



The Dark Age of Memory Corruption Mitigations in the Spectre Era

Andrea Mambretti, IBM Research Europe - Zurich
Alexandra Sandulescu, Google (formerly: IBM Research Europe - Zurich)

About us



Andrea Mambretti

System Security Research @ IBM Research Europe - Zurich

PhD in Cybersecurity @ Northeastern University, Boston

@m4mbr3 - <https://mbr.sh>

Alexandra Sandulescu

Security @ Google

(work done previously at IBM Research Europe - Zurich)





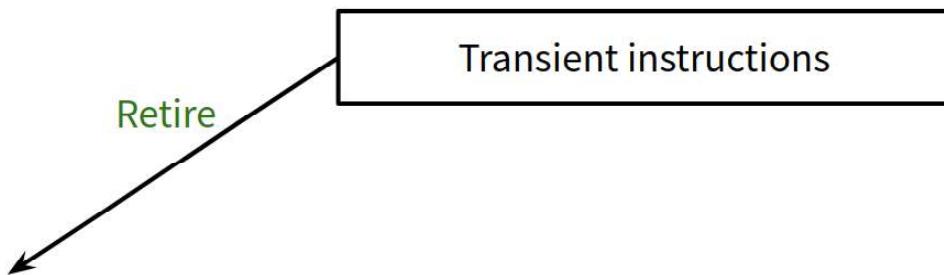
Background - transient execution



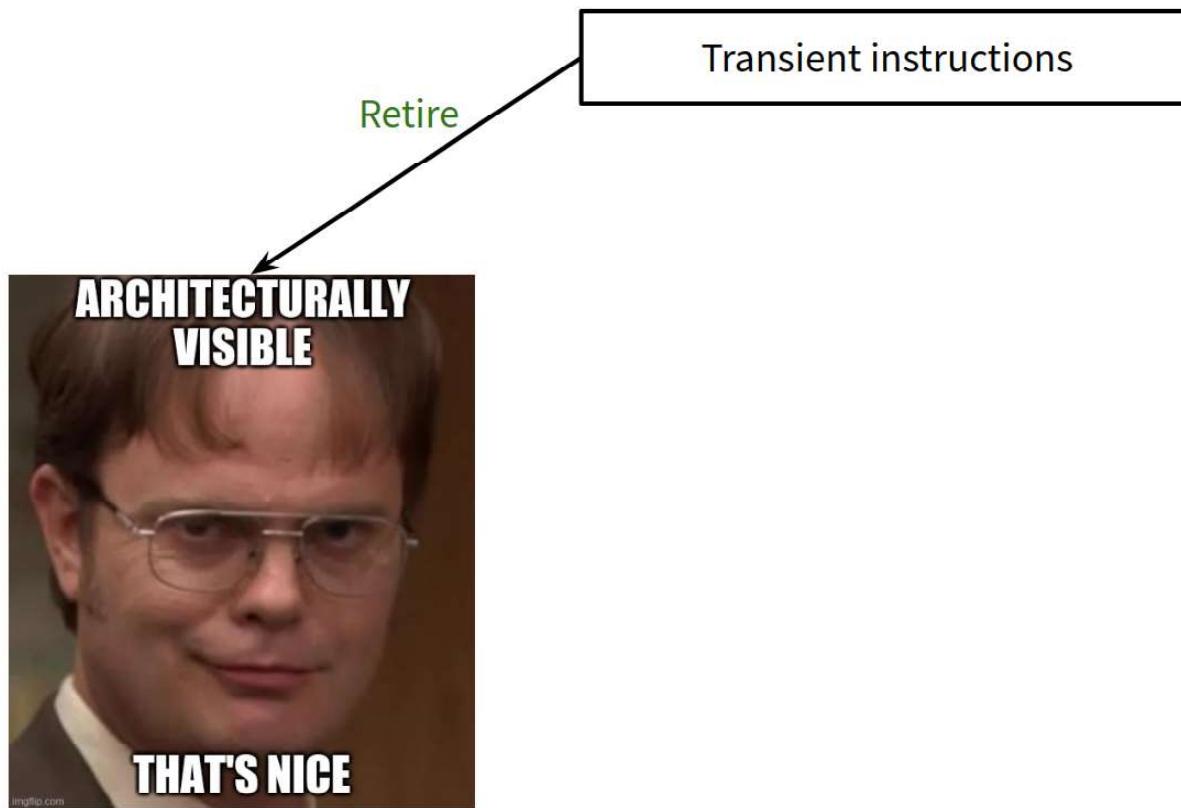
Background - transient execution

Transient instructions

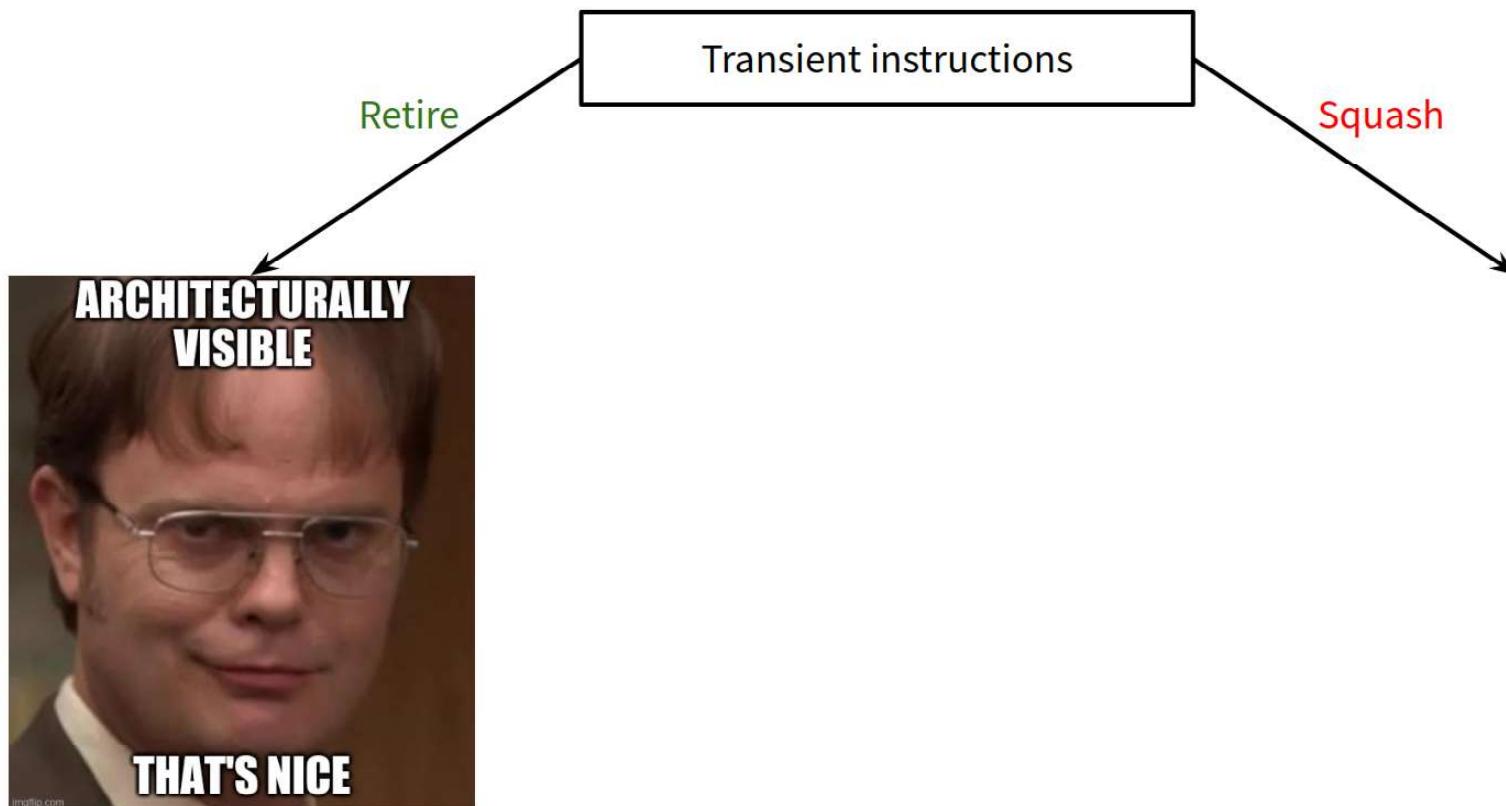
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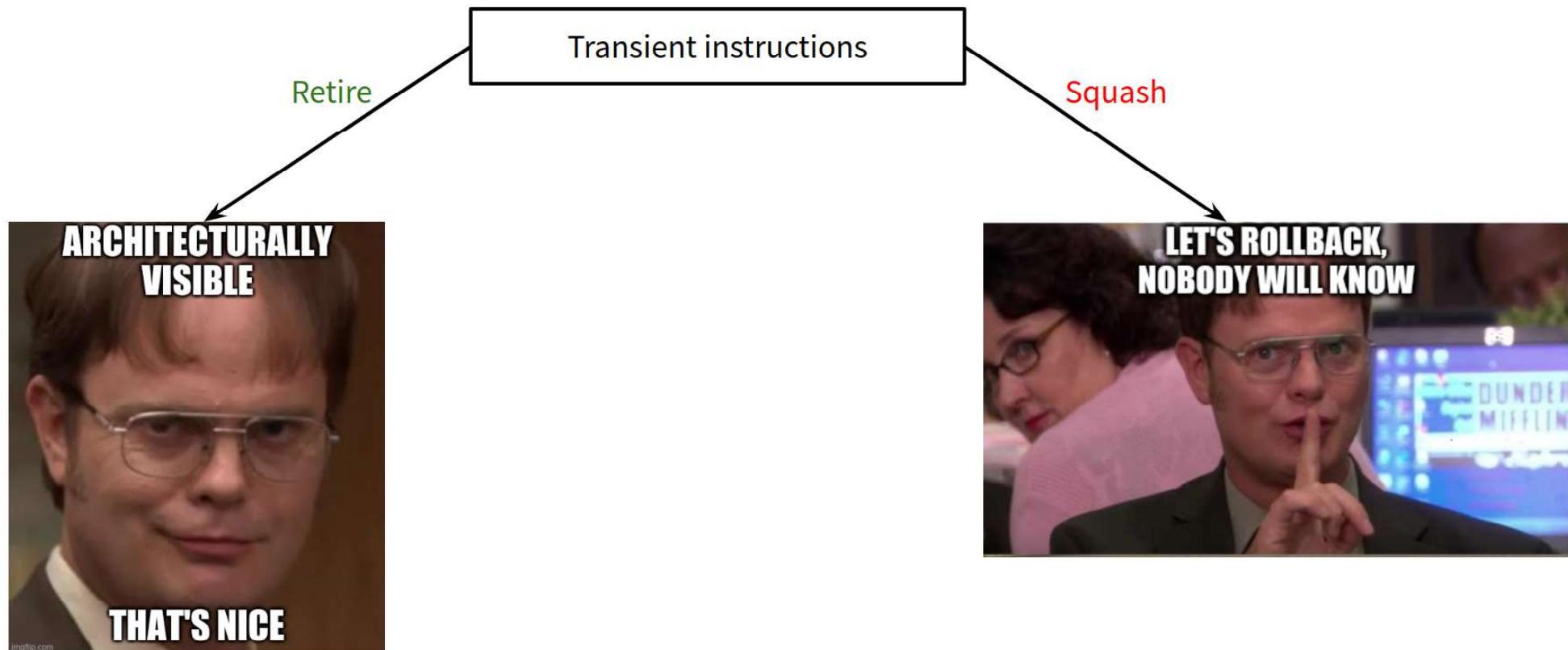
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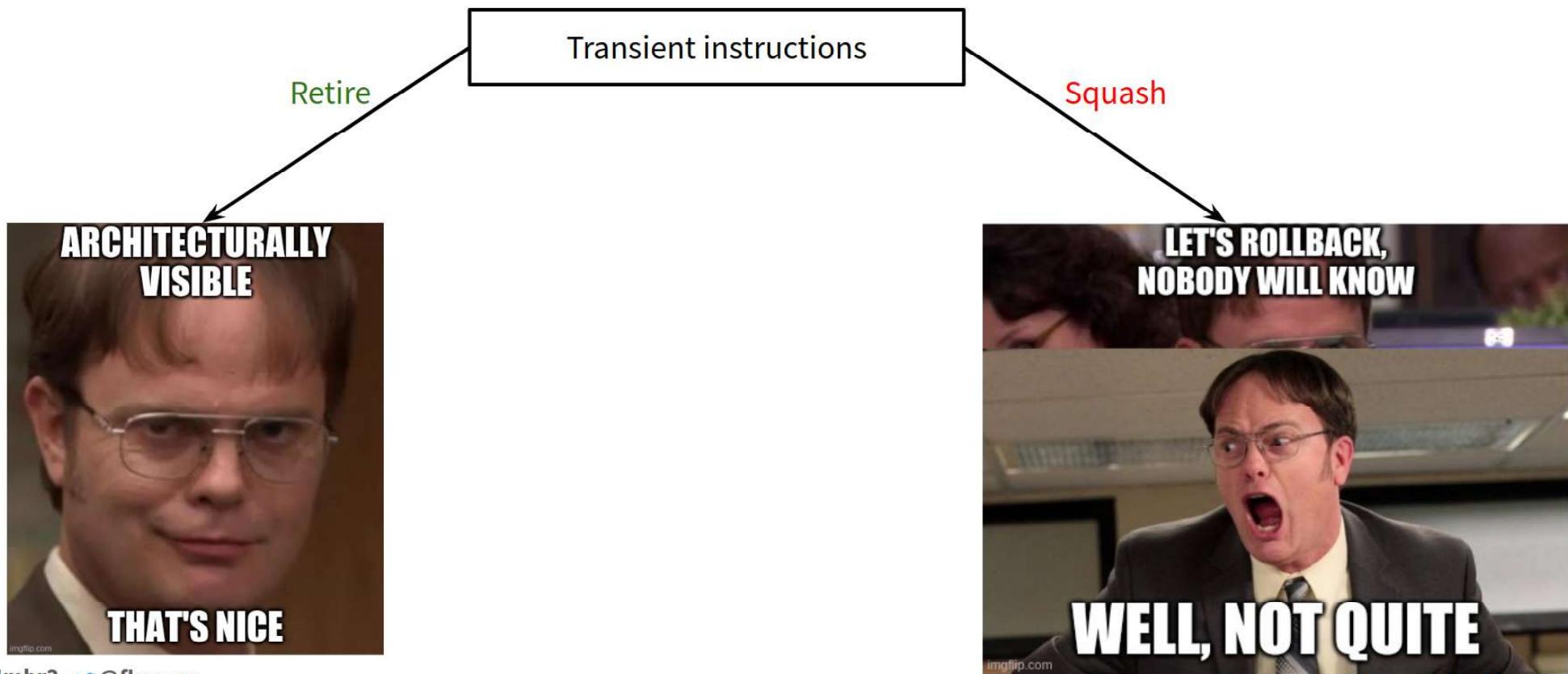
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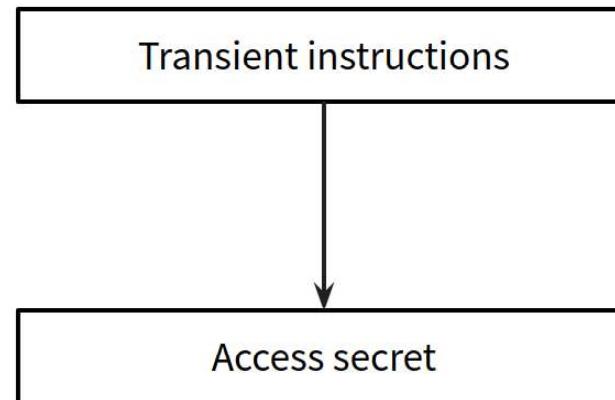




