Seguridad Informatica - Fall 2024

Module IV: Physical security

Lecture 5

Reasoning about speculative execution attacks

Marco Guarnieri

IMDEA Software Institute

Module IV

- Lecture 1 — Introduction
- Lecture 2 — Cache-based side channel attacks
- Lecture 3 — Speculative execution attacks
- Lecture 4 — Non-interference
- Lecture 5 — Automated detection of speculative leaks

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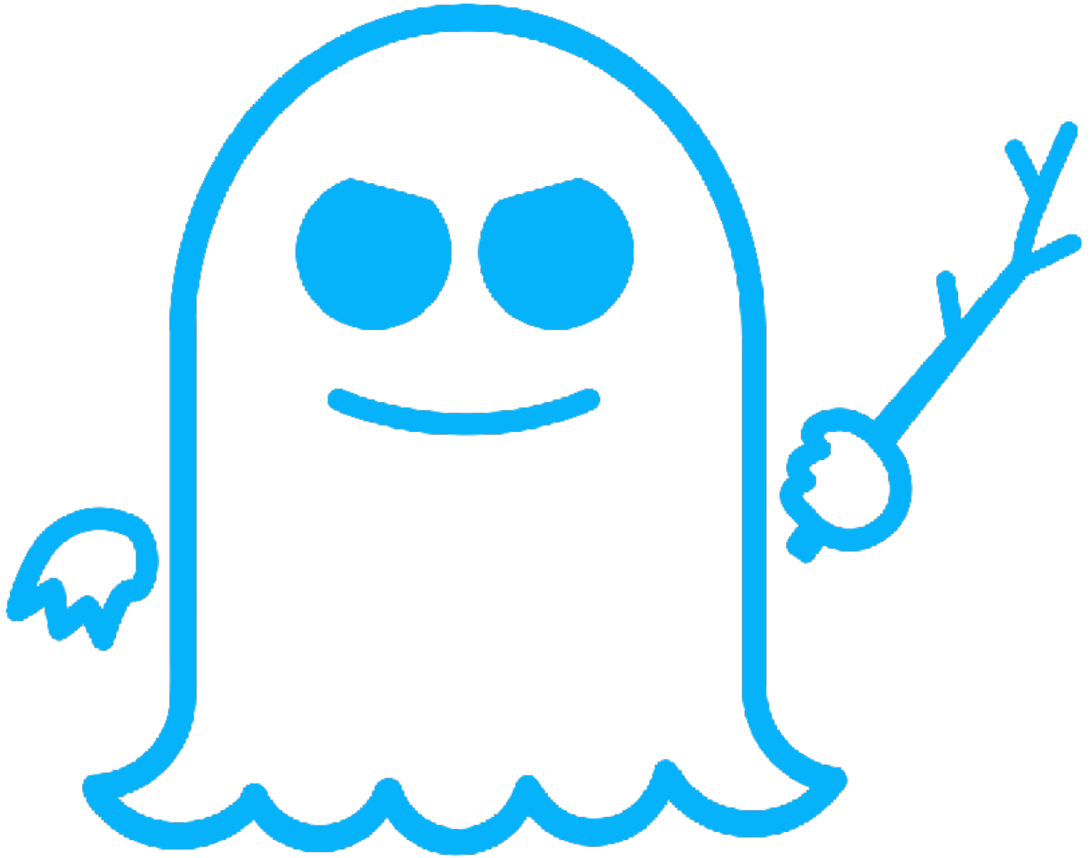
- Lecture 2 — Cache-based side channel attacks
- Lecture 3 — Speculative execution attacks
- Lecture 4 — Non-interference
- Lecture 5 — Automated detection of speculative leaks

Recommended reading

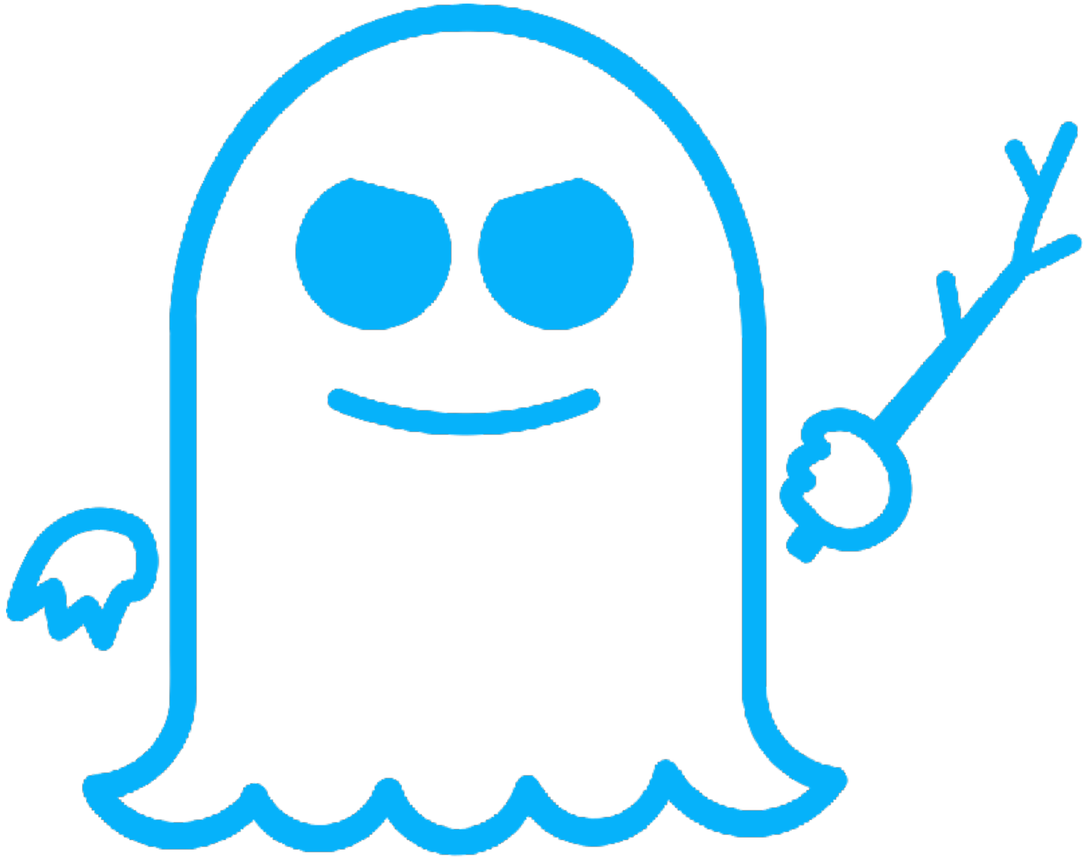
Spectector: Principled detection of speculative information flows by Marco Guarnieri, José F. Morales, Andrés Sánchez, Boris Köpf, Jan Reineke

Available at https://spectector.github.io/papers/spectector.pdf



SPECTRE

P. Kocher, J. Horn, A. Fogh, D. Genkin, D. Gruss, W. Haas, M. Hamburg, M. Lipp, S. Mangard, T. Prescher, M. Schwarz, Y. Yarom — Spectre Attacks: Exploiting Speculative Execution — S&P 2019



SPECTRE

Exploits ***speculative execution***

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Exploits ***speculative execution***

Almost ***all*** modern ***CPUs*** are ***affected***

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Countermeasures

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Long Term: Co-design of software and hardware countermeasures

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Short and Mid Term: Software countermeasures

Compiler-level countermeasures

- Example: insert LFENCE to selectively stop speculative execution

- Implemented in major compilers (Microsoft Visual C++, Intel ICC, Clang)

Countermeasures

Long Term: Co-design of software and hardware countermeasures

Short and Mid Term: Software countermeasures

PROBLEM SOLVED ?

Compiler-level countermeasures

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Spectre Mitigations in Microsoft's C/C++ Compiler

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February 13, 2018

https://www.paulkocher.com/doc/MicrosoftCompilerSpectreMitigation.html

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“compiler […] produces ***unsafe code*** when the static analyzer is unable to determine whether a code pattern will be exploitable”

"there is ***no guarantee*** that all possible instances of [Spectre] will be instrumented”

Bottom line: No guarantees!

Contributions

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1. ***Semantic notion*** of ***security***
   against ***speculative execution attacks***

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1. ***Semantic notion*** of ***security***
   against ***speculative execution attacks***

2. Analysis to ***detect vulnerability*** or ***prove security***

Outline

1. Speculative execution attacks 101
2. Speculative non-interference
3. Detecting speculative leaks
4. Spectector + Case studies

