barkhausen
institut

M^3: Applying Microkernel-Ideas to Hardware

Nils Asmussen

ROSS, 15th November 2021

Barkhausen Institut

- Research institute in Dresden, founded end of 2017
- Currently about 40 people
- Low-latency and secure IoT systems
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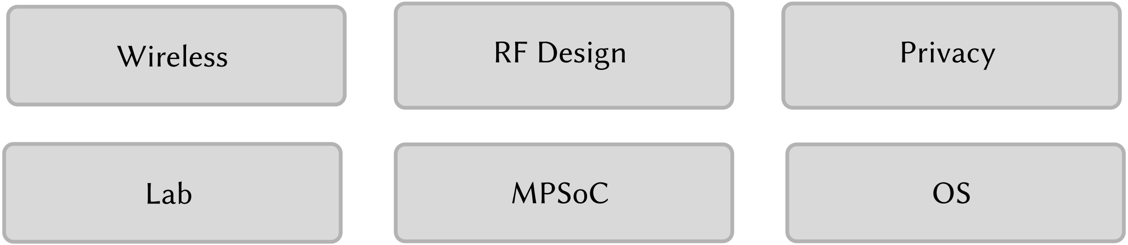

Wireless

RF Design

Privacy

Lab

MPSoC

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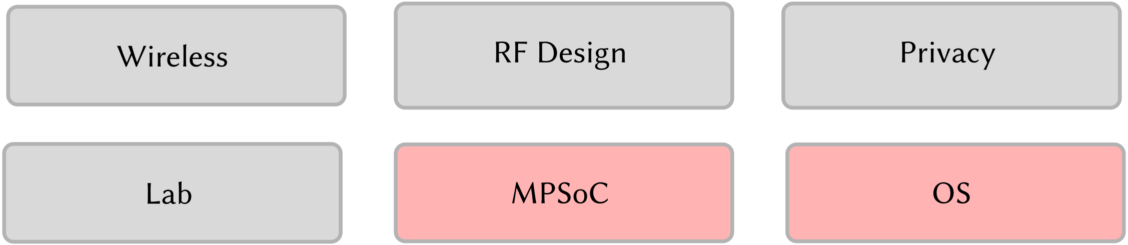

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- Microkernels in a nutshell
  - No isolation between components in monolithic OS
  - Single exploitable bug anywhere → game over
  - Microkernel-based systems split OS into isolated and unprivileged components
  - 96% of Linux CVEs would no longer be critical, 40% would be eliminated [1]

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- Microkernel-based systems have proven valuable for other objectives: Low-noise execution, real time, flexibility, ...
- Recently, new challenges are coming from the hardware side
  - Heterogeneous systems
  - Third-party components
  - Security issues of complex general-purpose cores

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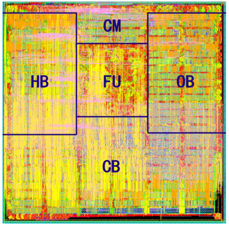
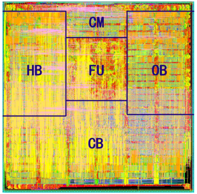
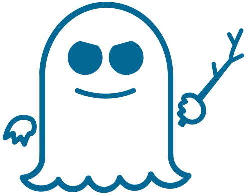
Hardware Complexity: Heterogeneity



- Demanded by performance and energy requirements
- Big challenge for OSes: single shared kernel on all cores does no longer work
- OSes need to be prepared for compute units with different feature sets

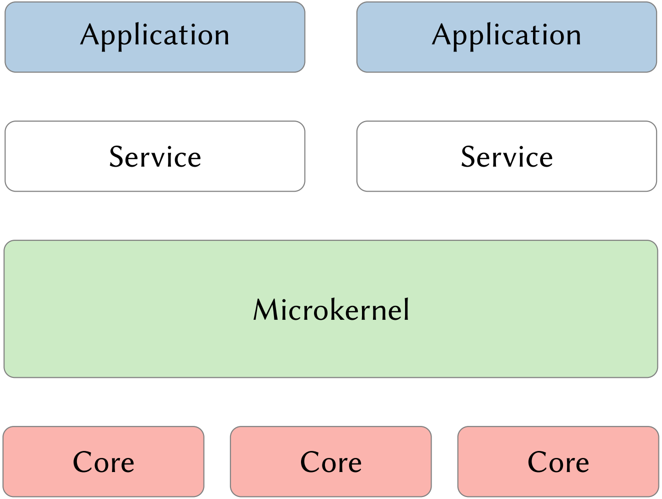
Hardware Complexity: Untrusted Hardware Components





- Provided by third-party vendors
- Bug in such a component can compromise whole system (see Broadcom incident)
- Side channels in modern cores allow attackers to leak private data; some bypass all security measures of the core (address spaces, virtualization, . . .)
- Have been lurking in CPUs for many years, also due to complexity

Microkernel-based System as Foundation



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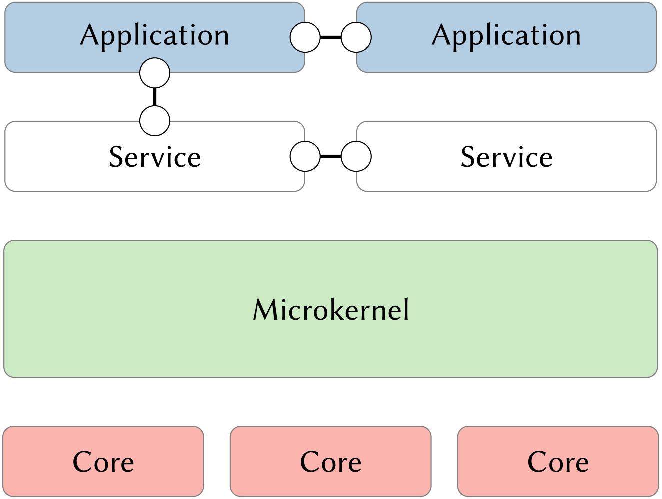

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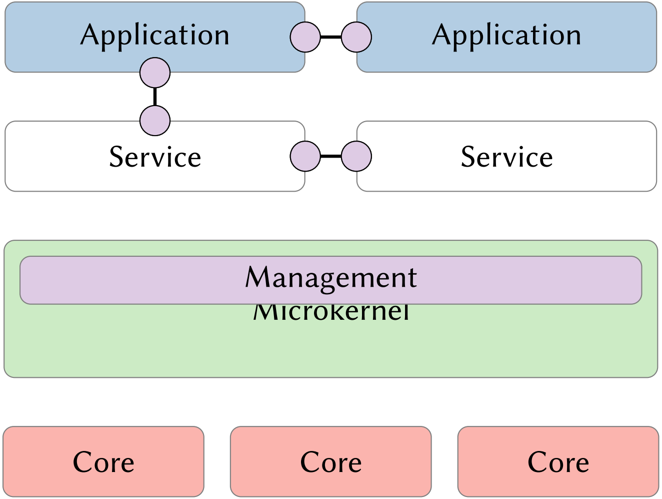

