CONFIDENTIAL COMPUTING SUMMIT 2025

OpenCCA: An Open Framework to Enable Research on Arm CCA

Andrin Bertschi, ETH Zurich

Confidential Computing is Exciting!

Industry Momentum

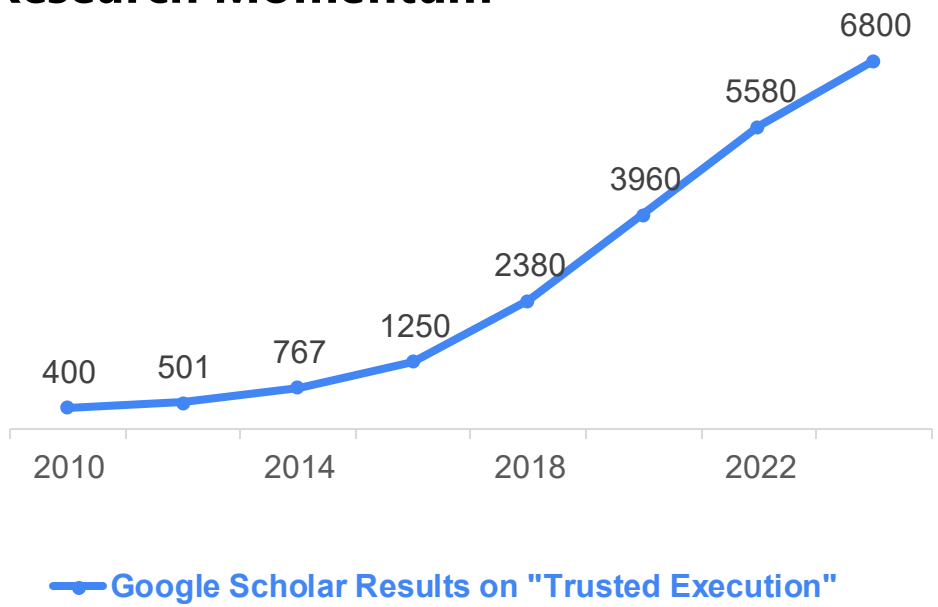
- Widely available in Hardware

CCA SEV-SNP TDX Keystone

- Deployed in the cloud

aws Azure Google Cloud Alibaba Cloud

Research Momentum

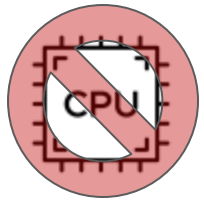


Arm CCA
19 academic papers in last 4 years

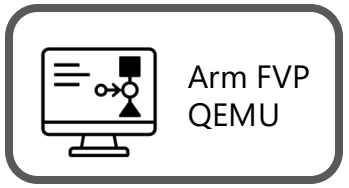
How to research on Arm CCA

Main Challenge on Arm CCA:

- No Hardware yet



1. Simulation



- Validate design + compatibility
- 17/19 papers

Academic Work	Simulation	Board Prototype	Board Arch.
Cage	FVP	Juno R2	8.0
Shelter	FVP	Juno R2	8.0
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virtCCA	–	Undisclosed	8.4
Sharing is Leaking	–	AmpereOne	8.6
CPC Maintenance	FVP	SEV SNP (x86)	–
GuaranTEE	FVP	–	–
Devlore	FVP	–	–
BarriCCAde	QEMU	–	–
Aster	QEMU	–	–

Source

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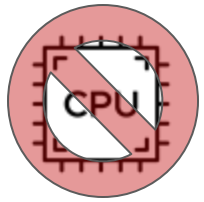

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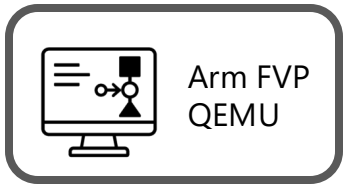
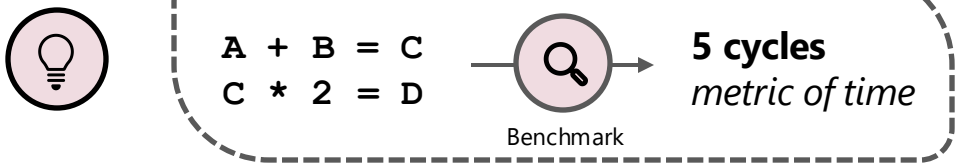


- Validate design + compatibility
- 17/19 papers

2. Board Prototype

- Validate performance
- 15/19 papers



*Includes **microarchitectural effects of complex hardware**: out-of-order exec, pipeline stalls, cache misses, ...*

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How to research on Arm CCA

Arm Juno R2

- 10 years old
- No longer manufactured
- Initial Price: 10k USD

https://developer.arm.com/-/media/Arm%20Developer%20Community/PDF/Juno%20r2%20datasheet.pdf

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Arm CCA

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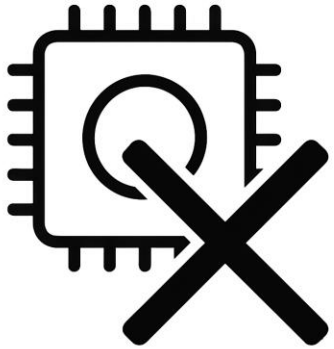
How to research on Arm CCA

No hardware performance evaluation at all



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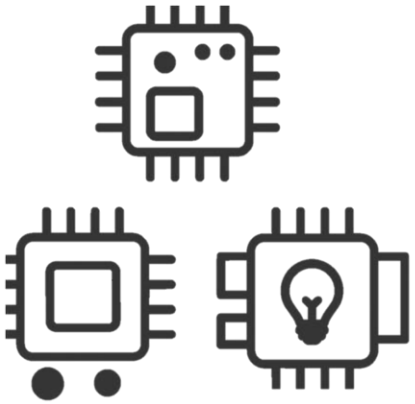
How to research on Arm CCA

Variety of different boards, all with different hardware features



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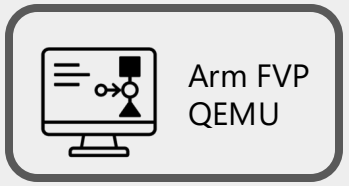
The Need for Open Framework for Performance Evaluation



Software Simulation:

✓ Functionality

✓ Compatibility

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Custom Ad-Hoc:

✕ Difficult to compare

✕ Difficult to reproduce

✕ Repeated engineering

OpenCCA: An Open Framework to Enable Arm CCA Research

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***Abstract*—Confidential computing has gained traction across major architectures with Intel TDX, AMD SEV-SNP, and Arm CCA. Unlike TDX and SEV-SNP, a key challenge in researching Arm CCA is the absence of hardware support, forcing researchers to develop ad-hoc prototypes on CCA emulators and non-CCA Arm boards. This approach leads to high barriers to entry or duplicated efforts leading to unsound and inconsistent comparisons. To address this, we present OpenCCA, an open research platform that enables the execution of CCA-bound code on commodity Armv8.2 hardware. By systematically adapting the software stack (including bootloader, firmware, hypervisor, and kernel), OpenCCA emulates CCA operations for performance evaluation while preserving functional correctness. We demonstrate its effectiveness with typical life-cycle measurements and case-studies inspired by prior CCA-based papers on an easily available Arm v8.2 Rockchip board that costs $250.**

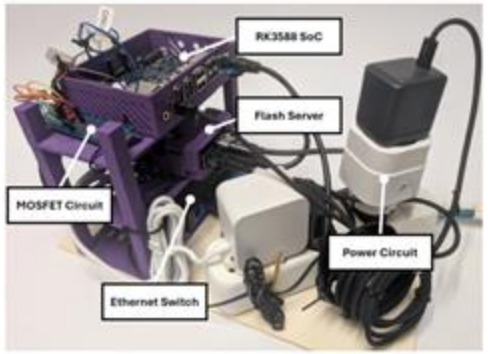


Figure 1. OpenCCA tooling. The RK3588 connects over ethernet to a flash server (Raspberry Pi). It controls a MOSFET and power circuit to flash new firmware and exposes UART access.

