# Ghostbusting: Mitigating Spectre with Intraprocess Memory Isolation

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# The Principle of Least Privilege

- It requires that the individual components of a system need to have a minimal set of permissions to perform their functionality.
  - Privilege separation and intraprocess memory isolation are just some of the ways of enforcing this principle.
  - Spectre V1 attack was an example of an intraprocess memory attack where a secret was leaked despite not being accessed by the program at all.
- In our paper:
  - We demonstrate how intraprocess isolation techniques such as Memory Protection Keys (MPKs) and ELF-based Access Control (ELFbac) can be effective in mitigating the Spectre V1 attack.
  - We enforce the policy that a secret after initialization must not be touched.

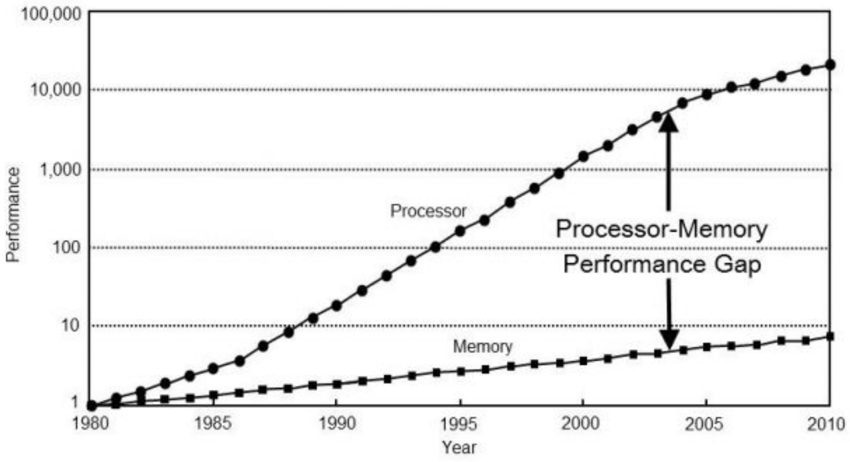
# Outline

- **Spectre V1**
- ELF-based Access Control
- Memory Protection Keys
- Evaluation
- Conclusions

Picture: https://en.wikipedia.org/wiki/Spectre_(security_vulnerability)

# Speculative Execution

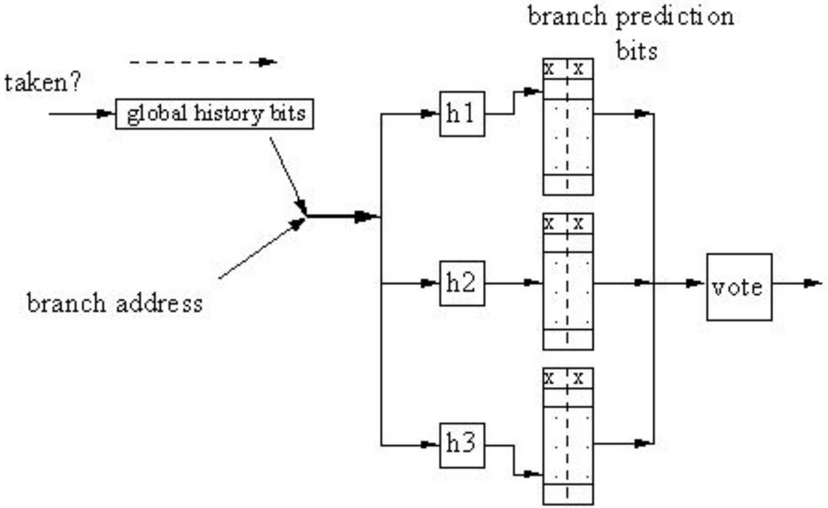
- Instructions within a pipeline are executed out of order.
- The results are later reordered and the dependencies are satisfied to assure semantics are maintained.
- *Speculative execution* predicts the control flow and executes instructions prior to knowing if they are required.




