Shesha: Multi-head Microarchitectural Leakage Discovery in new-generation Intel Processors

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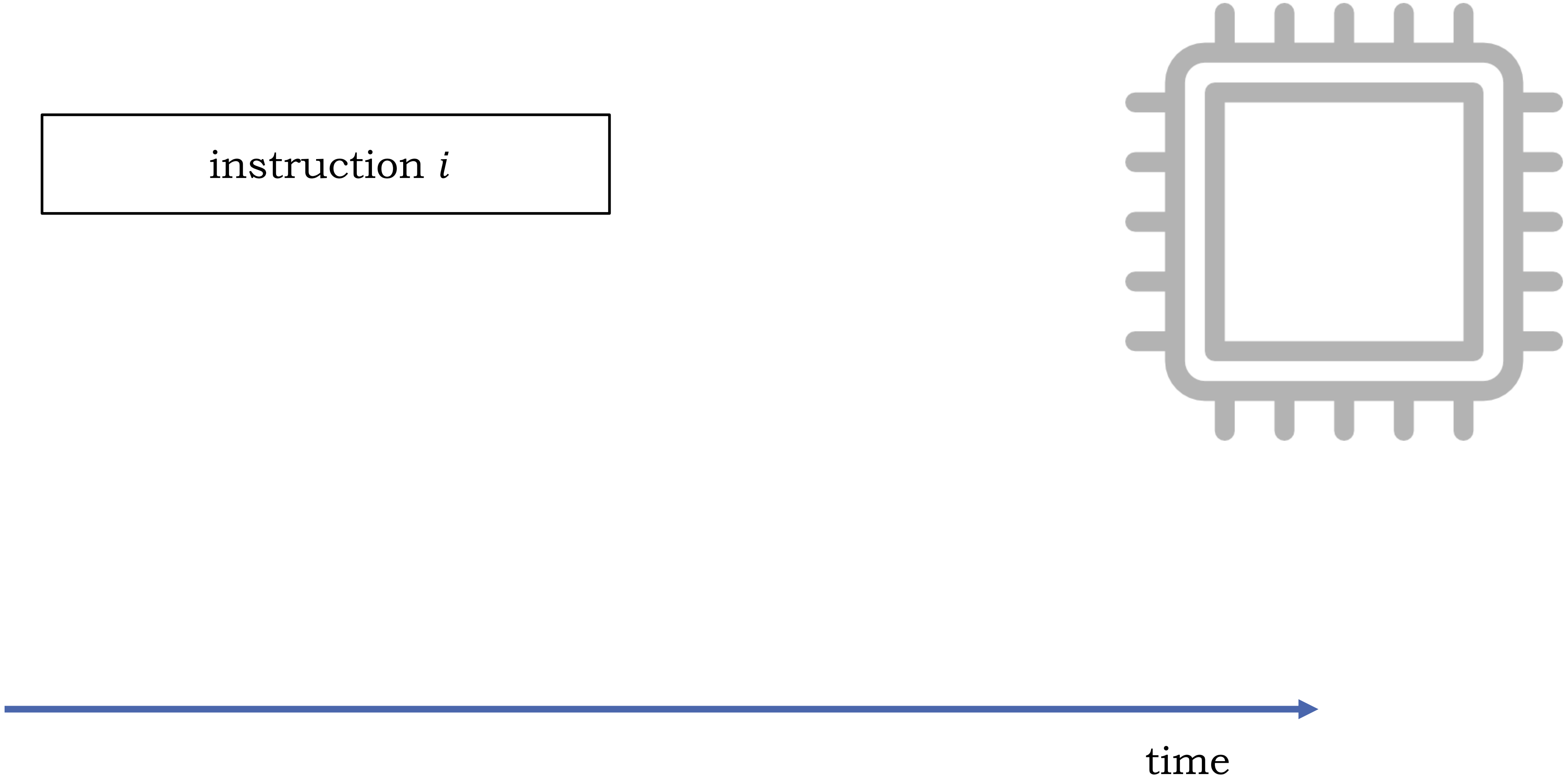
Transient Execution



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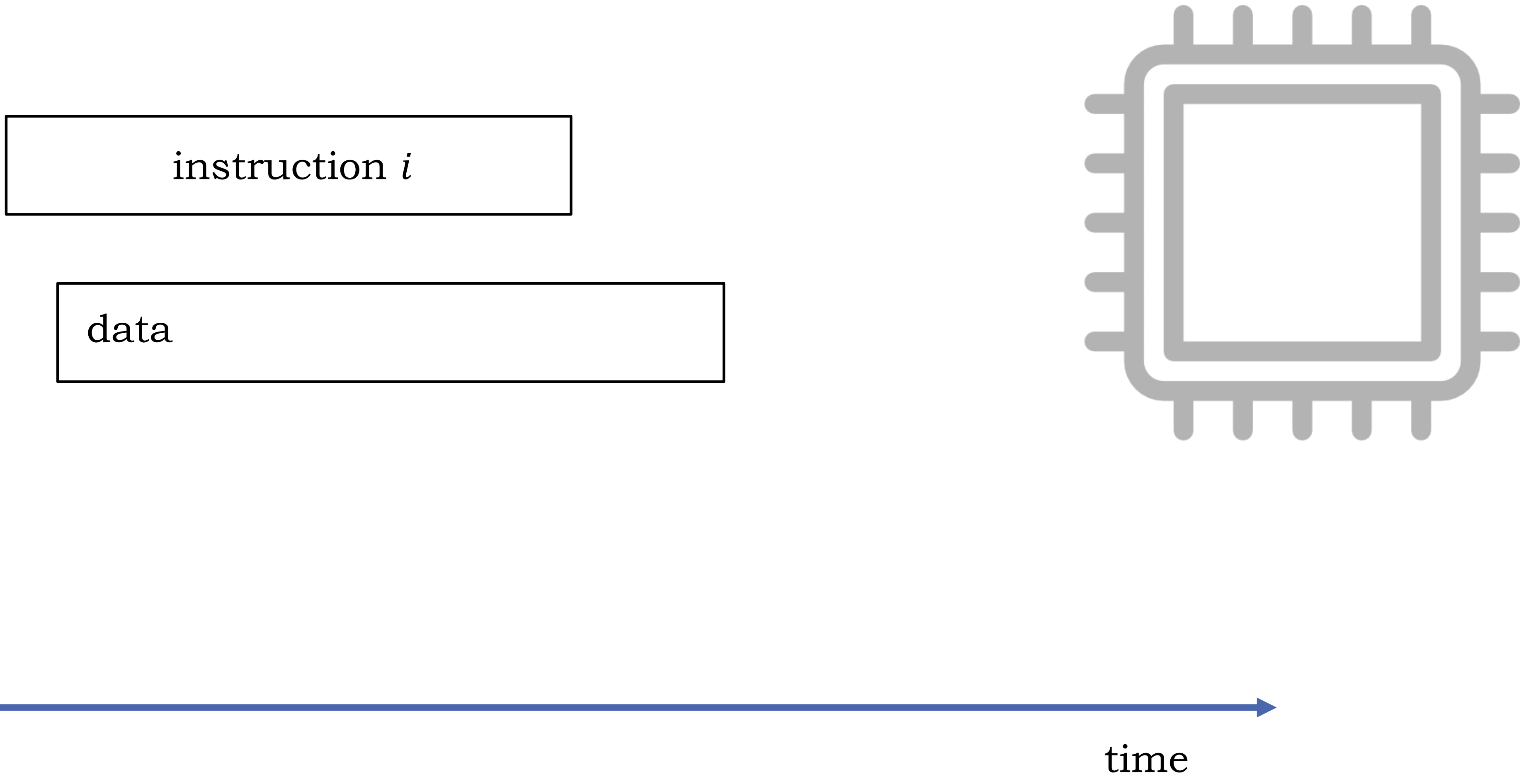

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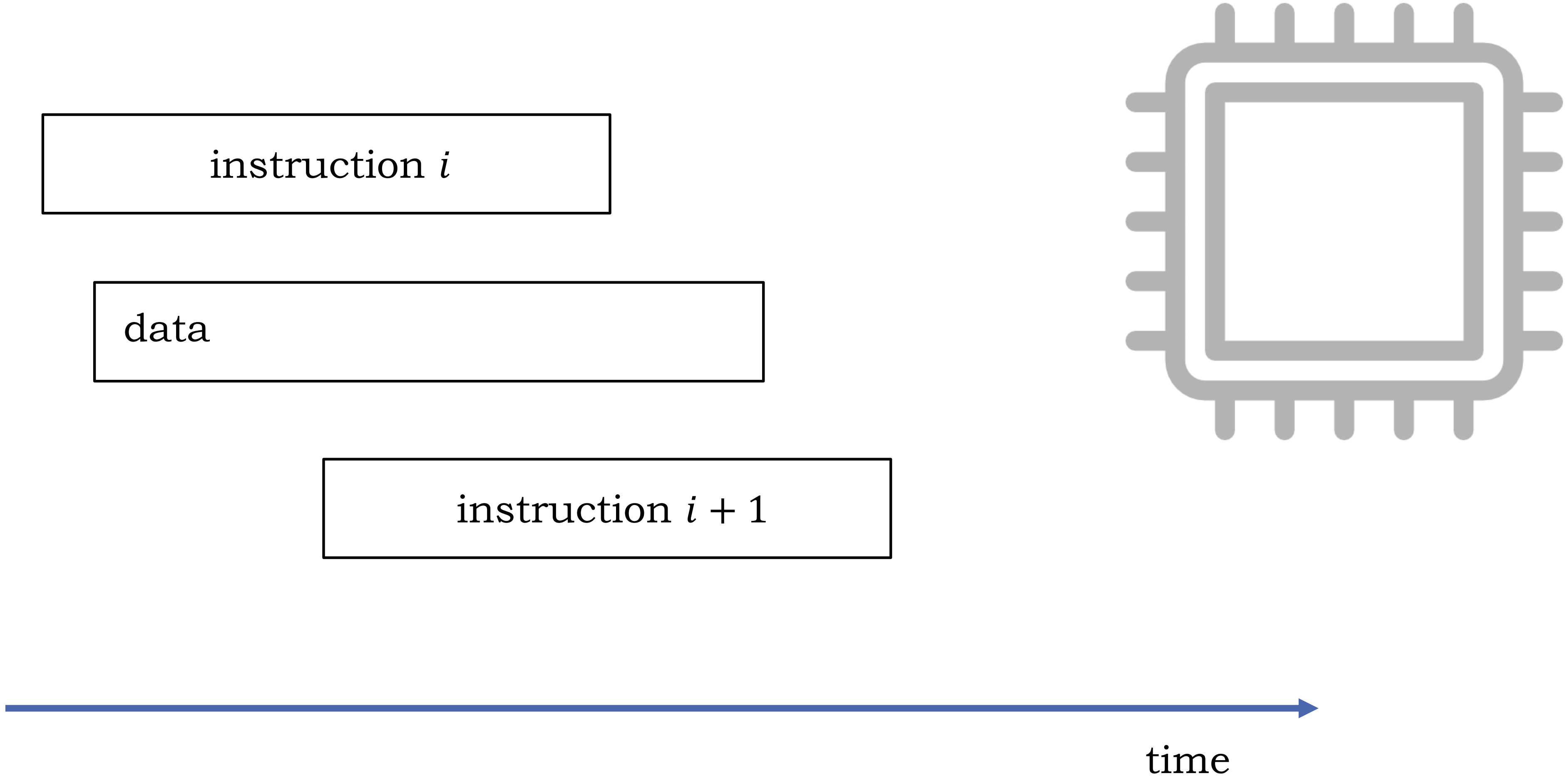

