Telling Your Secrets Without Page Faults:

Stealthy Page Table-Based Attacks on Enclaved Execution

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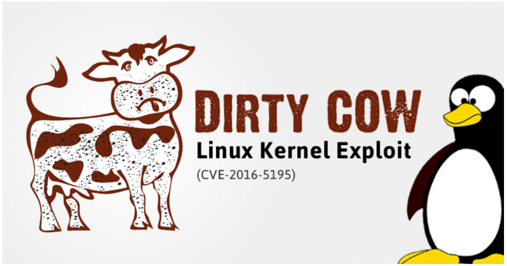
August 18, 2017

Road Map

thehackernews.com/2015/10/windows-patch-update.html

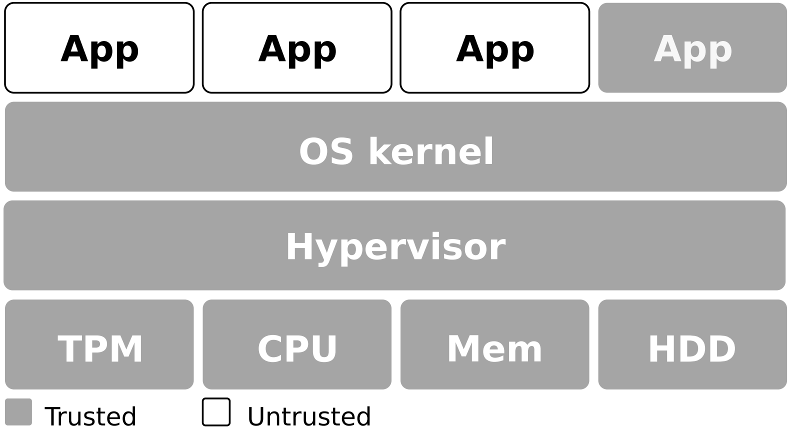
thehackernews.com/2017/06/cia-linux-hacking-tool-malware.html



thehackernews.com/2016/10/linux-kernel-exploit.html

thehackernews.com/2015/04/rootpipe-mac-os-x-vulnerability.html

Motivation: Application Attack Surface



Layered architecture $\rightarrow$ large **trusted computing base**

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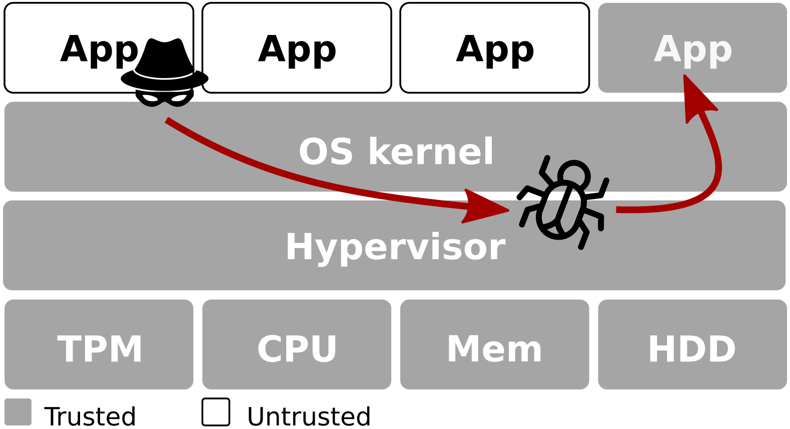

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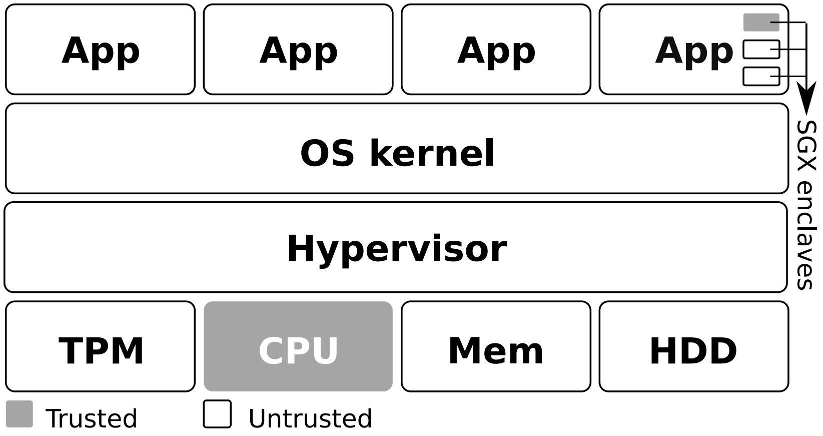

