Performance Evolution of Mitigating Transient Execution Attacks

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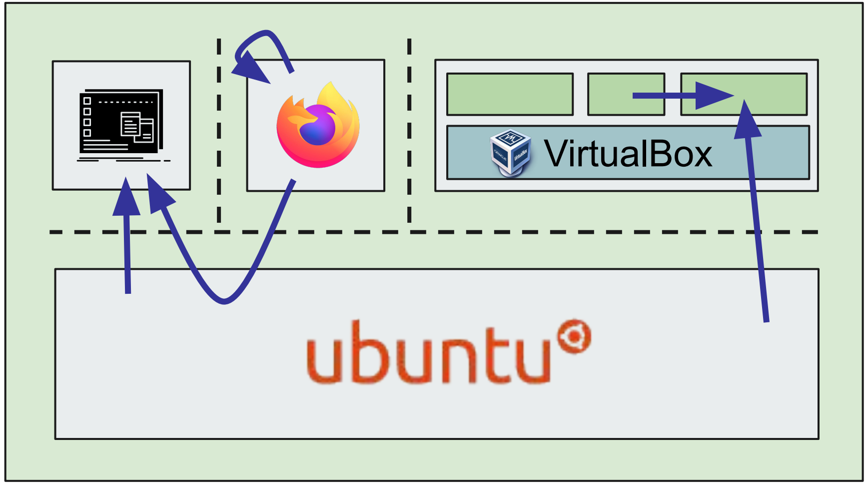
Transient execution attacks break isolation

- Enable programs to access information they shouldn't be able to.
- Different cases:
    a. Program reading information from the OS
    b. Program accessing information from another program
    c. Leaking information between websites visited in the same web browser



There are many different transient execution attacks

Mitigations restore security guarantees

- Involve either software changes or hardware fixes.
- Some have a large performance overhead, while others don't.

Attack	Mitigation
Meltdown	Page Table Isolation
L1TF	PTE Inversion Flush L1 Cache
LazyFP	Always save FPU
Spectre V1	Index Masking lfence after swapgs
Spectre V2	Generic Retpoline AMD Retpoline IBRS Enhanced IBRS RSB Stuffing IBPB
Spec. Store Bypass	SSBD
MDS	Flush CPU Buffers Disable SMT

Contributions: Understanding the performance evolution of mitigations

- End-to-end performance study over generations of processors
- Detailed microbenchmarking of individual mitigations
- New technique to measure speculation (not covered in this talk)

We evaluate the performance of mitigations not their security.

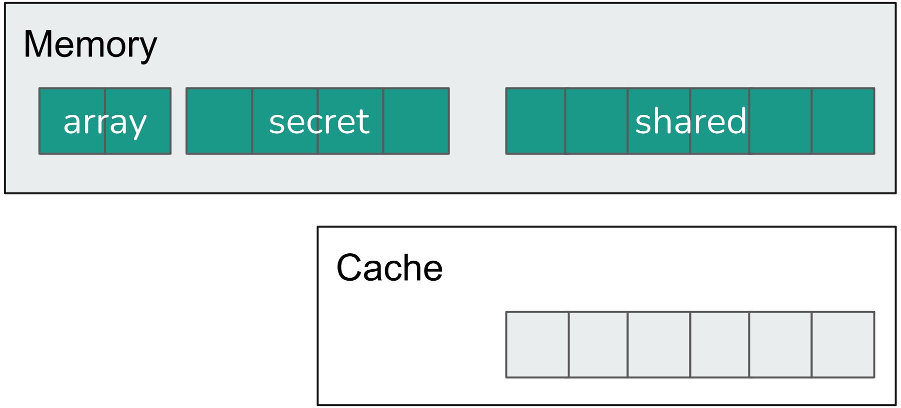
Example attack: Spectre V1

```
// vulnerable if index >= SIZE
if (index < SIZE) {

  y = array[index];
  z = shared[y * CACHE_LINE];
}



// userspace attacker code
secret = is_in_cache(&shared[0]);
```



