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Intravisor: Type-3 Hypervisor for Capability-Based Virtual Machines

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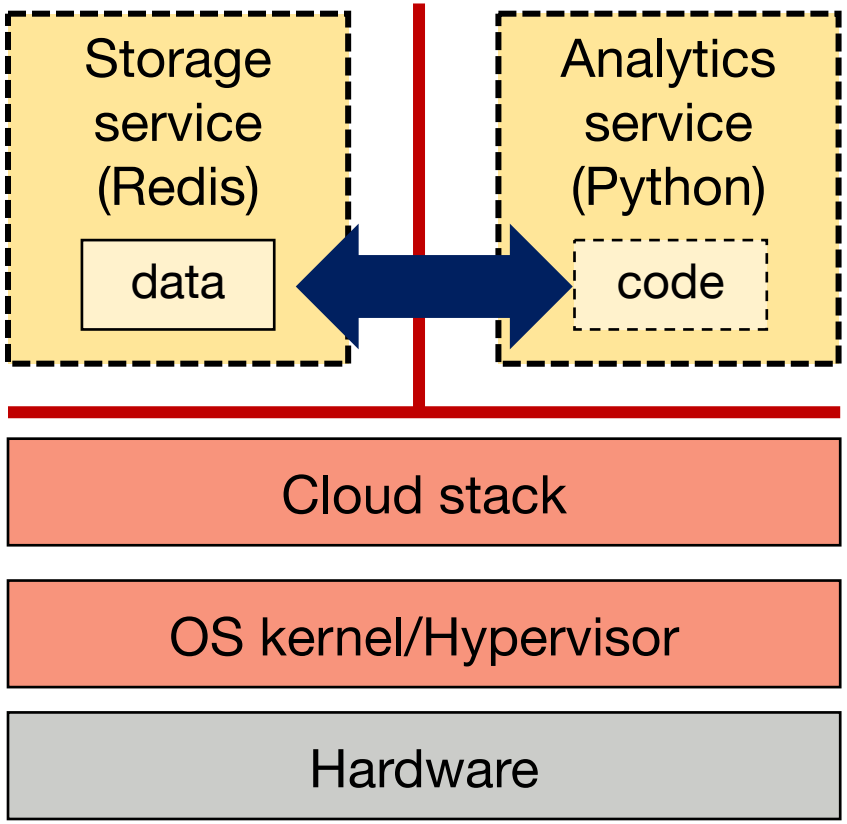
Clouds: Isolation vs. Sharing

Cloud services must be **isolated** from each other and the cloud stack

Services must **share** data efficiently by crossing isolation boundaries



VMs: Strong, Heavyweight Isolation

\+ Strong isolation guarantees

\+ Small(ish) trusted computing base (TCB)