Intel SGX promise: hardware-level **isolation and attestation**

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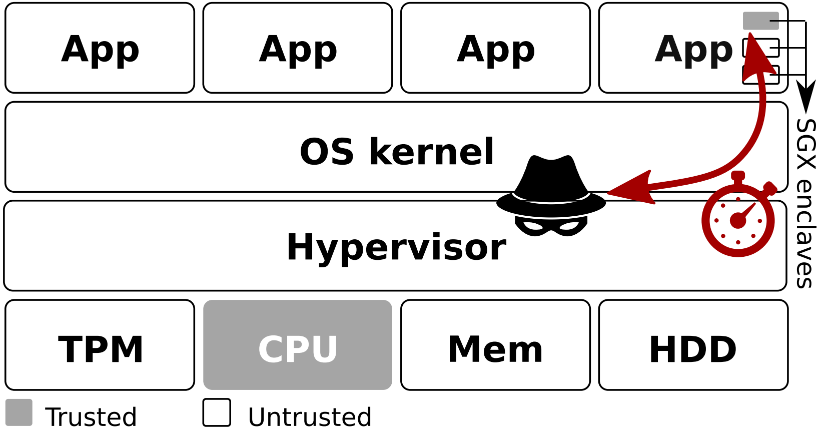
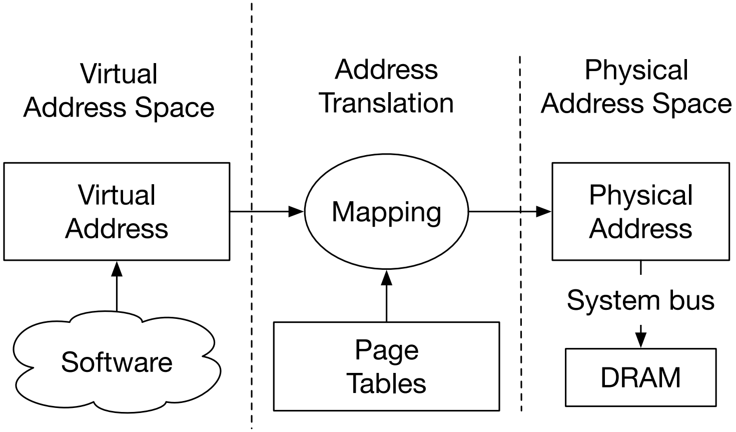


Untrusted OS → new class of powerful **side-channels**

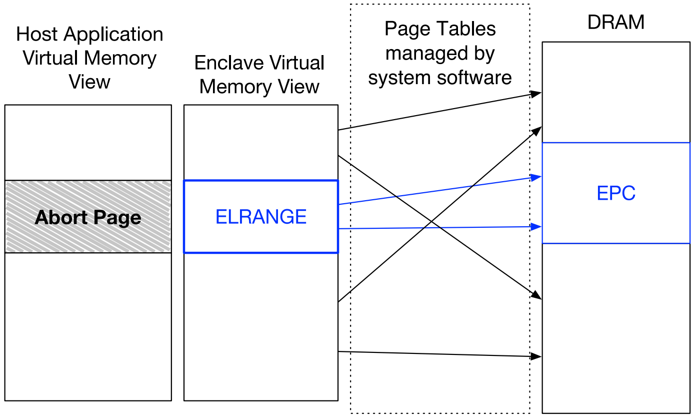
Road Map

The Virtual Memory Abstraction



Costan et al. "Intel SGX explained", IACR 2016 [CD16]

How Enclave Accesses are Enforced


Host Application Virtual Memory View
Abort Page
Enclave Virtual Memory View
ELRANGE
Page Tables managed by system software
DRAM
EPC

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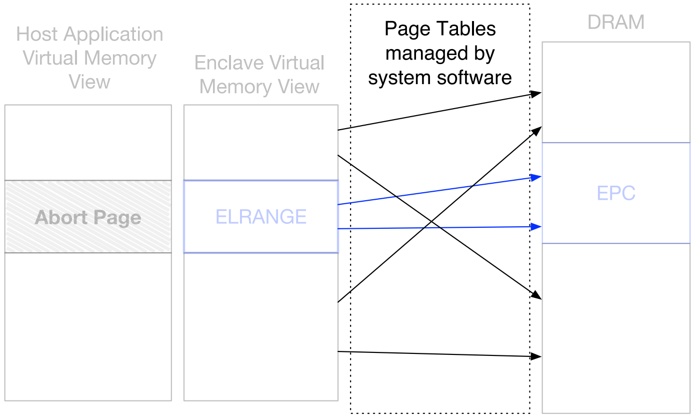
How Enclave Accesses are Enforced

