Seminar on Approaches for improving Cache Line Utilization in Database Systems

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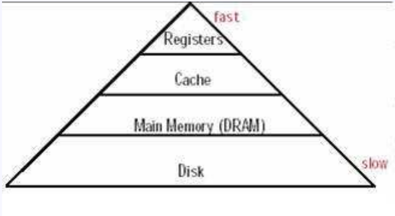
March 14, 2006

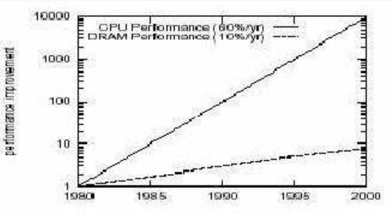
Motivation

- Growing need for efficient cache memory utilization in Modern Database Systems
- Different Approaches
    - Cache conscious index structures
    - New layout for data records
    - Explicit buffering of operators at specific points

Growing need for efficient cache utilization

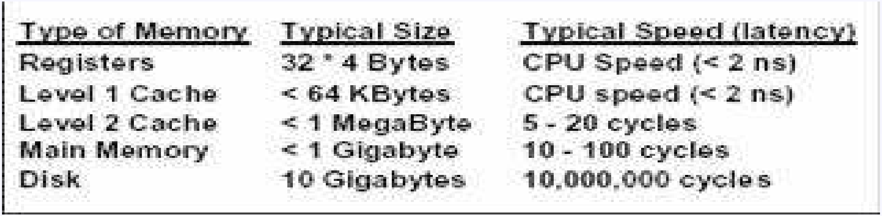
- CPU speeds have been increasing at a much faster rate than memory speeds
- Conclusion: improving cache behavior is going to be an imperative task in main memory data processing





Cache Memories

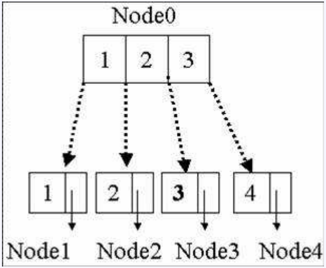
- Small, fast SRAM memories that improve performance by holding recently referenced data
- Memory reference: Cache Hit, Cache Miss
- Parameters:
  - Capacity
  - Block size (cache line)
  - Associativity



Type of Memory	Typical Size	Typical Speed (latency)
Registers	32 * 4 Bytes	CPU Speed (< 2 ns)
Level 1 Cache	< 64 KBytes	CPU speed (< 2 ns)
Level 2 Cache	< 1 MegaByte	5 - 20 cycles
Main Memory	< 1 Gigabyte	10 - 100 cycles
Disk	10 Gigabytes	10,000,000 cycles

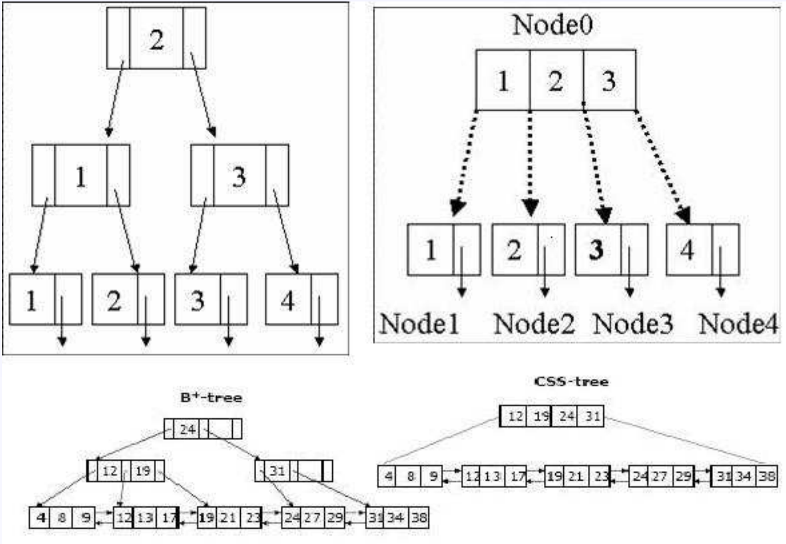
Cache conscious index structures

- Cache Sensitive Search (CSS) trees
  - Each node contains only keys and no pointers
  - Nodes are stored level by level from left to right
  - Arithmetic operations on offsets to find child nodes
  - Better Search Performance and Cache line utilization than B^+-Trees
  - Incremental updates difficult so suitable for DSS workloads only