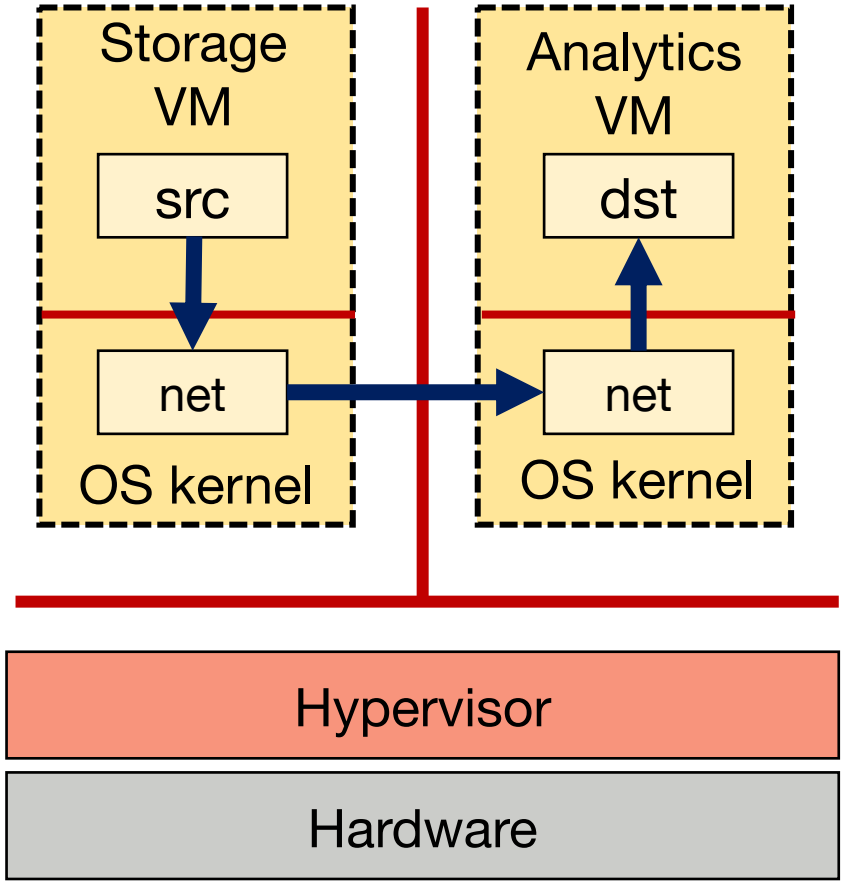
– Only hypervisor

\- Network communication for sharing → TCP/IP

– Requires data serialisation and copying

\- Expensive transitions between services

– Hypercalls ≈ 50 × syscalls

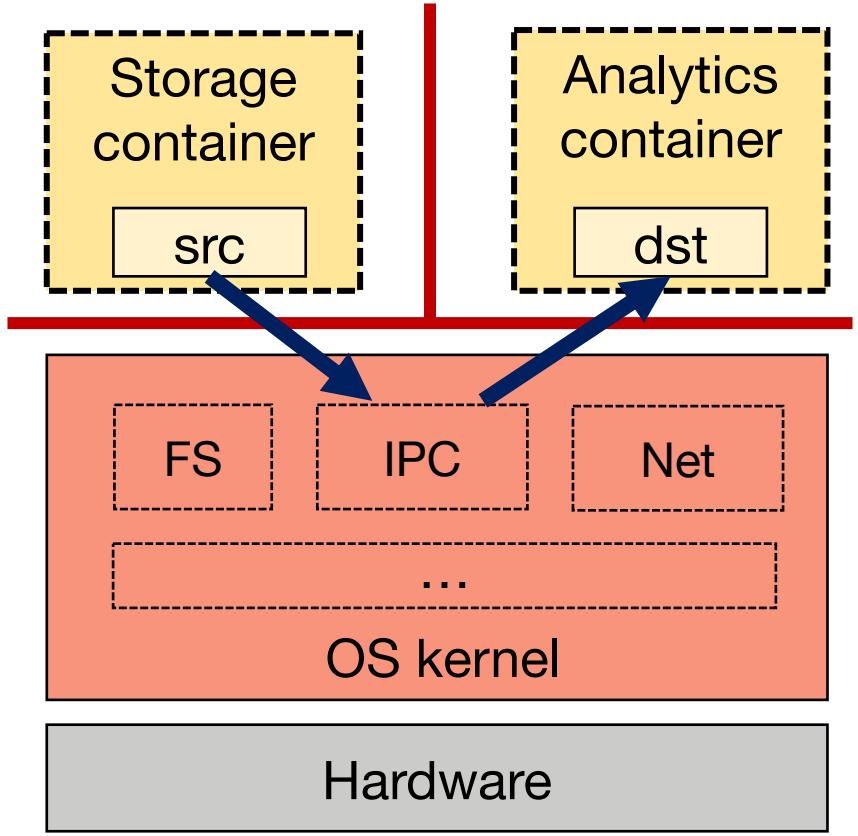


Containers: Weak, Lightweight Isolation

\+ Lightweight OS namespace isolation

\+ Efficient IPC mechanisms

\- Large TCB due to shared OS kernel
  – Shared kernel has much unnecessary functionality



→ Challenge: efficient data sharing with small TCB

VMs & Containers: The MMU Tax

Memory Management Unit (MMU) is a privileged entity

- Intermediary (kernel) is always involved in IPC → Shared TCB, sys/hyper-calls

MMU shares data at page granularity

- Sharing may expose extra data

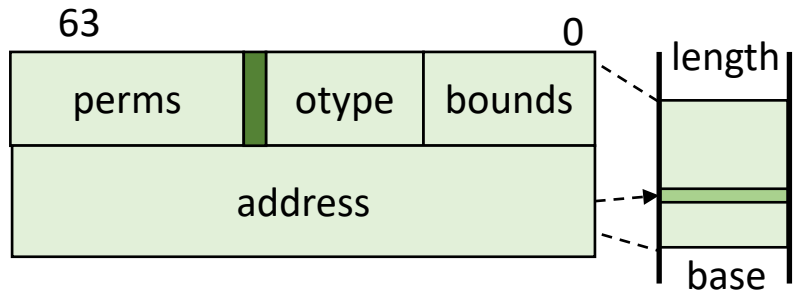
Can we use another technology for isolation and sharing?