Note: Untrusted OS controls *virtual-to-physical mapping*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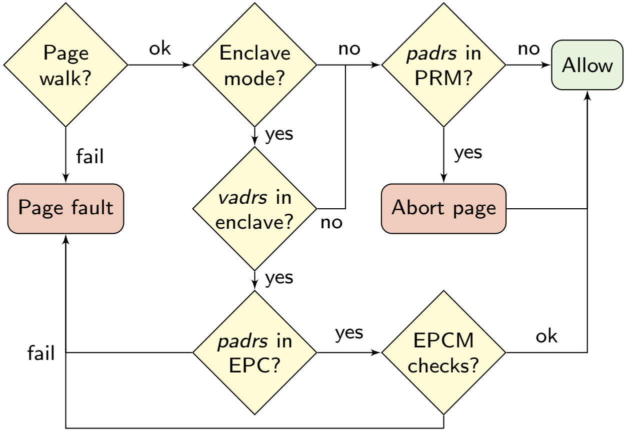
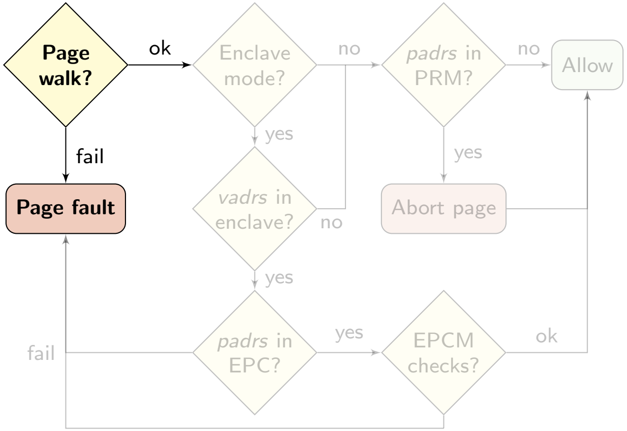
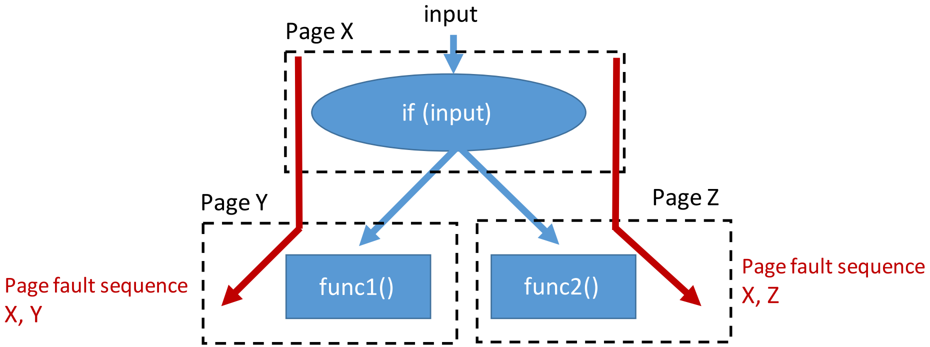


How Enclave Accesses are Enforced

Note: Additional checks *after* address translation



Page Faults as a Side-Channel



Xu et al.: "Controlled-channel attacks: Deterministic side channels for untrusted operating systems", Oakland 2015 [XCP15]

⇒ *Page fault traces leak private control flow/data accesses*

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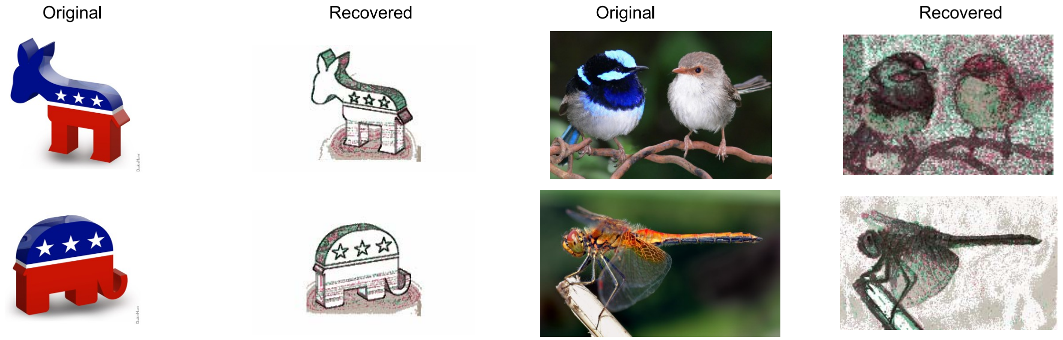

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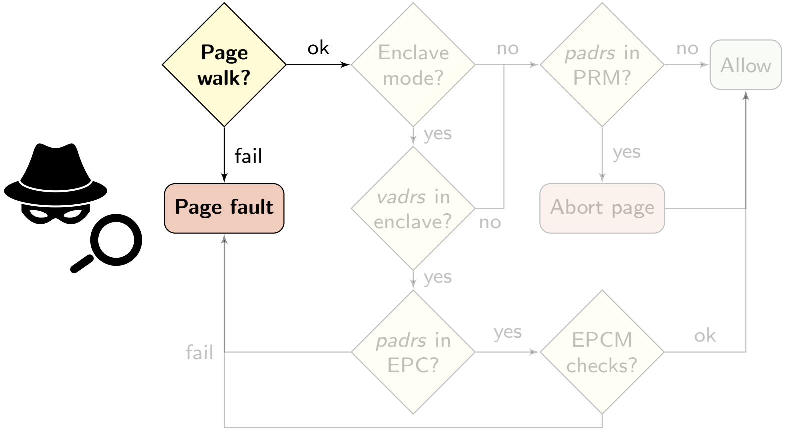
$\Rightarrow$ *Low-noise, single-run exploitation of legacy applications*