Speculative execution attacks 101

Speculative execution + branch prediction

Speculative execution + branch prediction

Size of array **A**

```
if (x < A_size)
    y = B[A[x]]
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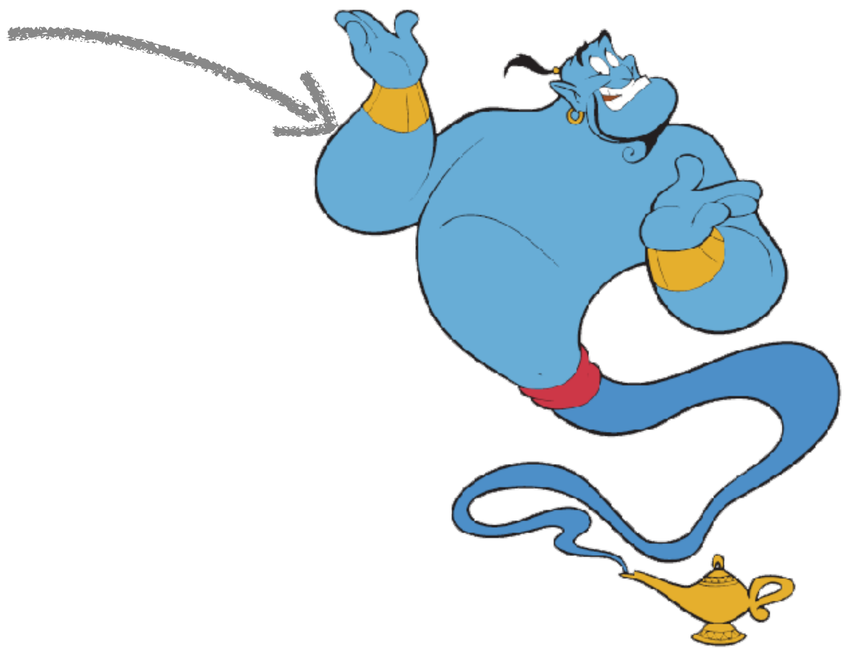

Branch predictor

Speculative execution + branch prediction

Prediction based on ***branch history*** & ***program structure***

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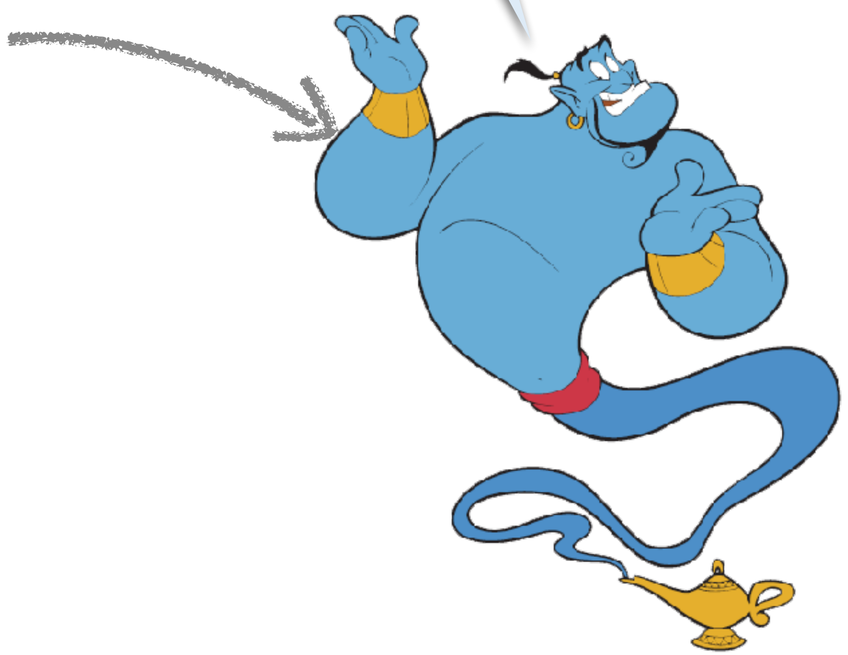

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Branch predictor

Wrong predicton? ***Rollback changes***!

- ✓ Architectural (ISA) state
- ✗ Microarchitectural state

Spectre V1

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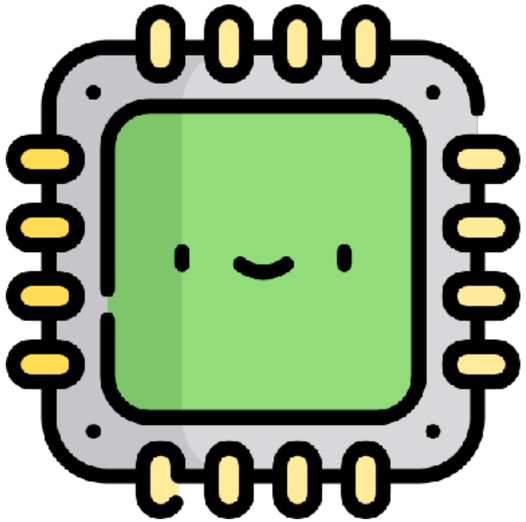

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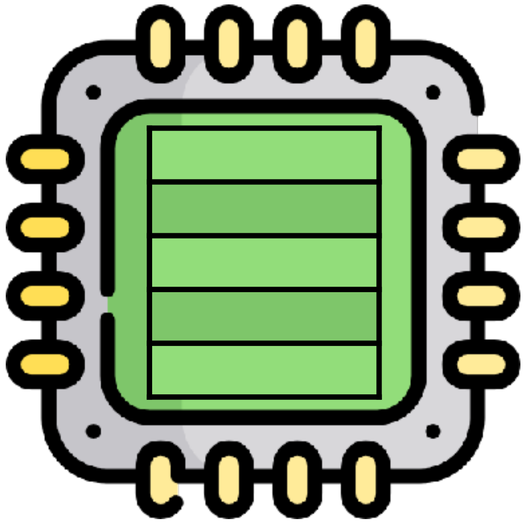

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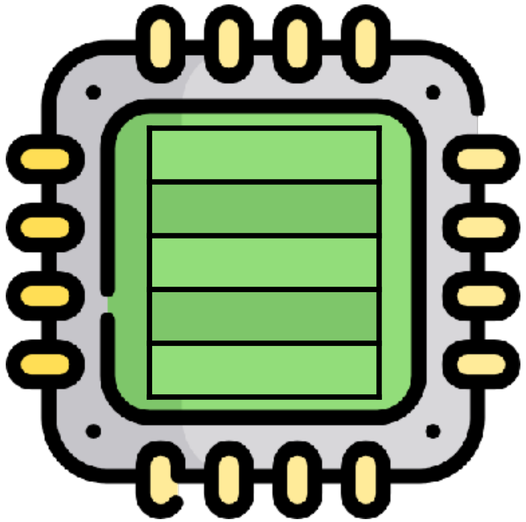

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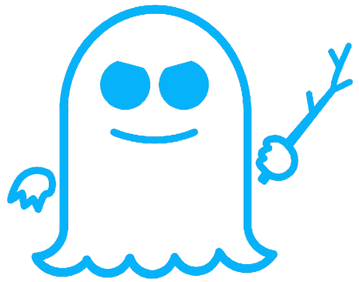

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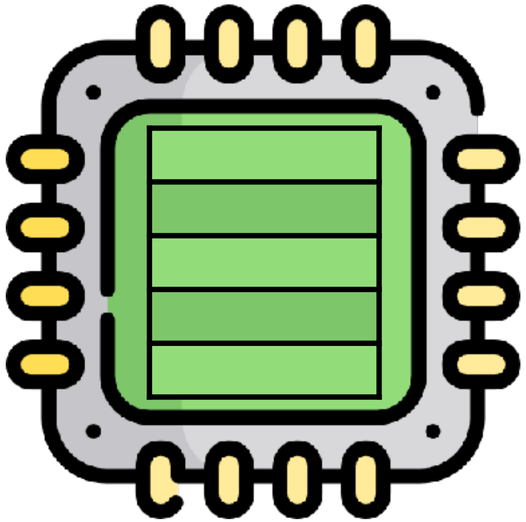

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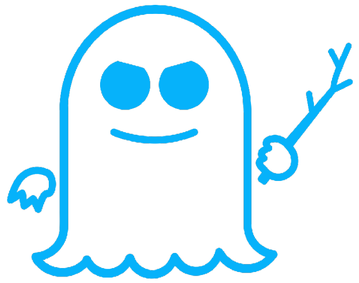

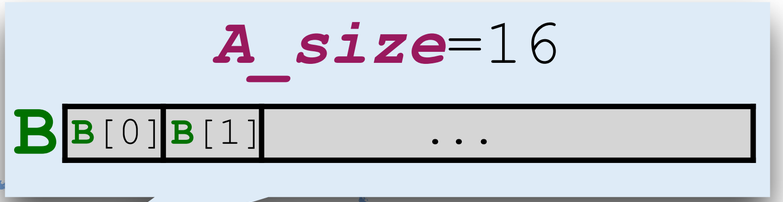


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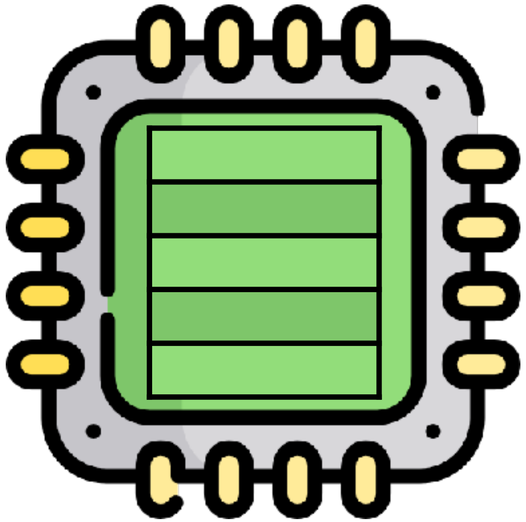

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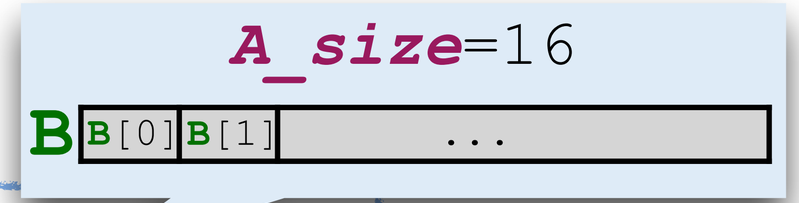


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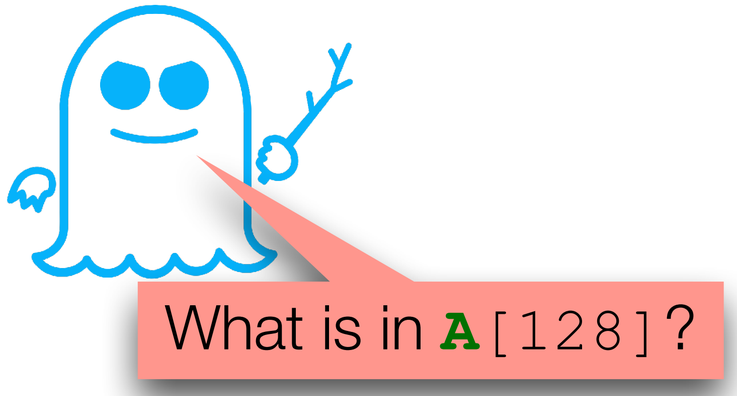

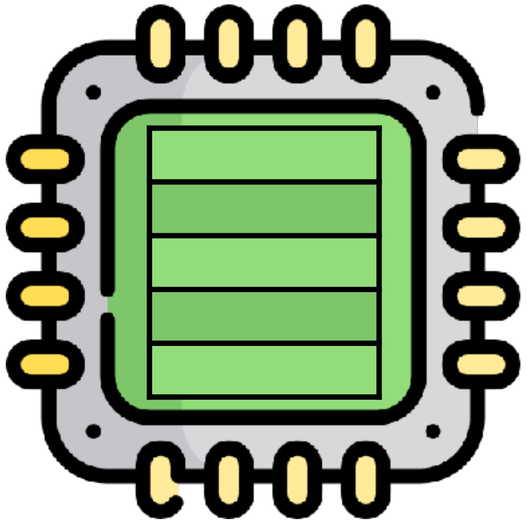

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void f(int x)
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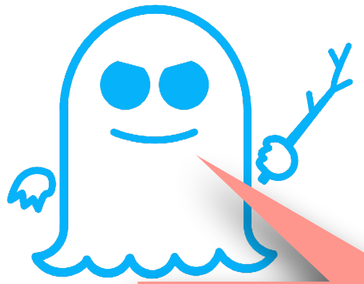
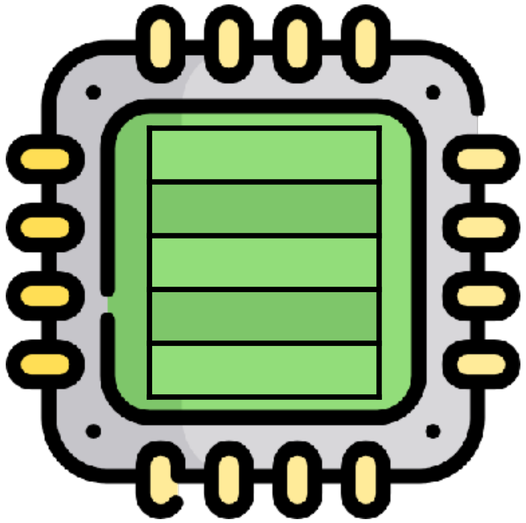
A_size=16



What is in A[128]?

1) Training



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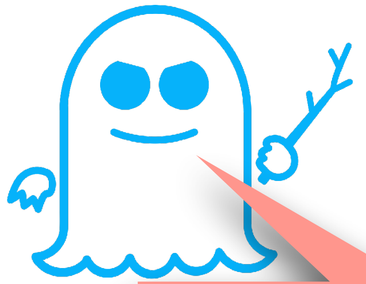

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`B` `B[0]` `B[1]` `...`

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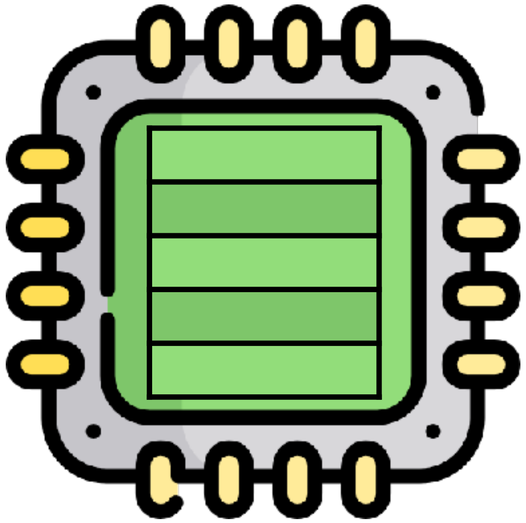

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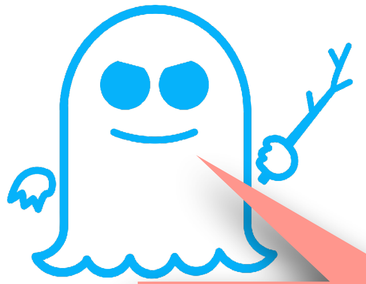

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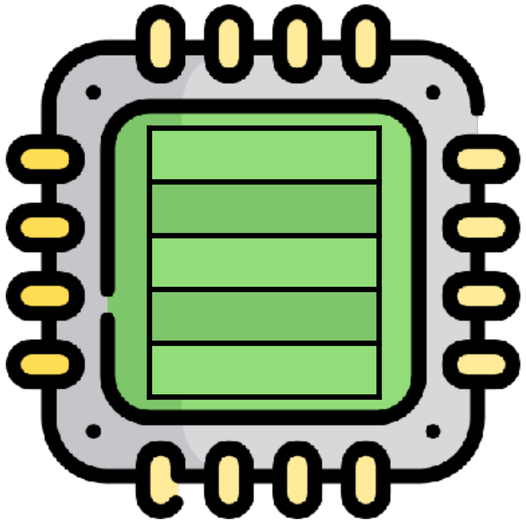

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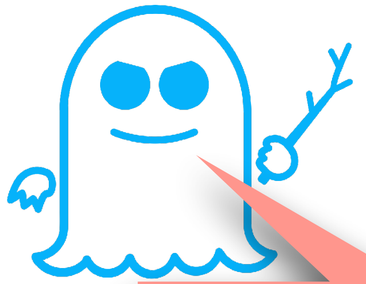

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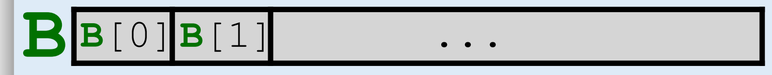


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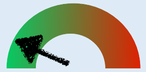
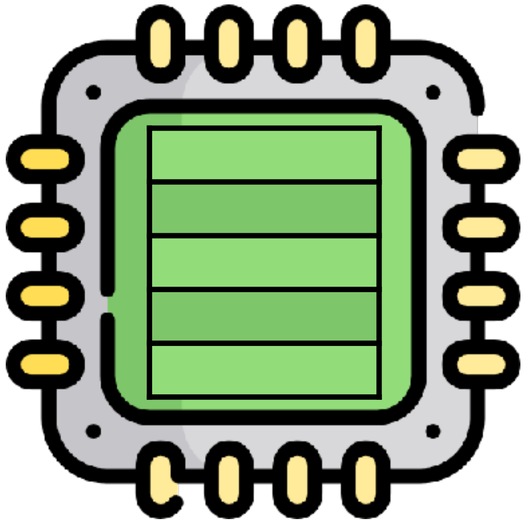
1) Training  `f(0);f(1);`



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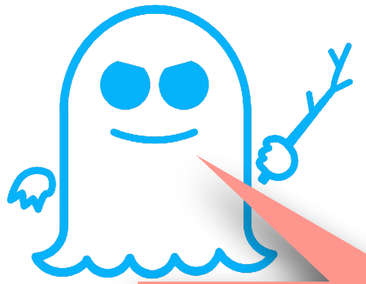

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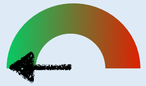
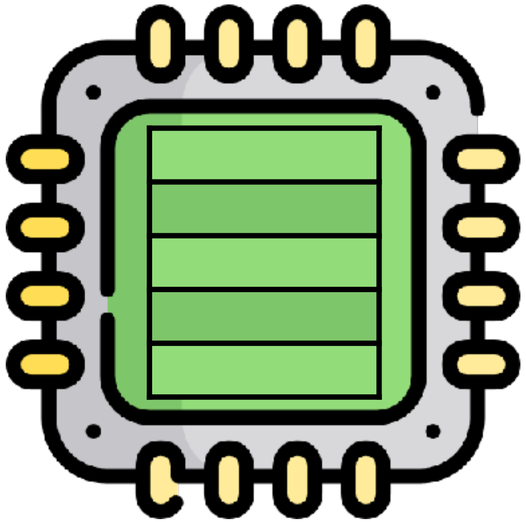
1) Training  f(0);f(1);f(2); …



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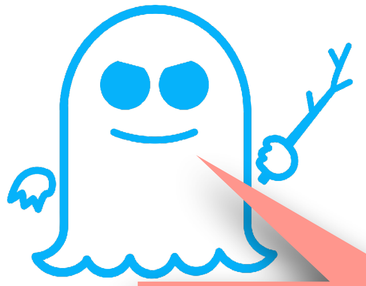

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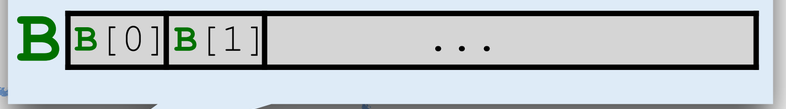


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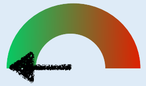
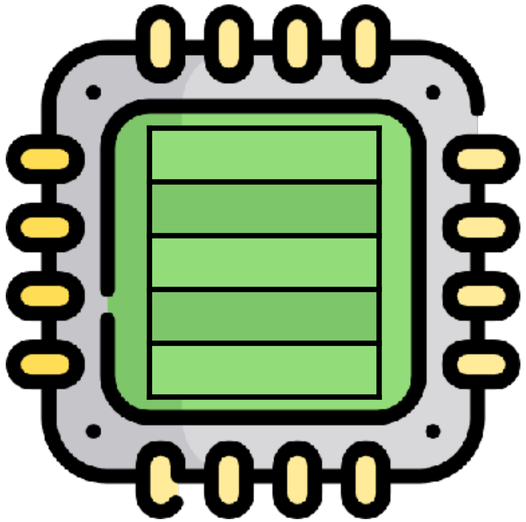
1) Training  f(0);f(1);f(2); …

2) Prepare cache



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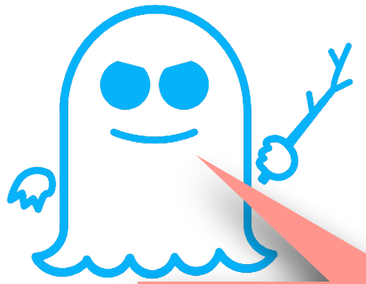

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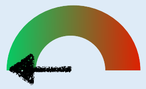
1) Training  `f(0);f(1);f(2); …`

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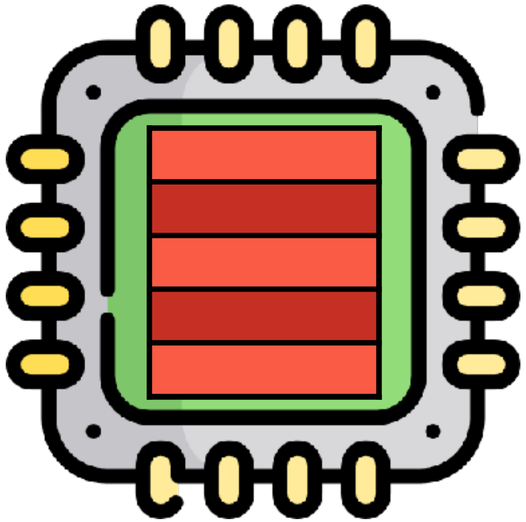

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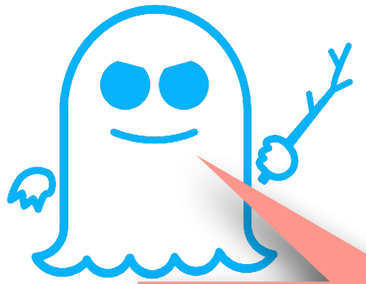

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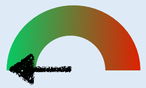
1) Training  `f(0);f(1);f(2); …`

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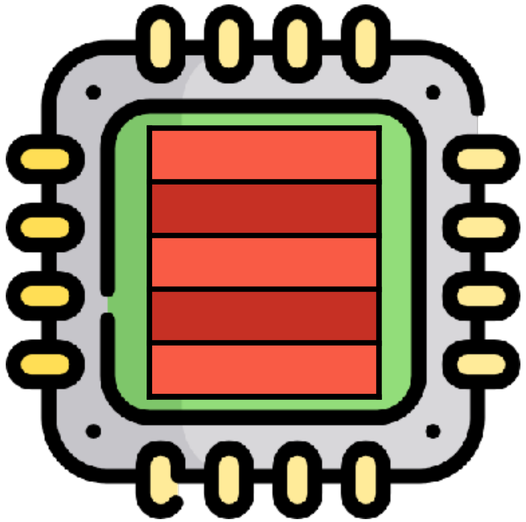
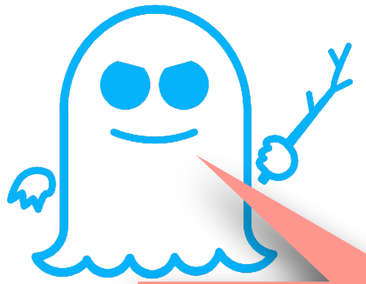