Source:
https://www.extremetech.com/computing/261792-what-is-speculative-execution

# Branch Prediction

- Dynamic Branch Predictors use:
  - Single bit: simply storing the last branch taken.
  - Multi bit: Pattern History Tables (PHTs)
- PHTs store the history of the branches taken to allow future branches to be predicted.
- Neural Networks have also been designed to predict branches.




http://web.engr.oregonstate.edu/~benl/Projects/branch_pred/

# Speculative Execution Attacks

- In 2018, CVE-2017-5753 introduced "Spectre"
- CPUs MUST flush pipeline when miss-speculation occurs.
- Flushing does occur for the pipeline, but not for the caches and microarchitectural *effects* remain after the transient instructions

**Apple issues Meltdown and Spectre patches for older versions of its Mac operating system — and you should install them right away (AAPL, INTC)**

TECH

**This new vulnerability affecting Intel processors sounds pretty scary**

By Andy Meek @aemeek
August 14th, 2018 at 6:32 PM

#TRENDING

PRIVACY AND SECURITY

**Intel's Never-Ending Spectre Saga Continues to Be a Hot Mess**

Alex Cranz
1/29/18 1:25PM • Filed to: INTEL

57 1

# Spectre V1

- There's a speculative bypass of the bounds check.
- The underlying technique for V1 is to exploit the branch prediction by poisoning the PHT to mispredict this conditional branch.
    - Train the CPU with valid values for x
    - Give a bad *x* value.
    - CPU speculates and caches an "index" into array2.
    - Use timing side channel to recover "secret" from array2.
- The program, however, never touches the "secret"

```
void victim_function(size_t x) {
  if (x < array1_size) {
    temp &= array2[array1[x] * 512];
  }
}
```

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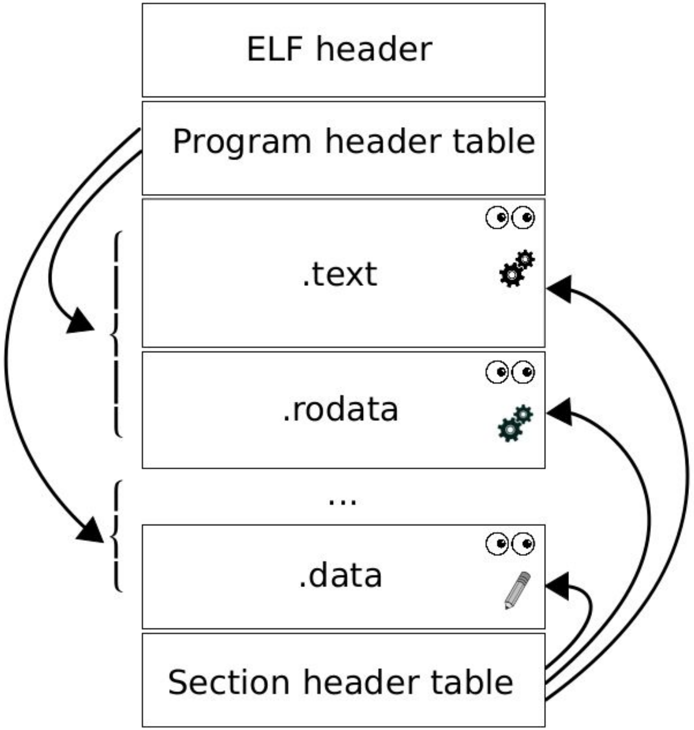
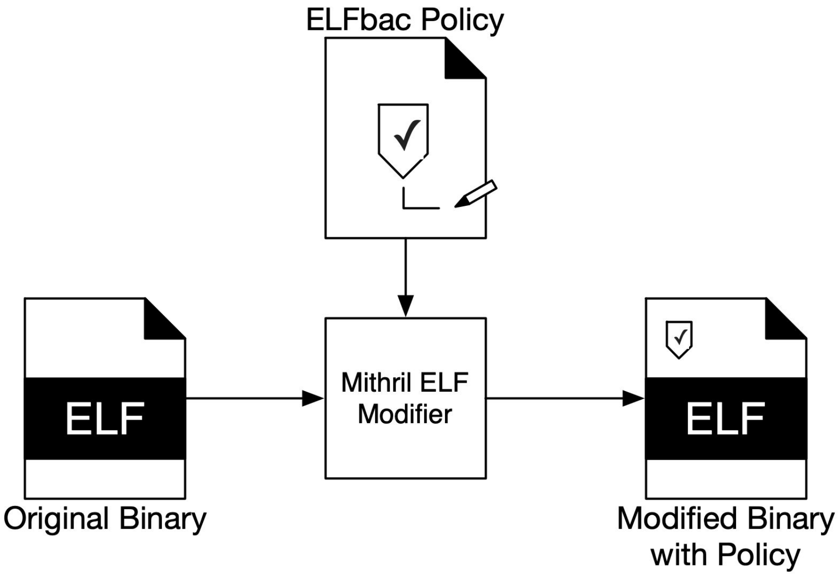
# ELF-based Access Control

- ELFbac uses *policy-infused* binaries.
- ELF binaries contain sections and segments.
  - Sections define semantically distinct units of a program: code, data, metadata, etc.
  - Segments group sections.
  - They define the permissions of the memory sections.
- What if we can enforce permissions on the sections instead of the segments? Fine-grained access control in binaries.



