Spectector: Principled detection of speculative information flows

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"Information Flow Tracking across the Hardware-Software Boundary"

SPECTRE

Exploits **speculative execution** to leak sensitive information

Almost all modern processors are affected

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

Countermeasures

Long Term: Co-Design of Software and Hardware countermeasures

Short and Mid Term: Software countermeasures

In particular: Compiler-level countermeasures

- ✓ *Example*: insert “fences” to selectively terminate speculative execution
- ✓ Implemented in major compilers (Microsoft Visual C++, Intel ICC, Clang)

PROBLEM SOLVED ?

Compiler-level countermeasures

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

Paul Kocher
February 13, 2018

"The countermeasure [...] is conceptually straightforward but **challenging in practice**"

"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!

Goals

1. Introduce **semantic notion of security** against **speculative execution attacks**

2. Static analysis to **detect vulnerability** or to **prove security**

Outline

1. Speculative execution attacks
2. Speculative non-interference
3. Spectector: Detecting speculative leaks
4. Challenges

1. Speculative execution attacks

Background: Speculative execution

- Predict instructions' outcomes and speculatively continue execution
- Rollback changes if speculation was wrong

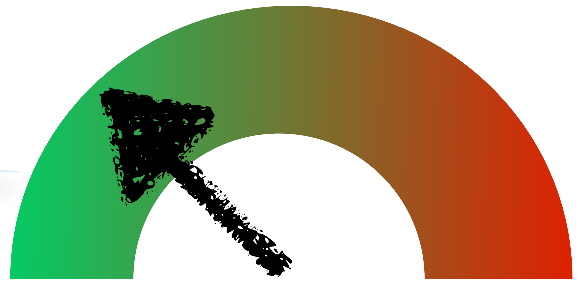
Only architectural (ISA, "logical") state,
not microarchitectural state

Background: Branch prediction

Size of array **A**

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

Predictions based on
branch history &
program structure



Spectre V1

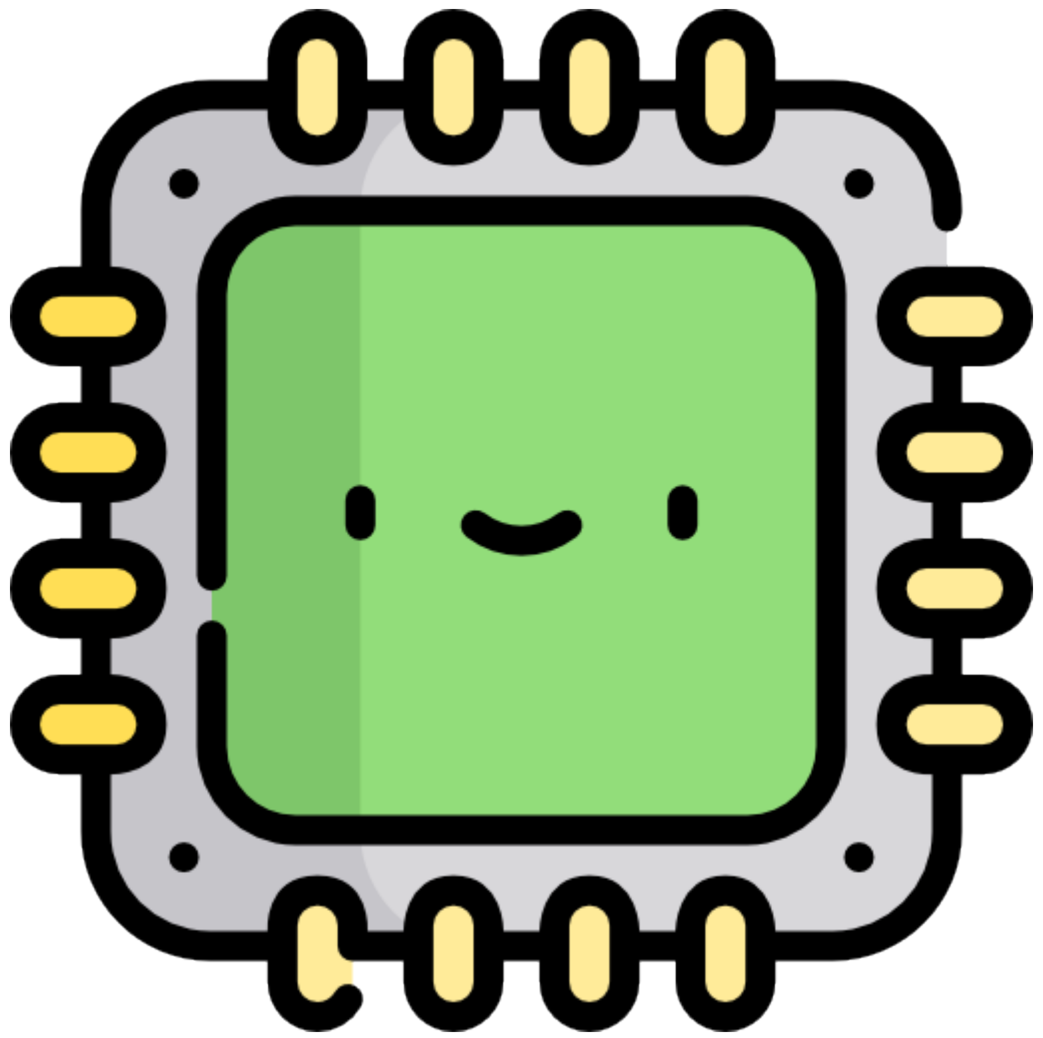
A_size=16

B | B[0] | B[1] | ...

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

What is in A[128]?

1a) Training



Cache state

Spectre V1

A_size=16

B | B[0] | B[1] | | B[A[128]] |

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

What is in A[128]?