Comparison between B^+-Tree and CSS Tree

- Cache line size=12 bytes, Key size=Pointer size=4 bytes
- Search key=3



Cache Sensitive B^+-Tree

- Goal
  - Retain good cache behaviour of CSS-Trees while at the same time being able to support incremental updates
  - This way it will be useful even for non-DSS workloads
- Idea
  - Use Partial Pointer Elimination Technique
  - Have fewer pointers per node than a B^+-Tree so more space for keys
  - Use limited amount of arithmetic on offsets to compensate for less number of pointers
- Structure
  - Put all child nodes of a given node in a *Node Group*
  - Store nodes within a node group contiguously and use offset arithmetic for access

B^+-Tree Vs CSB$^+$-Tree

- Cache line size=Node size=64 bytes
- Key and child pointer each occupy 4 bytes
- Keys per node for B^+-Tree=7
- Keys per node for CSB$^+$-Tree=14
- In CSB$^+$-Trees, number of cache lines to be searched are fewer

Example CSB$^+$-Tree

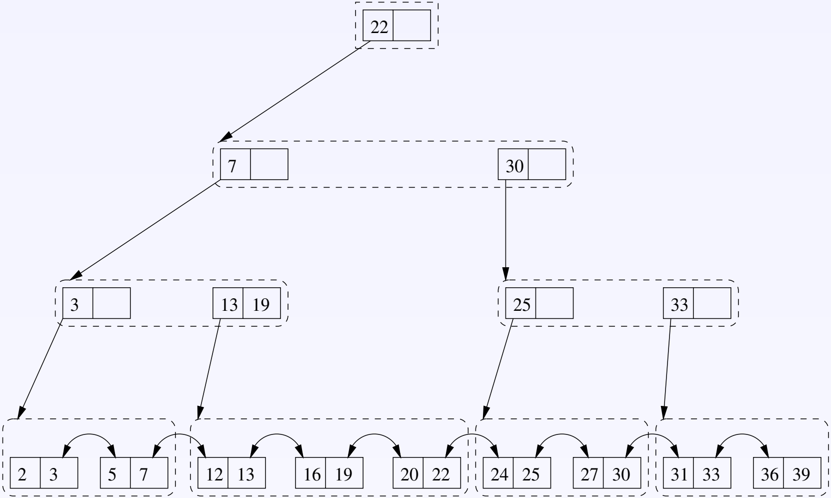


Figure 2: A CSB$^+$-Tree of Order 1

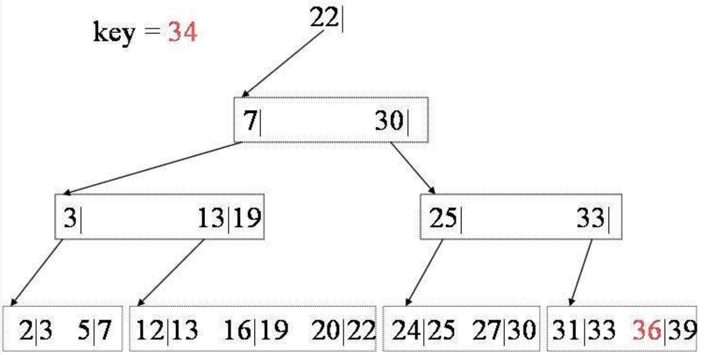
Operations on CSB$^+$-Tree

- Bulkload
  - Allocate space for leaf entries
  - Calculate how many nodes are needed at higher level and allocate them contiguously
  - Fill in the entries at higher level appropriately and set first child pointers
  - Continue with the same process until only one node remains i.e, root
- Search
  - Similar to B$^+$-Tree search algorithm
  - Locate rightmost key K in the node that is smaller than the search key and add the offset of K to the first child pointer to get the address of the child node

Operations on CSB$^+$-Tree ..contd.

