Spectre Attacks: Exploiting Speculative Execution

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Paul Kocher[1], Jann Horn[2], Anders Fogh[3], Daniel Genkin[4], Daniel Gruss[5], Werner Haas[6], Mike Hamburg[7], Moritz Lipp[5], Stefan Mangard[5], Thomas Prescher[6], Michael Schwarz[5], Yuval Yarom[8]

[1] Independent (www.paulkocher.com), [2] Google Project Zero, [3] G DATA Advanced Analytics, [4] University of Pennsylvania and University of Maryland, [5] Graz University of Technology, [6] Cyberus Technology, [7] Rambus, Cryptography Research Division, [8] University of Adelaide and Data61

What Is Spectre?

Spectre exploits traces left in covert channels (e.g., cache) by speculative execution to leak sensitive data. Vulnerability to such attacks is widespread and hard to fix.

SPECTRE

Background

Out-of-Order Execution

mov (%ebx), %edx

add %edx, %eax

imul %esi, %esi

imul %edi, %edi

add %esi, %edi

Instruction pointer

Loading (%ebx)…

Note: assume that all registers have a known initial value

Out-of-Order Execution

mov (%ebx), %edx ◁ Instruction pointer Loading (%ebx)…

imul %esi, %esi

imul %edi, %edi

add %esi, %edi

add %edx, %eax

Note: assume that all registers have a known initial value

Speculative Execution

cmp (%eax), %esi

Instruction pointer

Loading (%eax)…

jeq: (%eax) = %esi → take branch

jeq target

imul %edi, %ebx

…

:target

add %(edx), %ecx

mov %(ecx), %eax

add %eax, %ecx

…

Speculative Execution

cmp (%eax), %esi

Instruction pointer

Loading (%eax)…

jeq: (%eax) = %esi → take branch

jeq target

imul %edi, %ebx

…

:target

add %(edx), %ecx

mov %(ecx), %eax

Correct branch → time saved

add %eax, %ecx

…

Speculative Execution

```
cmp (%eax), %esi
jeq target
imul %edi, %ebx
…
:target
add %(edx), %ecx
mov %(ecx), %eax
add %eax, %ecx
…
```

Instruction pointer

Loading **(%eax)**…

(%eax) ≠ %esi → don't take branch

Transient instructions (add %(edx), %ecx; mov %(ecx), %eax)

Incorrect branch → rollback

Branch Prediction

```
cmp (%eax), %esi
jeq target
imul %edi, %ebx
…
:target
add %(edx), %ecx
…
```

