Optimizing Longhorn for High-Performance Hardware

Software Defined Storage Devroom, FOSCOM 2025

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Kubernetes, the container orchestration platform

- A cloud *operating system*?
  - Resource management
  - Networking
  - Failures
- The thin line between hardware and software—an abstraction
  - Primitives and conventions
  - Managed platform for development and deployment
- Portability of operations across platforms (with exceptions, as always)
  - Local (minikube, MikroK8s, k3s, kind, ...)
  - Cloud (Amazon EKS, Azure AKS, Google GKE, DigitalOcean Kubernetes, ...)
- Many extensions and third-party tools

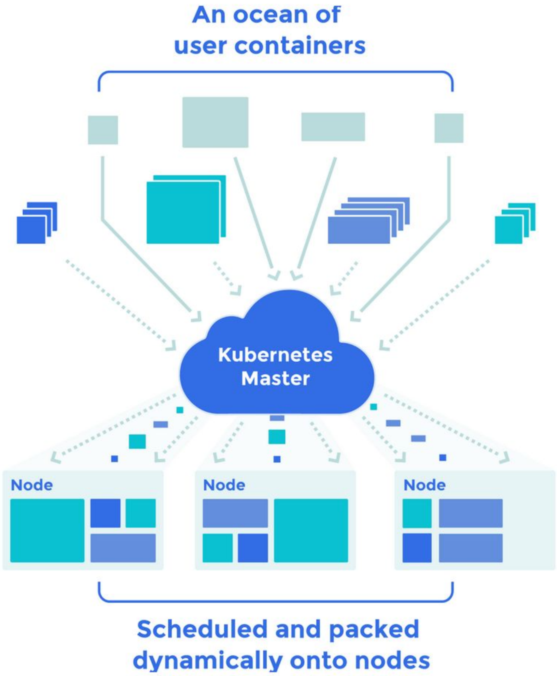

An ocean of user containers
Kubernetes Master
Node
Node
Node
Scheduled and packed dynamically onto nodes

Image source: https://discuss.newrelic.com/t/relic-solution-what-you-need-to-know-about-new-relic-when-deploying-with-docker/52492

Volume objects in Kubernetes

- The standard API uses PersistentVolumeClaims and PersistentVolumes
- A PersistentVolume represents actual storage space
    - Many StorageClasses (from one or more plugins) may be available
- A PersistentVolumeClaim is a request for storage → PVCs consume PVs

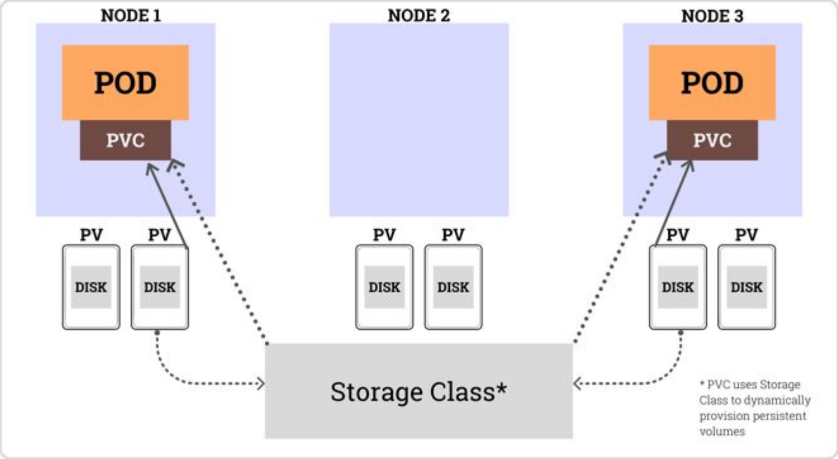


Image source: https://blog.mayadata.io/kubernetes-storage-basics-pv-pvc-and-storageclass

Container Storage Interface (CSI)

- API to interface with storage offerings
  - Implements the lifecycle of volumes and block devices
  - Adds/removes storage to a container
  - Supports snapshots, volume cloning
- Started as an effort to remove storage implementations from the Kubernetes source
- Many implementations → Mostly interfaces to external storage providers