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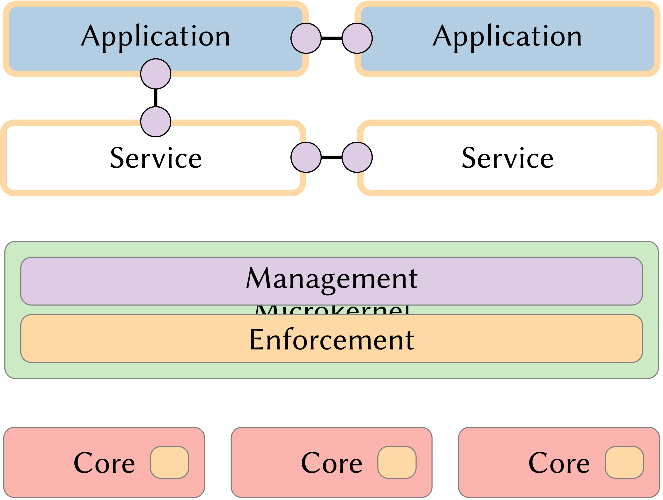

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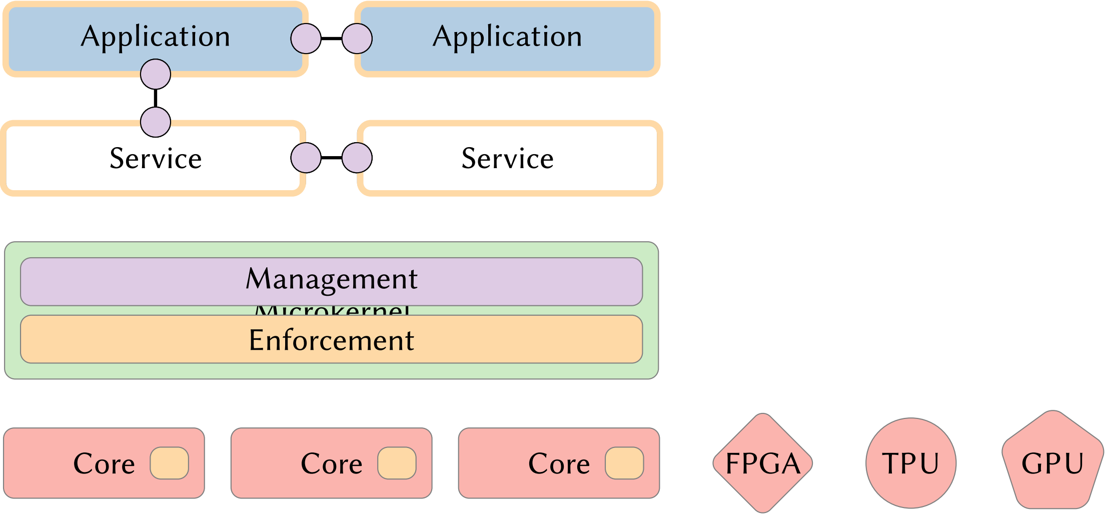

Application

Application

Service

Service

Management

Microkernel

Enforcement

Core

Core

Core

FPGA

TPU

GPU

M^3 System Architecture [1]

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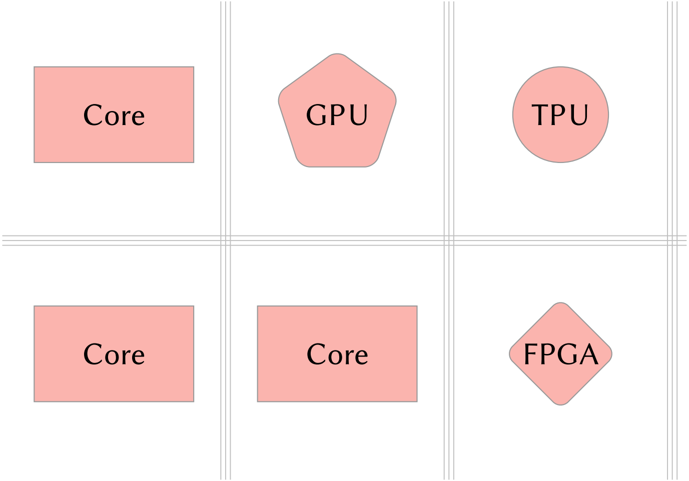

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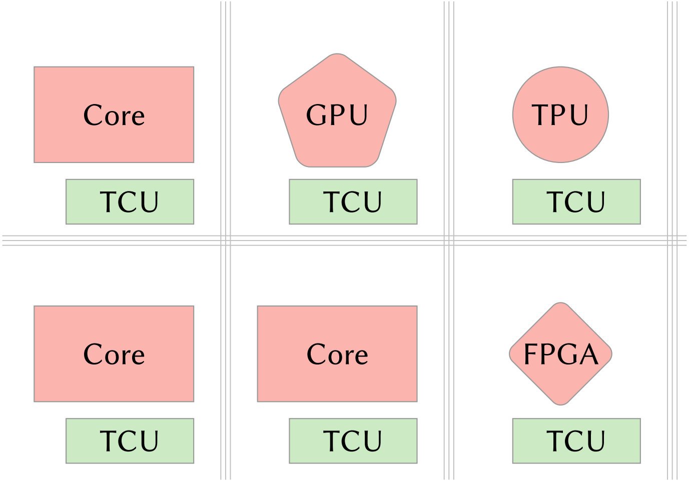

Key ideas:

- TCU as new hardware component

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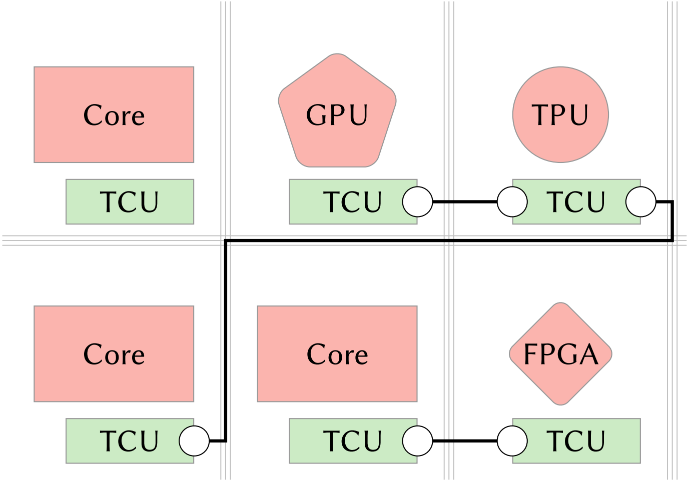