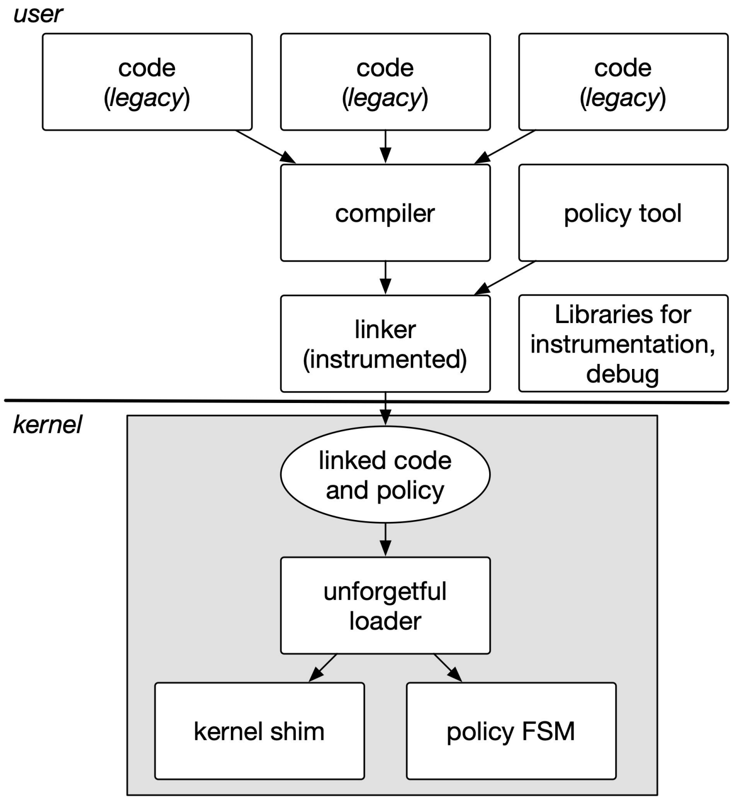
# Injecting the policy

- We isolate the global data such as the "secret" in the case of Spectre into a separate section using the `__attribute__` gcc syntax.
- The policy is described in a domain-specific language based on Ruby.
- The policy gets added to the binary as a separate ELF section.