→ CHERI: isolation at byte granularity, low dependency on the kernel

CHERI Capabilities

Fat pointers protected by hardware:

- base + length, cursor
- permission, tag
- byte-granularity*



Fine-grained isolation

Limited Dependency on OS kernel

Available: Arm CHERI Morello Boards (Armv8)

Capabilities can be created only from capabilities

- Using cap-aware instructions, but not the intermediary

Challenges of Cloud Stack with Hardware Capabilities

What would a cloud stack look like if hardware provided efficient mechanisms to share arbitrary-sized memory regions between otherwise isolated entities?

Challenges:

C1. Support capability-unaware software

C2. Provide small-TCB OS functionality

C3. Enable efficient capability-based IPC interfaces

cVM: Intra-Process VM-like Abstraction

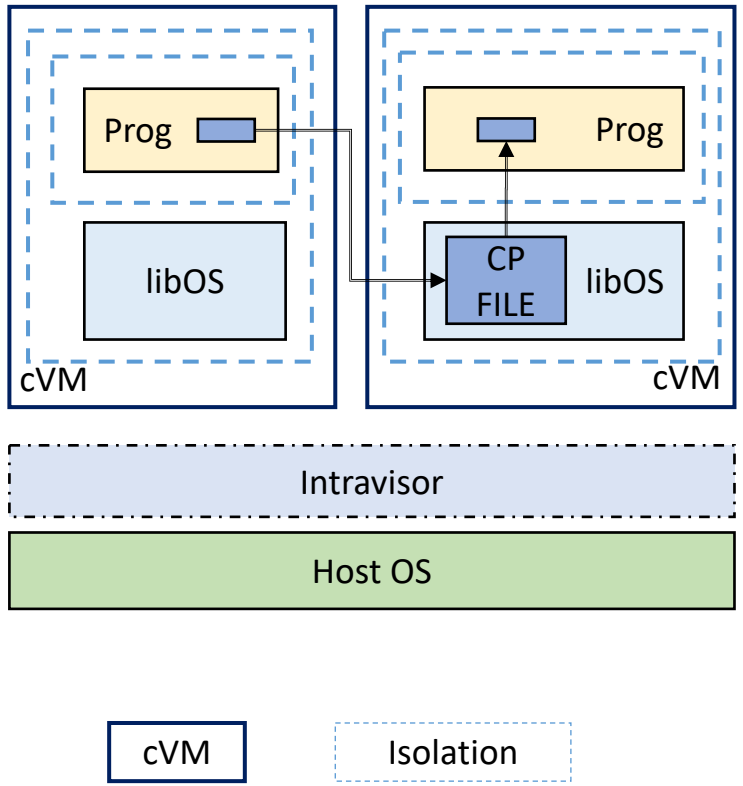
1. Support cap-unaware software

→ Isolated execution of native applications

2. Small shared TCB

→ Private namespaces by library OSs

3. Cap-based IPC interfaces
   - `CP_File`: efficient data sharing
   - `CP_Call`: remote code invocation



Capabilities can Isolate and Share

Native ABI: cap-unaware code

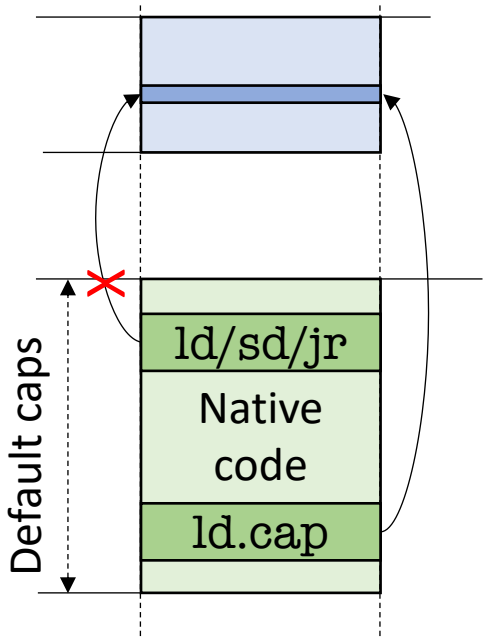
Pure-capability ABI: requires porting

Hybrid-capability ABI: native + cap-aware code

Fine-grained compartmentalisation:

- Cap-unaware instructions are constrained by *default* caps
- Hybrid code can use capability-aware instructions

→ Can be used for isolation and IPC primitives



Support for Native Software

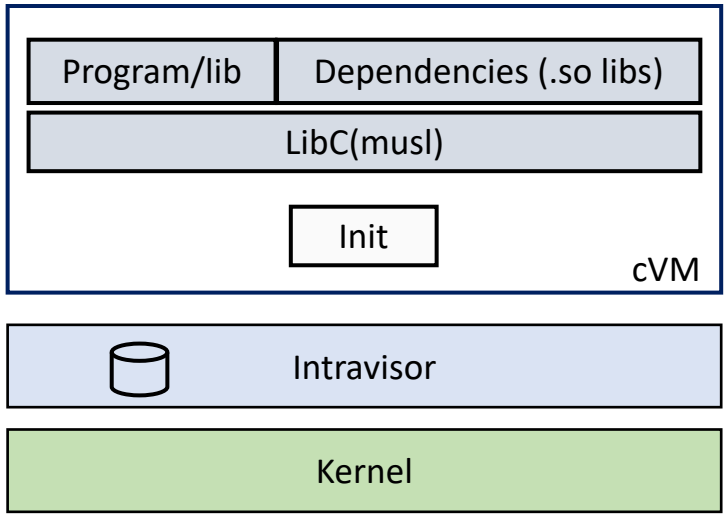
Goals:

- POSIX environment
- Cloud deployment model (e.g. Docker or VMs)

→ Service for cVM is shipped as disk image

- Native cap-unaware PIE binaries
- Compatibility: C standard library (musl libc)

→ Intravisor allocates cVM, loads Init and disk



Small-TCB OS Functionality

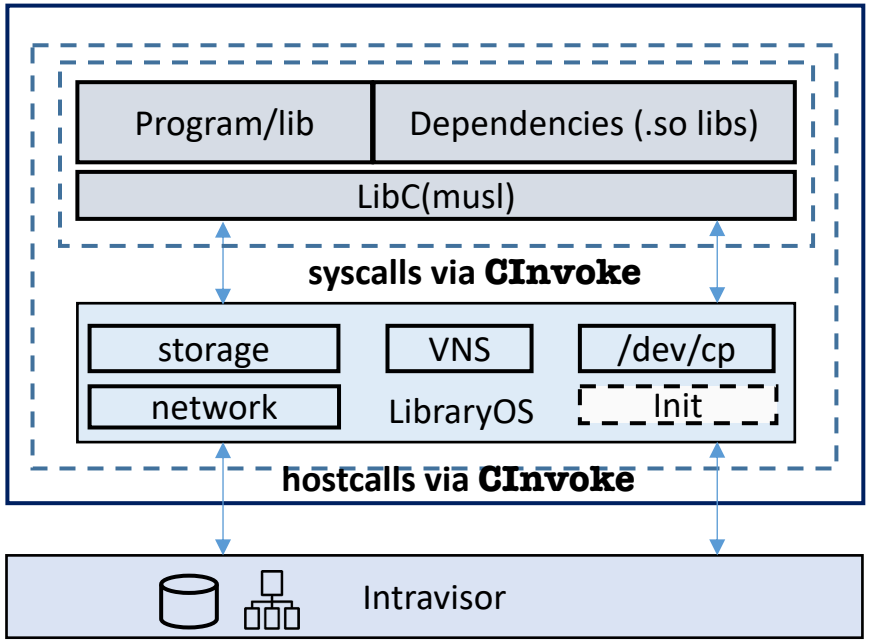
Goals:

- Necessary OS components
- Small attack surface

→ Private LibraryOSs provide OS functionality

→ Intravisor provides time/net/disk

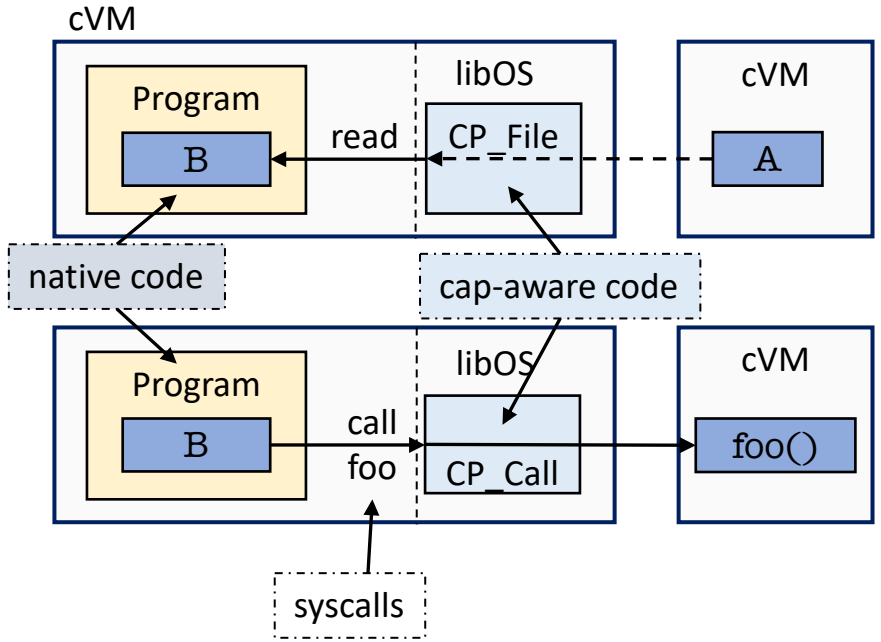
→ Nested Isolation layers



IPC-Like Interfaces Using Capabilities

Data sharing primitives efficient if:

- Non-shared and without intermediary on critical path
- Well-known API (POSIX)
- Usable by cap-unaware code



`CP_File` – read/write remote memory at byte granularity using caps

`CP_Call` – call a function in a cVM

IPC-Like Interfaces Using Capabilities

`CP_File` – asynchronous data access

`CP_Call` – notification mechanism

→ Base for complex IPC interfaces

`CP_Stream` – stream-oriented IPC interface

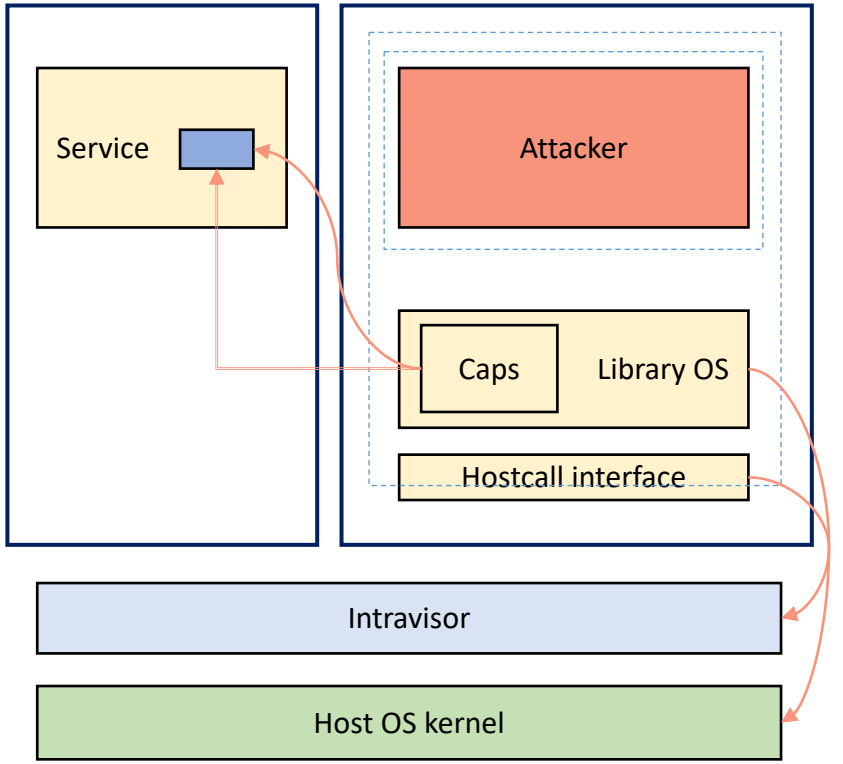
- Destination buffer unknown to the sender
- Recipient pre-registers input buffers and uses `cp_poll` to get a notification