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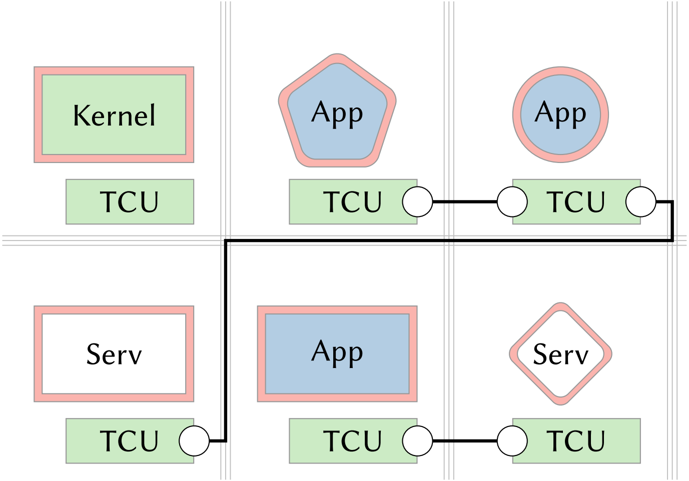

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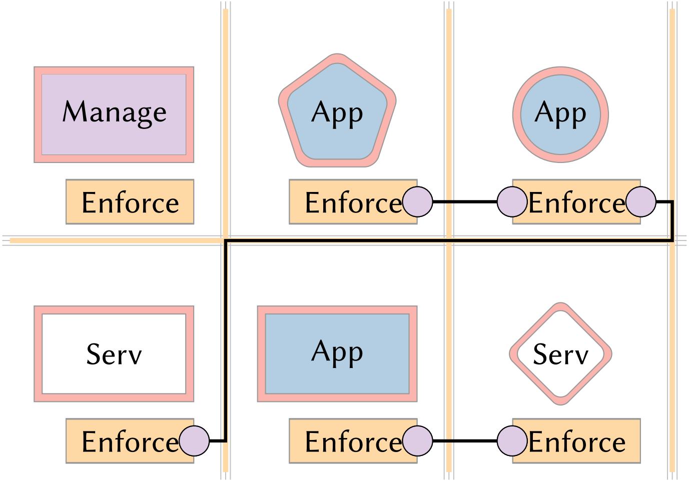

Key ideas:

- TCU as new hardware component
- Kernel on dedicated tile
- Kernel manages, TCU enforces

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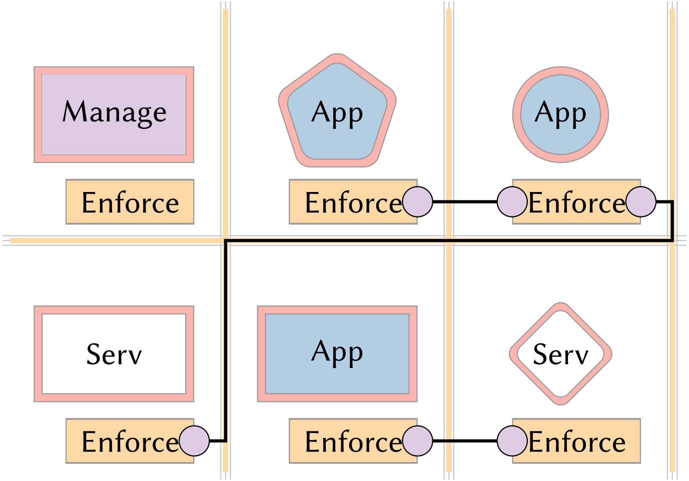
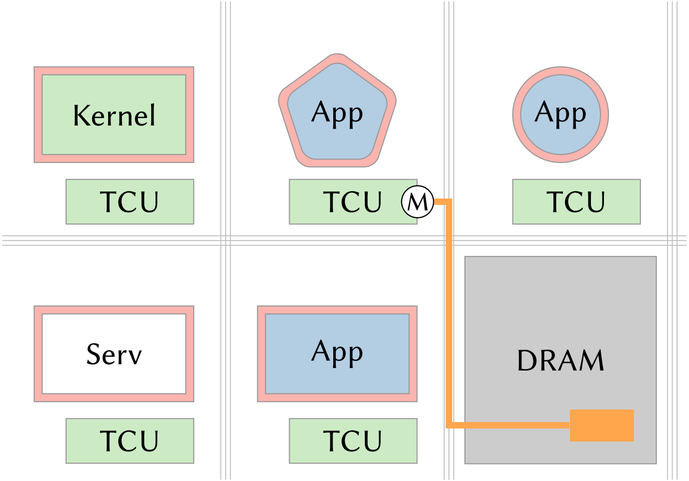


μ-kernel-ideas applied to HW:

- μ-kernel contains essence of monolithic kernel
- TCU contains essence of μ-kernel

TCU-based Communication



TCU provides *endpoints* to:

- Access memory (contiguous range, byte granular)

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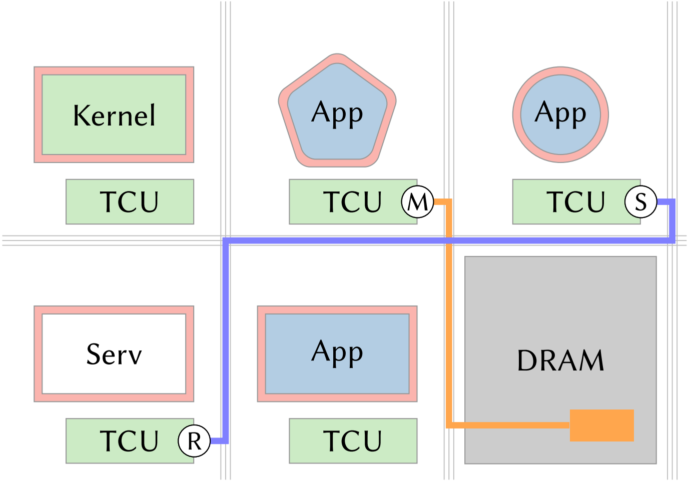