*Open*CCA: An Open Framework to Enable Research on Arm CCA

OpenCCA Design Goals

Minimal changes to CCA reference stack → Preserve functionality

No security guarantees

Only for benchmarking & accelerator support

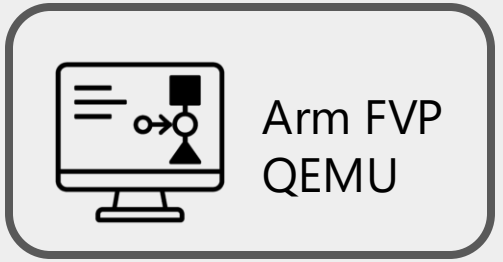
Target: Affordable & Available Armv8 Boards

Focus on *reusable* Framework

Not specific to a board

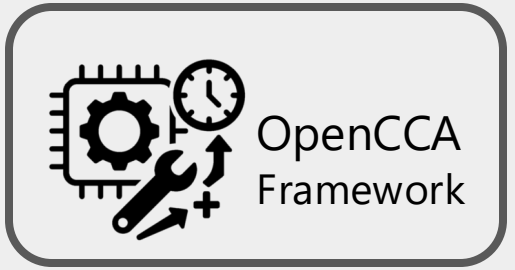
Performance estimation

Step 1: Simulation



Validate design

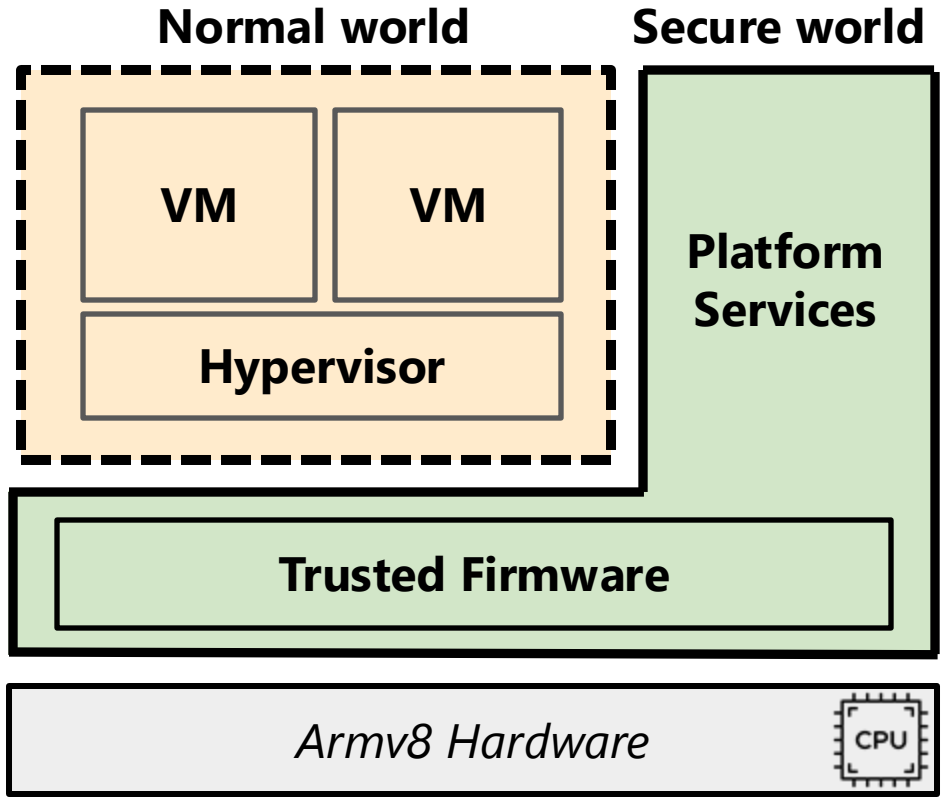
Step 2: Hardware Prototype



Evaluate & Compare Performance

Background on Arm CCA

- Before Armv9: TrustZone



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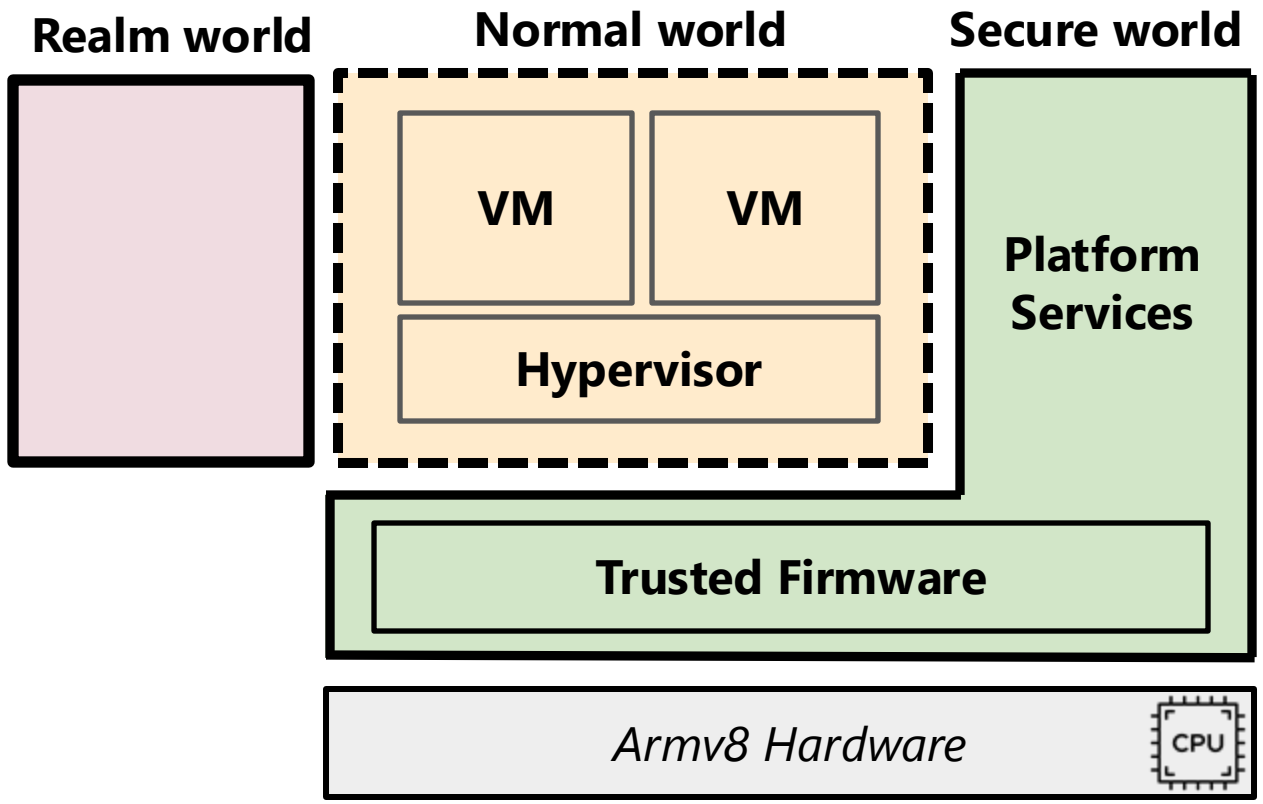

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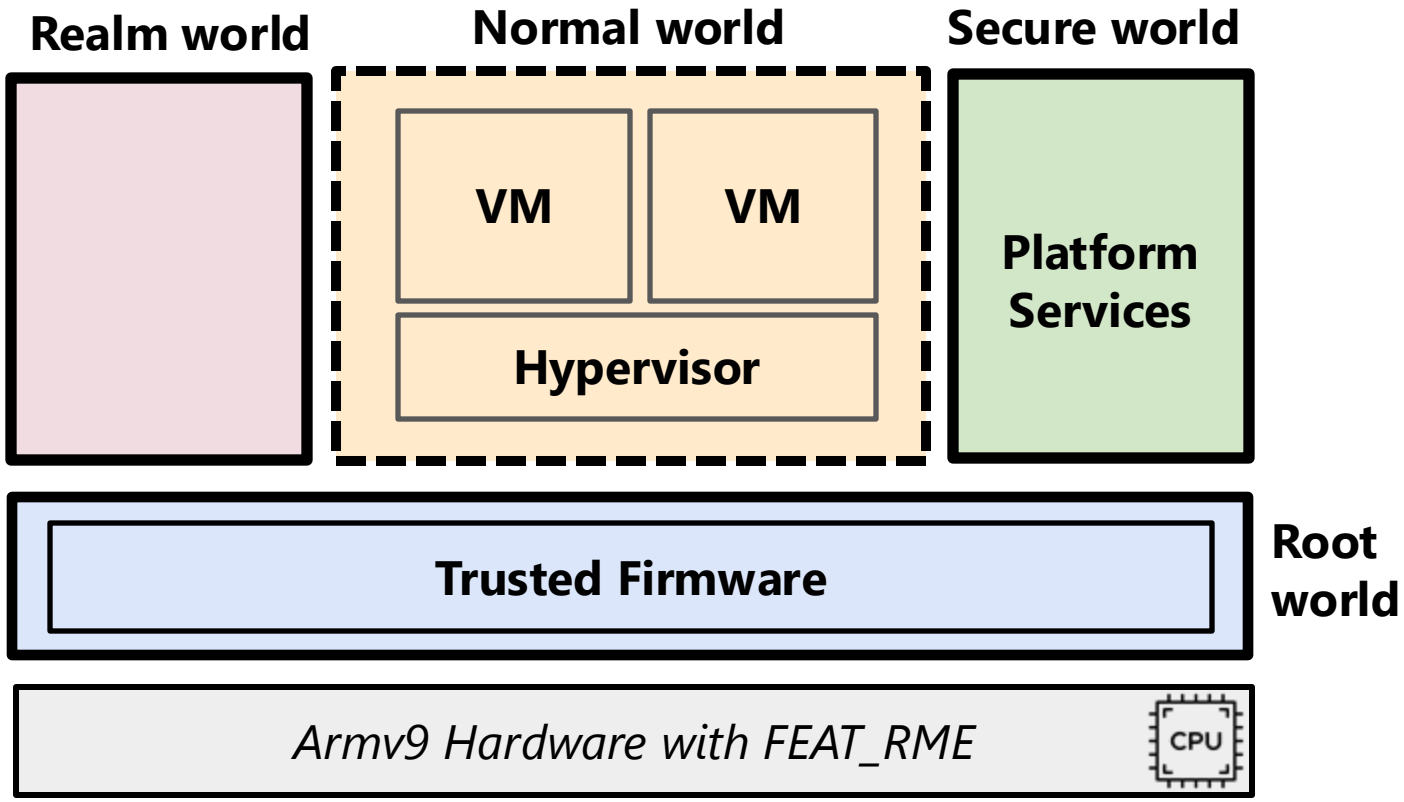