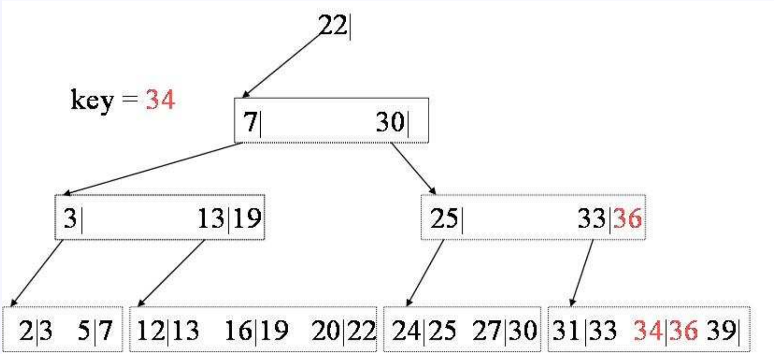
- Insertion
  - Again similar to B$^+$-Tree insertion algorithm
  - Pseudo-code
  - Search the leaf node n to insert the entry
  - If n is not full then insert the new entry into the appropriate place
  - Otherwise split n. Let p be the parent node of n, f be the first child pointer in p and g be the node group pointed to by f.
    - If p is not full then copy g to $g^{'}$ in which n is split in two nodes. Let f point to $g^{'}$
    - If p is full copy half of g to $g^{'}$. Let f point to $g^{'}$. Split the node group of p according to as above

Insertion example



a CSB+-Tree of Order 1

Insertion example



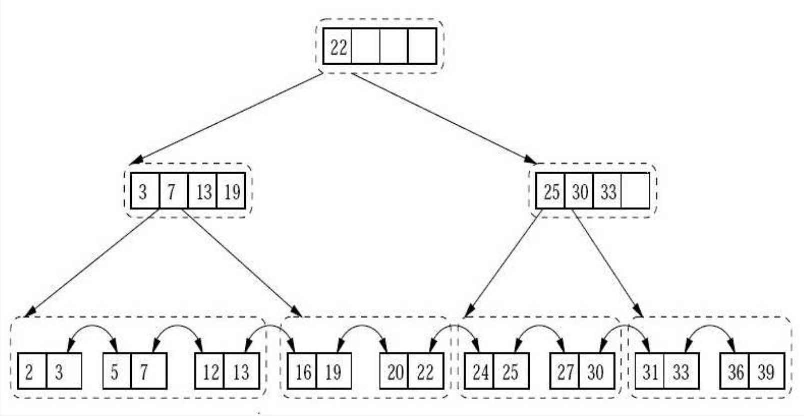
Operations on CSB$^+$-Tree ..contd.

- Deletion
    - Handled in a way similar to insertion
    - Lazy deletion - Locate the data entry, remove it but don't restructure the tree

Segmented CSB$^+$-Tree

- Problem: Increase in maximum size of the node group due to increase in cache line size means more copying of data in case of split
- Solution: Divide the child nodes into segments, store in each node pointers to segments and only child nodes in the same segment are stored contiguously

Segmented CSB$^+$-Tree



- Tree of order 2 with 2 segments

Variants of SCSB$^+$-Tree

- Two variants of SCSB$^+$-Tree:
- Fixed Size Segments
  - Start by filling the nodes in the first segment till it is full
  - Then fill the nodes in second segment, this requires copying nodes in this segment only
- Varying Size Segments
  - For bulkload, distribute nodes evenly among the segments
  - On every new node insertion, create a new segment for the segment to which the new node belongs
  - Touches only one segment in each insert as opposed to the fixed size variant

