Evaluation of Pointer Swizzling Techniques for DBMS Buffer Management

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Section 1

Pointer Swizzling as in “In-Memory Performance for Big Data”

Five Layer Architecture of a DBMS ([HR83] [HR85])

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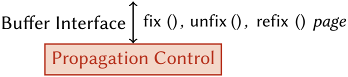
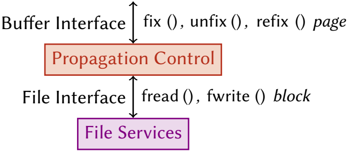


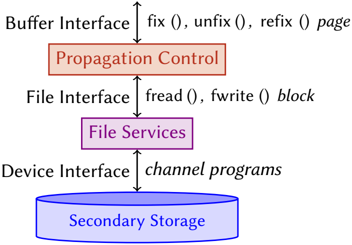
- Mainly consists of the *DBMS buffer bool*
- Pages can be fixed and unfixed by upper layers
- Offers copies of persistent data in main memory

Five Layer Architecture of a DBMS ([HR83] [HR85])



- Also called *file management*
- Offers dynamically growing files and blocks of different length
- Manages file addresses, block borders and unused space
- Abstracts from the different characteristics of *secondary storage devices*

Five Layer Architecture of a DBMS ([HR83] [HR85])


Buffer Interface fix (), unfix (), refix () *page*

Propagation Control

File Interface fread (), fwrite () *block*

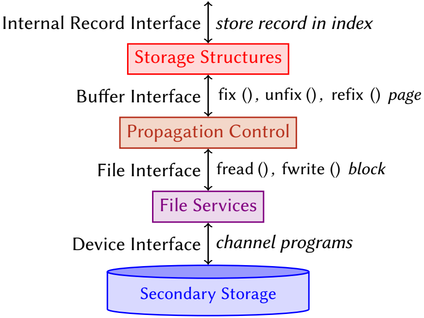
File Services

Device Interface *channel programs*

Secondary Storage

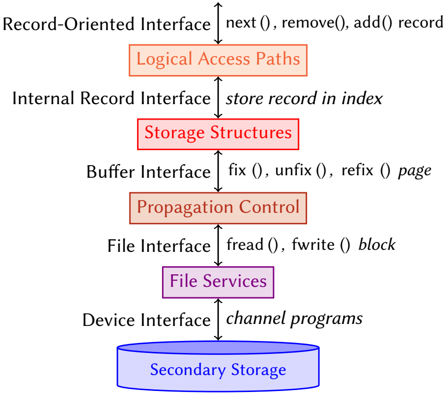
- HDDs, SSDs etc.
- Interface is partially device specific

Five Layer Architecture of a DBMS ([HR83] [HR85])



- Also called *record and access path management*
- B^* trees, hash indexes etc.
- Allows to navigate through those storage structures
- Maps records to pages
- Commonly offers variable-sized fields, large fields and references between records

Five Layer Architecture of a DBMS ([HR83] [HR85])



- Also called *navigational access layer*
- Offers an iterator interface over the resulting records
- Allows sorting and selection but no more complex operations
- Introduces data types
- Uppermost interface of *navigational* or *hierarchical databases*

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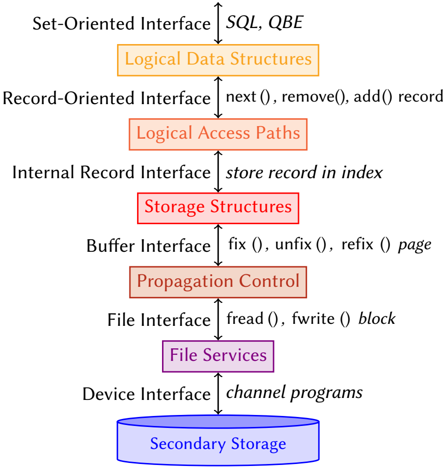


Set-Oriented Interface *SQL, QBE*

Logical Data Structures

Record-Oriented Interface next (), remove(), add() record

Logical Access Paths

Internal Record Interface *store record in index*

Storage Structures

Buffer Interface fix (), unfix (), refix () *page*

Propagation Control

File Interface fread (), fwrite () *block*

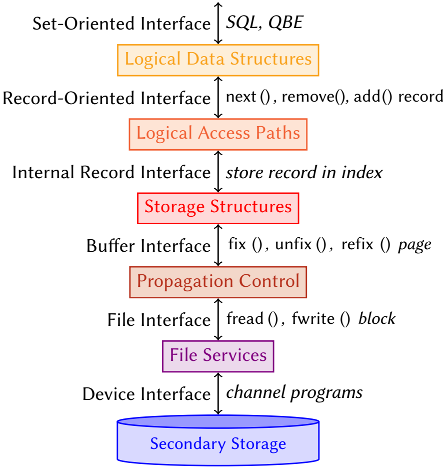
File Services

Device Interface *channel programs*

Secondary Storage

- Also called *non-procedural access layer*
- Offers complex descriptive query languages like *SQL*, *QBE* or *XQuery*
- Maps external identifiers of e.g. relations, views and tuples to internal identifiers using the *metadata management*

Five Layer Architecture of a DBMS ([HR83] [HR85])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Propagation Control

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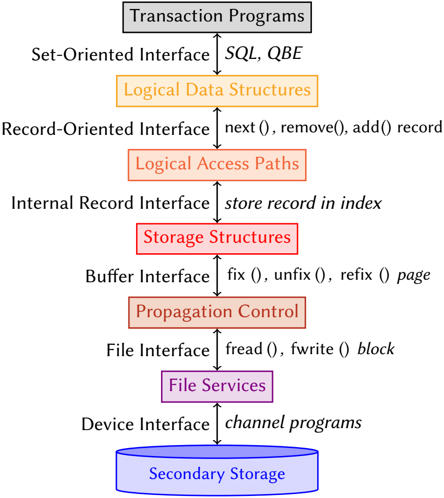
File Services

Device Interface *channel programs*

Secondary Storage

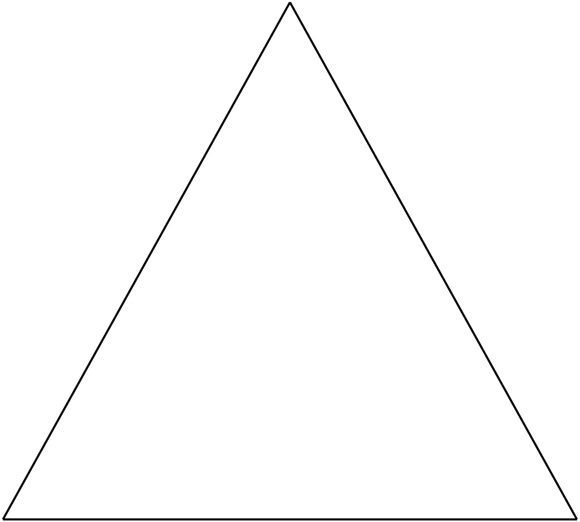
- Offers complex set operations
- Offers *data integrity*, *access control* and *transaction management*
- Most interesting target for the *query optimizer*

Five Layer Architecture of a DBMS ([HR83] [HR85])



- Application programs uses the service of the DBMS to store persistent data

Motivation for the Usage of a Buffer Pool (1)



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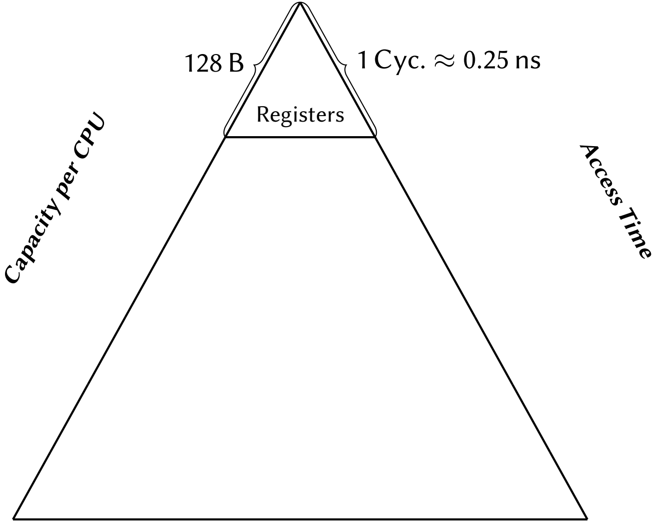

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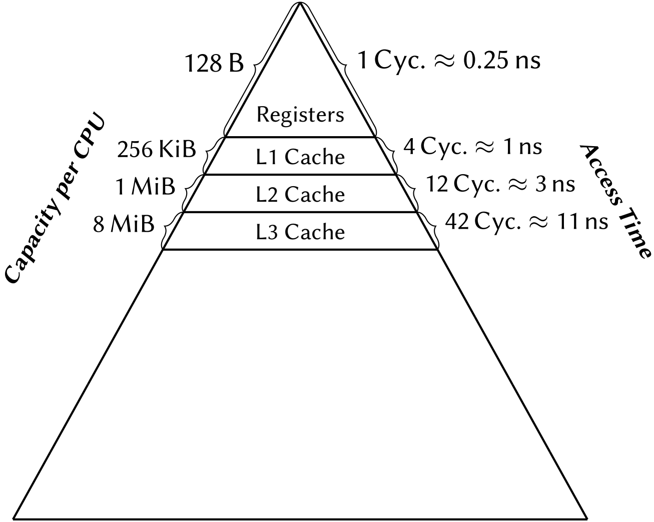

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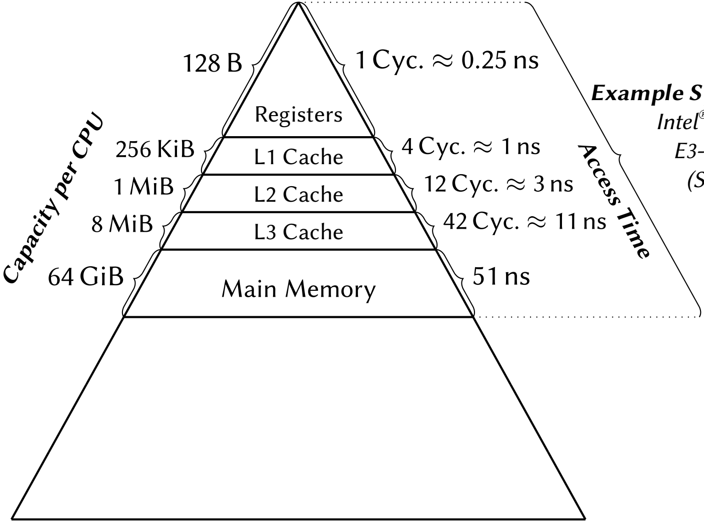

Example System:
Intel® Xeon®
E3-1280 v5
(Skylake)
[Pav]

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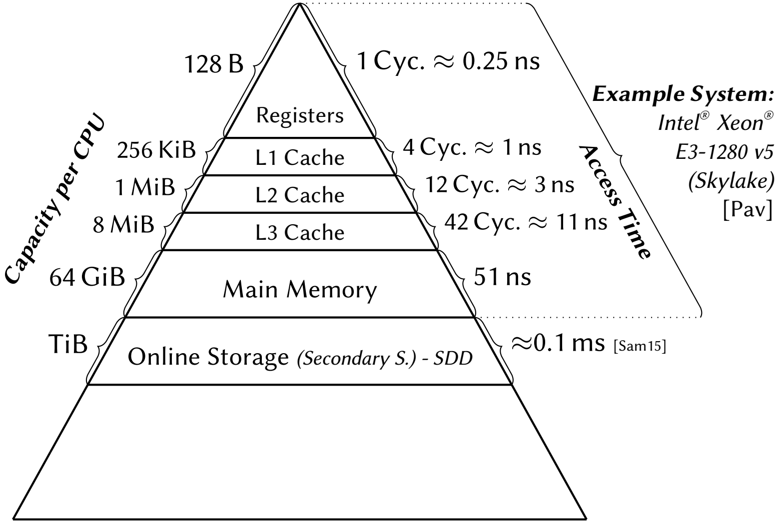

Capacity per CPU

128 B Registers 1 Cyc. ≈ 0.25 ns

256 KiB L1 Cache 4 Cyc. ≈ 1 ns

1 MiB L2 Cache 12 Cyc. ≈ 3 ns

8 MiB L3 Cache 42 Cyc. ≈ 11 ns

64 GiB Main Memory 51 ns

TiB Online Storage *(Secondary S.) - SDD* ≈0.1 ms [Sam15]

Access Time

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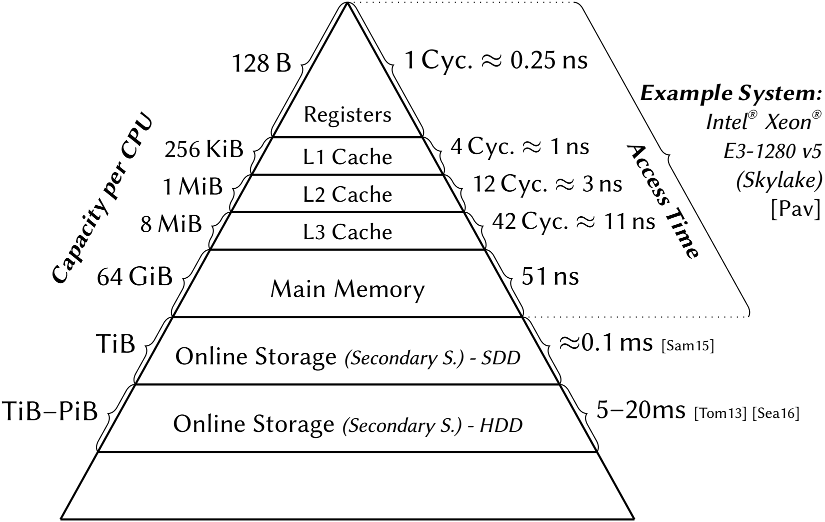

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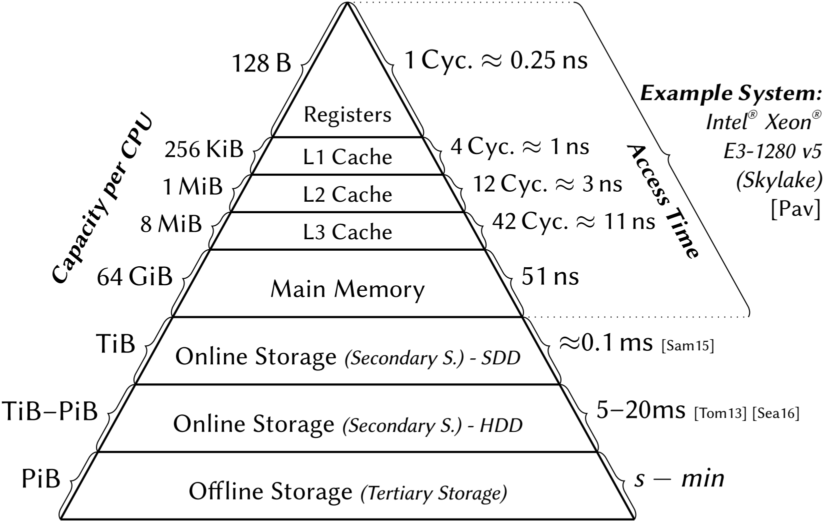

128 B	Registers	1 Cyc. ≈ 0.25 ns
256 KiB	L1 Cache	4 Cyc. ≈ 1 ns
1 MiB	L2 Cache	12 Cyc. ≈ 3 ns
8 MiB	L3 Cache	42 Cyc. ≈ 11 ns
64 GiB	Main Memory	51 ns
TiB	Online Storage *(Secondary S.) - SDD*	≈0.1 ms [Sam15]
TiB–PiB	Online Storage *(Secondary S.) - HDD*	5–20ms [Tom13] [Sea16]
PiB	Offline Storage *(Tertiary Storage)*	*s – min*

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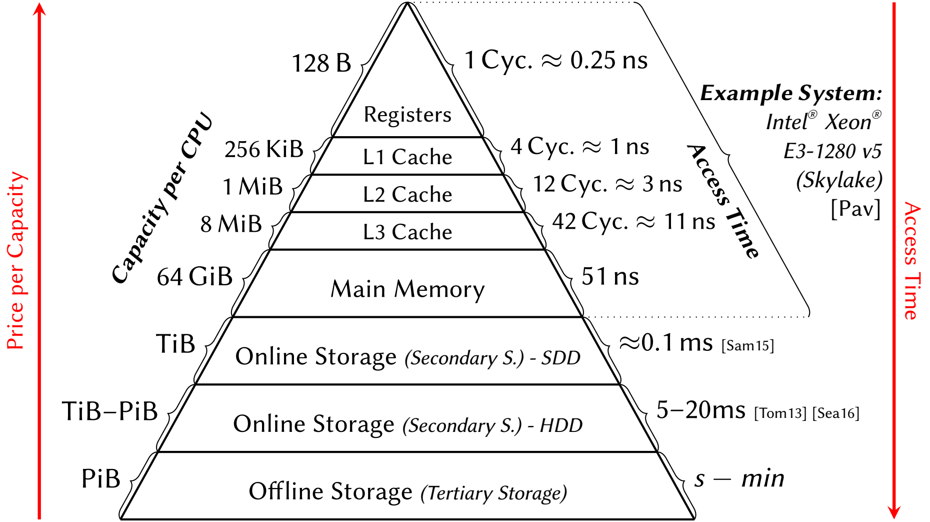

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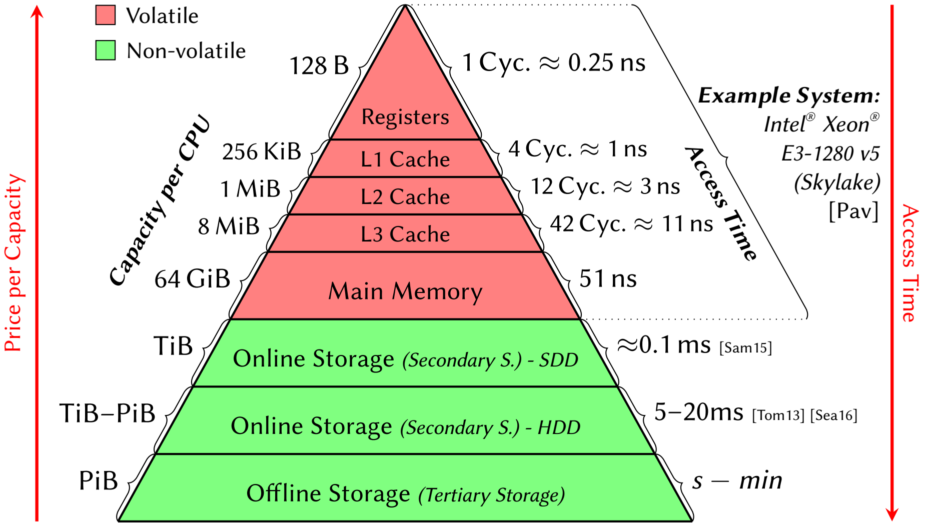

Motivation for the Usage of a Buffer Pool (2)

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Requirements of Memory for a DBMS

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- **Low latency**

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- **Low latency:** Main memory

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- **High capacity**

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- **Low latency:** Main memory
- **High capacity:** Secondary Storage

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- **High capacity:** Secondary Storage
- **Non-volatility**

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Requirements of Memory for a DBMS

- **Low latency:** Main memory
- **High capacity:** Secondary Storage
- **Non-volatility:** Secondary Storage
- **Byte-addressable**

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Requirements of Memory for a DBMS

- **Low latency:** Main memory
- **High capacity:** Secondary Storage
- **Non-volatility:** Secondary Storage
- **Byte-addressable:** Main memory

$\Longrightarrow$ **Caching:** Persistently store the database on *secondary storage* and cache a subset of it in *main memory*.

Subsection 1

Some Tasks of the DBMS Buffer Management

Memory Allocation in the Buffer Pool ([HR01])

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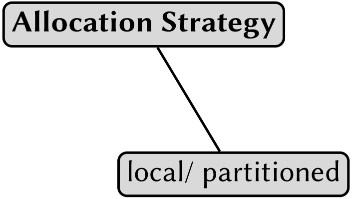
Allocation Strategy

Memory Allocation in the Buffer Pool ([HR01])



Allocation Strategy

local/ partitioned

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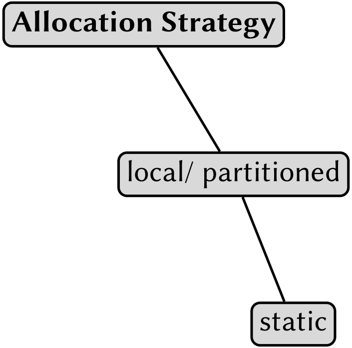

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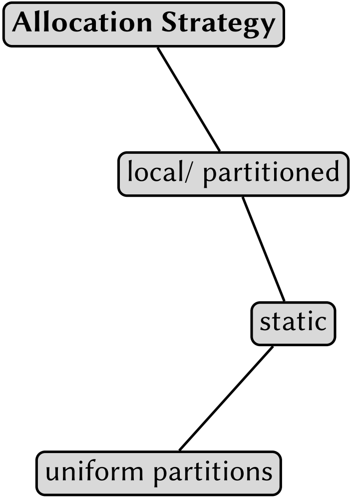

Allocation Strategy

local/ partitioned

static

uniform partitions

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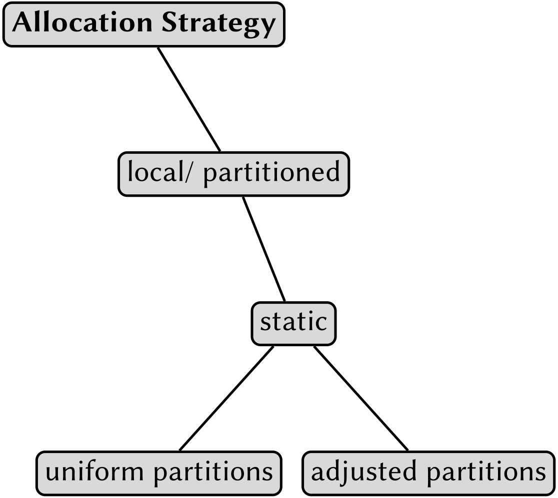

Allocation Strategy

local/ partitioned

static

uniform partitions

adjusted partitions

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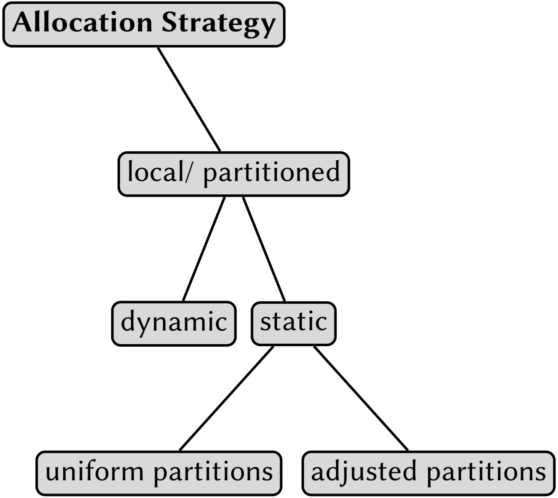

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local/ partitioned

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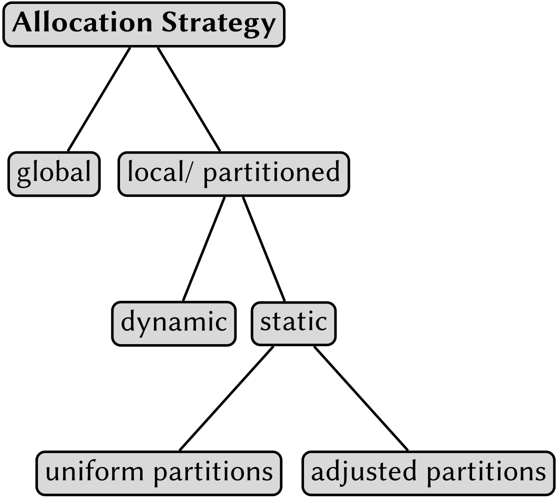

Allocation Strategy

global

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Concurrency Control

Concurrency Control

- **Pages** get accessed concurrently

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  - Latching for the pages

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- **Auxiliary data** gets accessed concurrently
  - Latching for the auxiliary data structures
  - … or the usage of special concurrent implementations of the data structures

Subsection 2

Locate Pages in the Buffer Pool without Pointer Swizzling

Overview of Search Strategies ([HR01])

