Spectector: Principled detection of speculative information flows

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Joint work with
Marco Guarnieri, Jose Morales, Andres Sanchez @ IMDEA Software, Madrid
Boris Köpf @ Microsoft Research, Cambridge, UK

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“Information Flow Tracking across the Hardware-Software Boundary”

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** to leak sensitive information

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Almost all modern processors are affected

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Long Term: Co-Design of Software and Hardware countermeasures

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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)

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Short and Mid Term: Software countermeasures

In particular: Compiler-level countermeasures

- ✓ *Example*: insert “fences” to selectively terminate speculative execution
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PROBLEM SOLVED ?

Compiler-level countermeasures

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

Paul Kocher
February 13, 2018

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

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Bottom line: No guarantees!

Goals

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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

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- Predict instructions' outcomes and speculatively continue execution

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

Background: Branch prediction

Size of array **A**

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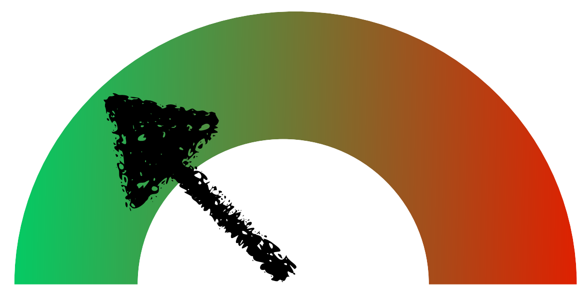

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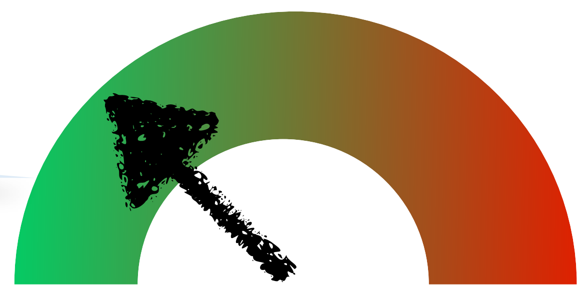

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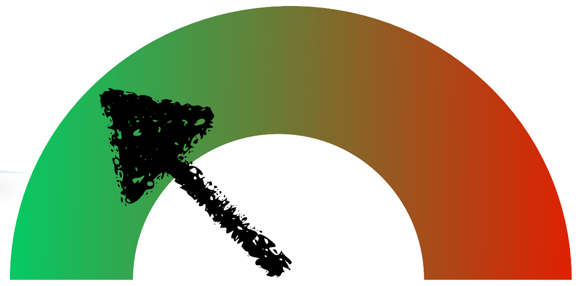

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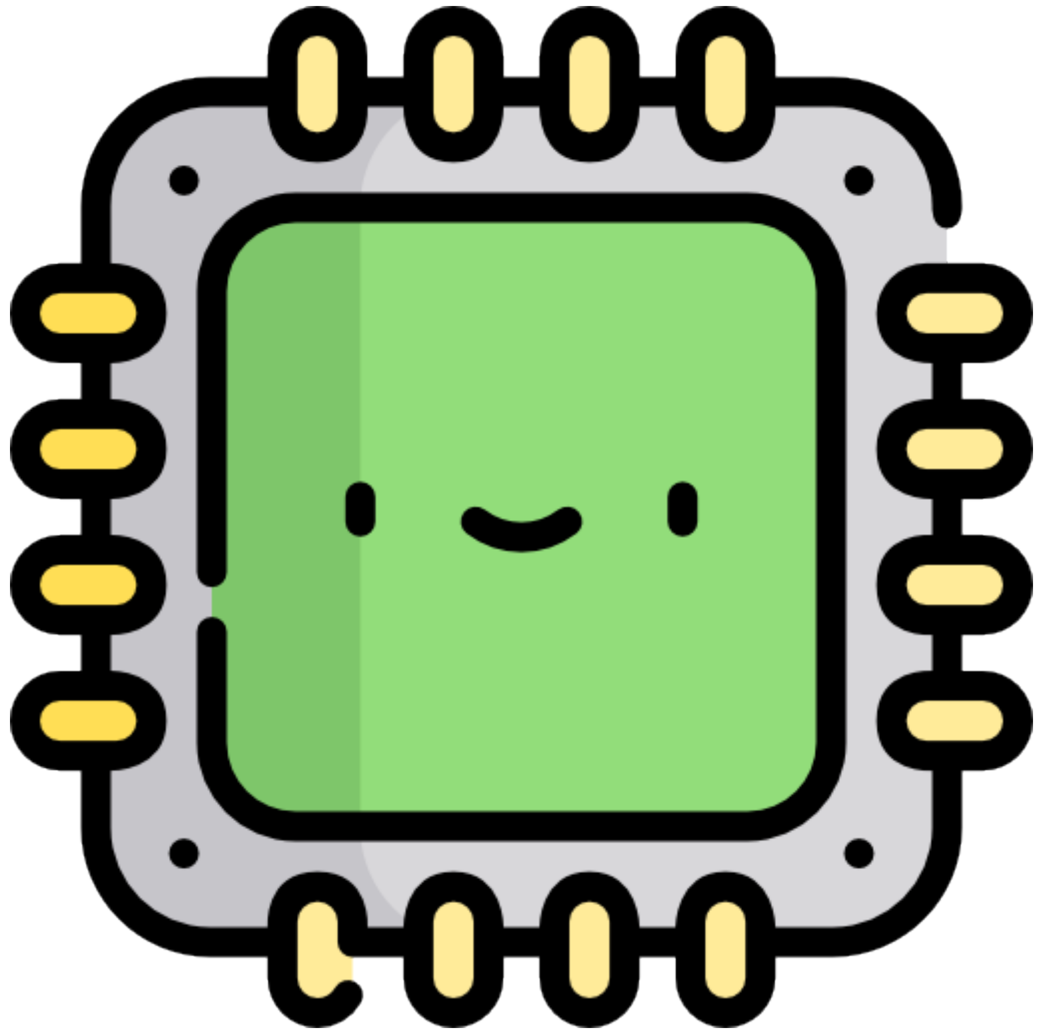

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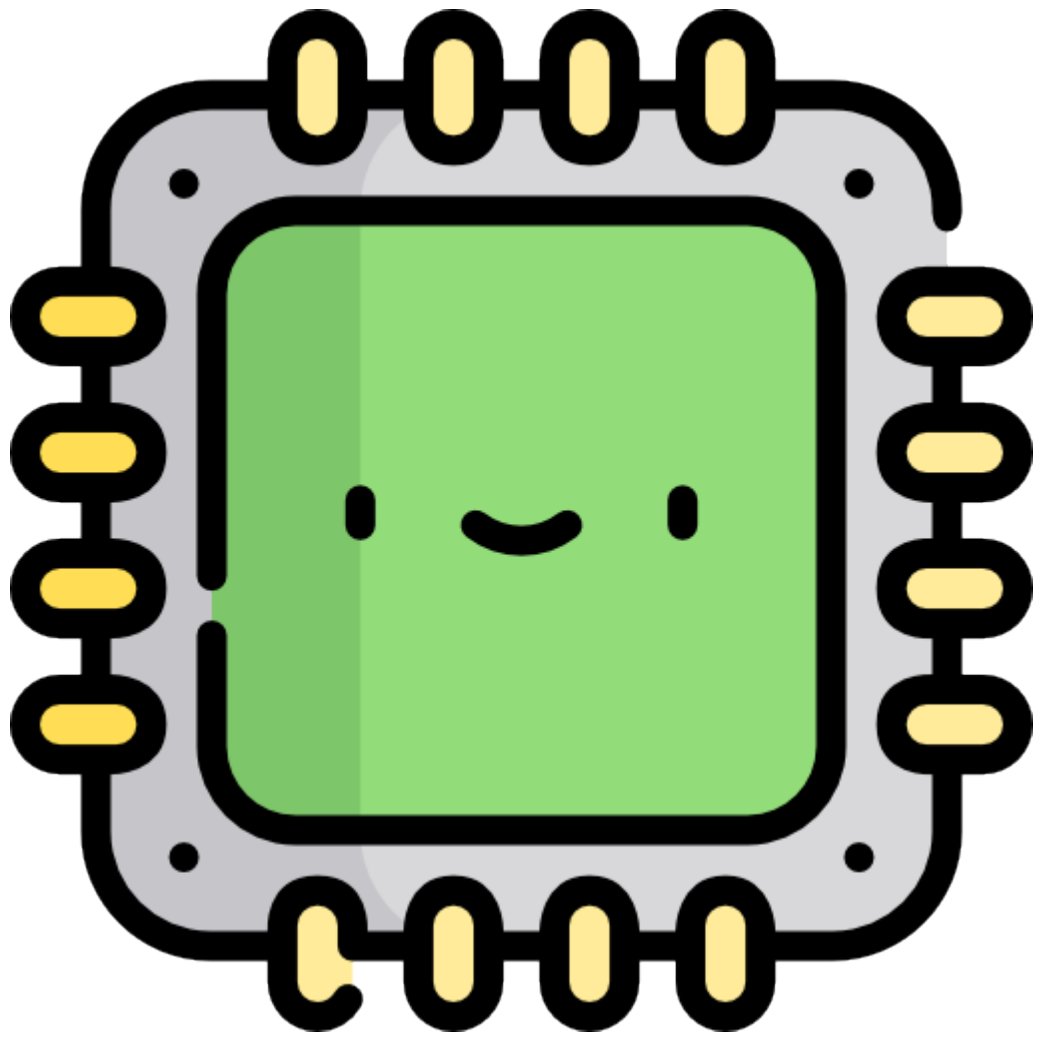

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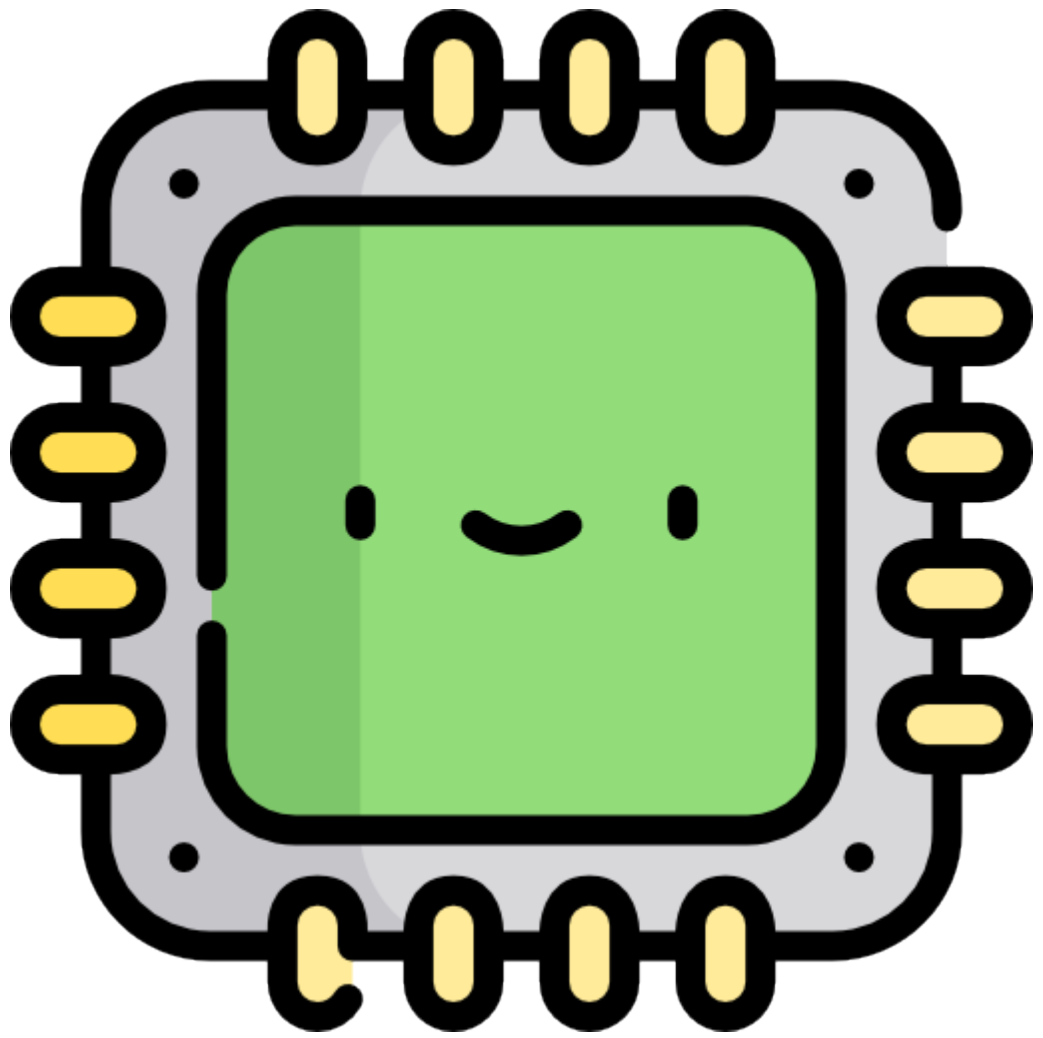

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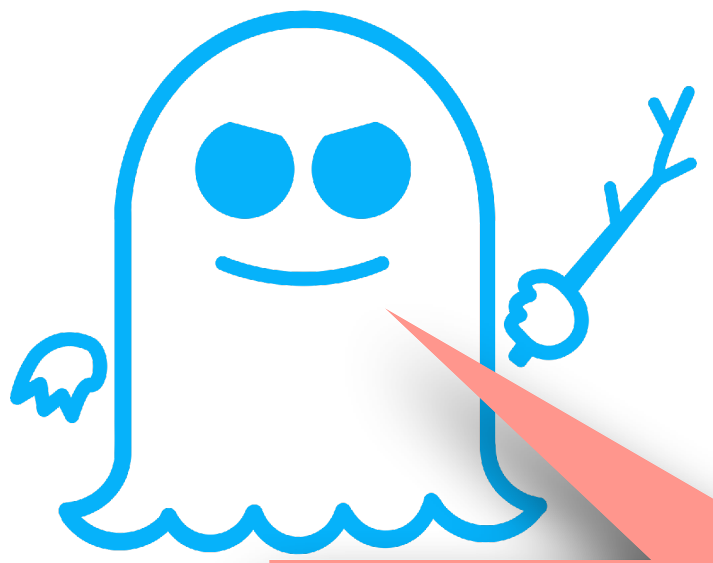

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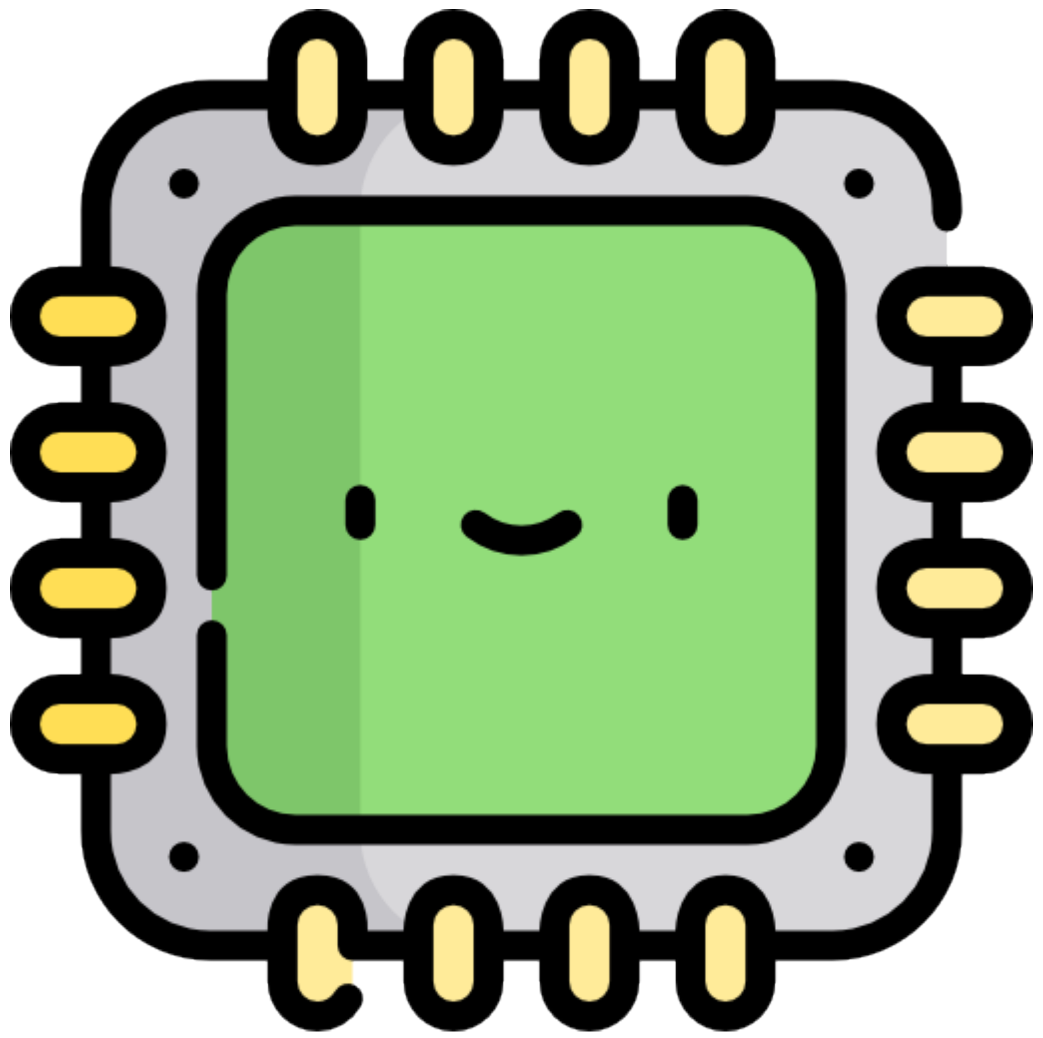

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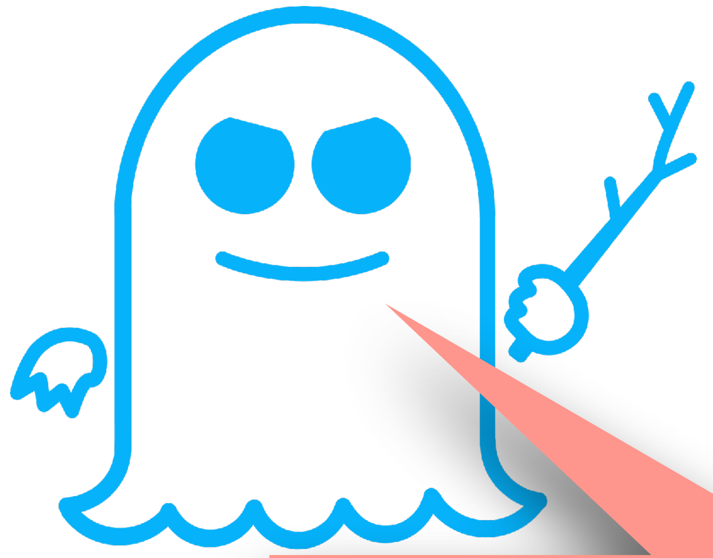

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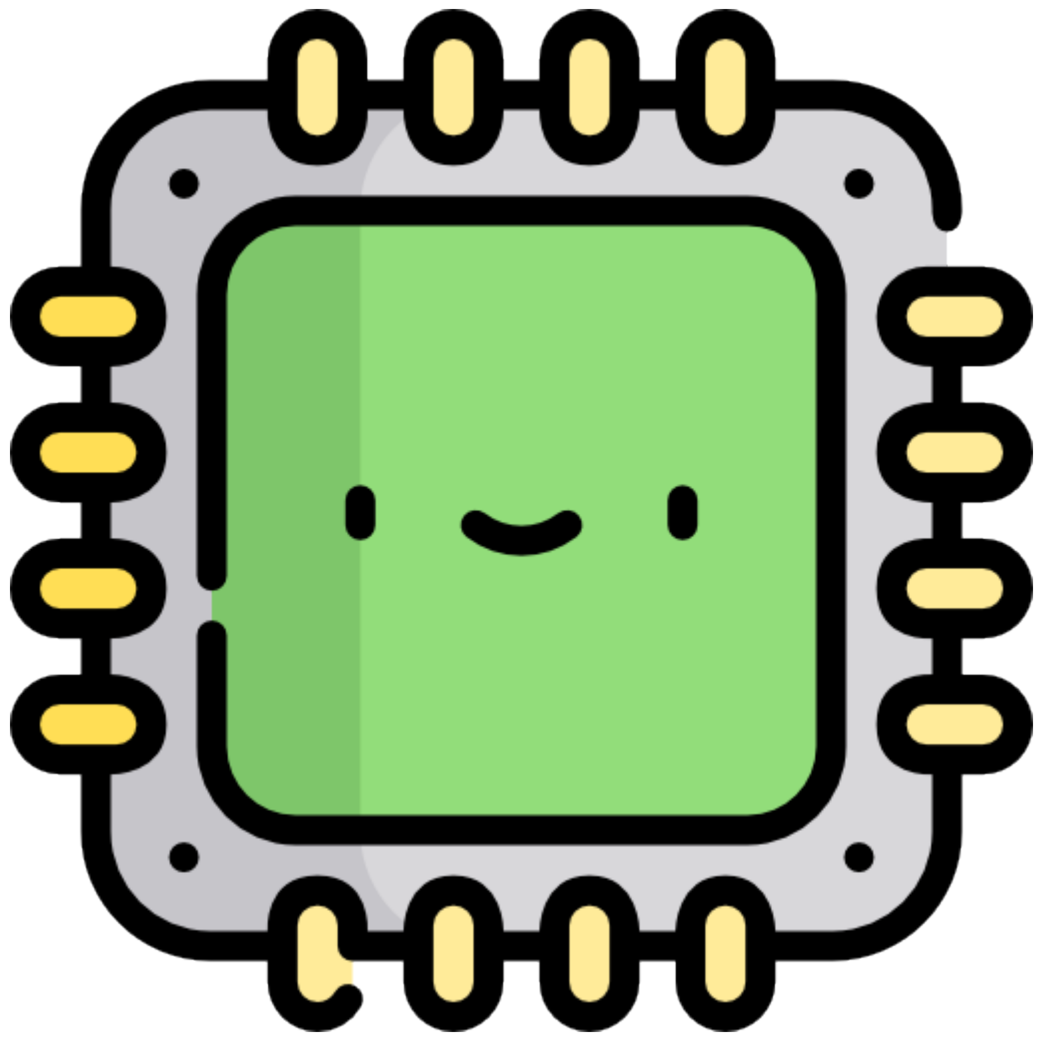

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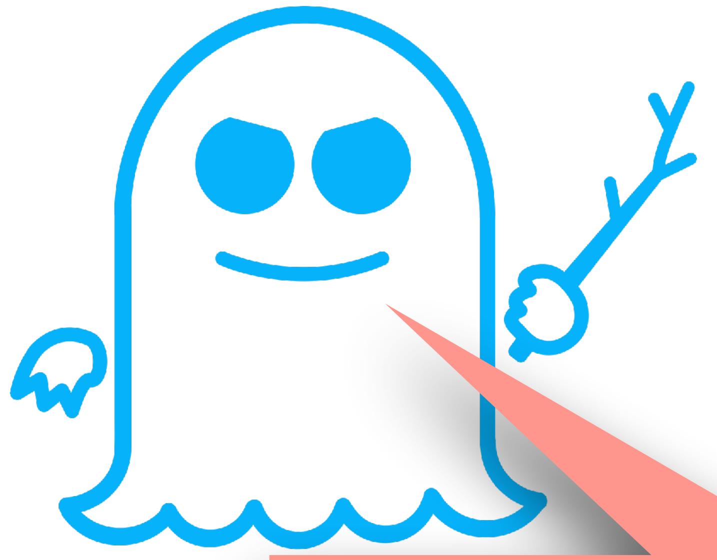

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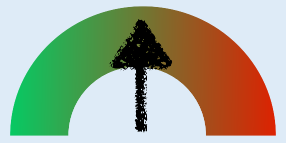
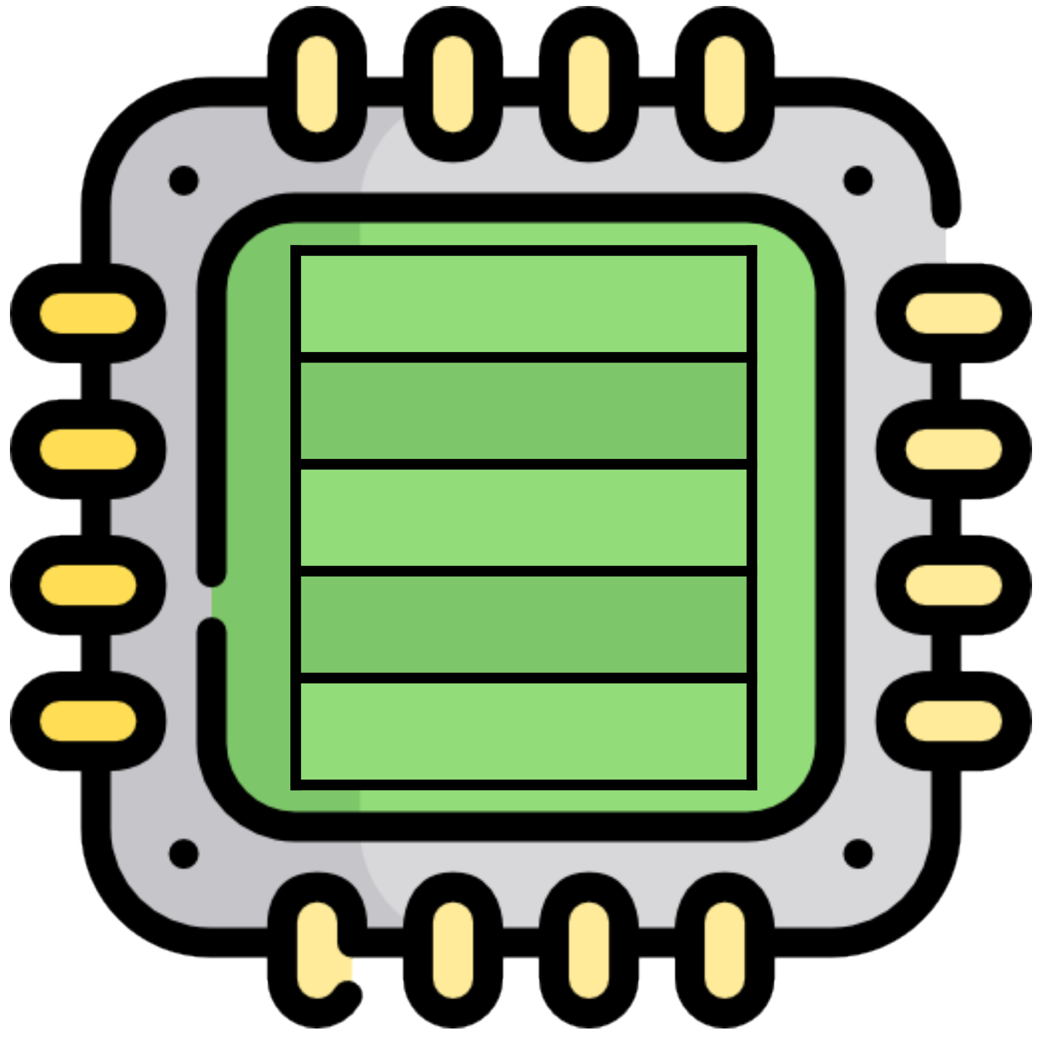
1a) Training 



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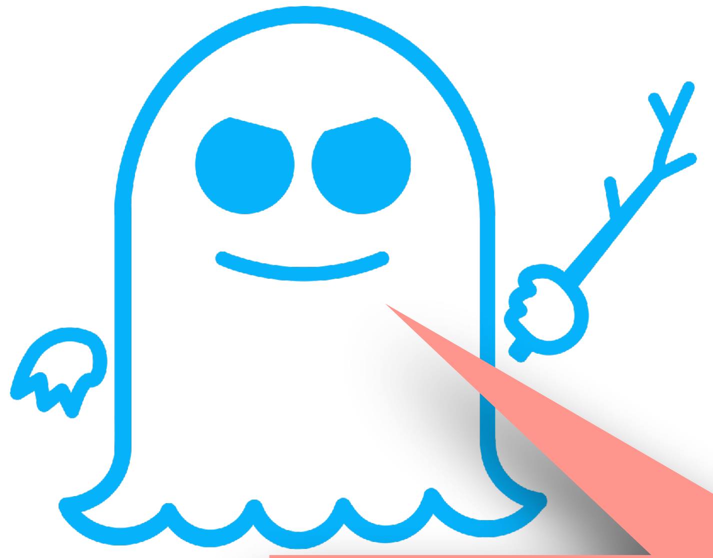

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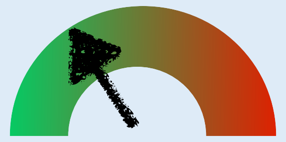
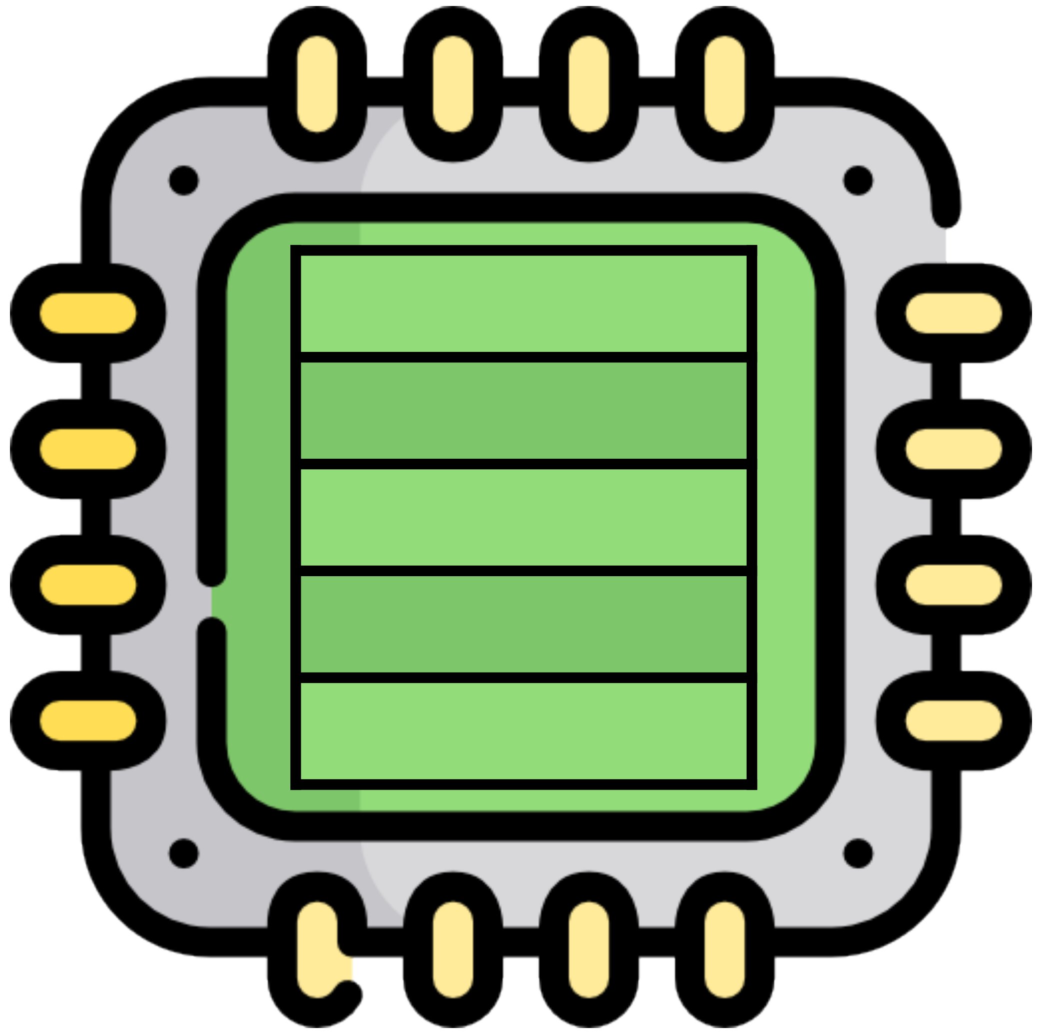
1a) Training  f(0);



