Technische Universität Braunschweig

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CumulusDB: Cloud-Native Databases and Unikernels

A Vision for Kernel-Integrated Application Co-Design

Viktor Leis (TU München), **Christian Dietrich (TU Braunschweig)**

August 29th, 2024

DBMS in the Cloud

- Cloud DBMS Market
  - Complete Market: $91B
  - Cloud Market: $50B (55%)

⇒ Optimize cloud DBMS!

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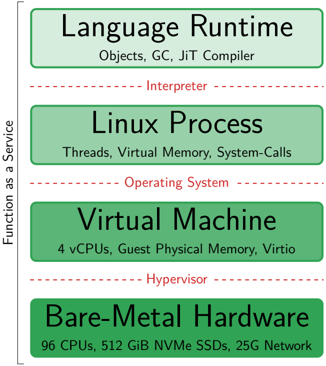

Function as a Service

Language Runtime

Objects, GC, JiT Compiler

Interpreter

Linux Process

Threads, Virtual Memory, System-Calls

Operating System

Virtual Machine

4 vCPUs, Guest Physical Memory, Virtio

Hypervisor

Bare-Metal Hardware

96 CPUs, 512 GiB NVMe SSDs, 25G Network

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  - Tax for redundant isolation
  - Elasticity and stranded resources

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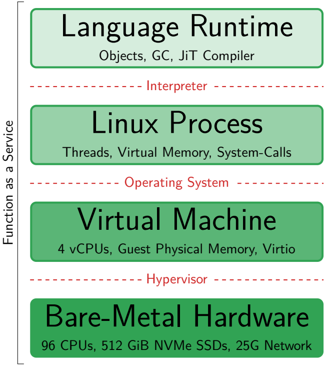

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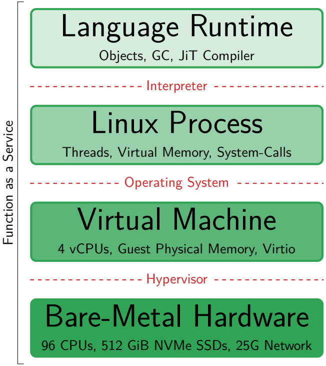
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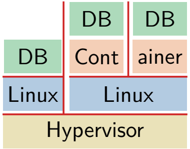

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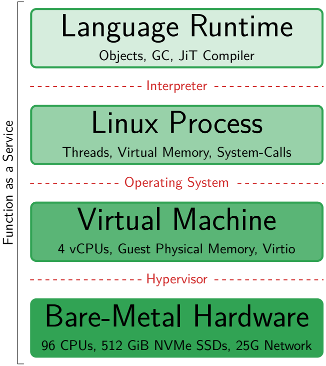
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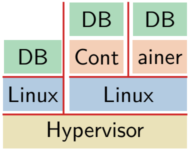

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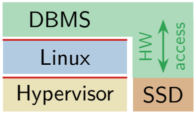

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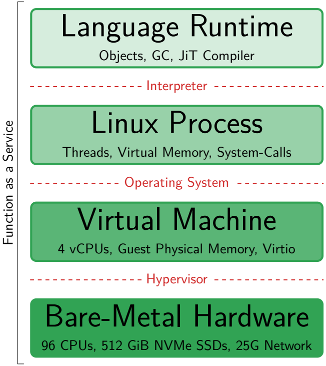

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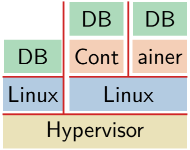

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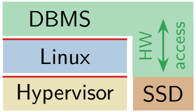

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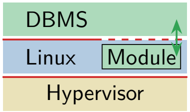

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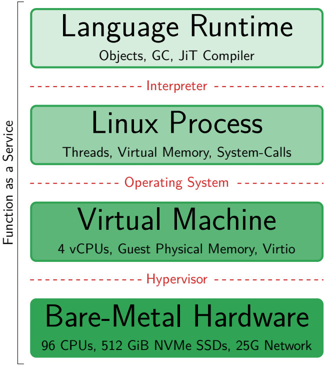

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We need a DBMS-OS Co-Design for the Cloud!

