Buffer Management

CPS 216

Advanced Database Systems

Announcements

- Reading assignment
  - Buffer management paper online
  - DB2 query rewrite paper available as hard copies
- Homework #3 was (finally) posted last night
  - Due in 14 days (Wednesday April 9)
- Recitation session this Friday (March 28)

Memory management for DBMS

- DBMS operations require main memory
  - While data resides on disk, it is manipulated in memory
  - Sometimes the more memory the better, e.g., sort
- One approach: let each operation pre-allocate some amount of "private" memory and manage it explicitly
  - Not very flexible
  - Limits sharing and reuse
- Alternative approach: use a buffer manager
  - Responsible for reading/writing data blocks from/to disk as needed
  - Higher-level code can be written without worrying about whether data is in memory or not

Buffer manager basics

- Buffer pool: a global pool of frames (main-memory blocks)
  - ☞Some systems use separate pools for different objects (e.g., tables and indexes) and for different operations (e.g., sorting and others)
- Higher-level code can pin and unpin a frame
  - Pin: I need to work on this frame in memory
  - Unpin: I no longer need this frame
  - A completely unpinned frame is a candidate for replacement
  - ☞In some systems you can hate a frame (i.e., suggesting it for replacement)
- A frame becomes dirty when it is modified
  - Only dirty frames need to be written back to disk
  - ☞Related to transaction processing (more on it later in the semester)

Standard OS replacement policies

- Example
  - Current buffer pool: 0, 1, 2
  - Past requests: 0, 1, 2
  - Incoming requests: 3, 0, 1, 2, 3, 0, 1, 2, 3, 4, 5, 6, 7, …
  - ☞Which frame to replace?
- Optimal: replace the frame that will not be used for the longest time (2)
- Random (0, 1, or 2 with equal probability)
- LRU: least recently used (0)
- LRU approximation: clock, aging
- MRU: most recently used (2)

Problems with OS buffer management

Stonebraker. "Operating System Support for Database Management." *CACM*, 1981 (in red book).

- Performance problems
  - Getting a page from the OS to user space is usually a system call (process switch) and copy
- Replacement policy
  - LRU, clock, etc. often ineffective
  - DBMS knows access pattern in advance and therefore should dictate policy → major OS/DBMS distinction
- Prefetch policy
  - DBMS knows of multiple "orders" for a set of records; OS only knows physical order
- Crash recovery
  - DBMS needs more control

Next

Chou and DeWitt. "An Evaluation of Buffer Management Strategies for Relational Database Systems." *VLDB* 1985 (in red book).

- Old algorithms
  - Domain separation algorithm
  - "New" algorithm
  - Hot set algorithm
- Query locality set model
- DBMIN algorithm

Domain separation algorithm

- Split work/memory into domains; LRU within each domain; borrow from other domains when out of frames
  - Example: one domain for each level of the B^+-tree
- Limitations
  - Assignment of pages to domains is static, and ignores how pages are used
    - Example: A data page is accessed only once in a scan, but the same data page is accessed many times in a NLJ
  - Does not differentiate relative importance between types of pages
    - Example: An index page is more important than a data page
  - Memory allocation is based on data rather queries → need orthogonal load control to prevent thrashing

The "new" algorithm

- ☞ Observations based on the reference patterns of queries
  - Priority is not a property of a data page, but of a relation
  - Each relation needs a "working set"
- Divide buffer pool into chunks, one per relation
- Prioritize relations according to how often their pages are reused
- Replace a frame from the least reused relation and add it to the chunk of the referenced relation
- Each active relation is guaranteed with one frame
- MRU within each chunk (seems arbitrary)
- Simulation look good; implementation did not beat LRU

Hot set algorithm

- ☞ Exploit query behavior more!
- A set of pages that are accessed over and over form a hot set
  - "Hot points" in the graph of buffer size vs. number of page faults
  - Example: For nested-loop join $R \bowtie S$, size of hot set is $B(S) + 1$ (under LRU)
- Each query is given enough memory for its hot set
- Admission control: Do not let a query into the system unless its hot set fits in memory
- Replacement: LRU within each hot set (seems arbitrary)
- Derivation of hot set assumes LRU, which may be suboptimal
  - Example: What is better for nested-loop join?