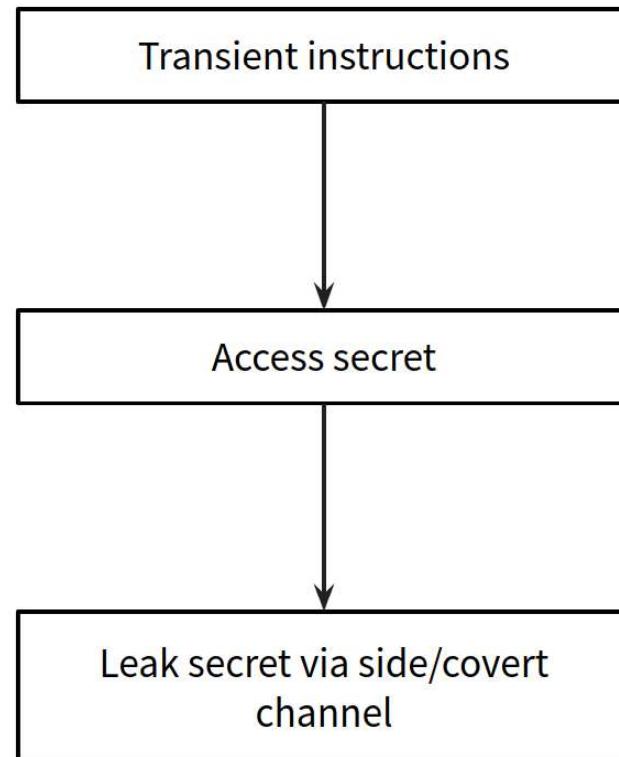
Background - transient execution attacks

Transient instructions

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Background - transient execution attacks





Threat model for Speculative Execution Attacks (SEAs)

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<secret data>
Victim Program

Threat model for Speculative Execution Attacks (SEAs)



Attacker
Program

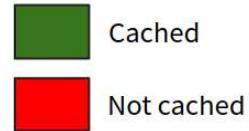


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Victim Program



Spectre v1.1 - speculative buffer overflow [KW18]

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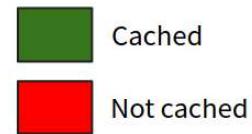


