Meltdown
CSE 351 Winter 2018

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*thanks to Eddie Yan for a subset/skeleton of the slides

Computer Architecture – The Basics

- Address Translation
  - Memory addresses in our program are virtual and require a translation

```
int myArray[42]; // software address: 0xdead00a8
                 // physical address: 0xffff00a8
```

Computer Architecture – The Basics

- Caching
  - CPUs have caches that speed up memory access!
  - Typically physically addressed (after address translation)
- Assume access below is valid and memory page is in DRAM

```
int x = myArray[42]; //goes to DRAM, sloooooow...
int y = myArray[42]; //goes to Cache, 1 CPU cycle
```

- Cache/memory accesses can be timed by user programs!

Computer Architecture – The Basics

- Out-of-Order Execution
  - Modern CPUs can run Out-of-Order (OoO)
- These lines can run in parallel!
  - Computation for **d** and **e** are independent
  - These operations may be executed by CPU in any order

```
int d = a + b + fac(c);
int e = a + b + c;
return d + e;
```

Computer Architecture – The Basics

- Speculation
  - Modern, high-performance processors can execute instructions (statements) speculatively
- Consider this code:

```
assert(idx < len);
result = data[idx];
```


Computer Architecture – The Basics

- Speculation
  - Modern, high-performance processors can execute instructions (statements) speculatively
- Consider this code:
  - The second line can execute before the check completes!

```
assert(idx < len);
result = data[idx];
```

Computer Architecture – The Basics

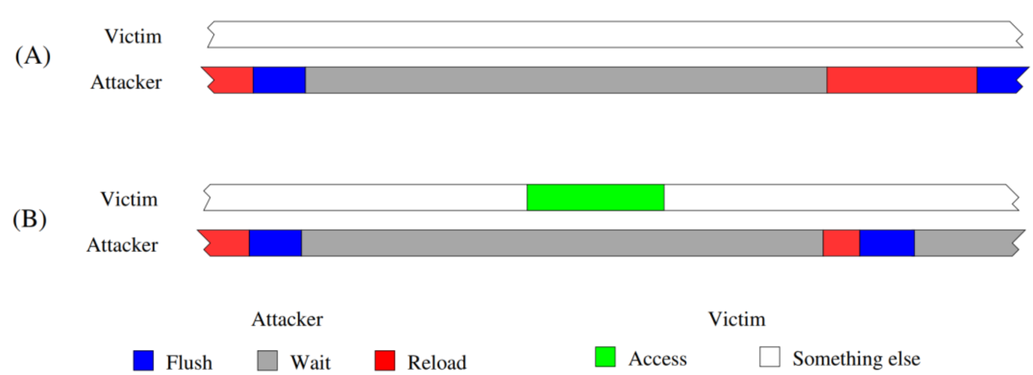
- Speculation
  - Modern, high-performance processors can execute instructions (statements) speculatively

- CPU often does something more like:

```
result = data[idx];
if (idx >= len)
  // assert should have fired!
  // CPU rolls back state
  do_assert();
```

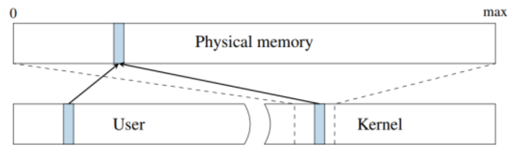

Flush + Reload

- Starting with a empty (cold) cache, an attacker can use timing information to determine if a cache block was loaded by the victim



Meltdown - Assumptions

- All of physical memory is mapped to kernel addresses in user process
  - Start address (VA in user process) of physical memory is known, A_k
  - Physical memory is K bytes total, and mapped directly, $[A_k \ldots (A_k + K - 1)]$



- An exception (illegal memory access) can be handled/suppressed
- Kernel Address Space Layout Randomization not used
  - Similar to randomizing start address of stack, kernel data structure start address can be randomized

Meltdown – Data Structures/Variables

- Two important data structures/variables

```
char probe_array[256 * 4096];    // 256 * 4KB = 256 pages

char* kernelAddr = {Ak … (Ak + K - 1)};
```

