DB 2

06 – Buffering and Caching

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1 Memory: Fast, But Tiny vs. Slow, But Large

- Recall the enormous **latency gaps** between accesses to the (L2) CPU cache, RAM, and secondary storage (SSD/HDD):

Memory	Actual Latency ⌛	Human Scale	Typical Size
CPU L2 cache	2.8 ns	7 s	$\frac{1}{4}$–16 MB
RAM	≈ 100 ns	4 min	4–256 GB
SSD	50–150 µs	1.5–4 days	$\frac{1}{2}$–4 TB
HDD	1–10 ms	1–9 months	1–16 TB

- Facts: faster memory is significantly smaller. We will not be able to build cache-only systems.
  - The lion share of data will live in slow memory.
  - Only selected data fragments may reside in fast memory. **Which fragments shall we choose?**

Spatial Locality

- In a DBMS (and most computing processes), **memory accesses are not random** but exhibit patterns of **spatial and/or temporal locality:**

1. **Spatial locality:** last memory access at address m, next access will be at address $m \pm \Delta m$ (Δm small).

- Often, $\Delta m \equiv$ machine word size: backward/forward scan of memory, i.e., iteration over an array.
- Block I/O does access and read data at m and its vicinity: |block accesses| « |memory accesses| 👍

Temporal Locality

2. **Temporal locality:** last memory access at *m* at time *t*, next access at *m* will be at time $t + \Delta t$ (Δt small).

   Memory that is relevant now will probably be relevant in the near future ⇒ DBMS **tracks frequency and recency of memory usage.** Uses both to decide whether to hold a page in fast memory.

   Found on multiple levels (concerns PgSQL *and* MonetDB):

Fast Memory	Slow Memory	Fast/Slow Size[1]
RAM	SSD / HDD	$^1/_{32}$
CPU L2 cache	RAM	$^1/_{16384}$
CPU L1 cache	CPU L2 cache	$^1/_{64}$

[1] Specified for this MacBook Pro (CPU Apple® M2 Max, 64/4096 KB L1/L2 cache, 64 GB RAM, 2 TB SSD).

Q_5 (Set of Queries) — Locality of References

Can the DBMS benefit if the **query workload** (≡ set of typical queries submitted to the DBMS) contains repeated data references, close in time?

```
◷=t₀:    SELECT t.a, t.b FROM ternary AS t;
◷=t₀+Δt: SELECT s.a, s.c FROM ternary AS s;
  ⋮
```

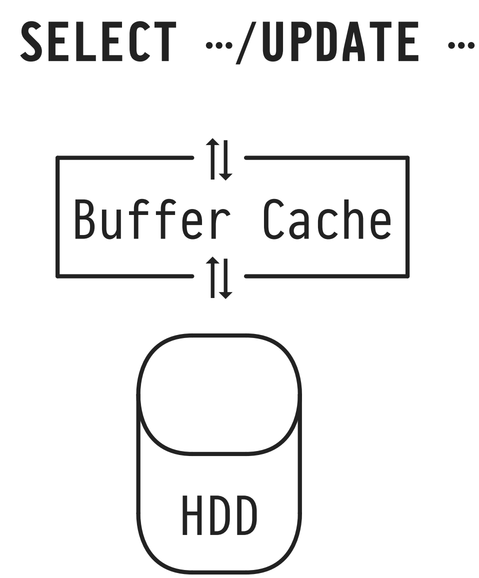
Set of referenced data pages overlap. We hope that I/O effort invested for earlier queries may benefit subsequent operations.

The Buffer Cache

The DBMS sets aside a dedicated section of RAM — the **buffer cache** (or simply **buffer**) — to temporarily hold pages.

- *All* DBMS page accesses are performed using the buffer ⇒ can track page usage.

- |buffer| << |RAM|. In PostgreSQL, see config variable shared_buffers (defaults to 128MB). Good practice: buffer size ≈ 25% of RAM.



Buffer Cache Interface (API)

- Any database transaction properly “brackets” page accesses using ReadBuffer() and ReleaseBuffer() calls:

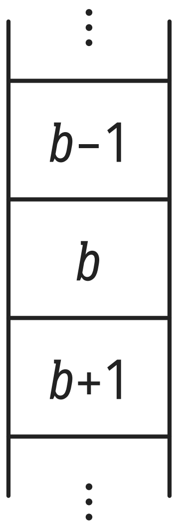
```
‹b,m› ← ReadBuffer(table, block);
  /* now may access 8 KB page starting at address m */
  ⋮
if (page at m has been written to)
 ⌊ MarkBufferDirty(b);
  ⋮
ReleaseBuffer(b);
  /* accesses to address m illegal from here on */
```

- Proper bracketing enables the DBMS to perform bookkeeping of buffer contents.