Threat Model

Attacker free to run any code, even cap-aware CHERI instructions

They can get access to entire cVM including compromised libOS

They may try to abuse `CP_Files`, `CP_Calls`, hostcall, and the kernel



Security Analysis

Kernel ignores syscalls

→ cannot abuse the kernel

`CP_Files` are data caps

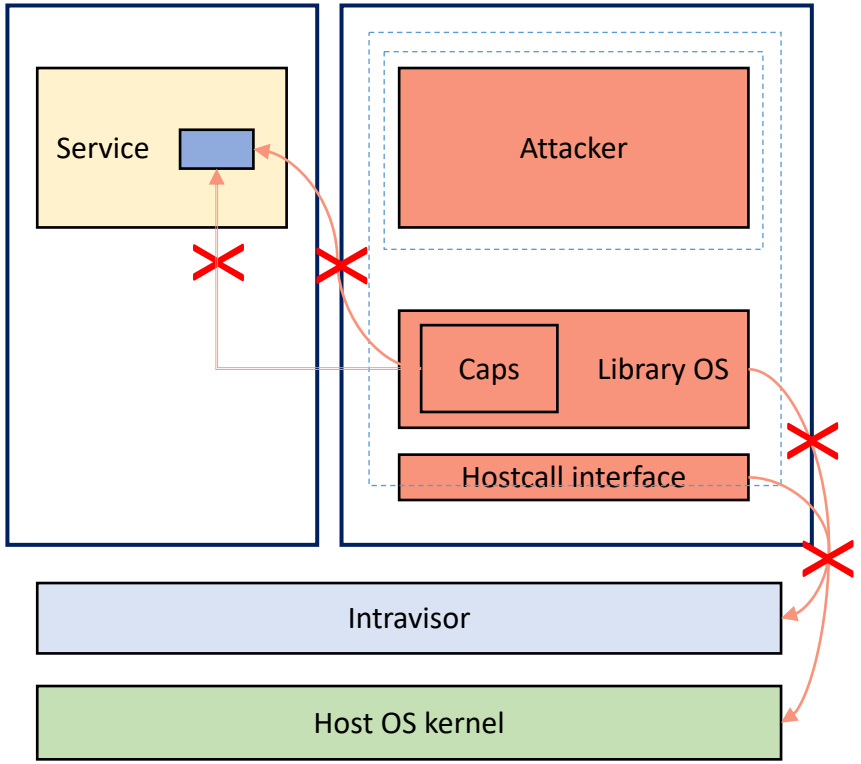
→ cannot be used for `CInvoke`

cVMs cannot store or export caps

→ cannot access revoked data

Hostcall caps are sealed

→ cannot be changed



→ Attacker cannot escape the cVM or gain unauthorised access to data

Prototype

Platforms:

- CHERI RISC-V64, QEMU, AWS F1 (agfi-026d853003d6c433a)
- CheriBSD (host), LKL v4.17 with musl v1.2.1 (cVMs)
- SiFive HiFive Unmatched (No CHERI, but multi-core)