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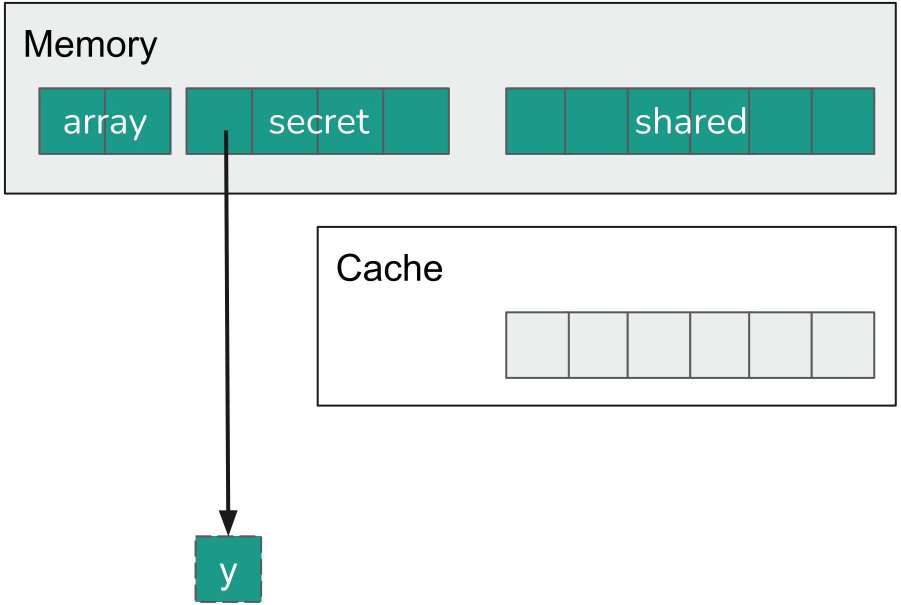

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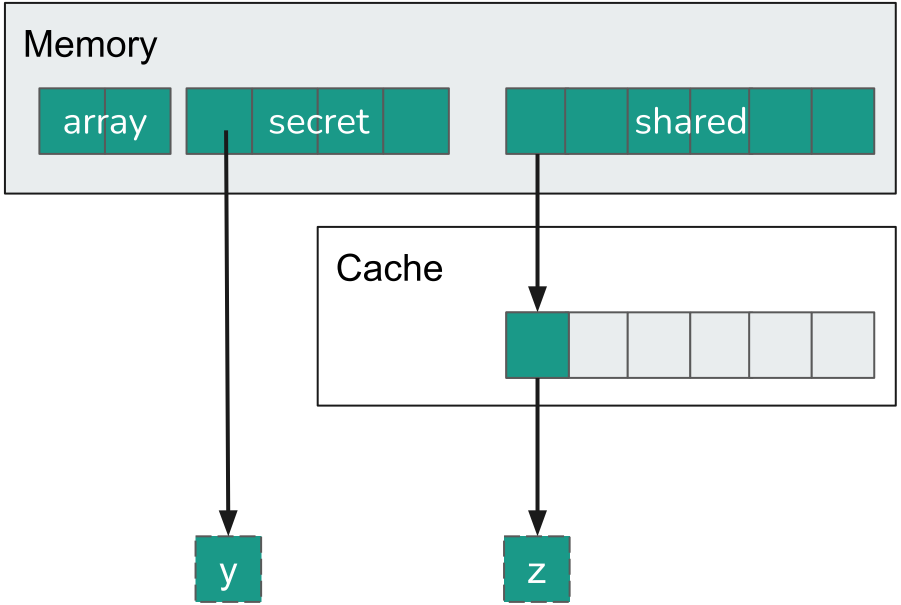