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- Receive messages into a receive buffer
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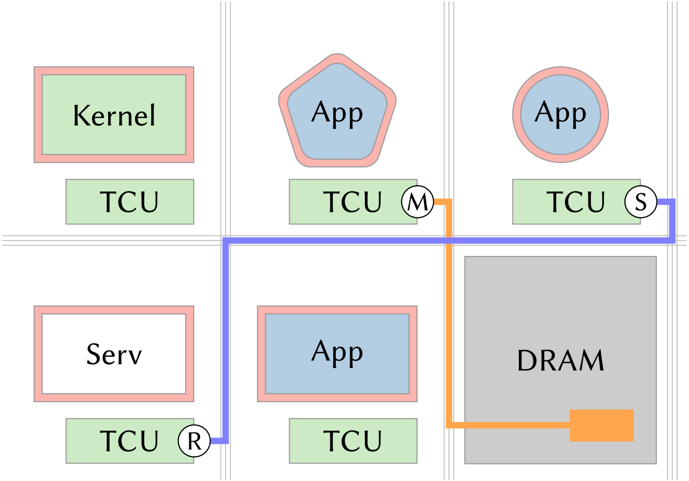
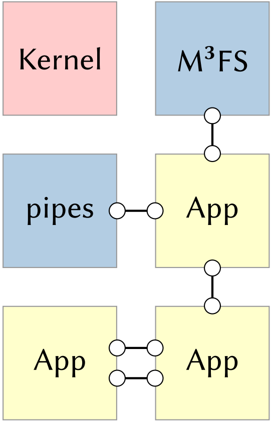


TCU provides *endpoints* to:

- Access memory (contiguous range, byte granular)
- Receive messages into a receive buffer
- Send messages to a receiving endpoint
- Replies for RPC

M3: The Operating System

- M3: **M**icrokernel-based syste**m** for het. **m**anycores (or L4 ± 1)
- Implemented from scratch in Rust and C++
- Drivers, filesystems, etc. implemented on user tiles
- Kernel manages permissions, using capabilities
- TCU enforces permissions (communication, memory access)
- Kernel is independent of other tiles



M^3-based Projects

- **M^{3}x: Autonomous Accelerators via Context-Enabled Fast-Path Communication**
  Nils Asmussen, Michael Roitzsch, Hermann Härtig, USENIX ATC 2019
- **SemperOS: A Distributed Capability System**
  Matthias Hille, Nils Asmussen, Pramod Bhatotia, Hermann Härtig, USENIX ATC 2019
- **Untrusted Cores in a Shared System**
  Under review for ASPLOS 2022
- Secure communication between devices (WIP)
- Compiler-based separation of components (WIP)