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Search Strategy

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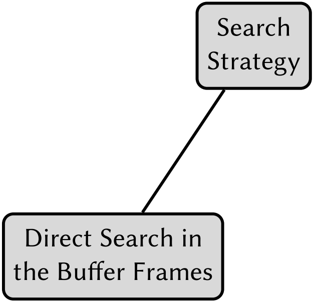
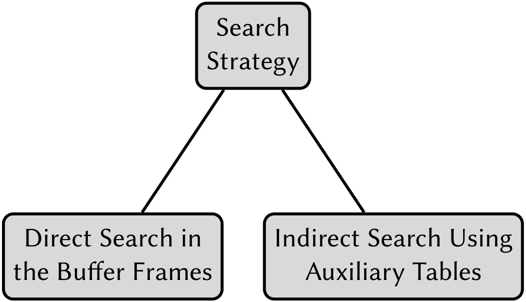

Search Strategy

Direct Search in the Buffer Frames

Overview of Search Strategies ([HR01])



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Indirect Search Using Auxiliary Tables

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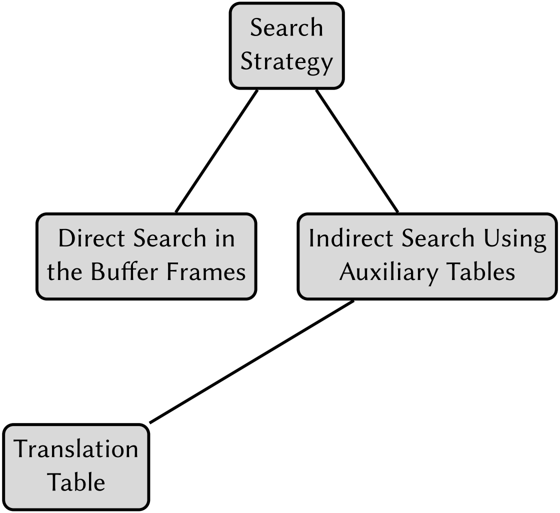

Search Strategy

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Translation Table

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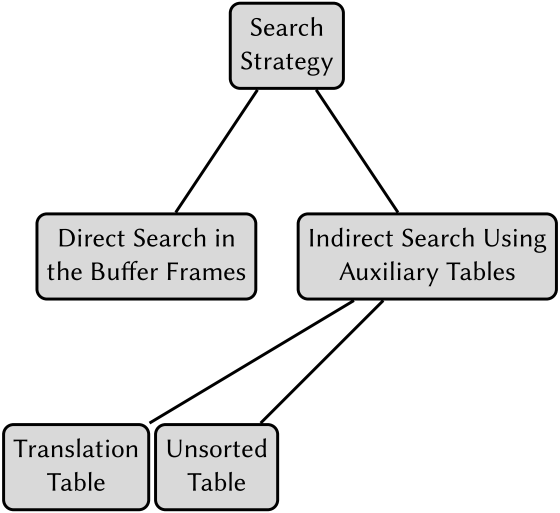

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Indirect Search Using Auxiliary Tables

Translation Table

Unsorted Table

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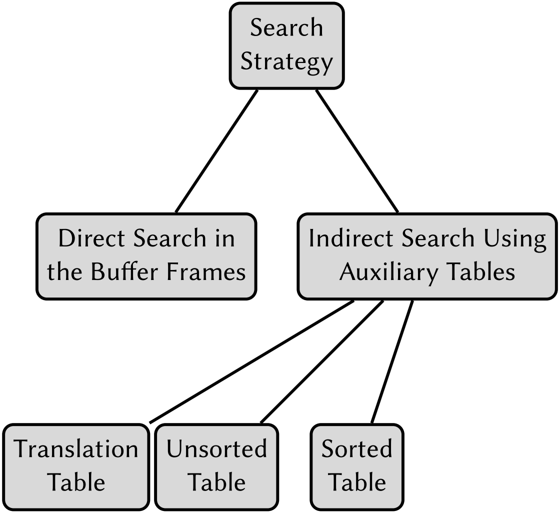

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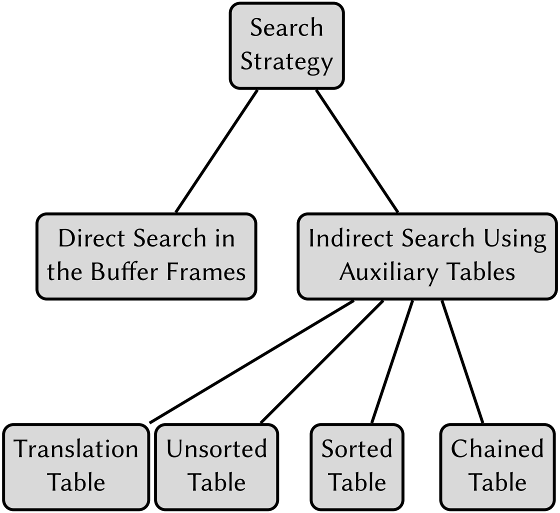
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Indirect Search Using Auxiliary Tables

Translation Table

Unsorted Table

Sorted Table

Chained Table

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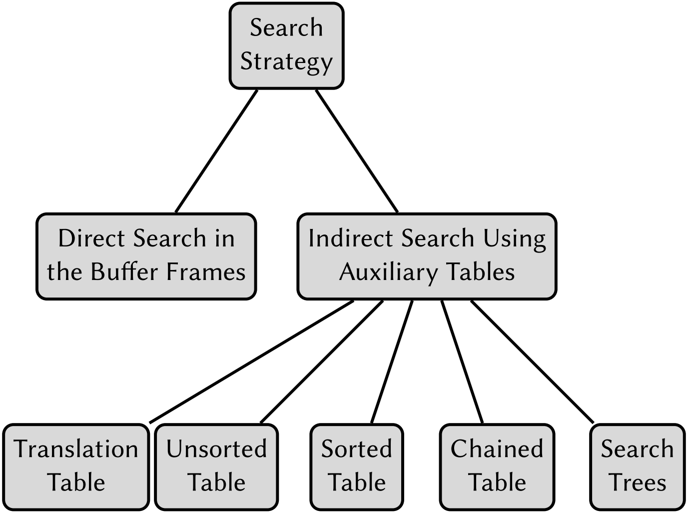

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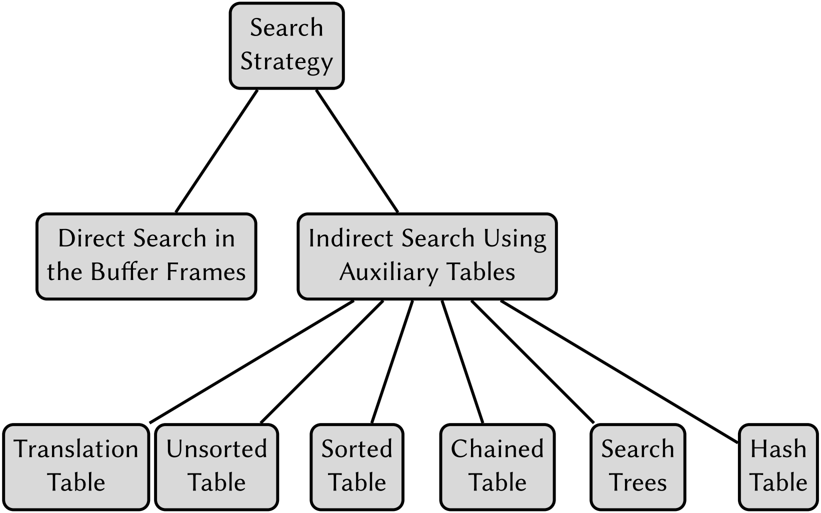

Search Strategy

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Indirect Search Using Auxiliary Tables

Translation Table

Unsorted Table

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Hash Table

Direct Search in the Buffer Frames & Unsorted Table

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Direct Search in the Buffer Frames & Unsorted Table

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Unsorted Table

- Auxiliary data structure of size $S_{\text{pace}} \in \mathcal{O}\left(n\right)$

0	1	2	3	4	5	6	7	8
7785	**6977**	**4347**	**3380**	**5610**	**6376**	**4877**	**3332**	**3354**

Figure: An unsorted table used to map buffer frames to page IDs.

Direct Search in the Buffer Frames & Unsorted Table

Direct Search in the Buffer Frames

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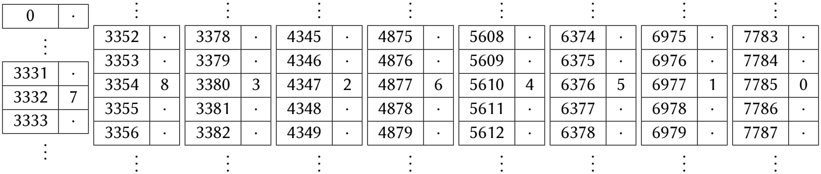
Translation Table

Translation Table

- Auxiliary data structure with one entry per page in the database $\Longrightarrow\ S_{\text{pace}} \in \mathcal{O}\left(p\right)$



0	·
⋮	
3331	·
3332	7
3333	·
⋮	

⋮		⋮		⋮		⋮		⋮		⋮		⋮		⋮	
3352	·	3378	·	4345	·	4875	·	5608	·	6374	·	6975	·	7783	·
3353	·	3379	·	4346	·	4876	·	5609	·	6375	·	6976	·	7784	·
3354	8	3380	3	4347	2	4877	6	5610	4	6376	5	6977	1	7785	0
3355	·	3381	·	4348	·	4878	·	5611	·	6377	·	6978	·	7786	·
3356	·	3382	·	4349	·	4879	·	5612	·	6378	·	6979	·	7787	·
⋮		⋮		⋮		⋮		⋮		⋮		⋮		⋮	

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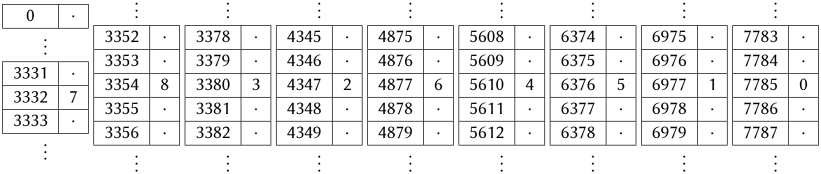
Translation Table

- Auxiliary data structure with one entry per page in the database
  $\Longrightarrow\ S_{\text{pace}} \in \mathcal{O}(p)$
- $T^{\text{search}} \in \mathcal{O}(1)$, $T^{\text{insert}} \in \mathcal{O}(1)$



0	·
⋮	
3331	·
3332	7
3333	·
⋮	

⋮		⋮		⋮		⋮		⋮		⋮		⋮		⋮	
3352	·	3378	·	4345	·	4875	·	5608	·	6374	·	6975	·	7783	·
3353	·	3379	·	4346	·	4876	·	5609	·	6375	·	6976	·	7784	·
3354	8	3380	3	4347	2	4877	6	5610	4	6376	5	6977	1	7785	0
3355	·	3381	·	4348	·	4878	·	5611	·	6377	·	6978	·	7786	·
3356	·	3382	·	4349	·	4879	·	5612	·	6378	·	6979	·	7787	·
⋮		⋮		⋮		⋮		⋮		⋮		⋮		⋮	

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- Auxiliary data structure using a table sorted by page ID only containing cached pages

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→ **7**	→ **8**	→ **3**	→ **2**	→ **6**	→ **4**	→ **5**	→ **1**	→ **0**

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Sorted Table

- Auxiliary data structure using a table sorted by page ID only containing cached pages
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}\left(\log_2 n\right)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}\left(n \log_2 n\right)$

3332	**3354**	**3380**	**4347**	**4877**	**5610**	**6376**	**6977**	**7785**
→ **7**	→ **8**	→ **3**	→ **2**	→ **6**	→ **4**	→ **5**	→ **1**	→ **0**

Figure: A sorted table used to map page IDs to buffer frames.

Sorted & Chained Table

Sorted Table

- Auxiliary data structure using a table sorted by page ID only containing cached pages
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}\left(\log_2 n\right)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}\left(n \log_2 n\right)$

3332	**3354**	**3380**	**4347**	**4877**	**5610**	**6376**	**6977**	**7785**
→ **7**	→ **8**	→ **3**	→ **2**	→ **6**	→ **4**	→ **5**	→ **1**	→ **0**

Figure: A sorted table used to map page IDs to buffer frames.

Chained Table

Sorted & Chained Table

Sorted Table

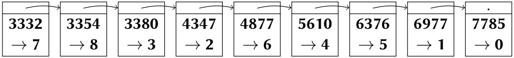
- Auxiliary data structure using a table sorted by page ID only containing cached pages
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}\left(\log_2 n\right)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}\left(n \log_2 n\right)$

3332 → **7**	**3354** → **8**	**3380** → **3**	**4347** → **2**	**4877** → **6**	**5610** → **4**	**6376** → **5**	**6977** → **1**	**7785** → **0**

Figure: A sorted table used to map page IDs to buffer frames.

Chained Table

- Auxiliary data structure using a linked list sorted by page ID only containing cached pages



3332 → **7**	**3354** → **8**	**3380** → **3**	**4347** → **2**	**4877** → **6**	**5610** → **4**	**6376** → **5**	**6977** → **1**	**7785** → **0**

Figure: A chained table used to map page IDs to buffer frames.

Sorted & Chained Table

Sorted Table

- Auxiliary data structure using a table sorted by page ID only containing cached pages
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}\left(\log_2 n\right)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}\left(n \log_2 n\right)$

3332	**3354**	**3380**	**4347**	**4877**	**5610**	**6376**	**6977**	**7785**
→ **7**	→ **8**	→ **3**	→ **2**	→ **6**	→ **4**	→ **5**	→ **1**	→ **0**

Figure: A sorted table used to map page IDs to buffer frames.

Chained Table

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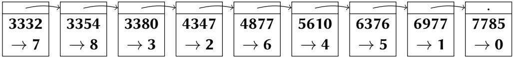
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}\left(\log_2 n\right)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}\left(\log_2 n\right)$



3332	**3354**	**3380**	**4347**	**4877**	**5610**	**6376**	**6977**	**7785**
→ **7**	→ **8**	→ **3**	→ **2**	→ **6**	→ **4**	→ **5**	→ **1**	→ **0**

Figure: A chained table used to map page IDs to buffer frames.

Sorted & Chained Table

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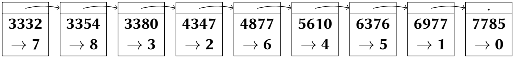
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}\left(\log_2 n\right)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}\left(n \log_2 n\right)$

3332 **→ 7**	**3354** **→ 8**	**3380** **→ 3**	**4347** **→ 2**	**4877** **→ 6**	**5610** **→ 4**	**6376** **→ 5**	**6977** **→ 1**	**7785** **→ 0**

Figure: A sorted table used to map page IDs to buffer frames.

Chained Table

- Auxiliary data structure using a linked list sorted by page ID only containing cached pages
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}\left(\log_2 n\right)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}\left(\log_2 n\right)$
- Binary search requires more links!



3332 **→ 7**	**3354** **→ 8**	**3380** **→ 3**	**4347** **→ 2**	**4877** **→ 6**	**5610** **→ 4**	**6376** **→ 5**	**6977** **→ 1**	**7785** **→ 0**

Figure: A chained table used to map page IDs to buffer frames.

Search Trees

Search Trees

- Auxiliary data structure is similar to the one of the chained table

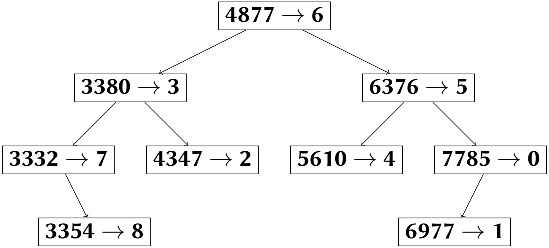


Figure: A balanced search tree used to map page IDs to buffer frames.

Search Trees

- Auxiliary data structure is similar to the one of the chained table
- Many different data structures like AVL-trees, red–black trees or splay trees can be used

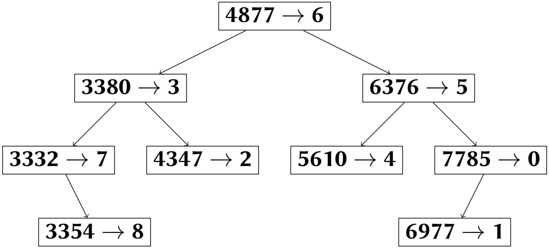
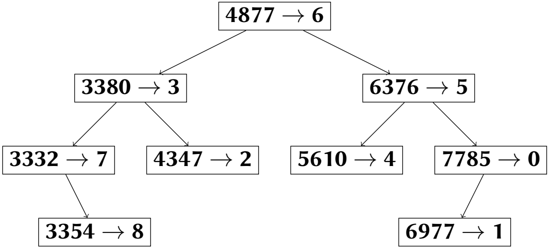


Figure: A balanced search tree used to map page IDs to buffer frames.

Search Trees

- Auxiliary data structure is similar to the one of the chained table
- Many different data structures like AVL-trees, red–black trees or splay trees can be used
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}(\log n)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}(\log n)$



4877 → 6

3380 → 3

6376 → 5

3332 → 7

4347 → 2

5610 → 4

7785 → 0

3354 → 8

6977 → 1

Figure: A balanced search tree used to map page IDs to buffer frames.

Search Trees

- Auxiliary data structure is similar to the one of the chained table
- Many different data structures like AVL-trees, red–black trees or splay trees can be used
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}(\log n)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}(\log n)$
- The worst case costs and the worst cases vary between the different search tree data structures

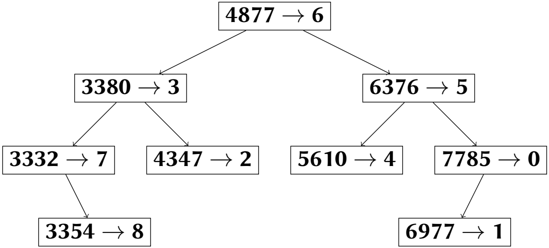
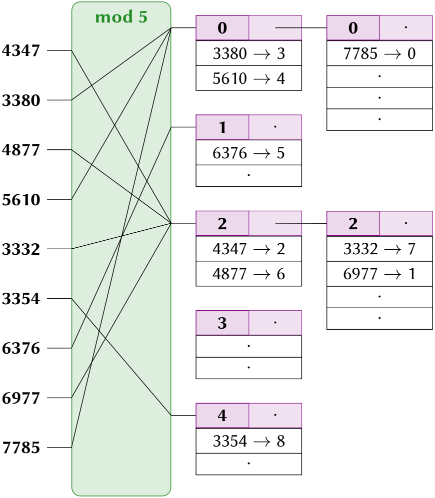


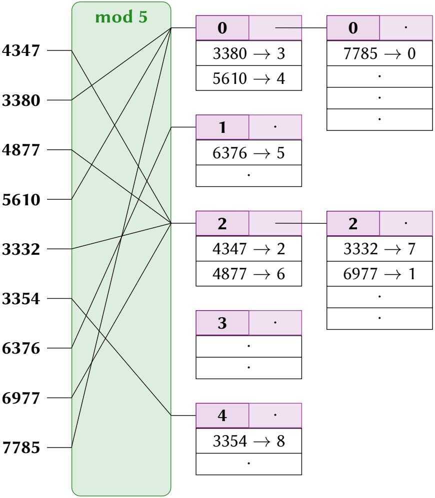
Figure: A balanced search tree used to map page IDs to buffer frames.

Hash Table

Hash Table

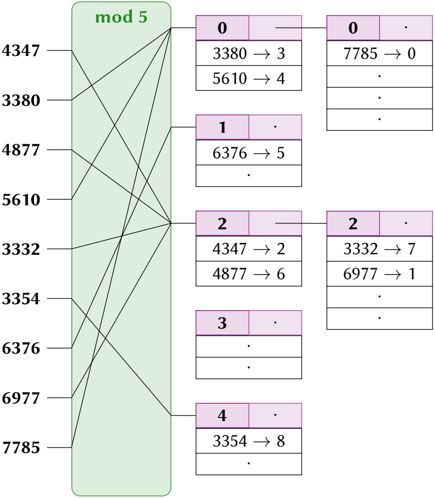

mod 5
4347
3380
4877
5610
3332
3354
6376
6977
7785
0
3380 → 3
5610 → 4
0
7785 → 0
1
6376 → 5
2
4347 → 2
4877 → 6
2
3332 → 7
6977 → 1
3
4
3354 → 8

Hash Table



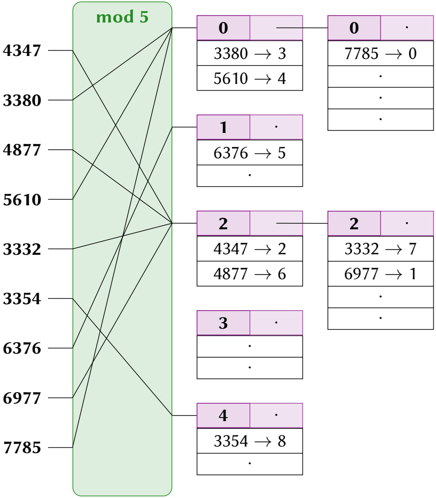
- Each page ID is mapped to a hash bucket using a hash function

Hash Table



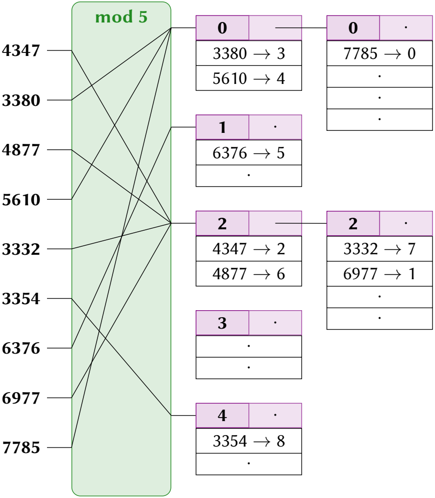
- Each page ID is mapped to a hash bucket using a hash function
- Only the page IDs of buffered pages are in the hash table

Hash Table



- Each page ID is mapped to a hash bucket using a hash function
- Only the page IDs of buffered pages are in the hash table
- If a hash bucket is full, a chained bucket gets added

Hash Table



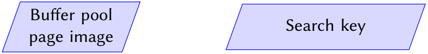
- Each page ID is mapped to a hash bucket using a hash function
- Only the page IDs of buffered pages are in the hash table
- If a hash bucket is full, a chained bucket gets added
- $T_{\text{avg}}^{\text{search}} \in \mathcal{O}(1)$, $T_{\text{avg}}^{\text{insert}} \in \mathcal{O}(1)$, $T_{\text{worst}}^{\text{search}} \in \mathcal{O}(n)$

Locate Pages in Buffer Pool with Hash Table ([Gra+14])

Locate Pages in Buffer Pool with Hash Table ([Gra+14])

Buffer pool page image

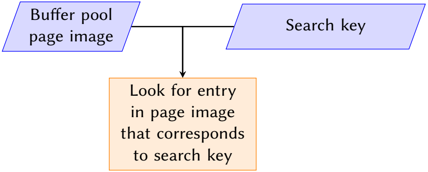
Locate Pages in Buffer Pool with Hash Table ([Gra+14])



Buffer pool page image

Search key

Locate Pages in Buffer Pool with Hash Table ([Gra+14])

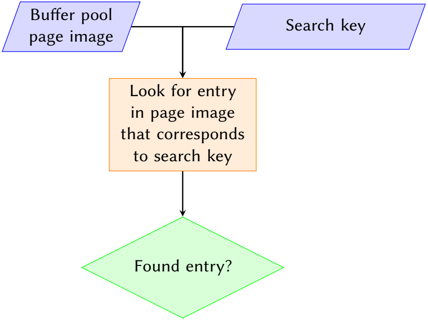


Buffer pool page image

Search key

Look for entry in page image that corresponds to search key

Locate Pages in Buffer Pool with Hash Table ([Gra+14])



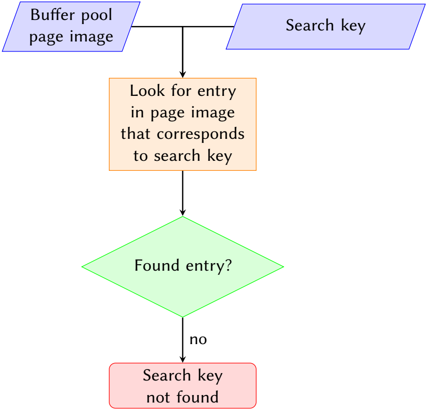
Buffer pool page image

Search key

Look for entry in page image that corresponds to search key

Found entry?

