StrongBox: A GPU TEE on Arm Endpoints

Yunjie Deng*, Chenxu Wang*, Shunchang Yu, Shiqing Liu, Zhenyu Ning, Kevin Leach, Jin Li, Shoumeng Yan, Zhengyu He, Jiannong Cao, Fengwei Zhang ✉

南方科技大学 SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY
THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學
湖南大學 HUNAN UNIVERSITY
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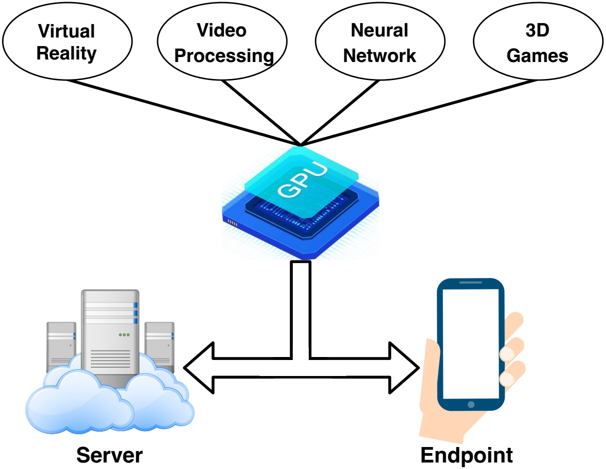
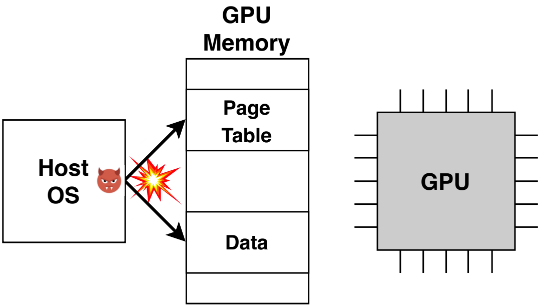
Wide Application of GPU



GPU Security

- Varied **sensitive data** are processed on GPU
  - face, fingerprints, voice ...
- The vulnerable host OS severely threats GPU computing
  - Privileged attackers can directly access the data, or
  - Break the page table isolation between GPU computation

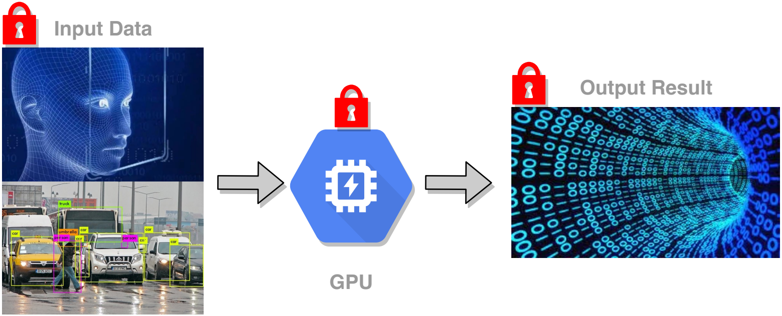


Trusted Execution Environments

- Processor IP developers introduce hardware-assisted **T**rusted **E**xecution **E**nvironment (TEE) for secure data storage and computation
  - Arm TrustZone
  - Intel Software Guard Extensions (SGX)
  - AMD Secure Encrypted Virtualization (SEV)

GPU TEEs

- Secure data transmission between OS and GPU
- Isolate GPU memory and GPU computation

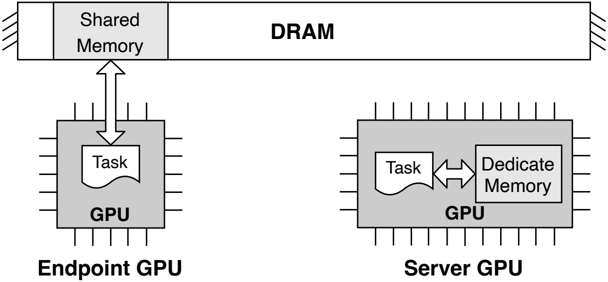


GPU Trusted Execution Environments

- TEEs have participated in secure GPU computing
  - **Graviton**: Trusted Execution Environments on GPUs (OSDI'18)
  - **HIX**: Heterogeneous isolated execution for commodity gpus (ASPLOS'19)
  - **HETEE**: Enabling Rack-scale Confidential Computing using Heterogeneous Trusted Execution Environment (S&P'20)
  - **LITE**: A Low-Cost Practical Inter-Operable GPU TEE (ICS'22)
  - **Secdeep** (IoTDI'21): Secure and Performant On-device Deep Learning Inference Framework for Mobile and IoT Devices
  - ...