Meltdown – Toy Example

```
raise_exception();
// the line below is never reached
access(probe_array[data * 4096]);
```

- Assume `data` is a value between 0 – 255, and value is unknown
- Assume a cold cache

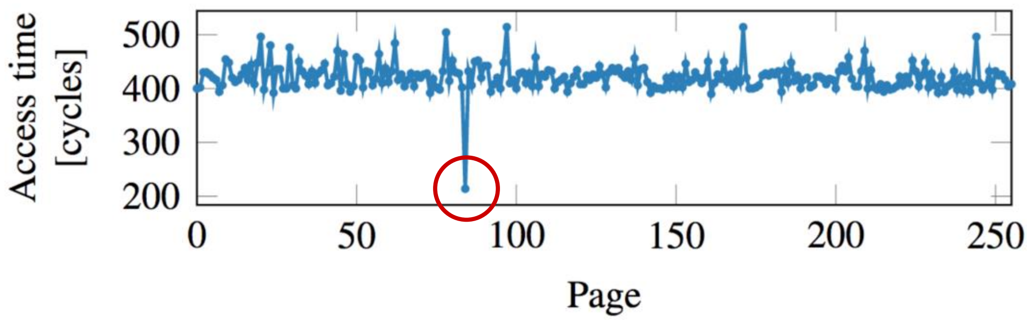
Meltdown – Toy Example

```
raise_exception();
// the line below is never reached
access(probe_array[data * 4096]);
```

- Assume the CPU executes the `probe_array` access ***Speculatively***, loading the element of the array into the cache.
- Even though the exception is raised and the architectural state is “rolled back”, the CPU still caches the memory access!

Meltdown – Toy Example

- After the speculative memory access, access all the elements of the **probe array**, looking for an unusually fast access (i.e., a cached access):



- The Page tells us what the value of **`data`** was!

Meltdown – Toy Example

- So, what did we accomplish?
  - `data` was an ***unknown*** value between 0 – 255
  - Based on the value of `data`, we speculatively loaded a cache line from `probe_array[data*4096]`
  - After the exception is handled/suppressed, iterate values of `data` from 0 – 255, and use timing code to determine if `probe_array[data*4096]` is a cache hit.

- If cache hit detected for a particular value of `data`, we learned the value of **`data`**!

Meltdown – the Exploit

- **Goal**: attempt to read physical memory by exploiting speculative and OoO execution, and the fact that all of physical memory is mapped to kernel addresses (virtual addresses) in a user process
- **Question**: if user process accesses a kernel address, an illegal memory access occurs, raising an exception. Does the CPU still speculatively perform the illegal load? And can we determine the value loaded?
- Yes!

Meltdown – the Exploit

```
// rcx = kernel address (kernelAddr)
// rbx = probe_array
retry:
  movb (%rcx), %al          // move a byte to %al (%rax)
  shl  0xc, %rax            // multiply by 4096 (<< 12)
  jz retry                  // retry if byte was 0**
  mov (%rbx,%rax), %rbx     // access probe_array[%al*4096]
```

** 0 is a special case, ignore for now

* Assume cold cache

Meltdown – the Exploit

```
1  // rcx = kernel address (kernelAddr)
2  // rbx = probe_array
3  retry:
4    movb (%rcx), %al          // WILL RAISE AN EXCEPTION!
5    shl  0xc, %rax
6    jz retry
7    mov (%rbx,%rax), %rbx
```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Meltdown – the Exploit

```
1  // rcx = kernel address (kernelAddr)
2  // rbx = probe_array
3  retry:
4    movb (%rcx), %al          // WILL RAISE AN EXCEPTION!
5    shl  0xc, %rax            // But, lines 5-7 executed
6    jz retry                  // speculatively!
7    mov (%rbx,%rax), %rbx
```