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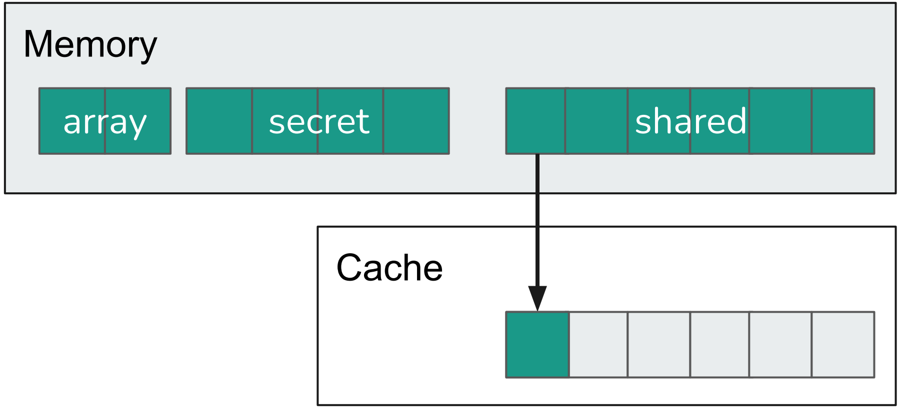

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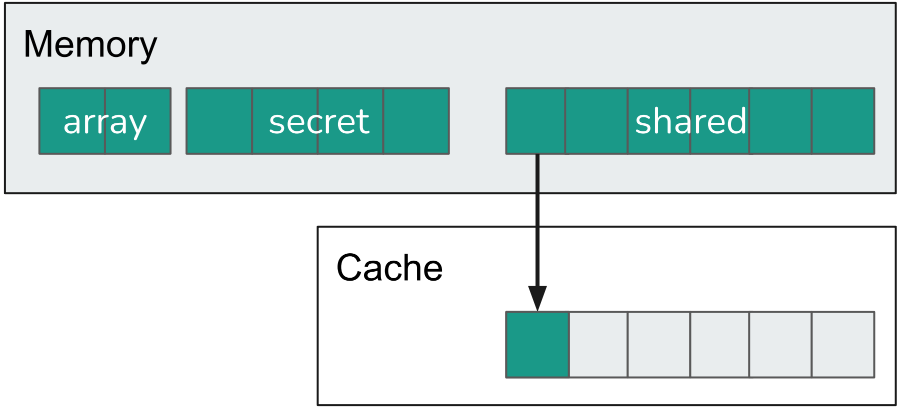
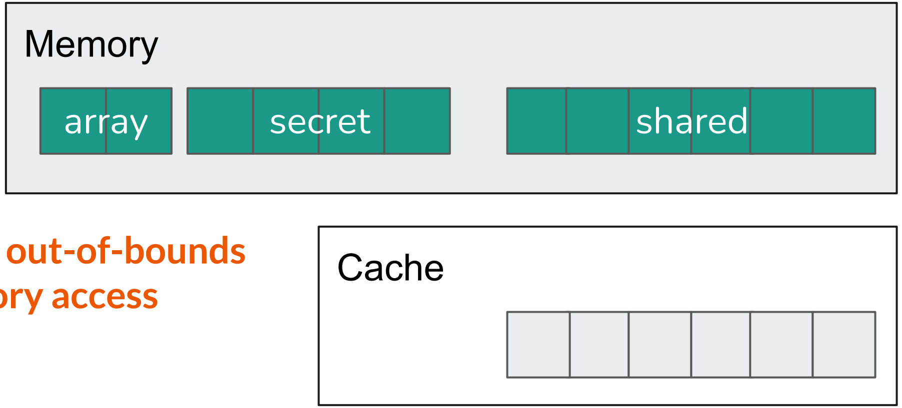


Example Mitigation

```
// vulnerable if index >= SIZE
if (index < SIZE) {
  index &= ~(long)(index|(SIZE-1-index))>>63;
  y = array[index];
  z = shared[y * CACHE_LINE];
}
```