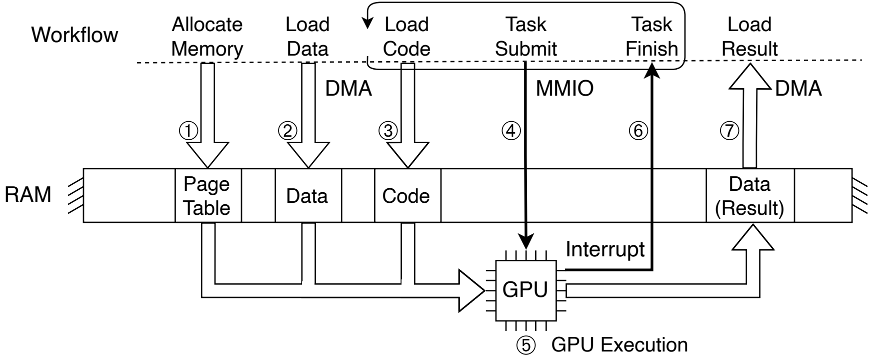
Challenges of Adapting Existing Works to Arm Endpoints

- Architecture
  - CPU Architecture: Intel vs. Arm
  - GPU Architecture: Dedicated-memory GPU vs. Shared-memory GPU



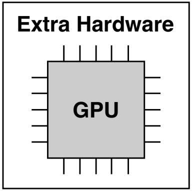
Challenges of Adapting Existing Works to Arm Endpoints

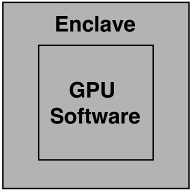
- Architecture
  - A typical workflow on Arm endpoint GPUs



Challenges of Adapting Existing Works to Arm Endpoints

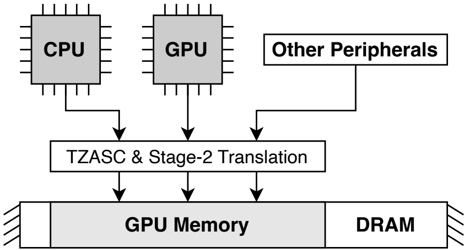
- Compatibility
  - Hardware modification on GPU chips or system architecture
- TCB size
  - Directly porting the vulnerable GPU software stacks into enclave





StrongBox Overview

- Architecture
  - Arm hardware features
    - ★ TrustZone Address Space Controller (TZASC)
    - ★ Stage-2 translation
  - Shared-memory GPU
    - ★ Reserve a memory region for sensitive GPU tasks
    - ★ Protect GPU memory by TZASC and Stage-2 translation



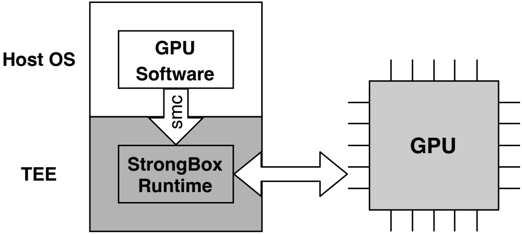
StrongBox Overview: Threat Model and Assumptions

- Compromised GPU software stacks
  - GPU runtime
  - GPU driver
  - Other peripheral drivers
  - System OS
- No hypervisor on Arm endpoints
- *Trusted secure OS and applications
- Out of scope: side-channel attacks, physical attacks, Denial-of-Service

