PostgreSQL's IO subsystem: Problems, Workarounds, Solutions

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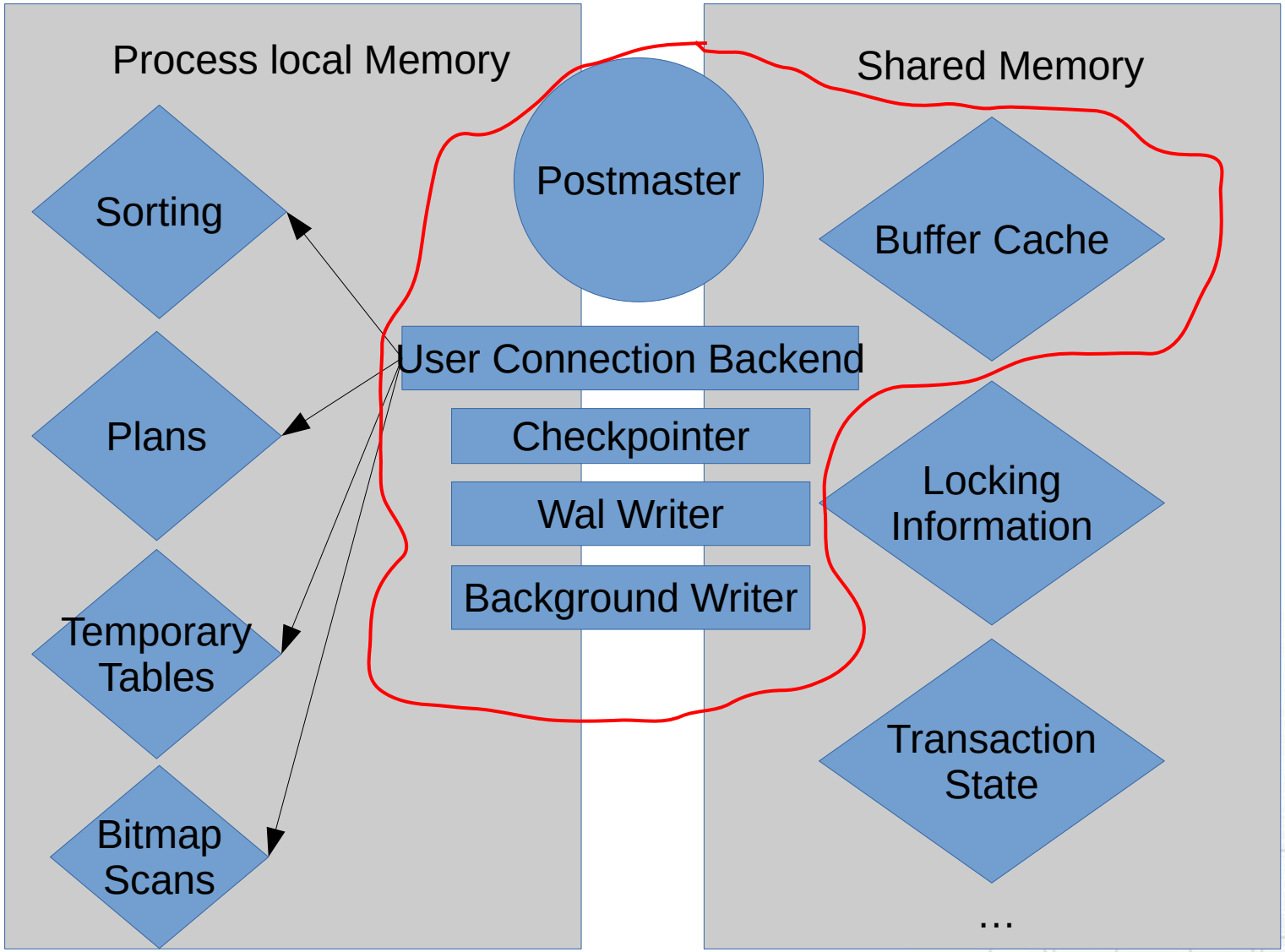
anarazel.de/talks/2019-09-13-pgopen-orlando-io/io.pdf

