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Cronus: Fault-isolated, Secure and High-performance Heterogeneous Computing for Trusted Execution Environment

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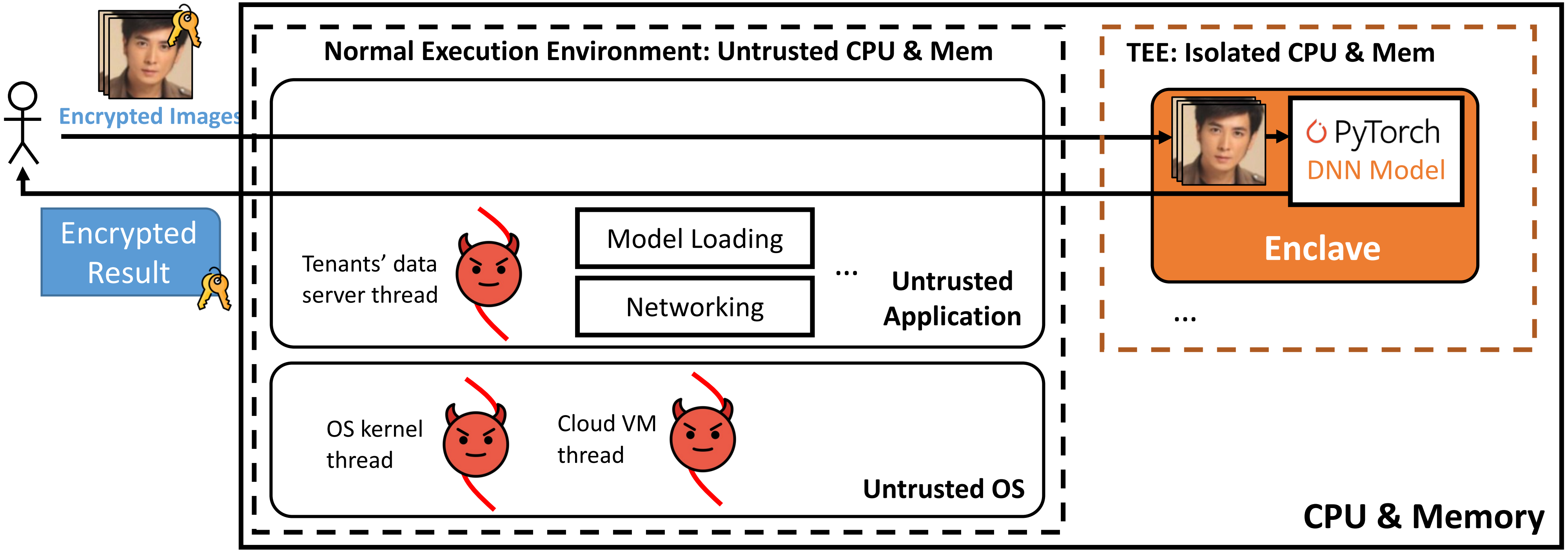
Trusted Execution Environment

➢ Trusted Execution Environment (TEE) is prominent for protecting sensitive user data in clouds and demands high computing capacity

- TEE (e.g., Arm TrustZone, Intel SGX, Keystone on RISC-V) provides an isolated execution environment (**enclave**) that cannot be seen or tampered with, and typically runs only data processing logic within the enclave
- Many AI application (DNN training) demands high computing capacity (e.g., 300TFLOPS) for high performance



Motivating example: Using TEE for protecting face recognition

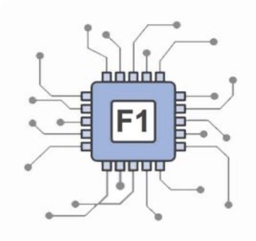
Integrating Accelerators into TEE is Highly Desirable

- More and more user sensitive data are being processed in accelerators for high performance
- Integrating accelerators into TEE is highly desirable for TEE to gain high computing capacity