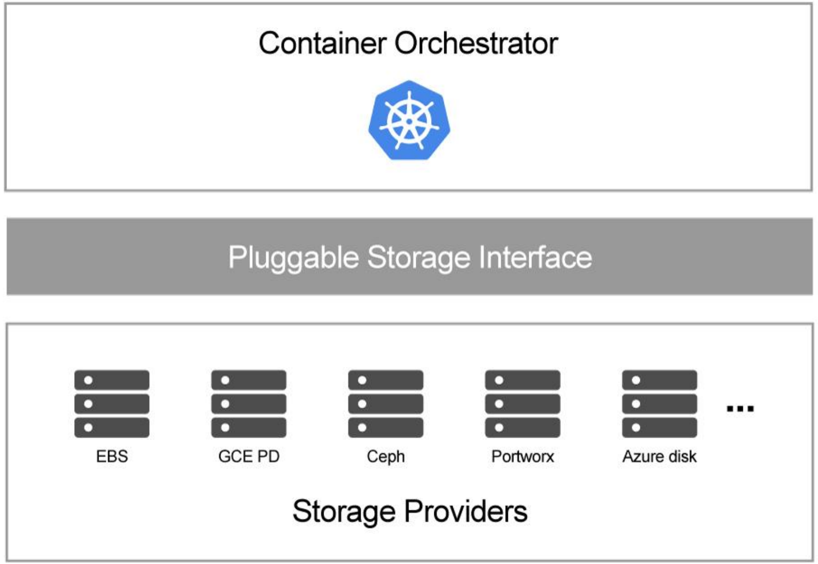
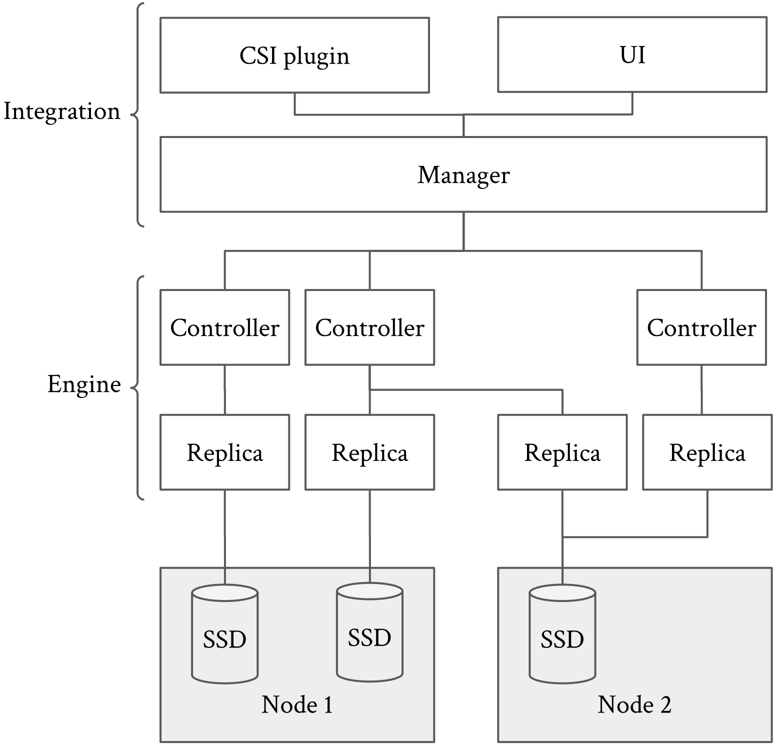


Image source: https://www.tuxera.com/blog/examining-container-storage-interface-csi-support-fusion-file-share-by-tuxera-in-kubernetes/

Longhorn

- Open-source, part of CNCF
- Complete software defined storage engine
  - “World’s smallest storage controller”
  - No reliance to a third-party storage provider
  - Advanced features (snapshots, backups)
- Modular architecture
  - CSI plugin → Interface to Kubernetes
  - UI → User-friendly operations dashboard
  - Manager → Control plane, volume orchestrator
  - Engine → Volume implementation, I/O path
- Each volume is implemented by one controller and multiple replicas

