Caching for
Client/Server Database Architectures

CPS 296.1

Topics in Database Systems

Roadmap

- ➢ Semantic (query) caching
  - Dar et al. "Semantic Data Caching and Replacement." *VLDB*, 1996
- Object caching (piggyback on queries)
  - Haas et al. "Loading a Cache with Query Results." *VLDB*, 1999

Client/Server Database Architectures

- Data shipping
  - Client performs query processing on a local, cached copy of the data retrieved from the server
  - Server primarily services faults
  - Used mostly by object-oriented database systems (OODBMS)
  - Able to exploit client resources
- Query shipping
  - Client sends queries to the server and receives results back
  - Server performs query processing
  - Used mostly by relational database systems (RDBMS)
  - Less able to exploit client resources

Client-side caching

- Traditional approaches to client-side caching for data-shipping architectures
  - Page caching
  - Tuple caching
- New approach that combines data-shipping and query-shipping ideas
  - Semantic caching

Page caching

- Client
  - Caches a collection of index/data pages
  - Processes queries over cached index/data pages
  - Faults in missing index/data pages from the server
  - Manages cache using LRU/LFU/MRU policies
  - ➢ Looks just like a DBMS buffer manager
- Server
  - Services page faults and returns pages to client
  - ➢ A.k.a. "page server"

Tuple caching

- Client
  - Caches a collection of tuples (objects)
  - Performs indexed scans like page caching
  - Performs non-indexed scans in two alternative ways
    - Ignores cache; sends constraint to server
    - Scans local cache; sends constraint/tuple list to server
  - Manages cache using LRU/LFU/MRU policies
- Server
  - Services tuple faults
  - Performs constrained scans and filters result tuples according to tuple lists provided by client

Semantic caching

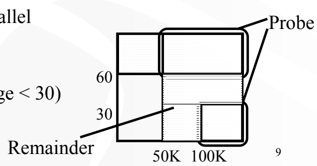
- Key idea: in addition to caching query results, remember the queries that generated these results
  - Provides an accurate, semantic description of the content of the cache
  - Supports semantic grouping of the cache content
  - Enables the testing of whether a query can be answering completely by the cache
  - Allows the formulation of a query to retrieve the exact set of missing result tuples from server

Semantic regions

- Cache is managed as a collection of disjoint semantic regions, each including
  - Constraint formula
    - Or really, a materialized view definition (limited to selection view in this paper)
    - Example: $\sigma_{\text{salary < 100K AND age < 30}}$ Employee
  - Tuple count
  - Collection of cached tuples
  - Replacement data
- The entire content can be expressed as the disjunction of all constraint formulas

Answering queries

- Say cache content is described by constraint formula *V*
- Each single-table selection query is split into two
  - Probe query: (query condition) AND *V*
    - Processed over cached data (no need to re-apply *V*)
  - Remainder query: (query condition) AND (NOT *V*)
    - If satisfiable, sent to the server and processed there
  - ➢ Can be processed in parallel
- Example
  - *V* = ((salary > 100K AND age < 30) OR age > 60)
  - *Q* = (salary > 50K)



Managing semantic regions

- A query splits an intersecting semantic region into two
  - One is the intersection of query and region
  - The other is the difference with respect to the query
- Results of the remainder query also form a region
- ➢ Number of regions potentially grows exponentially!
- Coalesce policy
  - Always coalesce two regions with same replacement value
  - Never coalesce
  - Heuristic: coalesce two regions with same replacement value only if either is < 1% of the cache size
    - Avoid coalescing big regions, which create big holes when replaced

Semantic cache replacement

- Replace semantic regions with lowest replacement value
- LRU: exploits temporal locality of reference
  - Replacement value = last access time
- Longest Manhattan distance: exploits spatial locality (semantically defined) of reference
  - Replacement value = – (Manhattan distance to the center of the most recent query)