OS Service Access for all Tiles

```
sh $ decode in.png | fft |  mul | ifft > out.raw
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OS Service Access for all Tiles

Shell

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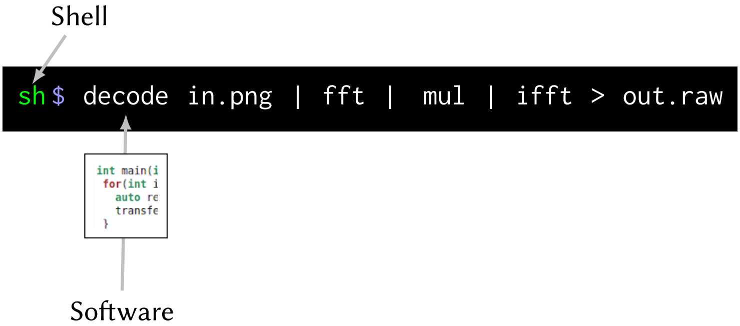

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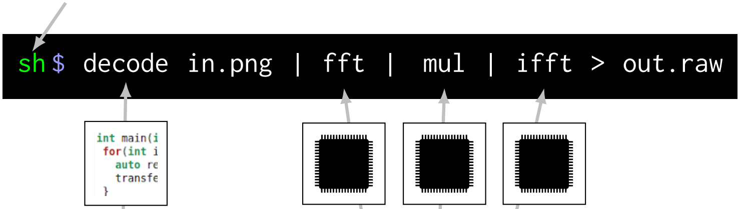

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Hardware accelerators for image processing

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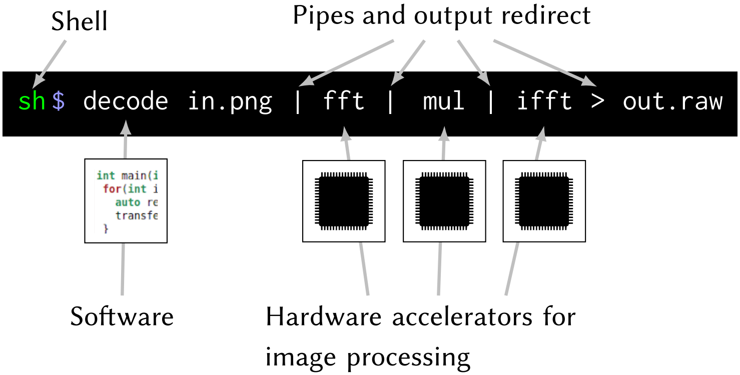

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Pipes and output redirect

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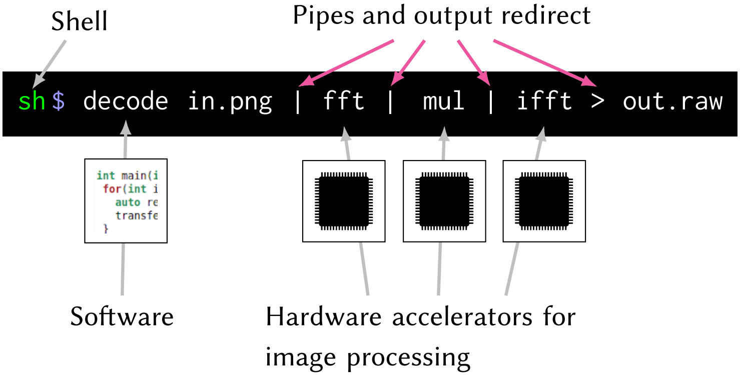

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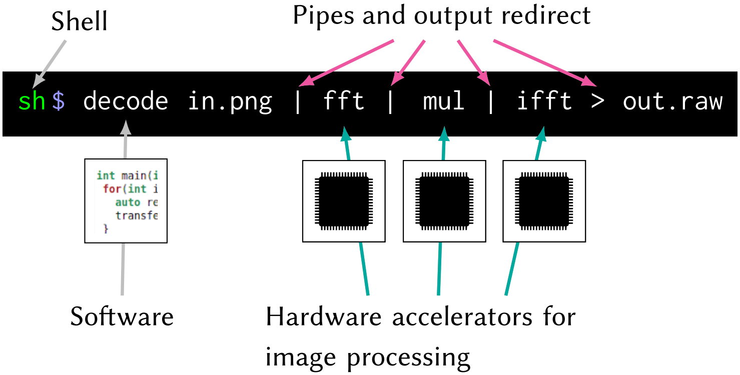

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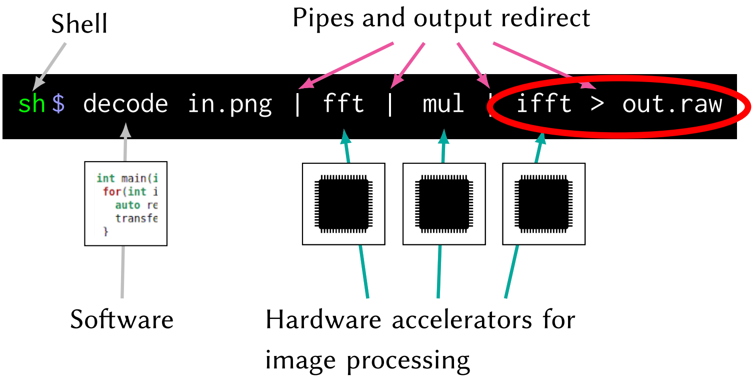

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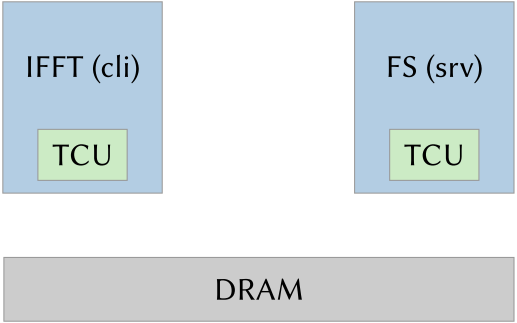

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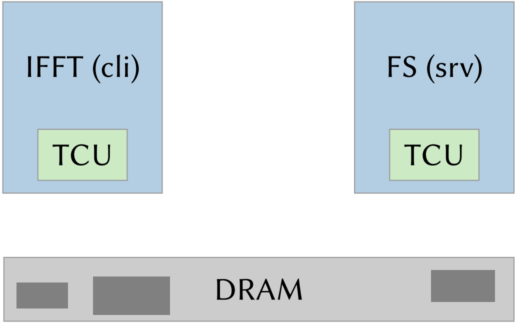

File protocol:

- Data in memory