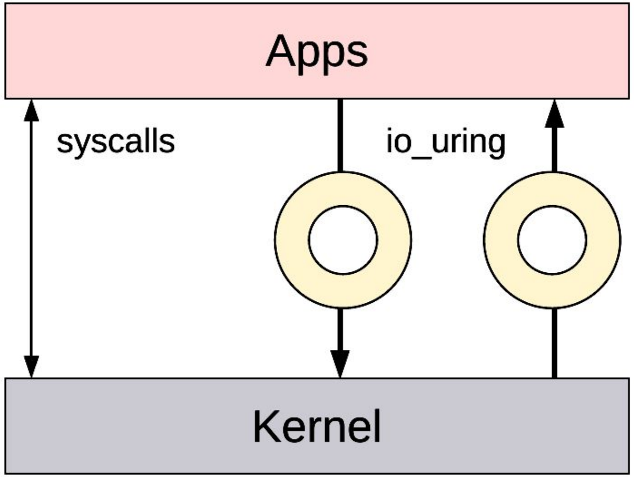


Issues and approach

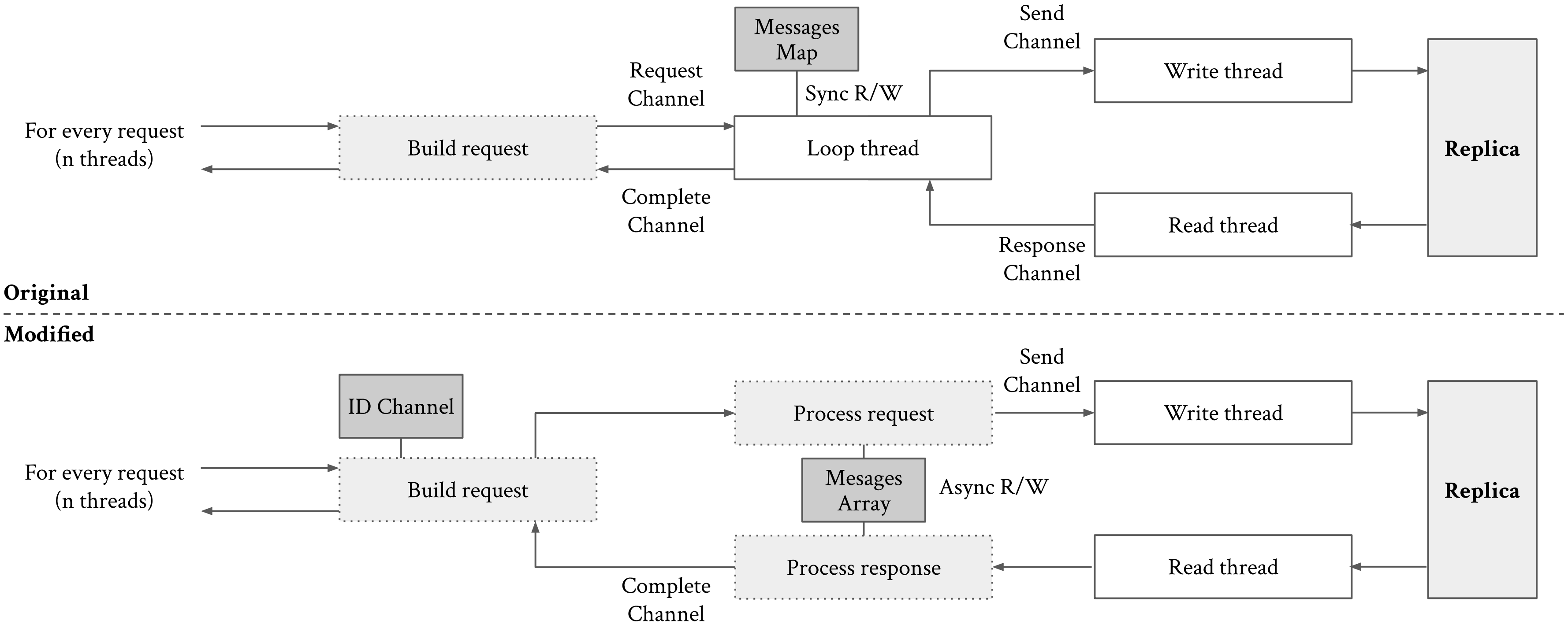
- Performance ok for cloud servers, but not on-prem → high-speed network and NVMe
  - Limited to about 50k/25k read/write IOPS, where the device supports > 400k IOPS (dev setup)
  - Cloud VMs usually have performance limits (~40k @ AWS, unless you pay more…)
- Isolate layers and identify bottlenecks at each step
  - Frontend → iSCSI implementation too slow (based on TGT)
  - Controller → Controller-replica communication protocol implementation serializes all operations
  - Replica → Sparse-file implementation limits write performance (especially with multiple snapshots)
- Explore alternatives
  - Frontend → Use ublk based on io_uring (available in Linux 6.x, Ubuntu 24.10)
  - Controller → Reimplement controller-replica communication
  - Replica → Implement Direct Block Store (DBS), a custom, direct-to-disk storage layer

ublk and io_uring

- io_uring is a Linux kernel system call interface
  - Supports asynchronous operations
  - Uses two circular buffers shared between the kernel and application
  - Extremely fast! (batching and less memory copies)
- ublk is a generic userspace block device leveraging io_uring technology
  - ublk driver in the kernel → Creates virtual device
  - ublksrv in userspace → Implements I/Os (modular)
  - Used for I/Os and admin tasks (add, remove devices)