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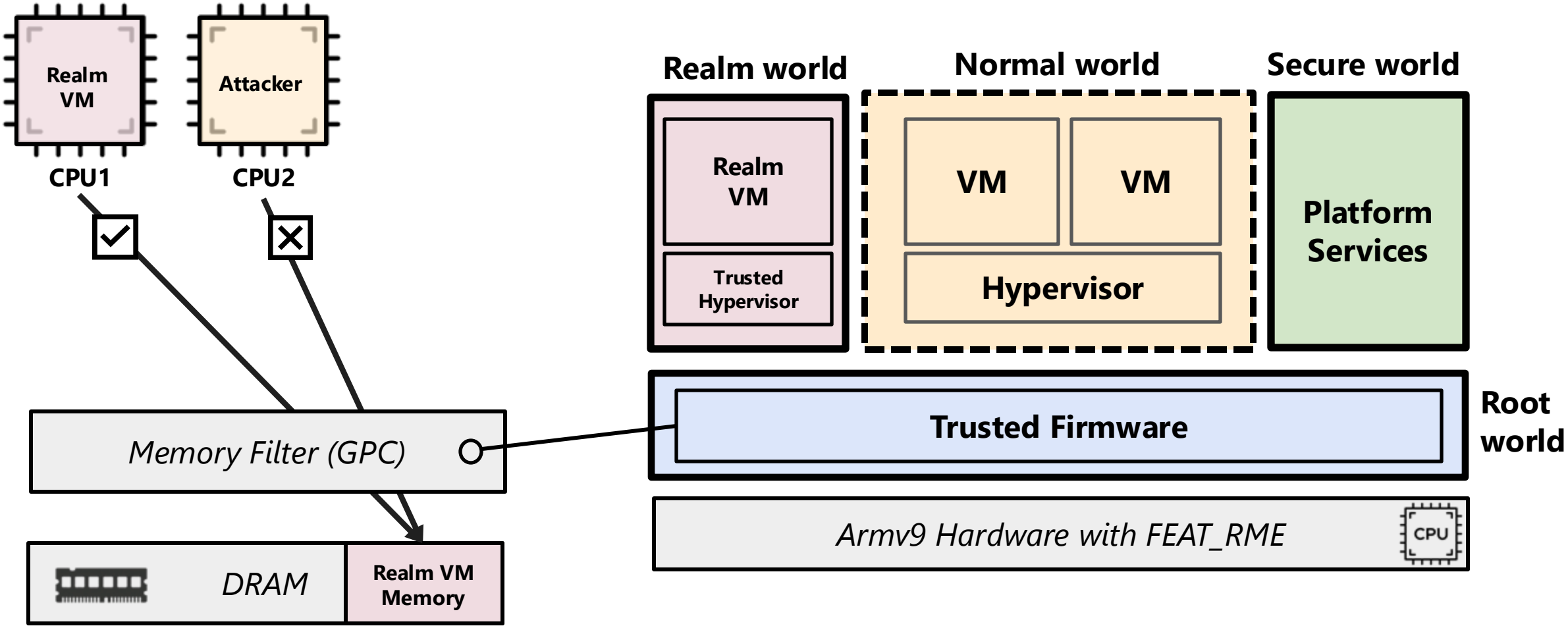
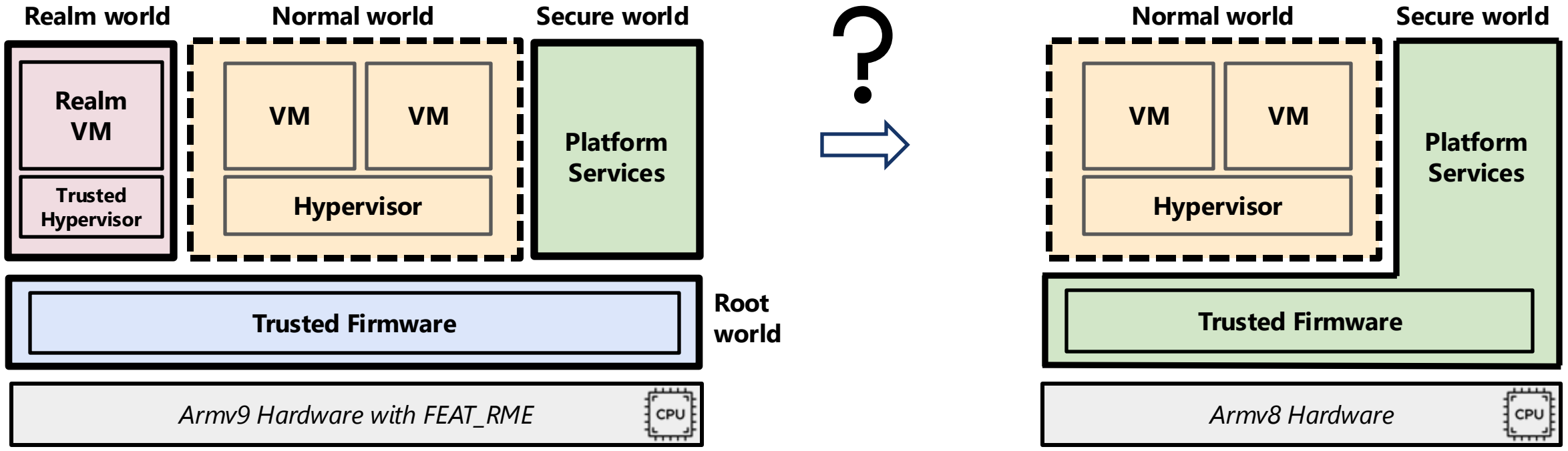


How do you even run Arm CCA on older Hardware?



Armv9

Armv8

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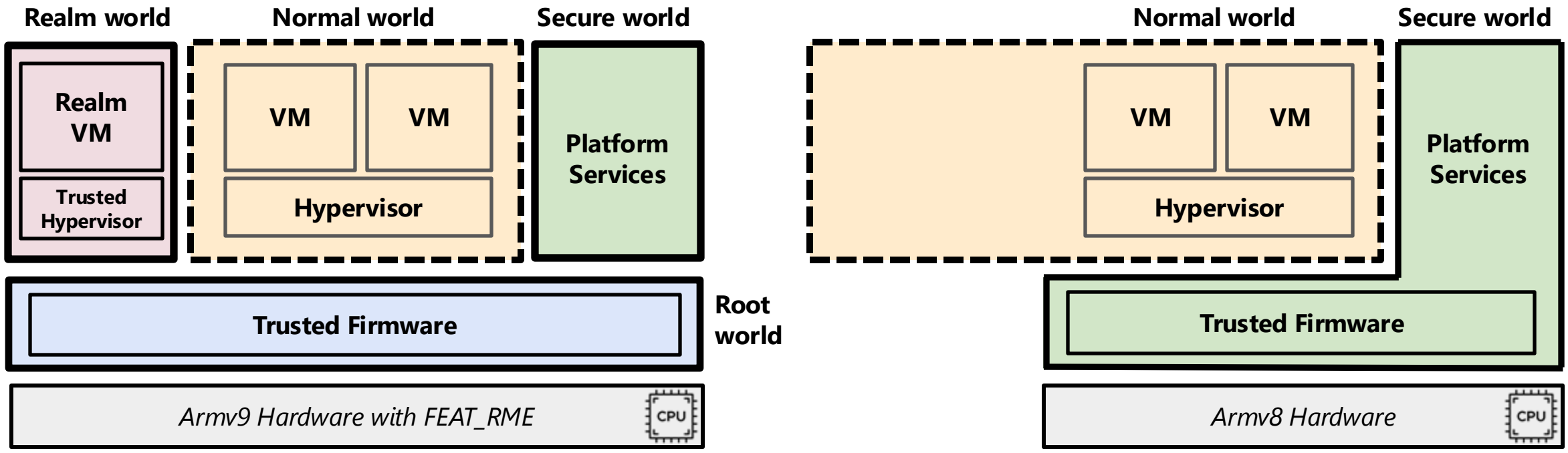