3) Run with `x = 128`



Spectre V1



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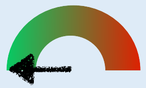
1) Training  `f(0);f(1);f(2); …`

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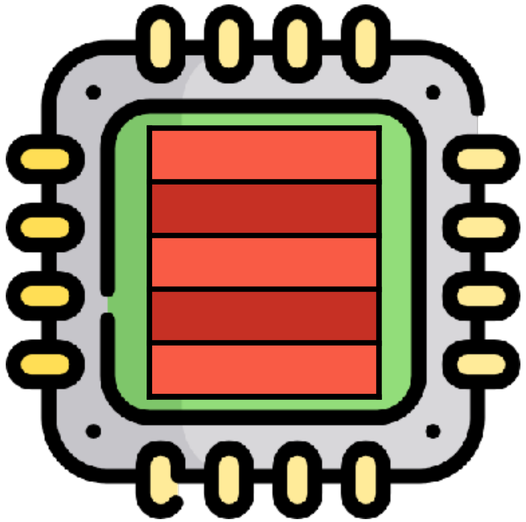

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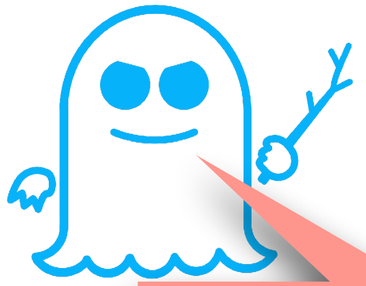

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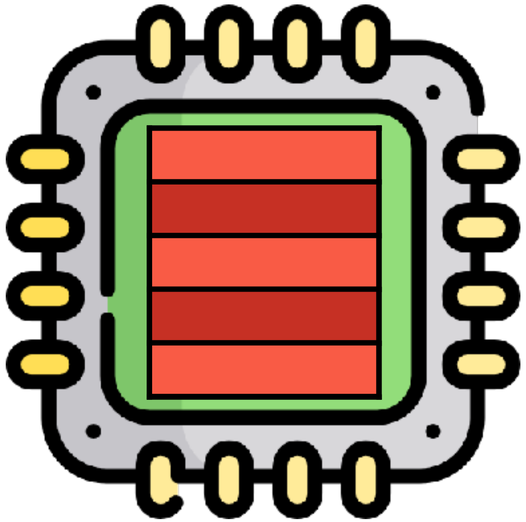
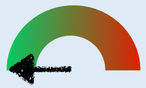


1) Training  `f(0);f(1);f(2); …`

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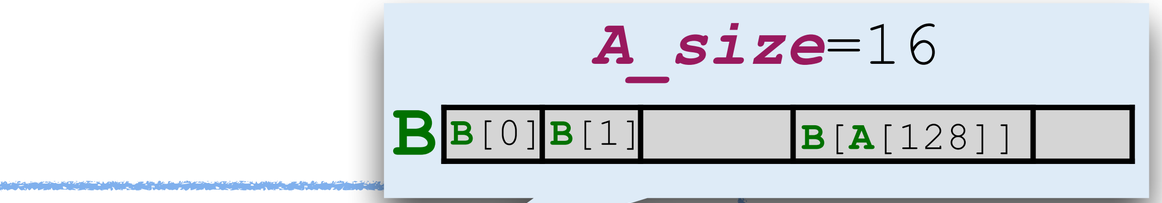

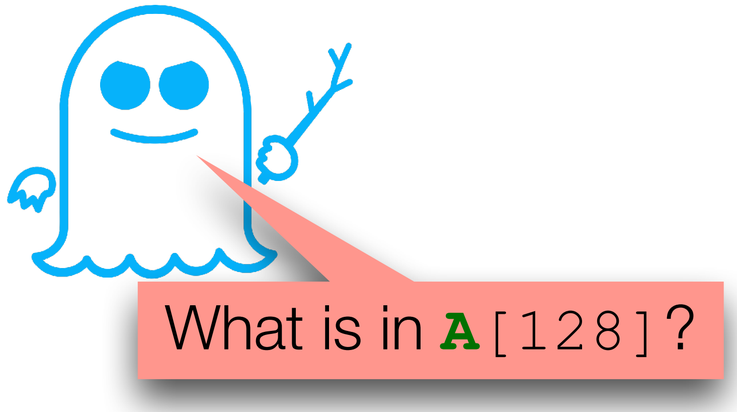


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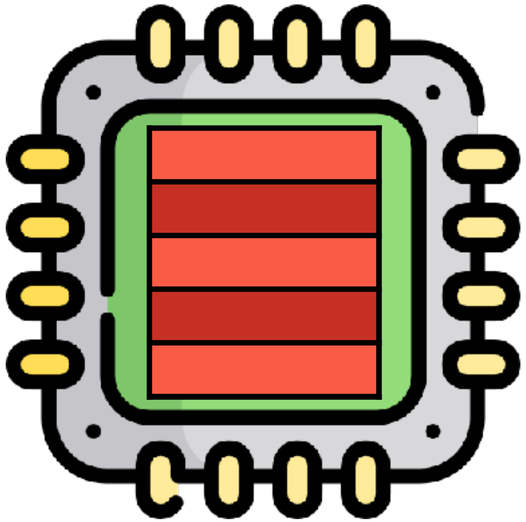
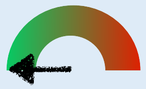


1) Training  `f(0);f(1);f(2); …`

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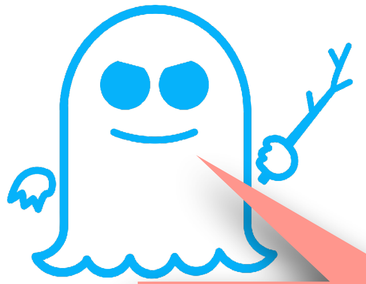

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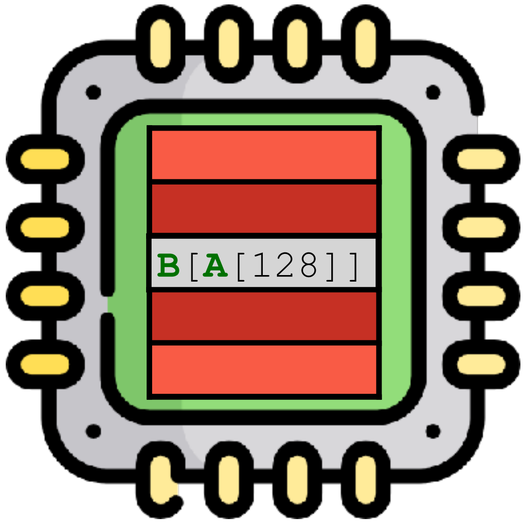
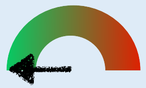


1) Training  `f(0);f(1);f(2); …`

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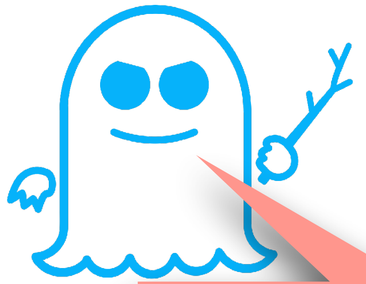

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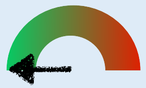
1) Training  `f(0);f(1);f(2); …`

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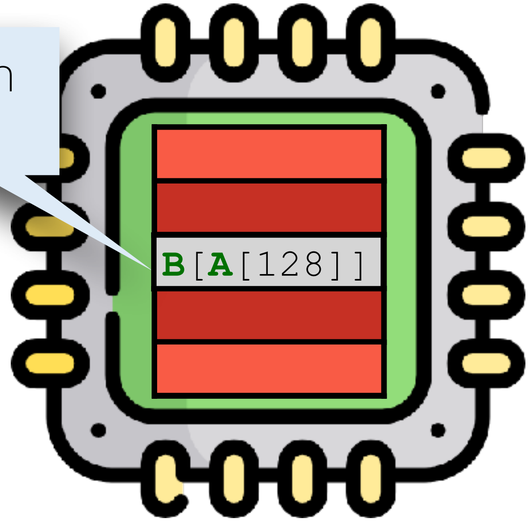

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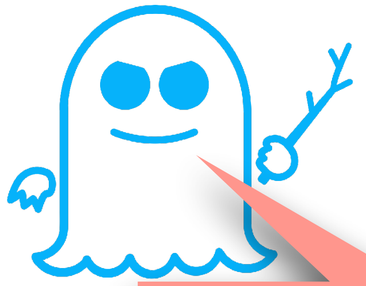

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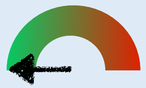
1) Training  f(0);f(1);f(2); …

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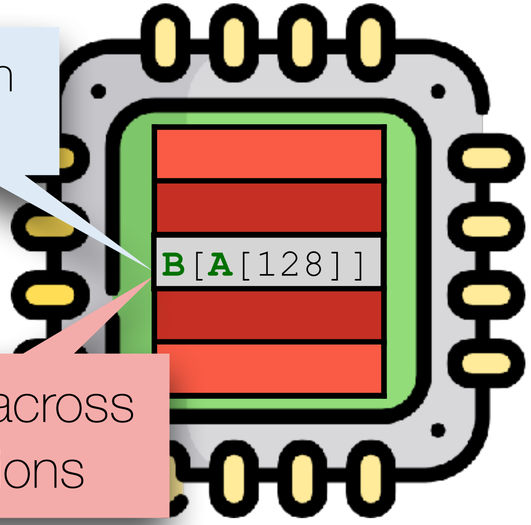
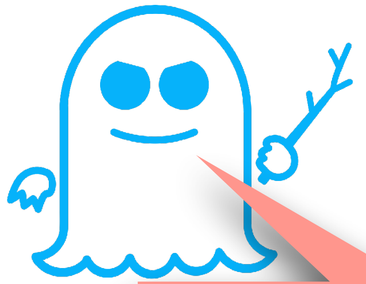


Persistent across speculations

Spectre V1



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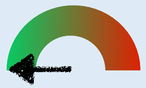
1) Training  `f(0);f(1);f(2); …`

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4) Extract from cache

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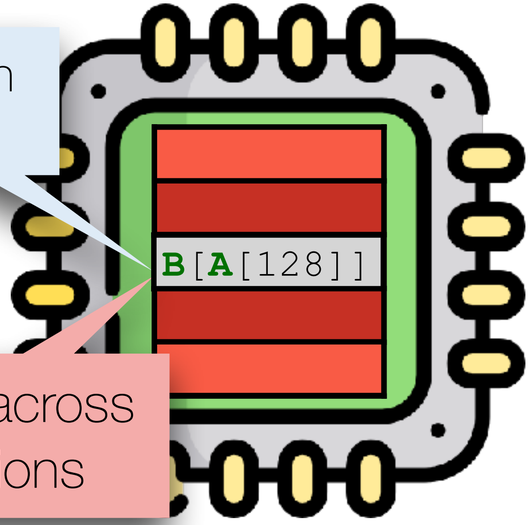

Persistent across speculations

Speculative non-interference

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Program **`P`** is **speculatively non-interferent** if

Speculative non-interference

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Informally:

Leakage of **`P`** in ***non-speculative*** execution

=

Leakage of **`P`** in ***speculative*** execution

How to capture leakage?

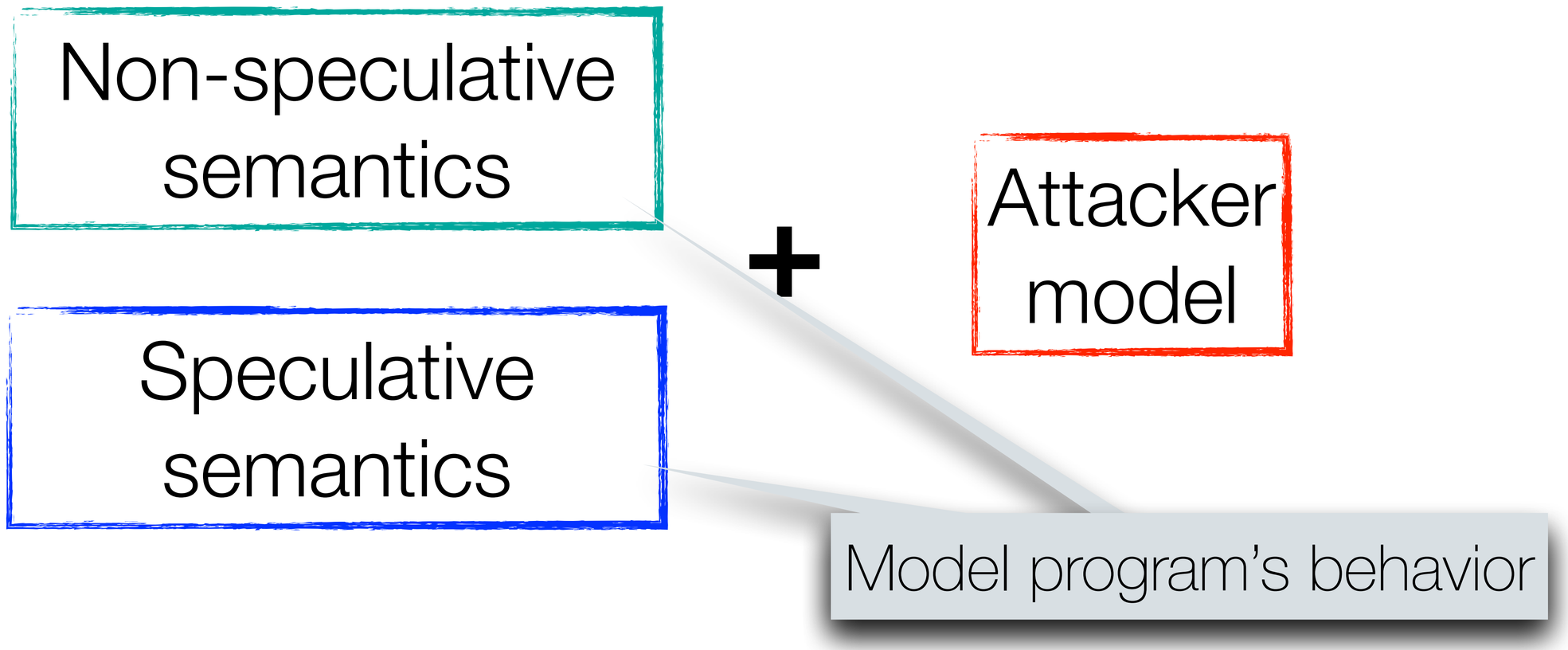
Non-speculative semantics

Speculative semantics

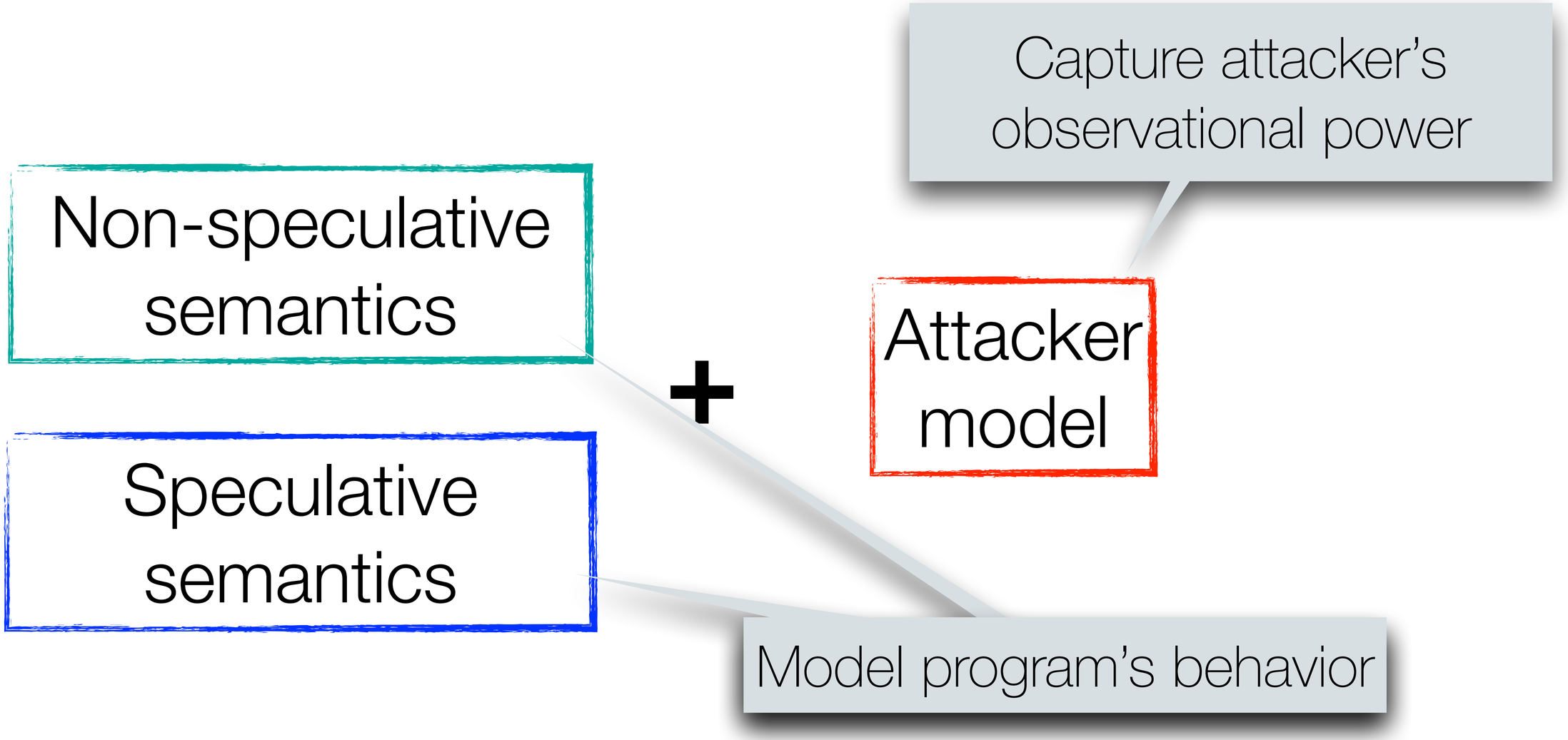
+

Attacker model

How to capture leakage?



How to capture leakage?



μAssembly + non-speculative semantics

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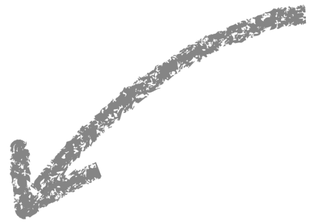

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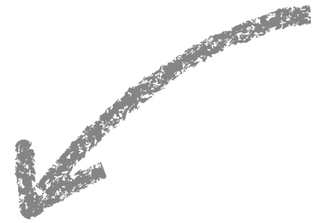

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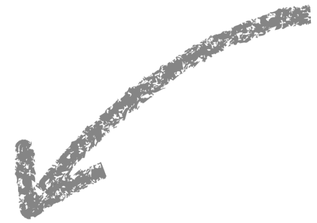

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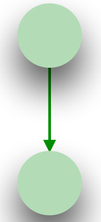

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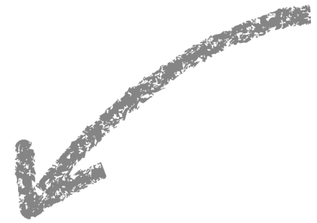

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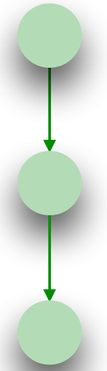

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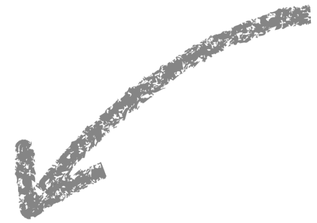

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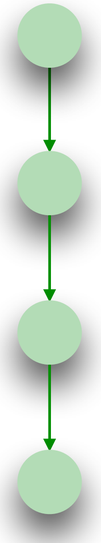

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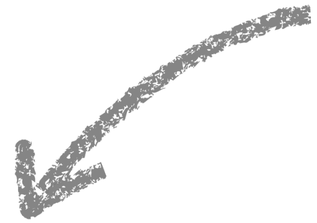

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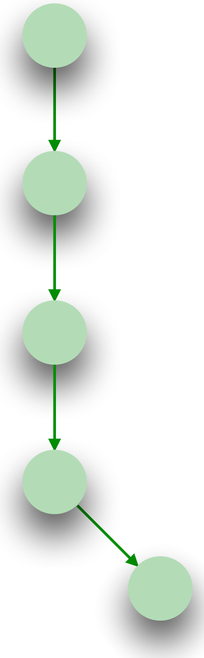

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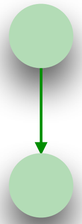

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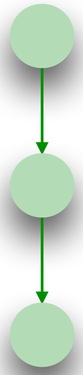

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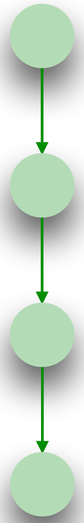