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return;
```

Spectre v1.1 - speculative buffer overflow [KW18]

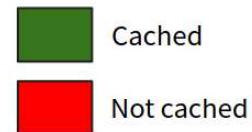
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```



saved RET
saved RBP
....
array1[size_array1 - 1]
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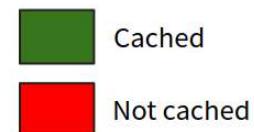
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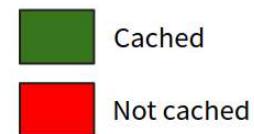
Speculative overflow
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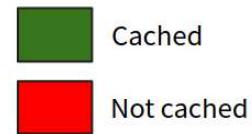


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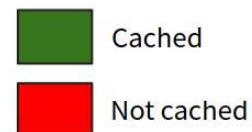
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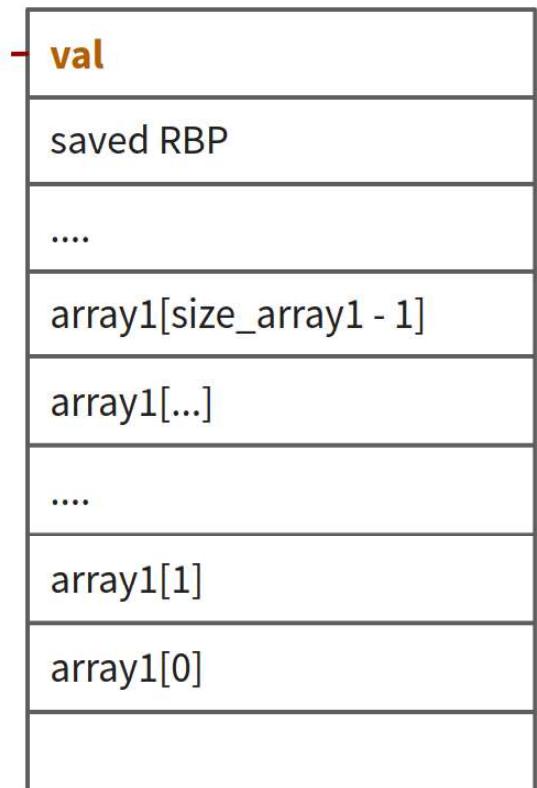
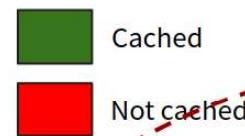
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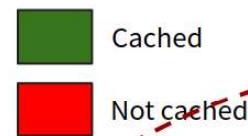
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Speculative Control Flow
Hijack





SPEculative ARchitectural control flow hijacks (SPEAR)

 @m4mbr3  @fkaasan

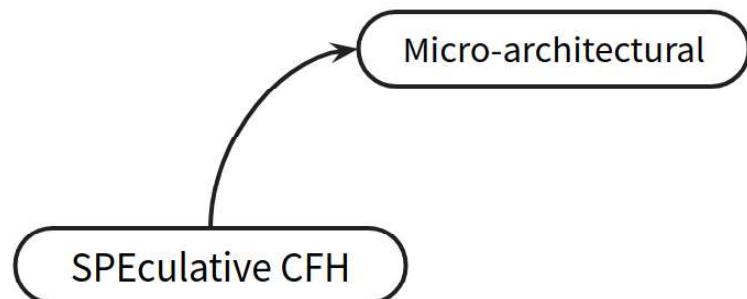
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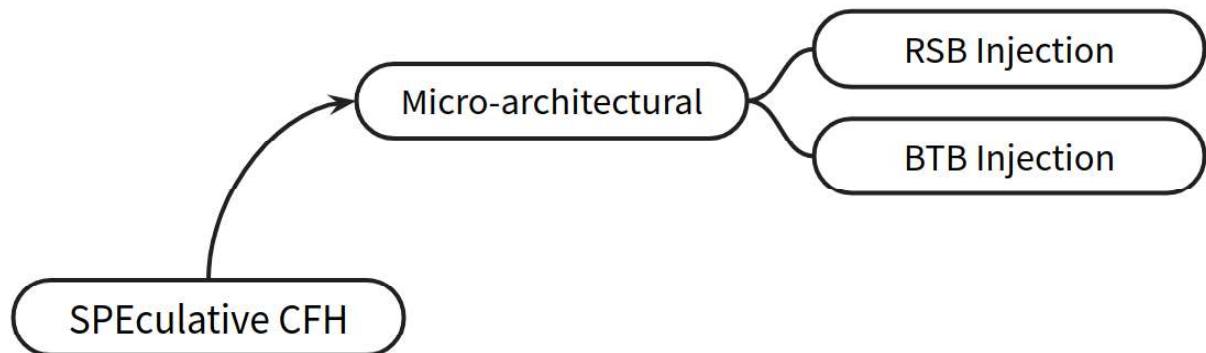
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SPEculative CFH

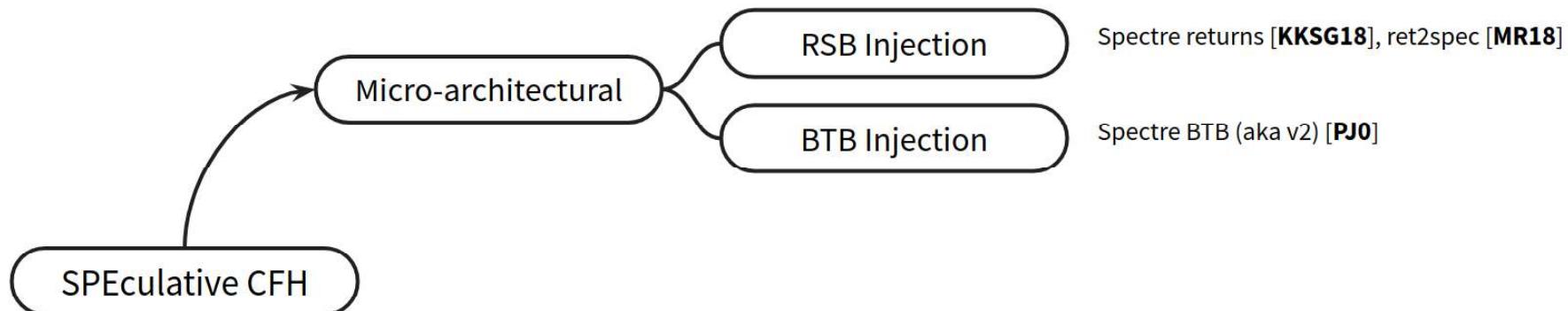
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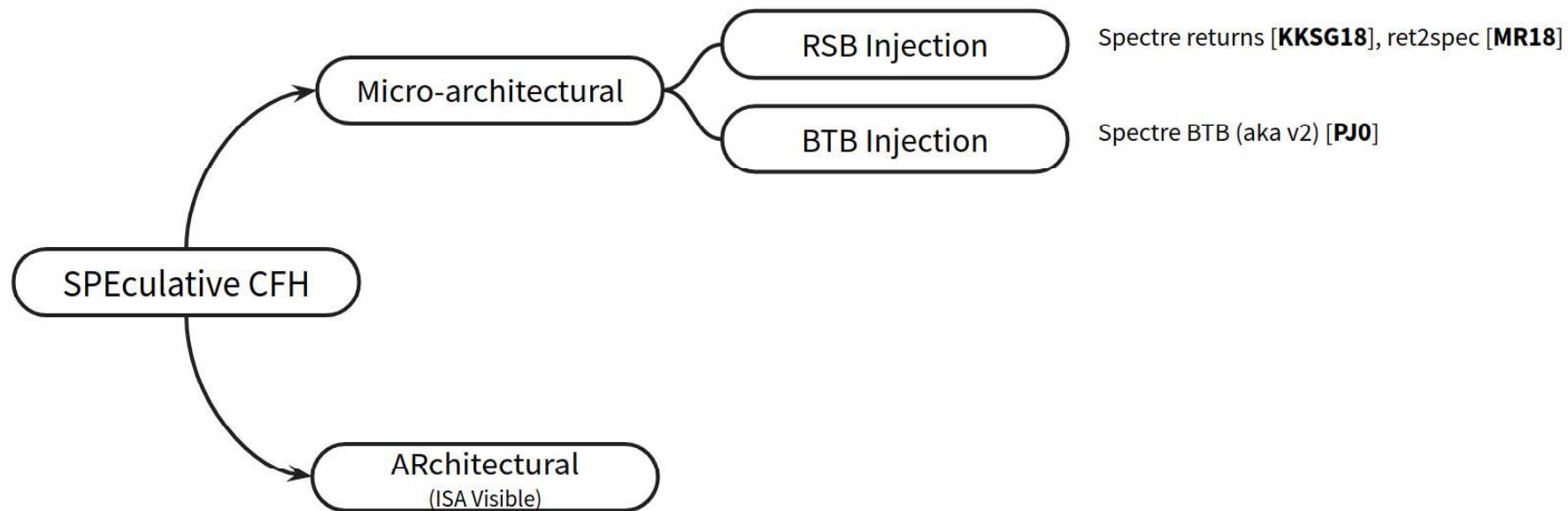
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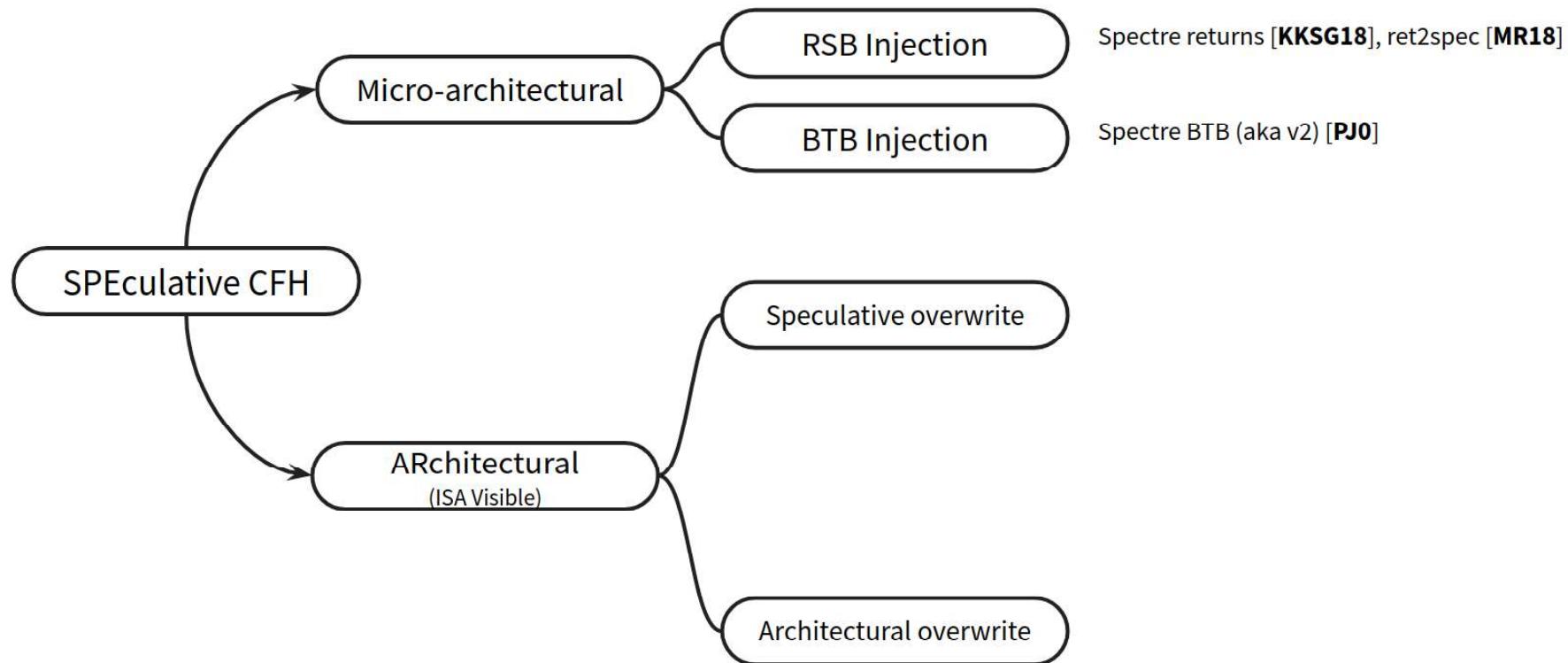
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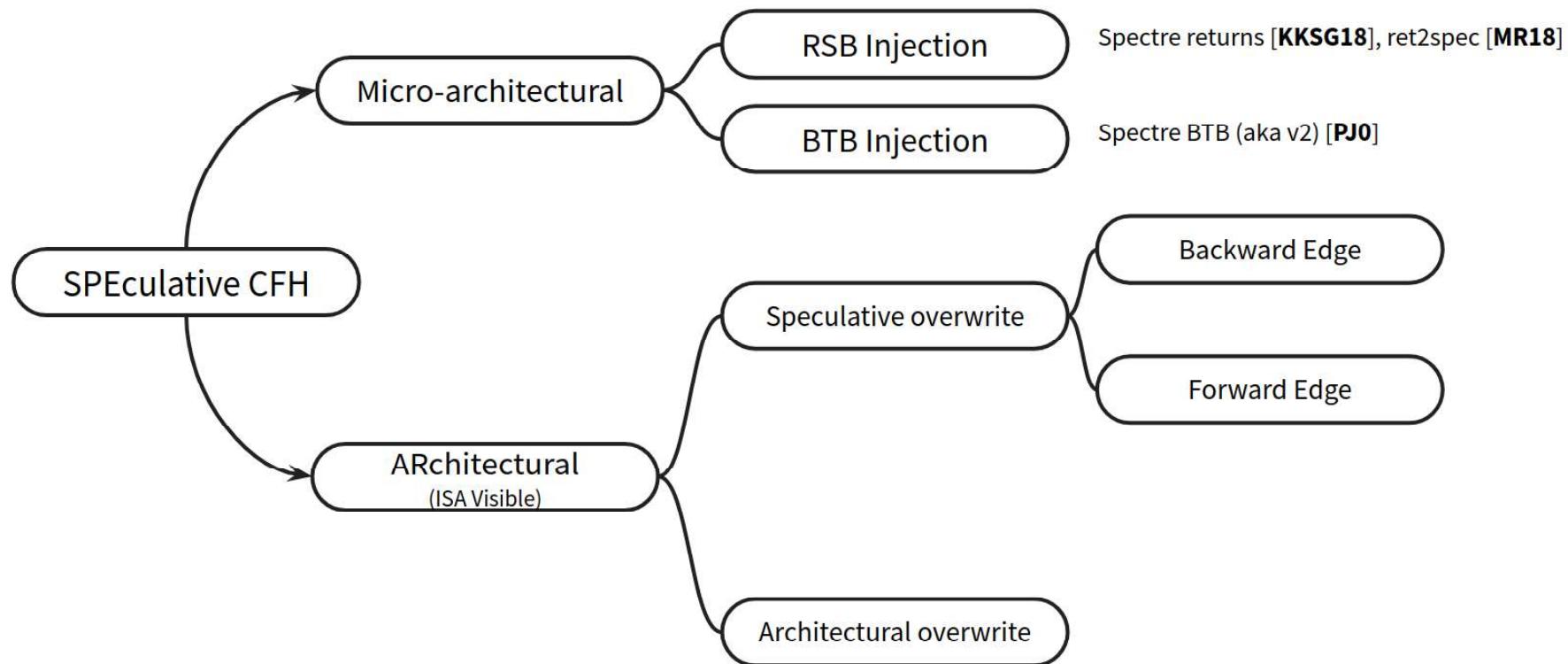
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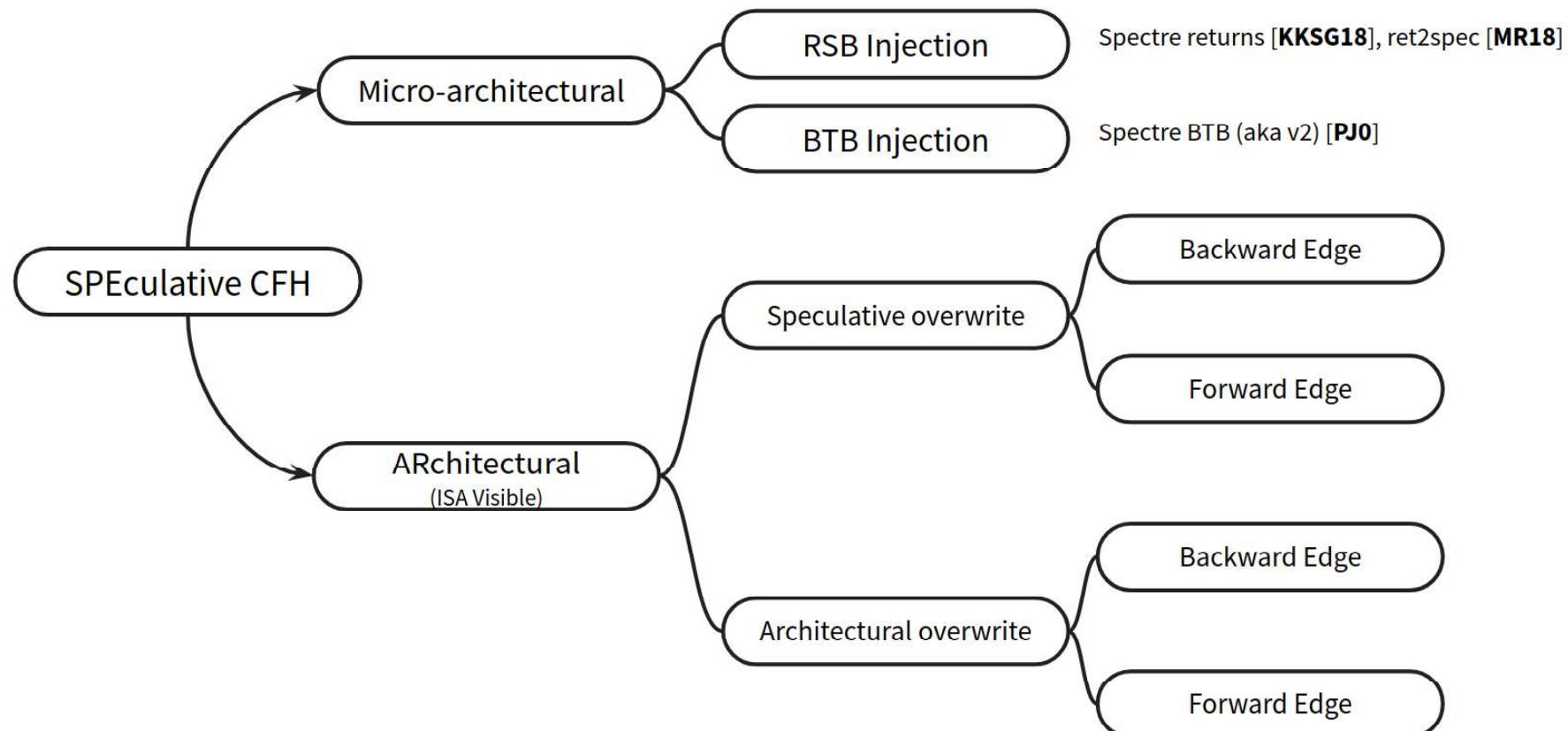
