Towards Memory Safe Python Enclave for Security Sensitive Computation

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ABSTRACT

Intel SGX Guard eXtensions (SGX), a hardware-supported trusted execution environment (TEE), is designed to protect security-sensitive applications. However, since enclave applications are developed with memory unsafe languages such as C/C++, traditional memory corruption is not eliminated in SGX. Rust-SGX is the first toolkit providing enclave developers with a memory-language. However, Rust is considered a Systems language and has become the right choice for concurrent applications and web browsers. Many application domains such as Big Data, Machine Learning, Robotics, Computer Vision are more commonly developed in Python programming language. Therefore, Python application developers cannot benefit from secure enclaves like Intel SGX and Rust-SGX. To fill this gap, we propose Python-SGX, which is a memory-safe SGX SDK providing enclave developers a memory-safe Python development environment. The key idea is to enable a memory-safe Python language in SGX by solving the following key challenges: (1) defining a memory-safe Python interpreter (2) replacing unsafe elements of Python interpreter with safe ones, (3) achieving comparable performance to non-enclave Python applications, and (4) not introducing any unsafe new code or libraries into SGX. We have proposed to build Python-SGX with PyPy, a Python interpreter written by RPython, which is a memory-safe SGX SDK providing enclave developers a memory-safe Python development environment. We have implemented Python-SGX and tested it with a series of benchmarks programs. Our evaluation results show that Python-SGX does not cause significant overhead.

1 INTRODUCTION

In current systems, there is a large attack surface, including OS, VMM (Virtual Machine Manager), and other running applications. Intel has made it nearly impossible to inspect code for exploitable bugs. Intel introduced Software Guard eXtensions (SGX) in 2013 to provide applications the capability to defend their secrets through the use of enclaves. An SGX enclave is a protected environment consisting of only application code and data which is protected from malware in OS, VMM, BIOS, drivers, and other applications. SGX code and data are always encrypted to and from CPU chip to memory. The SGX enclave programming model is based on a new set of CPU-privileged instructions that provides isolation from outside agents and other enclaves. SGX also offers a software attestation scheme which allows remote agents a method to authenticate the software running inside an enclave.

SGX was initially designed to protect small segments of an application that dealt with sensitive data (e.g., credit card numbers, signing keys), and also able to provide code secrecy [8]. The critical point is that the SGX-developed application itself must still be proven memory safe and free from vulnerabilities. Nonetheless, there would be huge benefits if legacy applications could be adapted to execute within SGX enclaves. Software developed in memory-unsafe languages such as C/C++ would be complicated to verify formally. The same traditional memory corruption vulnerabilities that exist running under OS control can also occur within the enclave. Even programming languages that are touted as memory safe (e.g., Python, Java, Go, Rust) either interface with unsafe libraries or have some features which can be exploited. There are several studies that have illustrated that memory hijacking attacks can still occur in SGX. [9, 17, 25].

There has been many defense mechanisms proposed to defeat memory corruption attacks, such as Stack Canaries [11], Data Execution Prevention (DEP) [29], Address Space Layout Randomization (ASLR) [16], Control Flow Integrity (CFI) [4], so on and so forth. However, they all are imperfect for various reasons, such as the performance cost outweighing the potential protection, incompatibility with legacy systems, relying on changes in the compiler toolchain, or requiring the access of program source-code. It is thus imperative to look for other alternatives to secure SGX enclave programs. By using memory-safe languages to develop enclave programs instead of these defense mechanisms is a better solution.

There is a current work Rust-SGX [12, 31, 32], which solved this problem by providing Rust memory-safe languages for enclave developers. However, Rust is still relatively new and not widely adopted. Rust has recently been chosen for security-sensitive web browsers. Python ranks as one of the top three most popular languages across all existing code repositories and is gaining by the most significant percentage each year. The application domain areas (Big Data, Machine Learning, Robotics, Computer Vision, Automation Testing) are heavily dependent on Python programming language. These application domains will never benefit from secure enclaves of SGX with only Rust-SGX alternative. Porting Python interpreter to SGX is not enough by using frameworks in the previous work [28, 30]. Python applications would still suffer memory corruptions since the interpreter and augmented runtime are all written in C/C++ code and thus contaminating the Python program’s memory safety.

