EnclaveFuzz: Finding Vulnerabilities in SGX Applications

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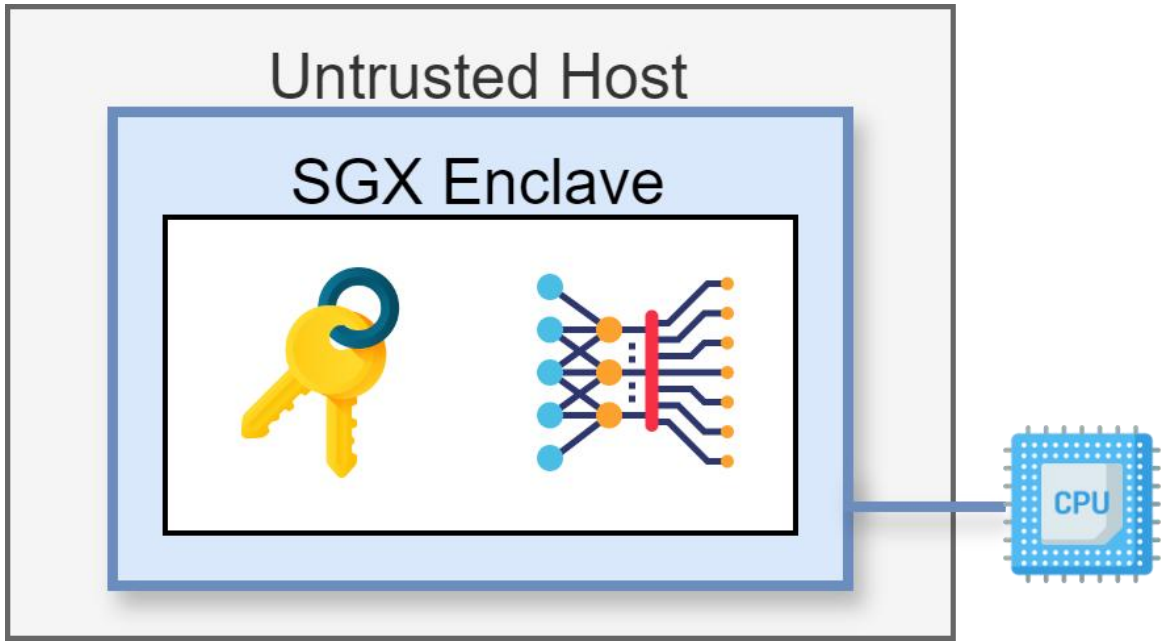
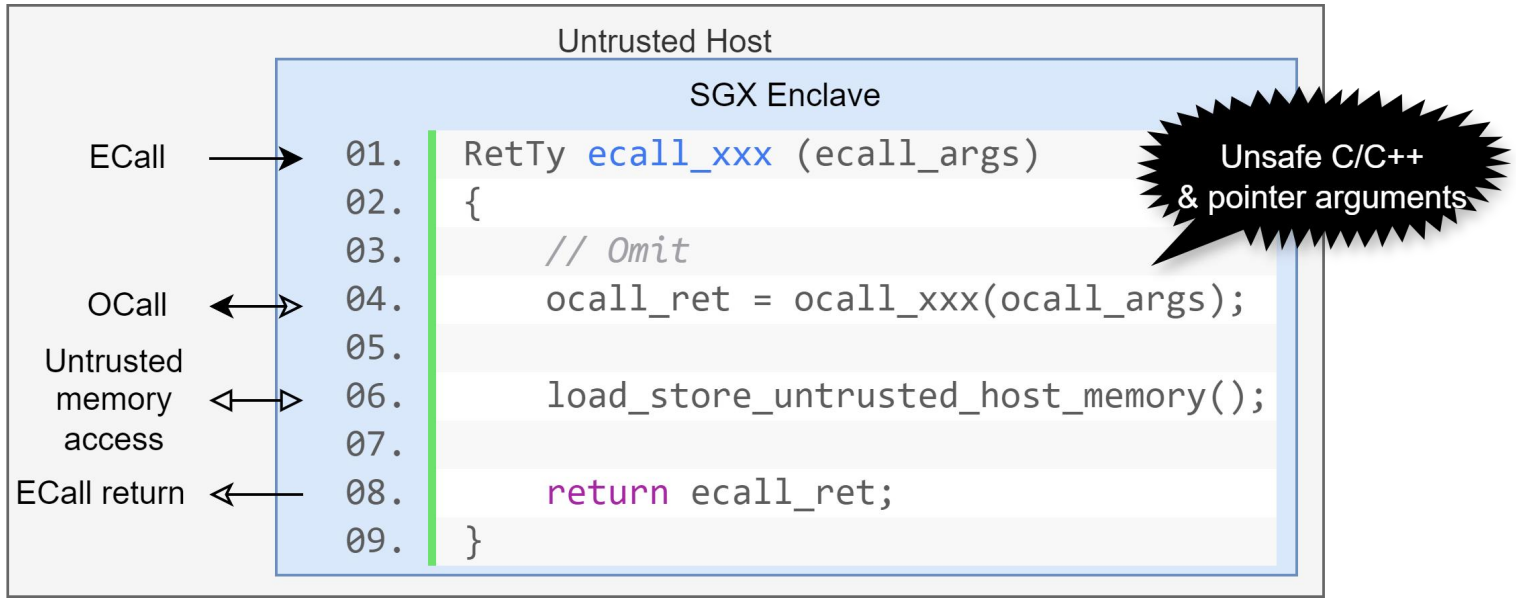
SGX Application

- Applications use hardware capabilities to defend against untrusted host.