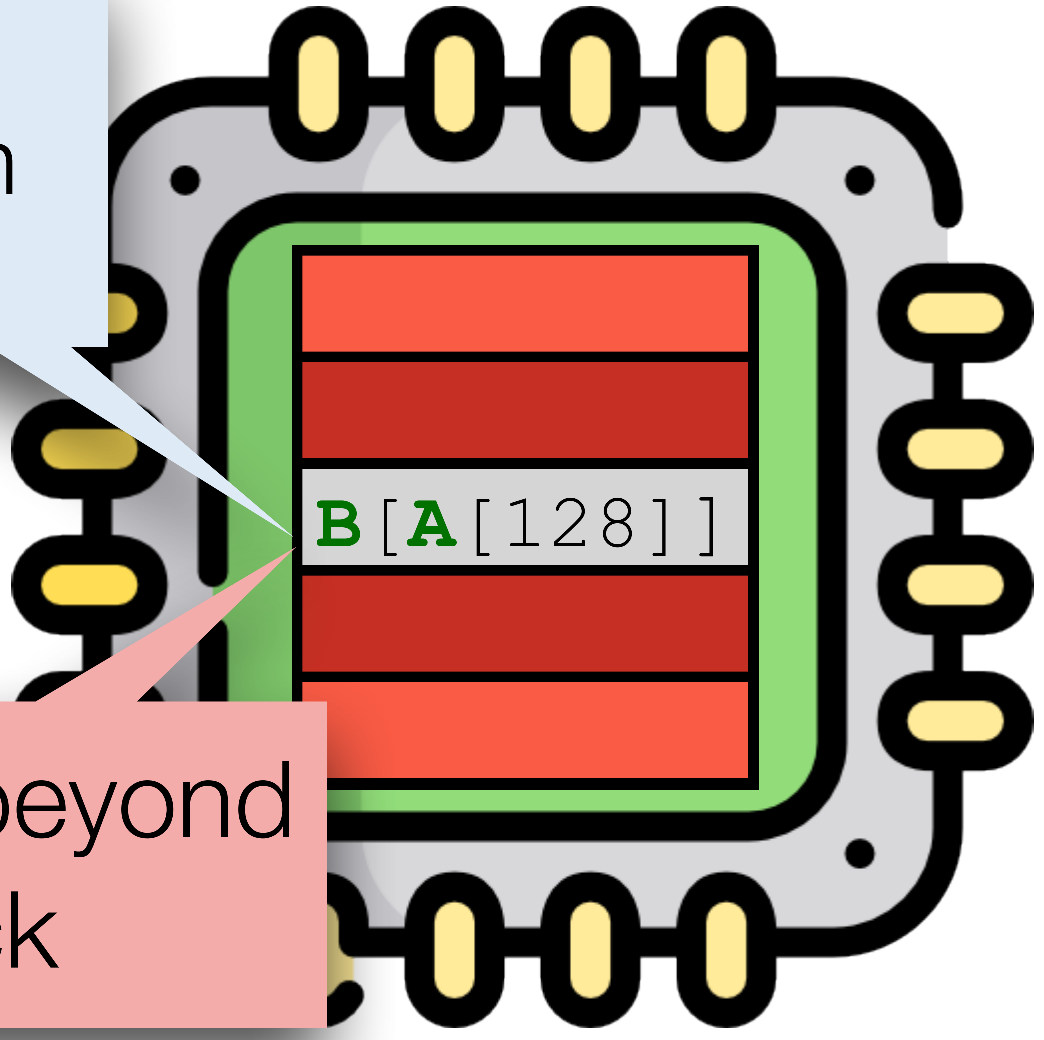
1a) Training f(0);f(1);f(2); ...

1b) Prepare cache

2) Run f(128)

3) Extract from cache

Address depends on A[128]

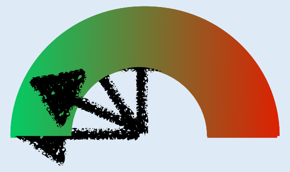


Persistent beyond rollback

Cache state

2. Speculative non-interference

Generalizing the Spectre V1 example

1a) Training  `f(0);f(1);f(2); …`

1b) Prepare cache

Attacker

Victim

2) Run `f` `(128)`

3) Extract from cache

Attacker

Generalizing the Spectre V1 example

1) Prepares microarchitectural state } Attacker

Victim { **2) Leaks information into microarchitectural state**

3) Extracts information from microarchitecture } Attacker

Speculative non-interference

Extended with policies

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

Informally:

Leakage of **P** in **non-speculative** execution	$\stackrel{?}{=}$	Leakage of **P** in **speculative** execution

More formally:

For all program states s and s':

$$P_{\texttt{non-spec}}(s) = P_{\texttt{non-spec}}(s')$$
$$\Rightarrow \quad P_{\texttt{spec}}(s) = P_{\texttt{spec}}(s')$$

How to capture leakage into microarchitectural state?

Non-speculative semantics

Speculative semantics

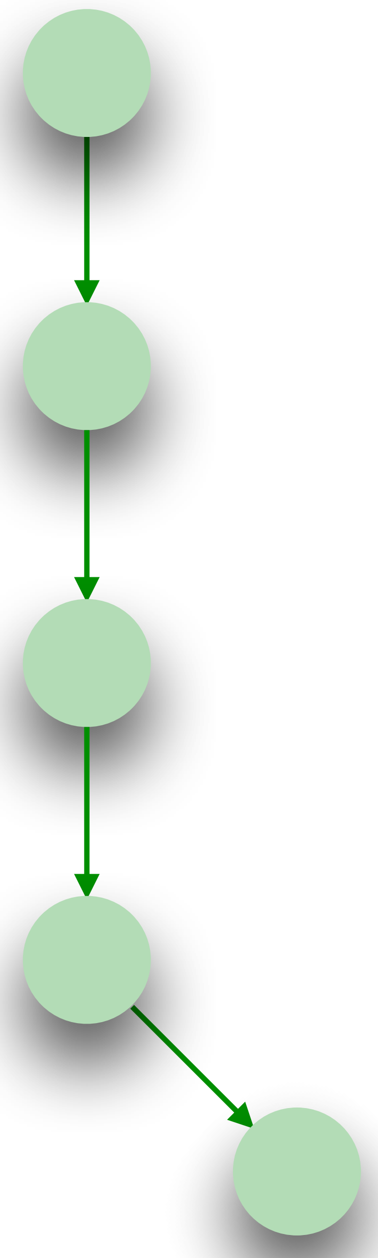
+

Attacker/Observer model

µAssembly + Non-speculative semantics

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

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



Non-speculative semantics: Inference Rules

Expression evaluation

$[\![n]\!](a) = n \qquad [\![x]\!](a) = a(x) \qquad [\![\ominus e]\!](a) = \ominus [\![e]\!](a) \qquad [\![e_1 \otimes e_2]\!](a) = [\![e_1]\!](a) \otimes [\![e_2]\!](a)$

Instruction evaluation

$$\textsc{Skip}\quad \frac{p(a(\mathbf{pc})) = \mathbf{skip}}{\langle m, a\rangle \to \langle m, a[\mathbf{pc} \mapsto a(\mathbf{pc})+1]\rangle}$$

$$\textsc{Barrier}\quad \frac{p(a(\mathbf{pc})) = \mathbf{spbarr}}{\langle m, a\rangle \to \langle m, a[\mathbf{pc} \mapsto a(\mathbf{pc})+1]\rangle}$$

$$\textsc{Assign}\quad \frac{p(a(\mathbf{pc})) = x \leftarrow e \qquad x \neq \mathbf{pc}}{\langle m, a\rangle \to \langle m, a[\mathbf{pc} \mapsto a(\mathbf{pc})+1, x \mapsto [\![e]\!](a)]\rangle}$$

$$\textsc{ConditionalUpdate-Sat}\quad \frac{p(a(\mathbf{pc})) = x \xleftarrow{e'} e \qquad [\![e']\!](a) = 0 \qquad x \neq \mathbf{pc}}{\langle m, a\rangle \to \langle m, a[\mathbf{pc} \mapsto a(\mathbf{pc})+1, x \mapsto [\![e]\!](a)]\rangle}$$

$$\textsc{ConditionalUpdate-Unsat}\quad \frac{p(a(\mathbf{pc})) = x \xleftarrow{e'} e \qquad [\![e']\!](a) \neq 0 \qquad x \neq \mathbf{pc}}{\langle m, a\rangle \to \langle m, a[\mathbf{pc} \mapsto a(\mathbf{pc})+1]\rangle}$$

$$\textsc{Terminate}\quad \frac{p(a(\mathbf{pc})) = \bot}{\langle m, a\rangle \to \langle m, a[\mathbf{pc} \mapsto \bot]\rangle}$$

$$\textsc{Load}\quad \frac{p(a(\mathbf{pc})) = \mathbf{load}\ x, e \qquad x \neq \mathbf{pc} \qquad n = [\![e]\!](a)}{\langle m, a\rangle \xrightarrow{\texttt{load}\ n} \langle m, a[\mathbf{pc} \mapsto a(\mathbf{pc})+1, x \mapsto m(n)]\rangle}$$

$$\textsc{Store}\quad \frac{p(a(\mathbf{pc})) = \mathbf{store}\ x, e \qquad n = [\![e]\!](a)}{\langle m, a\rangle \xrightarrow{\texttt{store}\ n} \langle m[n \mapsto a(x)], a[\mathbf{pc} \mapsto a(\mathbf{pc})+1]\rangle}$$