Locate Pages in Buffer Pool with Hash Table ([Gra+14])



Buffer pool page image

Search key

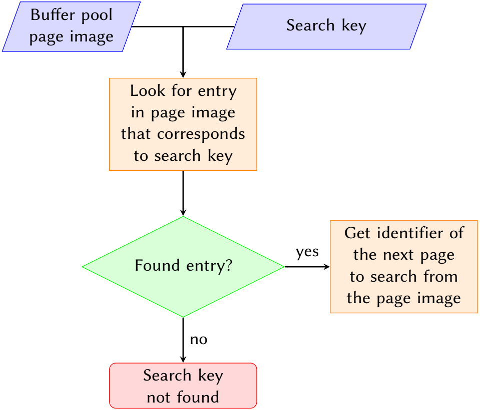
Look for entry in page image that corresponds to search key

Found entry?

no

Search key not found

Locate Pages in Buffer Pool with Hash Table ([Gra+14])



Buffer pool page image

Search key

Look for entry in page image that corresponds to search key

Found entry?

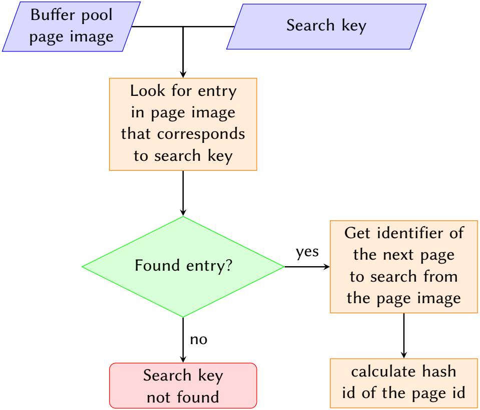
yes

Get identifier of the next page to search from the page image

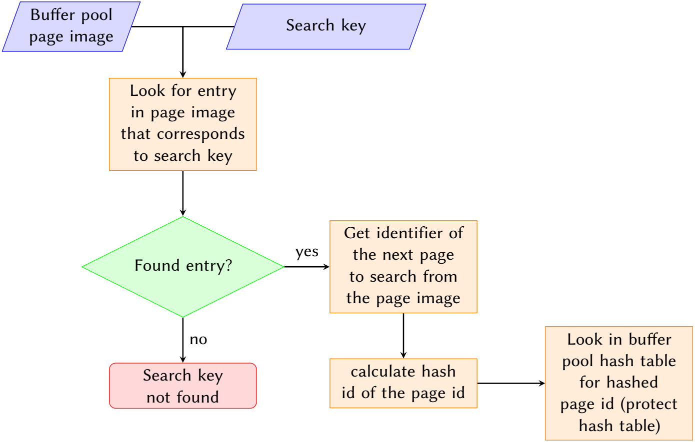
no

Search key not found

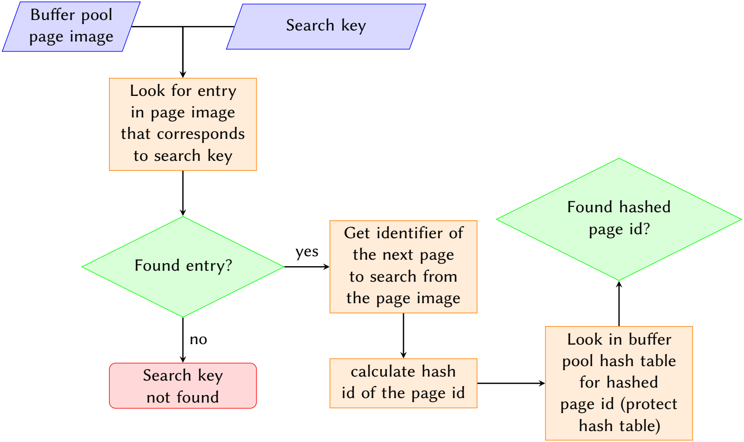
Locate Pages in Buffer Pool with Hash Table ([Gra+14])



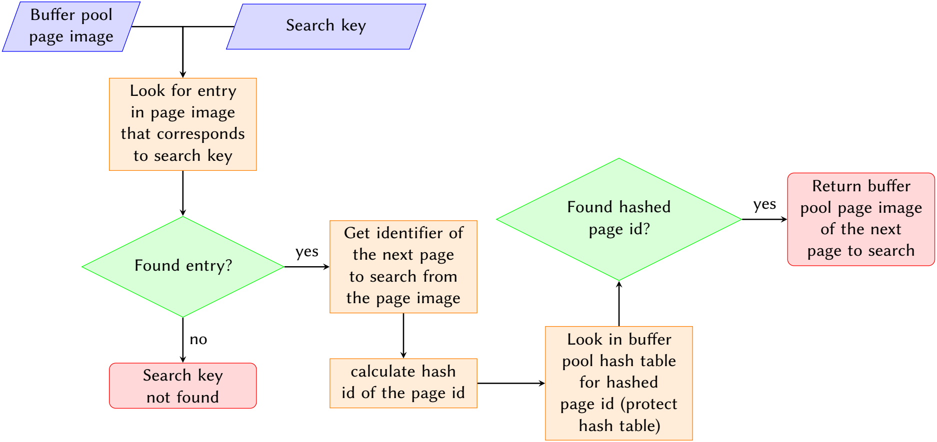
Locate Pages in Buffer Pool with Hash Table ([Gra+14])



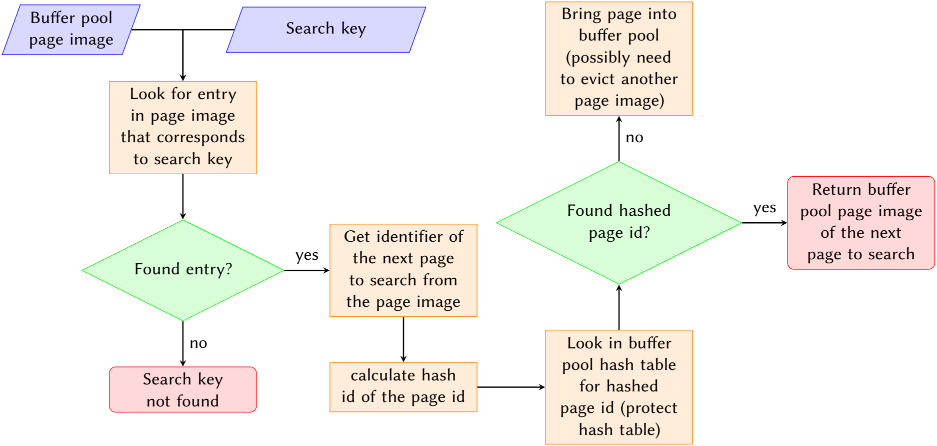
Locate Pages in Buffer Pool with Hash Table ([Gra+14])



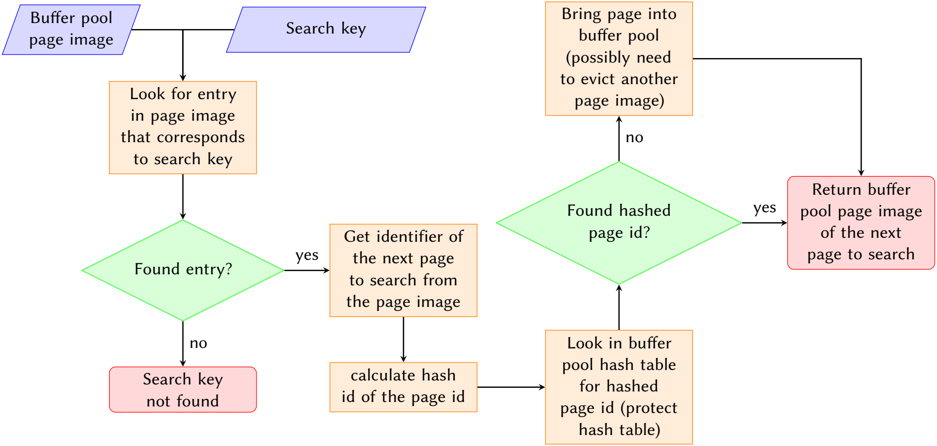
Locate Pages in Buffer Pool with Hash Table ([Gra+14])



Locate Pages in Buffer Pool with Hash Table ([Gra+14])



Locate Pages in Buffer Pool with Hash Table ([Gra+14])



Subsection 3

Locate Pages in the Buffer Pool with Pointer Swizzling

Pointer Swizzling

Definition

To swizzle a pointer means to transform the address of the persistent object referenced there to a more direct address of the transient object in a way that this transformation could be used during multiple indirections of this pointer ([Mos92]).

Classification of the Pointer Swizzling Approach following [WD95]

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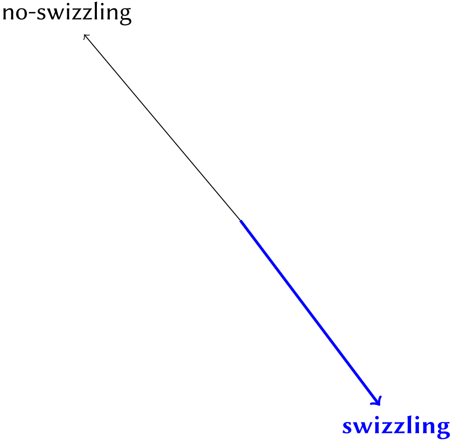
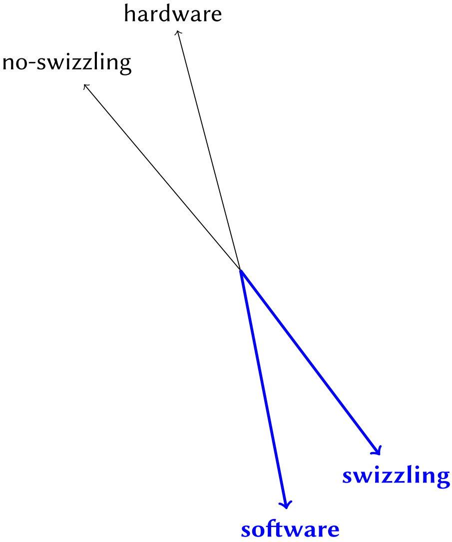
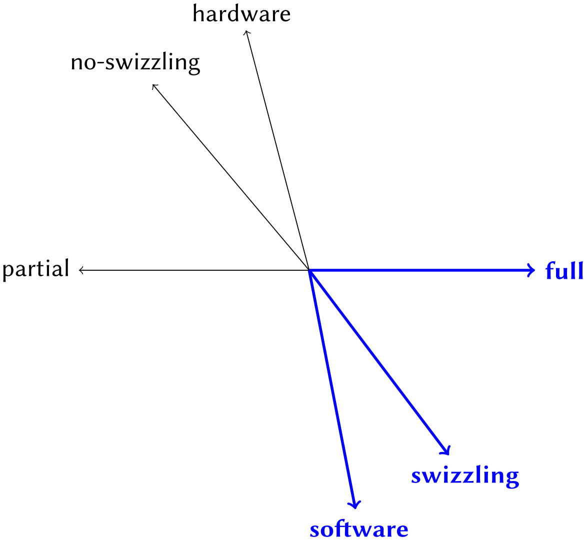


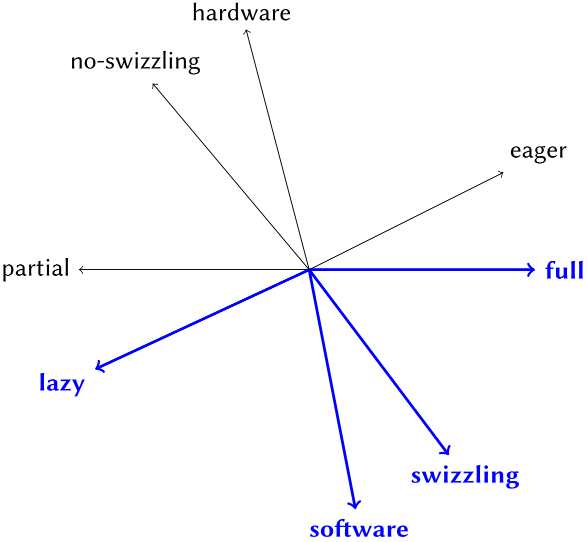
Classification of the Pointer Swizzling Approach following [WD95]



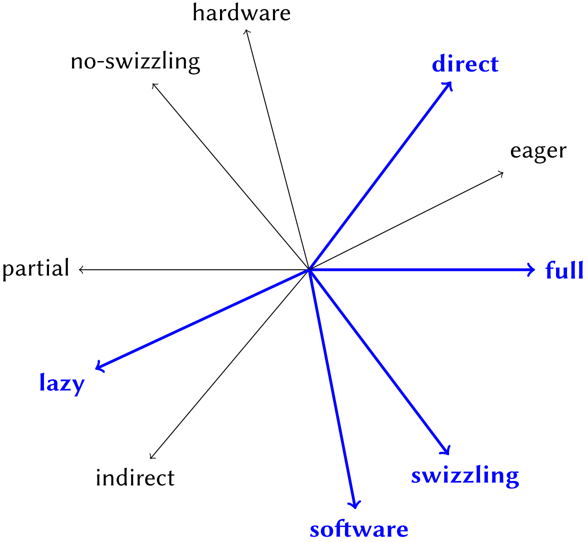
Classification of the Pointer Swizzling Approach following [WD95]



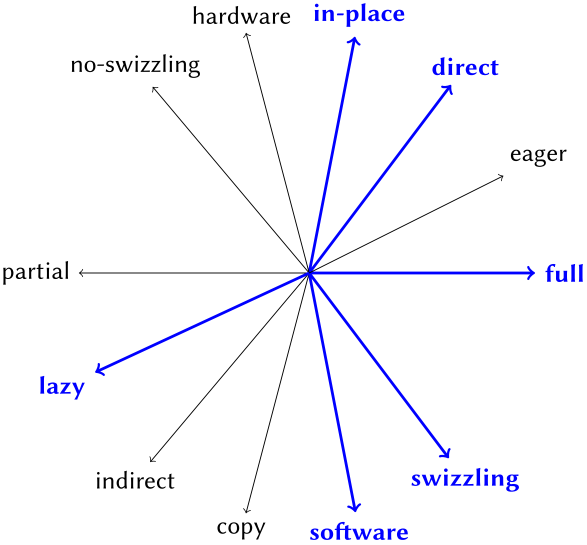
Classification of the Pointer Swizzling Approach following [WD95]



Classification of the Pointer Swizzling Approach following [WD95]



Classification of the Pointer Swizzling Approach following [WD95]



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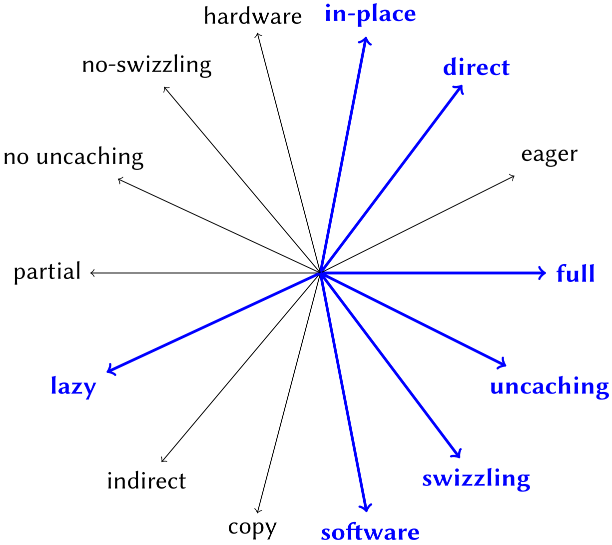


Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])

Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])

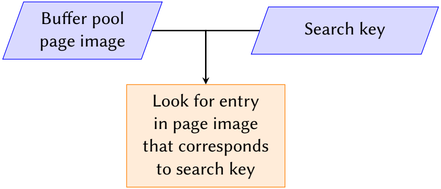
Buffer pool
page image

Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])

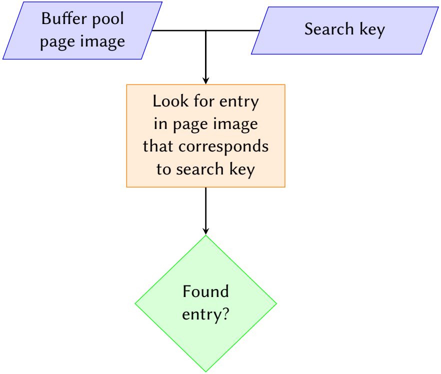

Buffer pool page image

Search key

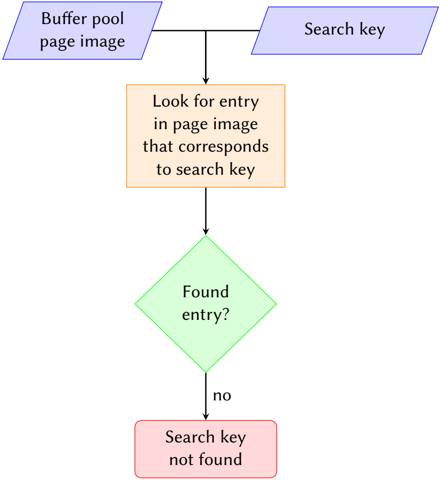
Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])



Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])



Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])



Buffer pool page image

Search key

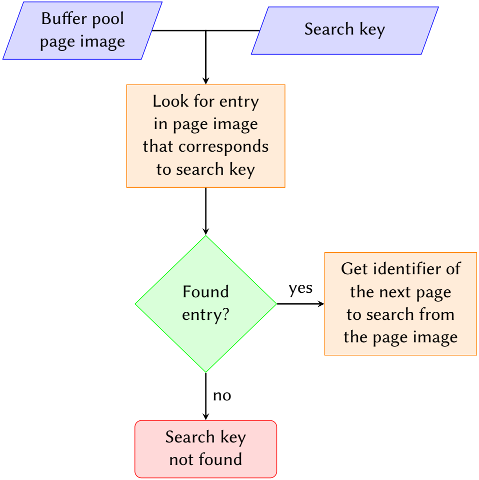
Look for entry in page image that corresponds to search key

Found entry?

no

Search key not found

Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])


Buffer pool page image

Search key

Look for entry in page image that corresponds to search key

Found entry?

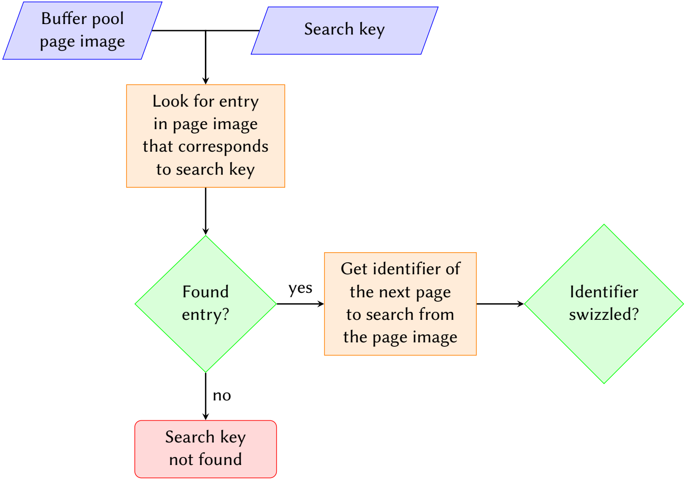
yes

Get identifier of the next page to search from the page image

no

Search key not found

Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])


Buffer pool page image

Search key

Look for entry in page image that corresponds to search key

Found entry?

yes

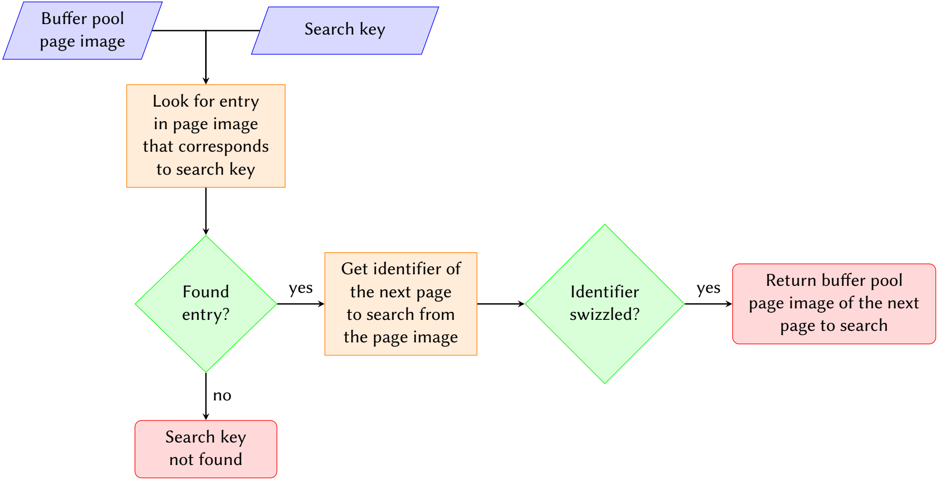
no

Get identifier of the next page to search from the page image

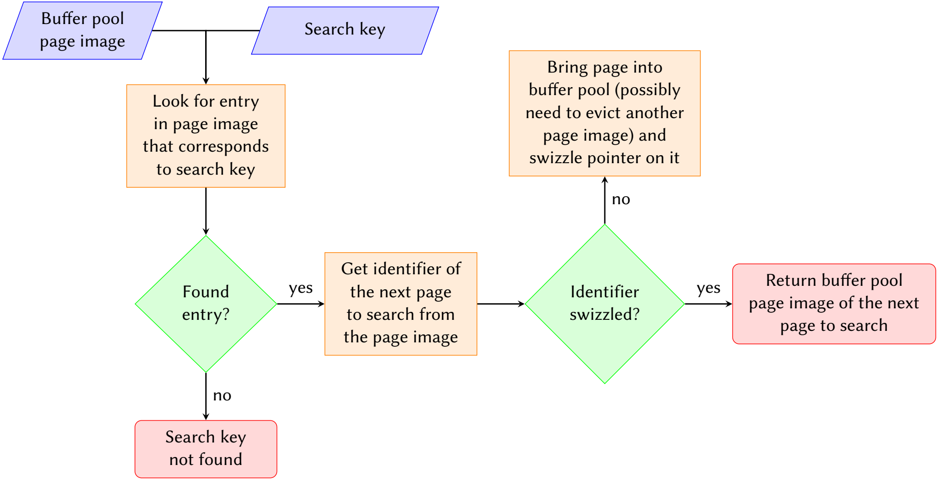
Identifier swizzled?

