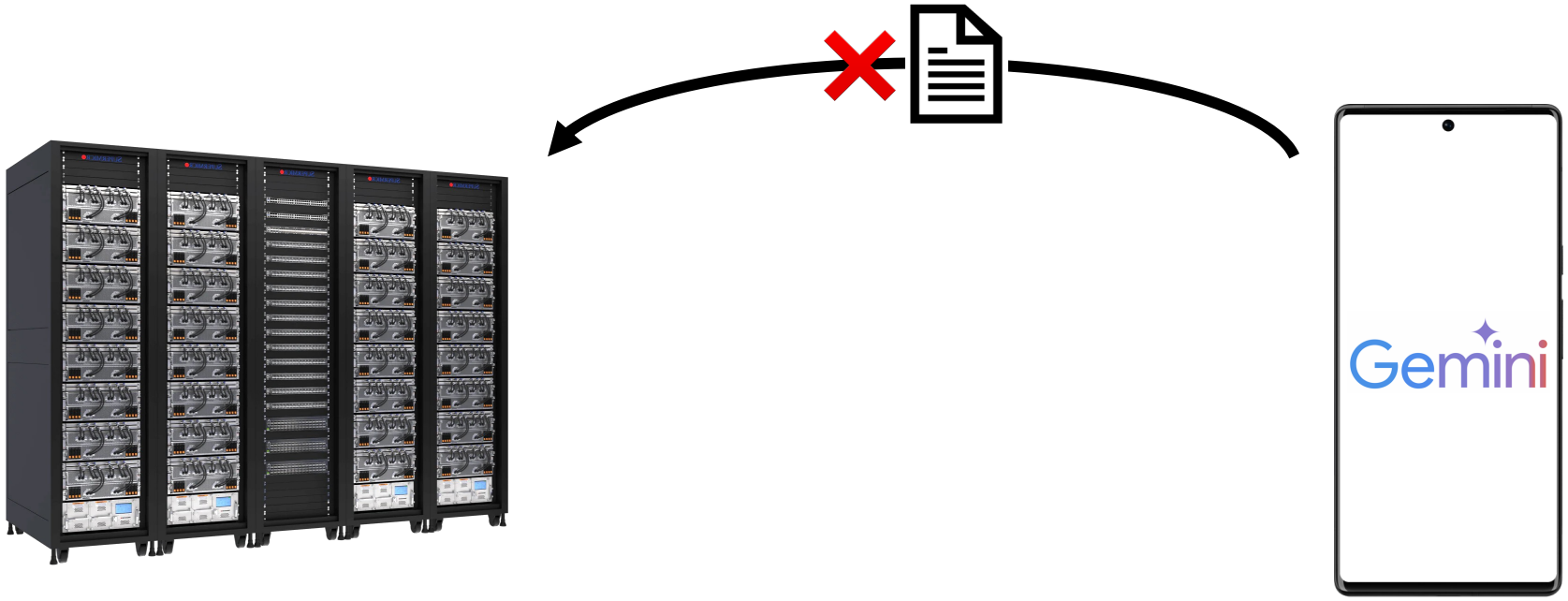
ASGARD: Protecting On-Device Deep Neural Networks with Virtualization-Based Trusted Execution Environments

Myungsuk Moon, Minhee Kim, Joonkyo Jung, Dokyung Song

YONSEI UNIVERSITY

Problem: On-Device DNN Protection from Device Owners

1 **On-device AI protects user data**
by not sending it



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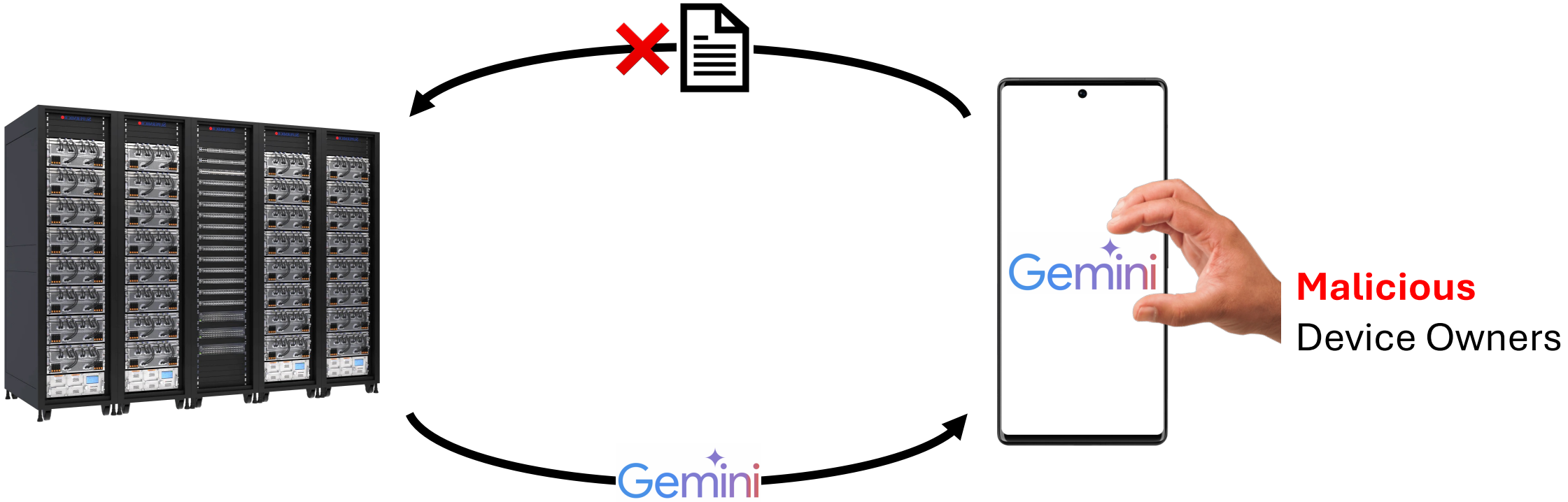
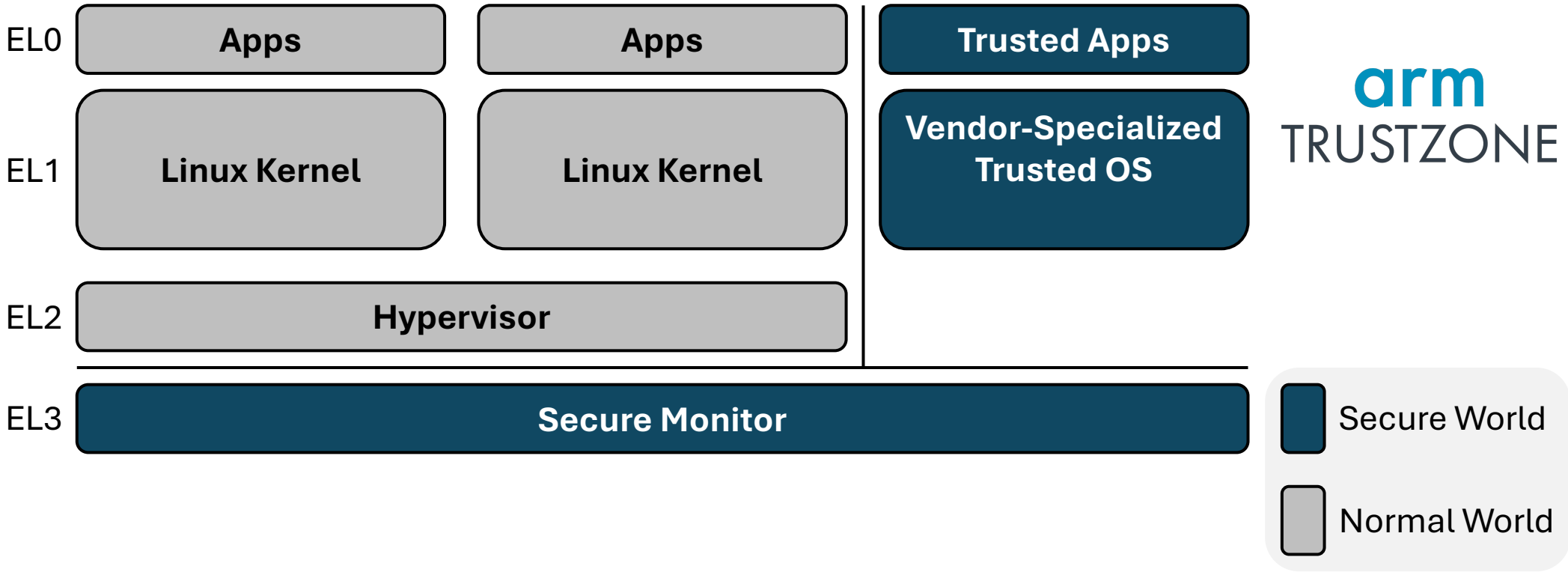


Malicious
Device Owners

2 **But on-device DNNs must be protected**
because they are sent to user devices

Prior Approaches with Arm TrustZone



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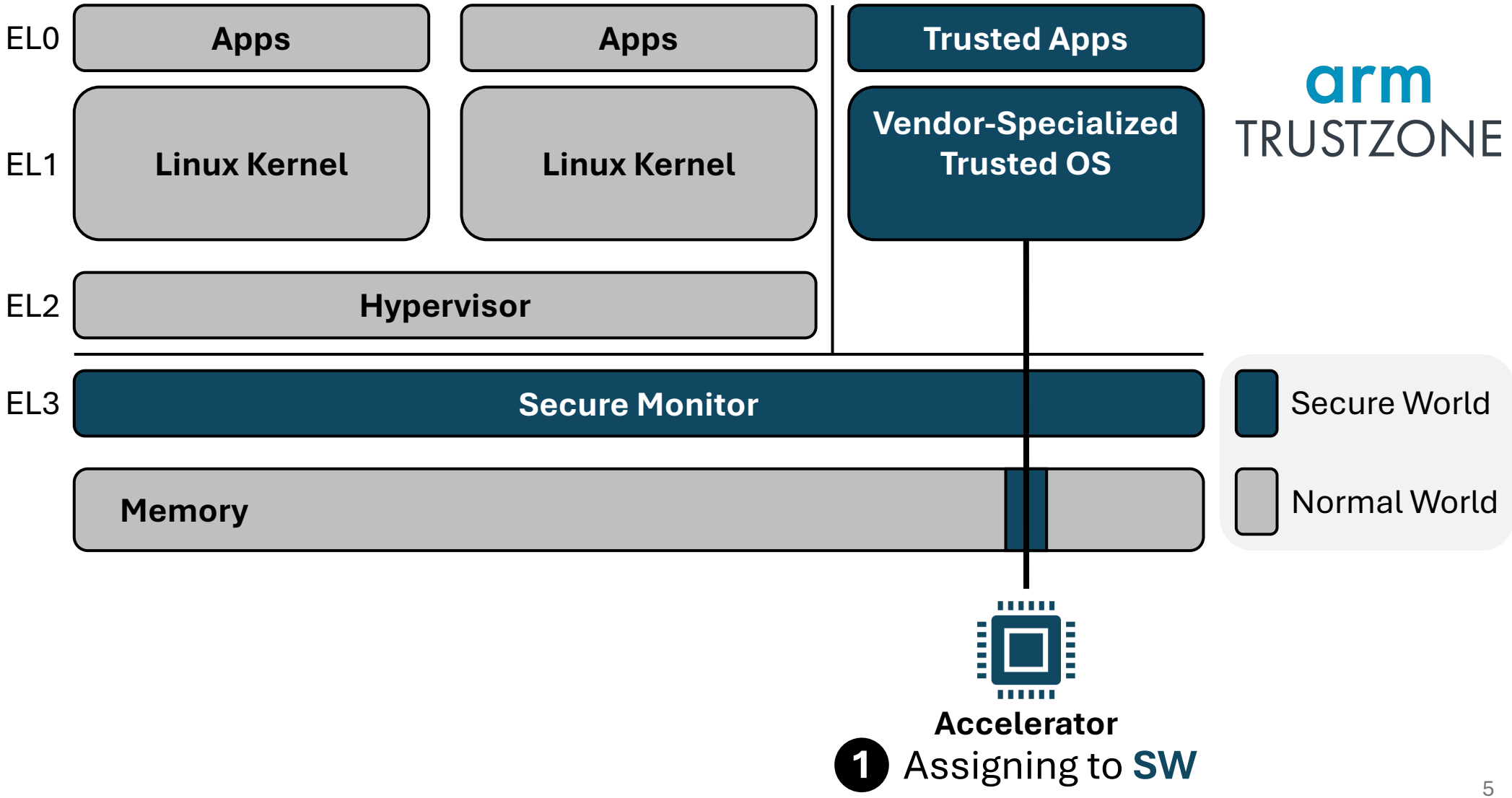

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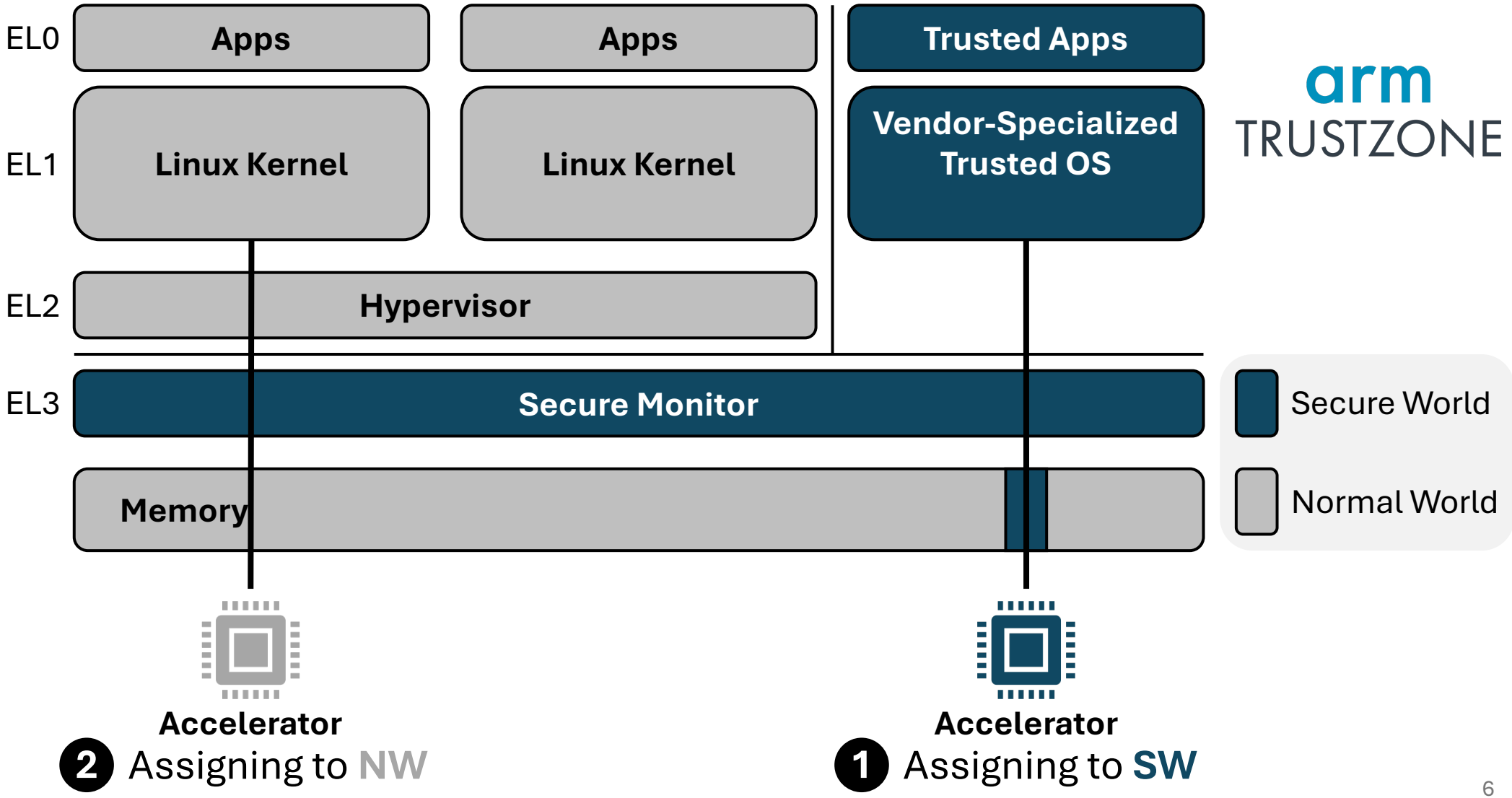
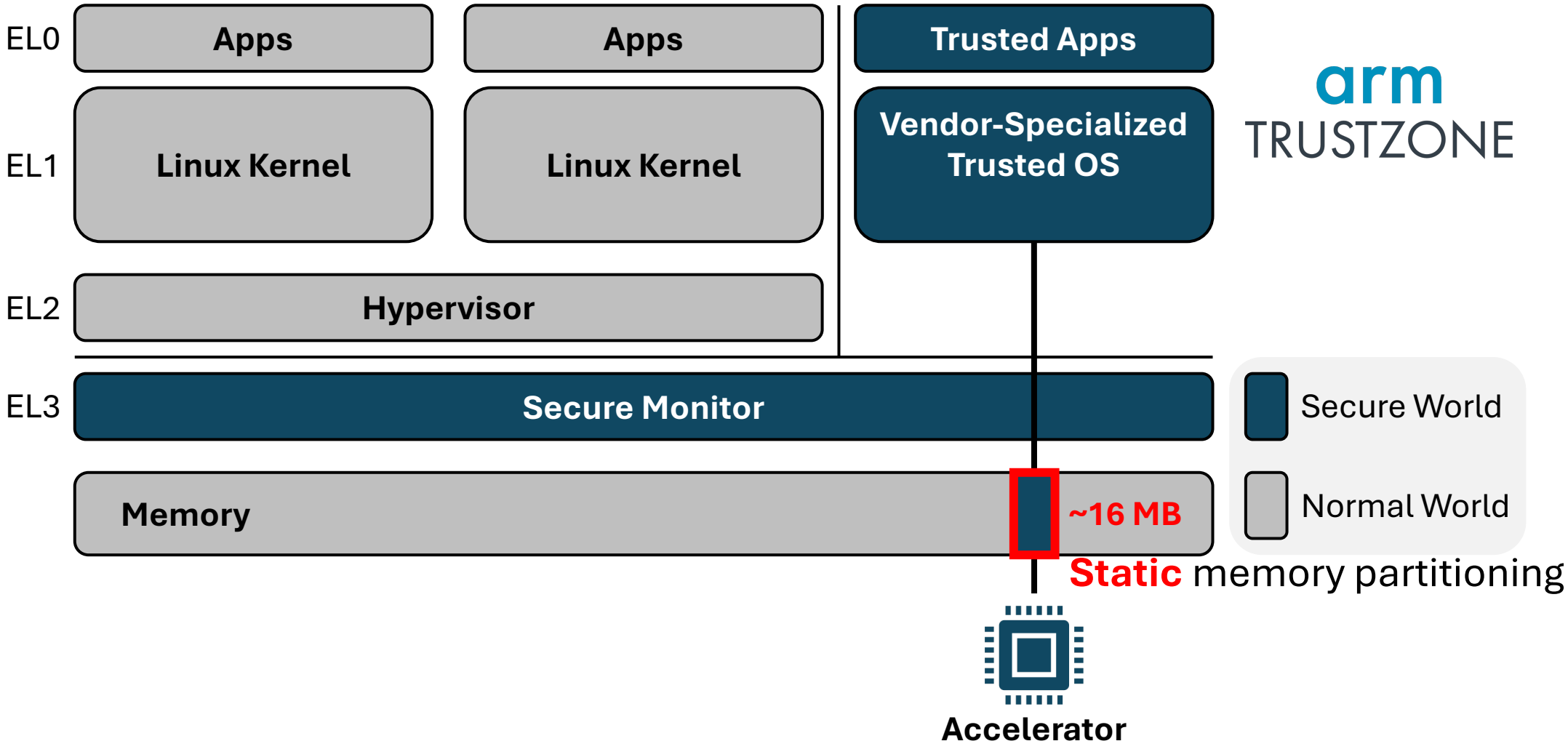