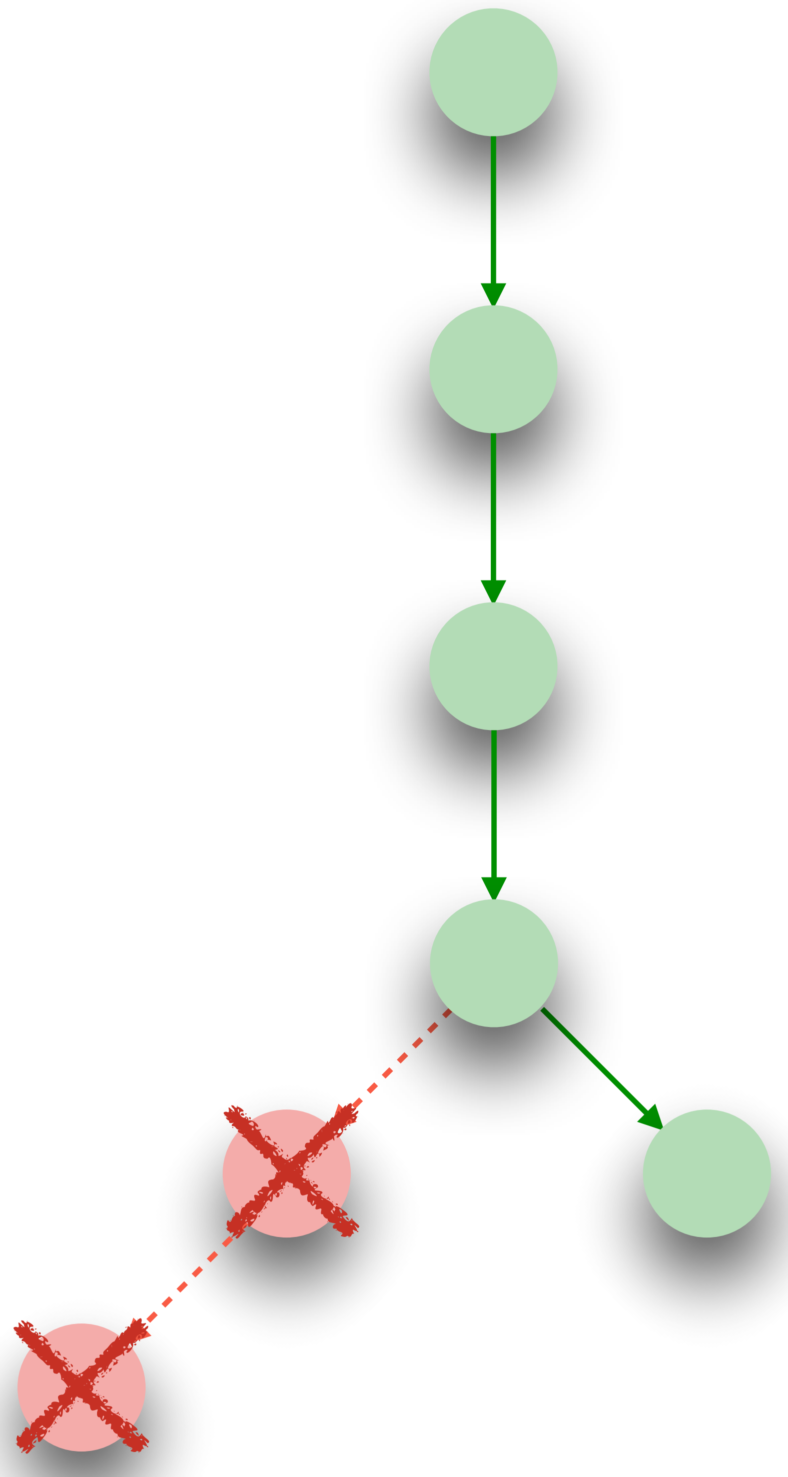
$$\textsc{Beqz-Sat}\quad \frac{p(a(\mathbf{pc})) = \mathbf{beqz}\ x, \ell \qquad a(x) = 0}{\langle m, a\rangle \xrightarrow{\texttt{pc}\ \ell} \langle m, a[\mathbf{pc} \mapsto \ell]\rangle}$$

$$\textsc{Beqz-Unsat}\quad \frac{p(a(\mathbf{pc})) = \mathbf{beqz}\ x, \ell \qquad a(x) \neq 0}{\langle m, a\rangle \xrightarrow{\texttt{pc}\ a(\mathbf{pc})+1} \langle m, a[\mathbf{pc} \mapsto a(\mathbf{pc})+1]\rangle}$$

$$\textsc{Jmp}\quad \frac{p(a(\mathbf{pc})) = \mathbf{jmp}\ e \qquad \ell = [\![e]\!](a)}{\langle m, a\rangle \xrightarrow{\texttt{pc}\ \ell} \langle m, a[\mathbf{pc} \mapsto \ell]\rangle}$$