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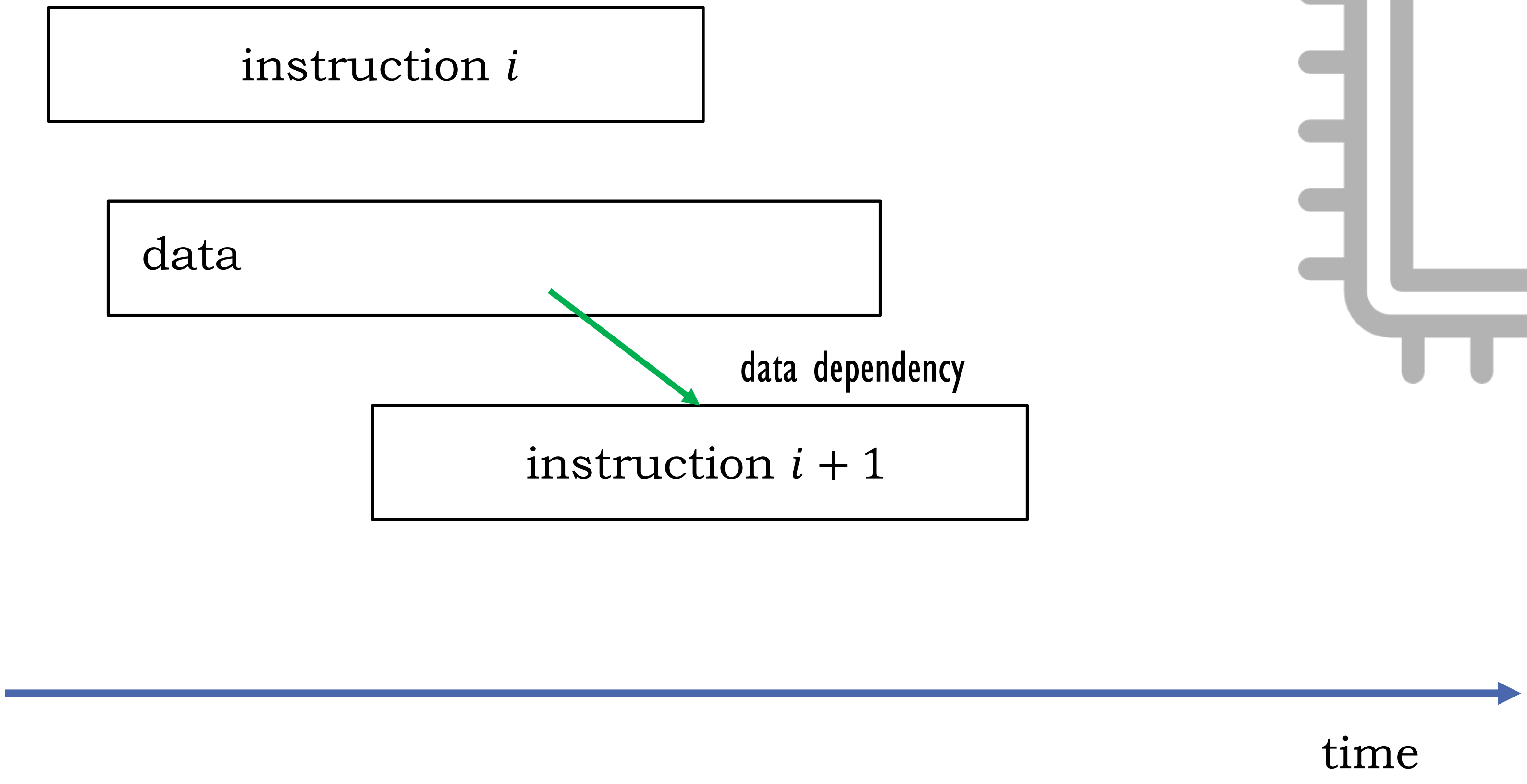

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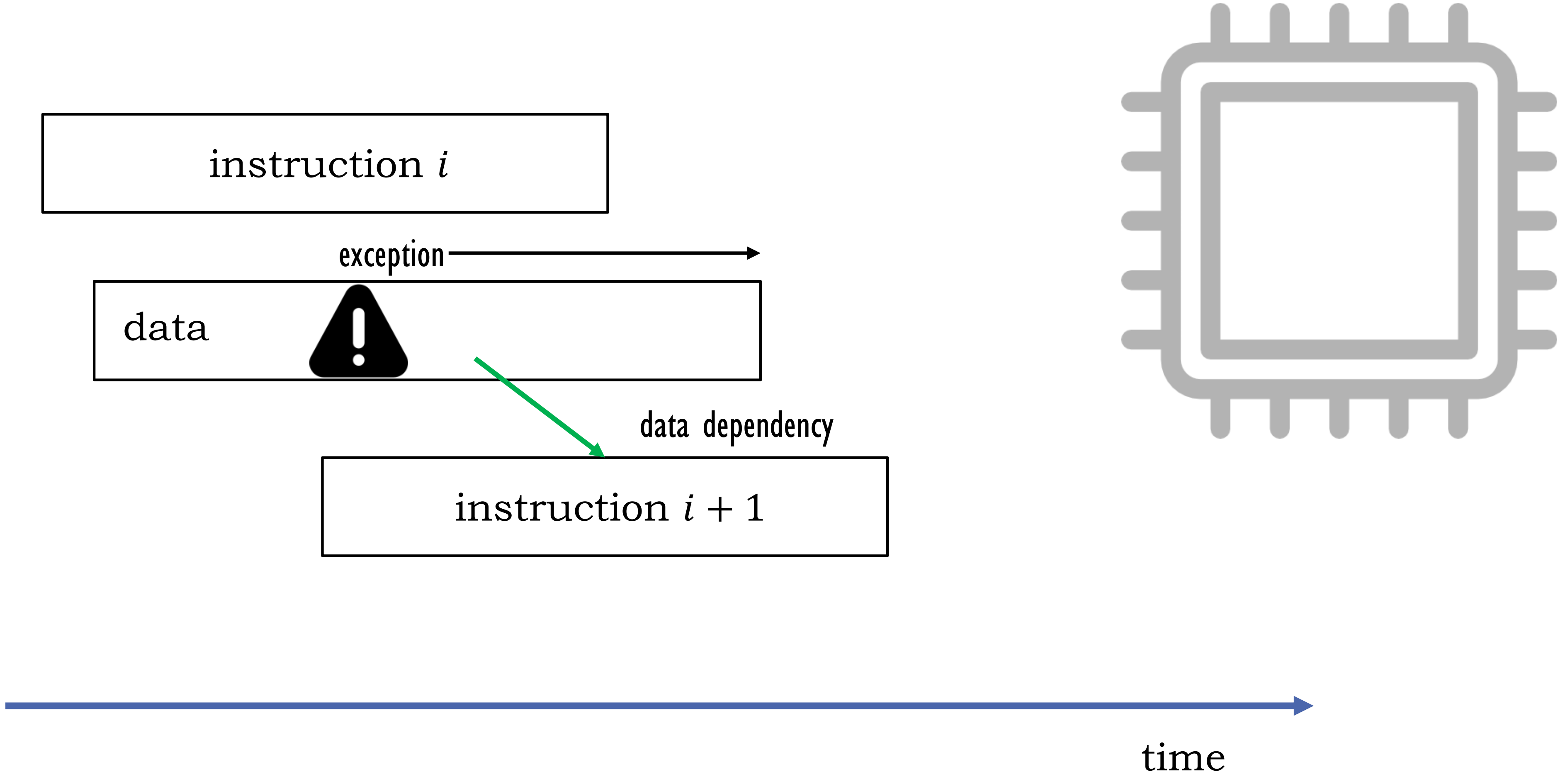

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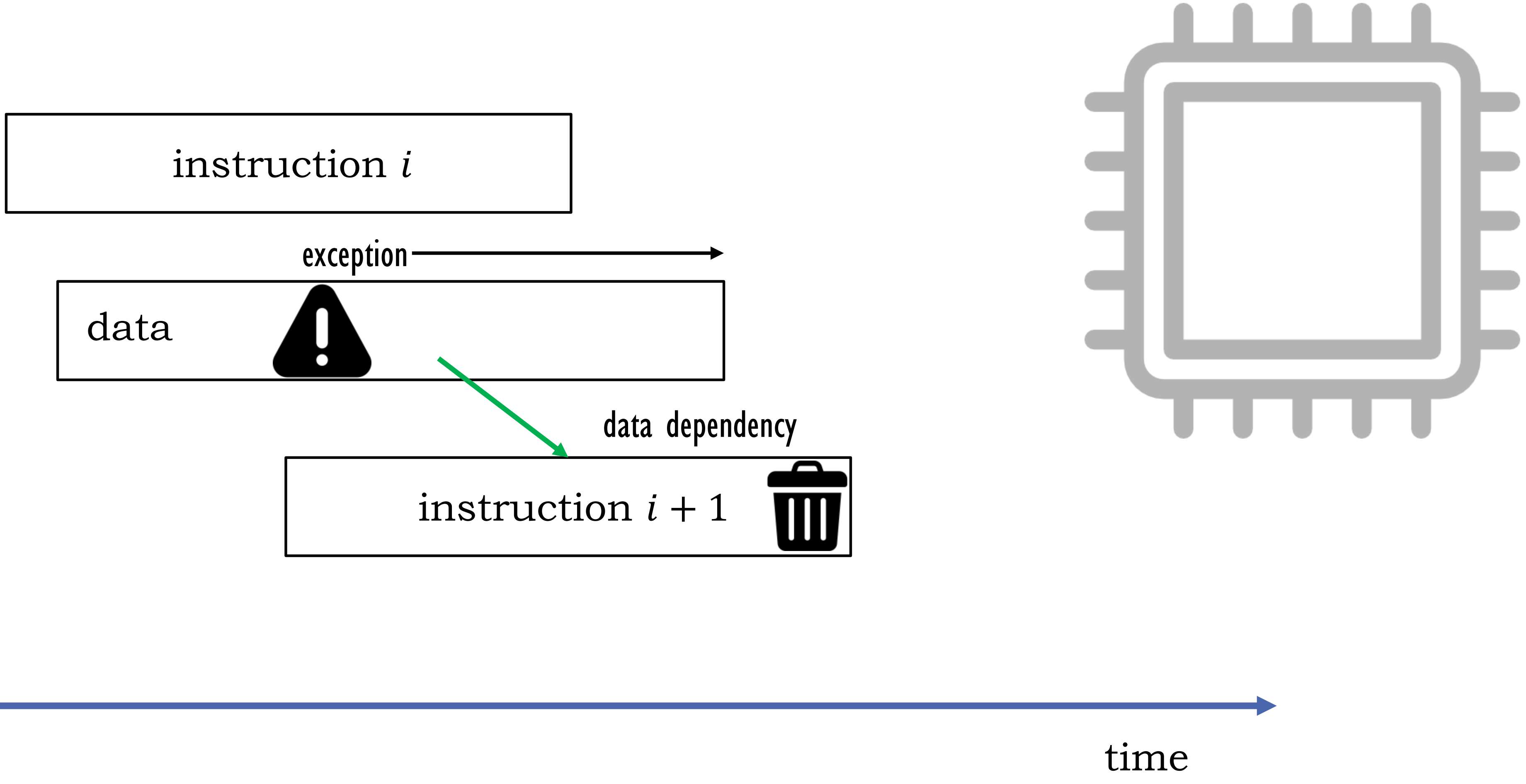

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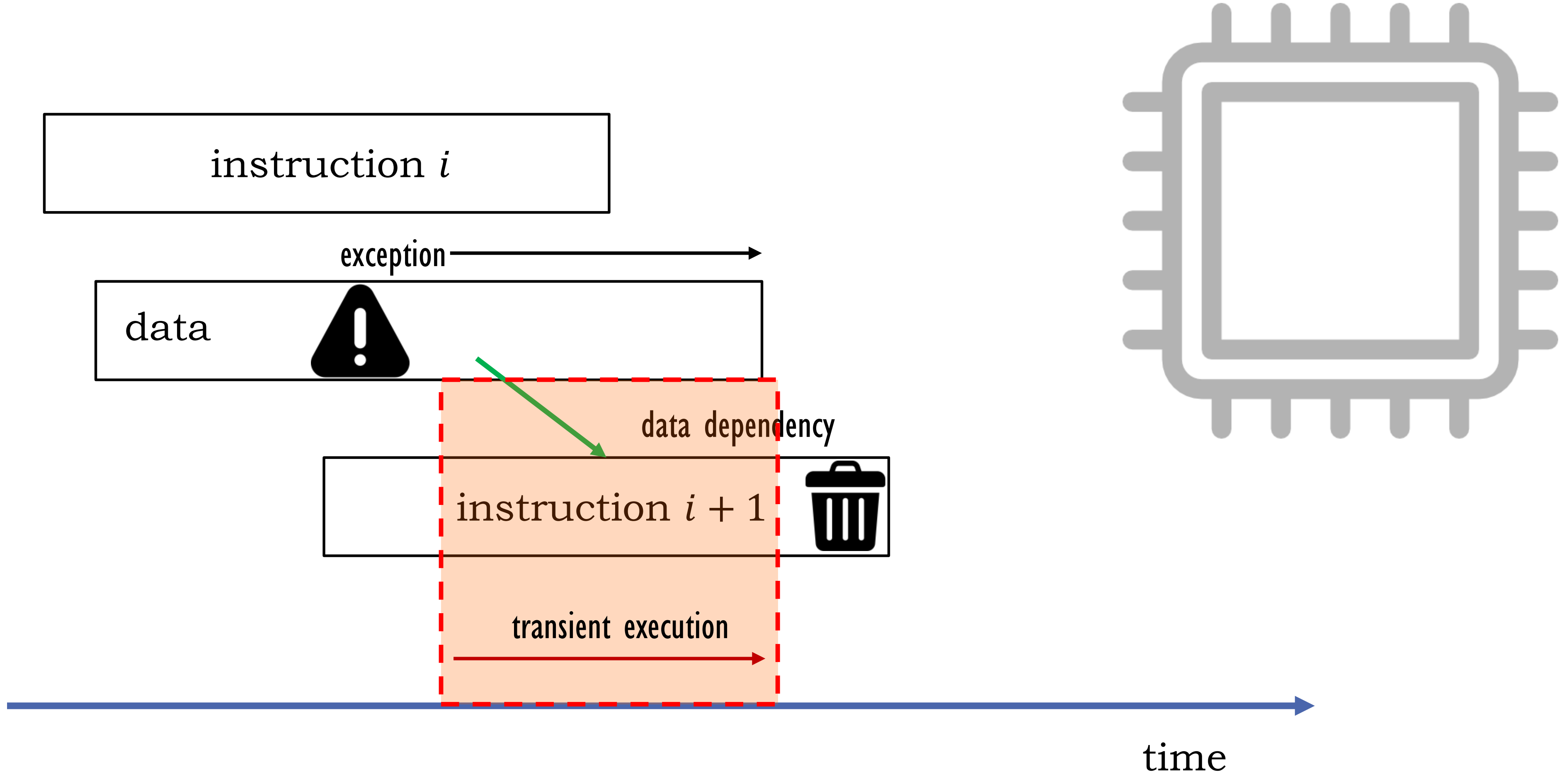