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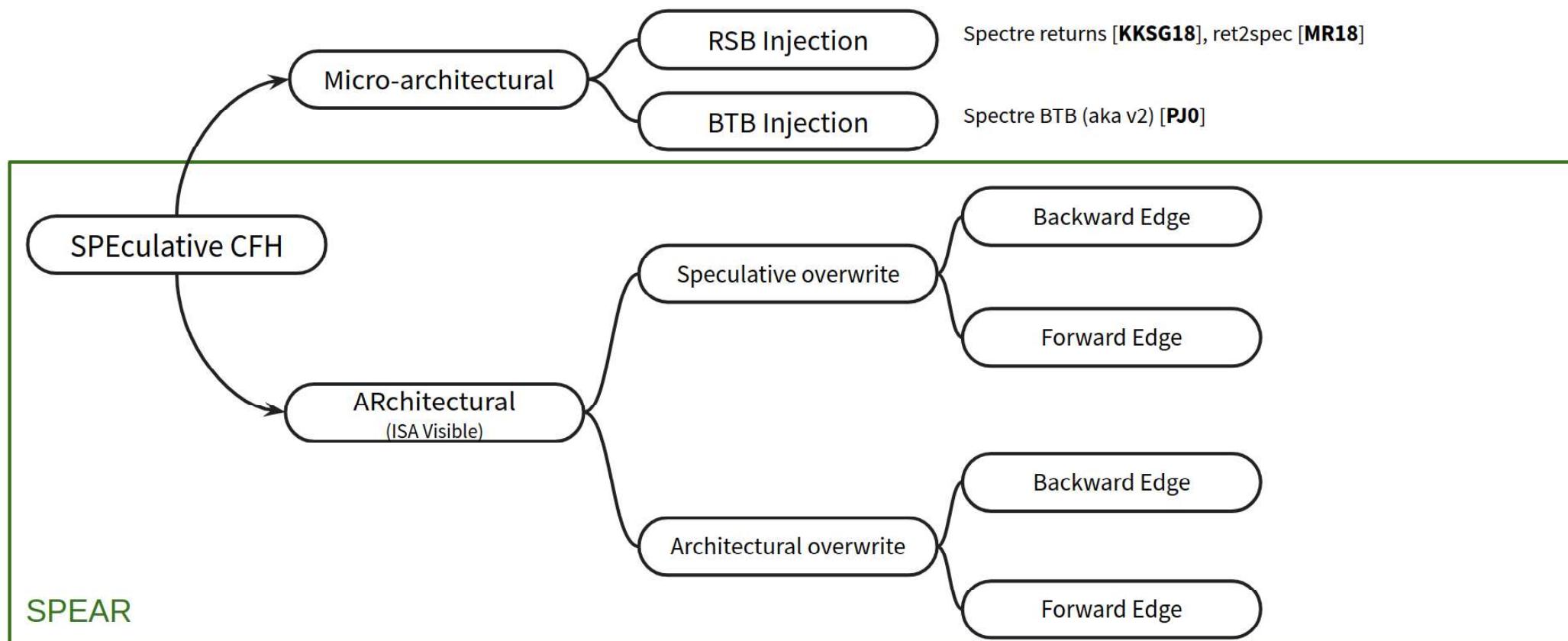
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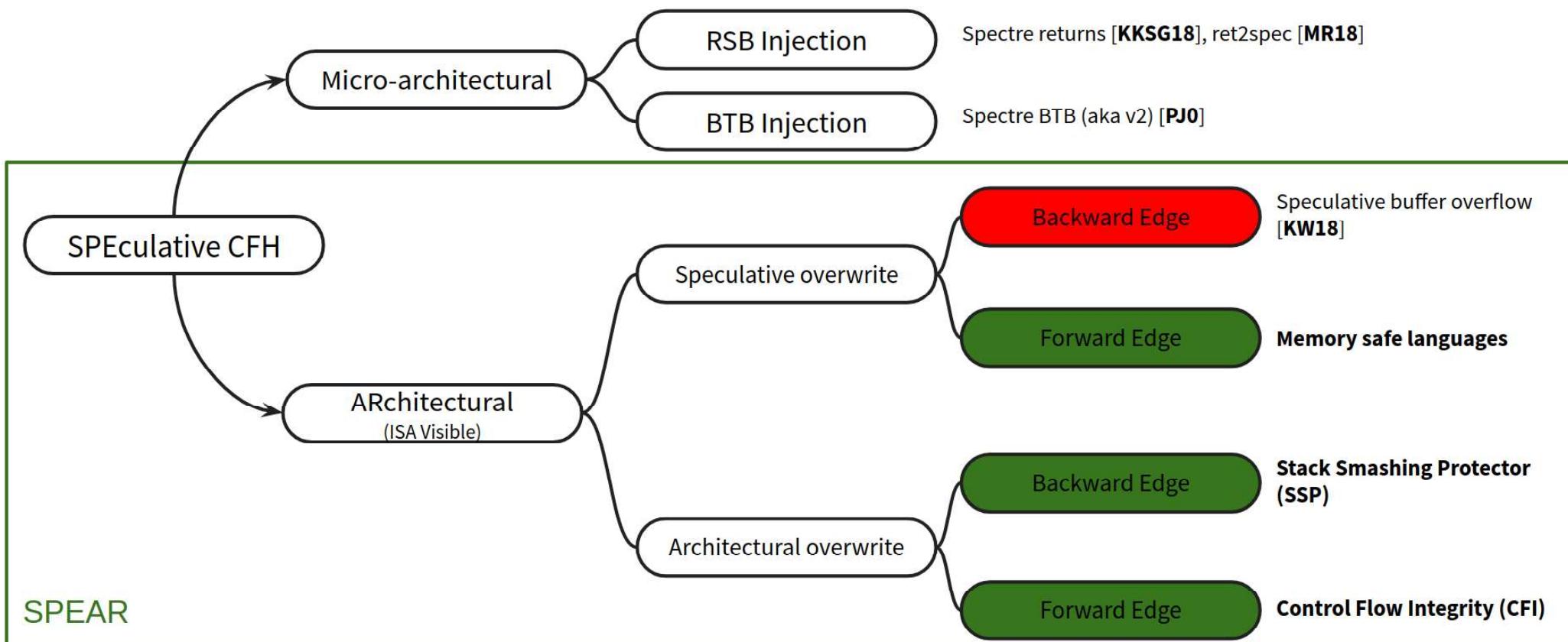
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Speculator [ACSAC19] - Control Flow Hijack Verification

 @m4mbr3  @fkaasan

<https://github.com/ibm-research/speculator>

#BHUSA @BlackHatEvents

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Test architectural overwrite backward edge

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Test architectural overwrite backward edge

Family	Architectural		Speculative	
	<i>Fwd</i>	<i>Bwd</i>	<i>Fwd</i>	<i>Bwd</i>
Intel Broadwell	99.5	94.9	99.5	98.7
Intel Skylake	97.6	98.3	98.2	92.1
Intel Coffee Lake	99.8	98.1	99.7	99.4
Intel Kabylake	99.5	95.9	100	99.5
AMD Ryzen	100	100	100	100

Success rates in % of our tests

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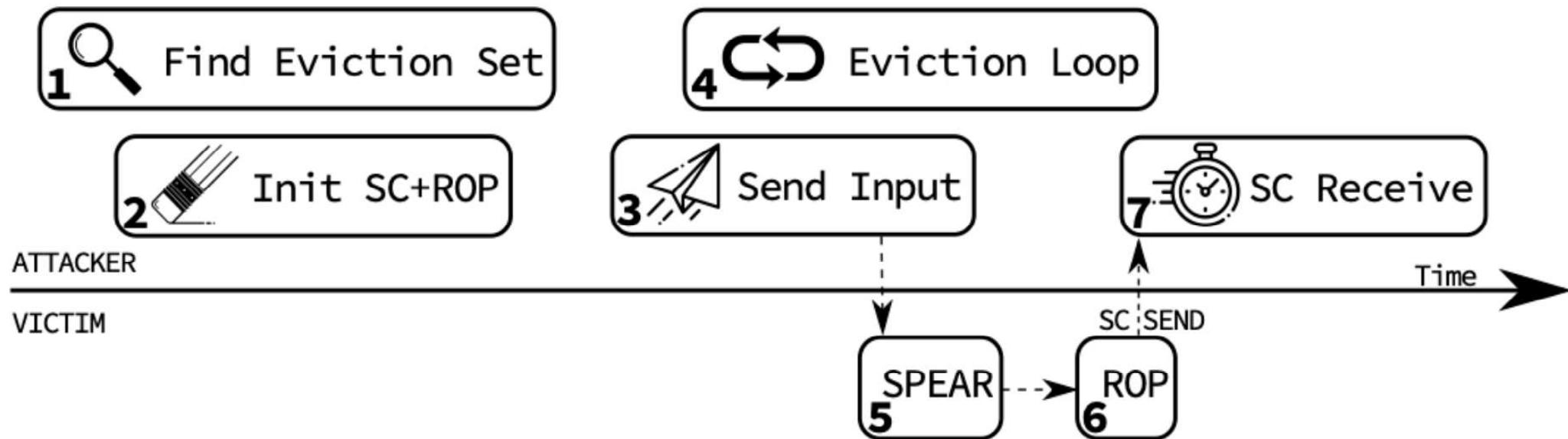
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Test architectural overwrite backward edge

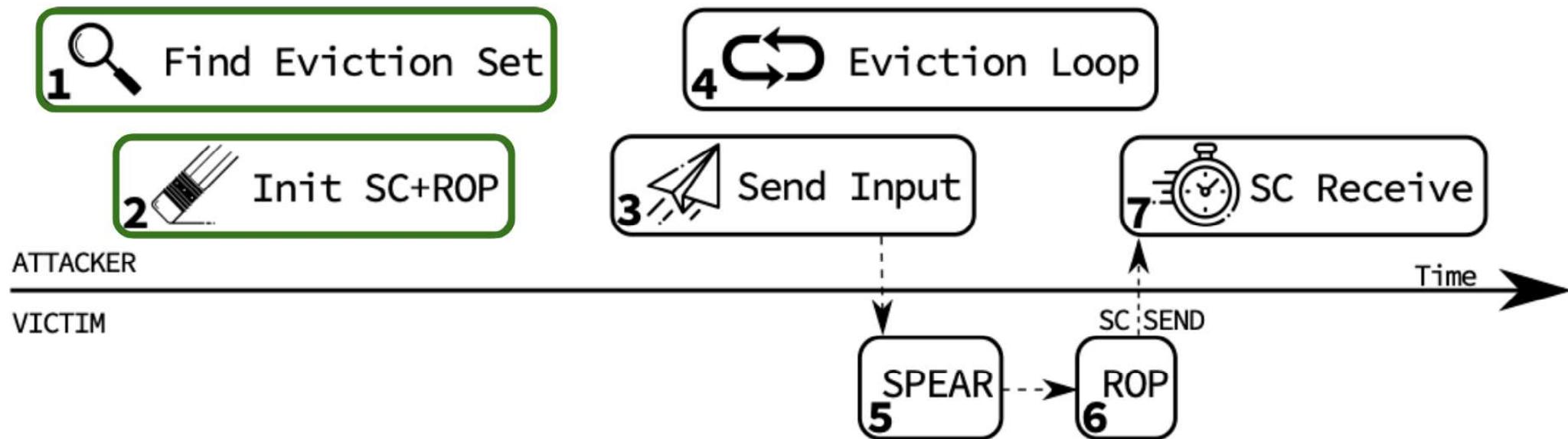
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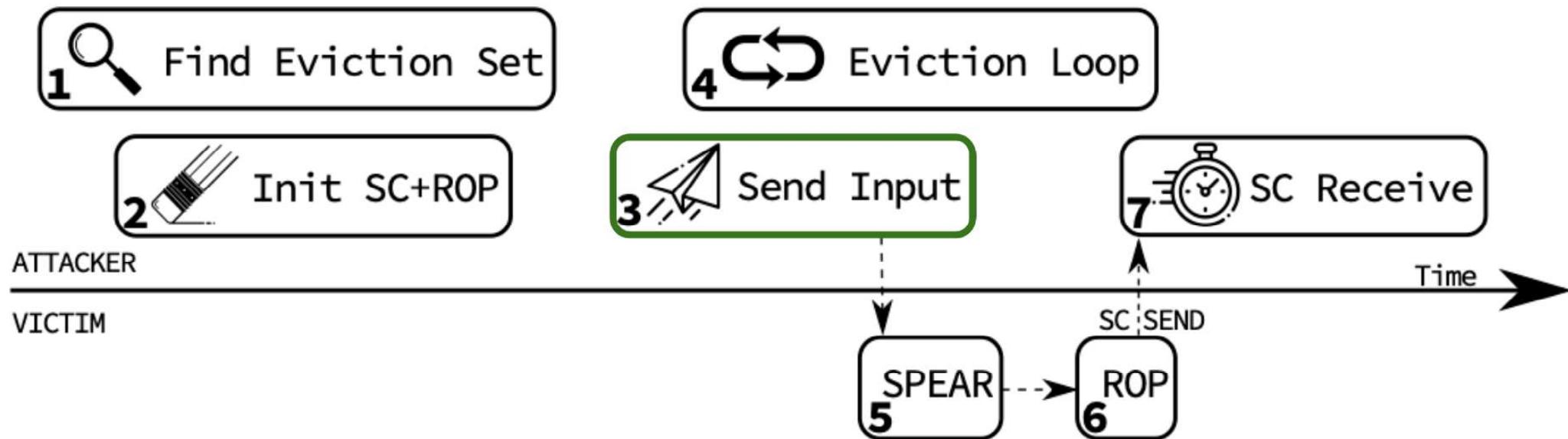
Local arbitrary memory read



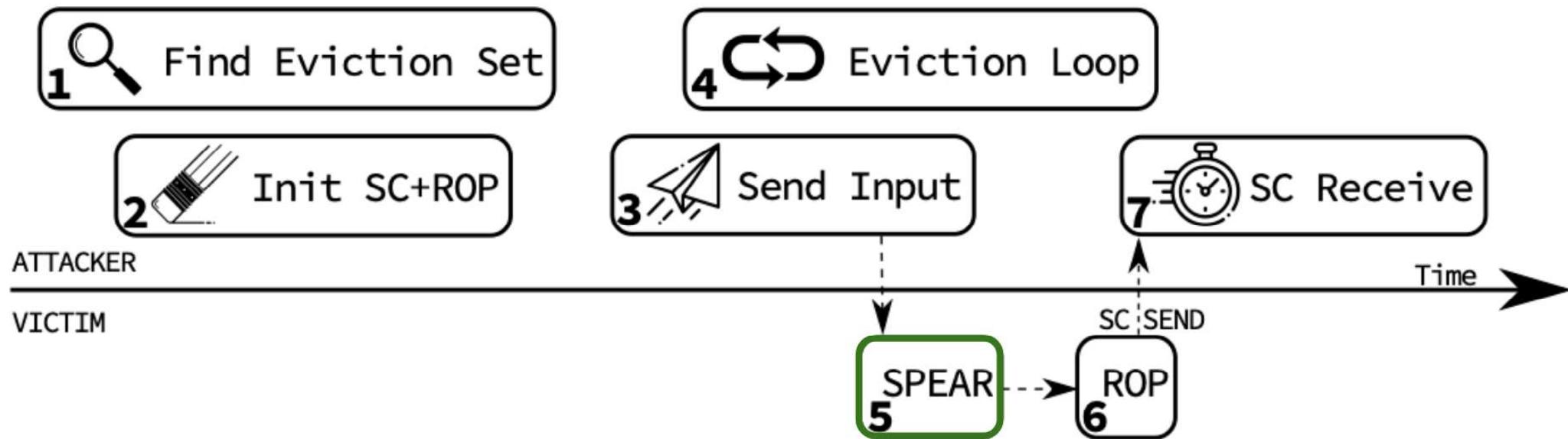
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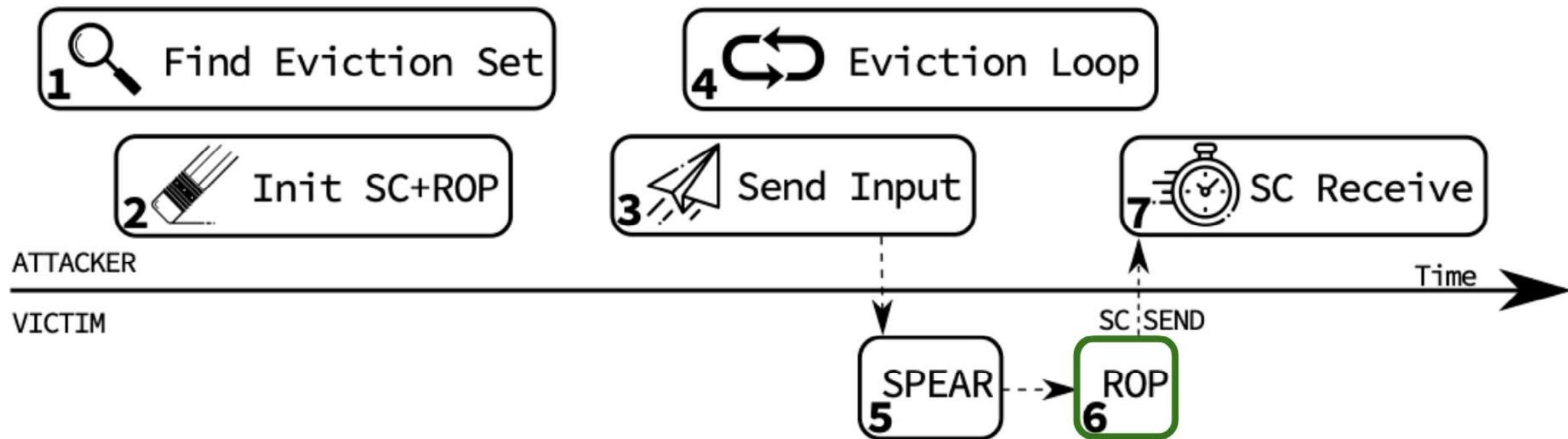
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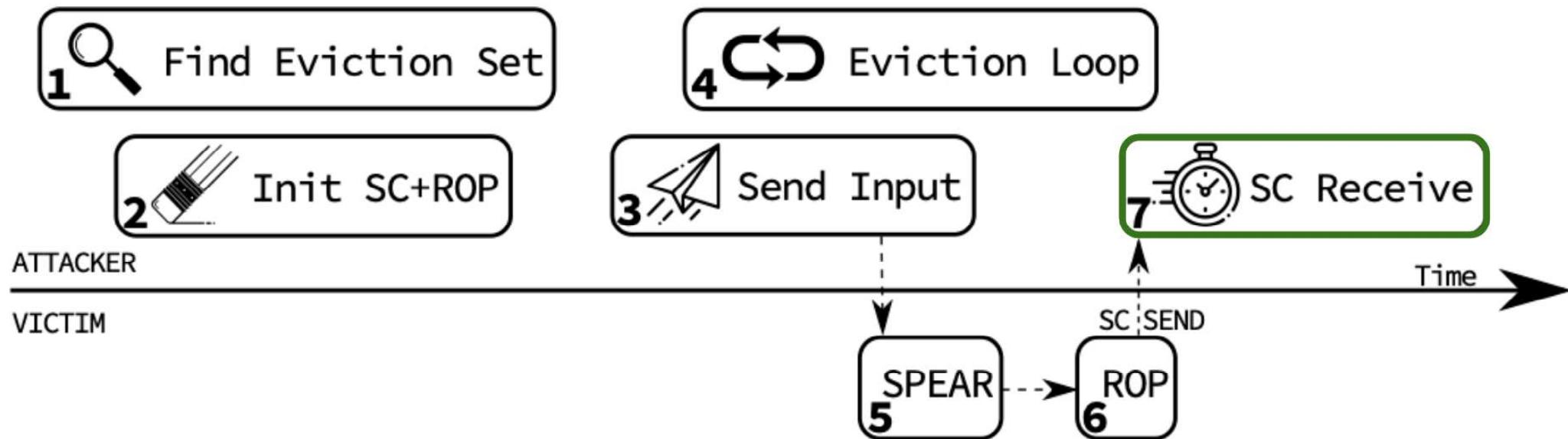
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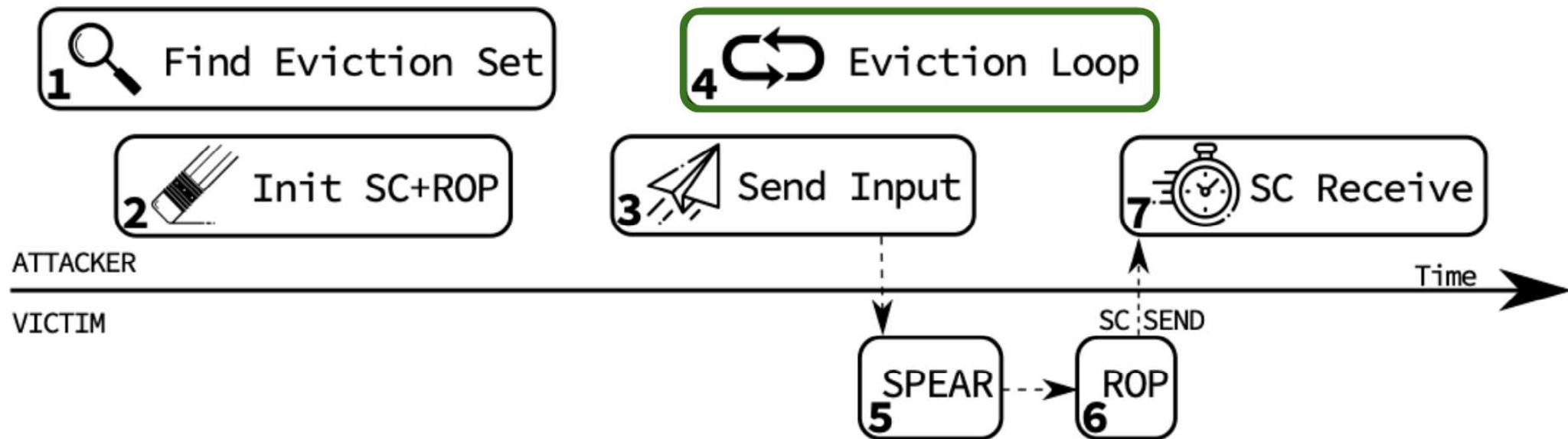
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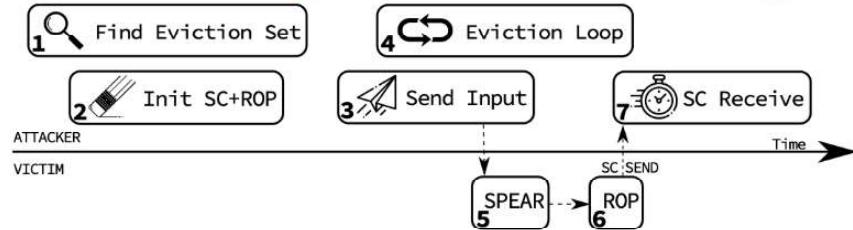