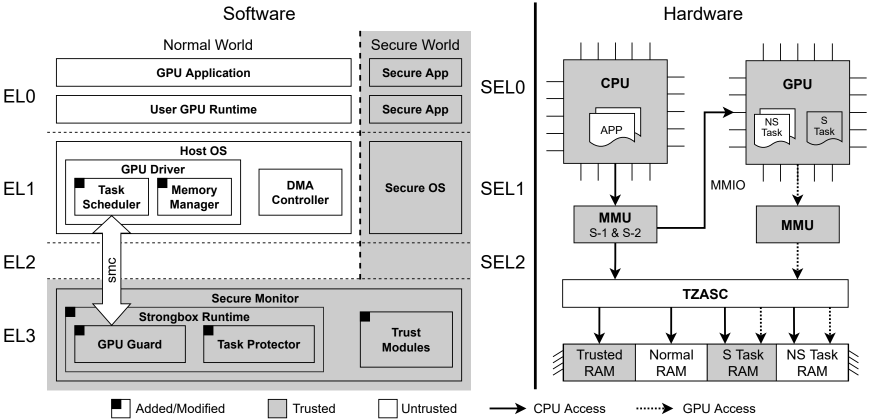
*: Addressed in future works

StrongBox Overview

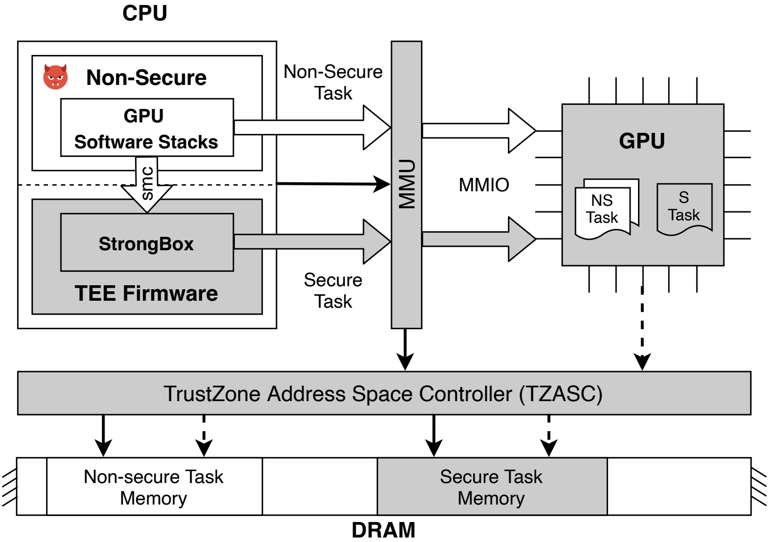
- High Compatibility
  - No hardware modification
- Minimal TCB
  - Reuse GPU software to fulfill functionality
  - Deploy lightweight StrongBox runtime to perform security check for sensitive computation tasks



StrongBox Overview



StrongBox Overview: Secure Tasks and Non-secure Tasks



Design Details

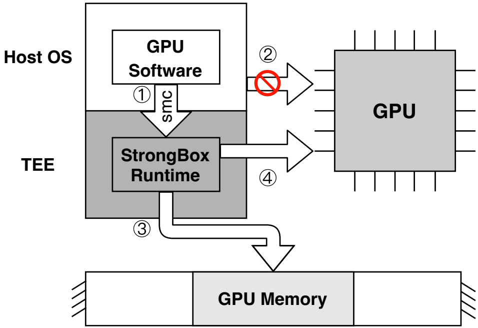
- Isolated Execution Environment
  - Prohibit the attackers access GPU and GPU memory when executing sensitive tasks
- Dynamic and fine-grained GPU memory access control
  - Prohibit the attackers access scattered sensitive data and code
- Reduce performance overhead
  - Optimize the protection overhead on multi-tasks GPU applications

Isolated Execution Environment

- Restrict two modes of data access
  - Host OS to GPU
  - Host OS to shared memory
- Approach
  - Route the control from GPU driver to StrongBox runtime inside TrustZone
  - Manage the access to the shared memory
- Other requirements
  - Small TCB
  - No hardware modification

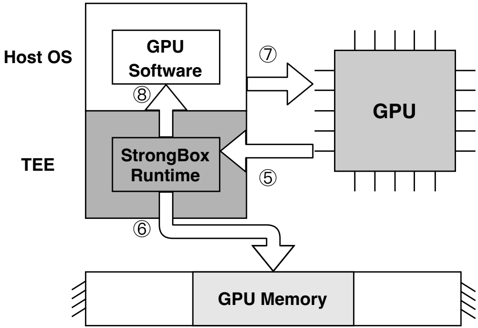
Isolated Execution Environment: Submission

- ①: Route control to StrongBox runtime
- ②: Forbid the Host OS to access GPU
- ③: Protect the sensitive data and code
- ④: Submit computation task to GPU



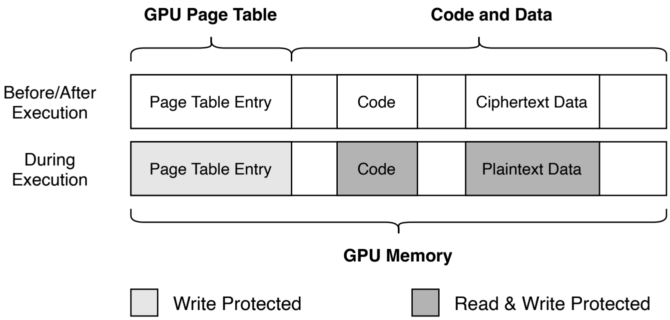
Isolated Execution Environment: Termination