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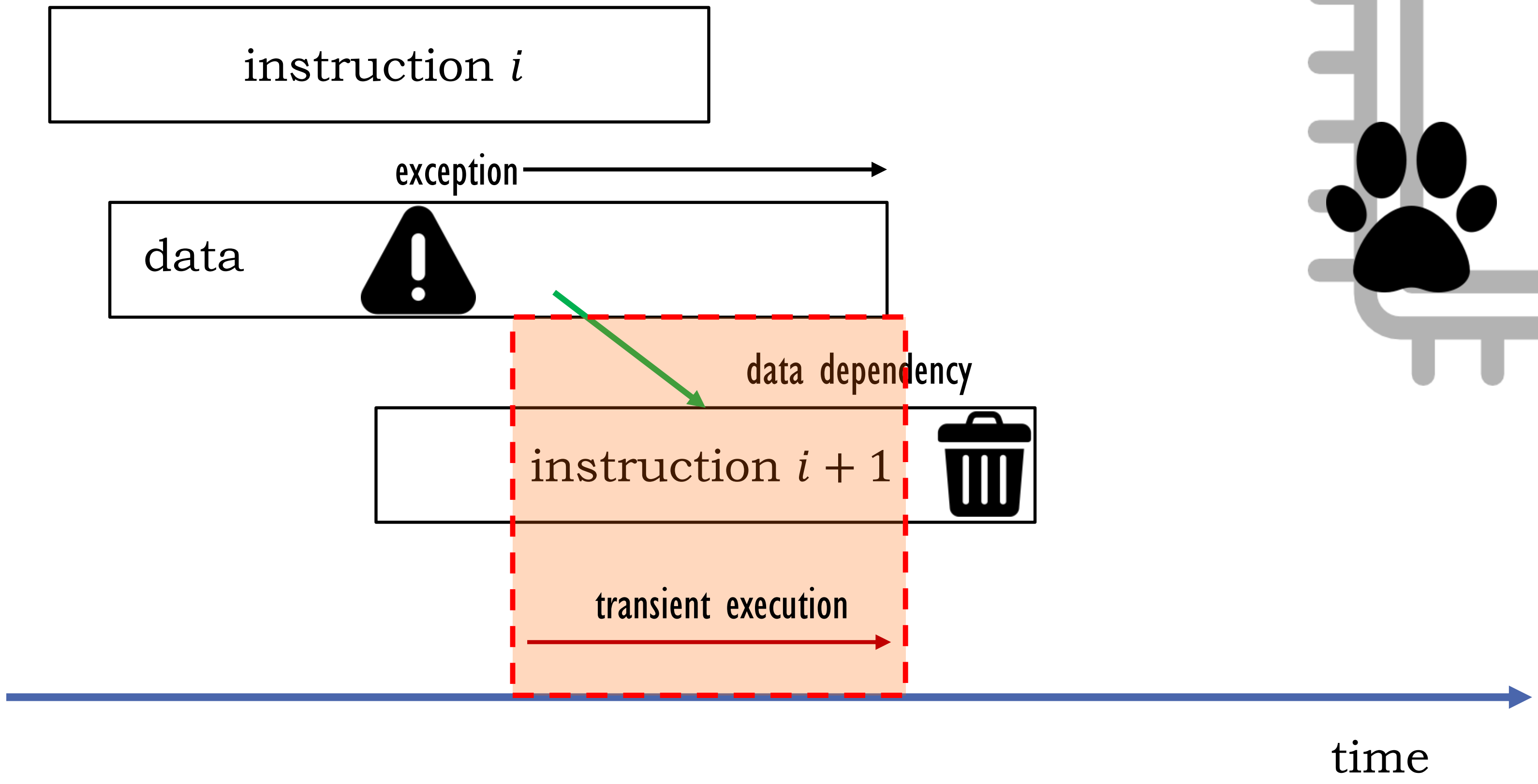

SPECTRE

MELTDOWN

FORESHADOW

MDS

SPECTRE

MELTDOWN

FORESHADOW

MDS

And many more …

Problem

Finding vulnerabilities in processors is a complex and time-consuming process

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Solution

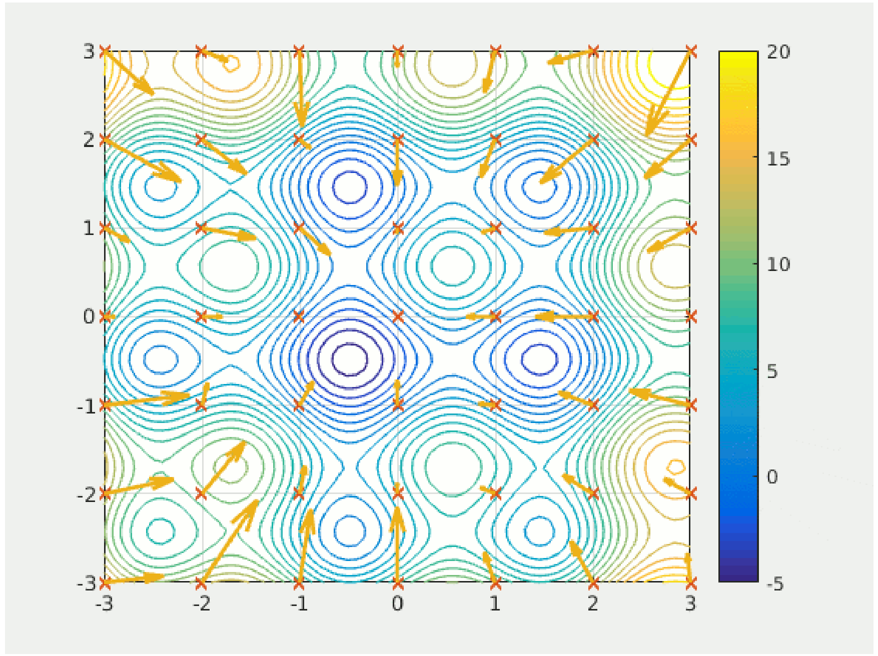
Automated process to discover new vulnerabilities

Types of Bad Speculation

- Microcode Assist
- Machine Clear

Particle Swarm Optimization

- A variant of Evolutionary Algorithm used for searching for an optimal solution in the solution space
- Advantage: Only objective function is needed



- **Exploration**: random choices that encourage the PSO for a random walk across the search space in hopes of finding newer paths to global optimums.

- **Exploitation**: greedy choices, encouraging the PSO to focus on a direct path to currently known optimums.

https://en.wikipedia.org/wiki/Particle_swarm_optimization#/media/File:ParticleSwarmArrowsAnimation.gif

SESHA: Particle Swarm Optimization-based Tool

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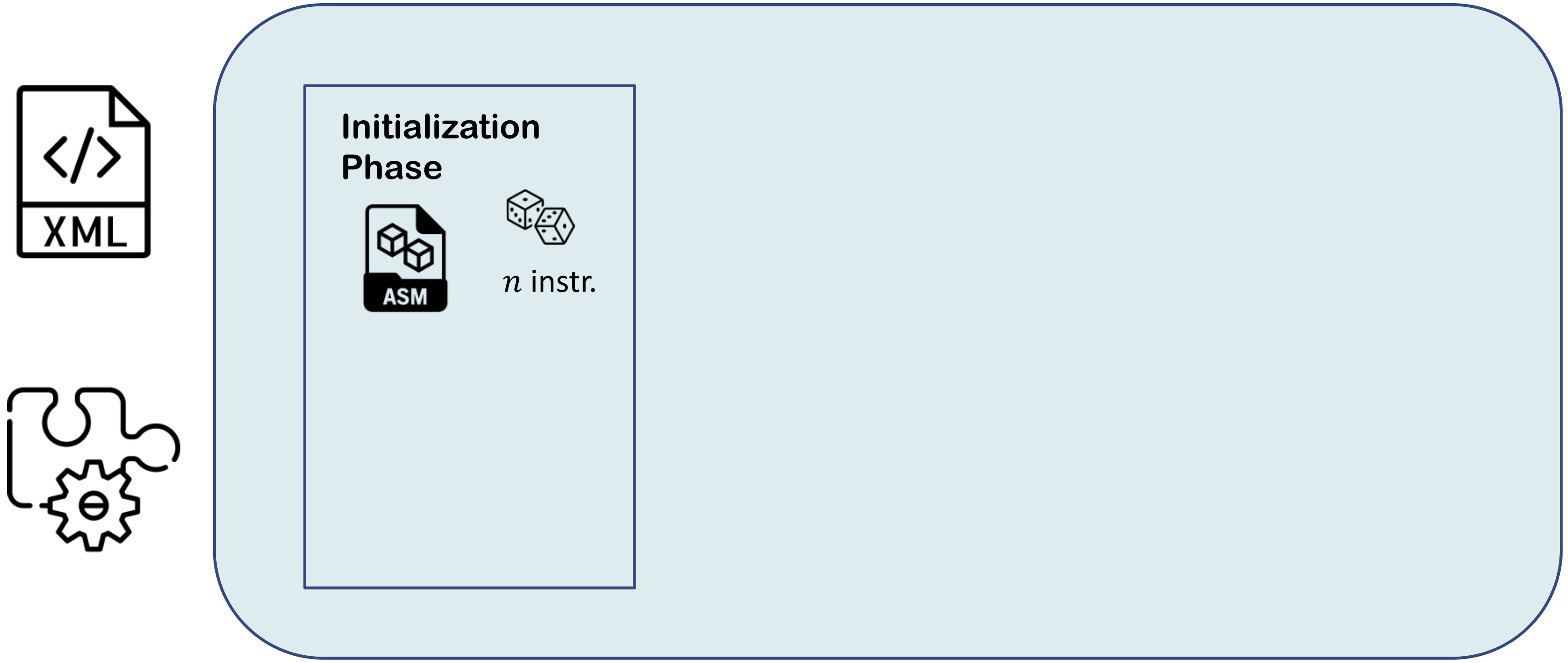