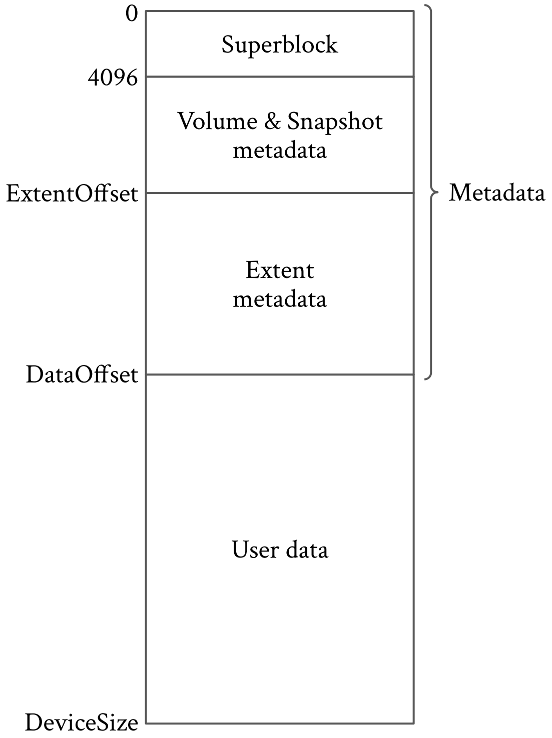


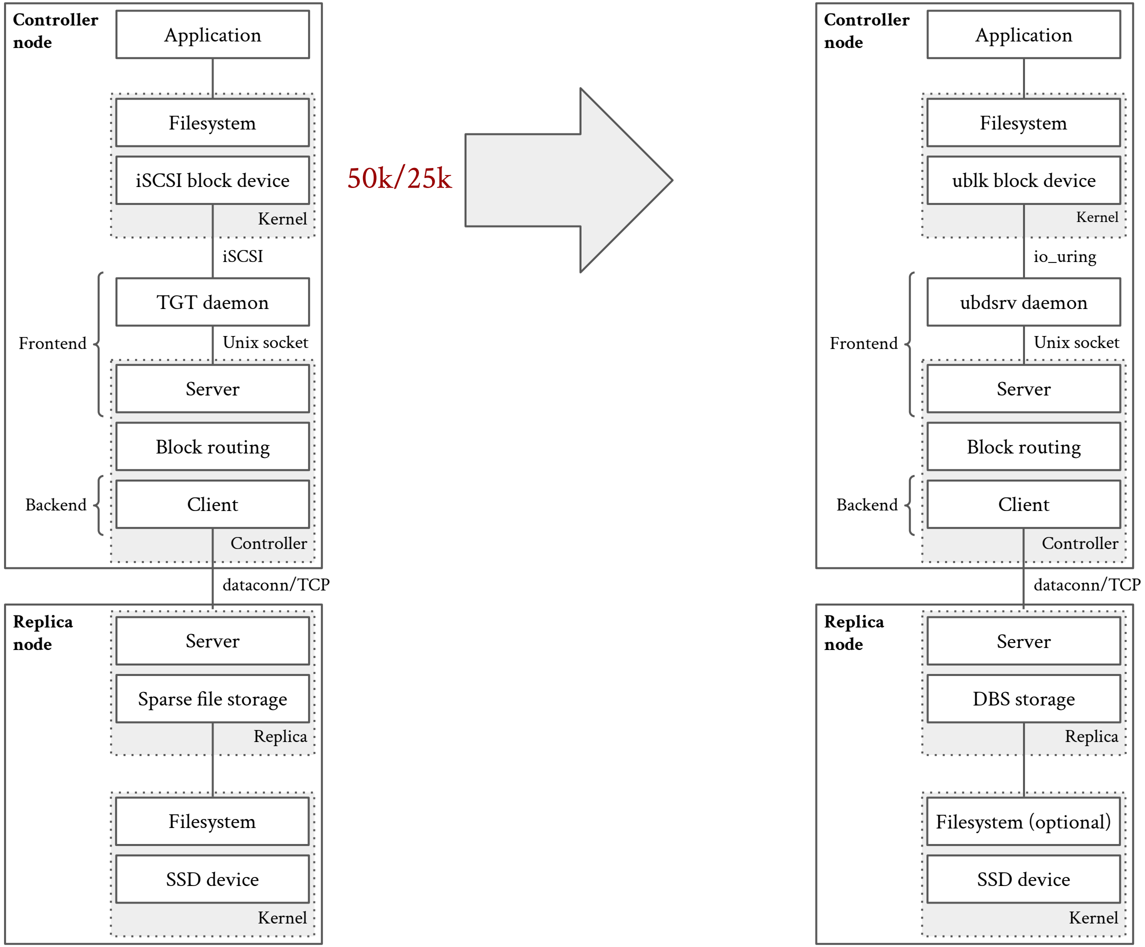
Controller-replica communication

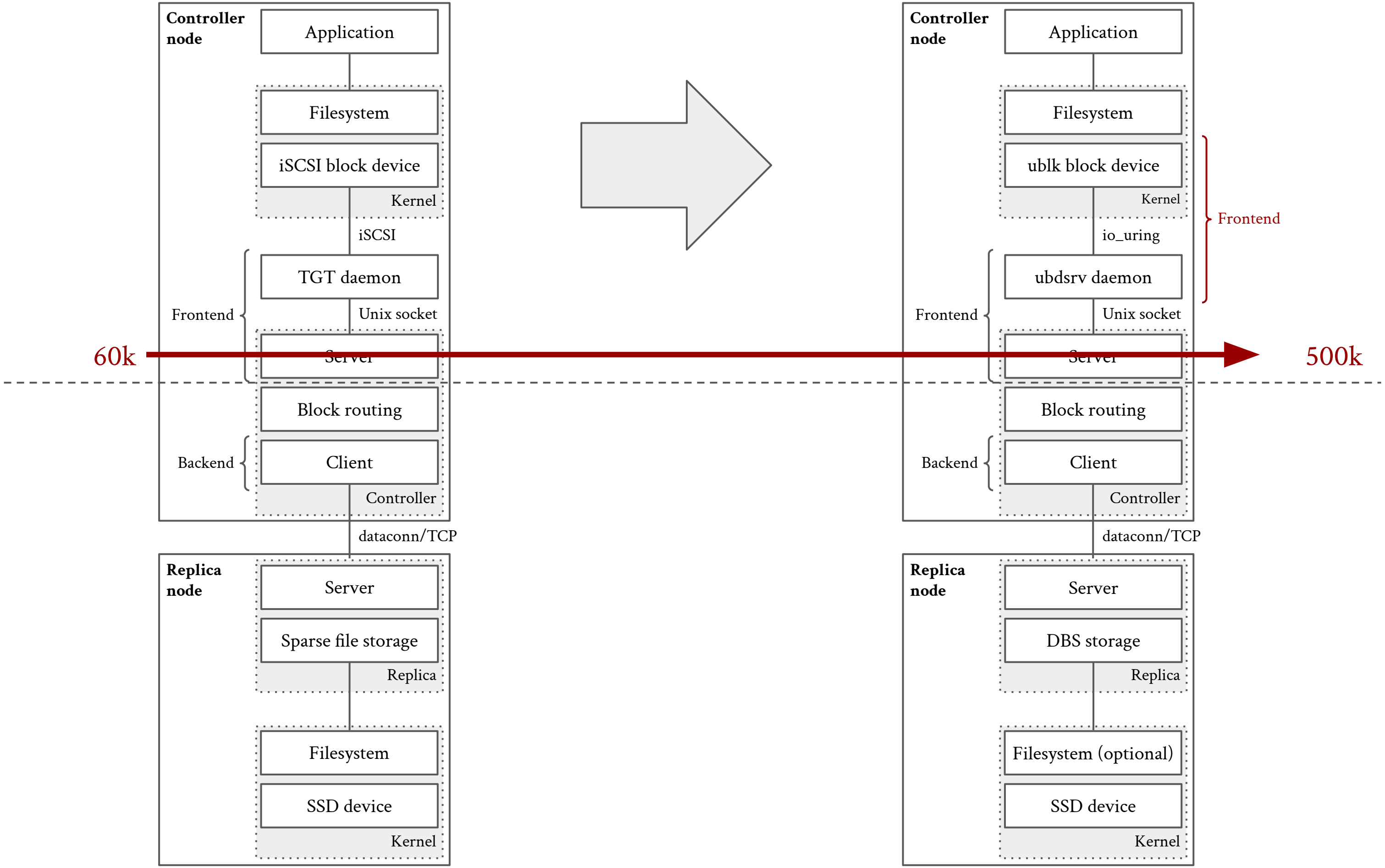


Direct Block Store (DBS)

- Can use a file or directly a device
- Supports multiple volumes, snapshots per volume (extensive API)
- Divides storage in four regions
  - Superblock
  - Volume & snapshot metadata
  - Extent metadata
  - User data → Actual blocks
- Light-weight and fast
  - Volume (snapshot) extent maps are kept in memory (~40 MB for 1 TB volume)
  - Extensive use of bitmaps
- Written in Golang and open source




