"Generic Database Cost Models for Hierarchical Memory Systems", Manegold, Boncz, Kersten, VLDB'02

Cost models for Main-Memory database systems

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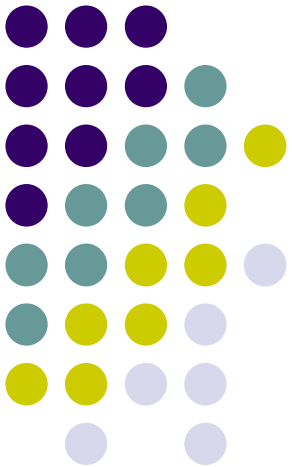

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Contents

- Cost Components
- Disk-based vs. Main-Memory: Physical Costs
- Memory Access Pattern
- Conclusions

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Introduction: Purposes of Cost Models

estimate / predict performance in order to

- understand and analyze algorithms
- tune algorithms
- optimize QEPs

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Introduction: Cost Components

- **Logical Costs / Data Volume:**
  - estimate (intermediate) result sizes
  - "purely algebraic", independent of algorithms
  - require statistics about the stored data
  - synopses, histograms, wavelets, sampling, etc.
- **Algorithmic Costs:**
  - complexity of algorithms
  - O-classes
- **Physical Costs:**
  - execution time, memory consumption, etc.
  - require knowledge about hardware

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Physical Costs: Disk-based DBMS

- I/O costs (disk access) dominate execution
- CPU costs are negligible

  $\Longrightarrow \quad T = \#_{I/O} * t_{I/O}$

- estimation of $\#_{I/O}$ is easy due to
- full control over buffer management:
  - known replacement strategy, pinning, exclusive access
  - full associativity $\Rightarrow$ no conflicts

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Physical Costs: Main-Memory DBMS

- no I/O
- only CPU costs and memory access costs

  $\Longrightarrow \quad T = T_{CPU} + \#_{mem} * t_{mem}$
- estimation of $\#_{mem}$ is difficult due to
- no control over cache management:

  - unknown replacement strategy, no pinning, shared caches

  - limited associativity $\Rightarrow$ conflicts
- analytical modeling of CPU costs is virtually impossible:

  coding style, compiler optimization, runtime optimization (CPU), etc.

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Memory Access Costs

- From Radix-work:
  - $T = T_{CPU} + M_{L1} * l_{L1} + M_{L2} * l_{L2} + M_{TLB} * l_{TLB}$
  - T_{CPU} is calibrated per operator
  - cache/memory characteristics are measured per system (The Calibrator)
- Problem:
  - hand-crafting the cost functions that estimate the cache miss rates is too expensive and not intuitive
  - we need a more generic solution

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Memory Access Pattern: The Idea

- specify basic memory access pattern and cost functions that calculate their cache miss rates
- use basic memory access pattern as building blocks to describe the memory access behavior of DB operators
  $\Longrightarrow$ compound memory access pattern
- provide rules to calculate the cache miss rates of compound memory access pattern using the cost functions of their building blocks

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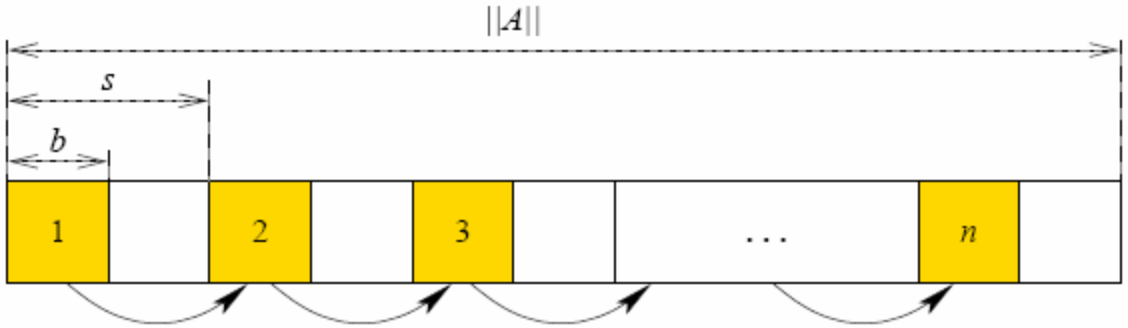
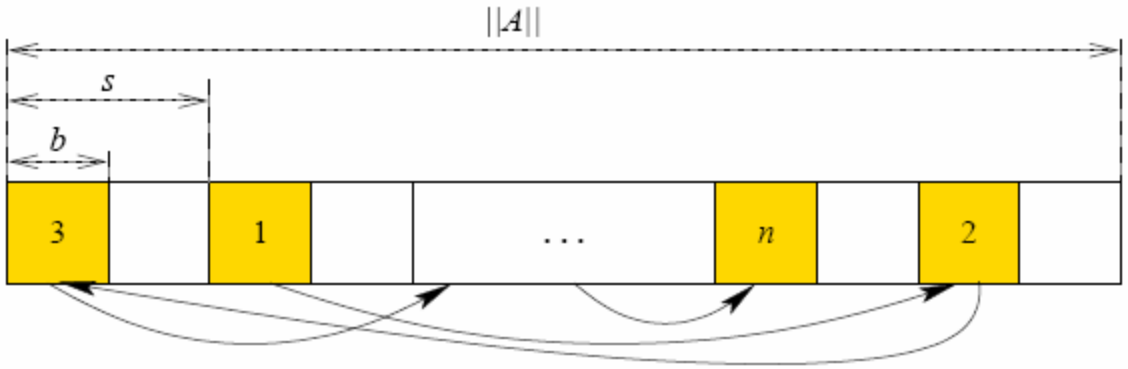
Simple Memory Access Pattern: $sMAP = (A, o, n, s, b)$