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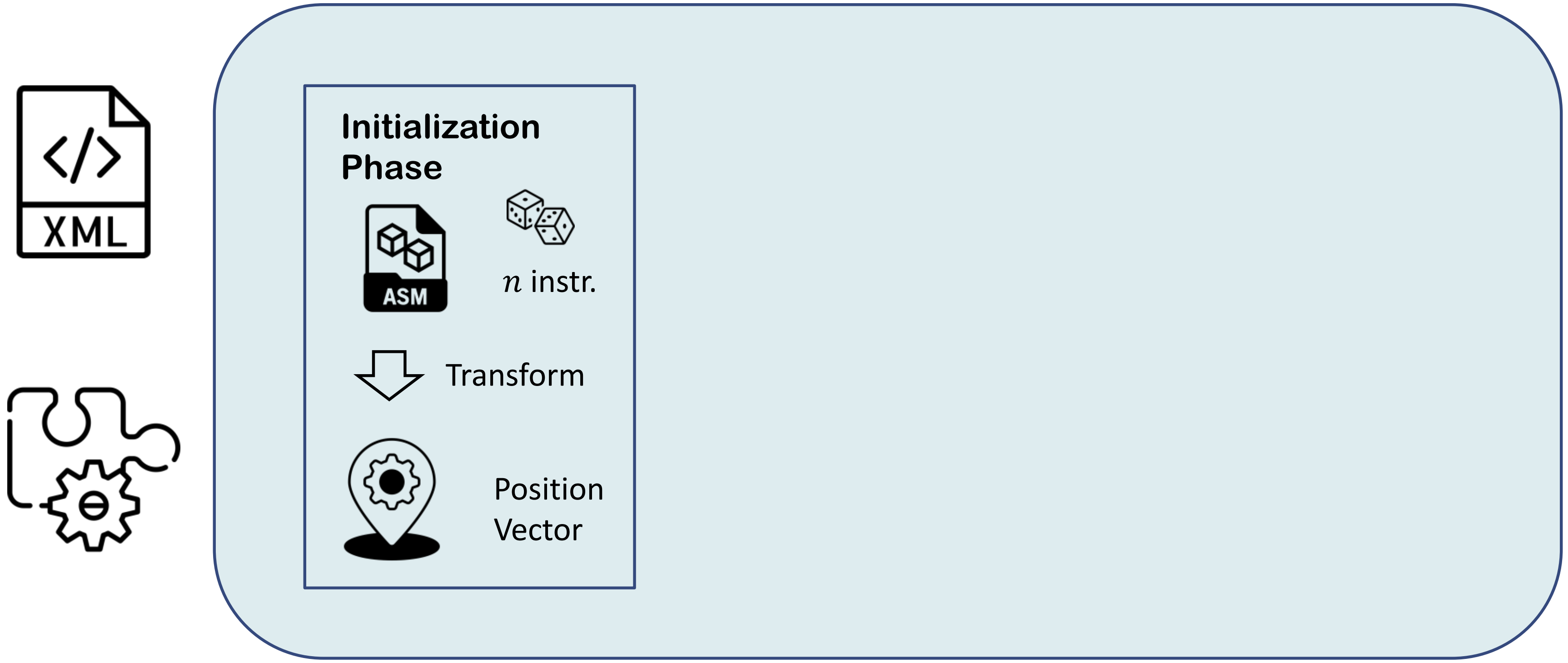

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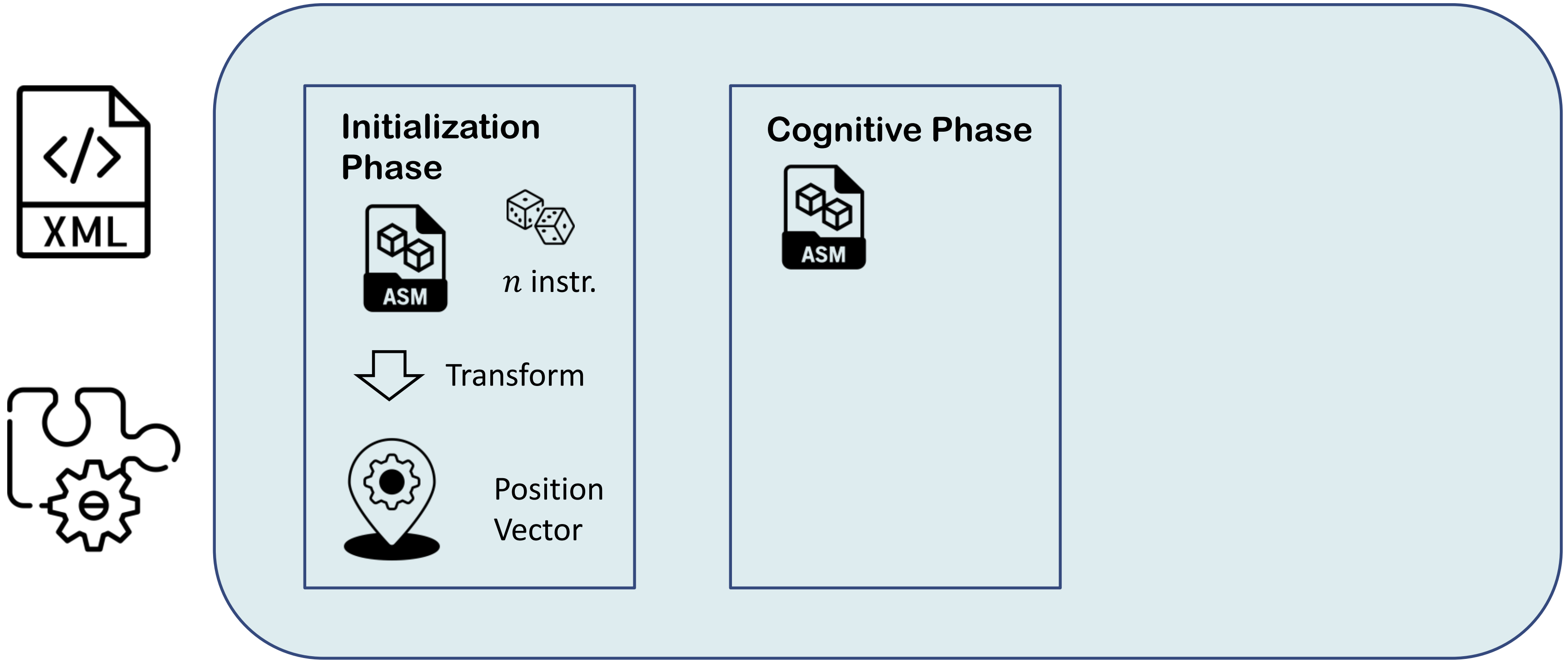

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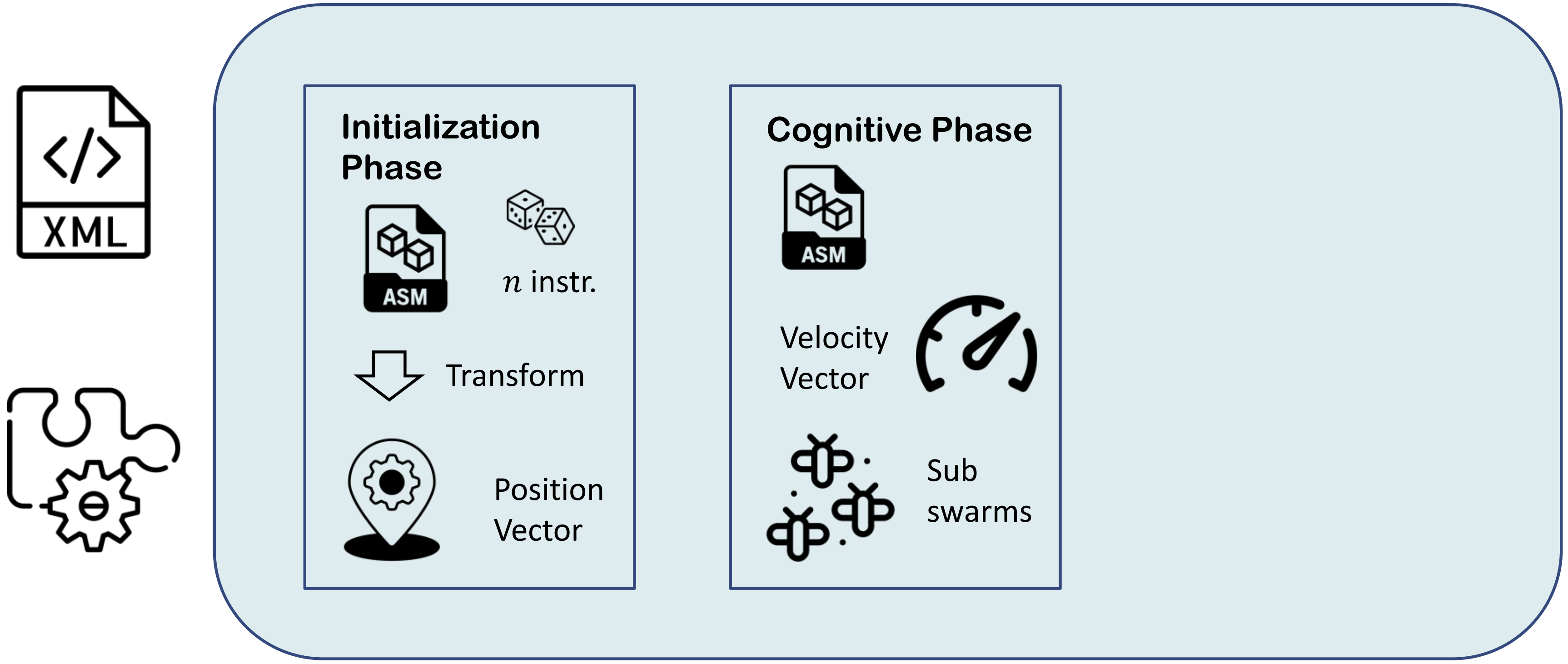

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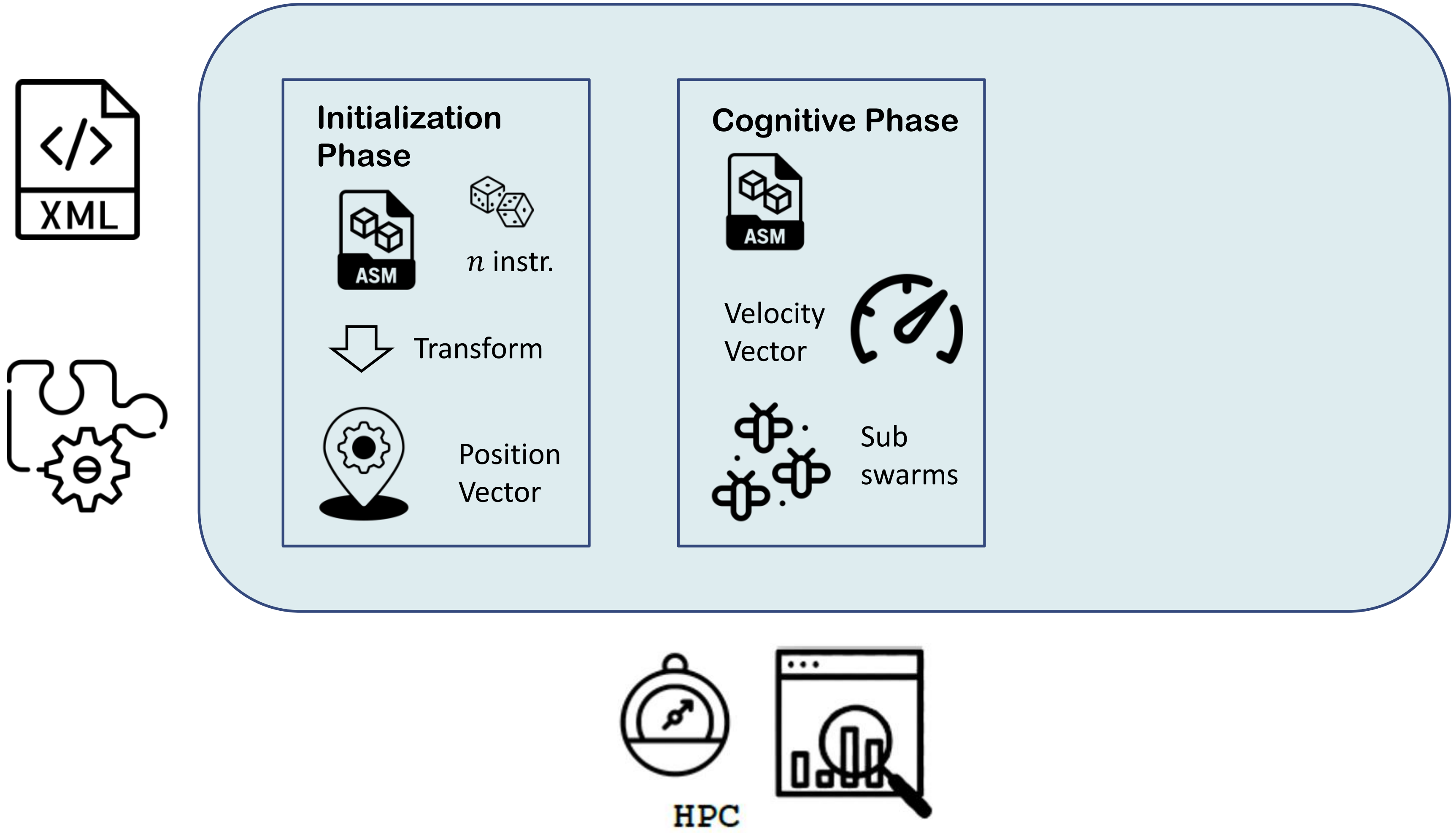