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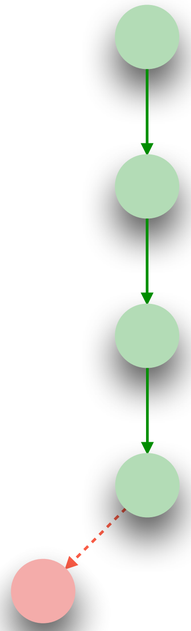

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Rolled back upon misspeculation

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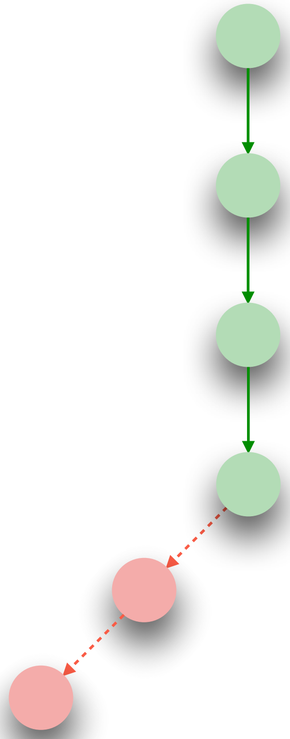

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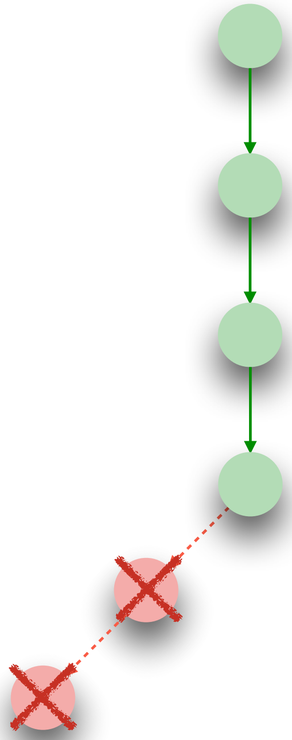

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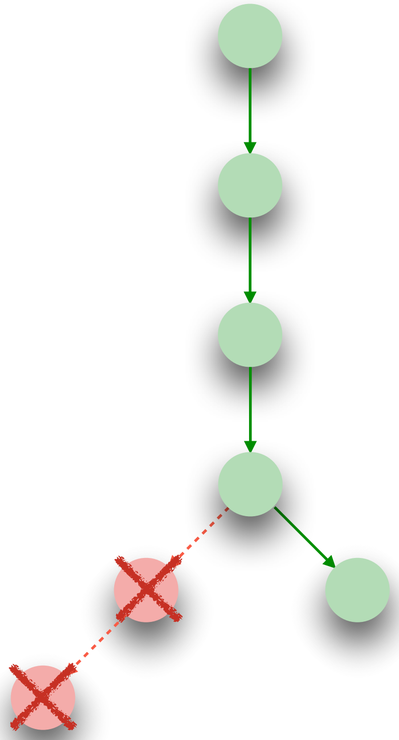

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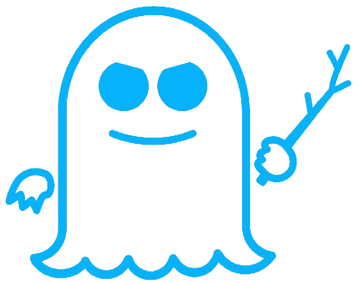

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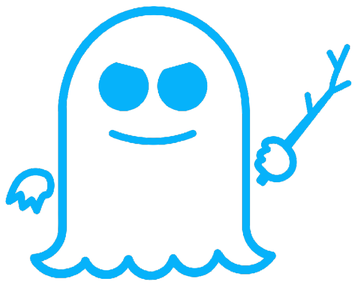

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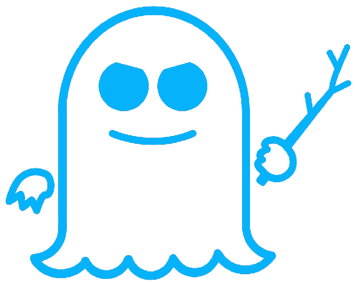

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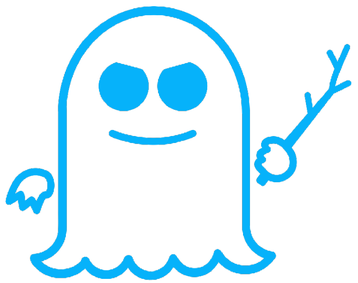

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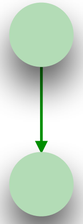

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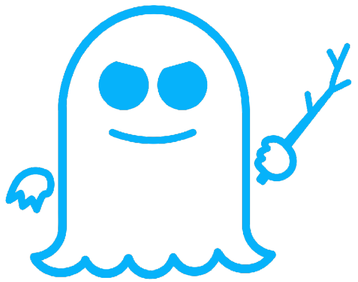

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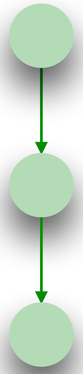

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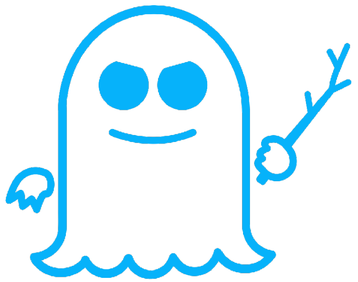

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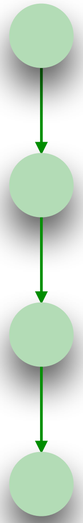

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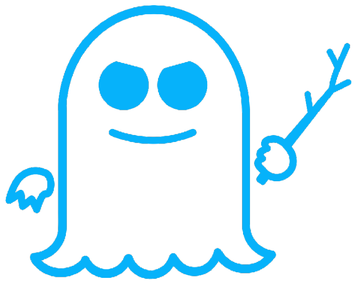

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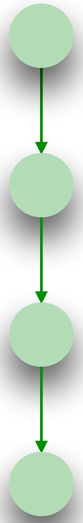

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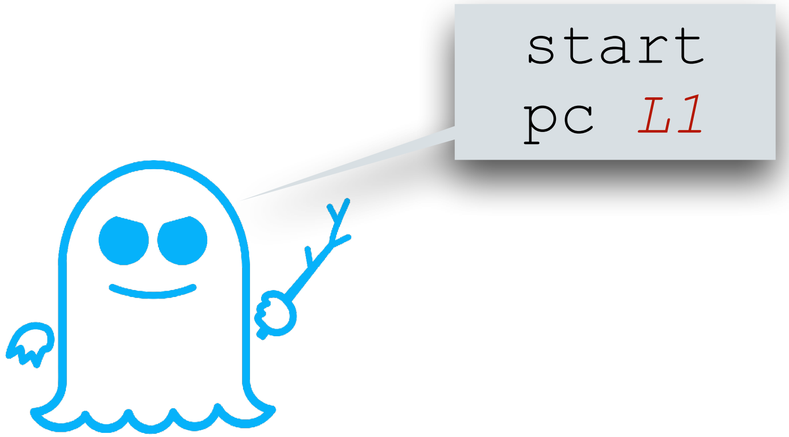

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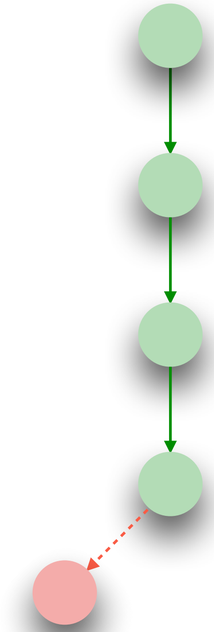

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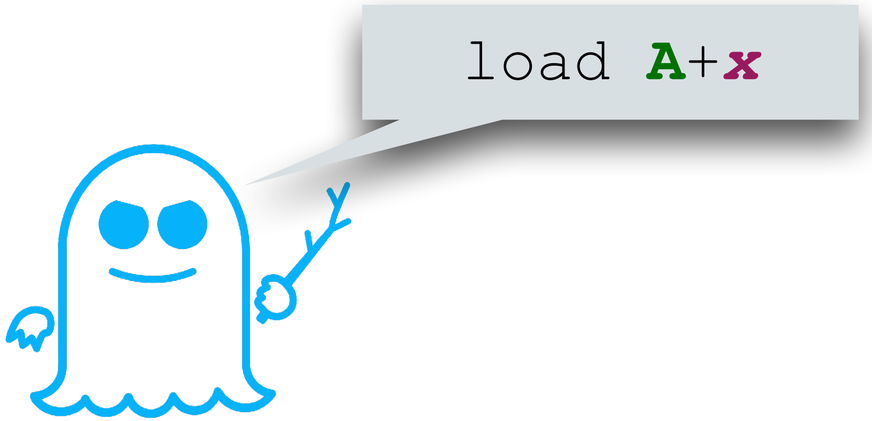

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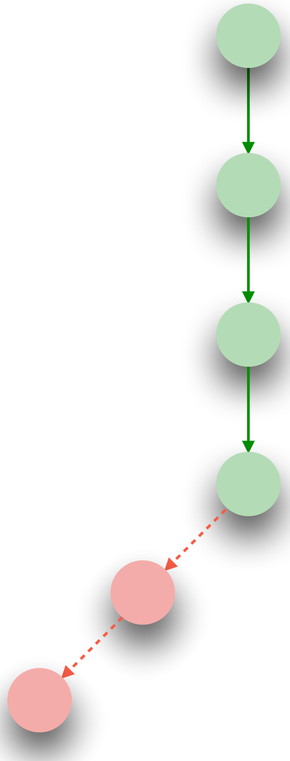

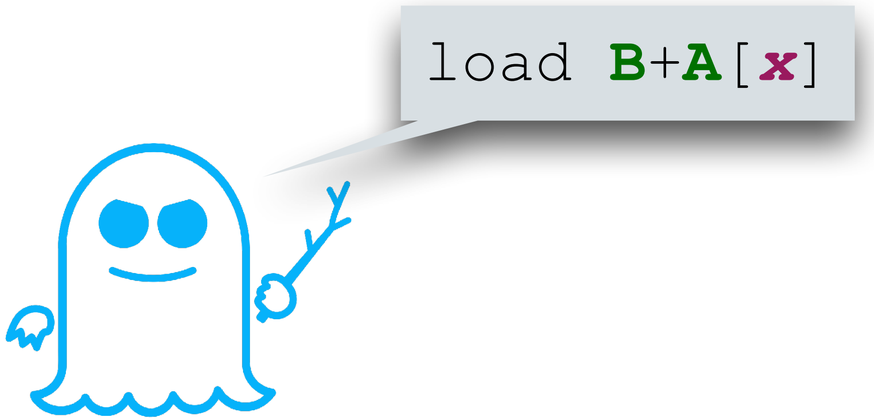

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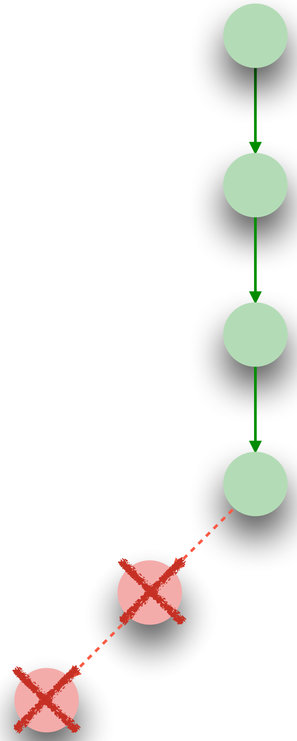

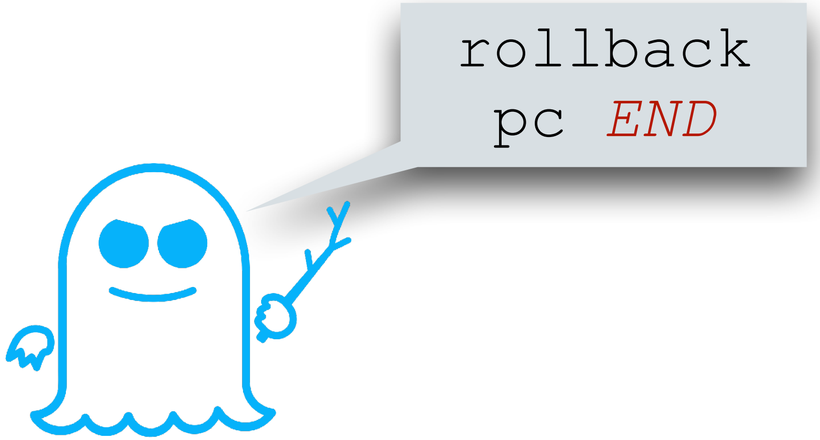

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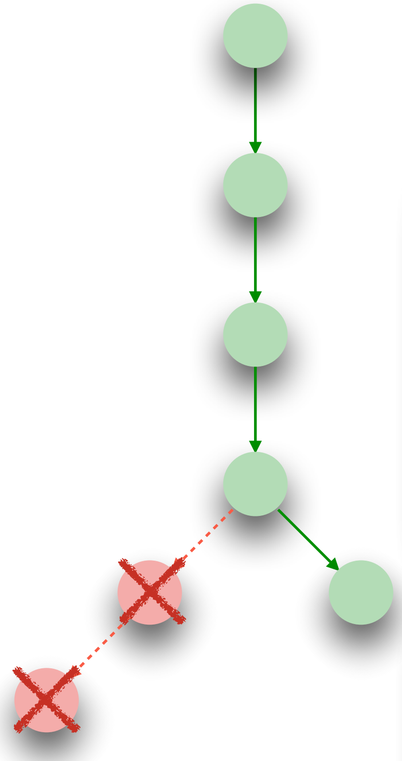

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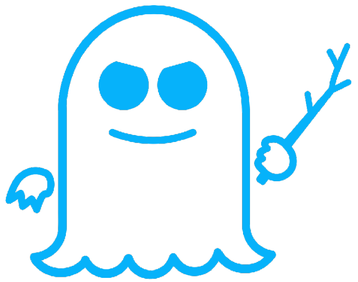

Speculative non-interference

Formally!

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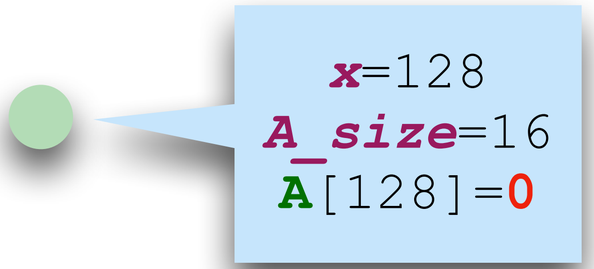

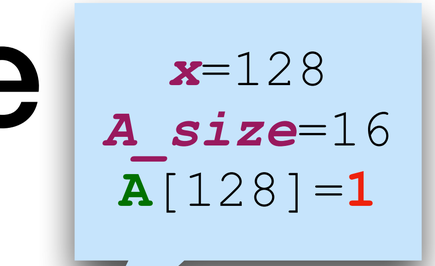

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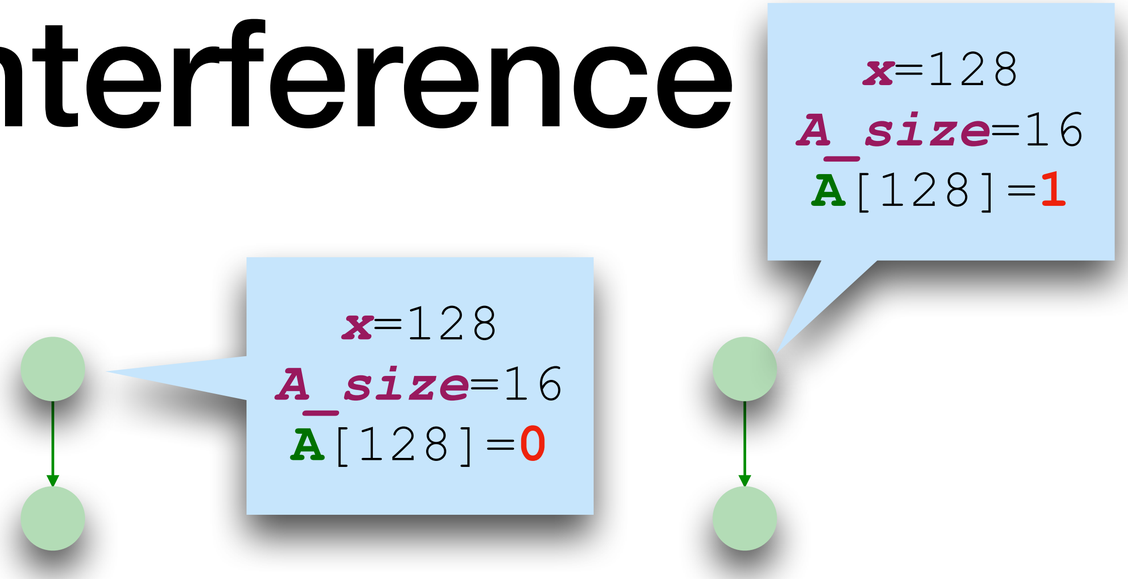

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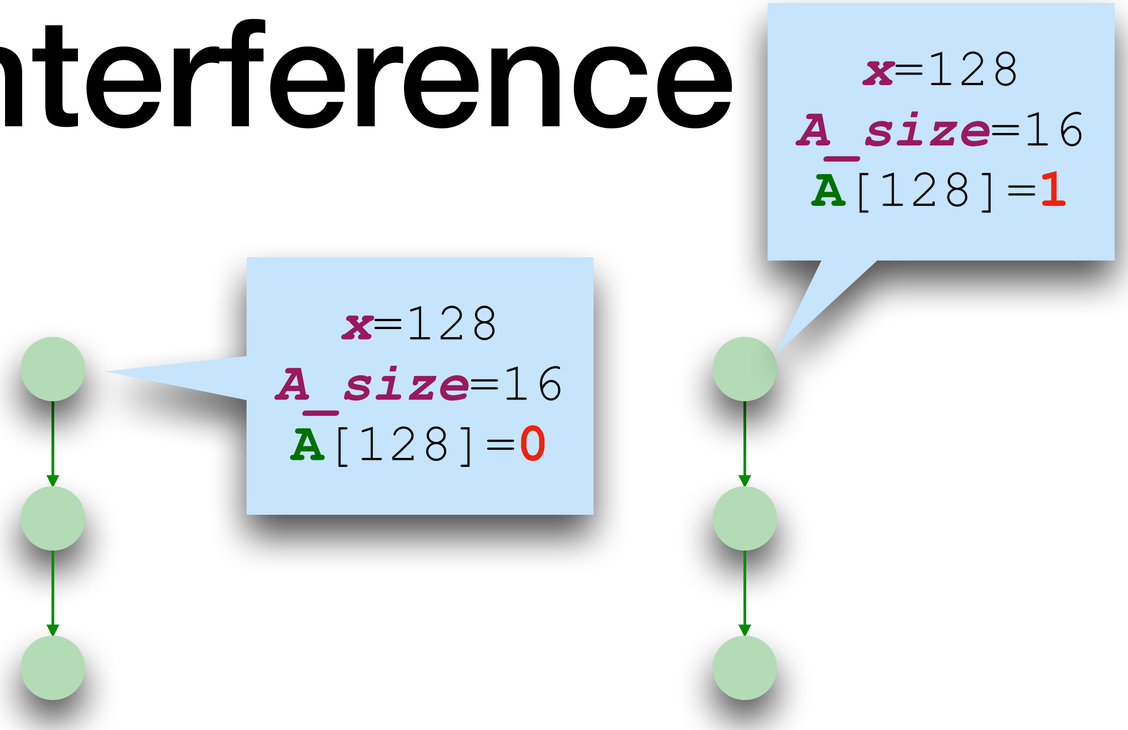

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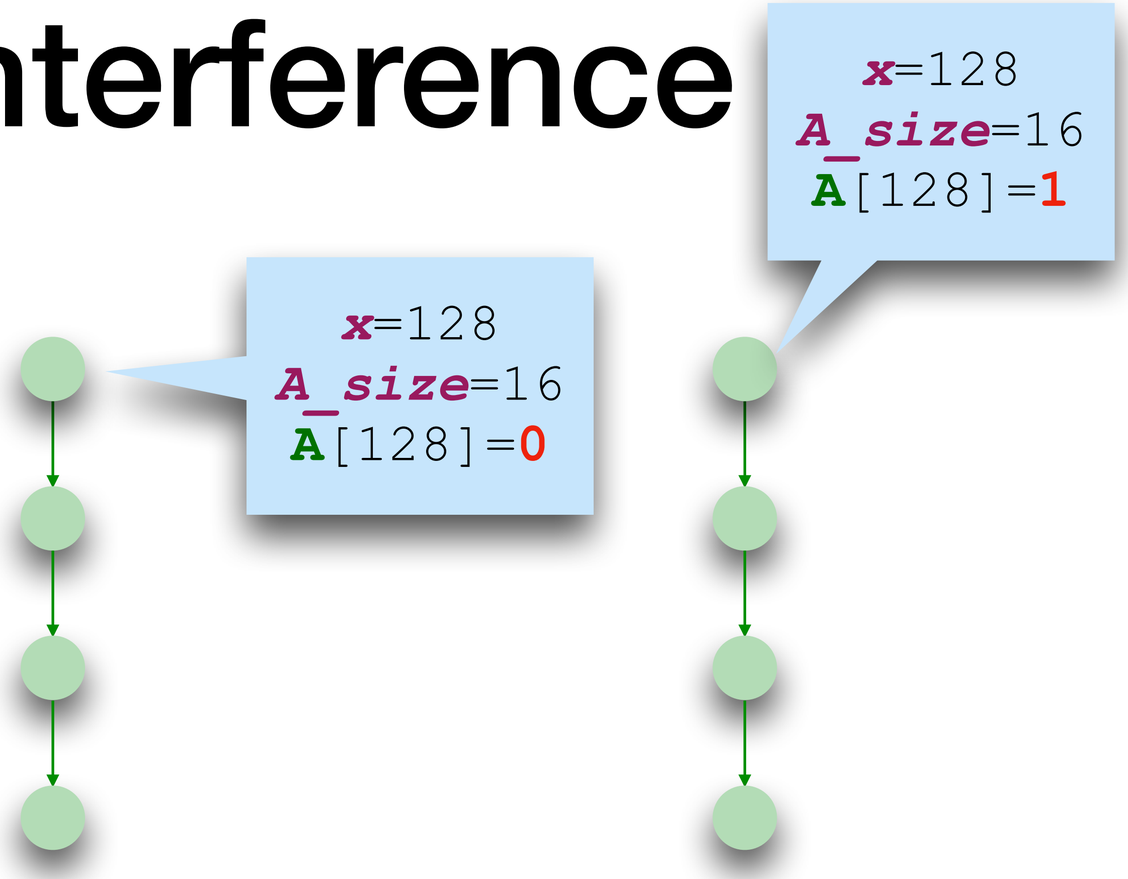

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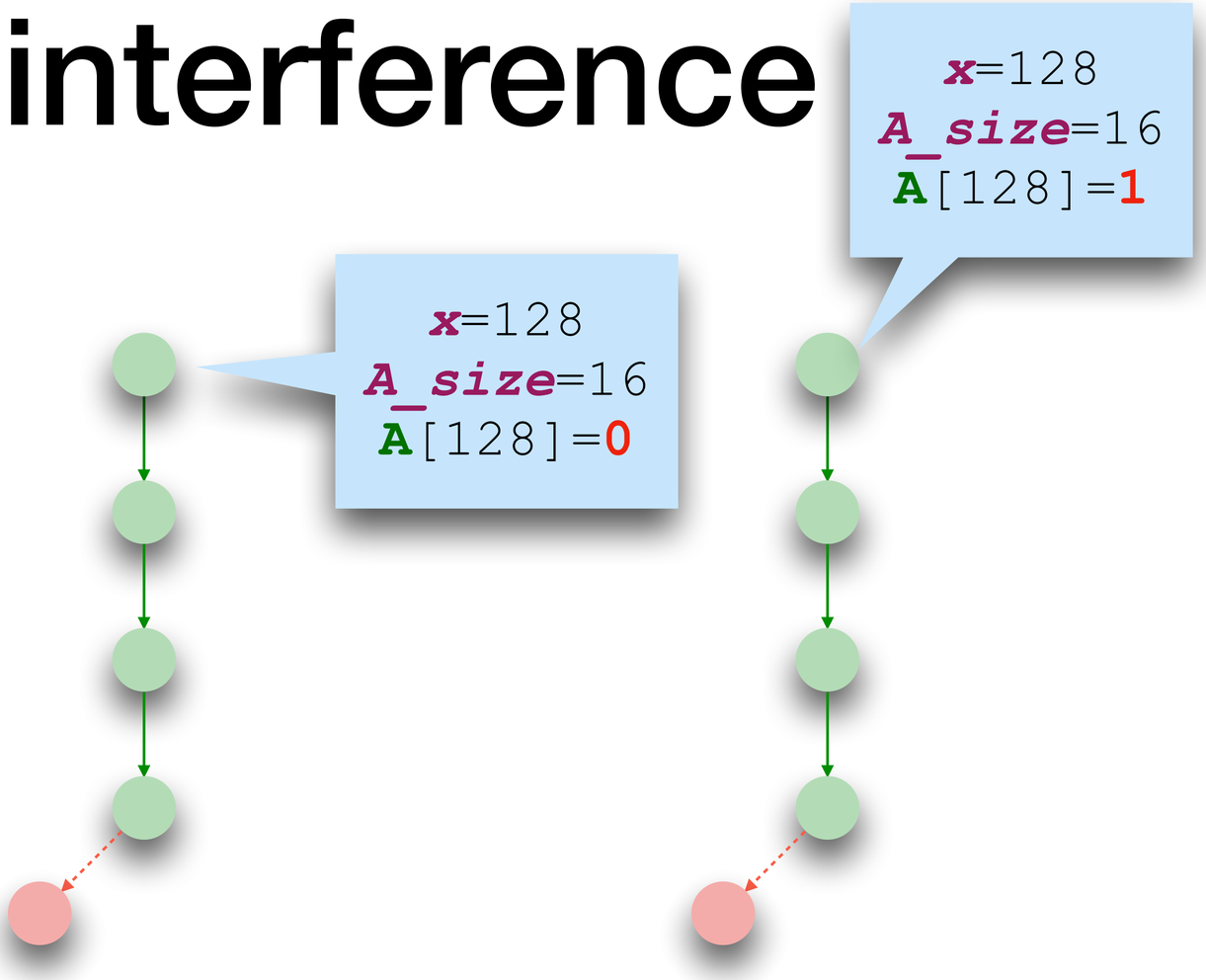

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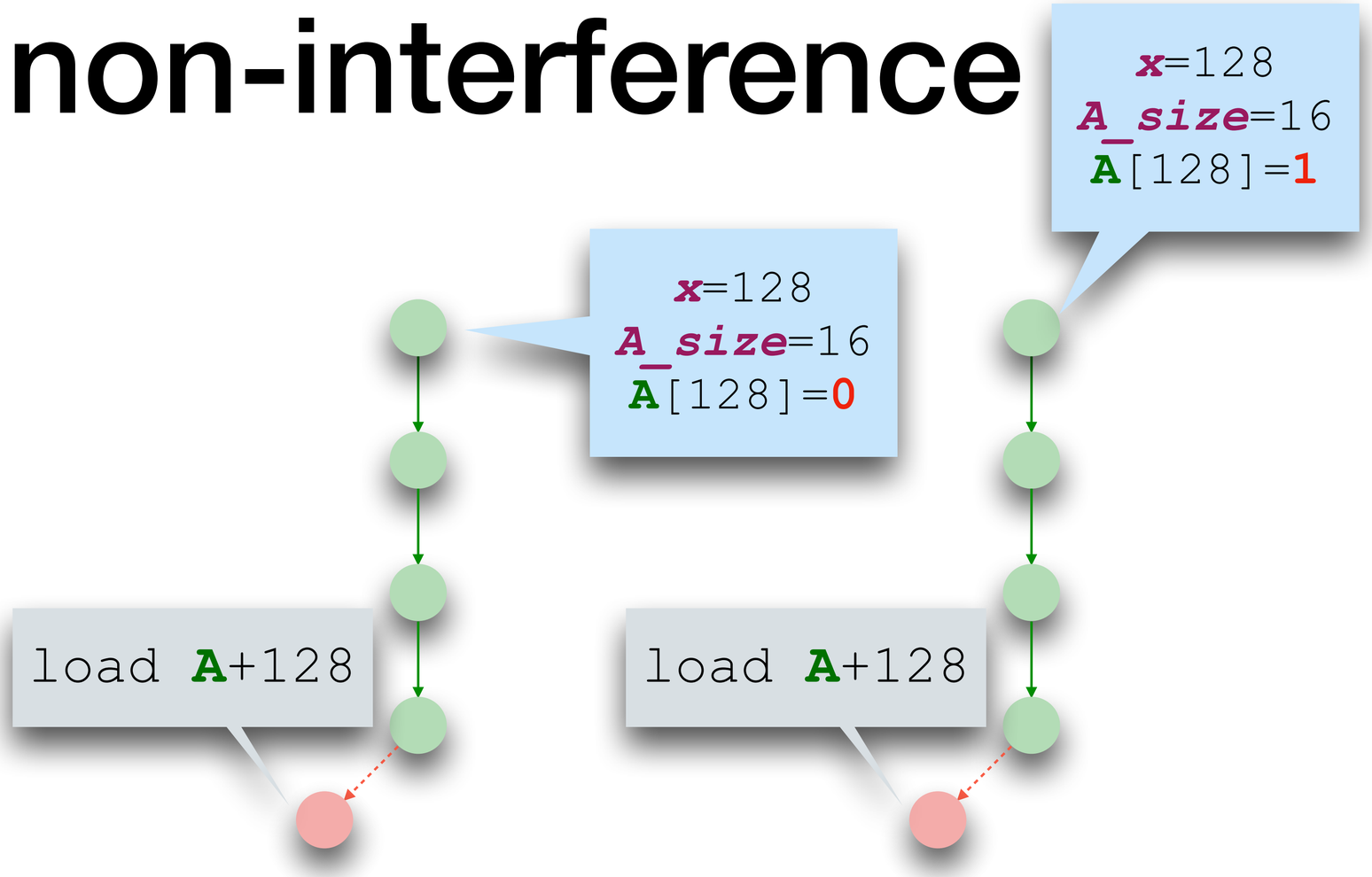

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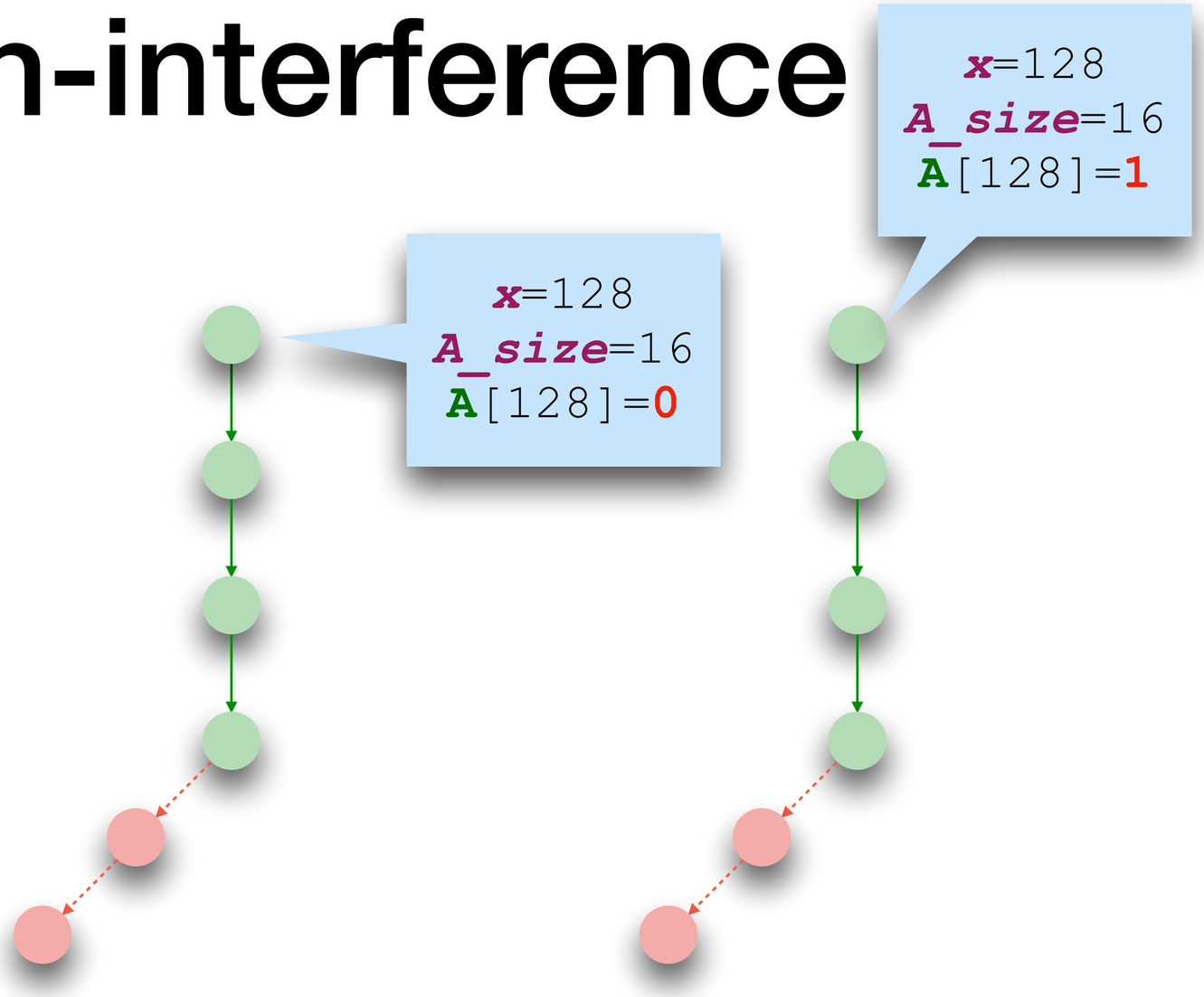

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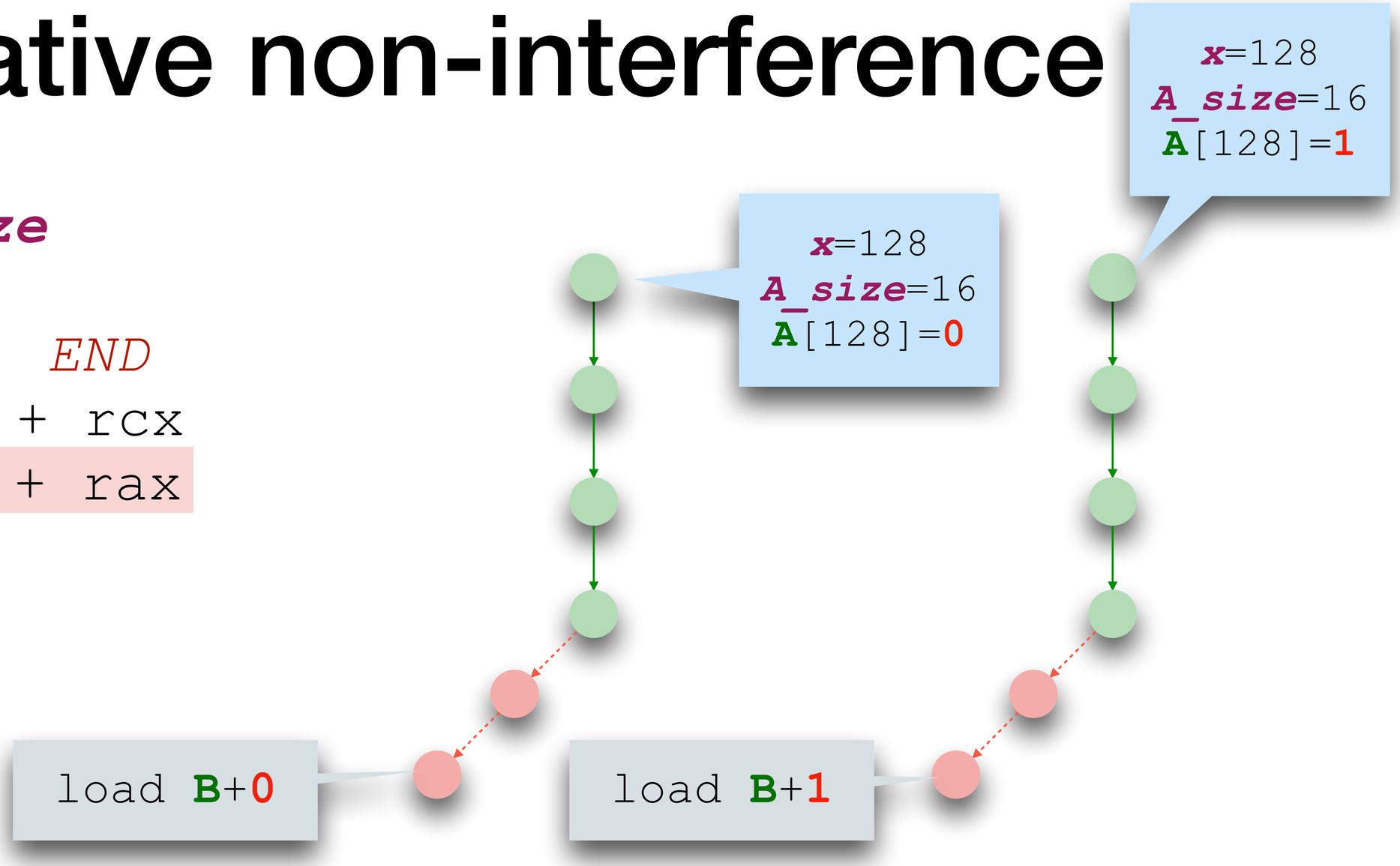

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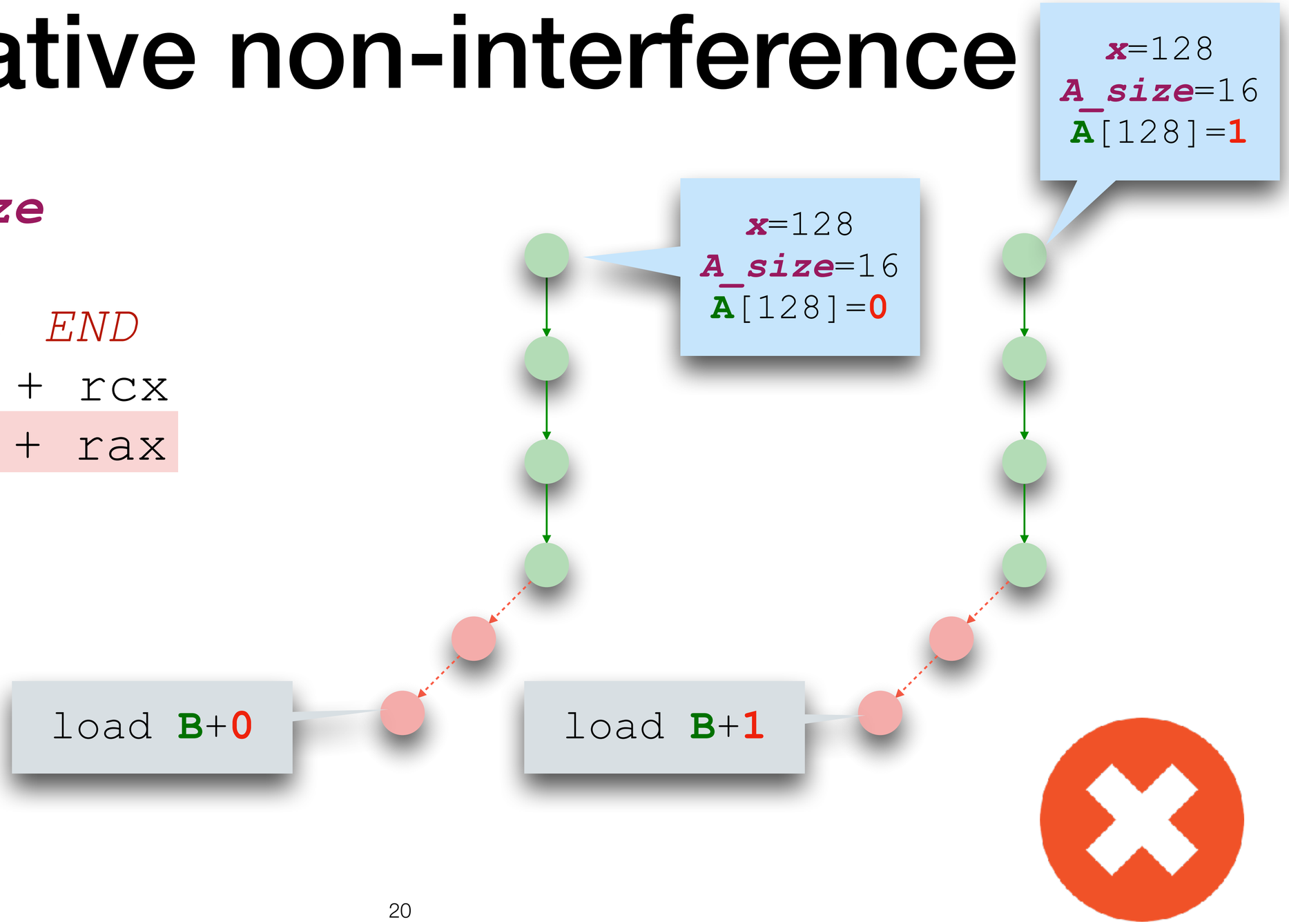

Reasoning about arbitrary oracles

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Mispredict ***all*** branch instructions

Fixed speculative window

Rollback of every transaction

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- Rollback of every transaction

Always-mispredict is ***worst-case***

$$\mathbf{P}_{\mathbf{am}}(s) = \mathbf{P}_{\mathbf{am}}(s') \iff \forall O.\ \mathbf{P}_{\mathbf{spec}}(s,O) = \mathbf{P}_{\mathbf{spec}}(s',O)$$

If program $\mathbf{P}$ satisfies

$$\forall s, s'.\mathbf{P}_{\mathbf{non\text{-}spec}}(s) = \mathbf{P}_{\mathbf{non\text{-}spec}}(s') \Rightarrow \mathbf{P}_{\mathbf{am}}(s) = \mathbf{P}_{\mathbf{am}}(s')$$

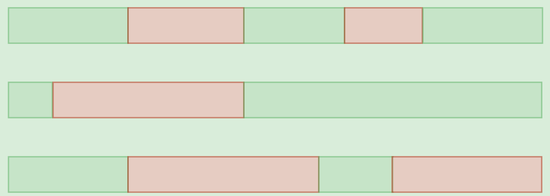
then $\mathbf{P}$ satisfies ***SNI*** w.r.t. all O

Detecting speculative leaks

Detecting speculative leaks