Memory Architecture



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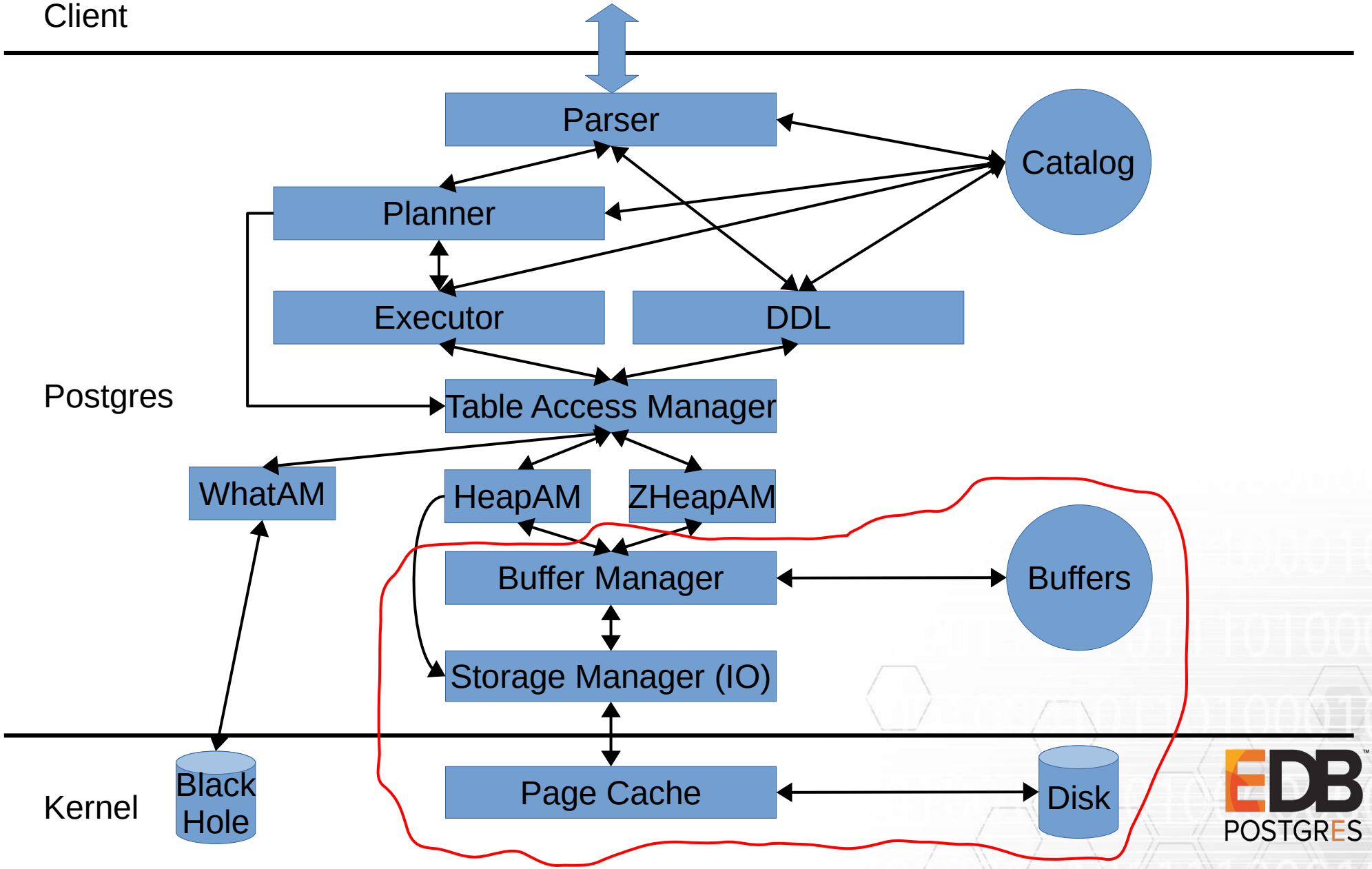

Client
Parser
Catalog
Planner
Executor
DDL
Postgres
Table Access Manager
WhatAM
HeapAM
ZHeapAM
Buffer Manager
Buffers
Storage Manager (IO)
Black Hole
Page Cache
Disk
Kernel

IO Performance

- Time till IO has finished
- CPU Overhead
  - polling IO, lots of threads, … can be faster, but eat a lot of CPU
- Synchronous Blocking Operation
  - buffered writes: often nonblocking
  - buffered reads: commonly blocking
  - non-buffered writes: blocking & asynchronously
  - non-buffered read: blocking & asynchronously
- Efficiency of IO internally to the drive
  - sequential writes faster than random writes
  - operations covering larger “blocks” of data usually faster

What Is What

- Backends
  - client connection, or “worker” for parallel query processing
- Checkpointer
  - writes out dirty data once every checkpoint_timeout
  - sorts data before writeout
  - allows to remove / recycle WAL
- Background Writer
  - tries to write out dirty buffers if needed by backends, i.e. working set bigger than memory
- WAL Writer
  - tries to write out WAL generated by backends
  - does most WAL writing when synchronous_commit = off
  - may do a fair bit of WAL writing when most transactions are longer