Speculative semantics

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



Starts **speculative transactions** upon branches

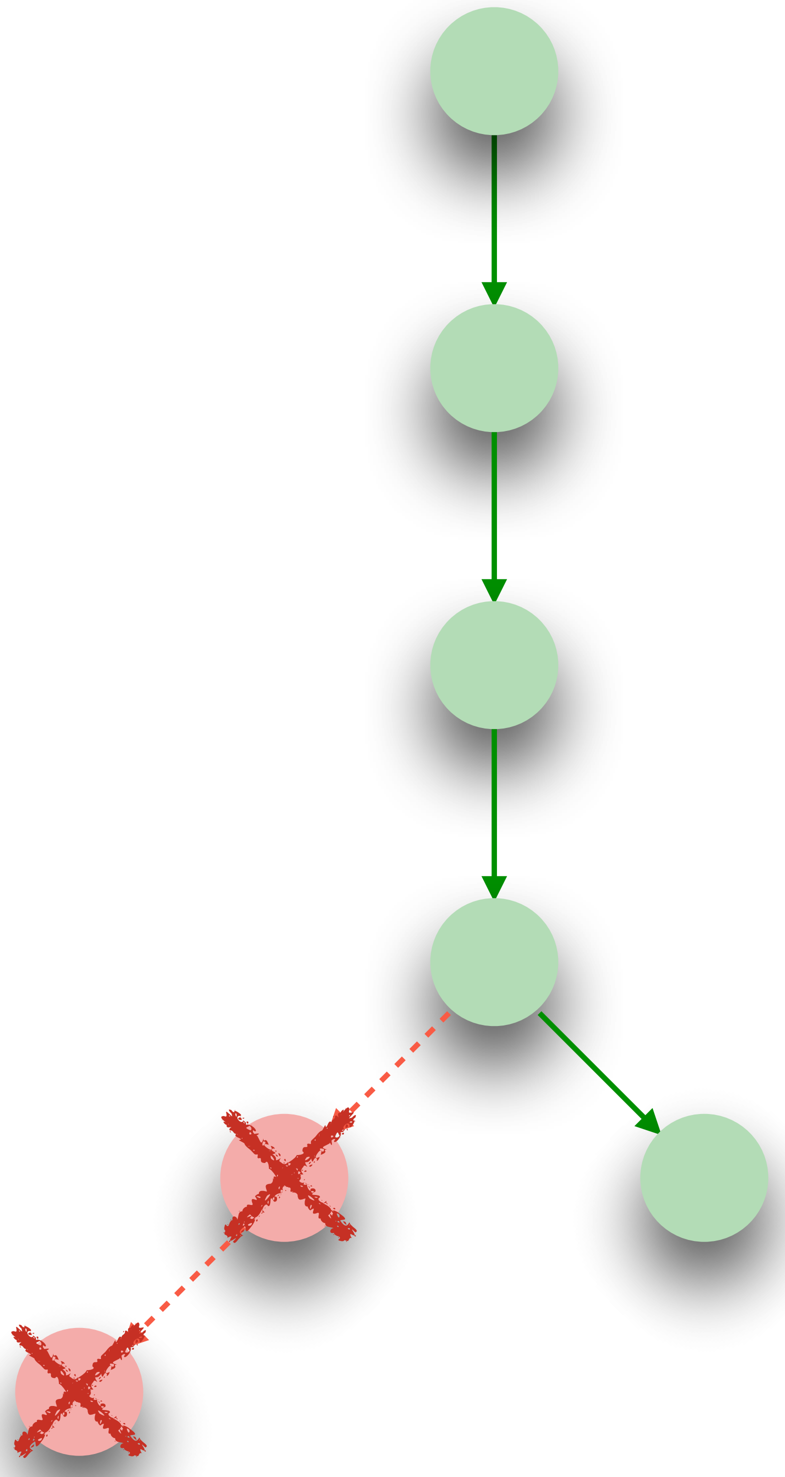
Committed upon correct speculation

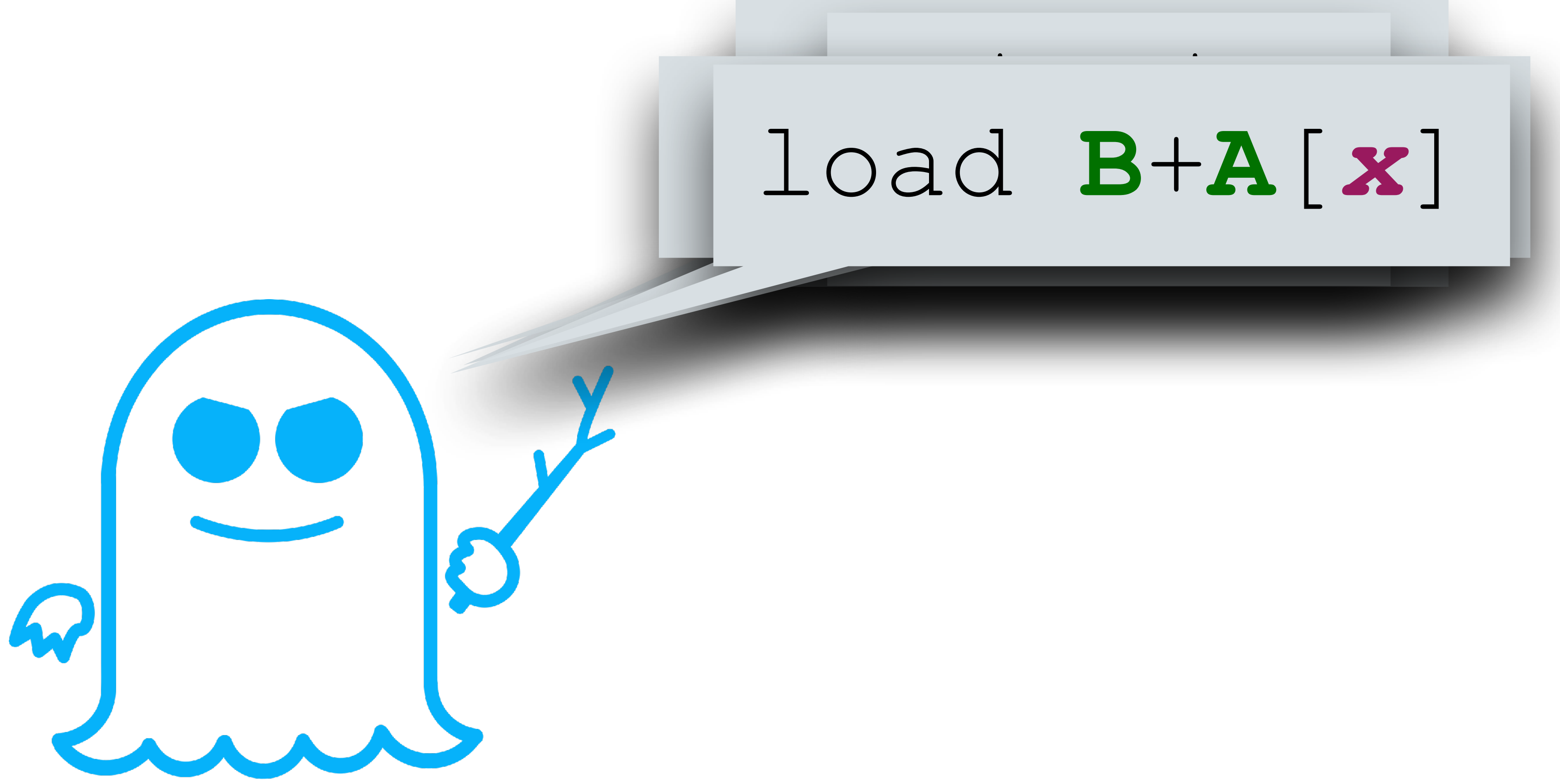
Rolled back upon misspeculation

Prediction Oracle O determines branch prediction + length of speculative window

Observer model: Leakage into μarchitectural state

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





Attacker can observe:

- locations of ***memory accesses***
- ***branch/jump*** targets
- ***start/end*** speculative execution

Inspired by "constant-time" programming requirements

No need for detailed model of memory hierarchy:

- possibly pessimistic
- more robust

Reasoning about arbitrary prediction oracles

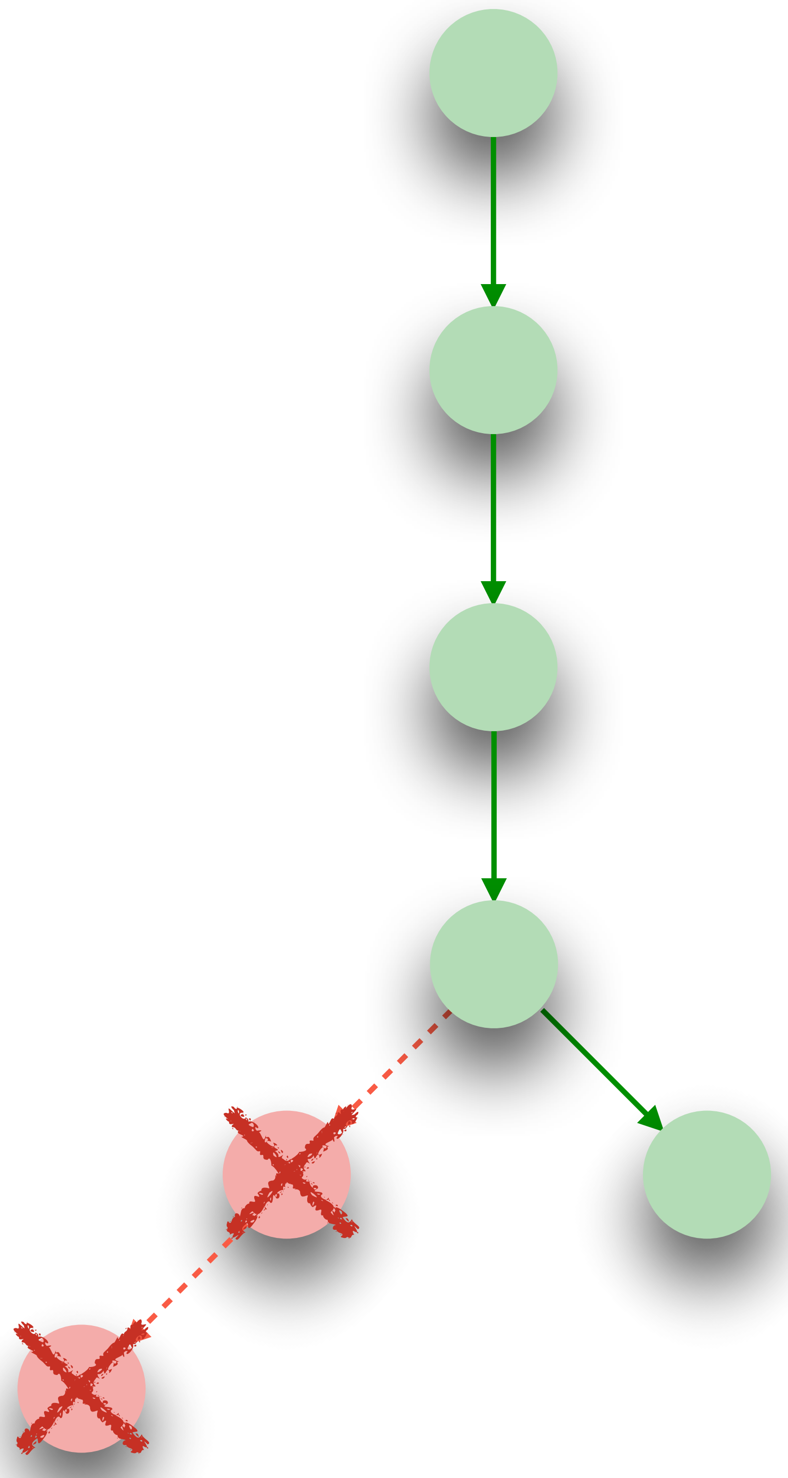
Speculative semantics
+
Prediction oracle

→

Always-mispredict speculative semantics

Always-mispredict speculative semantics

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



Always mispredict branch instructions' outcomes

Fixed speculative window

Rollback of every transaction

Always-mispredict speculative semantics: Inference Rules

SE-NoBranch

$$\frac{p(\sigma(\mathbf{pc})) \neq \mathbf{beqz}\ x, \ell \qquad \sigma \xrightarrow{\tau}_s \sigma' \qquad \mathit{enabled}'(s) \qquad s' = \begin{cases} \mathit{decr}'(s) & \text{if } p(\sigma(\mathbf{pc})) \neq \mathbf{spbarr} \\ \mathit{zeroes}'(s) & \text{otherwise} \end{cases}}{\langle \mathit{ctr}, \sigma, s \rangle \xRightarrow{\tau}_s \langle \mathit{ctr}, \sigma', s' \rangle}$$

SE-Branch-Symb

$$\frac{p(\sigma(\mathbf{pc})) = \mathbf{beqz}\ x, \ell'' \qquad \mathit{enabled}'(s) \qquad \sigma \xrightarrow{\mathtt{symPc}(se)\cdot\mathtt{pc}\ \ell'}_s \sigma' \qquad \ell = \begin{cases} \sigma(\mathbf{pc}) + 1 & \text{if } \ell' \neq \sigma(\mathbf{pc}) + 1 \\ \ell'' & \text{if } \ell' = \sigma(\mathbf{pc}) + 1 \end{cases} \qquad s' = s \cdot \langle \sigma, \mathit{ctr}, \mathit{min}(w, \mathit{wndw}(s) - 1), \ell \rangle \qquad \mathit{id} = \mathit{ctr}}{\langle \mathit{ctr}, \sigma, s \rangle \xRightarrow{\mathtt{symPc}(se)\cdot\mathtt{start}\ \mathit{id}\cdot\mathtt{pc}\ \ell}_s \langle \mathit{ctr} + 1, \sigma[\mathbf{pc} \mapsto \ell], s' \rangle}$$

SE-Rollback

$$\frac{\sigma' \xrightarrow{\tau}_s \sigma''}{\langle \mathit{ctr}, \sigma, s \cdot \langle \sigma', \mathit{id}, 0, \ell \rangle \rangle \xRightarrow{\mathtt{rollback}\ \mathit{id}\cdot\mathtt{pc}\ \sigma''(\mathbf{pc})}_s \langle \mathit{ctr}, \sigma'', s \rangle}$$

Always-mispredict leaks maximally

Speculative semantics
+
Prediction oracle

→

Always-mispredict speculative semantics

For all program states s and s':