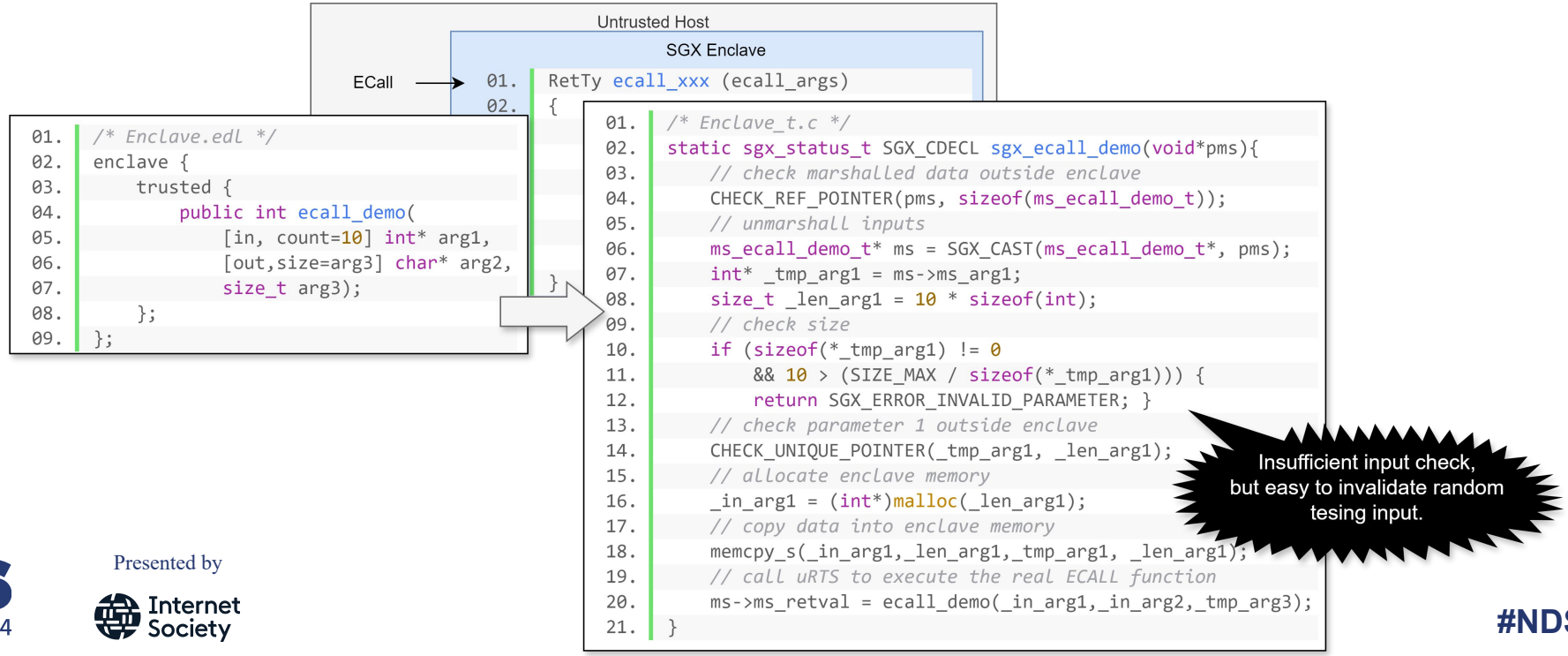
Problem

- Applications are unaware of specific security model.
- Memory unsafe language exacerbates the problem.



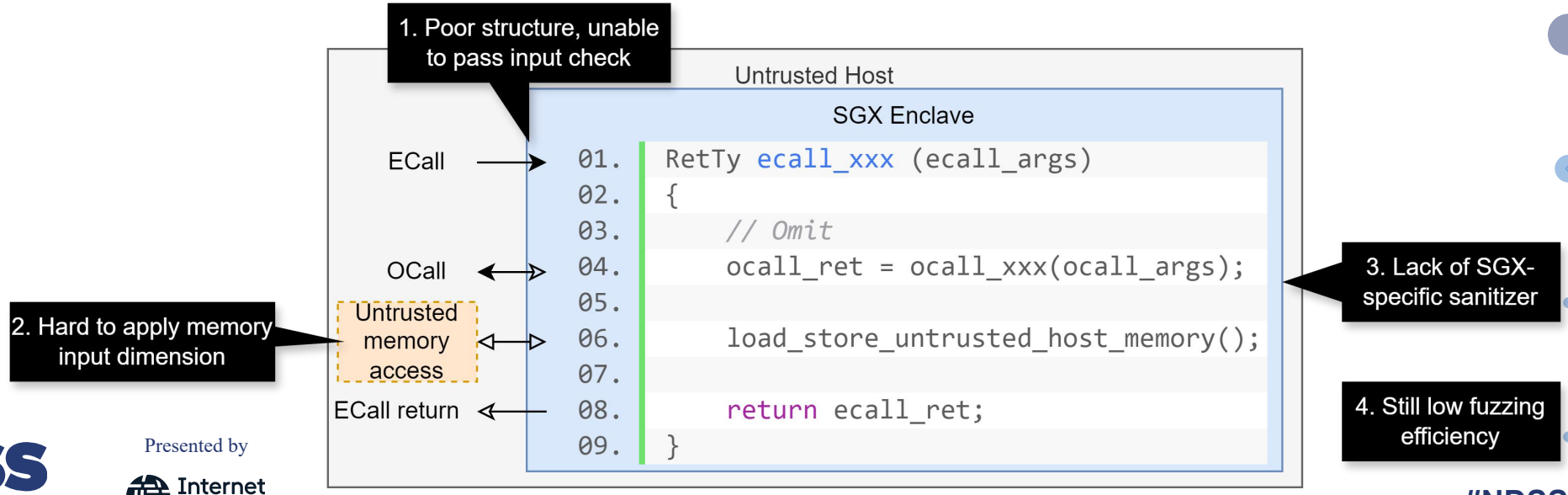
Insufficient Input Check

- SGX EDL only performs the basic checking rules, enclave itself needs a deeper check.
- *But it is easy to invalidate fuzzing input.*