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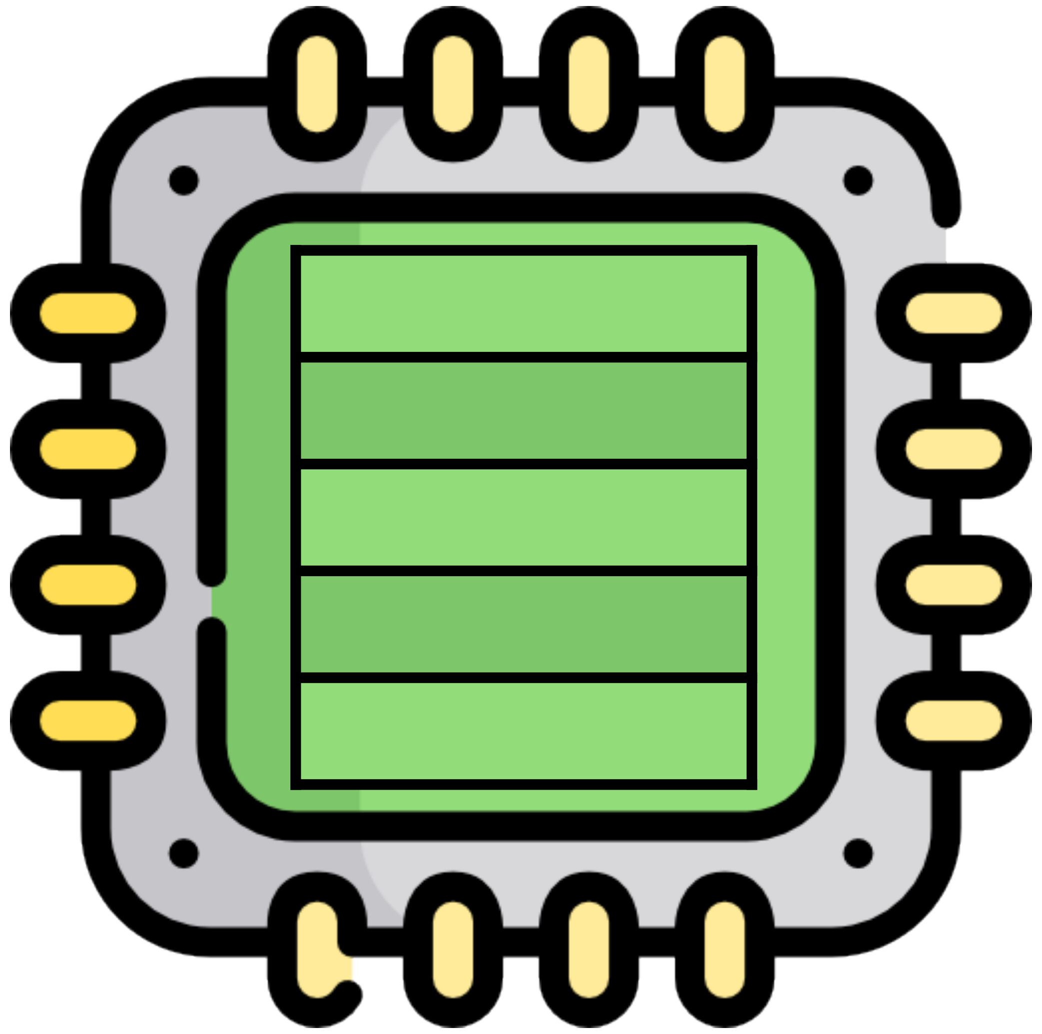

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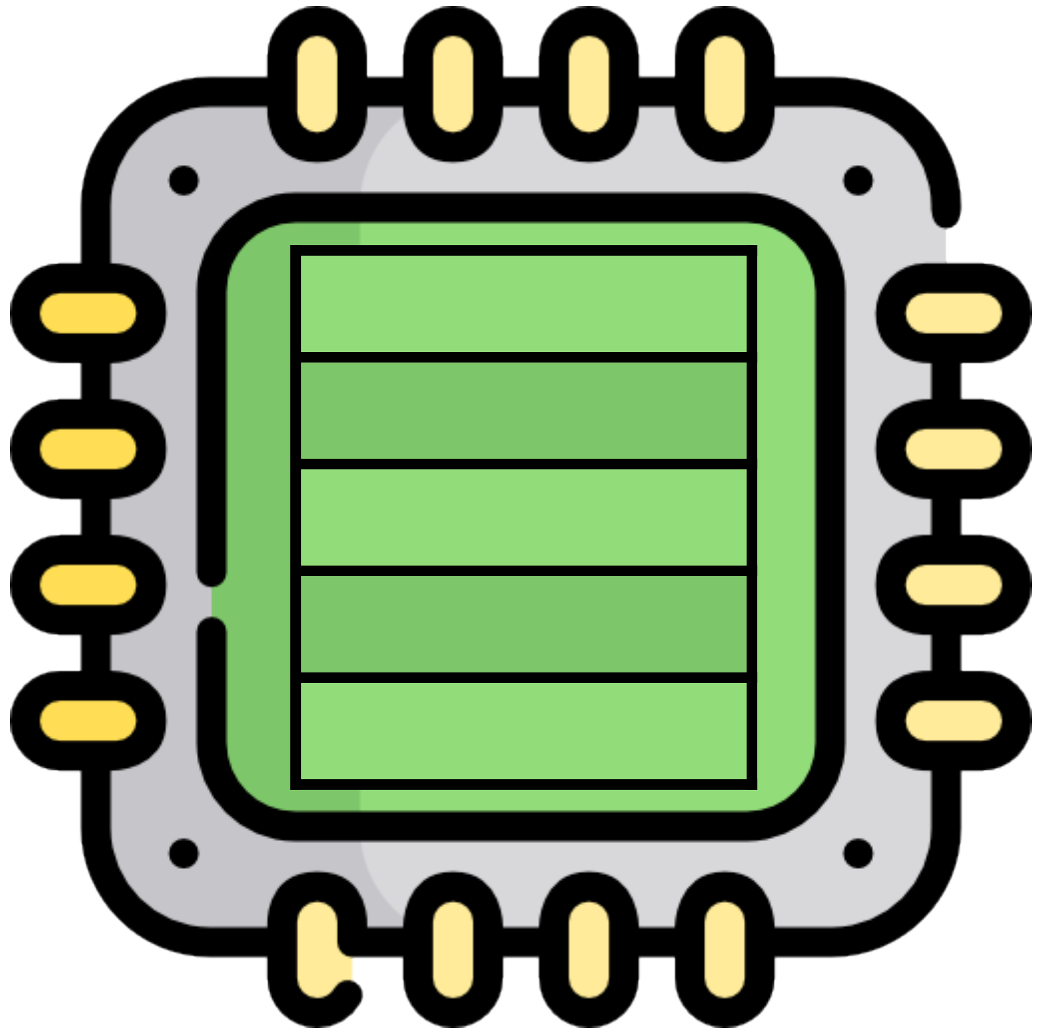

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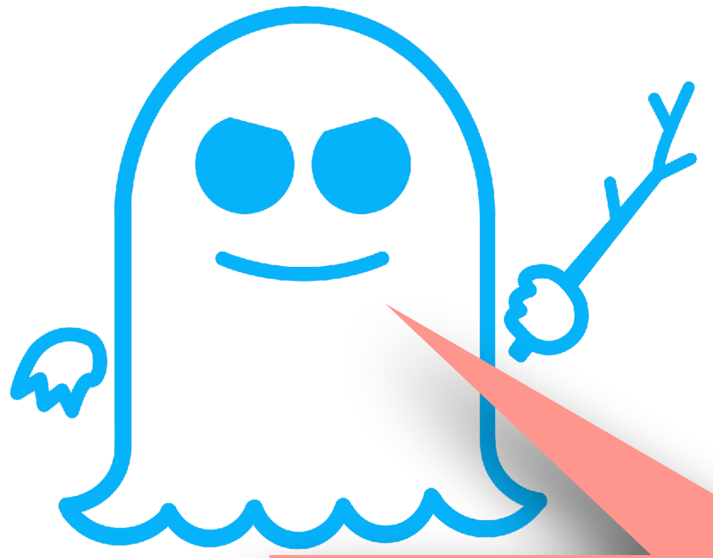

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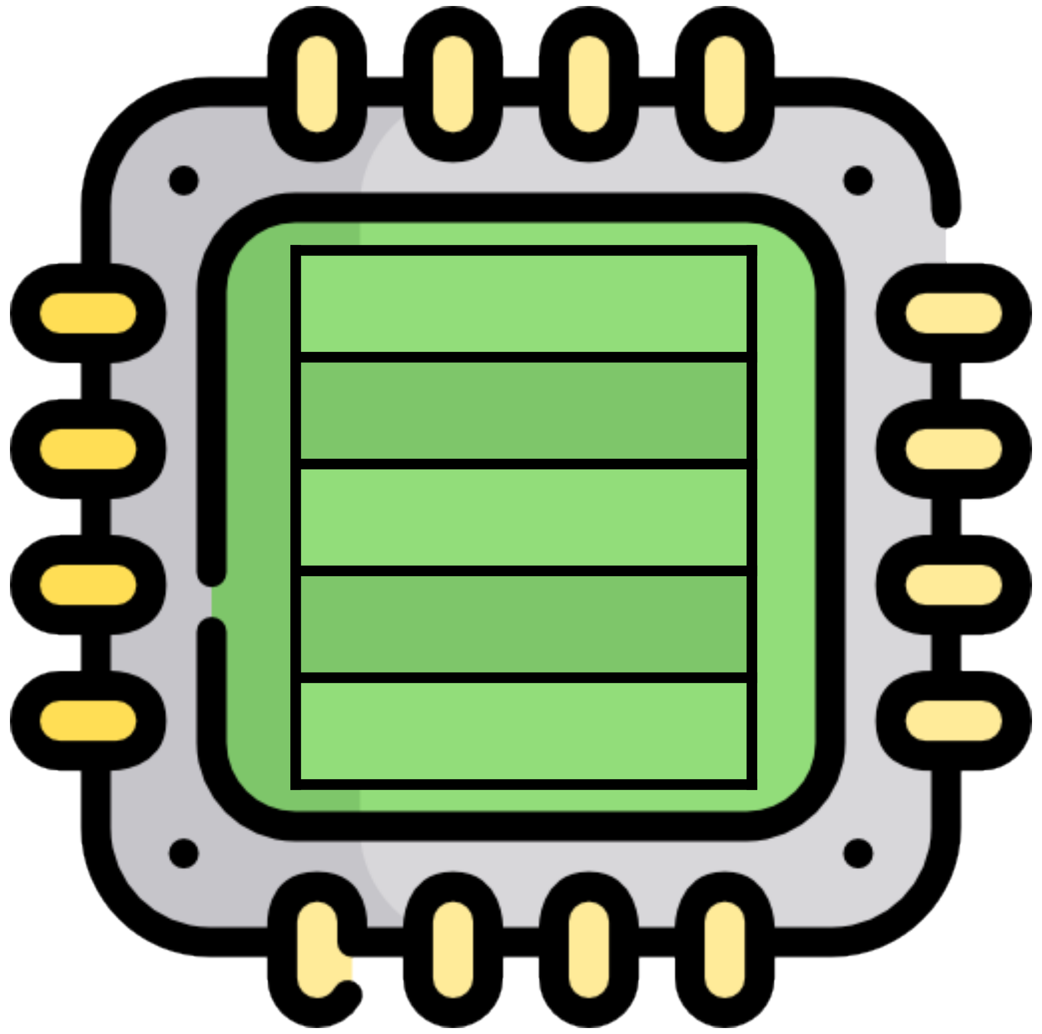

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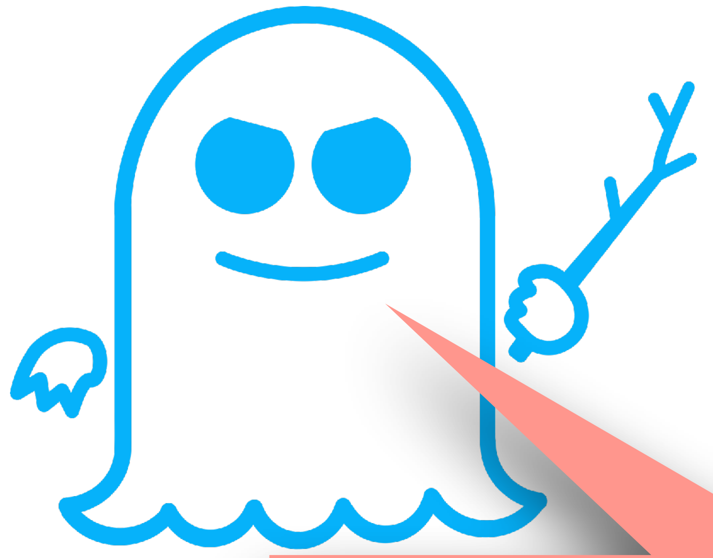

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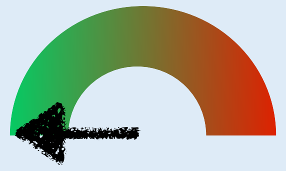
1a) Training  f(0);f(1);f(2); ...

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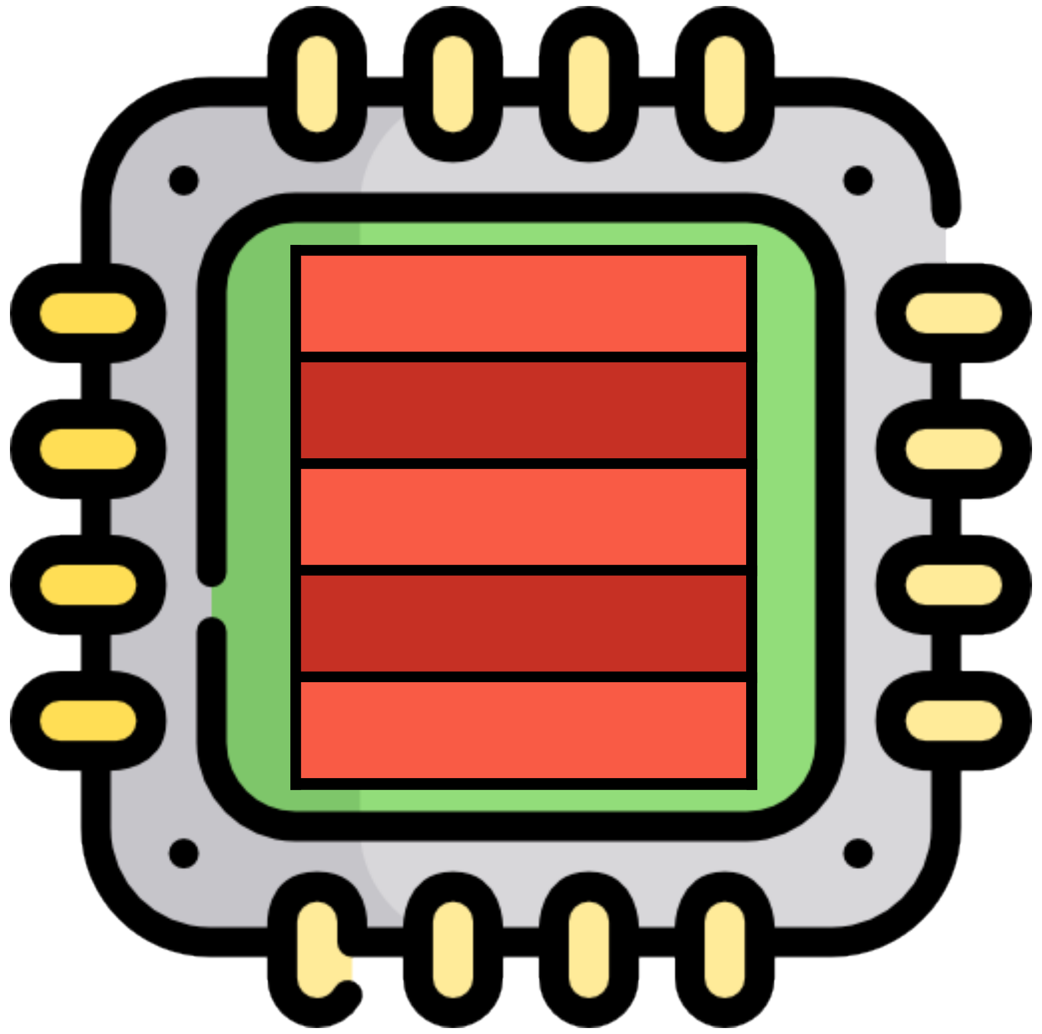

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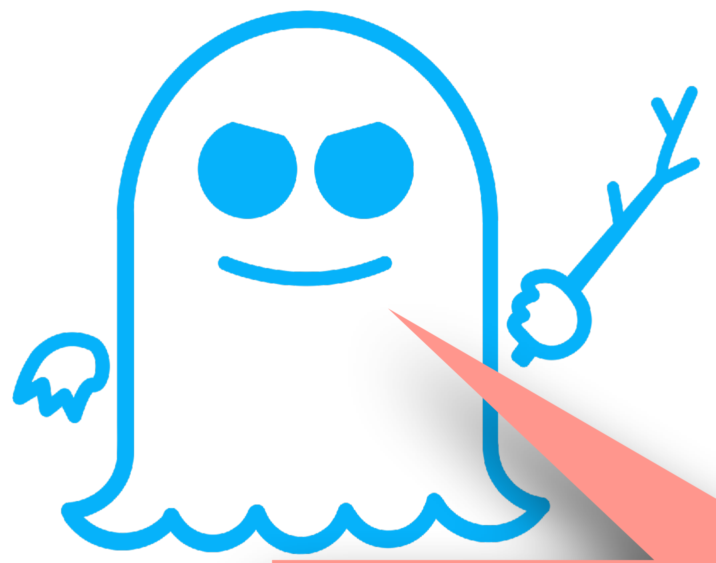

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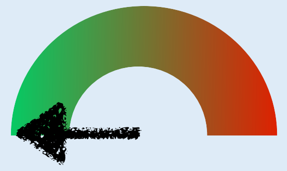
1a) Training  f(0);f(1);f(2); ...

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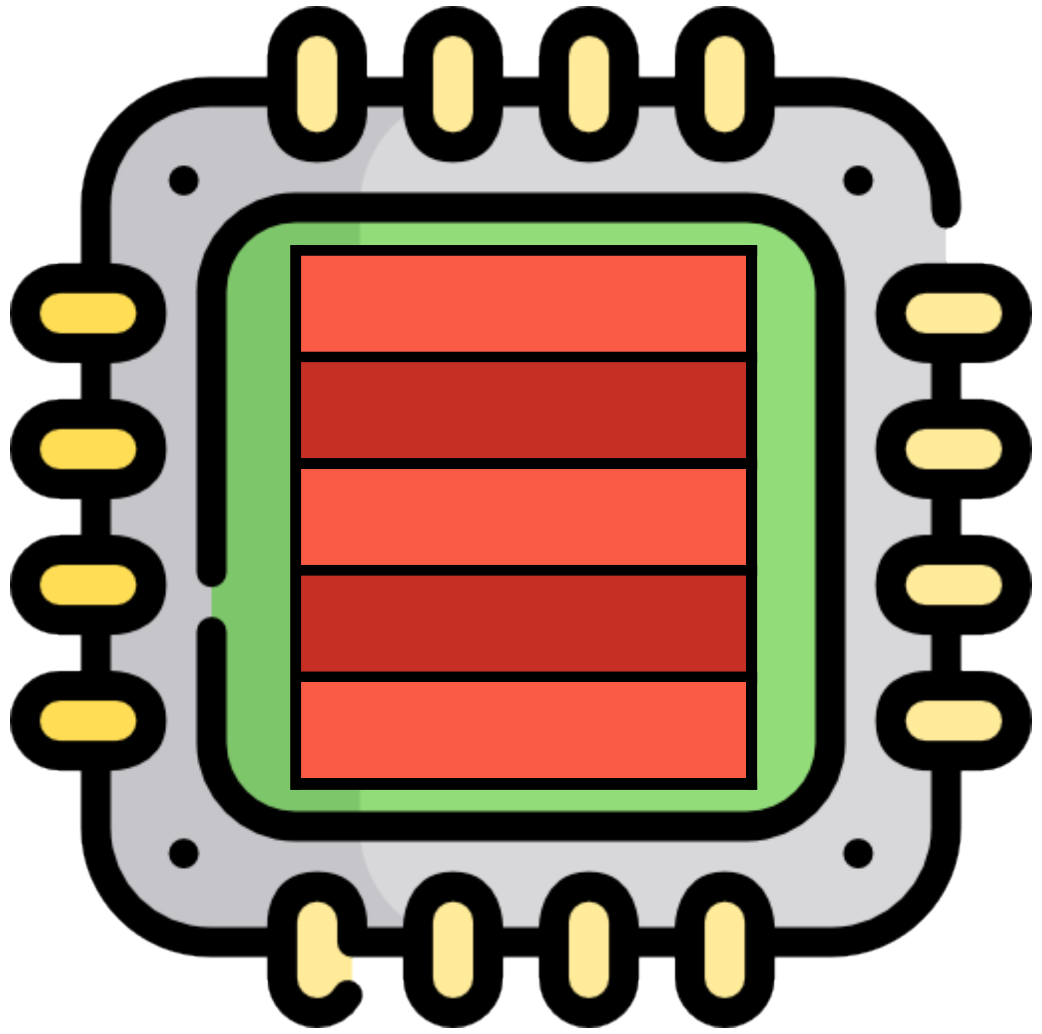
2) Run f(128)



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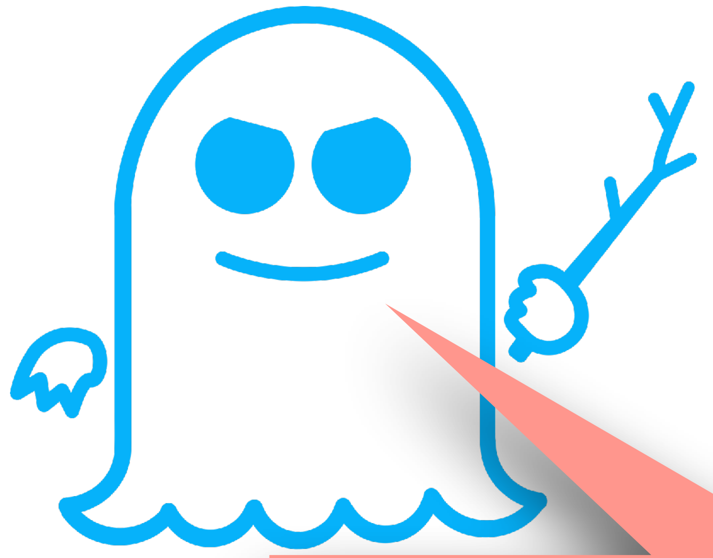

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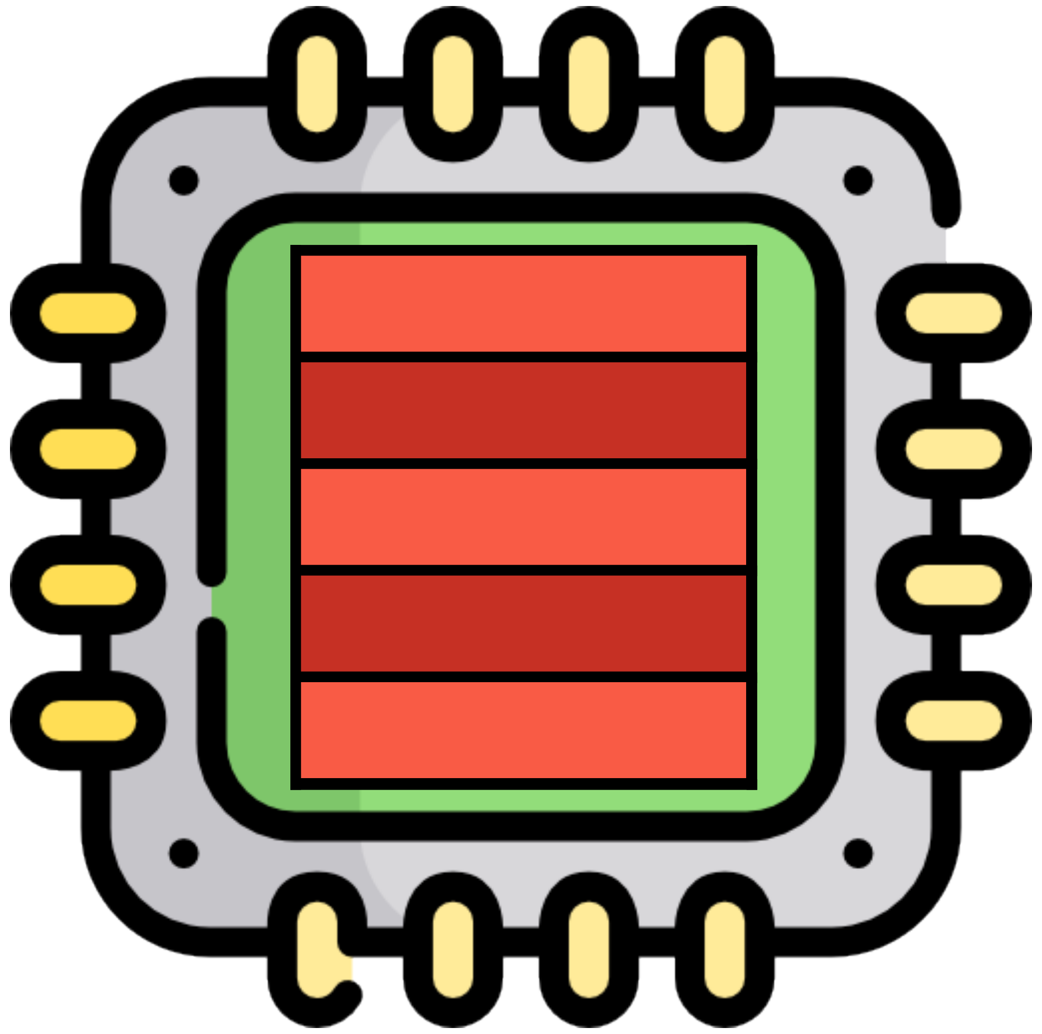

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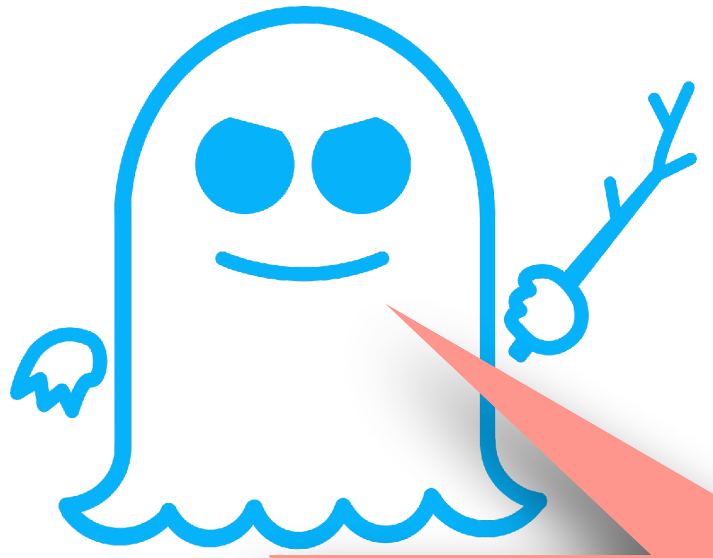

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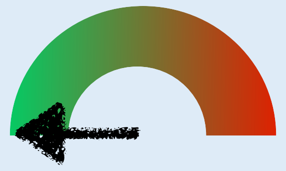
1a) Training  `f(0);f(1);f(2);` …

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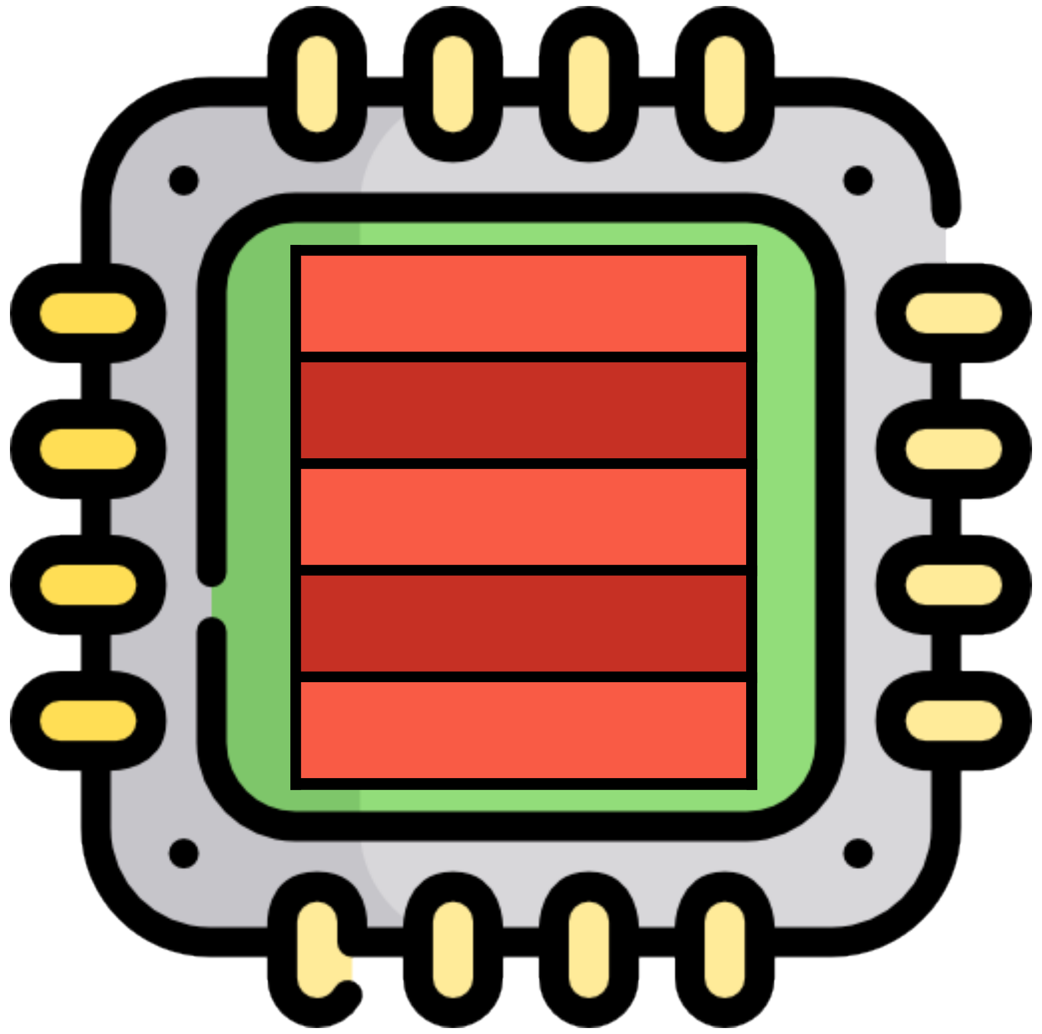

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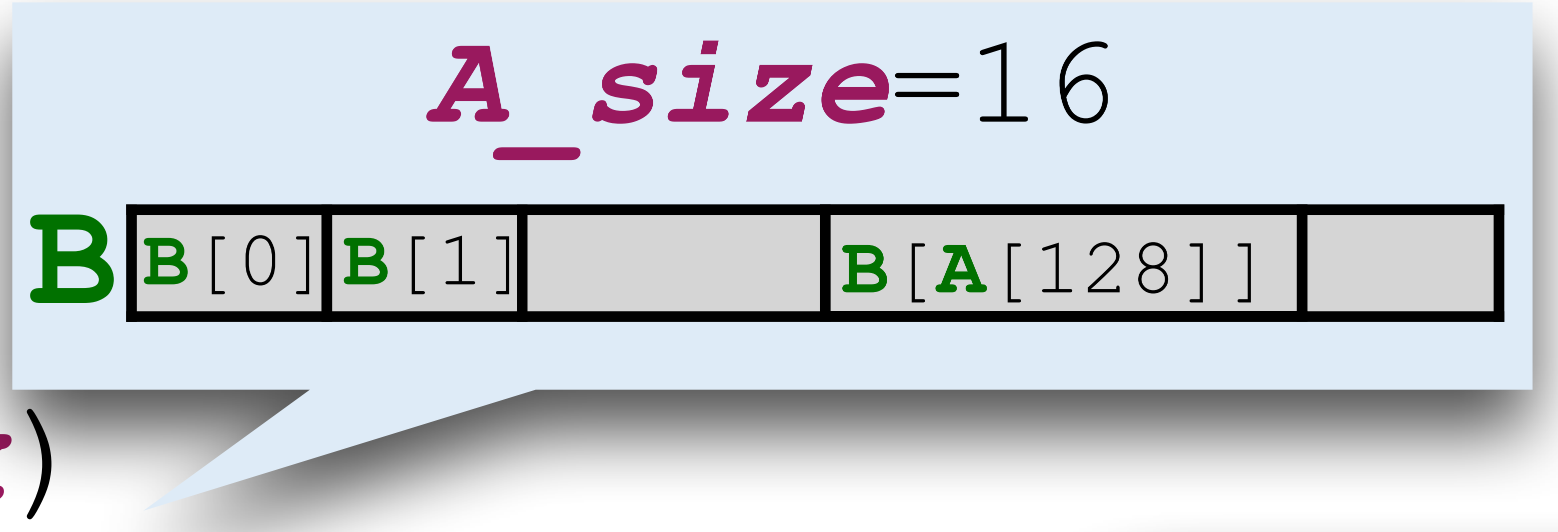