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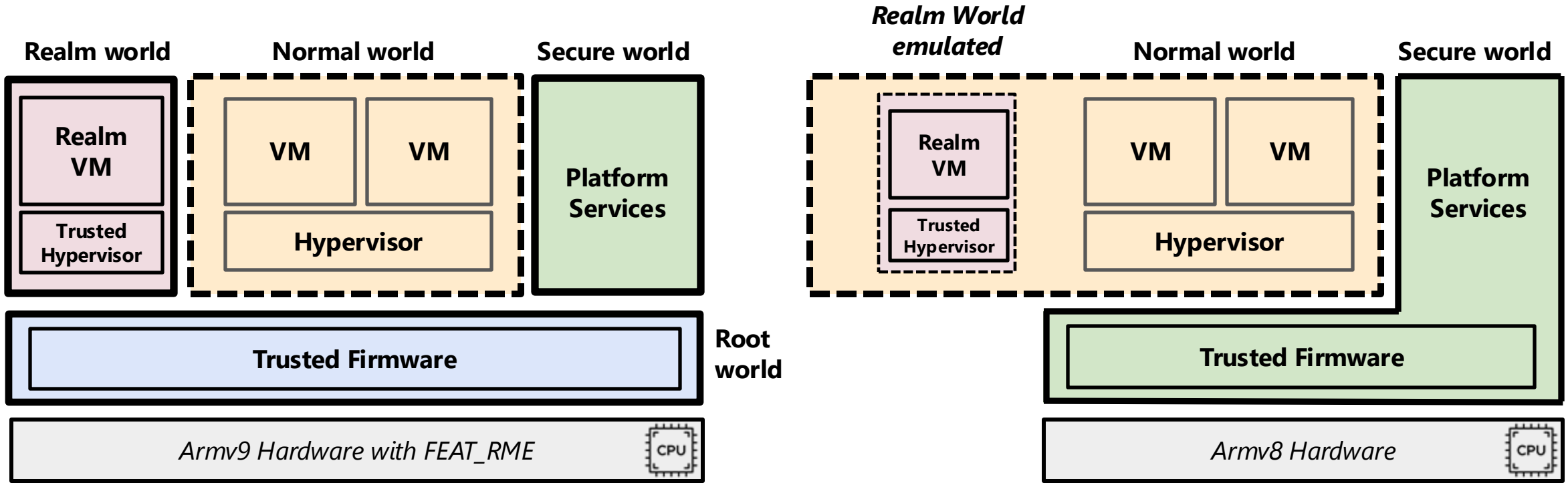

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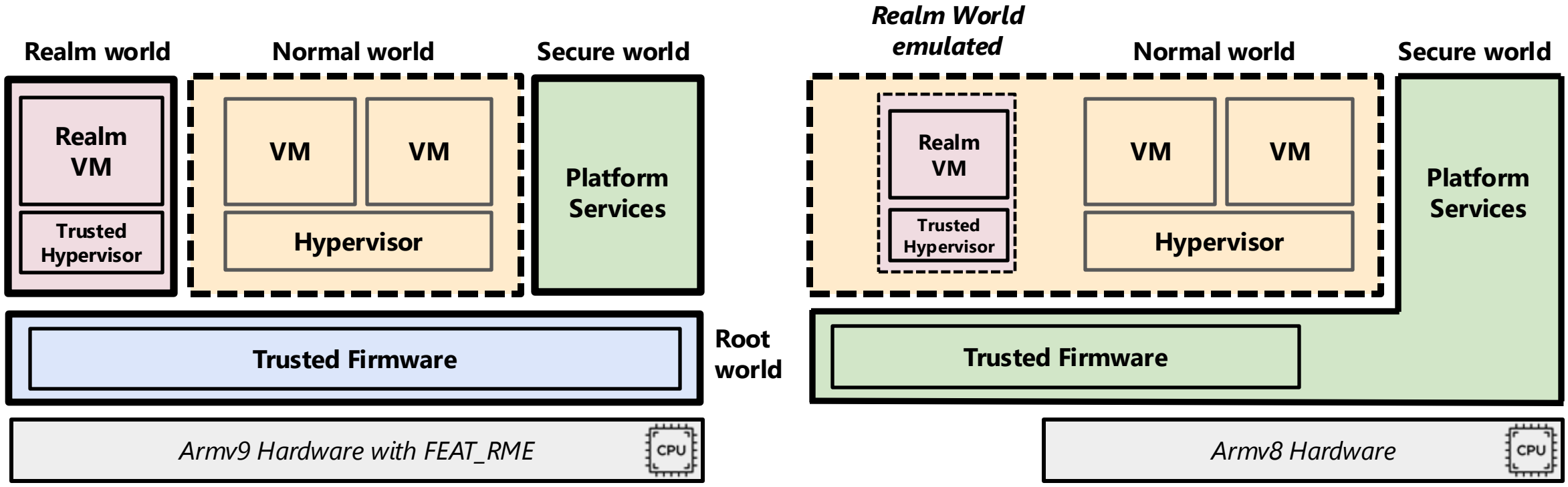

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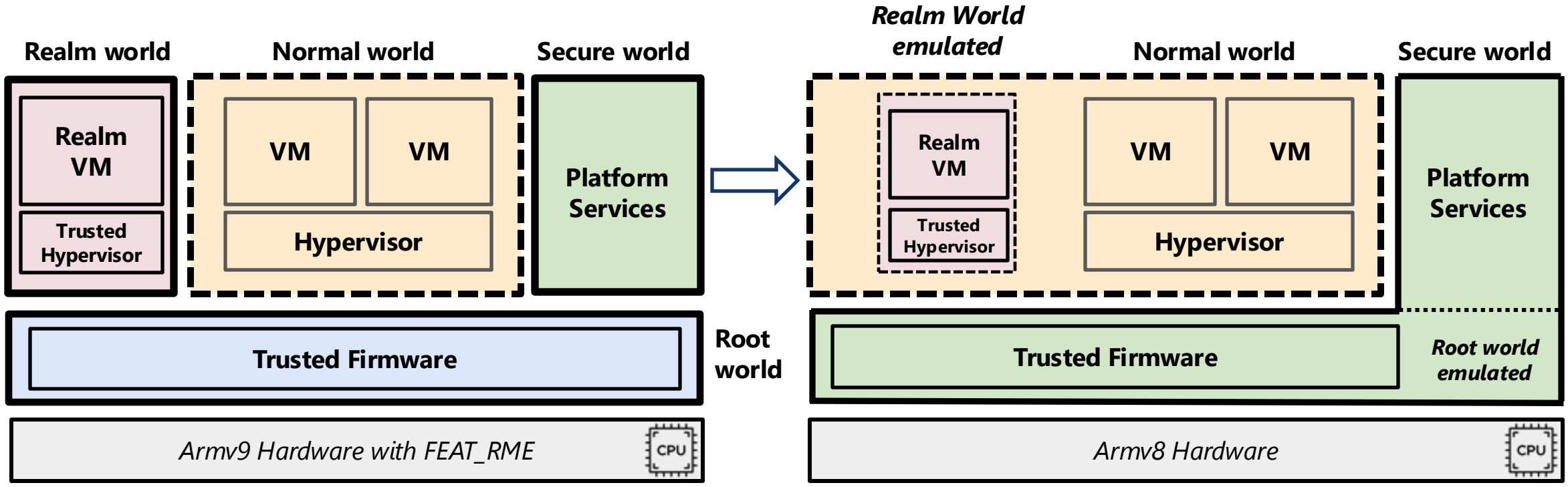
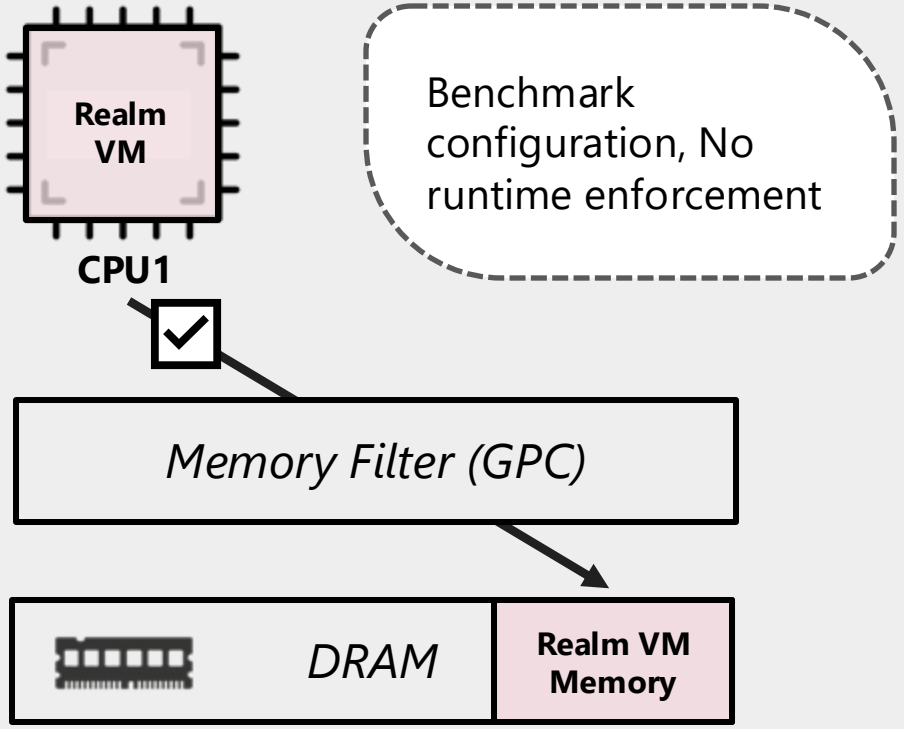


