Introducing Speculative Execution Attacks

HW3 due tonight!
Colloquium after class (Seaver North);
HW4 to be released Monday

For fun: https://leaky.page/

About speculative execution vulnerabilities in ARM-based and Intel CPUs

- Apple has released security updates for macOS Sierra and El Capitan with mitigations for Meltdown.
- Apple has released updates for iOS, macOS High Sierra, and Safari on Sierra and El Capitan to help defend against Spectre.
- Apple Watch is unaffected by both Meltdown and Spectre.

Security researchers have recently uncovered security issues known by two names, Meltdown and Spectre. These issues apply to all modern processors and affect nearly all computing devices and operating systems. All Mac systems and iOS devices are affected, but there are no known exploits

Image Credit: https://support.apple.com/en-us/101886

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Spectre Attacks: Exploiting Speculative Execution

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Abstract

Modern processors use branch prediction and speculative execution to maximize performance. For example, if the destination of a branch depends on a memory value that is in the process of being read, CPUs will try to guess the destination and attempt to execute ahead. When the memory value finally arrives, the CPU either discards or commits the speculative computation. Speculative logic is unfaithful in how it executes, can access the victim's memory and registers, and can perform operations with measurable side effects.

Spectre attacks involve inducing a victim to speculatively perform operations that would not occur during correct

attacks, which do not require external measurement equipment. Although some attacks exploit software logic errors, other software attacks leverage hardware properties to infer sensitive information. Attacks of the latter type include microarchitectural attacks exploiting cache timing[3, 6, 17] and branch prediction history.[1] Software-based techniques have also been used to induce computation errors, such as fault attacks that alter physical memory[11] or internal CPU values.[25]

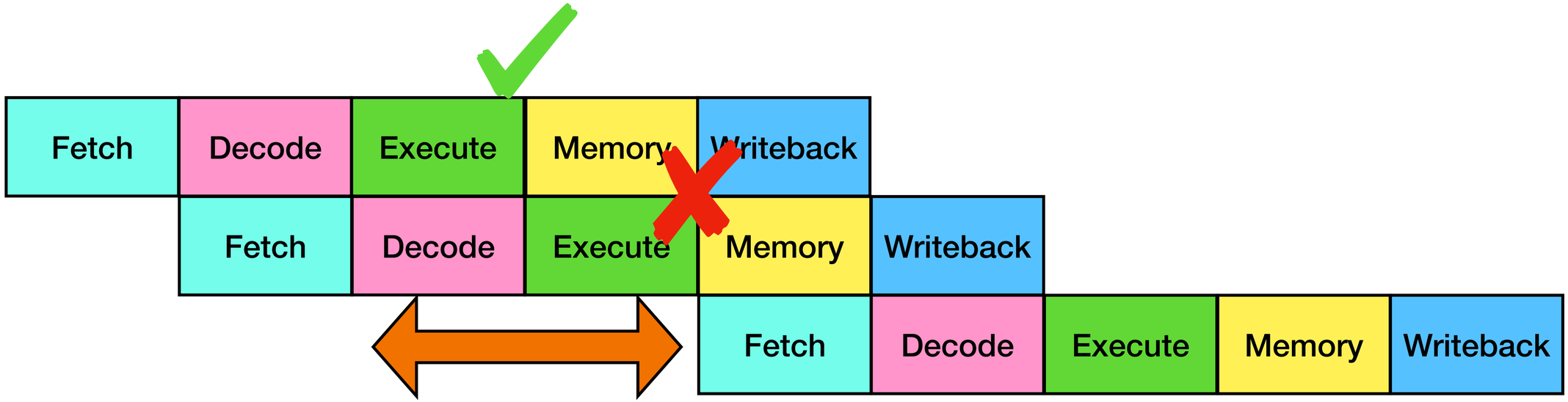
Several microarchitectural design techniques have facilitated the increase in processor speed over the past decades. One such advancement is speculative execution, which is widely used to increase performance and involves having

Image Credit: https://dl.acm.org/doi/pdf/10.1145/3399742

Outline

- Reasoning about incorrectly predicted branches
- Introducing speculative execution attacks