Search key not found

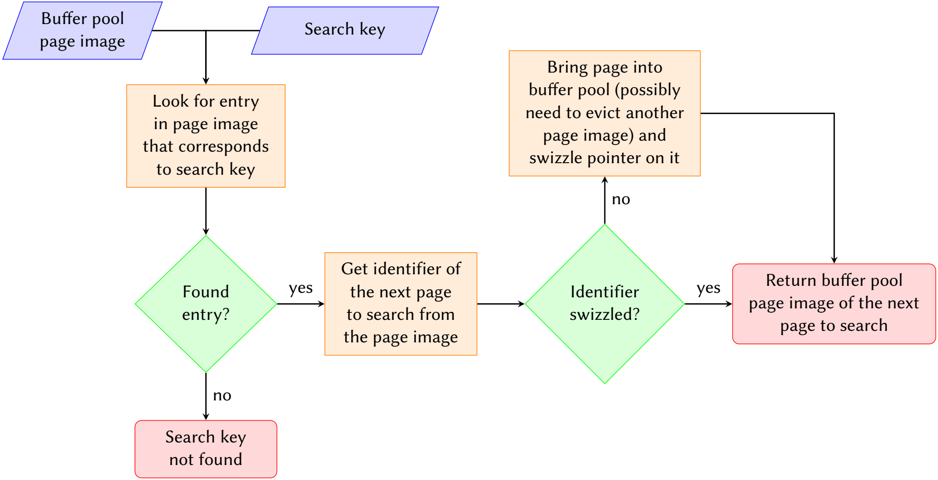
Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])



Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])



Locate Pages in Buffer Pool w/ Pointer Swizzling ([Gra+14])



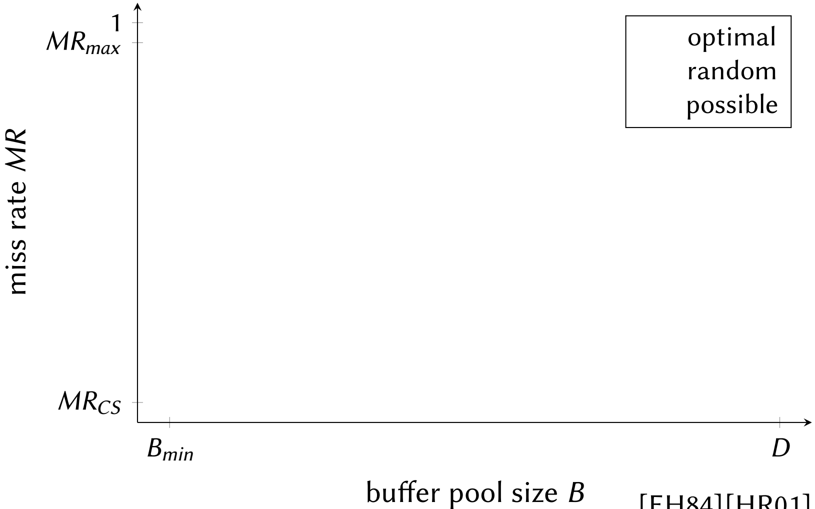
Section 2

Performance Evaluation of the Buffer Management Utilizing Pointer Swizzling

Subsection 1

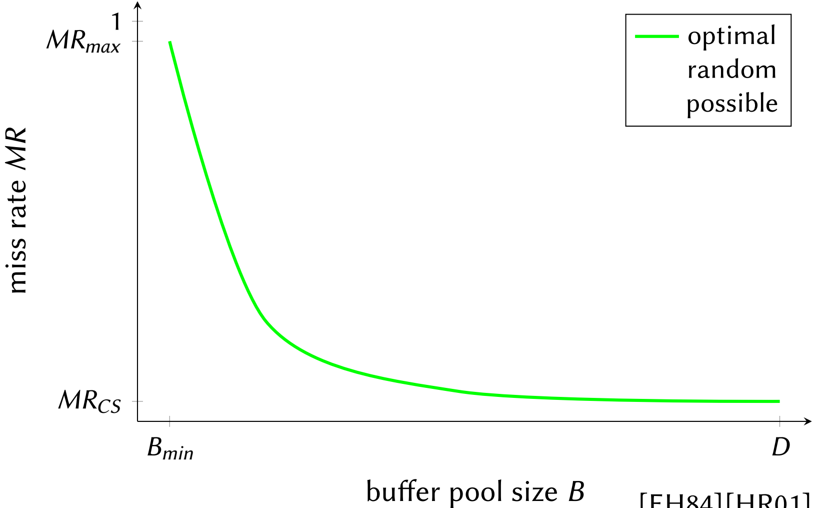
Expected Performance

Performance of Different Buffer Pool Sizes



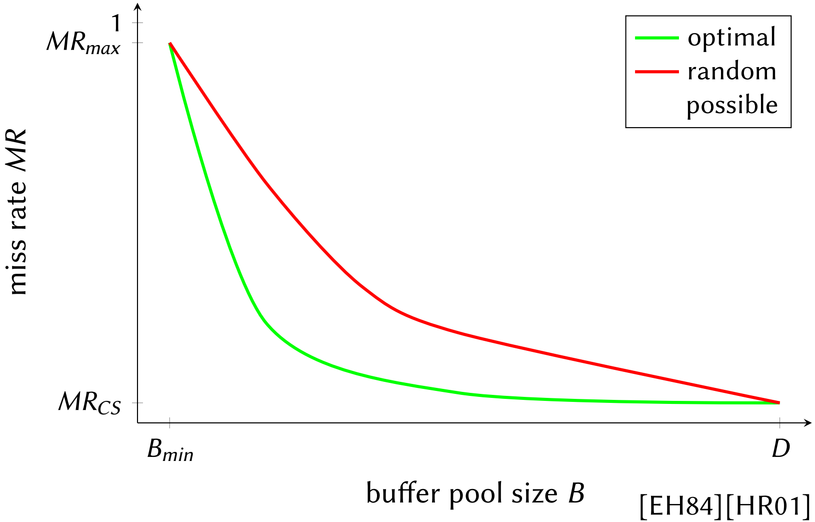
[EH84][HR01]

Performance of Different Buffer Pool Sizes



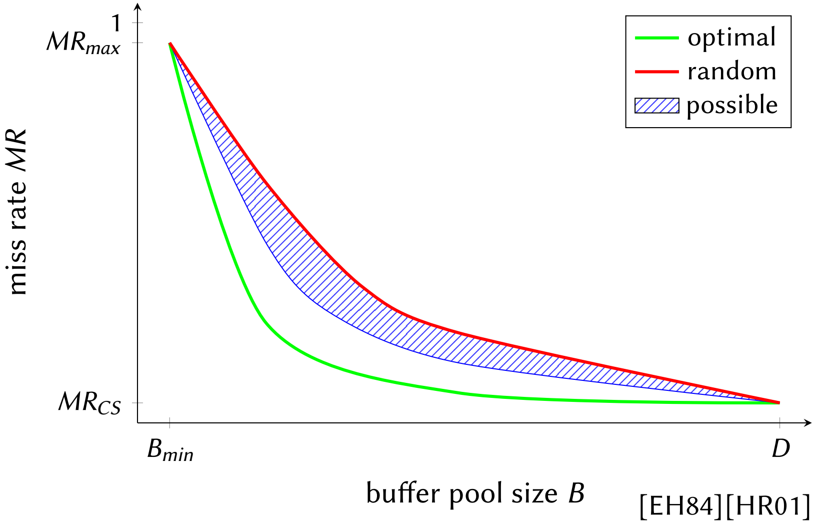
[EH84][HR01]

Performance of Different Buffer Pool Sizes



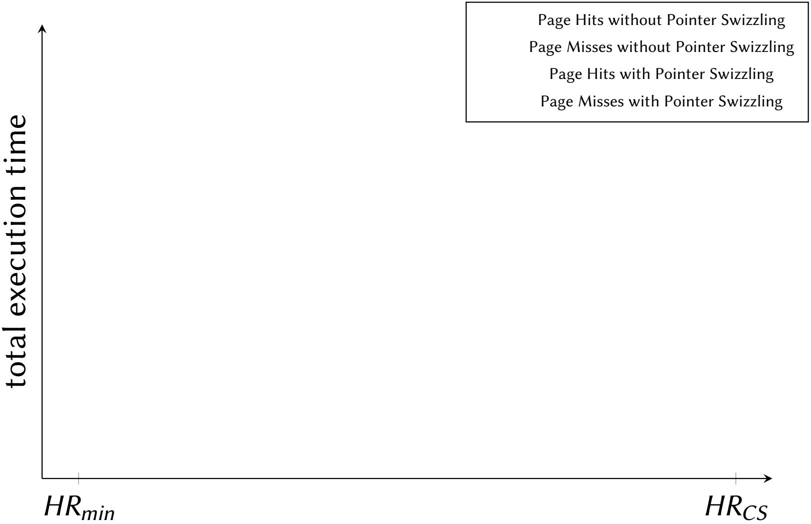
[EH84][HR01]

Performance of Different Buffer Pool Sizes

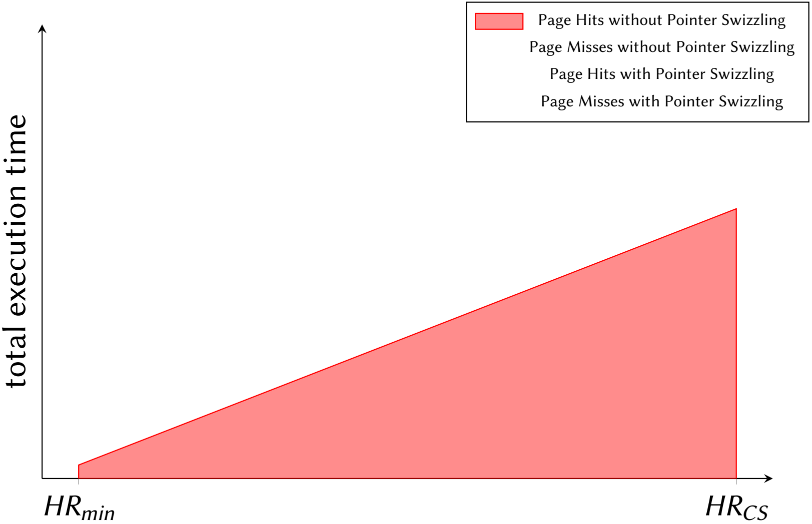


[EH84][HR01]

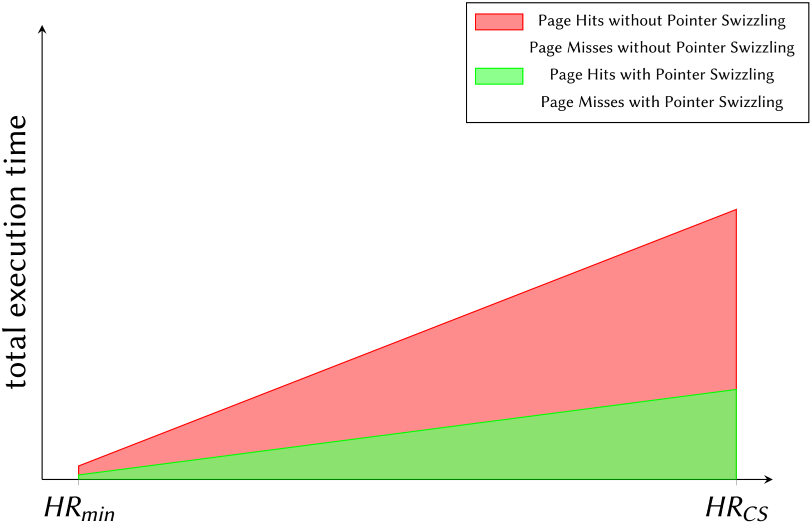
Buffer Management with and without Pointer Swizzling



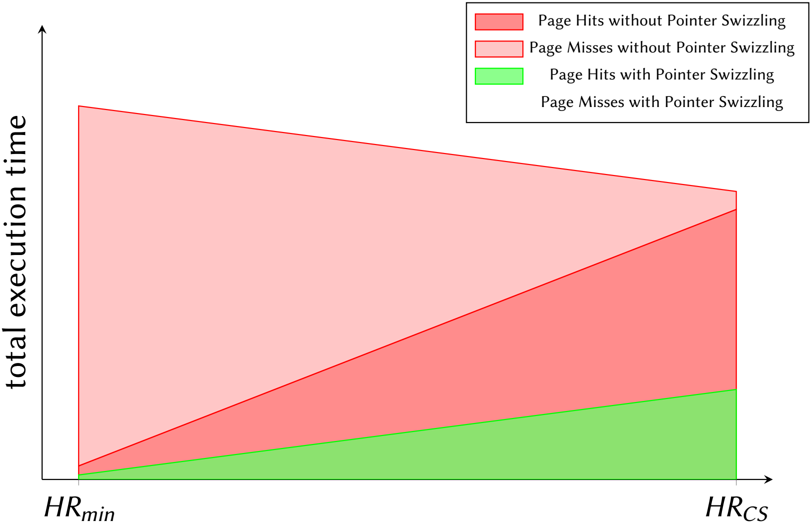
Buffer Management with and without Pointer Swizzling



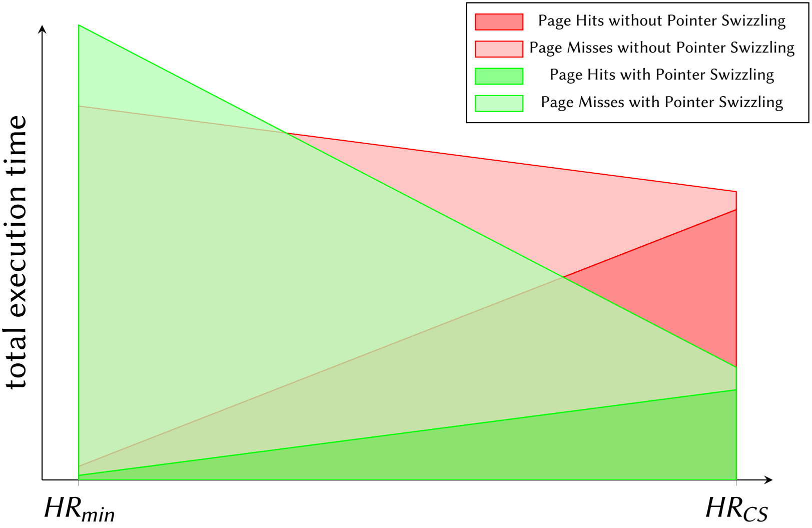
Buffer Management with and without Pointer Swizzling



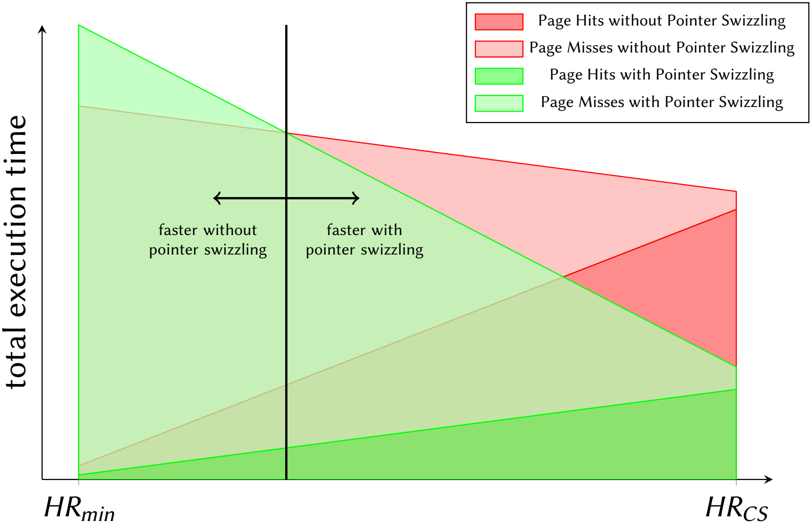
Buffer Management with and without Pointer Swizzling



Buffer Management with and without Pointer Swizzling



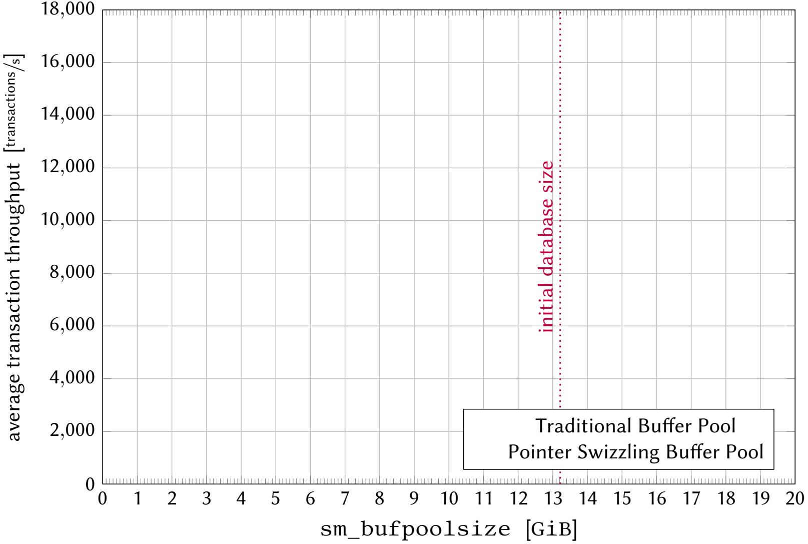
Buffer Management with and without Pointer Swizzling



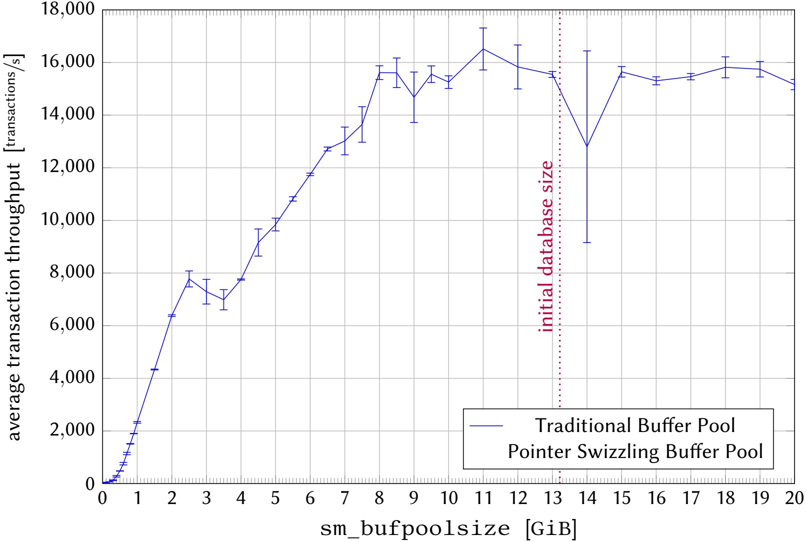
Subsection 2

Measured Performance

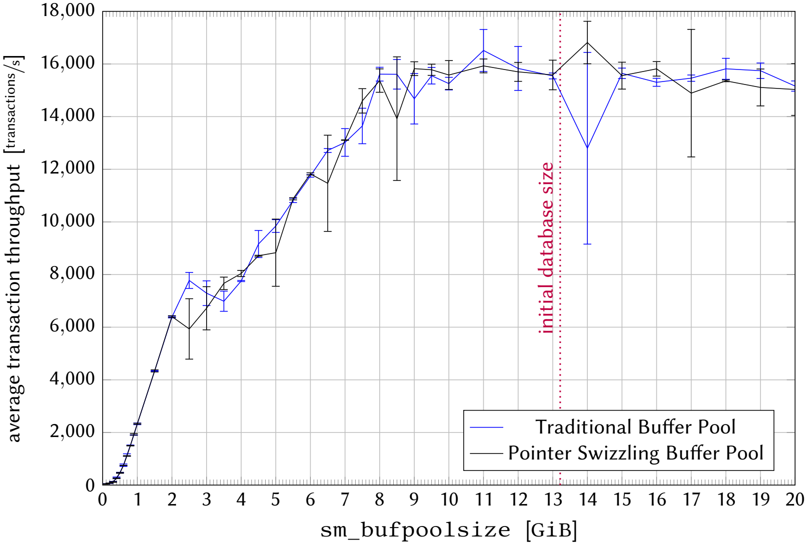
Transaction Throughput (TPC-C)



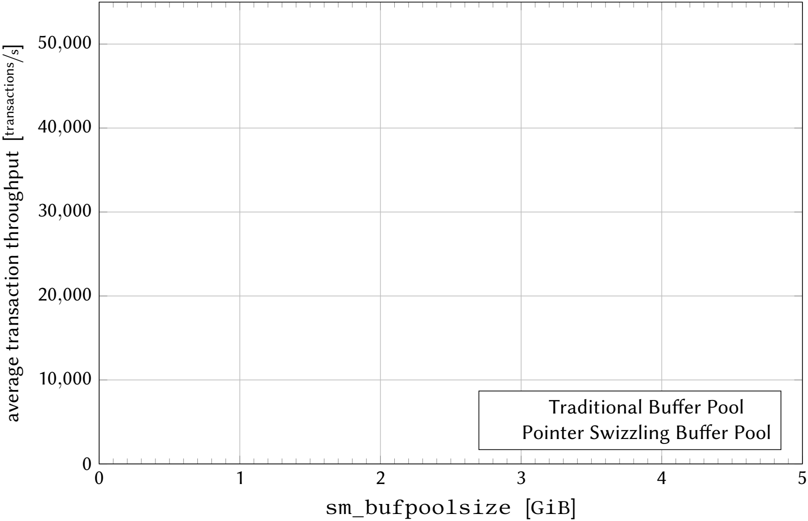
Transaction Throughput (TPC-C)



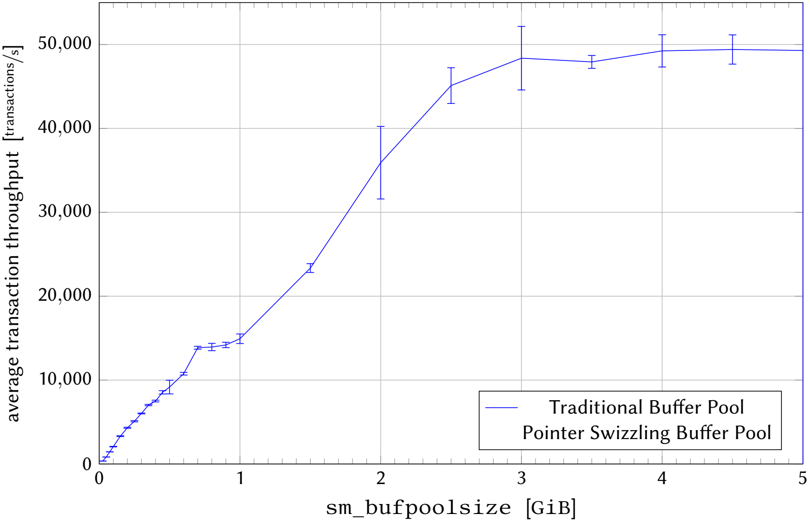
Transaction Throughput (TPC-C)



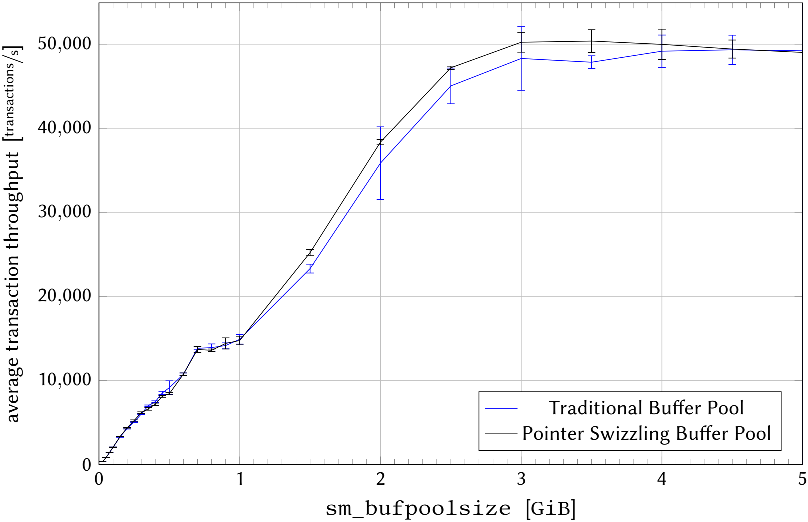
Transaction Throughput (TPC-B)



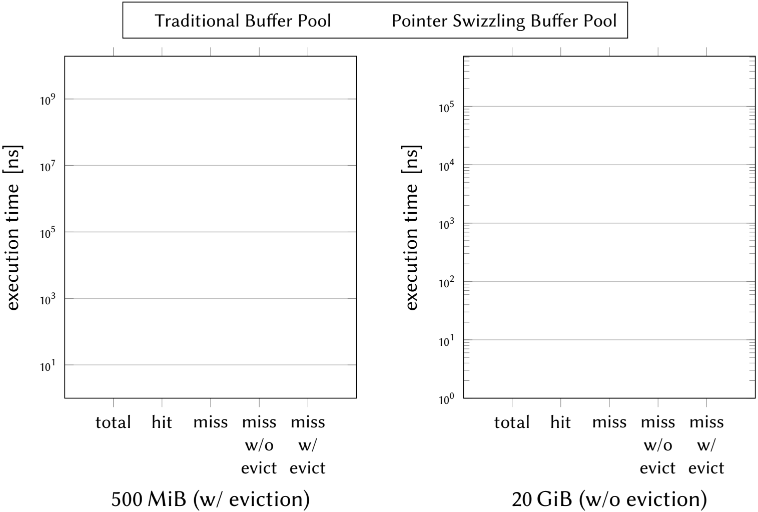
Transaction Throughput (TPC-B)



Transaction Throughput (TPC-B)



