

Transient Execution Emulator

Meltdown and Spectre Behind the Scenes

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- Topic
- Background
- Our task & approach
- Implementation
- Demos:
 - Meltdown
 - Spectre
- Conclusion

- Lab builds on SCA lecture
- Meltdown and Spectre mostly patched
- Difficult to experiment with
 - Personal computer often times not usable
- Goal: Vulnerable CPU Emulator that runs on many systems
 - Should offer a gdb-like interface

Background

- Frontend:
 - Fetches/Decodes instructions, maintains queue
 - Branch prediction
- Execution Engine:
 - Multiple sets of execution units
- Memory Subsystem:
 - Handles memory operations
 - Maintains L1 cache
 - Ensures data is loaded from other caches/memory

- Independent instruction streams
- Tomasulo algorithm:
 - Reservation stations
 - Common Data Bus
- Rollbacks

Speculative execution

- Predict results of branch instructions
- Prevent stalls
- BPU maintains counters
- Rollbacks

- Abuses out-of-order execution
- Meltdown-US-L1:
 - Define oracle array
 - Perform illegal read to steal secret
 - Embed secret-dependent oracle entry into cache
 - Await rollback and measure oracle access times
- Small time window

- Abuses speculative execution
- Different variations. Here: prediction of conditional branch instrs.
- Spectre v1: Deliberately train BPU used by victim process
- Make victim leak secret into cache
- Direct consequence of speculative execution

- Disable out-of-order execution
- Intel's microcode mitigation
 - Microprograms
- OS mitigations

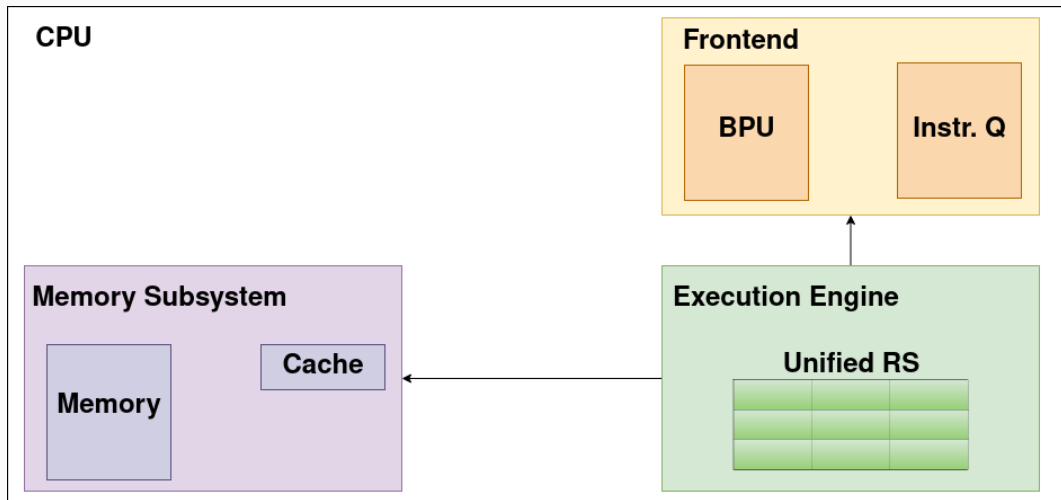
- Disable speculative execution:
 - Completely disable
 - fence instructions
- Flush entire cache after rollback

Our task

- Develop graphical CPU emulator vulnerable to:
 - Our version of Meltdown-US-L1
 - Spectre v1
- Must support single step, out-of-order, and speculative execution
- Implement Intel's microcode mitigation
- Other mitigations via microprograms
- Target audience: SCA students
 - Or anyone with basic knowledge of TE attacks

Our approach

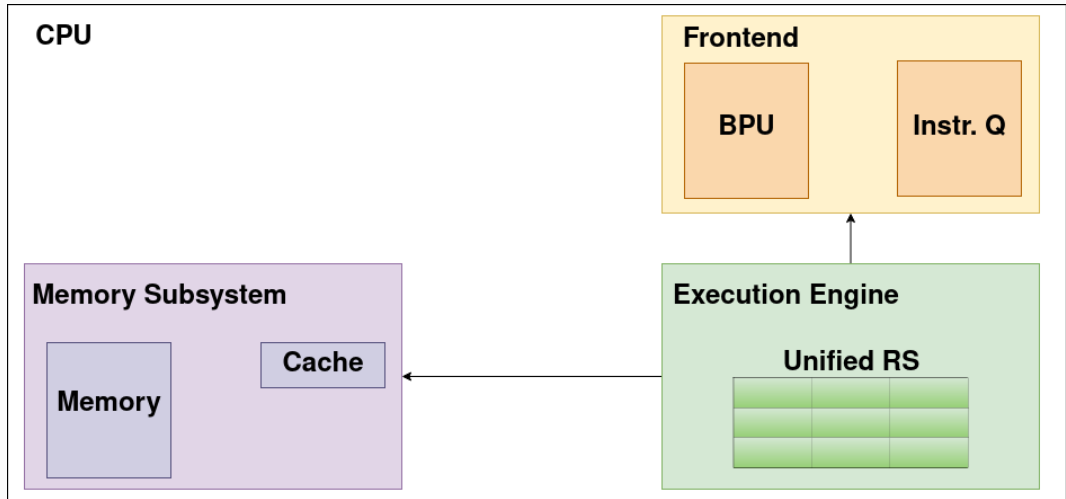
- Must-haves, nice-to-haves, future work
- At time of Meltdown/Spectre publication: Skylake
- Filter components needed for our Meltdown/Spectre versions
- Build simplified CPU