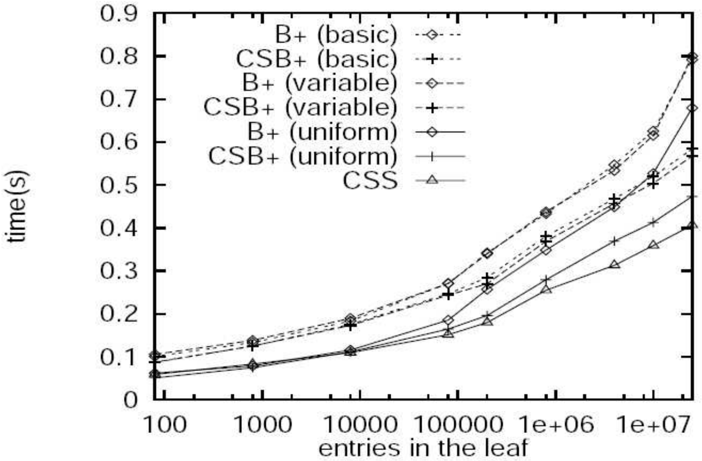
Full CSB$^+$-Tree

- Higer frequency of memory allocation and deallocation calls in CSB$^+$-Trees is a problem
- Another approach is to pre-allocate memory for entire node group
- Space-time tradeoff:
  - Node split in Full CSB$^+$-Tree is efficient than normal CSB$^+$-Tree
  - This efficiency comes at the expense of pre-allocated space

Implementation details

- Node size = Cache line size=64 bytes
- Key size=Pointer size= 4 bytes
- For CSS trees: 16 keys per node
- For B^+-Trees: Internal node 7 keys, 8 child pointers and number of keys used
- For CSB^+-Trees: Internal node 14 keys, first child pointer and number of keys used

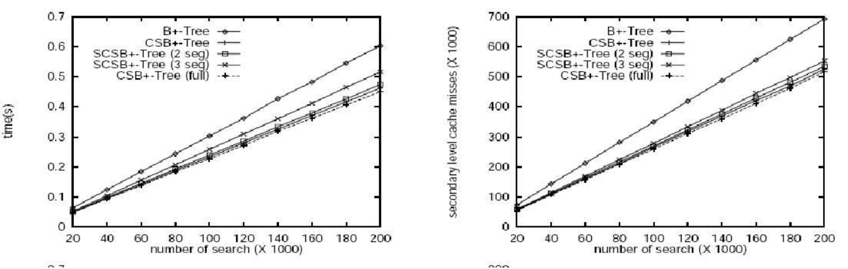
Pure Search Performance Graph



(a) Sun's CC

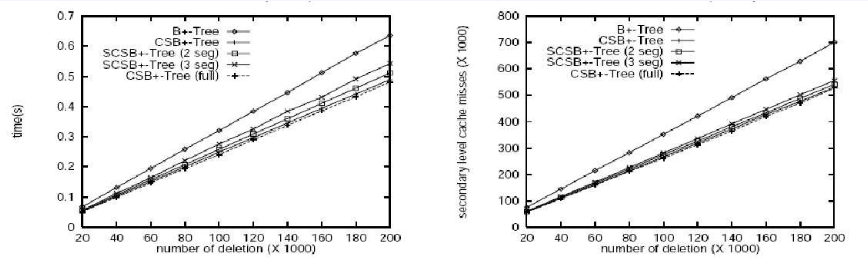
- Time for 200K searches
- B$^+$-Trees are more than 25% slower than CSB$^+$-Tree

Experiments on stabilized index structures-Search



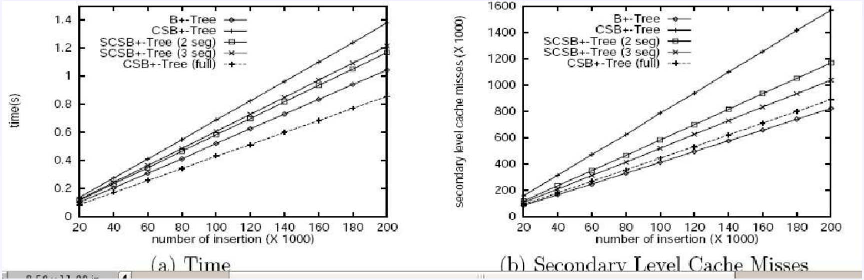
- Segmented CSB$^+$-Tree search slower than CSB$^+$-Tree because:branching factor of former is less (More cache misses) , extra comparisons needed to choose right segment

Experiments on stabilized index structures-Delete



- Because of lazy deletion most of the time is spent in locating the record, so delete performance similar to search.