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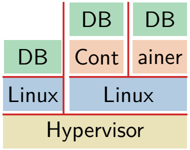

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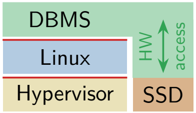

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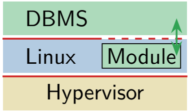
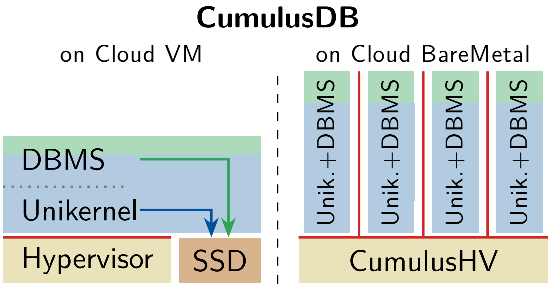
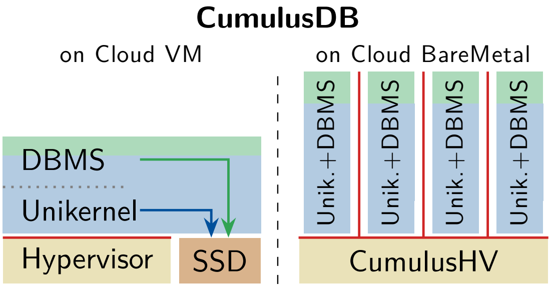


CumulusDB



Idea: Kernel-Integration instead of Kernel-Bypass!

CumulusDB



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

Benefits of Kernel Integration

- Kernel integration gives the DBMS access to privileged operations/interfaces

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  Computation & Scheduling

  - Manipulate IRQ-vector tables
  - Block IRQs, Send IPIs, Shutdown CPUs
  - **Goal**: Query-plan-aware task/thread scheduling

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- Concurrent Lock-Free Page-Table Access
- Partially inconsistent TLB-states
- **Goal**: Virtual-memory as an active abstraction

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- Direct access to NVMe queues
- Kernel-bypass on steroids
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- Hypercalls for synchronous signals
- HV-inspected shared memory regions
- **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

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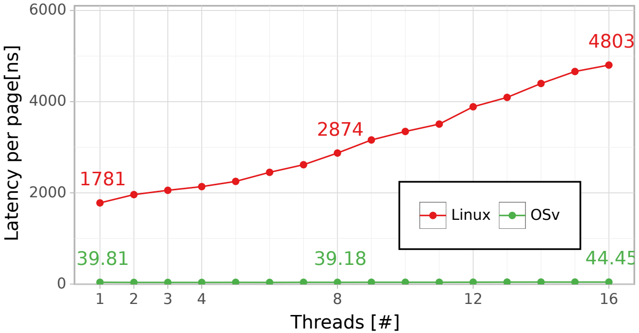

Host: AMD EPYC 9554P processor (64 cores, 128 HW threads, 384 GiB DRAM)
Virtual Machine: 16 cores, 12 GiB DRAM, QEMU, 4 GiB VMA
Workload: Random 4KiB Page

Summary

- The DBMS is not the average cloud workload
  - **New Problems**: isolation tax, resource elasticity
  - **Old Problems**: DBMS-OS mismatch, design barriers
  - A DBMS-OS Co-Design especially for the cloud is needed!