Block out-of-bounds memory access

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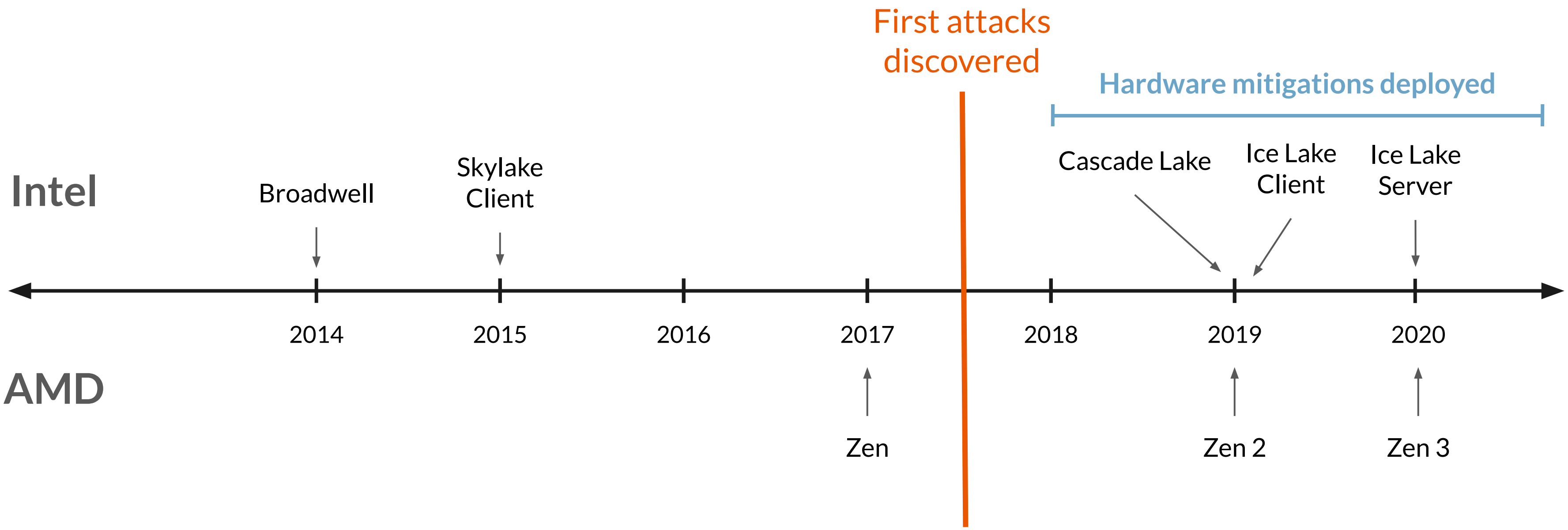
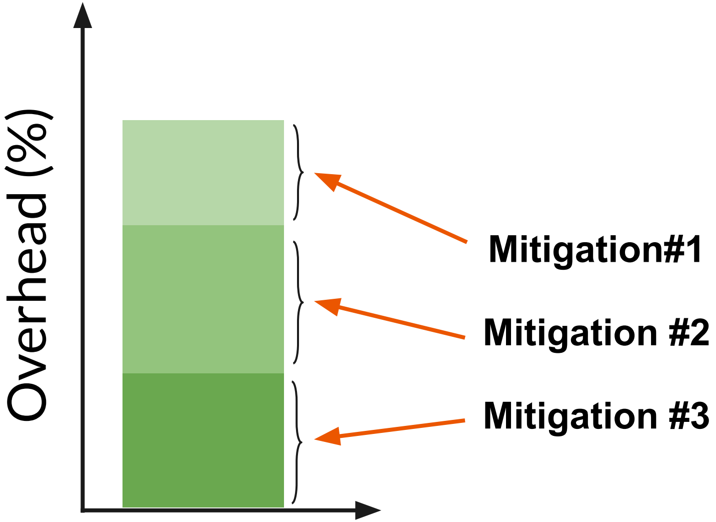
Understanding Performance Impact