Buffer Pool Performance Acquiring Shared Latches



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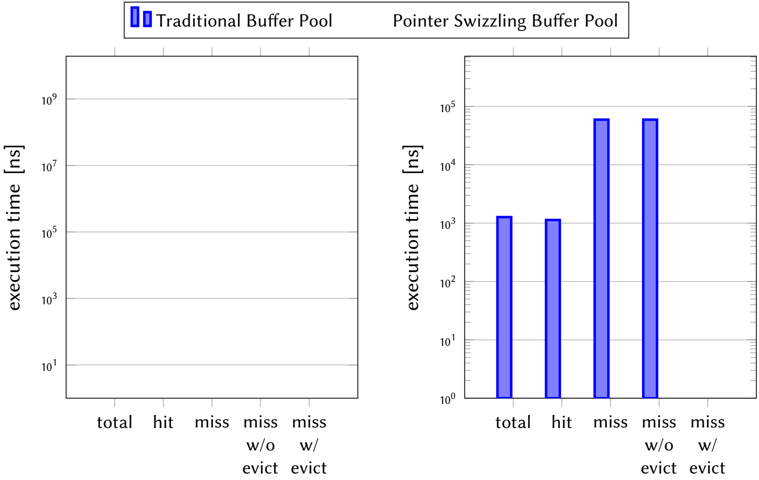
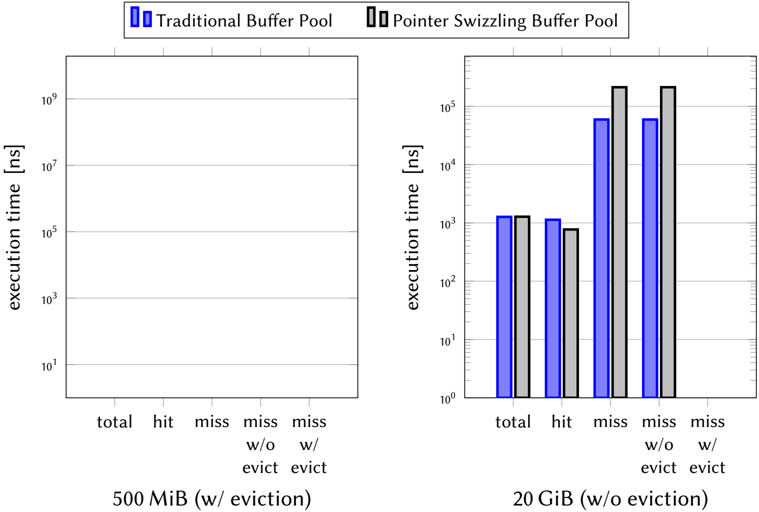


500 MiB (w/ eviction)

20 GiB (w/o eviction)

Buffer Pool Performance Acquiring Shared Latches



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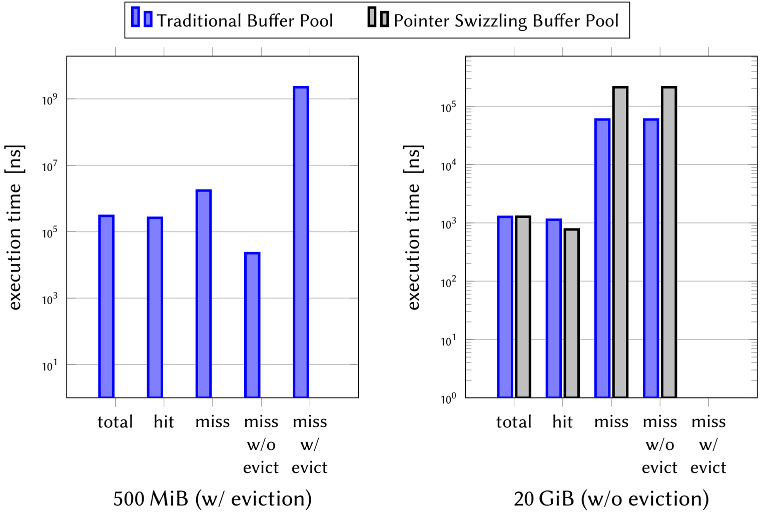

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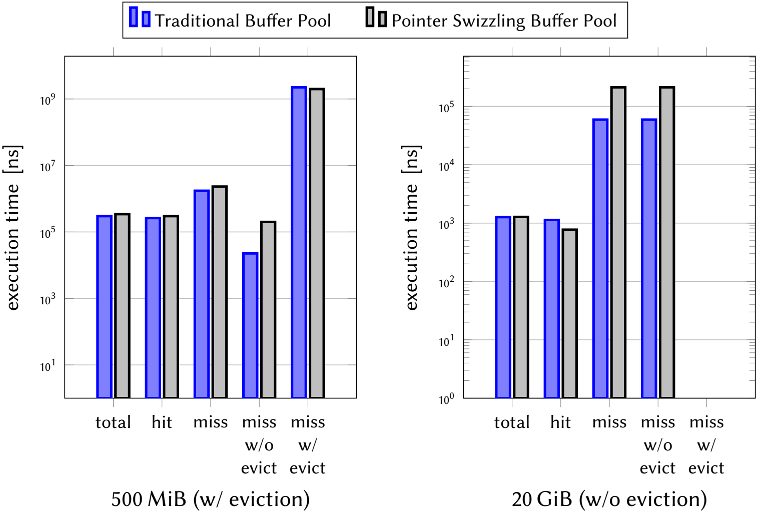

Subsection 3

Conclusion

Conclusion

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Overall Performance

Conclusion

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- A page hit is faster when pointer swizzling is activated.

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- A page hit is faster when pointer swizzling is activated.
- A page miss is slower when pointer swizzling is activated.

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- A continuously running DB with large buffer pool could profit from pointer swizzling.

Buffer Pool Performance

- A page hit is faster when pointer swizzling is activated.
- A page miss is slower when pointer swizzling is activated.
- After the cold start phase, activated pointer swizzling will improve the buffer pool performance for large buffer pools.

Section 3

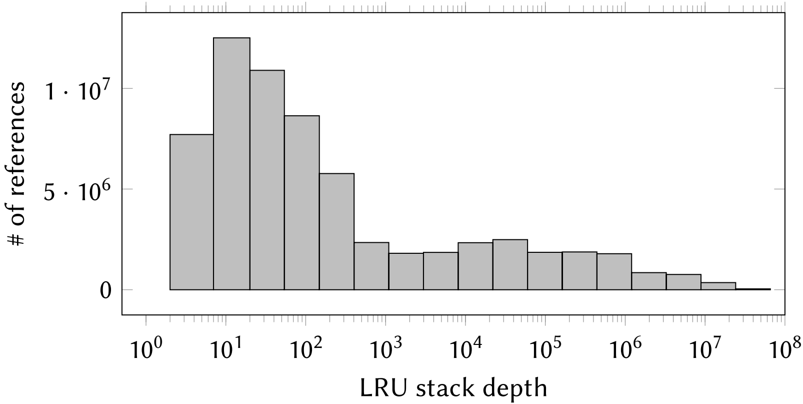
Page Eviction Strategies in the Context of Pointer Swizzling

Motivation not to Analyze Different Page Eviction Strategies

Motivation not to Analyze Different Page Eviction Strategies

- Even LRU results in decent hit rates

TPC-C with Warehouses: 100, Threads: 25



But ...

But ...

- Page reference pattern containing a loop slightly to long to fit in the buffer pool:

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  - **OPT:** Hit rate close to 1

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- Huge access time gap $\implies$ Every saved page miss significantly improves the performance
- Pointer swizzling even amplifies that effect

Subsection 1

Probable pitfalls when Implementing a Page Eviction Strategy for a DBMS Buffer Manager

General Problems Concerning DBMS Buffer Managers

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- Fixed pages cannot be evicted but a long timespan between a fix and an unfix of a page could make it a candidate for eviction.

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- Fixed pages cannot be evicted but a long timespan between a fix and an unfix of a page could make it a candidate for eviction.
- A page pinned for refix cannot be evicted but a long timespan in which a page is pinned could make it a candidate for eviction.
- Dirty pages cannot be evicted but a page being dirty for a long timespan due to the update propagation using write-back policy could make it a candidate for eviction.

Additional Problem When Using Pointer Swizzling

Additional Problem When Using Pointer Swizzling

- A page containing swizzled pointer cannot be evicted but a page unfixed before the last unfix of one of its child pages could make it a candidate for eviction before its child pages got evicted.

Solutions

Solutions

- Check each of the restrictions before the eviction of a page.

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- Update the statistics of the eviction strategy during an unfix, too.

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- Update the statistics of the eviction strategy during an unfix, too.
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- Use write-thru for update propagation or a page cleaner decoupled from the buffer pool as proposed in [SHG16].

Solutions

- Check each of the restrictions before the eviction of a page.
- Update the statistics of the eviction strategy during an unfix, too.
- Update the statistics of the eviction strategy during an pin and unpin, too.
- Use write-thru for update propagation or a page cleaner decoupled from the buffer pool as proposed in [SHG16].
- Use a page eviction strategy that takes into account the content of pages (like the structure of an B tree).

Subsection 2

Different Page Replacement Strategies

Some Page Replacement Algorithms

Consideration during selection decision				

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		Age		

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		**Age**		
		No consideration		

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		**Age**		
		No consideration		
References				

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		**Age**		
		No consideration		
References	**No consideration**			

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		**Age**		
		No consideration	**Since most recent reference**	**Since first reference**
References	**No consideration**			

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		**Age**		
		No consideration	**Since most recent reference**	**Since first reference**
References	**No consideration**			
	Most recent reference			
	All references			

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		Age		
		No consideration	Since most recent reference	Since first reference
References	No consideration			FIFO
	Most recent reference		LRU CLOCK	
	All references	LFU	GCLOCK-V1 DGCLOCK	LRD-V1
			LRU-K LRD-V2	

[EH84][HR01]

Some Page Replacement Algorithms

Consideration during selection decision		**Age**		
		No consideration	**Since most recent reference**	**Since first reference**
References	**No consideration**	RANDOM		FIFO
	Most recent reference		LRU CLOCK	
	All references	LFU	GCLOCK-V1 DGCLOCK	LRD-V1
			LRU-K LRD-V2	

[EH84][HR01]

Some Page Replacement Algorithms

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CLOCK
GCLOCK-V2</td><td></td></tr>
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DGCLOCK</td><td>LRD-V1</td></tr>
<tr><td colspan="2">LRU-K
LRD-V2</td></tr>
</table>

[EH84][HR01]

Some More Page Replacement Algorithms

PRIORITY-LRU

MRU

Clock-Pro

LIRS

WSclock

SEQ

CART

LRFU

MQ

HSS

ARC

EELRU

SLRU

PLRU

LFV

VAR-PAGE-LRU

Pannier

NFU

DEAR

[HR01][Wan01][HSS11][Wik17]

Some More Page Replacement Algorithms

PRIORITY-LRU

MRU

Clock-Pro

LIRS

CAR

WSclock

SEQ

CART

LRFU

MQ

HSS

ARC

EELRU

PLRU

LFV

SLRU

VAR-PAGE-LRU

NFU

Pannier

DEAR

[HR01][Wan01][HSS11][Wik17]

RANDOM

Overview

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Overview

- Simplest page eviction strategy

RANDOM

Overview

- Simplest page eviction strategy
- Evicts a random page that can be evicted

RANDOM

Overview

- Simplest page eviction strategy
- Evicts a random page that can be evicted
- Won't evict frequently used pages as they're latched all the time

GCLOCK

Overview

GCLOCK

Overview

- Slight enhancement of the CLOCK algorithm: *generalized CLOCK*

GCLOCK

Overview

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- Uses finer-grained statistics about the recency of page references

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GCLOCK

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    - $\boldsymbol{k = 1}$: CLOCK

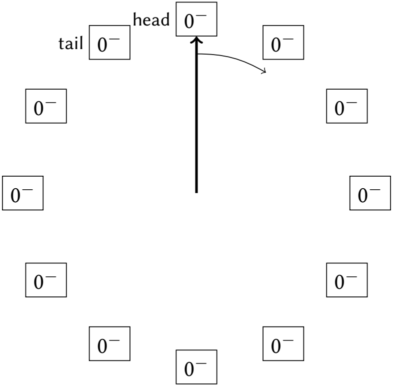
GCLOCK

Overview

- Slight enhancement of the CLOCK algorithm: *generalized CLOCK*
- Uses finer-grained statistics about the recency of page references
- Parameter k defines granulation of statistics
    - $\boldsymbol{k = 1}$**:** CLOCK
    - $\boldsymbol{k = \#}$**frames:** Similar to LRU

GCLOCK

Example



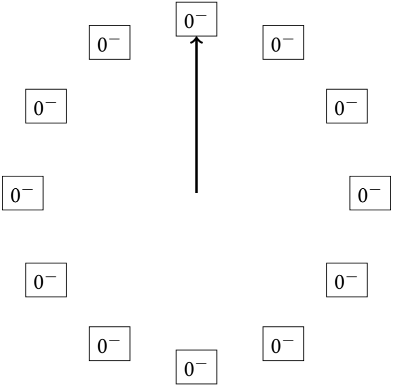
GCLOCK

Example

Cold Starting the Buffer Pool!

GCLOCK

Example



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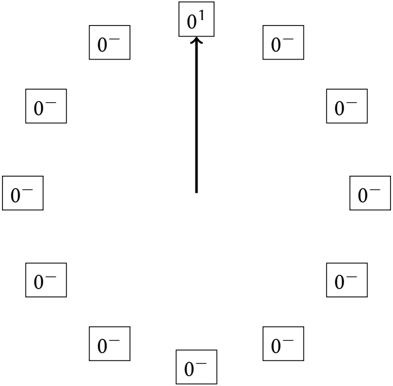
GCLOCK

Example



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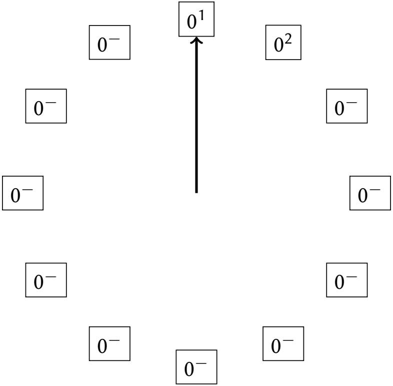
GCLOCK

Example



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GCLOCK

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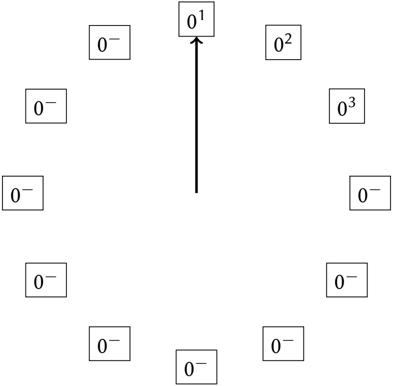

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GCLOCK

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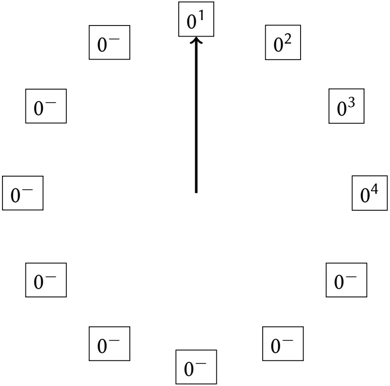

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GCLOCK

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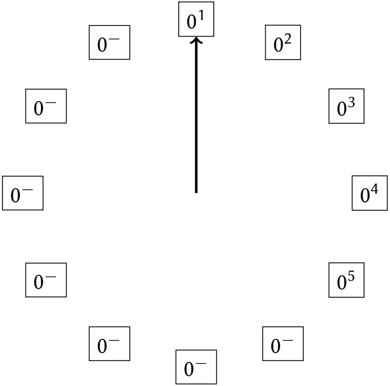

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GCLOCK

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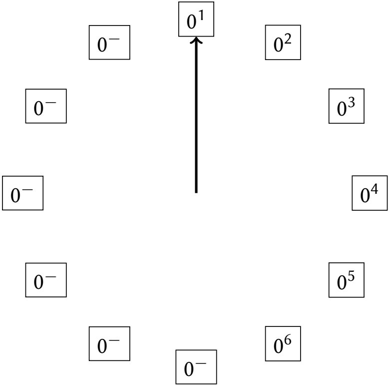

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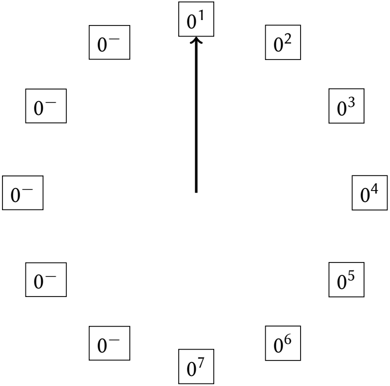

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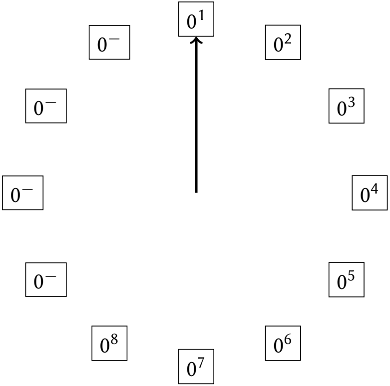

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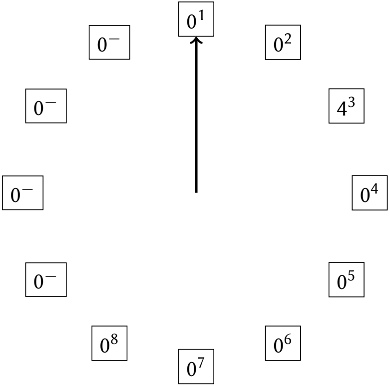

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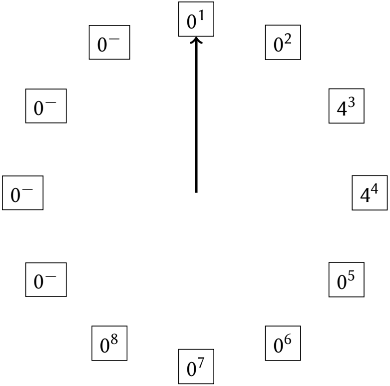

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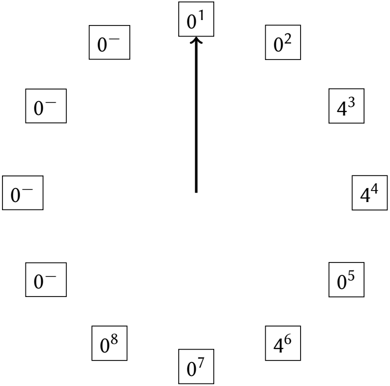

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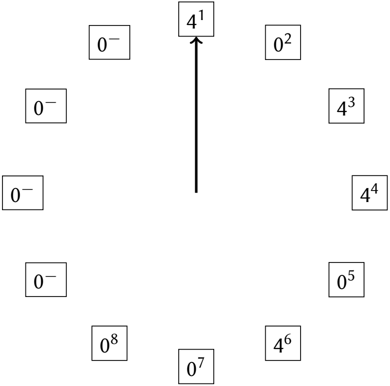

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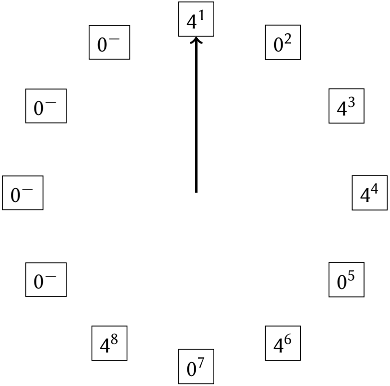

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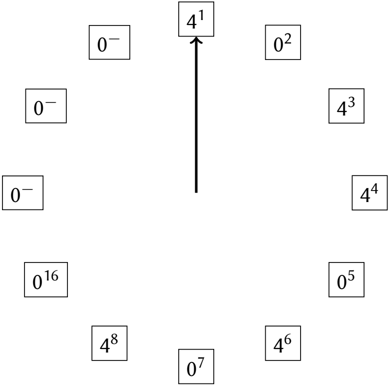

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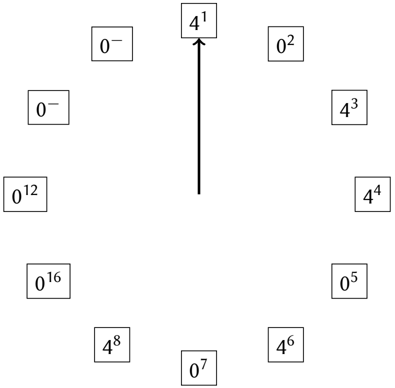

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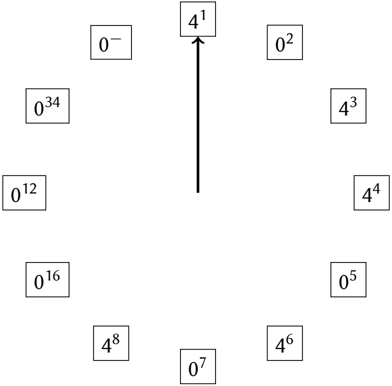

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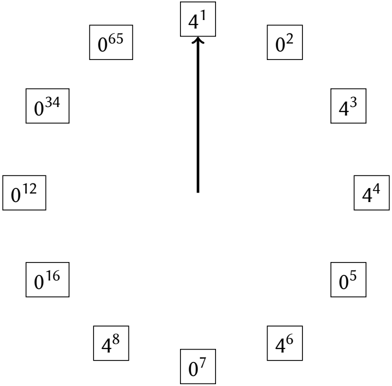
GCLOCK

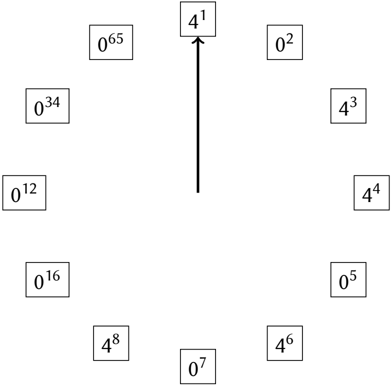
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

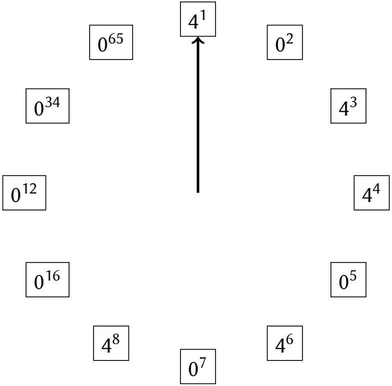
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

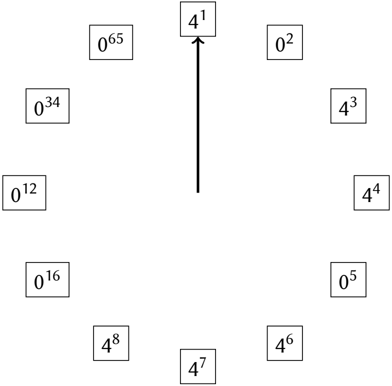
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

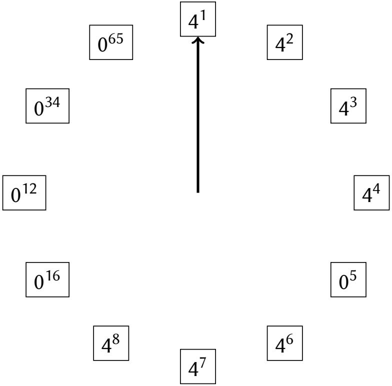
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

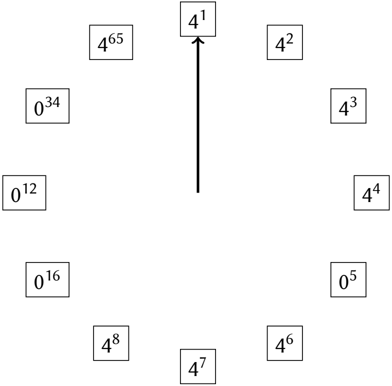
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

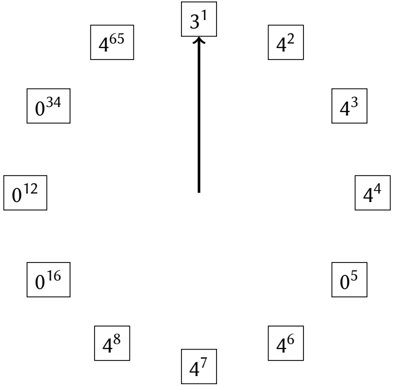
GCLOCK

Example

Evicting Pages!