NVIDIA DGX-2
with 16 A100

2 PetaFlops

DNN Training
DNN Inference



AWS F1 Instance
with 8 FPGA cards

100X Faster than CPU

Real-time Video Processing
Financial Analytics

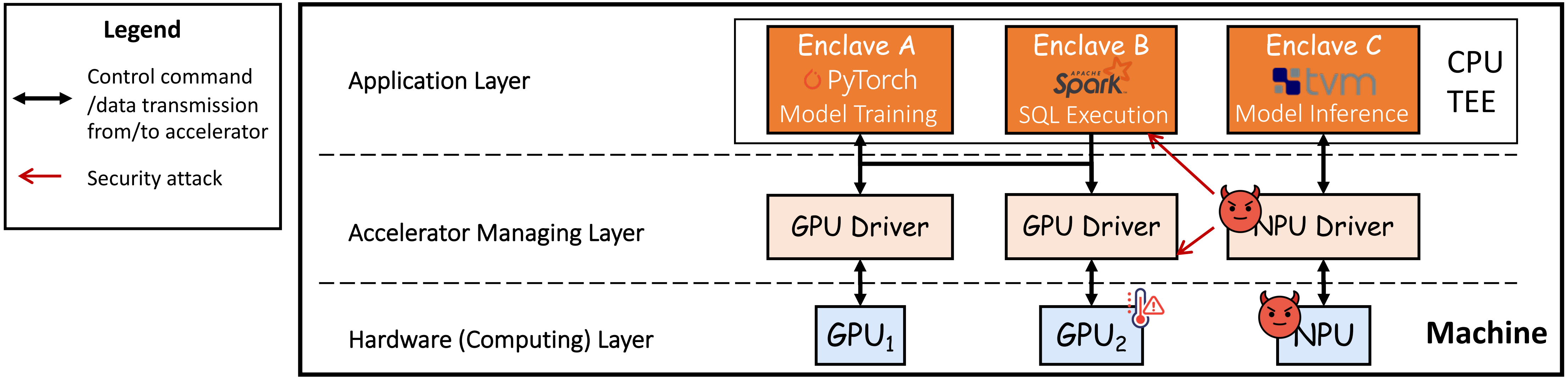
AMD server
with 8 Xilinx Alveo Cards

260 INT8 TOPs

DNN Inference
Video transcoding
Database search & analytics

Requirements for Integrating Accelerators into TEE

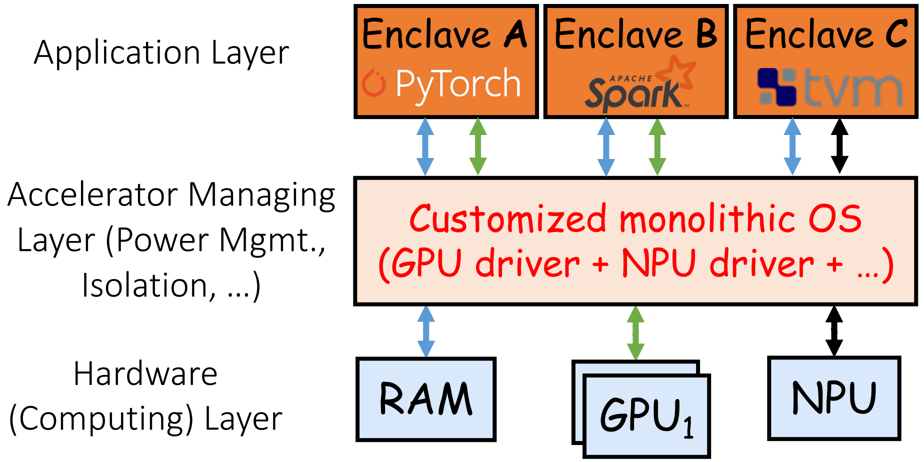
- **Unlike traditional TEE systems with only CPU, our paper takes the first step to identify three special requirements for TEE systems with accelerators**
  - ✓ **Requirement 1: Fault isolation -** an accelerator's failures will not affect other accelerators in the same machine
    - Servers w/ accelerators are 7X more likely to fail due to hardware/driver faults compared with servers w/o accelerators [SC'19]
  - ✓ **Requirement 2: Security isolation -** an accelerator's hardware or its managing software (driver) cannot attack other applications running on other accelerators in the same machine
    - Accelerators/SoC components can contain buggy or malicious code for the adversary to launch attacks [HotOS'21]
  - ✓ **Requirement 3:** A **general** accelerator can be **spatially shared** among enclaves (tenants)
    - Cloud services using GPU without spatial sharing achieve only 10% resource utilization on average [OSDI'20]