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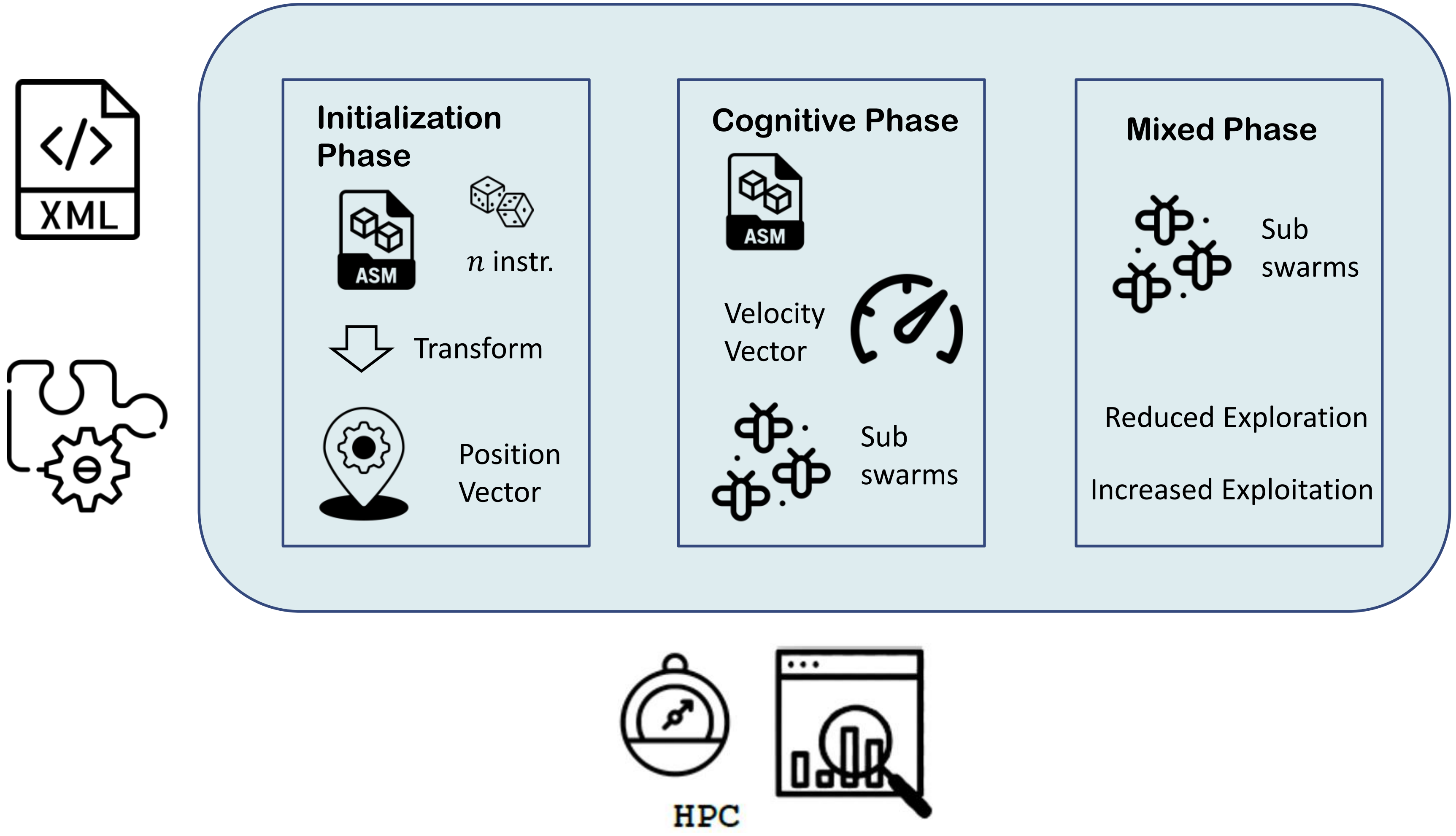

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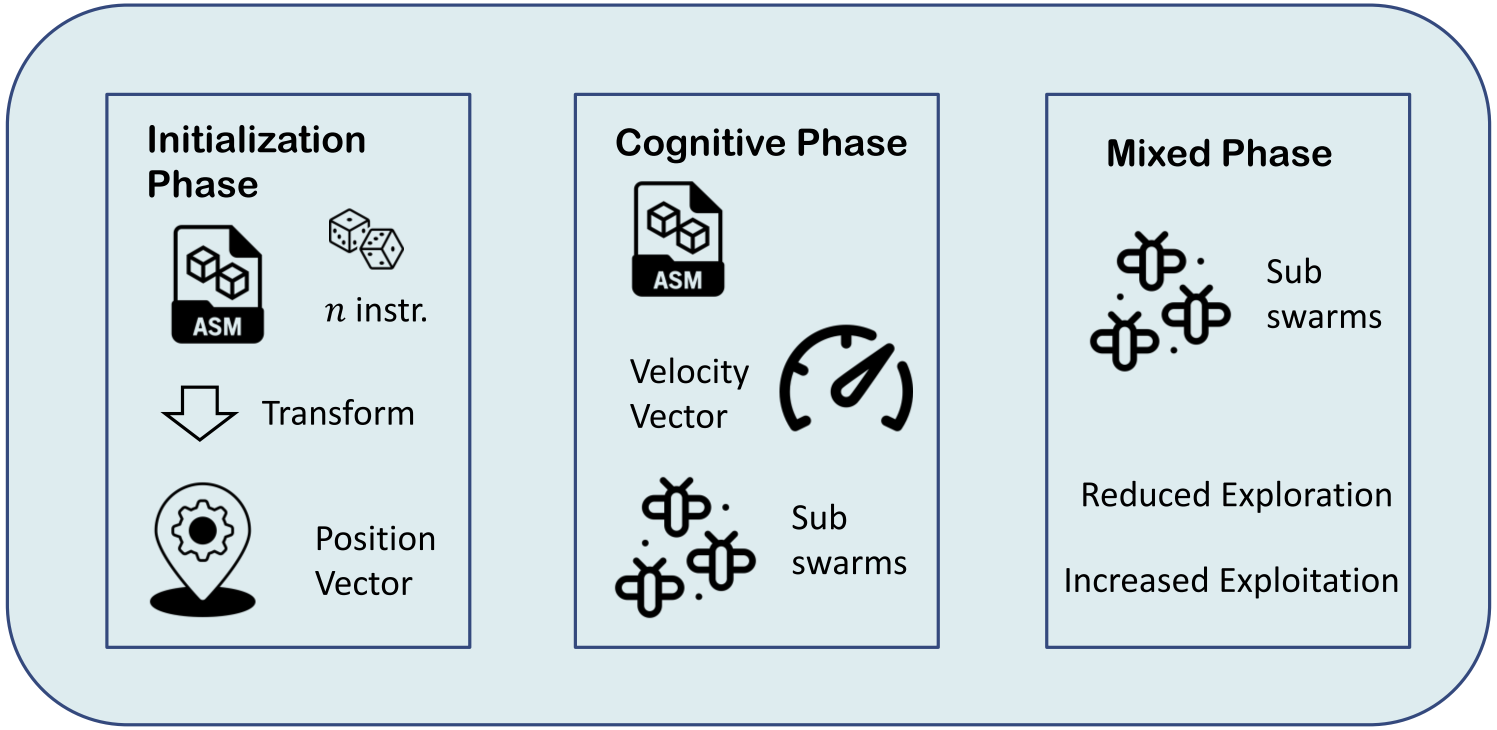

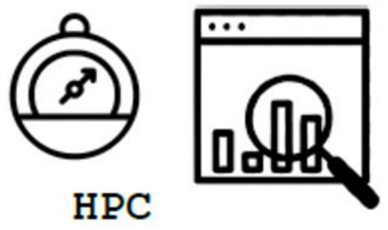

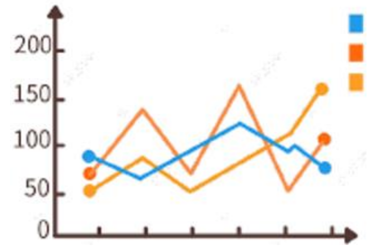

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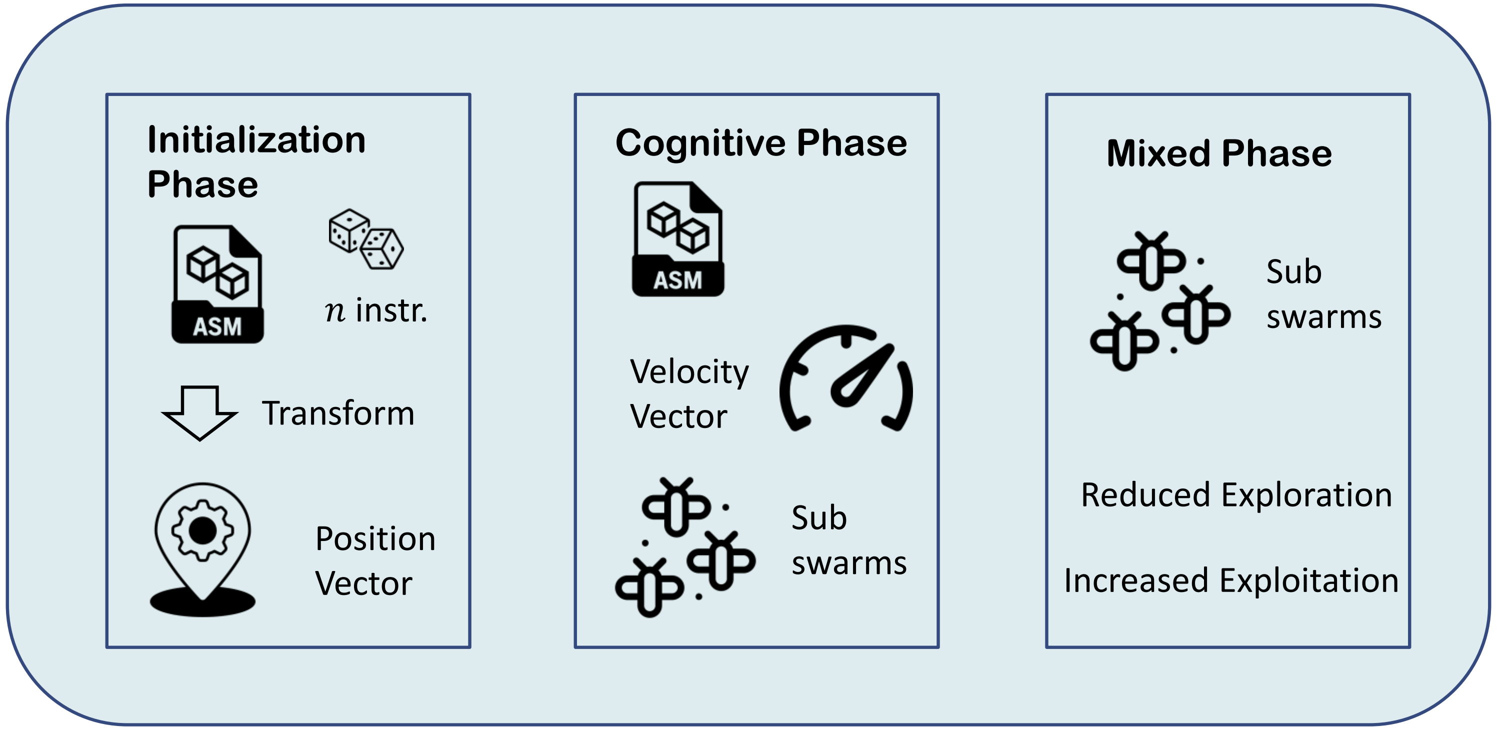