GCLOCK

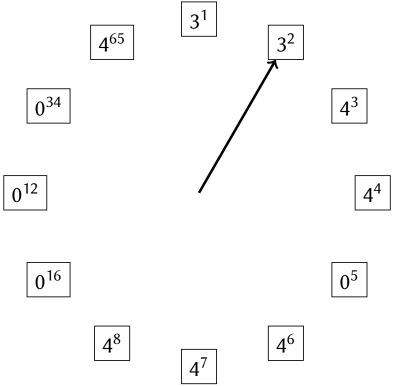
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

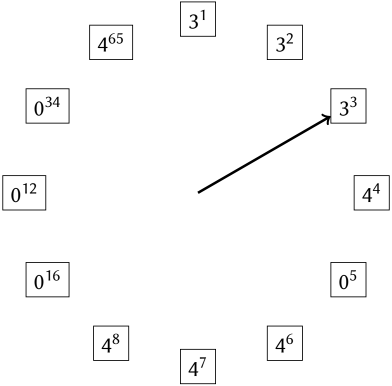
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

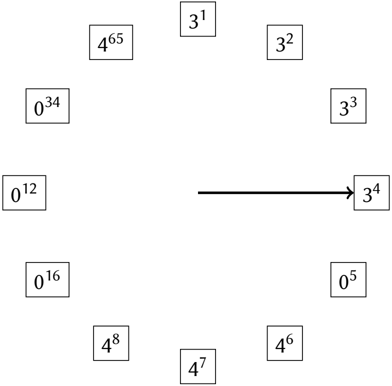
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

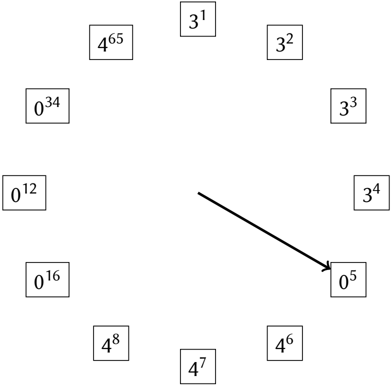
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

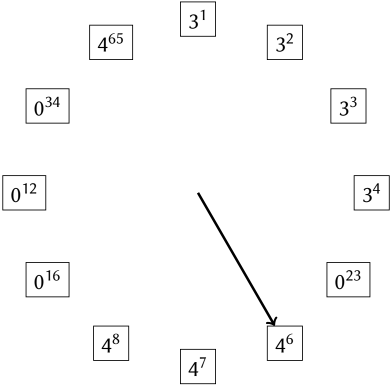
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

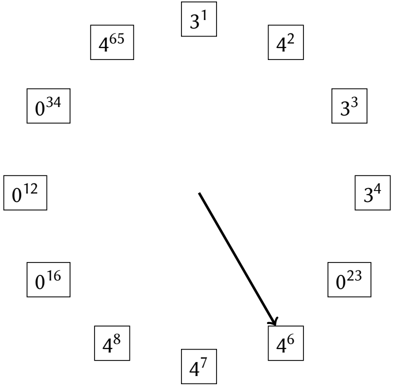
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

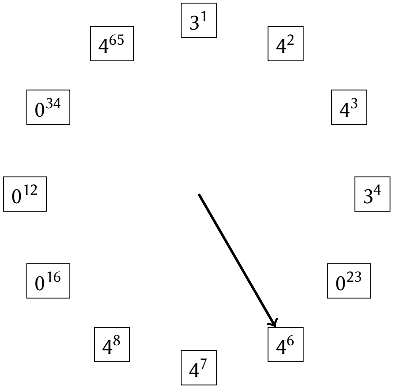
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

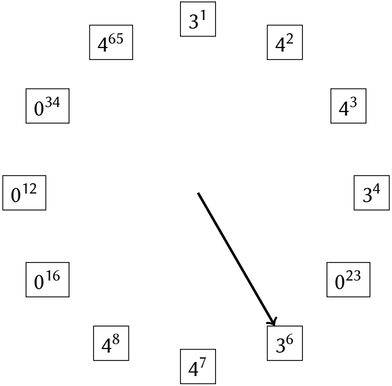
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

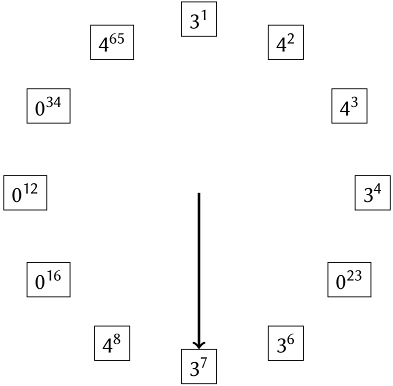
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

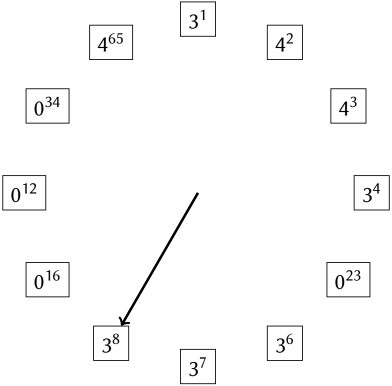
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

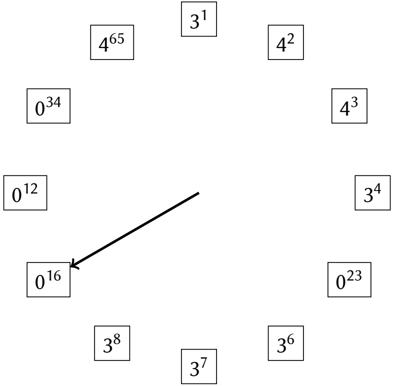
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

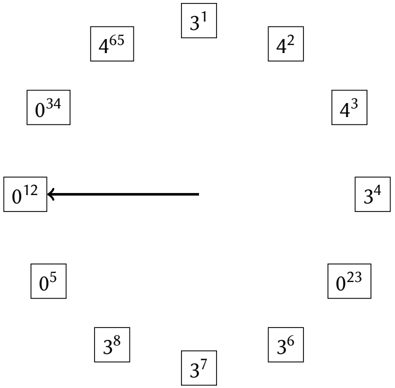
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

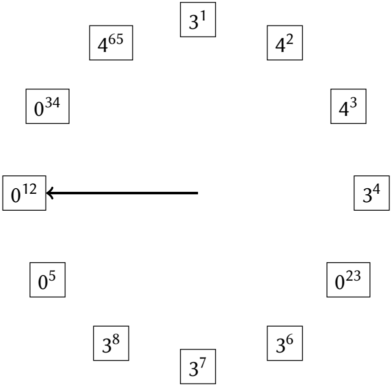
Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 5

GCLOCK

Example



Page References: 1, 2, 3, 4, 5, 6, 7, 8, 3, 4, 6, 1, 8, 16, 12, 34, 65, 3, 4, 7, 2, 65, 23, 2, 3, 1

GCLOCK

Algorithm (1)

GCLOCK

Algorithm (1)

```
procedure GET_PAGE($x$)

end procedure
```

GCLOCK

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in$ buffer pool then
    end if
end procedure
```

GCLOCK

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in$ buffer pool then
        $referenced[x] \leftarrow k$




    end if
end procedure
```

GCLOCK

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in$ buffer pool then
        $referenced[x] \leftarrow k$
    else if buffer pool is full then



    end if
end procedure
```

GCLOCK

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in$ buffer pool then
        $\mathit{referenced}\,[x] \leftarrow k$
    else if buffer pool is full then
        EVICT
        INSERT($x$)
        $\mathit{referenced}\,[x] \leftarrow 0$



    end if
end procedure
```

GCLOCK

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in$ buffer pool then
        $referenced\,[x] \leftarrow k$
    else if buffer pool is full then
        EVICT
        INSERT($x$)
        $referenced\,[x] \leftarrow 0$
    else


    end if
end procedure
```

GCLOCK

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in$ buffer pool then
        $referenced[x] \leftarrow k$
    else if buffer pool is full then
        EVICT
        INSERT($x$)
        $referenced[x] \leftarrow 0$
    else
        INSERT($x$)
        $referenced[x] \leftarrow 0$
    end if
end procedure
```

GCLOCK

Algorithm (2)

GCLOCK

Algorithm (2)

```
procedure EVICT
end procedure
```

GCLOCK

Algorithm (2)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do

    end while
end procedure
```

GCLOCK

Algorithm (2)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        $x \leftarrow$GET_NEXT



    end while
end procedure
```

GCLOCK

Algorithm (2)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        $x \leftarrow$GET_NEXT
        if $referenced[x] = 0$ then

        end if
    end while
end procedure
```

GCLOCK

Algorithm (2)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        $x \leftarrow$GET_NEXT
        if $referenced[x] = 0$ then
            $found \leftarrow$ true
            REMOVE_NEXT



        end if
    end while
end procedure
```

GCLOCK

Algorithm (2)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        $x \leftarrow$GET_NEXT
        if $referenced[x] = 0$ then
            $found \leftarrow$ true
            REMOVE_NEXT
        else


        end if
    end while
end procedure
```

GCLOCK

Algorithm (2)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        $x \leftarrow$GET_NEXT
        if $referenced[x] = 0$ then
            $found \leftarrow$ true
            REMOVE_NEXT
        else
            $referenced[x] \leftarrow referenced[x] - 1$
            MOVE_HAND
        end if
    end while
end procedure
```

GCLOCK

Advantage of Higher *k*-Values

GCLOCK

Advantage of Higher *k*-Values

Advantages of Lower *k*-Values

GCLOCK

Advantage of Higher *k*-Values

- More detailed statistics about page references
  $\Longrightarrow$ Higher hit rate
  $\Longrightarrow$ Higher performance

Advantages of Lower *k*-Values

GCLOCK

Advantage of Higher *k*-Values

- More detailed statistics about page references
  $\implies$ Higher hit rate
  $\implies$ Higher performance

Advantages of Lower *k*-Values

- Lower processing time required to find an eviction victim
  $\implies$ Higher performance

GCLOCK

Advantage of Higher *k*-Values

- More detailed statistics about page references
  $\Longrightarrow$ Higher hit rate
  $\Longrightarrow$ Higher performance

Advantages of Lower *k*-Values

- Lower processing time required to find an eviction victim
  $\Longrightarrow$ Higher performance
- Lower memory overhead due to shorter `referenced-numbers`

GCLOCK

Advantage of Higher *k*-Values

- More detailed statistics about page references
  $\Longrightarrow$ Higher hit rate
  $\Longrightarrow$ Higher performance

Advantages of Lower *k*-Values

- Lower processing time required to find an eviction victim
  $\Longrightarrow$ Higher performance
- Lower memory overhead due to shorter referenced-numbers

$\Longrightarrow$ Trade-off between CPU- and I/O-optimization

CAR

Overview

CAR

Overview

- Extensive enhancement of the CLOCK algorithm: *Clock with Adaptive Replacement* [BM04]

CAR

Overview

- Extensive enhancement of the CLOCK algorithm: *Clock with Adaptive Replacement* [BM04]
- Approximation of the ARC page eviction strategy

CAR

Overview

- Extensive enhancement of the CLOCK algorithm: *Clock with Adaptive Replacement* [BM04]
- Approximation of the ARC page eviction strategy
- Uses two clocks and two LRU-lists

CAR

Overview

- Extensive enhancement of the CLOCK algorithm: *Clock with Adaptive Replacement* [BM04]
- Approximation of the ARC page eviction strategy
- Uses two clocks and two LRU-lists
- Advantages of CAR compared to CLOCK:

CAR

Overview

- Extensive enhancement of the CLOCK algorithm: *Clock with Adaptive Replacement* [BM04]
- Approximation of the ARC page eviction strategy
- Uses two clocks and two LRU-lists
- Advantages of CAR compared to CLOCK:
    - Weighted consideration of reference recency and frequency

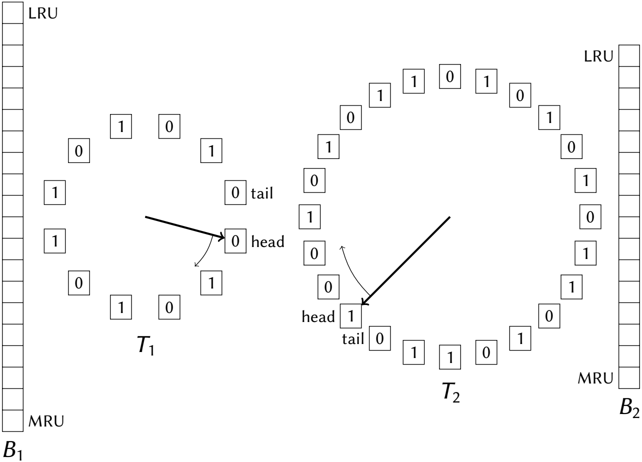
CAR

Overview

- Extensive enhancement of the CLOCK algorithm: *Clock with Adaptive Replacement* [BM04]
- Approximation of the ARC page eviction strategy
- Uses two clocks and two LRU-lists
- Advantages of CAR compared to CLOCK:
  - Weighted consideration of reference recency and frequency
  - Scan-resistence

CAR

Example


LRU
MRU
B_1
1 0 1 0 0 1 0 1 0 1 1 0
tail
head
T_1
0 1 0 1 0 1 0 1 1 0 1 0 1 1 0 1 0 0 1 0 1 0 1 1
head
tail
T_2
LRU
MRU
B_2

CAR

Algorithm (1)

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
    else
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
    else
        if $|T_1| + |T_2| = c$ then

        end if
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
    else
        if $|T_1| + |T_2| = c$ then
            EVICT




        end if
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
    else
        if $|T_1| + |T_2| = c$ then
            EVICT
            if $(x \notin B_1 \cup B_2) \wedge (|T_1| + |B_1| = c)$ then



            end if
        end if
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
    else
        if $|T_1| + |T_2| = c$ then
            EVICT
            if $(x \notin B_1 \cup B_2) \wedge (|T_1| + |B_1| = c)$ then
                REMOVE_NEXT($B_1$)


            end if
        end if
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
    else
        if $|T_1| + |T_2| = c$ then
            EVICT
            if $(x \notin B_1 \cup B_2) \wedge (|T_1| + |B_1| = c)$ then
                REMOVE_NEXT($B_1$)
            else if $(x \notin B_1 \cup B_2) \wedge (|T_1| + |T_2| + |B_1| + |B_2| = 2c)$ then

            end if
        end if
```

CAR

Algorithm (1)

```
procedure GET_PAGE($x$)
    if $x \in T_1 \cup T_2$ then
        $referenced[x] \leftarrow$ true
    else
        if $|T_1| + |T_2| = c$ then
            EVICT
            if $(x \notin B_1 \cup B_2) \wedge (|T_1| + |B_1| = c)$ then
                REMOVE_NEXT($B_1$)
            else if $(x \notin B_1 \cup B_2) \wedge (|T_1| + |T_2| + |B_1| + |B_2| = 2c)$ then
                REMOVE_NEXT($B_2$)
            end if
        end if
```

CAR

Algorithm (2)

```
    end if
end procedure
```

CAR

Algorithm (2)

```
        if $x \notin B_1 \cup B_2$ then



        end if
    end if
end procedure
```

CAR

Algorithm (2)

```
        if $x \notin B_1 \cup B_2$ then
            INSERT_INTO$(T_1, x)$
            $referenced[x] \leftarrow$ false

        end if
    end if
end procedure
```

CAR

Algorithm (2)

```
        if $x \notin B_1 \cup B_2$ then
            INSERT_INTO($T_1, x$)
            $referenced\,[x] \leftarrow$ false
        else if $x \in B_1$ then



        end if
    end if
end procedure
```

CAR

Algorithm (2)

```
        **if** $x \notin B_1 \cup B_2$ **then**
            INSERT_INTO$(T_1, x)$
            $referenced\left[x\right] \leftarrow$ false
        **else if** $x \in B_1$ **then**
            $p \leftarrow \min\left\{p + \max\left\{1, \frac{|B_2|}{|B_1|}\right\}, c\right\}$



        **end if**
    **end if**
**end procedure**
```

CAR

Algorithm (2)

```
        **if** $x \notin B_1 \cup B_2$ **then**
            INSERT_INTO$(T_1, x)$
            $referenced\,[x] \leftarrow$ false
        **else if** $x \in B_1$ **then**
            $p \leftarrow \min\left\{p + \max\left\{1, \frac{|B_2|}{|B_1|}\right\}, c\right\}$
            INSERT_INTO$(T_2, x)$
            $referenced\,[x] \leftarrow$ false

        **end if**
    **end if**
**end procedure**
```

CAR

Algorithm (2)

```
        if $x \notin B_1 \cup B_2$ then
            INSERT_INTO($T_1, x$)
            $referenced\left[x\right] \leftarrow$ false
        else if $x \in B_1$ then
            $p \leftarrow \min\left\{p + \max\left\{1, \frac{|B_2|}{|B_1|}\right\}, c\right\}$
            INSERT_INTO($T_2, x$)
            $referenced\left[x\right] \leftarrow$ false
        else



        end if
    end if
end procedure
```

CAR

Algorithm (2)

```
        if $x \notin B_1 \cup B_2$ then
            INSERT_INTO$(T_1, x)$
            $referenced[x] \leftarrow$ false
        else if $x \in B_1$ then
            $p \leftarrow \min\left\{p + \max\left\{1, \frac{|B_2|}{|B_1|}\right\}, c\right\}$
            INSERT_INTO$(T_2, x)$
            $referenced[x] \leftarrow$ false
        else
            $p \leftarrow \max\left\{p - \max\left\{1, \frac{|B_1|}{|B_2|}\right\}, 0\right\}$


        end if
    end if
end procedure
```

CAR

Algorithm (2)

```
        if $x \notin B_1 \cup B_2$ then
            INSERT_INTO$(T_1, x)$
            $referenced\left[x\right] \leftarrow \text{false}$
        else if $x \in B_1$ then
            $p \leftarrow \min\left\{p + \max\left\{1, \frac{|B_2|}{|B_1|}\right\}, c\right\}$
            INSERT_INTO$(T_2, x)$
            $referenced\left[x\right] \leftarrow \text{false}$
        else
            $p \leftarrow \max\left\{p - \max\left\{1, \frac{|B_1|}{|B_2|}\right\}, 0\right\}$
            INSERT_INTO$(T_2, x)$
            $referenced\left[x\right] \leftarrow \text{false}$
        end if
    end if
end procedure
```

CAR

Algorithm (3)

CAR

Algorithm (3)

```
procedure EVICT
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        if $|T_1| \geq \max\{1, p\}$ then
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        if $|T_1| \geq \max\{1, p\}$ then
            $x \leftarrow$ GET_NEXT_FROM$(T_1)$
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        if $|T_1| \geq \max\{1, p\}$ then
            $x \leftarrow$GET_NEXT_FROM$(T_1)$
            if $referenced[x] =$ false then



            end if
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        if $|T_1| \geq \max\{1, p\}$ then
            $x \leftarrow$ GET_NEXT_FROM$(T_1)$
            if $referenced[x] =$ false then
                $found \leftarrow$ true
                REMOVE_NEXT$(T_1)$
                INSERT_INTO$(B_1, x)$



            end if
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        if $|T_1| \geq \max\{1, p\}$ then
            $x \leftarrow$GET_NEXT_FROM$(T_1)$
            if $referenced[x] =$ false then
                $found \leftarrow$ true
                REMOVE_NEXT$(T_1)$
                INSERT_INTO$(B_1, x)$
            else


            end if
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        if $|T_1| \geq \max\{1, p\}$ then
            $x \leftarrow$GET_NEXT_FROM$(T_1)$
            if $referenced[x] =$ false then
                $found \leftarrow$ true
                REMOVE_NEXT$(T_1)$
                INSERT_INTO$(B_1, x)$
            else
                $referenced[x] \leftarrow$ false

            end if
```

CAR

Algorithm (3)

```
procedure EVICT
    $found \leftarrow$ false
    while $found \neq$ true do
        if $|T_1| \geq \max\{1, p\}$ then
            $x \leftarrow$GET_NEXT_FROM($T_1$)
            if $referenced[x] =$ false then
                $found \leftarrow$ true
                REMOVE_NEXT($T_1$)
                INSERT_INTO($B_1, x$)
            else
                $referenced[x] \leftarrow$ false
                MOVE_HAND($T_1$)
            end if
```

CAR

Algorithm (4)

```
        end if
    end while
end procedure
```

CAR

Algorithm (4)

```
        else




        end if
    end while
end procedure
```

CAR

Algorithm (4)

```
        else
            $x \leftarrow$ GET_NEXT_FROM($T_2$)
        end if
    end while
end procedure
```

CAR

Algorithm (4)

```
        else
            $x \leftarrow$ GET_NEXT_FROM($T_2$)
            if $referenced[x] = \text{false}$ then

            end if
        end if
    end while
end procedure
```

CAR

Algorithm (4)

```
        else
            $x \leftarrow$ GET_NEXT_FROM($T_2$)
            if $referenced[x] =$ false then
                $found \leftarrow$ true
                REMOVE_NEXT($T_2$)
                INSERT_INTO($B_2, x$)



            end if
        end if
    end while
end procedure
```

CAR

Algorithm (4)

```
        else
            $x \leftarrow$ GET_NEXT_FROM($T_2$)
            if $referenced[x] =$ false then
                $found \leftarrow$ true
                REMOVE_NEXT($T_2$)
                INSERT_INTO($B_2, x$)
            else


            end if
        end if
    end while
end procedure
```

CAR

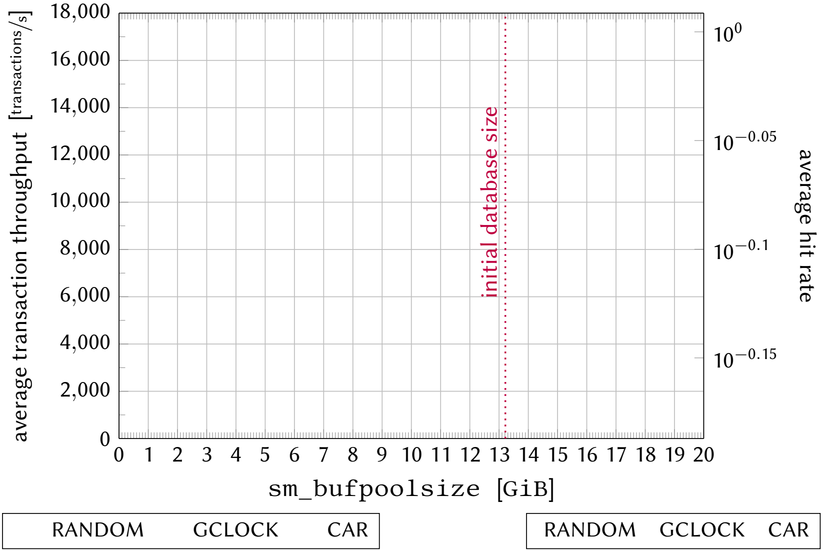
Algorithm (4)