Attacking Stack Smashing Protection (SSP)

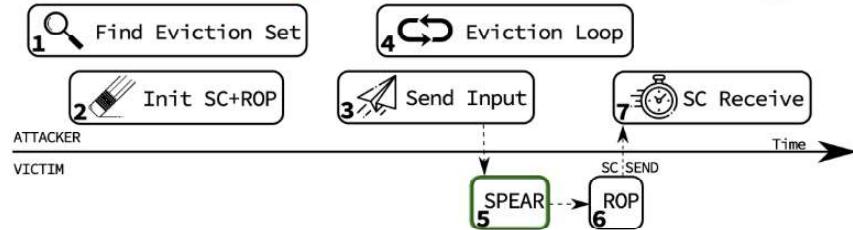
 @m4mbr3  @fkaasan

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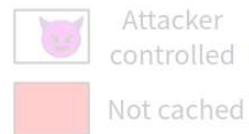


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void f() {  
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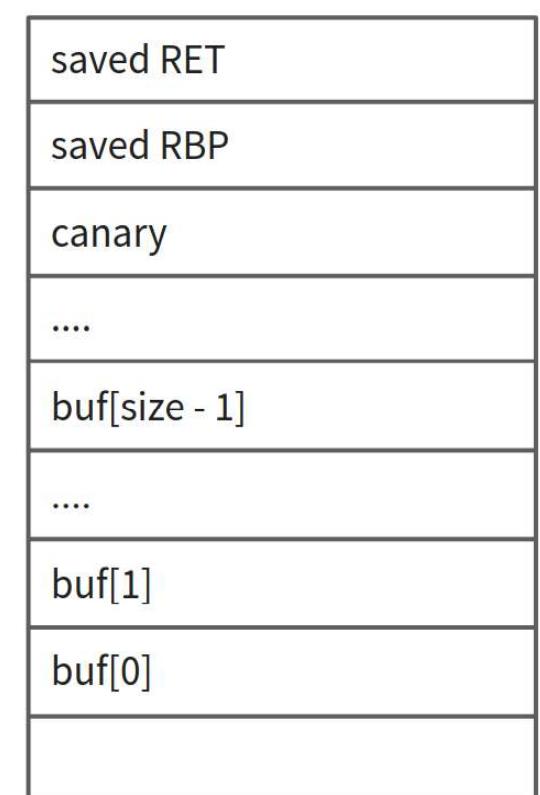
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Stack buffer overflow



#BHUSA @BlackHatEvents

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```

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@m4mbr3 @fkaasan

Stack buffer overflow



ROP gadget	
saved RBP	
canary	
....	
buf[size - 1]	
....	
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Speculative execution trigger



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```

; Store canary on stack
mov rbx, QWORD[fs:0x28]
mov QWORD[stack_canary], rbx

; Function body

; Check for corrupted canary
mov rbx, QWORD[stack_canary]
xor QWORD[fs:0x28], rbx
je exit
call __stack_chk_fail

exit:
; Epilogue
ret



Attacker
controlled



Not cached

ROP gadget	
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void f() {  
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    if (!ok(canary)) {  
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    }  
    return; // Speculative control flow hijack  
}  
} // architectural edge overwrite
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Speculative control flow hijack
architectural edge overwrite



Attacker
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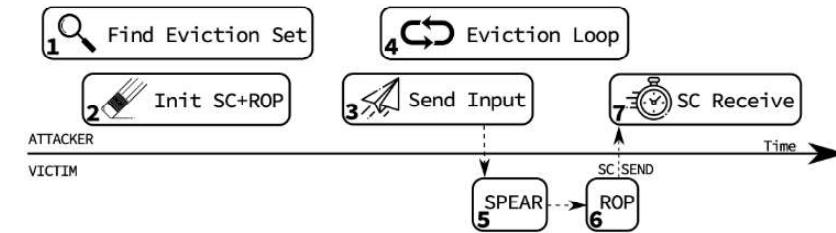


Canary eviction

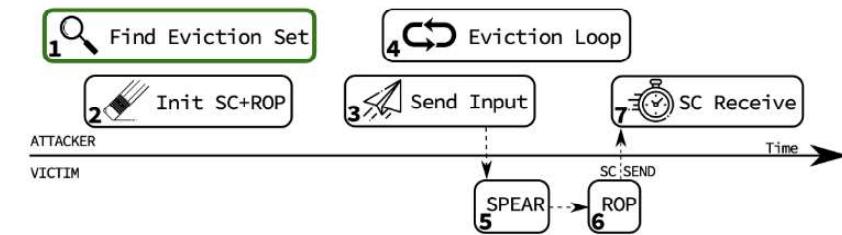