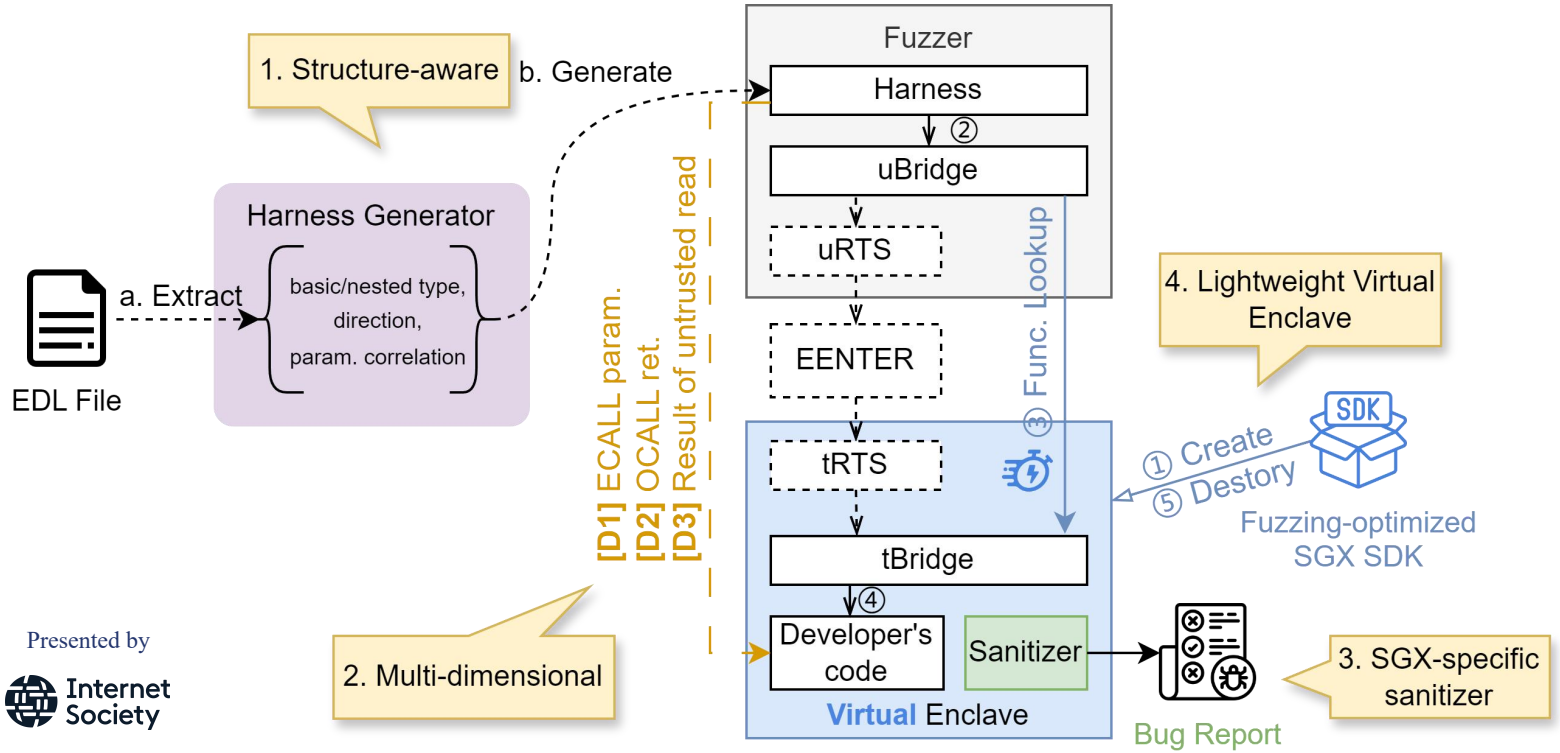
Related Works

1. **TeeRex**[SEC'20] and **COIN attacks**[ASPLOS'20] exploit symbolic execution but face state explosion in large-scale applications.
2. **SGXFuzz**[SEC'22] identifies input structures via page fault feedback, while **FuzzSGX**[EuroS&P'23] relies on host mutation, and they can only detect crashes or memory corruption.



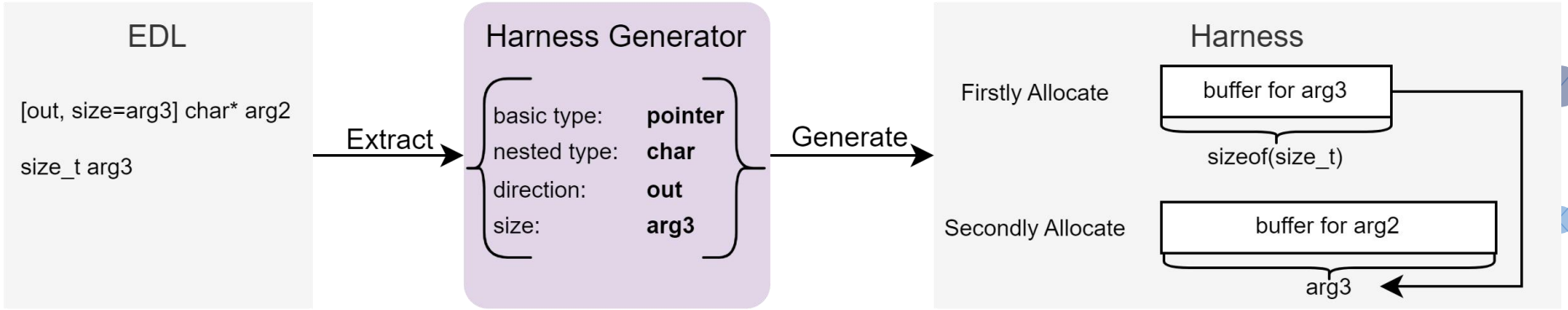
EnclaveFuzz Overview

1. & 2. A multi-dimensional structure-aware fuzzing harness.
3. A sanitizer for SGX-specific and memory corruption vulnerabilities.
4. An optimized SGX SDK to build a Virtual Enclave for faster fuzzing.