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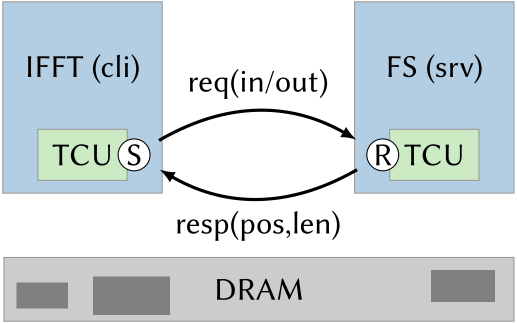

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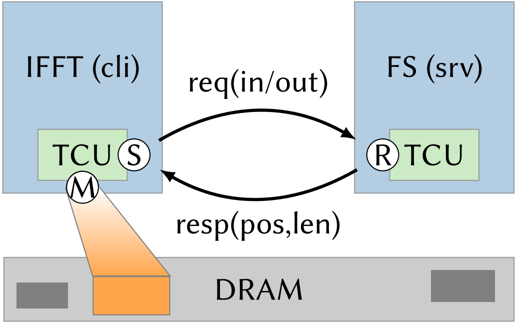

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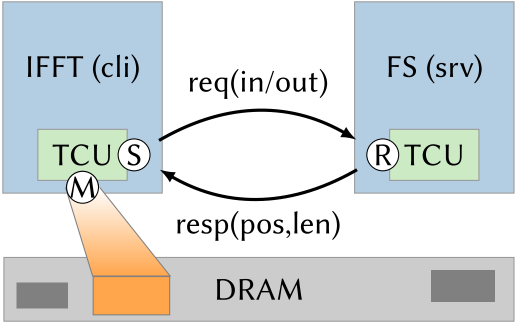

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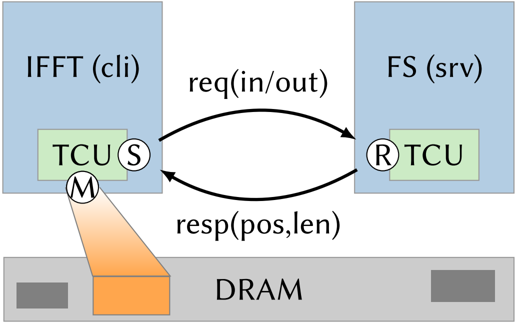

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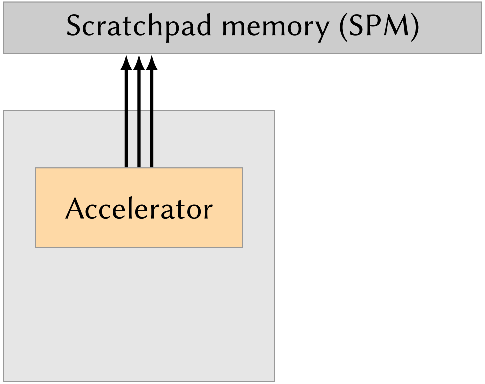
- Client accesses data via TCU
- Used by *all* tiles

Additions to Accelerator



Off-the-shelf accelerators

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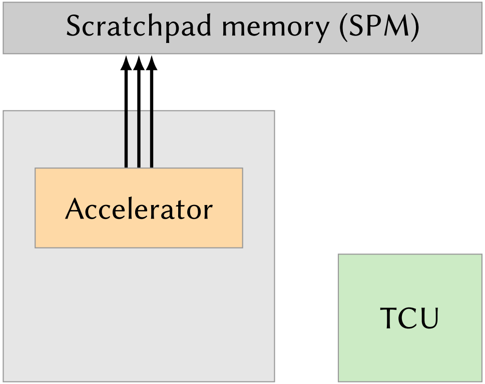

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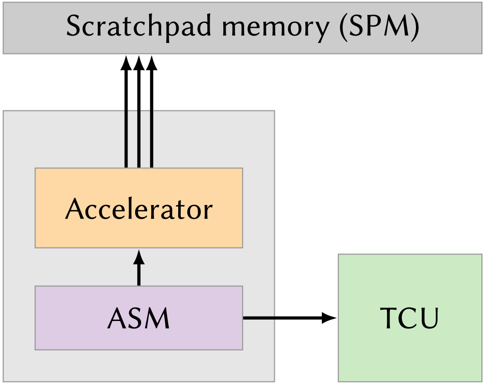

Off-the-shelf accelerators

Accelerator Support Module (ASM):

- Interacts with TCU and accelerator

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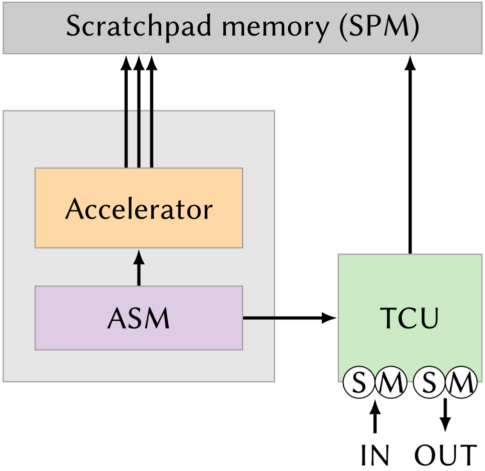
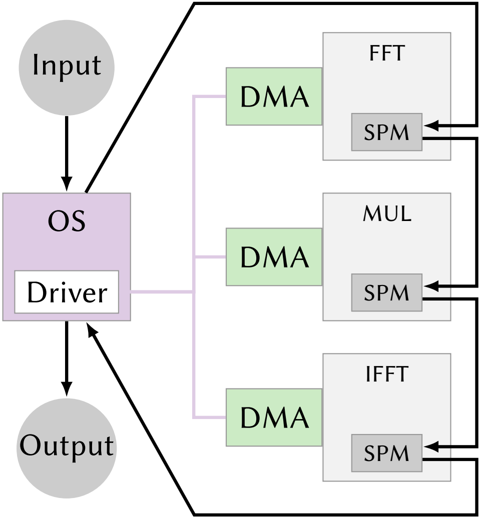


Off-the-shelf accelerators

Accelerator Support Module (ASM):

- Interacts with TCU and accelerator
- Implements file protocol for input and output channel