Prior Approach #1: Assigning Accelerator to Secure World



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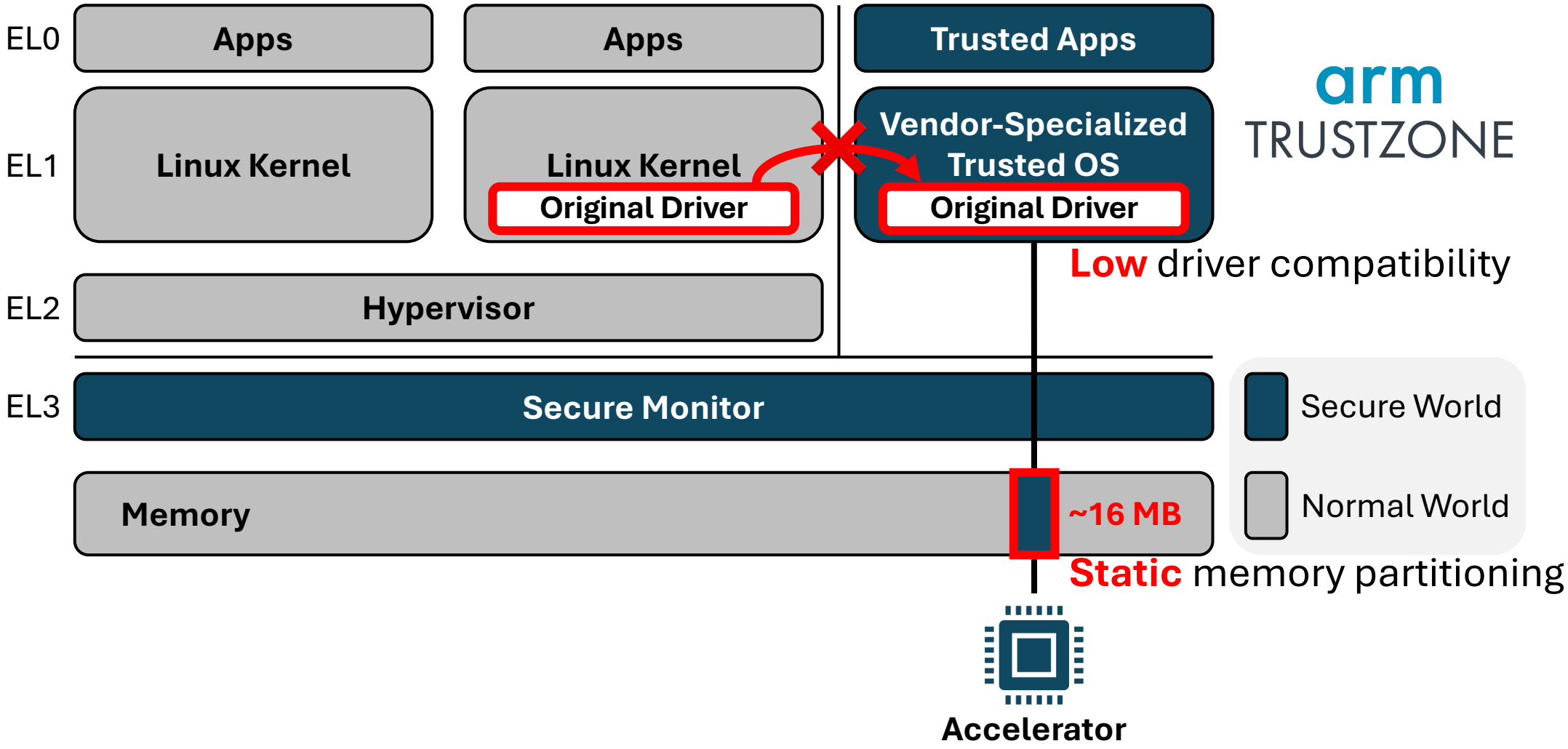

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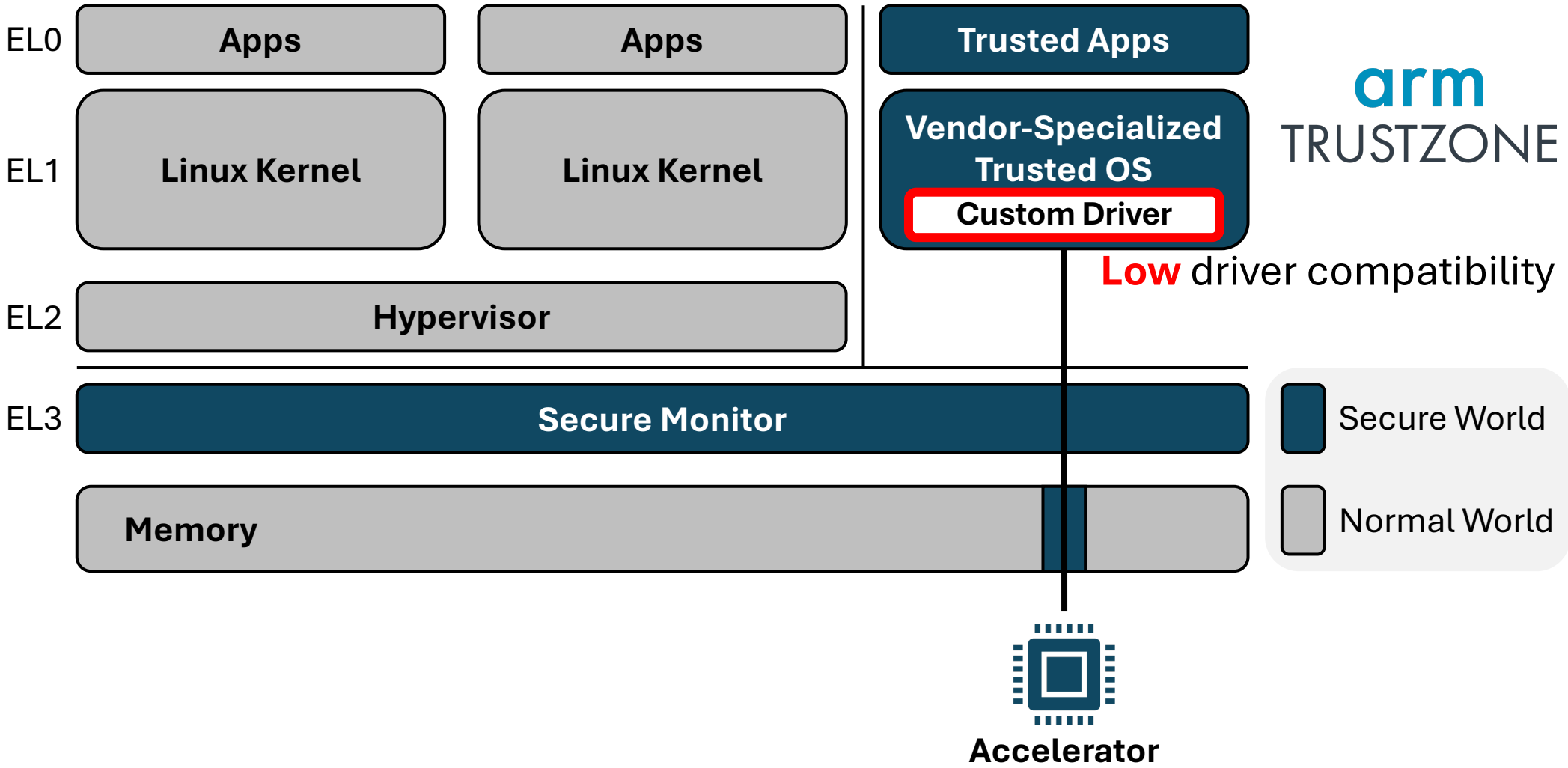

[1] Park and Lin, "GPUReplay: A 50-kb GPU stack for client ML," *ASPLOS '22*
[2] Guo and Lin, "Minimum viable device drivers for ARM TrustZone," *EuroSys '22*

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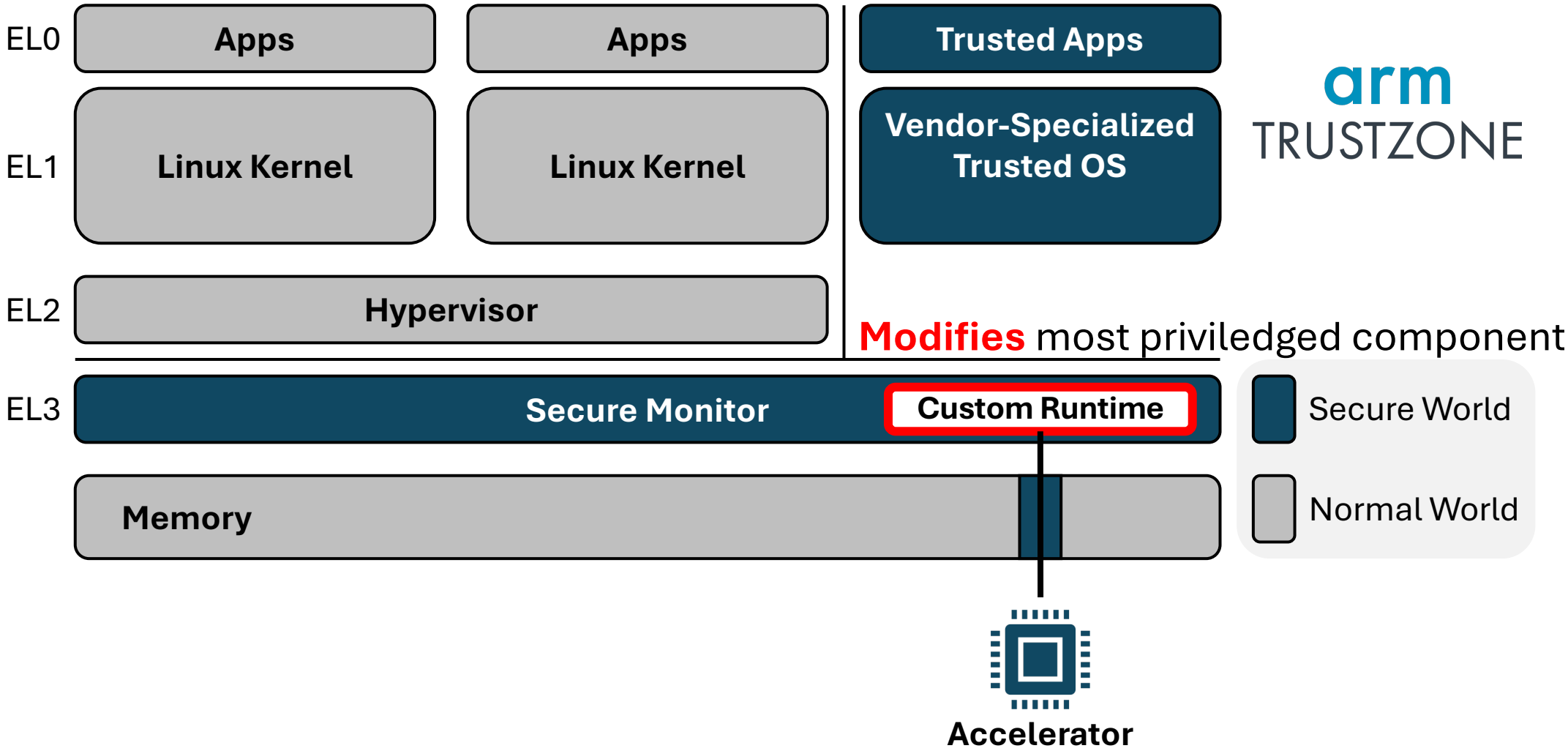
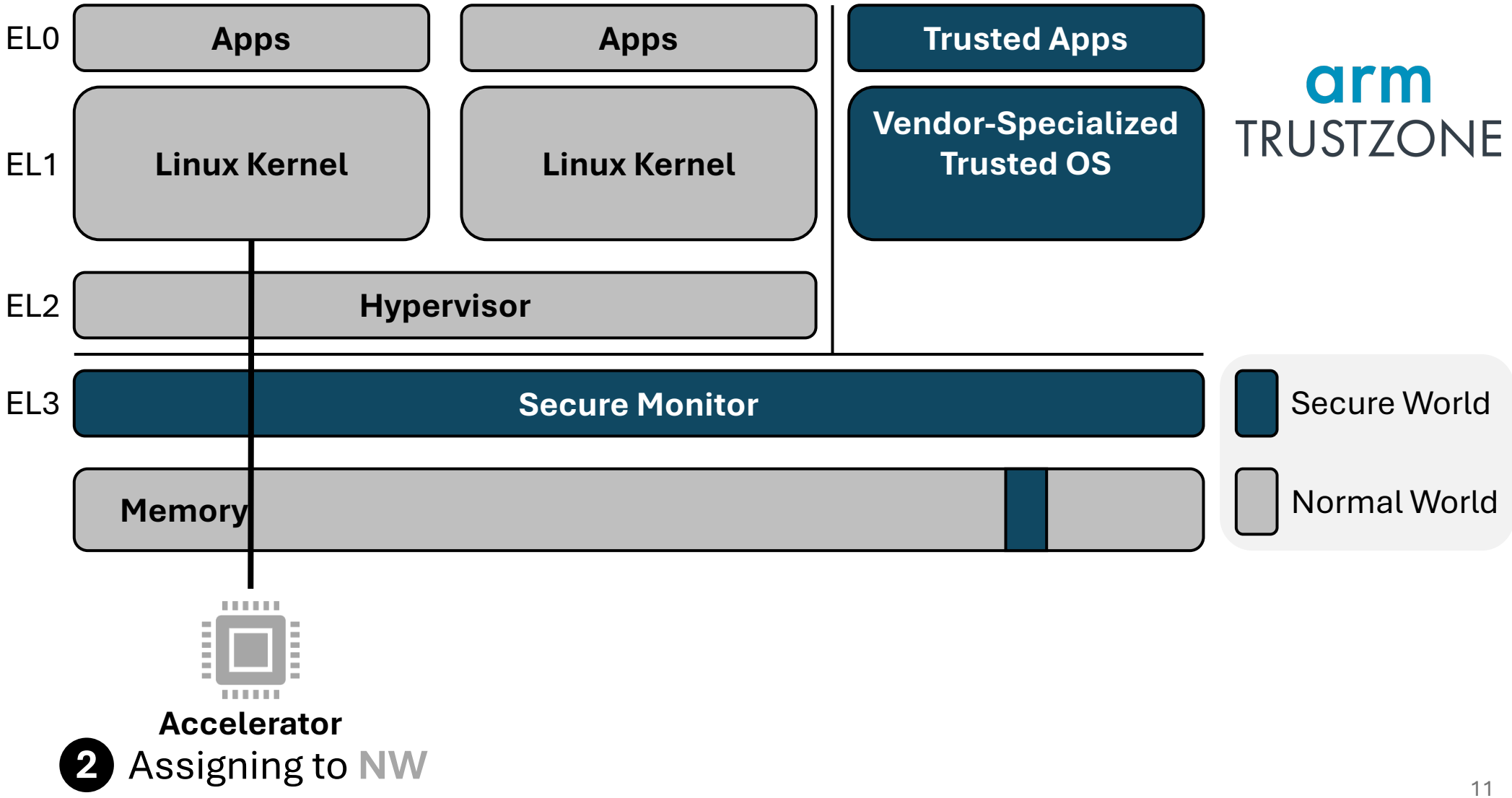


[3] Deng et al., "StrongBox: A GPU TEE on Arm endpoints," *CCS '22*

Prior Approach #2: Assigning Accelerator to Normal World



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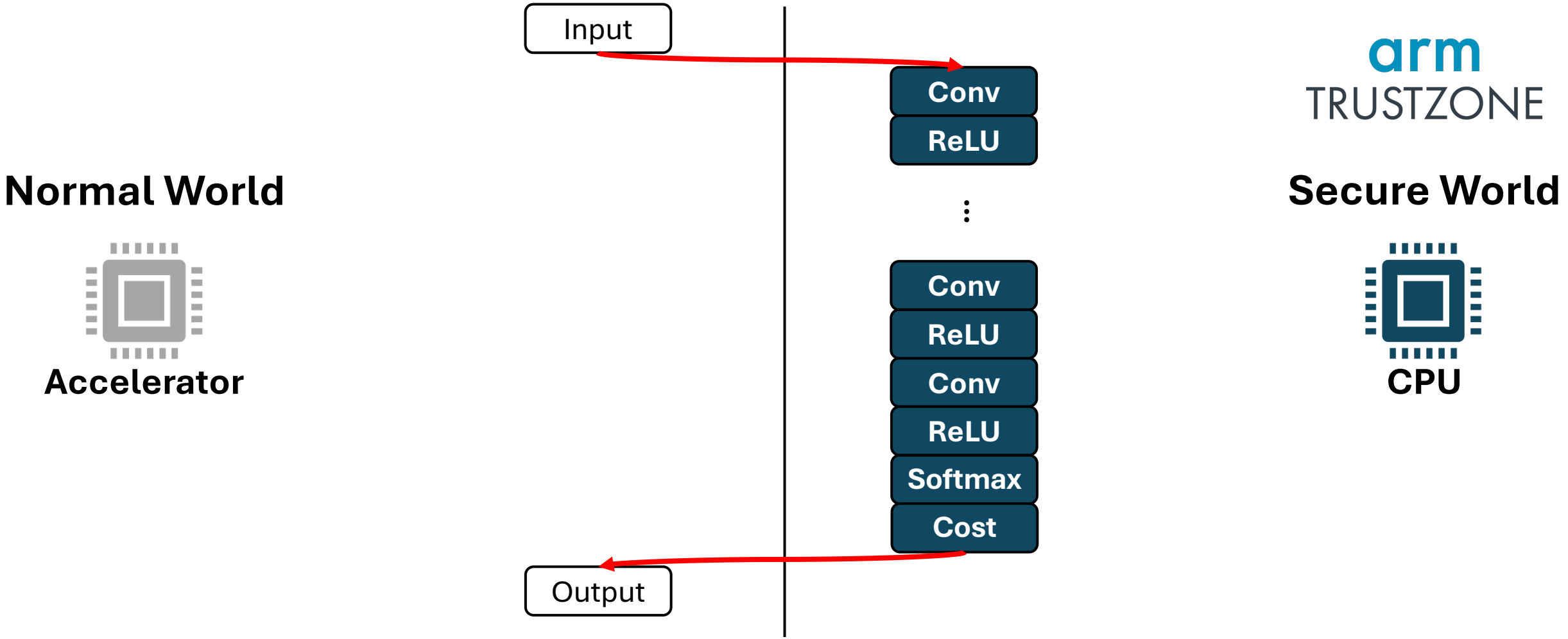

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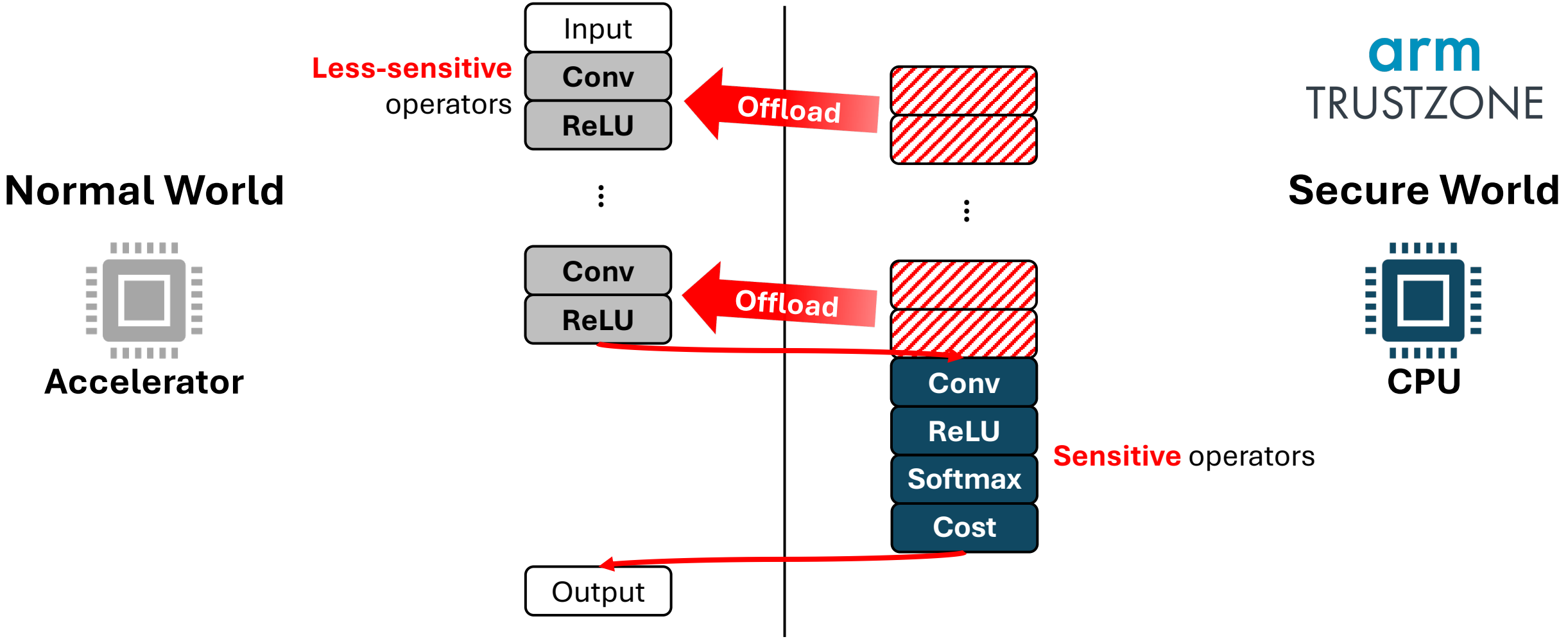