Structure-aware Fuzzing

- Extracts information from EDL and generates a structure-aware fuzzing harness, to pass basic input check.



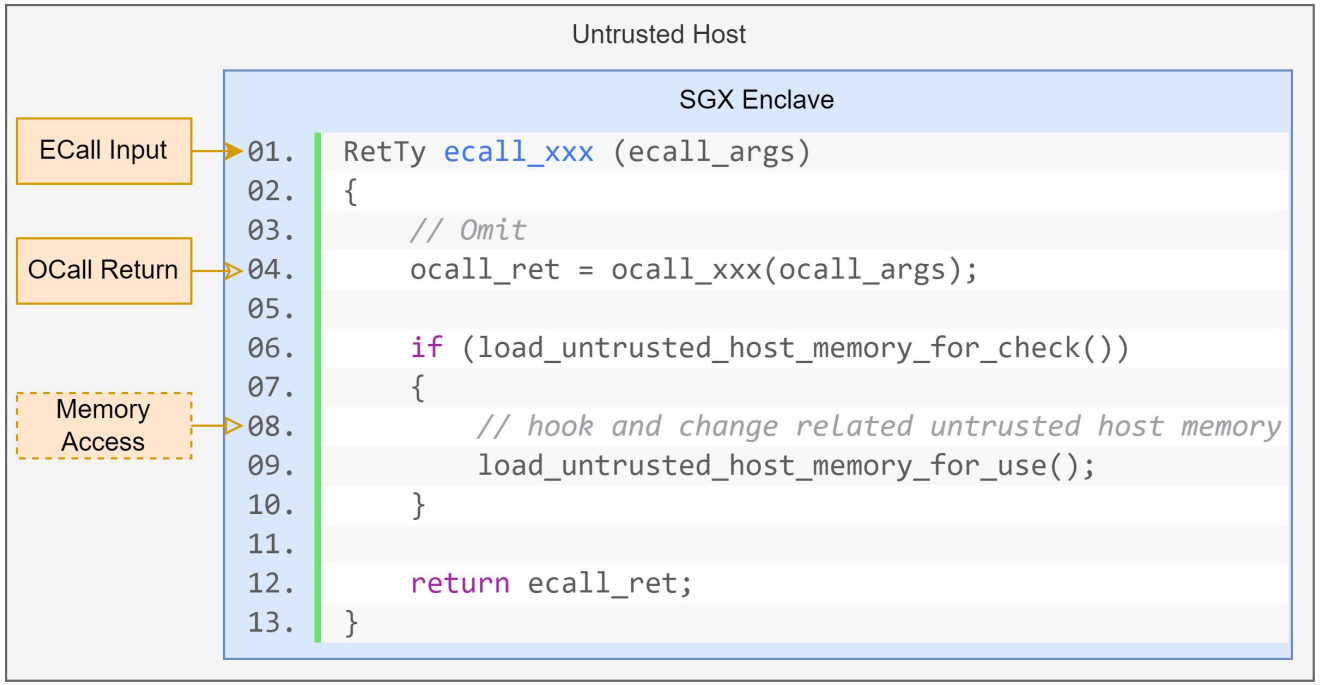
Structure Generation Policy

- Analyzes parameters and handles data directions based on EDL attributes.
- Dynamically provide a random size first and then the buffer when processing *user_check*.

Type	Dir. Attr.	Size Attr.	**Direction**	**Bytes** allocated
ECALL	IN	**Fixed:**	enter enclave ✔	**Fixed:**
	OUT	`size	count = val.`	exit enclave ✗	`value specified`
OCALL	IN	**Dynamic:**	exit enclave ✗	**Dynamic:**
	OUT	`size = param.` `user_check`	enter enclave ✔	`runtime decided`