To fill this gap, we propose Python-SGX, a memory-safe Python SGX SDK based on PyPy, a Python interpreter written in RPython, a subset of Python language. By taming all of the unsafe parts in PyPy using security hardening, formal verification, and memory-safe languages, Python-SGX provides a memory-safe Python interpreter - MesaPy. Since PyPy is dependent on the C standard library, and SGX has a minimal set of libraries, the previous method added a shim layer or utilized Library OS. However, by adding this layer, the extra C/C++ unsafe code was introduced. Python-SGX avoids this by properly customizing MesaPy. Therefore, Python-SGX provides a memory-safe development environment.
We have implemented Python-SGX and executed several benchmark programs for performance analysis. Our evaluation results show that Python-SGX only imposes modest overhead compared to running in native Linux. Python-SGX has been released as an open-source project in Nov, 2018.1.

In summary, our contributions are:
- We present MesaPy, a memory-safe Python interpreter, based on PyPy by using formal verification, type system enhancement, and memory-safe programming language to tame the unsafe parts in PyPy.
- We propose Python-SGX based on MesaPy, a practical approach to providing a memory-safe Python development environment for developers.
- We have implemented MesaPy, Python-SGX, and evaluated them with several benchmark programs. Our evaluation results show that Python-SGX provides a prototype of the Python enclave programming model and meanwhile does not impose any significant performance overhead.

2 BACKGROUND

2.1 Memory Safety
Computer programs consist of two main elements: execution control and memory data access. Memory data access can have either spatial and temporal problems. Spatial errors are when you can read or write to memory areas that should not be valid, which includes buffer overflows, double frees, and dangling pointers. Temporal errors are the result of memory access that should not be valid because of timing issues such as dereferencing pointer after free, uninitialized memory access. The whole idea of memory safety is to provide a secure execution environment void the types of spatial and temporal issues just presented.

2.2 Intel SGX
The main reason for Intel to introduce SGX is to provide applications the ability to execute code in a secure enclave and protect secrets with their own execution environment [3, 18]. As such, SGX provides software developers direct control over their application’s security without relying on any underlying system software such as the OS or hypervisor. This significantly reduces the trusted computing base (TCB) to the smallest possible footprint (only the code executed inside the enclave), and prevents various software attacks even when the OS, BIOS, or hypervisor are compromised. The main reason for Intel to introduce SGX is to provide applications the ability to execute code in a secure enclave and protect secrets with their own execution environment [3, 18]. As such, SGX provides software developers direct control over their application’s security without relying on any underlying system software such as the OS or hypervisor. This significantly reduces the trusted computing base (TCB) to the smallest possible footprint (only the code executed inside the enclave) and prevents various software attacks even when the OS, BIOS, or hypervisor are compromised.

2.3 PyPy
PyPy is an alternative implementation of the Python programming language, which often executes faster than the standard implementation of Python, CPython. PyPy uses just-in-time (JIT) compilation to translate Python code into machine-native assembly language while CPython is strictly an interpreter. PyPy uses optimization techniques found in other just-in-time compilers for dynamic languages. It analyzes running Python programs to determine the type of information of objects as they are created and used in programs, then uses that type of information as a guide to speed things up.

“Pure” Python applications which do not interface with C libraries or extensions execute most efficiently with PyPy. This is due to the overhead incurred by how PyPy must emulate CPython’s native binary interfaces. Longer-running programs benefit most from PyPy optimizations. The longer the program runs, the more run-time type information PyPy can gather, and the more optimizations it can make. Python used for system command scripting purposes will not benefit from the efficiency standpoint.

PyPy is interesting architecturally because it is the product of a technique called meta-tracing, which transforms an interpreter into a tracing JIT compiler. Since interpreters are usually easier to write than compilers but run slower, this technique can make it easier to produce efficient implementations of programming languages. PyPy’s meta-tracing toolchain is called RPython. PyPy compiles Python code, but it is not a compiler for Python code. Because of the way PyPy performs its optimizations and the inherent dynamism of Python, there is no way to emit the JIT-generated byte code as a standalone binary and re-use it.