Execution with Branch Prediction



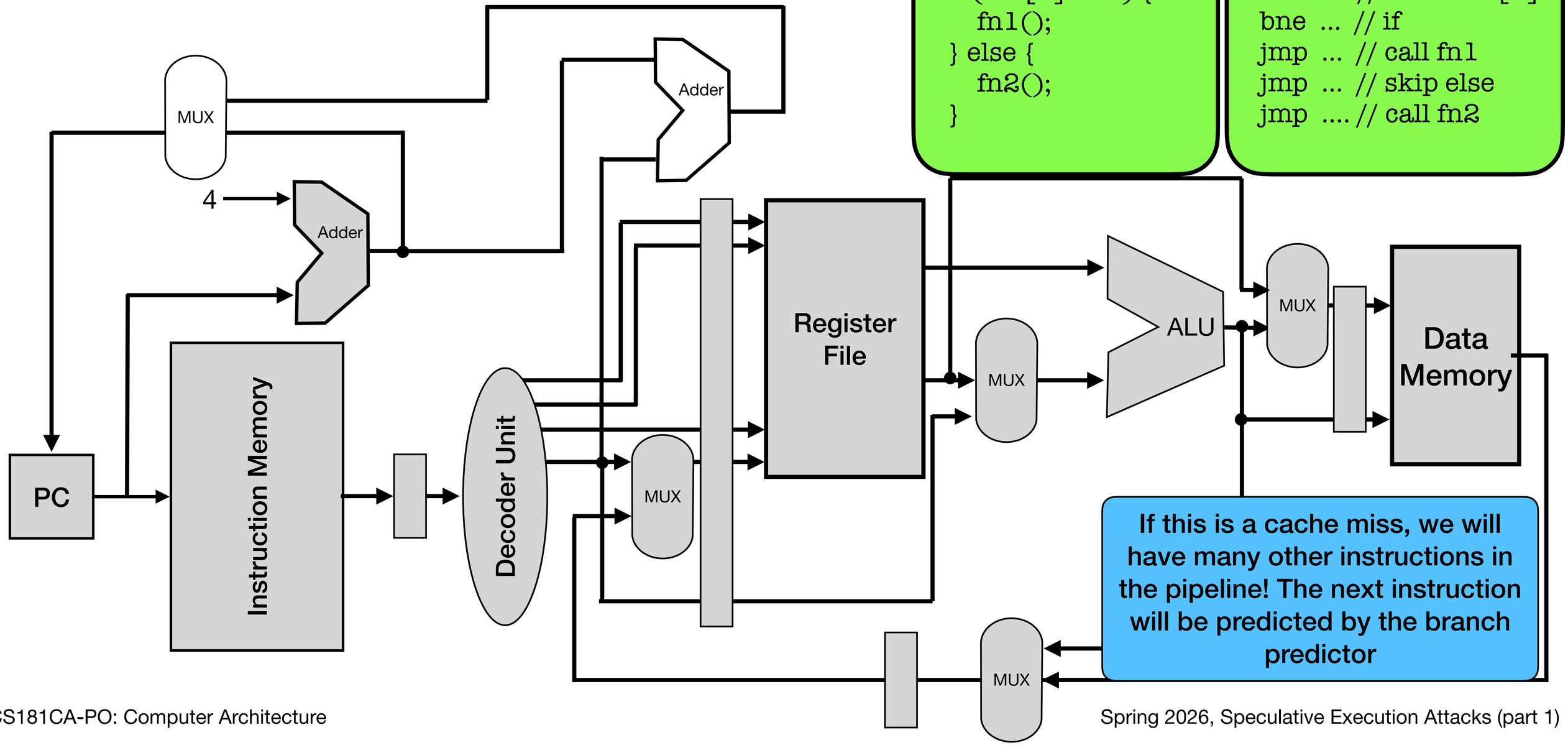
Chat with your neighbor(s)!

Think about the instructions executed *before* we detect the true outcome of the branch. What are these instructions? What are the implications of having them in the pipeline?