Approach: Evaluate a range of CPU generations

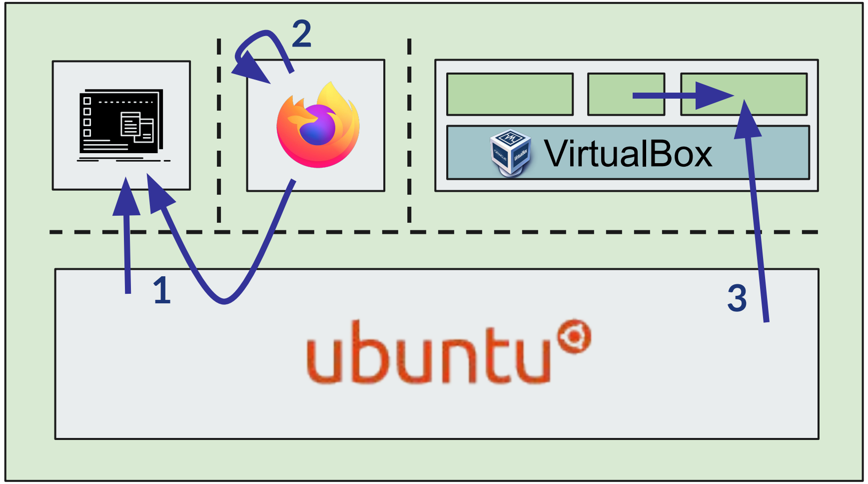


Goal: Attribute overhead to mitigations

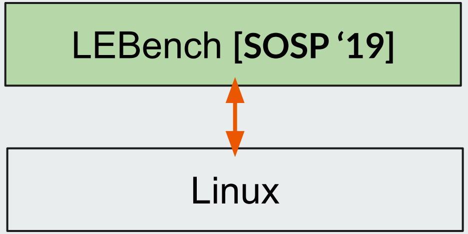


Workloads: focus on security boundaries

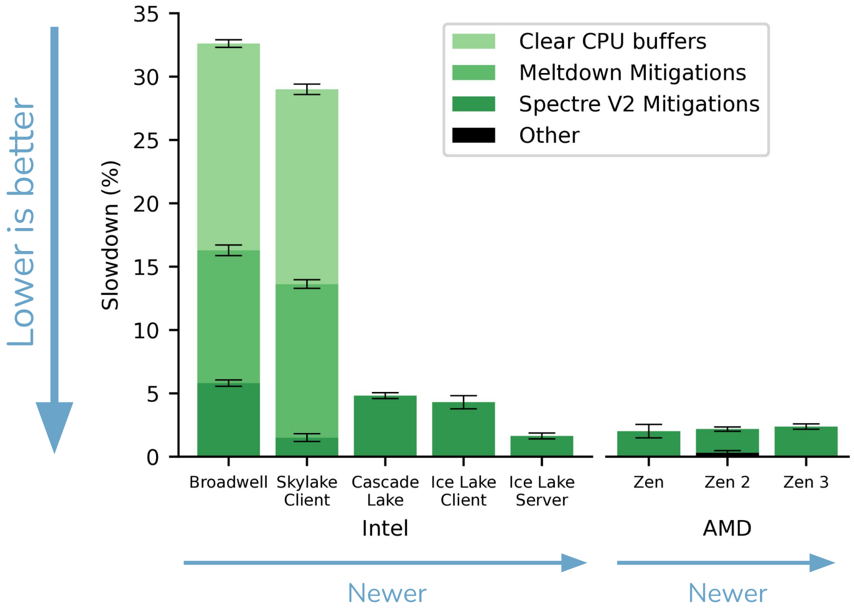
1. Operating system boundary
2. JavaScript sandbox
3. Virtual machines
    - Had minimal overhead; see paper for details



