Technische Universität Braunschweig

Institute of Operating Systems and Computer Networks
Reliable System Software

CumulusDB: Cloud-Native Databases and Unikernels

A Vision for Kernel-Integrated Application Co-Design

Christian Dietrich

March 14th, 2024

The Anabasis: Layers all the Way Down

- Modern hardware is tremendously capable
  - Up to ~100 cores, 100s of GiB DRAM
  - >1M 4KiB-random reads/s, 100/25G network
  - It is hard to fully exploit it

Bare-Metal Hardware
96 CPUs, 512 GiB NVMe SSDs, 25G Network

"Anabasis: Der Zug der Zehntausen",
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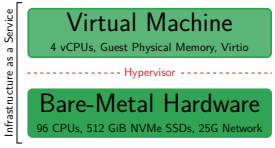

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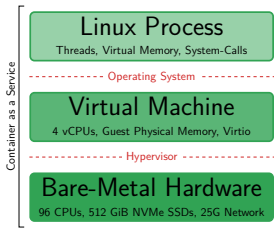

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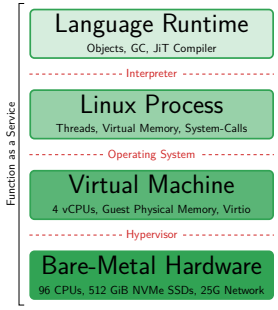

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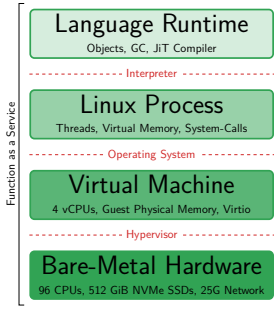

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  - \+ Simpler to develop and to deploy
  - \+ Cloud providers can co-locate more customers
  - – **We pay** for these abstractions

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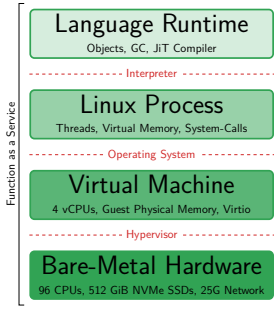

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⇒ **But some applications are experts!**

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The Katabasis: From Traditional DBMS to CumulusDB

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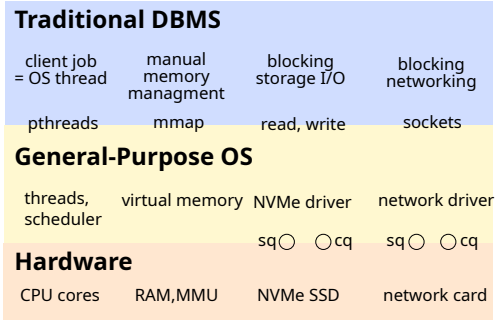
  - Fast enough for spinning disks



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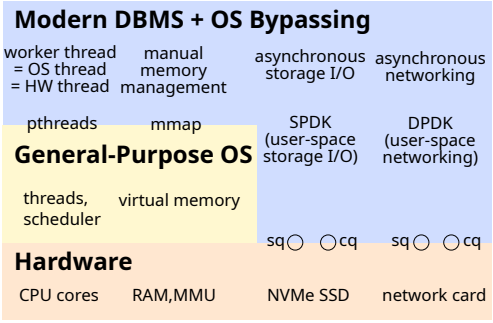

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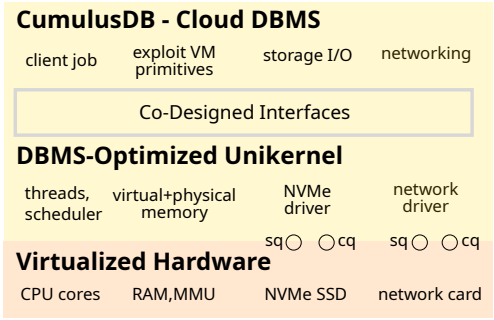

- **CumulusDB** – A Kernel-Integrated DBMS for the Cloud
  - Unikernel Principle: Melt OS and DBMS together, hypervisor brings isolation
  - Target Platform: Virtualized hardware is a uniform and stable ABI (x86, NVMe, virtio)
  - Kernel Integration: Vertically-integrated management of all resources

Benefits of Kernel Integration

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  - Manipulate IRQ-vector tables
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- Partially inconsistent TLB-states
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- **Goal**: Elastic Resource Allocation for VMs

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Virtual-Page–Presence Check

- Check if a virtual page is present
  - VM-based buffer managers[3]
  - OS treats VM as implementation detail
- Linux: `/proc/*/pagemap` interface
  - Accesses via `read(2)`
  - Architecture-independent format
- Unikernel: Shared MMU Structures
  - Lock-Free Page-Table Walk
  - Access to Physical Addresses[6]