- traverse a memory area A once; $||A|| = n \cdot s \ \wedge \ b \leq s$

$o =$ seq



$o =$ ran



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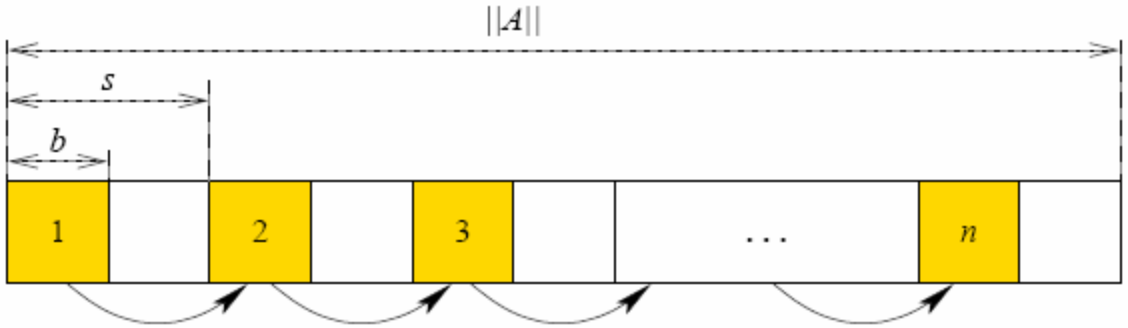
Simple Memory Access Pattern: $sMAP = (A, o, n, s, b)$

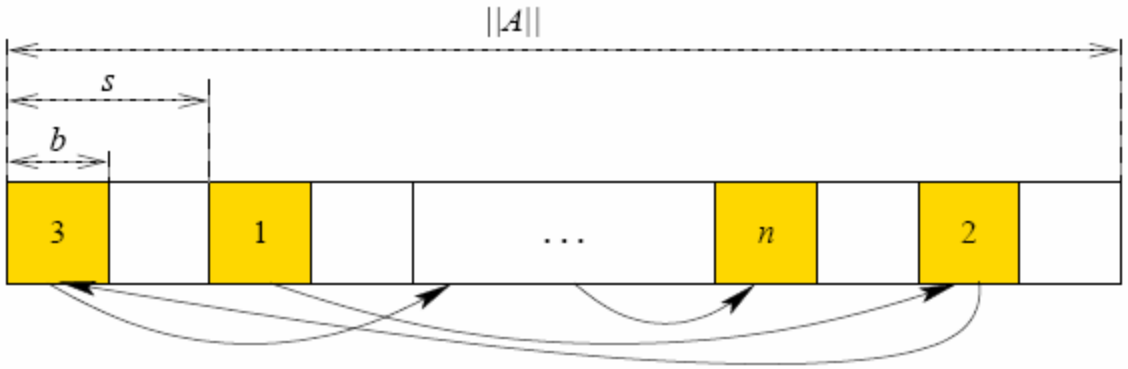
- traverse a memory area A once $||A|| = n \cdot s \ \wedge \ b \leq s$

Region size

$o = \text{seq}$



$o = \text{ran}$



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Simple Memory Access Pattern: Cache Misses

$$M_{\llcorner i}((A, o, n, s, b)) =$$

$$\begin{cases} n \cdot \left(\left\lceil \frac{b}{LS_{\llcorner i}} \right\rceil + \frac{(b-1) \bmod LS_{\llcorner i}}{LS_{\llcorner i}} \right), & \text{if } s - b \geq LS_{\llcorner i} \quad \text{Skippy Access} \\ |A|_{\llcorner i}, & \text{if } s - b < LS_{\llcorner i} \wedge o = \text{seq} \\ |A|_{\llcorner i} & \\ + (n - \min\{|\llcorner i|_{\llcorner i}, |\llcorner i|_s\}) \cdot \left(1 - \min\left\{1, \frac{||\llcorner i||}{||A||}\right\}\right), & \text{if } s - b < LS_{\llcorner i} \wedge o = \text{ran} \end{cases}$$

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Simple Memory Access Pattern: Cache Misses

$$M_{\mathsf{L}i}((A, o, n, s, b)) =$$

$$\begin{cases} n \cdot \left(\left\lceil \frac{b}{LS_{\mathsf{L}i}} \right\rceil + \frac{(b-1) \bmod LS_{\mathsf{L}i}}{LS_{\mathsf{L}i}} \right), & \text{if } s - b \geq LS_{\mathsf{L}i} \\ |A|_{\mathsf{L}i}, & \text{if } s - b < LS_{\mathsf{L}i} \wedge o = \text{seq} \\ |A|_{\mathsf{L}i} & \\ + (n - \min\{|\mathsf{L}i|_{\mathsf{L}i}, |\mathsf{L}i|_s\}) \cdot \left(1 - \min\left\{1, \frac{||\mathsf{L}i||}{||A||}\right\}\right), & \text{if } s - b < LS_{\mathsf{L}i} \wedge o = \text{ran} \end{cases}$$

Full sequential access

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Simple Memory Access Pattern: Cache Misses

$$M_{\llcorner i}((A, o, n, s, b)) =$$

$$\begin{cases} n \cdot \left(\left\lceil \frac{b}{LS_{\llcorner i}} \right\rceil + \frac{(b-1) \bmod LS_{\llcorner i}}{LS_{\llcorner i}} \right), & \text{if } s - b \geq LS_{\llcorner i} \\ |A|_{\llcorner i}, & \text{if } s - b < LS_{\llcorner i} \wedge o = \text{seq} \\ |A|_{\llcorner i} + (n - \min\{|\llcorner i|_{\llcorner i}, |\llcorner i|_s\}) \cdot \left(1 - \min\left\{1, \frac{||\llcorner i||}{||A||}\right\}\right), & \text{if } s - b < LS_{\llcorner i} \wedge o = \text{ran} \end{cases}$$

Random access: compulsory misses + data misses

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Simple Memory Access Pattern: Cache Misses

$$M_{\mathsf{L}i}((A, o, n, s, b)) =$$

$$\begin{cases} n \cdot \left(\left\lceil \frac{b}{LS_{\mathsf{L}i}} \right\rceil + \frac{(b-1) \bmod LS_{\mathsf{L}i}}{LS_{\mathsf{L}i}} \right), & \\ |A|_{\mathsf{L}i}, & \text{if } s - b < LS_{\mathsf{L}i} \wedge o = \mathsf{seq} \\ |A|_{\mathsf{L}i} + (n - \min\{|\mathsf{L}i|_{\mathsf{L}i}, |\mathsf{L}i|_s\}) \cdot \left(1 - \min\left\{1, \frac{||\mathsf{L}i||}{||A||}\right\}\right), & \text{if } s - b < LS_{\mathsf{L}i} \wedge o = \mathsf{ran} \end{cases}$$

Sequential memory access

Random memory access

Beware automatic prefetching!