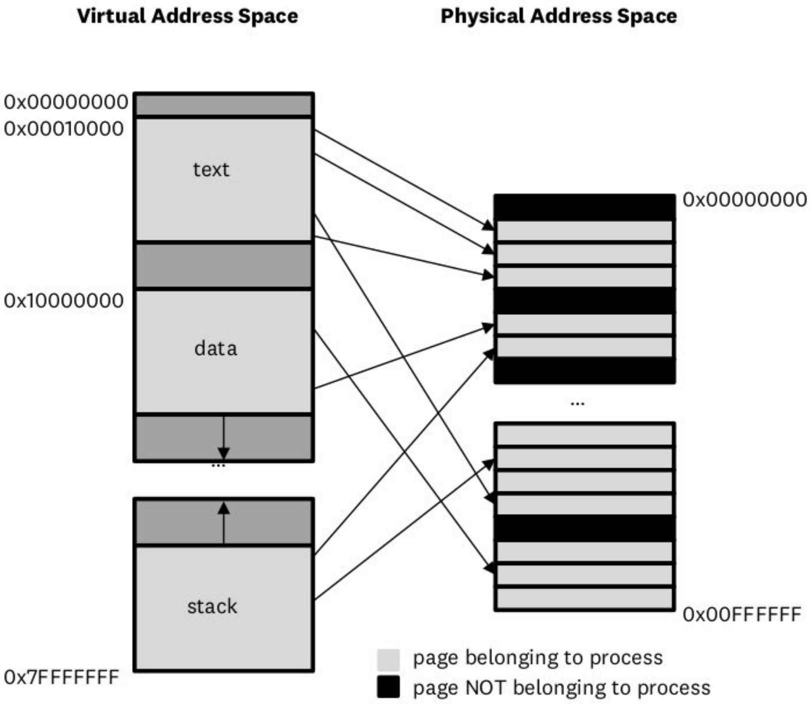


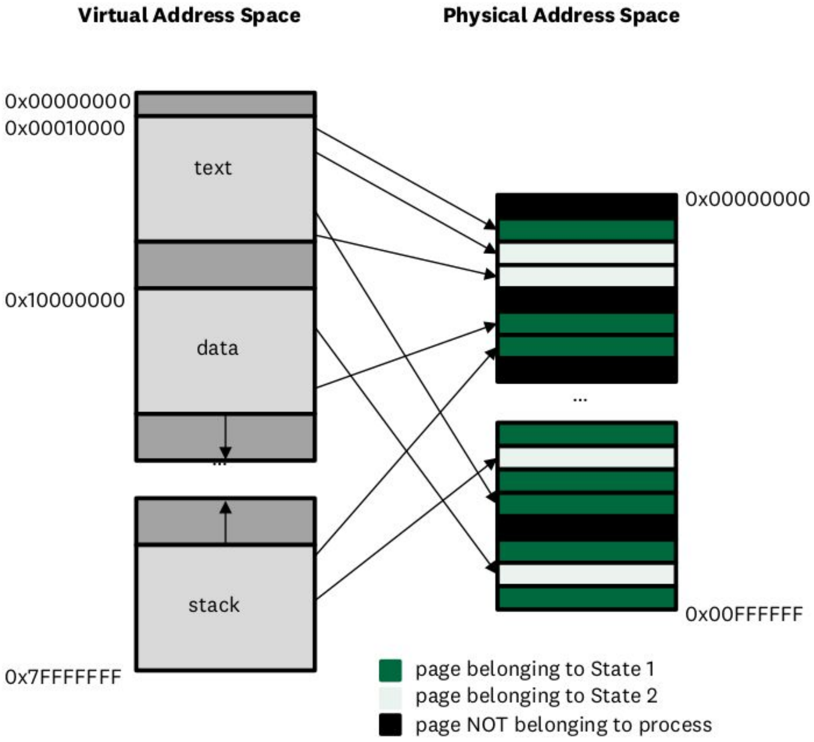
# How does ELFbac enforce policy?

- The loader is policy aware.
- The kernel enforces the policy:
  - All the pages are unmapped. At each new access, there is a page fault and the permissions are checked.
  - During a state transition, the TLBs are flushed to invalidate all the entries and the cache.
- So what does the program's address space look like?