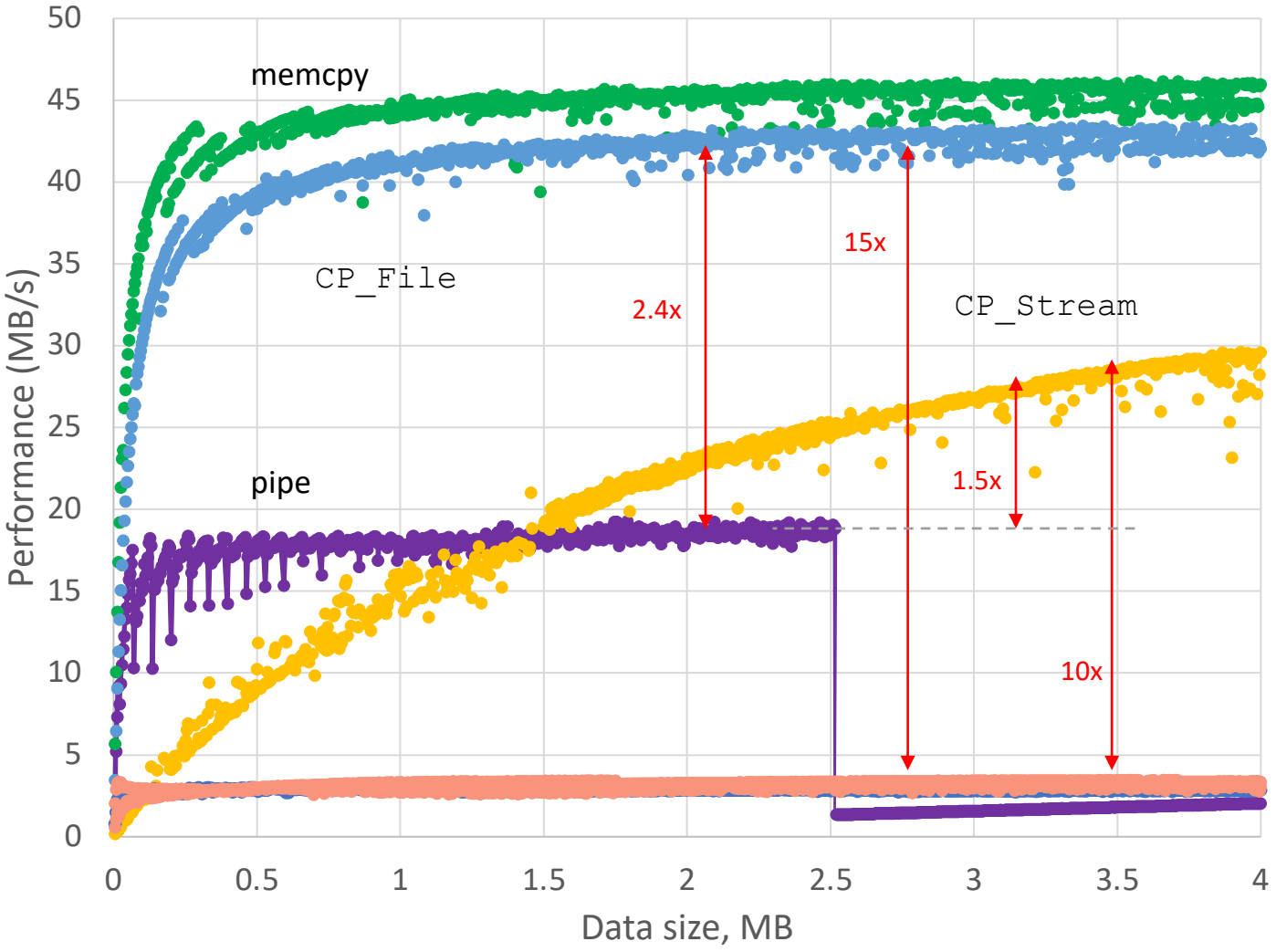
Application and services (In the paper):

- Redis, Data-processing utilities, Python3 with modules, SQLite, benchmarks
- Multi-tier microservice (NGINX with API gate, Redis – SiFive only)

Evaluation question: Performance of cVM IPC primitives?

- Basic: `memcpy`, `mmap+memcpy`
- cVMs: CP_File, CP_Stream
- FreeBSD: pipe, Unix, and TCP sockets

Comparing with IPC Mechanisms



`CP_FILE` vs. memcpy:

- 6% slower

`CP_Stream` faster (1.2 MB+)

- Privileged execution

Unix, TCP, mmap+memcpy:

- Less than 2.4-3.6 MB/s

Processes: 1.6 MB/s max

Conclusion

Small-TCB isolation with efficient data sharing in clouds is challenging:

- Containers → large shared TCB with relatively fast IPC mechanisms
- VMs → small TCB with slow IPC mechanisms

CAP-VMs provide VM-like abstraction:

- Secure isolation using memory capabilities
- Controlled shared TCB by private libraryOSs
- Efficient data sharing using capability-based IPC primitives

Sources

Available at http://github.com/lsds/intravisor:

- Runtime: musl-LKL, baremetal
- Musl-LKL: cp_file, cp_stream, docker-based images (Redis, NGINX), helloworld, python, sqlite
- Baremetal: two pure cVMs, two nested cVMs, hello world
- Arch: RISC-V

Future plans:

- Pure cVMs mostly
- Arm Morello
- Next major update: Jan’23

Thank You — Any Questions?

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