Current Solutions: Hiding Enclave Page Faults



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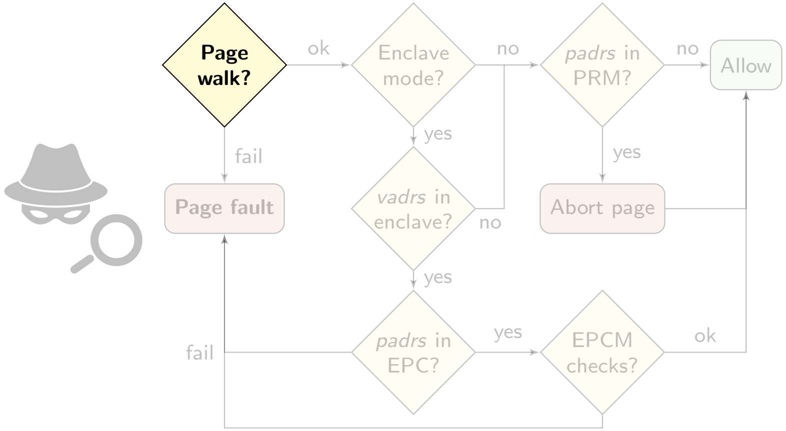

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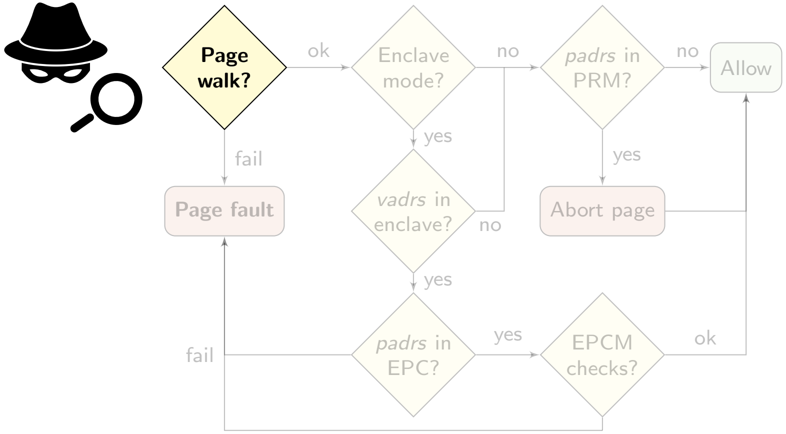

Defenses do not hold when attacker learns page accesses without triggering faults!

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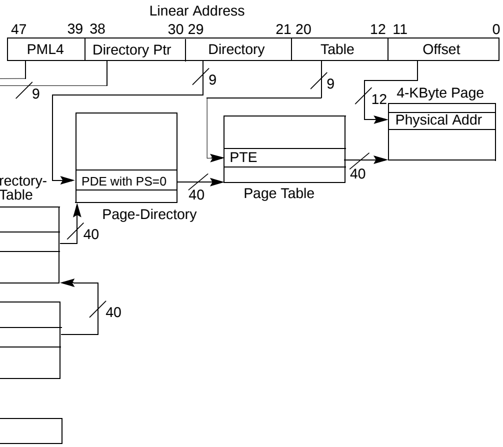

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Road Map

SGX Side-Channel Leakage: Page Table Entries

1. Attack vector: PTE **status flags**:
   - A(ccessed) bit
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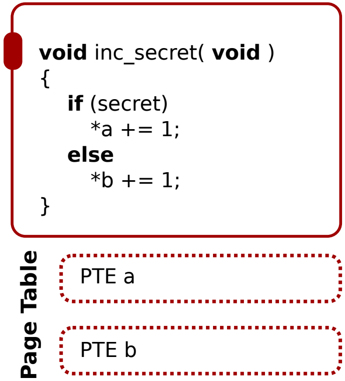

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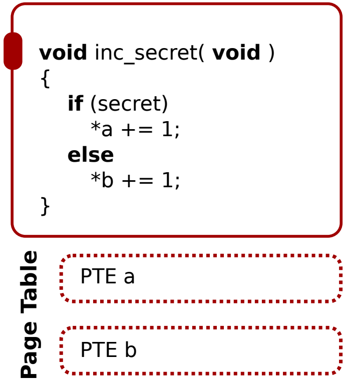

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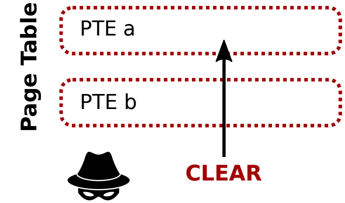

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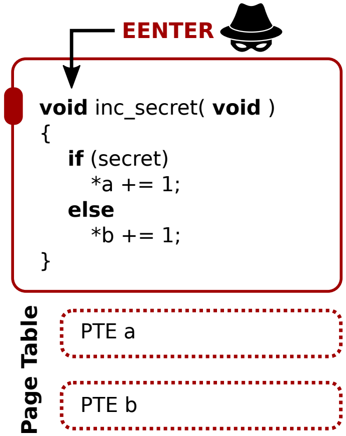