Experiments on stabilized index structures-Insert



(a) Time

(b) Secondary Level Cache Misses

- CSB$^+$-Trees are worse than B$^+$-Trees for insertion because of the split cost
- SCSB$^+$-Trees reduce split cost so give intermediate performance
- B$^+$-Trees have to allocate a new **node** on every split while Full CSB$^+$-Trees make allocation when **node group** is full.

Conclusion

- Full CSB$^+$-Trees are better than B$^+$-Trees in all aspects except for space
- In limited space environment CSB$^+$-Trees and Segmented CSB$^+$-Trees provide faster searches while still being able to support incremental updates
- Suitable for applications like Digital libraries, Online shopping- Searching much more frequent than updates

Weaving Relations for Cache Performance

Motivation for devising new data layout model

- Main Problem Being Addressed: **Only a fraction of data transferred to cache is useful for the query**
- Ill-effects caused by the problem:
    - Wastage of bandwidth
    - Polluting the cache
    - May result in replacing useful information

An illustrative example

- Most widely used N-ary Storage Model (NSM) stores relation's records sequentially in slotted disk pages
- Sample Query:
- select name from R where age $<$ 40
- Relation R contains three attributes SSN, Name and Age
- For the above query the NSM model has inferior cache performance that is shown in the next slide

NSM cache behaviour

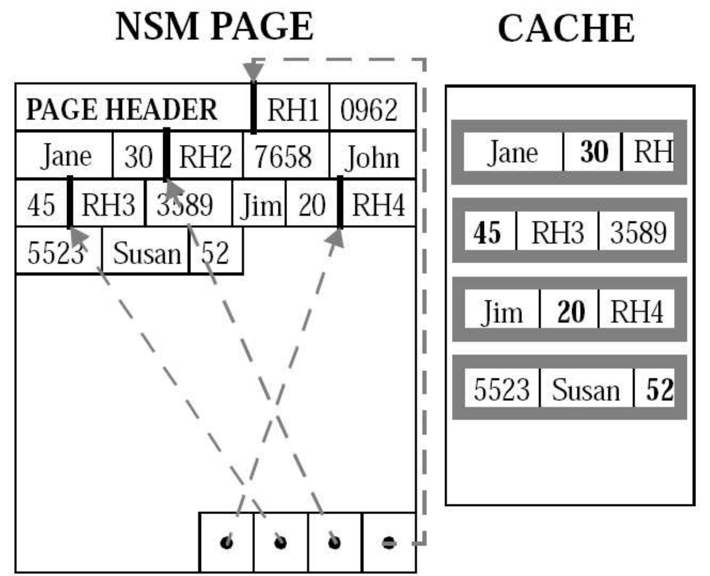
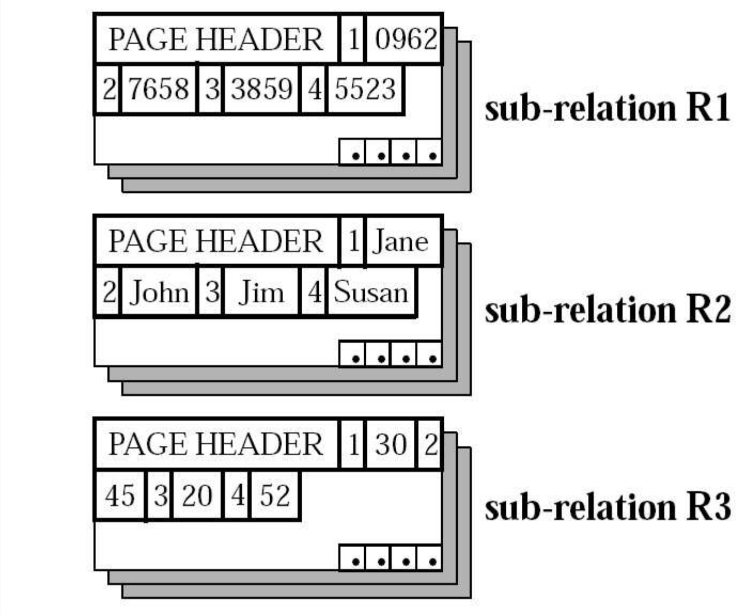