Buffer Page Bookkeeping

- Each page in the buffer is associated with meta data that reflects is current utility for the DBMS:

buffer pages



buffer descriptor

- ref_count(b) ⩾ 0: how often has this page been requested via ReadBuffer()?
- usage_count(b) ⩾ 0: how many r/w operations have been performed on this page?
- dirty?(b): does memory on this page differ from its disk image?

- ref_count(b) also commonly known as the *pin count of b*.

Reading a Buffer Page: Hit vs. Miss

```
ReadBuffer(table, block):
  if (a buffer page b already contains block of table)
  | ref_count(b) ← ref_count(b) + 1;
  | return ‹b, address of b's page›;      /* hit: no I/O */
  else                                    /* miss: I/O needed */
  | v ← free buffer page;                              /* ❶ */
  | if (there is no such free v)
  | | v ← FindVictimBufferPage();                      /* ❷ */
  | | if dirty?(v)
  | ⌊   ⌊ write page in v to disk block;
  | read requested block from disk into page of v;
  | ref_count(v) ← 1;
  | dirty?(v) ← false;
  ⌊ return ‹v, address of v's page›;
```

Clean vs. Dirty Buffer Pages

- Read-only transactions leave buffer pages **clean.** Clean victim pages may simply be overwritten when replaced.

- Marking buffer page *b* **dirty** (i.e., written to/altered):

```
MarkBufferDirty(b):
  dirty?(b) ← true;
```

- In regular intervals, the DBMS writes dirty buffer pages back (**checkpointing**) to match memory and disk contents.[2]
  - Checkpointing may lead to heavy I/O traffic.

[2] PostgreSQL: see config variable checkpoint_timeout (default: '5min'). SQL command CHECKPOINT forces immediate checkpointing.

Releasing a Buffer Page

- Release buffer page *b*. If ref_count(*b*) > 0, *b* is called **pinned**. If ref_count(*b*) = 0, *b* is **unpinned**:

```
ReleaseBuffer(b):
   ref_count(b) ← ref_count(b) - 1;              /* no I/O */
```

  - ⚠️ ReleaseBuffer() does *not* write the page of *b* back to disk, even if *b* is unpinned and dirty. **Quiz:** Why?
  - Any pinned buffer page is in active use by some transaction and thus may *never* be chosen as a victim for replacement.

Inspect Dynamic Buffer Behavior

PostgreSQL offers extension pg_buffercache, providing a tabular view[3] of the system's buffer cache descriptors:

```
SELECT b.bufferid, b.relblocknumber, b.isdirty, b.usagecount
FROM   pg_buffercache AS b
[ WHERE  b.relfilenode = ‹tbl› ];   -- focus on table ‹tbl› only
```

bufferid	relblocknumber	isdirty	usagecount
269	0	f	1
270	1	t	1
⋮	⋮	⋮	⋮

[3] N.B.: This is only a tabular representation of the buffer descriptors. Internally, the buffer and its descriptors are implemented as C arrays.

EXPLAIN: Buffer Hits and Misses

EXPLAIN can be instructed to show whether the DBMS experienced **buffer hits or misses** during query evaluation:

```
db2=# EXPLAIN (ANALYZE, BUFFERS, ‹opt›, ...) ‹Q›

┌──────────────────────────────────────────────────────┐
│                      QUERY PLAN                      │
├──────────────────────────────────────────────────────┤
│  ⋮                                                   │
│  Buffers: shared read=m ← I/O needed ≡ miss          │
│  ⋮                                                   │
│  Buffers: shared hit=h  ← page found in buffer, no I/O │
│  ⋮                                                   │
```

2 ┆ Picking a Free Buffer Page

After a buffer miss, **pick a buffer slot** that will hold the new to-be-loaded page from disk:

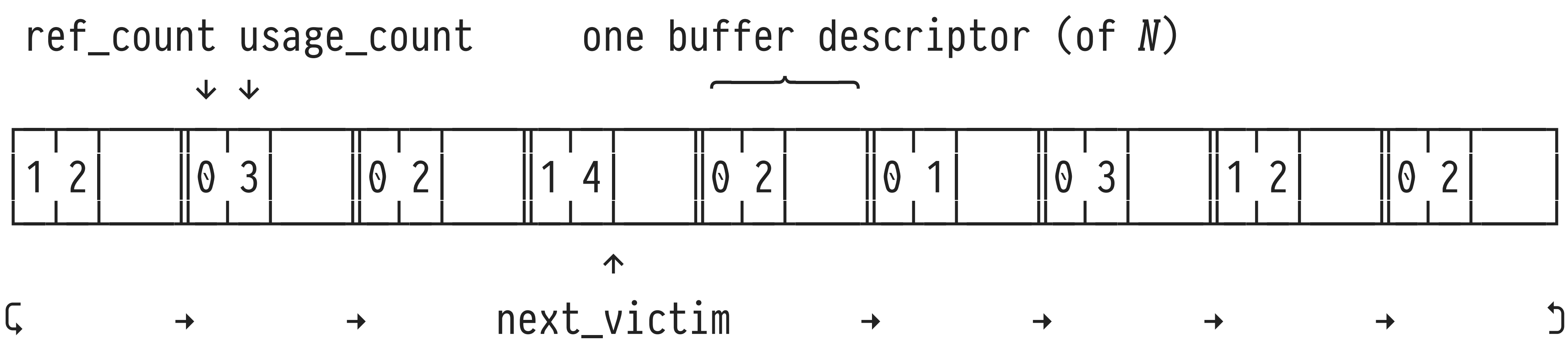
1. If the **free list** of buffer slots is non-empty, remove its head slot *v*. Pick *v* (see ❶ in ReadBuffer()).
   Buffer slot appended to free list when
   - database server (and buffer manager) starts up, or
   - a table or an entire database is dropped (DROP …).

2. If free list is empty, use the **buffer replacement policy** to identify a **victim page** *v*. Pick *v* (see ❷).

A Replacement Policy: Clock Sweep (≈ LRU)

Heuristic: The **least recently used (LRU)** page is a good victim *v* to pick. We assume *v* remains unused from now on. One approximation of LRU is **Clock Sweep:**

- Arrange buffer descriptors in a *circular* array (“clock”).
- Repeatedly “sweep” pointer next_victim through array:

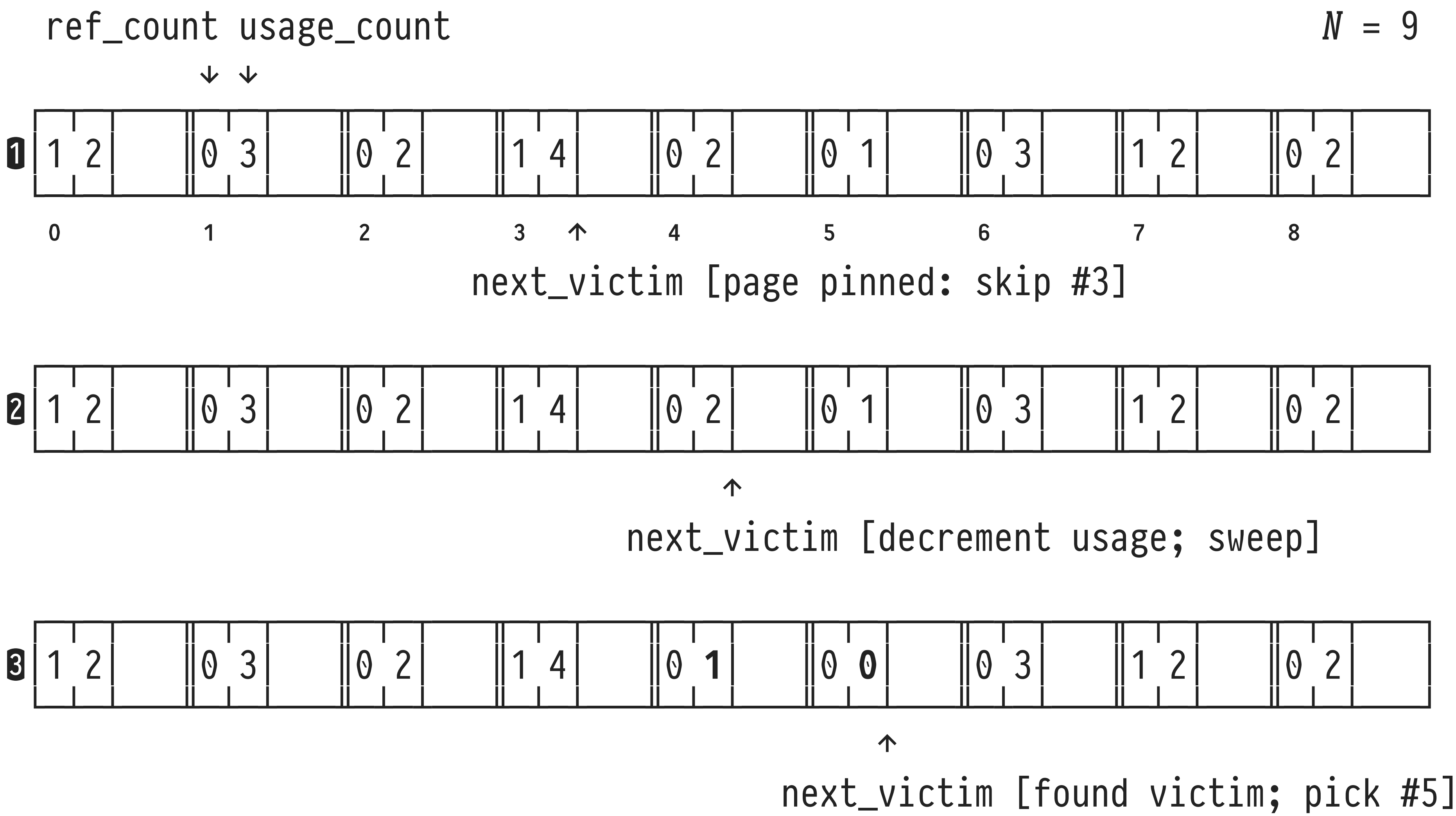


Clock Sweep

```
FindVictimPage():
  try ← 0;
  while (try < N)          /* one full round w/o progress? */
  | v ← buffers[next_victim];
  | if (ref_count(v) = 0)                     /* unpinned? */
  | | usage_count(v) ← usage_count(v) - 1;
  | | if (usage_count(v) = 0)         /* unpopular page? */
  | |  ⌊ return v;                       /* victim found */
  | | try ← 0;
  | else
  |  ⌊ try ← try + 1;
  ⌊ next_victim ← (next_victim + 1) % N;  /* skip/sweep */
  return out-of-buffer-space-↯;
```

- **N.B.:** usage_count() of pages may increase asynchronously.

Clock Sweep: Example



Challenges for LRU

LRU is a **heuristic** and may fail in specific scenarios. Consider:

1. Assume a 100-page index I with pages I_k and a table R with 10000 pages R_j. We repeatedly use I to look up rows in R. The **page access pattern** will be I_1, R_1, I_2, R_2, I_3, R_3, …
   Q: How will an LRU buffer of 100 slots operate? **A:** ✎

2. Transactions T_1, T_2, … access the same small fragment of the database. Transaction T_0 performs a *sequential scan* of a large table (think `SELECT * FROM wide_100M`).

More Page Replacement Heuristics

Other heuristics have been proposed to account for DBMS-specific page reference patterns:

- **LRU-*k*:** Like LRU, but consider the time passed between the *k* latest references to a page (typically, $k = 2$).
- **MRU** (most recently used): Replace the page that has been used just now.
- **Random:** Pick a victim randomly. (Straightforward implementation 👍.)

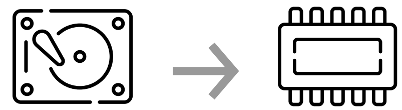
Q: What are the rationales behind these policies? **A:** ✎

Variants of LRU: Ring Buffering

PostgreSQL: To protect (small or busy) buffers from being "swamped" by large sequential scans, adopt a **ring buffering strategy**:

- SQL commands that may swamp the buffer:
  - SELECT … FROM *T* (if *T* larger than $\frac{1}{4} \times$ shared_buffers pages),
  - COPY *T* FROM …, CREATE TABLE *T* AS *Q*, ALTER TABLE *T* …,
  - VACUUM.
- If command may swamp the buffer:
  1. Use **ring buffer** of size $\leqslant \frac{1}{8} \times$ shared_buffers pages.
  2. Release ring buffer immediately after use.

3 ┆ Q_5 (Set of Queries) — Locality of References



How will a main-memory-based DBMS benefit if the **query workload** (≡ set of typical queries submitted to the DBMS) contains repeated data references, close in time?