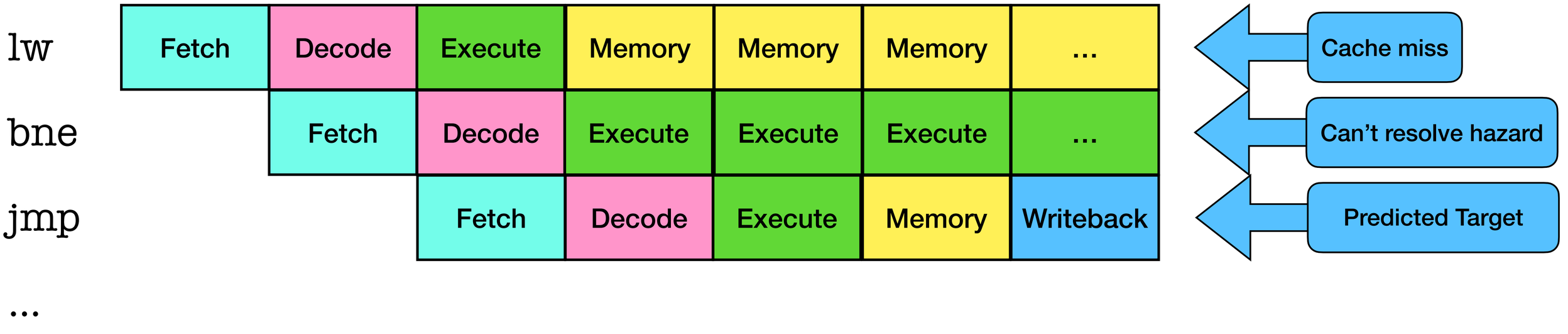
Slow to Resolve Branches

```
if (arr[0] == 1) {
   fn1();
} else {
   fn2();
}
```

```
lw    ... // fetch arr[0]
bne   ... // if
jmp   ... // call fn1
jmp   ... // skip else
jmp   .... // call fn2
```



Slow to Resolve Branches



Problem! We don't want to writeback the state of an instruction if we don't know that this instruction was the right one to execute!

Speculative processors have a temporary buffer where data is written back to called the "Reorder Buffer" (ROB), which decouples instruction *writeback* from *commit*

The Pitfalls of a Speculative Processor

- Branch predictors work from dynamic application behavior, as a result an adversary can *train* a branch predictor to guess the wrong side of an if-statement
- When executing a mispredicted branch in a transient state (e.g., when the processor is unsure which side of the branch is the true outcome), there are still implications on the *memory system*
- Often times, conditional branches are used for safety checks!

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Basically a buffer overflow vulnerability!

The following code is vulnerable to a Spectre variant 1 attack. Think about what is happening in the processor to execute this program. What features might an adversary exploit and what information can they leak?

```
void fn(x) {
  if (x < size) {
    y = array[x];
  } else ...
}
```

If the branch predictor will guess that the branch is *not taken* then the "if" condition will execute speculatively

An adversary can pass an input value `x` where `x > size` which will lead to a `load` from an arbitrary location in memory… bad!

Is this dangerous? From our cache side channels, all that the adversary can leak is that an address exists in the cache, not its data…

Components of a Speculative Execution Attack

- Processors predict the next instructions to execute, and incorrect predictions need to be rolled back
- Branch predictors track the behavior of programs dynamically at runtime, and can therefore be adversarially trained for what “expected” input behaviors could look like
- If a branch instruction depends on data from memory and the memory system is slow, then lots of execution will be performed speculatively while waiting for the branch to be resolved
- Once the unintended code has executed, a side channel needs to exist for the adversary to leak out the state of the data

The Premise of a Spectre Attack

- Adversary Goal: use the underlying microarchitectural state as a *covert channel* to get unintended code to leak secret information to an adversary
- The adversary will look for *gadgets* in the program state that will allow the processor to execute unintended instructions in a transient state
- Even if these instructions are not *committed*, accessed data will appear in the shared memory system
- For now, we should still be safe because the side channel attacks in the memory system only allow us to see the *addresses* in the memory system rather than the data contents itself… so no worries?

Takeaways

- When executing our programs, even code that we do not intend to execute may still be in the microarchitectural state
- Adversaries can exploit this behavior to expose secrets via the memory system or the ROB
- When designing for efficiency (e.g., speculation), security often falls by the wayside
- We cannot leak very much yet unless there is something meaningful to learn about the address being in the cache state from a speculative execution…