Controller node
Application
Filesystem
iSCSI block device
Kernel
iSCSI
TGT daemon
Frontend
Unix socket
Server
Block routing
Backend
Client
Controller
dataconn/TCP
Replica node
Server
Sparse file storage
Replica
Filesystem
SSD device
Kernel
50k/25k
Controller node
Application
Filesystem
ublk block device
Kernel
io_uring
ubdsrv daemon
Frontend
Unix socket
Server
Block routing
Backend
Client
Controller
dataconn/TCP
Replica node
Server
DBS storage
Replica
Filesystem (optional)
SSD device
Kernel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Block routing
Backend
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Replica node
Server
Sparse file storage
Replica
Filesystem
SSD device
Kernel
Controller node
Application
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ublk block device
Kernel
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ubdsrv daemon
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Frontend
Unix socket
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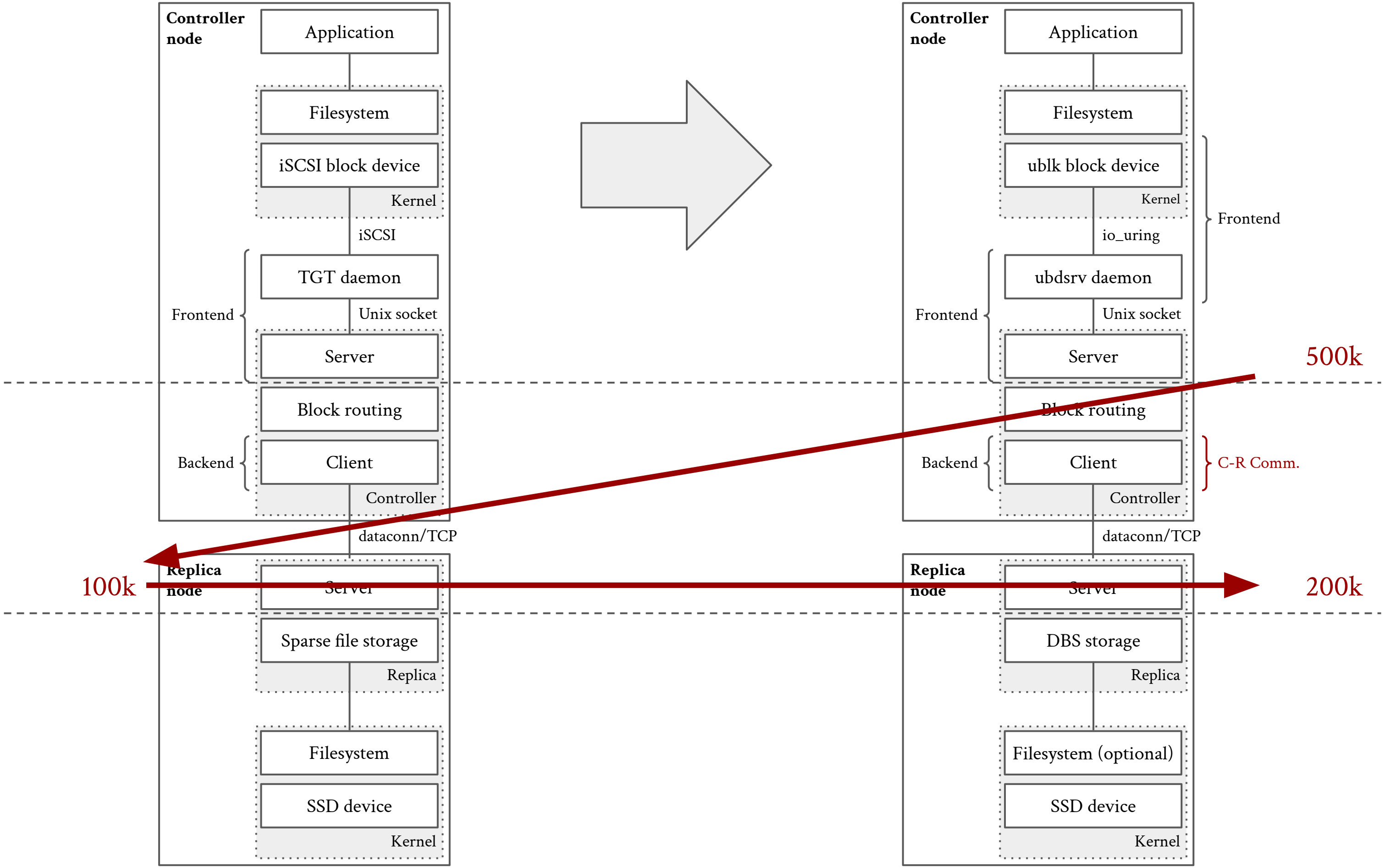
Replica node
Server
DBS storage
Replica
Filesystem (optional)
SSD device
Kernel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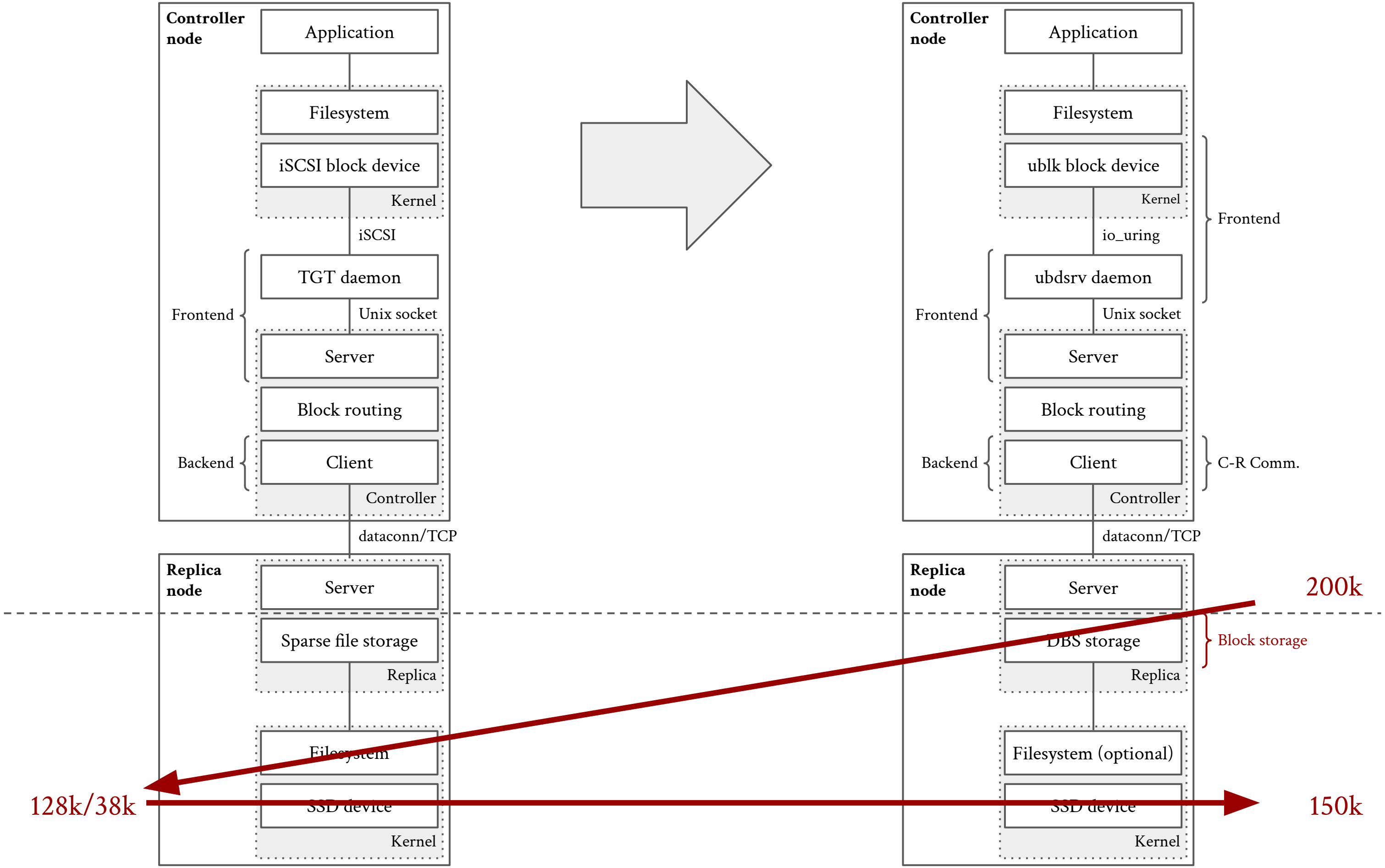
Replica node
Server
Sparse file storage
Replica
Filesystem
SSD device
Kernel
100k
Controller node
Application
Filesystem
ublk block device
Kernel
io_uring
Frontend
ubdsrv daemon
Frontend
Unix socket
Server
500k
Block routing
Backend
Client
C-R Comm.
Controller
dataconn/TCP
Replica node
Server
200k
DBS storage
Replica
Filesystem (optional)
SSD device
Kernel