FIGURE 1: *The cache behavior of NSM.*

DSM Example


PAGE HEADER
1
0962
2
7658
3
3859
4
5523
sub-relation R1
PAGE HEADER
1
Jane
2
John
3
Jim
4
Susan
sub-relation R2
PAGE HEADER
1
30
2
45
3
20
4
52
sub-relation R3

Decomposition Storage Model (DSM)

- Fully decomposed form of Vertical Partitioning
- Partitions an n-attribute relation into n sub-relations
- Each sub-relation contains two attributes: a logical record id and the attribute value
- Sub-relations are stored as regular relations in slotted pages
- Advantages:
  - High degree of spatial locality for sequential access of an attribute
  - Better I/O and Cache performance
- Disadvantage:
  - Performance significantly deteriorates for queries involving multiple attributes for each participating relation

Partition Attributes Across (PAX)

- Idea is to keep the attribute values of each record on the same page as in NSM while using a cache-friendly algorithm for placing them inside the page
- Vertically partition records within page, storing together values of each attribute in a minipage
- Advantages:
    - maximizes inter-record spatial locality thus improving cache performance
    - minimal record reconstruction cost
    - orthogonal to other design decisions as it affects only the data within a page
- The following slide shows the cache behaviour of PAX

Cache Behaviour of PAX

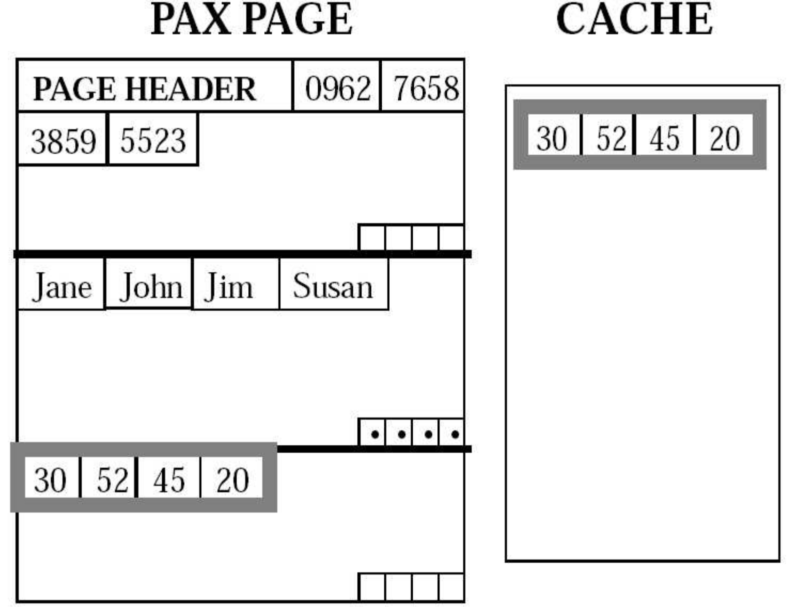


FIGURE 3: *The cache behavior of PAX.*

An example PAX page

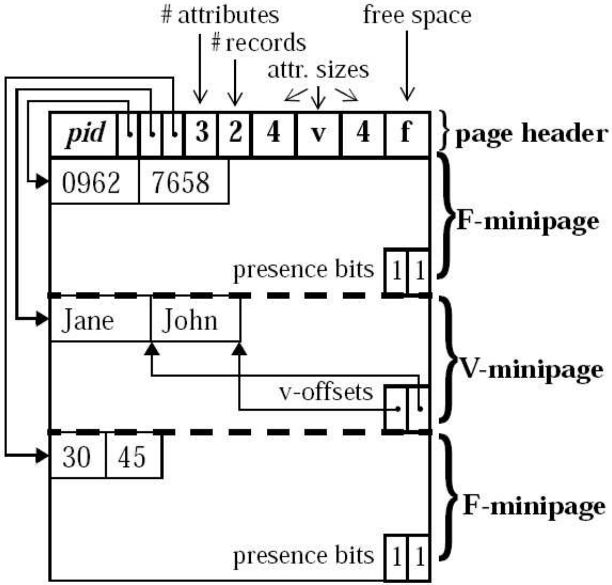


FIGURE 4: *An example PAX page.*

Design of Page in PAX

- For storing a relation of degree n, PAX partitions the page into n minipages
- Page Header contains pointers to begining of each minipage, number of attributes, the attribute sizes, current number of records on the page and free space available
- Fixed length attributes are stored in F-minipages. The end of F-minipage has presence bit vector
- Variable length attributes are stored in V-minipages. These are slotted with pointers to the end of each value