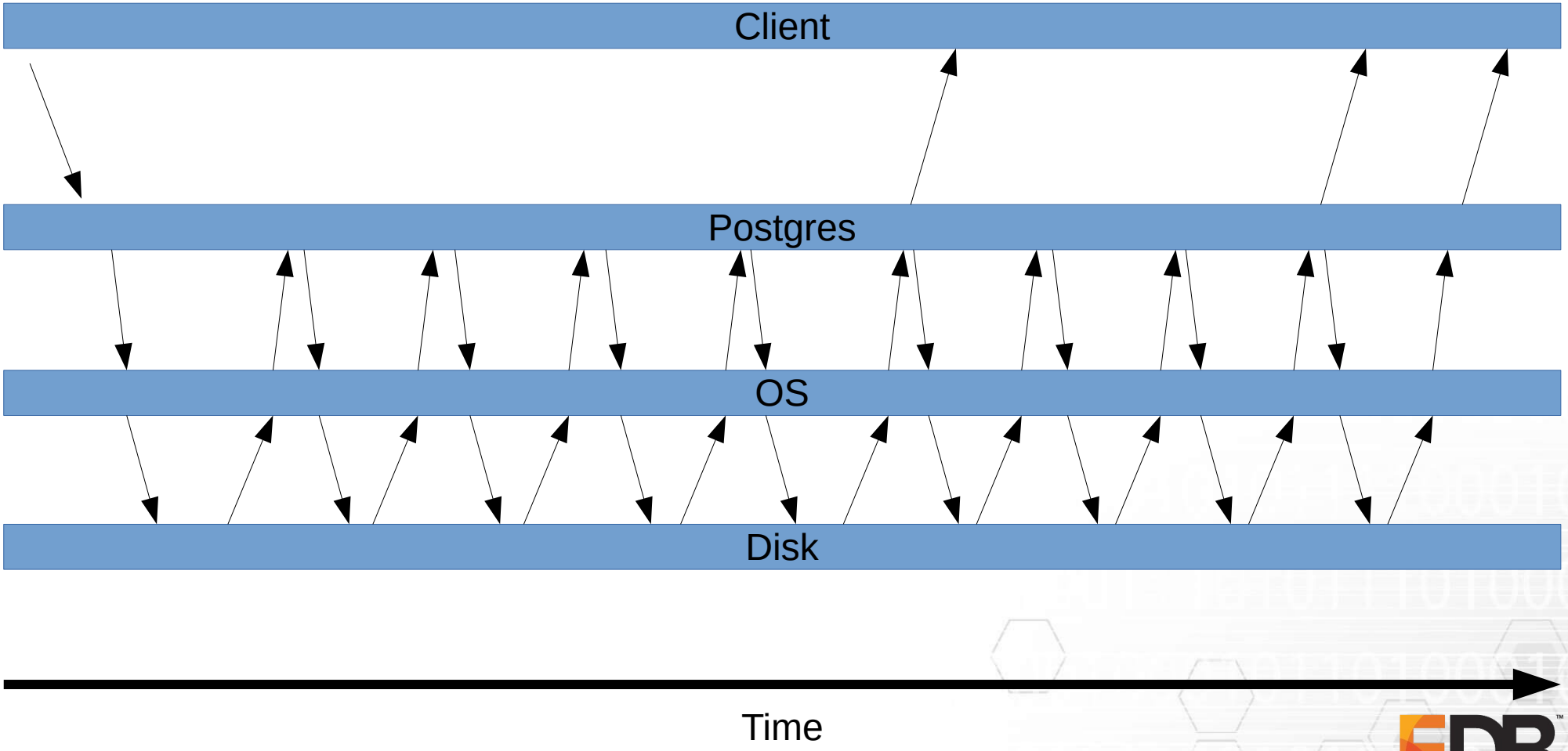
IO Properties

- Backends
  - Data:
    - synchronous random reads
    - read prefetches
    - sequential journal writes
    - under pressure: writeback
  - WAL
    - async append to pre-allocated journal
    - fdatasync on commit
- Checkpointer
  - Data:
    - paced ordered writes (in file order, with lots of gaps)
    - fsyncs all modified files
- Background Writer
  - Data:
    - “writeback”, allows cheap reuse of buffers
    - random writes
- WAL Writer
  - WAL
    - pre flushes WAL
    - commonly purely sequential (potential gaps)