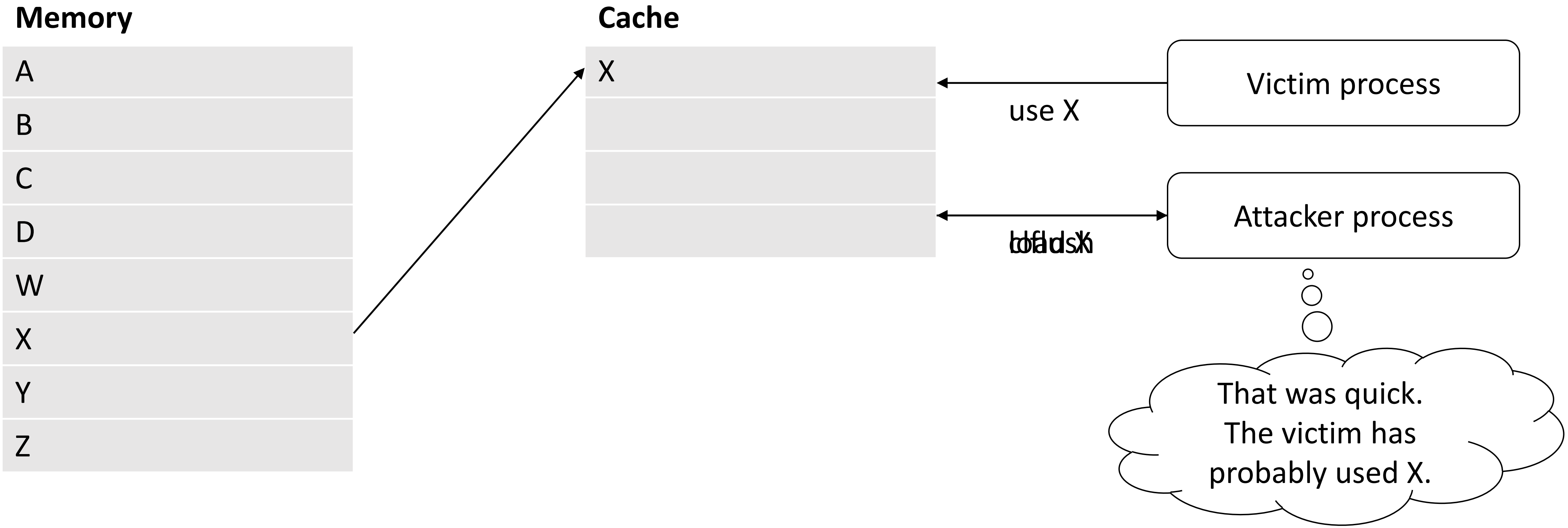
Instruction pointer

Loading (%eax)…

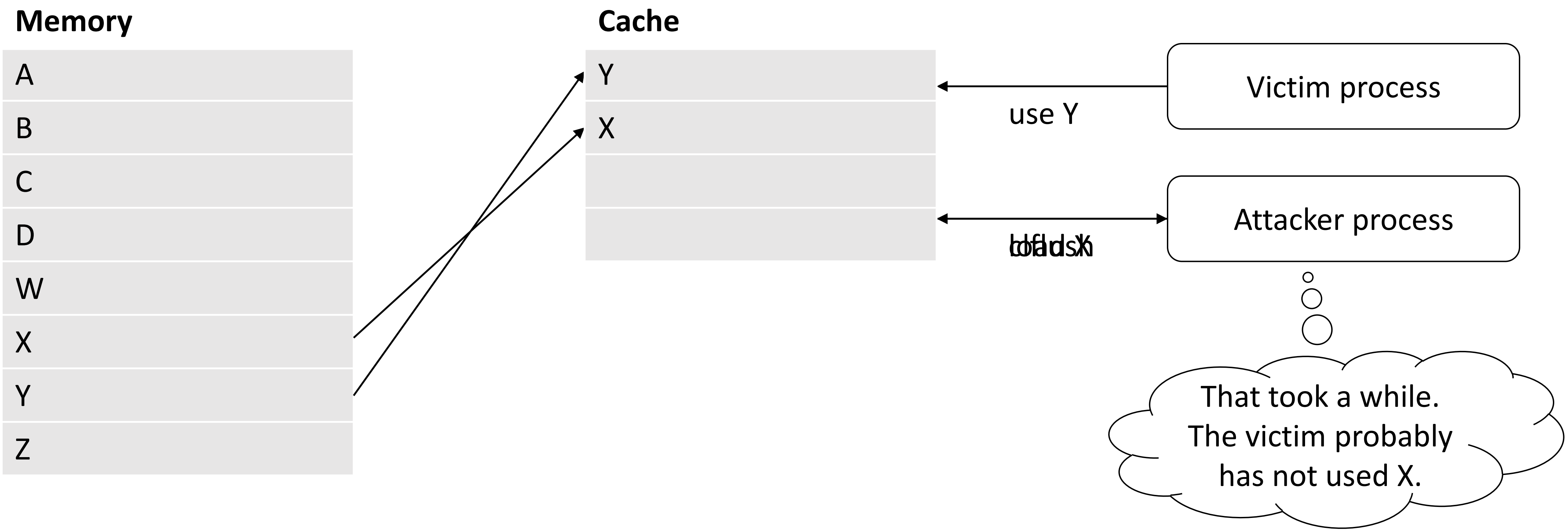
I'll take this branch

Recent branch outcomes:
taken
not taken
taken
taken

Cache (Flush+Reload / Evict+Reload)



Cache (Flush+Reload / Evict+Reload)



Performing Spectre Attacks

Exploiting Conditional Branch Misprediction

```
if (x < array1_size)
    y = array2[array1[x] * 4096];
```

- The attacker wants to determine the secret byte array1[x] for some out of bounds x
- The attacker is permitted to access array1 and array2
- array1[x] should be cached, but not array1_size and array2
- The attacker should have trained the processor to take the next branch
- Using Flush+Reload, the attacker can determine the loaded entry from array2 and deduce array1[x]

Example Implementation in C

- A huge variety of processors are vulnerable to the exploitation of conditional branch misprediction
- This method was implemented in C
- Data leakage rate is in the order of 10kB/s
- Very low error rate (<0.01%)