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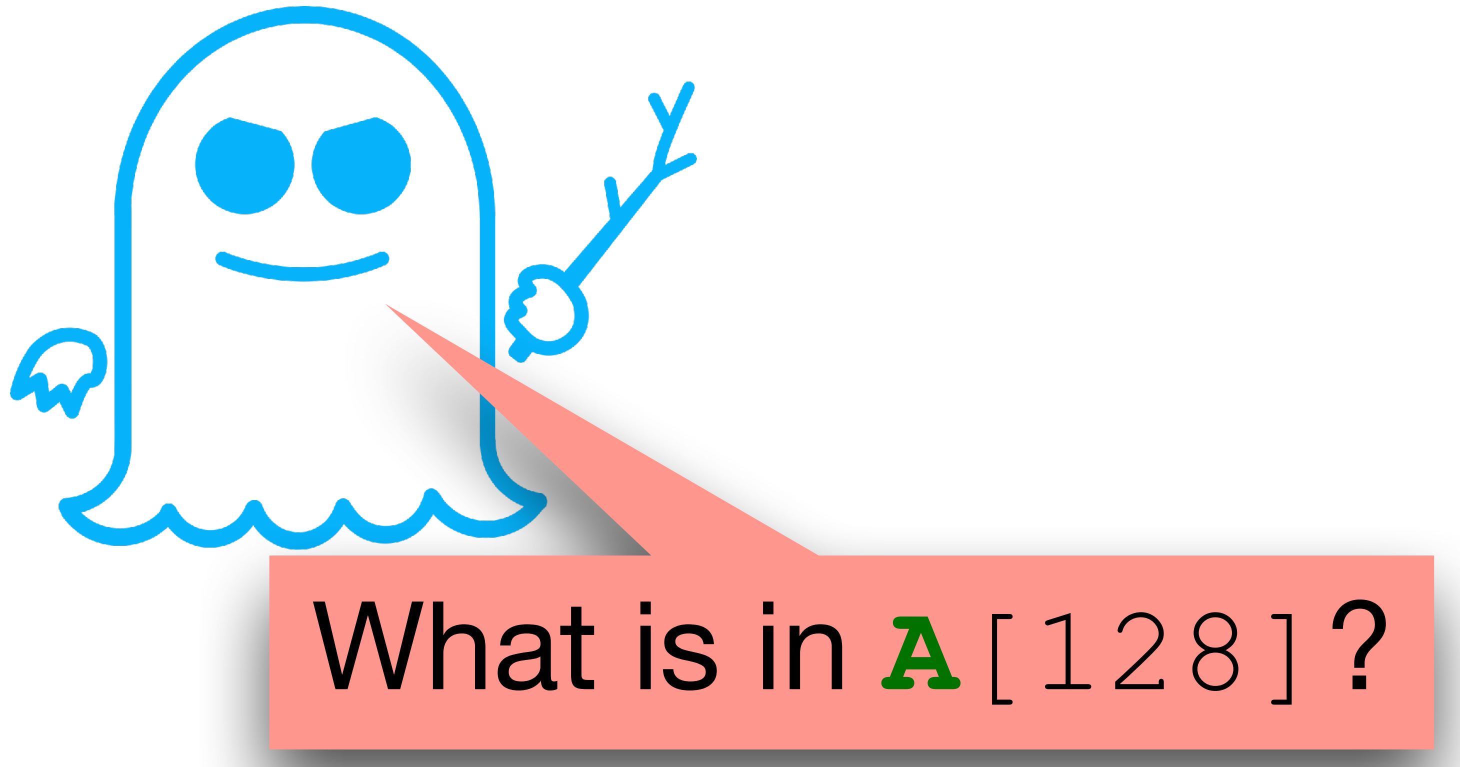

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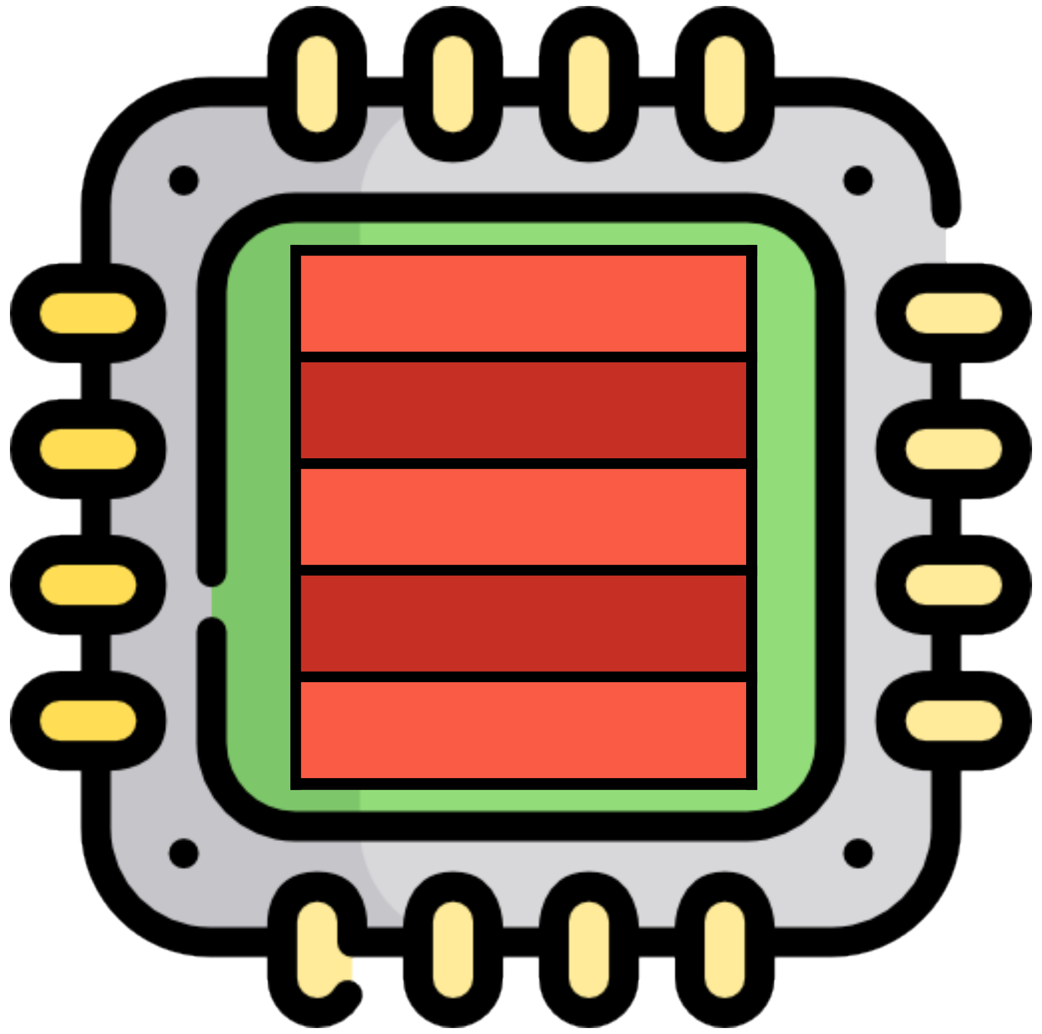

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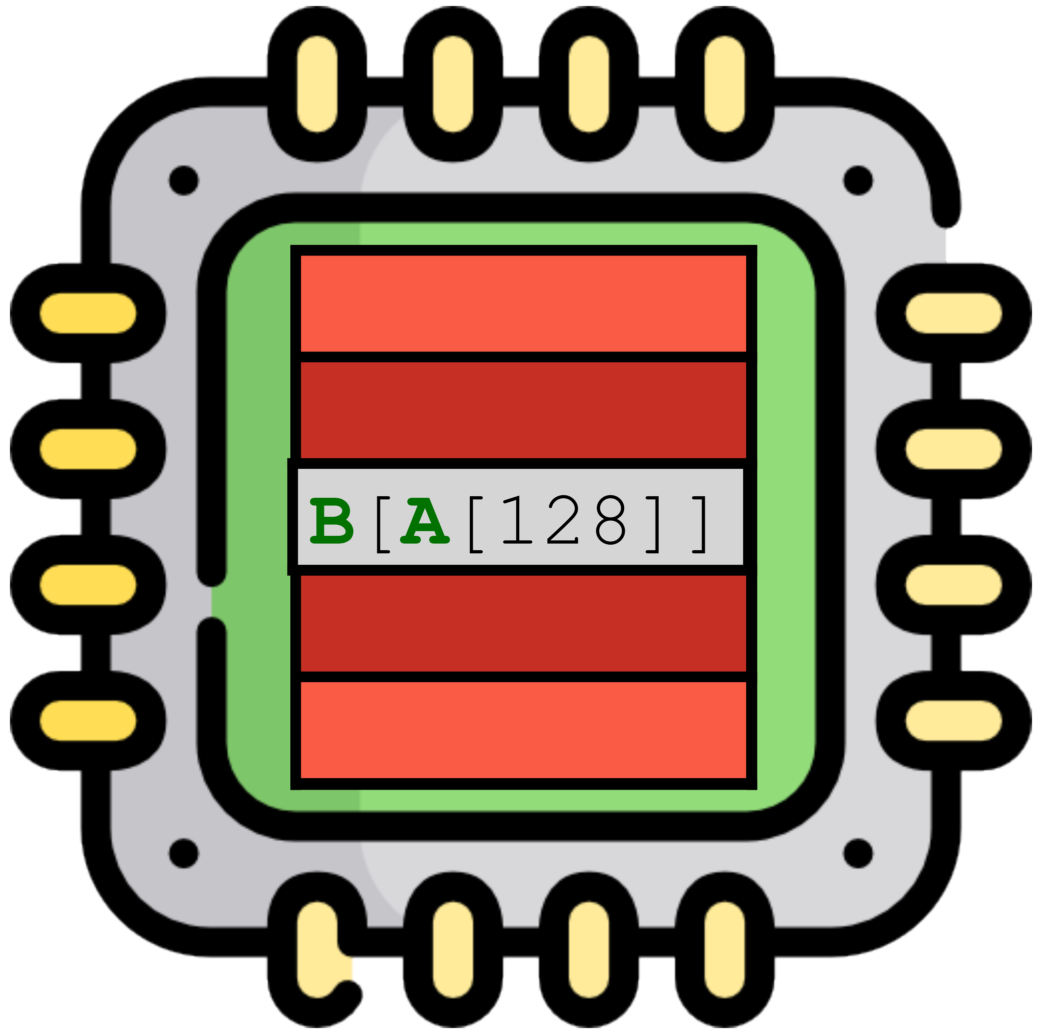

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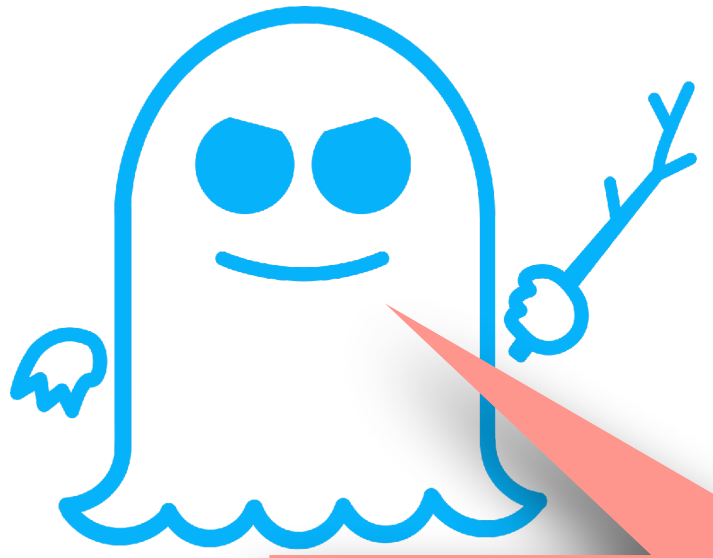

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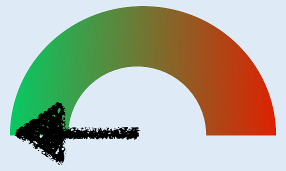
1a) Training  f(0);f(1);f(2); …

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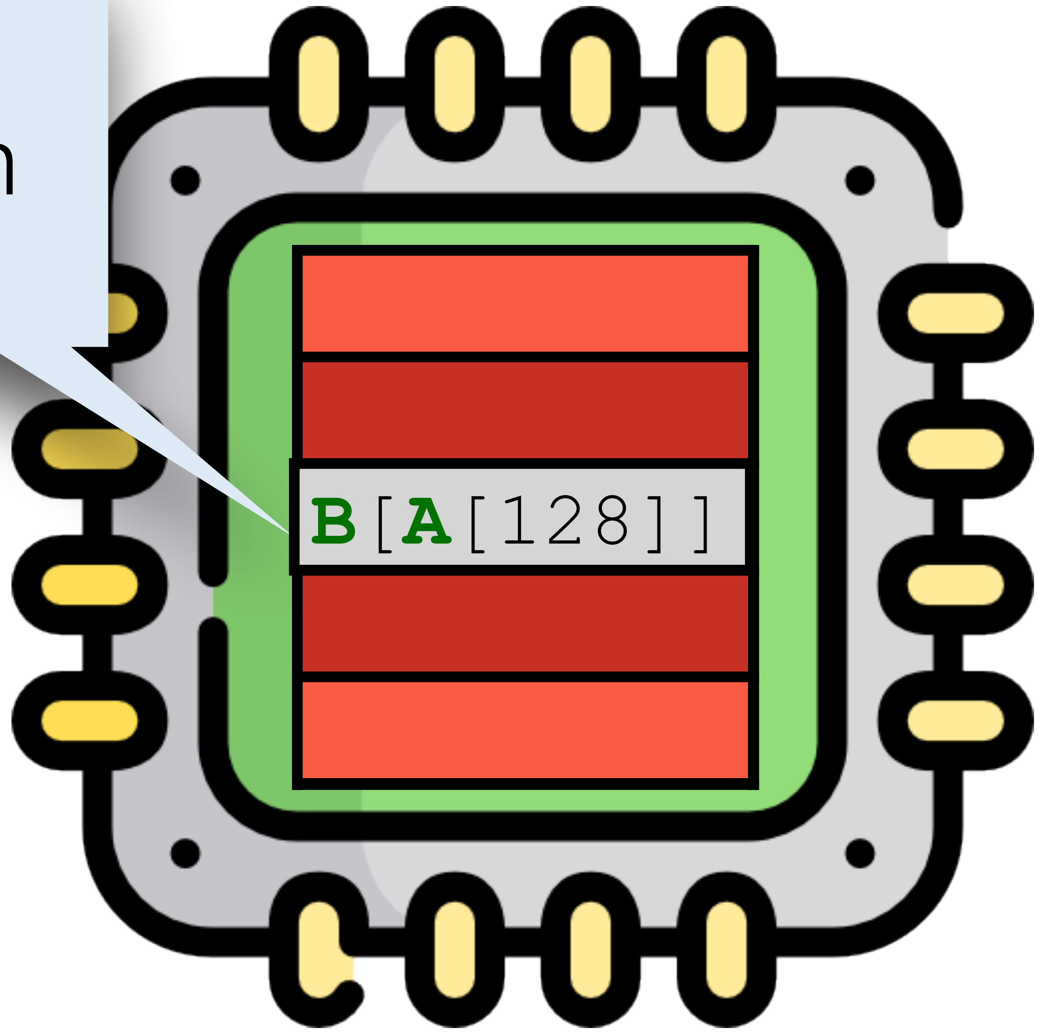
2) Run f(128)

Address depends on A[128]



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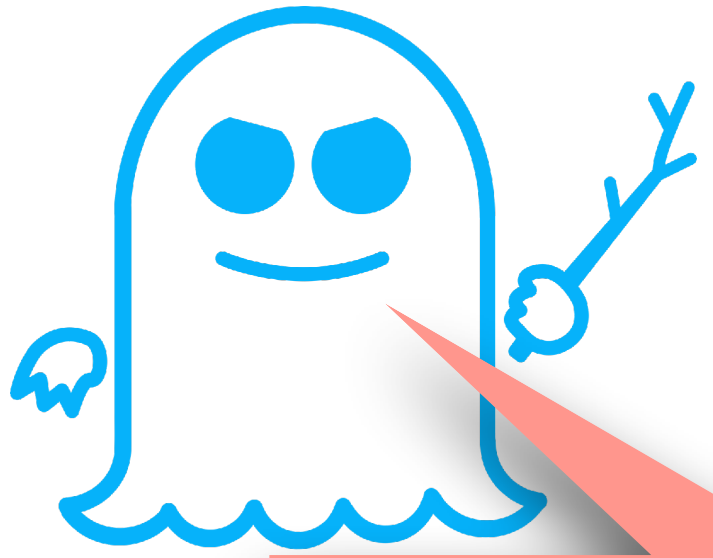

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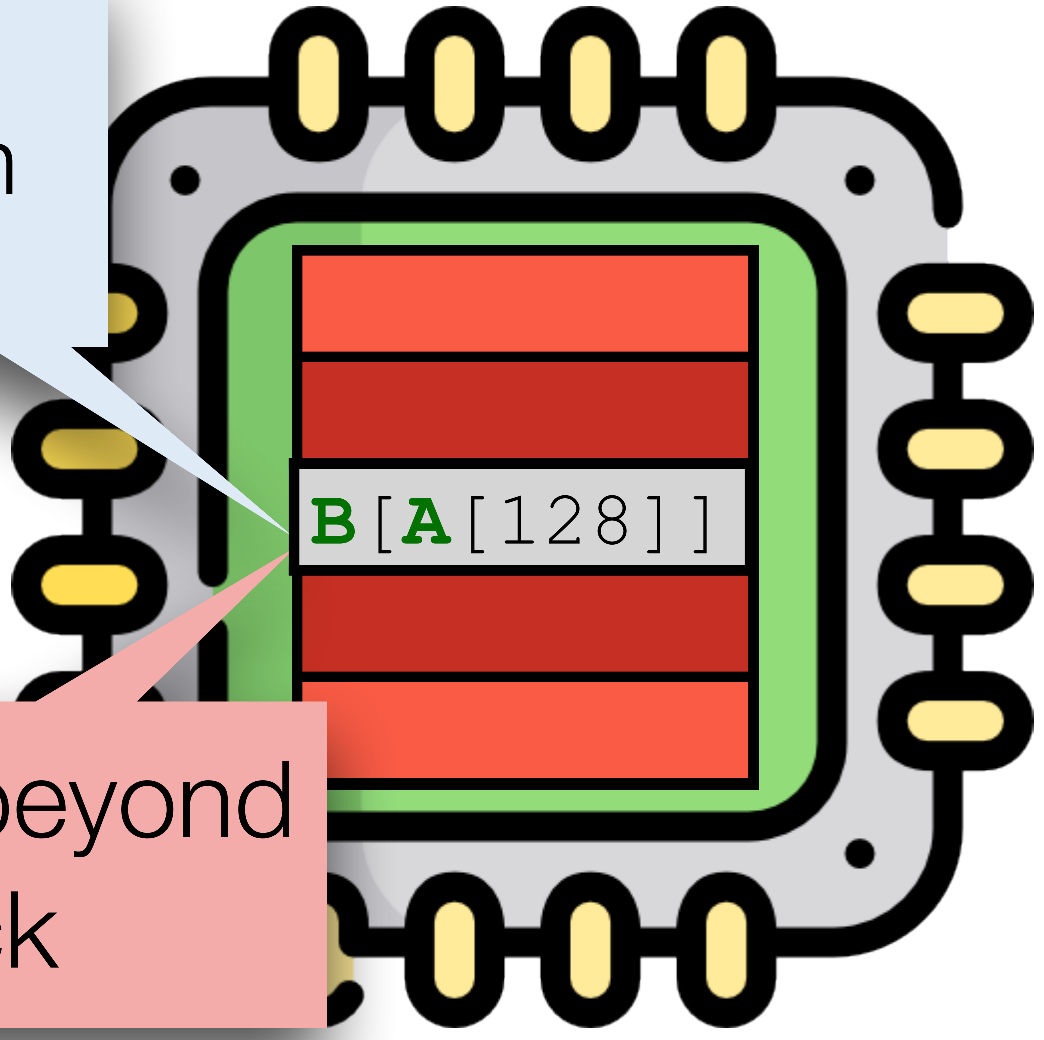

Persistent beyond rollback

Cache state

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What is in A[128]?

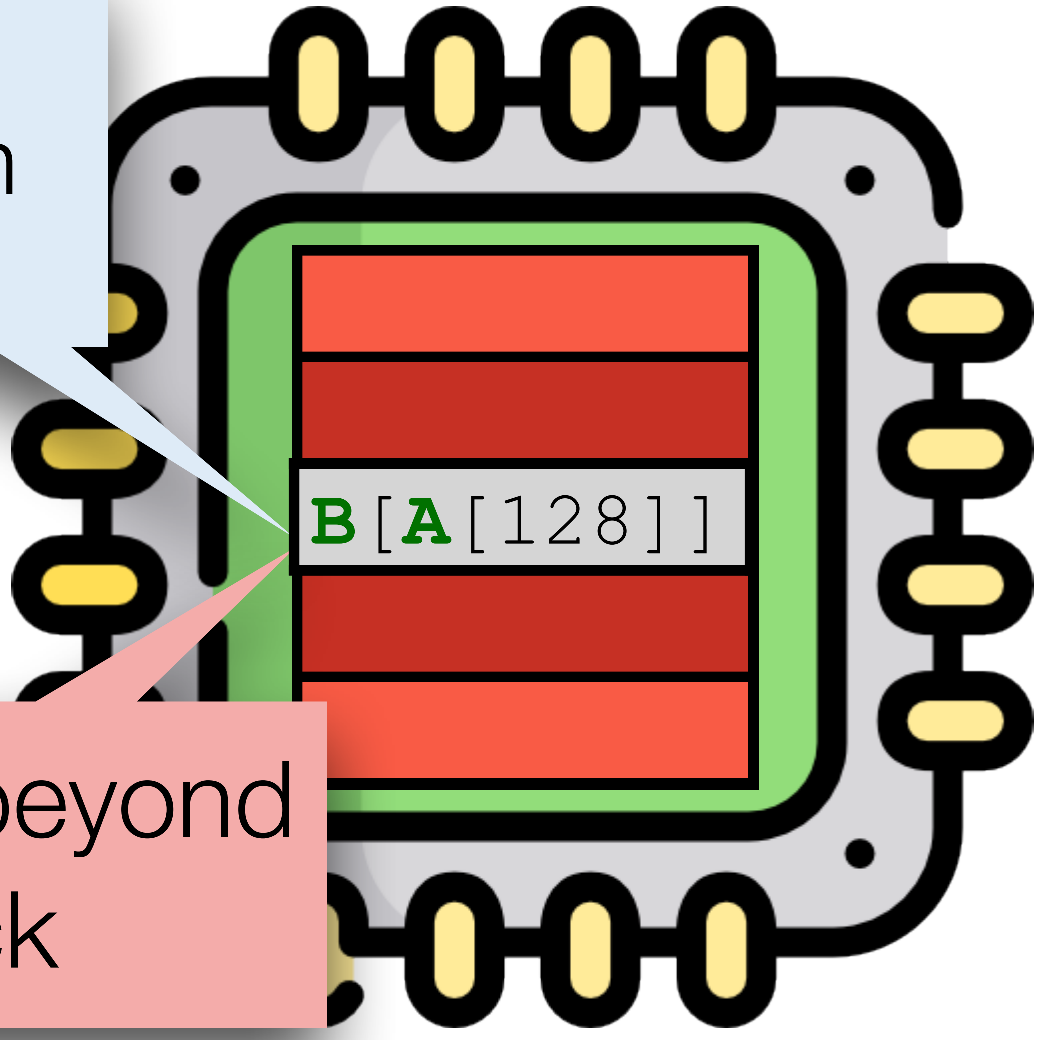
1a) Training f(0);f(1);f(2); …

1b) Prepare cache

2) Run f(128)

3) Extract from cache

Address depends on A[128]

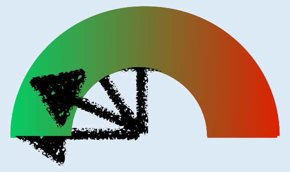


Persistent beyond rollback

Cache state

2. Speculative non-interference

Generalizing the Spectre V1 example

1a) Training  `f(0);f(1);f(2); …`

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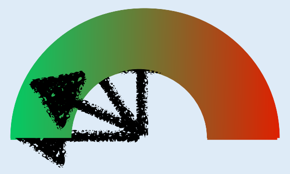
1a) Training  `f(0);f(1);f(2); …`

1b) Prepare cache

} Attacker

2) Run `f``(128)`

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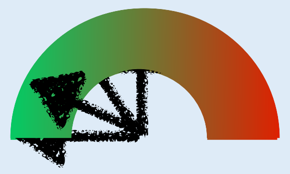
Generalizing the Spectre V1 example

1a) Training  `f(0);f(1);f(2); …`

1b) Prepare cache

Attacker (1a, 1b)

2) Run `f` `(128)`

Victim (2)

3) Extract from cache

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

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

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More formally:

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

Speculative non-interference

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More formally:

For all program states s and s':

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

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

More formally:

For all program states s and s':

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

Speculative non-interference

Extended with policies

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

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How to capture leakage into microarchitectural state?

How to capture leakage into microarchitectural state?

Non-speculative semantics

Speculative semantics

How to capture leakage into microarchitectural state?

Non-speculative semantics

Speculative semantics

+

Attacker/Observer model

µAssembly

```
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:
```

µAssembly + Non-speculative semantics

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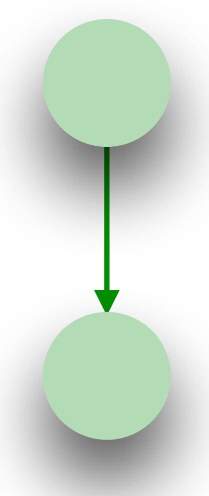

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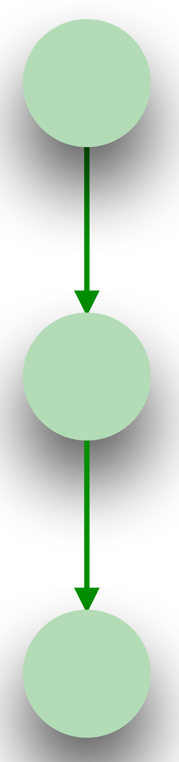

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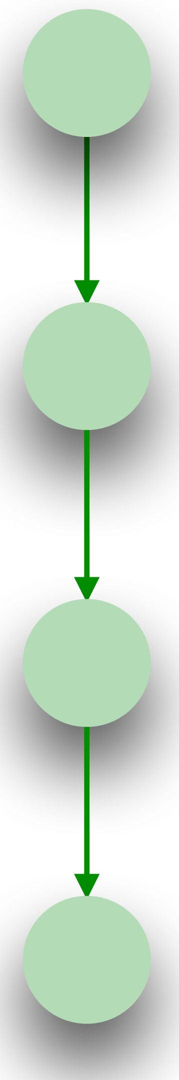

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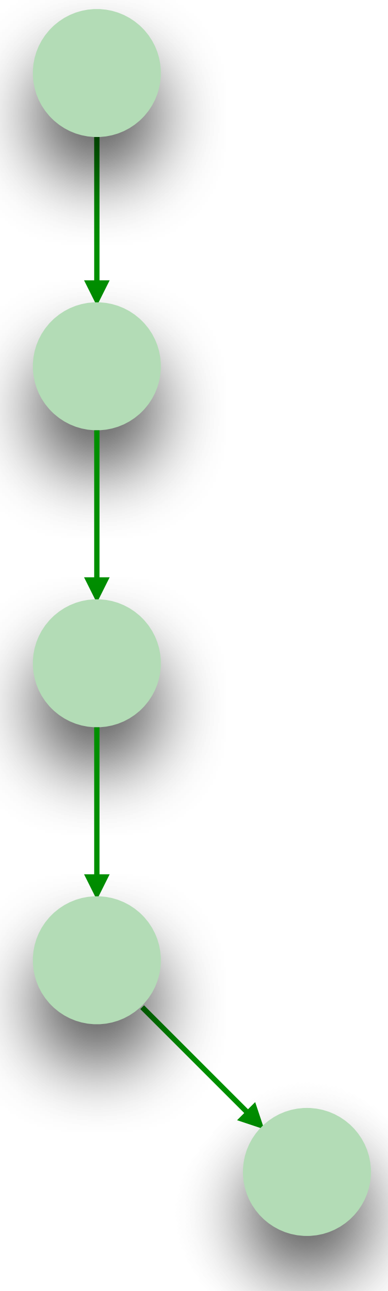