◷=t_0: **SELECT** t.a, t.b **FROM** ternary **AS** t;

◷=$t_0+\Delta t$: **SELECT** s.a, s.c **FROM** ternary **AS** s;

⋮

After the first query, the vectors for columns a, b are located in RAM or even the CPU cache. An additional DBMS-maintained buffer cache will *not* add value.

MMDBMS: Do *Not* Reimplement Caching

MMDBMS typically rely on the cache hierarchy already maintained by the underlying system:

- Recall: We use the OS' mmap(2) to map BATs from disk files into RAM ⇒ MMDBMS relies on the **OS file system buffer** to cache mapped file contents.

- Contents of RAM addresses accessed recently are found in the CPU's L2/L1 cache hierarchy ⇒ MMDBMS relies on **built-in CPU data cache replacement policies.**

Recall: It makes a significant difference whether accessed memory is present in the CPU data cache or only in RAM:

Operation	Actual Latency ⌛	Human Scale
CPU cycle	0.4 ns	1 s
L2 cache access	2.8 ns	7 s
RAM access	≈ 100 ns	4 min

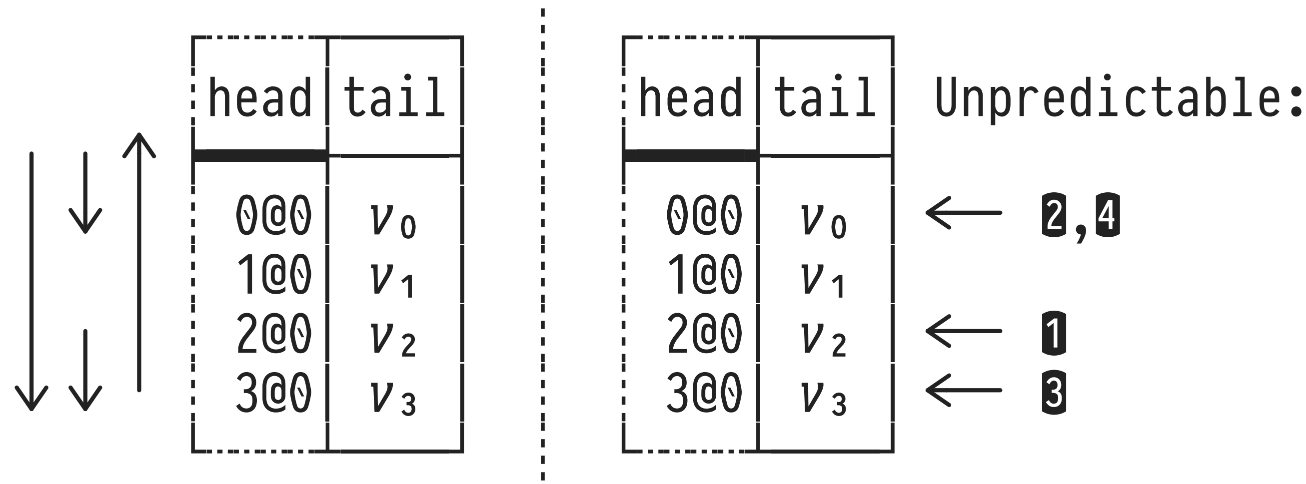
Excerpt of System Latencies (at Human Scale)

- Impact on MMDBMS implementation strategies:
    - When CPU has moved data from RAM into its cache, **make the best use of all that data:** data vectors / BATs. 👍
    - If possible, use **simple memory access patterns** such that CPU can **predict** which addresses are needed next.

Predictable Memory Access

Predictable access patterns:

- forward scans (possibly with skips)
- backward scans



- Predictable: CPU issues **asynchronous memory prefetch operations** to preload data cache and hide memory latency.
- Unpredictable: DBMS code adds explicit **software prefetch instructions**[4] for addresses needed in the future.

[4] No-ops with side effect on CPU cache, e.g. prefetcht1, loads data into L2 cache on Intel® Core i7.

Predictable (Sequential) File Access

Likewise, there is limited support to **inform the OS file system buffer** that future block references will be regular:

- Use madvise(2) to tune the OS's prefetching and caching strategy: “read/writes will be sequential (random)”, “blocks will definitely (not) be needed again”, *etc.*:

```
/* map file into memory */
map = mmap(NULL, size, PROT_READ, MAP_SHARED, fd, 0);
/* advise the OS that file access will be sequential */
madvise(map, size, MADV_SEQUENTIAL);
```

- **N.B.:** PostgreSQL asynchronously prefetches buffer pages via PrefetchBuffer(). Also see extension pg_prewarm.