Leaking Uninitialized Secure Enclave Memory via Structure Padding
(Extended Abstract)
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Abstract
Intel Software Guard Extensions (SGX) aims to provide an isolated execution environment, known as an enclave, for a user-level process to maximize its confidentiality and integrity. In this paper, we study how uninitialized data inside a secure enclave can be leaked via structure padding. We found that, during ECALL and OCALL, proxy functions that are automatically generated by the Intel SGX Software Development Kit (SDK) fully copy structure variables from an enclave to the normal memory to return the result of an ECALL function and to pass input parameters to an OCALL function. If the structure variables contain padding bytes, uninitialized enclave memory, which might contain confidential data like a private key, can be copied to the normal memory through the padding bytes. We also consider potential countermeasures against these security threats.

1 Introduction
Intel Software Guard Extensions (SGX) is a hardware-based trusted execution environment (TEE) technology that allows a user-level process to have an isolated execution environment, known as an enclave. Even system software, such as operating system and hypervisor, cannot access enclave memory, known as the enclave page cache (EPC), because Intel processor’s memory management unit (MMU) prohibits such attempts at hardware level. Further, physical attacks, such as a cold-boot attack, are not possible because every data stored in EPC banks is encrypted by the memory encryption engine (MEE) before it leaves from the processor package.

Intel SGX has two restricted interfaces to allow SGX enclaves to interact with non-enclave applications: ECALL and OCALL. Non-enclave applications should use the ECALL interfaces to execute trusted functions within enclaves. They cannot call any other enclave functions without corresponding ECALL interfaces. Also, SGX enclaves should use the OCALL interfaces to execute untrusted functions (e.g., system calls). Their any other attempts to execute untrusted functions (e.g., jumping into non-enclave code) result in faults.

Intel SGX Software Development Kit (SDK) is shipped with a tool called Edger8r [1] that automatically and securely generated code for ECALL and OCALL interfaces. Although SGX enclaves can access both EPCs and normal memory, non-enclave applications can only access the normal memory. Thus, all input and output values for the ECALL and OCALL interfaces between them need to be stored in the normal memory first and then copied to the memory of callee and caller later. The Edger8r tool creates all such edge routines automatically. It decodes the user-provided enclave definition language (EDL) files specifying ECALL and OCALL interfaces, and generates proxy functions to securely exchange input and output parameters for the interfaces. That is, the proxy functions copy data between enclaves and non-enclave applications as well as check the sanity of input or output data (e.g., they check the address range if a parameter is a pointer).

The proxy functions generated by Edger8r need to be secure because they are designed to copy certain data (i.e., input values to an OCALL interface and a return value of an ECALL interface) from the enclave to the normal memory. If the proxy functions have security problems, they might be exploited to extract sensitive data from the enclave that is neither input to OCALL nor output of ECALL, which results in incomplete confidentiality of Intel SGX.

In this paper, we explore the security problems of the proxy functions generated by the Edger8r tool for the ECALL and OCALL interfaces of Intel SGX. More specifically, we focus on the possibility of data leakage because of structure padding. When handling structure data types (e.g., struct in C), modern compilers intentionally align their members by putting some padding bytes, perhaps to reduce memory/cache access time [4]. These padding bytes, however, are usually ignored when initializing structure variables such that
typedef struct {
  uint64_t val1;
  uint8_t val2;
  /* 7-byte padding */
  uint64_t val3;
} test_struct;

Figure 1: Structure with padding (in x86_64). The total size of this structure is 24 bytes because of the padding.

they can contain uninitialized memory values [2]. If the proxy functions generated by Edger8r do not consider this security problem, uninitialized enclave data can be leaked through padding.

We confirm that when the data types of input values to an OCALL interface or a return value of an ECALL interface are structures containing padding bytes, uninitialized enclave data is copied to the normal memory via the padding bytes during OCALL or ECALL by the proxy functions. This is because the proxy functions are generated to copy the entire memory of a structure variable, not to copy its individual members. That is, they do not perform deep copy.

We expect that the impact of this data leakage problem through uninitialized structure padding is similar to that of the Heartbleed vulnerability. As Heartbleed does, this security problem allows us to leak a number of bytes from secure enclaves. More importantly, all data within secure enclaves is supposed to be in plaintext. This is because the secure enclaves, by design, ensure the data confidentiality and isolation such that we do not need to redundantly encrypt the data. That is, the secure enclaves likely manage the plaintext of sensitive information (e.g., RSA private key, password, and biometric information) in their memory, which can be leaked through the uninitialized structure padding. Therefore, when developing SGX applications, developers should carefully consider whether their applications can suffer from this critical security problem.

Possible countermeasures to this uninitialized padding problem are as follows: (1) perform per-member deep copy during ECALL and OCALL, (2) use the #pragma pack directive to avoid padding, (3) enforce memset to fully initialize structure variables, and (4) adopt advanced structure initialization techniques [2, 3].