- ⑤: Capture task finish interrupt
- ⑥: Restore the access permission to sensitive data and code
- ⑦: Allow Host OS to access GPU
- ⑧: Route the control to GPU driver

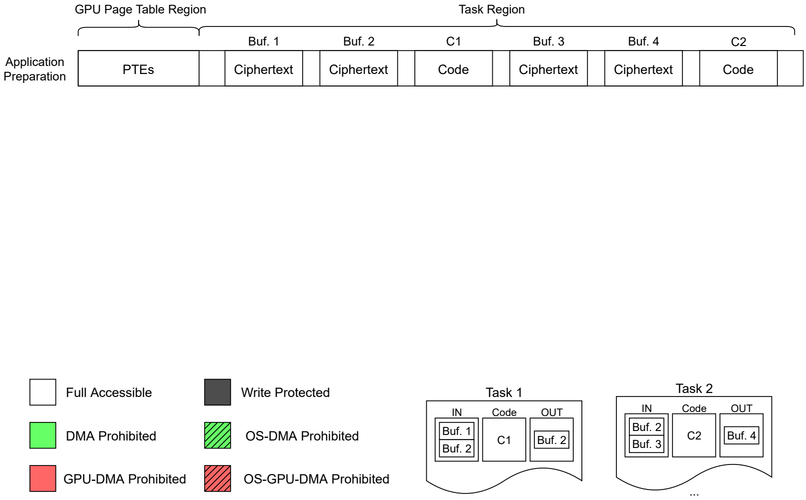


Dynamic and Fine-grained Memory Access Control

- Dynamic access control
  - Apply the protection to different GPU memory content
- Fine-grained protection
  - Combine Stage-2 translation (page-grained) and TZASC (slot-grained)
  - Prohibit the attackers access scattered sensitive data and code
  - Allow the GPU driver access the remaining non-sensitive region to fulfill functionality



Example of Memory Access Control



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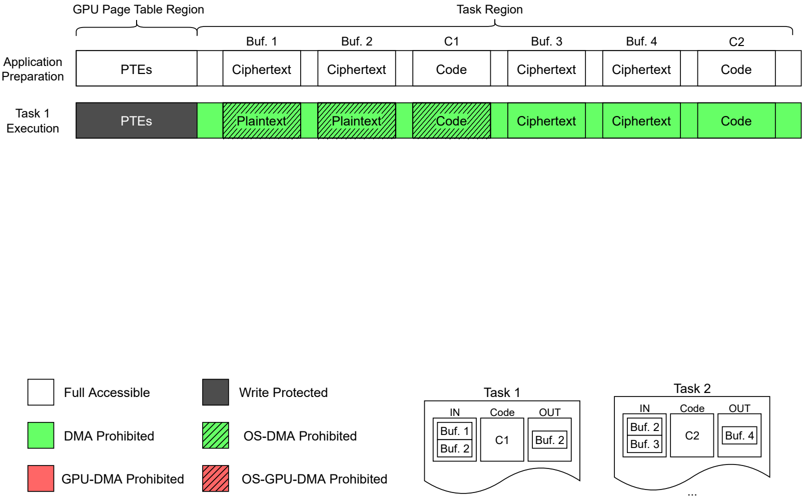

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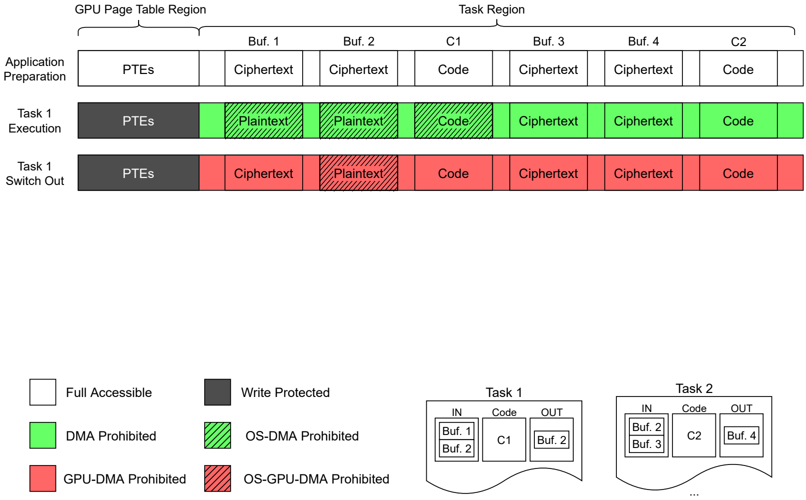