RPython is a Python-like language; specifically it is a restricted subset of the Python language. The restriction provides the power of type inference of the RPython program so that it could be translated into another language. The mechanism to achieve this byte code translation is through an associated toolchain provided by PyPy project along with an interpreter written in the C programming language. This code is then compiled into machine code, and the byte code runs on the compiled interpreter.

3 OVERVIEW

3.1 Objectives, Threat Model and Scope
The critical objective of Python-SGX is to provide a secure SGX enclave environment for Python software development free of memory-corruption vulnerabilities. Python-SGX should provide to the most extent possible the same capabilities and rich library support that is found in the native Linux environment. Applications should not have to undergo a significant rewrite to execute in Python-SGX. Moreover, finally, the design and implementation of Python-SGX should not impose significant performance overhead.

Python-SGX, like Intel SGX, only protects code and data running from within the enclave itself. The CPU processor protects code running in the enclave from being ‘spied on’ by other code, including OS processes, BIOS, hypervisor, or other applications. The enclave contents are unable to be read by any code outside the enclave, other than in encrypted format. This SGX model works securely and correctly as long as there are no memory safety issues (buffer overflow, use after free, invalid pointer). SGX programs are

1 The source code of Python-SGX has been released on GitHub at https://github.com/mesalock-linux/mesapy.
at risk of the same control flow hijacking as traditional applications when these memory safety rules are violated. Making matters more complicated, an SGX application is normally implemented with a trusted component running inside the enclave and an untrusted component running outside as an application software process. Since data and control must be passed back and forth between bridge functions (ECALL and OCALL), this opens another window of opportunities for attack. Python-SGX aims to defeat memory corruptions that exploit the insecure memory operations inside enclave programs. Side-channel attacks are orthogonal to the memory safety problem, so they are not in scope. Python-SGX will only focus on enabling application layer memory safety in SGX enclaves.

3.2 Challenge and Threat

In the previous work related to SGX memory safety, Rust-SGX focused on solving the unsafe interface between Rust and C languages. Python-SGX focuses on solving the memory safety of scripting language itself, in particular, its interpreter. Although Python is a type-safe scripting language, Python has to depend on an interpreter to execute. Python applications would still suffer memory corruption since the interpreter is not safe. The most popular Python interpreter is CPython, which is written in C, which is an unsafe language. Therefore, the first challenge is how to make Python’s interpreter memory safe. One method will be using formal verification tool to find and correct any potential memory corruptions in CPython; the other one will be rewriting CPython with memory-safe language. For the first one, CPython has 300k lines of C code, which will be a near-impossible task to accomplish. The second one comes to our solution. There is a Python interpreter, PyPy, which is written in RPython, which is a subset of Python. However, in PyPy, there are three unsafe parts, all related to RPython: type system, Translator/JIT backend, and external libraries. PyPy structural components are illustrated in Figure 1. Therefore, the challenge finally comes to how to secure these unsafe parts in PyPy interpreter. Python-SGX addresses this issue by using security hardening, formal verification, and memory safe programming language to eliminate the unsafe parts in the interpreter. The new memory-safe PyPy is called MesaPy, which can also be used in Linux environments.

The second challenge is the same one faced by Rust-SGX. Python-SGX is built on top of standard C library, not Intel SGX SDK. Since Python interpreter depends on the standard C library, it is impractical to have every component inside the SGX enclave to be memory safe. Therefore, Python-SGX will need to be re-designed to build on top of Intel SGX SDK.

Since PyPy depends on C standard library, and SGX can only utilize a subset of this library interface (I/O is forbidden, no system calls, etc.), PyPy can not be executed in SGX. The previous method was to add a shim layer or use Library OS. However, by adding this layer, the extra C/C++ unsafe code was introduced. Therefore, properly porting Python interpreter in Intel SGX without introducing any extra memory unsafe parts comes to another key challenge. Python-SGX addresses this issue by analyzing the mismatch between interpreter and SGX limited programming environment. This includes avoiding any extra C/C++ layer, following the SGX requirement, and modifying the interpreter, so it works correctly under SGX limited functionality.