Study 1:
Operating System Boundary



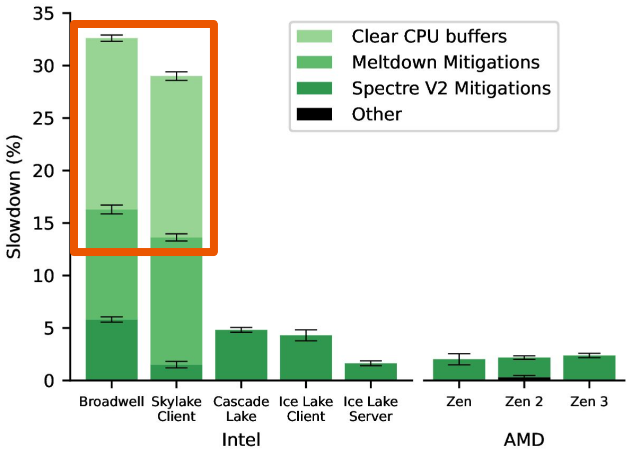
Operating system boundary overhead has decreased



- Declined from 30% → 3%.
- Only a few attacks impact performance.

Microarchitectural Data Sampling (MDS)

- Performance impact on Broadwell and Skylake Client
- Adds **15% overhead** to LEBench.



OS-level mitigation overhead

MDS: Hardware fix avoids costly mitigation

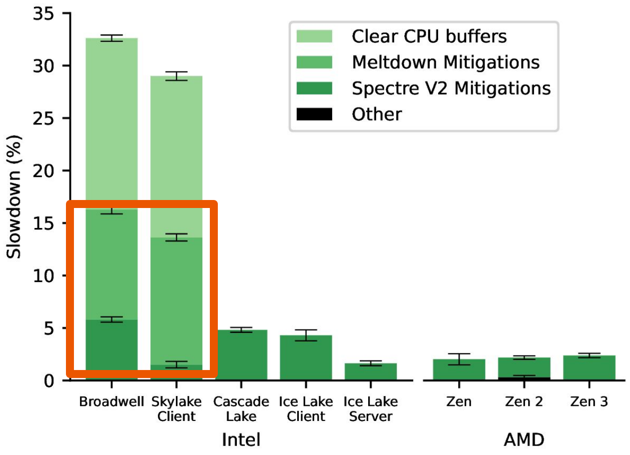
- Mitigated by executing a **verw** instruction after every system call.
- **Adds 500+ cycles overhead** to every system call.
- Only older Intel processors are vulnerable.

Vendor	CPU	Clear Cycles
Intel	Broadwell	610
	Skylake Client	518
	Cascade Lake	N/A
	Ice Lake Client	N/A
	Ice Lake Server	N/A
AMD	Zen	N/A
	Zen 2	N/A
	Zen 3	N/A

Cycles required to perform the MDS mitigation

Meltdown: Also expensive to mitigate

- Same two processors are affected.
- Causes **10% overhead** on LEBench.



OS-level mitigation overhead

Meltdown: Hardware fix avoids another mitigation

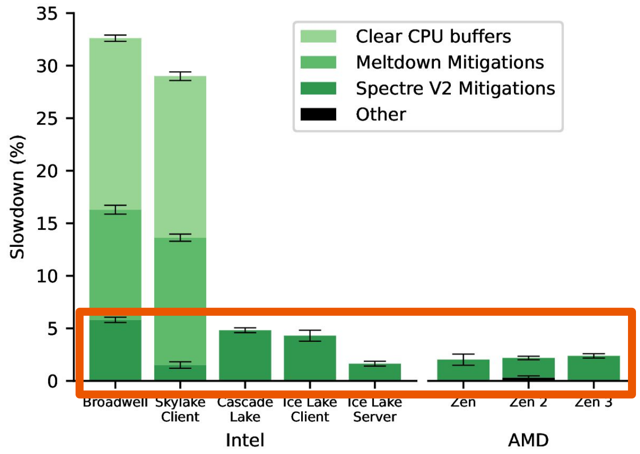
- Mitigated using **Kernel Page Table Isolation**
    - Requires switching page tables on every system call entry *and* exit.
- Cost far exceeds time spent changing privilege modes.
- Again, only older Intel processors are vulnerable

Vendor	CPU	KPTI Cycles
Intel	Broadwell	412
	Skylake Client	382
	Cascade Lake	N/A
	Ice Lake Client	N/A
	Ice Lake Server	N/A
AMD	Zen	N/A
	Zen 2	N/A
	Zen 3	N/A

Cycles spent on the mitigation during a system call

Spectre V2: Still around but modest cost

- Impacts all our processors.
- Overhead of **3-5%** on LEBench.