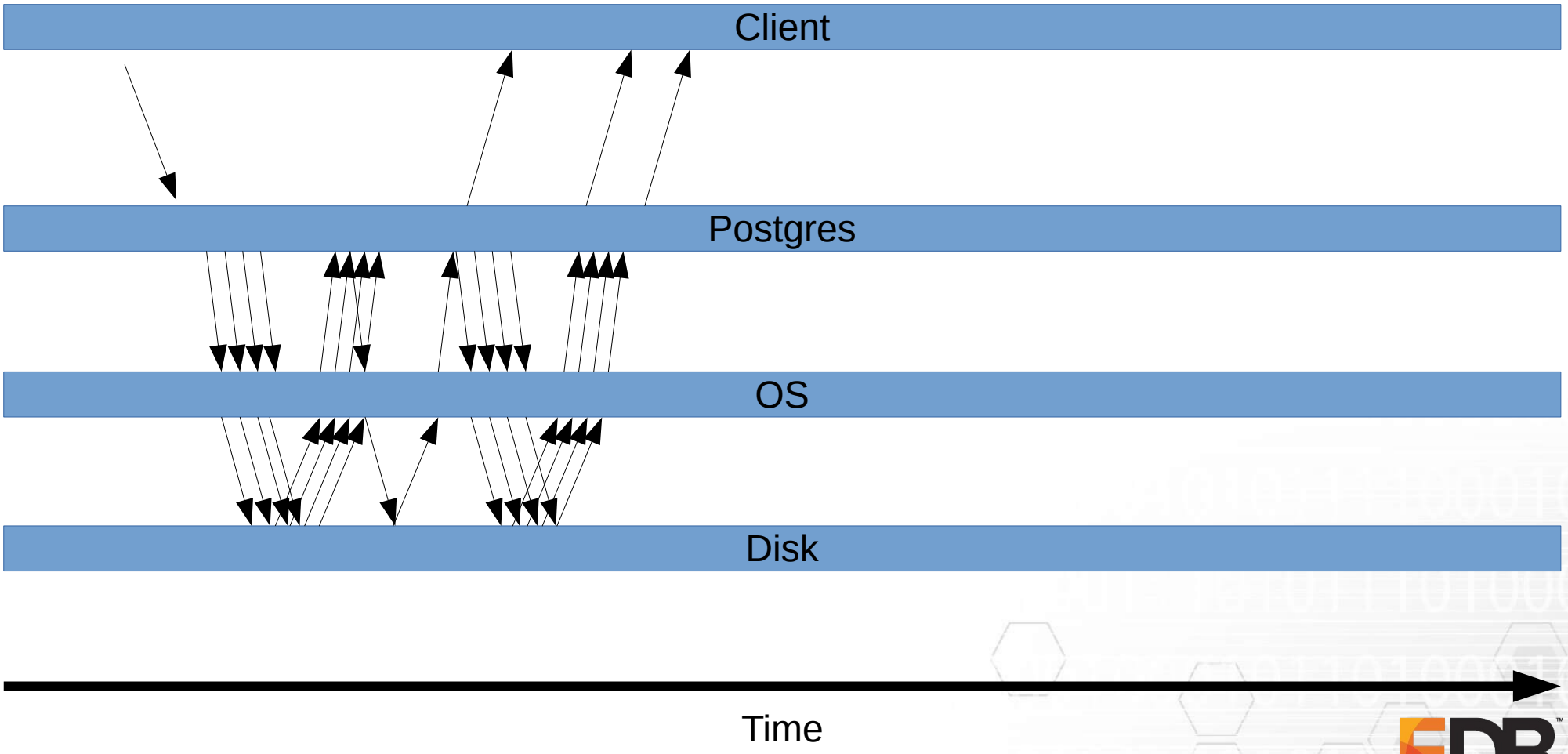
Problem: Postgres Reads

- Very little prefetching
  - partially a problem of the executor
  - partially a problem of the available interfaces
- No concurrent IO
  - especially bad on good SSDs, can process many many requests in IOs in parallel
- All reads are synchronous
  - the less SQL level concurrency, the worse this is
  - not that bad for nearly entirely cached or very concurrent workloads with just a read or two per “statement”
- Workarounds:
  - NVMe SSDs (low latency)