Non-speculative semantics: Inference Rules

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

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

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

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

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

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

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

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

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

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

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

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

Speculative semantics

```
    rax <- A_size
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L1: load rax, A + rcx
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Starts **speculative transactions** upon branches

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Committed upon correct speculation

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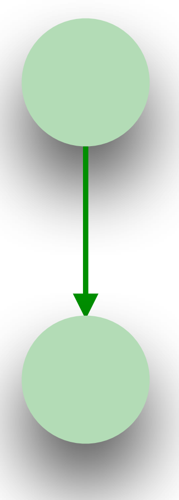

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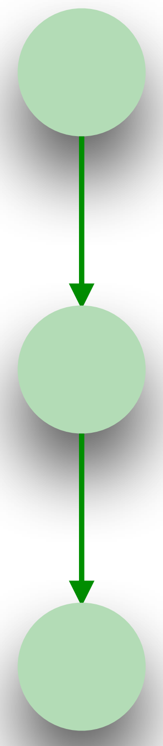

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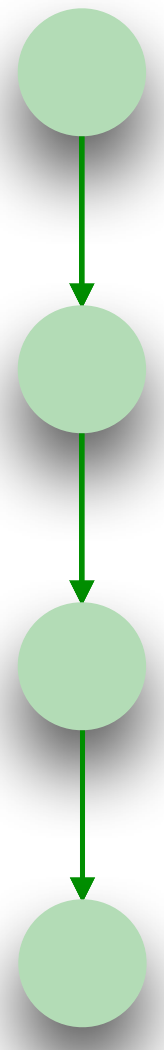

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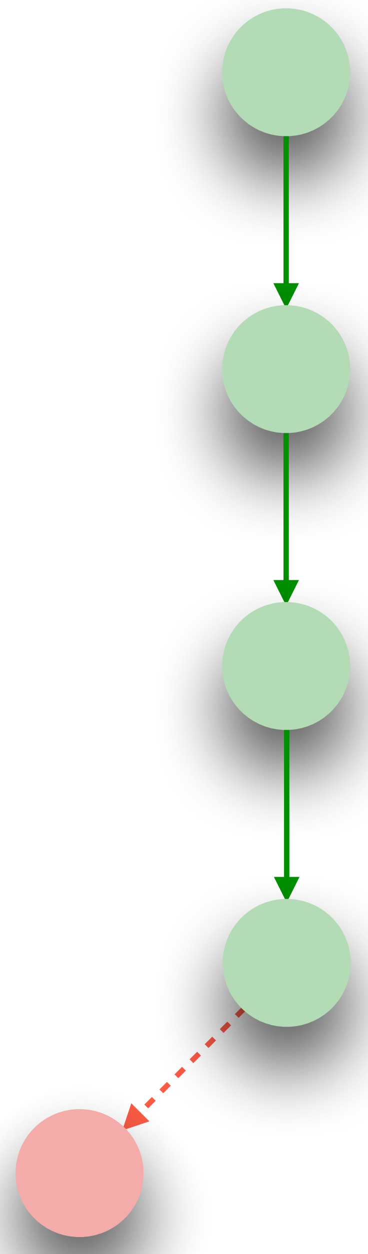

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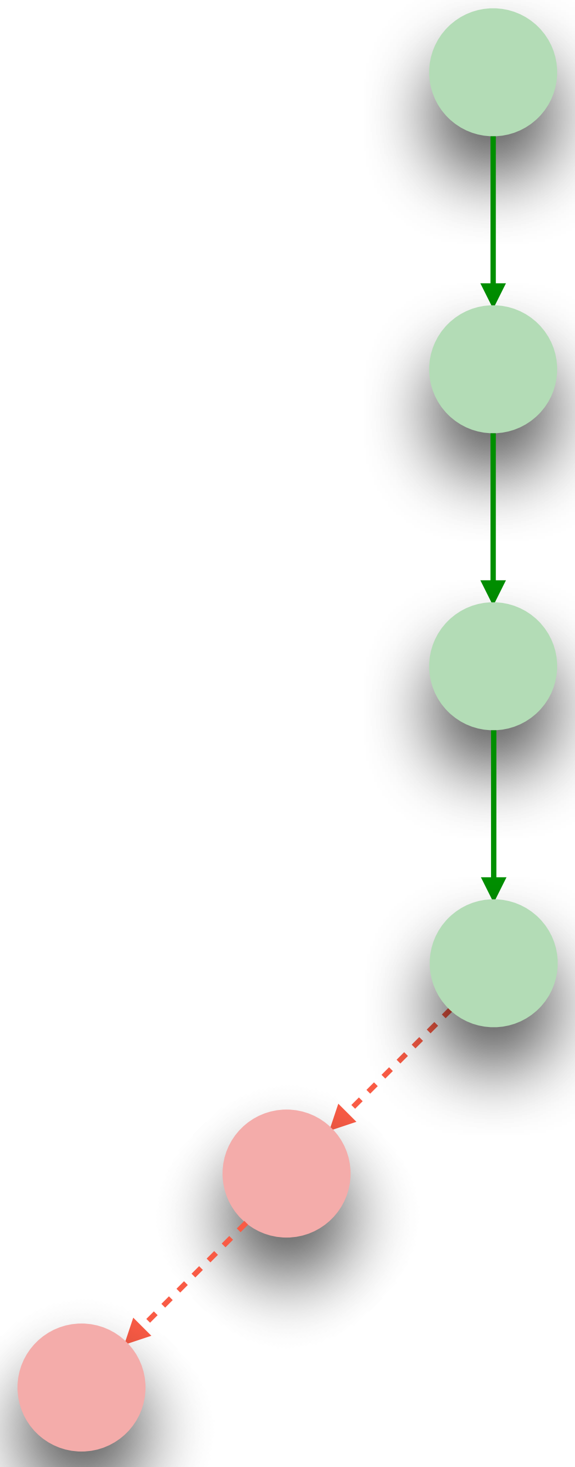

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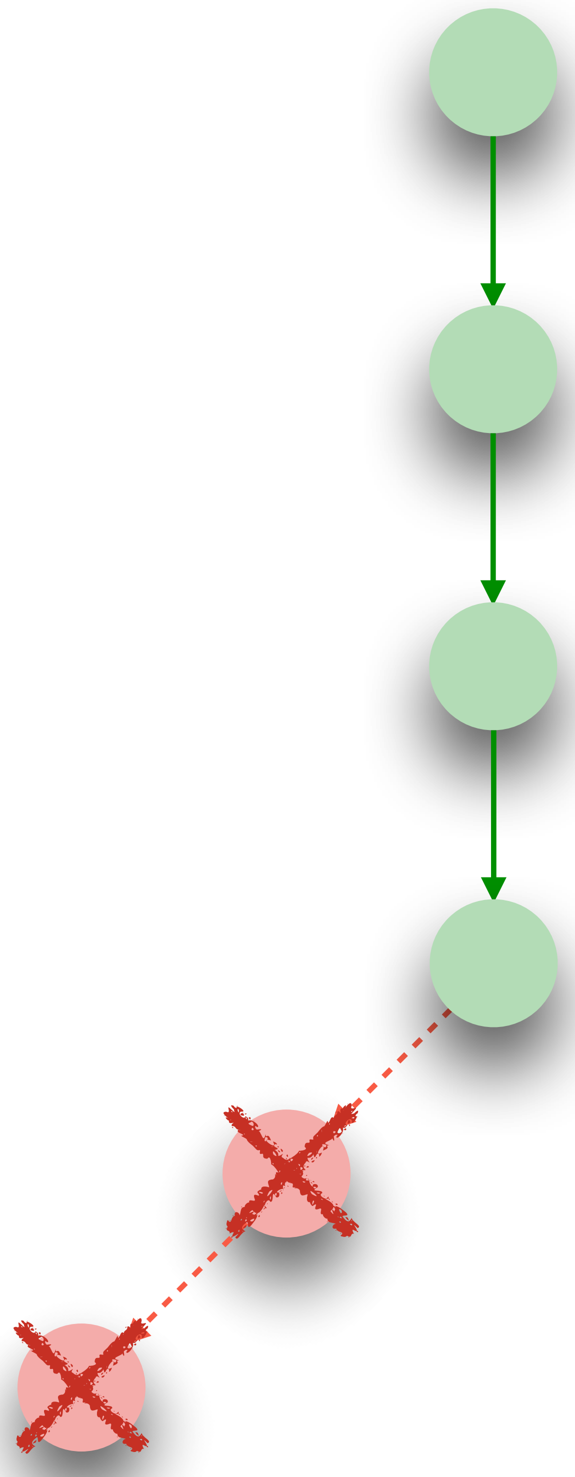

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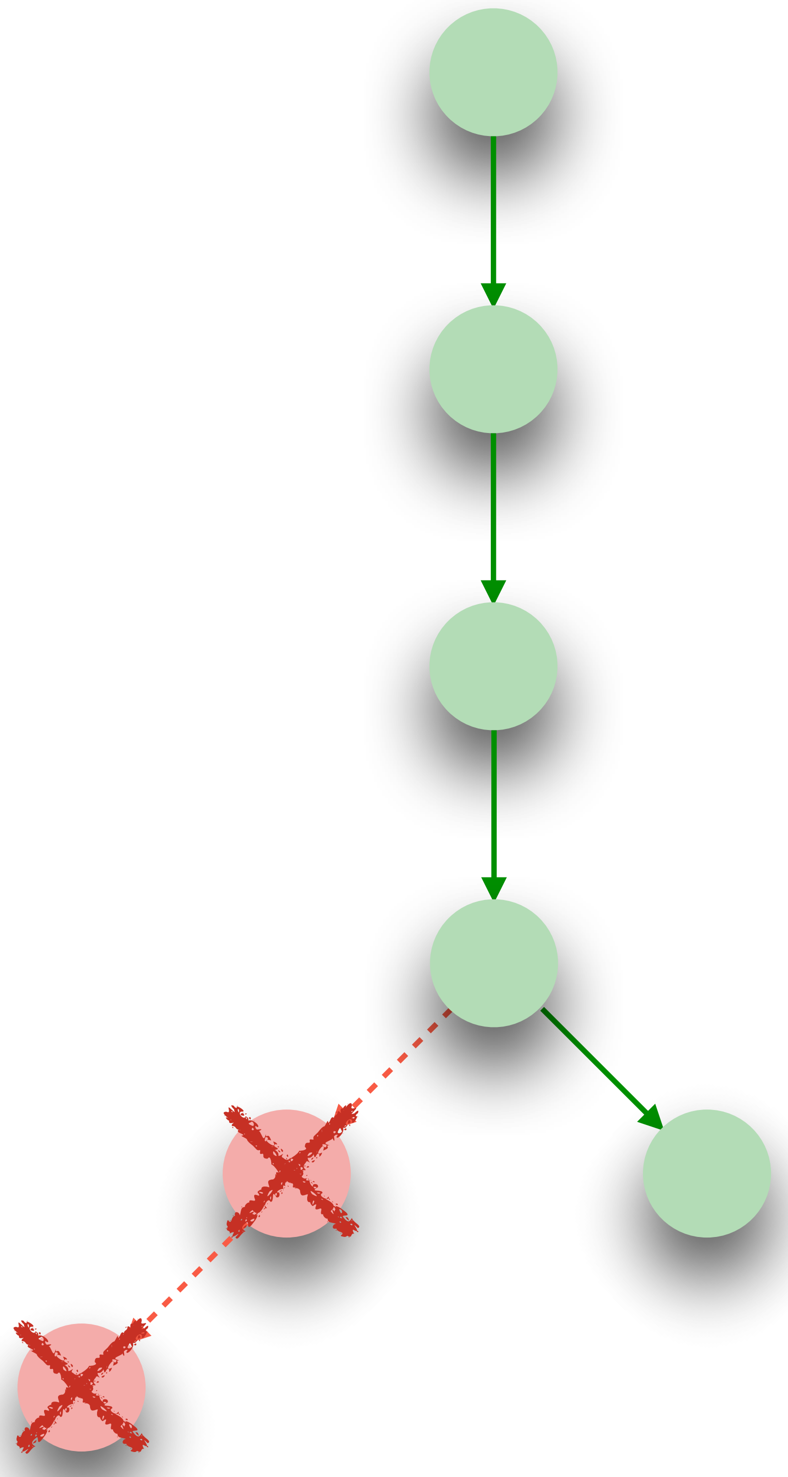

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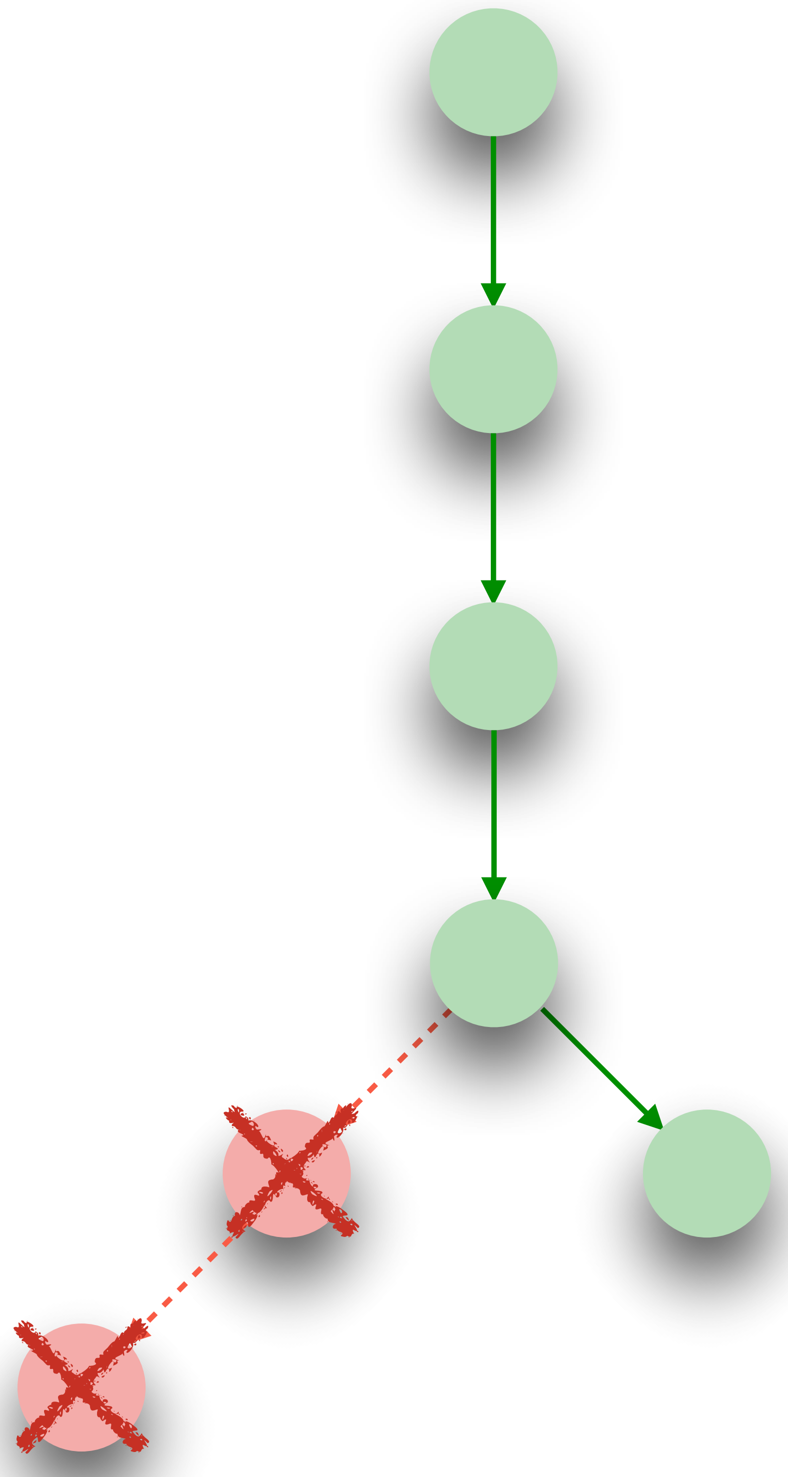

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Prediction Oracle O determines branch prediction + length of speculative window