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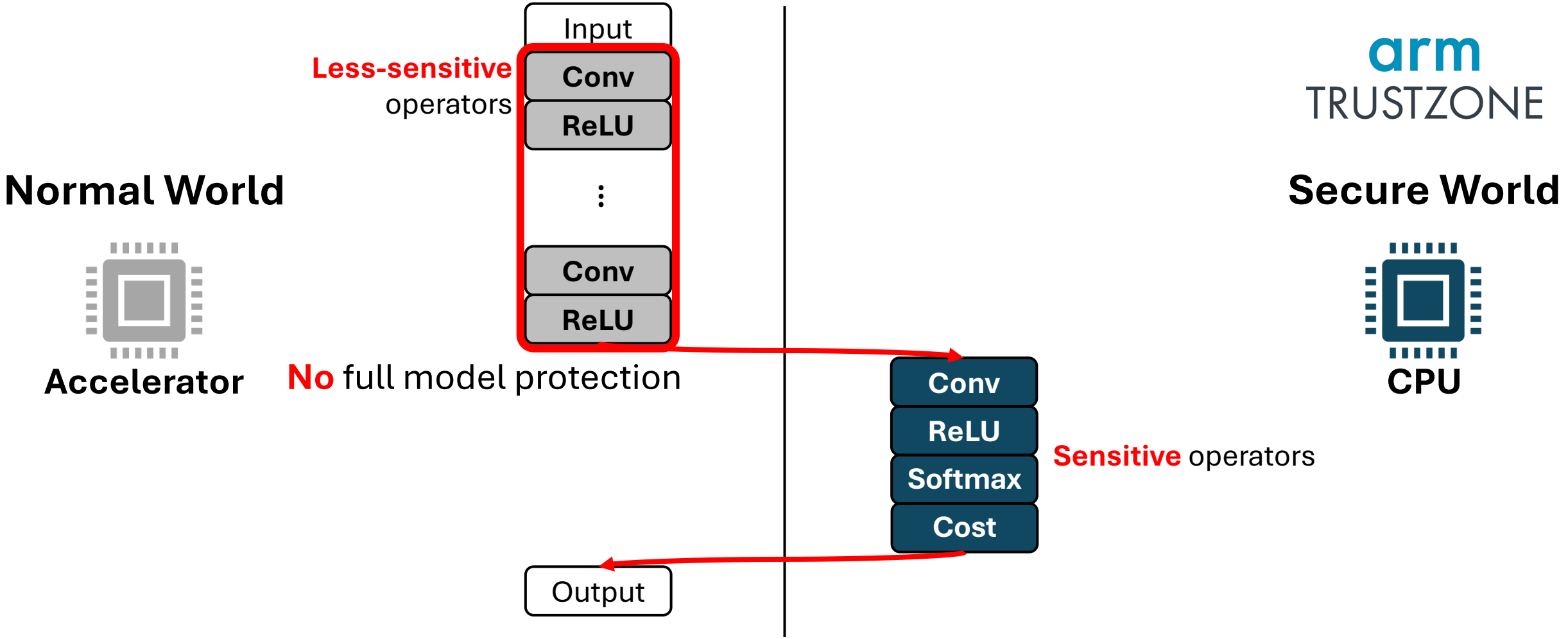

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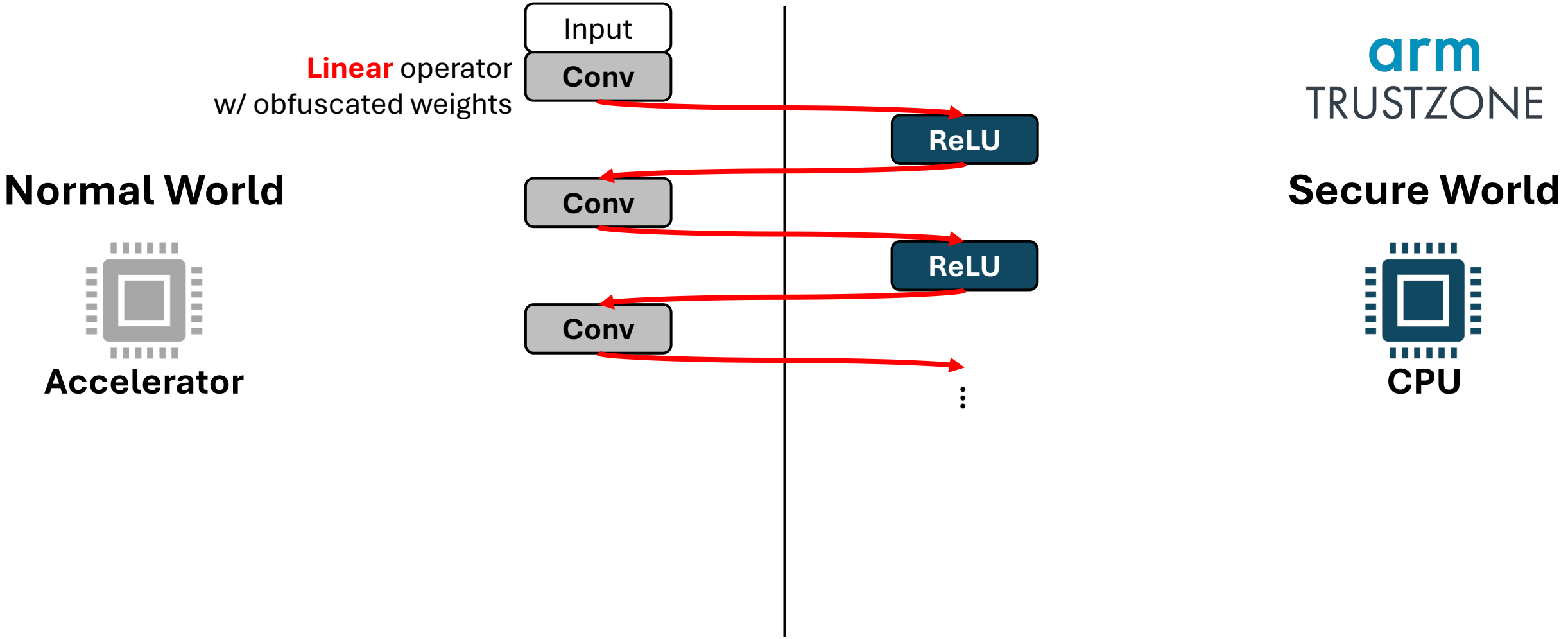

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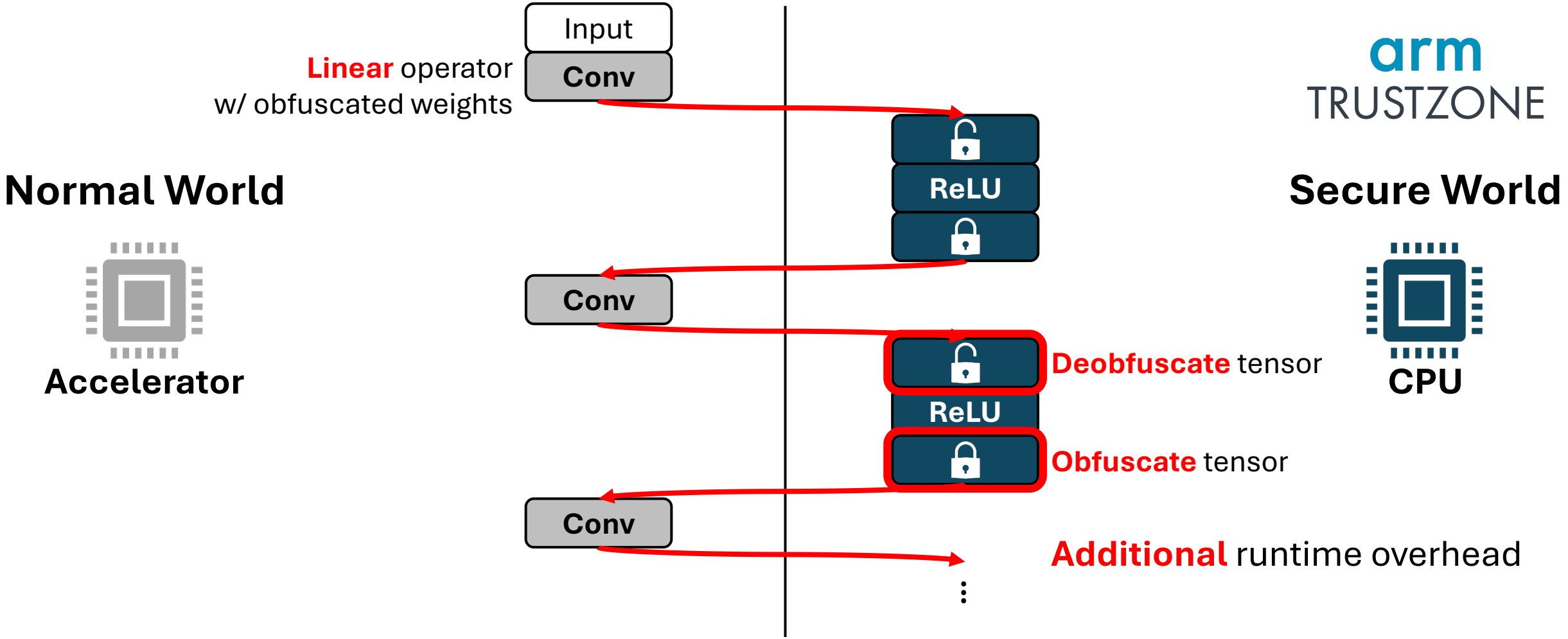

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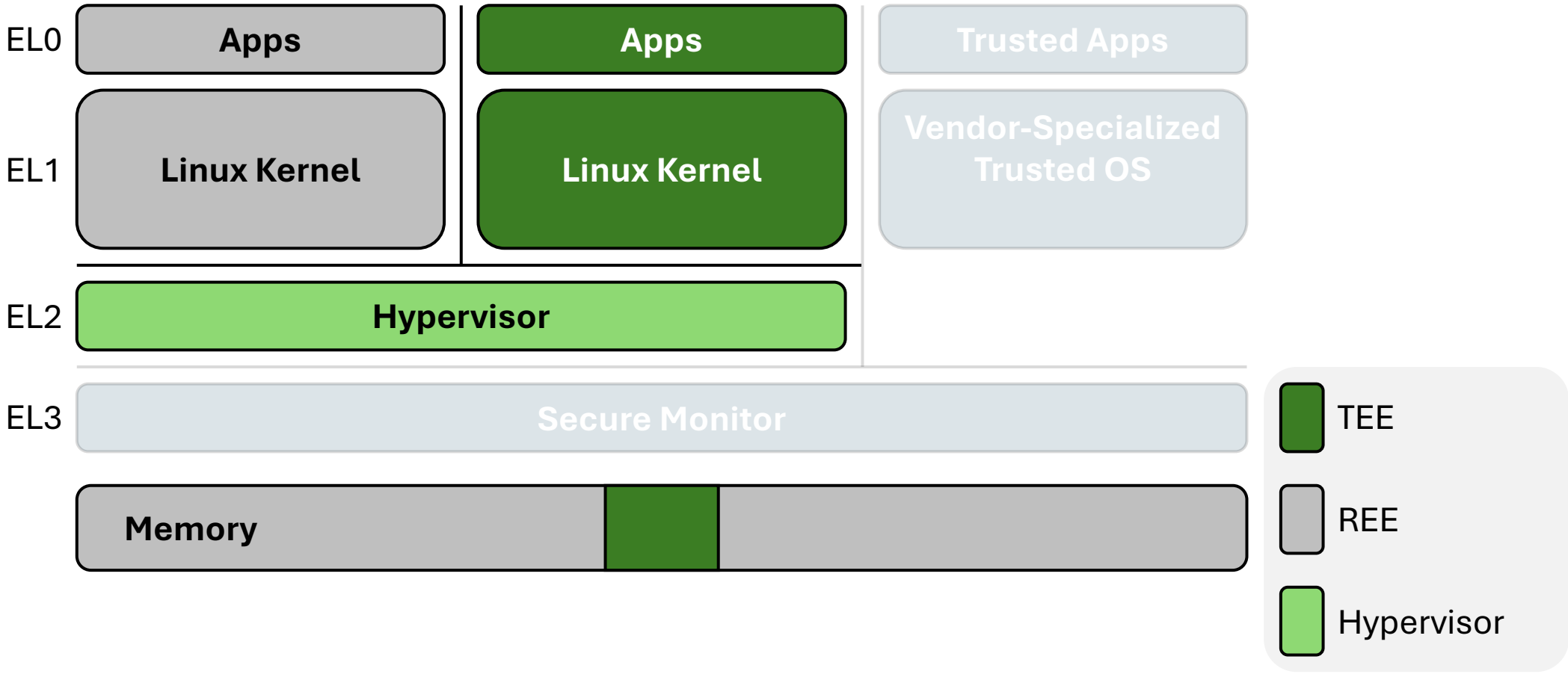
Our Approach: Protection with Virtualization-Based TEE



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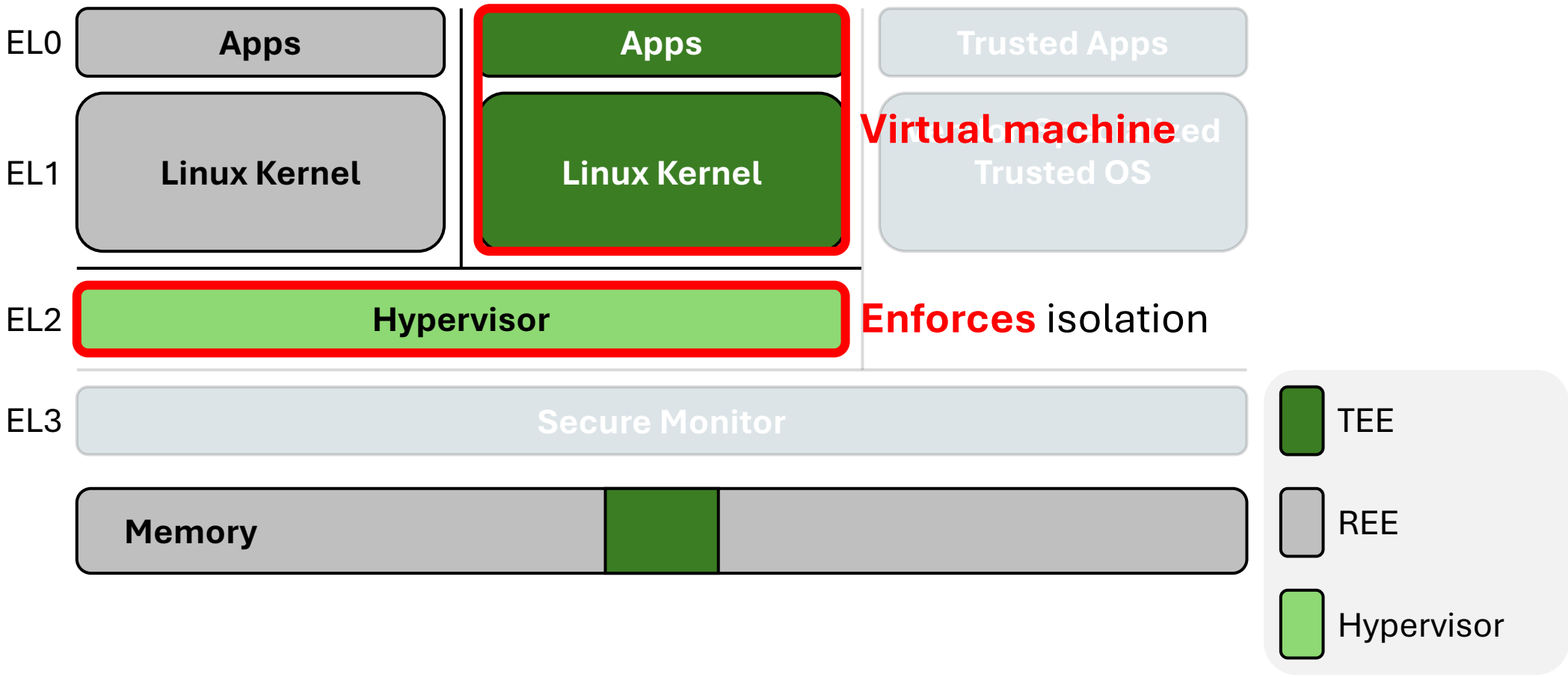

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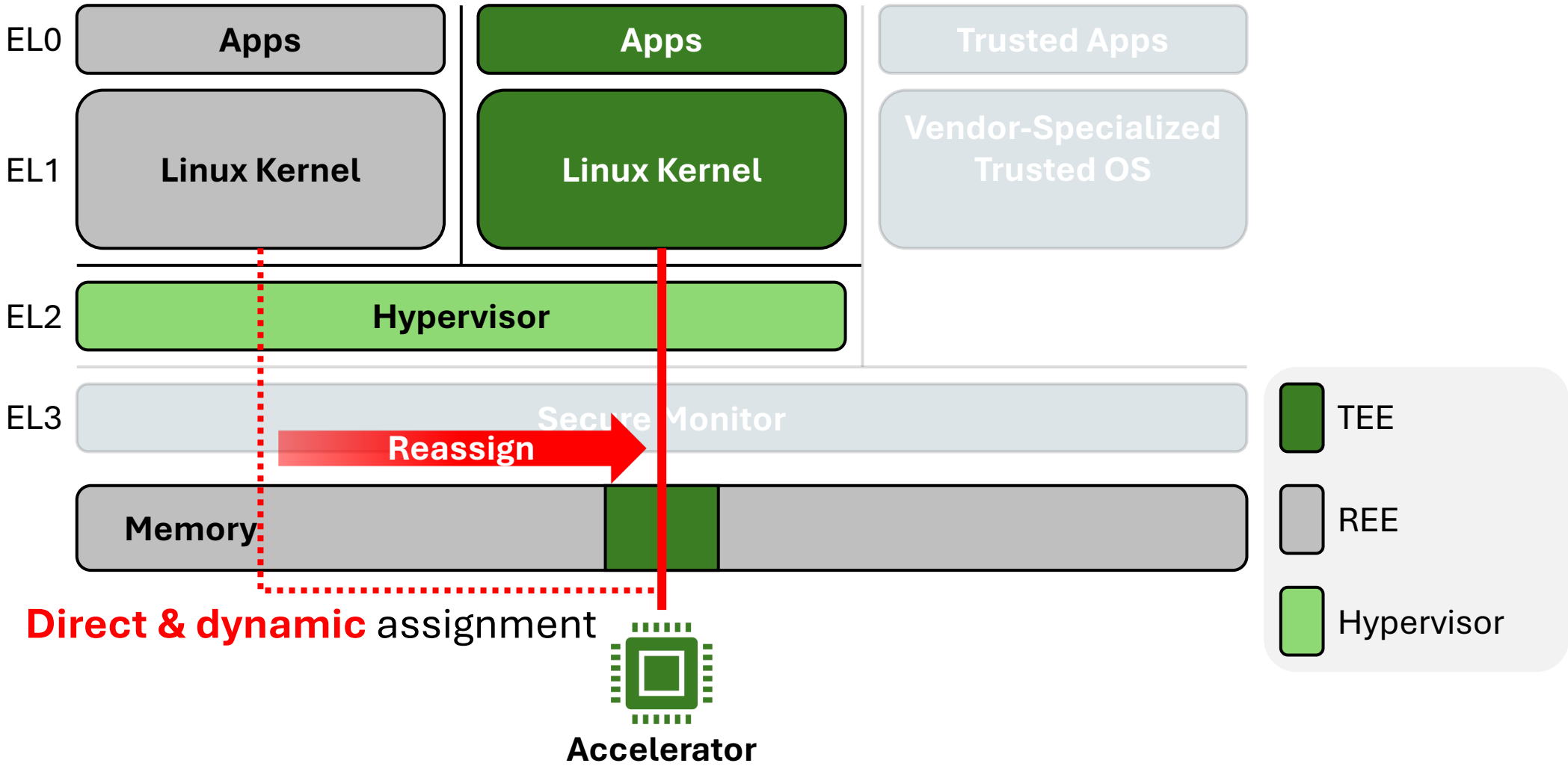
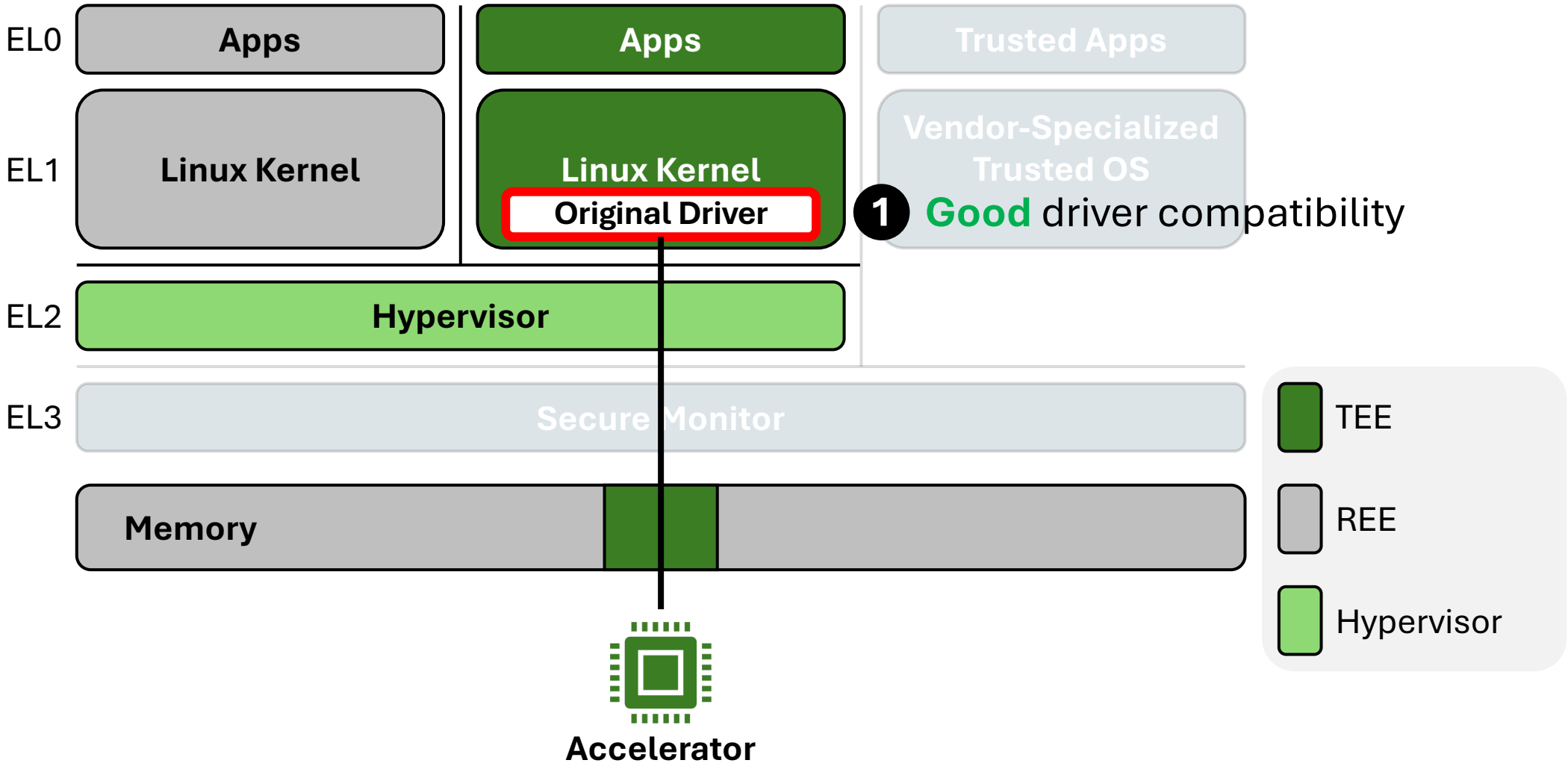