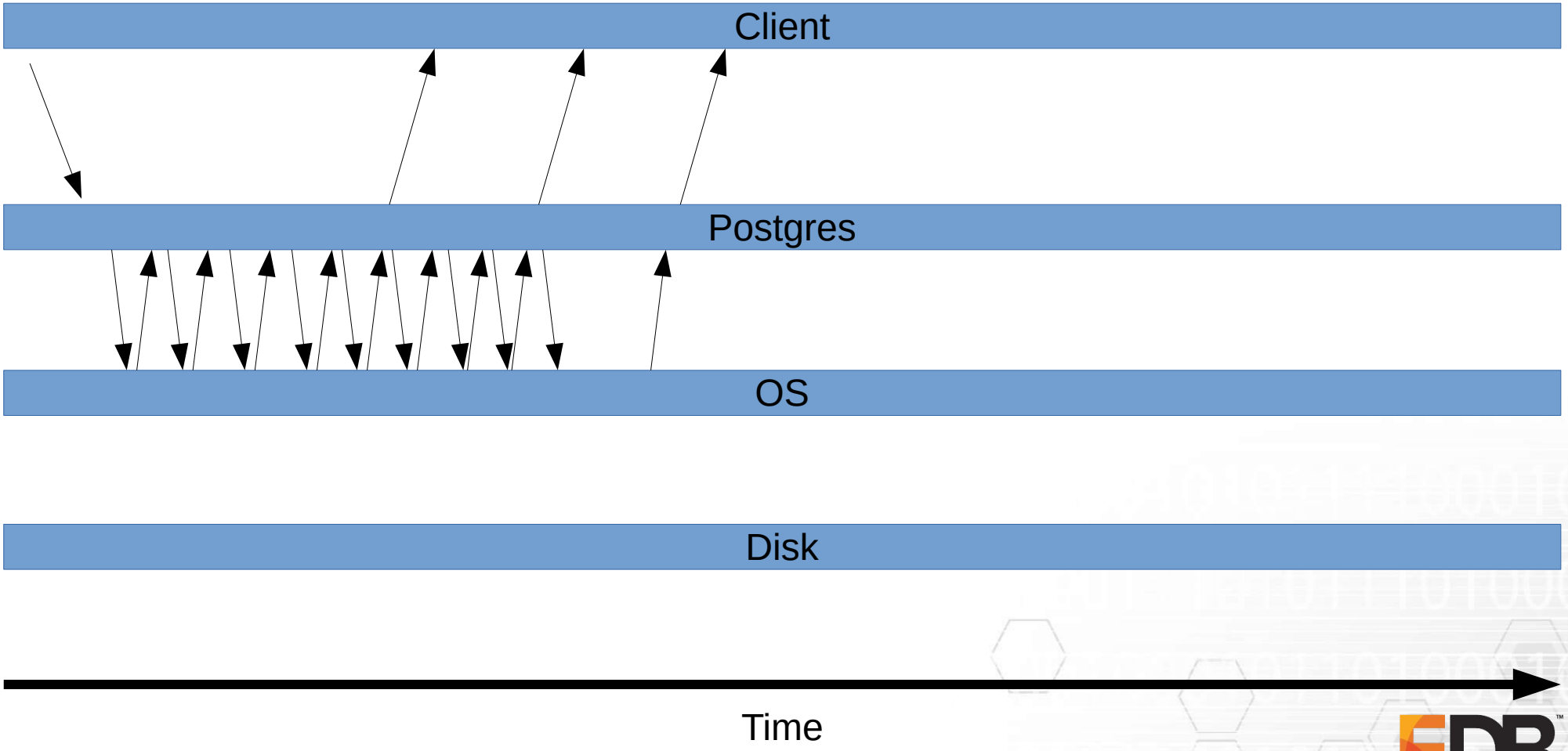
Reads: synchronous, not cached



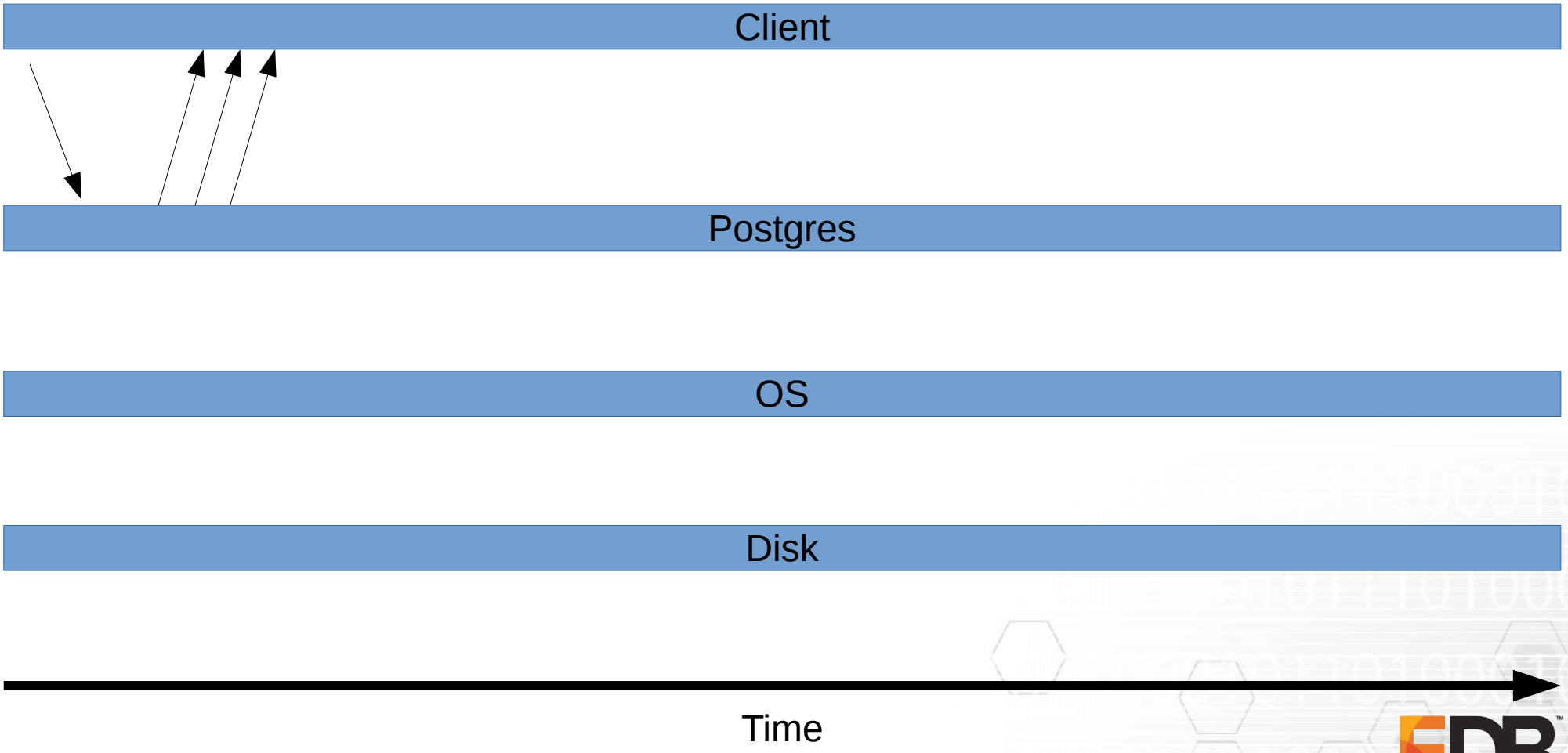
Reads: asynchronous, not cached



Reads: synchronous, OS cached