Sequential access is much cheaper
-5GB/s vs 500MB/s
Workaround: use "amoritzed laten
for sequential accesses

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Repetitive Memory Access Pattern: $rMAP = (S, r, d)$

- repeat $S = (A, o, n, s, b)$ r-times
- for $o =$ seq, we distinguish

  $d =$ uni(−directional) ("round-robin")

  $d =$ bi(−directional) ("back-and-forth")

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Repetitive Memory Access Pattern: Cache Misses

$$M_{\mathsf{L}i}((\mathcal{S}, r, d)) =$$

$$\begin{cases} M_{\mathsf{L}i}(\mathcal{S}), & \text{if } M_{\mathsf{L}i}(\mathcal{S}) \leq |\mathsf{L}i|_{\mathsf{L}i} \\ r \cdot M_{\mathsf{L}i}(\mathcal{S}), & \text{if } M_{\mathsf{L}i}(\mathcal{S}) > |\mathsf{L}i|_{\mathsf{L}i} \wedge d = \mathsf{uni} \\ M_{\mathsf{L}i}(\mathcal{S}) + (r-1) \cdot (M_{\mathsf{L}i}(\mathcal{S}) - K), & \text{else} \end{cases}$$

$$K = \begin{cases} |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \mathsf{seq} \\ \dfrac{|\mathsf{L}i|_{\mathsf{L}i}}{M_{\mathsf{L}i}(\mathcal{S})} \cdot |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \mathsf{ran} \end{cases}$$

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Repetitive Memory Access Pattern: Cache Misses

$$M_{\mathsf{L}i}((\mathcal{S}, r, d)) =$$

$$\begin{cases} M_{\mathsf{L}i}(\mathcal{S}), & \text{if } M_{\mathsf{L}i}(\mathcal{S}) \leq |\mathsf{L}i|_{\mathsf{L}i} \\ r \cdot M_{\mathsf{L}i}(\mathcal{S}), & \text{if } M_{\mathsf{L}i}(\mathcal{S}) > |\mathsf{L}i|_{\mathsf{L}i} \wedge d = \text{uni} \\ M_{\mathsf{L}i}(\mathcal{S}) + (r-1) \cdot (M_{\mathsf{L}i}(\mathcal{S}) - K), & \text{else} \end{cases}$$

Perfect reuse

$$K = \begin{cases} |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \text{seq} \\ \dfrac{|\mathsf{L}i|_{\mathsf{L}i}}{M_{\mathsf{L}i}(\mathcal{S})} \cdot |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \text{ran} \end{cases}$$

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Repetitive Memory Access Pattern: Cache Misses

$$M_{\mathsf{L}i}((\mathcal{S}, r, d)) =$$

$$\begin{cases} M_{\mathsf{L}i}(\mathcal{S}), & \text{if } M_{\mathsf{L}i}(\mathcal{S}) \leq |\mathsf{L}i|_{\mathsf{L}i} \\ r \cdot M_{\mathsf{L}i}(\mathcal{S}), & \text{if } M_{\mathsf{L}i}(\mathcal{S}) > |\mathsf{L}i|_{\mathsf{L}i} \wedge d = \text{uni} \\ M_{\mathsf{L}i}(\mathcal{S}) + (r-1) \cdot (M_{\mathsf{L}i}(\mathcal{S}) - K), & \text{else} \end{cases}$$

No reuse

$$K = \begin{cases} |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \text{seq} \\ \dfrac{|\mathsf{L}i|_{\mathsf{L}i}}{M_{\mathsf{L}i}(\mathcal{S})} \cdot |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \text{ran} \end{cases}$$

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Repetitive Memory Access Pattern: Cache Misses

$$M_{\mathsf{L}i}((\mathcal{S}, r, d)) =$$

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"LRU" reuse

$$K = \begin{cases} |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \mathsf{seq} \\ \dfrac{|\mathsf{L}i|_{\mathsf{L}i}}{M_{\mathsf{L}i}(\mathcal{S})} \cdot |\mathsf{L}i|_{\mathsf{L}i}, & \text{if } o = \mathsf{ran} \end{cases}$$

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Compound Memory Access Pattern: Sequential Execution

- $\mathcal{P}_1$, $\mathcal{P}_2$ memory access pattern

$$M_{\mathsf{L}i}(\mathcal{P}_1 ; \mathcal{P}_2) = M_{\mathsf{L}i}(\mathcal{P}_1) + M_{\mathsf{L}i}(\mathcal{P}_2)$$

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Compound Memory Access Pattern: Concurrent Execution

- $\mathcal{Q}_1$, $\mathcal{Q}_2$ memory access pattern that do not revisit/re-use cache lines

- $\mathcal{R}_1$, $\mathcal{R}_2$ memory access pattern that do revisit/re-use cache lines

$$M_{\mathsf{L}i}(\mathcal{Q}_1 || \mathcal{Q}_2) = M_{\mathsf{L}i}(\mathcal{Q}_1) + M_{\mathsf{L}i}(\mathcal{Q}_2)$$

$$M_{\mathsf{L}i}(\mathcal{Q}_1 || \mathcal{R}_1) = M_{\mathsf{L}i}(\mathcal{Q}_1) + M_{\mathsf{L}i}(\mathcal{R}_1) = M_{\mathsf{L}i}(\mathcal{R}_1 || \mathcal{Q}_1)$$

$$M_{\mathsf{L}i}(\mathcal{R}_1 || \mathcal{R}_2) = M_{\mathsf{L}i/2}(\mathcal{R}_1) + M_{\mathsf{L}i/2}(\mathcal{R}_2)$$