```
        else
            $x \leftarrow$ GET_NEXT_FROM($T_2$)
            if $referenced[x] = \text{false}$ then
                $found \leftarrow \text{true}$
                REMOVE_NEXT($T_2$)
                INSERT_INTO($B_2, x$)
            else
                $referenced[x] \leftarrow \text{false}$
                MOVE_HAND($T_2$)
            end if
        end if
    end while
end procedure
```

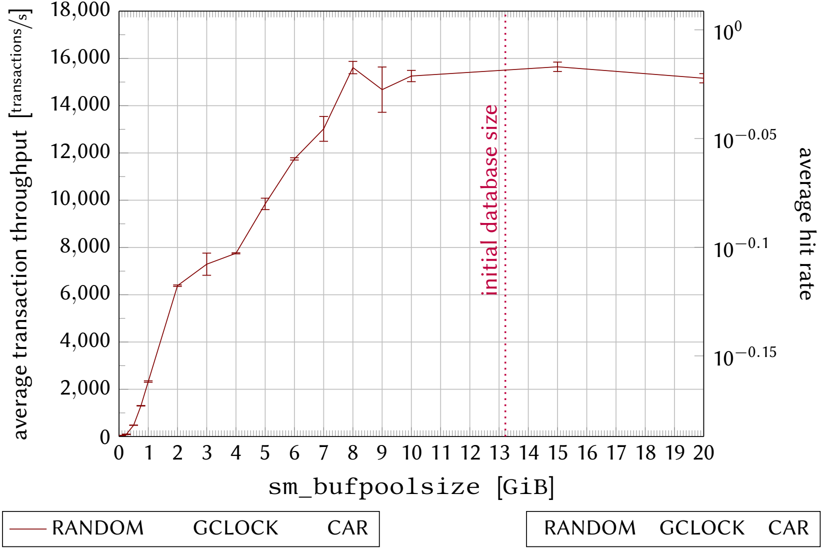
Subsection 3

Performance Evaluation

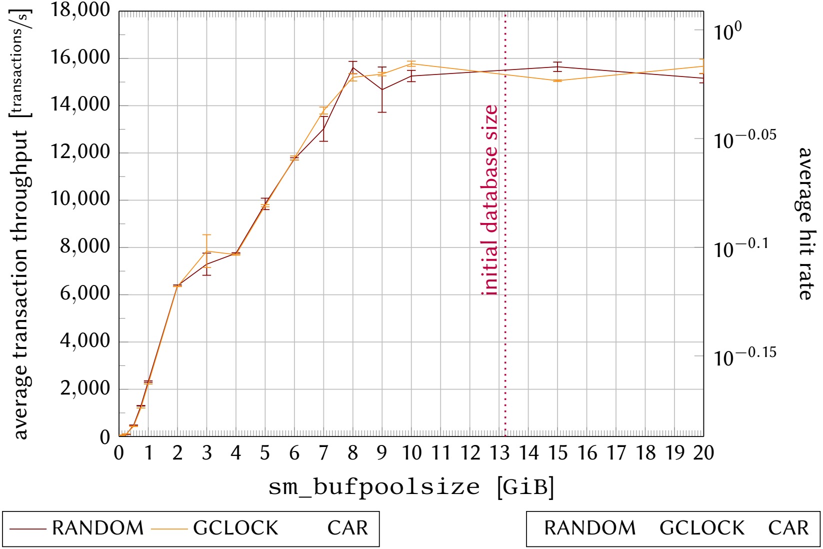
Buffer Pool Without Pointer Swizzling (TPC-C)



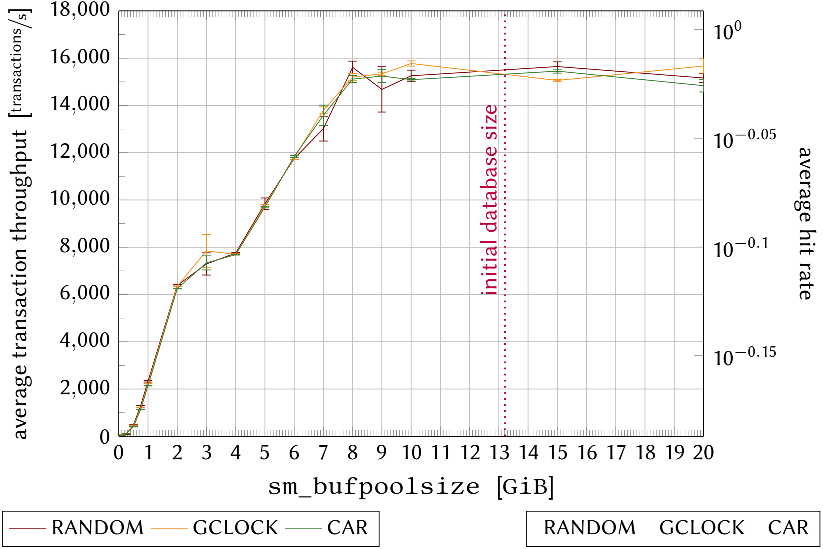
Buffer Pool Without Pointer Swizzling (TPC-C)



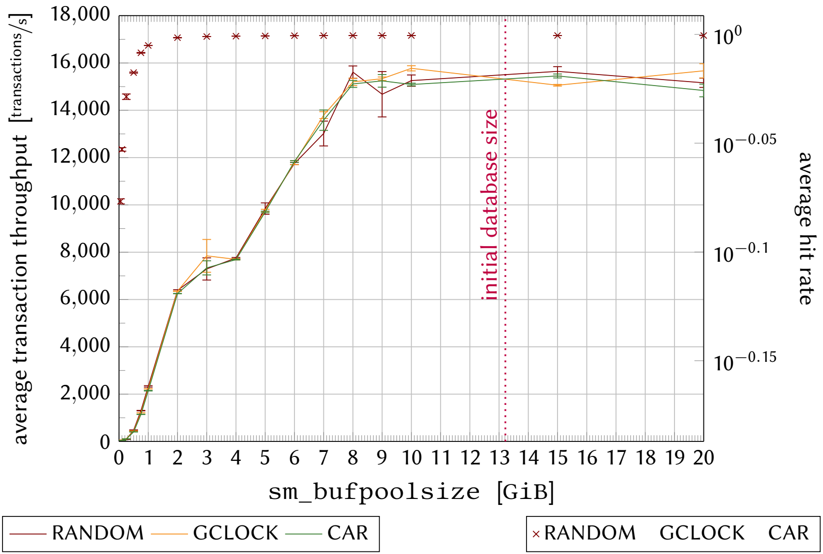
Buffer Pool Without Pointer Swizzling (TPC-C)



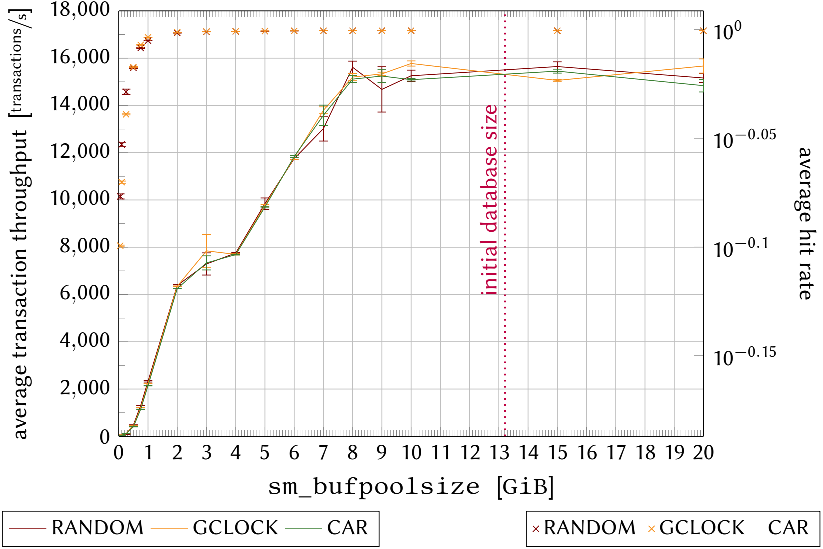
Buffer Pool Without Pointer Swizzling (TPC-C)



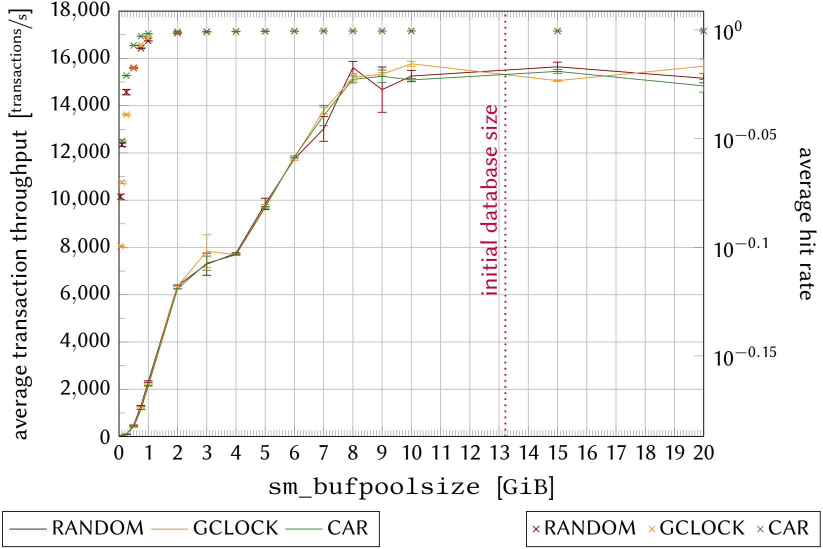
Buffer Pool Without Pointer Swizzling (TPC-C)



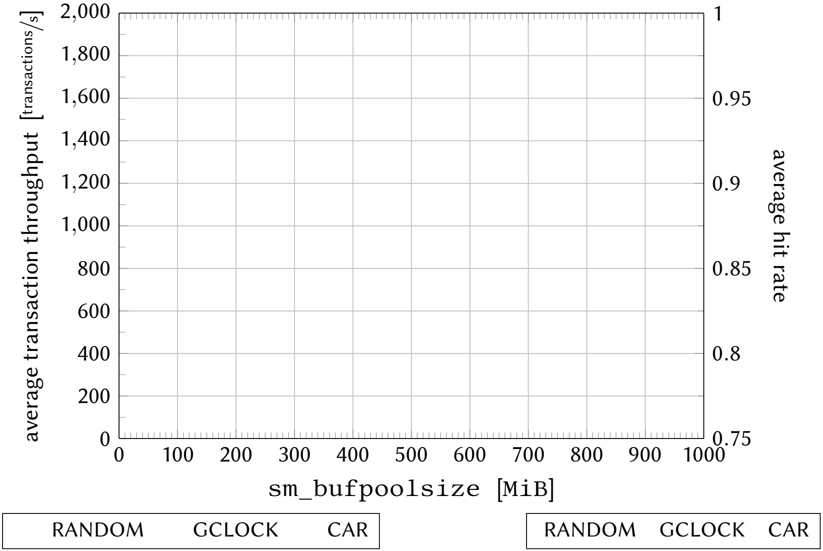
Buffer Pool Without Pointer Swizzling (TPC-C)



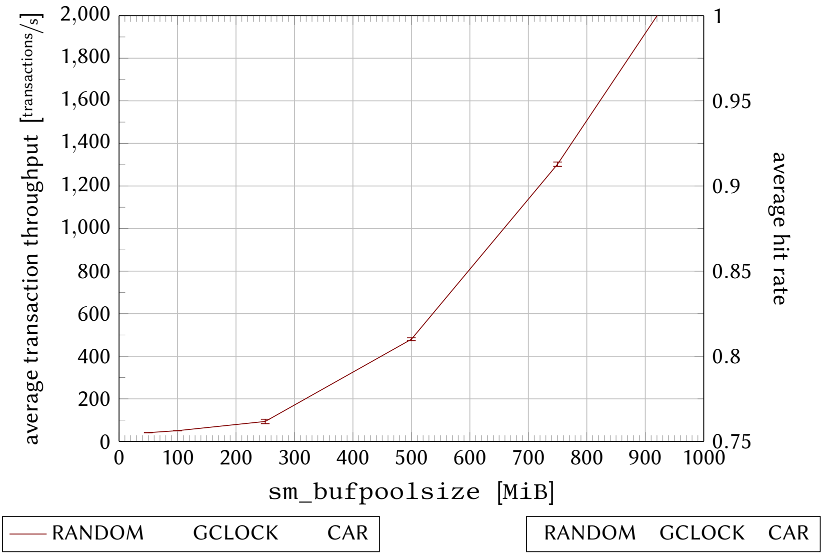
Buffer Pool Without Pointer Swizzling (TPC-C)



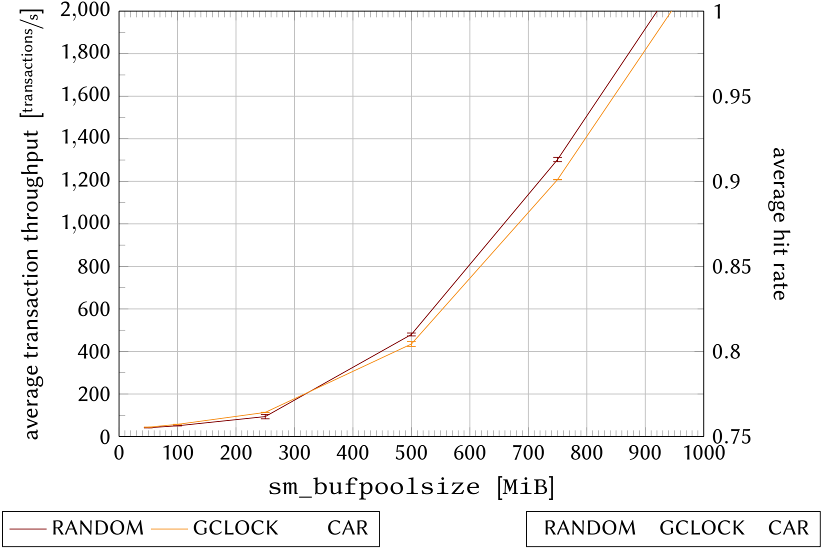
Buffer Pool Without Pointer Swizzling ($\leq$1 GiB, TPC-C)



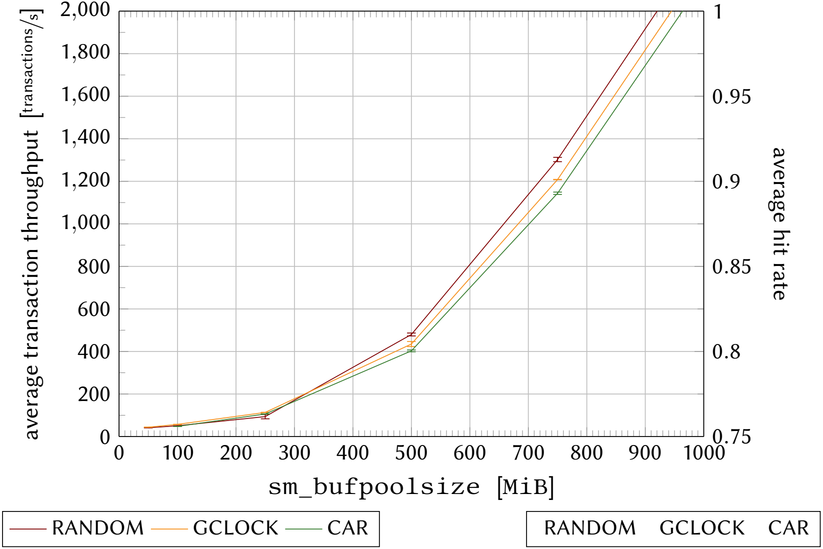
Buffer Pool Without Pointer Swizzling (≤1 GiB, TPC-C)



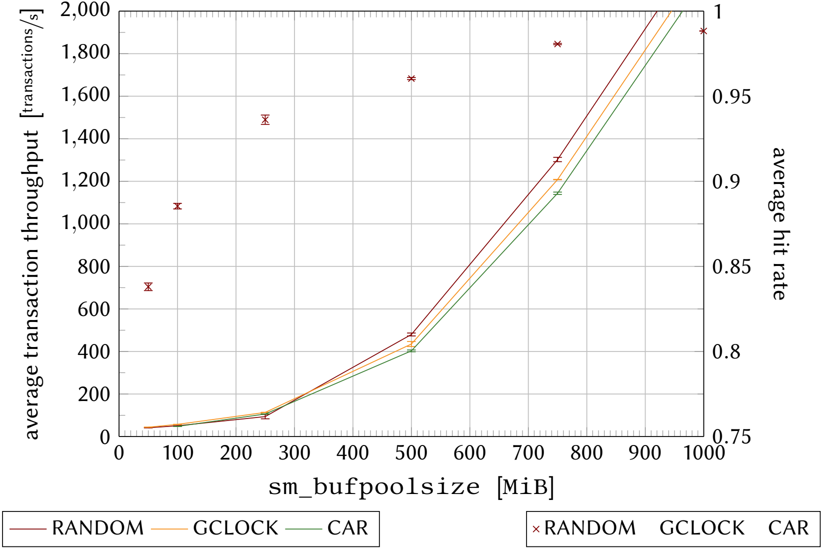
Buffer Pool Without Pointer Swizzling (≤1 GiB, TPC-C)



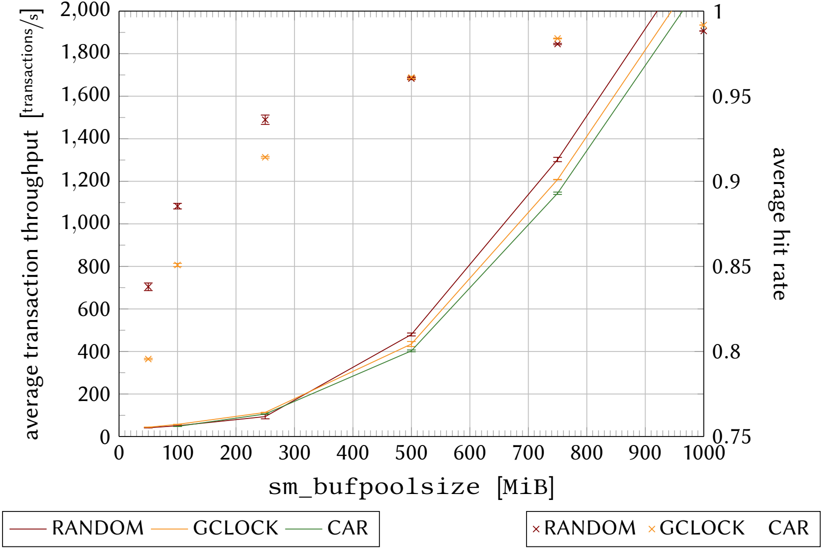
Buffer Pool Without Pointer Swizzling (≤1 GiB, TPC-C)



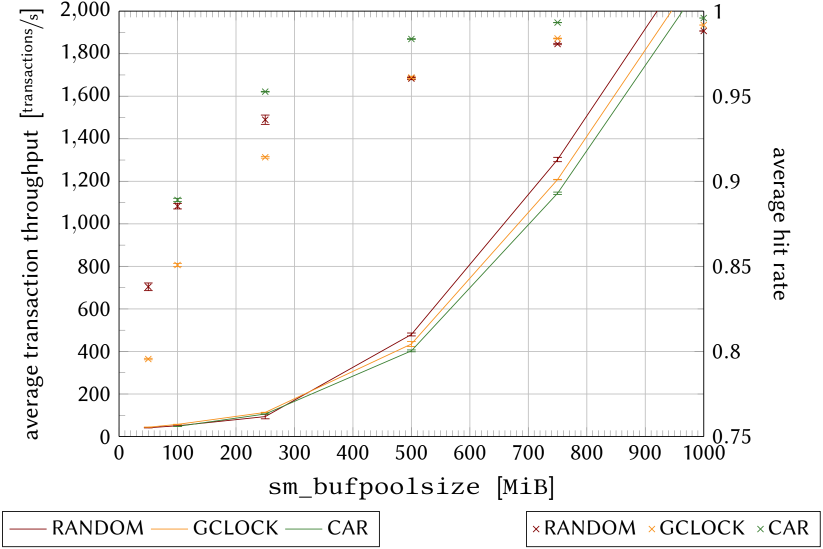
Buffer Pool Without Pointer Swizzling (≤1 GiB, TPC-C)



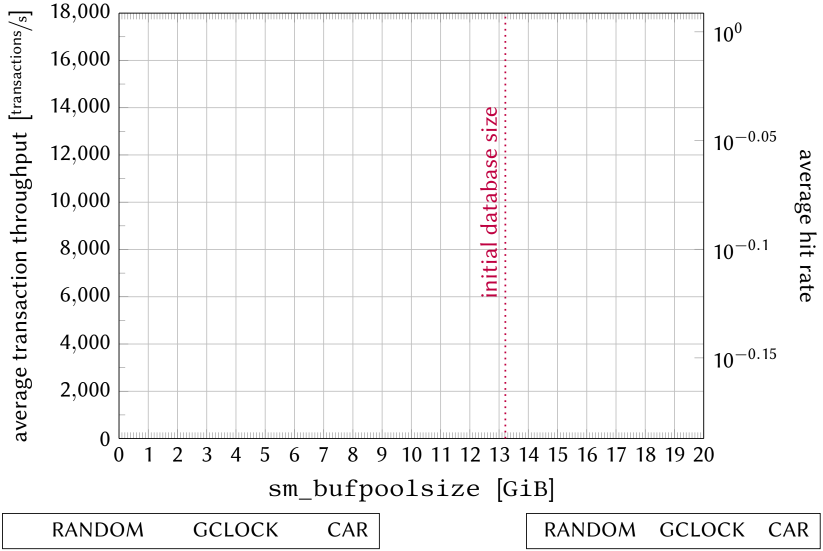
Buffer Pool Without Pointer Swizzling (≤1 GiB, TPC-C)



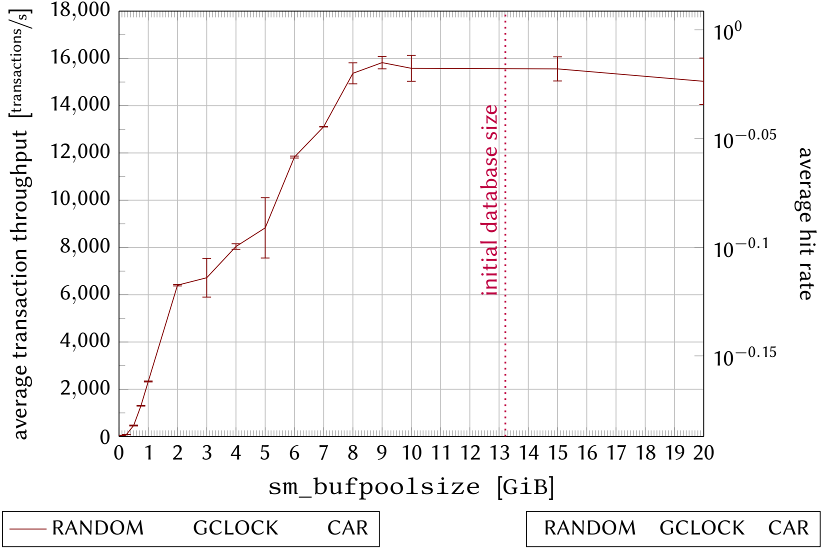
Buffer Pool Without Pointer Swizzling (≤1 GiB, TPC-C)



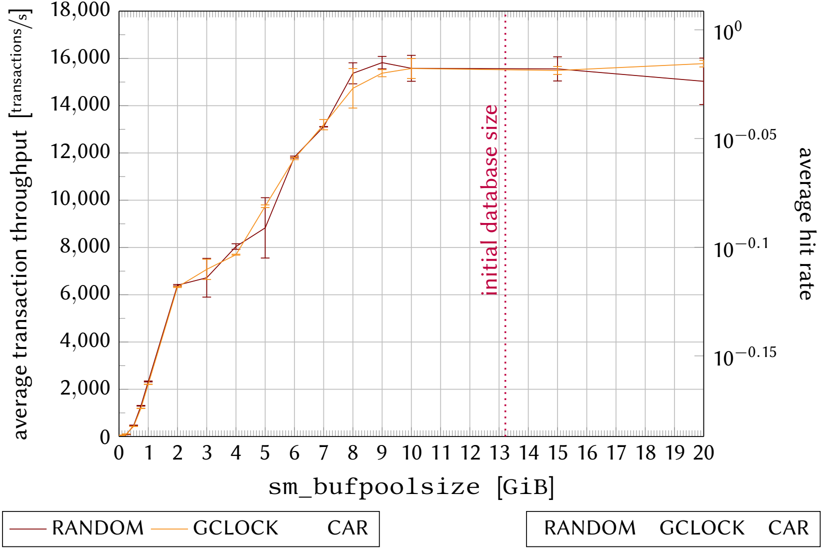
Buffer Pool With Pointer Swizzling (TPC-C)



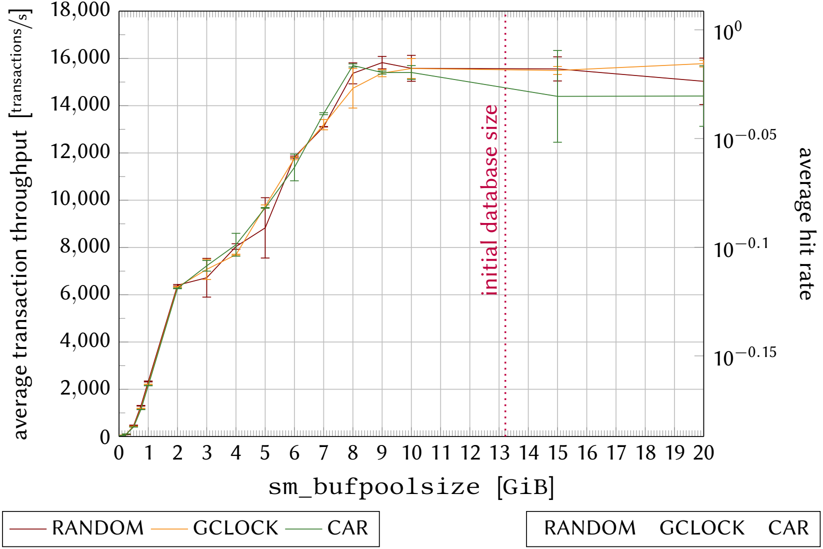
Buffer Pool With Pointer Swizzling (TPC-C)



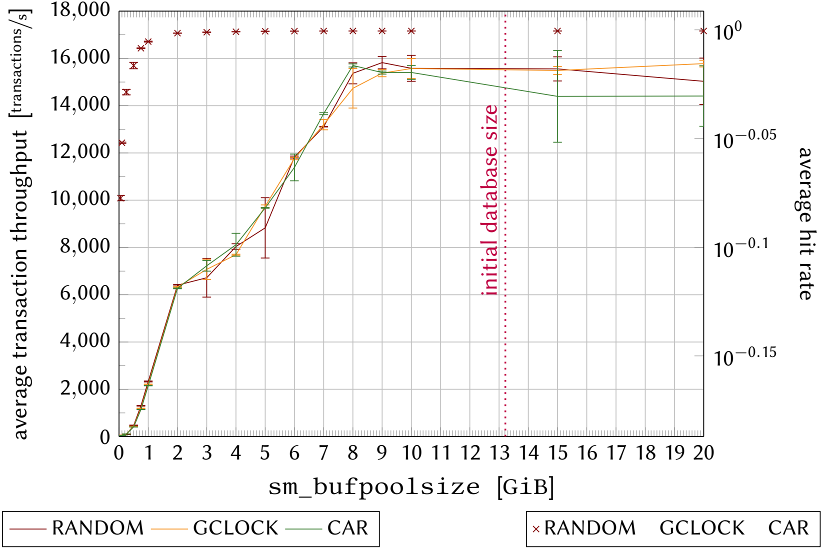
Buffer Pool With Pointer Swizzling (TPC-C)



Buffer Pool With Pointer Swizzling (TPC-C)



Buffer Pool With Pointer Swizzling (TPC-C)



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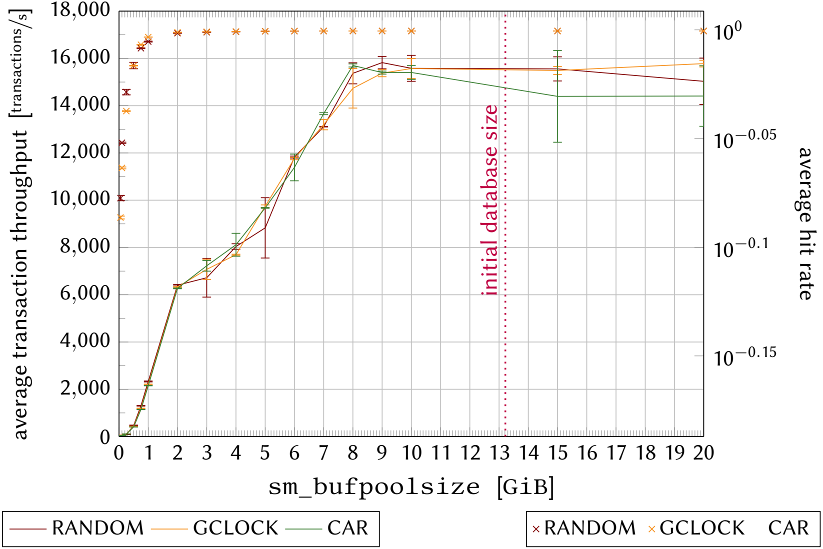
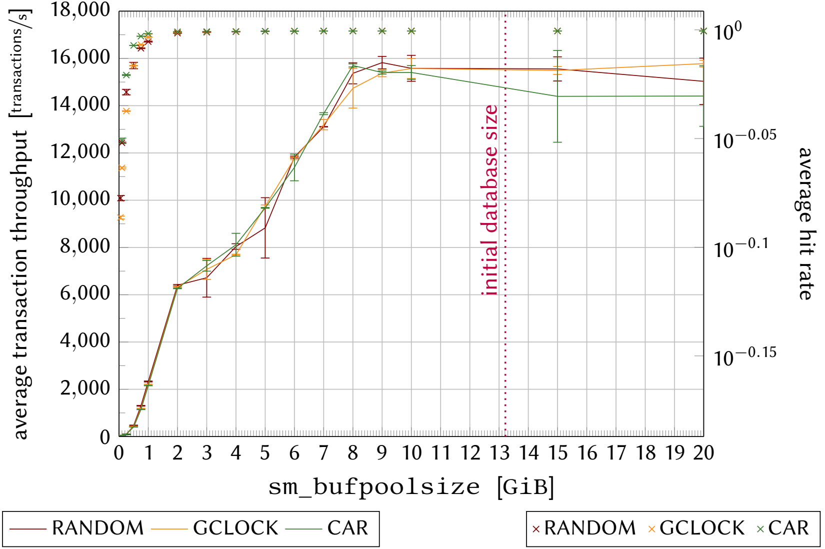
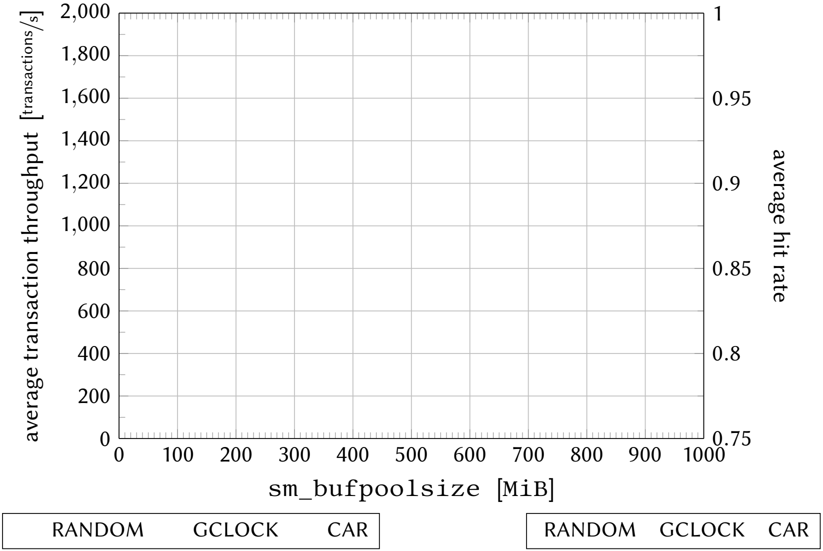