$$P_{spec}(s) = P_{spec}(s')$$

$$\Leftrightarrow \quad \forall O:\ P_{spec,O}(s) = P_{spec,O}(s')$$

Recap: Speculative non-interference

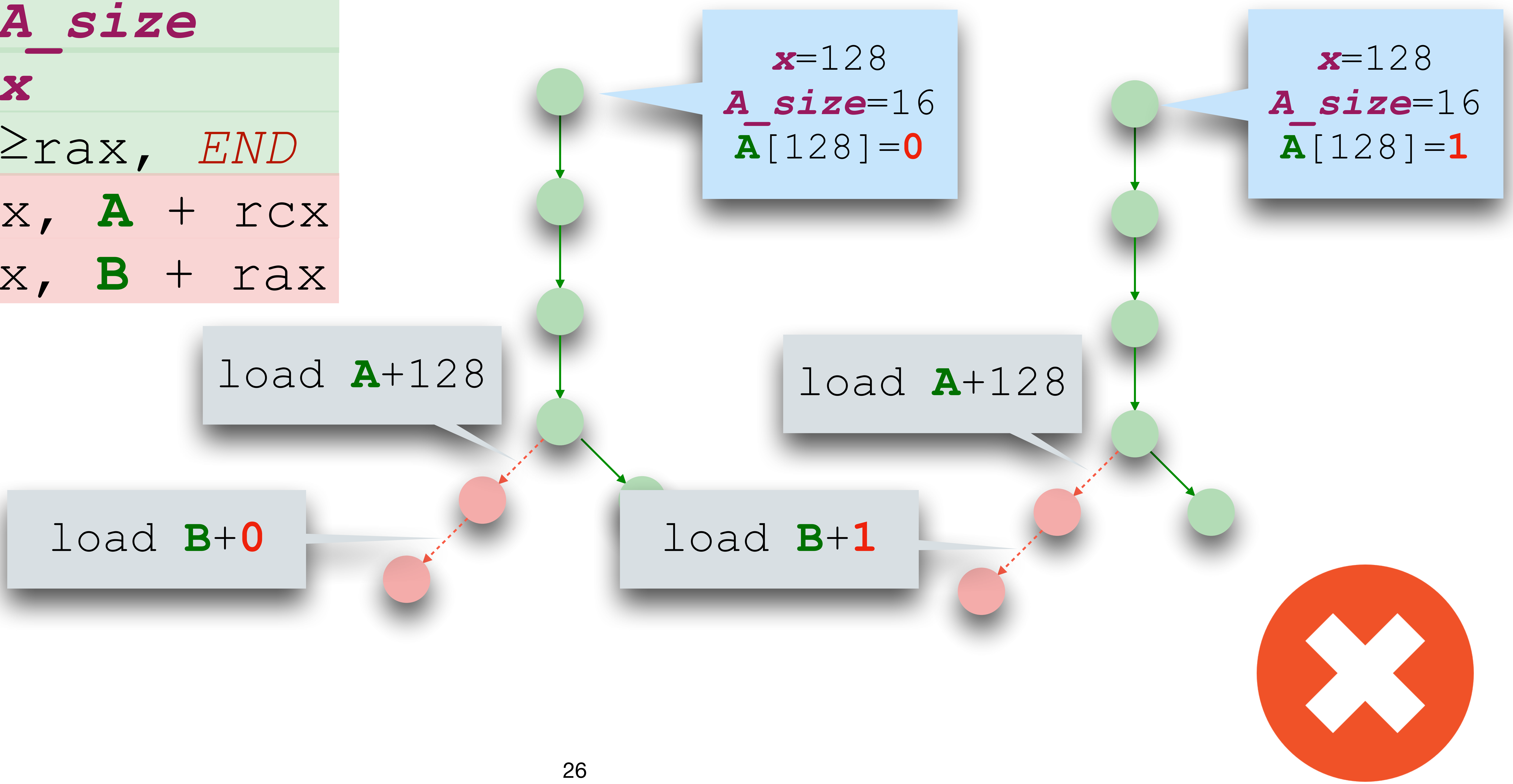
Program $\mathtt{P}$ is **speculatively non-interferent** if

For all program states $\mathtt{s}$ and $\mathtt{s'}$:

$$\mathtt{P}_{\mathtt{non\text{-}spec}}(\mathtt{s}) = \mathtt{P}_{\mathtt{non\text{-}spec}}(\mathtt{s'})$$
$$\Rightarrow \quad \mathtt{P}_{\mathtt{spec}}(\mathtt{s}) = \mathtt{P}_{\mathtt{spec}}(\mathtt{s'})$$