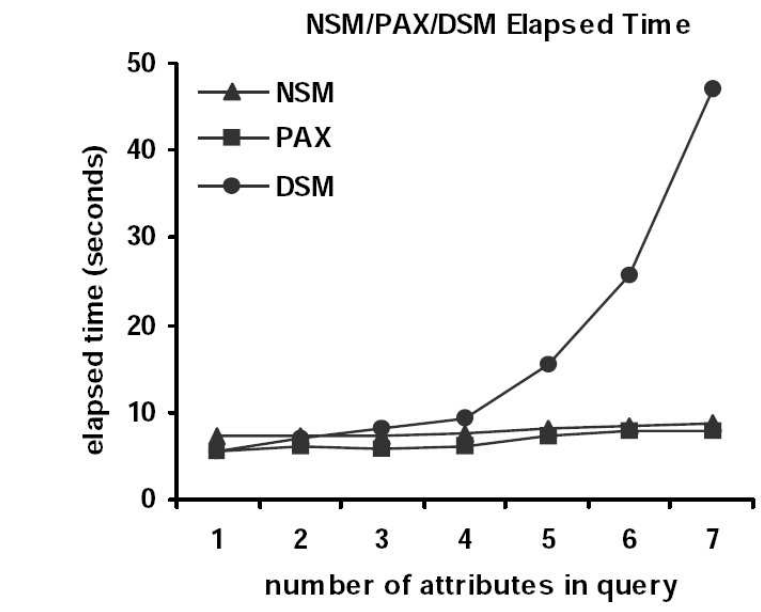
Data Manipulation Algorithms

- Bulk-loading and Insertions
  - Allocate each minipage on the page based on attribute value size
  - Inserts records by copying actual value to each minipage
  - When variable length values are present, minipage boundaries need to be adjusted to accomodate records as they are inserted in the page
  - PAX calculates the position of each attribute value of the page, stores the value and updates the bitmaps and offset arrays appropriately
- Updations
  - Find the position of the attribute value of the record and then update the value
  - Updates to variable length values may require minipage level reorganizations
  - If the space is not sufficient to accomodate and re-organization is not possible then record is moved to other page

Data Manipulation Algorithms...contd.

- Deletion
  - NSM uses slot array to mark an entry as deleted
  - PAX keeps track of deleted records using a bitmap at the start of the page and uses bitwise calculations to find whether a record is deleted
  - Reorganization can be done within minipage after deletion so as to minimize fragmentation
  - For deletion intensive workloads, reorganization can be deferred.

Experimental Results-1



Experimental Results-2

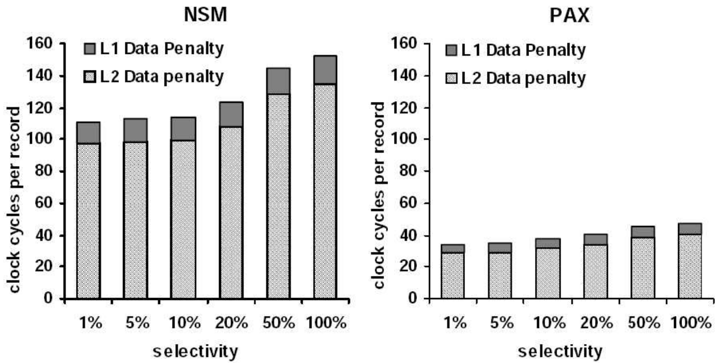
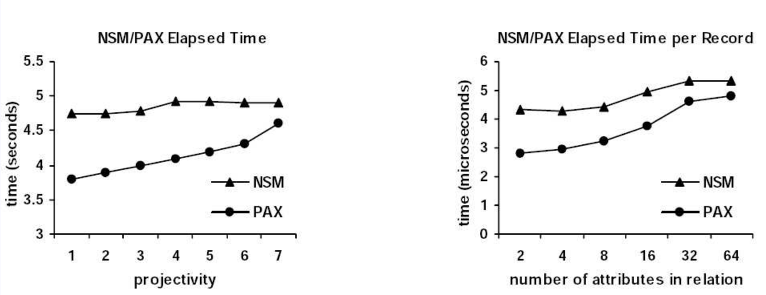