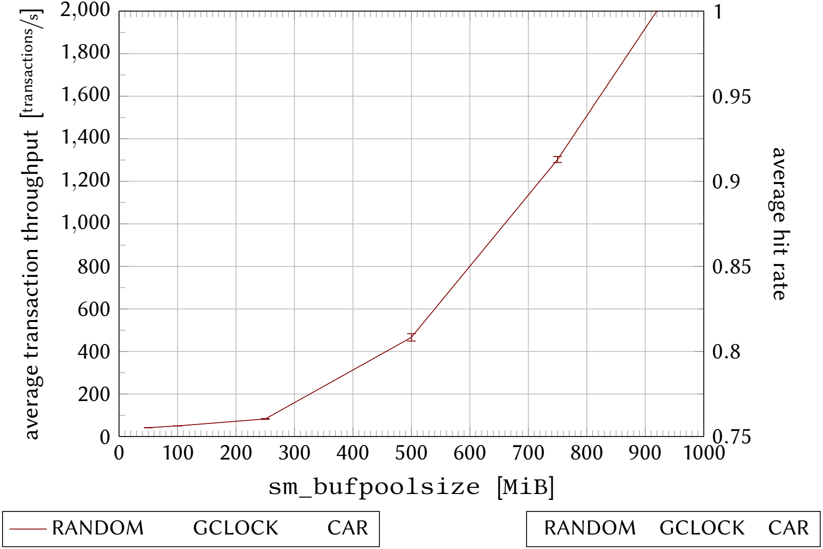
Buffer Pool With Pointer Swizzling (TPC-C)



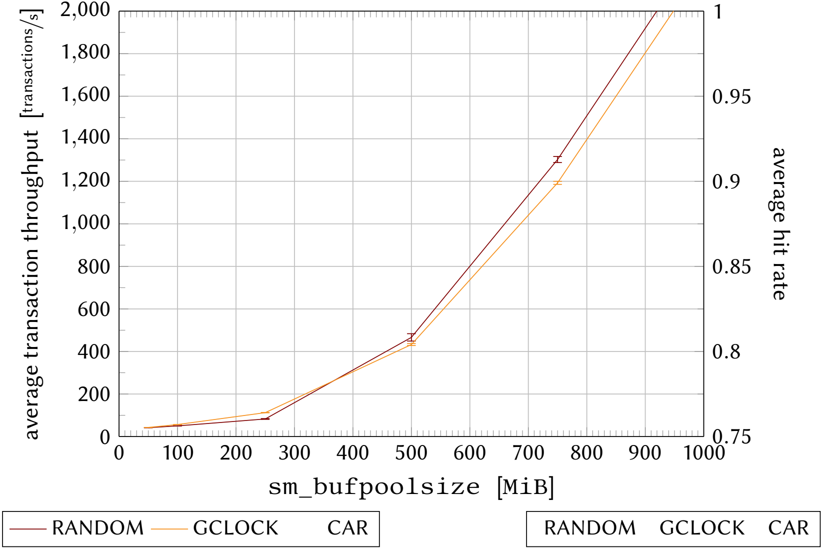
Buffer Pool With Pointer Swizzling (≤1 GiB, TPC-C)



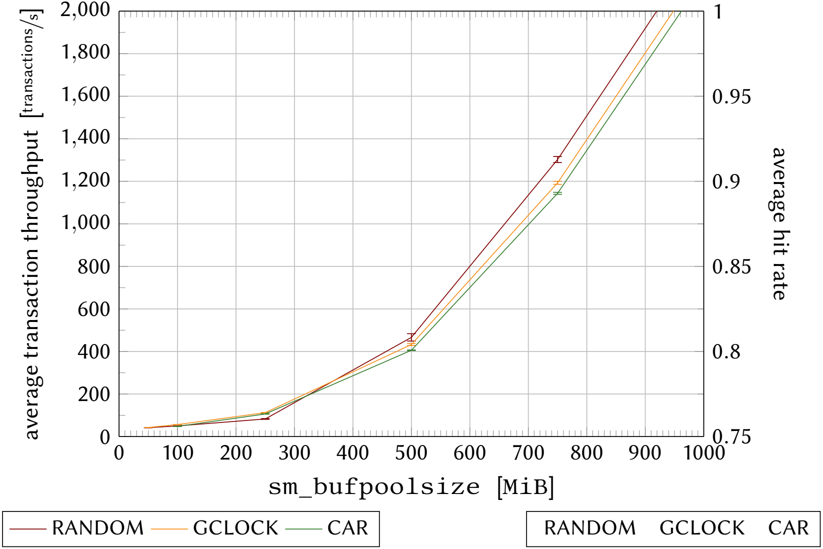
Buffer Pool With Pointer Swizzling (≤1 GiB, TPC-C)



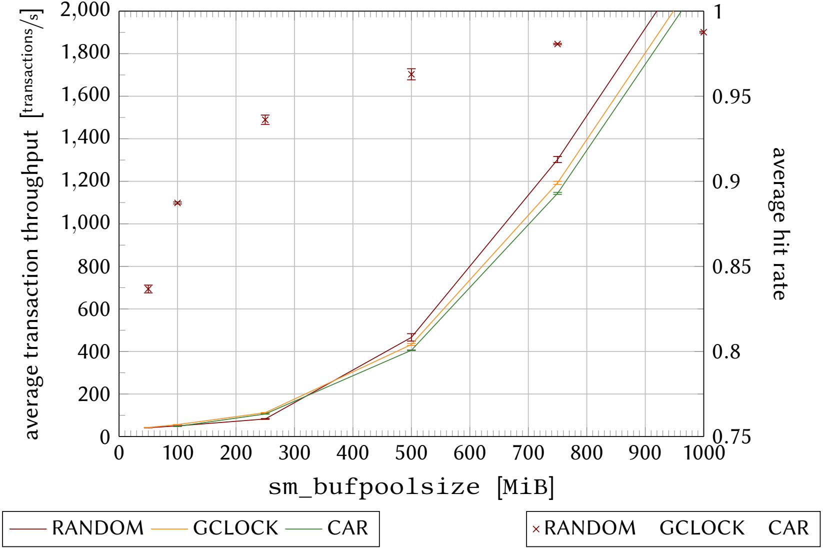
Buffer Pool With Pointer Swizzling (≤1 GiB, TPC-C)



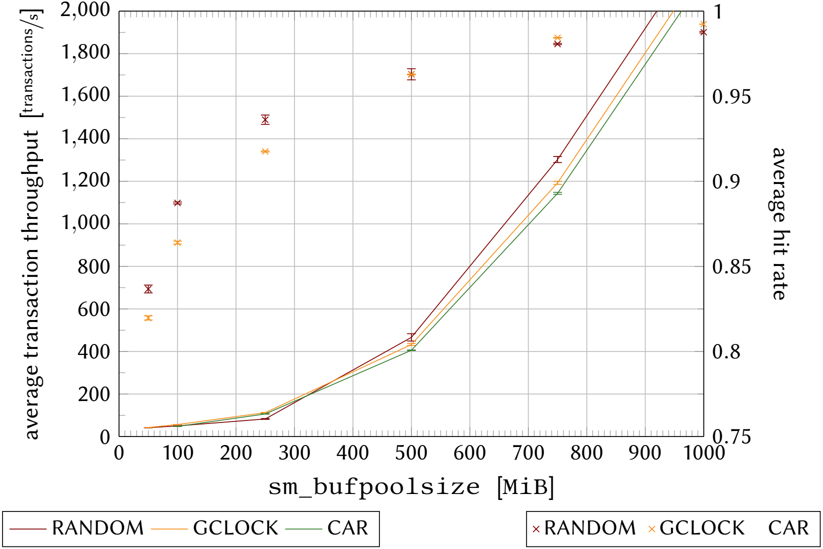
Buffer Pool With Pointer Swizzling (≤1 GiB, TPC-C)



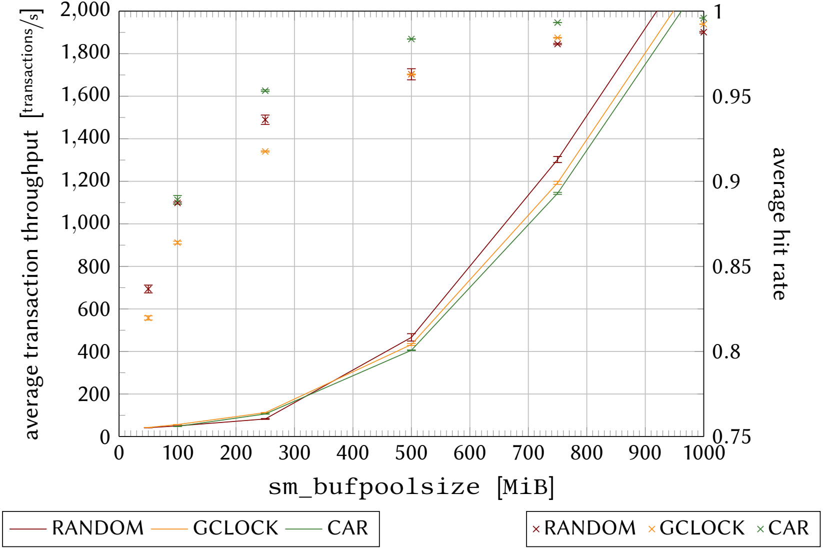
Buffer Pool With Pointer Swizzling (≤1 GiB, TPC-C)



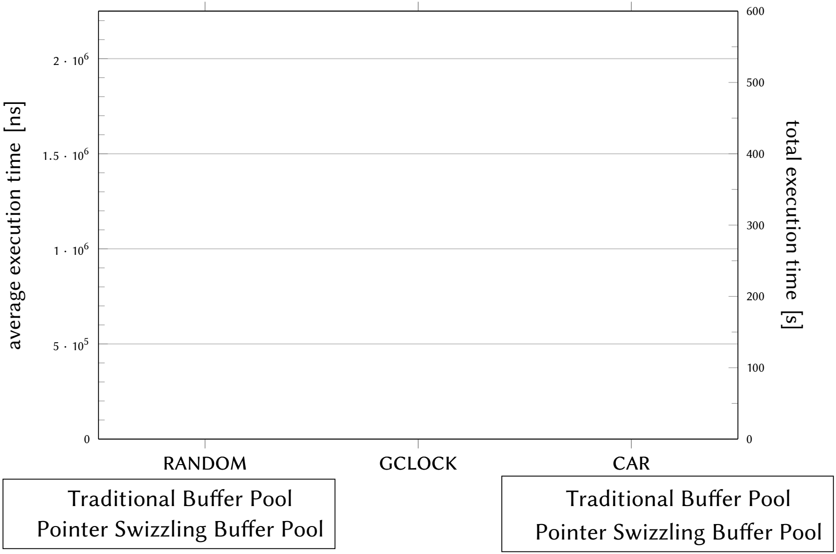
Buffer Pool With Pointer Swizzling (≤1 GiB, TPC-C)



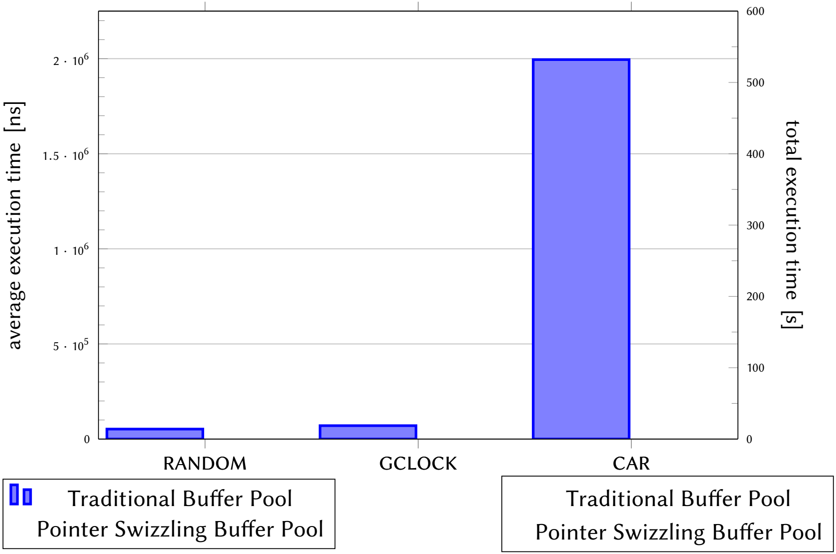
Buffer Pool With Pointer Swizzling (≤1 GiB, TPC-C)



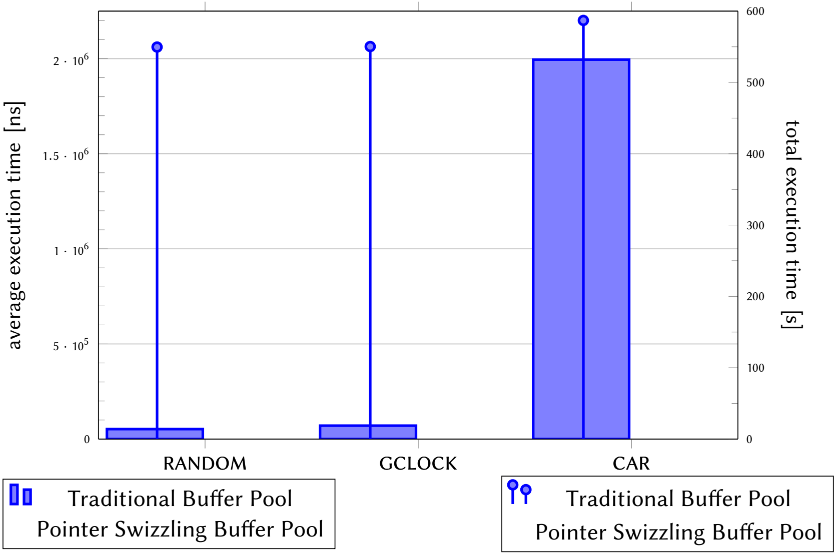
Operation Performance



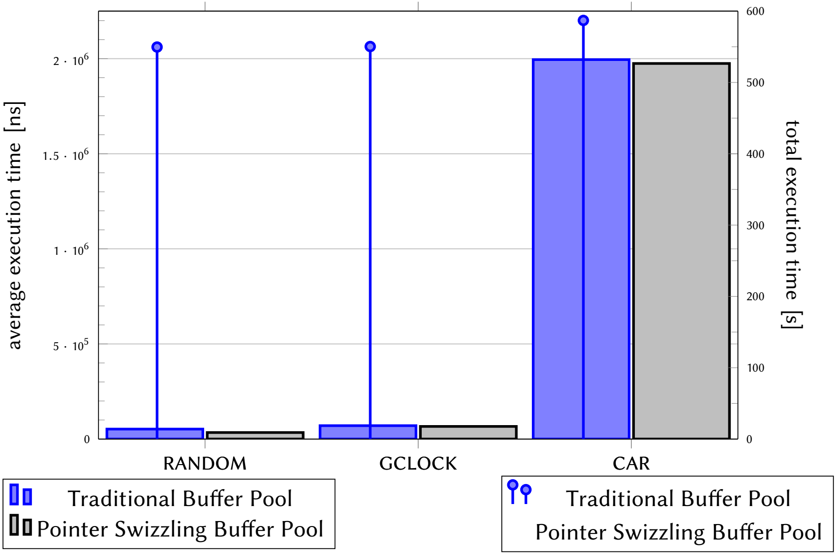
Operation Performance



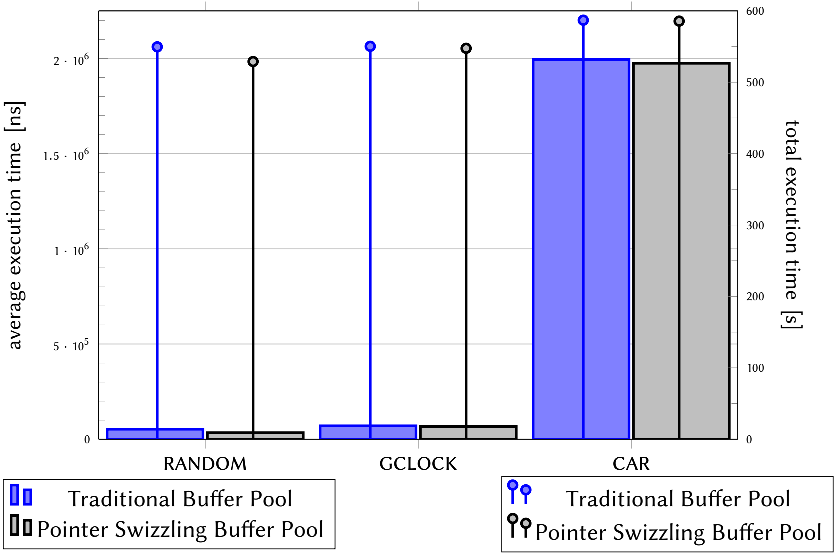
Operation Performance



Operation Performance



Operation Performance



Subsection 4

Conclusion

Conclusion

Performance

Conclusion

Performance

- CAR has a significantly higher hit rate than RANDOM or GCLOCK

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- The hit rate of GCLOCK isn't significantly higher than the one of RANDOM

Conclusion

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- The hit rate of GCLOCK isn't significantly higher than the one of RANDOM
- Major differences in hit rate are only for buffer pool sizes of $\leq \frac{1}{10}$ of the database size

Conclusion

Performance

- CAR has a significantly higher hit rate than RANDOM or GCLOCK
- The hit rate of GCLOCK isn't significantly higher than the one of RANDOM
- Major differences in hit rate are only for buffer pool sizes of $\leq \frac{1}{10}$ of the database size
- The computational effort spent to do CAR eviction is 27–58 times higher

Conclusion

Performance

- CAR has a significantly higher hit rate than RANDOM or GCLOCK
- The hit rate of GCLOCK isn't significantly higher than the one of RANDOM
- Major differences in hit rate are only for buffer pool sizes of $\leq \frac{1}{10}$ of the database size
- The computational effort spent to do CAR eviction is 27–58 times higher
- The overall performance of CAR isn't better than the one of RANDOM or GCLOCK

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