Reads: synchronous, postgres cached



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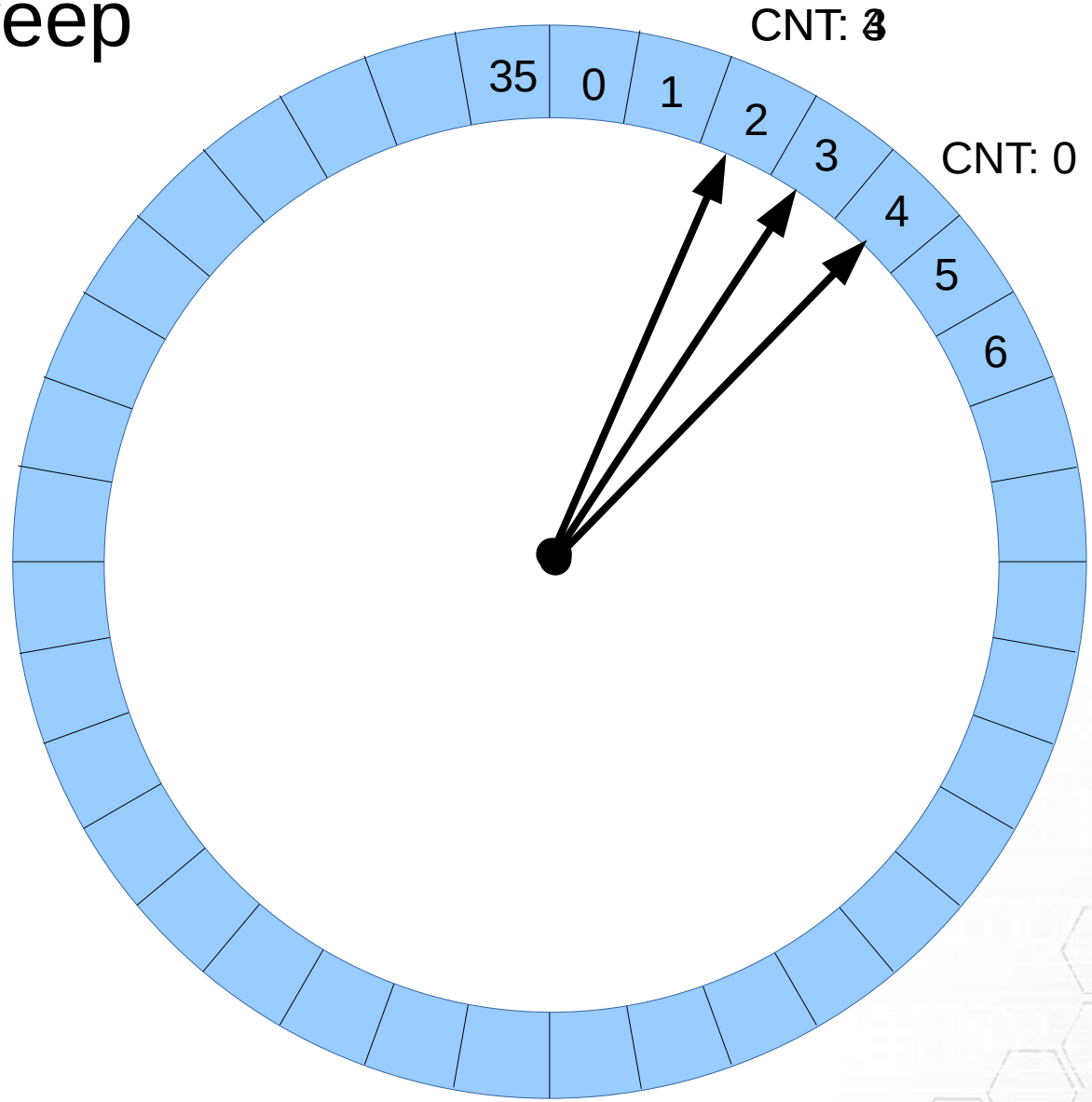
Solution: Postgres Reads