Observer model: Leakage into μarchitectural state

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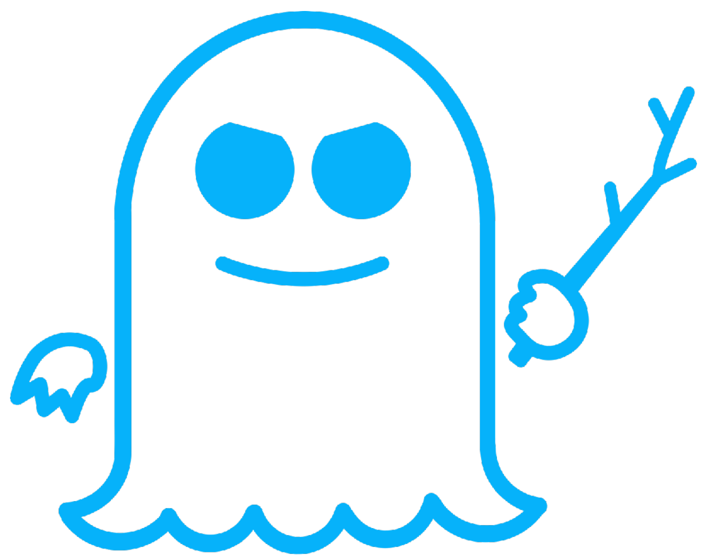
Attacker can observe:
- locations of *memory accesses*
- *branch/jump* targets
- *start/end* speculative execution



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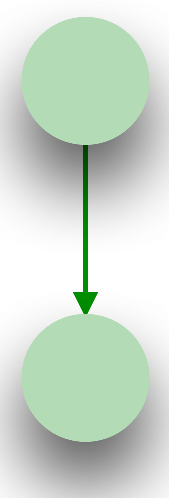

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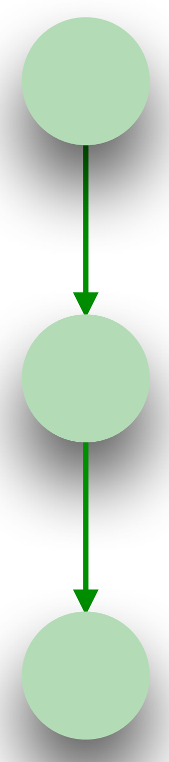

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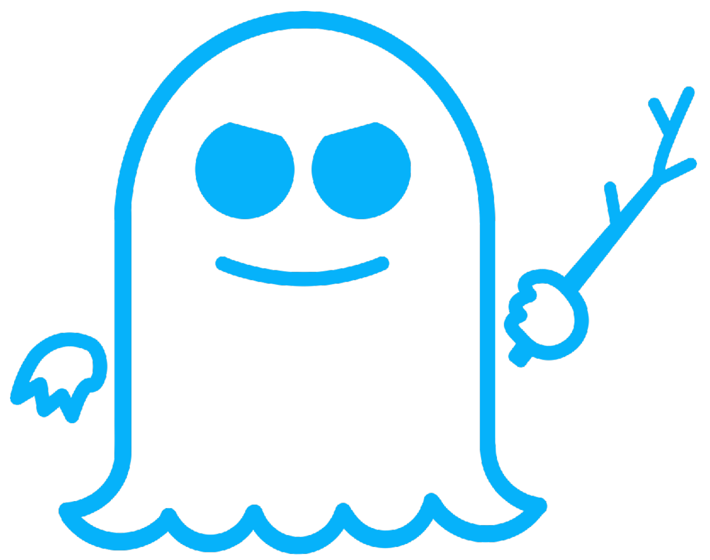

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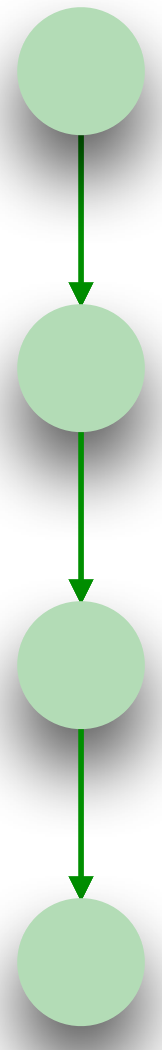

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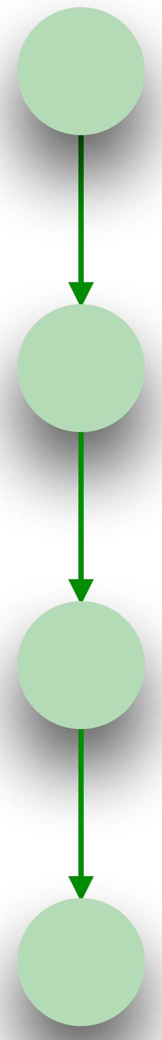

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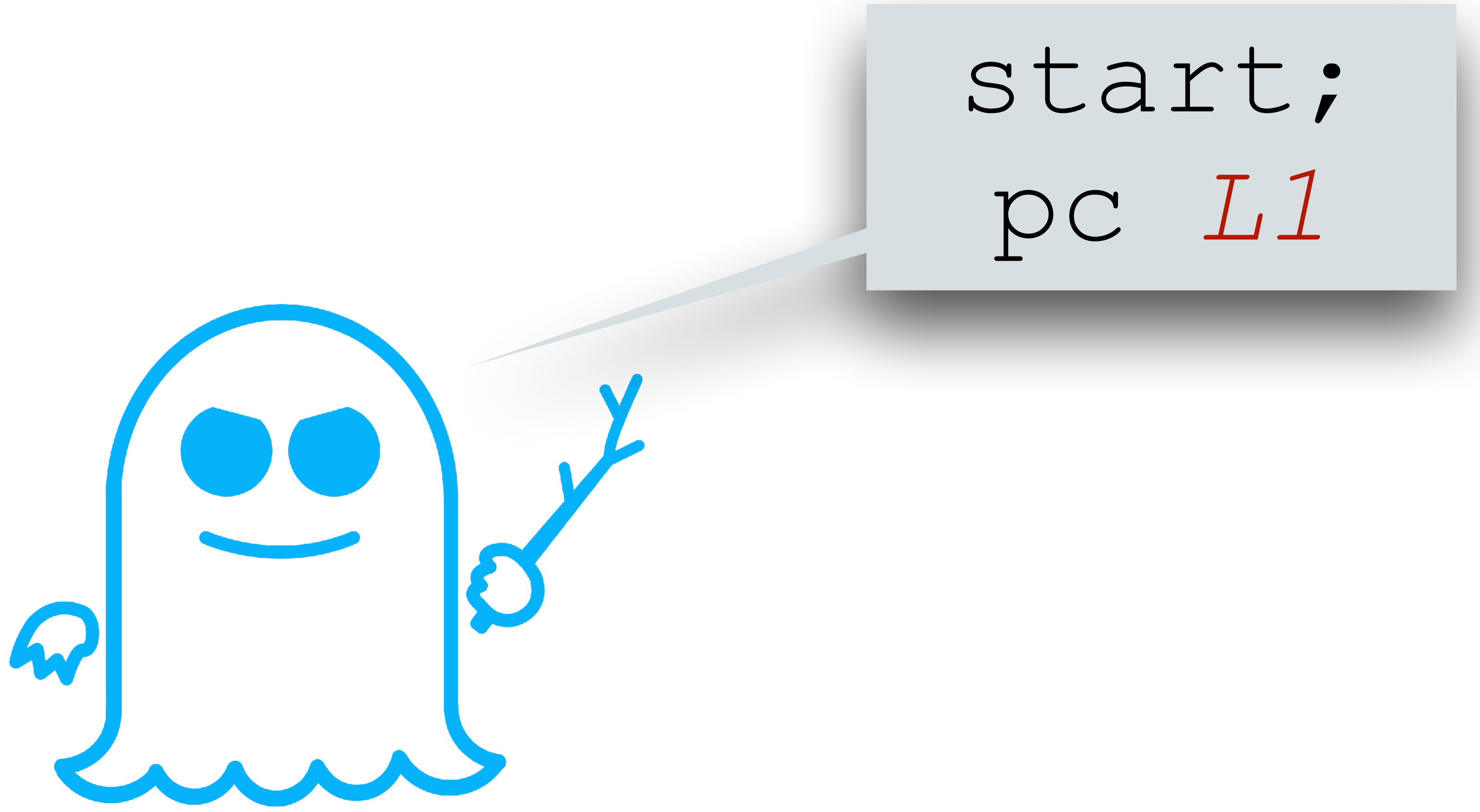

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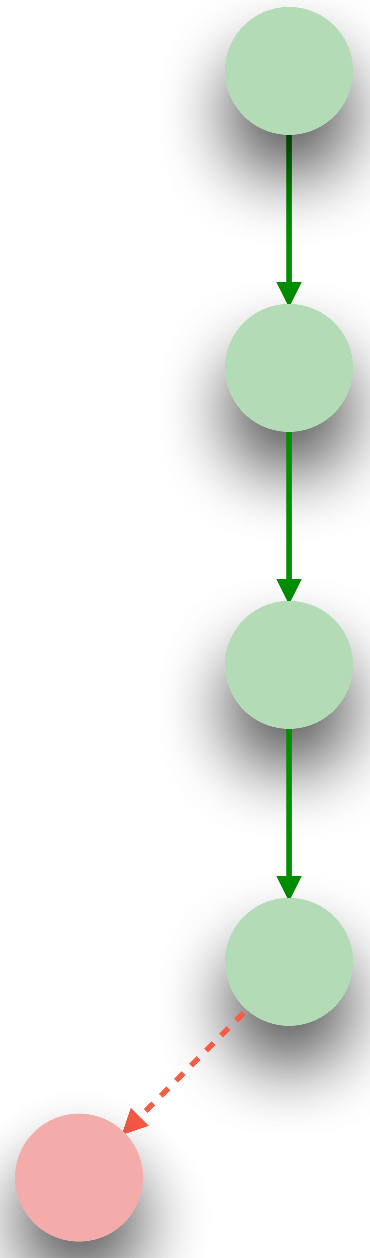

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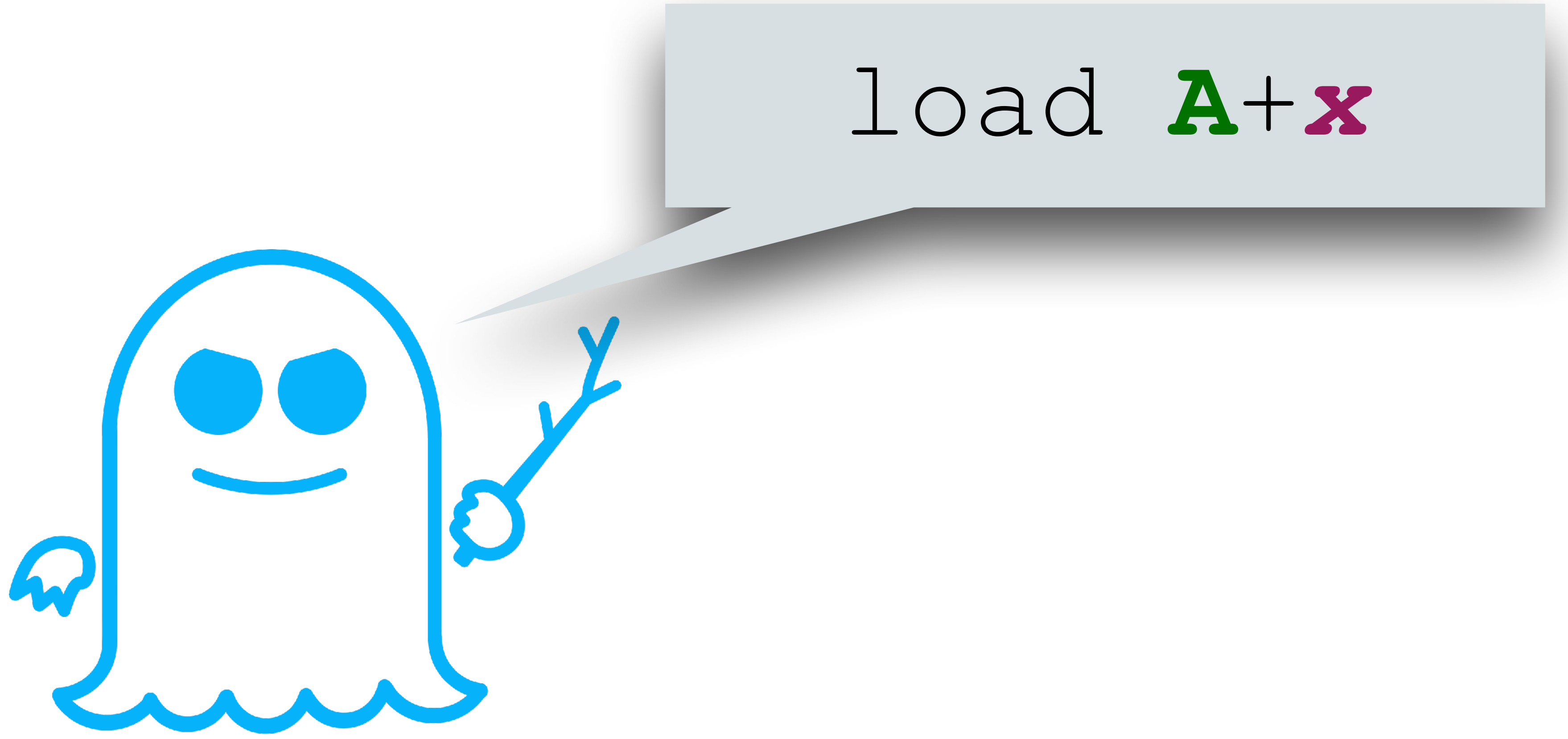

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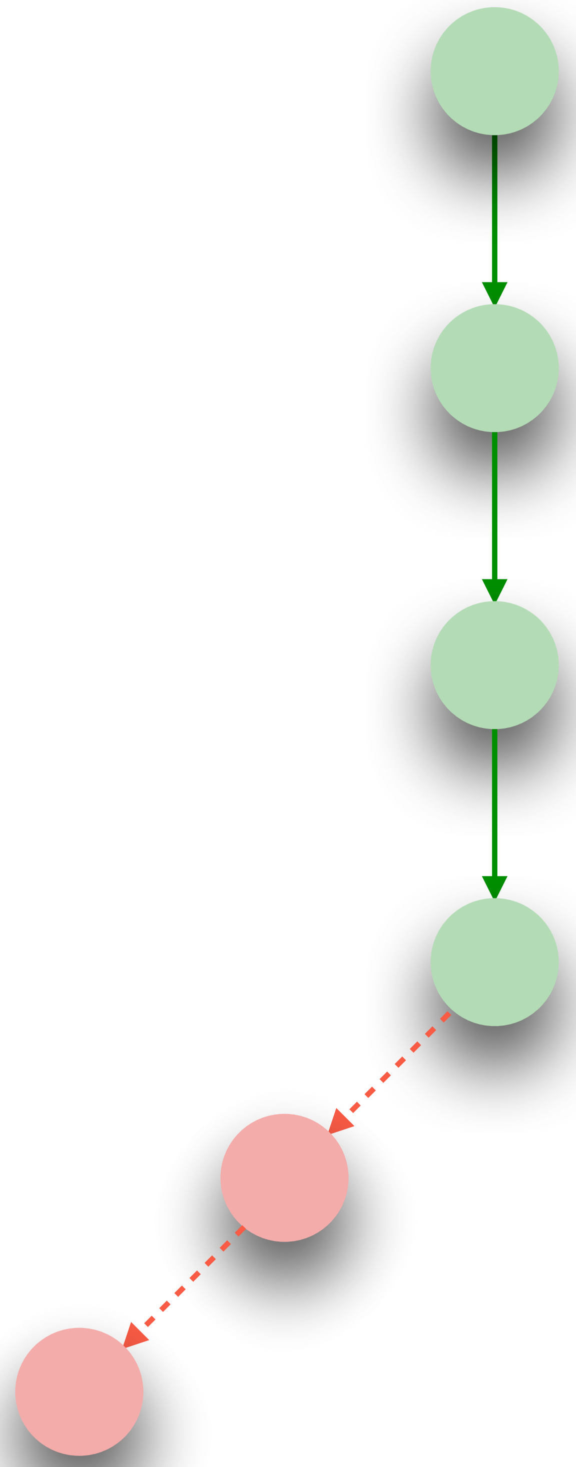

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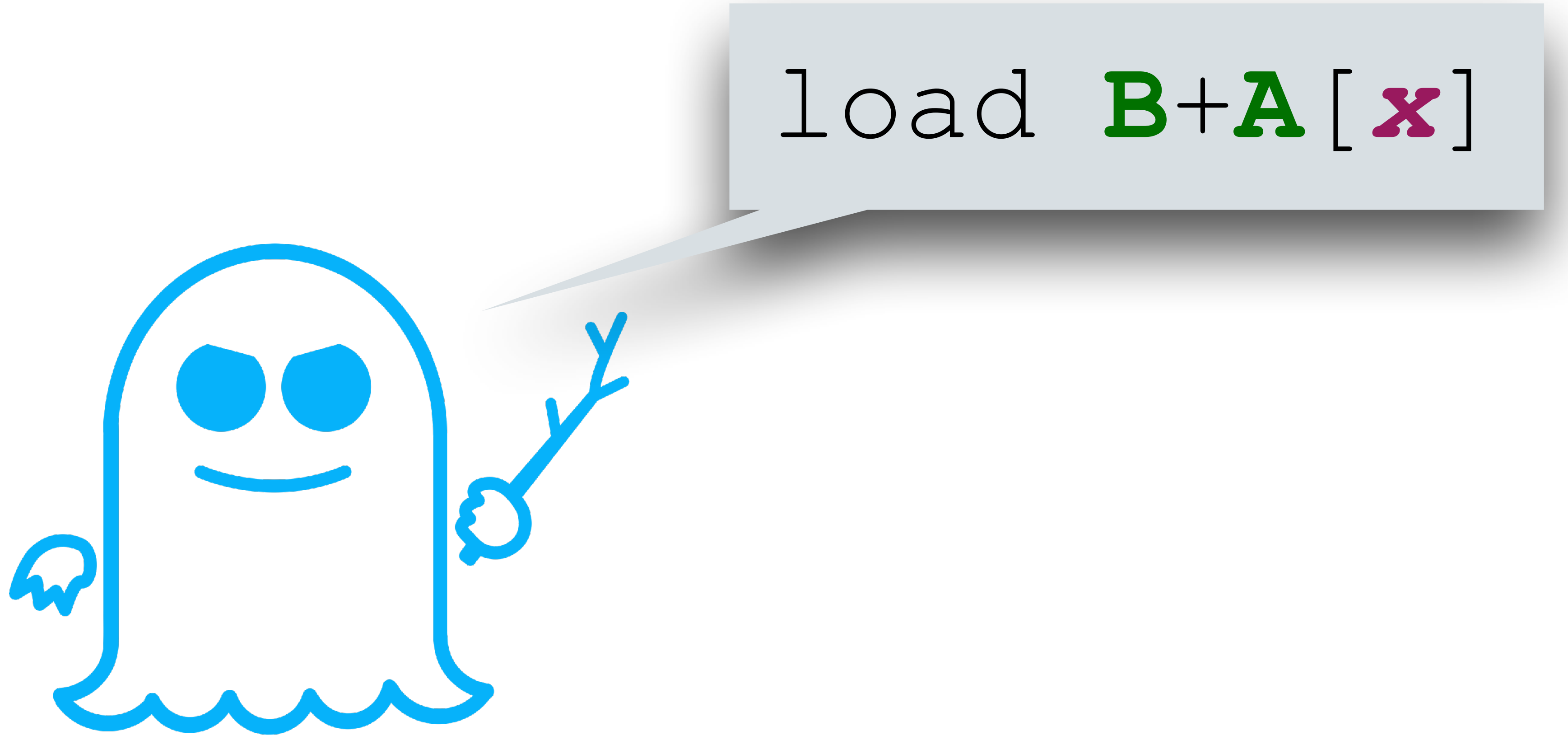

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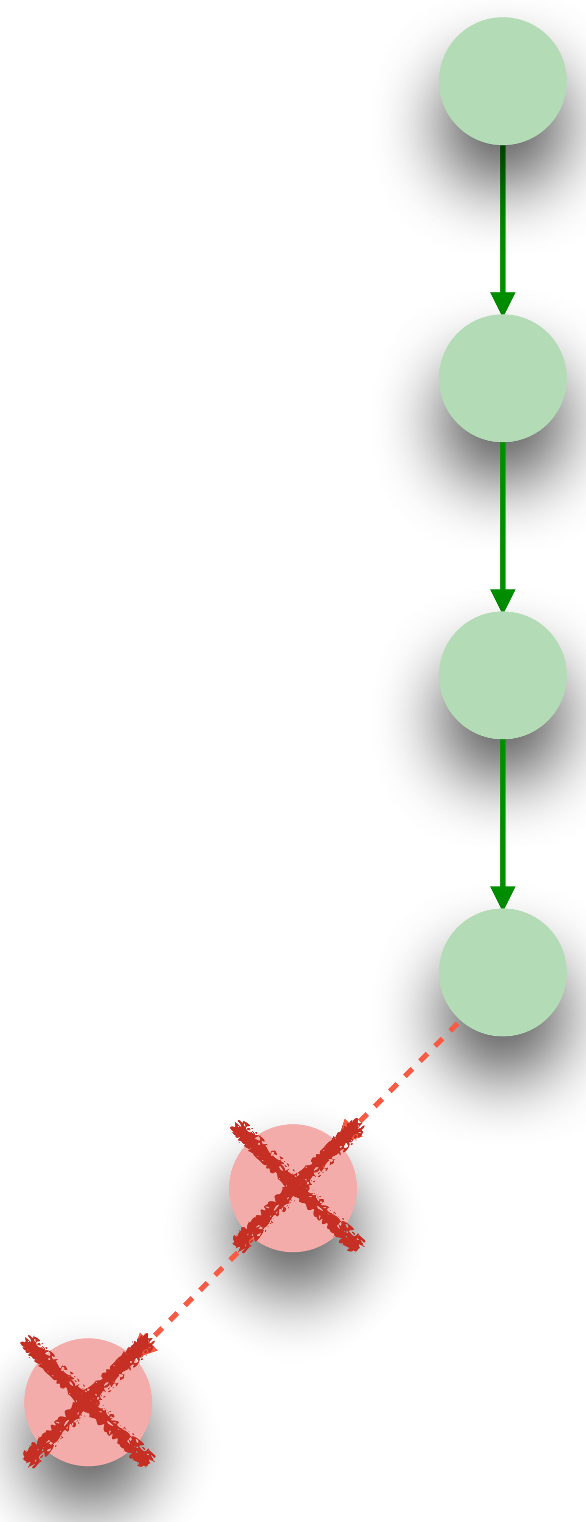

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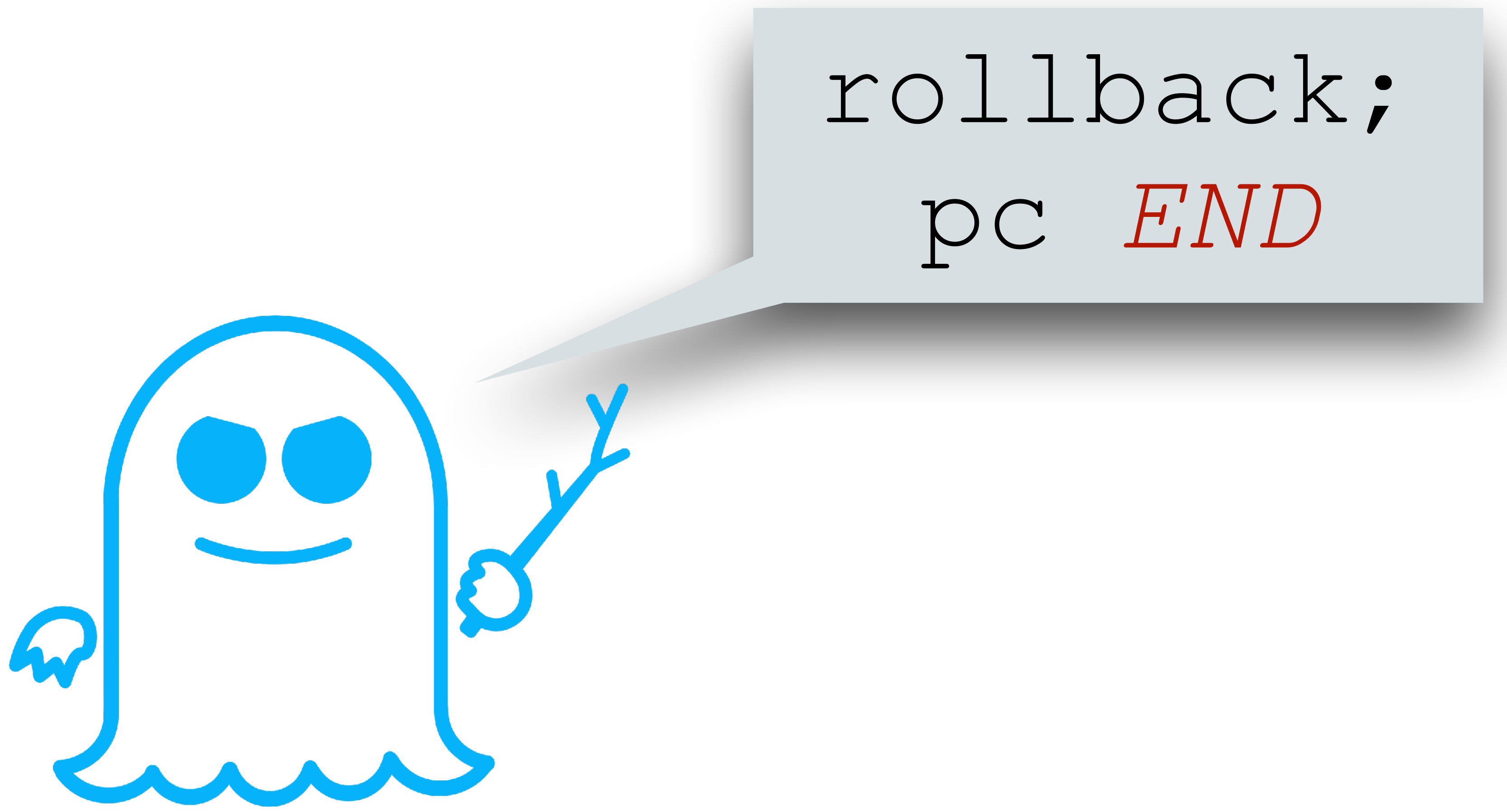

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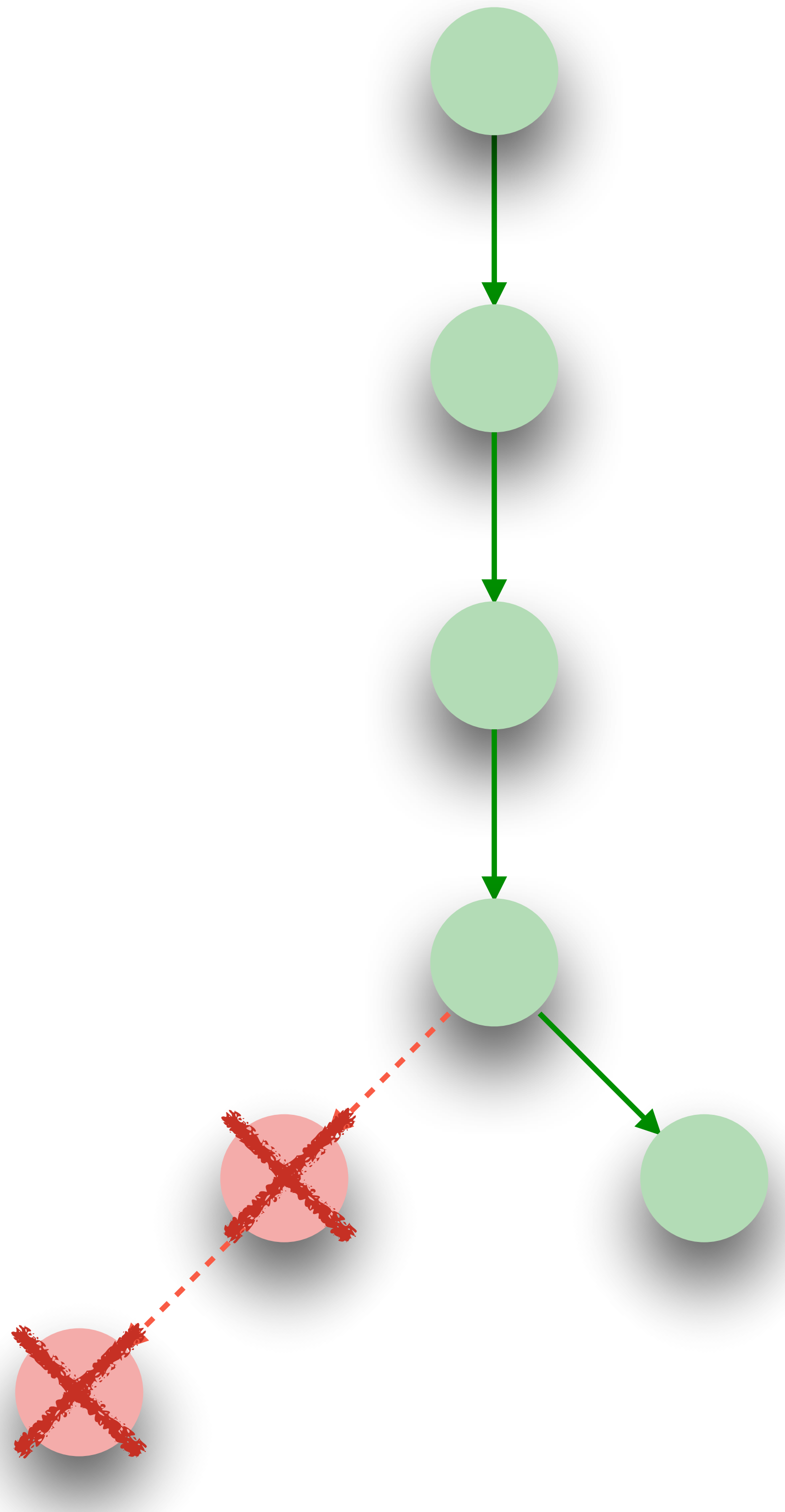

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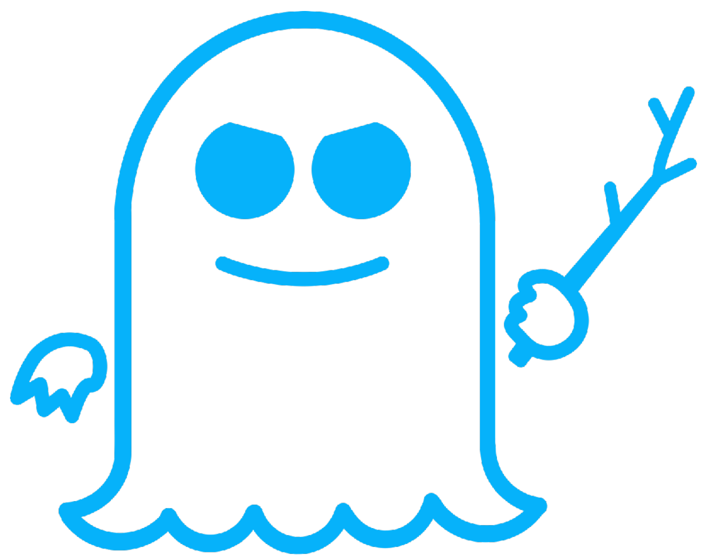

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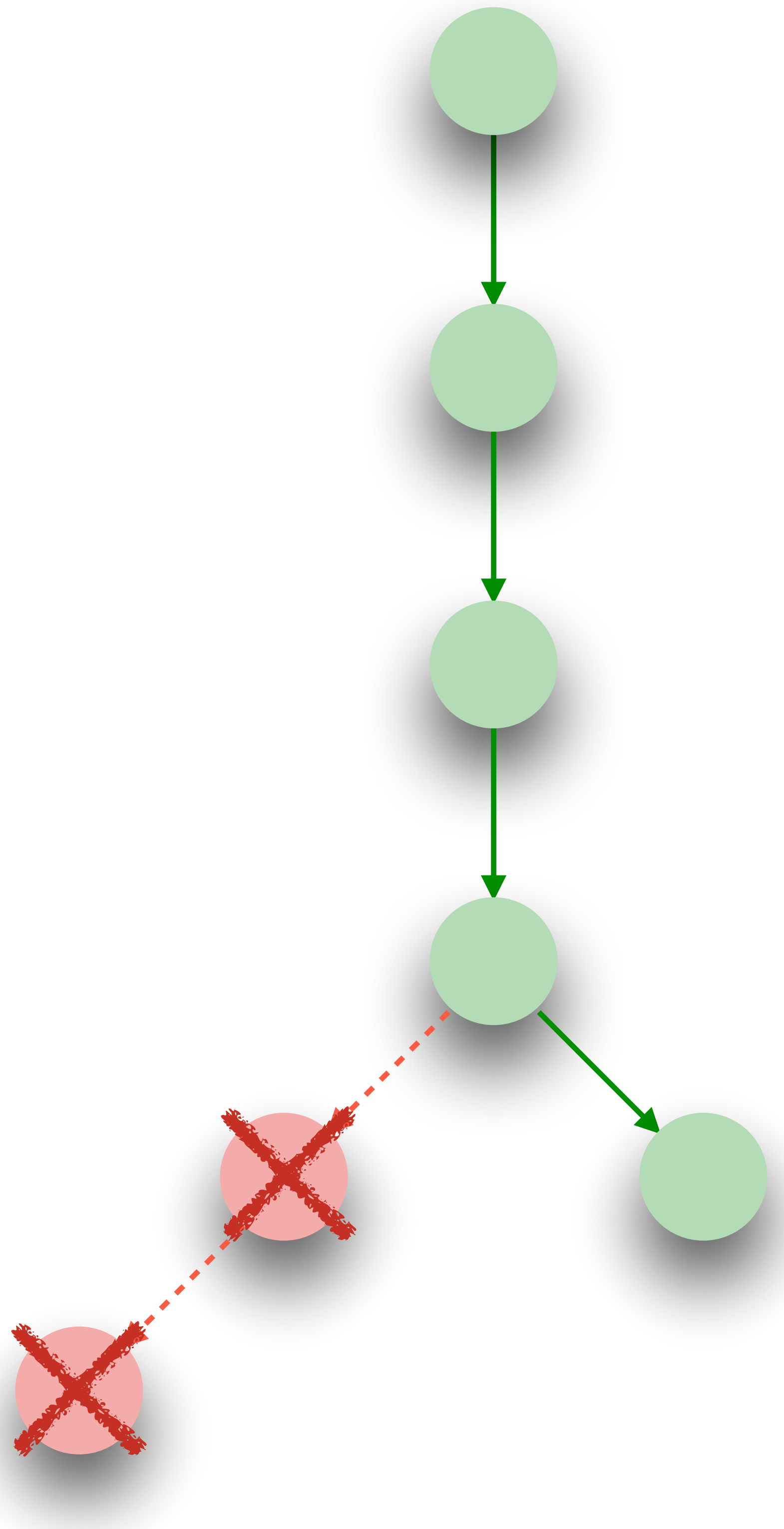

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Inspired by “constant-time” programming requirements