Assisted vs. Autonomous



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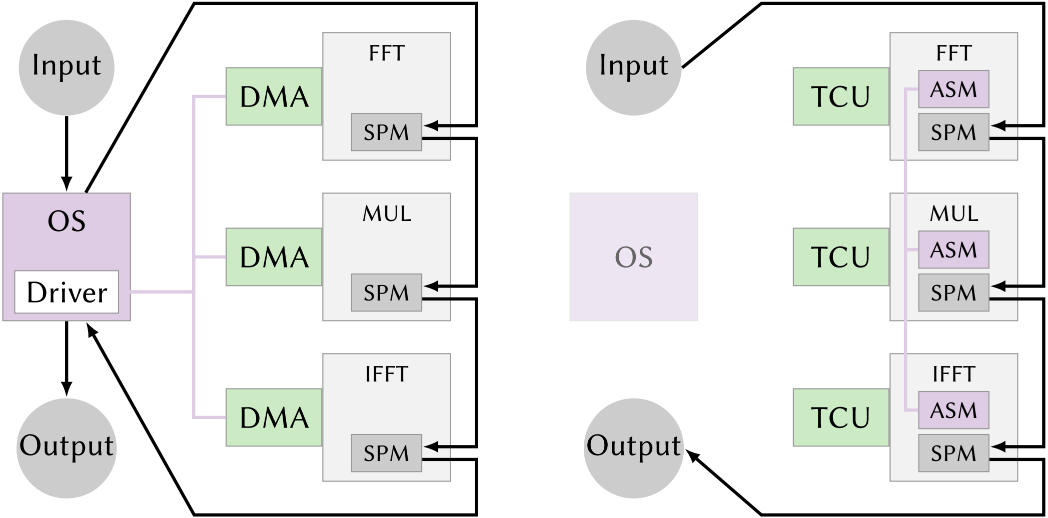

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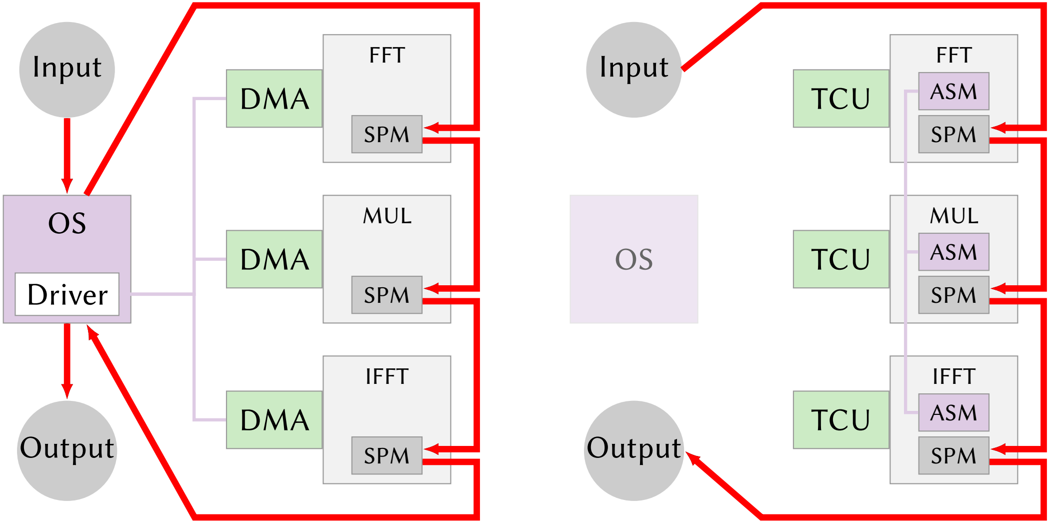

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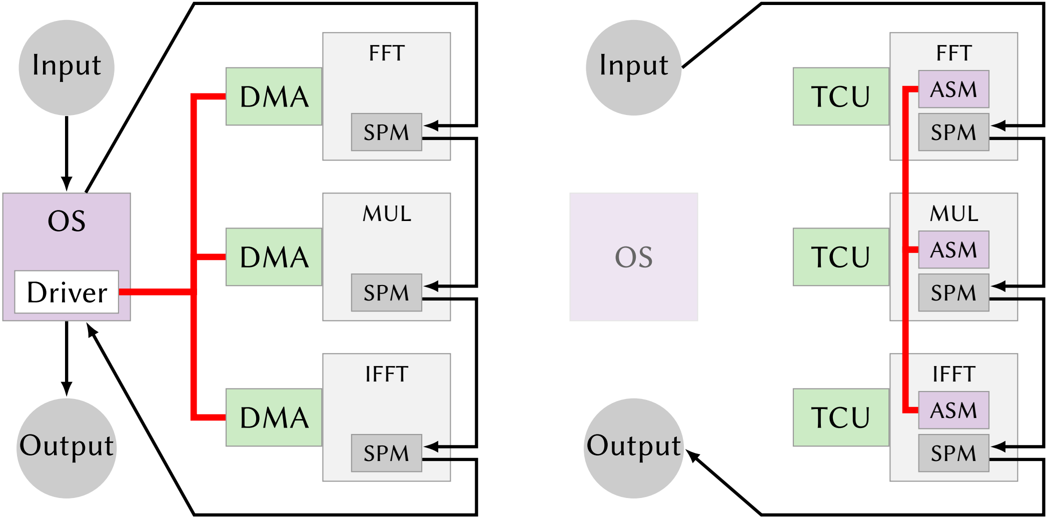
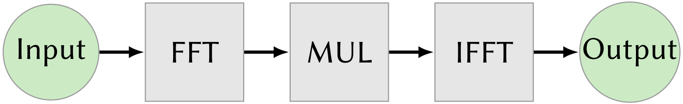


Accelerator Chains: Evaluation



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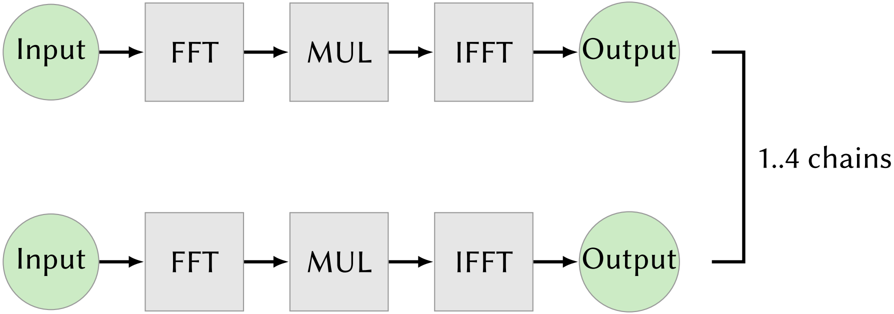

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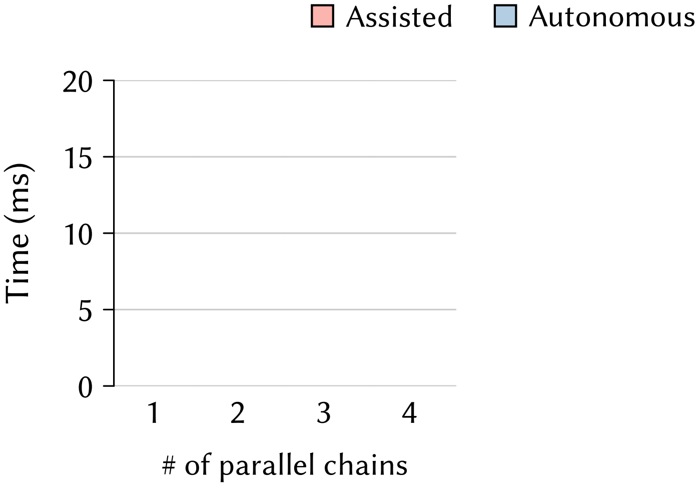

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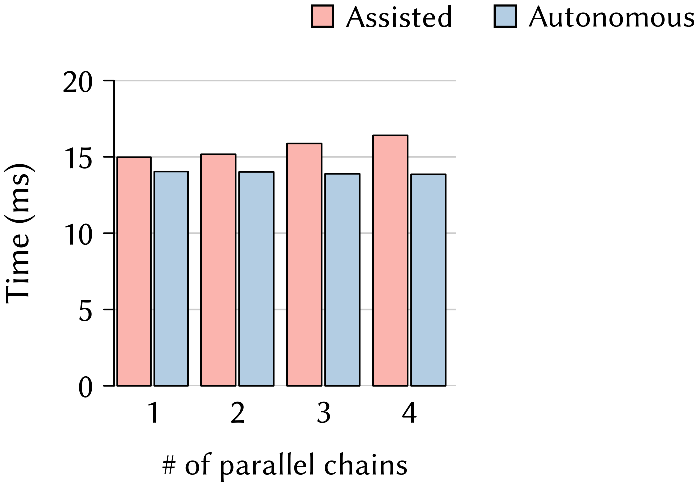

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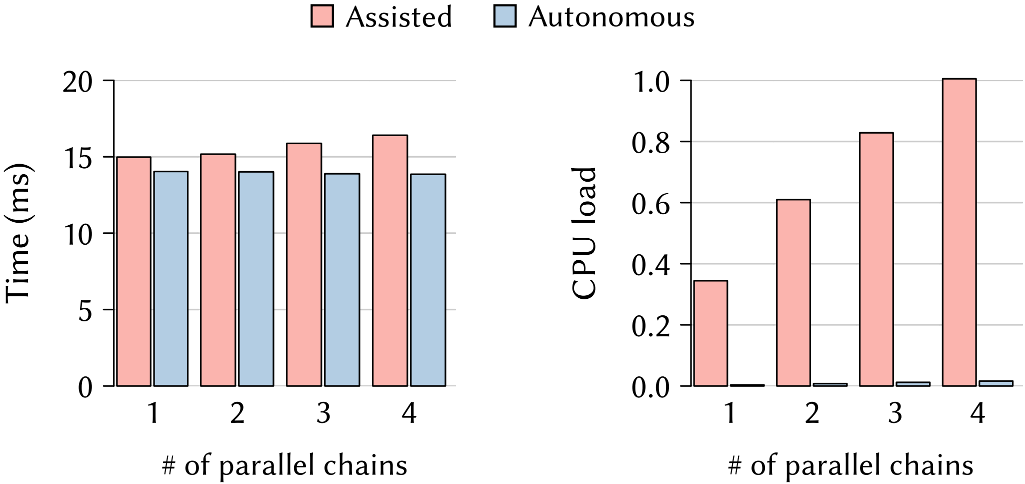
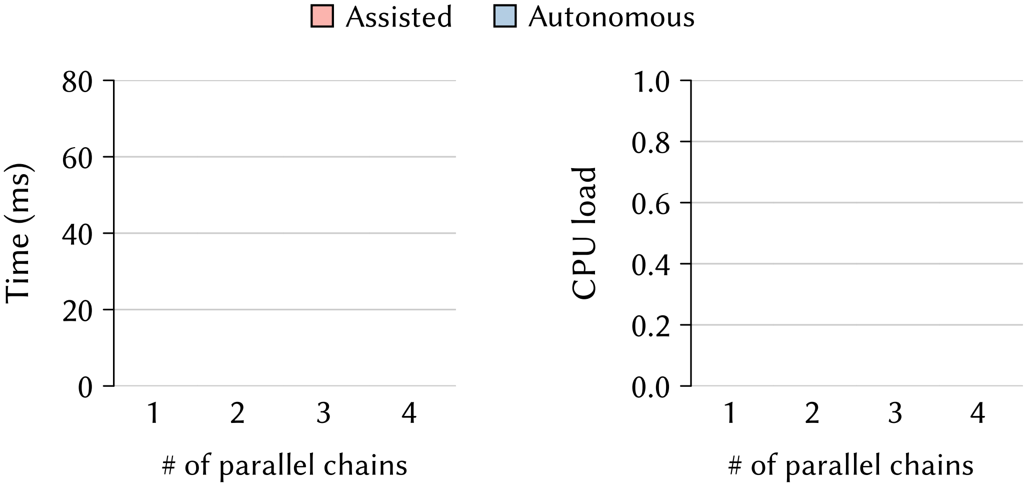


Accelerator Chains: Results (PCIe-like Latency)



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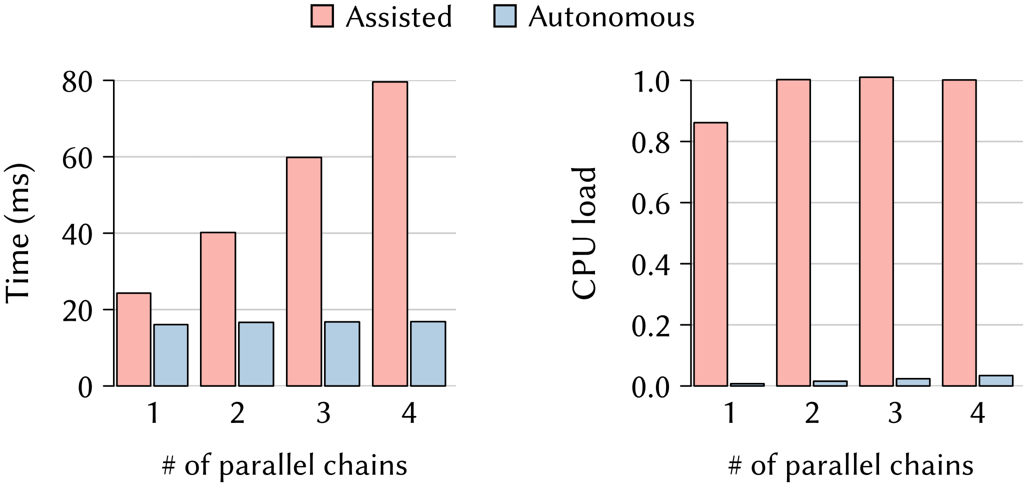

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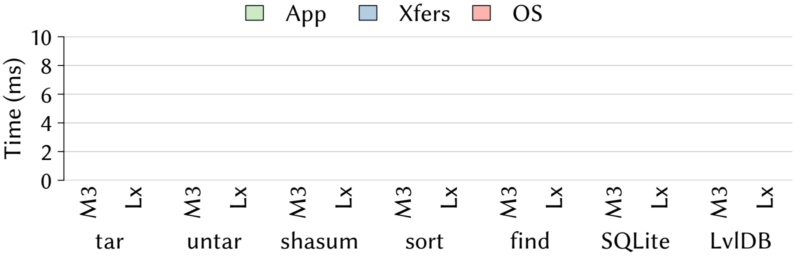

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- Traced on Linux, replayed on M^3
- M^3FS vs. Linux tmpfs