Emulate CCA in software within the constraints of Armv8 Hardware

Example: Emulating Hardware in Software

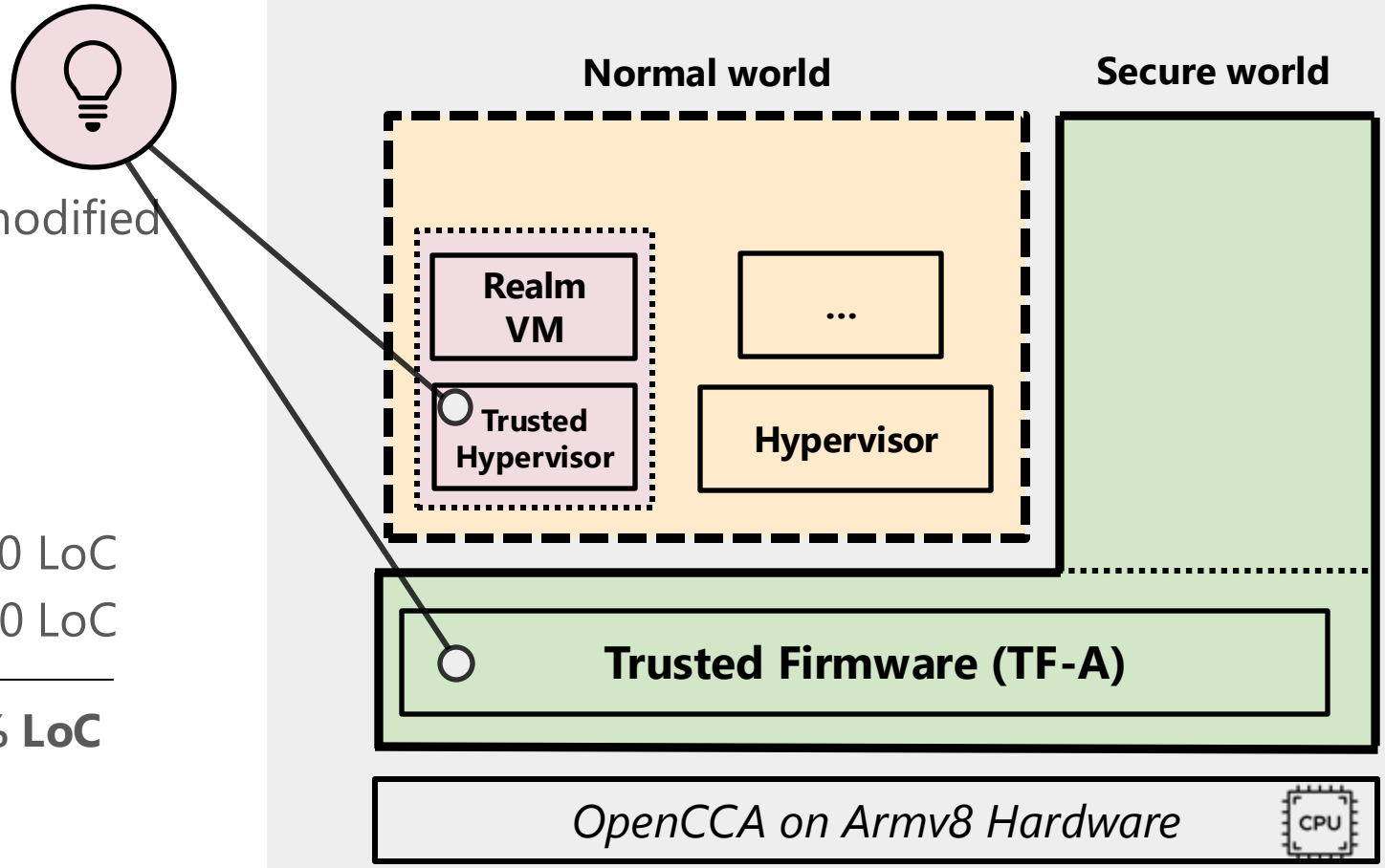
- **Tradeoff** between **Compatibility** & **Overhead**
- **Fake missing parts in software** while keeping changes small
- Return **predefined values** instead of querying the hardware

- Example: Memory Filters not on Armv8



Details: Implementation

- Run general purpose realm VMs
- Enlighten 2 firmware components
- Keeping rest of reference stack unmodified



Software changes:

- Trusted Hypervisor (RMM): +1440 LoC
- Trusted Firmware (TF-A): + 940 LoC

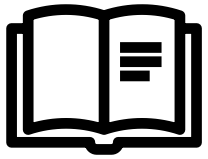
Changes (C/C++/Asm) < +1% LoC

Preserve functionality without security

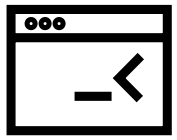
Choosing a Hardware Platform

Selection Criteria

No Vendor lock
Firmware flashable

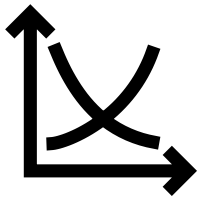


Documentation
Technical Reference Manual

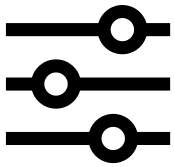


Support for Firmware
Arm Trusted Firmware

Also relevant



Price &
Availability



Modern Hardware
Features

Board	Released	SoC	GIC	Price (USD)	Cores	GPU	TF-A Code
Intel Stratix 10 SX DK	2013	Intel Stratix 10	GICv2	9,000	A53	N/A	✓
AmloGIC Meson S905 (GXBB)	2015	S905	GICv2	unknown	A53	Mali 450	✓
HiKey	2015	Kirin 620	GICv2	75-100	A53	Mali 450	✓
Arm Juno r2	ca. 2015	Juno r2 SoC	GICv2	10,000	A72, A53	Mali T624	✓
NXP i.MX7 WaRP7	2016	i.MX 7 Solo	GICv2	100	A7, M4	N/A	✓
A64-OLinuXino	2016	Allwinner A64	GICv2	100	A53	Mali 400	✓
AmloGIC Meson S905x (GXL)	2016	S905x	GICv2	unknown	A53	Mali 450 MP3	✓
NXP i.MX 8QM MEK	2016/17	i.MX 8QM	GICv3	1,200	A72, A53, M4F	GC7000XSVX	✓
NXP i.MX 8MQ EVK	2016/17	i.MX 8MQ	GICv3	500	A53, M4	GC7000Lite	✓
NXP i.MX 8ULP EVK	2016/17	i.MX 8 ULP	GICv3	550-650	A53, M33	GC520	✓
Xilinx Zynq ZCU102 EVK	ca. 2017	2FFVB1156E	GICv2	3,200	A53, R5F	Mali 400 RP2	✓
AmloGIC Meson A113D (AXG)	2017	S400	GICv2	unknown	A53	2D GFX Engine	✓
HiKey 960	2017	Kirin 960 SoC	GICv2	250	A73, A53	Mali G71 MP8	✓
AmloGIC Meson S905X2 (G12A)	2018	S905x2	GICv2	unknown	A53	Mali-G31 MP2	✓
HiKey 970	2018	Kirin 970	GICv2	300	A73, A53	Mali G72 MP12	✓
Raspberry Pi 3 (B+)	2018	BCM2837B0	custom	25	A53	VideoCore IV	✓
Intel Agilex 7M HBM2e DK	2019	Intel Agilex 7	GICv2	10,000	A53	N/A	✓
Marvell CEx7 CN9132 EVB	2019	CN9132	GICv2	600-700	A72	N/A	✓
Ziver MTK8183 Dev. Board	2019	MT8183	GICv3	150	A73, A53	Mali G72 MP3	✓
Raspberry Pi 4	2019	BCM2711	GICv2	35	A72	VideoCore VI	✓
Huawei Mate 30 Pro	2019	Kirin 990	unknown	300	A76, A55	Mali-G76	✗
Arm Neoverse N1 SDP	2020	Dawn Ares	GICv4.1	10,000	N1	HDLCD	✓
Aspeed AST2700 EVB	2020	AST2700	GICv3	unknown	A35, M4	AST2700 2D VE	✓
RK3399 Rock4	2021	RK3399	GICv3	<200	A72, A53	Mali-T864	✓
NVIDIA Jetson TX2 NX DK	2021	Tegra X2	GICv2	350	Denver2, A57	GP10B	✓
MediaTek 8186	2021	Kompanio 520	GICv3	unknown	A76, A55	Mali-G52 MP2	✓
MediaTek 8192	2021	Kompanio 820	GICv3	unknown	A55, A76	Mali G57 MC5	✓
MediaTek 8188	2022	Kompanio 838	GICv3	unknown	A55, A78	Mali G57 MC3	✓
MediaTek 8195	2022	Kompanio 1380	GICv3	unknown	A55, A78	Mali G57 MC5	✓
Genio 700 (MT8390)	2023	MT8390	GICv3	700	A78, A55	Mali-G57	✓
Orange Pi 5 Plus	2023	RK3588	GICv3	<200	A76, A55	Mali-G610	✓
Supermicro MegaDC (Server)	2023	AmpereOne	unknown	unknown	custom built	N/A	✗
Raspberry Pi 5	2023	BCM2712	GICv2	120	A76	VideoCore VII	✓
Radxa Rock 5b (OpenCCA)	**2023**	**RK3588**	**GICv3**	**250**	**A76, A55**	**Mali-G610**	✓
NXP i.MX 93 QS EVK	ca. 2024	i.MX 93	GICv3/v4	300	A55, M33	N/A	✓
Arrow AXE5-Eagle DK	2024	Intel Agilex 5	GICv3	900-1,000	A55, A76	N/A	✓
Radxa Orion O6	2024	Cix CD8180	GICv4	500-600	A720, A520	Imtls. G720 MC6	✗