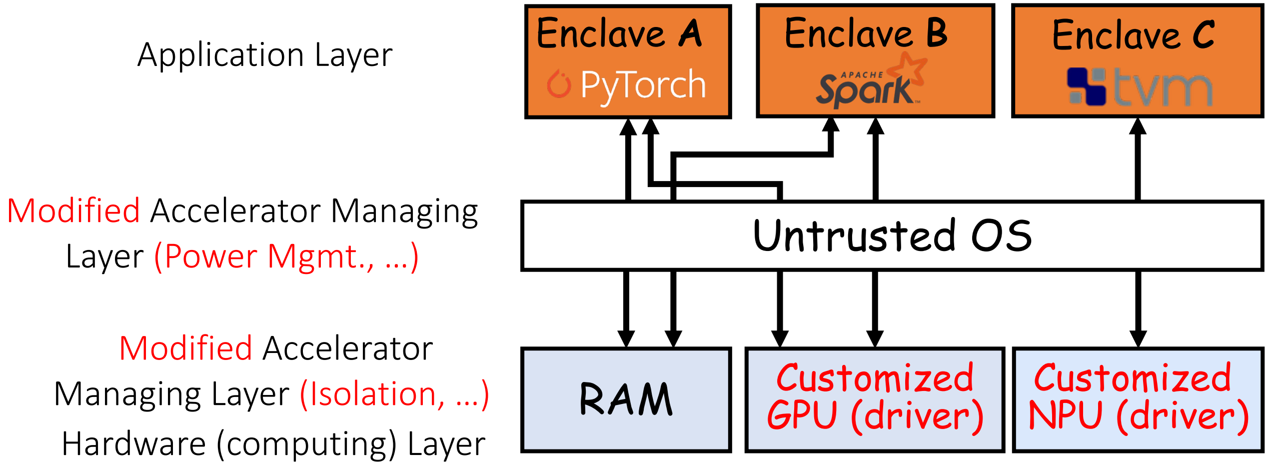
Existing Monolithic Design cannot Meet all Requirements

- Monolithic OS Kernel Approach (SeCloak [MobiSys'18], PROTECTION [NDSS'20], StrongBox [CCS'22]): Integrating all accelerators' drivers into a monolithic trusted (TEE) OS (e.g., Linux)
  - ✓ **Support spatial sharing of general accelerators (R3)**
  - ✗ No fault isolation (violating R1)
  - ✗ No security isolation (violating R2)
- Monolithic Hardware Approach (Gravition [OSDI'18], SGX-FPGA [DAC'21], GuardNN [DAC'22]): Integrating the accelerator's managing logic (driver) into the accelerator
  - ✓ **Enforce fault isolation (R1) and security isolation (R2)**
  - ✗ Cannot support spatial sharing on general (non-modified) accelerators (violating R3)