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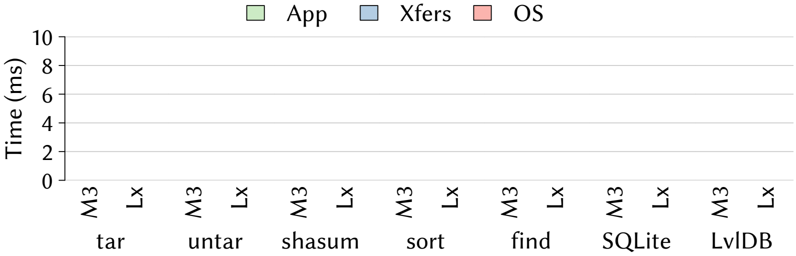

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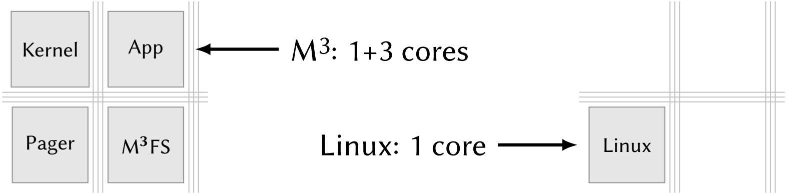


Kernel

App

Pager

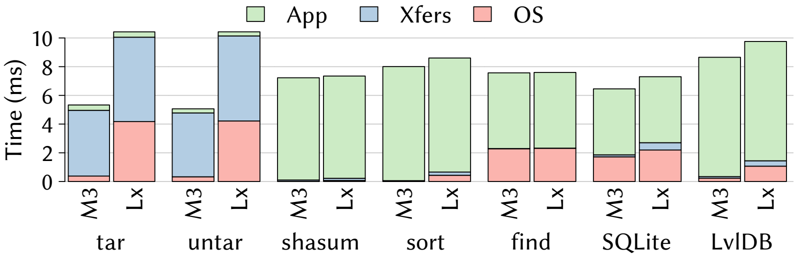
M^3FS

M^3: 1+3 cores

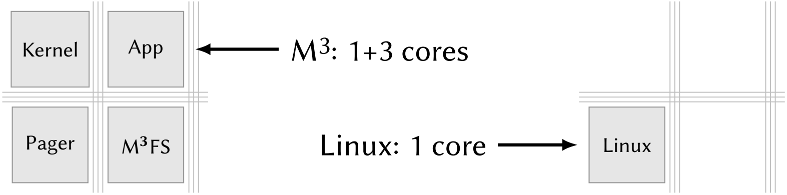
Linux: 1 core

Linux

Performance Comparison with Linux



- M^3 vs. Linux 4.10
- Traced on Linux, replayed on M^3
- M^3FS vs. Linux tmpfs



Kernel

App

Pager

M^3FS

M^3: 1+3 cores

Linux: 1 core

Linux

Conclusion

- M^3 applies microkernel ideas to hardware
  - Add trusted communication component (TCU) next to each compute unit
  - TCU contains essence of a traditional microkernel
  - Microkernel-based system called M^3 takes advantage of TCU

Conclusion

- M^3 applies microkernel ideas to hardware
  - Add trusted communication component (TCU) next to each compute unit
  - TCU contains essence of a traditional microkernel
  - Microkernel-based system called M^3 takes advantage of TCU
- M^3x introduced accelerator chaining
  - Improves performance compared to traditional approach
  - Reduces CPU load to almost zero → accelerators run autonomously