2 Background: Structure with Padding

Figure 1 shows an example C structure, test_struct, which contains padding bytes used for aligning its member variables. The test_struct structure has three member variables, val1, val2 and val3, in which the first and third member variables' sizes are eight bytes whereas the second member variable’s size is one byte. If there is no #pragma pack directive, modern C compilers will put seven-byte padding between val2 and val3 to align all of the three member variables for memory access efficiency [4], so that the size of test_struct will be 24 bytes. That is, if we have a variable ts whose type is test_struct, initializing its individual members (i.e., ts.val1=0, ts.val2=0, ts.val3=0) is not enough to fully clean up this variable such that its padding bytes can contain uninitialized data. Instead, we have to explicitly initialize padding bytes by using memset(&ts, 0, sizeof(test_struct)).

3 Uninitialized Enclave Memory Leakage via Padding

In this section, we explain how uninitialized enclave memory can be leaked through structure padding. We focus on the following two cases: (1) ECALL returning a structure variable with padding (§3.1) and (2) OCALL having an input structure variable with padding (§3.2).

We used Intel SGX SDK for Linux version 1.9 and a real system with Core i7-6700K to test the explained problems and confirmed that all the problems really existed.

3.1 ECALL Returning Padded Structure

We explain how ECALL functions returning a structure variable can leak sensitive enclave data through

```c
typedef struct {
  char encrypted_input[
  size_t input_size];
} test_struct;
```

```c
test_struct ecall_test_struct(char *encrypted_input,
  size_t input_size) {
  char *input;
  test_struct *ret;
  input = (char*)malloc(sizeof(char) * input_size);
  decrypt_fun(encrypted_input, input, input_size);
  /* Do something */
  ret = (test_struct*)malloc(sizeof(test_struct));
  /* Do something */
  ret->val1 = ...;
  ret->val2 = ...;
  ret->val3 = ...;
  return *ret;
}
```

Figure 2: ECALL returning test_struct. The padding inside test_struct is not initialized.
padding. Figure 2 shows an example ECALL function that returns a padded structure, test_struct, explained in §2. This function receives two input values, performs some computations with them, and eventually returns test_struct. Since this function does not clear the padding bytes of test_struct, they can contain uninitialized enclave data and be returned to a proxy function generated by the Edger8r tool.

Figure 3 represents a proxy function for the ecall_test_struct function, which is automatically generated by Edger8r to be executed inside an enclave. As shown in Line 16, this proxy function just fully copies the return value of ecall_test_struct into ms->ms_retval, a non-enclave marshalled structure for storing input and out values for this ECALL function, instead of individually copying its members to pms->ms_retval.

Therefore, we conclude that an ECALL proxy function can copy uninitialized padding bytes from an enclave to a non-enclave memory region when returning a structure variable, which can potentially contain uninitialized sensitive enclave data.

3.2 OCALL Receiving Padded Structure as Input

Next, we explain how OCALL functions receiving a structure variable as input can leak sensitive data through padding. Figure 4 shows an example OCALL function, ocall_test_struct, that receives a padded structure, test_struct, as input. This function tries to access every single byte of a test_struct variable, ts, implying that if this input struct contains padding with sensitive enclave data, this function can access them it also.

Figure 5 shows a proxy function of ocall_test_struct that will be executed inside an enclave. This function allocates a non-enclave memory region for a marshalled structure (Line 16) and copies an input structure variable, ts, into it (Line 25) while doing not handle the individual members of the structure.

Therefore, we conclude that an OCALL proxy function can copy uninitialized padding bytes from an enclave to a non-enclave memory region when the corresponding OCALL function receives a structure variable as input,
which can potentially contain uninitialized sensitive enclave data.

4 Potential Countermeasures

In this section, we explain possible countermeasures against the sensitive enclave data leakage problem because of padding, which can be implemented in the future. First, we can revise the Edger8r tool to generate proxy functions that individually copy the member of a structure variable during ECALL and OCALL (i.e., deep copy). For example, in Figure 5, we can do $ms->ms_ts.val1=ts.val1$, $ms->ms_ts.val2=ts.val2$, and $ms->ms_ts.val3=ts.val3$, instead of $ms->ms_ts=ts$ to do not leak uninitialized padding. However, it makes proxy functions be complicated especially when they are dealing with a complex structure variable recursively containing other structures. Second, we can enforce #pragma pack directive to eliminate any padding, but it introduces performance overhead because of a lack of memory alignment. Third, whenever we allocate a structure variable inside an enclave, we can use memset() to fully initialize all of its memory. This countermeasure can avoid any potential data leakage problems, but it can experience performance degradation. Fourth, as Lu et al. [2] and Milburn et al. [3] do, we can implement advanced memory initialization techniques to selectively initialize padding bytes only when they can leak sensitive data. We believe that this is the most practical solution against the explored problems such that, in the future, we will figure out the best memory initialization technique for Intel SGX to eradicate the uninitialized enclave data leakage problem.

Responsible Disclosure

We have reported this uninitialized padding problem to Intel on June 23, 2017. After having numerous discussions with us, Intel SGX SDK developers informed that this padding issue will be explicitly warned in the SDK documentation to describe this issue and potential mitigation approaches.

References

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