(1) Monolithic OS kernel approach

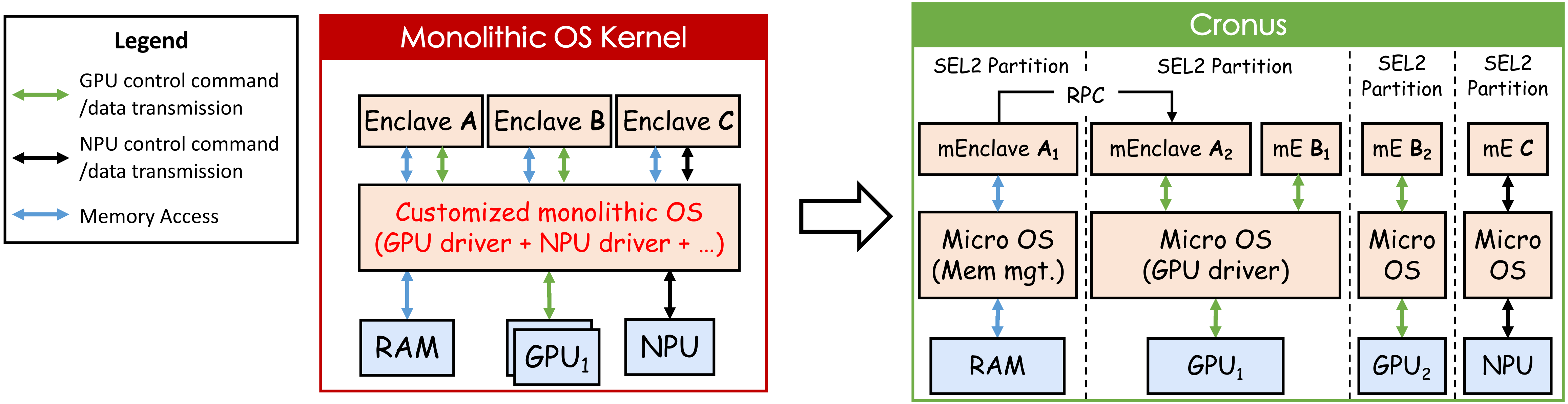


(2) Monolithic hardware approach



Cronus – a Microkernel-inspired OS for Acc. TEE

- A monolithic TEE OS kernel is partitioned into isolated Micro OS (mOS), where each mOS manages only one accelerator; a monolithic enclave is partitioned into mEnclaves running different types of computation
  - ✓ **Security Isolation (R1):** An mOS trusts only its software stack and the managing accelerator
  - ✓ **Fault Isolation (R2):** A failure from mOS or its managing accelerator will not cause failures of other mOSes and accelerators
- Leveraging existing hardware primitives for isolation and spatial sharing **(R3)**
  - Leveraging SecureIO (originally used for protecting sensors) to ensure secure connection between TEEs and accelerators
  - Leveraging hardware isolation techniques (e.g., ARM TrustZone SEL2) to isolate accelerators' software and hardware stack
  - Leveraging accelerators' isolation primitives (e.g., GPU context) to spatially share an accelerator among enclaves with isolation



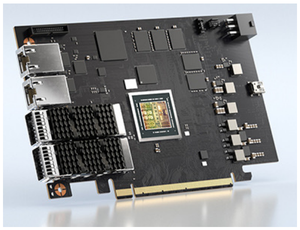
Cronus is a One-fit-all TEE for General Accelerators

- ➢ Cronus is a **one-off developed**, **one-fit-all** TEE for general accelerators to support trusted execution
  - ➢ As long as the machine running Cronus has SecureIO supports (e.g., ARM TrustZone and RISC-V)
- ➢ Cronus does not require time/money-consuming hardware customization for an accelerator
  - ➢ Customizing NVIDIA GPU (H100) with confidentiality supports takes more than two years
  - ➢ Customizing accelerators with trusted execution requires millions of dollars for design and validation [HotOS'18]
- ➢ Accelerator vendors can focus on only improving accelerators' computing performance (throughput/latency)

Nvidia A100

Xilinx U250

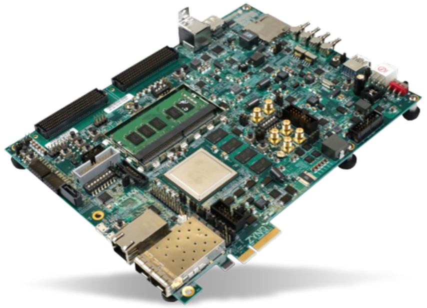
Intel PAC D5005



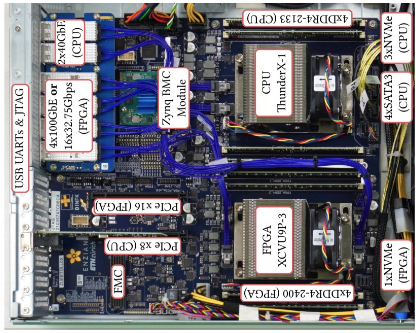
Nvidia BlueField-2 DPU

Cronus Supports Accelerators on SoCs

- A System on a Chip (SoC) integrates more and more accelerator components
  - An SoC can contain more than five FPGA components for accelerating computation or improving I/O performance (Enzian [ASPLOS'22], Coyote [OSDI'20])
  - Different SoC components may be developed by different hardware vendors
- A tenant may leverage its used accelerator of an SoC to attack other tenants using other accelerators on the same SoC
  - Different accelerator components on an SoC can be assigned to different tenants for maximizing utilization
  - A network acceleration component's hardware/software can contain buggy/malicious code suspected of attacks [HotOS'21]
- Cronus is a one-off developed TEE system for general SoCs
- Cronus's security isolation can tackle this attack [future work]
  - As long as the machine running Cronus has SecureIO supporting the accelerators