FIGURE 7: *PAX impact on memory stalls*

- NSM Vs PAX Impact on cache behaviour
  - PAX reduces data penalty at both cache levels L1 and L2 and reduces stall time
  - This reduction in number of misses results in further reduction of instruction cache misses as cache space is judiciously used

Experimental Results-3



NSM/PAX Sensitivity Analysis

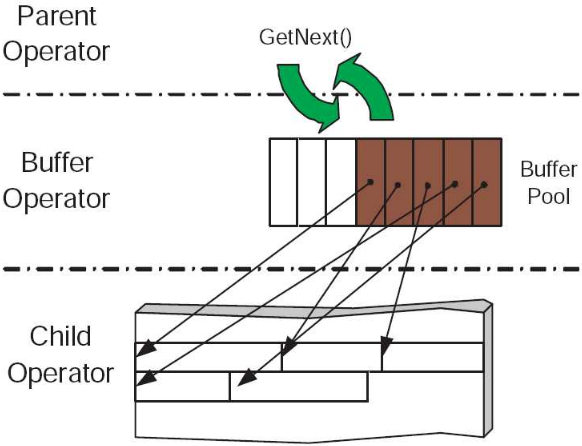
- Query execution time of NSM and PAX converge as the number of projected attributes increase
- As the degree of relation increases other factors such as buffer manager start to play a dominant role.

Buffering Database Operations for Enhanced Instruction Cache Performance

A typical scenario

- In a demand-driven query execution plan child operator returns control to parent operator immediately after generating one tuple
- So the operator execution sequence is like 'PCPCPCPCPCPCP..'
- Instruction cache thrashing can occur when the combined size of two operators exceeds the size of the smallest, fastest cache unit

Buffer operator



Solution that uses buffering

- Given a query, add a special buffer operator at certain places between a parent operator/operator group and child operator/operator group
- Buffer operator above child has an array of pointers that point to intermediate result tuples
- This effectively changes the execution sequence to 'PCCCCCPPPPPCCCCCPPPPP..'
- The execution sequence shows that number of instruction cache misses decrease substantially
- The reduced cache misses are due to improved instruction spatial and temporal locality

New Buffer Operator

- Given a query plan identify the execution groups that are candidate units for buffering
- Add a new explicit buffering operator above the execution group, if necessary
- Implementation of buffer operator:
  - Supports open-next-close interface
  - Maintains two states : Whether end-of-tuples is received from the child operator and Whether its buffered tuples have been consumed
  - Maintains an array of pointers to tuples that are stored in child operator's space
- Benefits of buffer operator:
  - Increase in query throughput due to decrease in instruction cache misses
  - Better hardware branch prediction

Other Details

- All operators don't benefit from buffering e.g. small cardinality operators, blocking operators like sort
- The placement of buffer operators in a query plan can be done by using a bottom-up pass of the plan tree
- This however needs some mechanism of estimating the memory needed by various query operators

Conclusion

- We looked at three approches for improving cache performance
- CSB$^+$-Tree approach was able to give better search performance while at the same time allowing incremental updates
- PAX approach changed the data layout model to ensure that cache space is occupied by useful data and it also remained orthogonal to other design decisions
- Buffering approach tried to solve the problem of improving instruction cache performance for demand-driven pipelined query execution environment

References

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- Anastassia Ailamaki, David J. DeWitt, Mark D. Hill, Marios Skounakis: Weaving Relations for Cache Performance. VLDB 2001:169-180
- Jingren Zhou, Kenneth A. Ross: Buffering Database Operations for Enhanced Instruction Cache Performance. SIGMOD Conference 2004:191-202

Thank You!