Our Approach: Advantages



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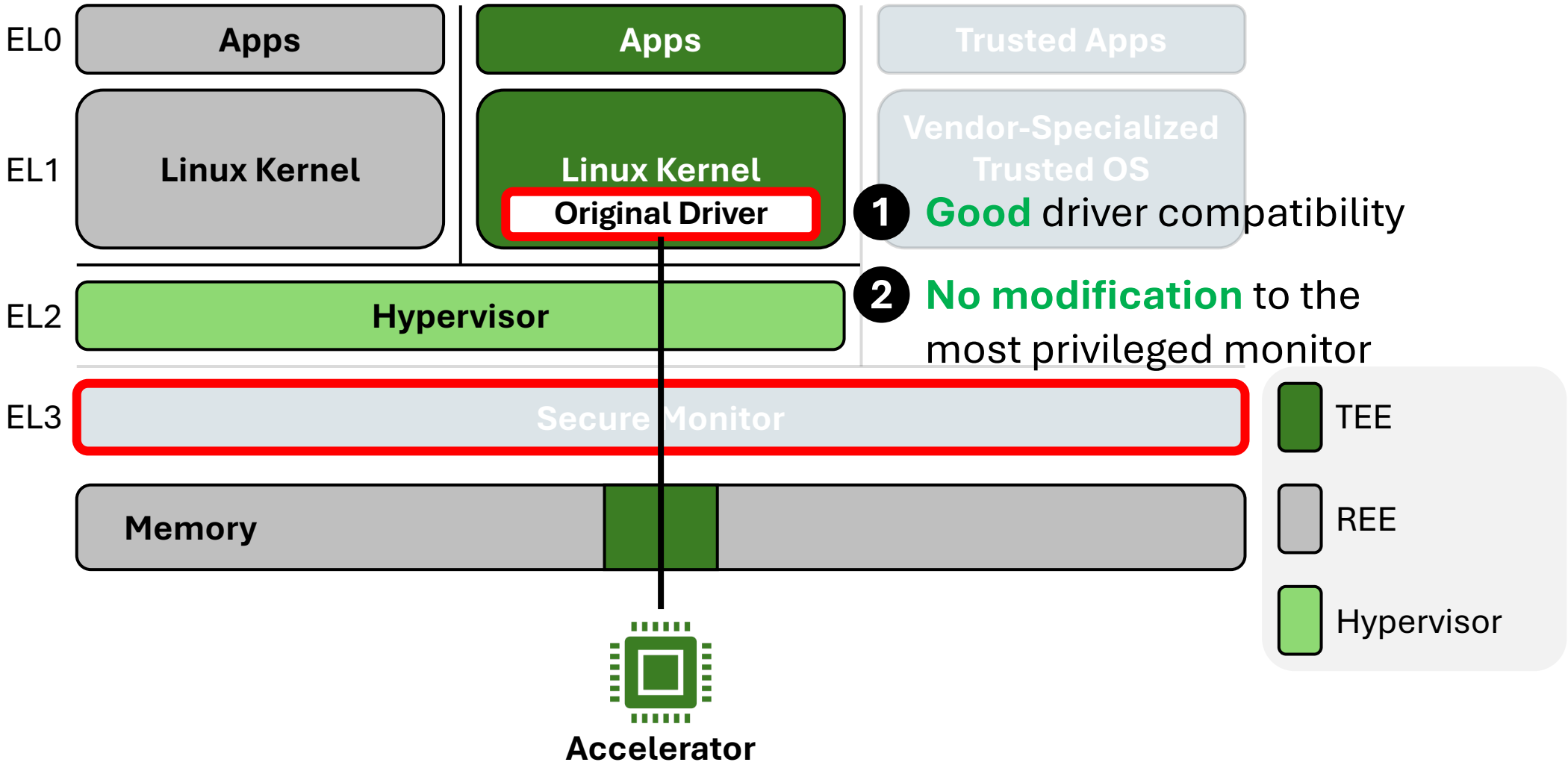

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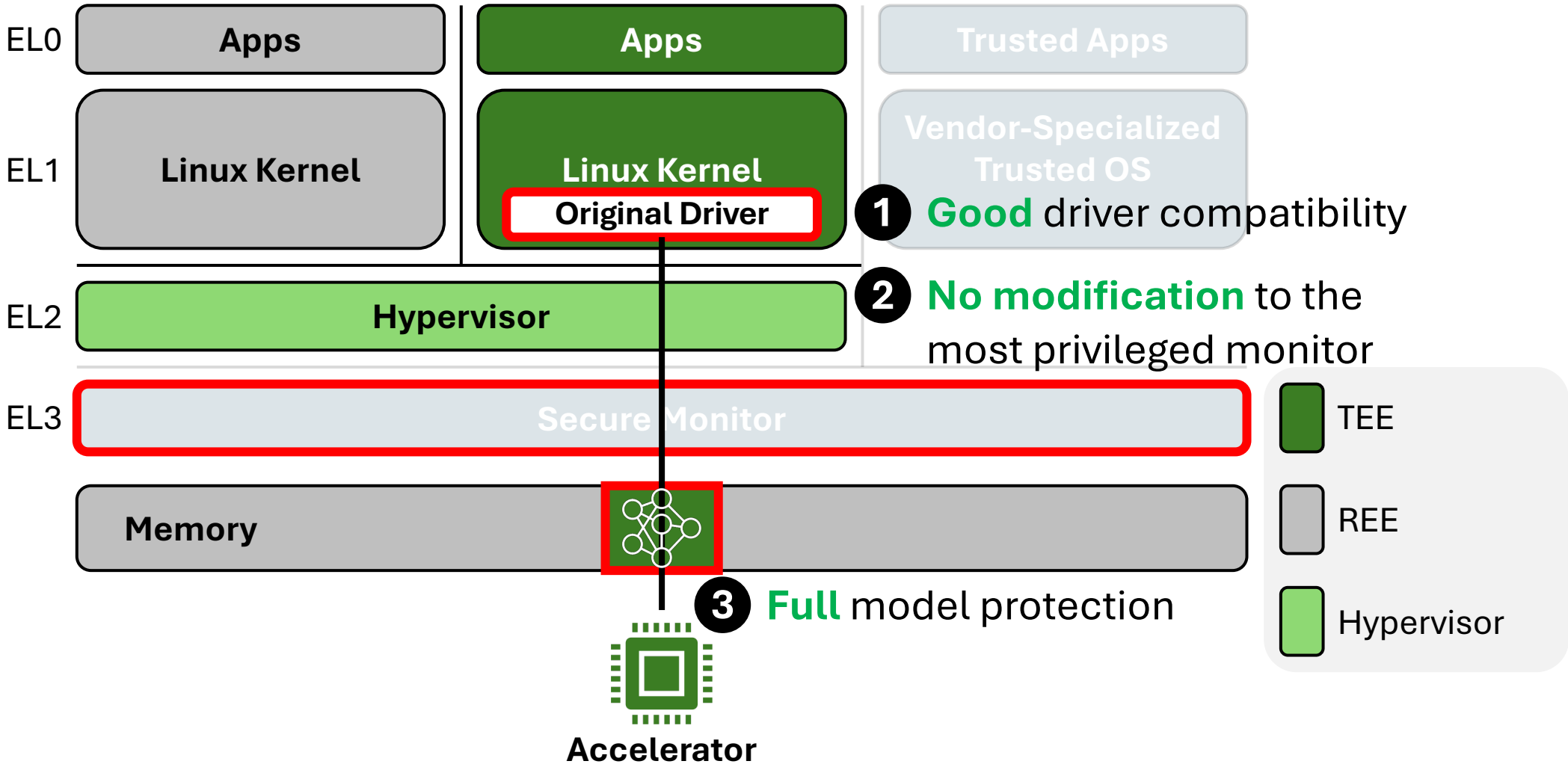
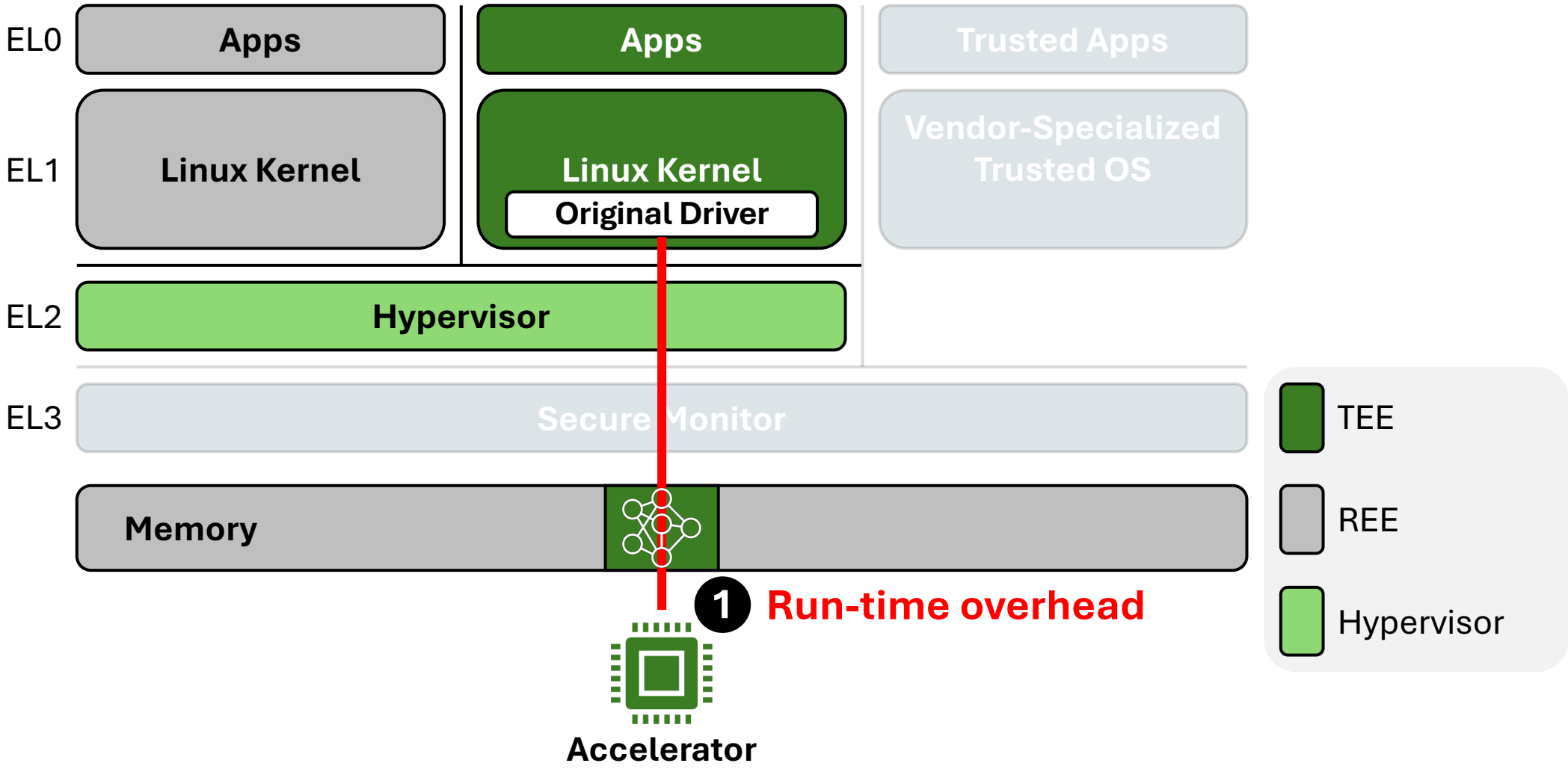


Our Approach: Challenges



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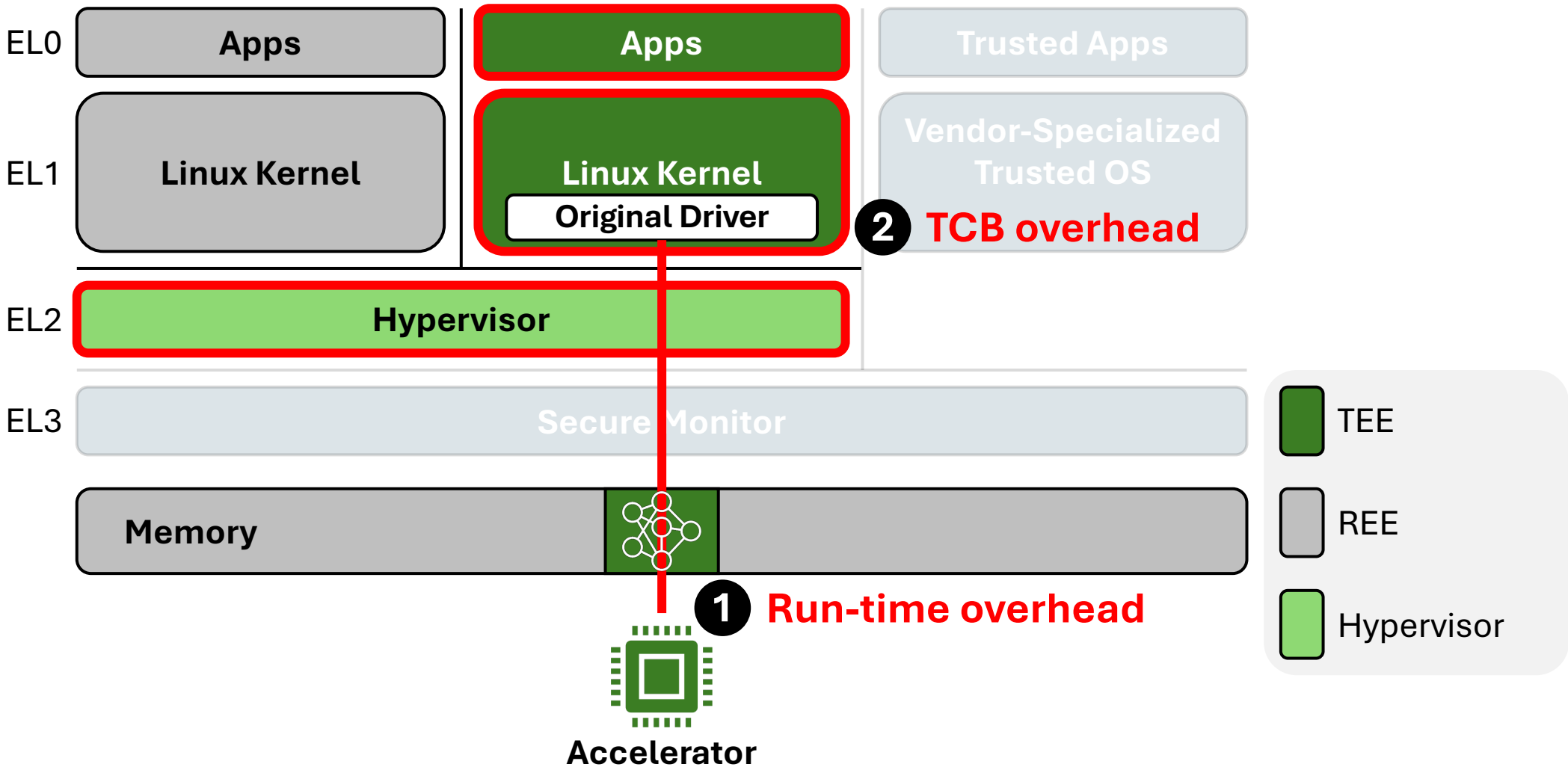

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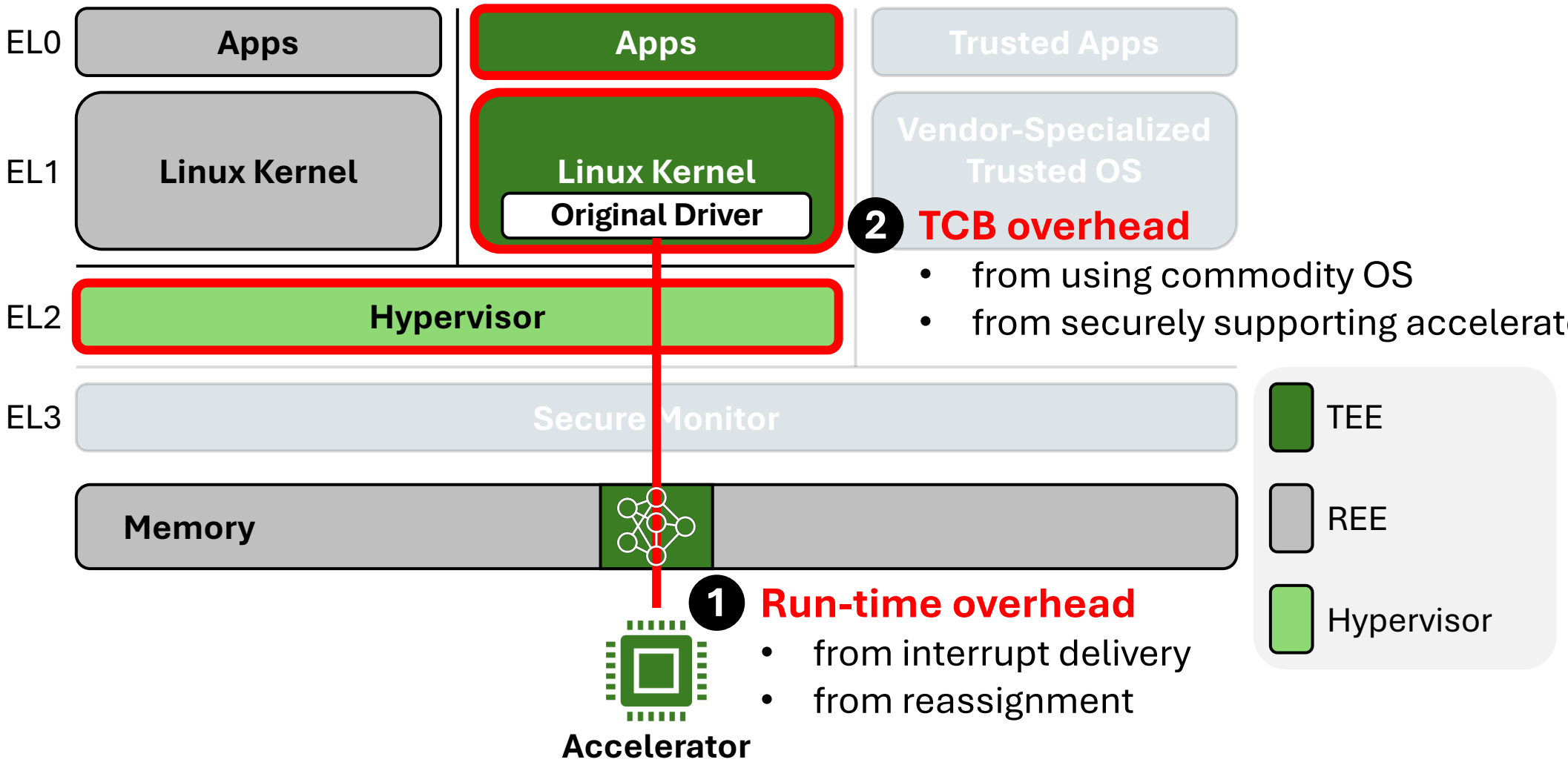