Exploring Hardware Boards
for OpenCCA

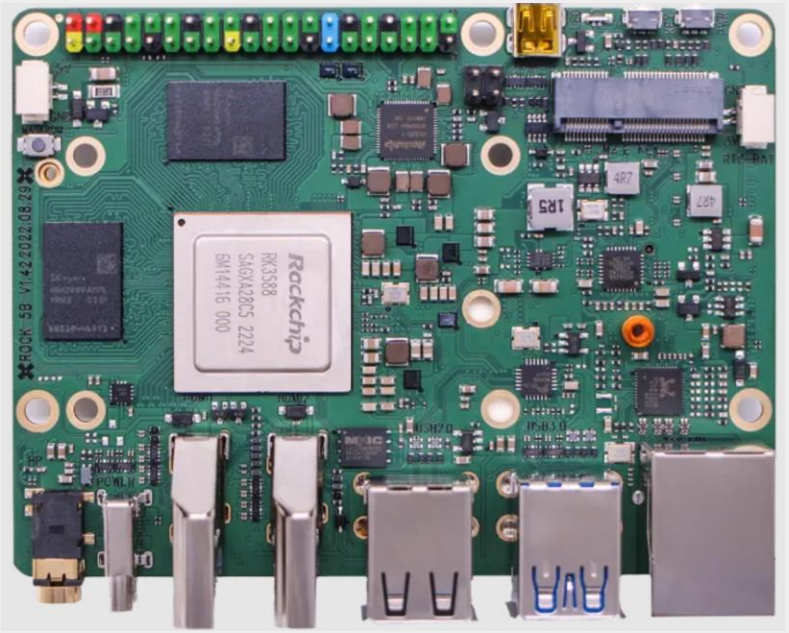
RK3588 SoC as a Platform

Key Specs:

- Armv8.2 Architecture
- CPU: 4x Cortex-A76 + 4x Cortex A55
- GPU: Arm Mali G610
- Up to 32 GB RAM
- I/O: PCIe 3.0, USB, HDMI

RK3588 Rock5b Board:

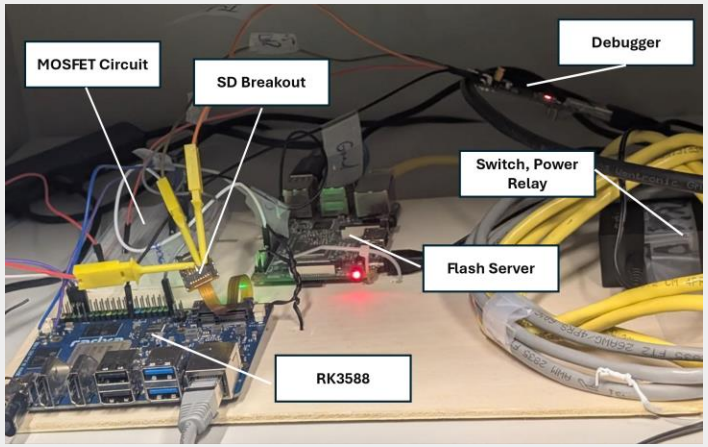
✓ Not vendor locked
✓ Well documented
✓ Affordable & Available
✓ Support System

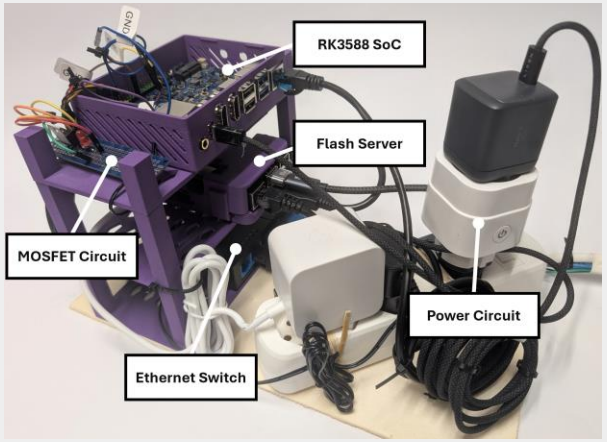


Radxa Rock5b RK3588
~ 250 USD

https://radxa.com/products/rock5/5b/

OpenCCA on RK3588



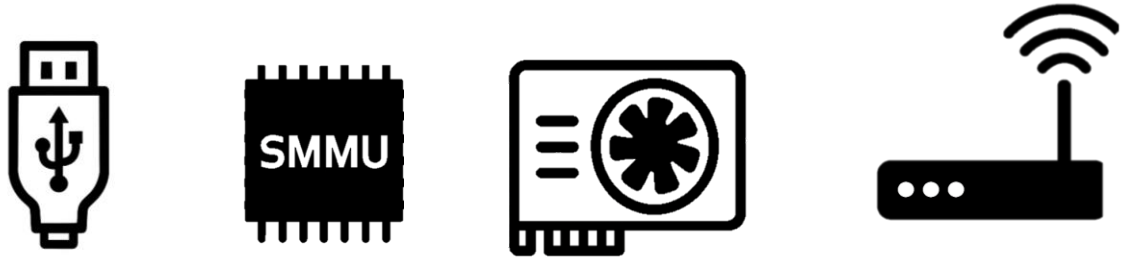


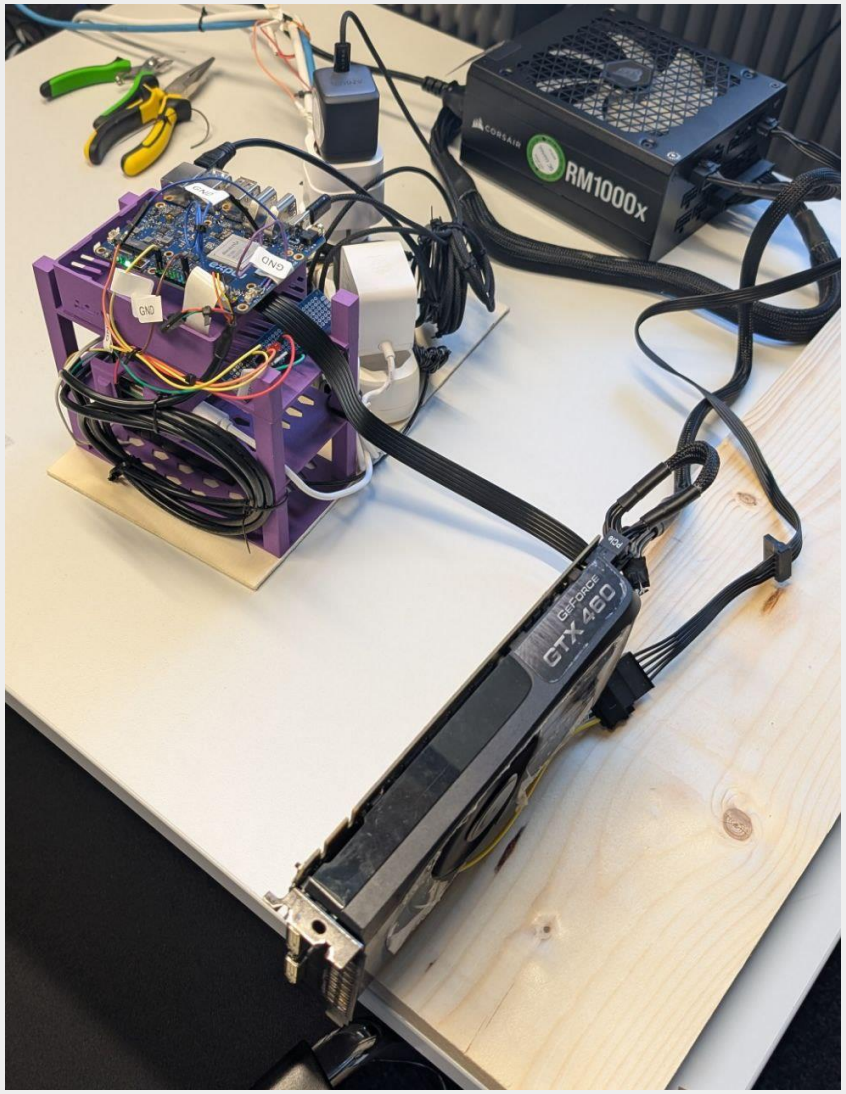
- OpenCCA “Box” with support for hardware debugging, firmware flashing and power management