- **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

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- More Virtual-Memory Details in the Paper!
  - Fork-like VM snapshots: Fast Lock-Free Copy-on-Write Snapshots
  - Ad-hoc parallelization: Instead of blocking, others help to complete a task
  - Joint TLB management: Distribute the chores of TLB management between reader and writer

Advisement Block

- The **Extended** Vision
  - Keynote by Viktor Leis
  - CloudDB Workshop, 14:00-15:00

- We're hiring @ TU Braunschweig
  - PhD on CumulusDB or Physical Memory Management/CXL
  - OS/System-Level Aspects

Backup

Virtual-Memory-based Database Snapshots

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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Linux

- Process-based snapshots [2]
  - `fork()` new process
  - Analytics in second process
  - Copy-on-Write

- During the copy
  - Single-threaded PT copy
  - OLTP threads have to block
- During the Analysis
  - TLB-shootdown storm
  - OLAP slows down OLTP

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CumulusDB

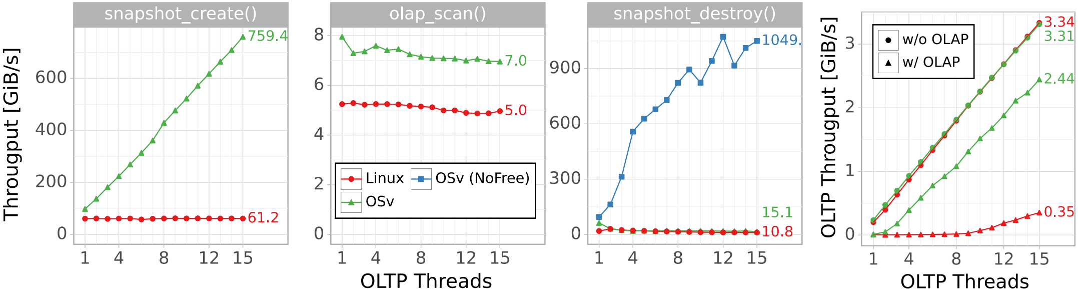
- Fine-Grained VM Snapshot [7]

  ```
  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

Host: AMD EPYC 9554P processor (64 cores, 128 HW threads, 384 GiB DRAM, 1 NUMA domain)
Virtual Machine: 16 cores, 12 GiB DRAM, QEMU, 4 GiB Snapshot Area



(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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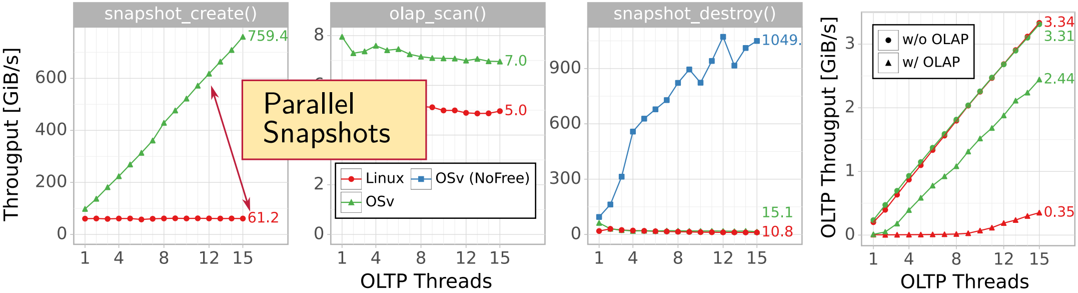

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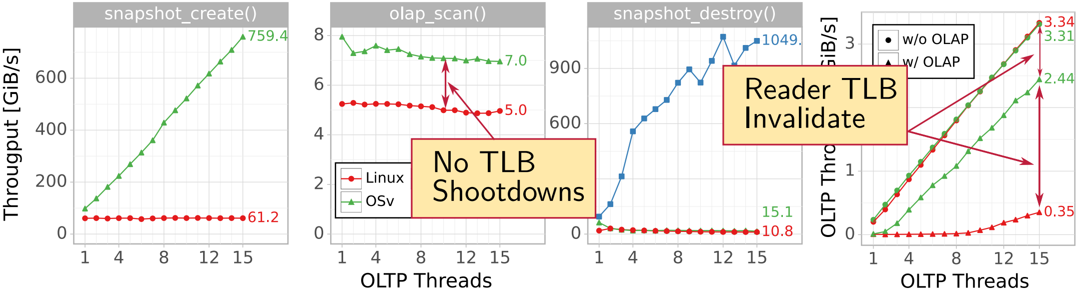