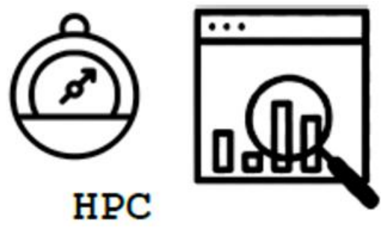

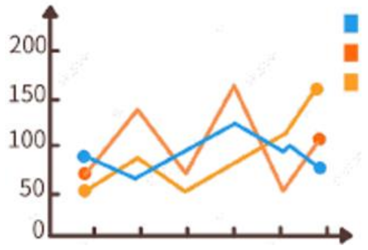

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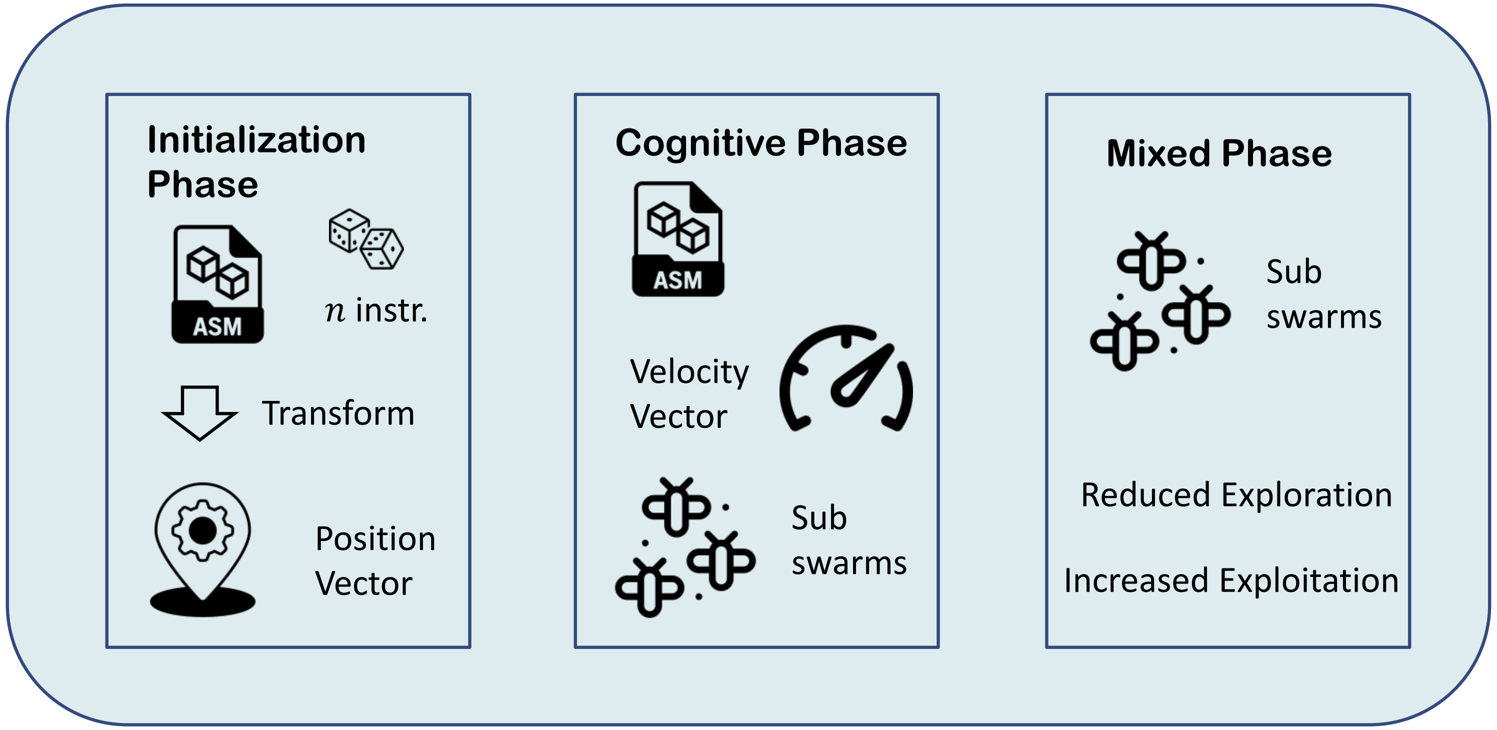
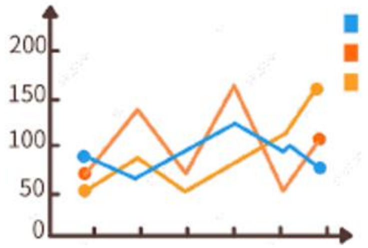


HPC



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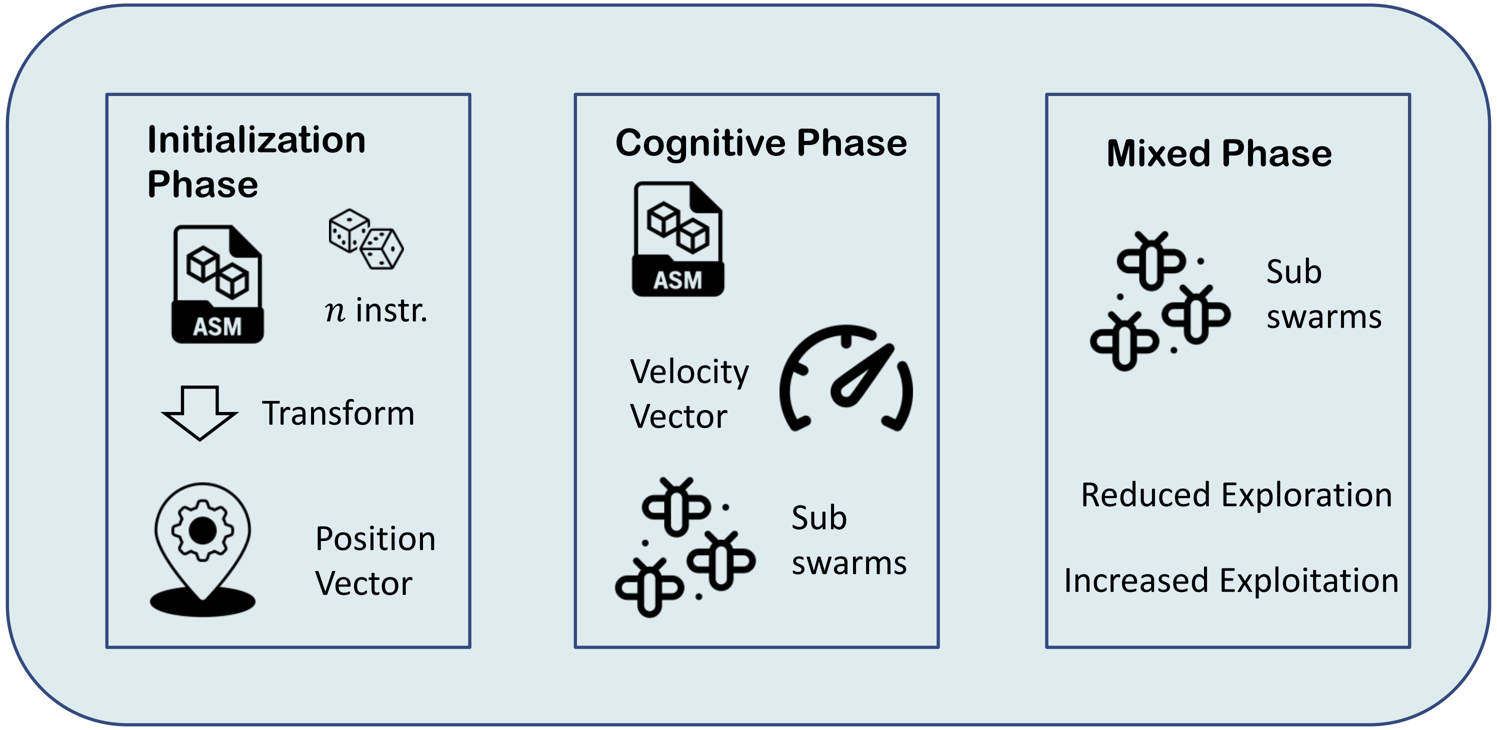
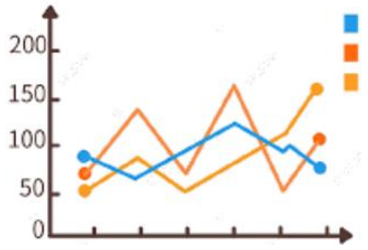




SESHA: Novel Leakage Variants Discovered

Operation	Bad Speculation Type	Affected Generations	Attack Type
SIMD-Vector intermixing	Self Modifying Code SSE-AVX Mix	12G ✓ , 11G × 4X ✓ , 3X ×	Leak
Single-Double precision mixing	Hardware Assist Memory Ordering Self Modifying Code	12G ✓ , 11G × 4X ✓ , 3X ×	Leak
Fused Multiply-Add	Floating Point Assist	12G ✓ , 11G ✓ 4X ✓ , 3X ✓	Leak, Injection
SSE-AES intermixing	Floating Point Assist Self Modifying Code	12G ✓ , 11G ✓ 4X ✓ , 3X ✓	Leak, Injection

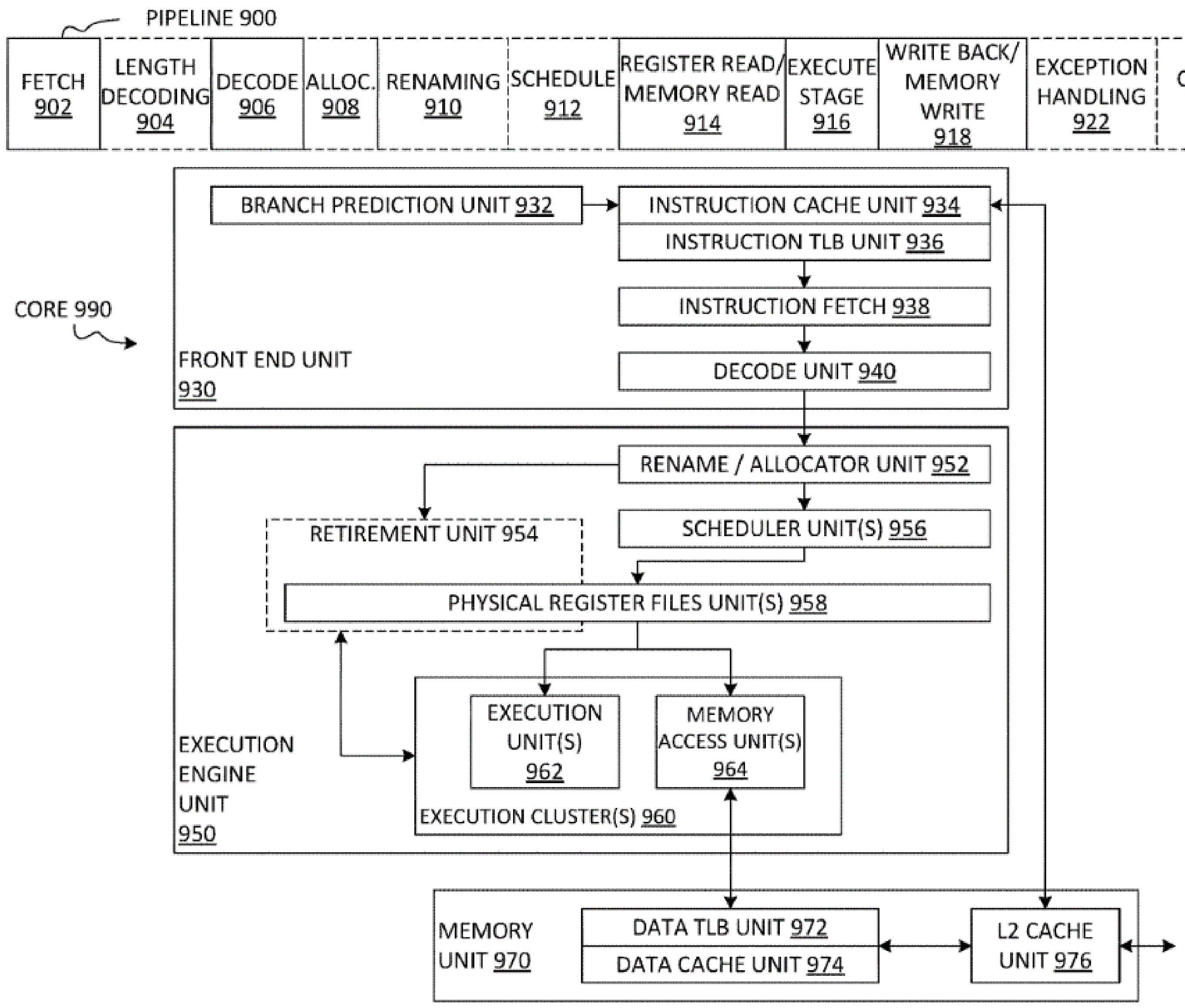
12G: Intel 12 Gen; 11G: Intel 11 Gen; 4X: 4 Gen Xeon; 3X: 3 Gen Xeon

Vulnerability in Fused Multiply Add Unit

The classic FMA family of instructions can support operations like:

1. fused multiply-add
2. fused multiply-subtract
3. fused multiply add/subtract interleave
4. signed-reversed multiply on fused multiply-add and multiply-subtract.