Xilinx Zynq Ultrascale+



Enzian with many FPGA chips

Cronus Improves Accelerator Utilization with TEE

- Spatial sharing on accelerators significantly improves resource utilization and saves money
  - Public clouds without spatial sharing incur only 10% resource utilization in production (Antman [OSDI'20])
  - Employing spatial sharing of GPU in PaaS services (e.g., DNN training) results in high (e.g., 70%) resource utilization
- PaaS services employ spatial sharing in accelerators but do not have TEE protection
  - AWS's EMR processes sensitive database data using NVIDIA's RAPIDS Accelerator
  - Azure's Cognitive Services processes user sensitive face data using GPU
- Cronus is suitable for securing PaaS services with high resource utilization (low costs)
  - Cronus enables spatial sharing and trusted execution simultaneously on accelerators

aws EMR

Microsoft Cognitive Services

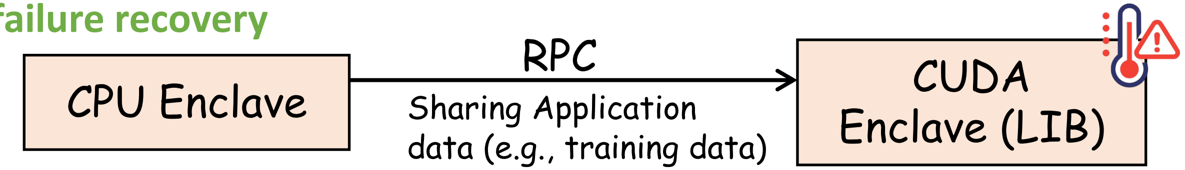
Cronus has Broad Applications

- AI computing and microservices are security-critical and performance-critical
  - AI computing (e.g., DNN training) and microservices (e.g., firewall) process sensitive user data (e.g., face data, social network), and are developed by different parties (e.g., PyTorch by Meta, TensorRT by Google)
  - Microservices demand fast bootup and failover (~seconds)
  - DNN inference on GPT3-2.7B requires 7 TFLOPS for each layer for low inference latency (<1s)
- Cronus's mEnclave/mOS abstraction are lightweight for bootup and failover (<1s)
- Cronus is suitable for running AI computing and microservice [future work]
  - Cronus's fast bootup and failover are favorable for AI computing and microservices
  - Cronus's security isolation can isolate different tenants' AI computing services and microservices within the service suit

PyTorch tvm AWS Lambda Microsoft Azure Automation

Implementation and Evaluation Details

- **Technical Challenges:** Efficient and crash-safe RPCs between mEnclaves managed by different mOSes
  - **Solution: A Streaming RPC (sRPC) protocol that ensures fast communication through secure shared memory, and guarantees safety during failure recovery**



- **Other protocols in Cronus and implementation details:**
  - Remote and local attestation protocols for attesting the integrity of accelerators
  - Automatic partition of a monolithic enclave into multiple mEnclaves
  - Built Cronus on ARM TrustZone and implemented both DNN training and inference (i.e., PyTorch and TVM) on Cronus

arm TRUSTZONE PyTorch tvm

- **Baseline frameworks:**
  - TrustZone (Optee) and HIX-TrustZone [ASPLOS'19]
- **Evaluation setup:**
  - Hardware: 4 NVIDIA 2080Ti GPU and a simulated TVM VTA device
  - Benchmarks: two microbenchmarks (Rodinia and VTA Bench), and two real-world applications (DNN training and inference) on 5 DNN models (LeNet, ResNet, VGG, DenseNet, and Yolo) using the MNIST and ImageNet dataset

4 X  1 X 

VTA FSIM

Evaluation Questions

- What is the **end-to-end performance** of Cronus in microbenchmarks and real-world applications?
- What is the performance gain of **spatial sharing**?
- How fast can Cronus **recover from faults**?
- Can Cronus support multiple accelerators?