```
        rax <- A_size
        rcx <- x
        jmp rcx≥rax, END
L1:     load rax, A + rcx
        load rax, B + rax
END:
```

Symbolic execution



Detect leaks

Detecting speculative leaks

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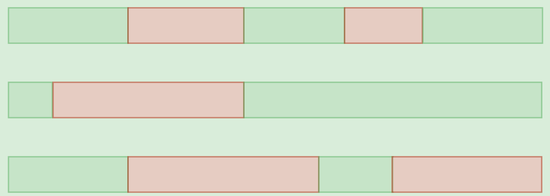
Symbolic execution



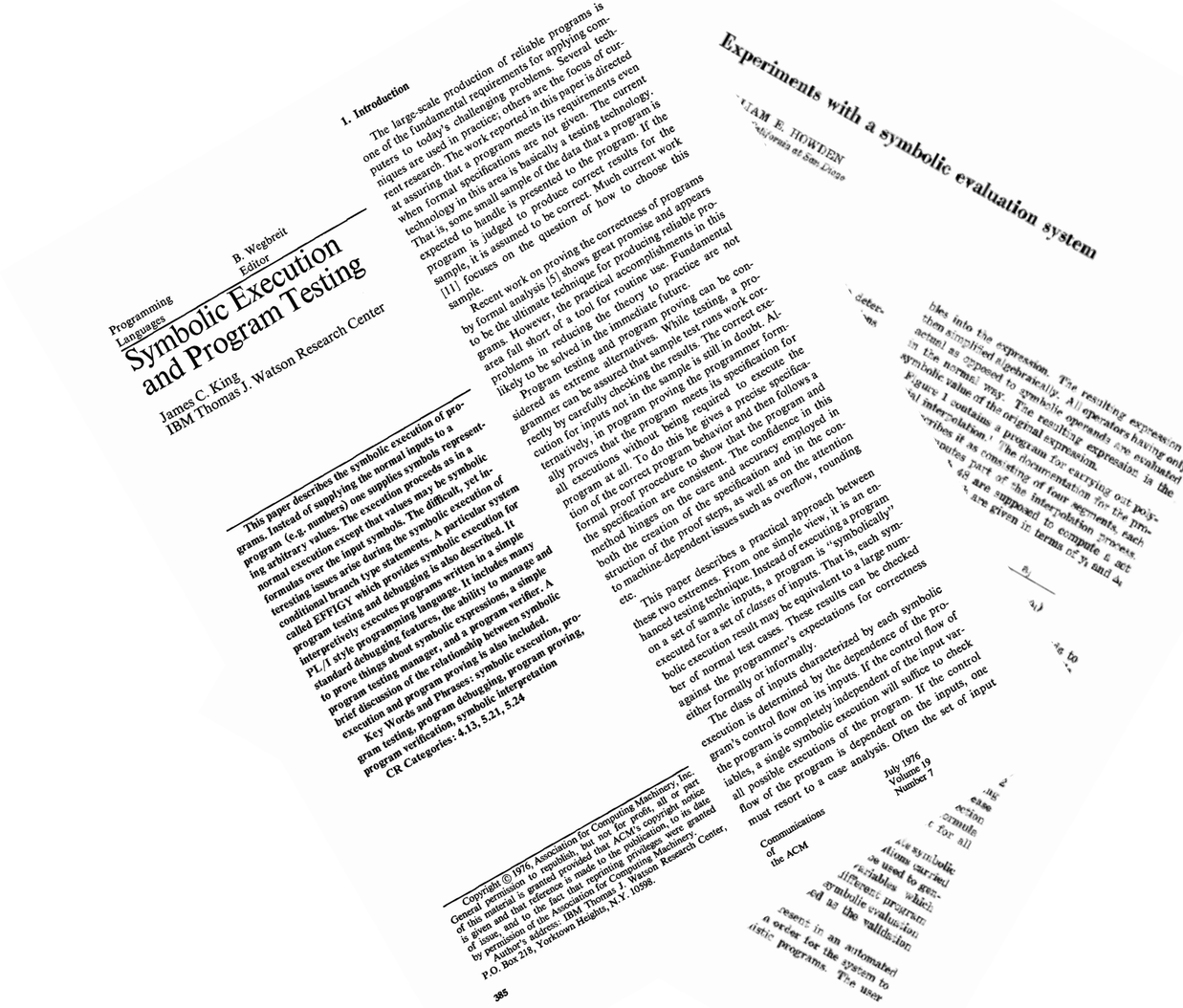
Detect leaks

Symbolic trace: path condition + observations along the symbolic path

Symbolic execution

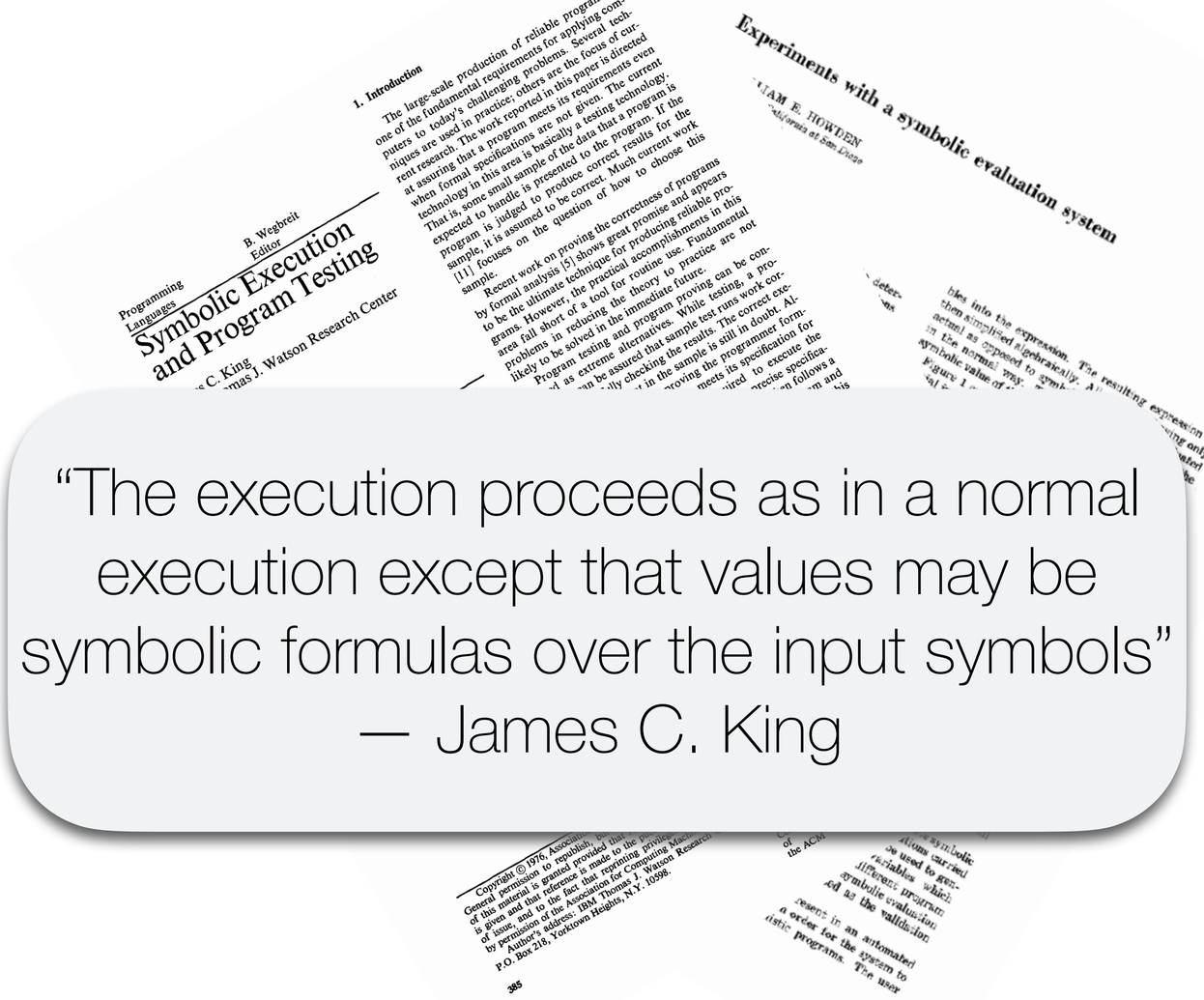
Symbolic execution

- Program analysis technique



Symbolic execution

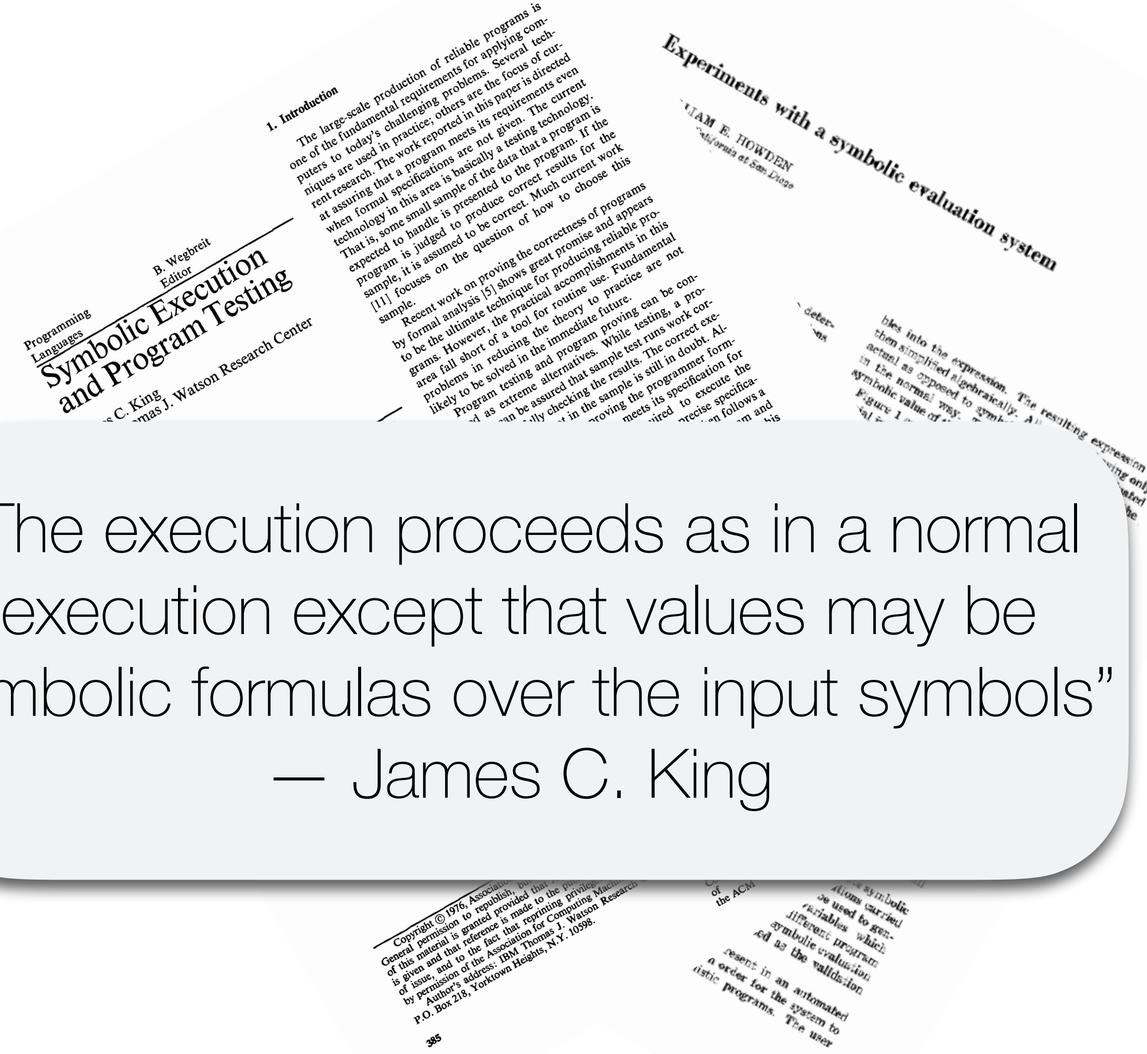
- Program analysis technique
- Execute programs over symbolic values



"The execution proceeds as in a normal execution except that values may be symbolic formulas over the input symbols"
— James C. King

Symbolic execution

- Program analysis technique
- Execute programs over symbolic values
  - Explore all paths, each with its own path constraint



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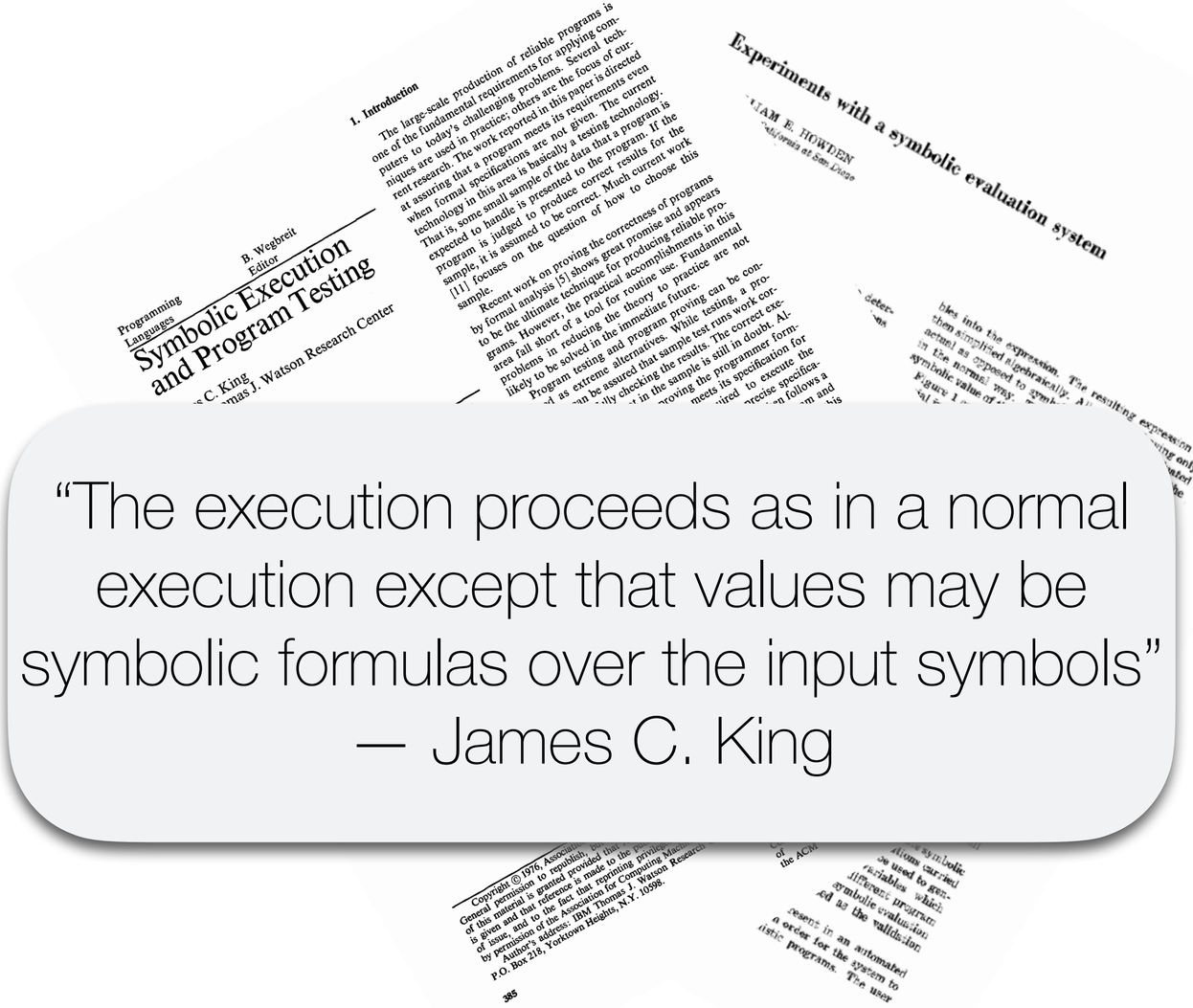
Symbolic execution

- Program analysis technique

- Execute programs over symbolic values

  - Explore all paths, each with its own path constraint

  - Each path represents all concrete executions satisfying the constraint



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Symbolic execution

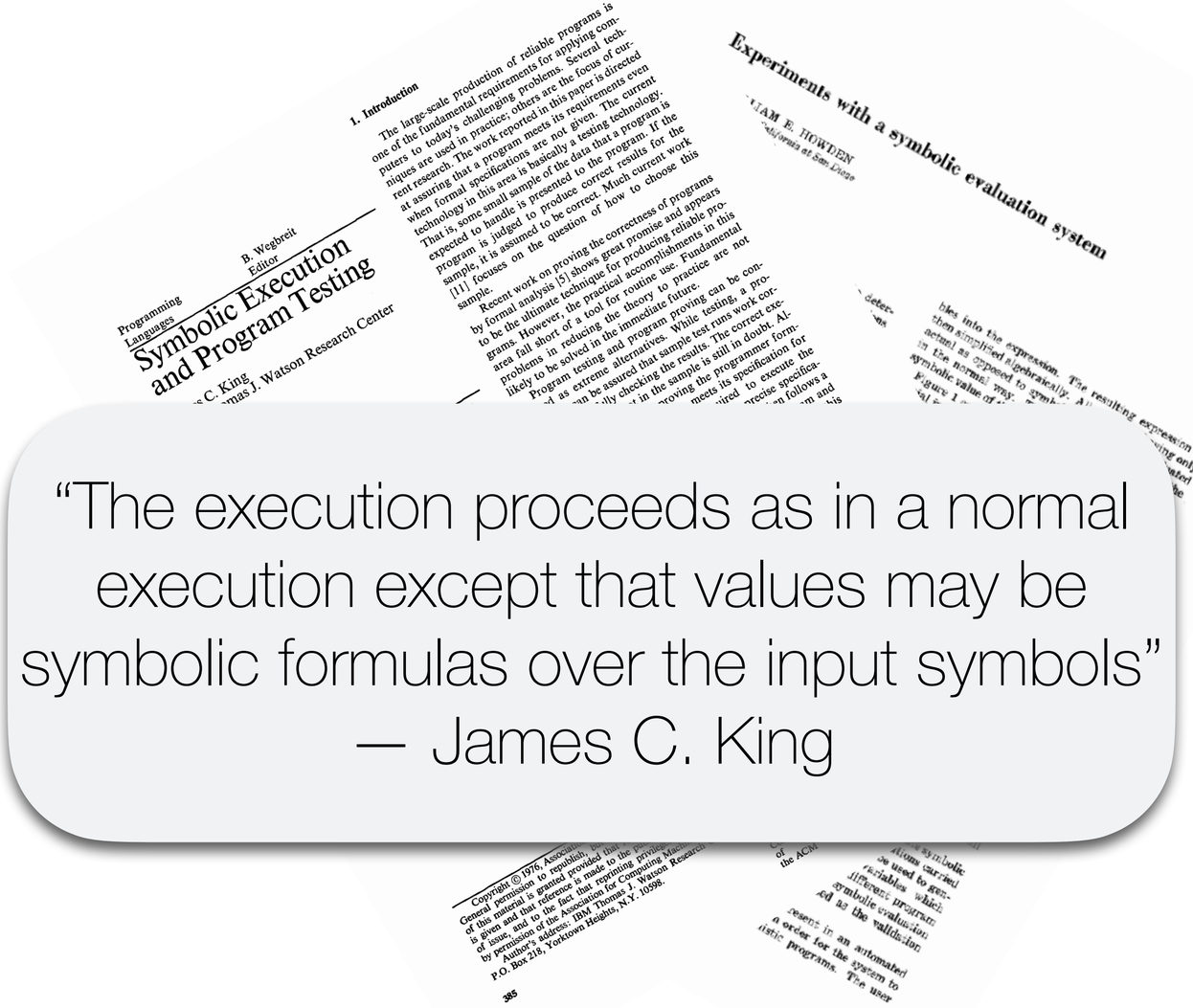
- Program analysis technique

- Execute programs over symbolic values

  - Explore all paths, each with its own path constraint

  - Each path represents all concrete executions satisfying the constraint

  - Branch and jump instructions: fork paths and update path constraint



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Symbolic execution