Speculative non-interference: Example

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

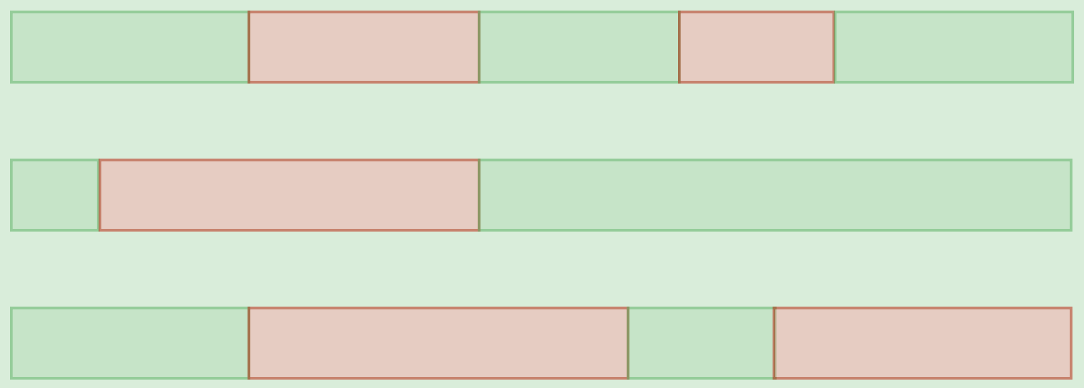


3. Spectector: Detecting speculative leaks

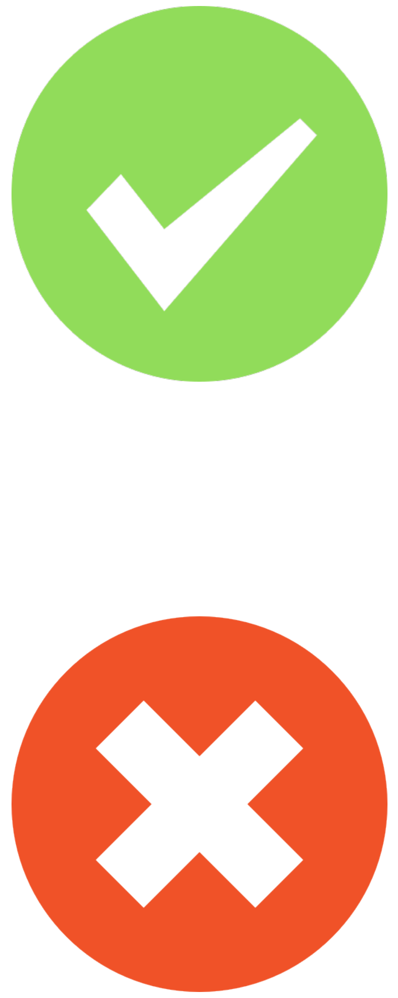
Spectector: Detecting speculative leaks

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

Symbolic execution

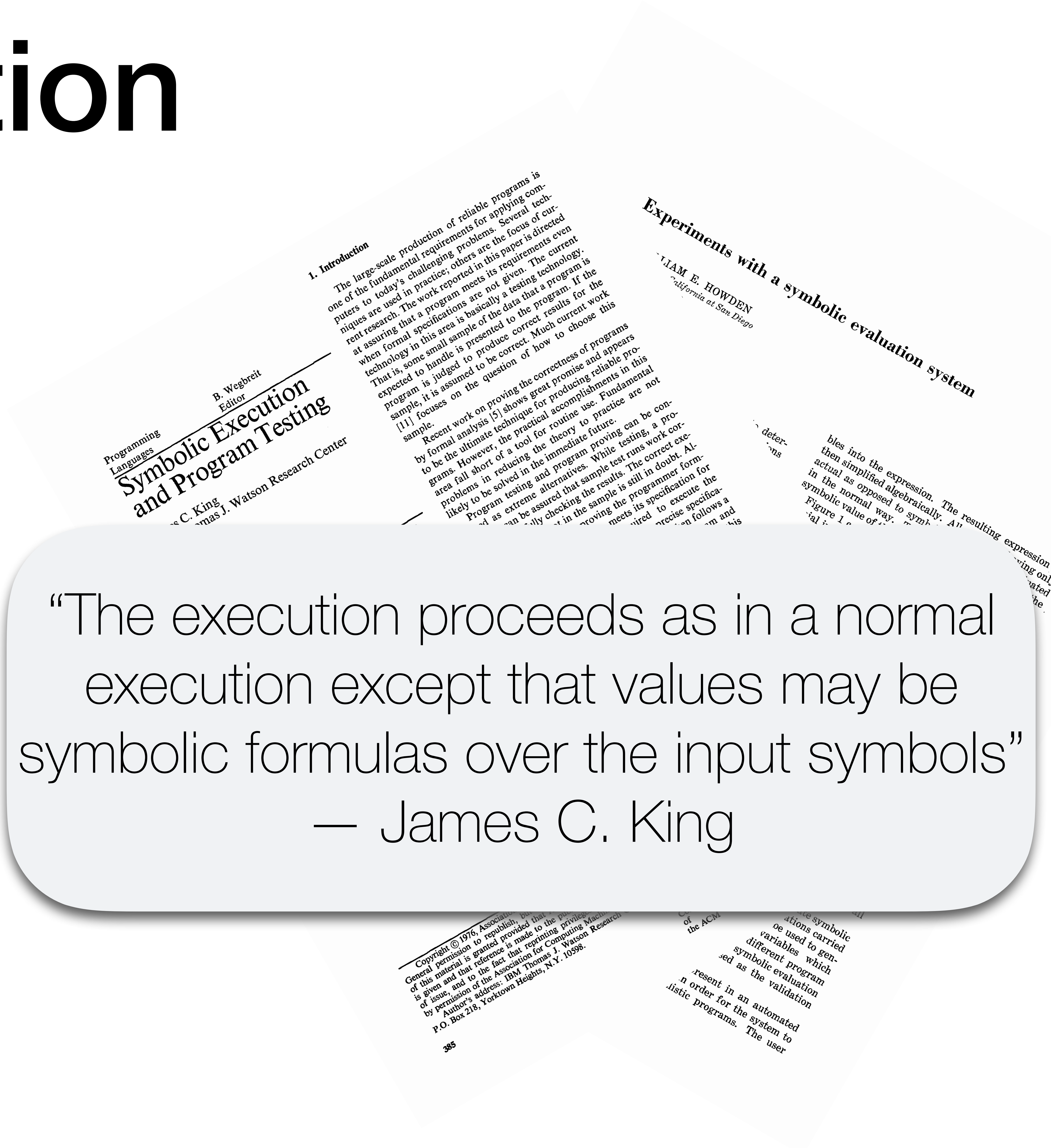


Detect leaks



Symbolic execution

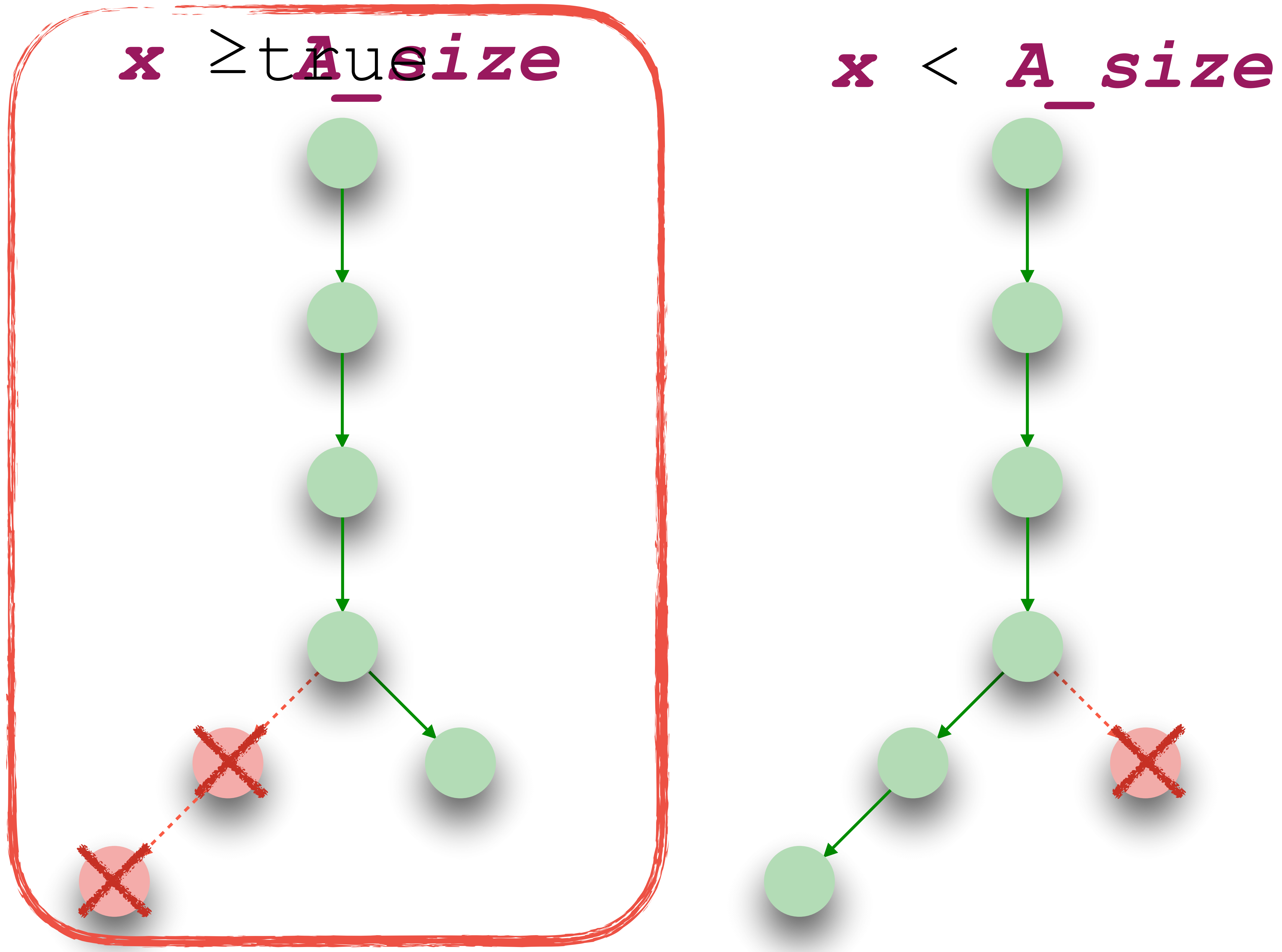
- Program analysis technique
- Execute programs over symbolic values
  - Explore all paths, each with its own path constraint
  - Each path represents all possible executions satisfying the constraints
  - Branch and jump instructions: fork paths and update path constraint



