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Outline

• Problem Statement
• Attack Surface and Overview
• Programming environment
  – System programming view
  – Day in the life of an enclave
• SGX Access Control & Off Chip protections
• Attestation and Sealing
• Developing with SGX
• Summary
The Basic Issue: Why Aren’t Compute Devices Trustworthy?

Protected Mode (rings) protects OS from apps ...

... and apps from each other ...

... UNTIL a malicious app exploits a flaw to gain full privileges and then tampers with the OS or other apps.

Apps not protected from privileged code attacks
Reduced attack surface with SGX

Application gains ability to defend its own secrets
- Smallest attack surface (App + processor)
- Malware that subverts OS/VMM, BIOS, Drivers etc. cannot steal app secrets

Familiar development/debug
- Single application environment
- Build on existing ecosystem expertise

Familiar deployment model
- Platform integration not a bottleneck to deployment of trusted apps

Scalable security within mainstream environment
SGX Programming Environment

Trusted execution environment embedded in a process

With its own code and data
Provide Confidentiality
Provide integrity
With controlled entry points
Supporting multiple threads
With full access to app memory
Life Cycle of An Enclave

Virtual Addr Space

Code/Data
Code/Data

Physical Addr Space

Plaintext Code/Data
Plaintext Code/Data
System Memory
Enclave Page Cache
SECS

ECREATE (Range)
EADD (Copy Page)
EEXTEND
EINIT
EENTER
EEXIT
EREMOVE

MRENCLAVE

Build
SGX Access Control

Linear Address

Traditional IA Page Table Checks

Physical Address

Enclave Access?

Yes

Address in EPC?

No

Enclave Access

No

Signal Fault

Yes

Check EPCM

No

Checks Pass?

Yes

Replace Address With Abort Page

Non-Enclave Access

Address in EPC?

Yes

Allow Memory Access

No
Protection vs. Memory Snooping Attacks

1. Security perimeter is the CPU package boundary
2. Data and code unencrypted inside CPU package
3. Data and code outside CPU package is encrypted and/or integrity checked
4. External memory reads and bus snoops see only encrypted data

Non-Enclave Access

Security perimeter is the CPU package boundary
Data and code unencrypted inside CPU package
Data and code outside CPU package is encrypted and/or integrity checked
External memory reads and bus snoops see only encrypted data
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The Challenge – Provisioning Secrets to the Enclave

• An enclave is in the clear before instantiation
  – Sections of code and data could be encrypted, but their decryption key can’t be pre-installed

• Secrets come from outside the enclave
  – Keys
  – Passwords
  – Sensitive data

• The enclave must be able to convince a 3rd party that it’s trustworthy and can be provisioned with the secrets

• Subsequent runs should be able to use the secrets that have already been provisioned
Trustworthiness

• A service provider should vet the enclave’s Trusted Computing Base (TCB) before it should trust it and provide secrets to it
  - The enclave’s software
  - The CPU’s hardware & firmware

• Intel® SGX provides the means for an enclave to securely prove to a 3rd party:
  - What software is running inside the enclave
  - Which execution environment the enclave is running at
  - Which Sealing Identity will be used by the enclave
  - What’s the CPU’s security level
Attestation – Software TCB

• When building an enclave, Intel® SGX generates a cryptographic log of all the build activities
  - Content: Code, Data, Stack, Heap
  - Location of each page within the enclave
  - Security flags being used

• MRENCLAVE ("Enclave Identity") is a 256-bit digest of the log
  - Represents the enclave’s software TCB

• A software TCB verifier should:
  - Securely obtain the enclave’s software TCB
  - Securely obtain the expected enclave’s software TCB
  - Compare the two values
Local Attestation

- “Local attestation”: The process by which one enclave attests its TCB to another enclave on the same platform.
- Using Intel® SGX’s EREPORT and EGETKEY instructions:
  - EREPORT generates a cryptographic REPORT that binds MRENCLAVE to the target enclave’s REPORT KEY.
  - EGETKEY provides the REPORT KEY to verify the REPORT.