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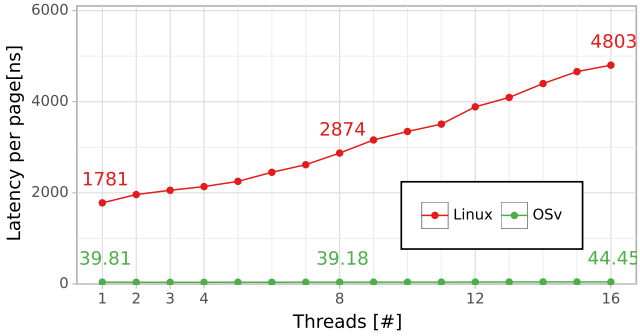

Host: AMD EPYC 9554P processor (64 cores, 128 HW threads, 384 GiB DRAM)
Virtual Machine: 16 cores, 12 GiB DRAM, QEMU, 4 GiB VMA
Workload: Random 4KiB Page

Use-Case Scenario

```
DB *G;   // Database

void olap(){ // 1 OLAP thread
  D = snapshot_create(global);
  res r = olap_scan(D);
  snapshot_destroy(D);
}

void oltp(){ // N OLTP threads
  while (1) {
    G[rand()]->modify();
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- Copy-on-Write Snapshots
  - Consistent of VM area
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- Process-based snapshots [2]
  - `fork()` new process
  - Analytics in second process
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- During the copy
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  - OLTP threads have to block
- During the Analysis
  - TLB-shootdown storm
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CumulusDB

- Fine-Grained VM Snapshot [8]

