Restricting Control Flow During Speculative Execution

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Meltdown and Spectre Attacks

Meltdown and Spectre
- Exploit out-of-order and speculative execution
- Leak secret data via cache side channels

Existing software defenses
- Retpoline
- Load fence
- Spectre-resistant SFI
- Speculative load hardening

Still vulnerable to Branch Target Injection

Venkman: Our Software Solution

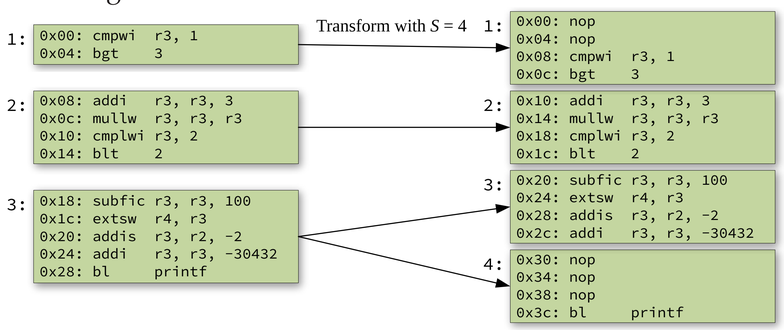
Two Spectre defenses
- Bundle Alignment + Branch Target Restrictions
  Defeats Branch Target Injection [**?**]
- Spectre-Resistant SFI on Stores
  Defeats Read-only Protection Bypass on code segment [**?**]

Must instrument all code in the system
- Use a system that controls native code generation (e.g., SVA)
- Use an OS-level binary verifier (e.g., Google's NaCl)

Bundle Alignment

Bundles
- Instruction sequences
- Sized and aligned at a same fixed power of 2 (2^S)
- Control-flow transfers to the beginning of a bundle
  - Functions and basic blocks aligned at 2^S
  - Function calls at the end of a bundle

Transform programs to bundles
- Break larger basic blocks into smaller basic blocks
- Add `NOP`s to the beginning of smaller basic blocks
- Ensure instructions that must be co-located are not separated
- Align all basic blocks at boundaries of 2^S



Branch Target Restrictions

Restrict branch targets
- All the branch targets point to the beginning of a bundle
- All the branch targets within code segment

Bit-masking instrumentations on indirect branches
- If the bundle size is 2^S bytes:
  Clear the lower S bits of the target address
- If the code segment is placed in the first 2^T bytes:
  Clear the upper $(64 - T)$ bits of the target address
- Dedicated returns transformed to indirect jumps
- Co-locate instrumentations and the indirect branch in the same bundle

Example of indirect function call ($S = 4$ and $T = 32$)

```
1 mtctr   r27          1 clrrdi  r27, r27, 4
2 bctrl          ⇒     2 clrldi  r27, r27, 32
                       3 mtctr   r27
                       4 bctrl
```

Example of return ($S = 4$ and $T = 32$)

```
1 mtlr    r0           1 clrrdi  r0, r0, 4
2 blr            ⇒     2 clrldi  r0, r0, 32
                       3 mtlr    r0
                       4 blr
```

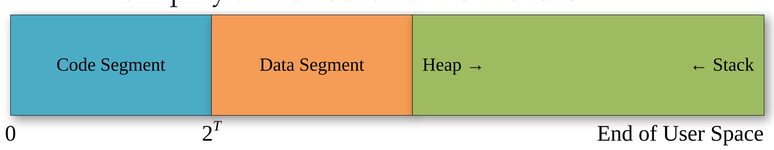
Mitigate BTB/RSB poisoning with Bundle Alignment
- Only the starting address of a bundle can go into BTB/RSB
- Prevent existing Spectre defenses from being bypassed
- Form a *complete* defense against Branch Target Injection

Speculative Code Segment Integrity

Spectre can break read-only memory protection [**?**]
- Overwrite code segment speculatively

Spectre-resistant SFI [**?**] on stores
- Create a data dependence between the SFI check and the store
- Prevent stores from (speculatively) writing to code segment
- Ensure the SFI check and the store are in the same bundle

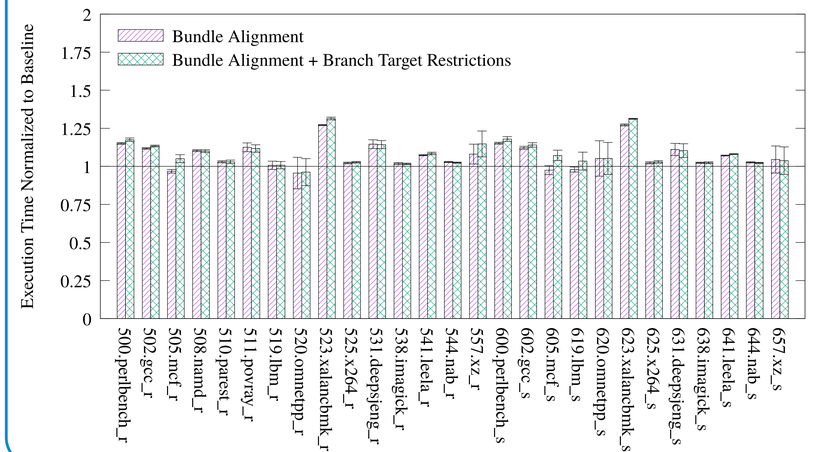
Rearrange programs' address space map
- Make all code reside in one portion of virtual address space (below 2^T)
- Strategically place code and data segments
  - Simplify SFI to use fewer instructions



Implementation and Preliminary Results

Prototype implementation
- Built on a 64-bit IBM POWER8 machine
- Use LLVM compiler infrastructure
- Implemented in two separate `MachineFunctionPass`es
- Spectre-resistant SFI on stores not implemented yet

Evaluation on SPEC CPU 2017



Future Work

- Complete prototype implementation
  - Implement Spectre-resistant SFI on stores
- Incorporate existing defenses
- Apply Venkman on OS kernel
- Measure memory overhead
- Evaluation on more programs

Acknowledgements

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References