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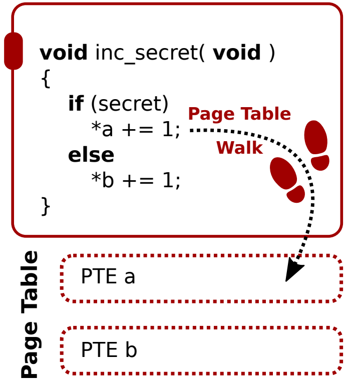
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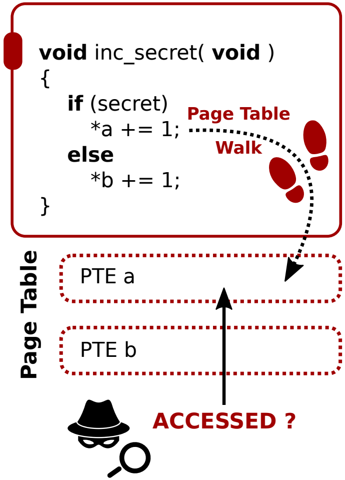

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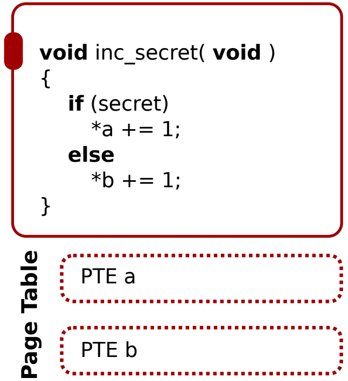

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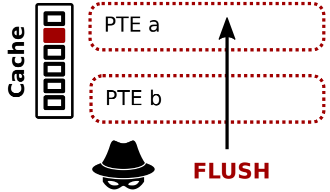

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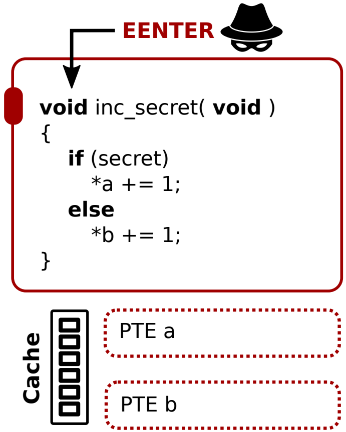

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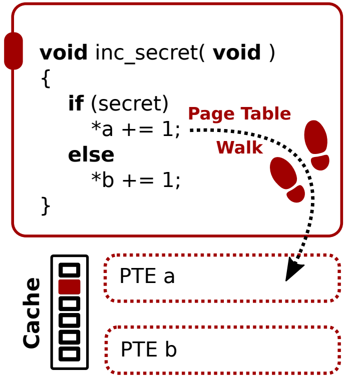

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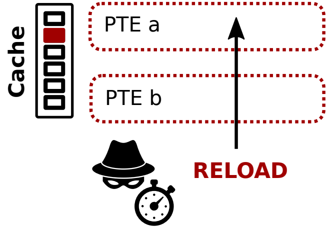

#PF-Less Challenges: Monitoring Repeated Accesses

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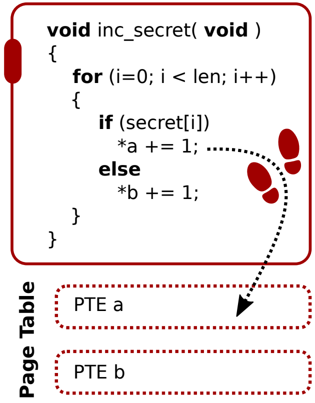

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SECRET = 01010

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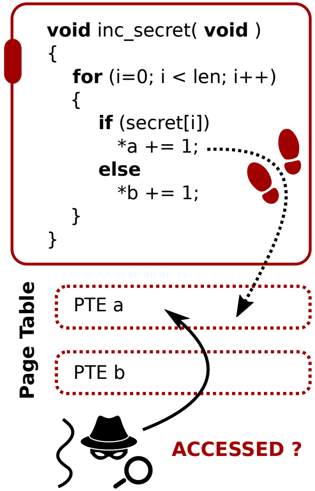
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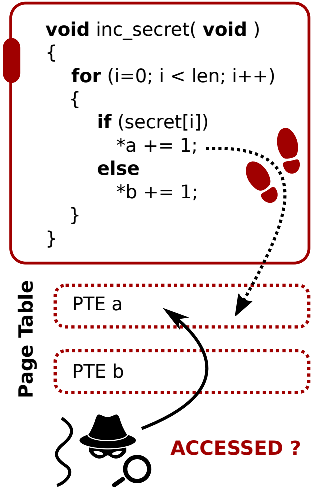

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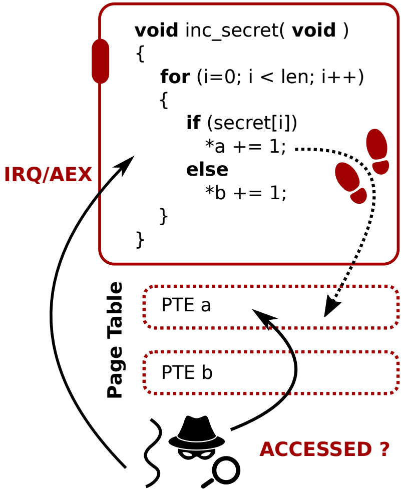