Qualitative comparison

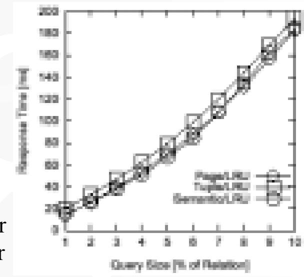
- Data granularity
  - Page caching: coarse; tied to a particular clustering of tuples
  - Tuple caching: fine; high overhead of cache management
  - Semantic caching: semantic grouping; adapts to query load
- Remainder query vs. faulting
  - Page and tuple caching: faulting
  - Semantic caching: remainder query; small messages and parallelism
- Cache replacement policy
  - Page and tuple caching: traditional spatial/temporal locality
  - Semantic caching: + semantic locality

Simulation environment

- Simulation environment
  - Disk modeled in detail
  - Overlap of disk I/O and network transmission considered
  - CPU cost of cache management not modeled (!)
    - ➢ Semantic caching may have higher management cost?
- Workload
  - Simple selection queries, whose size varies
  - 90% of the queries are "centered" around a region containing 10% of the data; rest of the queries are distributed uniformly
    - ➢ This distribution tends to favor Manhattan distance

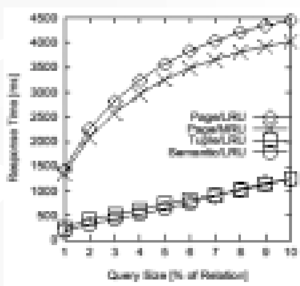
Selection on indexed clustered column

- Tuple/LRU: high overhead means fewer tuples fit in cache
- Page/LRU: good spatial locality (because of clustering)
- Semantic/LRU: cache utilization falls for bigger queries because of bigger semantic regions (and therefore holes)



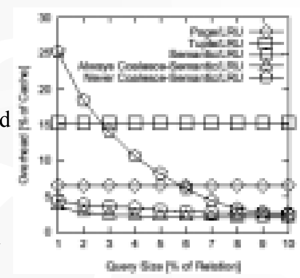
Selection on indexed, non-clustered column

- Page/LRU, MRU: both suffer from non-clustered data
- Tuple/LRU: can adapt better to non-clustered accesses
- Semantic/LRU: semantic grouping offsets non-clustered data; lower overhead



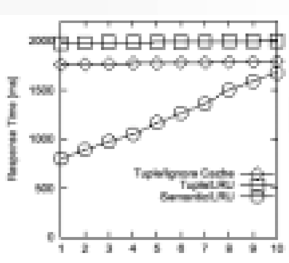
Overhead

Selection on both columns
- Tuple/LRU: high overhead
- Page/LRU: low compared with tuple/LRU
- Semantic/LRU: depends on coalescing strategy
  - Never coalesce: too much overhead
  - Heuristic works well



Selection on unindexed, non-clustered column

- Page: not shown; suffers from non-clustered data
- Tuple/LRU: must scan local cache before retrieving missing tuples
- Tuple/ignore cache: goes to server directly
- Semantic/LRU: probe and remainder queries can be processed in parallel



Additional experiments

- As expected
  - Manhattan works better than LRU
  - In a mobile navigation application, directional Manhattan works better than LRU, MRU

➢ Give applications the control of the cache replacement policy

Summary of semantic caching

- Materialized views for caching
- Application-dependent semantic locality
- Big concern: How complicated will the constraint formulas become?
  - Without any simplification, constraint formula for each semantic region grows linear with each query
  - Coalescing reduces the number of regions, but not necessarily the complexity of constraint formulas
  - Semantic caching may be no better than tuple caching
  - ➢ DynaMat consciously avoids complex constraint formulas
- And what about joins?