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Compound Memory Access Pattern: Concurrent Execution

- $\mathcal{Q}_1$, $\mathcal{Q}_2$ memory access pattern that do not revisit/re-use cache lines

- $\mathcal{R}_1$, $\mathcal{R}_2$ memory access pattern that do revisit/re-use cache lines

$$M_{\mathsf{L}i}(\mathcal{Q}_1 || \mathcal{Q}_2) = M_{\mathsf{L}i}(\mathcal{Q}_1) + M_{\mathsf{L}i}(\mathcal{Q}_2)$$

$$M_{\mathsf{L}i}(\mathcal{Q}_1 || \mathcal{R}_1) = M_{\mathsf{L}i}(\mathcal{Q}_1) + M_{\mathsf{L}i}(\mathcal{R}_1) = M_{\mathsf{L}i}(\mathcal{R}_1 || \mathcal{Q}_1)$$

$$M_{\mathsf{L}i}(\mathcal{R}_1 || \mathcal{R}_2) = M_{\mathsf{L}i/2}(\mathcal{R}_1) + M_{\mathsf{L}i/2}(\mathcal{R}_2)$$

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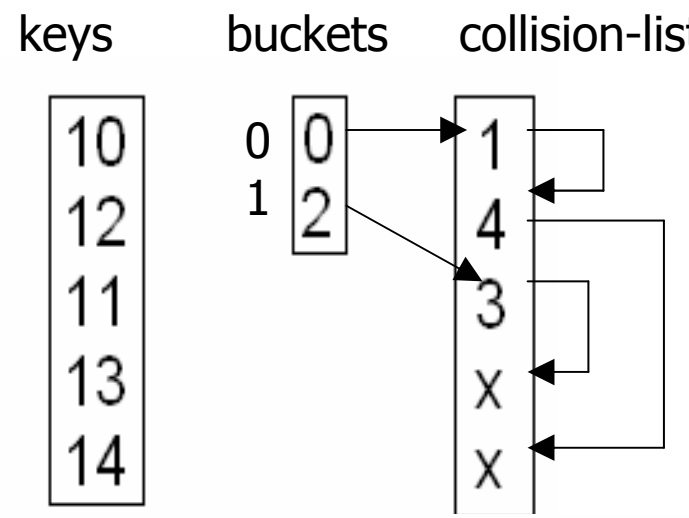
Compound Memory Access Pattern: Hash Join $B := L \bowtie R$

$$\begin{aligned}\texttt{Build} = (\ & (R \quad\quad\quad\quad, \texttt{seq}, R.\texttt{BATcount}, R.\texttt{BUNsize}, R.\texttt{BUNsize}) \\ \| & (R \rightarrow \texttt{link}, \texttt{seq}, R.\texttt{BATcount}, 4 \quad\quad, 4 \quad\quad) \\ \| & (R \rightarrow \texttt{mask}, \texttt{ran}, R.\texttt{BATcount}, 4 \quad\quad, 4 \quad\quad))\end{aligned}$$



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$$\begin{aligned}\texttt{Lookup} = (\ & (R \rightarrow \texttt{mask}, \textsf{ran}, L.\texttt{BATcount}, 4 \quad\quad, 4 \quad\quad) \\ & \|(R \rightarrow \texttt{link}, \textsf{ran}, B.\texttt{BATcount}, 4 \quad\quad, 4 \quad\quad) \\ & \|(R \quad\quad\quad\quad, \textsf{ran}, B.\texttt{BATcount}, R.\texttt{BUNsize}, R.\texttt{BUNsize}))\end{aligned}$$

$$\begin{aligned}\texttt{HashJoin} = (\texttt{Build}; (\ & (L \quad\quad\quad\quad, \textsf{seq}, L.\texttt{BATcount}, L.\texttt{BUNsize}, L.\texttt{BUNsize}) \\ & \| \texttt{Lookup} \\ & \|(B \quad\quad\quad\quad, \textsf{seq}, B.\texttt{BATcount}, B.\texttt{BUNsize}, B.\texttt{BUNsize})))\end{aligned}$$

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Compound Memory Access Pattern: Hash Join $B := L \bowtie R$

Writes are non-blocking ⇒ Latency = 0

$$\begin{aligned}\texttt{Build} = (\ & (R \quad\quad\quad\quad, \textsf{seq}, R.\texttt{BATcount}, R.\texttt{BUNsize}, R.\texttt{BUNsize}) \\ & \|(R \rightarrow \texttt{link}, \textsf{seq}, R.\texttt{BATcount}, 4 \quad\quad, 4 \quad\quad) \\ & \|(R \rightarrow \texttt{mask}, \textsf{ran}, R.\texttt{BATcount}, 4 \quad\quad, 4 \quad\quad))\end{aligned}$$