```
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     rcx <- x
     jmp rcx≥rax, END
L1:  load rax, A + rcx
     load rax, B + rax
END:
```

Symbolic execution

```
     rax <- A_size
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L1:  load rax, A + rcx
     load rax, B + rax
END:
```

Always mispredict branch instructions

Symbolic execution

```
     rax <- A_size
     rcx <- x
     jmp rcx≥rax, END
L1:  load rax, A + rcx
     load rax, B + rax
END:
```

true

Always mispredict
branch instructions

Symbolic execution

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      rax <- A_size
      rcx <- x
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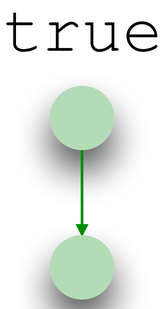
```

Always mispredict branch instructions



Symbolic execution

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L1:  load rax, A + rcx
     load rax, B + rax
END:
```

Always mispredict
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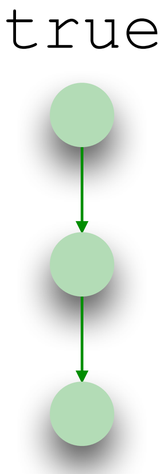

Symbolic execution

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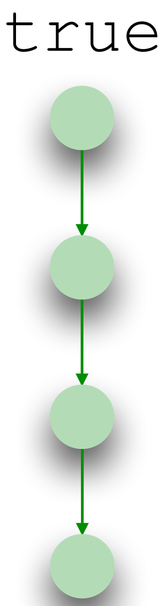

Symbolic execution

```
     rax <- A_size
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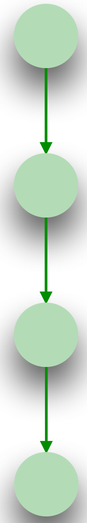
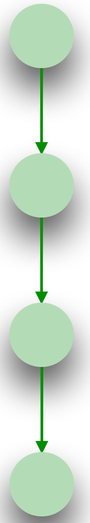
L1:  load rax, A + rcx
     load rax, B + rax
END:
```

Always mispredict branch instructions

$x \geq$ *A_size*



$x <$ *A_size*



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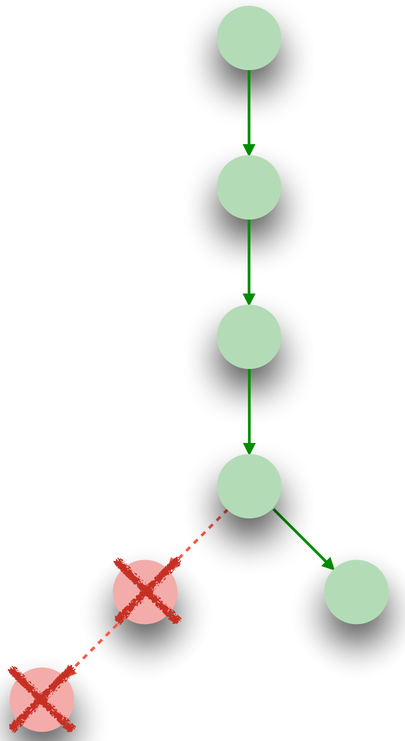

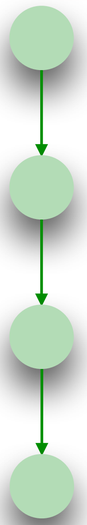

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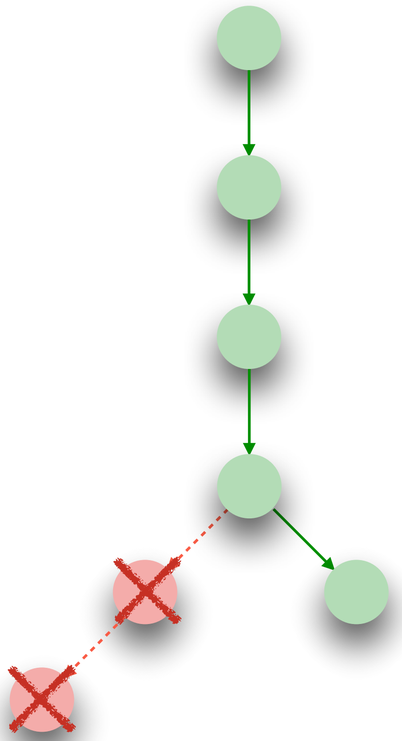

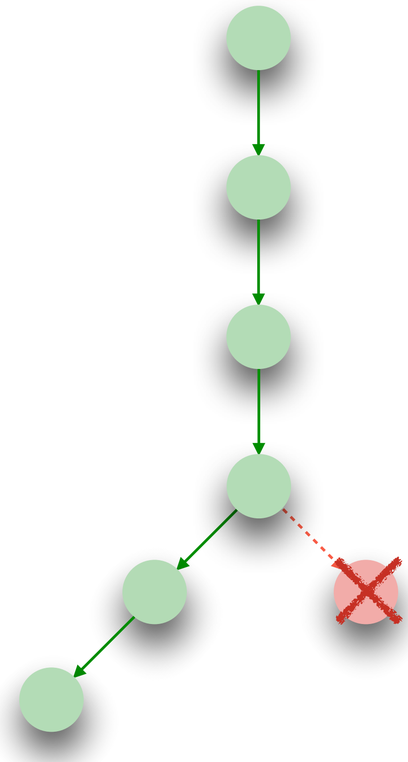

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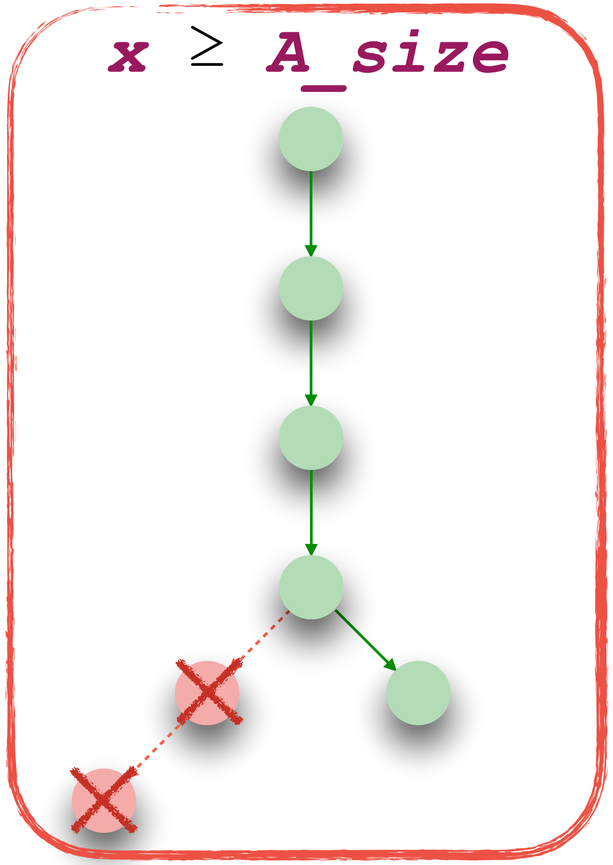

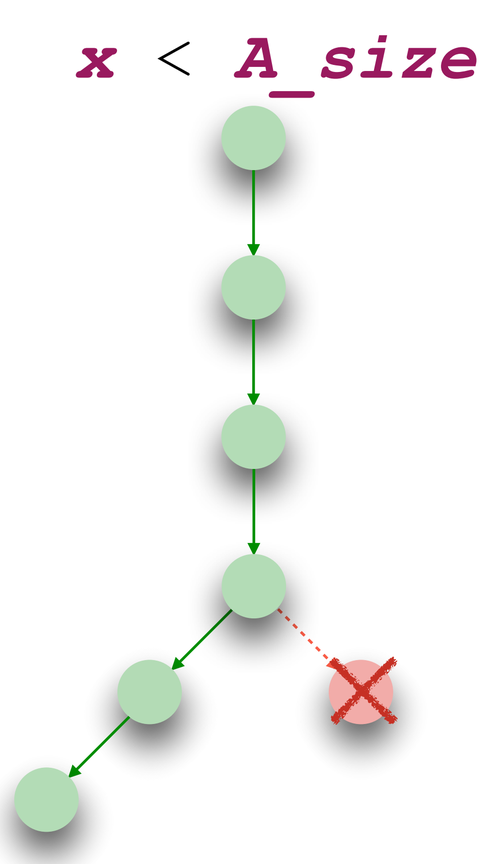

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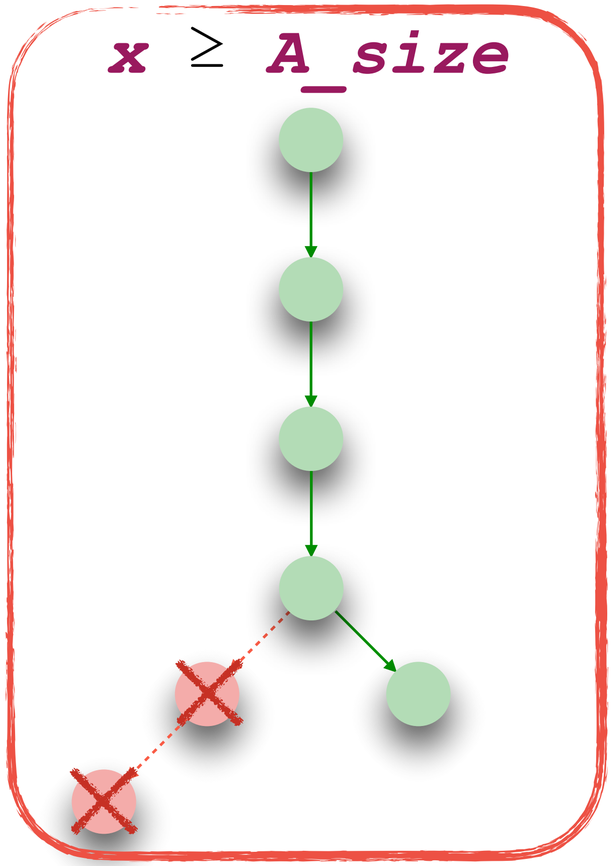

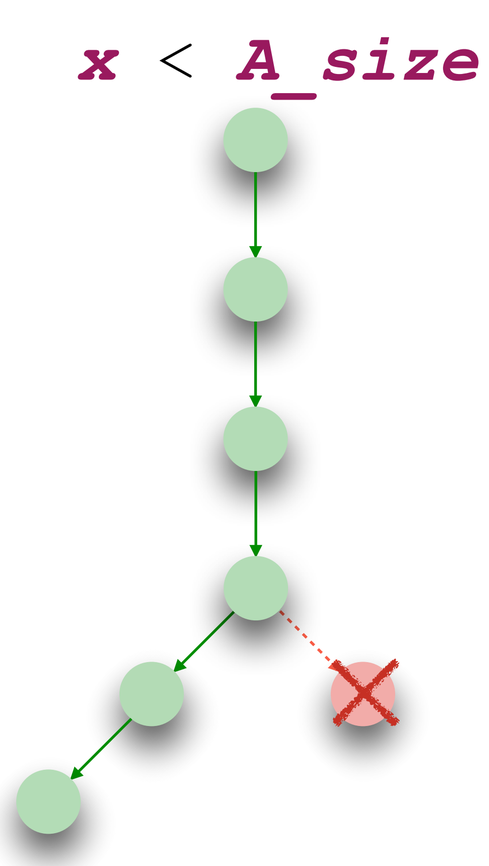


```
start pc L1 load A+x load B+A[x] rollback pc END
```

Symbolic execution

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     rax <- A_size
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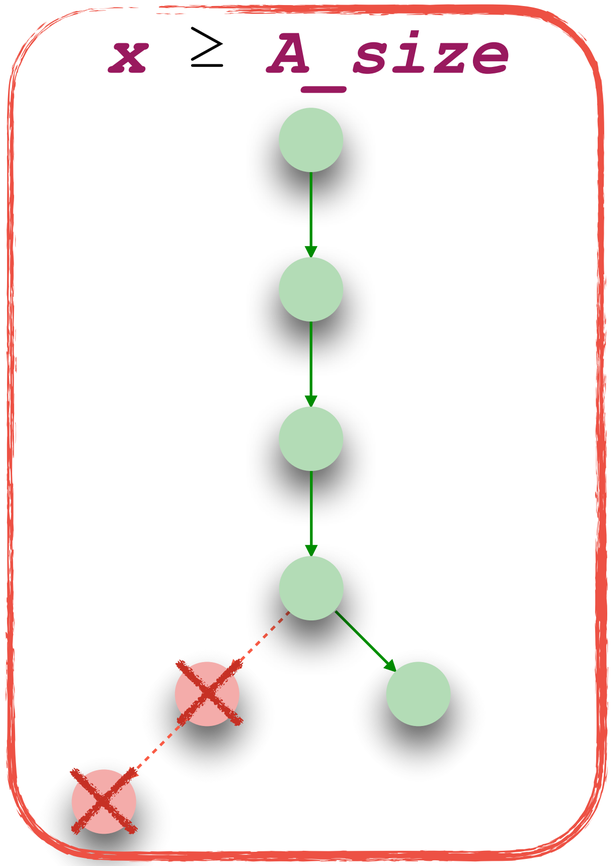
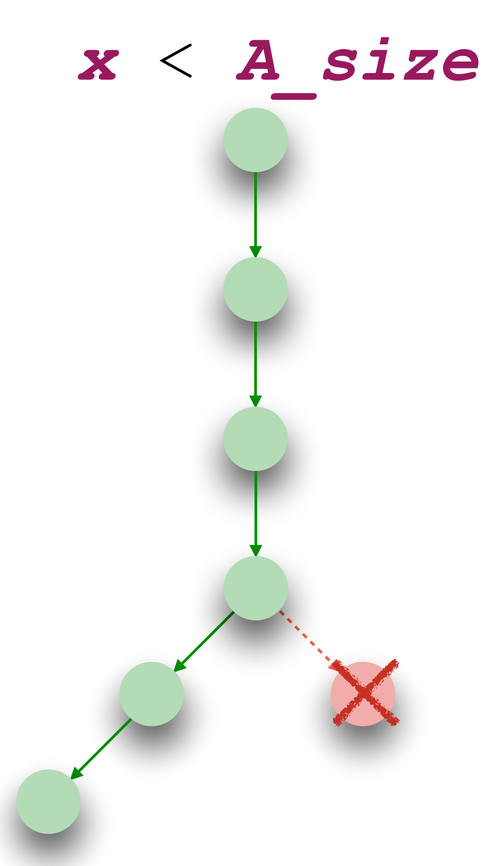
L1:  load rax, A + rcx
     load rax, B + rax
END:
```