Roadmap

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➢ Object caching (piggyback on queries)
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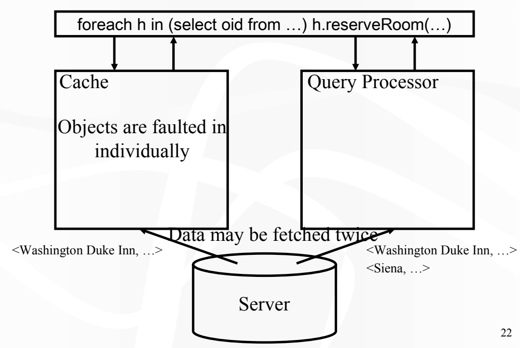
Background and motivation

- Applications ask queries to select objects and invoke methods on relevant objects
  - Example: find hotels and reserve rooms

```
foreach h in   (select h.oid from hotels h, cities c
                where h.city_oid = c.oid and c.name = 'Durham')
        h.reserveRoom(1, "2002-04-01", "2002-04-03")
```

  - ➢ Query results alone are insufficient for method invocation
- In traditional client-server systems
  - Queries are executed by clients and servers
  - Methods are executed by clients with caching
  - ➢ Query processing is independent of caching

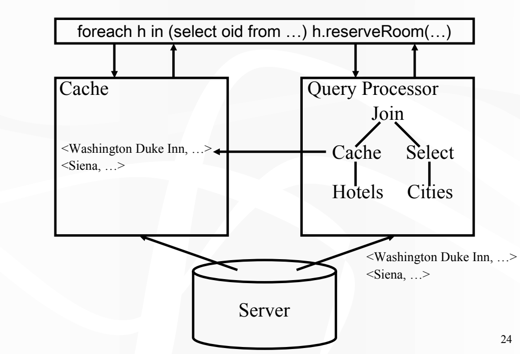
Traditional system



Solution

- Load cache as a by-product of queries
- Introduce cache operators in a query plan to copy objects during query execution
  - A cache operator requires its subplan to preserve objects in their entirety (i.e., no projection)
  - The cache operator then removes from its output stream any attributes that are irrelevant to the query
  - Above the cache operator, the plan is free to perform any additional projection
- Extend the query optimizer to add cache operators into a query plan

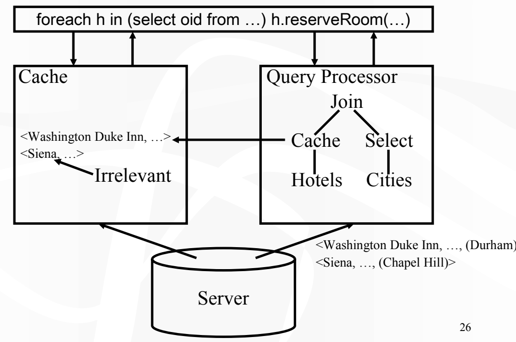
Loading cache with a query



Tradeoffs

- What to cache?
  - Cost of the cache operator must be smaller than the savings obtained by it
- When to cache?
  - Late in the plan, so only relevant objects are cached
  - Early in the plan, so other operators are not affected
    - Cache operators may increase the cost of lower operators by forcing them to process objects in entirety

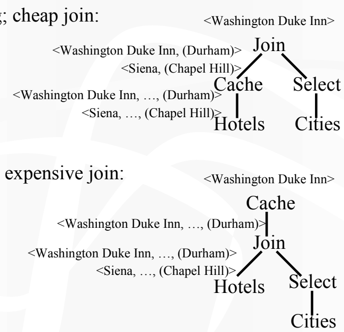
Copying irrelevant objects



Expensive late caching

Early caching; cheap join:

Late caching; expensive join:



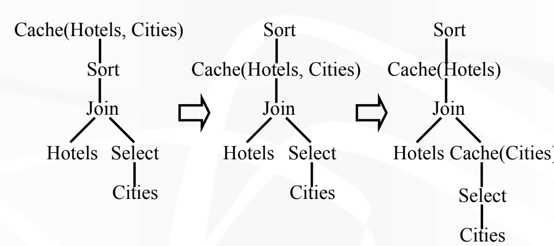
Alternative approaches

- What to cache (determining candidate collections)
  - Perform dataflow analysis of the application program
  - Analyze SELECT clause of the query; cache if oid is returned
- When to cache
  - Heuristic: caching at the top
  - Heuristic: caching at the bottom
  - Cost-based approach