Vulnerability in Fused Multiply Add Unit



- Fabian Boemer and Vinodh Gopal. Fused multiple multiplication and addition-subtraction instruction set, September 21 2023. US Patent App. 17/695,554

- Jesus Corbal, Robert Valentine, Roman S Dubtsov, Nikita A Shustrov, Mark J Charney, Dennis R Bradford, Milind B Girkar, Edward T Grochowski, Thomas D Fletcher, Warren E Ferguson, et al. Systems, apparatuses, and methods for chained fused multiply add, December 4 2018. US Patent 10,146,535

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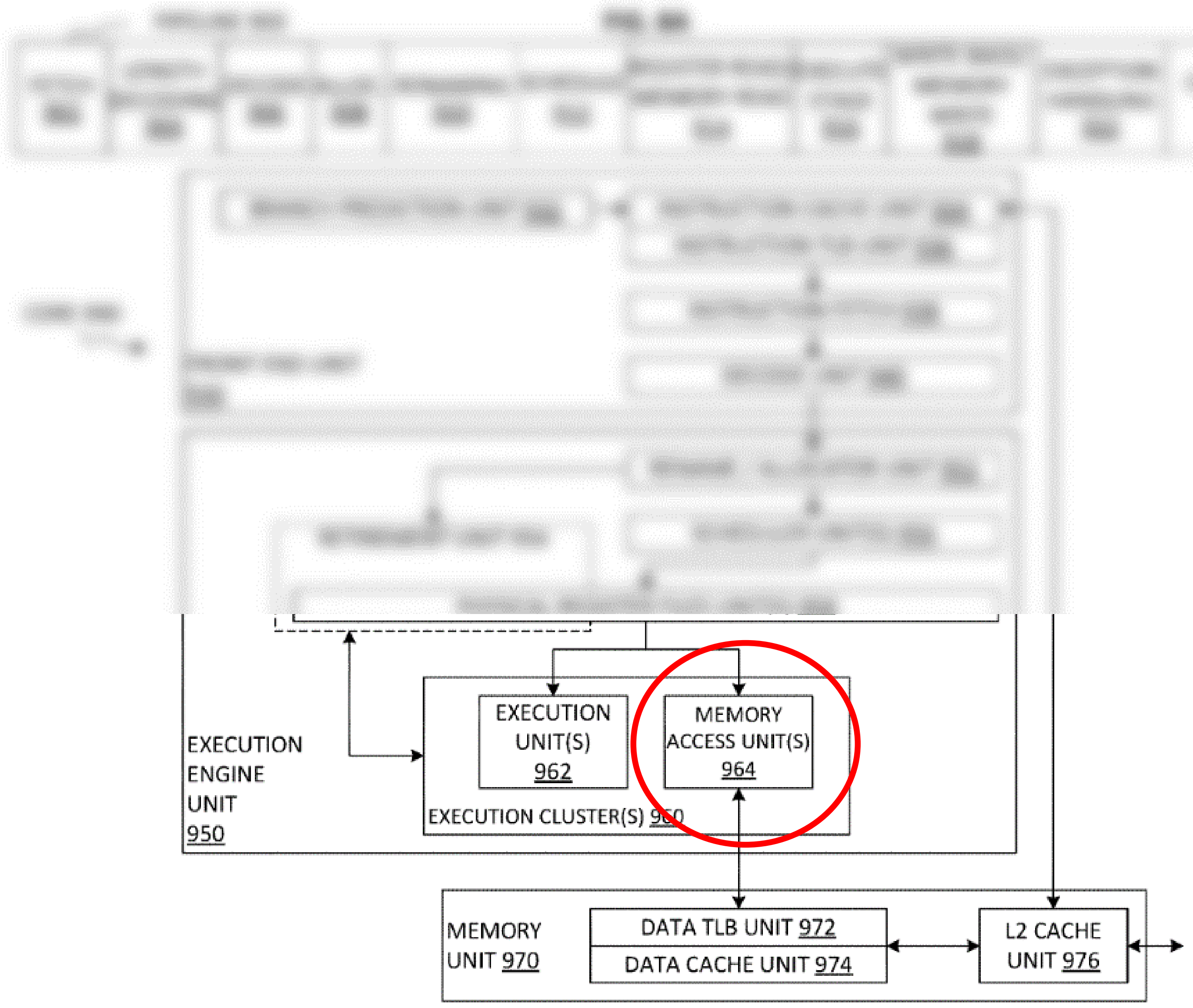

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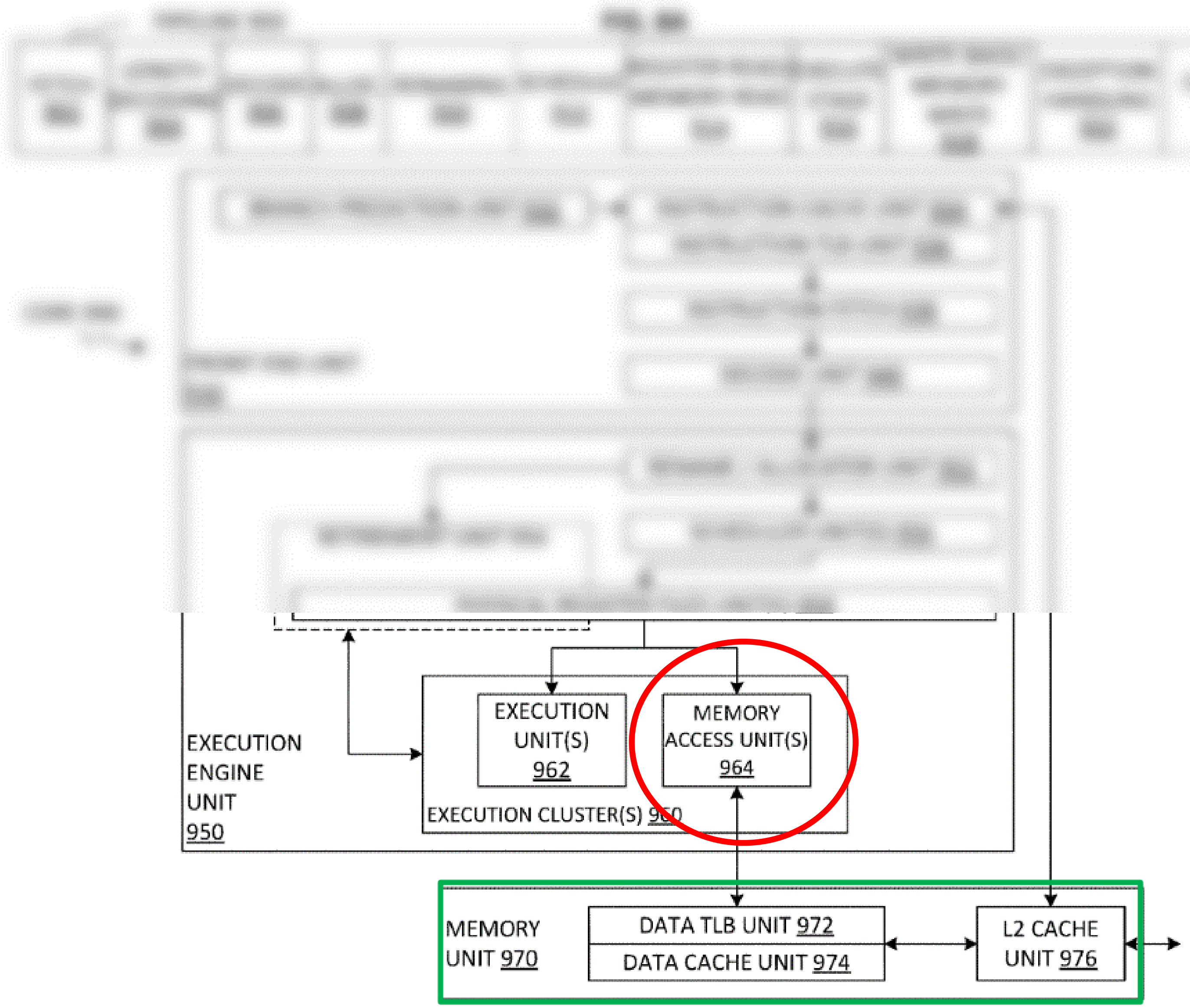

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Vulnerability in Fused Multiply Add Unit

Victim thread

- Execute FMA instruction in a tight loop

```
VFMADD213PD zmm1, zmm2,
zmmword PTR [rcx]
```

- `[rcx] := 0xfa`

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- Execute FMA instruction in a tight loop

```
VFMADD213PD zmm1, zmm2,
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```
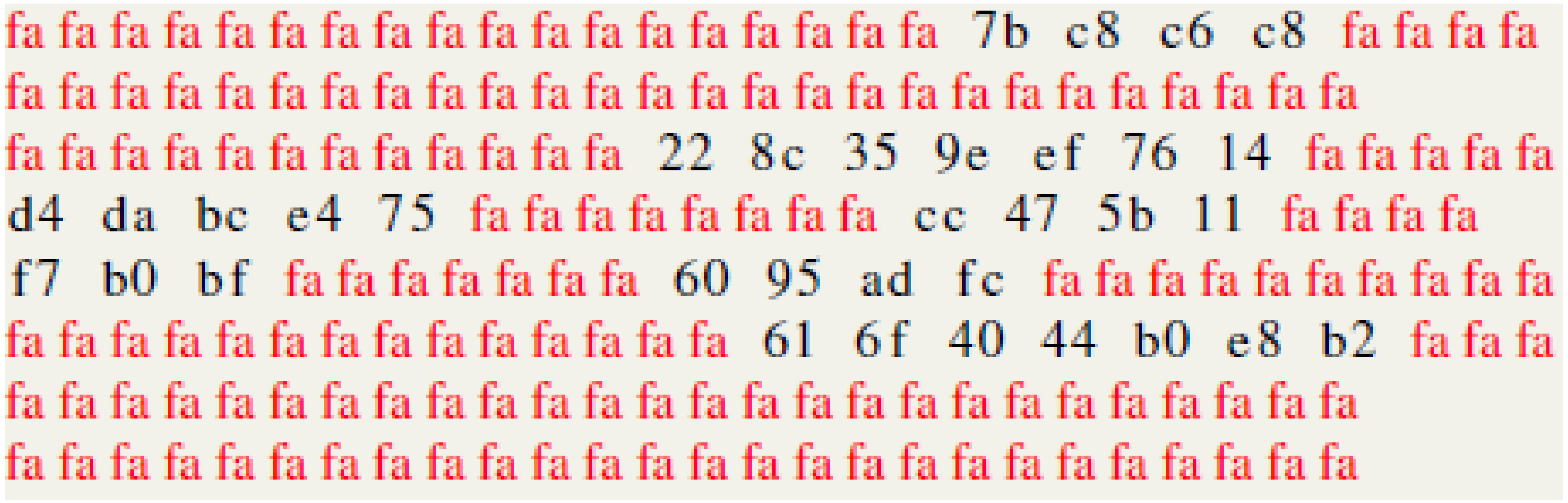

- `[rcx] := 0xfa`

Attacker thread

- Forces AVX transient execution on registers zmm1 and zmm2
- Uses `gather` instructions to leak data from shared buffer
- Uses Flush+Reload covert channel to sniff the leaked data from cache

Vulnerability in Fused Multiply Add Unit



```
fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa 7b c8 c6 c8 fa fa fa fa
fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
fa fa fa fa fa fa fa fa fa fa fa fa 22 8c 35 9e ef 76 14 fa fa fa fa fa
d4 da bc e4 75 fa fa fa fa fa fa fa fa cc 47 5b 11 fa fa fa fa
f7 b0 bf fa fa fa fa fa fa fa 60 95 ad fc fa fa fa fa fa fa fa fa fa fa
fa fa fa fa fa fa fa fa fa fa fa fa fa fa 61 6f 40 44 b0 e8 b2 fa fa fa
fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
```

Leakage when victim executes `VFMADD213PD zmm1, zmm2, zmmword PTR [rcx].`

Attack on Cryptographic Applications

“Almost” Montgomery Multiplication

- Uses IFMA instructions to speed up modular exponentiation