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algorithm	pattern description		name
$W \leftarrow select(U)$	$\mathsf{s\_tra}(U) \odot \mathsf{s\_tra}(W)$		
$W \leftarrow nested\_loop\_join(U,V)$	$\mathsf{s\_tra}(U) \odot \mathsf{rs\_tra}(U.n, \mathtt{uni}, V) \odot \mathsf{s\_tra}(W)$	$=:$	$\mathsf{nl\_join}(U,V,W)$
$H \leftarrow hash\_build(V)$	$\mathsf{s\_tra}(V) \odot \mathsf{r\_tra}(H)$	$=:$	$\mathsf{build\_hash}(V,H)$
$W \leftarrow hash\_probe(U,H)$	$\mathsf{s\_tra}(U) \odot \mathsf{r\_acc}(U.n, H) \odot \mathsf{s\_tra}(W)$	$=:$	$\mathsf{probe\_hash}(U,H,W)$
$W \leftarrow hash\_join(U,V)$	$\mathsf{build\_hash}(V,H) \oplus \mathsf{probe\_hash}(U,H,W)$	$=:$	$\mathsf{h\_join}(U,V,W)$
$\{U_j\}\|_{j=1}^{m} \leftarrow cluster(U,m)$	$\mathsf{s\_tra}(U) \odot \mathsf{nest}(\{U_j\}\|_{j=1}^{m}, m, \mathsf{s\_tra}(U_j), \mathtt{ran})$	$=:$	$\mathsf{part}(U,m,\{U_j\}\|_{j=1}^{m})$
$W \leftarrow part\_nl\_join(U,V,m)$	$\mathsf{part}(U,m,\{U_j\}\|_{j=1}^{m}) \oplus \mathsf{part}(V,m,\{V_j\}\|_{j=1}^{m})$ $\oplus \mathsf{nl\_join}(U_1,V_1,W_1) \oplus \ldots \oplus \mathsf{nl\_join}(U_m,V_m,W_m)$		
$W \leftarrow part\_h\_join(U,V,m)$	$\mathsf{part}(U,m,\{U_j\}\|_{j=1}^{m}) \oplus \mathsf{part}(V,m,\{V_j\}\|_{j=1}^{m})$ $\oplus \mathsf{h\_join}(U_1,V_1,W_1) \oplus \ldots \oplus \mathsf{h\_join}(U_m,V_m,W_m)$		

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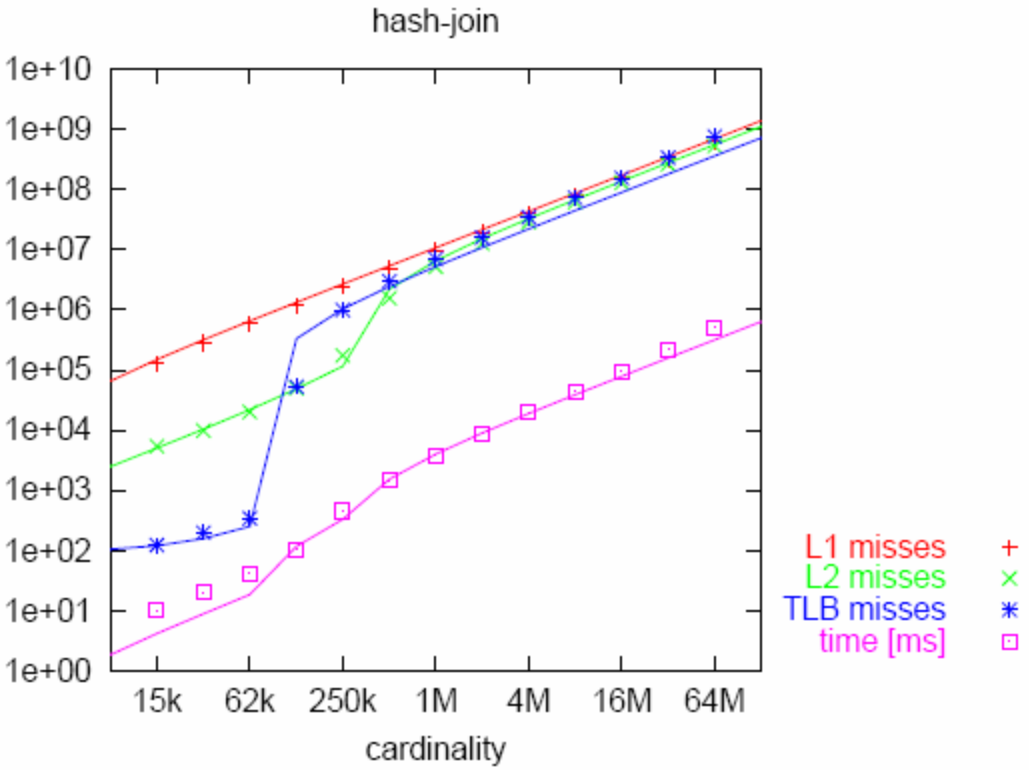
Compound Memory Access Pattern: Hash Join



MonetDB

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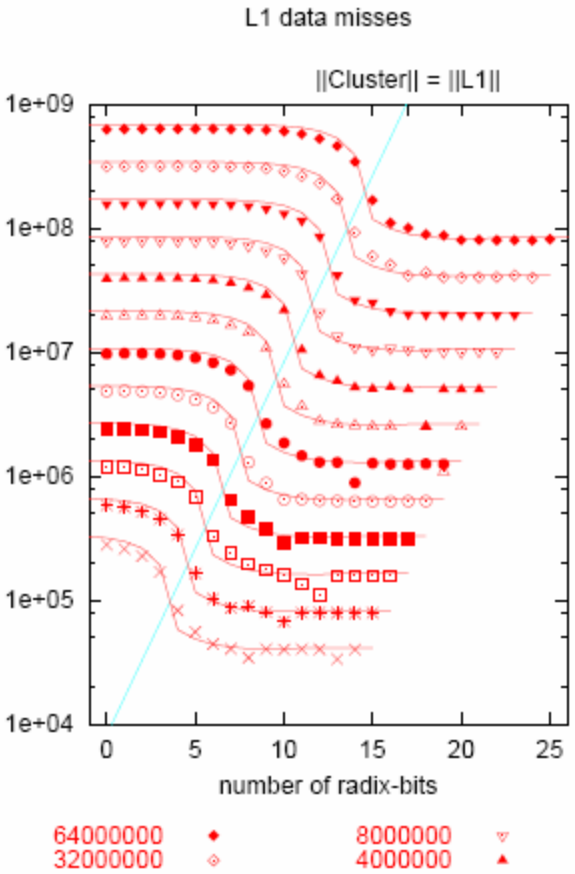
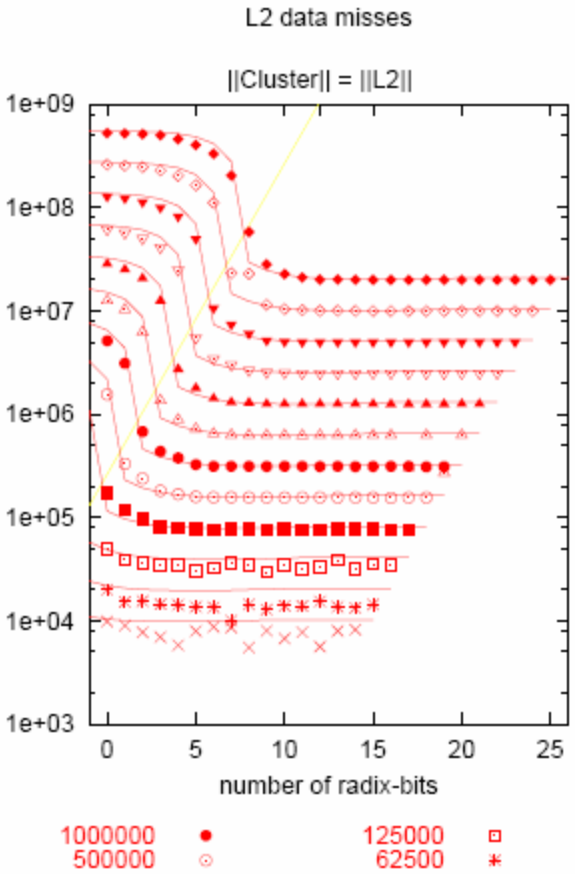
Compound Memory Access Pattern: Partitioned Hash Join