4 DESIGN AND IMPLEMENTATION

PyPy, a Python interpreter written primarily in RPython §2.3, has built-in memory safety and speed efficiency as a result of its JIT compiler feature. However, there are still three unsafe parts which are: (1) RPython Type System, (2) RPython’s Translator/JIT backend, and (3) RPython’s external libraries. In the following sections, we introduce solutions to ensure safety in these three areas shown in Figure 2 and securely porting of MesaPy in SGX.

4.1 Unsafe RPython Type System - Security Hardening

For complete memory safety, both spatial (out of bound) and temporal (use-after-free) errors must be prevented without false negatives. Type-safe languages usually enforce both spatial and temporal safety by checking object bounds at array accesses and using automatic garbage collection.

RPython utilizes garbage collection to prevent temporal safety. However, by auditing RPython implementation in PyPy, we found that RPython has a potential risk since it does not check the boundaries of list and arrays, which will break spatial safety. We need to generate exceptions for unsafe functions operating outside the legal boundaries of the list and arrays. By performing security hardening on RPython’s type system, we improve RPython’s spatial safety.

4.2 Unsafe RPython’s Translator/JIT backend

There are approximately 1000 lines of runtime C code in RPython’s Translator/JIT backend, which contain potential memory bugs.
These few lines of C code are difficult to eliminate since they are often referenced. Although testing can be very effective at finding bugs, it cannot uncover all issues because exhaustively enumerating all program inputs is not possible. Therefore, formal verification is a complementary approach that can be effectively used to prove the absence of bugs in addition to finding them. Since this C code is isolated, its logic is not complicated and it is a critical piece, we can deploy formal verification methods to guarantee four memory issues cannot occur: (1) buffer overflow, (2) buffer over-read, (3) null pointer dereference, and (4) memory leak.

Two approaches are used for formal verification. The first one is the Abstract Interpretation (AI) based verification. Abstract Interpretation is a framework of program analysis based on approximating a possibly infinite set of states into a single abstract state. This leads to a computable set of states representing safe approximations of the behavior of the program. The second approach is using Software Model Checking (SMC). SMC is a method that verifies the correct functioning of a system design model typically represented by finite state machines (FSM). SMC uses efficient algorithms to verify that execution behavior adheres to formal specification and creating counterexamples for any violations. SMC is more robust with more complex control-driven programs with a large number of finite states. AI is more robust with data-dependent programs since it performs more exhaustive verification of abstract value space.

In practice, we deployed tools that cover both approaches in order for cross-validation. We utilize two state-of-the-art verification tools – SeAHORN [13] and SMACK [23] to reach a high degree of certainty. We applied both tools on the RPython backend C programs. To as well as AI-based analyzer IKOS for checking program invariants. Constrained Horn Clauses (CHC) for the back-end process. Seahorn takes LLVM IR bytecode and emits Contrained Horn Clauses (CHC) for the back-end process. SMACK converts LLVM IR bytecode to Boogie IVL, which is an expressive mathematical language based on memory map regions instead of dynamic memory. Finally, both tools have back-end verification engines to fulfill program validation.

The four aspects (buffer overflow, buffer over-read, null pointer dereference, and memory leak) are the verification target scopes. We applied both tools on the RPython backend C programs. To evaluate the verification result, we manually checked each of the alarms reported by both tools. By looking into the intermediate results, mapping the semantics to the source code manually, we can prove the results of back-end verification engines.

By formal verification, we found several cases could be potential vulnerabilities. Here, we list two cases to show the verification results.

In Figure 3, there could be a potential Integer Overflow at line 10 since K could be any value, including these greater than 32. In such a case, x will be overflowed.

In Figure 5, A potential invalid memory access could happen at line 10. Since skiplist-search could return NULL, node could be NULL, thus node->key will cause a crash.

We fixed all tool detected potential memory corruptions manually one by one and then iteratively revalidated all code updates against the verification tools until no potential risks existed. The correction of potential corruptions in Figure 3 and Figure 5 are shown in Figure 4 and Figure 6.
In RPython, there are external libraries written in C/C++, such as zlib, openssl, expat, etc. These external libraries written in C/C++ can have potential memory issues. Since it is hard to audit the libraries depending on the size of libraries, how can memory safety be guaranteed? There are two solutions for these unsafe external libraries; one is to use memory safe programming languages to rewrite them, the other one is to use formal verification to verify the correctness. However, external libraries are often not scalable and have a large amount of complicated code and dependencies. It is impractical to use formal verification to achieve memory safety. For unsafe external libraries, using memory safe programming language to rewrite them is a better approach. In practice, we replaced zlib with miniz-oxide, which a minizlib was written by Rust.