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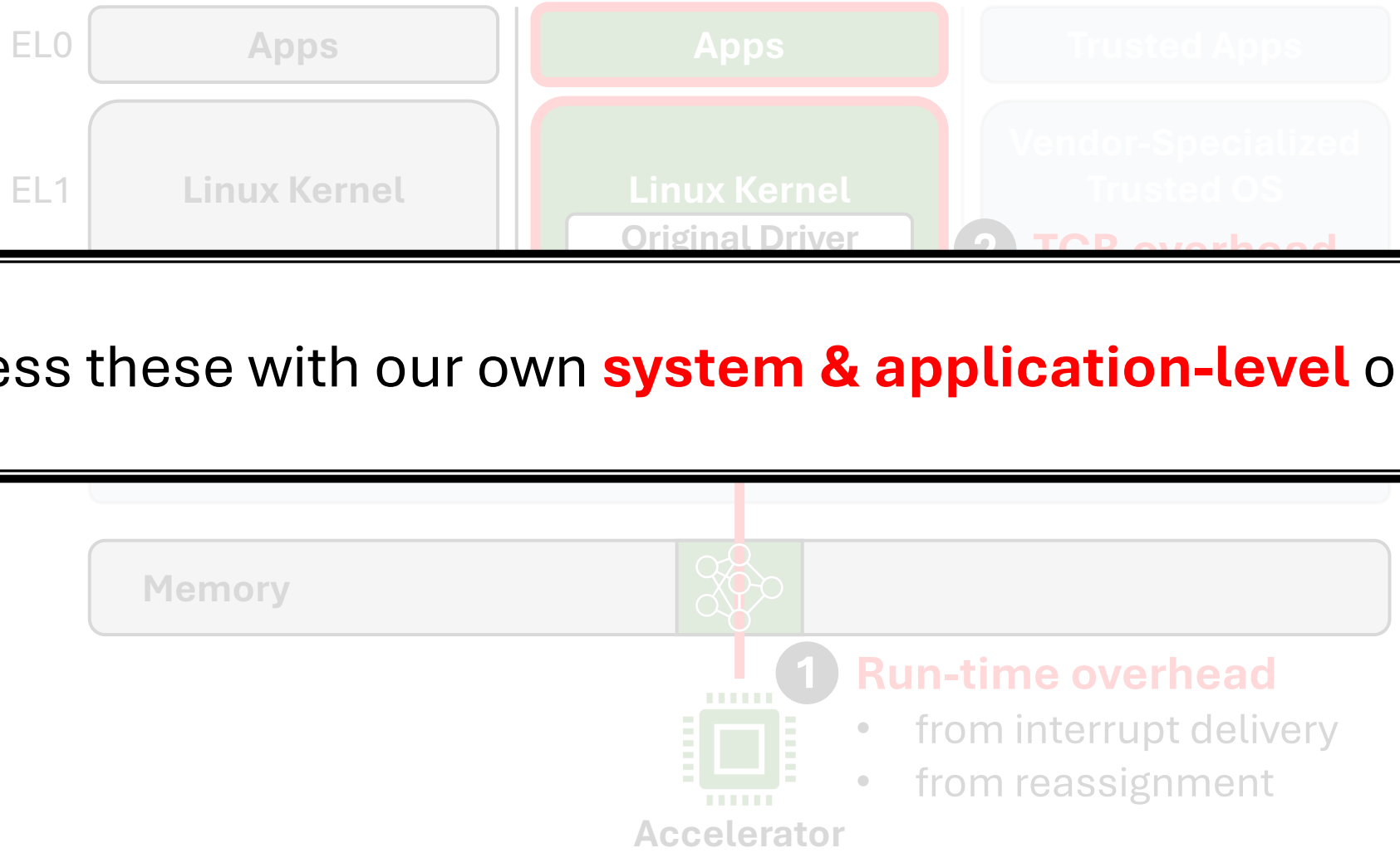
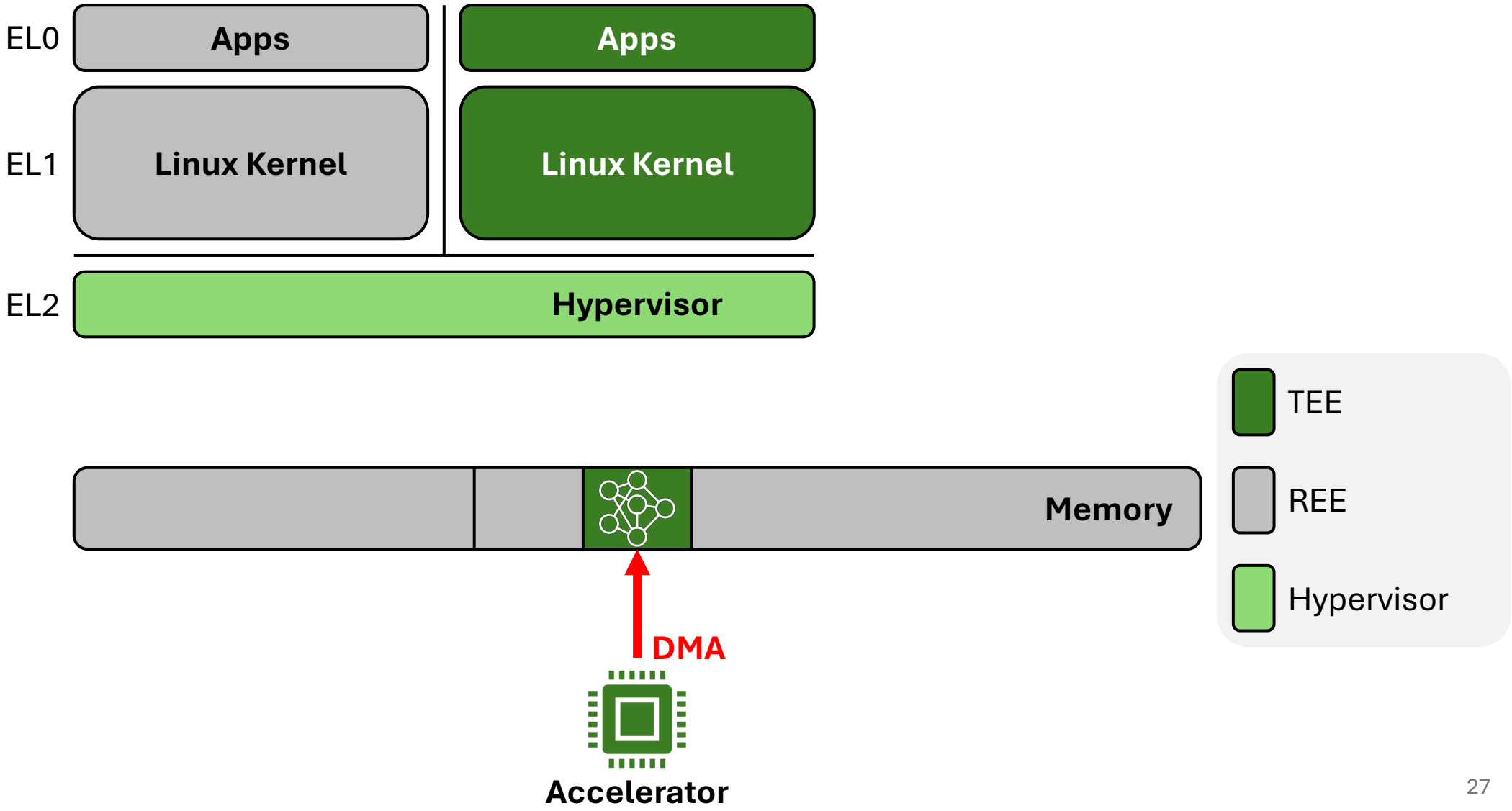


We address these with our own **system & application-level** optimizations!

System-level Optimization: Fast & Secure Reassignment



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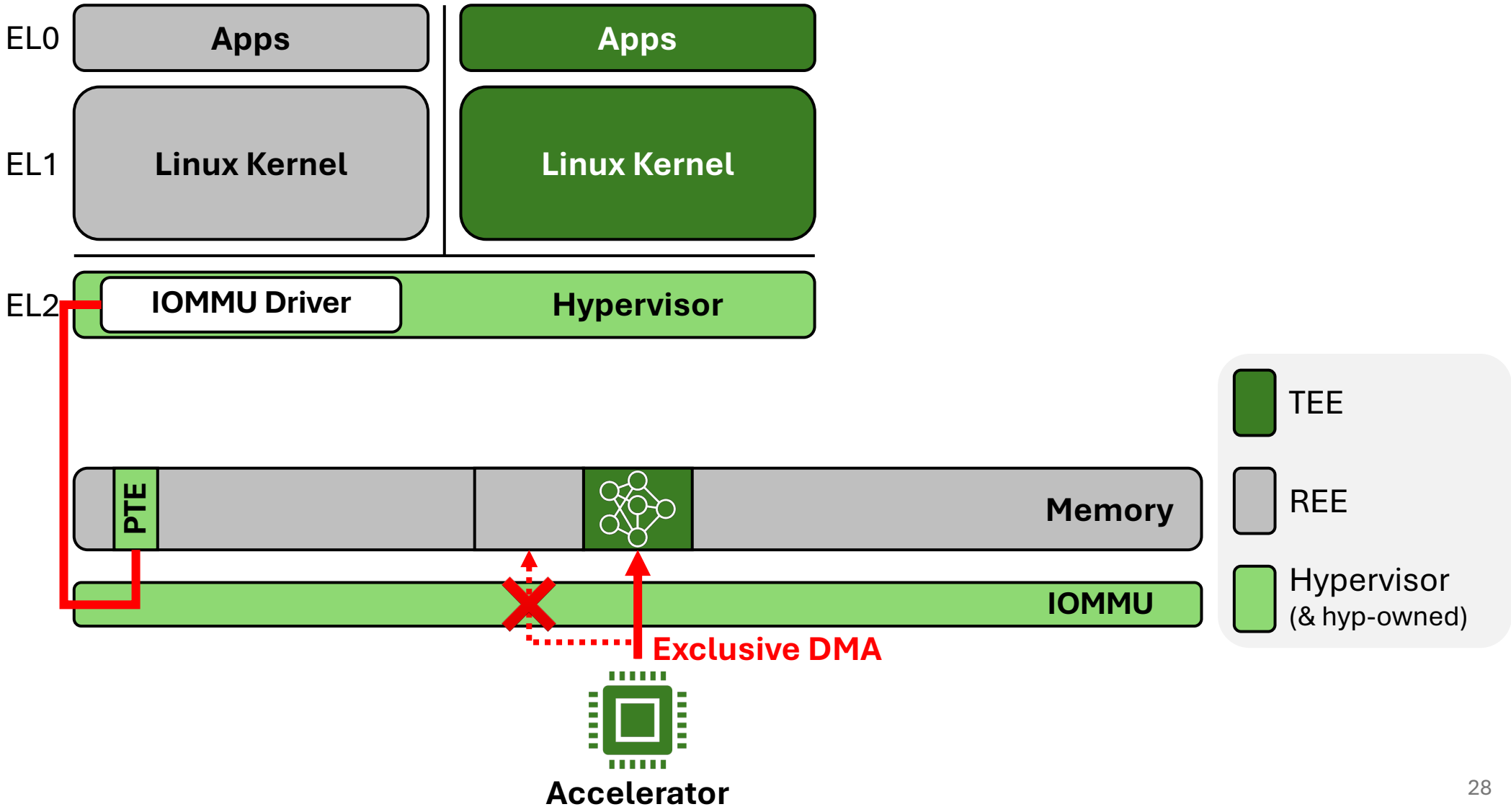

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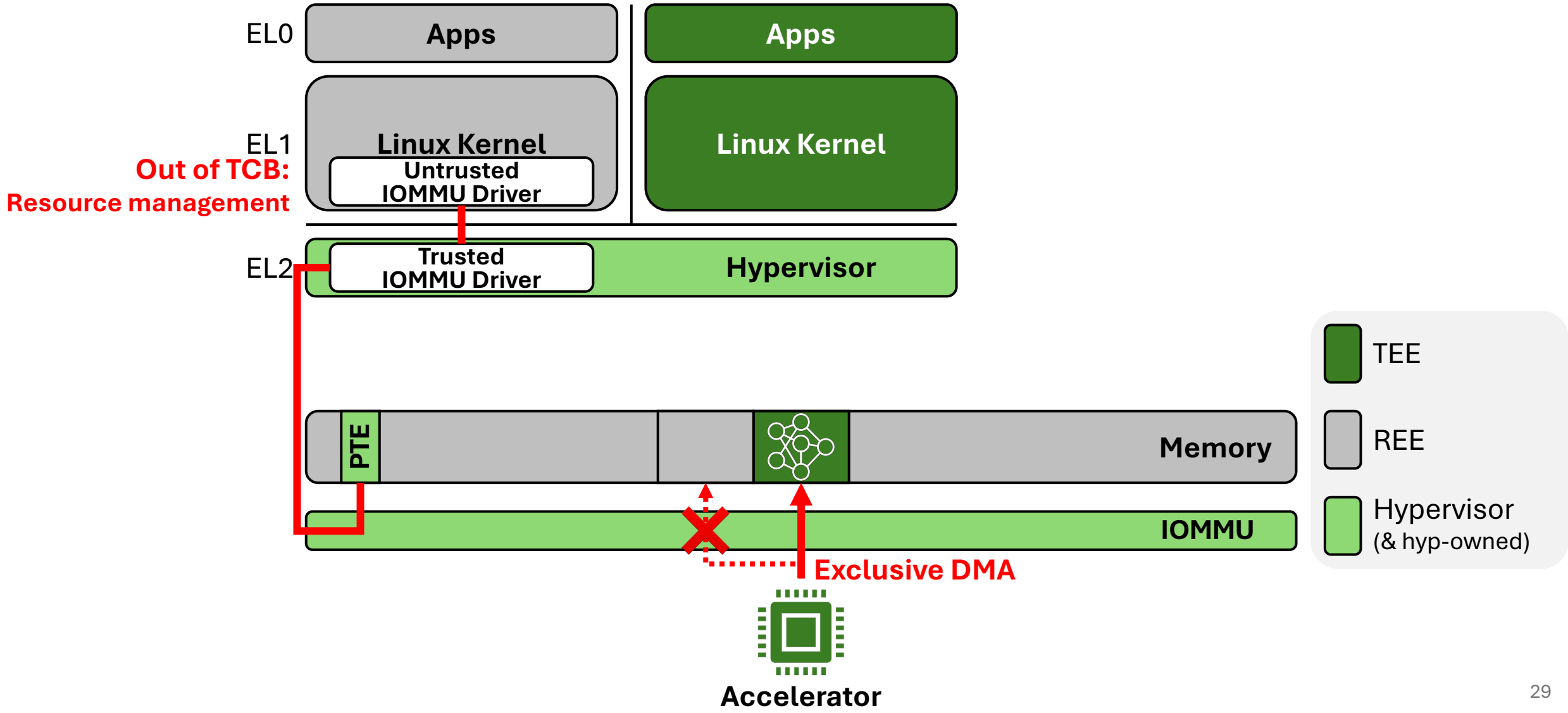

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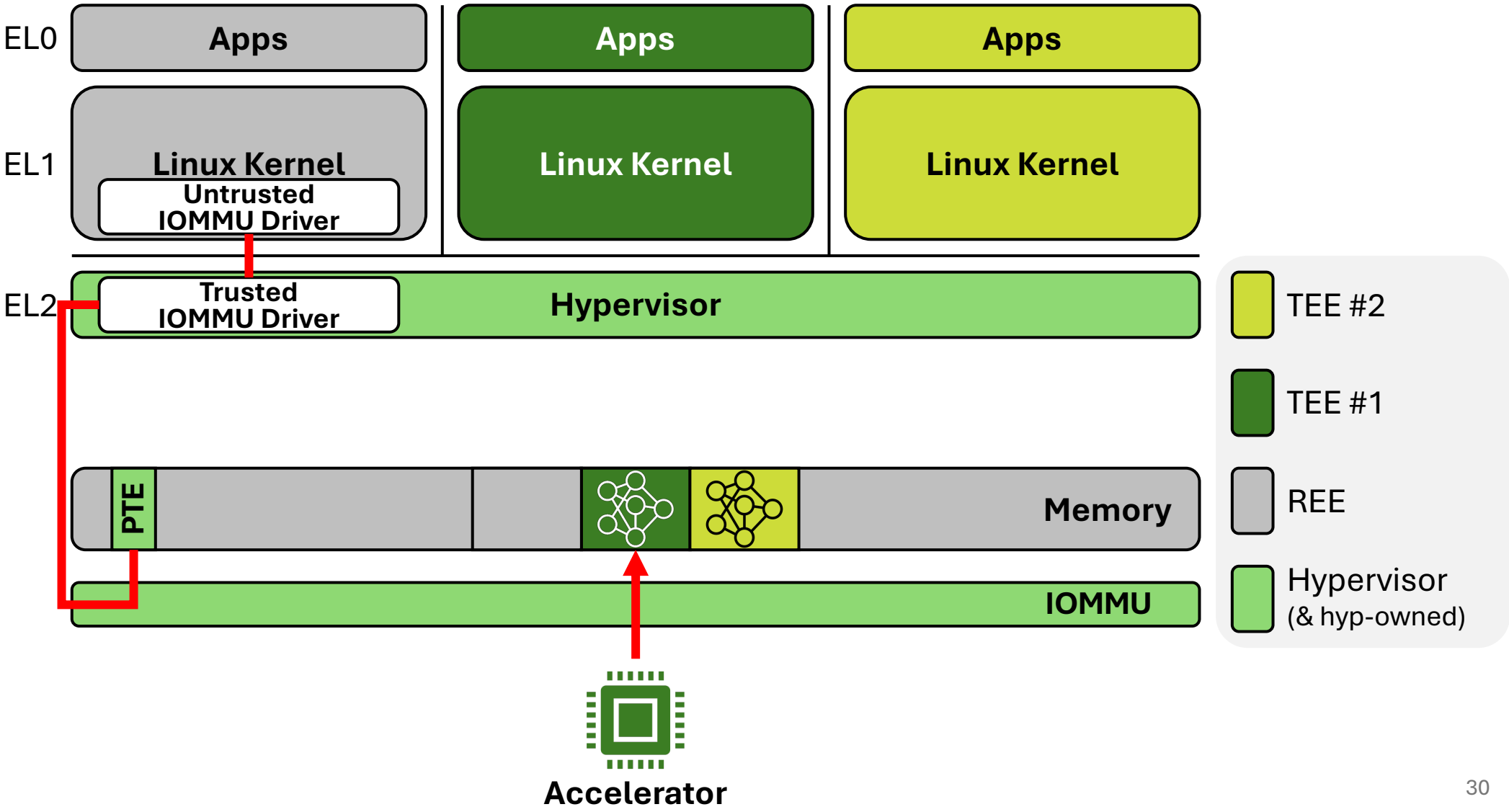

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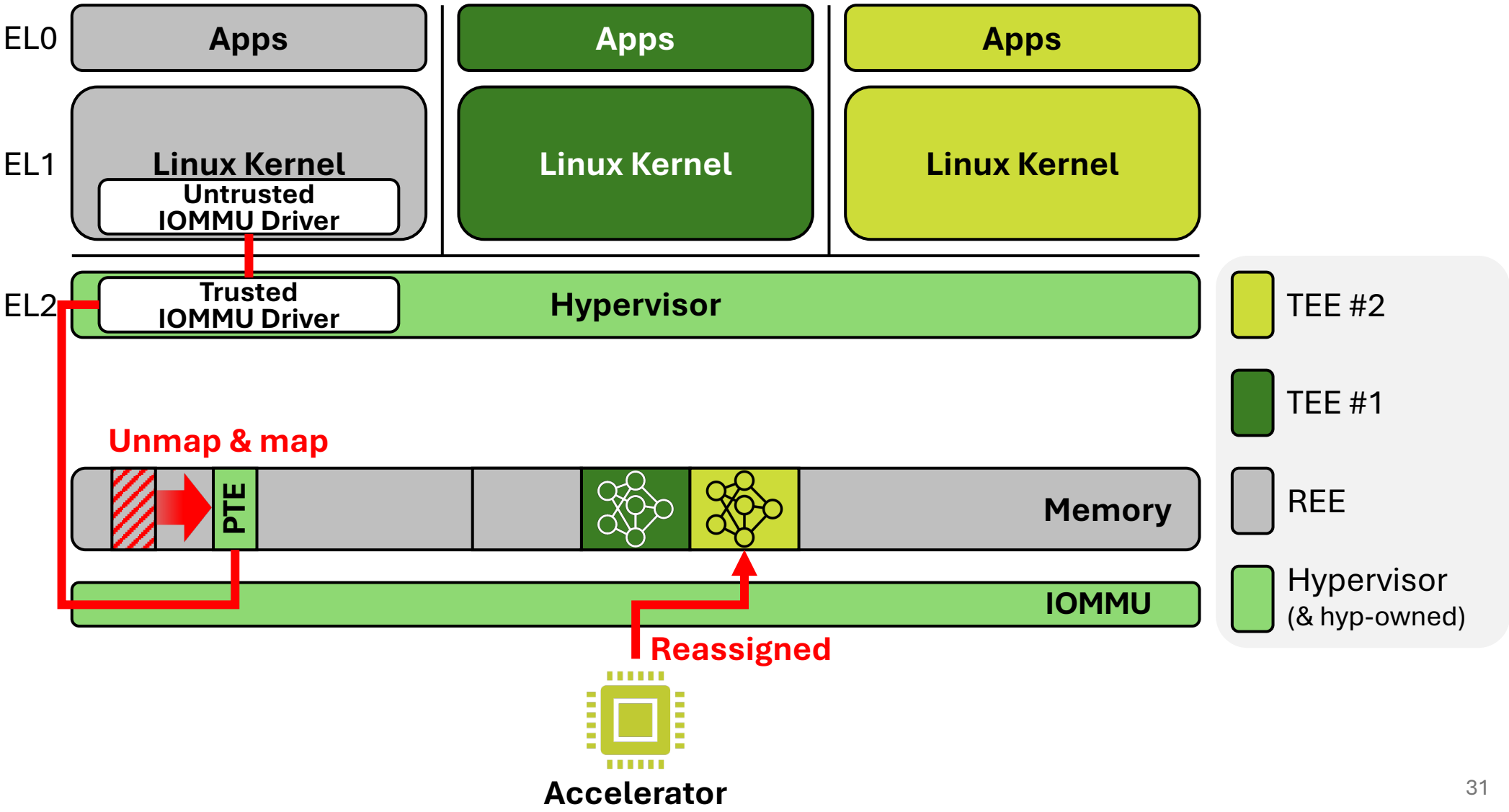