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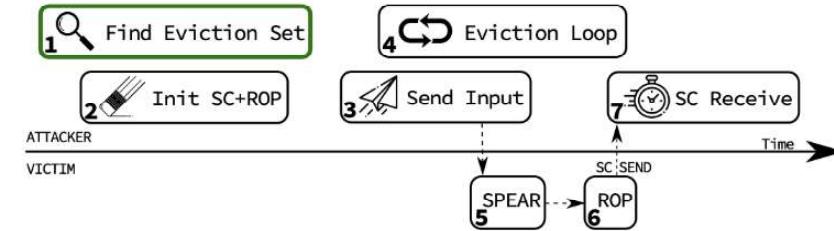
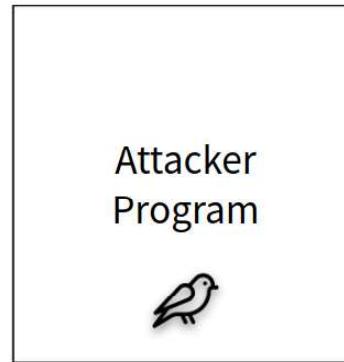
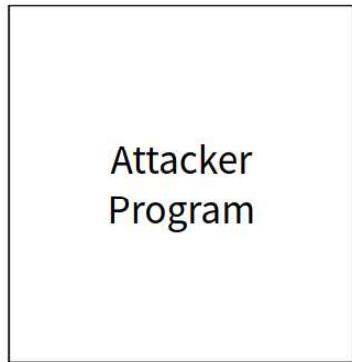
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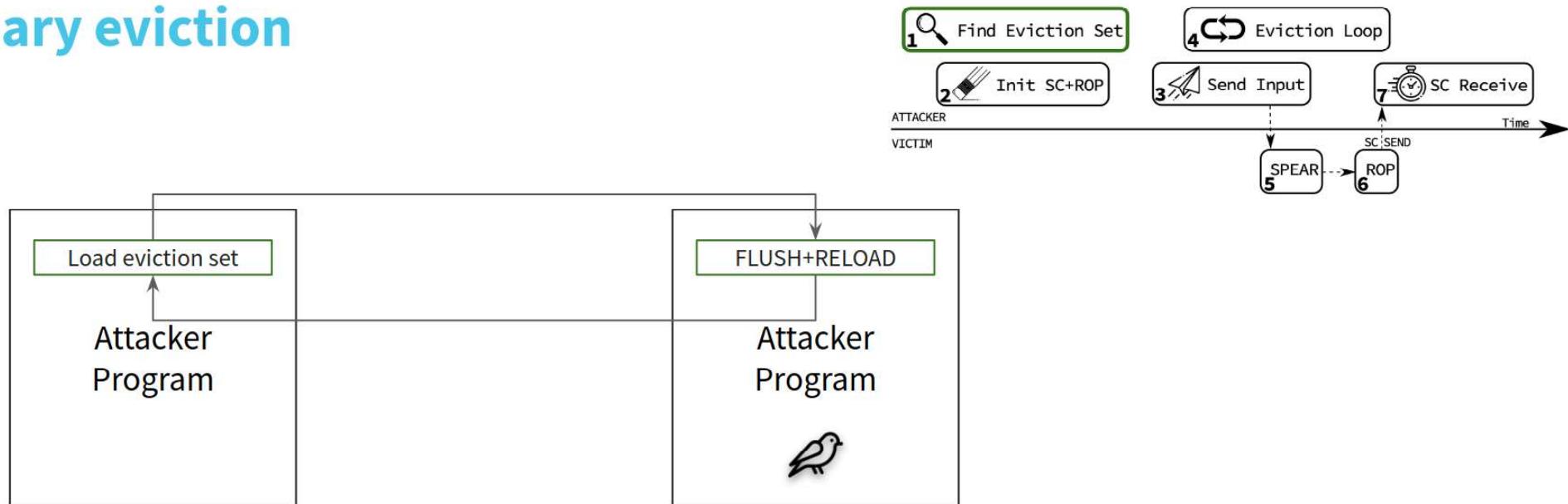
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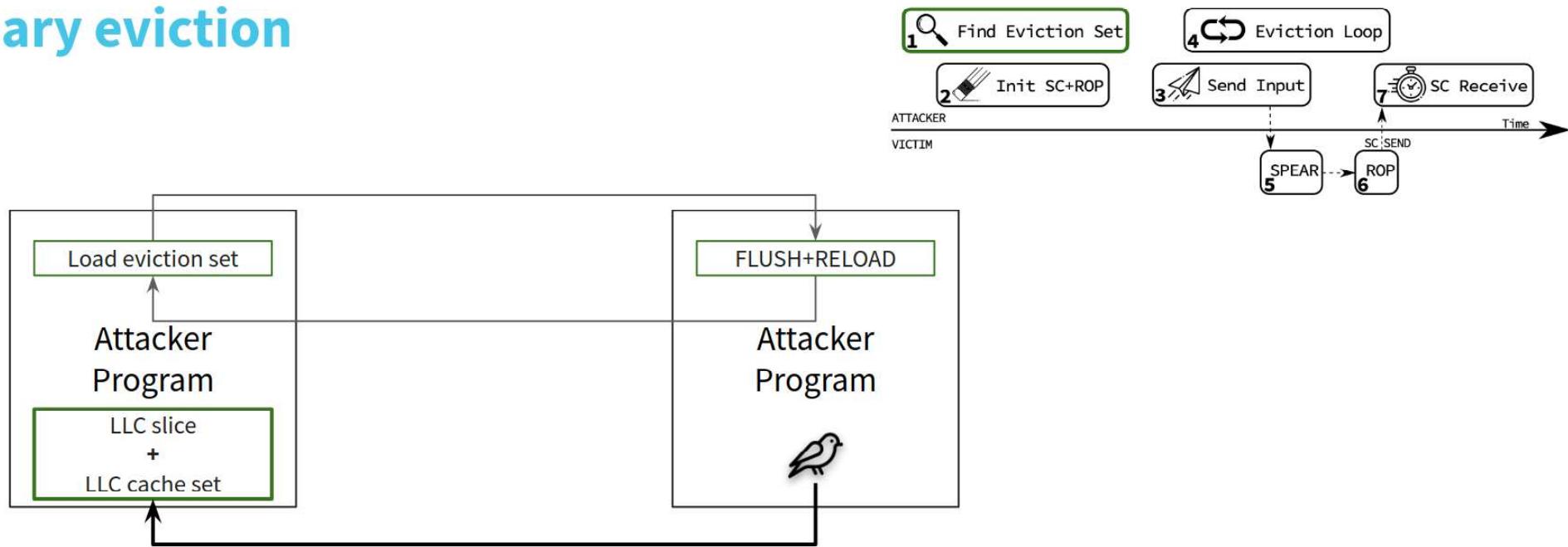
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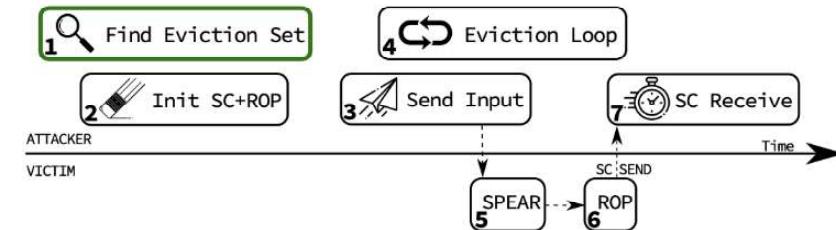
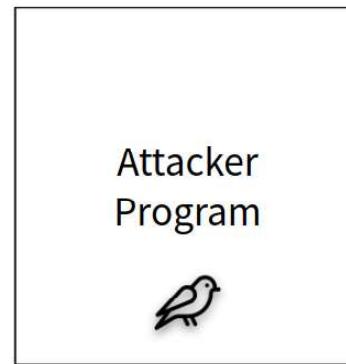
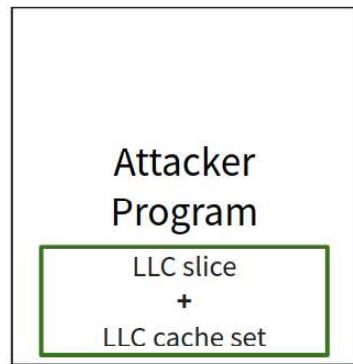
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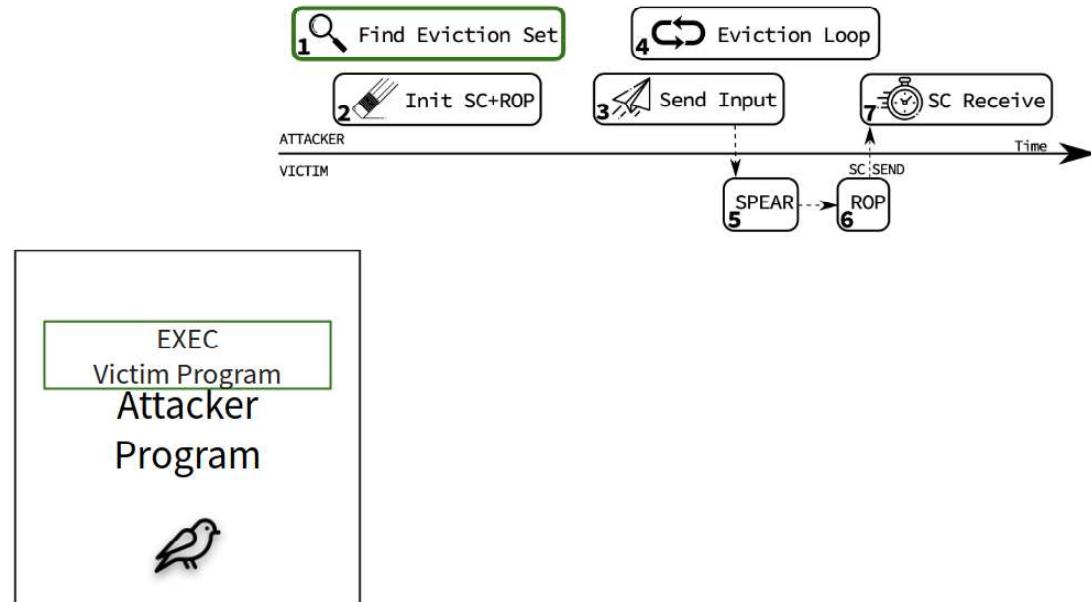
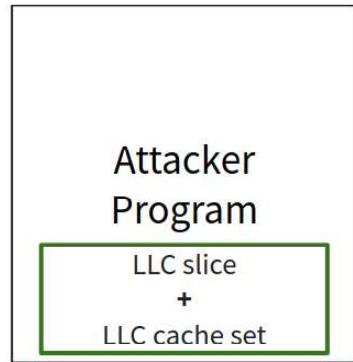
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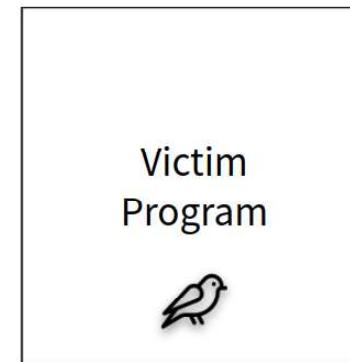
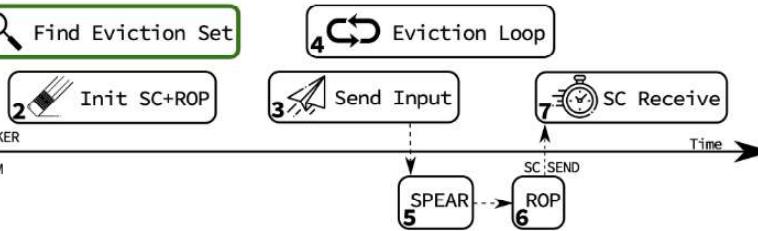
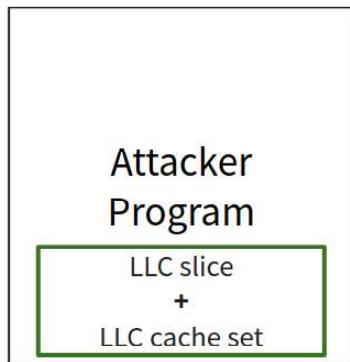
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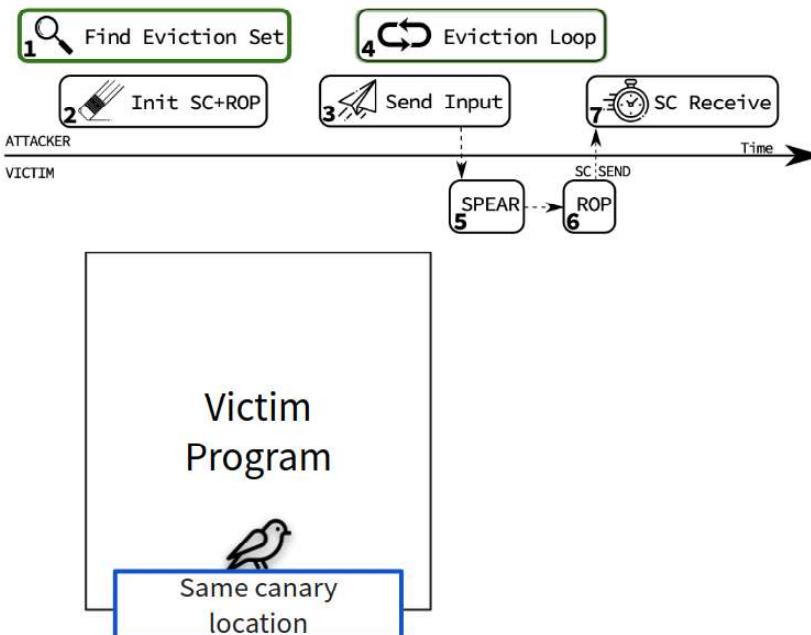
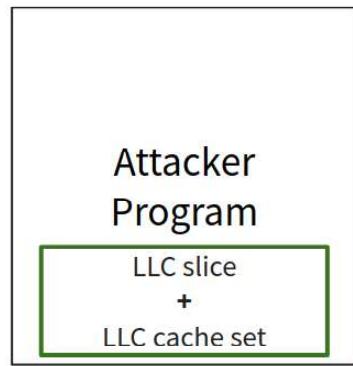
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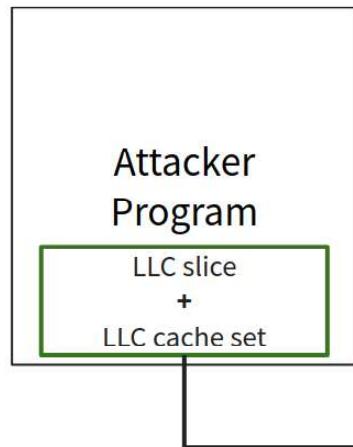
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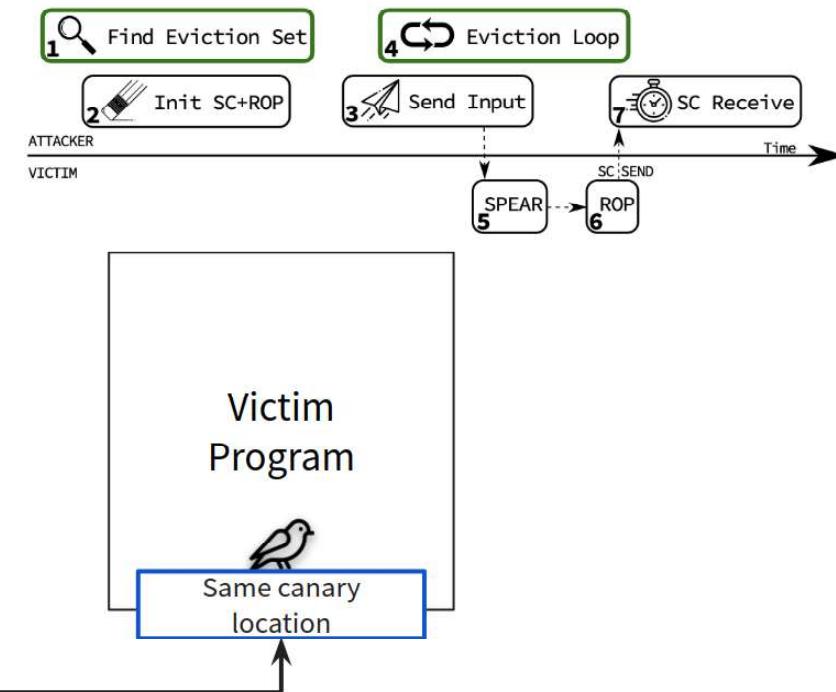
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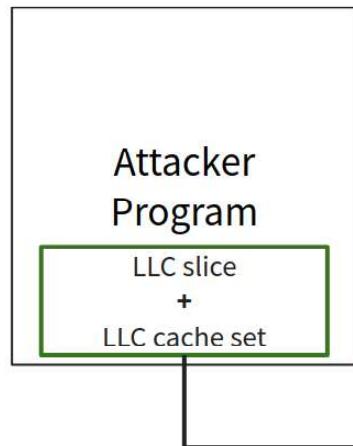
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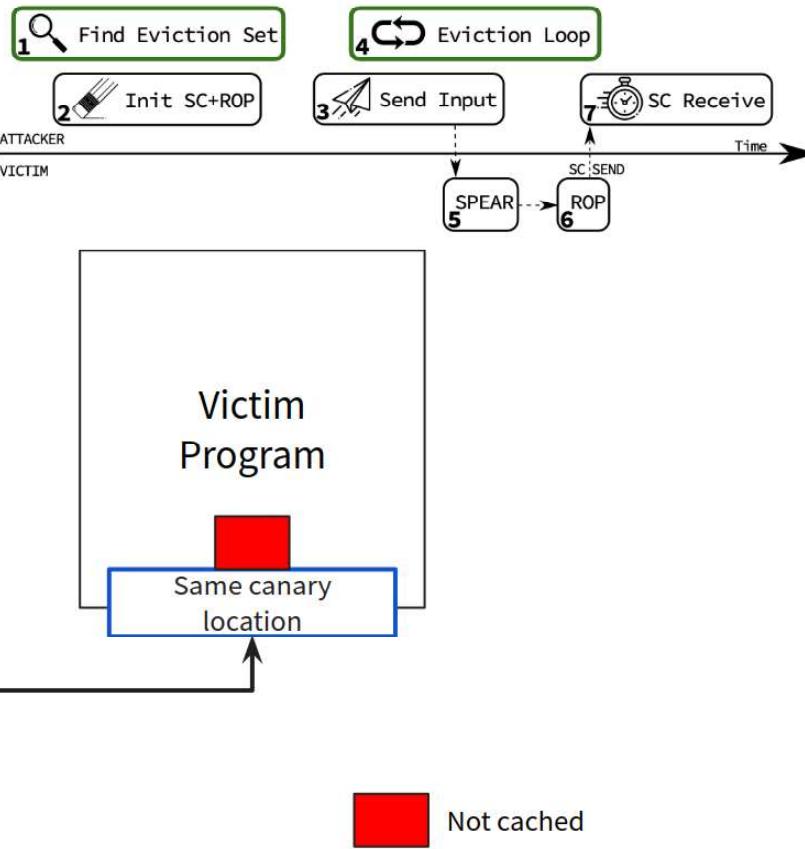
Eviction Loop



Canary eviction



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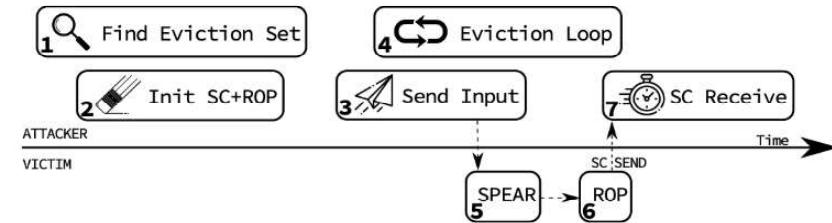


Speculative ROP

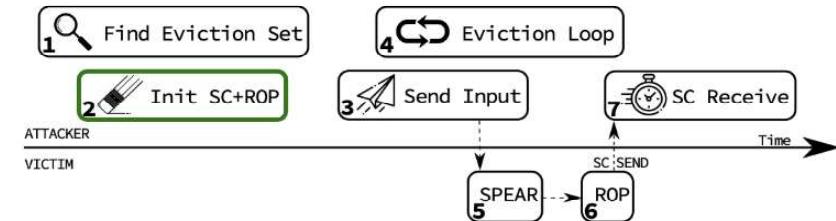
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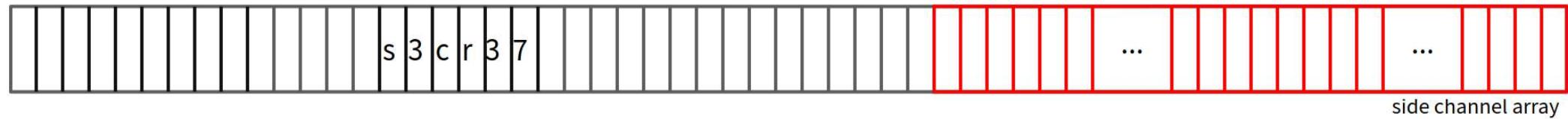