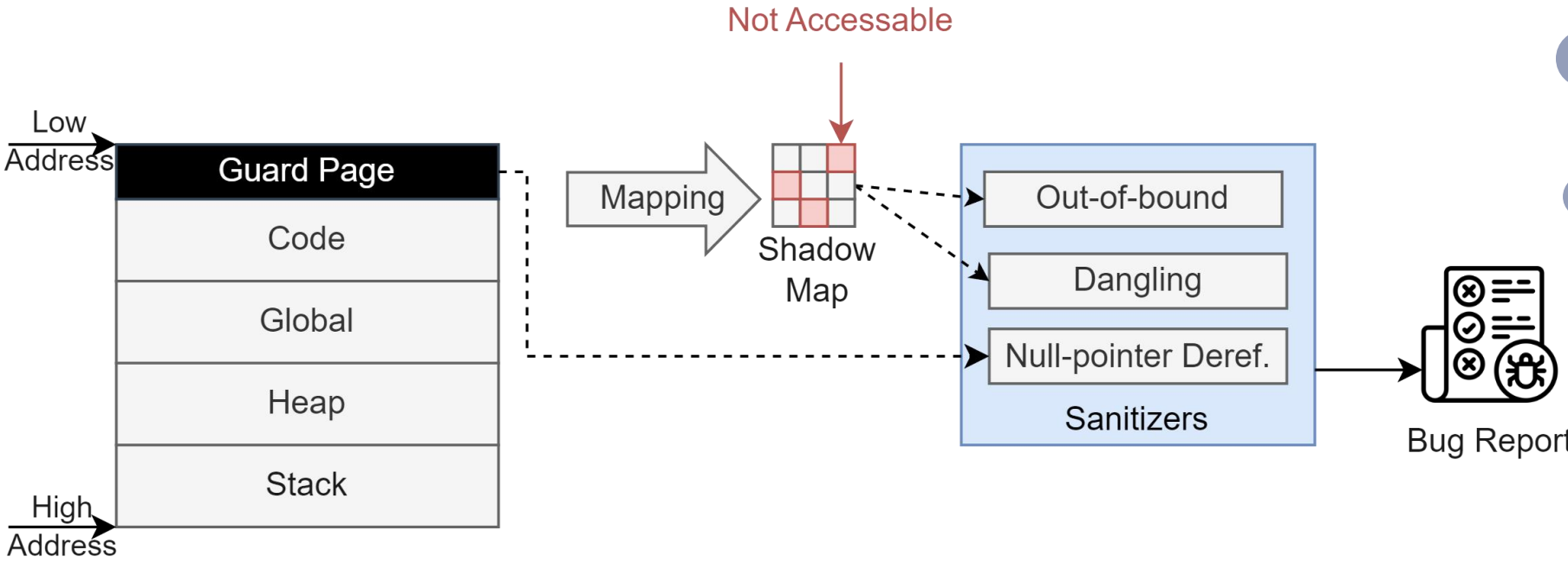
Multi-dimensional Fuzzing

- Besides E/OCall, EnclaveFuzz also hooks untrusted memory accesses and conditionally modifies them to break consistency at potential TOCTOUs to avoid huge overhead.