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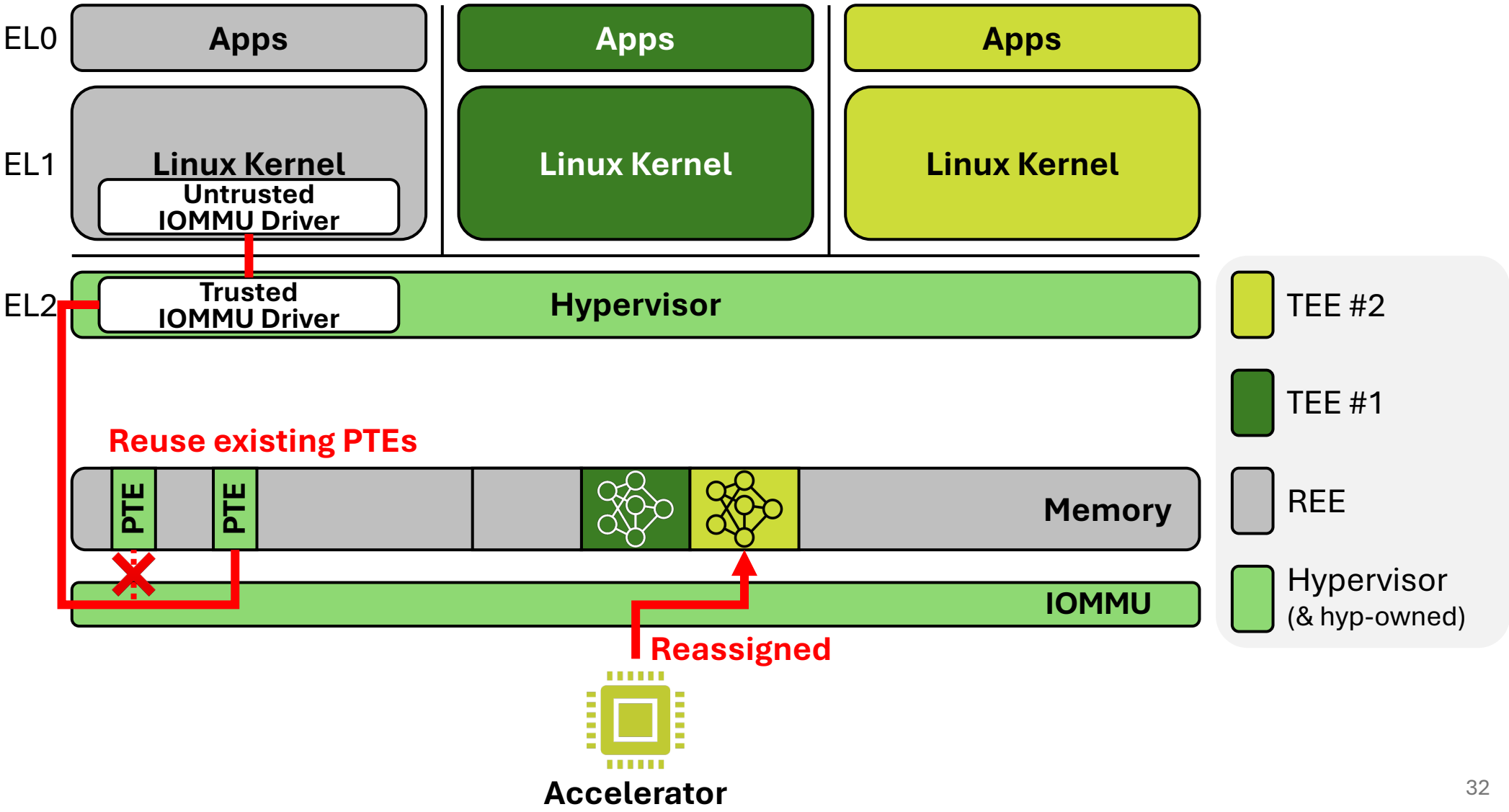

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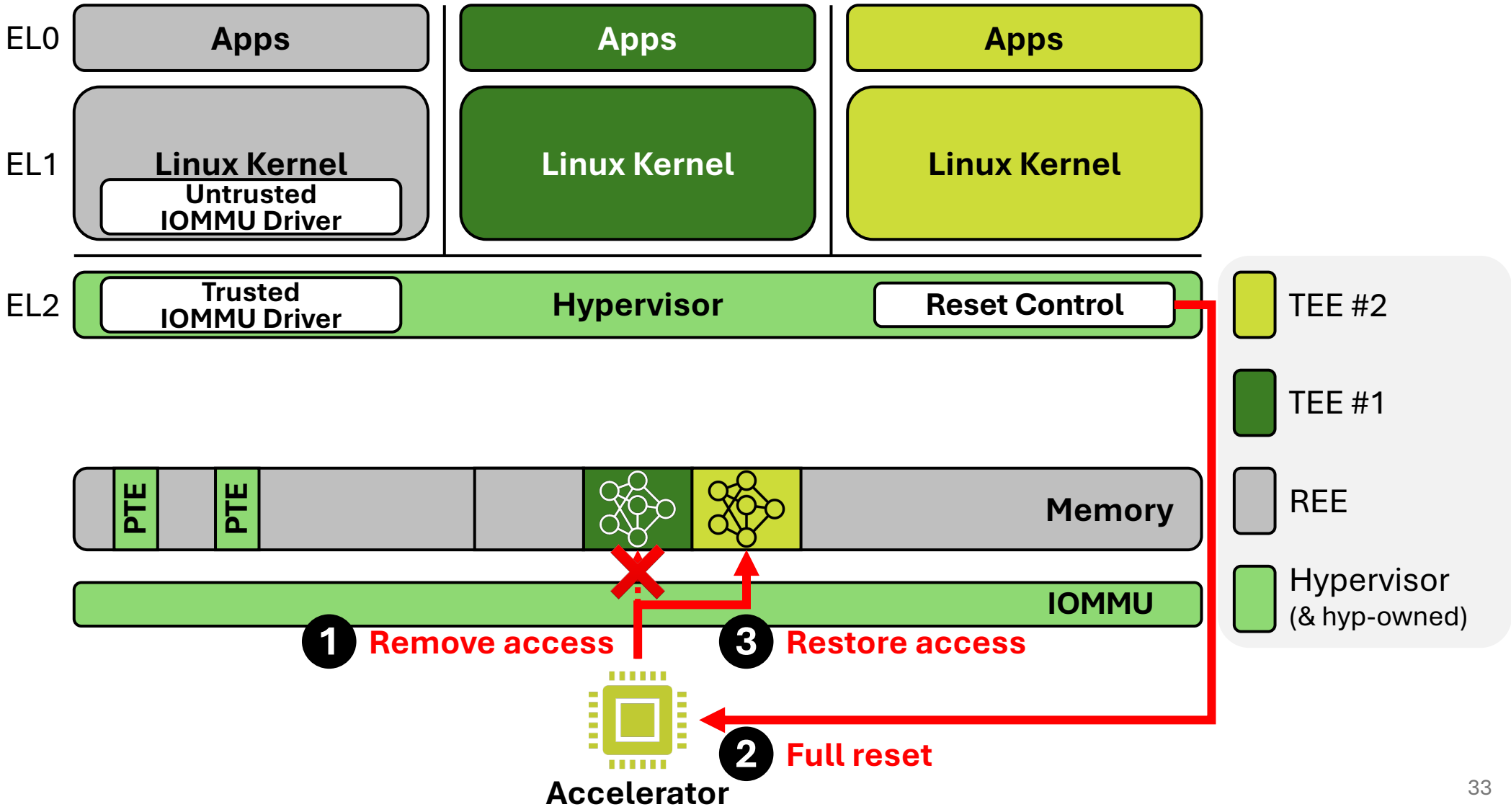
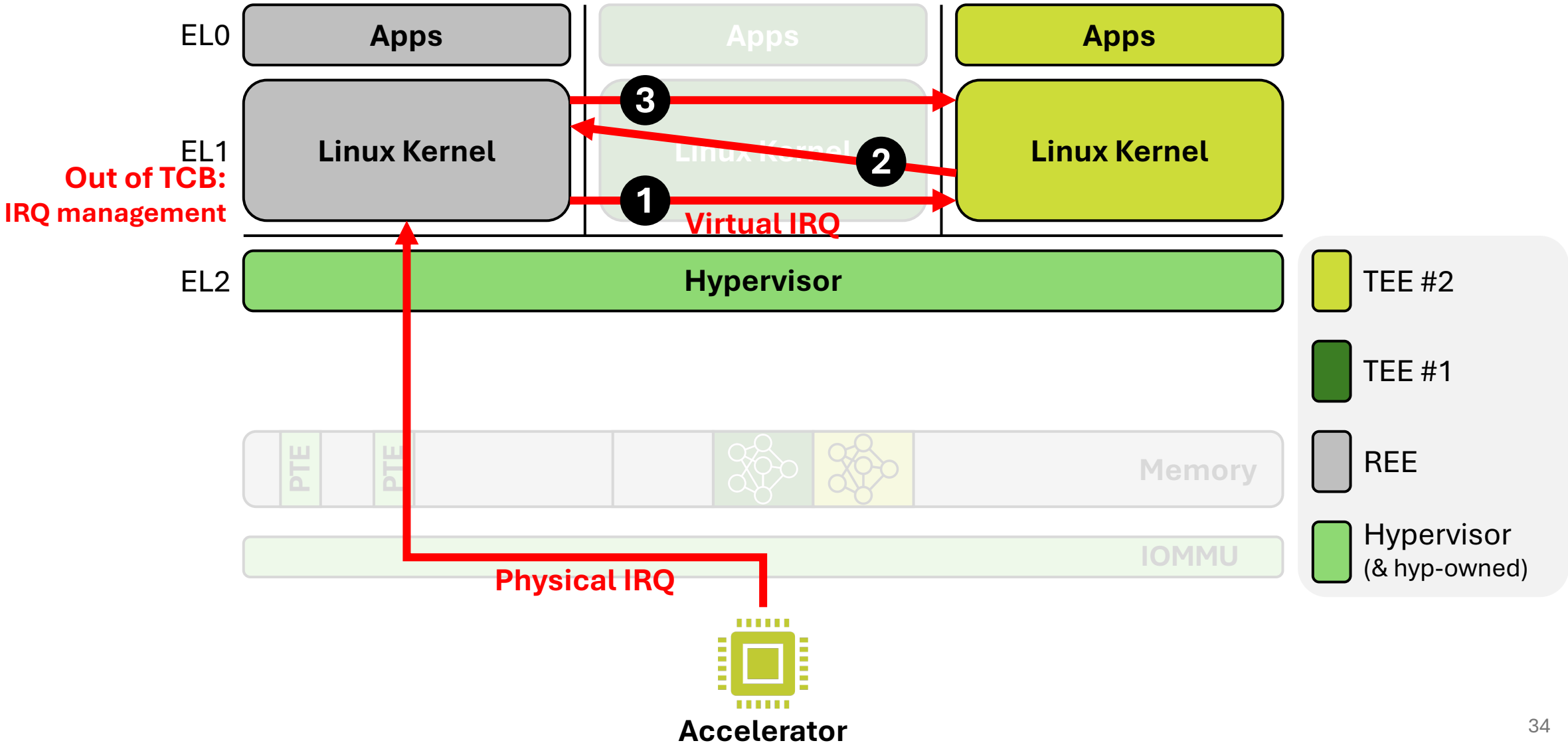
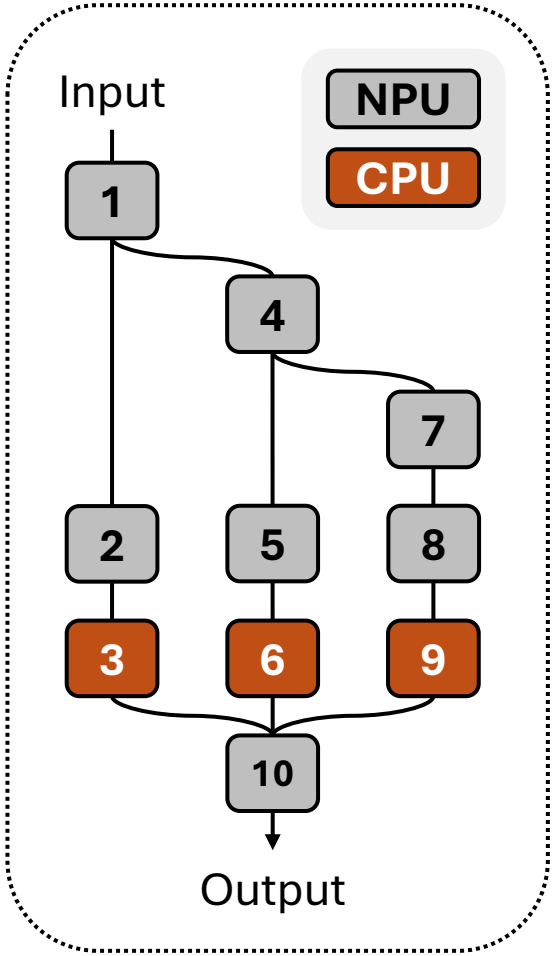


Challenge: Run-time Overhead from Interrupt Delivery



App-level Optimization: Exit-Coalescing Execution Planning



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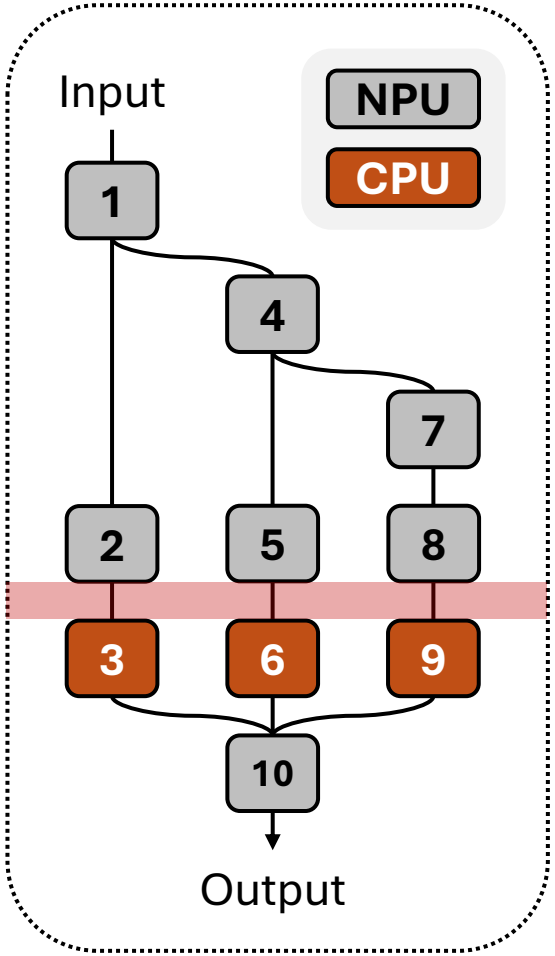

IRQs are delivered

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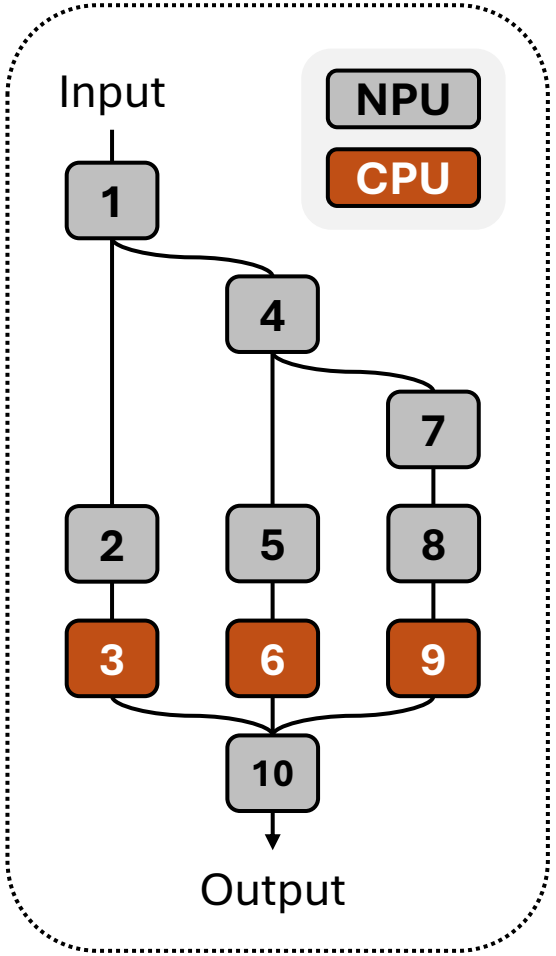