End-to-end Performance

- We compared the latency of Rodinia benchmark (Fig. 1) and real-world DNN training (Fig. 2); we also compared the throughput of VTA-bench benchmark (Fig. 3a) and latency of DNN inference (Fig. 3b)

Figure 1

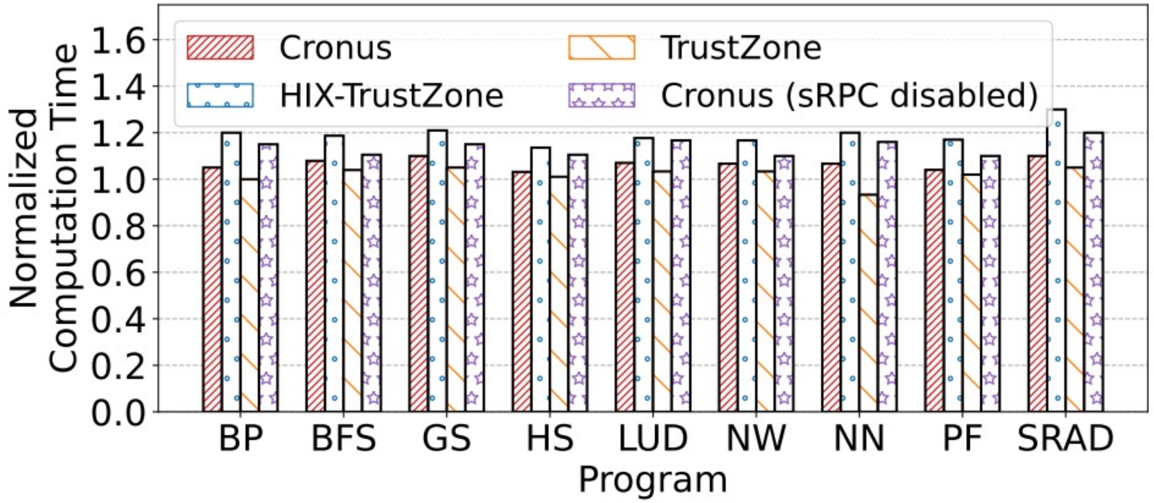


Figure 2

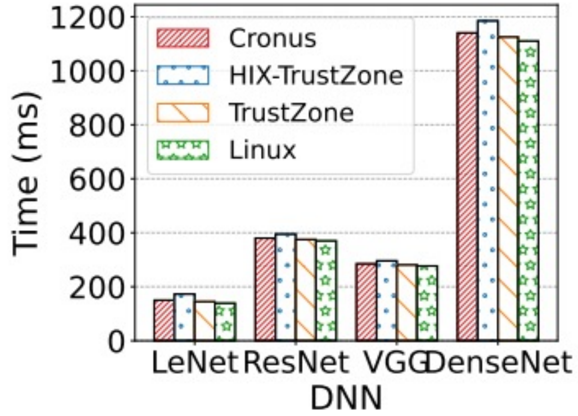
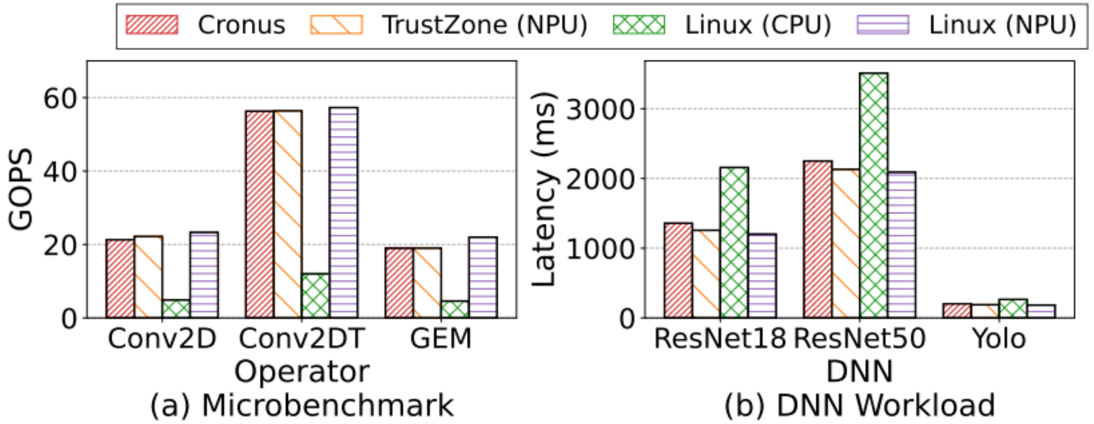