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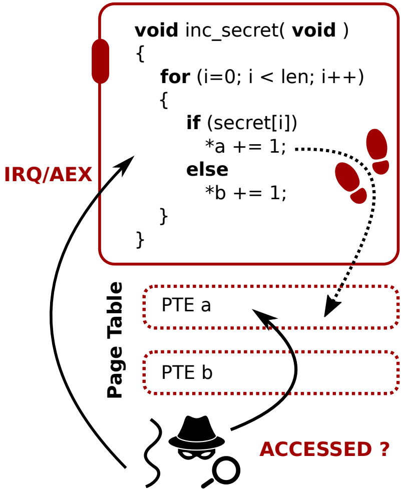

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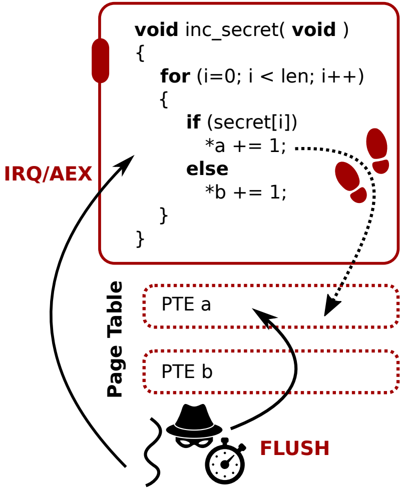
   ⇝ Precise **Flush+Flush** technique



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PTE Flush+Flush: A High-Resolution, Low-Latency Channel

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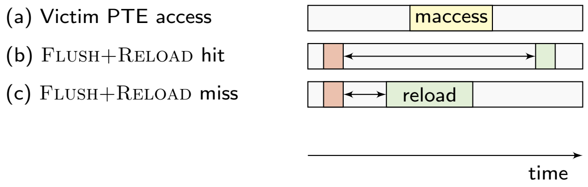

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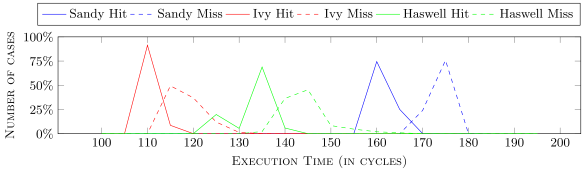
- ☺ Flush+Flush: `clflush` completes earlier for uncached data



Gruss et al. “Flush+Flush: a fast and stealthy cache attack”, DIMVA 2016 [GMWM16]

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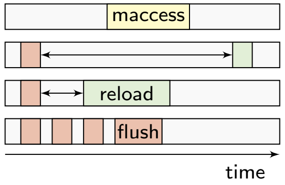
- ☺ Flush+Flush: interrupt *within trigger instruction* ($>$ 99.8%)

(a) Victim PTE access

(b) Flush+Reload hit

(c) Flush+Reload miss

(d) Flush+Flush hit



Attacking Libgcrypt EdDSA

```
if (mpi_is_secure (scalar)) {
    /* If SCALAR is in secure memory we assume that it is the
       secret key we use constant time operation. */
    point_init (&tmppnt);

    for (j=nbits-1; j >= 0; j--) {
        _gcry_mpi_ec_dup_point (result, result, ctx);
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        point_swap_cond (result, &tmppnt, mpi_test_bit (scalar, j), ctx);
    }
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EdDSA secret scalar *not* stored in "secure memory" !

Attacking Libgcrypt EdDSA

```
if (mpi_is_secure (scalar)) {
    /* If SCALAR is in secure memory we assume that it is the
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    for (j=nbits−1; j >= 0; j−−) {
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    }
}
```

Secret-dependent control flow

Attacking Libgcrypt EdDSA: A/D Channel

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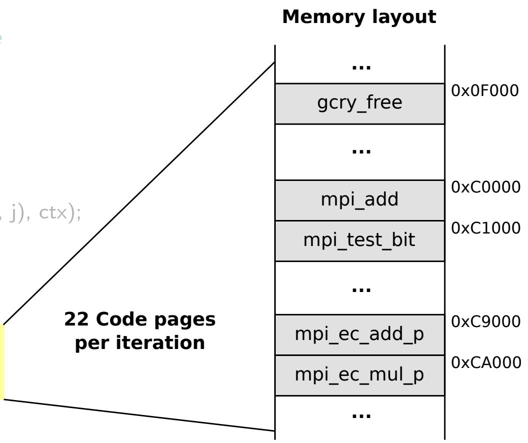
```



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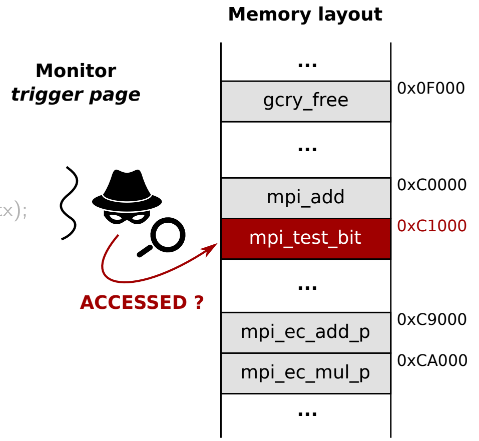