Poisoning Indirect Branches

- Find a snippet of code in the victim that can be maliciously used to leak data (called a Spectre gadget)
- Requirements to set up the attack:
  - The attacker controls registers R1 and R2 and knows their initial values
  - R1 contains the address of the desired secret byte
  - The Spectre gadget adds (or other arithmetic) the memory at address R1 to R2 and then loads from memory at address R2
  - The attacker has trained the branch predictor to the gadget’s address
- Using Evict+Reload, the attacker can deduce the secret data

Other Varieties of Spectre Attacks

Instruction Timing

```
if (false but mispredicts as true)
    multiply R1, R2  // R1 and R2 are secret
multiply R3, R4      // R3 and R4 are public
```

- Advantages: Independent from the cache
- Disadvantages: May not provide concrete value of secret data

Contention on the Register File

```
if (false but mispredicts as true)
    if (condition on R1)  // R1 is secret
        if(condition)
```

- If the secret data meets the condition in the second if statement, three checkpoints of registers will be kept for speculative execution rather than only two; the attacker may then notice slowdown
- Advantage: Independent from the cache
- Disadvantage: Some processors may not allow multiple layers of speculative execution

Exploiting Interrupt Returns

- Poison the return from an interrupt instead of an indirect branch in the victim's code

- Initiate attack by causing an interrupt

- Advantage: Less dependent on victim's code

- Disadvantage: Not applicable to Intel CPUs

Arbitrary Observable Effects

```
if (x < array1_size)  // Mispredict as true
    y = array1[x];
    // Do something using y that leaves observable side effects
```

- Advantages: Less picky with required code snippets, not dependent on any single microarchitectural element
- Disadvantage: May require more specialized code on the attacker's side

Preventing Spectre Attacks

Disabling Speculative Execution

- Disable speculative execution entirely
- Protect specific branches with lfence instructions
- Advantages: Easy to implement, very effective
- Disadvantage: Reduces performance

Separate Processes (Web Browsers)

- Run websites in separate processes
- Used by Chrome
- Advantages: Can be implemented on current hardware, reasonably effective
- Disadvantage: Requires a lot of resources

Index Masking

```
if (x < array1_size)
    y = array2[array1[x & 0xff] * 4096];
```

- AND array indexes with a mask
- With a proper mask, resulting indexes may be no larger than 2 times the array length
- Advantage: Very cheap
- Disadvantages: Doesn’t protect from all types of Spectre attacks, data right behind the array can still be loaded

Preventing Sensitive Data From Entering Covert Channels

- While speculatively executing, do not allow operations on sensitive data that leave detectable traces, e.g., usage as a memory address

- Advantages: Effective, good trade-off between performance and security

- Disadvantage: Not supported by current processors

Degrading the Clock

- Add jitter or reduce resolution
- Sometimes done in JavaScript
- Advantages: Very cheap, slows potential attacks
- Disadvantages: Can be detrimental to benign processes, can be weakened by repeated use of Evict+Reload

Preventing Branch Poisoning

- Prevent effects of branches from less privileged processes
- Added to ISA by Intel and AMD
- Advantage: Implemented on current processors
- Disadvantage: Ineffective against other variants of Spectre attacks

Conclusion

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Spectre attacks can exploit traces of incorrectly speculatively executed instruction to deduce secret data on various CPUs. Due to the variety of performance improving components of modern processors, Spectre vulnerabilities are nearly impossible to fix.

Strengths

Strengths

- Widespread vulnerability
- Variety of possible covert channels
- Hard to fully prevent on modern hardware, especially without greatly reducing performance
- Simplicity

Weaknesses

Weaknesses

- Needs to know the location of secret data and exploitable pieces of code
- Can struggle with complex networks of processes
- Limited by its permissions

Alternatives and Possible Improvements

Alternatives and Improvements

- Give processes with sensitive data an entire CPU core
- Do not modify the cache during speculative execution
- Flag branches where branch mispredictions occurred at least n times

Discussion

Possible Discussion Starters

- How to detect Spectre attacks

- What data would you want to extract with / protect from Spectre

- Any other suggestions for improvements in attack / defense

Discussion: How to Detect Spectre Attacks

That process is acting sus

Discussion: What Sensitive Data to Extract / Protect

Discussion: Ideas for Attack or Defense

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