### 4.4 Porting PyPy into SGX

SGX reduces the size of the required Trusted Computing Base (TCB) significantly. However, this restrictive system model also limits SGX programs’ capability of acquiring computation resources from the outside untrusted environment, including hardware and software interrupts. These features are disabled in SGX enclaves, and their associated services from the OS, I/O subsystem, and memory mapping are unavailable.

Since SGX has limited library support, the key challenge is having PyPy run correctly inside SGX with the minimal TCB while not introducing unsafe code in SGX. The SGX security guide must be followed during the development of new libraries.

PyPy interpreter has RFFI parts which contain system calls and I/O related operations. This introduces environment variables, disk files, dynamic load, etc. which are not supported by SGX. The challenge becomes how to fix these I/O and system call-related requirements.

Previous works have focused on building a bridge for the limitations. However, it increases the TCB and also adds an extra layer inside SGX, which is written in C/C++ language introducing more potential memory corruption.

Instead, the PyPy interpreter has been modified directly for Python-SGX without adding an unsafe C/C++ code. Also, we performed analysis for all I/O and system call functions used by PyPy, so that they could either be eliminated or replaced with equivalent safe implementation. For instance, there is a requirement to read files from disk in PyPy for booting. As an alternative, we can have these files prepared inside SGX for reading. Since PyPy interpreter no longer requires a dynamic loading feature inside SGX, we can disable this function and replace it with static loading. By searching through RPython FFI, we remove all of the I/O and system calls that are not allowed.

In order to provide more details on this practice, let us examine pypy-setup–home function which implements PyPy interpreter setup and performs lib-py python and lib-pypy initialization. During this process, these libraries need to read files from disk, which is outside of SGX. In order to remove potential risk from reading files from an unsafe source, we can hardcode these two libraries inside SGX. Moreover, since PyPy is also supported by libc, which contains unsafe code, all libc functionality will be replaced with sgx tlibc.

As another example, garbage collection initialization needs to read system information about the total memory size. This part is redesigned so that there is no need to read from the file system by defining the size accurately. Further analysis is performed for unnecessary code, which may contain unsafe actions reducing the threat surface area. PyPy interpreter then becomes self-contained in SGX and isolated from potential risks.

## 5 Evaluation

In this section, we provide a performance evaluation of Python-SGX. Two areas are identified as the criteria for performance evaluation: (1) MesaPy versus PyPy (both running in Linux), and (2) porting overhead (MesaPy in Linux versus MesaPy in Python-SGX). Note, we do not compare a Python program with a C/C++ program since the comparison is inappropriate. That would necessarily be the comparison compiled versus interpreted code. Since we have not developed any SGX-specific APIs written in Python yet, we will also not have micro-benchmarks to evaluate that part yet. The source code of all of our benchmarks is released at Github at https://github.com/mesalock-linux/mesapy-benchmarks.

Our performance experiments were executed on a 16.04.1-Ubuntu system comprised of a 6-core Intel Core i7-8086K CPU running at 4.00GHz, with 32 GB memory, and 1Gbit/s Ethernet Connection I219-LM. We installed the latest Intel SDK, SGX driver(version 2.5).

### 5.1 MesaPy benchmarks

Our benchmarks in this part aim to evaluate the overhead of MesaPy compared to native PyPy. Particularly, we set up two sets of evaluation environments: (1) PyPy with Linux, 2) MesaPy with Linux. We have 19 PyPy [2] and game-related programming [1] benchmarks that are selected and modified for execution. The evaluation result for these benchmarks is presented in Figure 7. We can see that all 16 programs running in MesaPy have the overhead ranging from 1% to 12% greater than native PyPy. The reason that native PyPy has better performance than MesaPy is due to the list and array index check in MesaPy. There are three benchmarks, and running on MesaPy are slightly faster than native PyPy. The reason is mainly from noise.
5.2 Porting overhead

Our benchmarks in this part aim to evaluate the overhead of porting MesaPy in Python-SGX compared to native MesaPy in Linux. We set up two sets of evaluation environments: 1) running with MesaPy in Linux, 2) running under Python-SGX. We measured the execution time by utilizing the operating system clock running outside of the enclave. In particular, we first start the clock outside an enclave, execute ECALL, which will call a Python function inside the enclave, and then stop the clock to calculate the total execution time.