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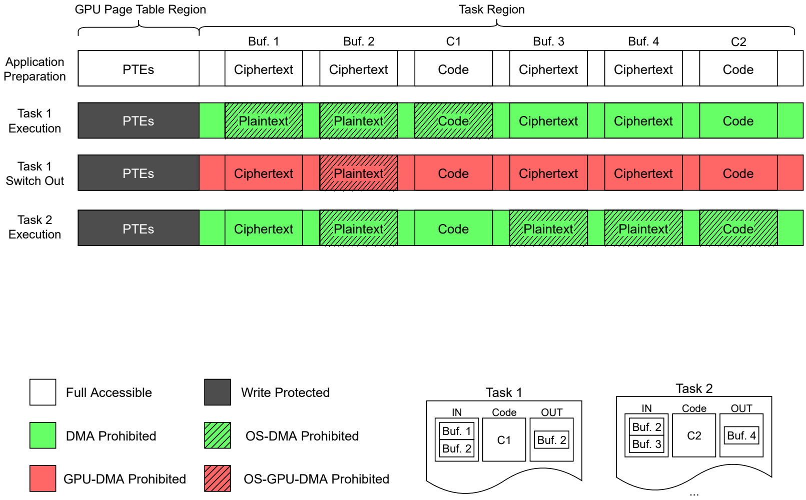

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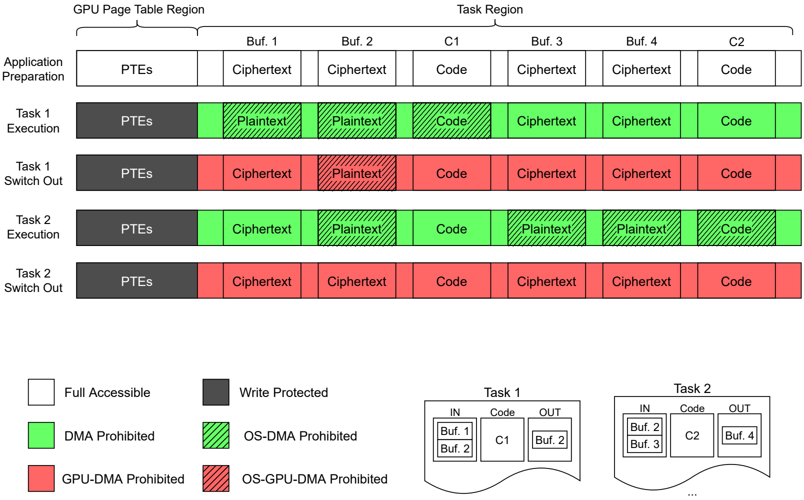

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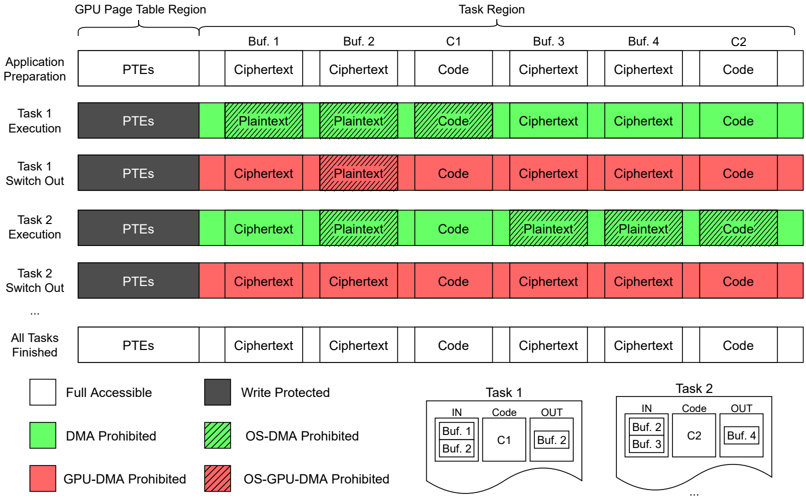
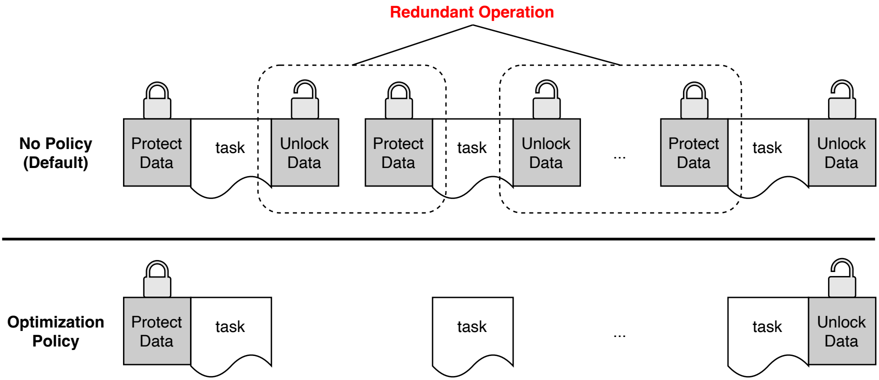


