Formal Verification of an Open-Source Secure Enclave

Pranav Gaddamadugu
pranavsaig@berkeley.edu

Problem Definition

- **Verifying hyperproperties about the Keystone Security monitor**
- **Secure Remote Execution (SRE) : a 2-safety hyperproperty that can be decomposed into guarantees on:**
    - **Integrity**
    - **Confidentiality**
    - **Measurement**

- **Previous models assume a fixed implementation of a TEE, our work allows for easy compositional verification of various hardware components and Keystone plugins**

Prior Work

- **‘A Formal Foundation for Secure Remote Execution of Enclaves’**
  - **Subramanyan, Sinha, et al. at CCS ‘17**

- **Introduces a model of a Trusted Abstract Platform (TAP)**

- **Defines three separate adversary models:**
  - **M, MC, MCP**

- **Proves SRE for Intel SGX and MIT Sanctum**

Proof Methodology

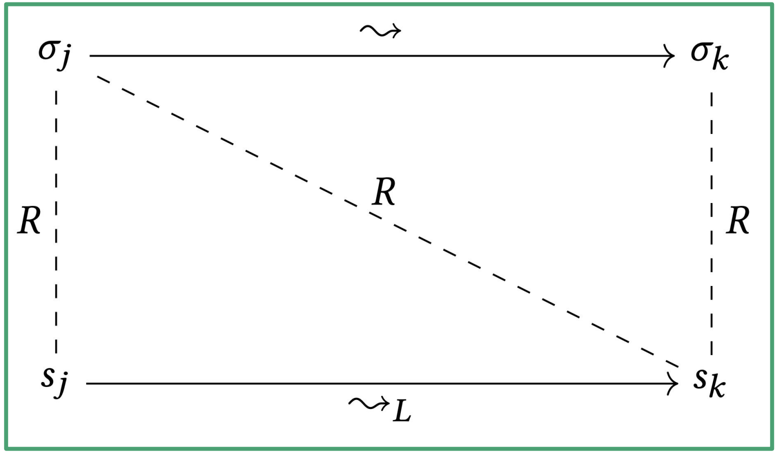
- **Show that TAP guarantees SRE under the three adversary models**
- **Show that models of SGX and Sanctum are refinements of the TAP model under specific adversarial parameters**

$$\sigma_i, \sigma_j \in \textbf{States of TAP Model}$$

$$s_i, s_j \in \textbf{States of Keystone Model}$$

$$\leadsto, \leadsto_L \; := \textbf{Transition Relations}$$

$$R \; := \textbf{Refinement Relation}$$



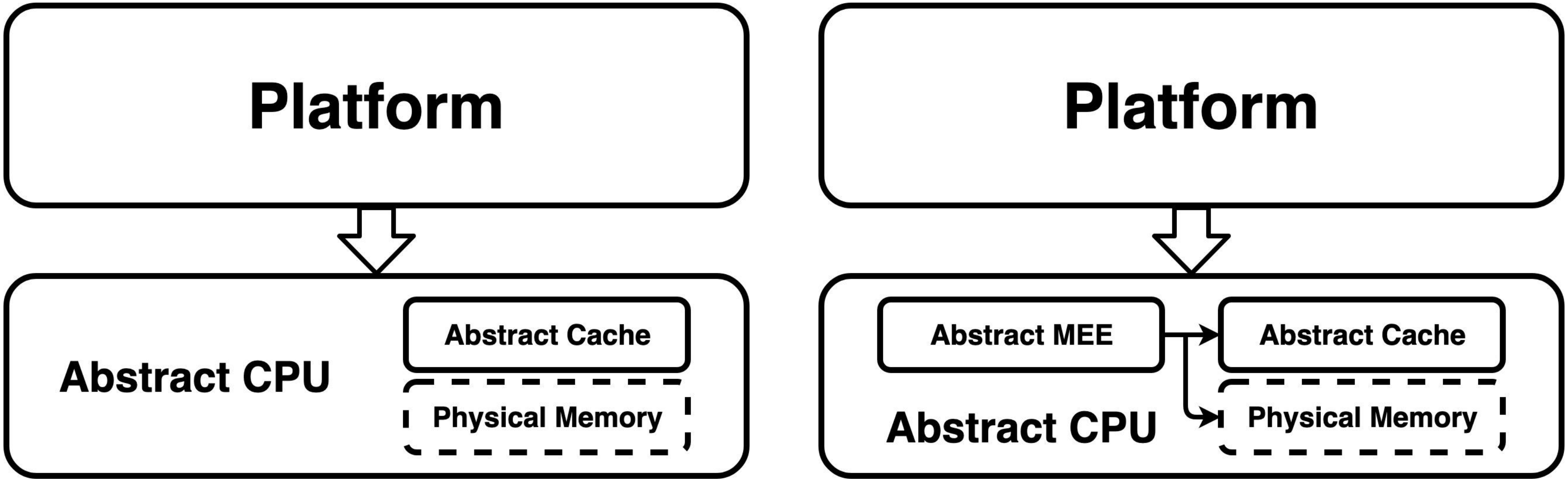
Redesigning the Model for Modular Verification