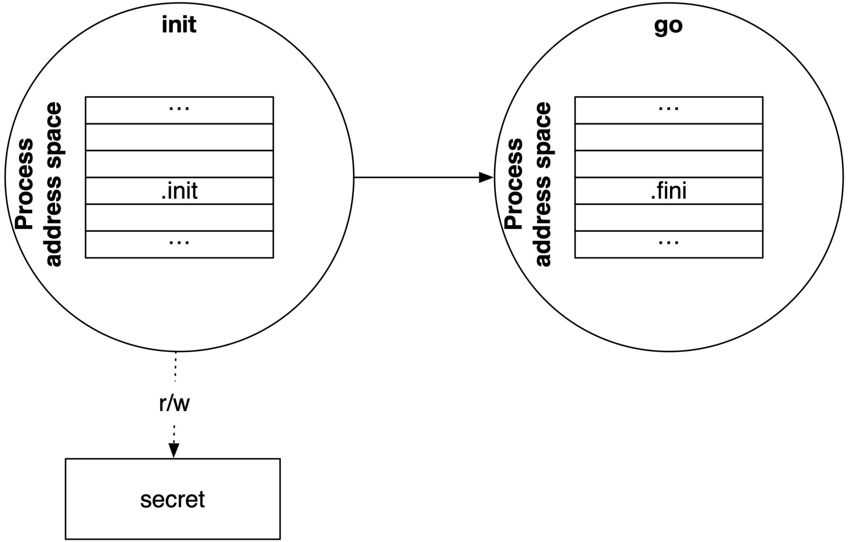
# Process view vs. Kernel View



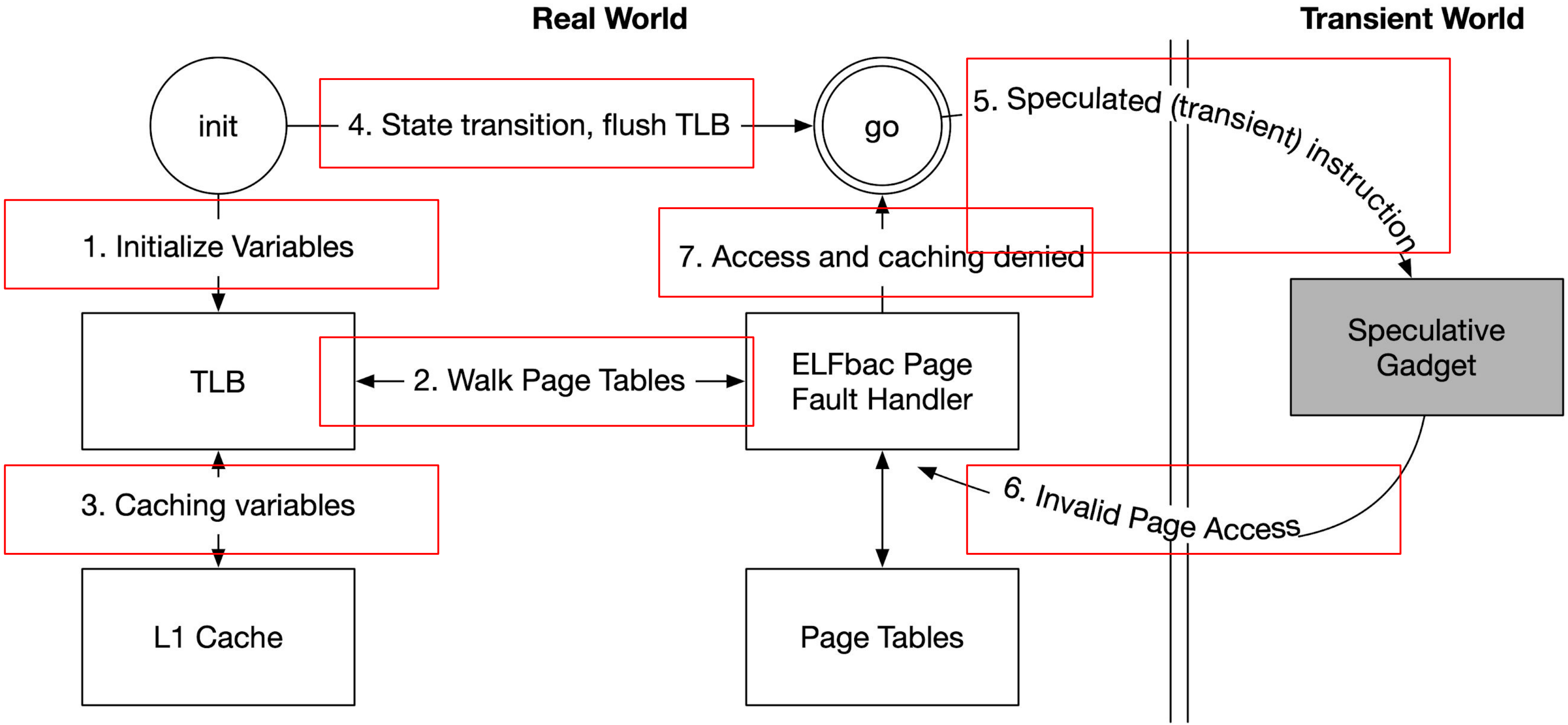



# ELFbac policy vs. Spectre

- In the V1 PoC, apart from initialization, the rest of the program does not touch the variable “secret”
- We divide the program into two states.
  - Only the *init* state has access to the secret.
  - The program transitions to the *go* immediately after initialization of all the globals.