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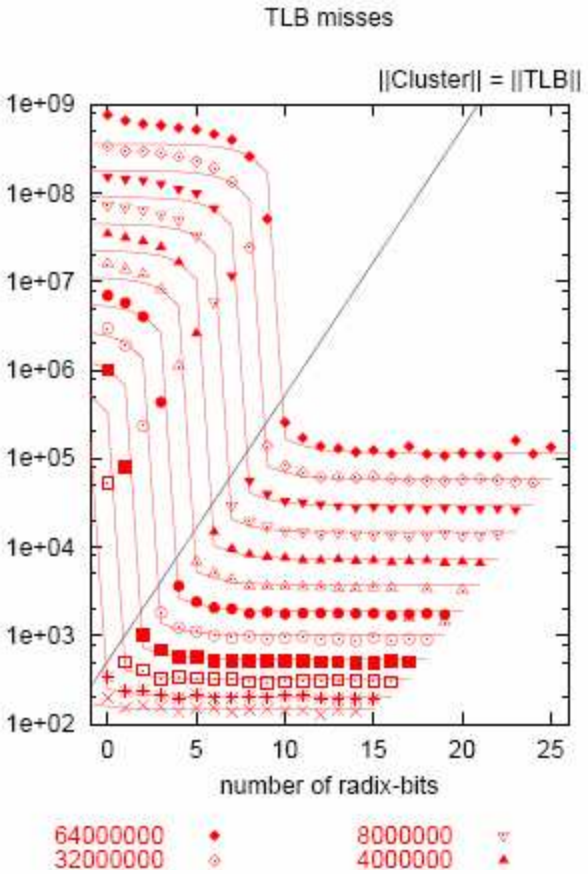
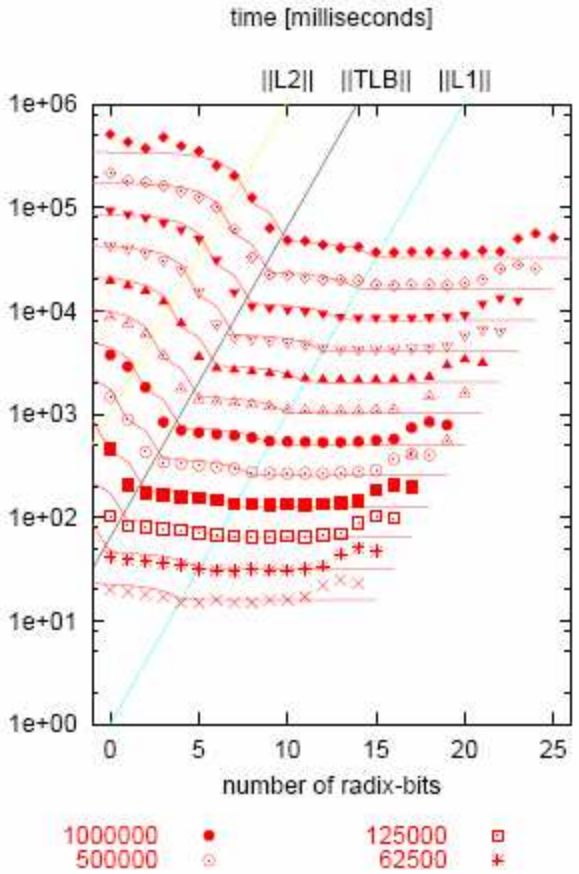
Compound Memory Access Pattern: Partitioned Hash Join