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 Cached
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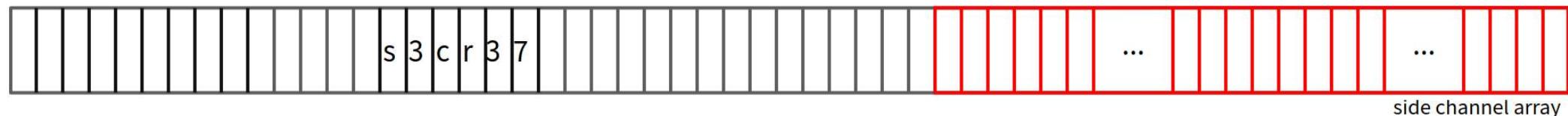
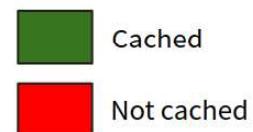
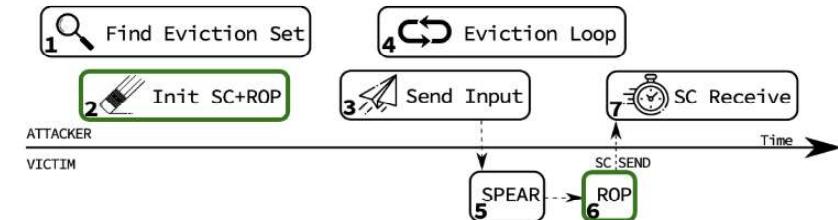
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; Load victim secret
mov rax, BYTE[victim_addr]
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; Compute side-channel array entry
shl rax, 8
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; Add side-channel array base
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; Access side-channel array entry
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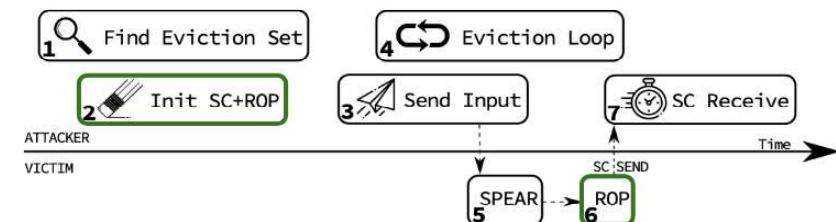
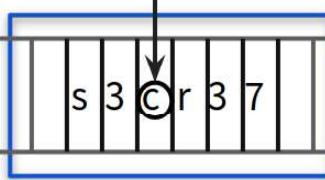
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side channel array
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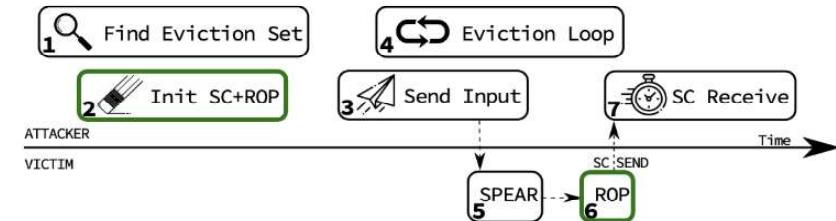
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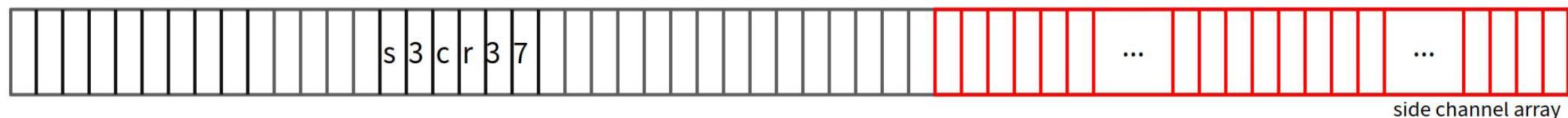
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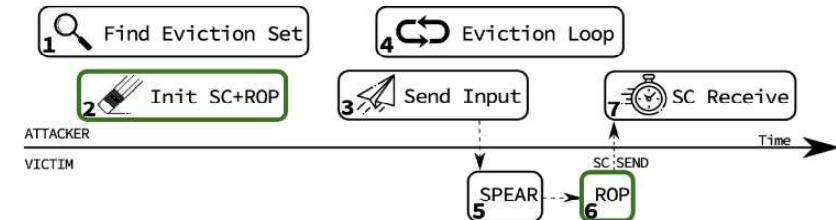
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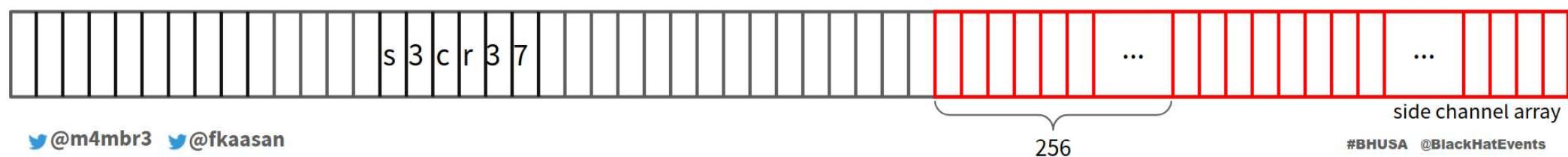
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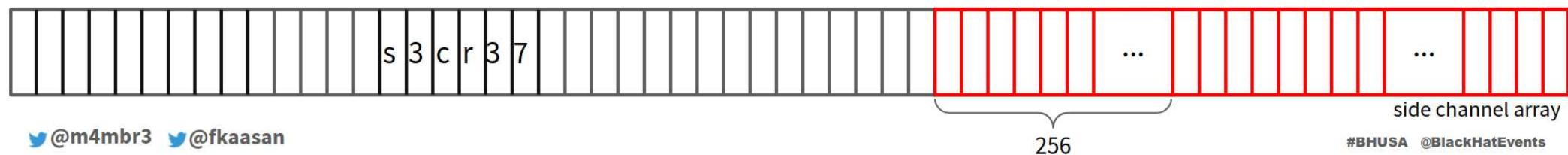
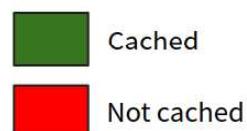
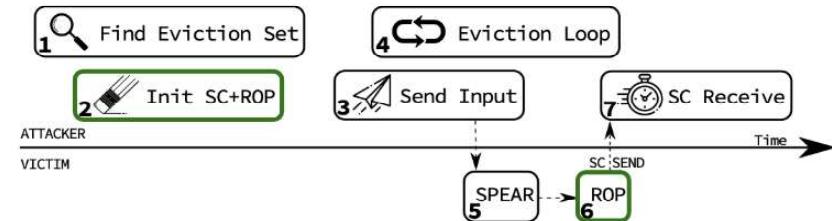
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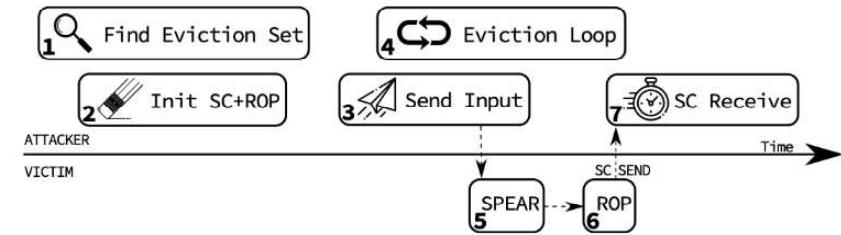
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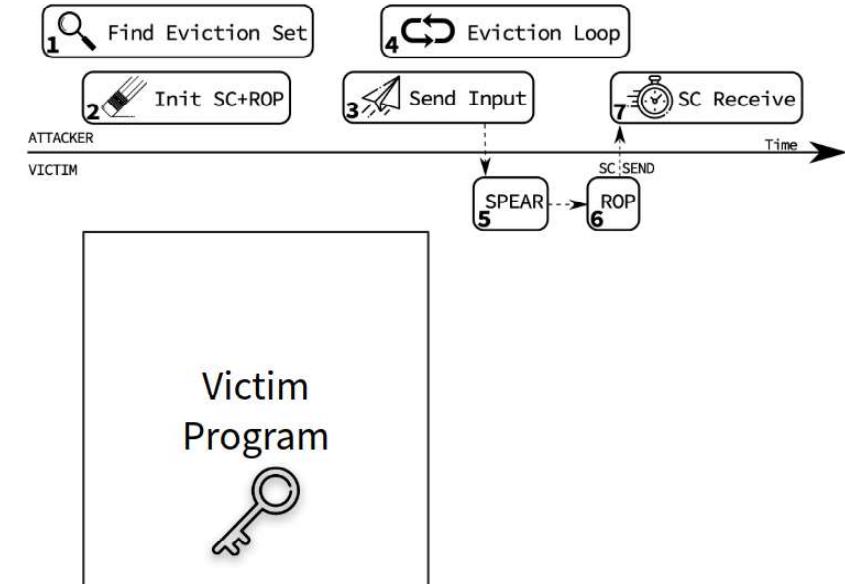
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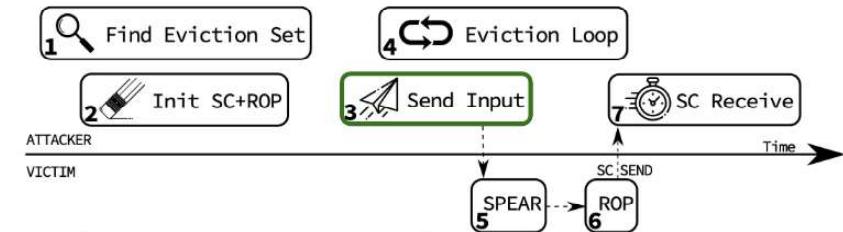