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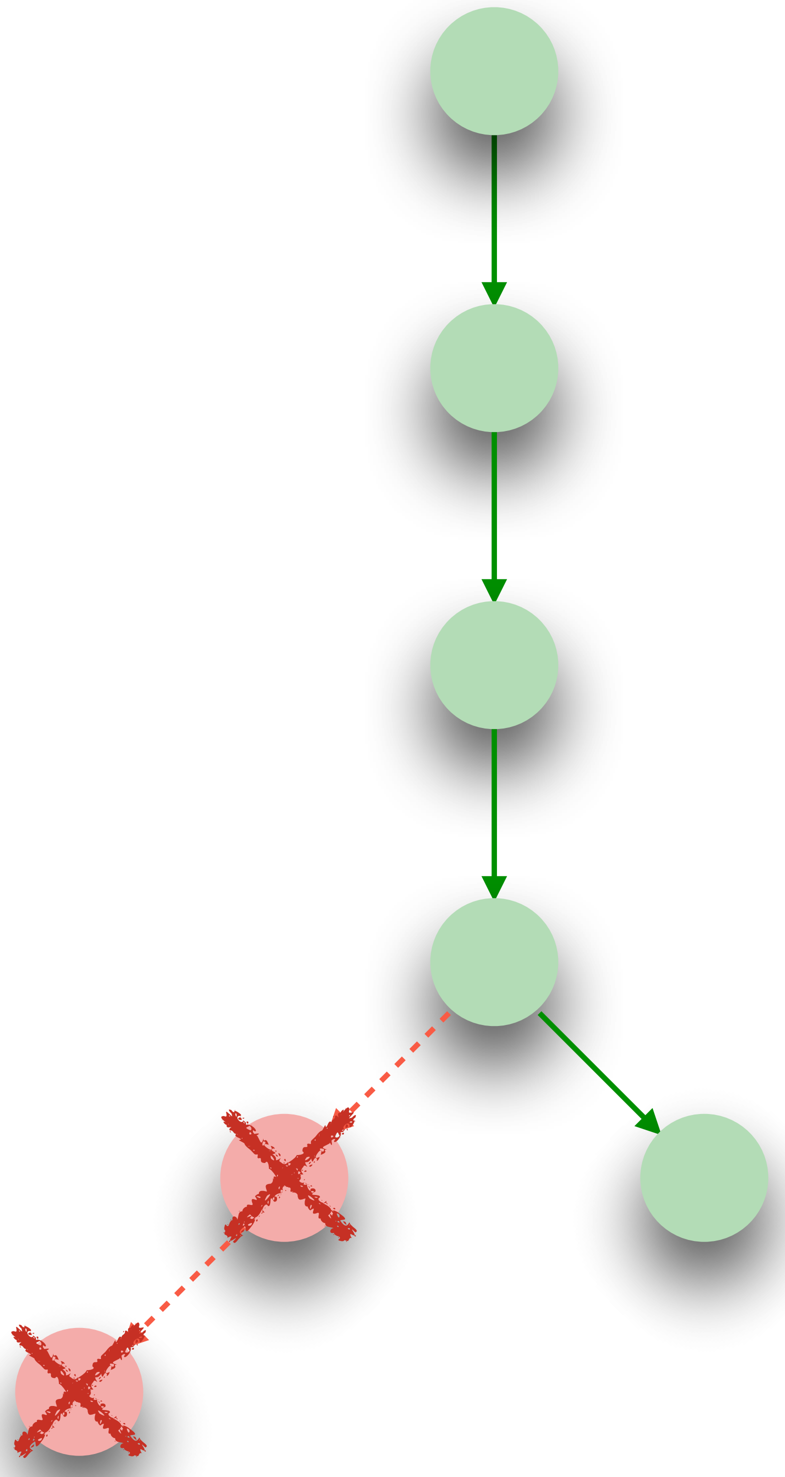

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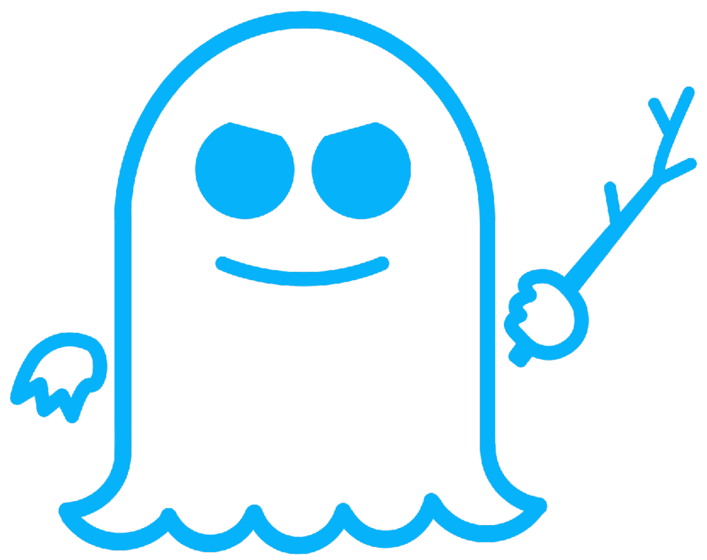
Inspired by "constant-time" programming requirements

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

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    rcx <- x
    jmp rcx≥rax, END
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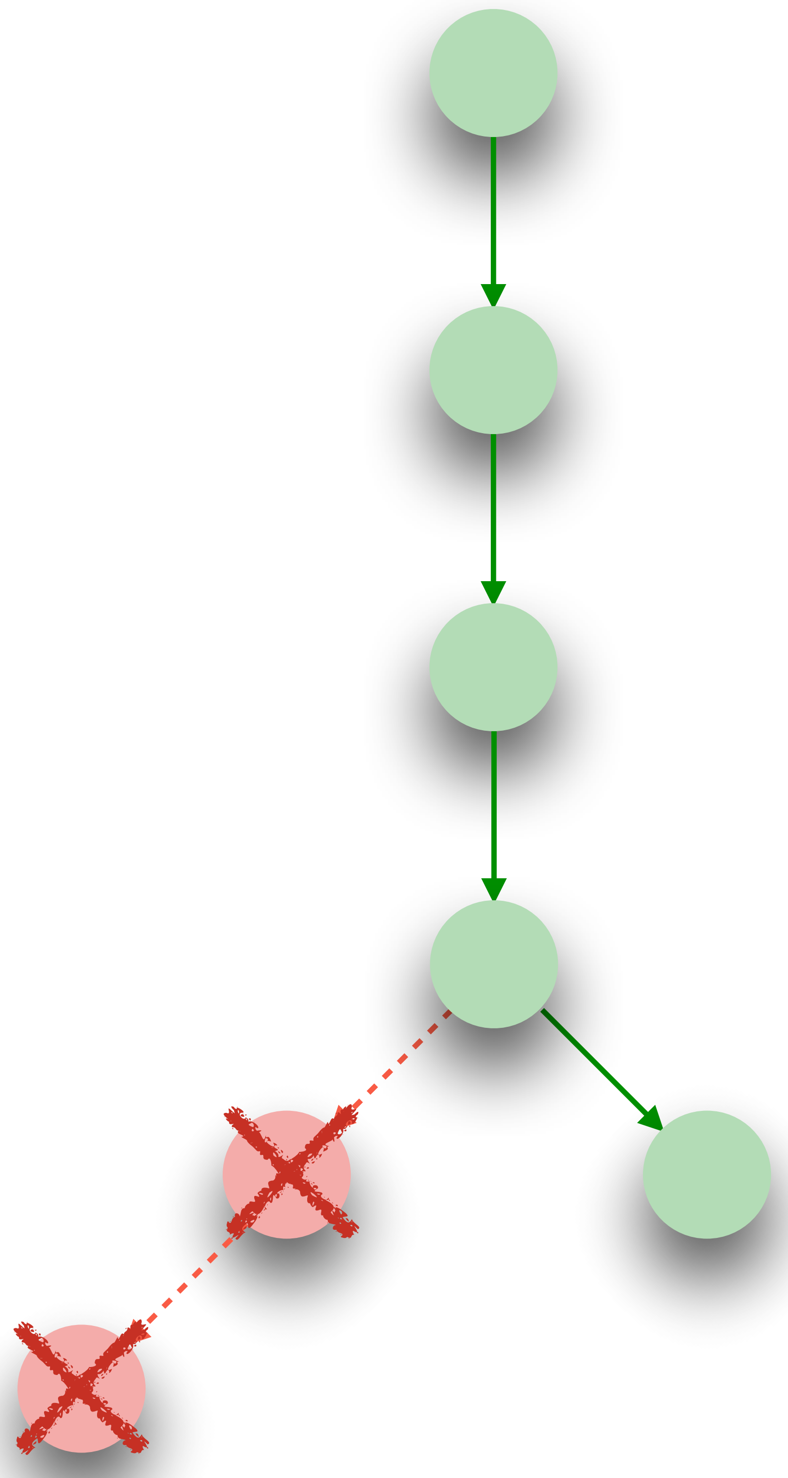

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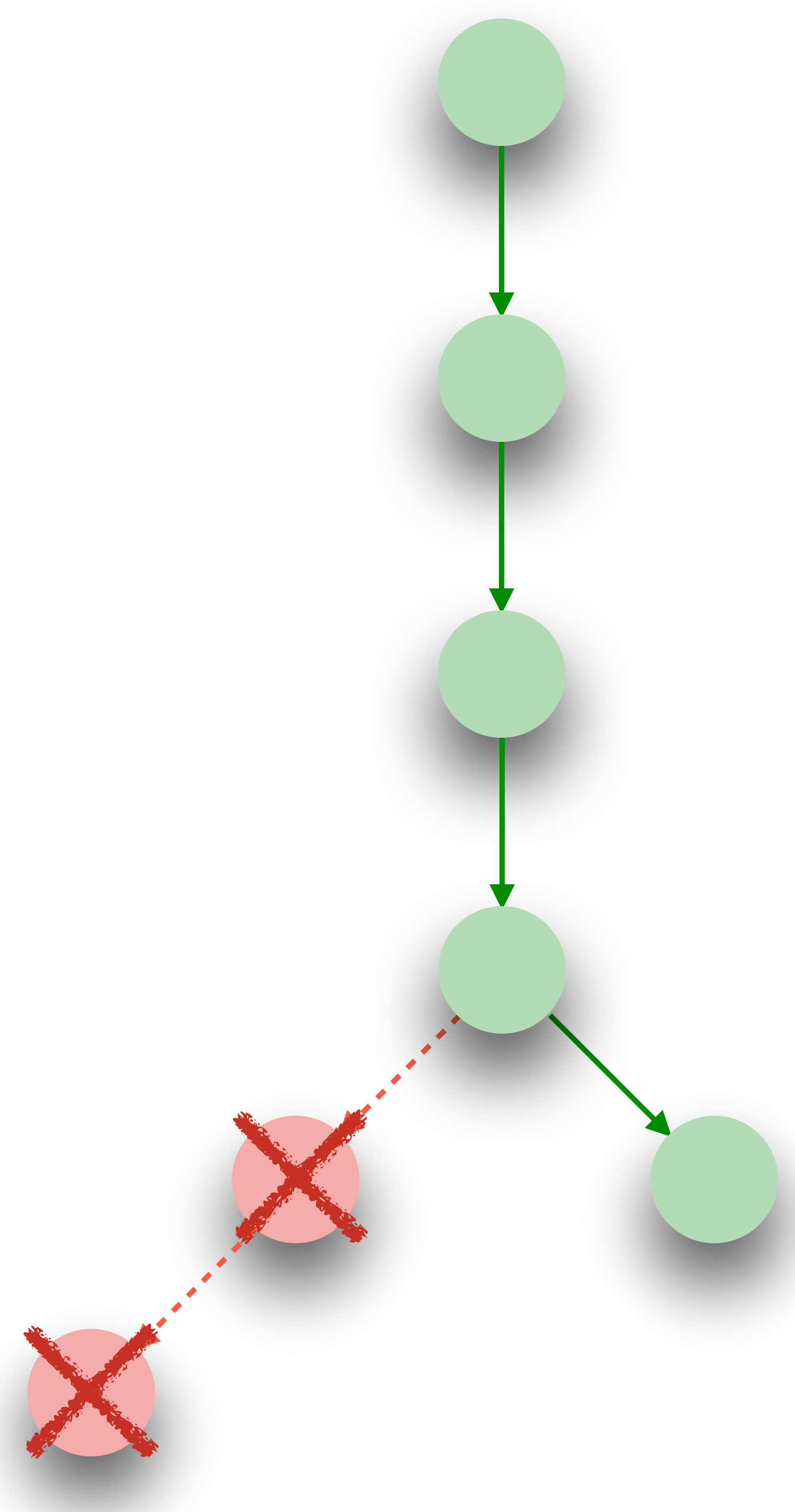

Always mispredict branch instructions' outcomes

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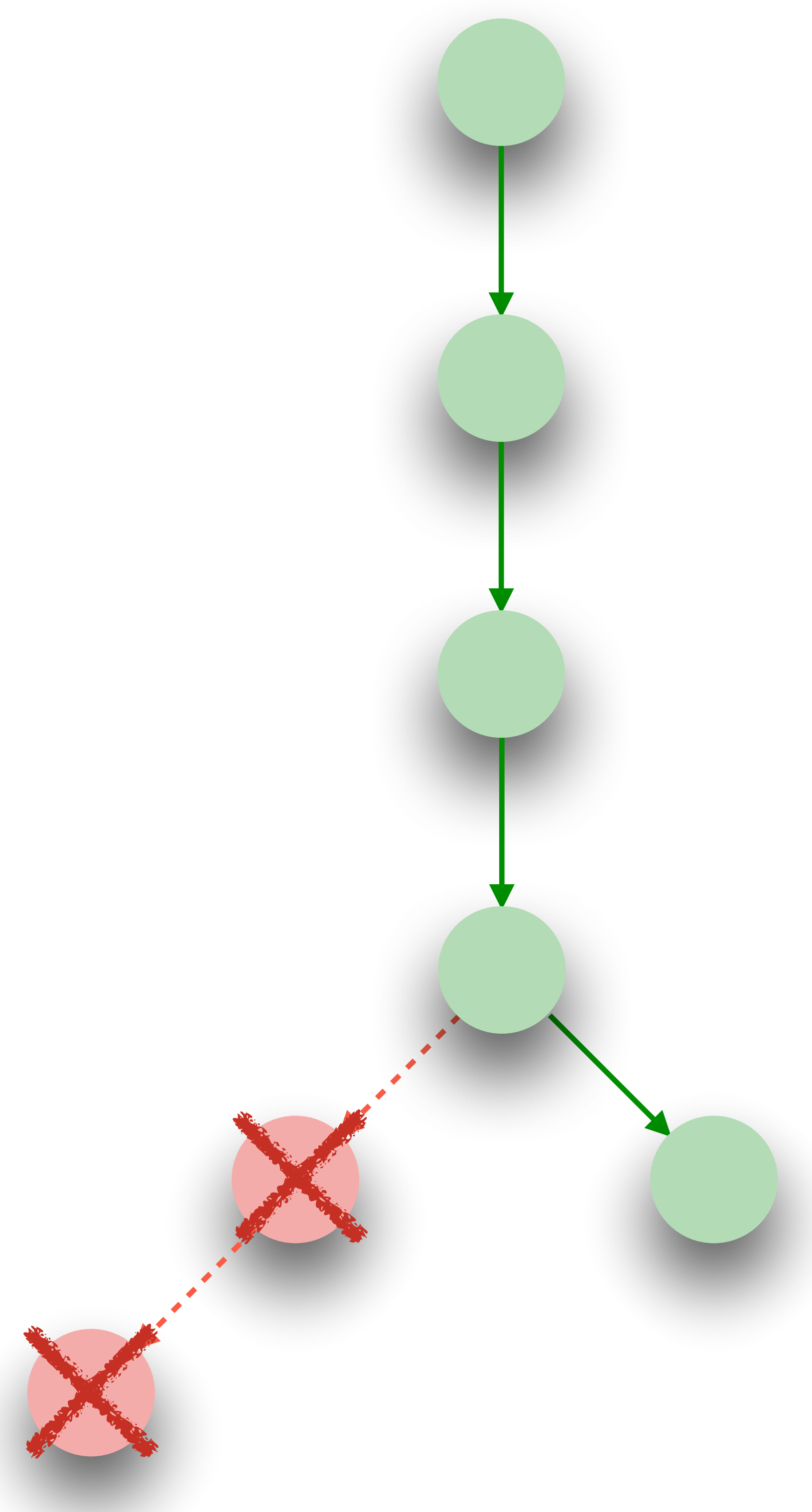

Always mispredict branch instructions' outcomes

Fixed speculative window

Always-mispredict speculative semantics

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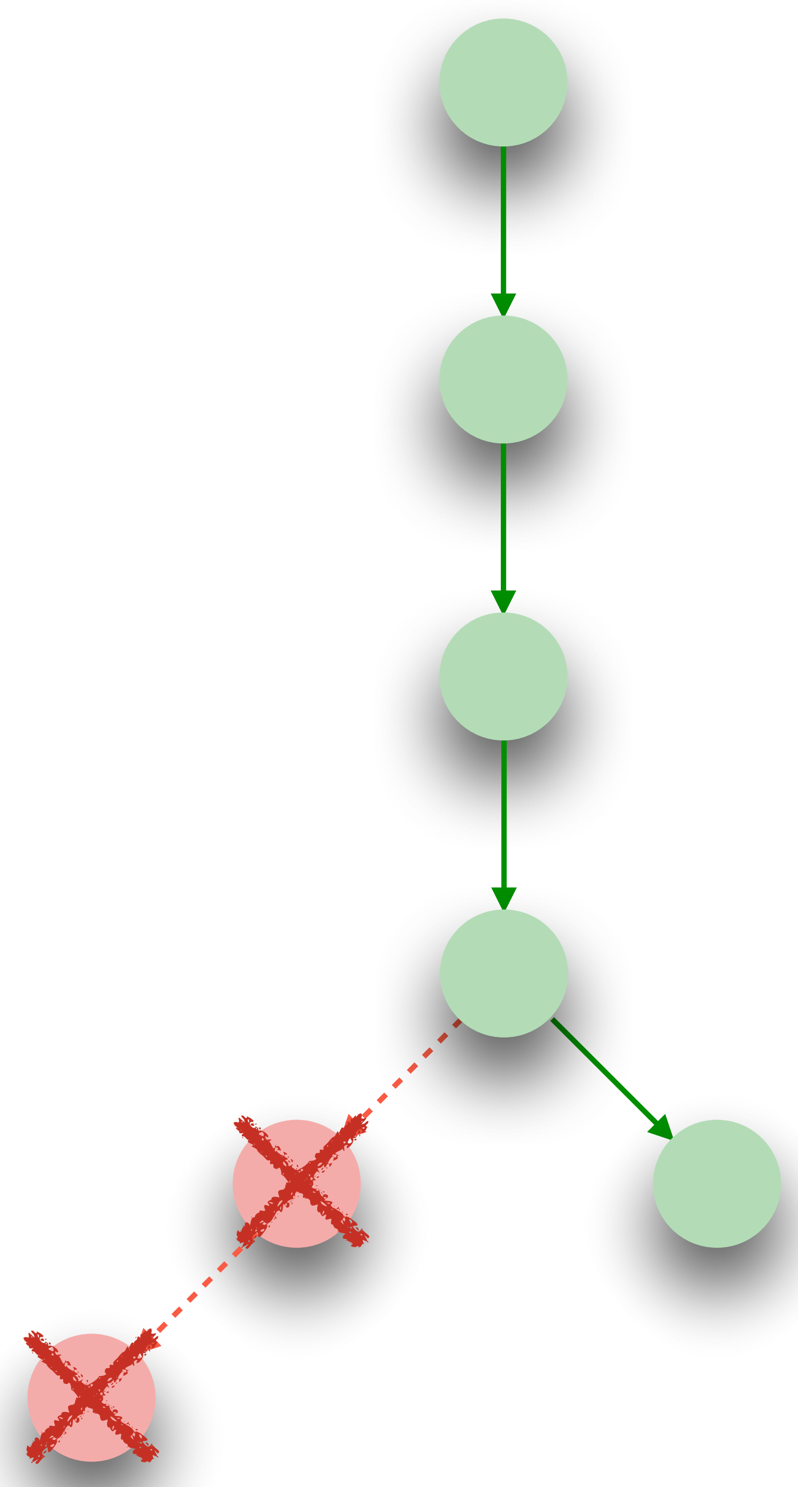

Always mispredict branch instructions' outcomes

Fixed speculative window

Rollback of every transaction

Always-mispredict speculative semantics: Inference Rules

SE-NOBRANCH

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

SE-BRANCH-SYMB

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

SE-ROLLBACK

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

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

For all program states s and s':

$$\texttt{P}_{\texttt{non-spec}}(s) = \texttt{P}_{\texttt{non-spec}}(s') \Rightarrow \texttt{P}_{\texttt{spec}}(s) = \texttt{P}_{\texttt{spec}}(s')$$

Speculative non-interference: Example

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    rax <- A_size
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```

x=128
A_size=16
A[128]=0

x=128
A_size=16
A[128]=1

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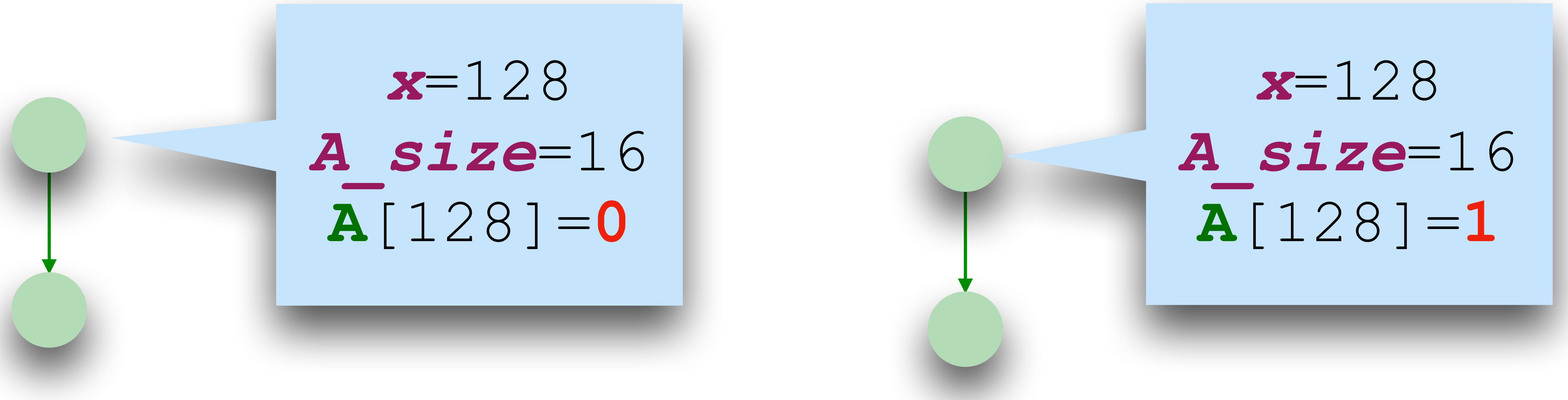