Controller node
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iSCSI block device
Kernel
iSCSI
TGT daemon
Frontend
Unix socket
Server
Block routing
Backend
Client
Controller
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Replica node
Server
Sparse file storage
Replica
Filesystem
SSD device
Kernel
128k/38k
Controller node
Application
Filesystem
ublk block device
Kernel
io_uring
ubdsrv daemon
Frontend
Frontend
Unix socket
Server
Block routing
Backend
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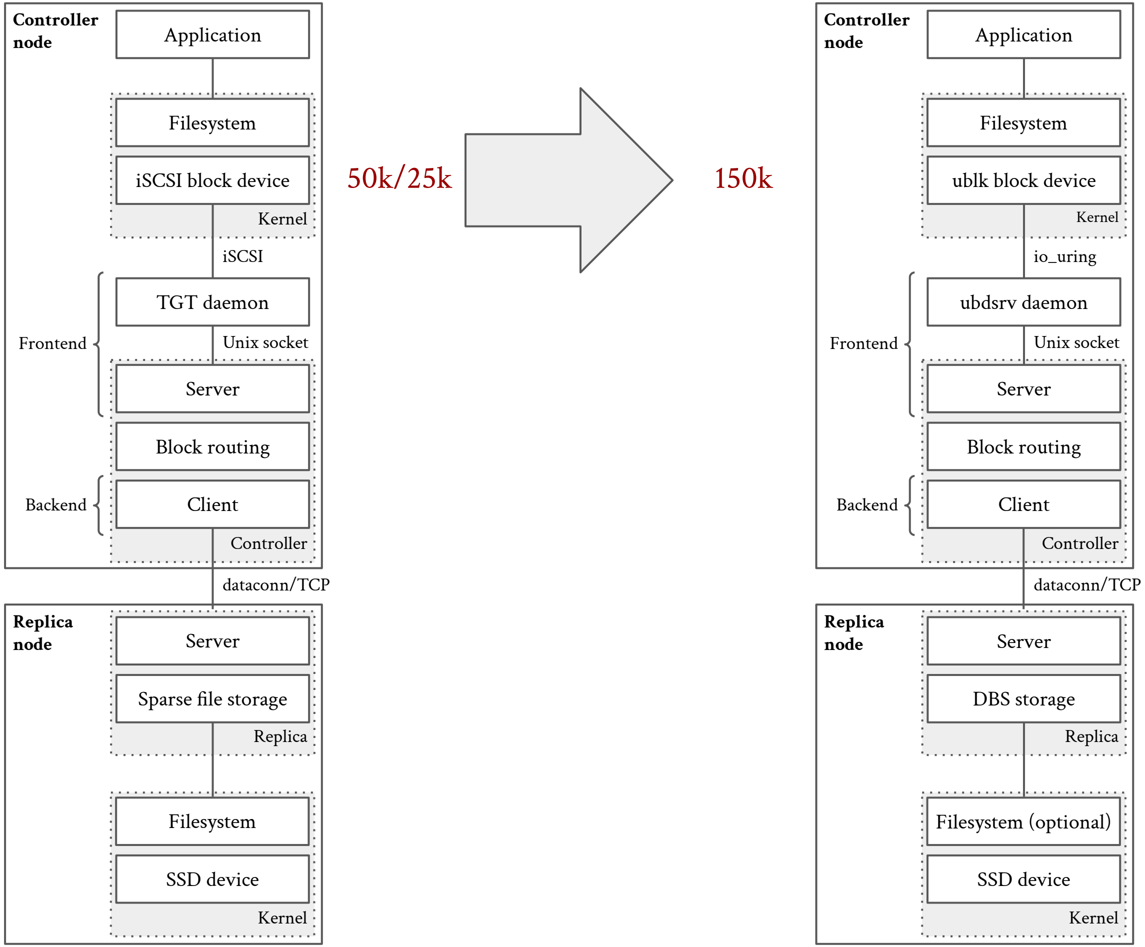
DBS storage
Block storage
Replica
Filesystem (optional)
SSD device
Kernel
150k