- **Translated TAP model from Boogie to UCLID5**
    - **Toolkit for formal specification and verification of compositional systems**
    - **Suited for reasoning about the composition of Keystone and additional plugins**
    - **Future work on automatic invariant generation**
- **Extensions to UCLID5**
    - **Support for modular procedure-level verification, additional features for easier programmability, modifications to proof techniques**

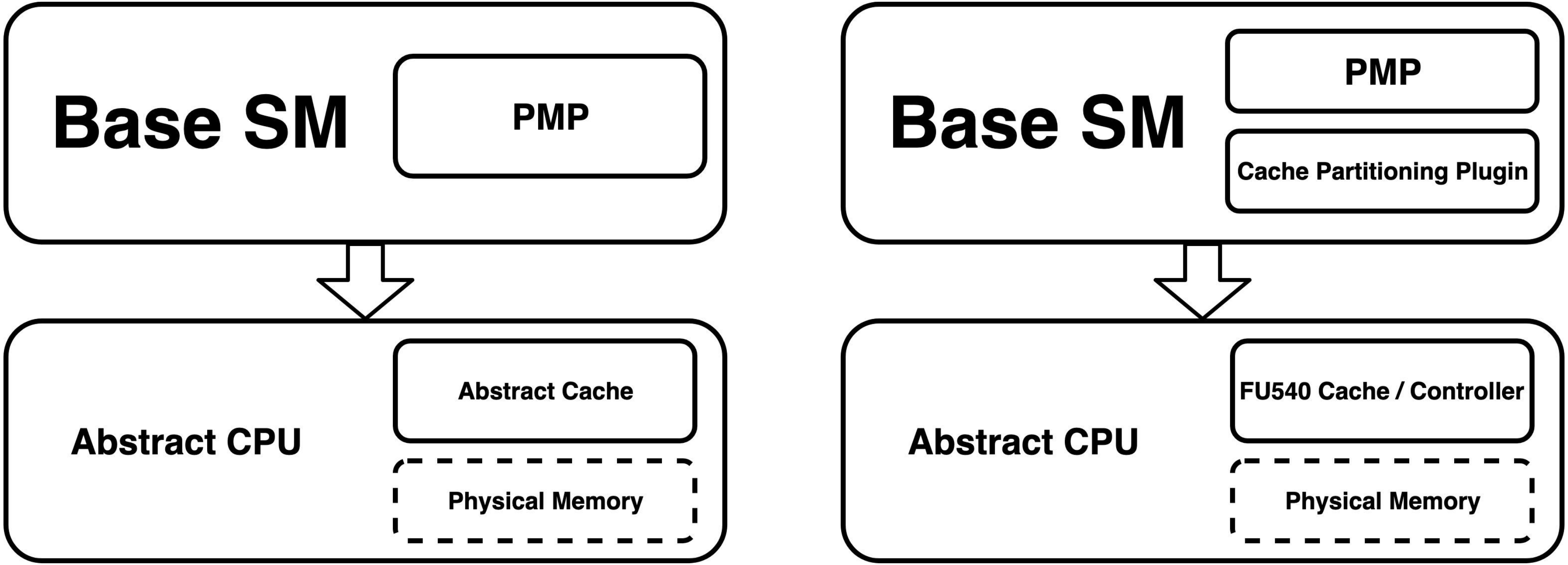
Extending the Model

- **Extension of the adversary model to physical attackers**
    - **Enclave platforms also provide guarantees ‘physical attackers’**
    - **We define a physical attackers as ‘an adversary with the capability to observe or tamper with any signal leaving the chip package’**
    - **Involves the addition of an abstract memory encryption engine, as well as a semantic embedding of ciphertext and plaintext**

TAP Model Design



Keystone Model and Augmentation



Future Work

- **Write the Abstract MEE model and augment proofs to show that TAP+MEE provides SRE under a physical adversary**
  - **Refinement proof (once Memory Encryption is added to Keystone)**

- **Exploring automatic invariant generation**
  - **Implementing a native SyGuS solver in UCLID5**
  - **Generating invariants based off of TAP and Keystone model sketches**

Thank you! Any questions?