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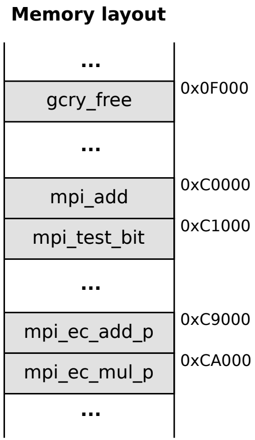
INTERRUPT



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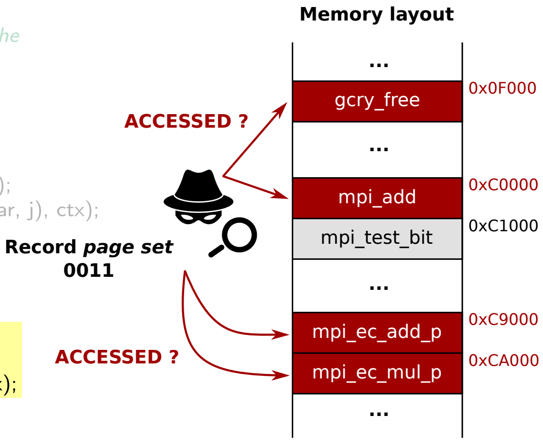

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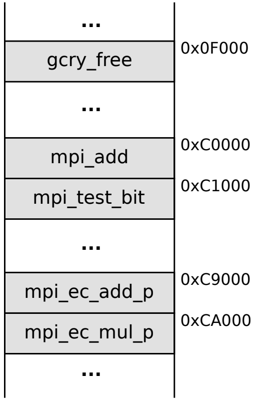
```

RESUME

Full 512-bit key recovery, single run

Memory layout



Attacking Libgcrypt EdDSA: Cache-Only Channel

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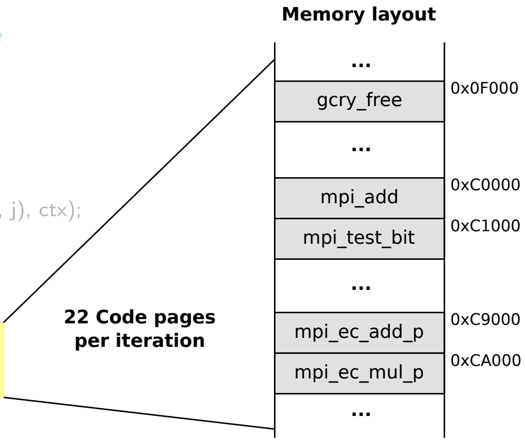

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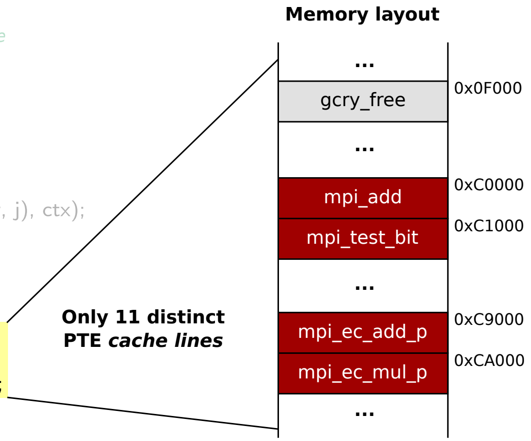

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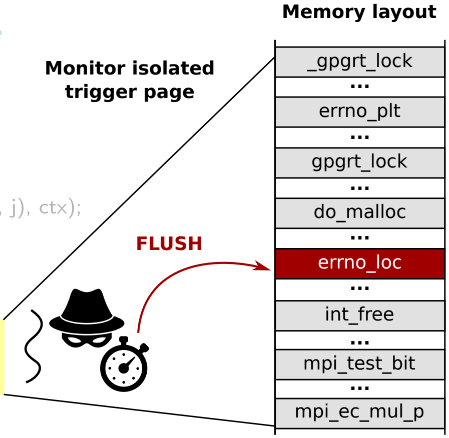

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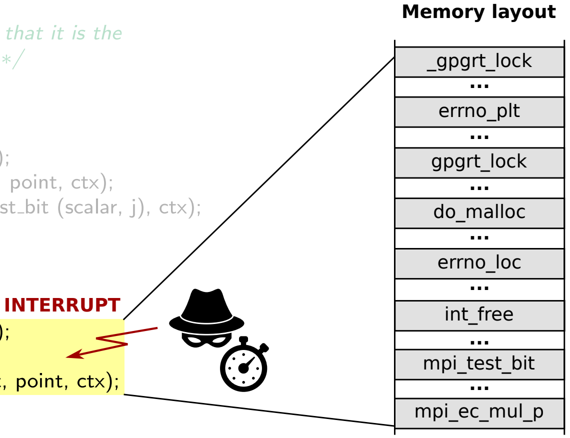

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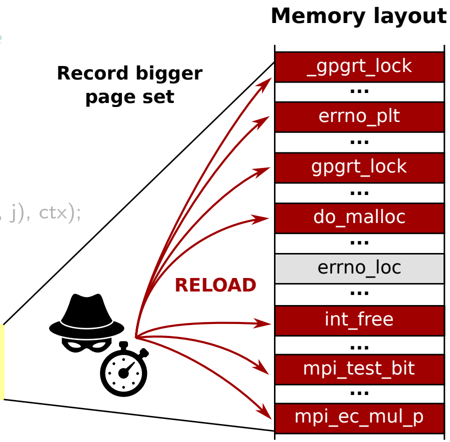

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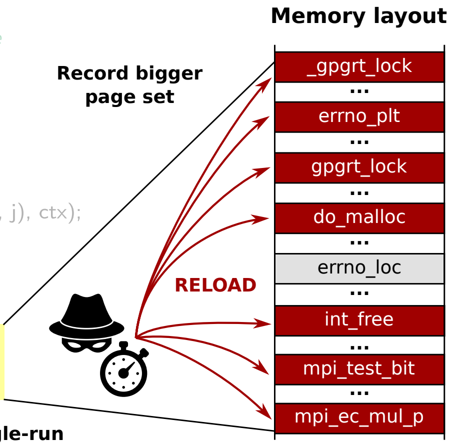


Regex pattern match -> 485/512-bit recovery, single-run

Road Map

Conclusion

Take-Away Message

Enclave memory accesses can be learned *without* triggering page faults.

Conclusion

Take-Away Message

Enclave memory accesses can be learned *without* triggering page faults.

$\Rightarrow$ Do not focus on attack **side-effects** (faults, frequent enclave preemptions)

Conclusion

Take-Away Message

Enclave memory accesses can be learned *without* triggering page faults.

⇒ Do not focus on attack **side-effects** (faults, frequent enclave preemptions)

⇒ Address **root causes of information leakage:**

- Unprotected page table memory (Sanctum [CLD16])
- Secret-dependent control flow/data access (Libgcrypt patch)

Thank you! Questions?

`https://github.com/jovanbulck/sgx-pte`

References I

V. Costan and S. Devadas.
Intel SGX explained.
Technical report, Computer Science and Artificial Intelligence Laboratory MIT, 2016.
`https://eprint.iacr.org/2016/086.pdf`.

V. Costan, I. Lebedev, and S. Devadas.