Caching at the top

- Policy
  - Cache all candidate collections
  - Cache no irrelevant objects
- Algorithm
  - Start with the original plan
  - Place a cache operator at the top of the plan
  - Push down the cache operator through non-reductive operators (so only relevant objects are cached)

Cache operator push down



Push-down reduces the cost of non-reductive operators without causing irrelevant objects to be cached

Caching at the bottom

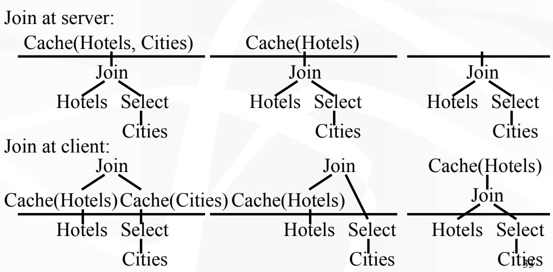
- Policy
  - Cache all candidate collections
  - Increase cost of other operators as little as possible
- Algorithm
  - Start with the original plan
  - Place a cache operator on every leaf that accesses a candidate collection
  - Pull up cache operators that sit below pipelining operators (e.g., filters or nested-loop joins, but not sort)
    - Pull-up reduces the number of irrelevant objects that are cached without increasing the cost of pipelining operators

Cost-based cache operator placement

- Try to find the best possible plan
  - Introduce cache operators only if they are beneficial
  - Find the best locations for cache operators in the plan
  - Join order and site selection depend on caching
- Extend a Selinger-style query optimizer
  - Enumerate all plans with/without caching
  - Estimate cost and benefit of cache operators
  - Extend pruning condition for dynamic programming

Enumerating all caching plans

- In addition to enumerating normal (thin) subplans, enumerate caching (thick) subplans



Costing cache operators

- Overhead of a cache operator
  - Cost to probe hash table for every object
  - Cost to copy objects that are not yet cached
  - Cost to perform projection
- Benefit of a cache operator
  - Relevant objects are not re-fetched
  - Savings depend on
    - Cost to fault in an object
    - Number of objects in the query result that are actually fetched by the application
- Cost = overhead – benefit
  - Only operators with cost < 0 are useful

Summary of approaches

- Heuristics
  - Simple to implement
  - Very little additional optimization overhead
  - Poor plans in certain cases
- Cost-based
  - Very good plans
  - Huge search space slows down optimization

Single-table query

	UDB	Notes	WWW
no caching	47.8	22.9	3538.5
traditional caching	22.9	18.2	1762.3
enhanced caching	2.2	12.7	11.9

- Plain caching still helps a lot
- Heuristic and cost-based approaches return the same caching plan

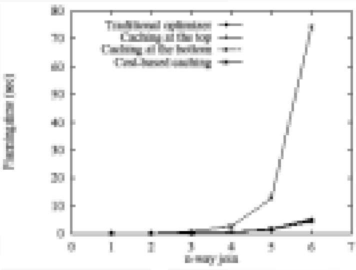
Three-table join

	Q1(large)	Q1(med)	Q2	Q3
no caching	405.5	405.5	842.5	129.2
traditional caching	405.5	405.5	842.7	129.9
caching at the top	71.3	71.3	49.8	177.5
caching at the bottom	76.0	415.8	34.9	141.9
cost-based caching	71.4	71.4	35.1	130.7

- Cost-based approach consistently picks better plans
  - But notice that for each individual case, cost-based caching never produces the best plan!
- For Q3, caching is just not beneficial

Query optimization time

- Heuristics: very little overhead
- Cost-based: very high overhead—could be higher than the cost of faulting in objects
  - ➢ "Meta-optimization" is needed



Summary

- Piggyback on queries to load an object cache
- Not clear whether cost-based approach is better than simple heuristics even when the number of tables in the join is small
  - One strategy is to pick the best of the three plans
    - No caching
    - Caching at the top
    - Caching at the bottom
  - ➢ This strategy would consistently beat cost-based approach according to the experiments presented in the paper