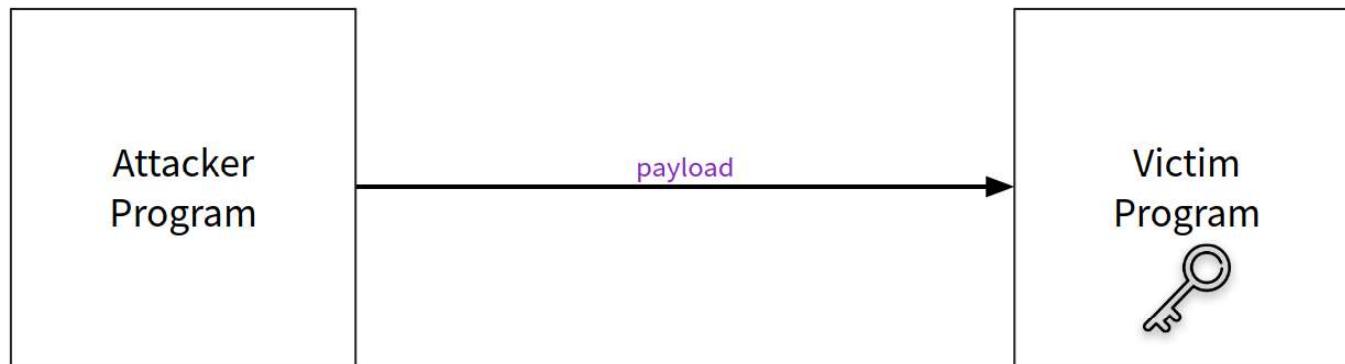
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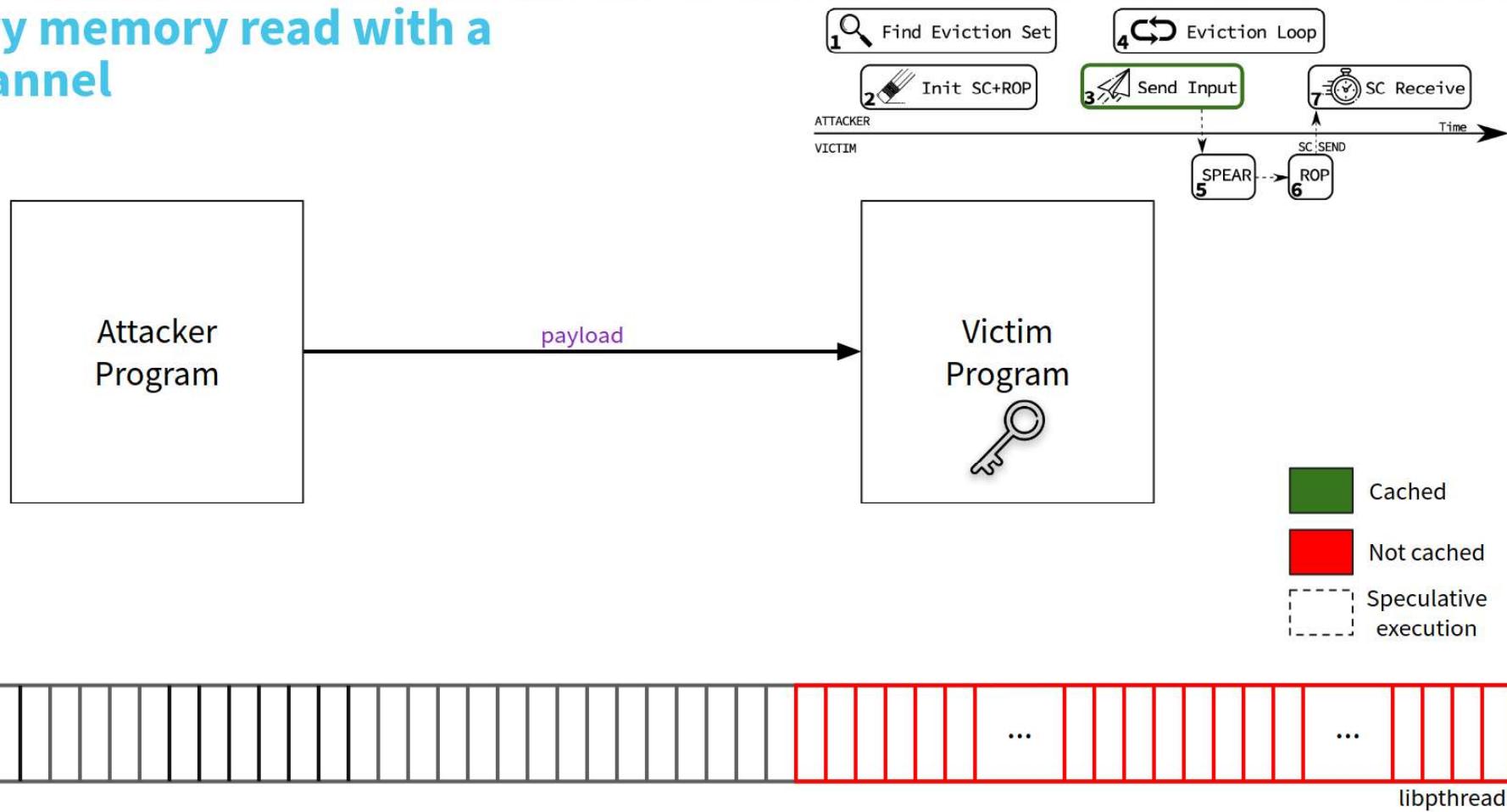
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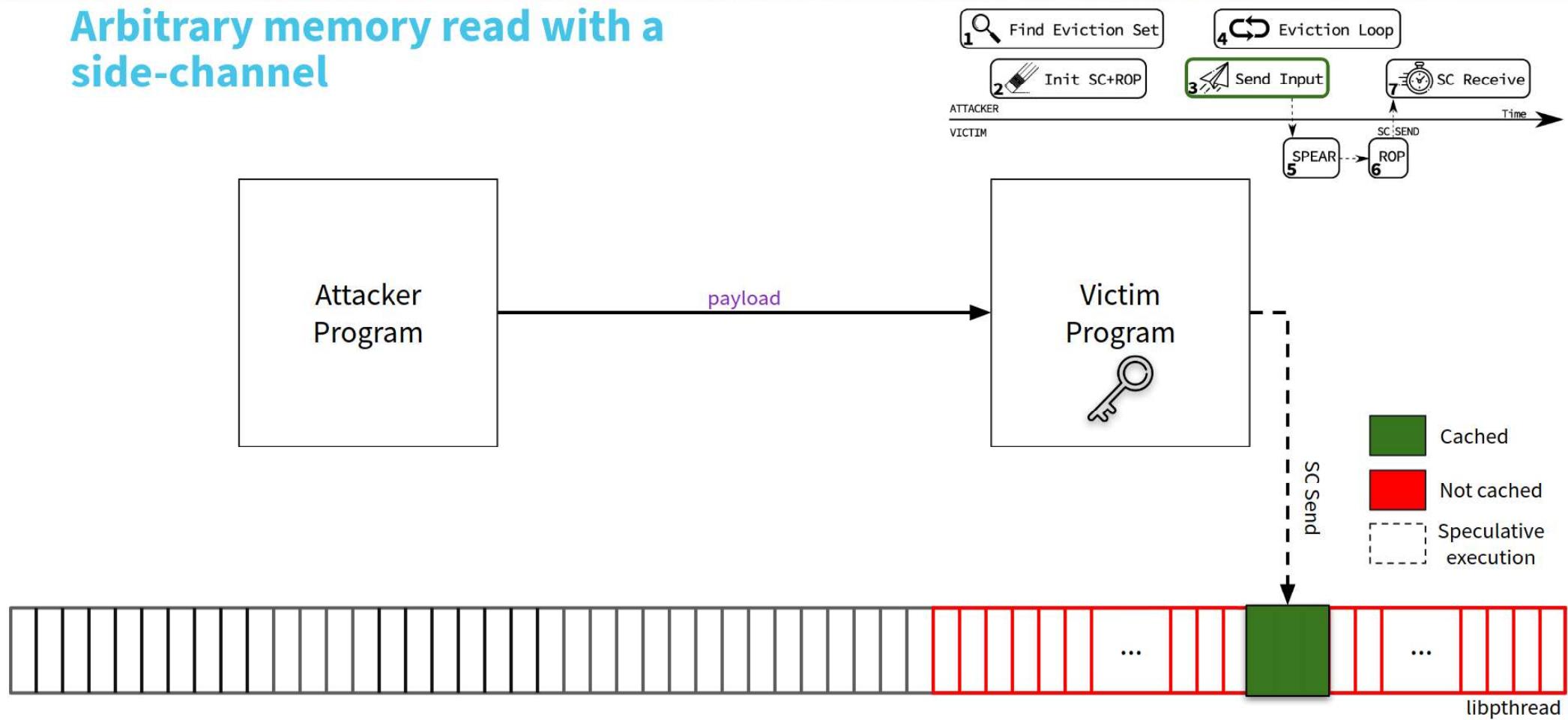
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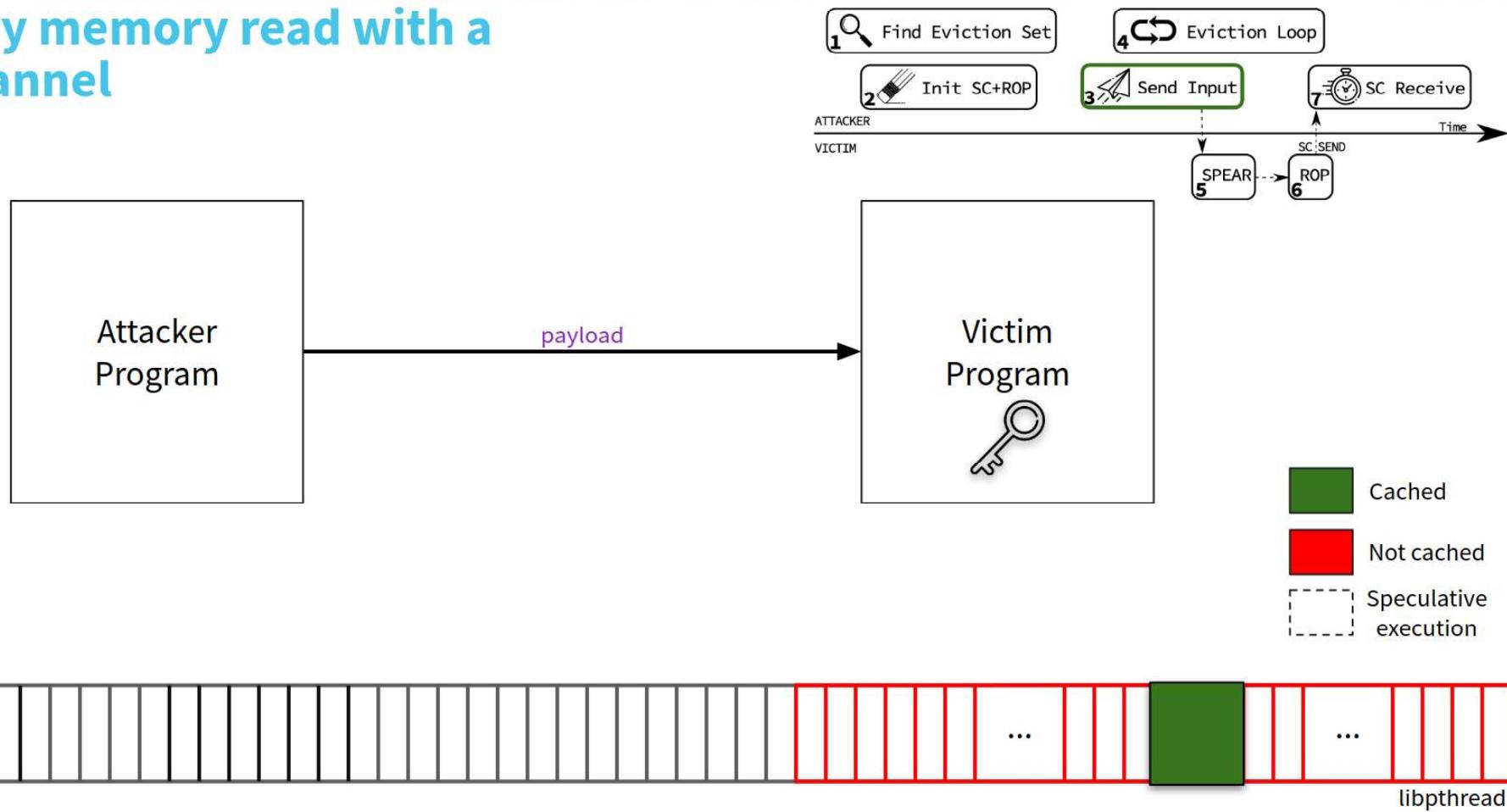
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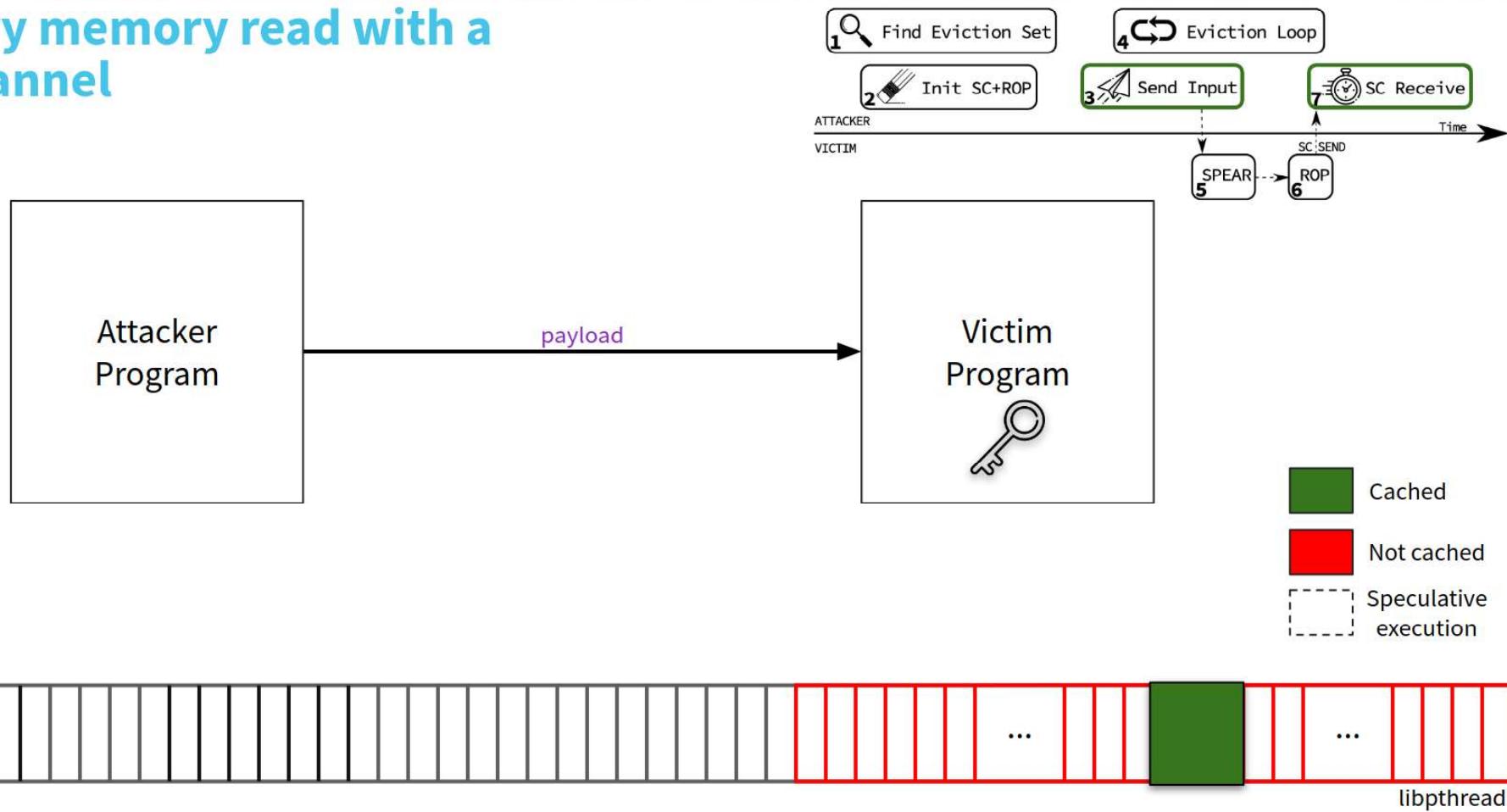
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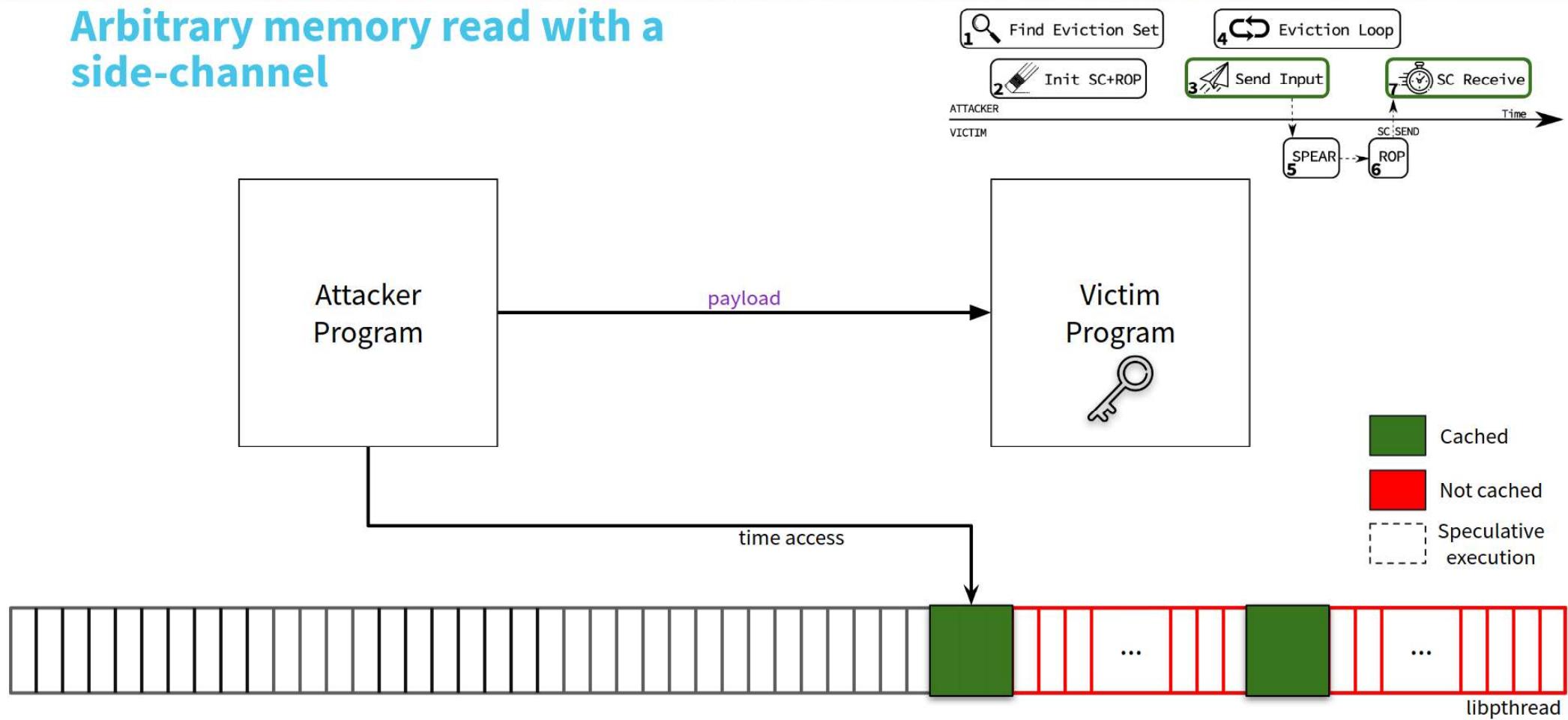
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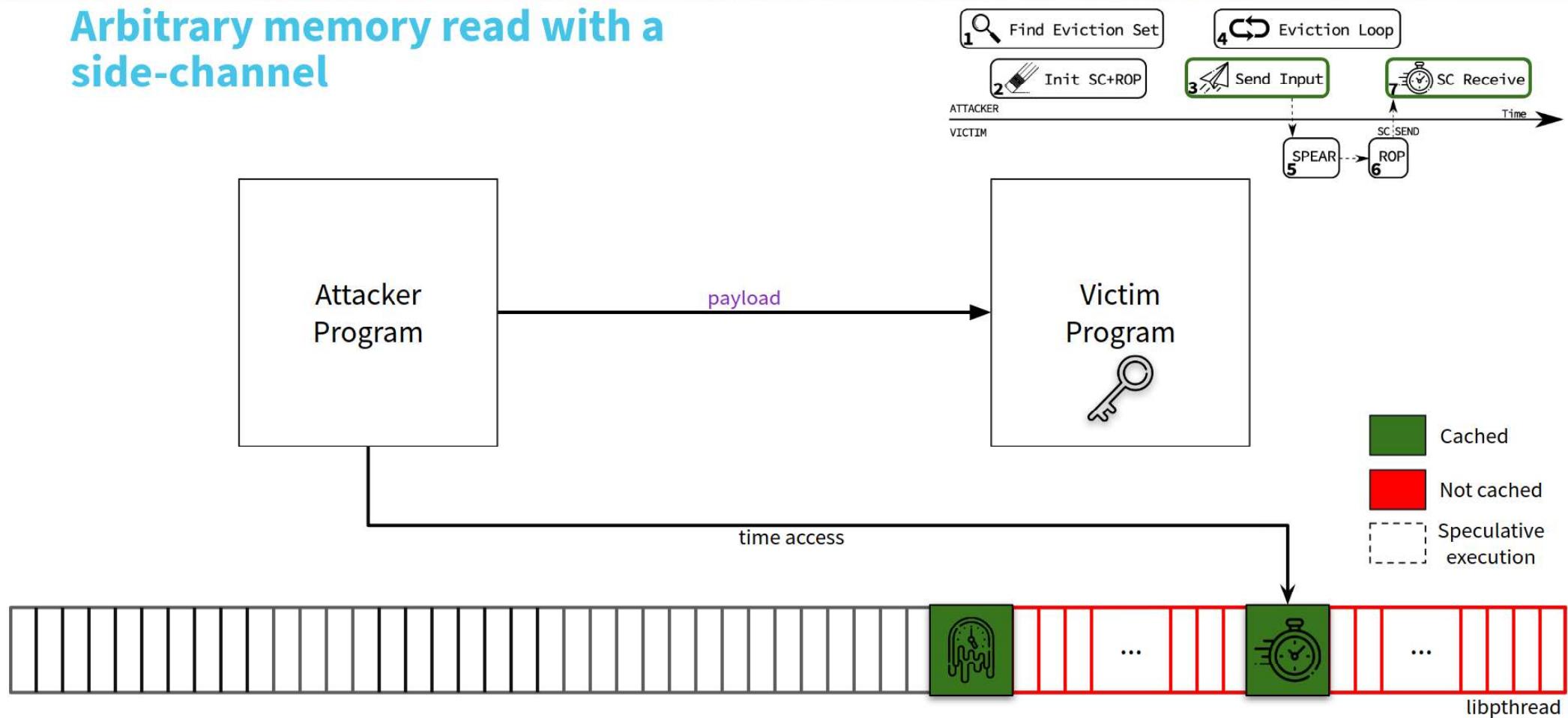
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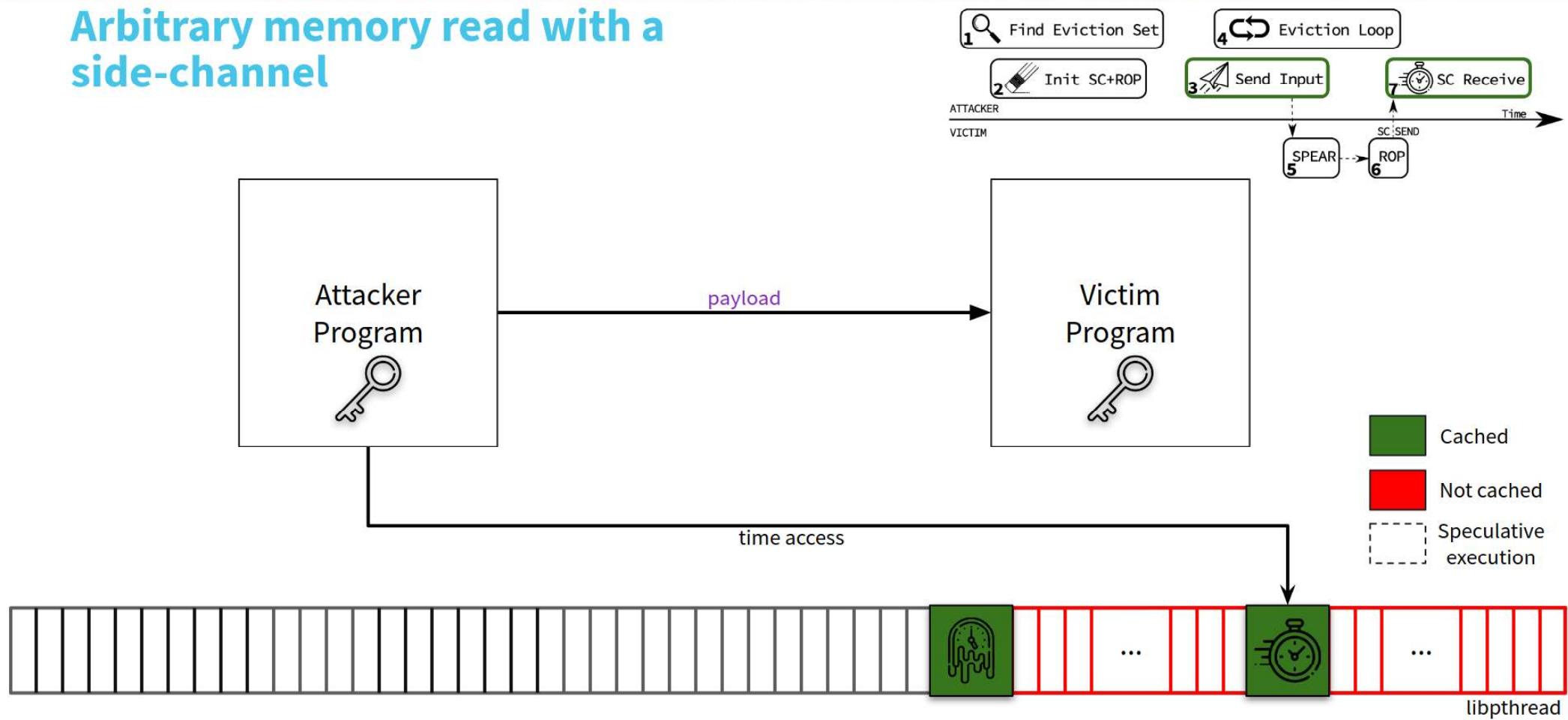
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Results

Local arbitrary victim memory read

Leak rate for 2-digits sized secret: **0.3 Bytes per second**

100 attack runs per byte to reduce noise (shared library as side-channel array)

Works on Intel **Skylake** and **Coffee Lake** with all Spectre mitigations enabled

Slight success rate change between Ubuntu 16.04 and Ubuntu 20.04

Discussion about attack optimization and better synchronization are in our paper



Other SPEAR case - memory safe languages

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Only available in future iterations of CPUs



Takeaways

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SEAs are a significant research and industry challenge for the next decade (tools, attacks and defences)

References

- [PJ0] J. Horn Tech. Report <https://googleprojectzero.blogspot.com/2018/01/reading-privileged-memory-with-side.htm>, 2018
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