Sanctum: Minimal hardware extensions for strong software isolation.
In *25th USENIX Security Symposium*, pp. 857–874. USENIX Association, 2016.

D. Gruss, C. Maurice, K. Wagner, and S. Mangard.
Flush+flush: A fast and stealthy cache attack.
In *Detection of Intrusions and Malware, and Vulnerability Assessment (DIMVA)*, 2016.

S. Shinde, Z. L. Chua, V. Narayanan, and P. Saxena.
Preventing page faults from telling your secrets.
In *Proceedings of the 11th ACM on Asia Conference on Computer and Communications Security (ASIA CCS)*, pp. 317–328. ACM, 2016.

M.-W. Shih, S. Lee, T. Kim, and M. Peinado.
T-SGX: Eradicating Controlled-Channel Attacks Against Enclave Programs.
In *24th Annual Network and Distributed System Security Symposium (NDSS)*, 2017.

C.-C. Tsai, D. E. Porter, and M. Vij.
Graphene-SGX: A practical library OS for unmodified applications on SGX.
In *2017 USENIX Annual Technical Conference (USENIX ATC)*. USENIX Association, 2017.

References II

Y. Xu, W. Cui, and M. Peinado.
Controlled-channel attacks: Deterministic side channels for untrusted operating systems.
In *2015 IEEE Symposium on Security and Privacy*, pp. 640–656. IEEE, 2015.

IPI Latency Microbenchmarks

Table: IPI latency in terms of the number of instructions executed by the victim after accessing the trigger page.

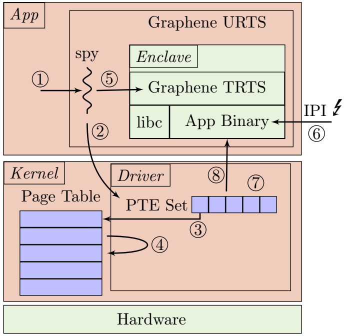
	ACCESSED		FLUSH+FLUSH		
Experiment	**Mean**	σ	**Mean**	σ	**Zero %**
`nop`	431.70	34.11	0.65	17.65	99.84
add register	176.30	14.60	0.15	6.18	99.94
add memory	32.45	2.79	0.06	1.92	99.88
`nop` nocache	0.02	0.39	–	–	–

Putting it All Together: Inferring Page Access Patterns

Re-usable attack framework: Graphene-SGX [TPV17]

- Explicitly monitor **trigger page(s)**
- Capture max info in **page sets** $\leftrightarrow$ #PF-sequences
- Offline analysis: extract **access patterns**

$\Rightarrow$ overcome measurement *noise/ latency/ granularity*


App
Graphene URTS
spy
Enclave
Graphene TRTS
libc
App Binary
IPI
① ② ③ ④ ⑤ ⑥ ⑦ ⑧
Kernel
Driver
Page Table
PTE Set
Hardware