# ELFbac policy vs. Spectre (contd.)



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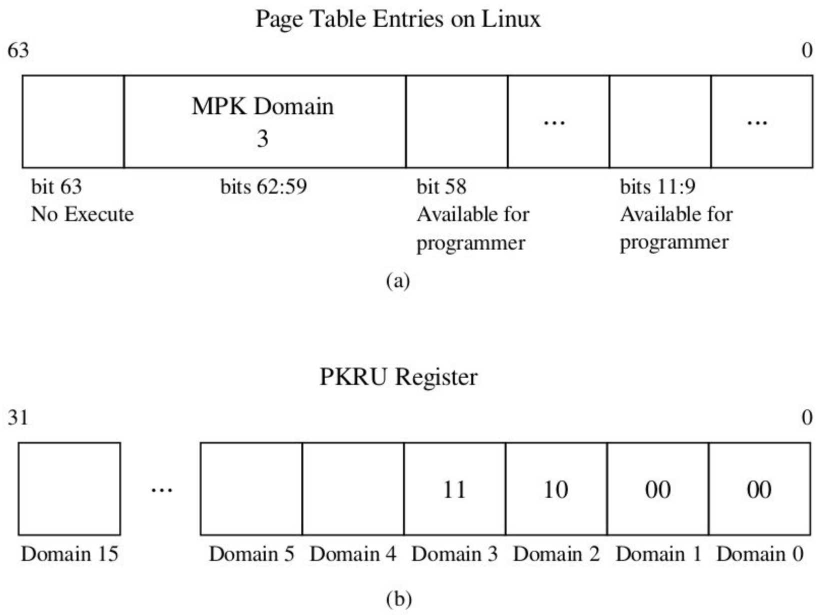
# Memory Protection Keys

- Since the permission enforcement happens via page faults and TLB flushes, this does incur a huge overhead.
- Page table entries on Linux include 4 bits reserved for the security domain or state in which this page would be accessible.
- The PKRU register stores 2 bits for each state or security domain: read and write permissions for the domain.



# Memory Protection Keys (contd.)

- We implemented the same state machine as earlier.
  - Init state where initialization is allowed.
  - *Go* state where access to the secret is revoked.
- We revoked permissions to the secret after it was initialized.

```
int real_prot = PROT_NONE;

int pkey = pkey_alloc (0,
PKEY_DISABLE_WRITE);

int ret =
pkey_mprotect(secret ,
getpagesize (),real_prot ,
pkey);
```

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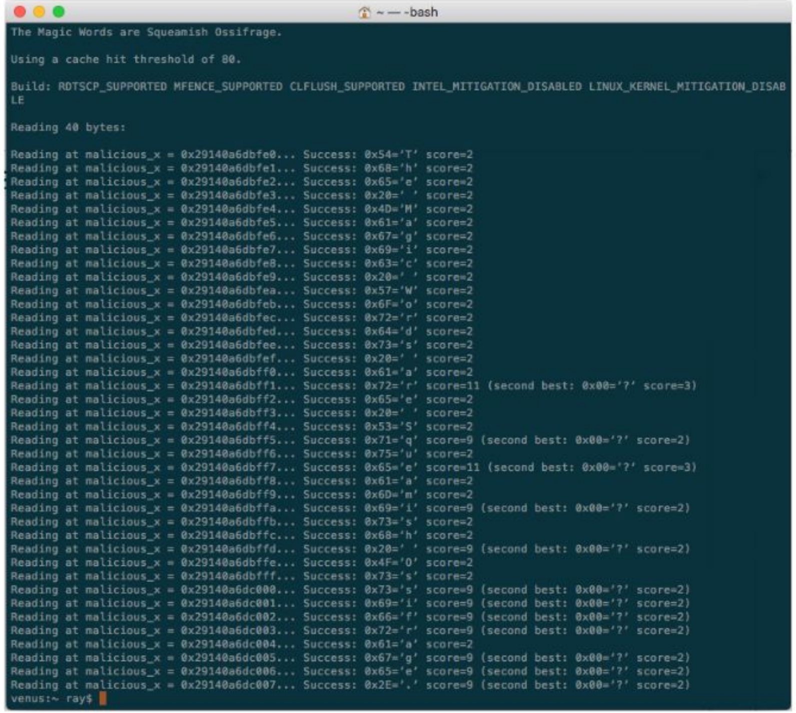
# Evaluation