Query locality set model

- Observations
  - DBMS supports a limited set of operations
  - Reference patterns are regular and predictable
  - Reference patterns can be decomposed into simple patterns
- Reference pattern classification
  - Sequential
  - Random
  - Hierarchical

Sequential reference patterns

- Straight sequential: read something sequentially once
  - Example: selection on unordered table
  - ☞Each page is only touched once, so just buffer one page
- Clustered sequential: repeatedly read a "chunk" sequentially
  - Example: merge join; rows with the same join column value are scanned multiple times
  - ☞Keep all pages in the chunk in buffer
- Looping sequential: repeatedly read something sequentially
  - Example: nested-loop join
  - ☞Keep as many pages as possible in buffer, with MRU replacement

Random reference patterns

- Independent random: truly random accesses
  - Example: index scan through a non-clustered (e.g., secondary) index yields random data page access
  - ☞The larger the buffer the better?
- Clustered random: random accesses that happen to demonstrate some locality
  - Example: in an index nested-loop join, inner index is non-clustered and non-unique, while outer table is clustered and non-unique
  - ☞Try to keep in buffer data pages of the inner table accessed in one cluster

Hierarchical reference patterns

- Example: operations on tree indexes
- Straight hierarchical: regular root-to-leaf traversal
- Hierarchical with straight sequential: traversal followed by straight sequential on leaves
- Hierarchical with clustered sequential: traversal followed by clustered sequential on leaves
- Looping hierarchical: repeatedly traverse an index
  - Example: index nested-loop join
  - ☞Keep the root index page in buffer

DBMIN algorithm

- Associate a chunk of memory with each file instance (each table in FROM)
  - This chunk is called the file instance's locality set
  - Instances of the same table may share buffered pages
  - But each locality set has its own replacement policy
    - ☞Based on how query processing uses each relation (finally!)
    - ☞No single policy for all pages accessed by a query
    - ☞No single policy for all pages in a table
- Estimate locality set sizes by examining the query plan and database statistics
- Admission control: a query is allowed to run if its locality sets fit in free frames

DBMIN algorithm (cont'd)

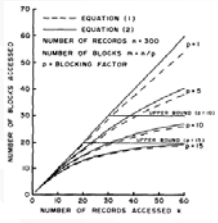
- Locality sets: each "owns" a set of pages, up to a limit *l*
- Global free list: set of "orphan" pages
- Global table: allow sharing among concurrent queries
- Query *q* requests page *p*
  - If *p* is in memory and in *q*'s locality set
    - Just update usage statistics of *p*
  - If *p* is in memory and in some other query's locality set
    - Just make p available to q; no further action is required
  - If *p* is in memory and in the global free list
    - Add *p* to *q*'s locality set; if *q*'s locality set exceeds its size limit, replace a page (release it back to the global free list)
  - If *p* is not in memory
    - Use a buffer from global free list to get *p* in; proceed as in the previous case

Locality sets for various ref. patterns

- Straight sequential
  - Size = 1
  - Just replace as needed
- Clustered sequential
  - Size = number of pages in the largest cluster
  - FIFO or LRU
- Looping sequential
  - Size = number of pages in the table
  - MRU

Locality sets for more ref. patterns

- Independent random
  - Size = 1 (if odds of revisit is low), or *b* (expected number of block accessed by a given number *k* of random record accesses; Yao, 1977)
    - Use $(k - b) / b$ to choose between 1 and *b*
  - Replacement policy does not matter
- Clustered random
  - Size = number of blocks in the largest cluster (≈ number of tuples because of random access, or use Yao's formula)
  - LRU or FIFO (why?)



Locality sets for more ref. patterns

- Straight hierarchical, hierarchical/straight sequential: just like straight sequential
  - Size = 1
  - Just replace as needed
- Hierarchical/clustered sequential: like clustered sequential
  - Size = number of index pages in the largest cluster
  - FIFO or LRU
- Looping hierarchical
  - At each level of the index you have random access among pages
  - Use Yao's formula to figure out how many pages need to be accessed at each level
  - Size = sum over all levels that you choose to worry about
  - LIFO with 3-4 buffers should be okay