Always mispredict branch instructions






```
start pc L1 load A+x load B+A[x] rollback pc END
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Symbolic execution

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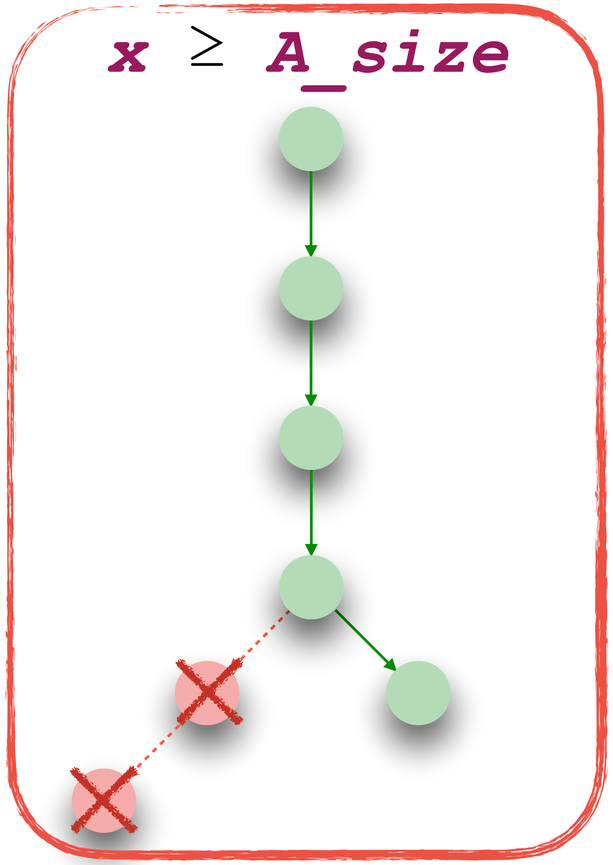

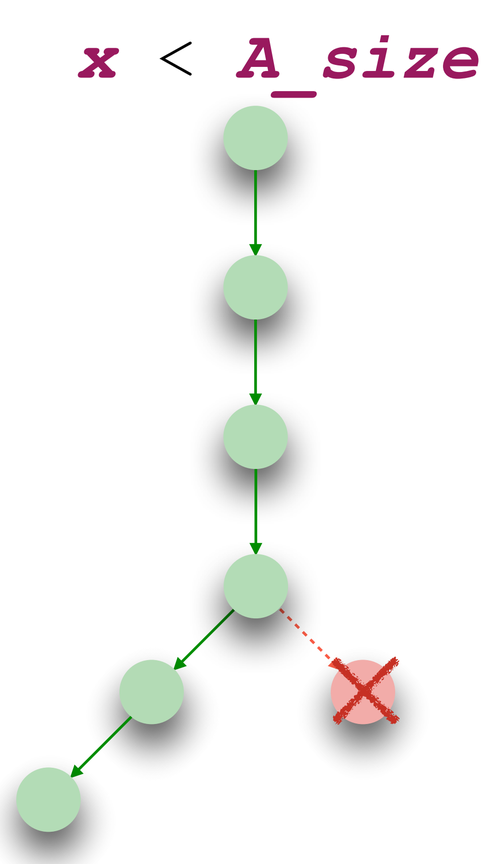

`start pc L1 load A+x load B+A[x] rollback pc END`

Detecting speculative leaks

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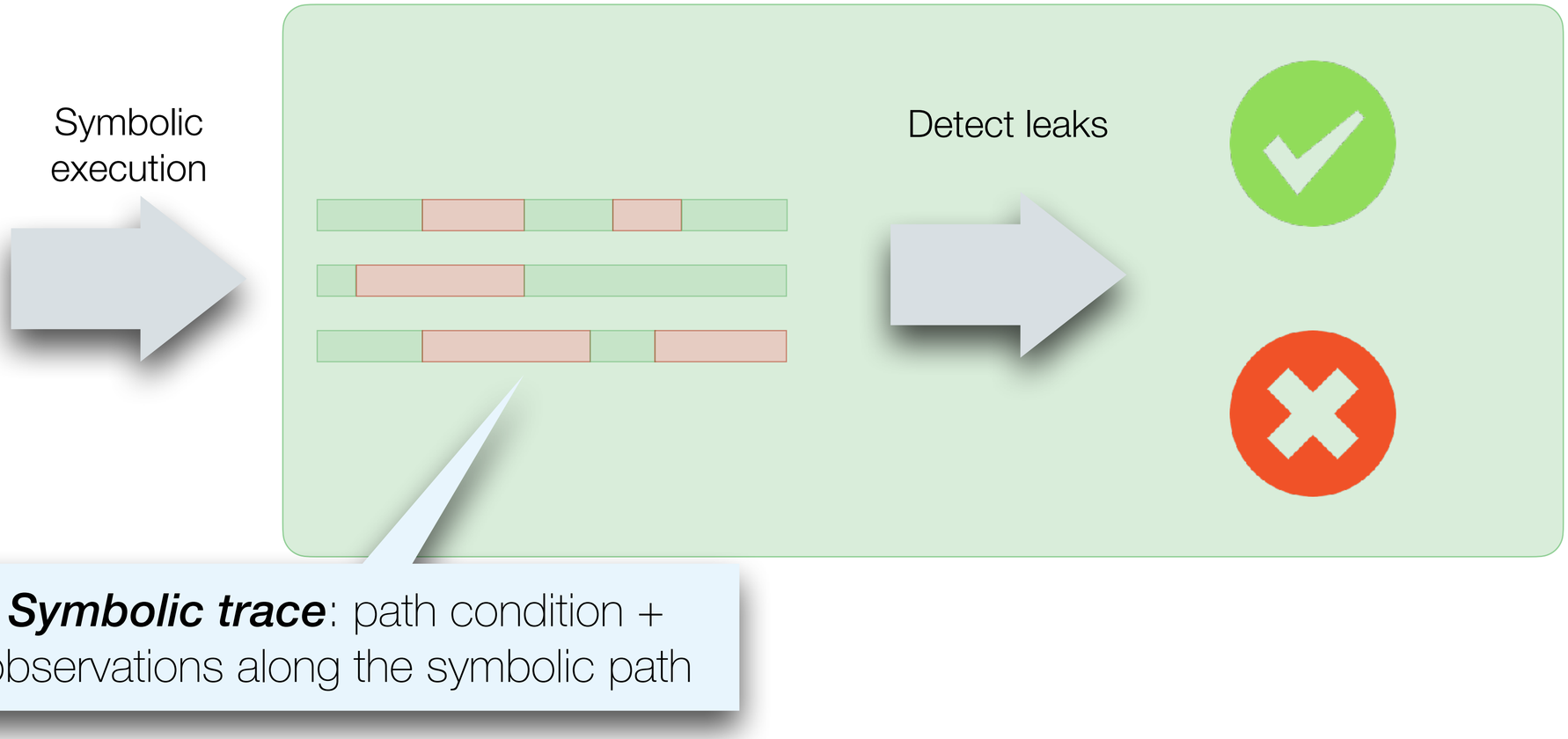


Detecting speculative leaks

```
        rax
        rcx
        jmp
L1:     loa
        loa
END:
```

For each symbolic trace $\tau \in traces(prg)$

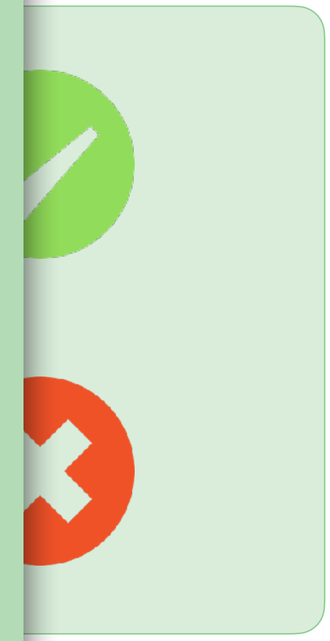
if $MemLeak(\tau)$ **then**

return *INSECURE*

if $CtrlLeak(\tau)$ **then**

return *INSECURE*

return *SECURE*



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        loa
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if $MemLeak(\tau)$ **then**

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if $CtrlLeak(\tau)$ **then**

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return *SECURE*

Memory leaks

Speculative memory accesses ***must*** depend only on

- Non-sensitive information
- Non-speculative observations

Memory leaks

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τ 

Memory leaks

Speculative memory accesses ***must*** depend only on

- Non-sensitive information
- Non-speculative observations

τ

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

Memory leaks

Speculative memory accesses ***must*** depend only on

- Non-sensitive information
- Non-speculative observations

Check with self-composition

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

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s_1

s_2

Memory leaks

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Equivalent wrt ***policy***

s_1

s_2

Memory leaks

Speculative memory accesses ***must*** depend only on

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Check with self-composition

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

Equivalent wrt ***policy***

$$s_1 \models \varphi$$

$$s_2 \models \varphi$$

Memory leaks

Speculative memory accesses ***must*** depend only on

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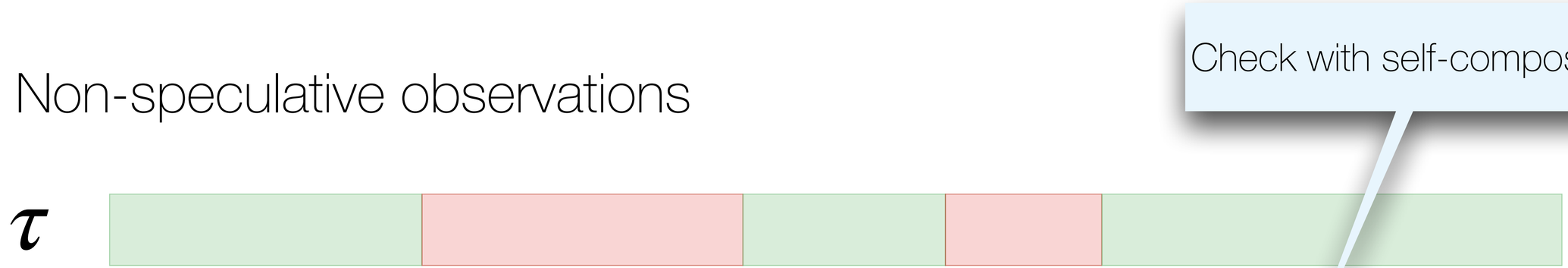

Memory leaks

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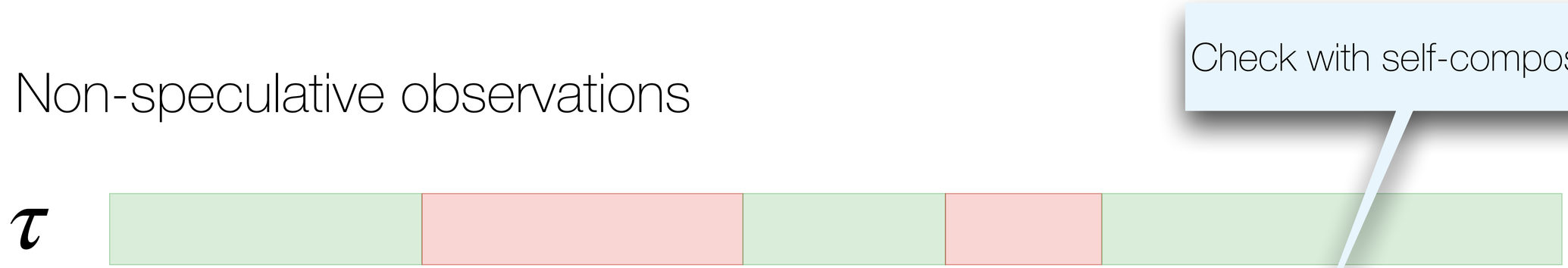

Memory leaks

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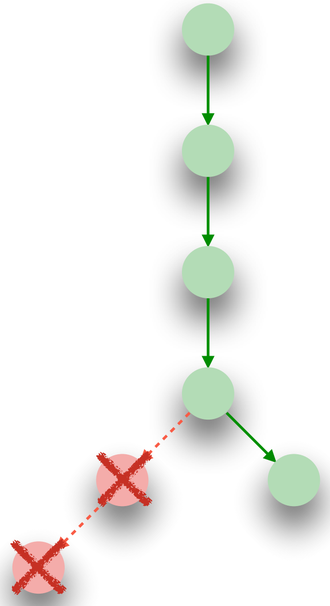
```



Policy

x, **A_size**, **A**, **B** are public

start pc *L1* load **A**+**x** load **B**+**A**[**x**] rollback	pc *END*

Memory leaks

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     rax <- A_size
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L1:  load rax, A + rcx
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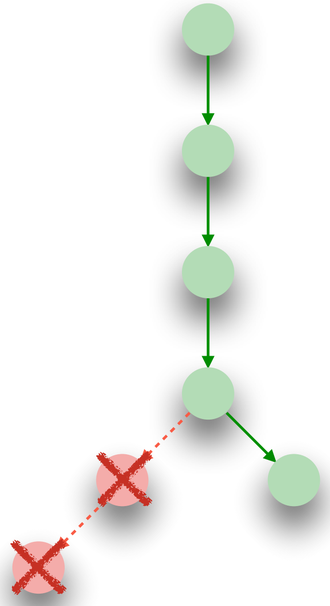

Policy

x, **A_size**, **A**, **B** are public

start	pc	L1	load	A+x	load	B+A[x]	rollback	pc	END

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

Memory leaks

```
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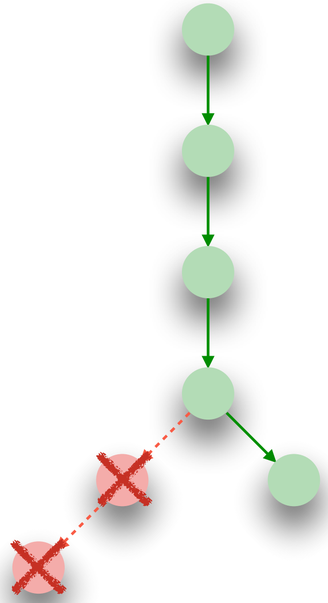

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s_1

s_2

Memory leaks

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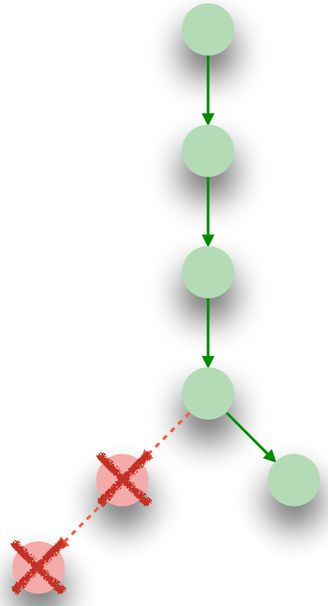

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s_1

s_2

$x_1{=}x_2 \wedge A\_size_1{=}A\_size_2 \wedge A_1{=}A_2 \wedge B_1{=}B_2$

Memory leaks

```
     rax <- A_size
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     jmp rcx≥rax, END
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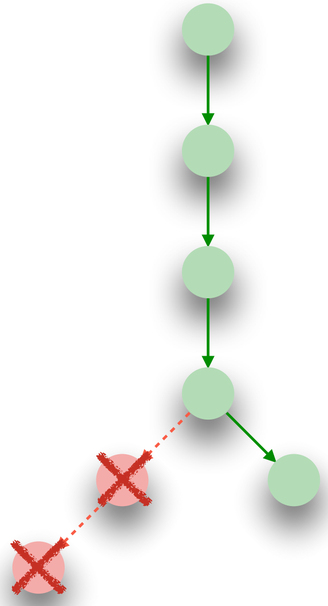
END:
```



Policy

x, **A_size**, **A**, **B** are public

start	pc	*L1*	load **A**+**x**	load **B**+**A**[**x**]	rollback	pc	*END*

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

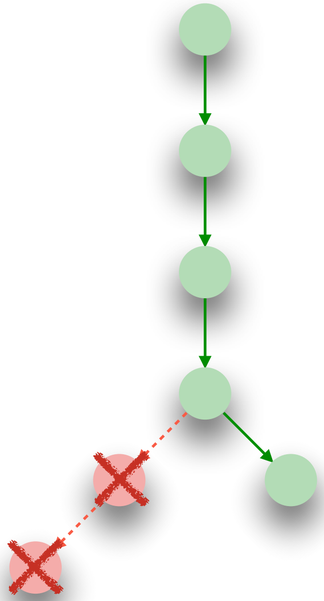
$s_1 \models$ $x_1 \geq A\_size_1$

$s_2 \models$ $x_2 \geq A\_size_2$

$x_1 = x_2 \wedge A\_size_1 = A\_size_2 \wedge A_1 = A_2 \wedge B_1 = B_2$

Memory leaks

```
     rax <- A_size
     rcx <- x
     jmp rcx≥rax, END
L1:  load rax, A + rcx
     load rax, B + rax
END:
```



Policy

x, **A_size**, **A**, **B** are public

```
start pc L1 load A+x load B+A[x] rollback pc END
```

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

$s_1 \models$ **$x_1 \geq A\_size_1$**

$s_2 \models$ **$x_2 \geq A\_size_2$**

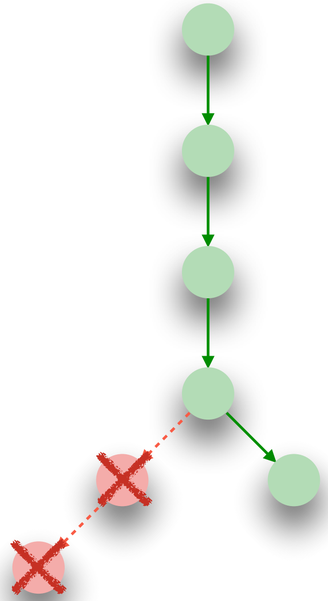
=

Always true!

$x_1 = x_2 \wedge A\_size_1 = A\_size_2 \wedge A_1 = A_2 \wedge B_1 = B_2$

Memory leaks

```
     rax <- A_size
     rcx <- x
     jmp rcx≥rax, END
L1:  load rax, A + rcx
     load rax, B + rax
END:
```



Policy

x, **A_size**, **A**, **B** are public

start	pc	*L1*	load **A**+**x**	load **B**+**A**[**x**]	rollback	pc	*END*

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

$s_1 \models$ $x_1 \geq A\_size_1$

$s_2 \models$ $x_2 \geq A\_size_2$

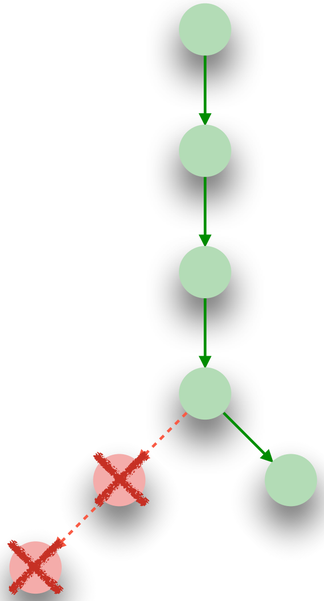
$\Vert$

$x_1 = x_2 \wedge A\_size_1 = A\_size_2 \wedge A_1 = A_2 \wedge B_1 = B_2$

Always true!

Memory leaks

```
      rax <- A_size
      rcx <- x
      jmp rcx≥rax, END
L1:   load rax, A + rcx
      load rax, B + rax
END:
```



Policy

x, **A_size**, **A**, **B** are public

```
start pc L1 load A+x load B+A[x] rollback pc END
```

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

$s_1 \models$ $x_1 \geq A\_size_1$

$s_2 \models$ $x_2 \geq A\_size_2$

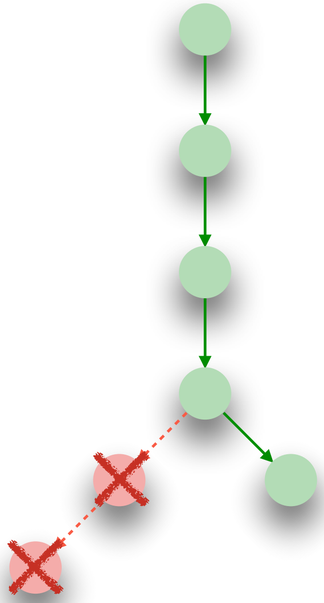
$A_1 + x_1$ ≠ $A_2 + x_2$

$x_1 = x_2 \wedge A\_size_1 = A\_size_2 \wedge A_1 = A_2 \wedge B_1 = B_2$

Always true!

Memory leaks

```
      rax <- A_size
      rcx <- x
      jmp rcx≥rax, END
L1:   load rax, A + rcx
      load rax, B + rax
END:
```



Policy

x, **A_size**, **A**, **B** are public