We have eight benchmarks that are supported by MesaPy under both Linux and SGX execution environments. Note that due to the limitation of SGX memory, we run performance testing with tree depth as 18 in binary-tree, and have 10 as input for testing fasta, and execute pidigits with input as 1. The results are shown in Figure 8. The benchmarks reporting performance overhead is between 36% to 150% higher for MesaPy under Python-SGX compared to MesaPy under Linux. The overhead is introduced by SGX and MesaPy porting.

6 DISCUSSION

6.1 Limitation of current work.

In the current version, Python-SGX only supports basic computation and some built-in modules. Support for multi-threading and full standard library is still under development.

6.2 The future work.

There is work remaining to perfect Python-SGX, including porting more Python libraries into Python-SGX and replacing remaining external C libraries. Furthermore, we still need to verify more components using current state-of-the-art verification tools. To have Python-SGX adopted by a larger developer community, we will be implementing additional useful libraries and SGX specific features for real-world use cases.

The audit of translation from RPython to C will be included in the next scope.

7 RELATED WORK

There exist many defense-related works regarding memory safety. G-Free is a work defeating return-oriented programming through gadget-less binaries [22]. Hyppersafe is a lightweight approach to provide lifetime hypervisor control-flow integrity [33]. Pointguard TM is protecting pointers from buffer overflow vulnerabilities [10]. CCured is doing type-safe retrofitting of legacy code [21]. [24] presents a Practical Dynamic Buffer Overflow Detector. Baggy Bounds Checking [7] is an Efficient and Backwards-Compatible Defense against Out-of-Bounds Errors. [34] is protecting C programs from attacks via invalid pointer dereferences. [15] presents backward-compatible bounds checking for arrays and pointers in C programs. Cling [5] is using a Memory Allocator to Mitigate Dangling Pointers. CETS [20] presents compiler enforced temporal safety for C. [6] is preventing memory error exploits with WIT. Body Armor for Binaries [26] is preventing Buffer Overflows Without Recompilation. Stackguard [11] presents automatic adaptive detection and prevention of buffer-overflow attacks.

Since the root cause of all vulnerabilities is memory corruption, every exploit starts by triggering a memory error. Enforcing memory safety eliminates all memory corruption exploits. While achieving memory safety, both spatial and temporal errors must be prevented without false negatives. Type-safe languages enforce both spatial and temporal safety by checking object bounds at array accesses and using automatic garbage collection. We can transform existing unsafe code to enforce similar policies by embedding low-level reference monitors. This instrumentation can appear within the source code itself, intermediate representation, or at the binary level. We should solve this problem for both spatial and temporal safety [27].

Spatial safety with pointer bounds. Enforcing spatial safety is to keep track of pointer bounds. CCured [21] provides an extension of the C type system with explicit types for pointers into arrays with dynamic typing. Cyclone [14] use "fat pointers". However, these systems need source code annotations so that it is not practical for large codebases. Also, any pointer representation changes the memory layout and breaks binary compatibility. SoftBound [19] addresses the compatibility problem of pointer representation by separating metadata from the pointer.

8 CONCLUSION

In summary, we have presented Python-SGX, a framework based on a safely ported PyPy interpreter to SGX providing enclave developers a memory-safe Python development environment. We show that with Python-SGX, enclave developers can perform sensitive security computations without significant overhead.

In order to be more practical, we plan to bring in additional Python libraries and SGX-specific features for real-world use cases. We also plan to review the translation audit from RPython to C for increased memory safety evaluation.

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Figure 7: Percentage overhead of running Python benchmarks in MesaPy normalized against PyPy native execution.

Figure 8: Percentage overhead of running Python benchmarks in Python-SGX normalized against MesaPy in Linux.

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