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

Symbolic execution

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



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

Detecting speculative leaks

```
     rax <- A_s
     rcx <- x
     jmp rcx≥ra
L1:  load rax,
     load rax,
END:
```

For each $\tau \in$ **sym-traces**(P)

  if $\mathit{MemLeak}(\tau)$ **then**

    return $\mathit{INSECURE}$

  if $\mathit{CtrlLeak}(\tau)$ **then**

    return $\mathit{INSECURE}$

return SECURE

Memory leaks

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

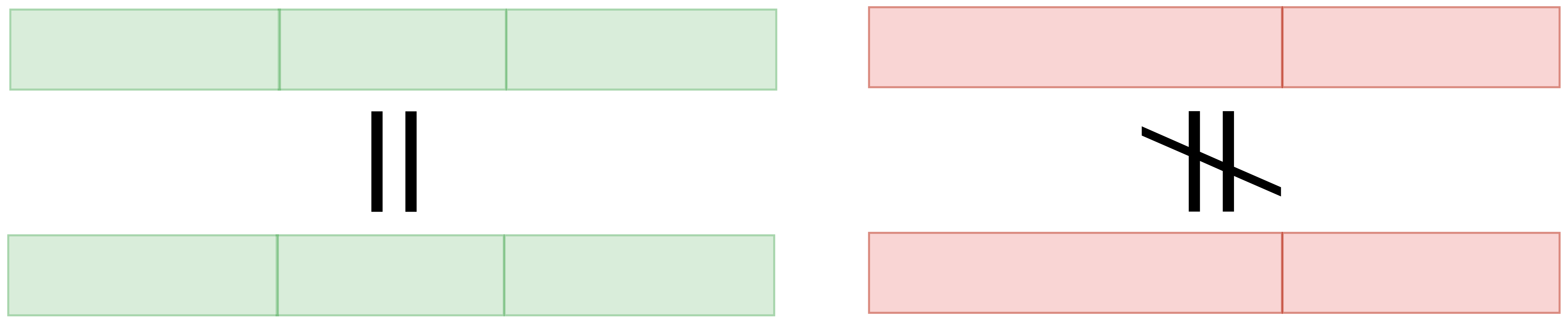
- Non-sensitive information (determined by policy), *or*
- be determined by non-speculative observations

τ

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

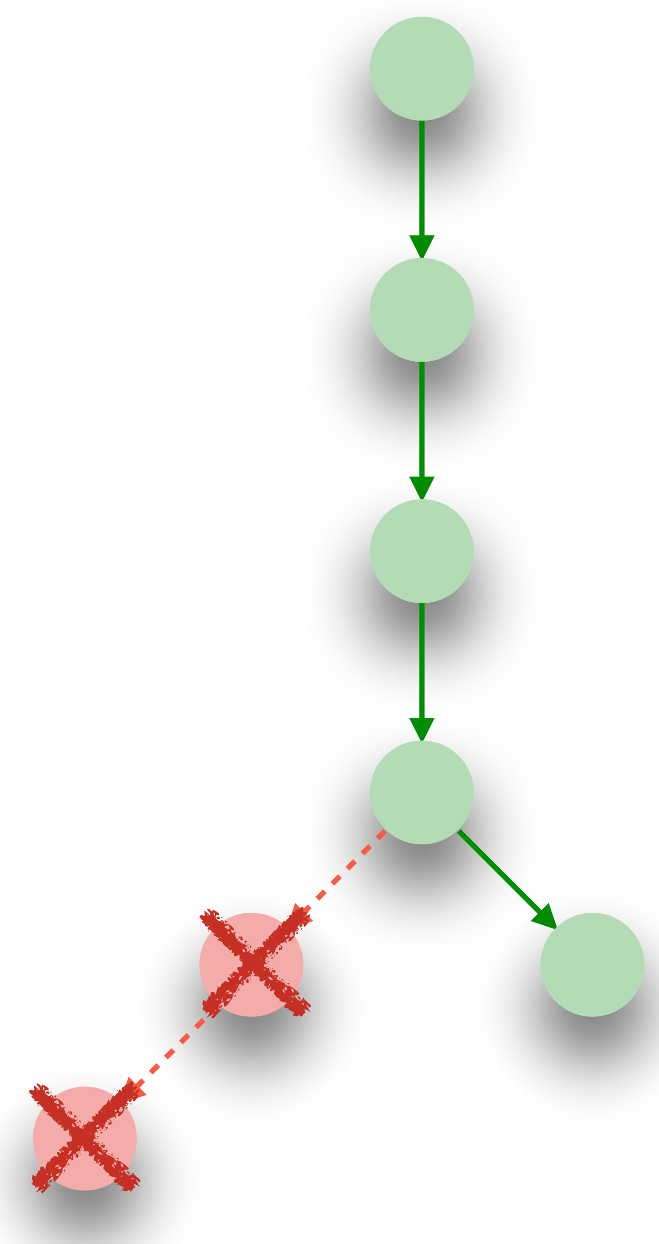
$s_1 \models \varphi$

$s_2 \models \varphi$



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

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

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

$s_1 \models$ $x_1 \geq A\_size_1$ pc END A_1+x_1 $B_1+A_1[x_1]$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \| \quad\quad \not\Vert \quad \vee \quad \not\Vert$

$s_2 \models$ $x_2 \geq A\_size_2$ pc END A_2+x_2 $B_2+A_2[x_2]$

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

Always true!

Experimental r

No counterme

Automated inser fences

Speculative load hardening

15 Spectre variants from Paul Kocher

ICC

CLANG

SLH

−O0 −O2

Summary

- Leak
  (exce
- Conf
- Prog
  - Bu
- Prog

l Kocher

Performance

- Programs ~20-200 lines of assembly code
- Analysis terminates in less than 30 sec
- Except for example #05 (< 2 min)

13	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	●	●	○	○	●	●	○	●

4. Challenges

Scalable analysis

Goal:
Analysis of large, security-critical applications:

- Intel SGX SDK
- Xen hypervisor
- microkernels

Need: Scalable analysis of speculative non-interference

- Exploit "locality" of speculative execution
- Develop scalable abstractions

Verifying compiler-level countermeasures

```
mov     rax, A_size
mov     rcx, x
cmp     rcx, rax
jae     END
mov     rax, A[rcx]
shl     rax, 9
mov     rax, B[rax]
```

Inserting fences

```
mov     rax, A_size
mov     rcx, x
cmp     rcx, rax
jae     END
lfence
mov     rax, A[rcx]
shl     rax, 9
mov     rax, B[rax]
```

Speculative load hardening

```
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]
```

How can we **verify** such countermeasures?

A sound HW/SW security contract

Instruction-set architecture: to weak for security guarantees

HW/SW security contract

Microarchitecture: not available publicly, and too detailed for analysis

Find out more in the paper:
https://arxiv.org/abs/1812.08639

To appear in: *IEEE Symposium on Security & Privacy, 2020*

I am looking for PhD students and postdocs!
Feel free to get in touch by email.

Thank you for your attention!

Backup

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]
```

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

Example #10 - SLH

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

Leaks A[x]==0 via control-flow
We detect the leak!

Example #08 - FEN

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

lfence is unnecessary

```
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]
```