<table>
<thead>
<tr>
<th>TCB component</th>
<th>Attestation</th>
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</thead>
<tbody>
<tr>
<td>CPU Firmware &amp; hardware</td>
<td>Symmetric - CPU REPORT KEY</td>
</tr>
<tr>
<td>Software</td>
<td>MRENCLAVE</td>
</tr>
</tbody>
</table>
Remote Attestation

• “Remote attestation”: The process by which one enclave attests its TCB to another entity outside of the platform

• Intel® SGX Extends Local attestation by allowing a Quoting Enclave (QE) to use Intel® EPID to create a QUOTE out of a REPORT
  - Intel® EPID is a group signature scheme

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</table>
1. Verifying enclave sends its MRENCLAVE to reporting enclave
2. Reporting enclave creates a cryptographic REPORT that includes its MRENCLAVE
3. Verifying enclave obtains its REPORT key and verifies the authenticity of the REPORT
Remote Attestation - Flow

1. Verifying enclave becomes the Quoting Enclave.
2. After verifying the REPORT the, QE signs the REPORT with the EPID private key and converts it into a QUOTE.
3. Remote platform verifies the QUOTE with the EPID public key and verifies MRENCLAVE against the expected value.
Sealing Authority

• Every enclave has an Enclave Certificate (SIGSTRUCT) which is signed by a Sealing Authority
  - Typically the enclave writer
  - SIGSTRUCT includes:
    - Enclave’s Identity (represented by MRENCLAVE)
    - Sealing Authority’s public key (represented by MRSIGNER)

• EINIT verifies the signature over SIGSTRUCT prior to enclave initialization
Sealing

• “Sealing”: Cryptographically protecting data when it leaves the enclave.

• Enclaves use EGETKEY to retrieve an enclave, platform persistent key and encrypts the data

• EGETKEY uses a combination of enclave attributes and platform unique key to generate keys
  - Enclave Sealing Authority
  - Enclave Product ID
  - Enclave Product Security Version Number (SVN)
Example: Secure Transaction

1. Enclave built & measured against ISV’s signed certificate
2. Enclave calls EREPORT to obtain a REPORT that includes enclave specific data (ephemeral key)
3. REPORT & user data sent to Quoting Enclave who signs the REPORT with an EPID private key
4. QUOTE sent to server & verified
5. Ephemeral key used to create a trusted channel between enclave and remote server
6. Secret provisioned to enclave
7. Enclave calls EGETKEY to obtain the SEAL KEY
8. Secret is encrypted using SEAL KEY & stored for future use
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Intel® SGX Software Development

Windows DLL / Enclave

- SGX SDK Libraries
- Glue Code

Architectural Enclaves

Intel SGX enabled CPU

Application

- App Code
  - Processing Component
    - Glue Code
    - SGX SDK Libraries

- SGX SDK Tools

- Software Developer decides which components should execute within an enclave
- Development Environment allows the Developer to quickly develop enclave enabled binaries
- Including support for common software libraries, exporting interfaces, and support for provisioning
SGX Technical Summary

• Provides any application the ability to keep a secret
  • Provide capability using new processor instructions
  • Application can support multiple enclaves

• Provides integrity and confidentiality
  • Resists hardware attacks
  • Prevent software access, including privileged software and SMM

• Applications run within OS environment
  • Low learning curve for application developers
  • Open to all developers

• Resources managed by system software
Links

Joint research poster session: http://sigops.org/sosp/sosp13/


HASP Workshop: https://sites.google.com/site/haspworkshop2013/workshop-program
Intel Labs: Security and Privacy Research

Looking for researchers with the following skills:

- Cloud Computing
- Operating Systems
- Virtualization
- BIOS and Firmware
- Mobile Security
- Machine Learning Algorithms

Contact Jennifer.M.Muir@intel.com
Thank You
Backup
SGX Paging Introduction

Requirement:
• Remove an EPC page and place into unprotected memory. Later restore it.
• Page must maintain same security properties (confidentiality, anti-replay, and integrity) when restored

Instructions:
• EWB: Evict EPC page to main memory with cryptographic protections
• ELDB/ELDU: Load page from main memory to EPC with cryptographic protections
• EPA: Allocate an EPC page for holding versions
• EBLOCK: Declare an EPC page ready for eviction
• ETRACK: Ensure address translations have been cleared
Page-out Example

EWB Parameters:
• Pointer to EPC page that needs to be paged out
• Pointer to empty version slot
• Pointers outside EPC location

EWB Operation
• Remove page from the EPC
• Populate version slot
• Write encrypted version to outside
• Write meta-data, PCMD

All pages, including SECS and Version Array can be paged out
**Page-in Example**

**ELD Parameters:**
- Encrypted page
- Free EPC page
- SECS (for an enclave page)
- Populated version slot

**ELD Operation**
- Verify and decrypt the page using version
- Populate the EPC slot
- Make back-pointer connection (if applicable)
- Free-up version slot