- Add support for asynchronous reads
  - Highly platform dependent
  - typically only supports “direct IO”, i.e. IO bypassing the kernel page cache
  - linux has new interface, io_uring, that is a lot more flexible
  - lots of work
- Emit better prefetching requests
  - not that hard in individual cases, but a lot of places

Problem: Background Writer

- Refresher for bgwriter:
  - writes data back to OS when working set doesn't fit in shared buffers
  - reduces writes needing to be done by backends
- Background writer does not change recency information (perform clock sweep)
  - when all blocks "recently" used → can't do anything
  - configuration complicated
- All IO buffered synchronous
  - throughput / IO utilization too low, and thus falling behind
- A lot of random IO
  - victim buffer selection usage and buffer pool position dependent
  - hard to efficiently combine writes for neighboring blocks currently (hash mapping)

Clock-Sweep



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Problem: Background Writer

- Consequences:
  - backends to a lot of IO, a lot of it random (slow)
  - high jitter, depending on bgwriter temporarily doing things or not
- Partial Workarounds
  - reduce bgwriter_delay significantly
  - increase shared_buffers and/or decrease checkpoint_timout (all sequential writes)
  - sometimes: set backend_flush_after (for jitter reduction)

Solution: Background Writer

- Perform Clock Sweep
  - avoids inability to find work
- Queue of clean buffers
  - removes pacing requirements
- Asynchronous Writes / Writeback
  - improves IO throughput / utilization, especially with random IO
- Write Combining
  - reduces random IO
  - requires shared_buffer mapping datastructure with ordering support