```
void *snapshot_create
       (addr, length);
```

- **Ad-Hoc Parallelization**
  On CoW pagefault, the OLTP threads help an ongoing snapshot to copy page tables.
- **Reader-Side TLB invalidation**
  - No TLB Shootdown
  - CPU-local TLB-entry flush before every OLTP page access

Results: Linux vs. Modified OSv Unikernel

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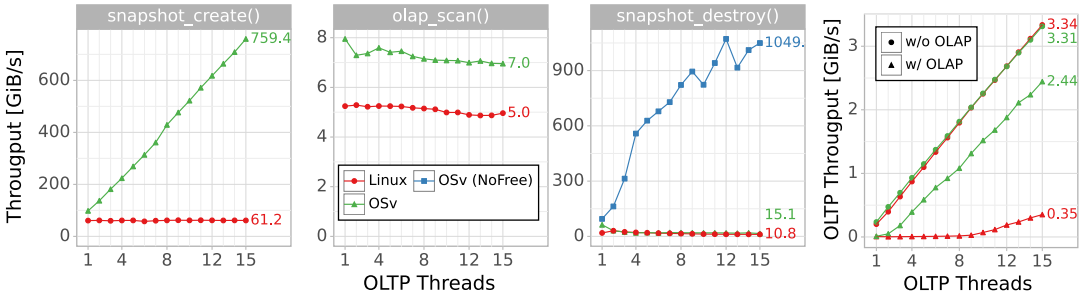

(a) Phases of an OLAP Job on an Copy-on-Write Snapshot

(b) Impact on OLTP Operations

Figure 2: Snapshot Copy-On-Write Benchmark

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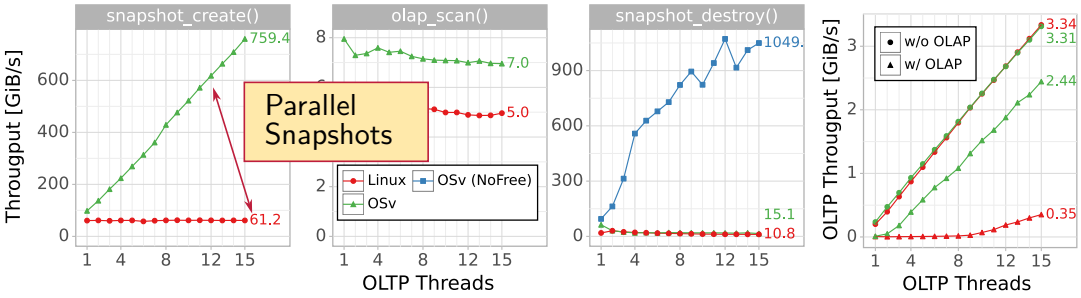

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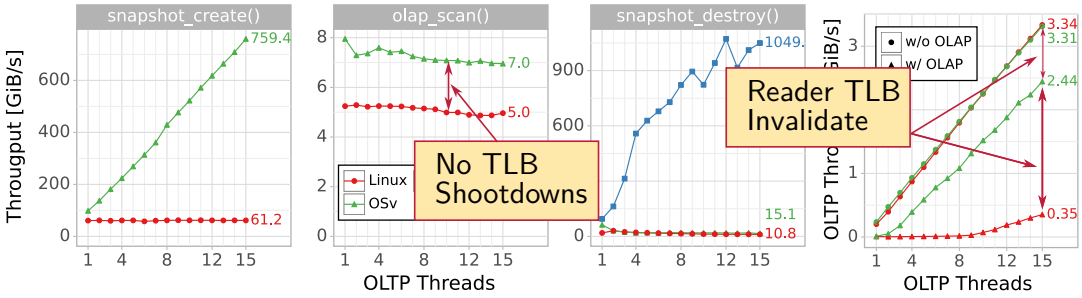

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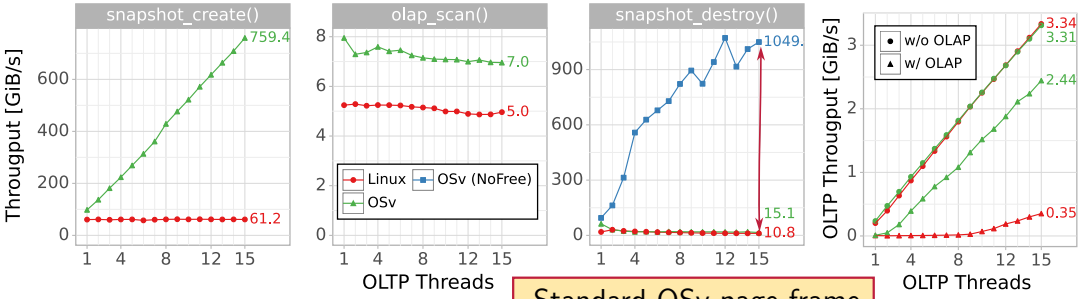

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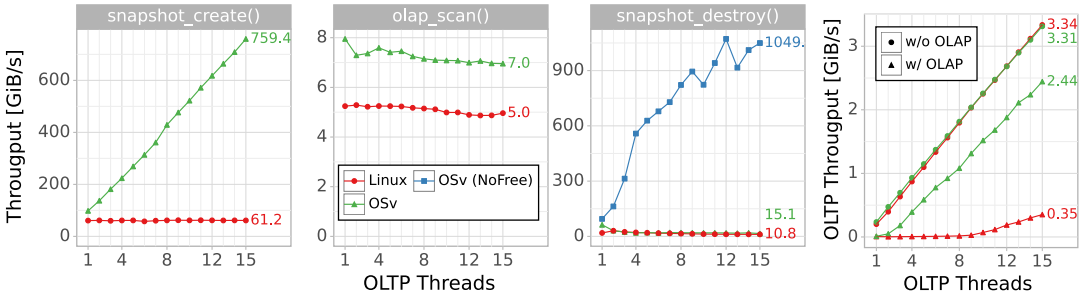

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More Details in our VLDB'24 Vision Paper[4]

Related DBMS–OS Co-Design Projects

- **DBOS** – A DBMS-oriented Operating System — Stanford, MIT, Google, VMware [5, 9]
  - OS components sit on top of distributed database
  - Each node runs a minimal microkernel (DBOS-brick) — still missing
  - DBOS is a cloud orchestrator. CumulusDB runs on a single node.

- **MxKernel** – Runtime System for Heterogeneous Many-Core Systems — Osnabrück, Dortmund [7]
  - Run-to-completion tasks, Dynamic system partitions (habitats, cells)
  - Kernel–application boundary, Isolation domains, RPC between components
  - MxKernel aims for heterogeneous systems, CumulusDB targets the unified cloud environment

- **COD** Open up the OS for the DBMS — Giceva et.al [1]
  - Problem: DBMS lacks knowledge that the OS already has.
  - Resource-allocation protocol between OS and DBMS
  - COD transports information, CumulusDB forwards hardware access

Summary

- The cloud attracts abstractions layers like a lamp on midsummer night
  - Good for the average application and its developer (not for his purse)
  - Database management systems are not the average application!

- **CumulusDB**: A Cloud-Native DBMS based on Kernel-Integration
  - Combine a Unikernel and a DBMS into a single VM image without isolation
  - Vertical-integrated resource management and privileged hardware access
  - The virtualized hardware is a portable machine model

- New Primitives for the DBMS
  - Page-Table Walk — Directly access MMU data for in-core check
  - Ad-hoc parallelization: — Instead of blocking, others help completing the snapshot
  - Joint TLB management: — Distribute the chores of TLB management between reader and writer

Advisement Block

We're hiring!
If you're interested in doing an PhD on CumulusDB, get in touch!

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References I

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[3] Viktor Leis, Adnan Alhomssi, Tobias Ziegler, et al. “Virtual-Memory Assisted Buffer Management”. In: Proceedings of the ACM SIGMOD/PODS International Conference on Management of Data. Seattle, WA, USA: ACM, June 2023. DOI: 10.1145/3588687.

[4] Viktor Leis and Christian Dietrich. “Cloud-Native Database Systems and Unikernels: Reimagining OS Abstractions for Modern Hardware [Vision]”. In: Proceedings of the 50th International Conference on Very Large Data Bases. Vision Paper, Accepted with availability check. Guangzhou, China: VLDB Endowment, Aug. 2024.

[5] Qian Li, Peter Kraft, Kostis Kaffes, et al. “A Progress Report on DBOS: A Database-oriented Operating System”. In: CIDR. 2022.

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