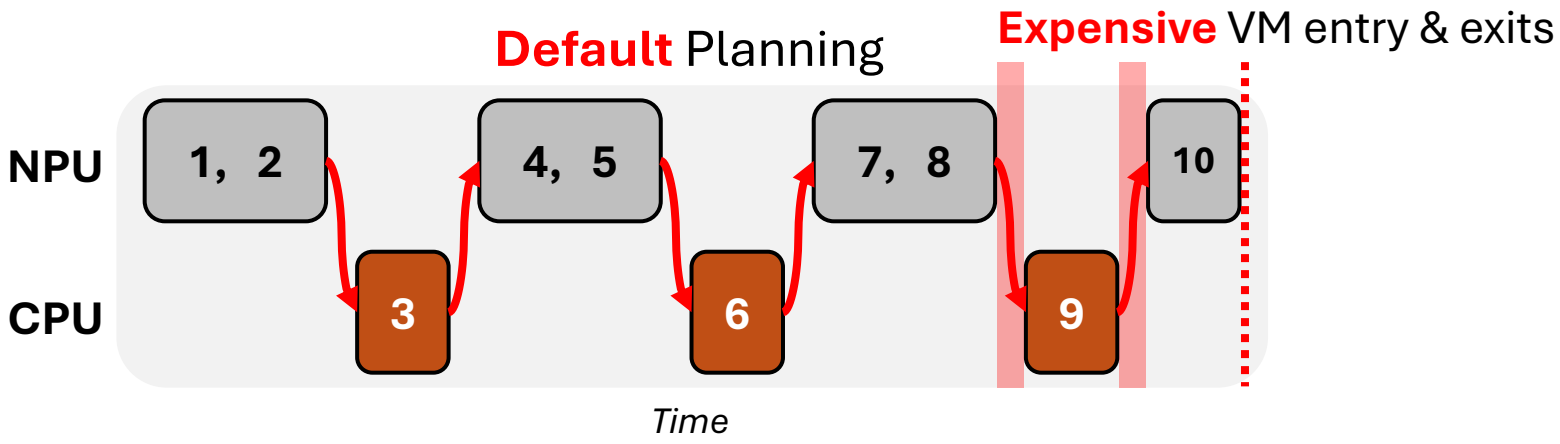

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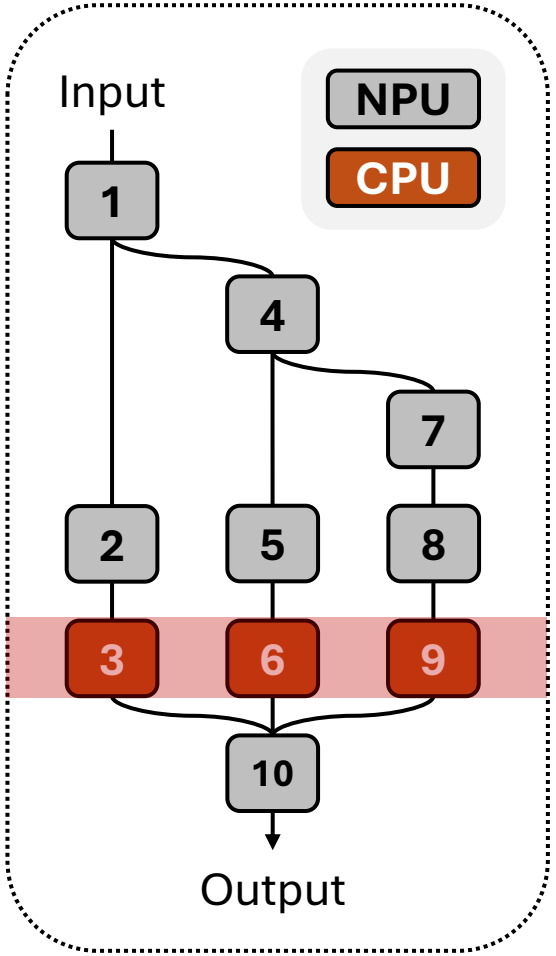
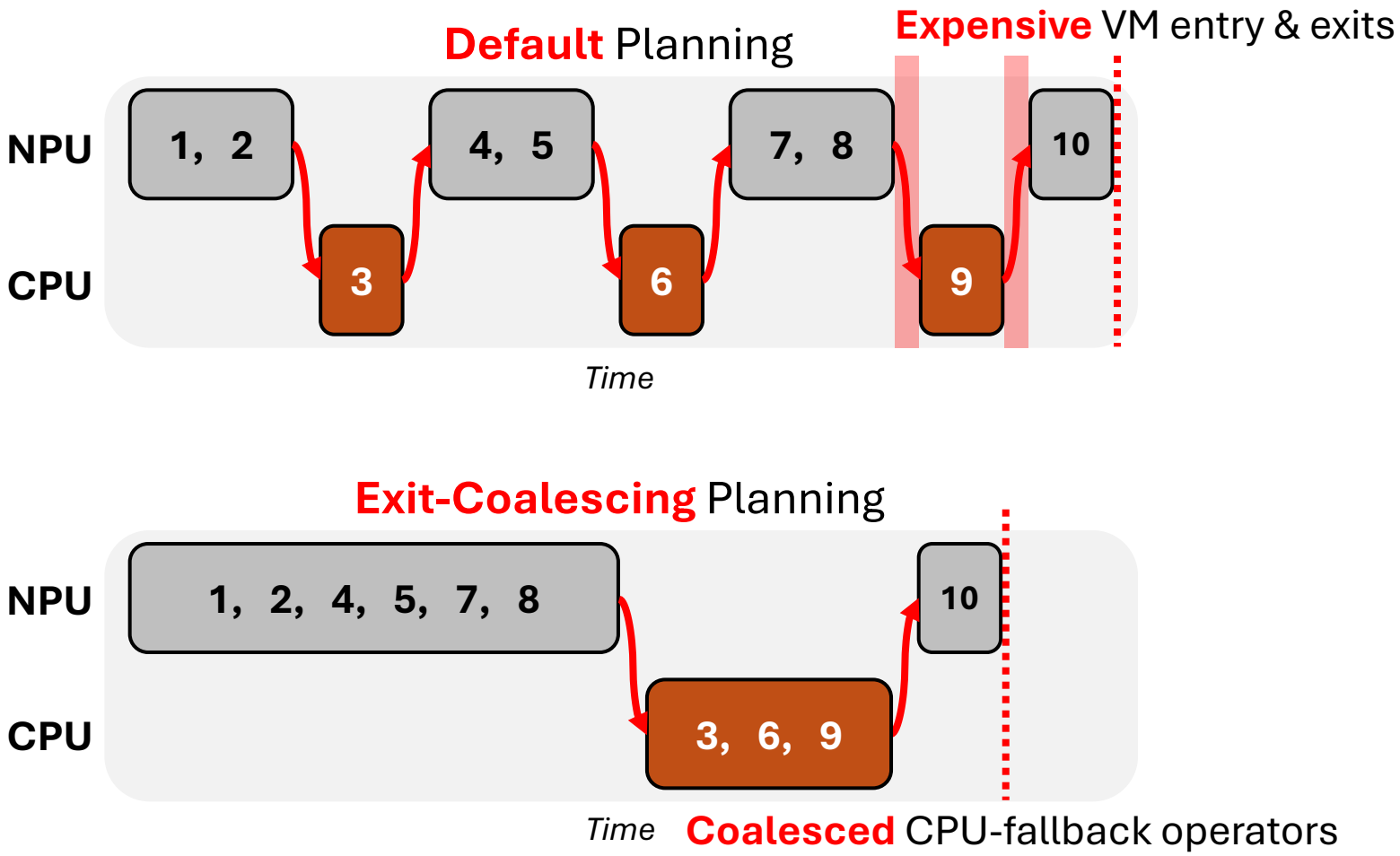
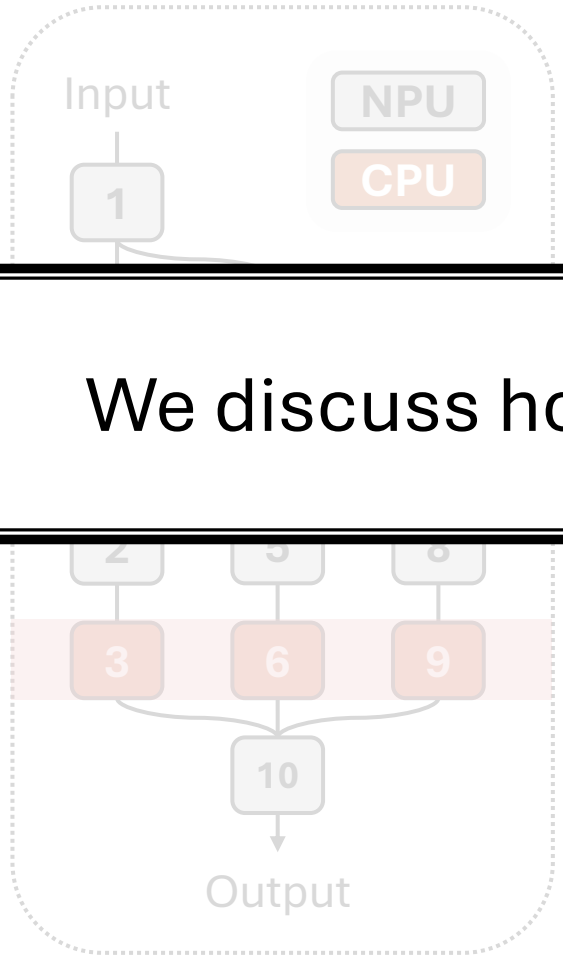
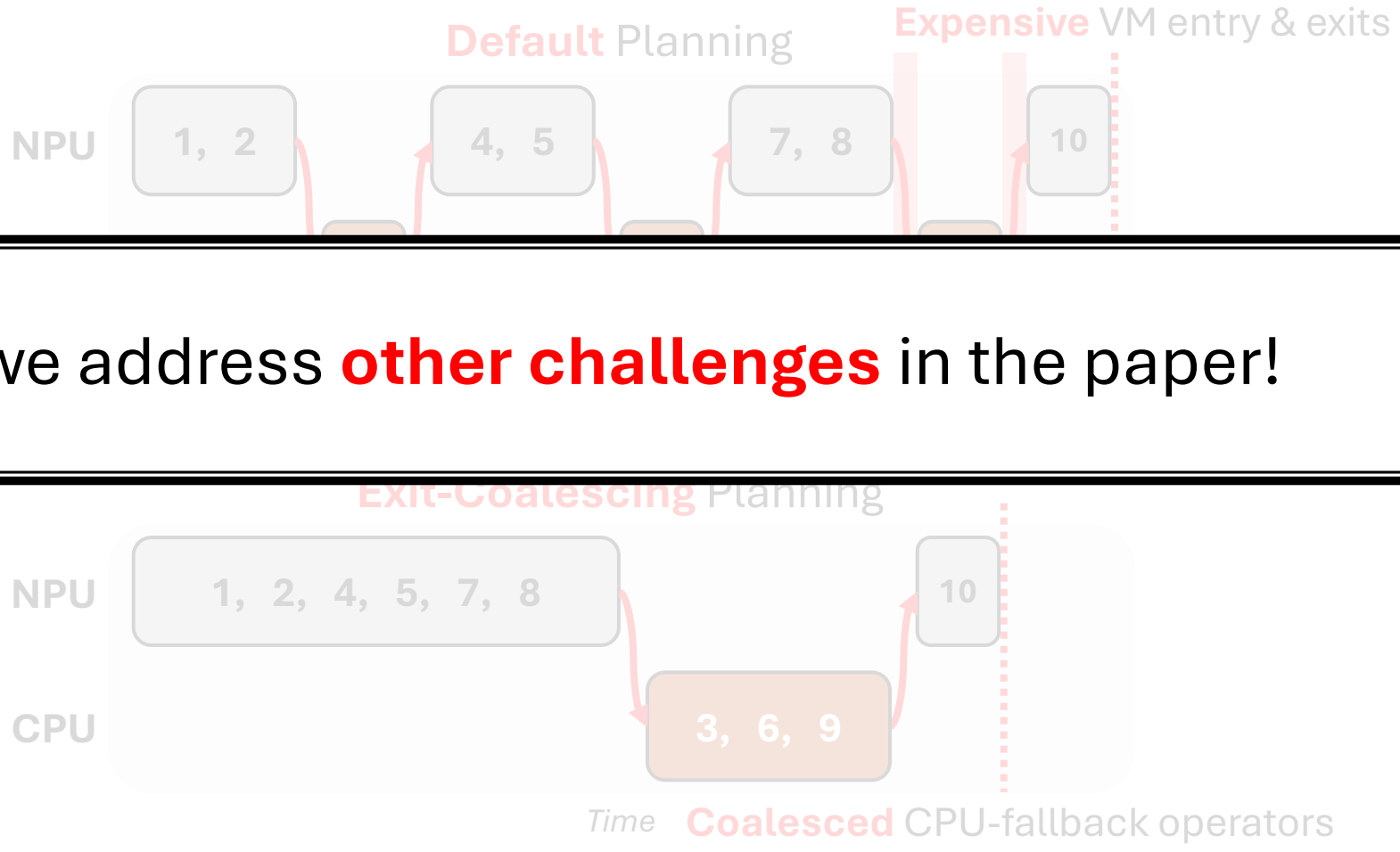




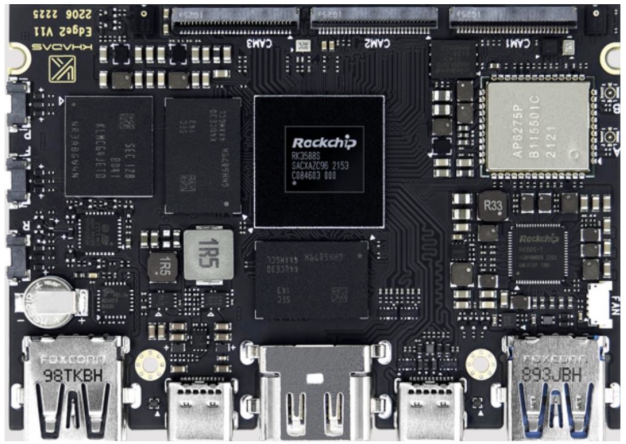
Solution #2: Exit-Coalescing DNN Execution Planning





We discuss how we address **other challenges** in the paper!

Prototype Implementation



Armv8.2-A Legacy SoC w/ Integrated NPU
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Android 13 pKVM + Google CROSVM

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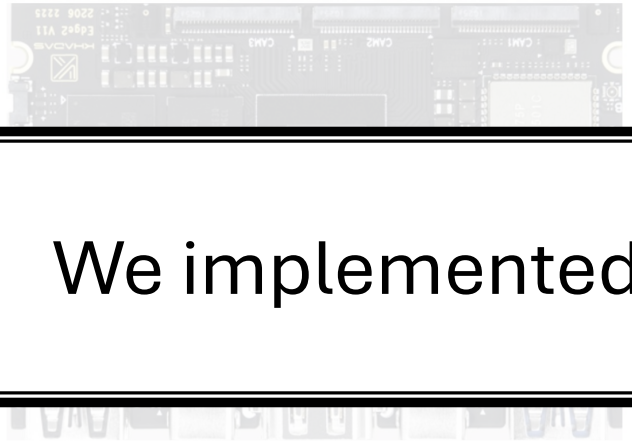

We implemented our prototype on a **legacy SoC**!

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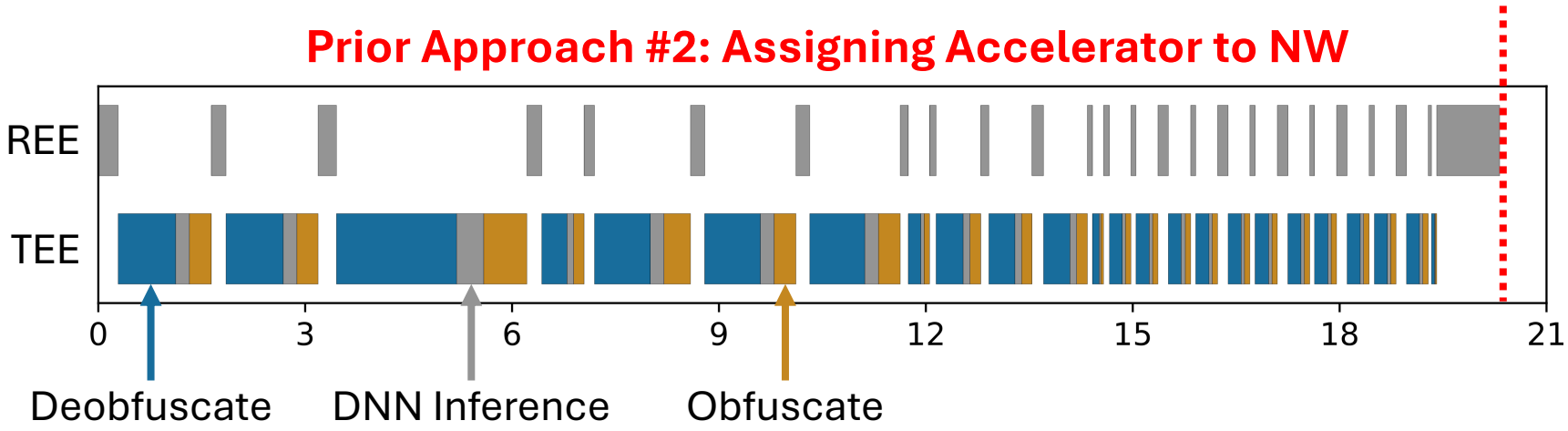
Evaluation #1: DNN Inference Latency with MobileNetV1



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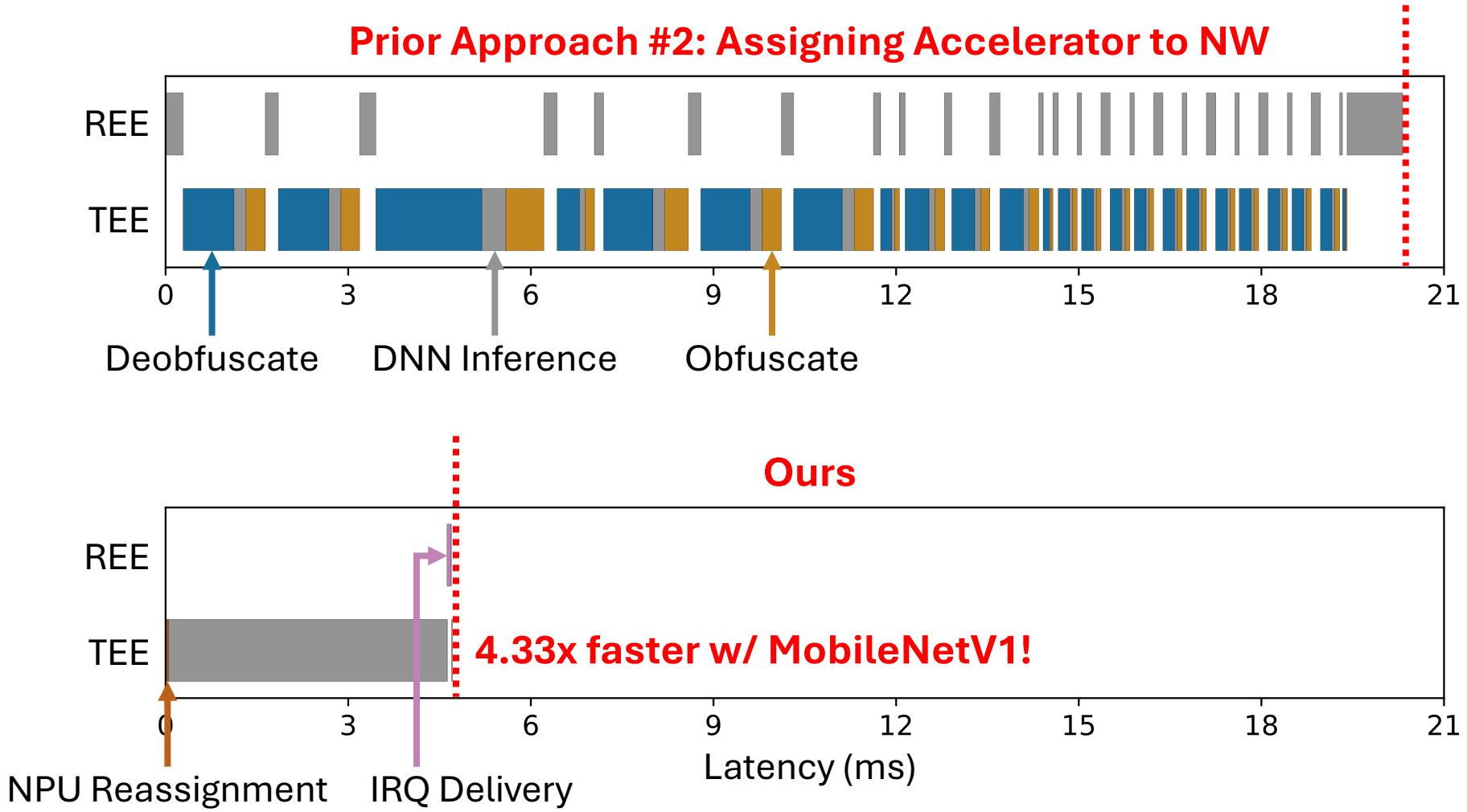

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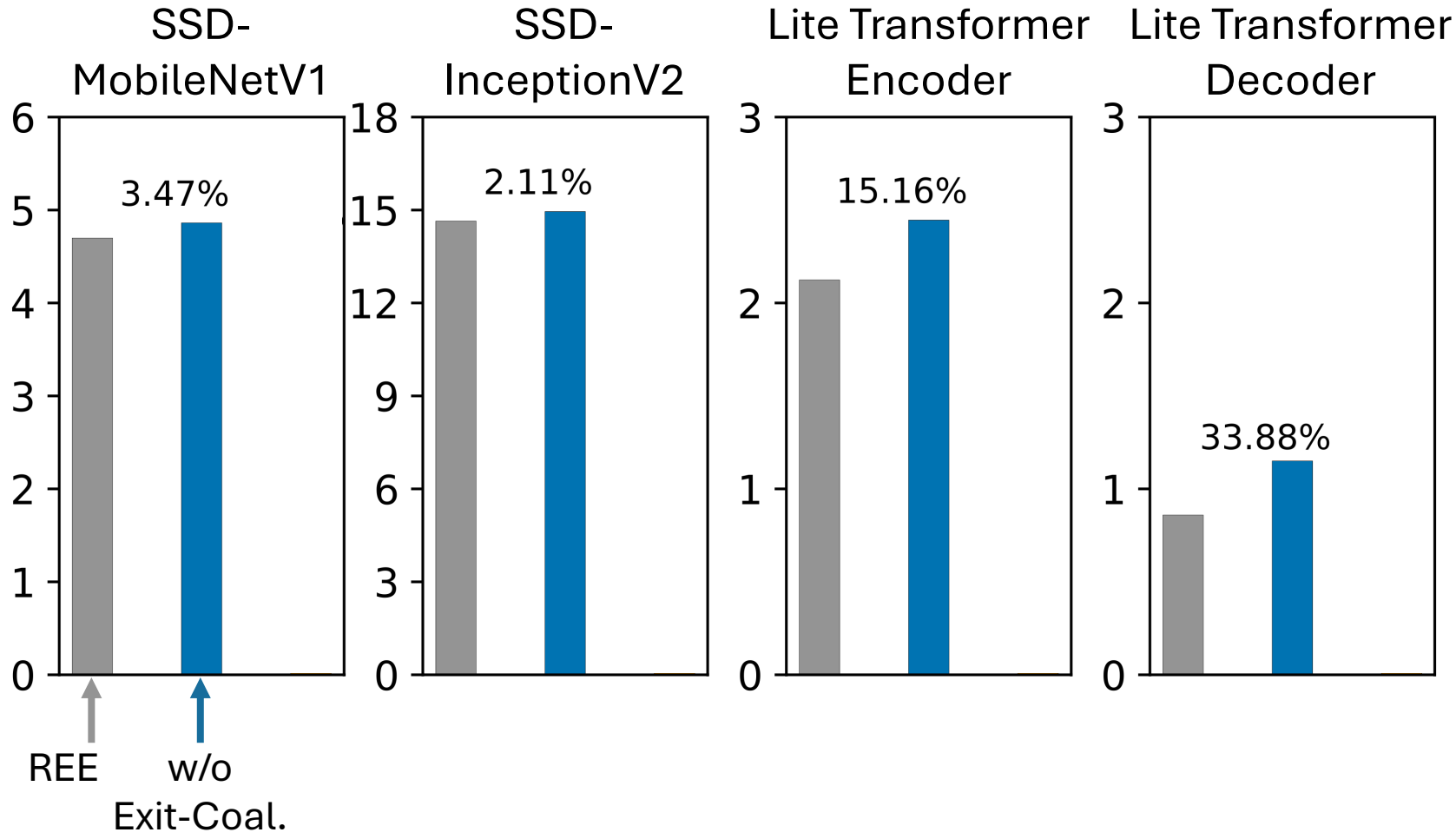
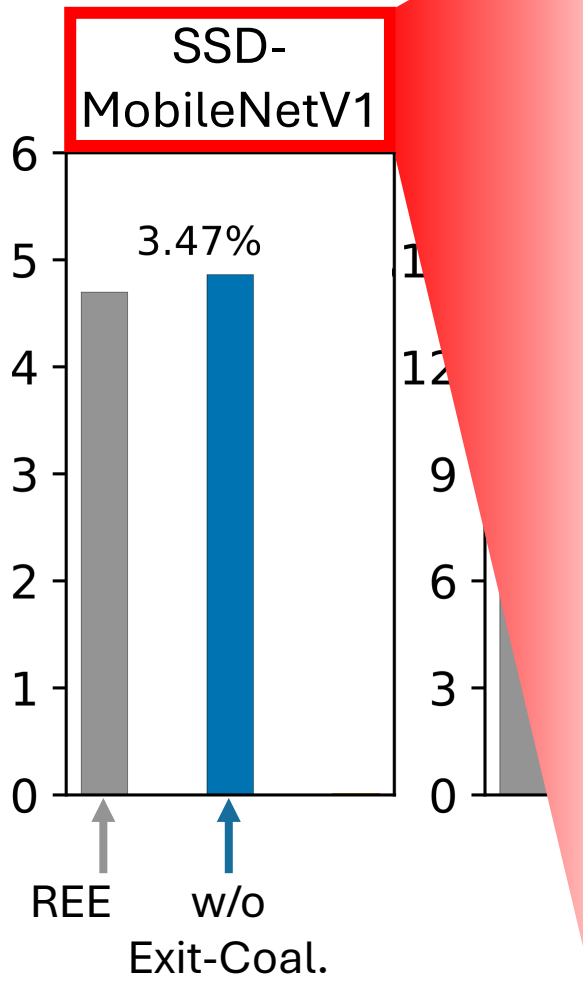
Evaluation #2: Exit-Coalescing DNN Execution Planning