```
.set i, 0
; Initialize X_i in zmm0
; Initialize A_curr in zmm1
; X_i = VPMADD52LUQ X_i, A_curr, A_i
VPMADD52LUQ i(%rcx), %zmm0, %zmm1
.rept N     ; iteration bounds (i+1, z)
  vpxord %zmm3, %zmm3, %zmm3  ; T = 0
  ; T = VPMADD52LUQ ZERO, A_curr, A_i
  VPMADD52LUQ i(%rcx), %zmm1, %zmm3
  vpslld $1, %zmm3, %zmm3  ; T = T << 1
  vpaddd %zmm1, %zmm1, %zmm3 ; X_i = X_i + T
.set i, i+1
.endr
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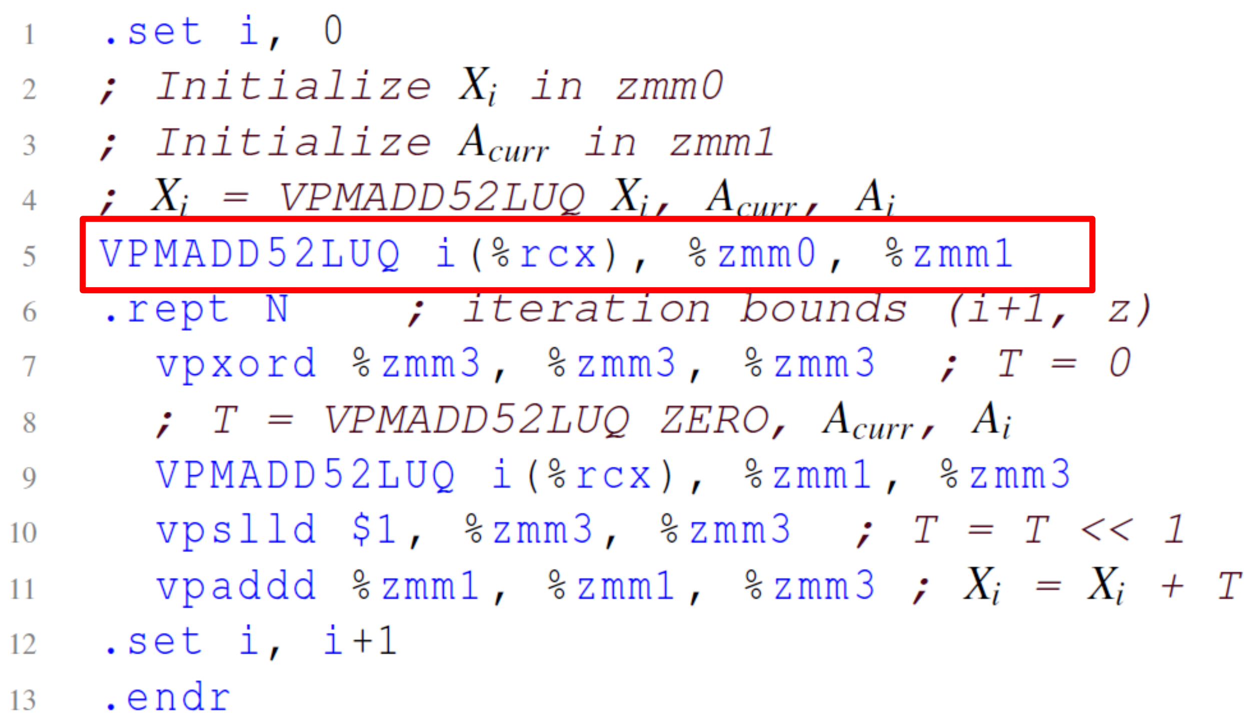

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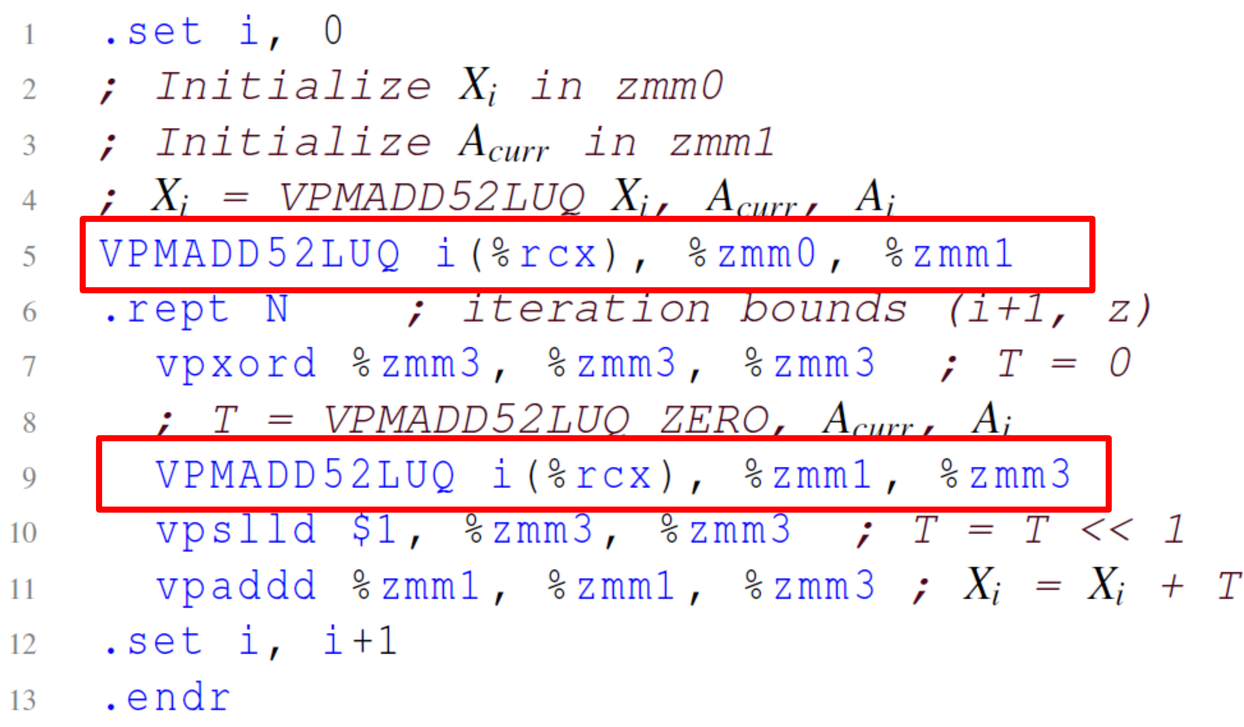

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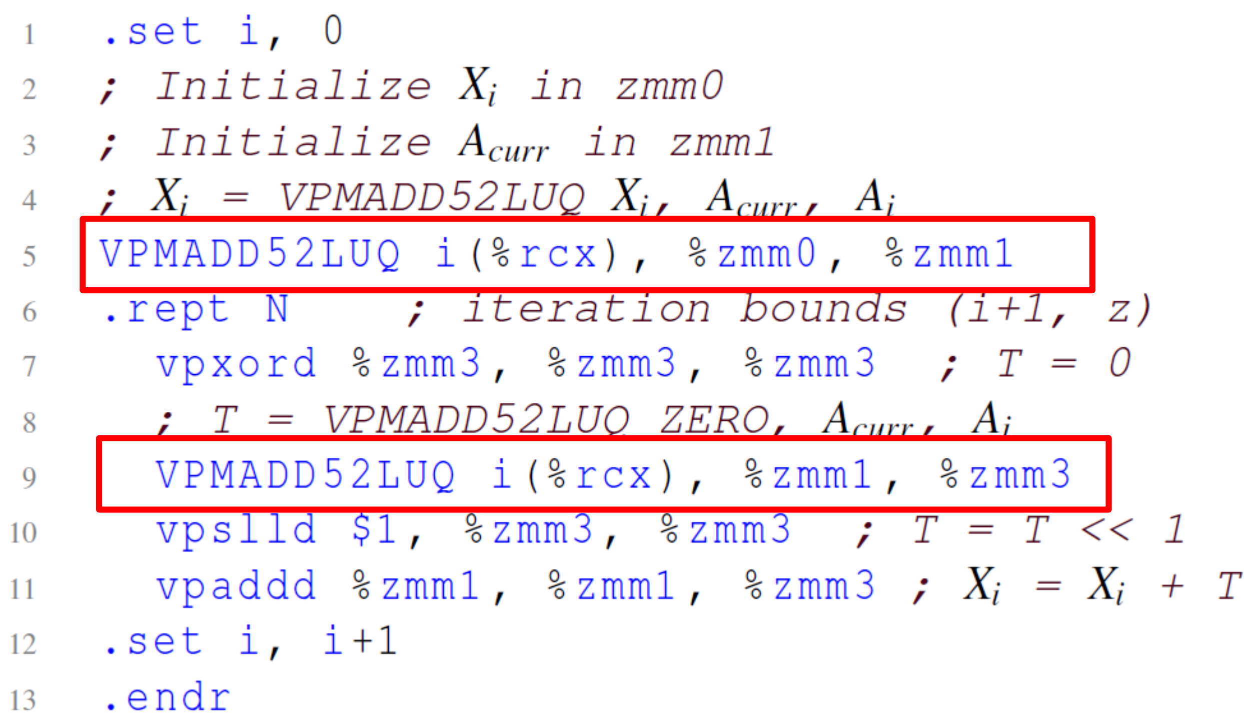
- leaked value is the multiplicand A_i: $i \in \{i+1, i+2, \ldots, z\}$



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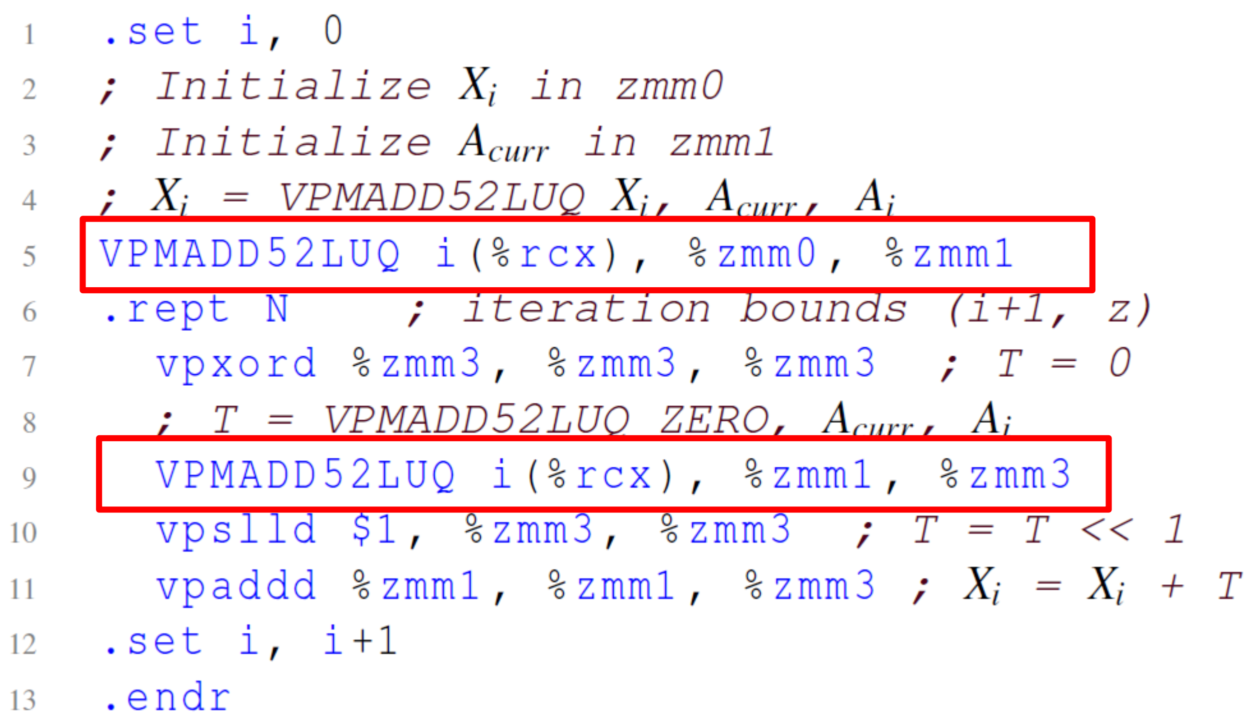
- leaked value is the multiplicand A_i: $i \in \{i+1, i+2, \dots, z\}$
- Similar leakage has been found in IFMA based implementations of Cumulative Supersingular Isogeny Diffie-Hellman (CSIDH) and Supersingular Isogeny Key Encapsulation (SIKE)



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```

Conclusion

- Automation process to discover new vulnerabilities in x86 processors
- Evolutionary Algorithms that are efficient in search optimizations can be an efficient tool
- We establish the concept of equivalent classes that represent disjointedly fragmented sub-spaces of bad speculation
- **Shesha** is a vulnerability detection tool based on PSO principles
- Data from FMA execution engine is speculatively forwarded to AVX execution engine
- Use of IFMA instructions in crypto applications make them vulnerable

GitHub