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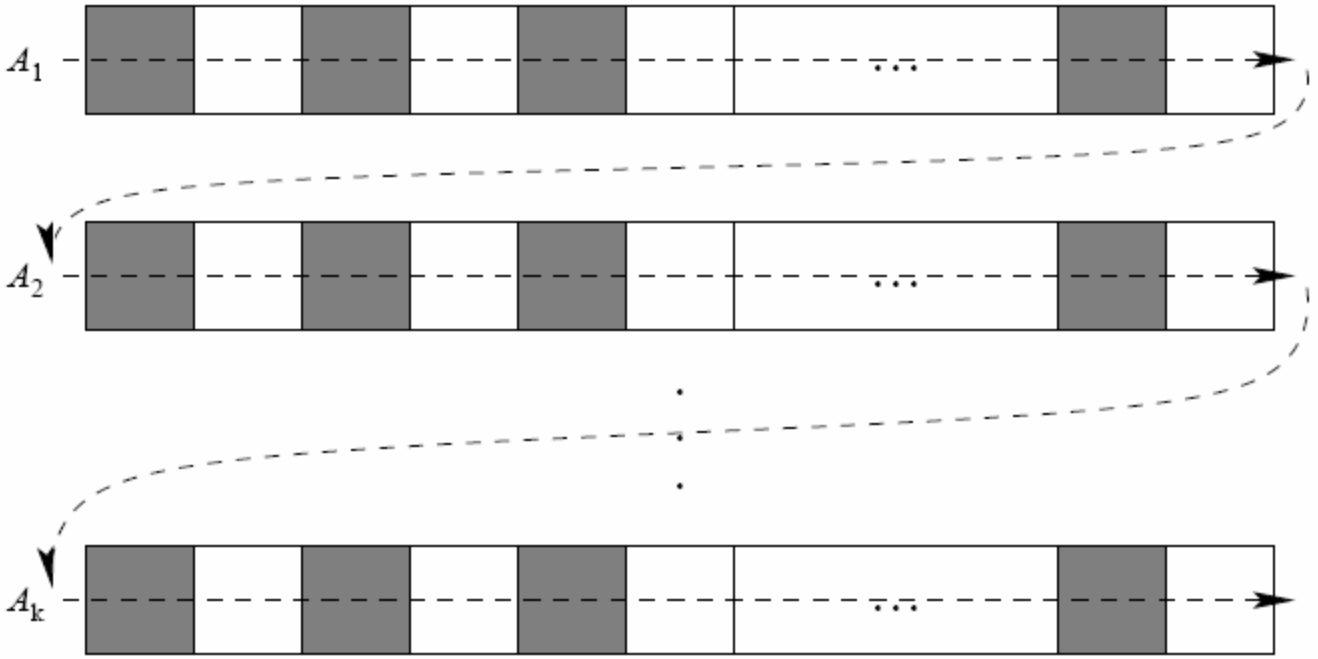
Nested Memory Access Pattern: $nMAP = (<S_1, \ldots, S_k>, Y, O, D)$



$Y = \text{con(catenated)}, \quad O = \text{seq}, \quad D = \text{uni}$

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Nested Memory Access Pattern: Cache Misses

$$M_{\mathsf{L}i}\left((<\mathcal{S}_1,\ldots,\mathcal{S}_k>,Y,O,D)\right) =$$

$$\begin{cases} k \cdot M_{\mathsf{L}i}\left(\mathcal{S}_j\right), & \text{if } Y = \mathsf{con} \wedge s-b < LS_{\mathsf{L}i} \\ M_{\mathsf{L}i}\left(\mathcal{S}(O)\right), & \text{if } Y = \mathsf{int} \wedge o = \mathsf{ran} \wedge n = 1 \\ M_{\mathsf{L}i}\left(\mathcal{S}(o)\right) + X & \text{if } Y = \mathsf{int} \wedge o = \mathsf{seq} \wedge \\ & \quad s-b < LS_{\mathsf{L}i} \wedge k \cdot \left\lceil \frac{b}{LS_{\mathsf{L}i}} \right\rceil > |\mathsf{L}i|_{\mathsf{L}i} \\ M_{\mathsf{L}i}\left(\mathcal{S}(o)\right), & \text{else} \end{cases}$$

$$\mathcal{S}(x) = \left(\bigcup_{j=1}^{k} A_j, x, k \cdot n, s, b\right)$$

$$X = (n-1)\cdot(k-h)\ , \qquad h = \begin{cases} 0, & \text{if } O = \mathsf{seq} \wedge D = \mathsf{uni} \\ |\mathsf{TLB}|, & \text{if } O = \mathsf{seq} \wedge D = \mathsf{bi} \\ \frac{|\mathsf{TLB}|}{k} \cdot |\mathsf{TLB}|, & \text{if } O = \mathsf{ran} \end{cases}$$

"Generic Database Cost Models for Hierarchical Memory Systems", Manegold, Boncz, Kersten, VLDB'02

Compound Memory Access Pattern: Radix Cluster

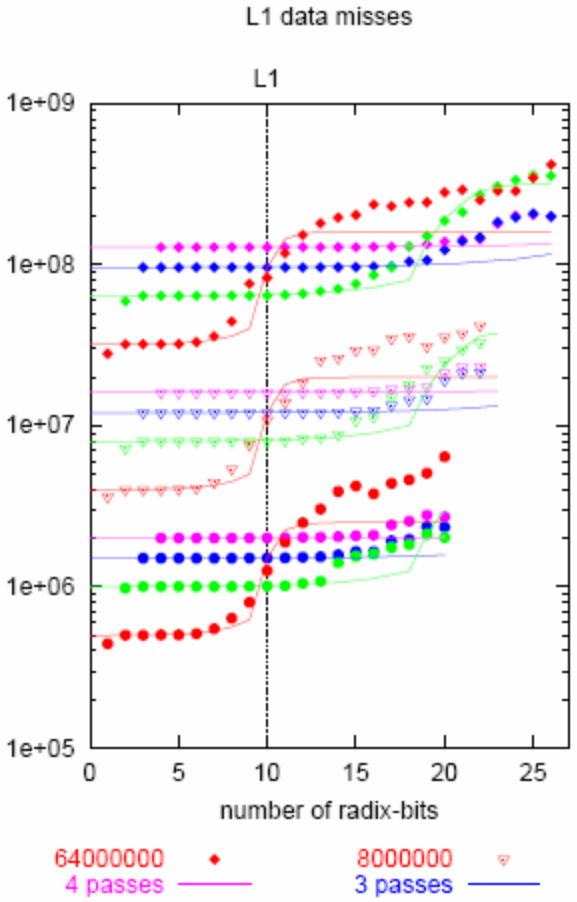
$$\mathcal{S}_j = (S_j, \mathsf{seq}, S_j.\mathtt{BATcount}, S_j.\mathtt{BUNsize}, S_j.\mathtt{BUNsize})$$