Controller node
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Sparse file storage
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Filesystem
SSD device
Kernel
50k/25k
150k
Controller node
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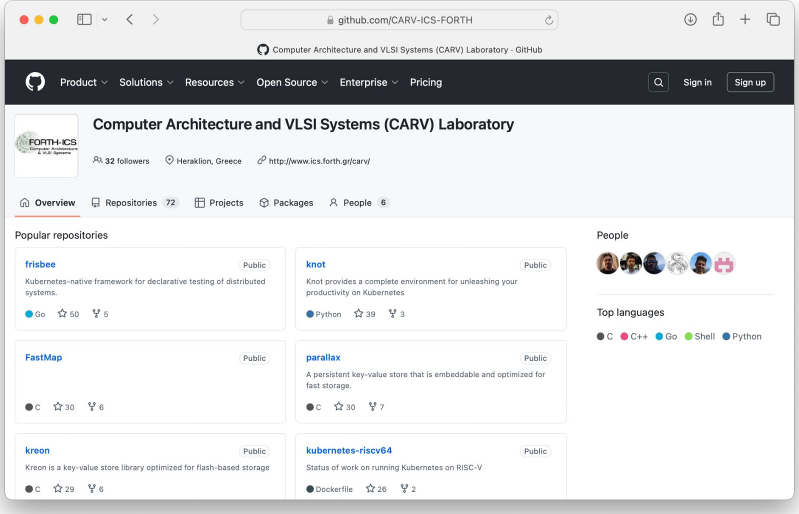
Conclusion

- ublk has the biggest impact in accelerating I/O
  - Is NVMe-oF necessary? (especially when over-the-network operations are not necessary)
- Further performance improvements should be possible (esp. in the controller)
  - Working on optimizations and more features
- DBS is not novel, but may prove a helpful utility for other projects

PRs have been submitted, DBS and other projects are available at https://github.com/CARV-ICS-FORTH



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Popular repositories

frisbee Public
Kubernetes-native framework for declarative testing of distributed systems.
Go ☆ 50 ⑂ 5

knot Public
Knot provides a complete environment for unleashing your productivity on Kubernetes
Python ☆ 39 ⑂ 3

FastMap Public
C ☆ 30 ⑂ 6

parallax Public
A persistent key-value store that is embeddable and optimized for fast storage.
C ☆ 30 ⑂ 7

kreon Public
Kreon is a key-value store library optimized for flash-based storage
C ☆ 29 ⑂ 6

kubernetes-riscv64 Public
Status of work on running Kubernetes on RISC-V
Dockerfile ☆ 26 ⑂ 2

People

Top languages
● C ● C++ ● Go ● Shell ● Python

Acknowledgements

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