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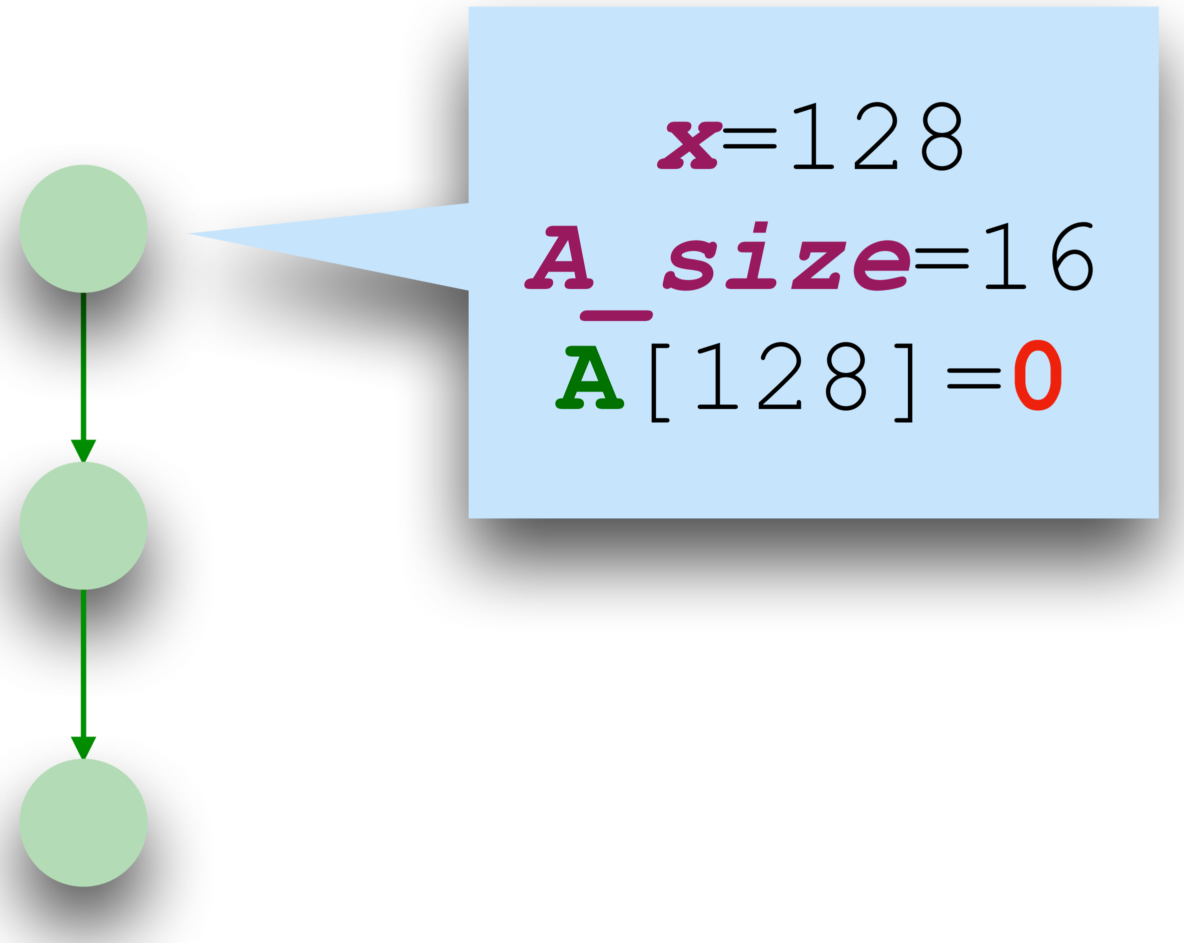

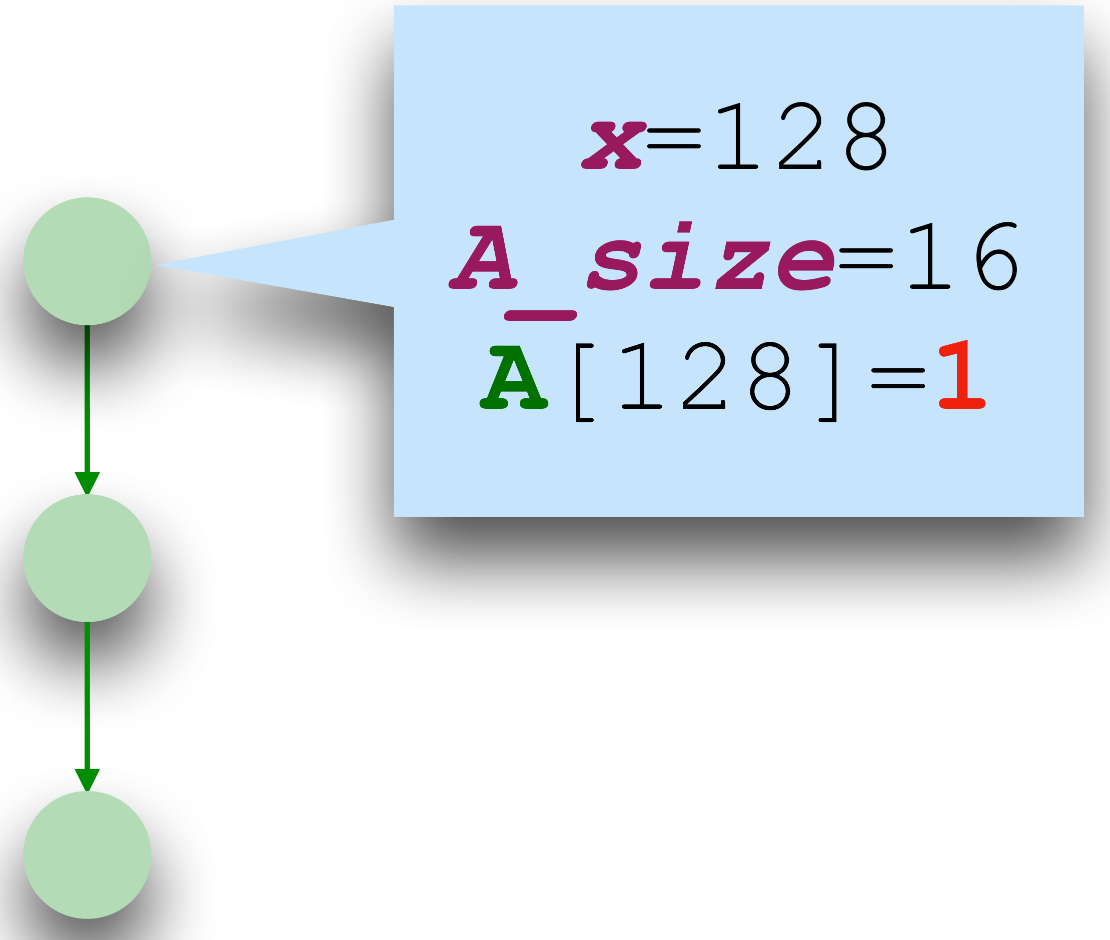

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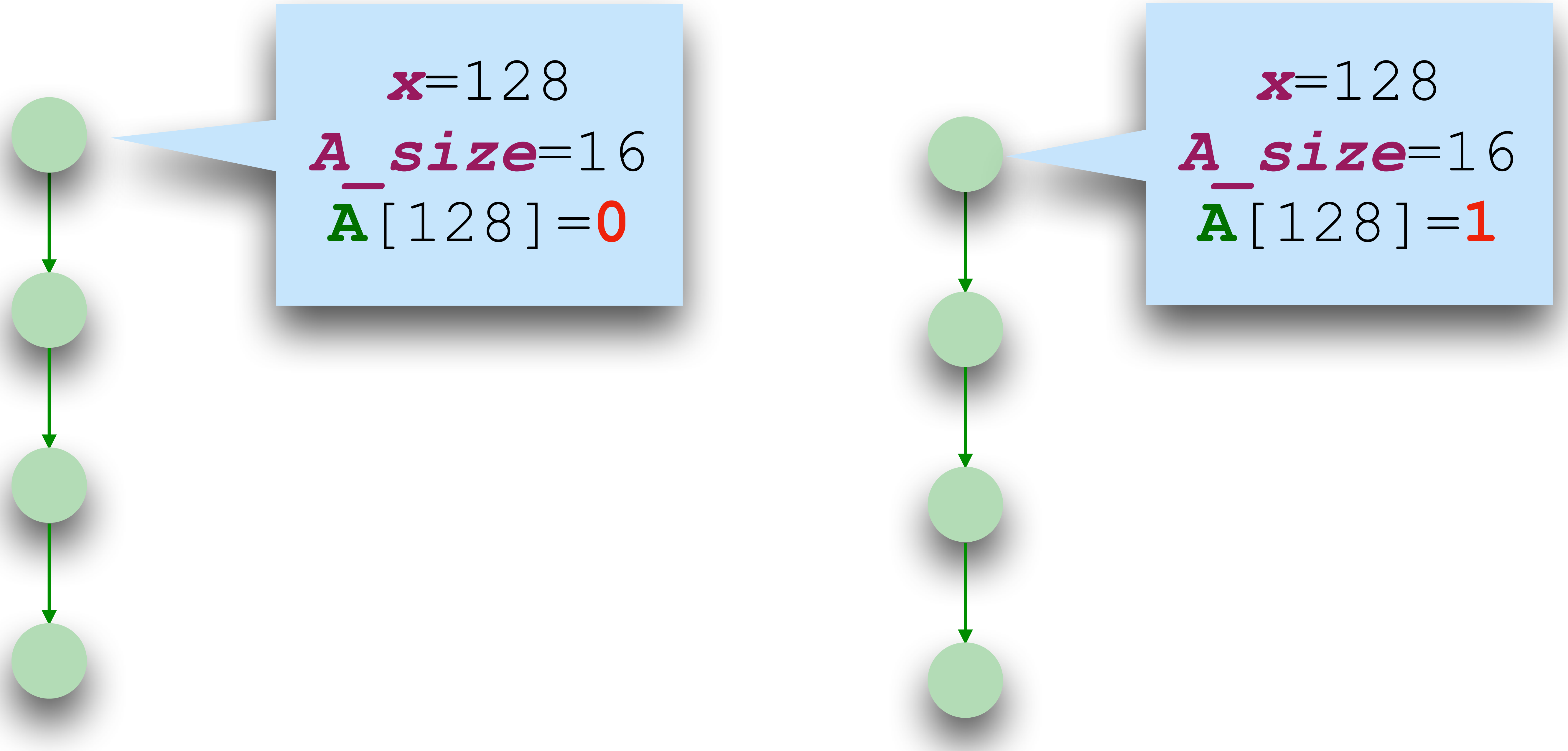

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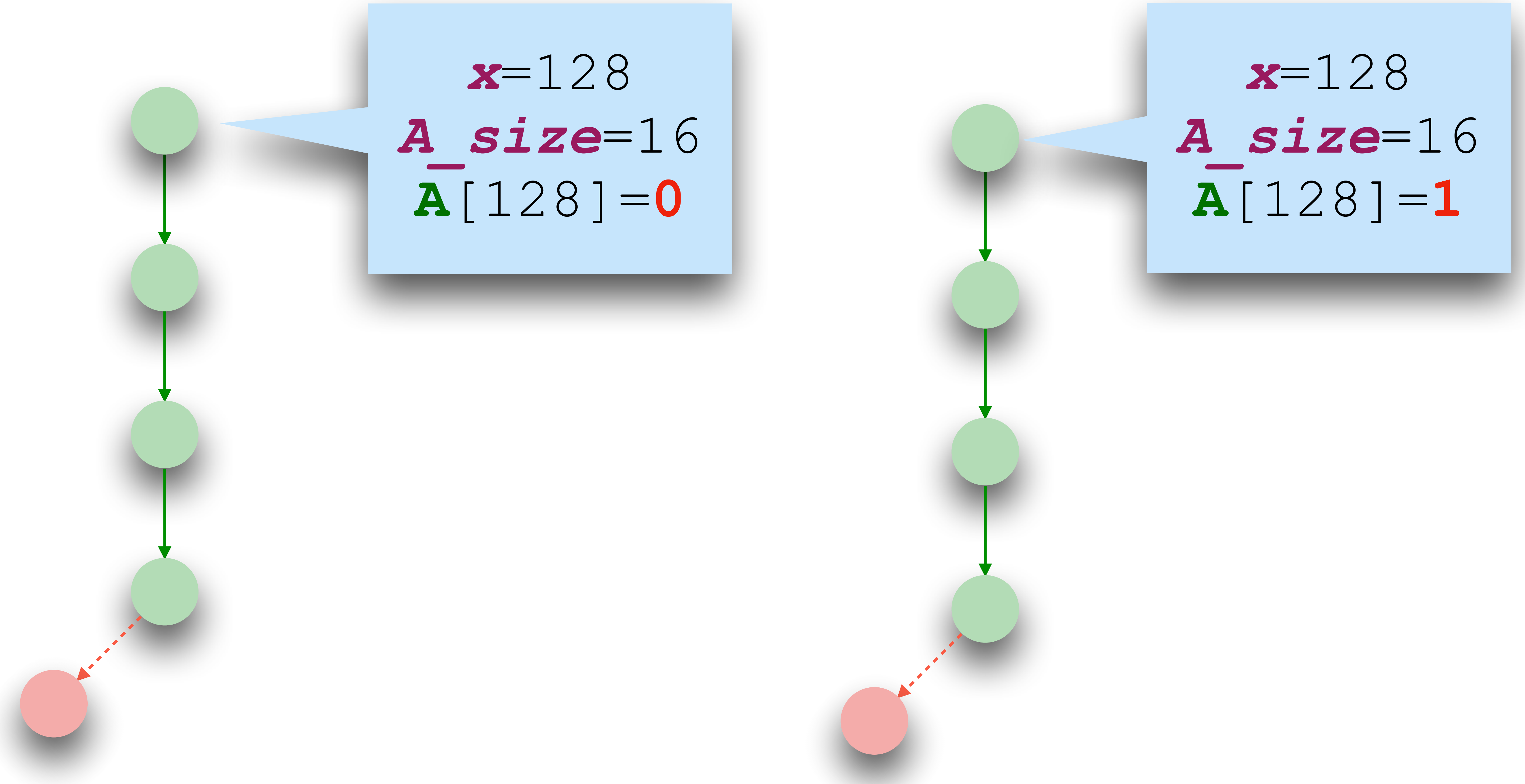

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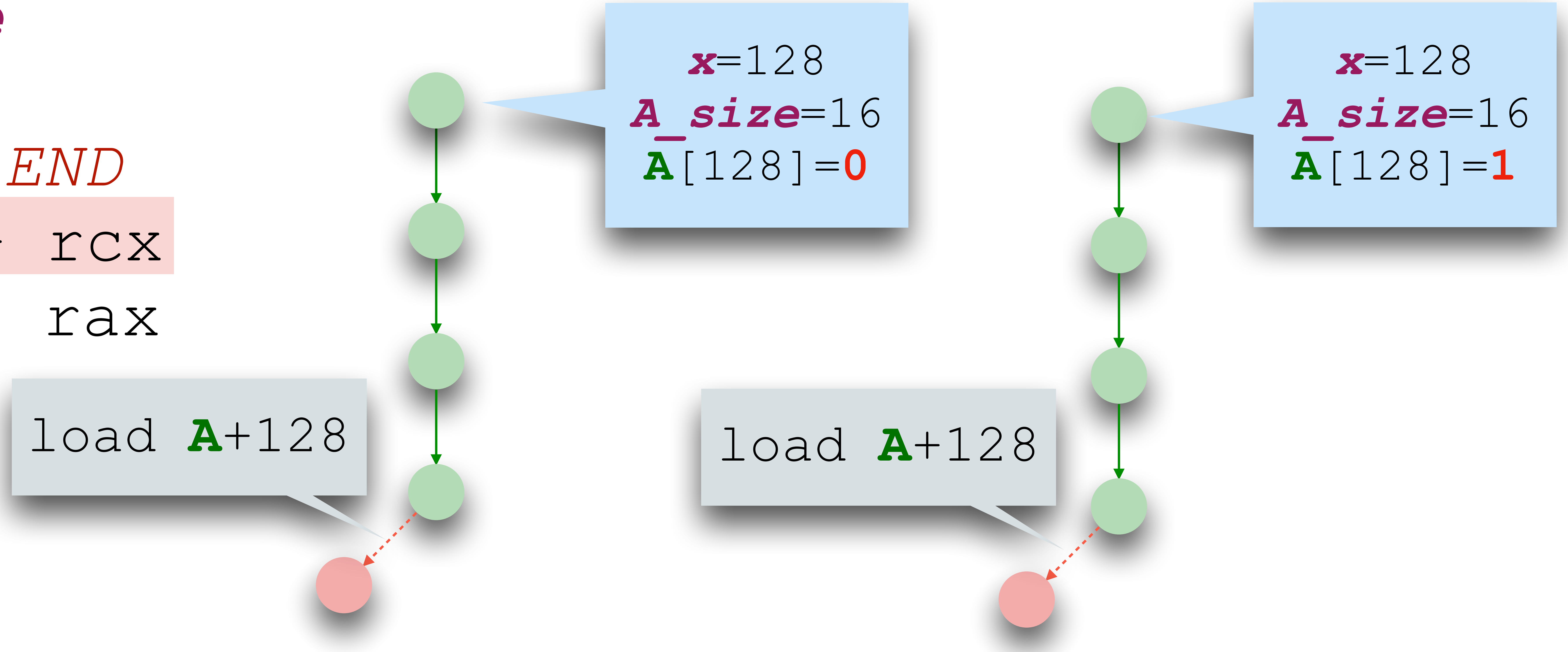

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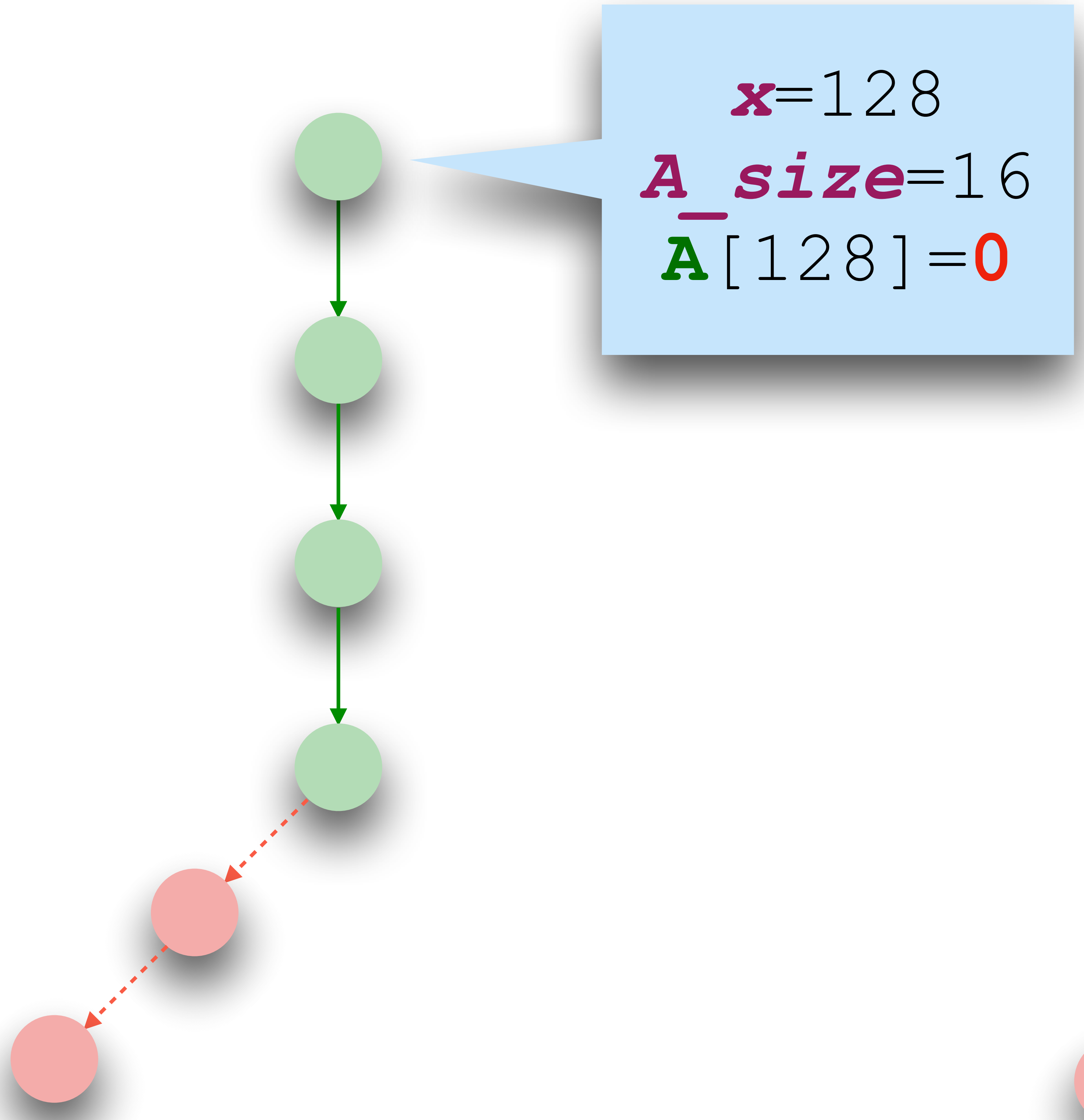

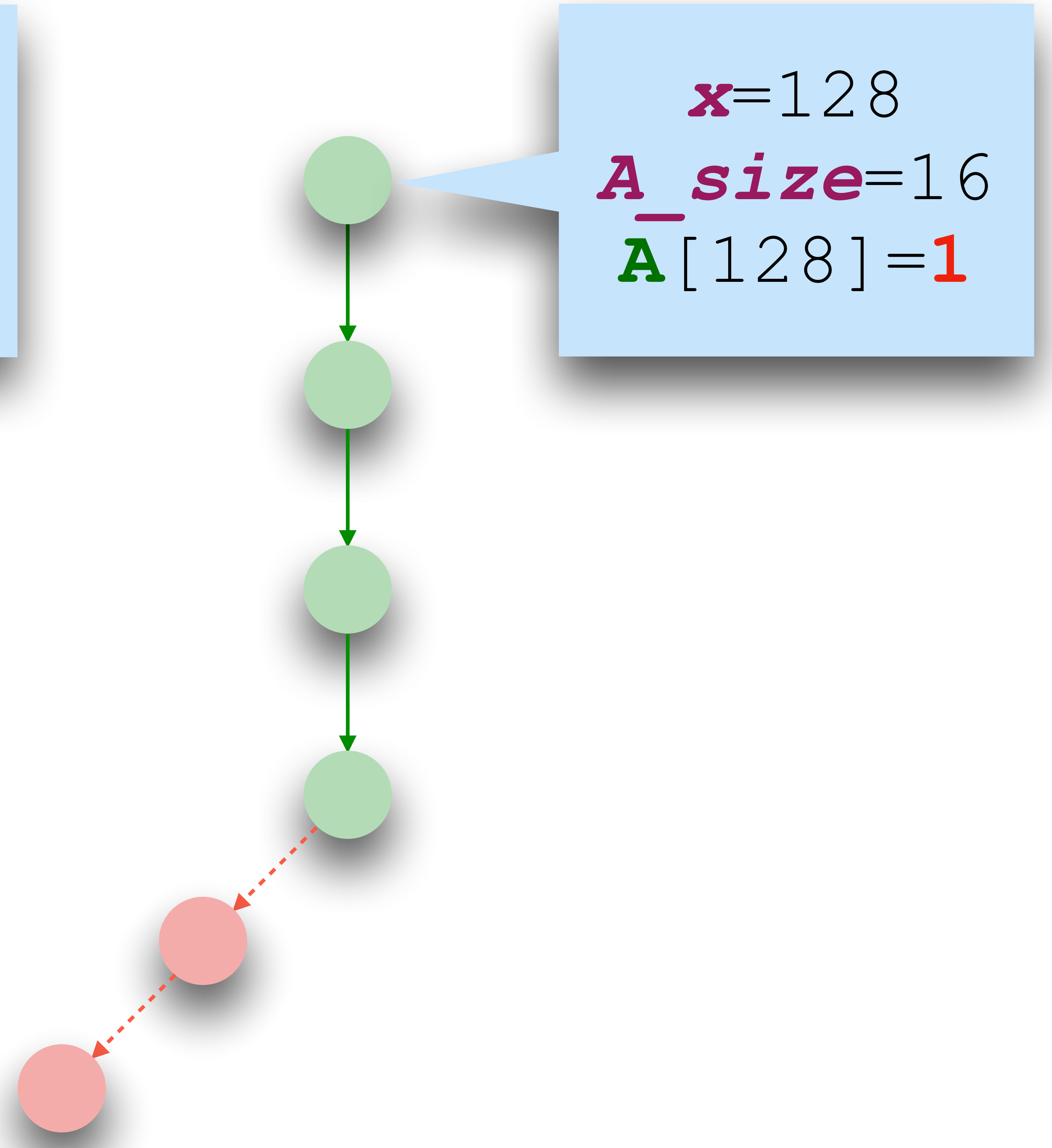

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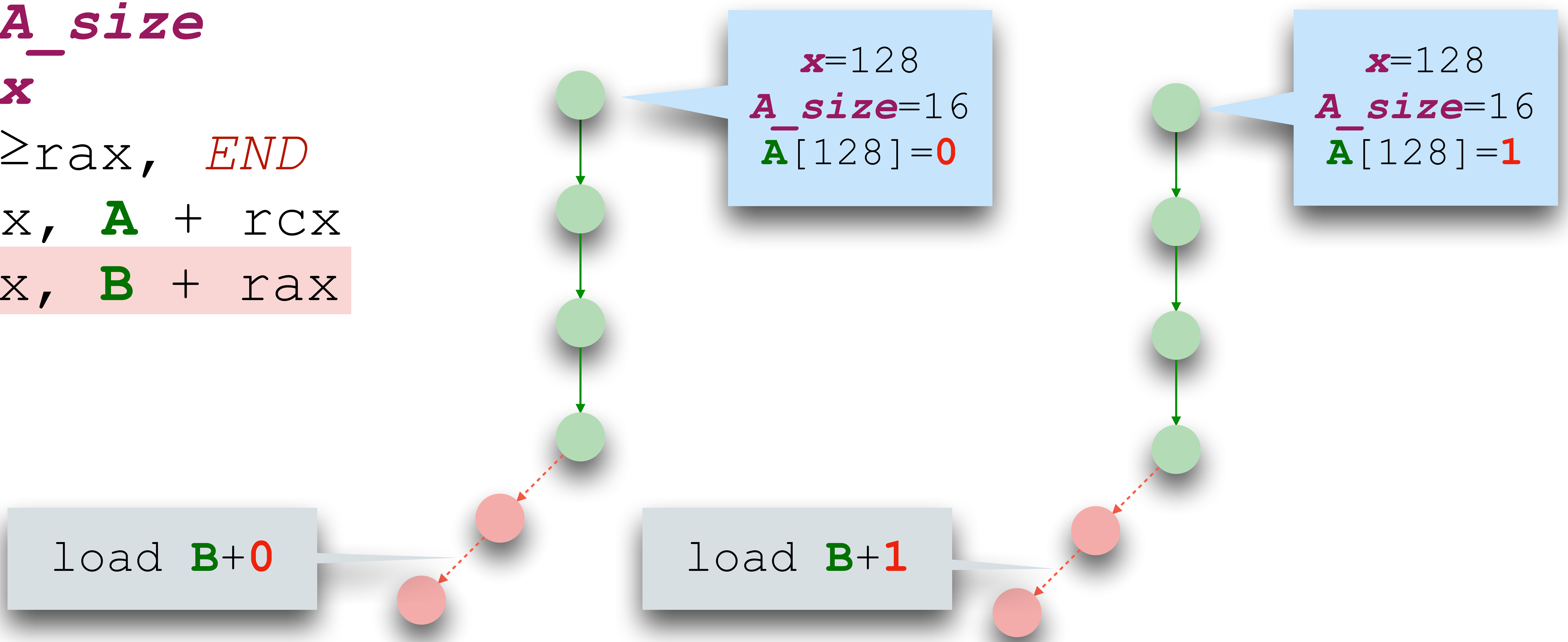

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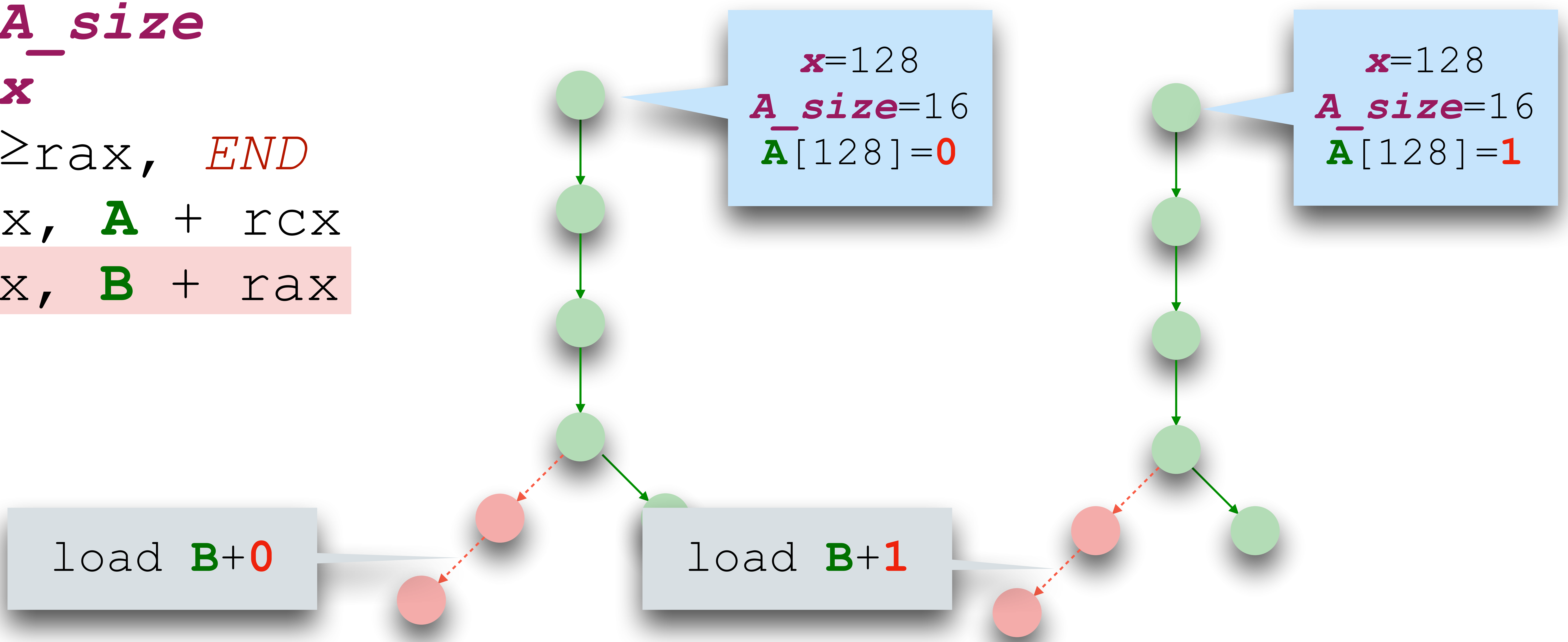

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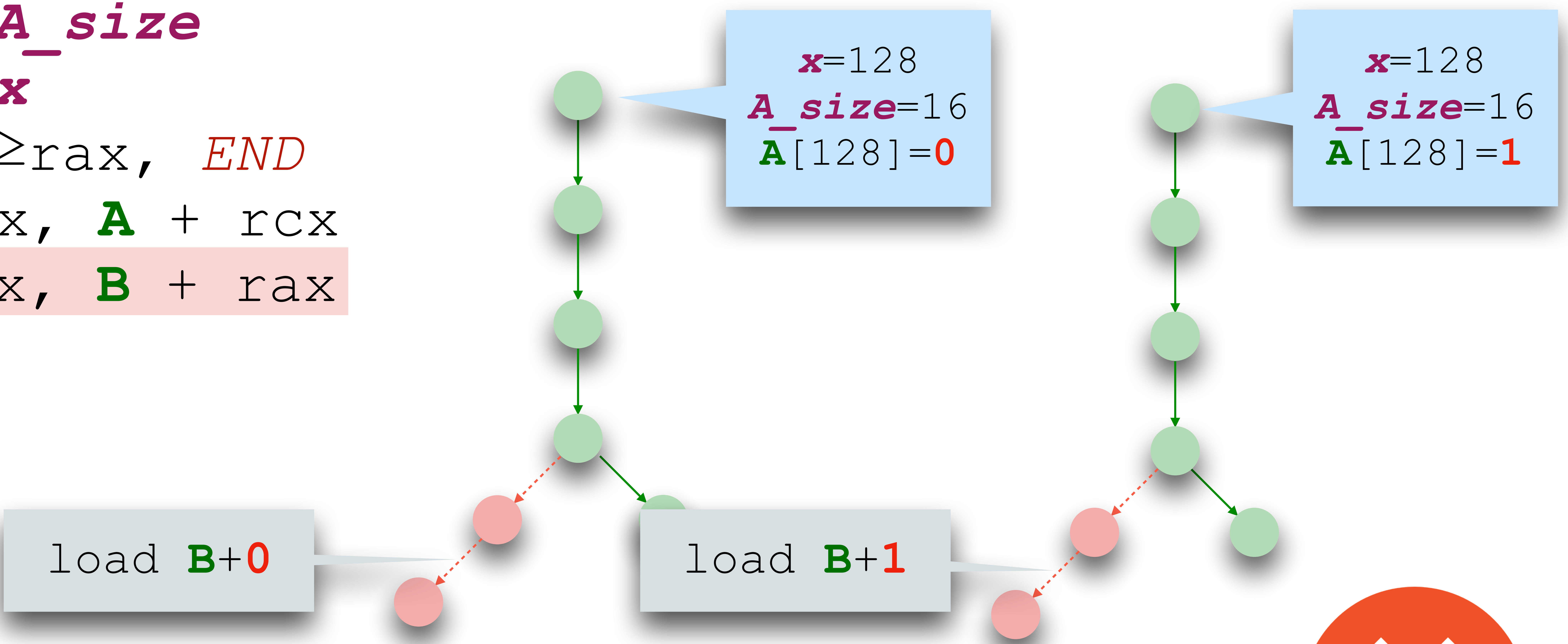

3. Spectector: Detecting speculative leaks

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Symbolic execution

Spectector: Detecting speculative leaks

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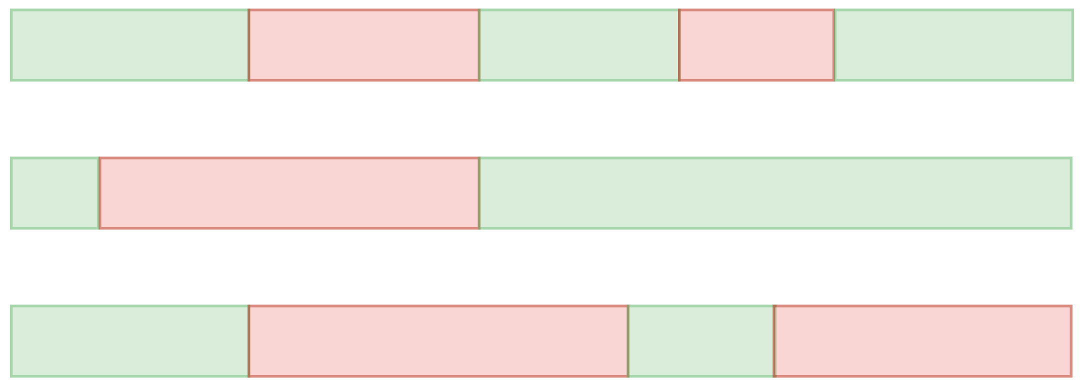
Symbolic execution



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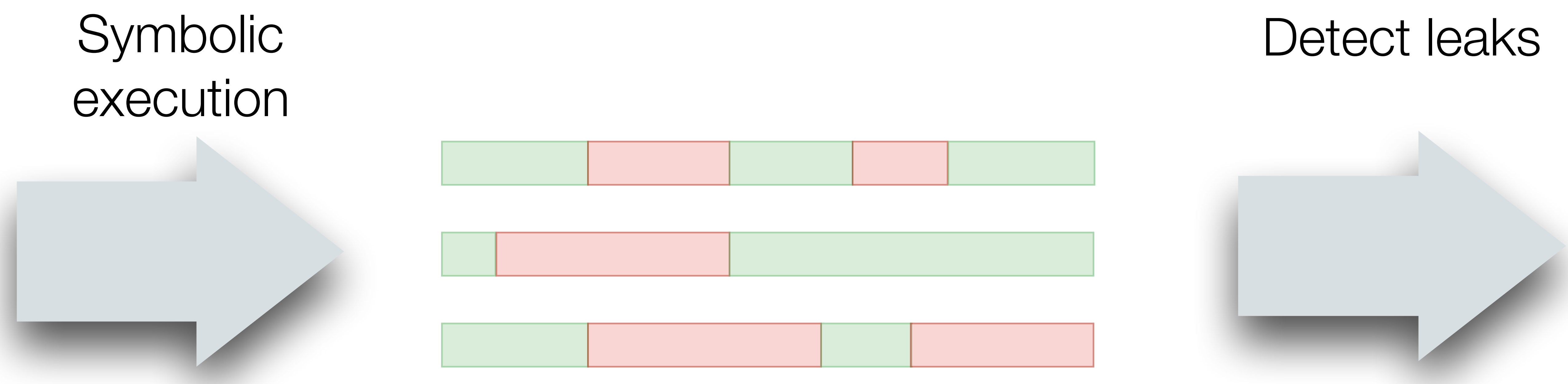

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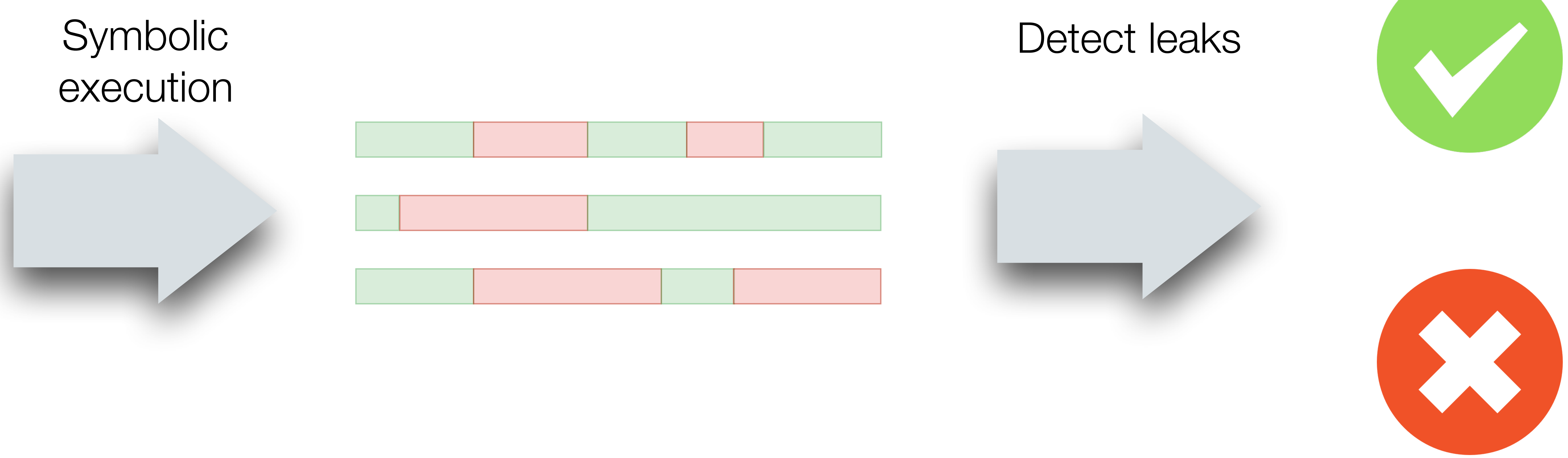

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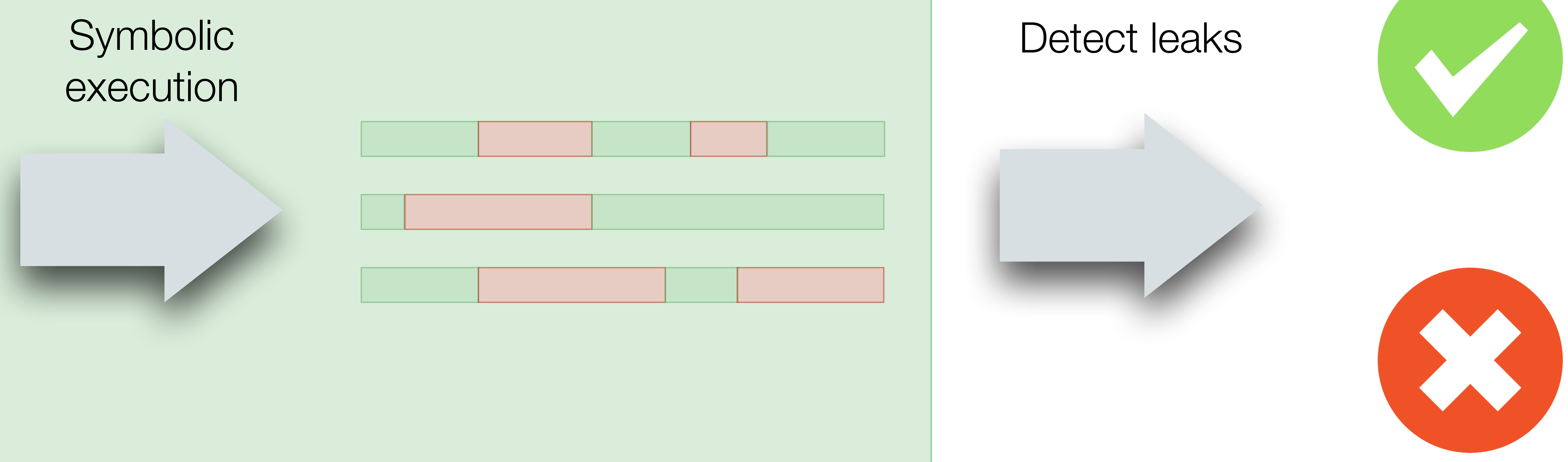
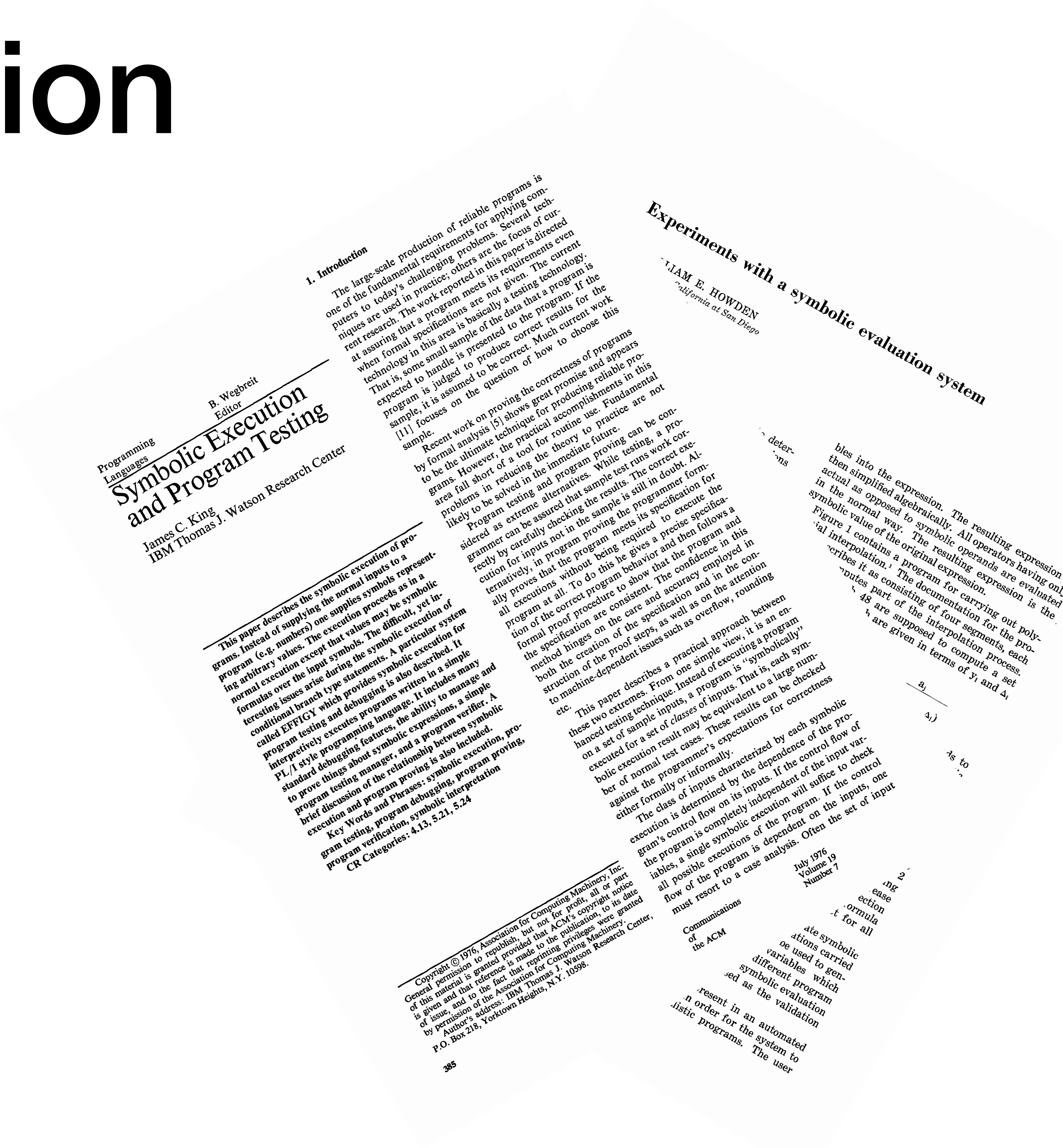


Symbolic execution

Symbolic execution

- Program analysis technique



Symbolic execution

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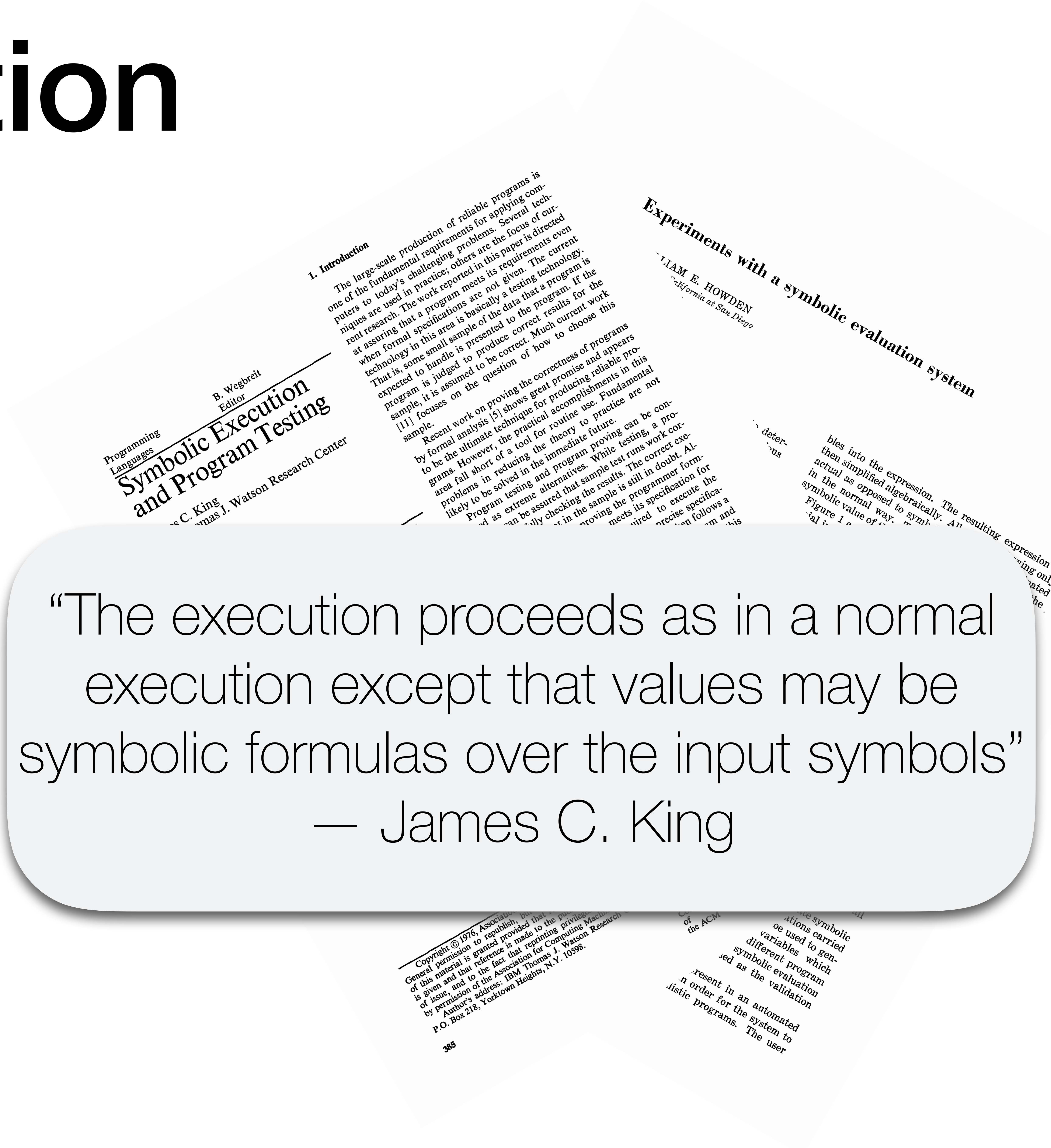

“The execution proceeds as in a normal execution except that values may be symbolic formulas over the input symbols”
— James C. King

Symbolic execution

- Program analysis technique