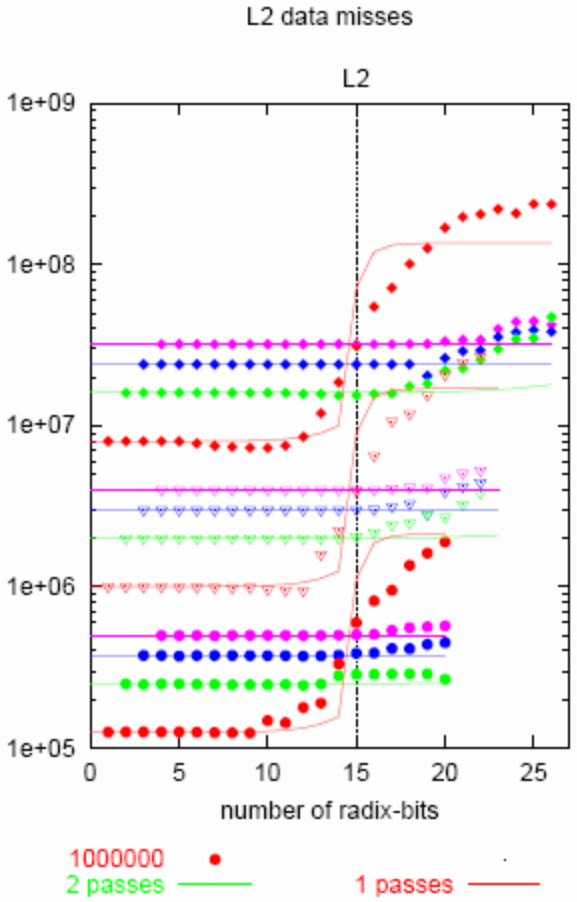
$$\mathtt{RadixCluster} = (\ (R, \mathsf{seq}, R.\mathtt{BATcount}, R.\mathtt{BUNsize}, R.\mathtt{BUNsize}) \\ \| (< \mathcal{S}_1, \ldots, \mathcal{S}_k >, \mathsf{int}, \mathsf{ran}) \ )$$

MonetDB

"Generic Database Cost Models for Hierarchical Memory Systems", Manegold, Boncz, Kersten, VLDB'02

Compound Memory Access Pattern: Radix Cluster

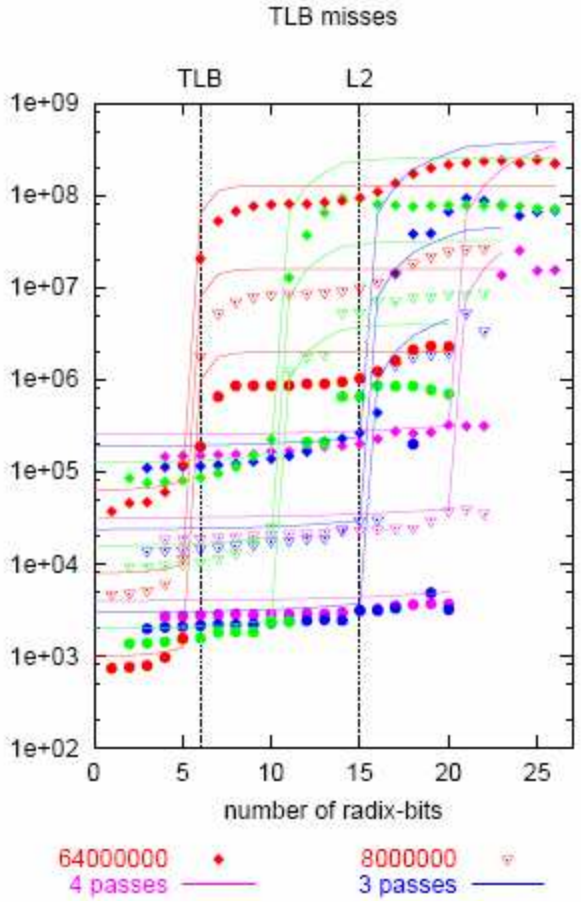


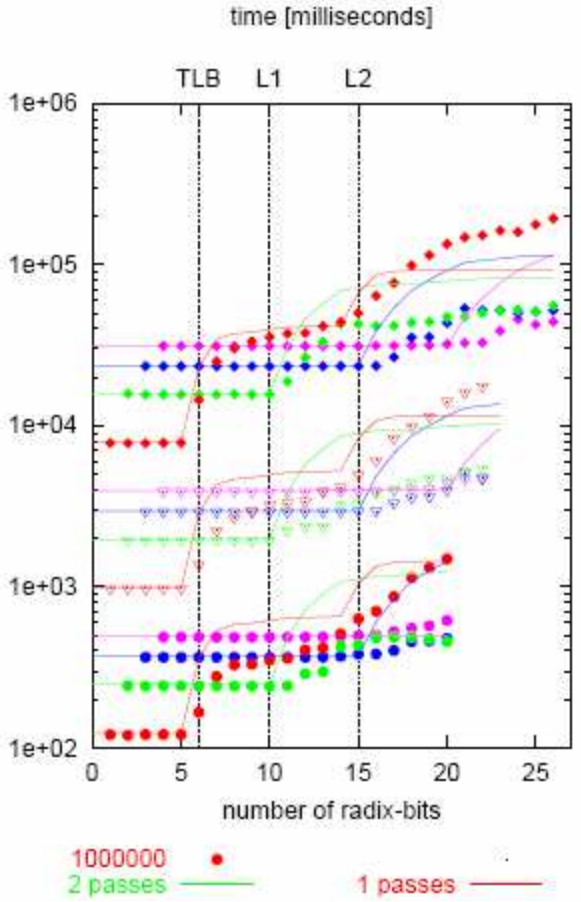


MonetDB

"Generic Database Cost Models for Hierarchical Memory Systems", Manegold, Boncz, Kersten, VLDB'02

Compound Memory Access Pattern: Radix Cluster





"Generic Database Cost Models for Hierarchical Memory Systems", Manegold, Boncz, Kersten, VLDB'02

Conclusions

- generic, architecture-independent main-memory cost-modeling is possible (at least in Monet)
- cache impact is crucial for intra-operator costs
- use operator cost functions to always pick *the best* algorithm
  $\Rightarrow$ optimization on higher levels can use simpler cost models