Meltdown – the Exploit

```
1  // rcx = kernel address (kernelAddr)
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3  retry:
4    movb (%rcx), %al          // WILL RAISE AN EXCEPTION!
5    shl  0xc, %rax            // But, lines 5-7 executed
6    jz retry                  // speculatively!
7    mov (%rbx,%rax), %rbx     // Races with Exception!
```


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Meltdown – the Exploit

```
1  // rcx = kernel address (kernelAddr)
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3  retry:
4    movb (%rcx), %al          // move a byte to %al (%rax)
5    shl  0xc, %rax            // multiply by 4096 (<< 12)
6    jz retry                  // retry if byte was 0
7    mov (%rbx,%rax), %rbx     // access probe_array[%al*4096]
```
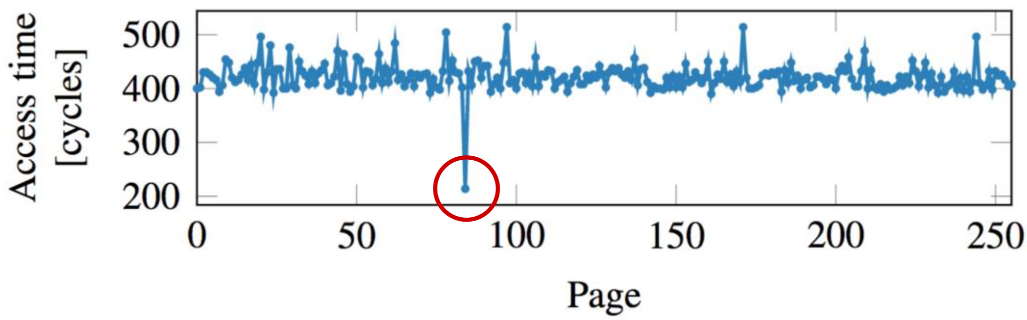

- So, what did we do? Attempt to load a byte from kernel memory (this is illegal for our user process!). Then, use that loaded byte in a speculative access to the probe_array, loading a cache line to our cold cache.
- How do we determine what the byte was?

Meltdown – the Exploit

- After the speculative memory access, access elements of the **probe array**, looking for an unusually fast access:



- Access `probe_array[data * 4096]`, timing the access for a cache hit. If hit detected, the value of **`data`** is the **byte read from the kernel address**!!!

Meltdown – Explained

- Race between raising exception for illegal kernel address access (from user process) and the probe array access.
  - Race is due to OoO and speculative execution in the CPU
- If the exception wins the race, the register %rax is zeroed to prevent leaking information
- If the probe array access wins the race, a cache line is loaded from memory. The line to load is determined by the value of the illegal load (byte %al) and uses %rax before it is zeroed by the exception.
- We can find the cache line that hits in the probe array on a second access, which tells us the value of the byte %al we loaded illegally!

Meltdown – the Exploit – what about 0?

```
// rcx = kernel address (kernelAddr)
// rbx = probe_array
retry:
  movb (%rcx), %al          // move a byte to %al (%rax)
  shl  0xc, %rax            // multiply by 4096 (<< 12)
  jz retry                  // retry if byte was 0**
  mov (%rbx,%rax), %rbx     // access probe_array[%al*4096]
```

** %rax will be 0 if the Exception wins the race with the probe_array access. Thus, if a zero is seen, try again. Either, a non-zero byte is used to perform the speculative access, or don't perform the speculative access at all! Then, when scanning probe_array, no hits will occur, and we can be reasonably confident the byte was 0.

Meltdown - Summary

- Allows a user process to read **all** of physical memory on the system, which is mapped in kernel addresses and by extension in user process address space
- Speculative execution occurs in the *exploit* (leak arises from CPU speculating in the *attacker's* code)

Meltdown - Mitigation

- Meltdown relies on the kernel address space being mapped into user process address space, and all of physical memory being mapped to kernel address space.
- KAISER (patch by Gruss et al.) implements a stronger isolation between kernel and user space. It leaves physical memory unmapped in kernel address space.
- Or, use an AMD processor, which doesn't bypass memory protection during speculative execution.