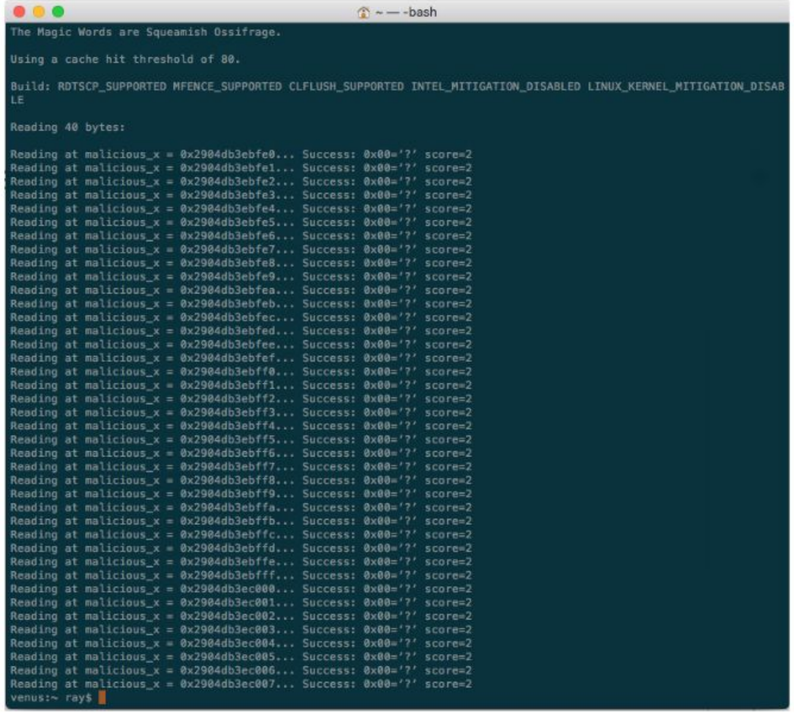
- Is intraprocess memory isolation effective against SpectreV1?
- What is the programmer effort required to build a policy for ELFbac and to modify the existing source code?
- How does ELFbac compare in terms of programmer effort to other mitigation techniques against Spectre V1?
- What is the performance impact due to ELFbac and MPKs in comparison to other mitigations?

# ELFbac and MPKs vs. Spectre V1

- We built two policies for ELFbac: one allowing Spectre V1 PoC to execute, and another to disallow it.
- We also built two modifications of our MPK implementation to again allow and disallow the attack.
- In both cases, when the protections are turned on, we found that the secret was not found since the speculative branch is unable to access the secrets.

# Demo of the PoC



# Programmer Effort

- Using serializing instructions such as *lfence* would only include adding one line of code.
- However, we would need to identify every instance of code that can be speculatively executed and add an *lfence.*
- The process of building the right ELFbac policy involves a lot of trial and error.

| | **LoC added for ELFbac** | **LoC added for MPKs** |
|---|---|---|
| Original Spectre V1 PoC | 3 | 5 |
| Policy code in DSL | 33 | 0 |

# Performance

- We performed our ELFbac experiments on an Intel Xeon E31245 3.30 GHz processor with four cores and 4GB RAM running a modified ELFbac kernel and Loader.
- MPK experiments were done on an Intel Xeon Platinum 8168 instance on Microsoft Azure Cloud with support for MPKs with one core and 2GB RAM.

| | Page Faults | Context Switches | Time Elapsed | State Transitions |
|---|---|---|---|---|
| Original Spectre PoC | 170 | 88 | 0.01s | NA |
| `lfence` solution | 170 | 89 | 0.02s | NA |
| Spectre V1 exploit with ELFbac Policy 1 | 304 | 86 | 0.01s | 0 |
| Spectre V1 exploit with ELFbac Policy 2 | 320 | 92 | 1.31s | 1 |
| Spectre V1 mitigation with ELFbac Policy 2 | 320 | 98 | 1.36s | 1 |
| Spectre Allowed with MPKs | 92 | 83 | 0.02s | NA |
| Spectre V1 mitigation with MPKs | 92 | 83 | 0.01s | NA |

# Discussion and Conclusions

- Our work using ELFbac and MPKs are isolated to Intraprocess memory attacks such as Spectre V1.
    - SpectreRSB and Spectre 1.1 are also intraprocess memory attacks and *could* be mitigated using the same technique.
    - SpectreRSB attacks exploiting multiple processes and the Intel SGX, however, are not in the scope of ELFbac that targets intraprocess memory attacks.
- ELFbac does need some speed enhancements. We are working on a version of ELFbac that uses MPKs for intraprocess isolation.
- Neither ELFbac nor MPKs mitigate vulnerabilities entirely, but isolate them and make life harder for attackers.

# Thank You

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