- Prototype seems to work well

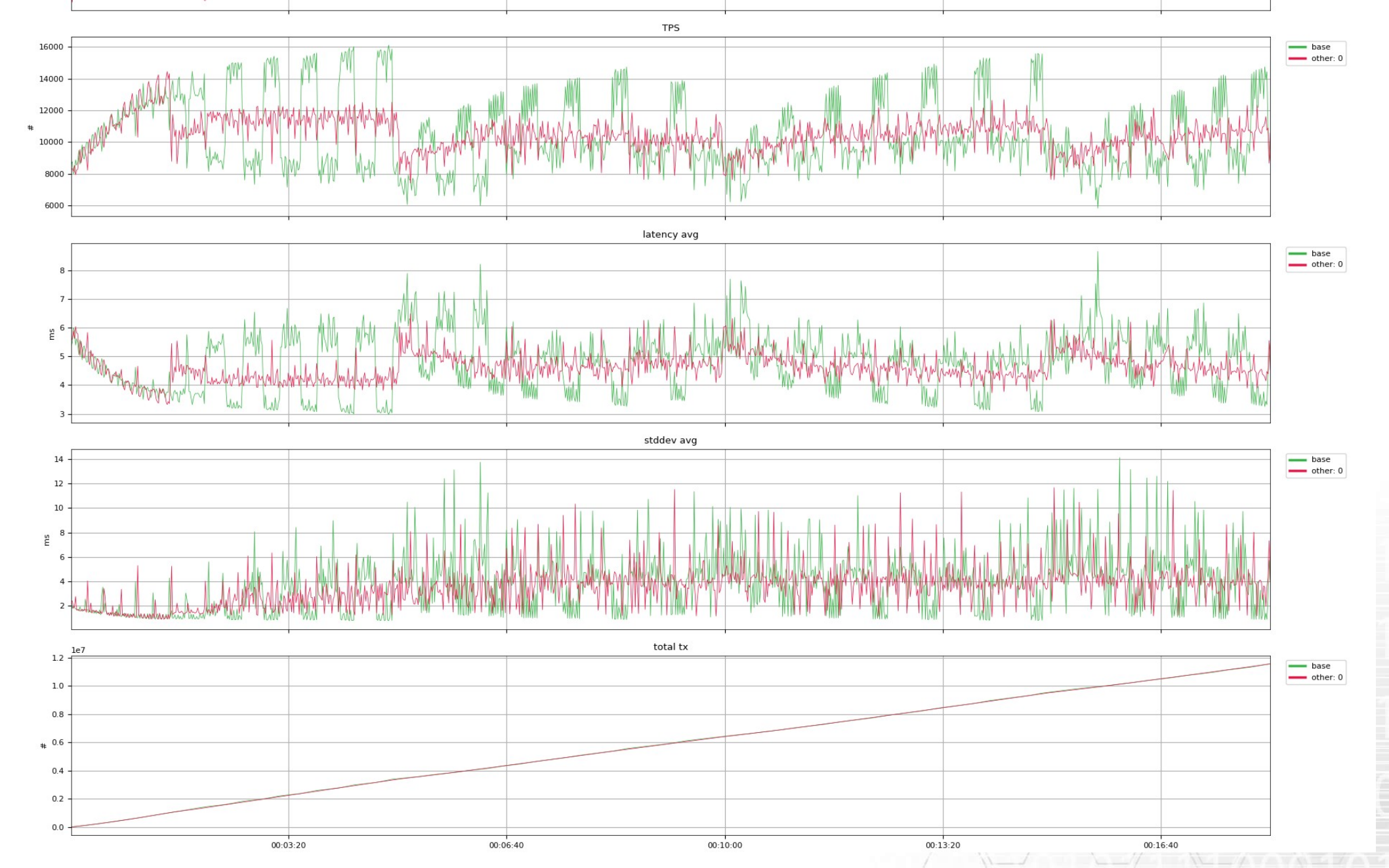

TPS
base
other: 0
#
latency avg
ms
stddev avg
total tx
00:01:40
00:03:20
00:05:00
00:06:40
00:08:20
00:10:00
00:11:40
00:13:20

Problem: Backend Writeback

- takes time away from query execution
- unpredictable latency
  - query - due to having to write
  - write - due to kernel cache
- Diagnose:
  - pg_stat_statements.blk_write_time etc, for readonly queries
  - EXPLAIN (ANALYZE, BUFFERS)
- Workarounds:
  - tune background writer to be aggressive
  - set backend_flush_after
- Solutions:
  - new bgwriter

Problem: Jitter

- query performance can be unpredictable
- Causes:
  - kernel has a lot of dirty buffers → decides to write back
  - postgres issues IOs at an unpredictable rate
  - kernel readahead randomly makes reads take longer
- Workarounds:
  - set backend_flush_after, reduce other *_flush_after settings
  - disable kernel readahead (can be bad for sequential scans)
  - make bgwriter more aggressive
- Solutions:
  - disable kernel readahead, perform our own readahead / prefetching
  - prioritize / throttle different IO causes differently
  - improve cache hit ratio


TPS
16000
14000
12000
10000
8000
6000
#
base
other: 0
latency avg
8
7
6
5
4
3
ms
base
other: 0
stddev avg
14
12
10
8
6
4
2
ms
base
other: 0
total tx
1e7
1.2
1.0
0.8
0.6
0.4
0.2
0.0
#
base
other: 0
00:03:20
00:06:40
00:10:00
00:13:20
00:16:40

Why Buffered IO?

- Parts of Postgres' IO stack have, uh, baggage
- Portability
- Needs far less tuning
  - PG buffer cache size less critical, extends to kernel page cache
  - IO issue rate to drive doesn't need to be controlled
- Why is having less tuning crucial:
  - DBAs / sysadmins don't exist for vast majority of systems (if they exist, they don't know hardware that well)
  - workloads continously change
  - machines / OS instances are heavily overcommitted and shared
  - adapting shared memory after start is hard (PG architecture, OS)
- Consequence
  - PG defaults to 128MB shared buffers ("page cache")
  - works OK for low-medium heavy load

Why Direct IO?

- Much higher IO throughput, especially for writes
- locking for buffered writes limits concurrency
- no AIO without DIO for most platforms (but io_uring)
- No Double Buffering
- Writeback behavior of kernel leads to hard to predict performance
- kernel page cache scales badly for large amounts of memory
- kernel page cache lookups are not cheap, so need to be avoided anyway (copy_to_user + radix tree lookup, syscalls after security fixes)