Simulation study

- Hybrid simulation model
  - Trace-driven simulation
    - Recorded from a real system (running Wisconsin Benchmark)
    - For each query, record its execution trace
      - Page read/write, file open/close, etc.
  - Distribution-driven simulation
    - Generated by some stochastic model
    - Synthesize the workload by merging query execution traces
- Simulator models CPU, memory, and one disk
- Performance metric: query throughput

Workload

Query Type	CPU Demand	Disk Demand	Memory Demand
I	Low	Low	Low
II	Low	High	Low
III	High	Low	Low
IV	High	High	Low
V	High	Low	High
VI	High	High	High

Query Classification

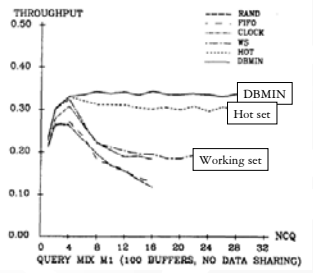
Query #	Query Operators	Selectivity	Access Path of Selection	Join Method	Access Path of Join
I	select(A)	1%	clustered index	-	-
II	select(B)	1%	non-clustered index	-	-
III	select(A) join B	2%	clustered index	index join	clustered index on B
IV	select(A') join B	10%	sequential scan	index join	non-clustered index on B
V	select(A) join B'	3%	clustered index	nested loops	sequential scan over B'
VI	select(A) join A'	4%	clustered index	hash join	hash on result of select(A)

A,B:10K tuples; A':1K tuples; B':300 tuples; 182 bytes per tuple.

Description of Base Queries

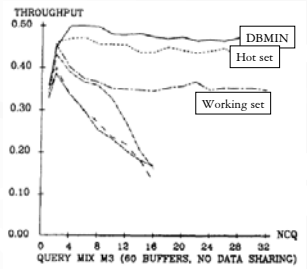
- Mix 1: all six types equally likely
- Mix 2: I and II together appear 50% of the time
- Mix 3: I and II together appear 75% of the time

Mix 1 (no data sharing)



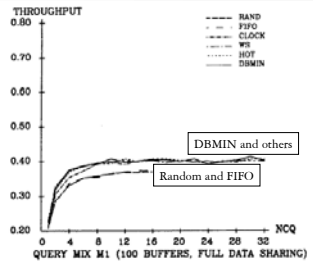
- Thrashing is evident for simple algorithms with no load control
- Working set (a popular OS choice) fails to capture join loops for queries with high memory demand (types V and VI)
  - It still functions (though suboptimally) with large number of current queries (NCQ)

Mix 3 (no data sharing)



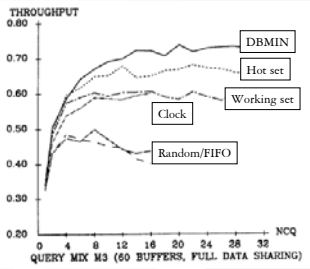
- Thrashing is still evident
- Working set fares better because mix 3 has more simple queries and fewer ones of types V and VI

Mix 1 (full data sharing)



- With full data sharing, locality is easier to capture
  - Performance improves across the board and the gap disappears
  - Random and FIFO do not capture locality as effectively as others

Mix 3 (full data sharing)

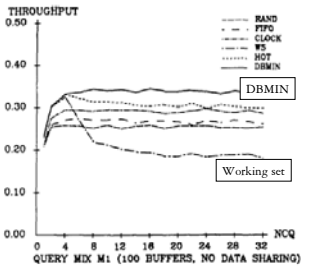


- Performance starts to diverge again
  - Mix 3 is dominated by lots of small queries, and locality becomes harder to capture

Load control

- Mechanism to check resource usage in order to prevent system from overloading
- Rule of thumb: "50% rule"—keep the paging device busy half of the time
- Implementation
  - Estimator measures the utilization of device
  - Optimizer analyzes measurements and decides whether/what load adjustment is appropriate
  - Control switch activates/deactivates processes according to optimizer's decisions

Mix 1 (load control, no data sharing)



- DBMIN still the best
- (Simple algorithms + load control) outperforms working set!
- Cons of load control
  - Runtime overhead
  - Non-predictive
    - Only responds after undesirable condition occurs

Conclusion

- Same basic access patterns come up again and again in query processing
- Make buffer manager aware of these access patterns

☞ Look at the workload, not just the content

- Contents can at best offer guesses at likely workloads