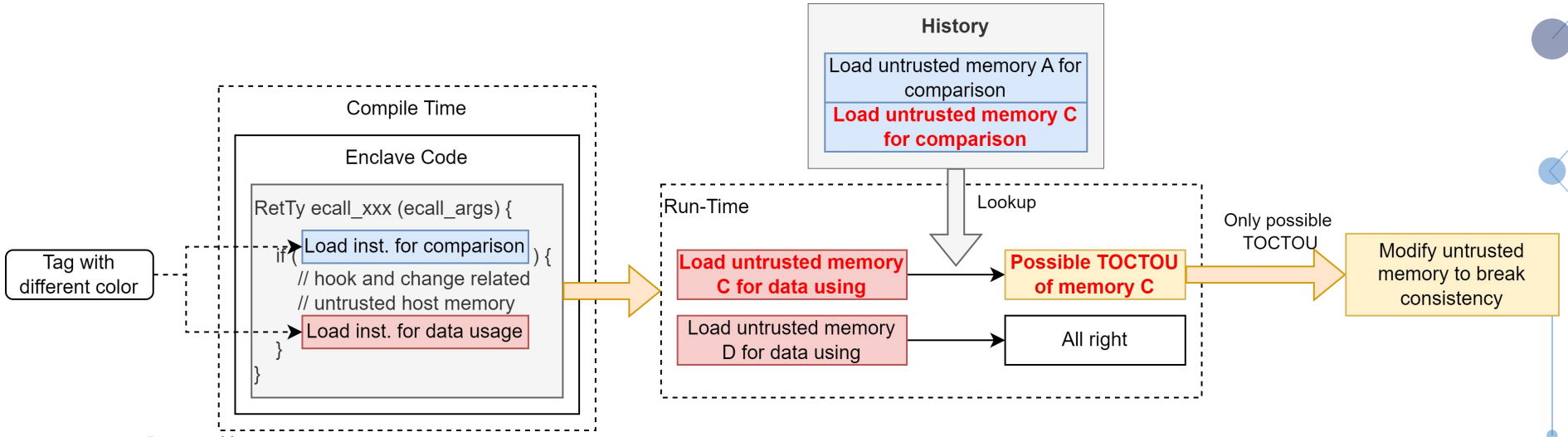
Vulnerability Detection

1. Miagrated ASan for memory corruption detection. (Normal way)



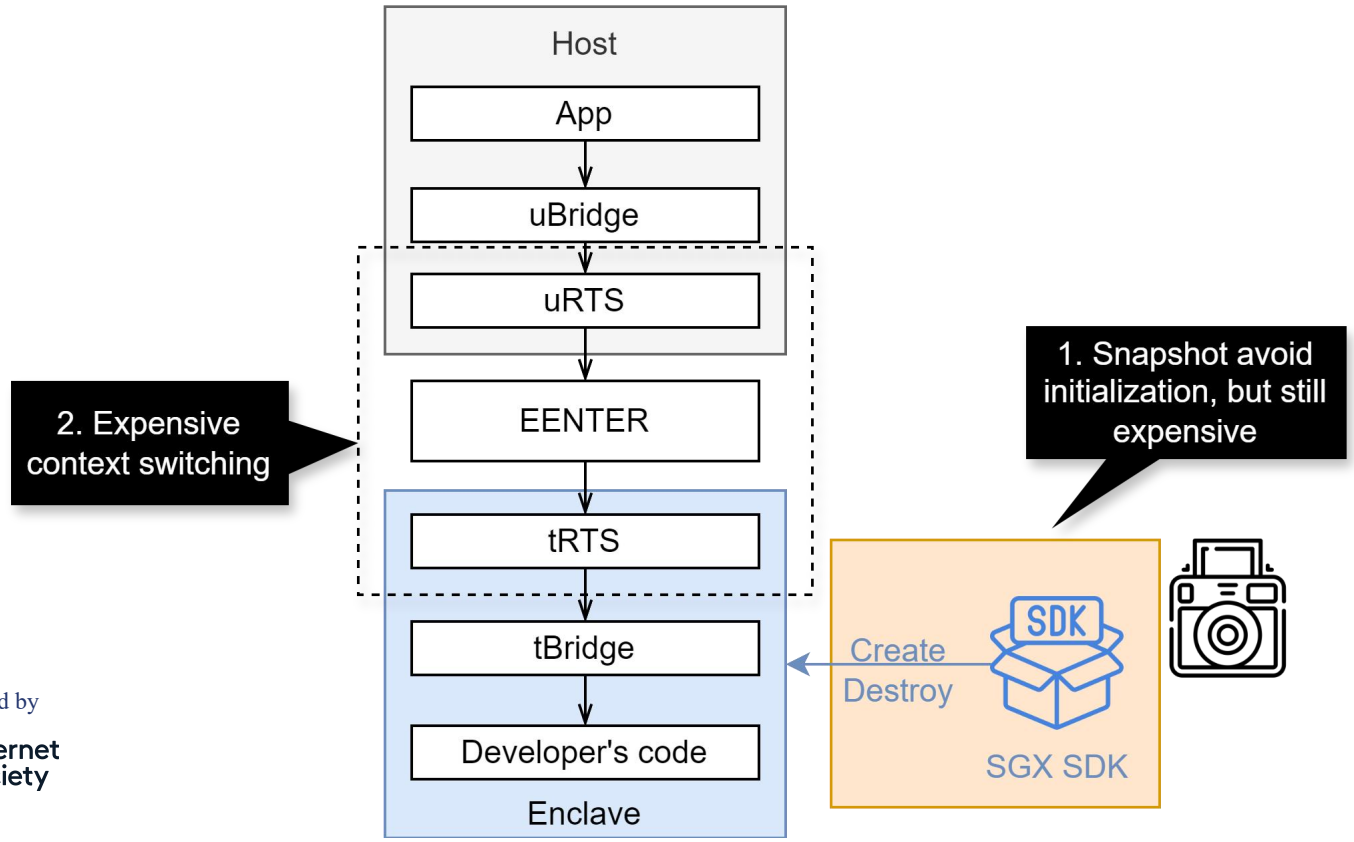
Vulnerability Detection

2. TOCTOU detection
   a) Different tags are given to load instructions during compilation.
   b) Hooking load instructions at runtime to detect loads from the same untrusted address forms a TOCTOU.
   c) To avoid huge overhead, only modify untrusted memory to break consistency when a potential TOCTOU is found.



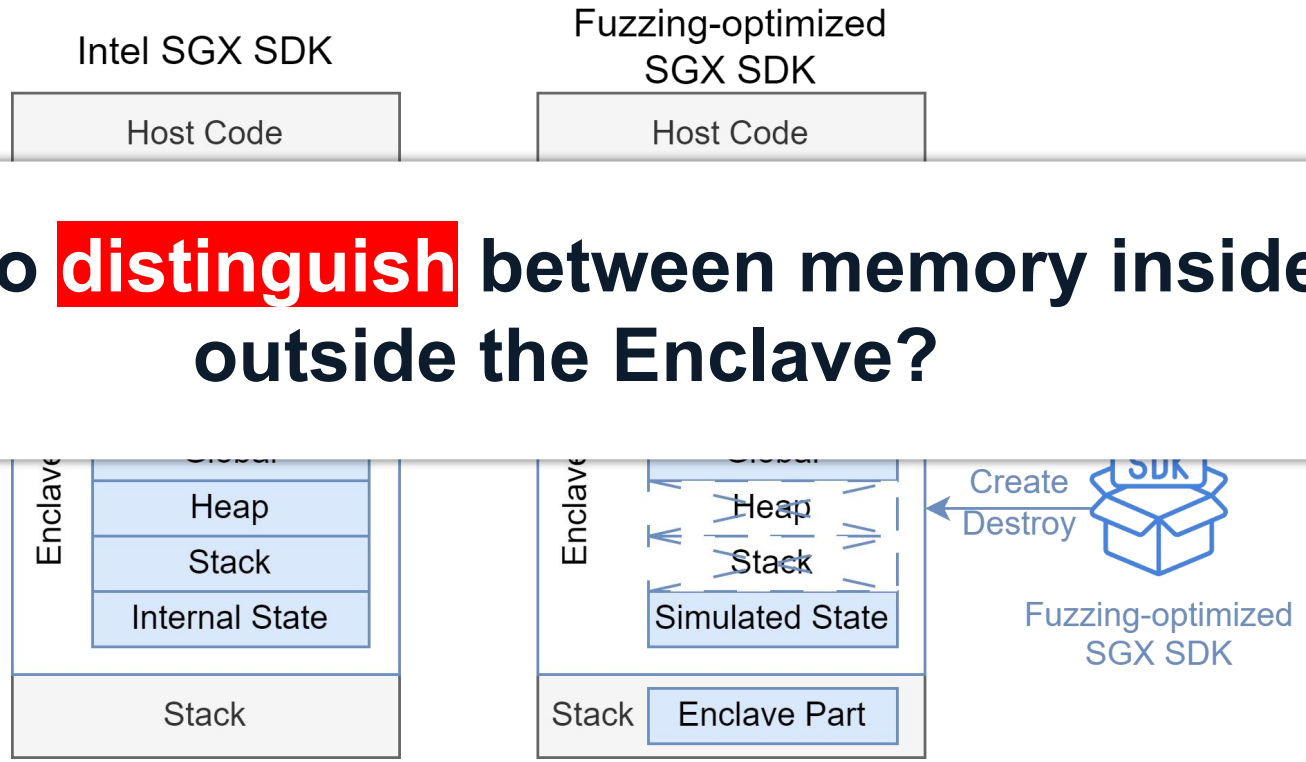
Slow fuzzing speed of related works

- Snapshot mode is still slow compared to persistent mode.
- Context switching is also expensive.