Figure 3



- ✓ Compared with **native (unprotected) computation** (i.e., Linux in the figure), Cronus incurs **less than 7% performance overhead** for both microbenchmarks and real-world DNN training/inference; Cronus's performance is close to the monolithic OS kernel approach and is faster than HIX-TrustZone

Spatial Sharing and Failure Recovery

- We ran concurrent enclaves sharing accelerator temporally and spatially in Cronus (Fig. 4a)
- We ran two tasks (A and B) at two different mOSes and made Task A fail deliberately (Fig. 4b)

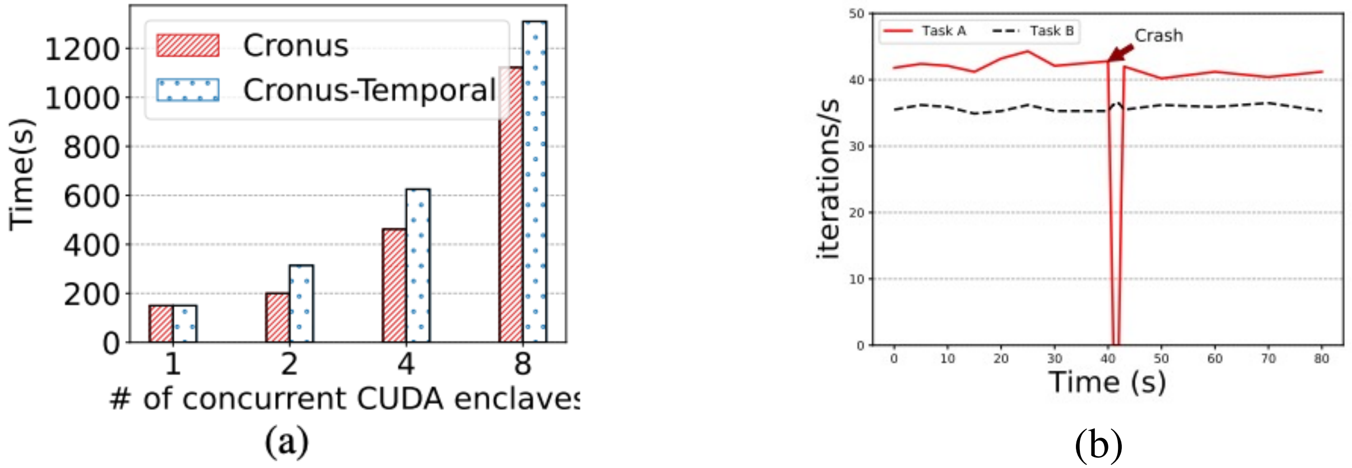


Figure 4

- **Figure 4a:** Compared with Cronus without spatial sharing, **Cronus with spatial sharing decreased up to 43% of the total computation time**.
- **Figure 4b**: Cronus achieves **fault isolation** and **fast failure recovery**: recovering from faults with hundreds of milliseconds.

Conclusion

- In this paper, we design Cronus with a new MicroTEE architecture that enables fault-isolated, high-performance and secure heterogeneous computing
  - The first TEE system that requires only one-off development for enabling trusted execution within general accelerators with security isolation, fault isolation and spatial sharing on accelerators among tenants
- Cronus's future work is broad:
  - Cronus can support distributed workloads on different machines
  - Cronus can be integrated with other TEE hardware (e.g., Keystone [Eurosys'20])
  - Cronus can support diverse accelerators on SoCs and new applications (e.g., microservices)
- Cronus's artifact is available on https://github.com/hku-systems/cronus