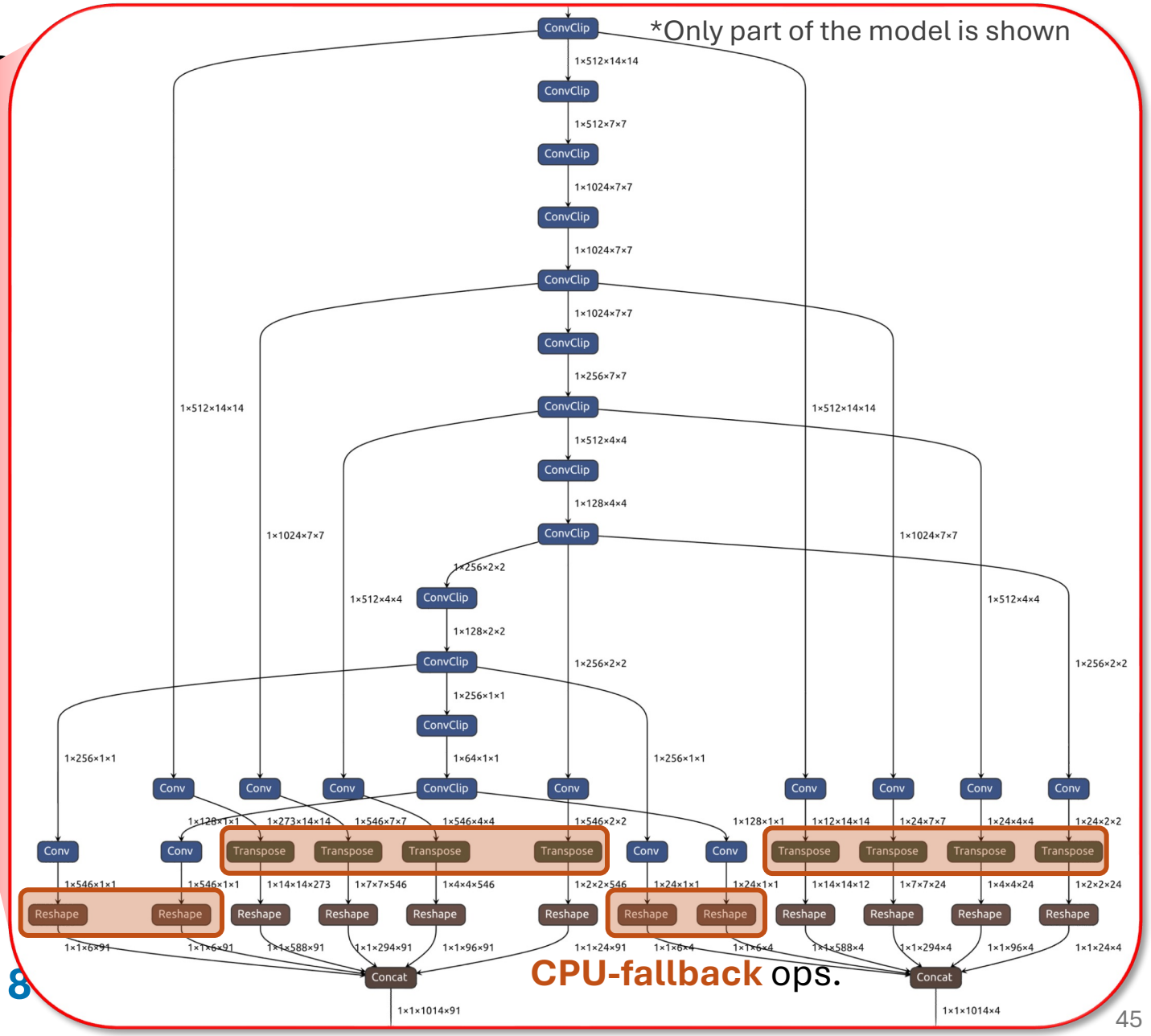
Number of exits: **13** **18** **26** **38**

Evaluation #2: Exit-Coal

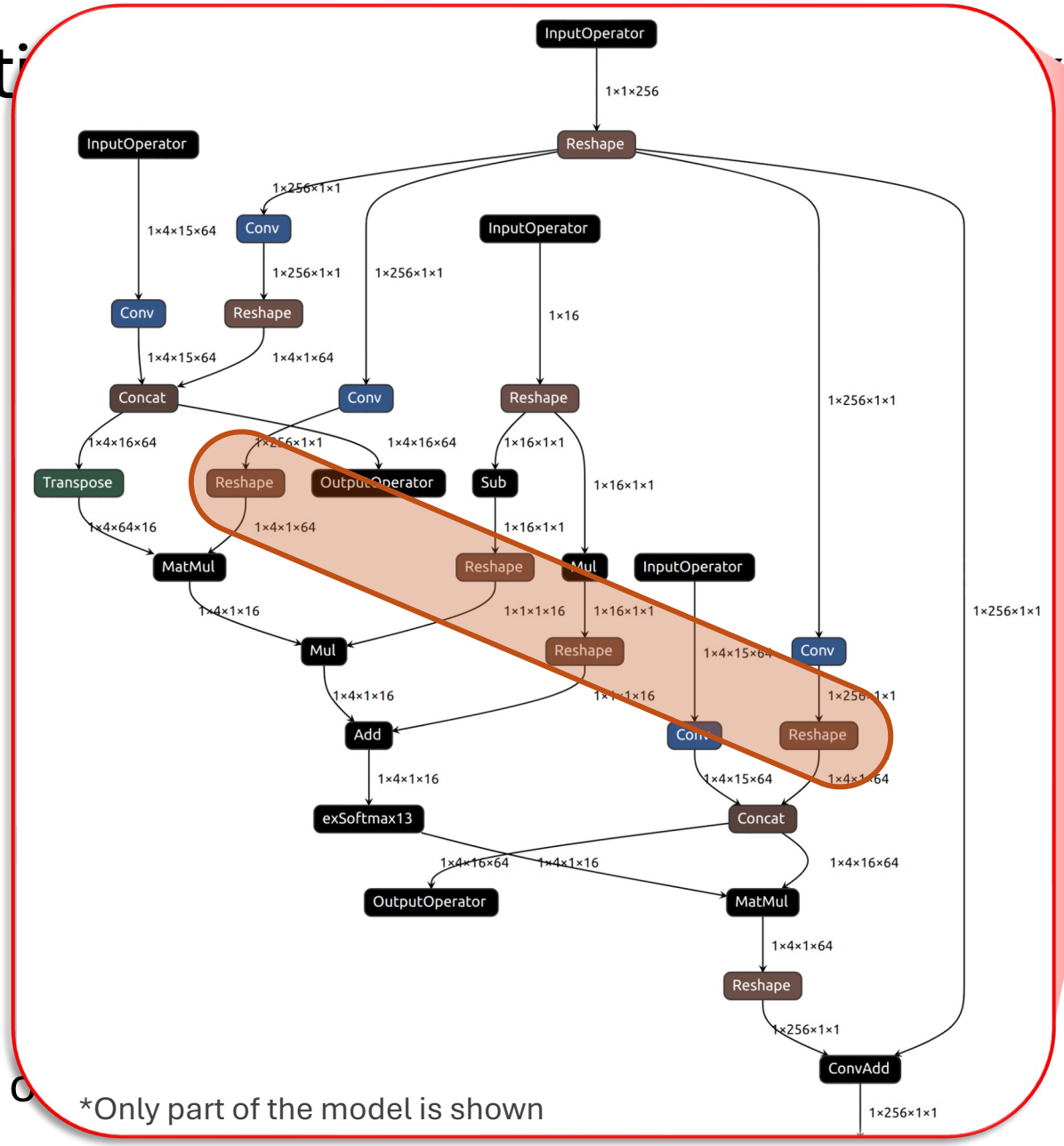


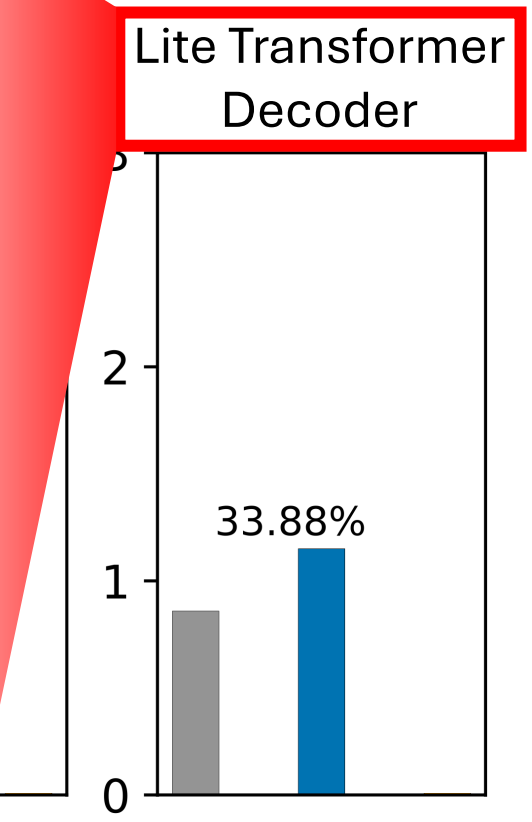
Number of exits: **13**

18



Evaluati ecution Planning



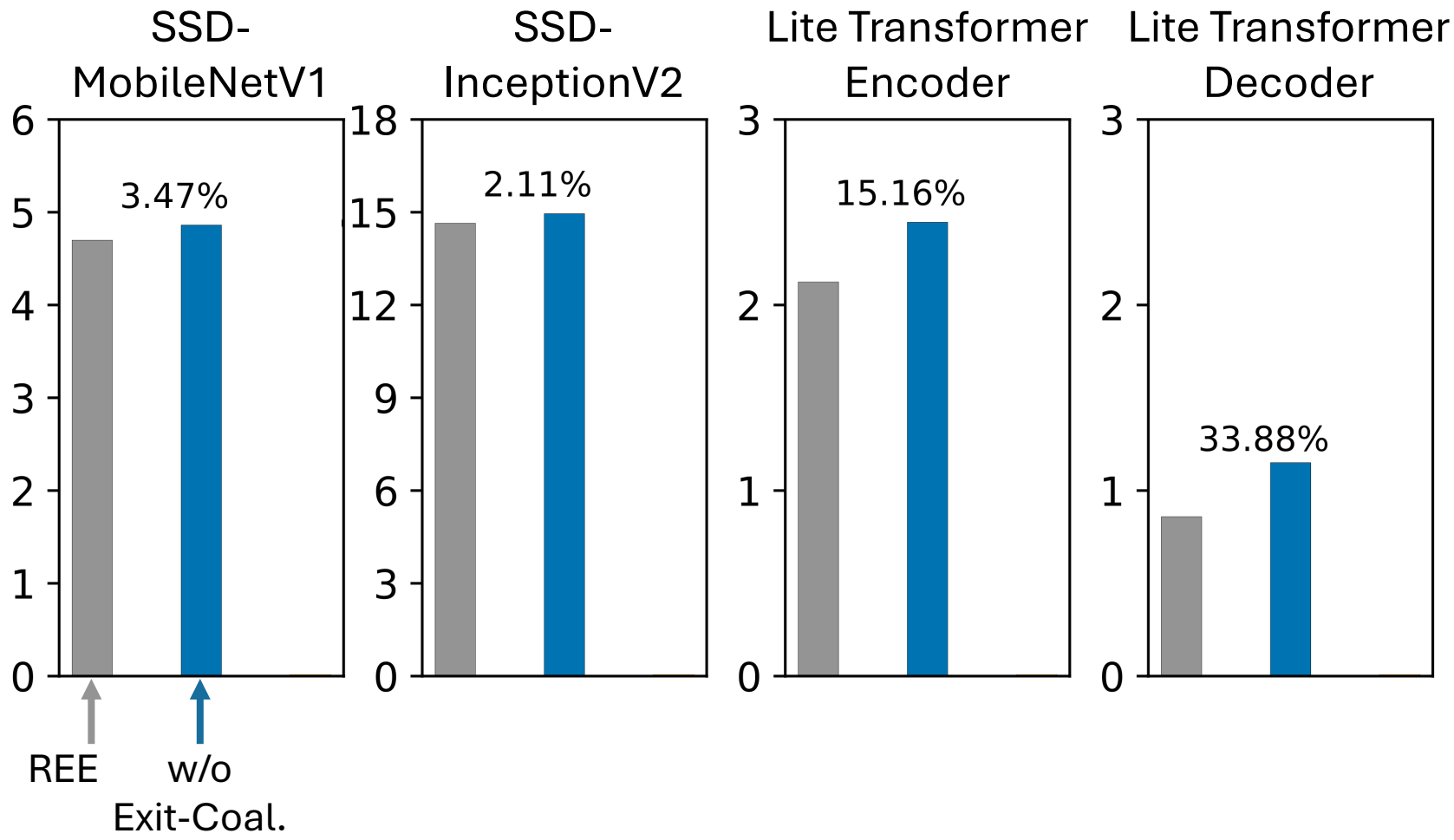


Number o

*Only part of the model is shown

38

Evaluation #2: Exit-Coalescing DNN Execution Planning



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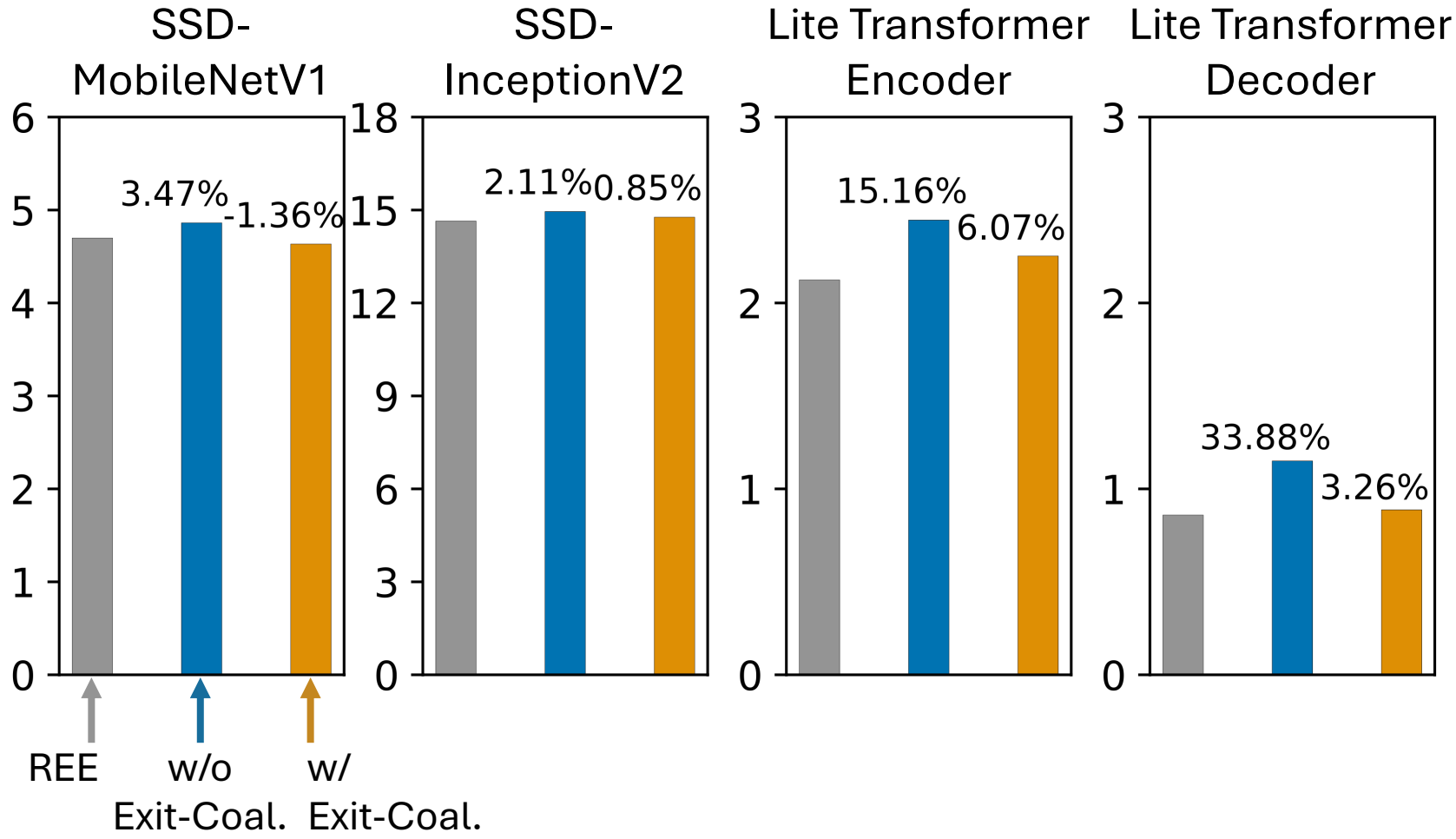
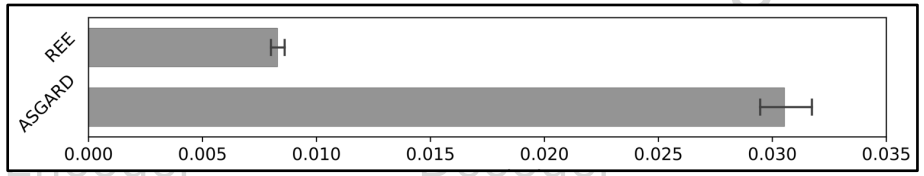


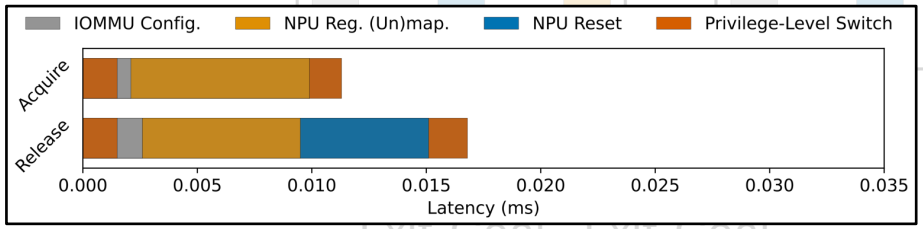
Number of exits: **13 → 2** **18 → 10** **26 → 16** **38 → 20**

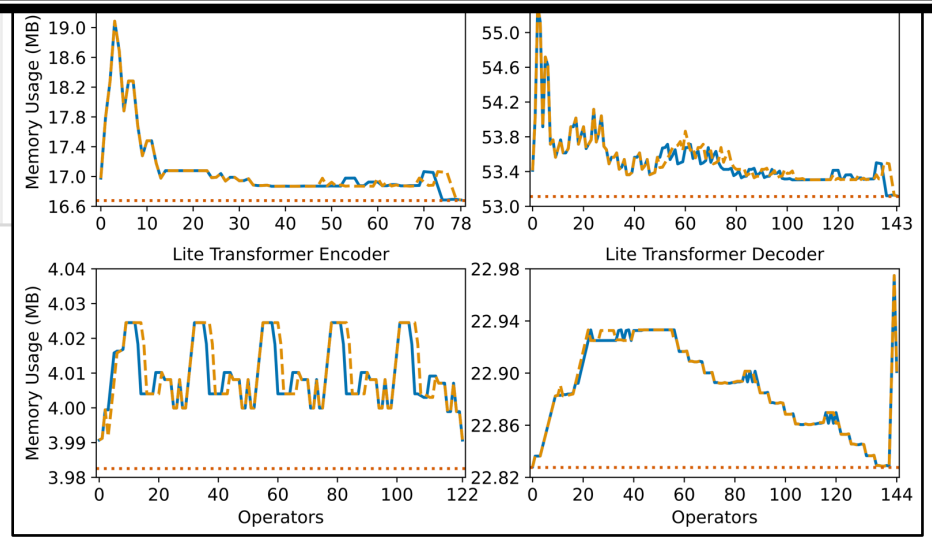
Mode	Component	Size		
		Before	After	(Reduction)
User	Core Utilities	0.831	**0.000**	**(–100.0%)**
	DNN Application	0.023	0.023	(–0.0%)
	DNN Runtime & User-Mode NPU Driver	5.610	5.610	(–0.0%)
	C/C++ Standard Libraries & Linker	4.015	**3.870**	**(–3.6%)**
	Total	10.479	**9.503**	**(–9.3%)**
Kernel	Security Features	7.000	**3.928**	**(–43.9%)**
	Application-Specific Features	6.564	**0.039**	**(–99.4%)**
	Kernel-Mode NPU Driver	0.284	0.284	(–0.0%)
	Core Kernel	3.685	3.685	(–0.0%)
	Total	17.533	**7.936**	**(–54.7%)**



More evaluation results are available in the paper!

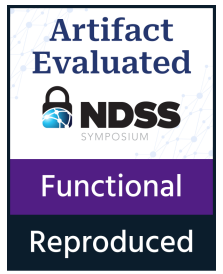
(E.g., security analysis, TCB size, IRQ delivery latency, NPU reassignment latency, memory usage, etc.)





Conclusion

- The **first system** that protects on-device DNNs with virtualization-based TEEs in legacy SoCs.
- The virtualization overheads could be contained with our **system & application-level** optimizations.
- Check our paper for many more details!



Thank you!

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Artifact: https://github.com/yonsei-sslab/asgard