Implementation of our emulator

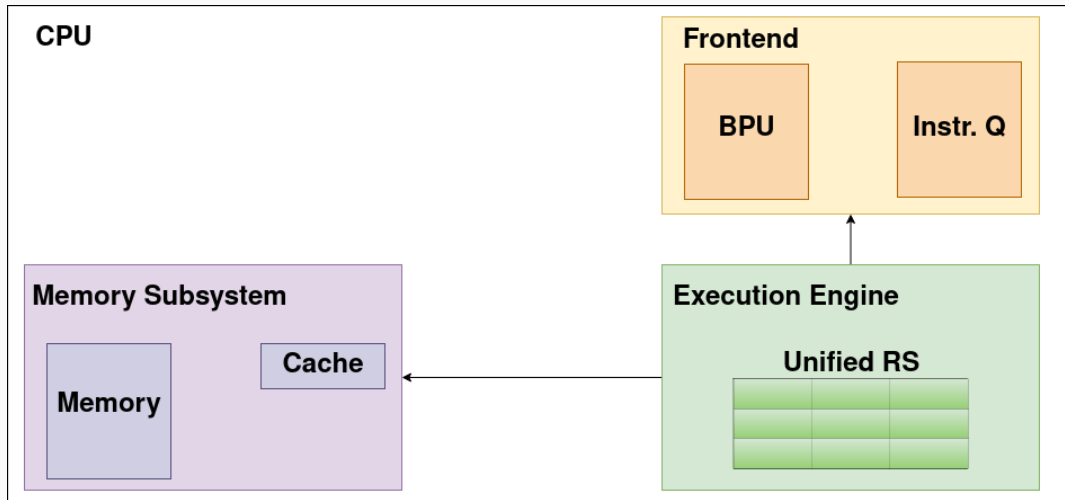
Implementation of our emulator

- overview over our whole emulator
- Out-of-order execution
- Speculative execution
- Fault handling and rollbacks



- Assembler style source code
- Arithmetic, branch and memory instructions, fence, rtdsc
- Provides an instruction list
- Only one type of instructions

CPU components



- Execution engine
- Tomasulos algorithm
 - Unified reservation station
 - Instructions wait for their operands
 - Keeping track of operands and results

- Resolve operands and target register
- Two kinds of register values: Word and SlotID
- Put register content into operand list
- Put SlotID into target register

Example Reservation Station

| -----[Reservation Stations]----- | | | | | |
|------------------------------------|------|--------------|--------|--------|-------------------------------------|
| 0 | addi | r1, r0, 0x3 | 0x0000 | 0x0003 | <input checked="" type="checkbox"/> |
| 1 | slli | r2, r1, 0x8 | 0x0003 | 0x0008 | <input type="checkbox"/> |
| 2 | addi | r2, r2, 0x42 | RS 001 | 0x0042 | <input type="checkbox"/> |
| 3 | sw | r2, r0, 0x4 | RS 002 | 0x0000 | <input type="checkbox"/> |
| 4 | lb | r4, r0, 0x5 | 0x0000 | 0x0005 | <input type="checkbox"/> |

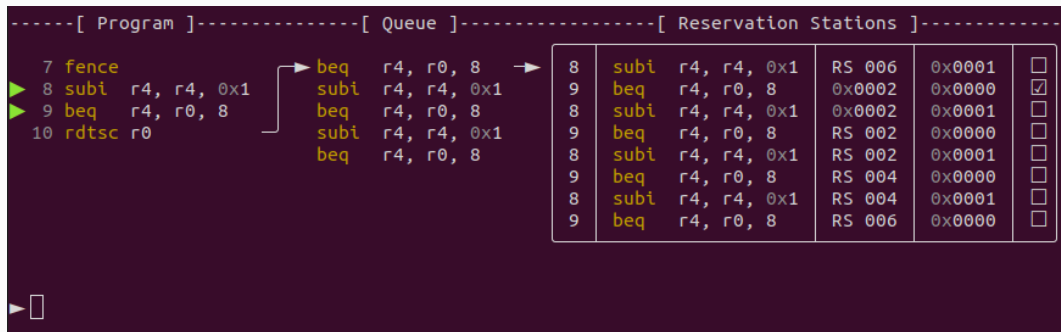
- Execute instructions in reservation station
- Broadcast the result over the CDB
 - Registers
 - Reservation station slots
 - At most once per cycle

- Predict outcome of branch instructions
- Resume execution based on this prediction
- Two central components
 - Branch prediction unit (BPU)
 - CPU frontend with instruction queue

