Trusted Execution Environments

Chapter 4

[1] J. Szefer, "Principles of secure processor architecture design," *Synth. Lect. Comput. Archit.*, vol. 13, no. 3, pp. 1–173, 2018.

Protecting Software Within Trusted Execution Environment (TEE)

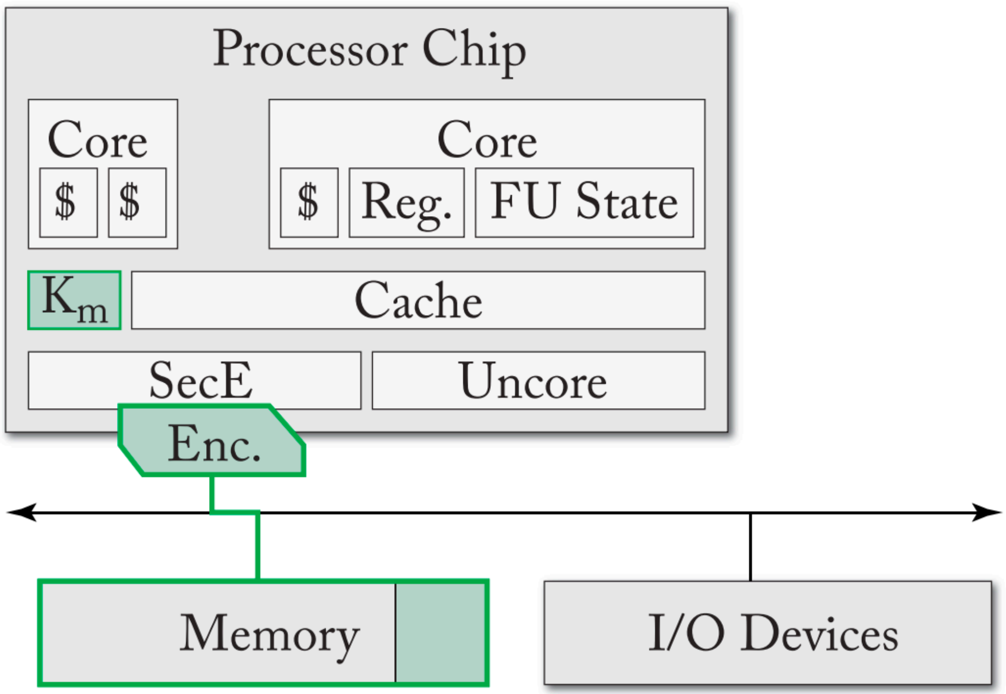
- TCB is responsible for creating TEE
- Software within TEE is protected against a range of software and hardware attacks (range is a function of threats model of SP, but TEE is executed in GPP not SP!!))
- Approximations
  - Protect Trusted Software Modules (TSM) or Enclaves
  - Protect VMs or containers
- All software within TEE is given the same set of protections (apart from the privilege levels differentiation in VMs)
- Users should be carefully about what code runs inside the TEE, especially external code

Protections offered by the TCB to the TEE

- Confidentiality and integrity from potential attacks by other sw and hw outside the TCB
- No protection against malicious TCB or malicious TEE
- Multiple TEE/Enclaves running simultaneously is possible (e.g., from different users): TCB should prevent cross TEE attacks

Enforcing Confidentiality Through Encryption

- Off-chip access untrusted by default → Hardware cyphering of the memory content (with a ephemeral key)