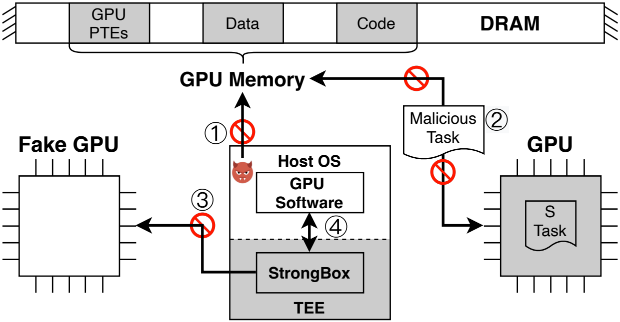
Reduce Performance Overhead

- In multi-task applications, the output of one task can be used as the input of the next task
- Eliminate redundant operations to reduce performance overhead



Evaluation: Security Analysis

- ①: Directly access the sensitive data and code ×
- ②: Attack with malicious tasks ×
- ③: Attack with fake GPU ×
- ④: Attack with compromised GPU software ×



Evaluation: Rodinia Benchmark

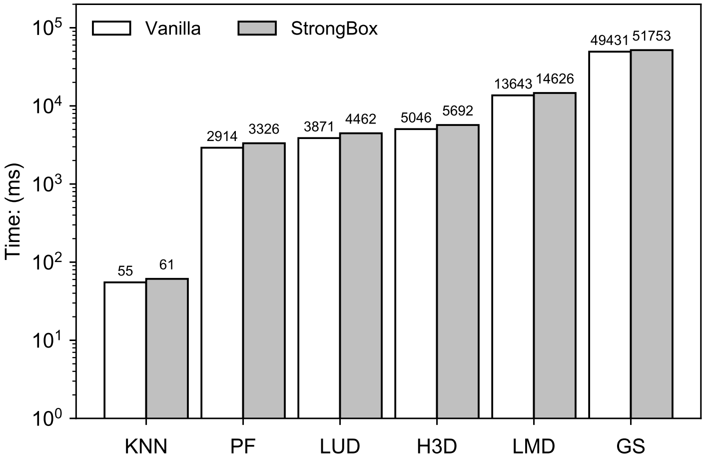


Figure: Evaluation on Rodinia benchmarks (overhead 4.70% - 15.26%).

Evaluation: Optimization

- Optimization on redundant protection

Benchmark		No Optimization		StrongBox	
		TProtect	Total	TProtect	Total
Single Task	KNN	7.31 (11.55%)	63.30	4.86 (7.95%)	61.10
	LMD	1,227.88 (8.27%)	14,854.08	977.46 (6.68%)	14,626.98
Multi Task	PF	3,495.99 (54.50%)	6,414.31	399.48 (12.01%)	3,326.04
	LUD	97,179.42 (95.24%)	102,032.57	338.10 (7.58%)	4,462.57
	H3D	196,457.42 (96.87%)	202,797.82	332.82 (5.85%)	5,692.59
	GS	2,149,460.48 (97.40%)	2,206,881.00	694.52 (1.34%)	51,753.57

Conclusion on StrongBox

- First GPU TEE on Arm Endpoints
  - Ensure secure and isolated computation on Arm endpoint GPUs
  - Entail a minimal TCB to reduce potential attack surface
  - Maintain high compatibility
- Source code
  - https://github.com/Compass-All/CCS22-StrongBox

Thank You