Optimized SGX SDK

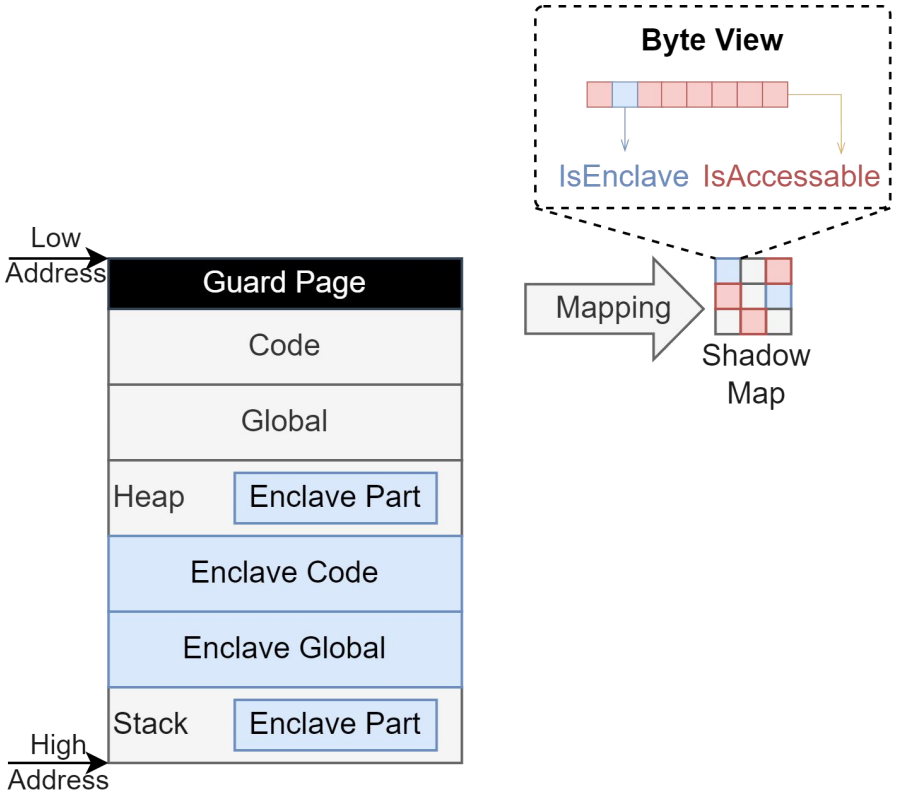
1. Remove independent memory to reduce creation/destruction overhead.



But how to distinguish between memory inside and outside the Enclave?

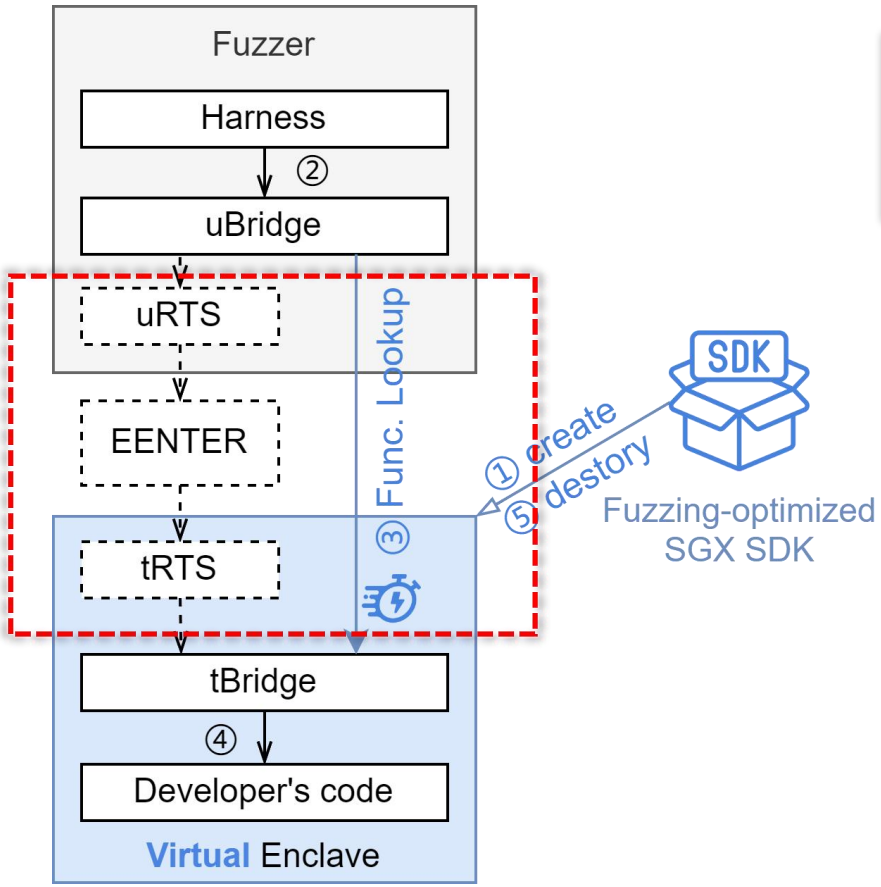
Optimized SGX SDK

1. Remove independent memory to reduce creation/destruction overhead.
2. Reuse shadow byte to distinguish memory inside and outside the Enclave.



Optimized SGX SDK

3. Replace expensive context switches with function table lookups



Bugs found can be reproduced in HW mode

Bugs Found

- EnclaveFuzz found 162 bugs in 14/20 real-world open source enclaves.

Mostly Null-Pointer Dereference & TOCTOU. The nuances of SGX security were overlooked, especially cross-boundary pointers.