- Simplified version
- Array of predictions
- 2-bit-saturating counter to handle predictions

CPU frontend with instruction queue

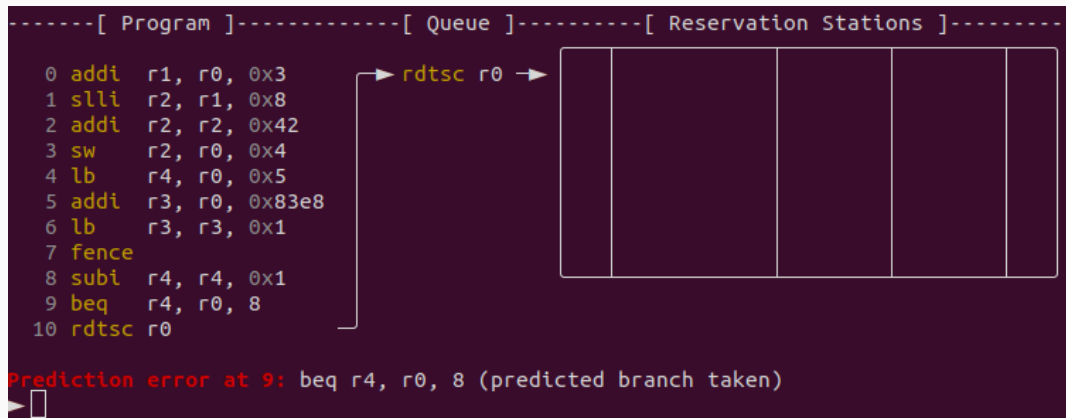
- Interface between instruction list and execution unit
- Involved in speculative execution
- Manages instruction queue



- Microarchitectural fault situation that has to be handled before we can resume our execution
 - Mispredicted branches
 - Attempt to access inaccessible memory
- Have to handle the effects of transient execution

- Only rollback the register state and the memory contents
- No rollback in Cache and BPU
- Restore register state via snapshots
- Prevent memory rollbacks by executing stores in-order
- Handle faults in program order

Rollback after mispredicted branch



Thank you for your attention

Do you have any questions so far?

Demo



Demo - Meltdown

```
lb r1, r0, 0xc000
slli r1, r1, 4
lb r2, r1, 0x1000
```

Encode byte into oracle array

```
fence
addi r1, r0, 0
addi r2, r0, 0xFFFF
addi r3, r0, 0x0000
addi r4, r0, 0x0FF0
```

| r1 | r2 | r3 | r4 |
|------------------|-----------------------|-------------------|----------------|
| shortest load | shortest load time | current offset | last offset |

```
probe:
fence
rdtsc r5
lb r7, r3, 0x1000
fence
rdtsc r6
sub r5, r6, r5
```

Measure access time

```
bgtu r5, r2, skip
addi r1, r3, 0
addi r2, r5, 0
skip:
```

update shortest

```
addi r3, r3, 0x10
bgeu r4, r3, probe
```

increment and loop

- Demonstrate mechanism behind Spectre-type attacks
- BPU can be trained for targeted misprediction
- Requires code sequence that encodes leaked value into cache

Spectre-Type Attack: Overview

- Prepare victim array: 8 elements, all `0x01`
 - Followed by secret value `0x41`
- Victim loops over the array and encodes each value into the cache
 - BPU is trained to predict that the loop continues
- Final loop condition will be mispredicted
 - During transient execution: Additional iteration with out-of-bounds index
 - Secret value accessed and encoded into cache

Spectre-Type Attack: Preparation

```
// Set up array at 0x1000, 8 elements, all 0x01
addi r1, r0, 0x1000
addi r2, r0, 0x01
sb r2, r1, 0
sb r2, r1, 1
sb r2, r1, 2
sb r2, r1, 3
sb r2, r1, 4
sb r2, r1, 5
sb r2, r1, 6
sb r2, r1, 7
// Followed by one out-of-bounds 0x41 value
addi r2, r0, 0x41
sb r2, r1, 8
```

Spectre-Type Attack: Execution

```
// Loop over array, encode every value in cache
addi r2, r0, 0    // r2: Loop index
addi r3, r0, 8    // r3: Array length
loop:
// Load array element
lb r4, r2, 0x1000
// Encode value in cache
slli r4, r4, 4
lb r4, r4, 0x2000
// Increment loop index
addi r2, r2, 1
// Loop while index is in bounds
bne r2, r3, loop
```

Attack Demo

- Flush cache after rollback
- Prevents using cache as transmission channel
- Implementation: Inject microcode after rollback
 - Inject `flushall` instruction after mispredicted branch

Mitigation Demo

- Goal: CPU Emulator
 - Out-of-Order Execution
 - Branch Prediction
 - Transient Execution Attacks
 - Mitigations

- More Spectre and Meltdown variants
 - Meltdown: Load, Store, Line-Fill Buffers
 - Spectre: elaborate BPU
- Multiple execution contexts
- Operating System
- UI Improvements