Real Hardware = Real Accelerators

OpenCCA runs on real hardware and can interact with real devices.

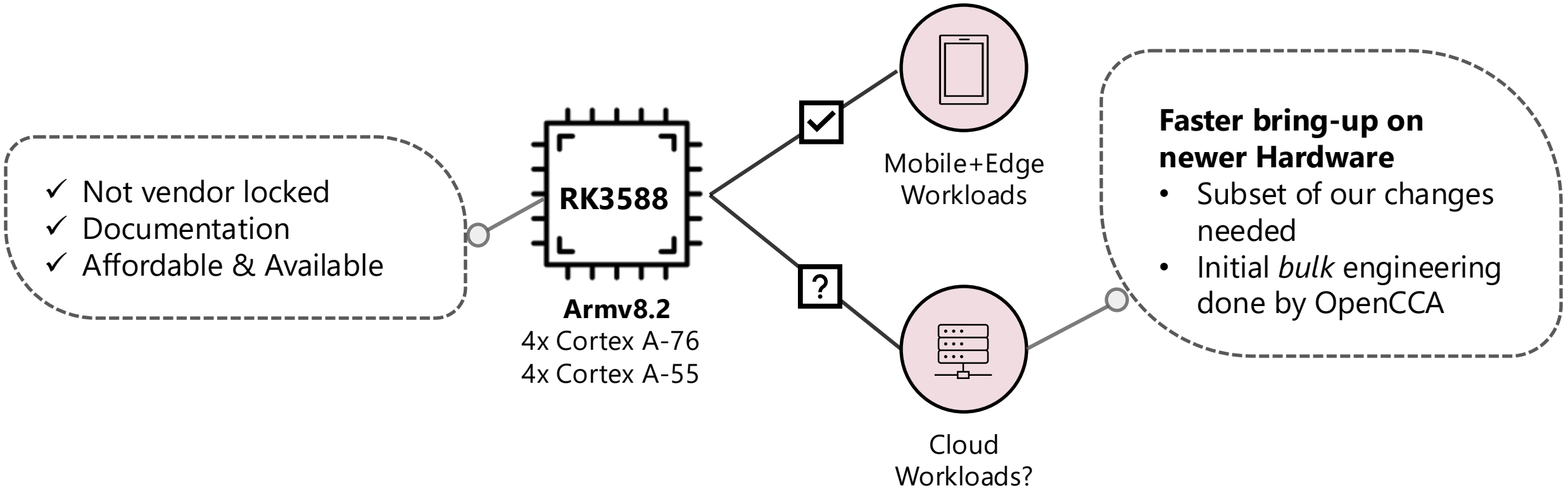
- RK3588 exposes PCIe lanes over NVMe slot
- Example: Research on Arm CCA with PCIe devices





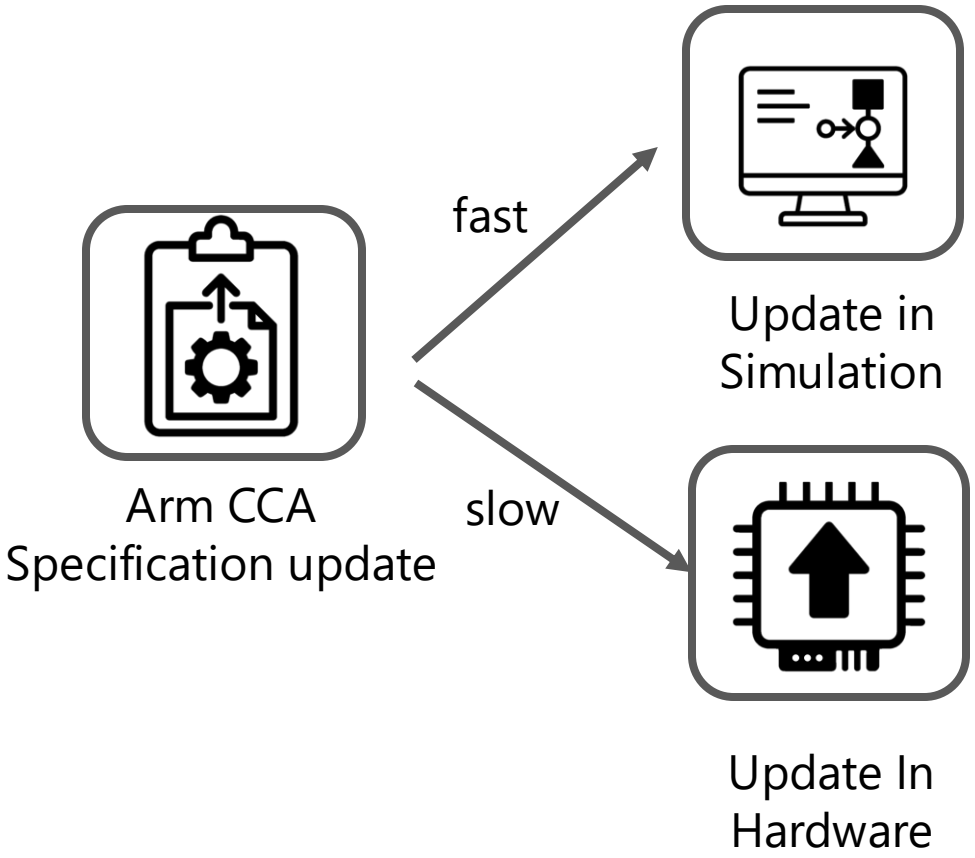
Connect Discrete GPU to OpenCCA

Suitable Workloads on RK3588 and Porting Work to other boards



What about OpenCCA once we have CCA Hardware?

OpenCCA bridges Gap between Specification and Hardware for Performance Estimation



Example Case: Arm CCA Planes

- Alpha spec released, likely not in first iteration of hardware

Estimate in Software with OpenCCA to experiment with Feature

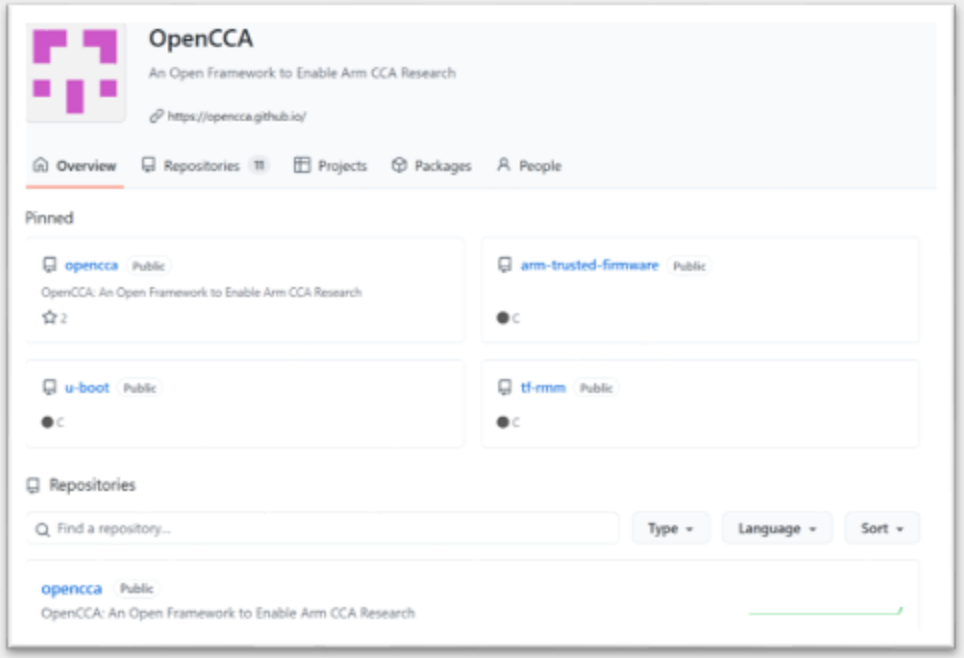
Current Status & Next Steps

Current Status

- Run confidential VMs with Arm reference stack
  - TF-A: v2.11
  - RMM: v0.5.0
  - Linux 6.12 (cca/full-v5+v7)
  - Kvmtool (cca/v3)
- Initial version Open Source