```
start pc L1 load A+x load B+A[x] rollback pc END
```

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

$s_1 \models$ $x_1 \geq A\_size_1$

$s_2 \models$ $x_2 \geq A\_size_2$

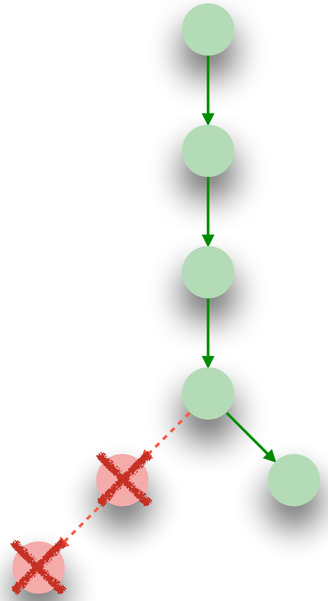
$x_1 = x_2 \wedge A\_size_1 = A\_size_2 \wedge A_1 = A_2 \wedge B_1 = B_2$

$A_1 + x_1$ ∦ $A_2 + x_2$

Always true!

Memory leaks

```
      rax <- A_size
      rcx <- x
      jmp rcx≥rax, END
L1:   load rax, A + rcx
      load rax, B + rax
END:
```



Policy
x, ***A_size***, **A**, **B**
are public

start	pc	*L1*	load	**A**+***x***	load	**B**+**A**[***x***]	rollback	pc	*END*

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

$s_1 \models$ $x_1 \geq A\_size_1$

$s_2 \models$ $x_2 \geq A\_size_2$

$x_1 = x_2 \wedge A\_size_1 = A\_size_2 \wedge A_1 = A_2 \wedge B_1 = B_2$

$\not\parallel$

$A_1 + x_1$ $\not\parallel$ $A_2 + x_2$

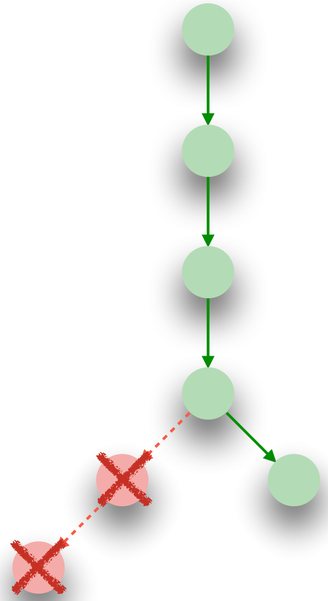
$\vee$

$B_1 + A_1[x_1]$ $\not\parallel$ $B_2 + A_2[x_2]$

Always true!

Memory leaks

```
     rax <- A_size
     rcx <- x
     jmp rcx≥rax, END
L1:  load rax, A + rcx
     load rax, B + rax
END:
```



Policy
x, ***A_size***, **A**, **B**
are public

`start pc L1 load A+x load B+A[x] rollback pc END`

$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

$s_1 \models$ $x_1 \geq A\_size_1$

$s_2 \models$ $x_2 \geq A\_size_2$

$x_1 = x_2 \wedge A\_size_1 = A\_size_2 \wedge A_1 = A_2 \wedge B_1 = B_2$

$\not\parallel$

$A_1 + x_1$ $\not\parallel$ $A_2 + x_2$ $\vee$ $B_1 + A_1[x_1]$ $\not\parallel$ $B_2 + A_2[x_2]$

Always true!

Spectector + Case studies

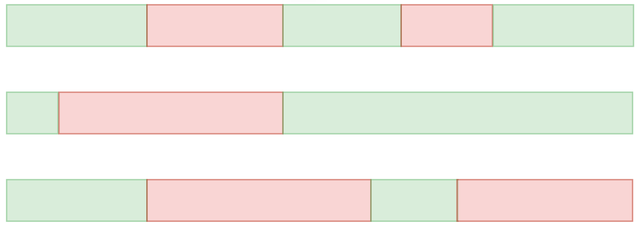
Spectector

```
    mov     rax, A_size
    mov     rcx, x
    cmp     rcx, rax
    jae     END
L1: mov     rax, A[rcx]
    mov     rax, B[rax]
```

x64 to μASM

```
        rax <- A_size
        rcx <- x
        jmp rcx≥rax, END
L1:     load rax, A + rcx
        load rax, B + rax
END:
```

Symbolic execution



Check for speculative leaks

Spectector

```
    mov     rax, A_size
    mov     rcx, x
    cmp     rcx, ra
    jae     END
L1: mov     rax, A[
    mov     rax, B[
```

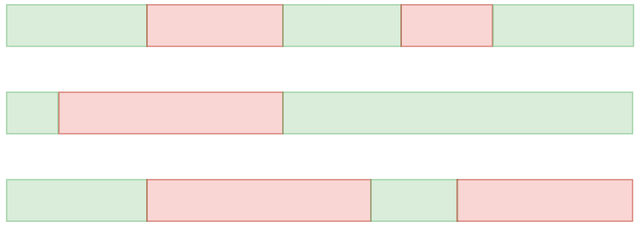
x64 to μASM

More details

- Built in Prolog
- **Z3** for symbolic execution and leak detection

```
rax <- A_size
rcx <- x
jmp rcx≥rax, END
load rax, A + rcx
load rax, B + rax
```

Symbolic execution



Check for speculative leaks

Case study: compiler mitigations

Target:

- 15 variants of Spectre V1 by Paul Kocher*
- Compiled with Microsoft Visual C++, Intel ICC, and Clang with different mitigations and optimization levels
- 240 assembly programs of up to 200 instructions each

How:

- Use Spectector to prove security or detect leaks

* Paul Kocher - Spectre Mitigations in Microsoft C/C++ Compiler — https://www.paulkocher.com/doc/MicrosoftCompilerSpectreMitigation.html

Results

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Ex.	VCC						ICC				CLANG					
	UNP		FEN 19.15		FEN 19.20		UNP		FEN		UNP		FEN		SLH	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Ex.	VCC						ICC				CLANG					
	UNP		FEN 19.15		FEN 19.20		UNP		FEN		UNP		FEN		SLH	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

No countermeasures

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Automated insertion of fences

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Speculative load hardening

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

Ex.	VCC						ICC				CLANG					
	UNP		FEN 19.15		FEN 19.20		UNP		FEN		UNP		FEN		SLH	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○												●	●	●
02	○	○												●	●	●
03	○	○												●	●	●
04	○	○												●	●	●
05	○	○												●	●	●
06	○	○												●	●	●
07	○	○												●	●	●
08	○	●												●	●	●
09	○	○												●	●	●
10	○	○												●	●	○
11	○	○												●	●	●
12	○	○												●	●	●
13	○	○												●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Summary

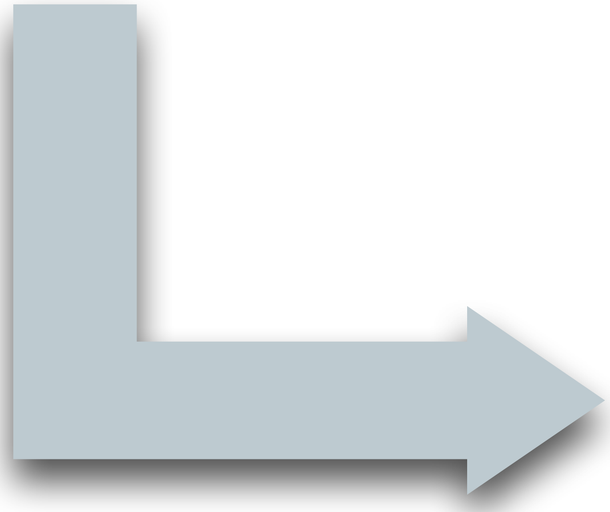
- Leaks in all unprotected programs (except example #08 with optimizations)
- Confirm all vulnerabilities in VCC pointed out by Paul Kocher
- Programs with fences (ICC and Clang) are secure
  - Unnecessary fences
- Programs with SLH are secure except #10 and #15

Example #01 - SLH

```
if (x < A_size)
   y = B[A[x]*512]
```

Example #01 - SLH

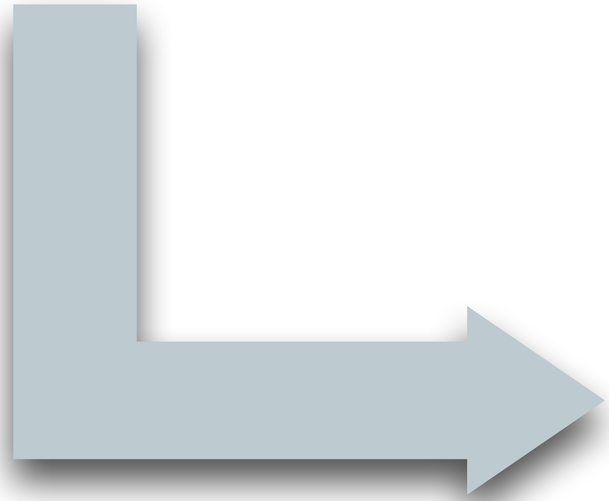
```
if (x < A_size)
   y = B[A[x]*512]
```



```
mov     rax, A_size
mov     rcx, x
mov     rdx, 0
cmp     rcx, rax
jae     END
cmovae  -1, rdx
mov     rax, A[rcx]
shl     rax, 9
or      rax, rdx
mov     rax, B[rax]
```

Example #01 - SLH

```
if (x < A_size)
   y = B[A[x]*512]
```



`rax` is -1 whenever ***x*** ≥ ***A_size***
We can prove security

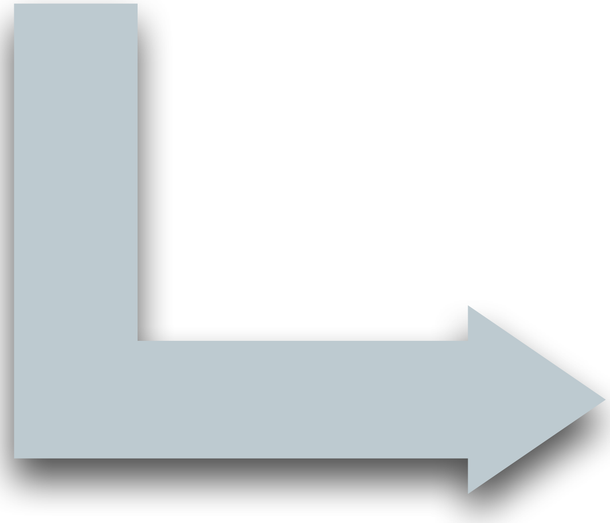
```
mov     rax, A_size
mov     rcx, x
mov     rdx, 0
cmp     rcx, rax
jae     END
cmovae  -1, rdx
mov     rax, A[rcx]
shl     rax, 9
or      rax, rdx
mov     rax, B[rax]
```

Example #10 - SLH

```
if (x < A_size)
   if (A[x]==k)
      y = B[0]
```

Example #10 - SLH

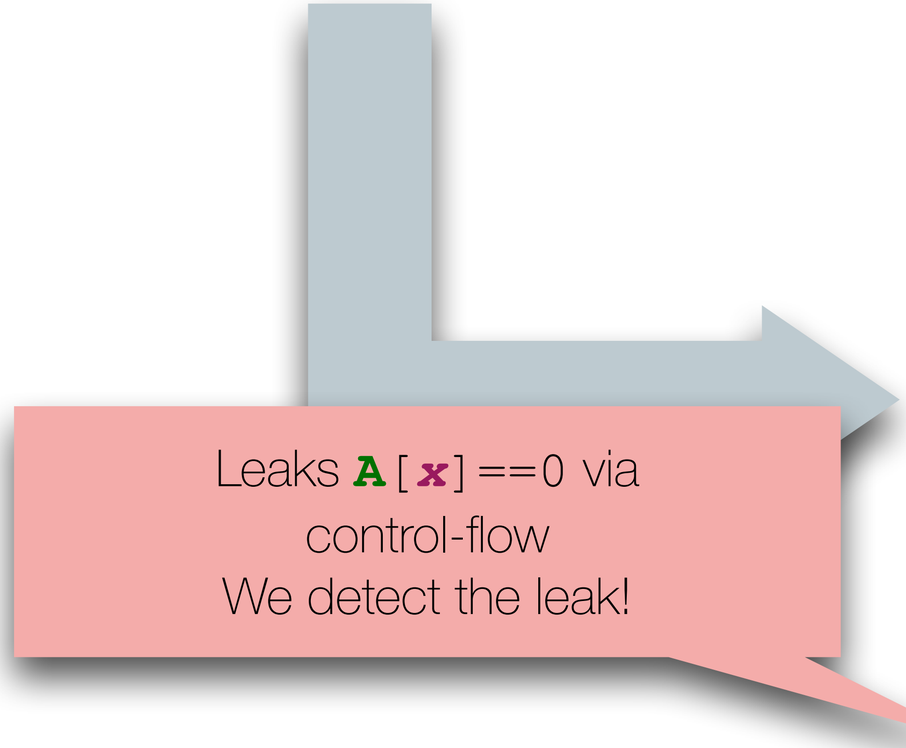
```
if (x < A_size)
   if (A[x]==k)
      y = B[0]
```



```
mov     rax, A_size
mov     rcx, x
mov     rdx, 0
cmp     rcx, rax
jae     END
cmovae  -1, rdx
mov     rax, A[rcx]
jne     rax, END
cmovne  -1, rdx
mov     rax, [B]
```

Example #10 - SLH

```
if (x < A_size)
   if (A[x]==k)
      y = B[0]
```



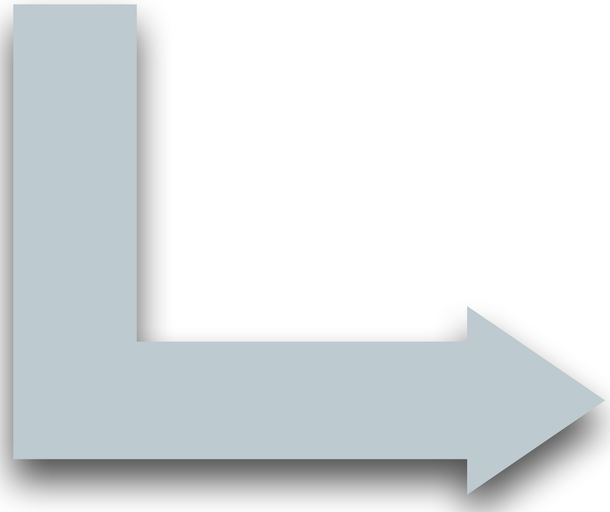

```
mov     rax, A_size
mov     rcx, x
mov     rdx, 0
cmp     rcx, rax
jae     END
cmovae  -1, rdx
mov     rax, A[rcx]
jne     rax, END
cmovne  -1, rdx
mov     rax, [B]
```

Example #08 - FEN

```
y = B[A[x<A_size?(x+1):0]*512]
```

Example #08 - FEN

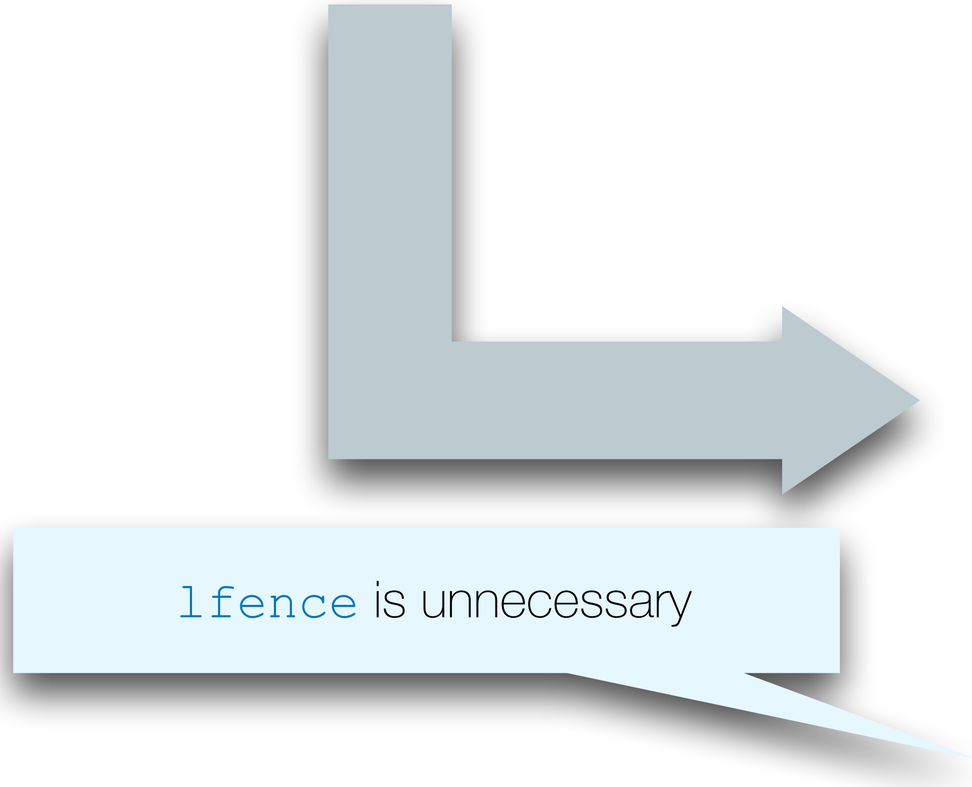
```
y = B[A[x<A_size?(x+1):0]*512]
```



```
mov     rax, A_size
mov     rcx, x
lea     rcx, [rcx+1]
xor     rdx,rdx
cmp     rcx, rax
cmovae  rdx, rcx
mov     rax, A[rdx]
shl     rax, 9
lfence
mov     rax, B[rax]
```

Example #08 - FEN

```
y = B[A[x<A_size?(x+1):0]*512]
```




```
mov     rax, A_size
mov     rcx, x
lea     rcx, [rcx+1]
xor     rdx,rdx
cmp     rcx, rax
cmovae  rdx, rcx
mov     rax, A[rdx]
shl     rax, 9
lfence
mov     rax, B[rax]
```

Conclusion

Speculative non-interference

Formally!

Program **P** is **speculatively non-interferent** for prediction oracle ***O*** if

For all program states ***s*** and ***s′***:

$$\mathbf{P}_{\text{non-spec}}(s) = \mathbf{P}_{\text{non-spec}}(s') \Rightarrow \mathbf{P}_{\text{spec}}(s,O) = \mathbf{P}_{\text{spec}}(s',O)$$

Spectector

```
    mov     rax, A_size
    mov     rcx, x
    cmp     rcx, rax
    jae     END
L1: mov     rax, A[rcx]
    mov     rax, B[rax]
```

x64 to μASM

```
    rax <- A_size
    rcx <- x
    jmp rcx≥rax, END
L1: load rax, A + rcx
    load rax, B + rax
END:
```

Symbolic execution

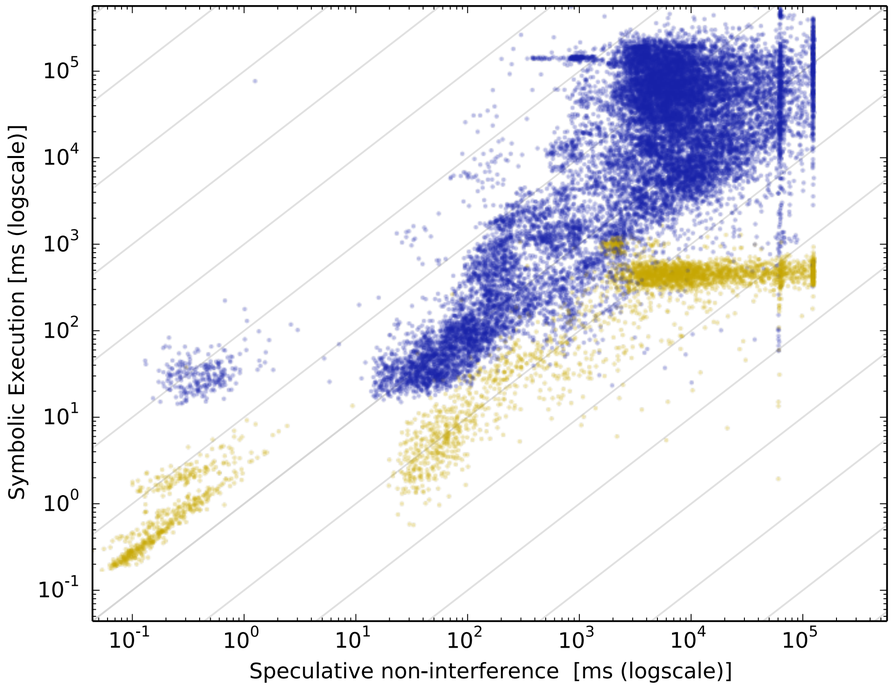
Check for speculative leaks

Results

Ex.	Vcc						Icc				Clang					
	Unp		Fen 19.15		Fen 19.20		Unp		Fen		Unp		Fen		Slh	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	●	●	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Results

- SNI 10x-100x faster
  - 20.2% traces
- SNI ≤10x faster
  - 41.9% traces
- SNI ≤10x slower
  - 26.9% traces
- SNI 10x-100x slower
  - 7.9% traces



Speculative non-interference

Formally!

Program **P** is **speculatively non-interferent** for prediction oracle ***O*** if

For all
Pnon

Spectector

```
mov     rax, A_size
mov     rcx, x
cmp     rcx, rax
jae     END
L1: mov rax, A[rcx]
```

x64 to μASM

```
rax <- A_size
rcx <- x
jmp rcx≥rax, END
L1: load rax, A + rcx
load rax, B + rax
END:
```

Symbolic execution

Spectector

https://spectector.github.io

@ marco.guarnieri@imdea.org

@MarcoGuarnier1

Results

Ex.	Vcc															
	Unp		Fen 19.15													
	-O0	-O2	-O0	-O2												
01	○	○	●	●												
02	○	○	●	●												
03	○	○	●	○												
04	○	○	○	○												
05	○	○	●	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	●	●	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○	●

- SNI ≤10x slower
  - 26.9% traces
- SNI 10x-100x slower
  - 7.9% traces