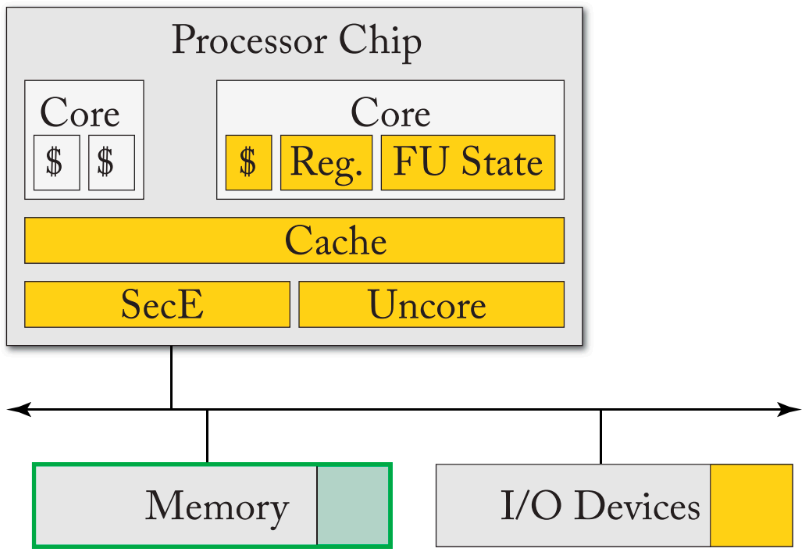


Enforcing Confidentiality Through Isolation

- Page tables of Extended Page tables primary objective is isolation
- But, if Hypervisor/OS is untrusted the mechanism is not trusted
- If TCB should enforce isolation additional mechanism should be provided (e.g., Adding another level of translation) or architected as dedicated memory management in TCB that replace the table page based mechanism

Enforcing Confidentially Through State Flush

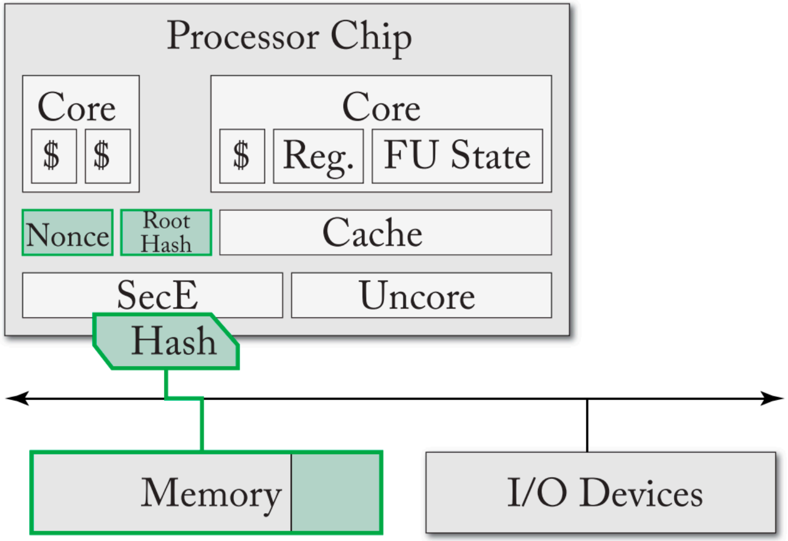
- Non architectural-state should be flushed once used by TEE
- Any register or execution dependent piece of information of the TEE should be deleted once the untrusted software continues after TEE
  - Speculative engines, cache contains, I/O traces, ….



Yellow == has to be flushed

Enforcing Integrity Through Cryptographic Hashing

- Add integrity to data going off-chip
- Event with data encrypted, some-one can change system behavior with out decrypting the data (e.g., replay attacks)
  - Add a nonce to prevent it.



Examples of Architectures for Protecting Enclaves

- Cell Broadband Engine and Processor Vault
  - Reserve a Synergistic Processing Element (SPE) for TEE.
  - SPE uses dedicated memory (is not shared across SPEs by design)
  - Uses public-key cryptography to be sent to processor vault and execute only signed code
- ARM TrustZone
  - Two separate worlds to execute trusted (secure OS) and untrusted (normal OS)
  - Memory and buses are tagged, allowing that some parts of the SoC are available to secure OS
- Intel SGX
  - Protection for trusted secure modules (called Enclaves)
  - Off-chip memory is protected via encryption
  - Was weak against side-channel (encryption keys can be accessed)
  - Now can be protected via Resource Director (e.g., cache partitioning)

Limitations of TCBs and TEEs

- Vulnerabilities in TCBs
  - Current susceptible to TCB-resident attacks: SMM-based and ME-based rootkits
  - Unable to get-rid of it (from the administrator perspective)
  - Once TCB is compromised, TEE is no longer secure: e.g., foreshadow
- Opaque TCB execution
  - Often there is no means for auditing the code executed by TCB
  - Proprietary code (usually trade secret) with infrequent updates and signed
  - Code running TEE should be fingerprinted continuously (i.e. attestation via hashing or performance signature)
  - Its not the case: in closed hardware it's a closed box != open hw (riscv) **Keystone-enclaves**
- TEE-Based Attacks
  - Use the TEE as an attack vector: e.g., SGX-Bomb, plundervolt
- TEE Code Bloat
  - Not a good idea to increase the size of the code inside the TEE (e.g., run containers inside SGX or an Hypervisor running inside SMM are proposed for flexibility).