Next Steps:

- Update to latest version of reference stack
- Software Bring Up for RK3588
- Explore Android Support on RK3588



https://opencca.github.io

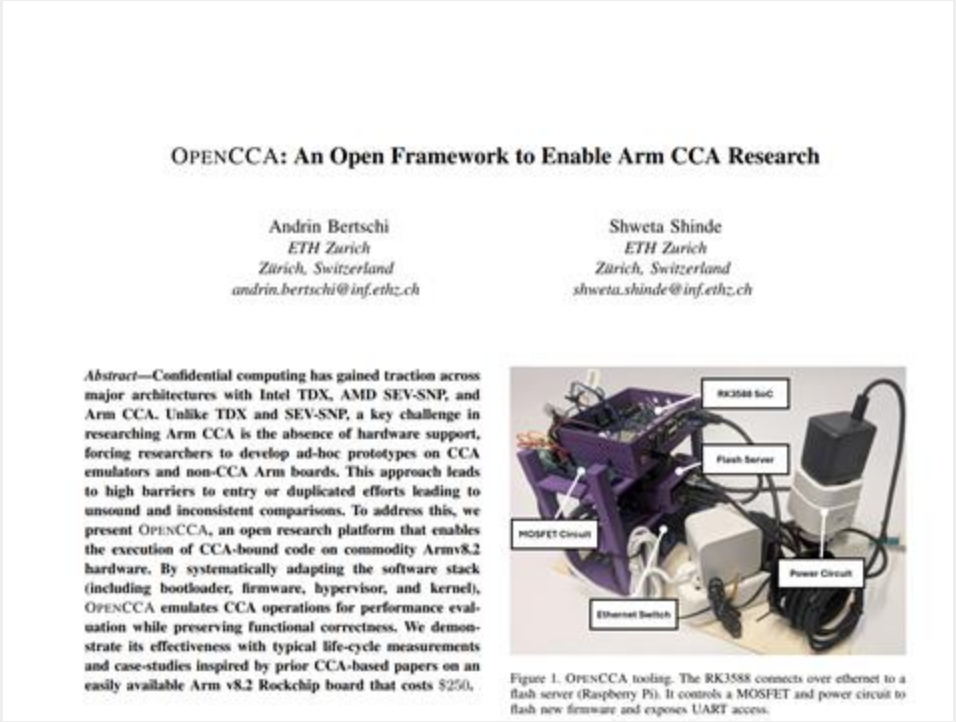
Live Demo

Thank You

- Paper and source code is online
- Get in touch!

OpenCCA:

- Open *Framework* for Performance Estimations
- Enable CCA on commodity Armv8 hardware for performance and accelerators support



OPENCCA: An Open Framework to Enable Arm CCA Research

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***Abstract*—Confidential computing has gained traction across major architectures with Intel TDX, AMD SEV-SNP, and Arm CCA. Unlike TDX and SEV-SNP, a key challenge in researching Arm CCA is the absence of hardware support, forcing researchers to develop ad-hoc prototypes on CCA emulators and non-CCA Arm boards. This approach leads to high barriers to entry or duplicated efforts leading to unsound and inconsistent comparisons. To address this, we present OPENCCA, an open research platform that enables the execution of CCA-bound code on commodity Armv8.2 hardware. By systematically adapting the software stack (including bootloader, firmware, hypervisor, and kernel), OPENCCA emulates CCA operations for performance evaluation while preserving functional correctness. We demonstrate its effectiveness with typical life-cycle measurements and case-studies inspired by prior CCA-based papers on an easily available Arm v8.2 Rockchip board that costs $250.**

Figure 1. OPENCCA tooling. The RK3588 connects over ethernet to a flash server (Raspberry Pi). It controls a MOSFET and power circuit to flash new firmware and exposes UART access.

Source

X: andrinbertschi

email: andrin.bertschi@inf.ethz.ch

web: https://opencca.github.io

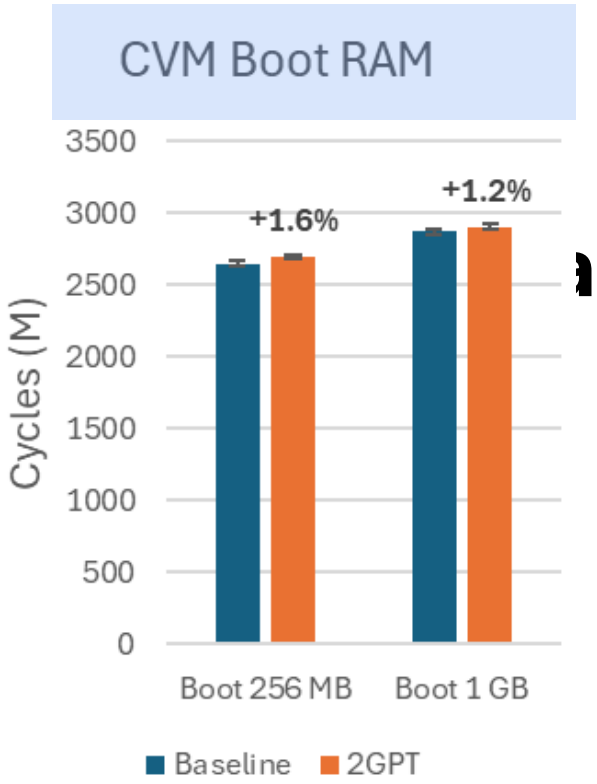
See paper

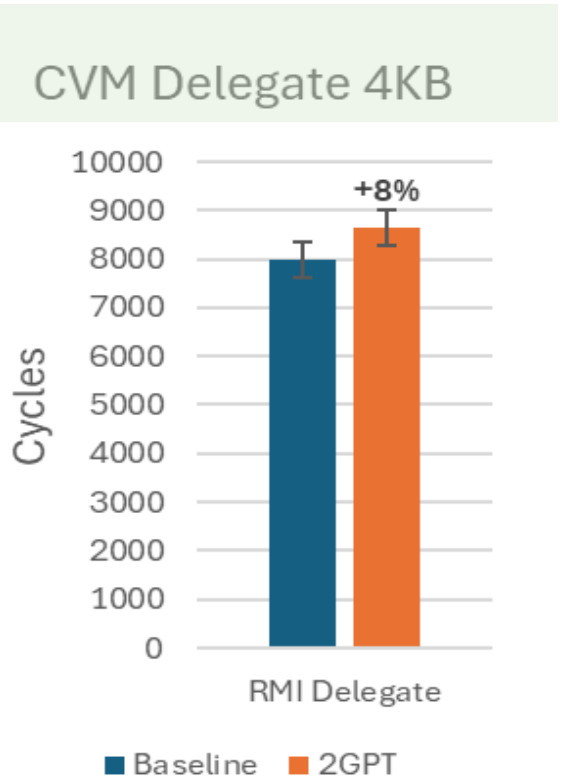
TABLE 6. EVALUATION, RT: ROUND TRIP, DELEGATE: 4KB

Benchmark	Mean		Scale
	Instr	Cycles	
	OPENCCA		
CVM Boot 256 MB	1900	2647	1M
CVM Boot 1 GB	2015	2869	1M
RMI Delegate	2865	7988	1
RMI Version	994	3583	1
RMI RT	932	3370	1
SMC RT	182	421	1
	Two-GPT Case Study		
CVM Boot 256 MB	1928	2690	1M
CVM Boot 1 GB	2039	2902	1M
RMI Delegate	3488	8654	1

a

as





See paper

TABLE 6. EVALUATION, RT: ROUND TRIP, DELEGATE: 4KB

Benchmark	Mean		Stdev		Scale
	Instr	Cycles	Instr	Cycles	
OPENCCA					
CVM Boot 256 MB	1900	2647	6	15	1M
CVM Boot 1 GB	2015	2869	8	18	1M
RMI Delegate	2865	7988	187	365	1
RMI Version	994	3583	120	222	1
RMI RT	932	3370	115	209	1
SMC RT	182	421	44	68	1
Two-GPT Case Study					
CVM Boot 256 MB	1928	2690	9	10	1M
CVM Boot 1 GB	2039	2902	7	18	1M
RMI Delegate	3488	8654	182	372	1