No TLB Shootdowns

Reader TLB Invalidate

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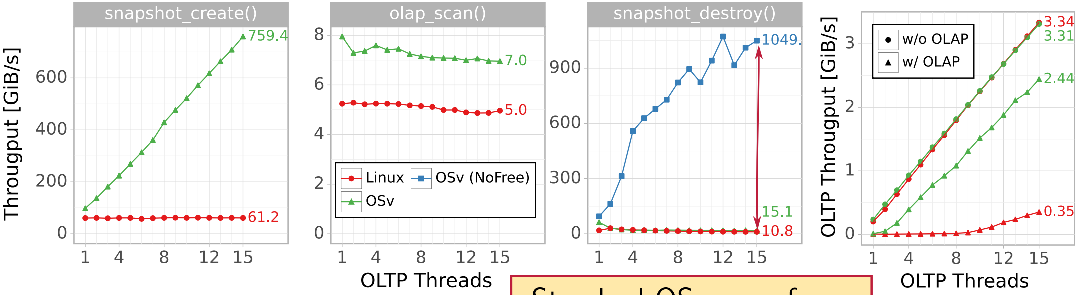

Standard OSv page frame allocator is slow

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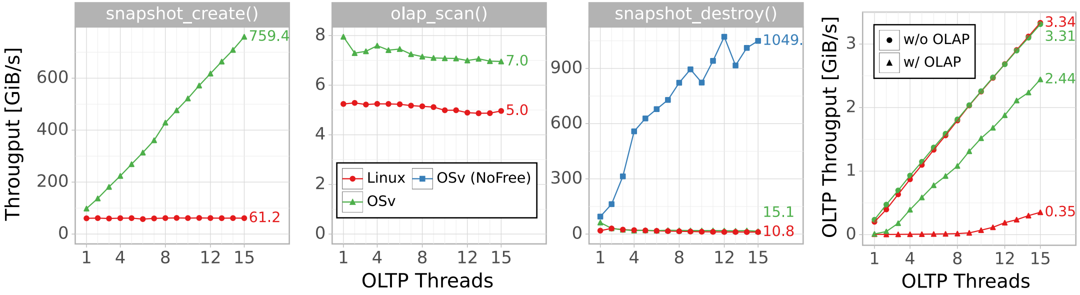

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More Details in our VLDB'24 Vision Paper[4]

Related DBMS–OS Co-Design Projects

- **DBOS** – A DBMS-oriented Operating System Stanford, MIT, Google, VMware [5, 8]
  - 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 [6]
  - 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

References I

[1] Jana Giceva, Tudor-Ioan Salomie, Adrian Schüpbach, et al. “COD: Database / Operating System Co-Design”. In: CIDR. 2013.

[2] Alfons Kemper and Thomas Neumann. “HyPer: A hybrid OLTP&OLAP main memory database system based on virtual memory snapshots”. In: ICDE. 2011. DOI: 10.1109/ICDE.2011.5767867.

[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.

[6] Jan Mühlig, Michael Müller, Olaf Spinczyk, et al. “mxkernel: A Novel System Software Stack for Data Processing on Modern Hardware”. In: Datenbank-Spektrum 20.3 (2020). DOI: 10.1007/s13222-020-00357-5.

References II

[7] Ankur Sharma, Felix Martin Schuhknecht, and Jens Dittrich. “Accelerating Analytical Processing in MVCC using Fine-Granular High-Frequency Virtual Snapshotting”. In: SIGMOD. 2018. DOI: 10.1145/3183713.3196904.

[8] Athinagoras Skiadopoulos, Qian Li, Peter Kraft, et al. “DBOS: A DBMS-oriented Operating System”. In: PVLDB 15.1 (2021). DOI: 10.14778/3485450.3485454.