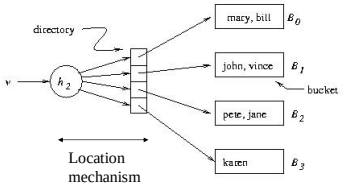
Extendable Hashing – Example



v	$h(v)$
pete	11010
mary	00000
jane	11110
bill	00000
john	01001
vince	10101
karen	10111

Extendable hashing uses a directory (level of indirection) to accommodate family of hash functions

Suppose next action is to insert sol, where $h(sol) = 10001$.

Problem: This causes overflow in B_1

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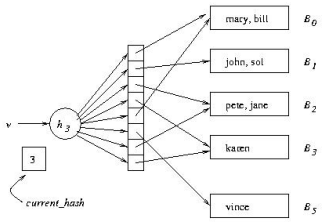
Example (cont'd)



Solution:

1. Switch to h_3
2. Concatenate copy of old directory to new directory
3. Split overflowed bucket, B, into B and B', dividing entries in B between the two using h_3
4. Pointer to B in directory copy replaced by pointer to B'

Note: Except for B', pointers in directory copy refer to original buckets.

current_hash identifies current hash function.

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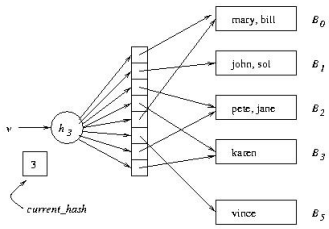
Example (cont'd)



Next action: Insert judy, where $h(judy) = 00110$

B_2 overflows, but directory need not be extended

Problem: When B_i overflows, we need a mechanism for deciding whether the directory has to be doubled

Solution: *bucket_level[i]* records the number of times B_i has been split. If *current_hash* > *bucket_level[i]*, do not enlarge directory

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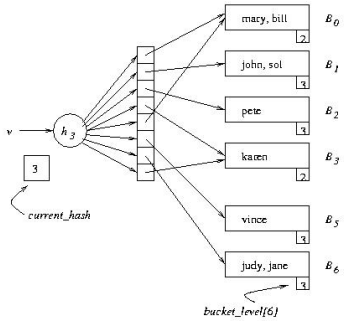
Example (cont'd)



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Extendable Hashing

- Deficiencies:
  - Extra space for directory
  - Cost of added level of indirection:
    - If directory cannot be accommodated in main memory, an additional page transfer is necessary.

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Choosing An Index

- An index should support a query of the application that has a significant impact on performance
  - Choice based on frequency of invocation, execution time, acquired locks, table size

Example 1:
```
SELECT  E.Id
FROM    Employee E
WHERE   E.Salary < :upper  AND  E.Salary > :lower
```

– This is a range search on *Salary*.
– Since the primary key is Id, it is likely that there is a clustered, main index on that attribute that is of no use for this query.
– Choose a secondary, B^+ tree index with search key *Salary*

Choosing An Index (cont'd)

Example 2:
```
SELECT  T.StudId
FROM    Transcript T
WHERE   T.Grade = :grade
```

- This is an equality search on *Grade*.
- Since the primary key is (*StudId*, *Semester*, *CrsCode*) it is likely that there is a main, clustered index on these attributes that is of no use for this query.
- Choose a secondary, B+ tree or hash index with search key *Grade*

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Choosing an Index (cont'd)

Example 3:
```
SELECT   T.CrsCode, T.Grade
FROM     Transcript T
WHERE    T.StudId = :id  AND  T.Semester = 'F2000'
```

– Equality search on *StudId* and *Semester*.
– If the primary key is (*StudId*, *Semester*, *CrsCode*) it is likely that there is a main, clustered index on this *sequence* of attributes.
– If the main index is a B^+ tree it can be used for this search.
– If the main index is a hash it cannot be used for this search. Choose B^+ tree or hash with search key *StudId* (since *Semester* is not as selective as *StudId*) or (*StudId*, *Semester*)

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Choosing An Index (cont'd)

Example 3 (cont'd):
```
SELECT   T.CrsCode, T.Grade
FROM     Transcript T
WHERE    T.StudId = :id  AND  T.Semester = 'F2000'
```

- Suppose Transcript has primary key (*CrsCode*, *StudId*, *Semester*). Then the main index is of no use (independent of whether it is a hash or B^+ tree).

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