Type	Enclave	#Bugs	Total
Null-Pointer Dereference	sgx-wallet	7	68
	intel-sgx-ssl	1	
	mbedtls-SGX	2	
	TaLoS	44	
	sgx-dnet	1	
	plinius	1	
	sgxwallet	2	
	sgx-reencrypt	4	
	trusted-function-framework	1	
	wasm-micro-runtim	4	
	BiORAM-SGX	1	
Use After Free	intel-sgx-ssl	2	6
	SGX_SQLite	2	
	mbedtls-SGX	2	
TOCTOU	TaLoS	37	38
	wasm-micro-runtim	1	
Stack Overflow	SGX_SQLite	1	5
	ehsm	1	
	BiORAM-SGX	1	
	SGXCryptoFile	2	
Heap Overflow	sgx-wallet	3	18
	TaLoS	2	
	sgxwallet	1	
	ehsm	11	
	wasm-micro-runtim	1	
Int Overflow	TaLoS	13	15
	sgx-dnet	1	
	plinius	1	
Arbitrarily Read/Write/Execute	trusted-function-framework	1	11
	wasm-micro-runtim	10	
Unchecked Size	trusted-function-framework	1	1
Total	14 Apps		162

Compare with SOTA

1. Effectiveness of structured test cases is nearly 3 times that of SOTA, and the coverage is nearly 4 times.

Enclave Name	Code Coverage[1]						Input Validity		Bug Findings	
	Enclave Cov.		Interesting Cov.		Effectiveness					
	SGXFuzz	EnclaveFuzz	SGXFuzz	EnclaveFuzz	SGXFuzz	EnclaveFuzz	SGXFuzz	EnclaveFuzz	SGXFuzz	EnclaveFuzz
intel-sgx-ssl	0.75%	18.04%	0.02%	18.39%	1.66%	99.66%	0%	100%	0	3
AE LE	3.85%	11.67%	14.29%	32.08%	1.98%	15.25%	26.89%	100%	0	0
AE PCE	4.10%	13.94%	22.53%	45.34%	3.49%	15.30%	17.48%	100%	0	0
AE PVE	2.36%	8.63%	10.05%	16.95%	6.32%	22.62%	33.15%	100%	0	0
AE QE	2.64%	3.20%	13.23%	6.68%	3.60%	16.13%	5.52%	100%	0	0
SGX_SQLite	2.39%	6.78%	1.45%	7.20%	26.64%	99.96%	30.39%	100%	0	3
TaLoS	5.86%	9.78%	4.66%	10.00%	36.56%	99.58%	53.50%	100%	90	96
mbedtls-SGX	6.54%	30.64%	8.16%	32.64%	53.68%	99.66%	21.23%	100%	1	4
wolfssl	3.64%	42.44%	0.38%	45.00%	7.72%	99.78%	38.27%	99.99%	0	0
sgx-wallet	8.52%	33.10%	12.68%	79.39%	1.42%	39.72%	30.06%	99.99%	1	10
sgx-dnet	5.64%	0.97%	1.13%	0.51%	7.00%	34.92%	69.15%	100%	2	2
plinius	3.07%	2.24%	1.10%	2.19%	7.41%	73.47%	68.41%	100%	2	2
sgxwallet	6.33%	51.81%	7.21%	43.50%	7.74%	25.44%	20.74%	100%	2	3
BiORAM-SGX	4.30%	17.95%	0.55%	1.08%	5.45%	1.66%	48.43%	82.95%	0	2
bolos-enclave	6.71%	7.85%	1.17%	0.48%	4.86%	4.01%	40.10%	84.09%	0	0
ehsm	3.69%	16.91%	3.81%	15.00%	76.97%	81.60%	0%	91.79%	0	12
sgx-reencrypt	8.60%	33.31%	14.92%	31.26%	20.26%	28.26%	84.38%	100.00%	2	4
SGXCryptoFile	5.85%	17.62%	15.04%	80.56%	4.15%	5.88%	0%	100.00%	0	2
trusted-function-frame	2.53%	1.97%	2.13%	1.53%	75.64%	75.22%	0%	100.00%	0	3
wasm-micro-runtime	3.95%	1.67%	2.08%	0.94%	32.64%	46.04%	78.04%	100.00%	5	15
average	4.57%	16.53%	6.83%	23.54%	19.26%	49.21%	33.29%	97.94%	5.25	8.05

Compare with SOTA

2. Improve the test speed of real-world applications by nearly 7 times.

Enclave Name	EnclaveFuzz-SIM	EnclaveFuzz-HW	EnclaveFuzz (Opt.SDK)
	ECALLs executed in 24 hours		
intel-sgx-ssl	18K	217	19K
AE LE	155M	63M	454M
AE PCE	153M	58M	483M
AE PVE	123M	44M	11M
AE QE	42M	27M	50M
SGX_SQLite	40M	15M	160M
TaLoS	448K	194K	120K
mbedtls-SGX	1M	122K	1M
wolfssl	370K	17K	23K
sgx-wallet	86M	21M	137M
sgx-dnet	354k	94k	504k
plinius	71k	54k	501k
sgxwallet	430k	218k	1.9M
BiORAM-SGX	1M	26K	9M
bolos-enclave	96M	30M	505M
ehsm	227K	163K	212K
sgx-reencrypt	14M	10M	15M
SGXCryptoFile	2M	467K	18M
trusted-function-frame	13M	3M	3M
wasm-micro-runtime	4M	1M	40M
Speedup rate	2.67×	1×	6.91×

See paper for more ablation studies.

Takeaway

- EnclaveFuzz is a multi-dimensional structure-aware fuzzer for SGX applications, with an SGX-specified sanitizer and a fuzzing-optimized SGX SDK.

https://github.com/vul337/EnclaveFuzz

https://netsec.ccert.edu.cn/vul337