OS-level mitigation overhead

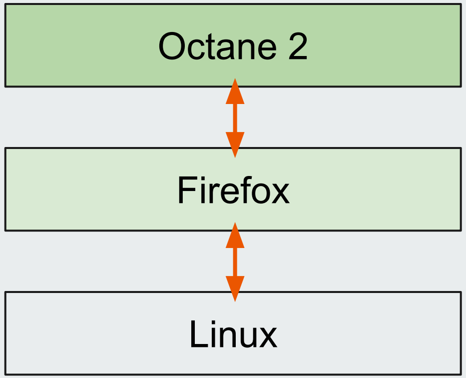
Spectre V2: Involves many mitigations

- Many different mitigations, both hardware and software.
    - See paper for a detailed look

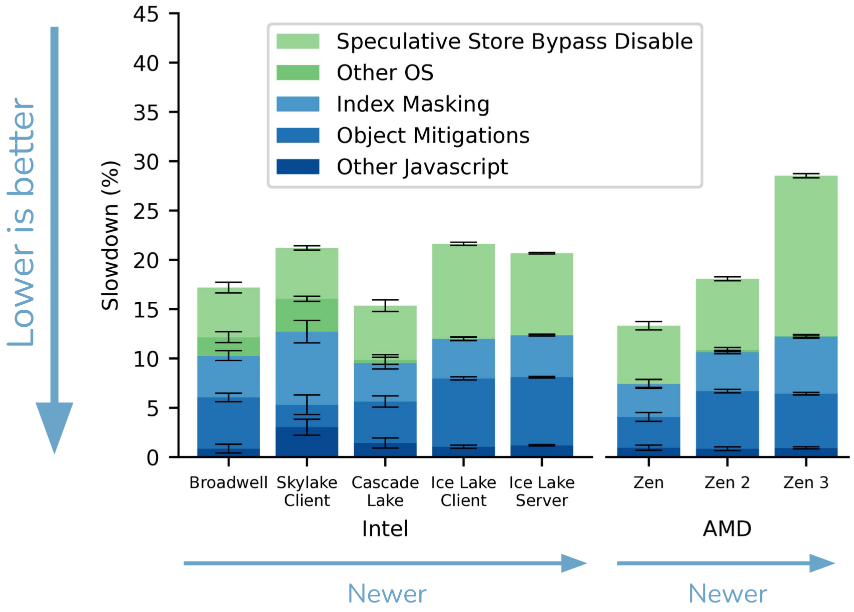
Mitigation	Broadwell	Skylake Client	Cascade Lake	Ice Lake Client	Ice Lake Server	Zen	Zen 2	Zen 3
Retpoline	✓	✓				✓	✓	✓
IBRS								
eIBRS			✓	✓	✓			
RSB Stuffing	✓	✓	✓	✓	✓	✓	✓	✓
IBPB	✓	✓	✓	✓	✓	✓	✓	✓

The different mitigations for Spectre V2 and which processors use each.

Study 2: JavaScript Sandbox



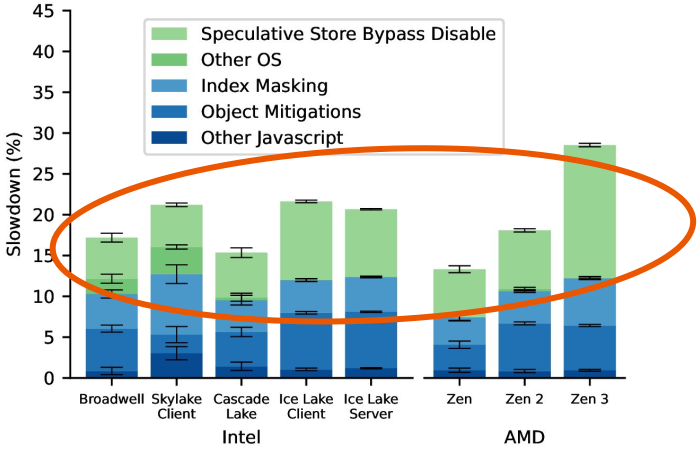
Javascript sandbox overhead has not improved



- **No improvement** across generations
- Slowdown is in relative terms: Zen 3 is actually far faster than any of the others

Speculative Store Bypass: Impacts Firefox if enabled

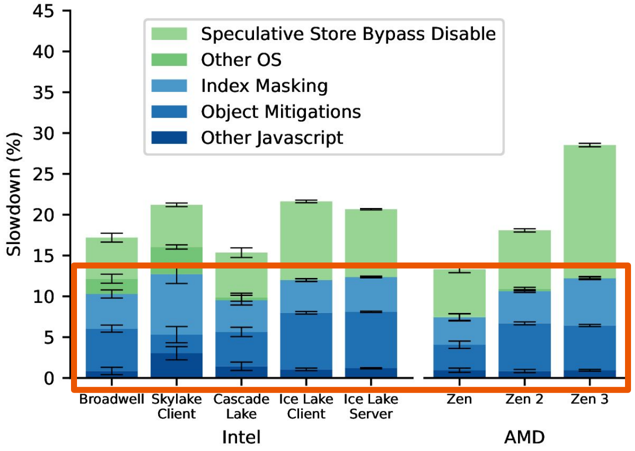
- All our processors are vulnerable, but protection is opt-in.
- **Most programs do not use the mitigation.**
  - Firefox did when we tested, but future versions seem not to.
- ISA provides a flag to detect if a processor is vulnerable.
  - Suggests that future processors might not be.



JavaScript mitigation overhead

Spectre V1: Only impacts Firefox

- Major slowdown for JavaScript.
- Mitigated using **index masking**, **object mitigations**, and a few others.
    - Automatically by a JIT (JavaScript)
    - Or manually applied by the programmer (C code)



JavaScript mitigation overhead

Takeaways

- Operating system boundary: new processors eliminate nearly all the overhead
- JavaScript sandboxing: overhead is still high
  - Better Spectre V1 mitigations could have a big impact
- Overhead on new CPUs is only from **Spectre V1**, **Spectre V2**, and **Speculative Store Bypass**
  - All three attacks have been known since 2018.
  - Attacks discovered since don't cause much overhead.

Limitations

- Workloads may not be representative of all applications
  - To find out how your specific application is impacted, benchmark it!
- Some security boundaries aren't covered (e.g. the eBPF-kernel boundary)
- Future is uncertain:
  - New processor generations might be different
  - Other attacks might be discovered
  - Existing mitigations might actually be flawed

Related work

- Many attack papers; a couple surveys including **Hill [MICRO ‘19]**, **Canella [CoRR ‘18]**, and **Xiong [ACS ‘22]**.
- Lots of work on hardware and software fixes.
    - **SpecShield [PACT ‘19]**, **Speculative Taint Tracking [MICRO ‘19]**, **NDA [MICRO ‘19]**, **MuonTrap [ISCA ‘20]**, and **Speculative Data-Oblivious Execution [ISCA ‘20]**.
    - **Site Isolation** in Firefox and Chrome and **Swivel [USENIX Security]** all for WASM bytecode.
    - **Retpolines** and **Kernel Page Table Isolation**.
- Top-level benchmarks from **Phoronix** and others.
    - We go further by attributing overheads to specific mitigations, and measuring Javascript mitigations.

Conclusion

- We benchmarked the effect of mitigations over a range of processor generations and workloads.
- Hardware changes significantly speed up OS-level workloads, while JavaScript overheads remain.
- JavaScript Spectre V1 mitigations are a good direction for further optimization.

github.com/mit-pdos/spectrebench

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