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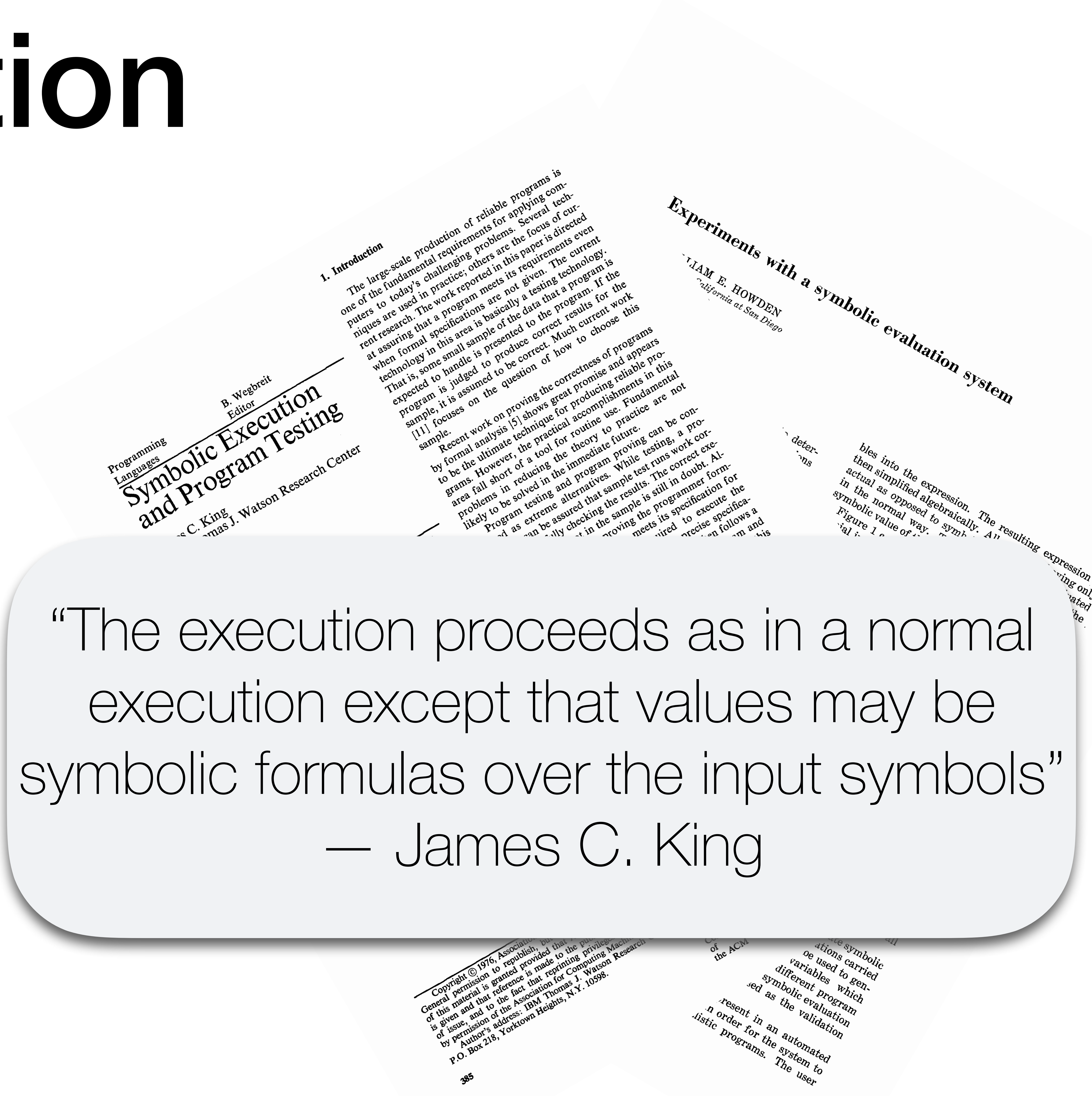

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Symbolic execution

- Program analysis technique
- Execute programs over symbolic values
  - Explore all paths,
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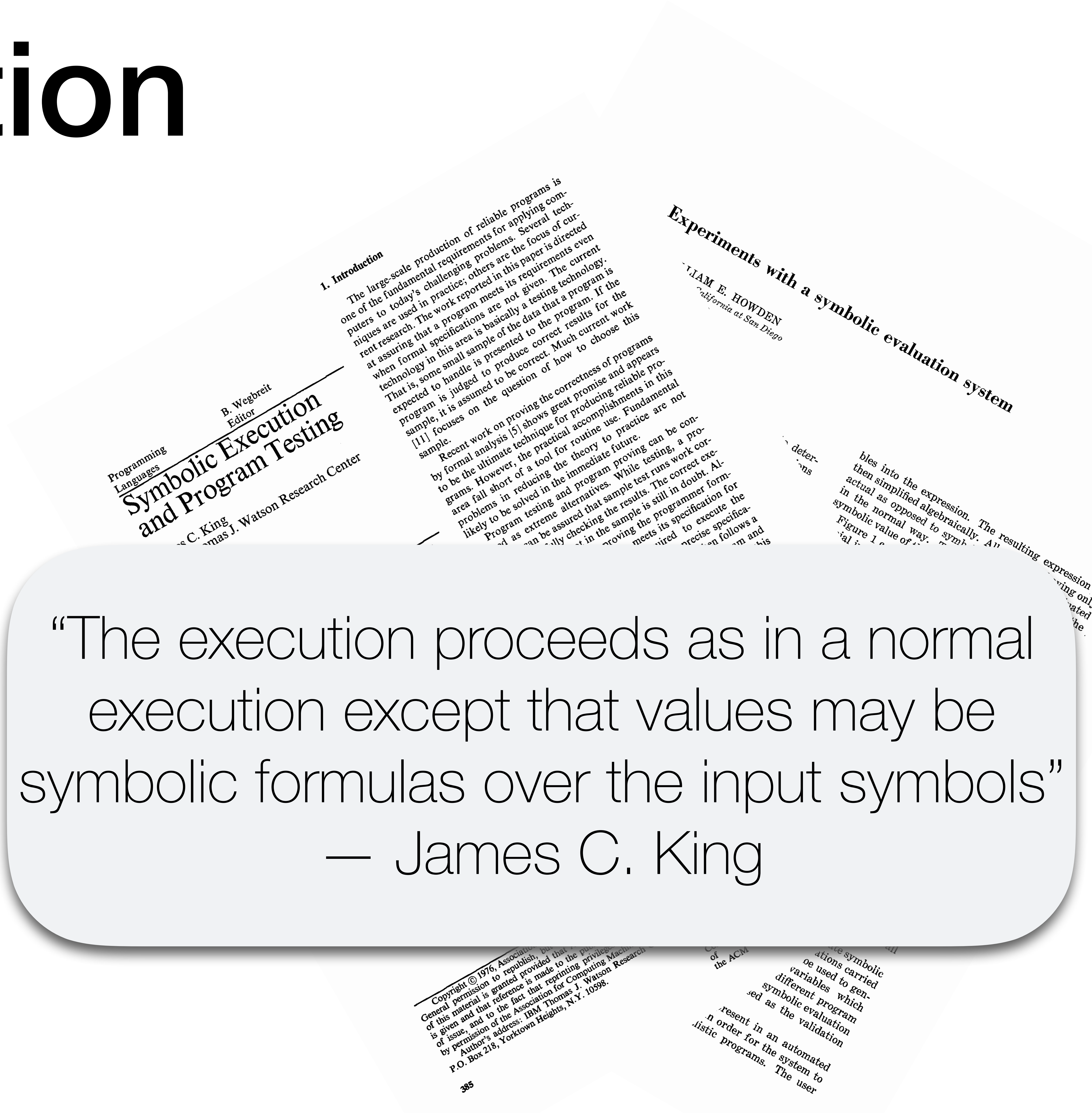

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Symbolic execution

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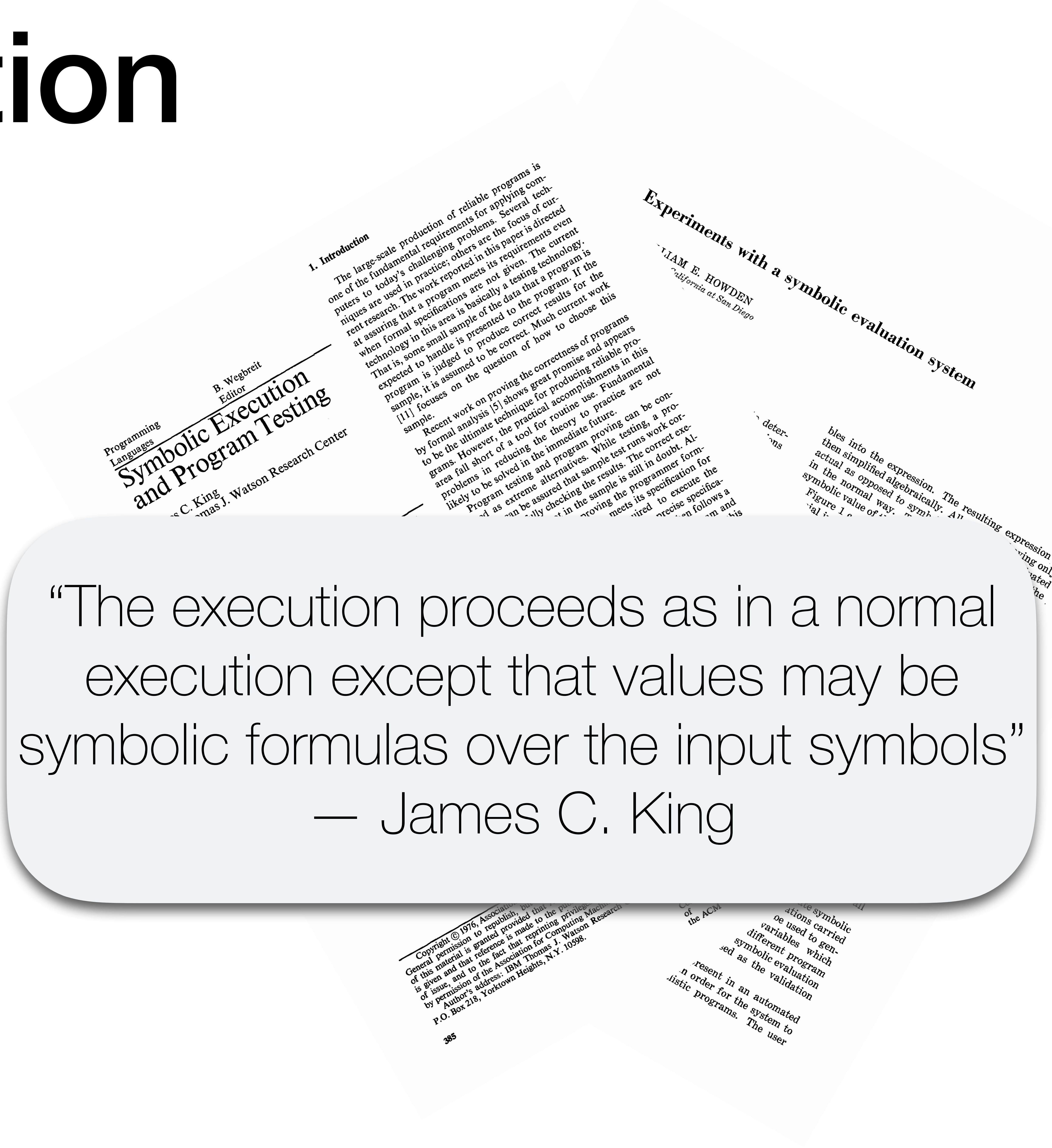

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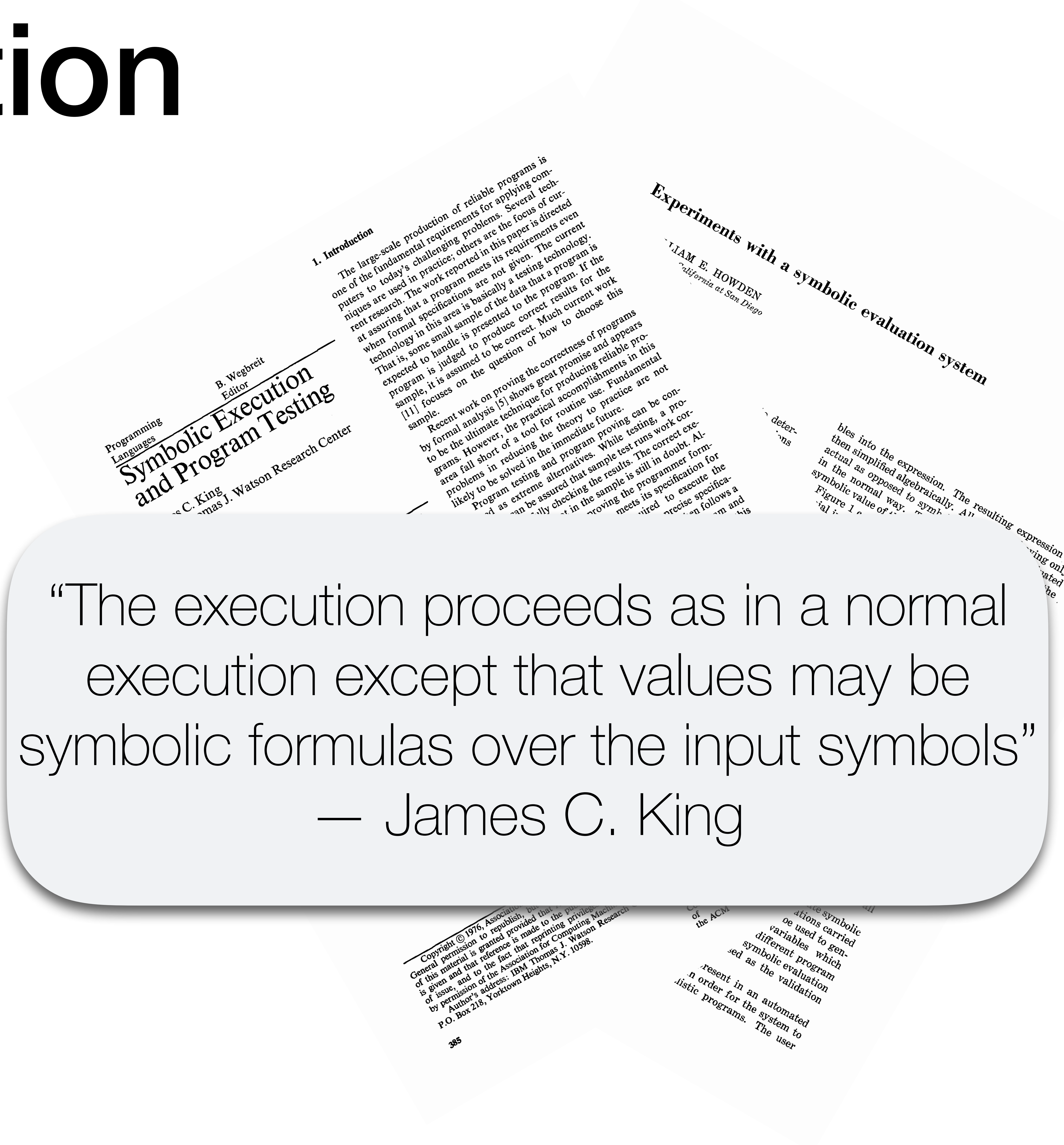
Symbolic execution

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



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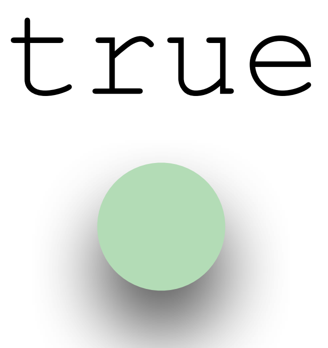

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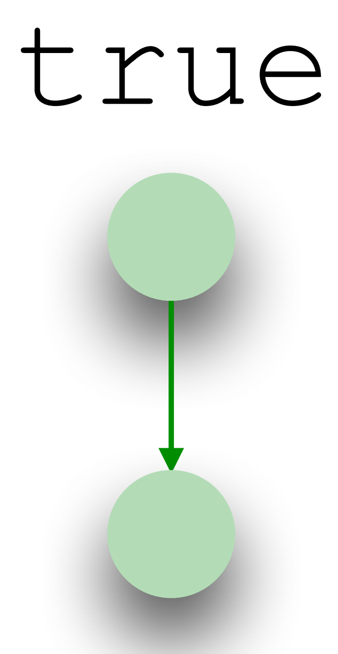

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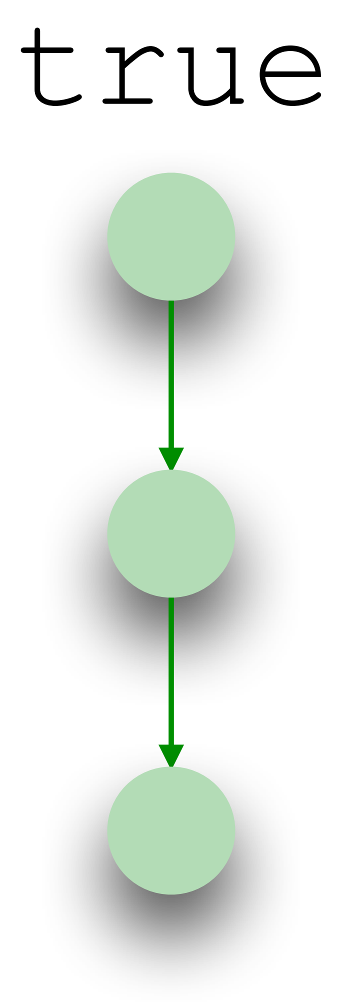

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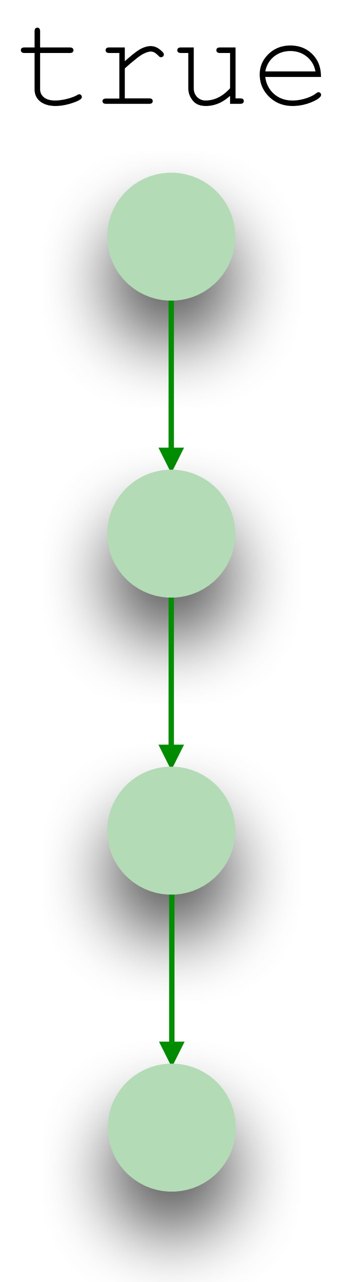

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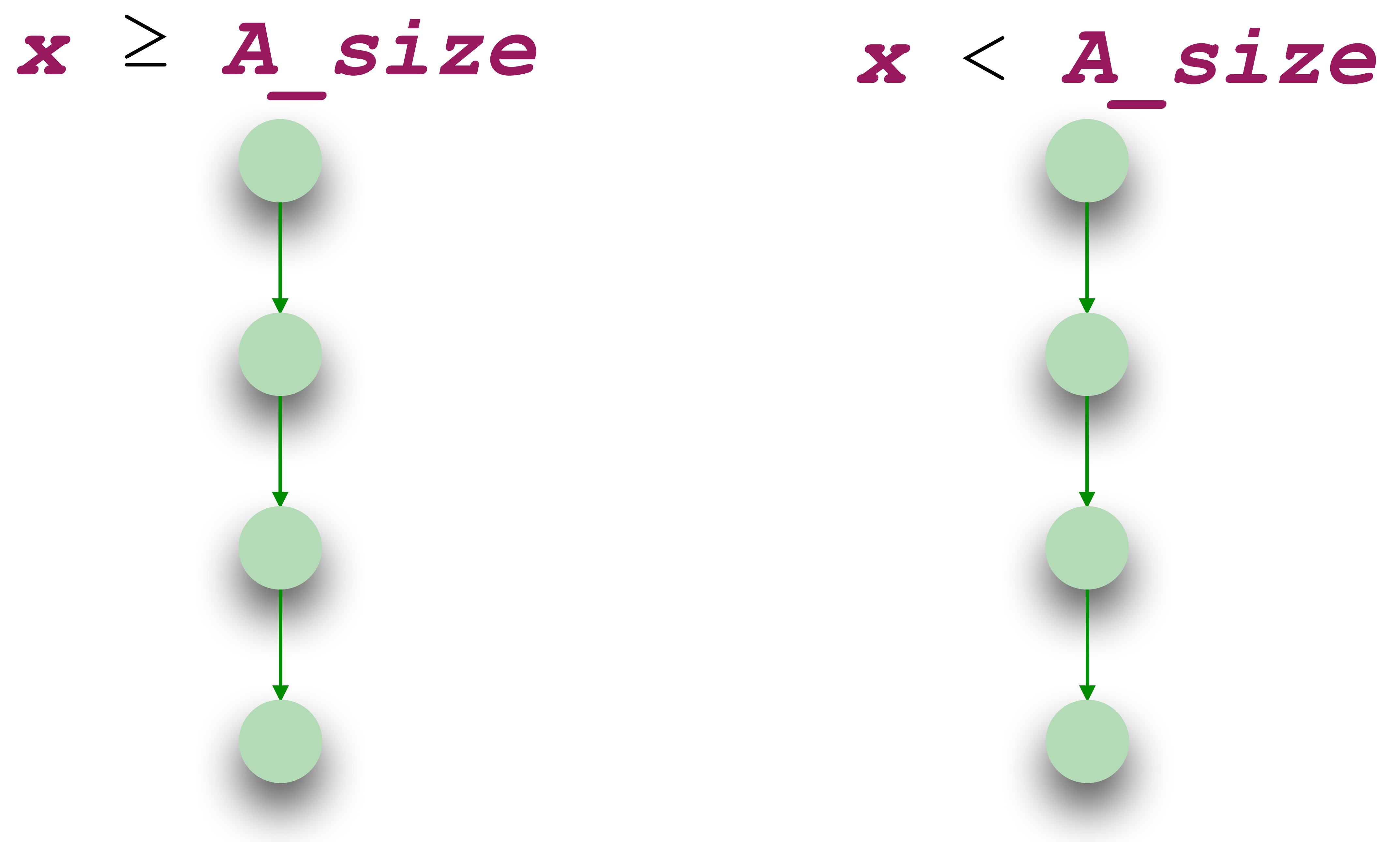

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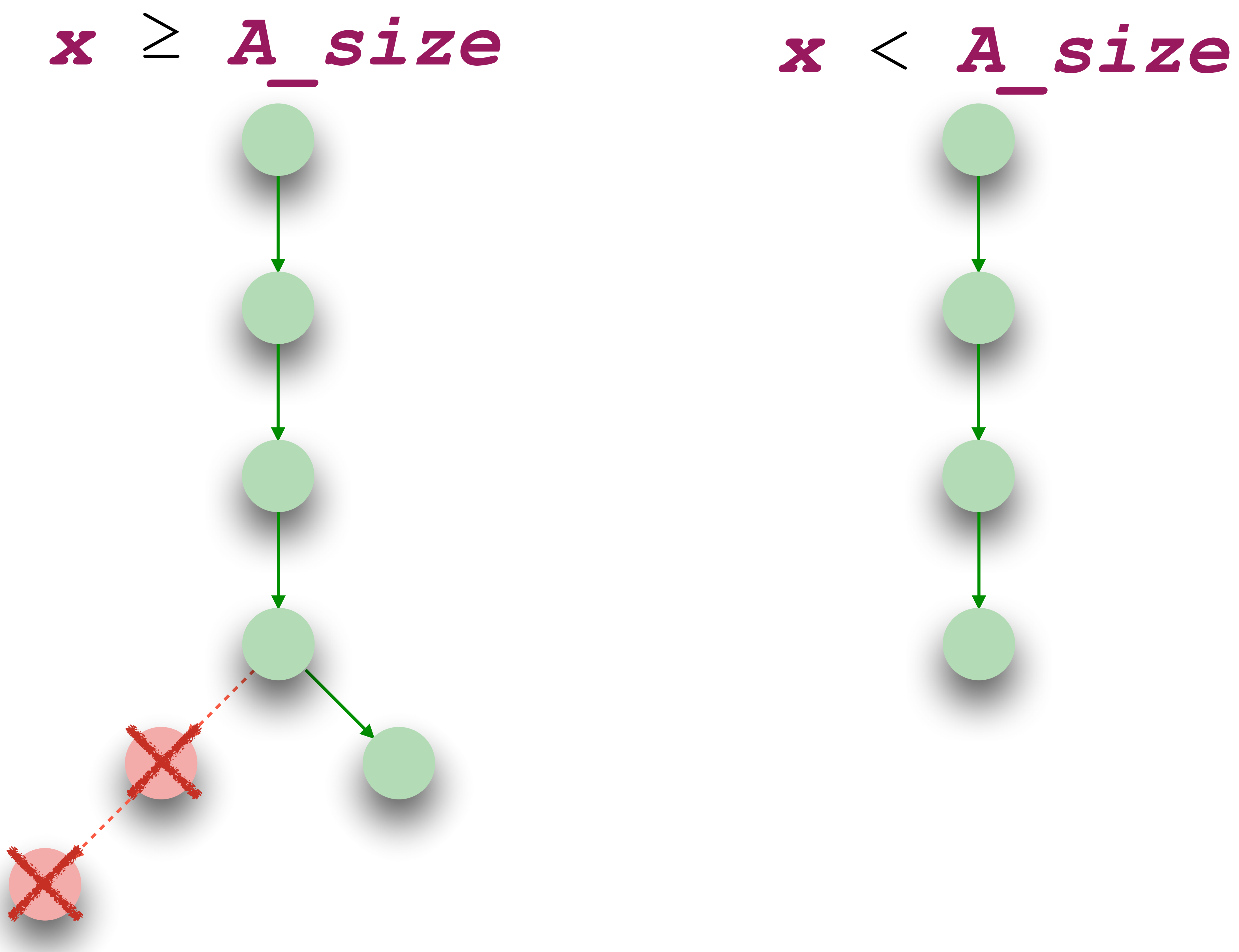

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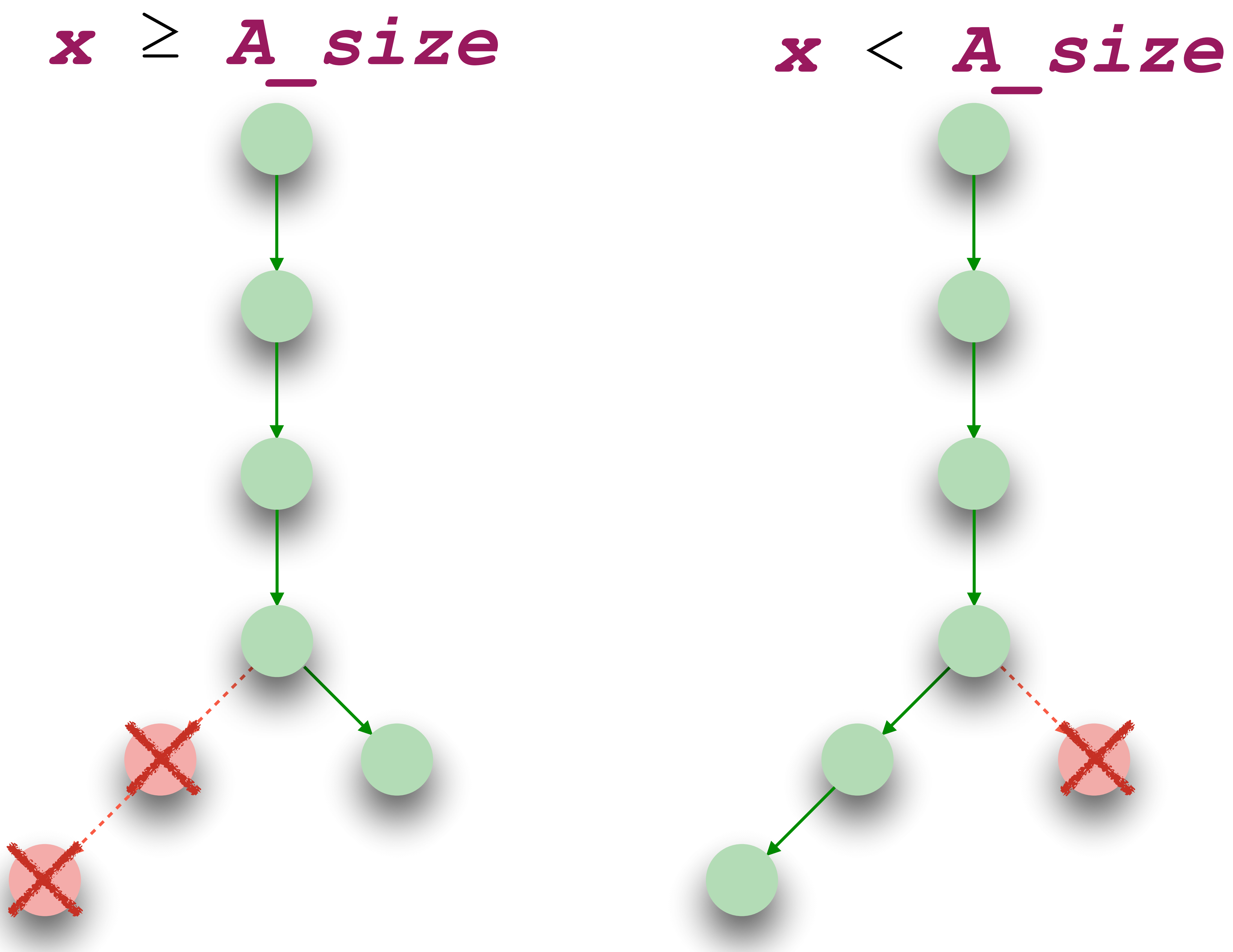

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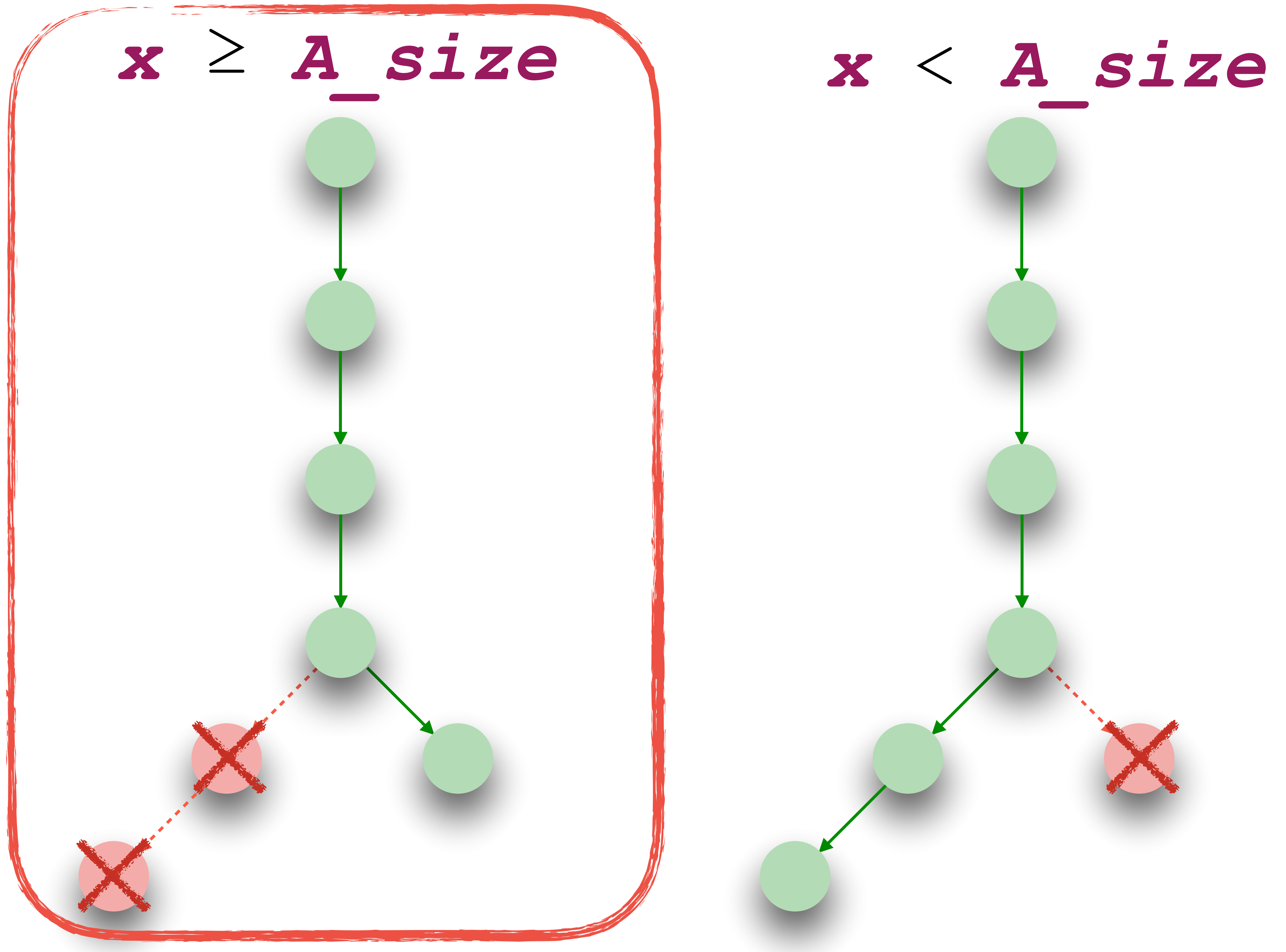

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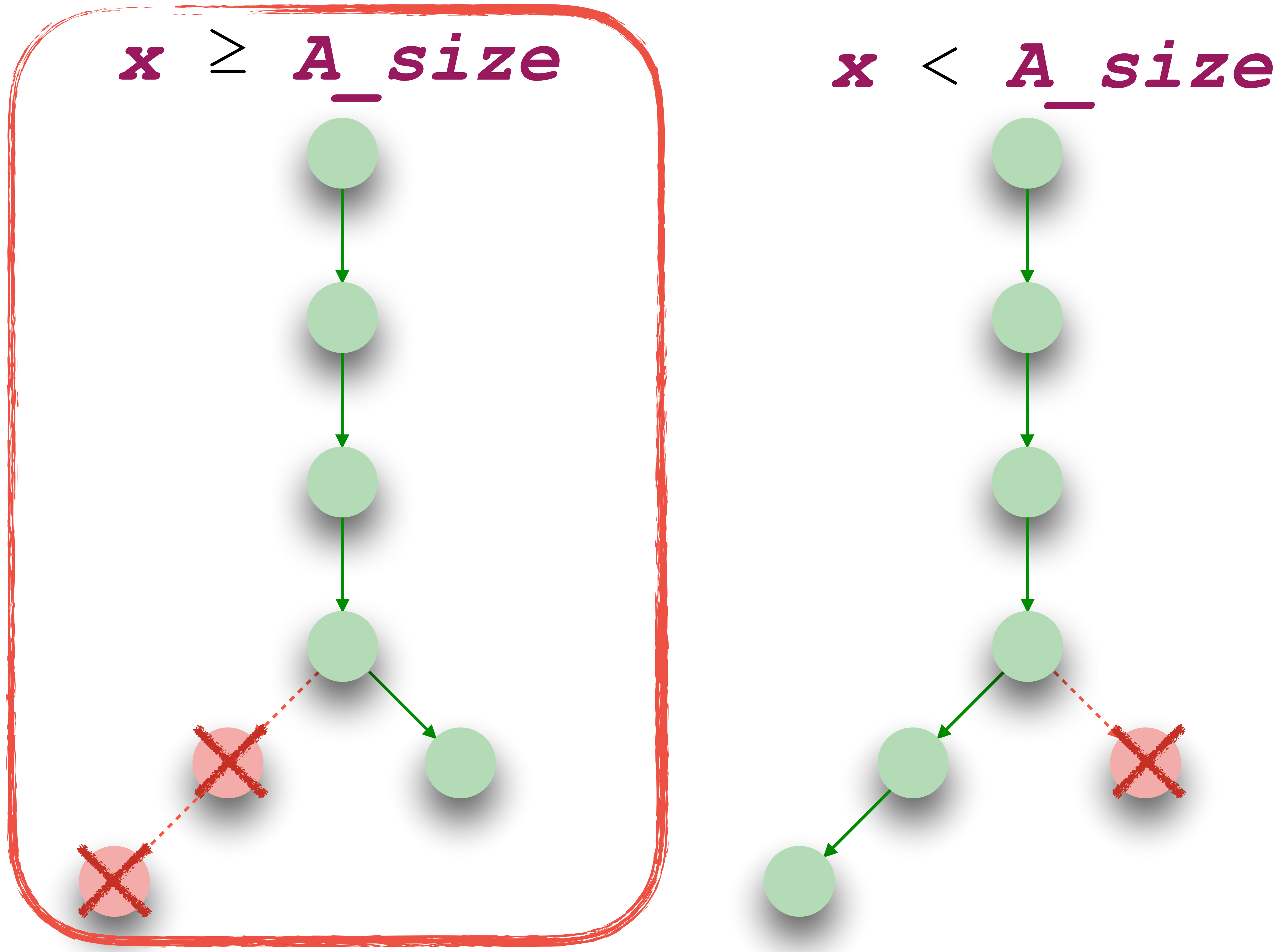

`start; pc L1; load A+x; load B+A[x]; rollback; pc END`

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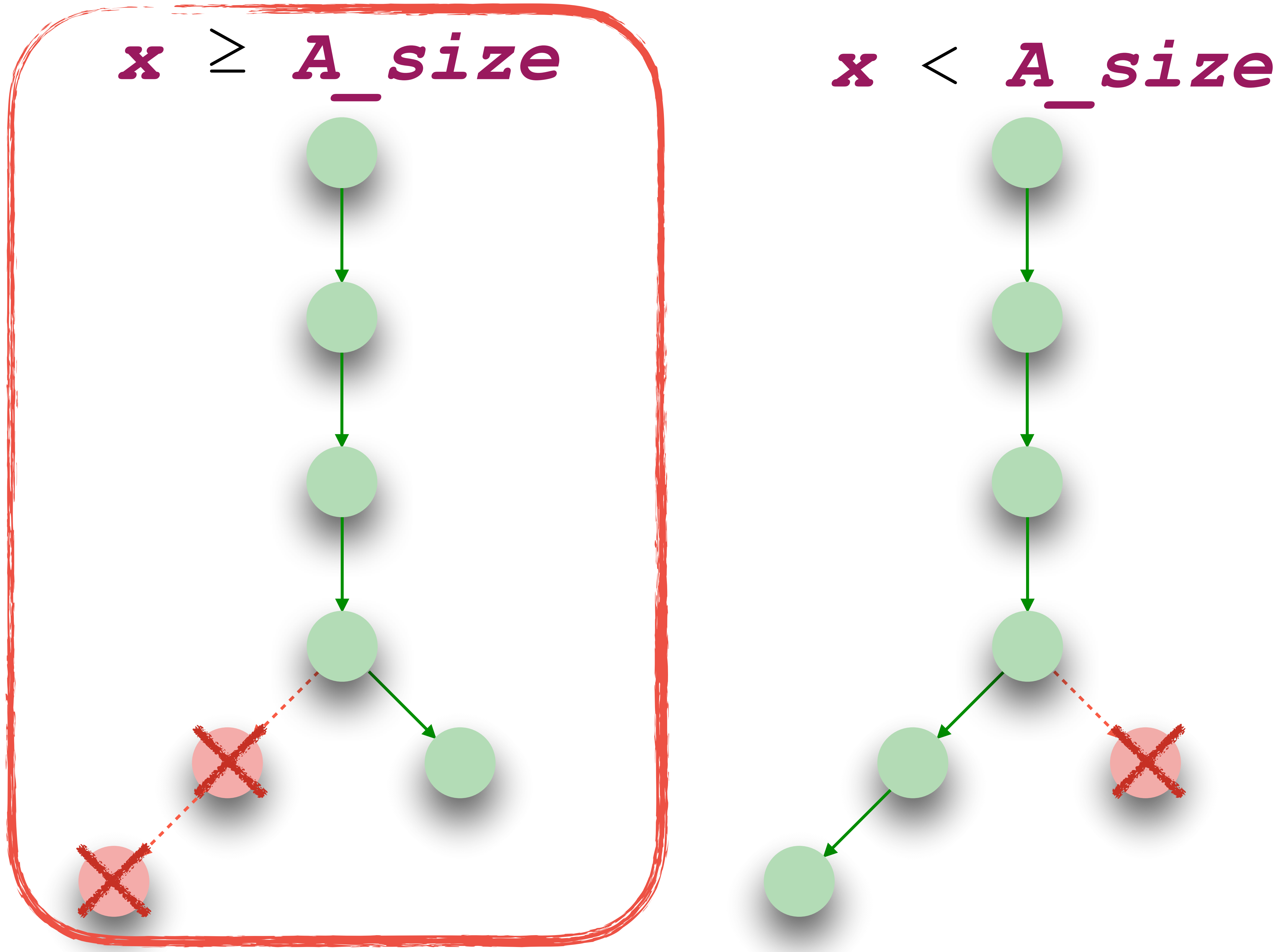

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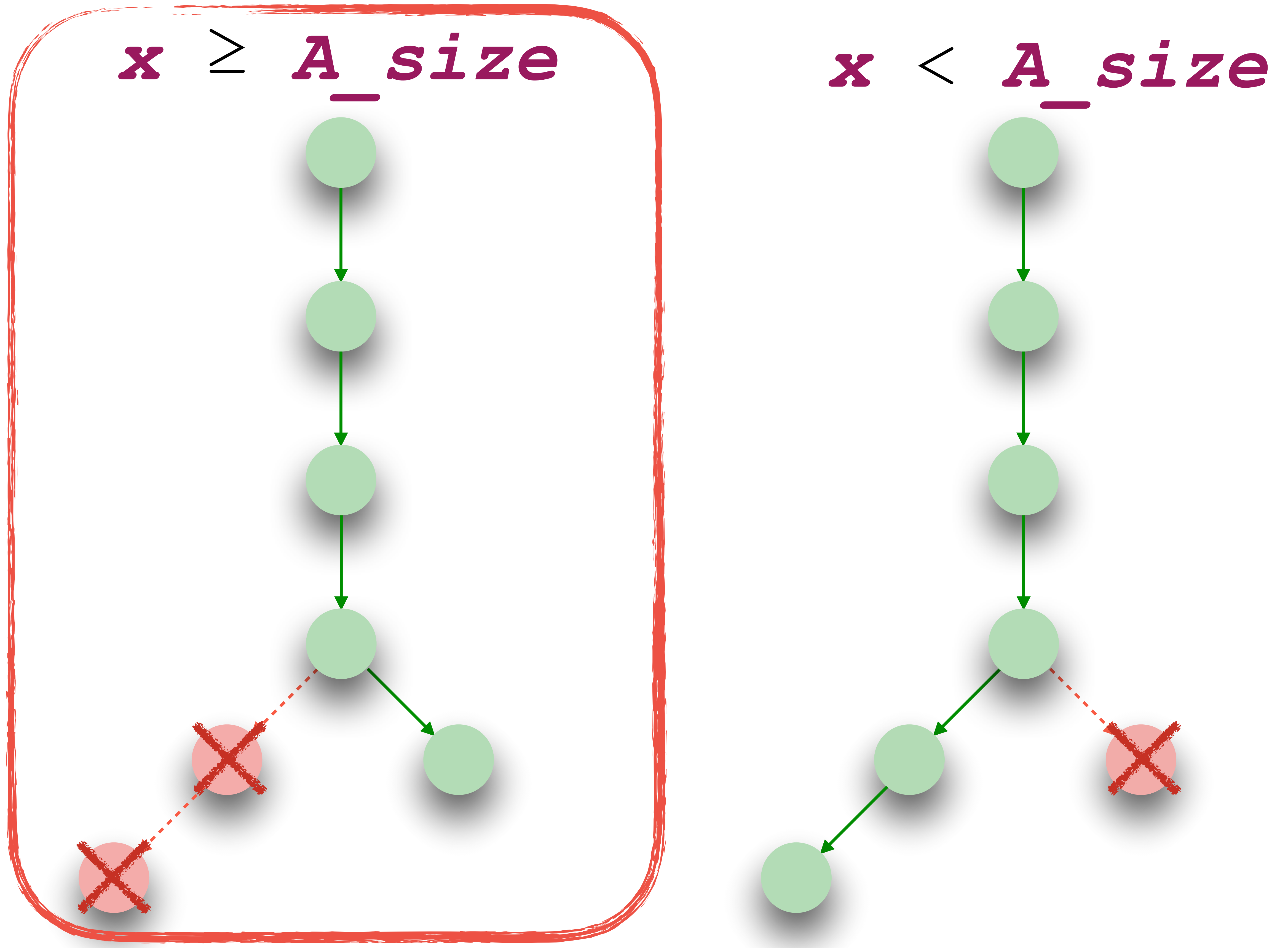

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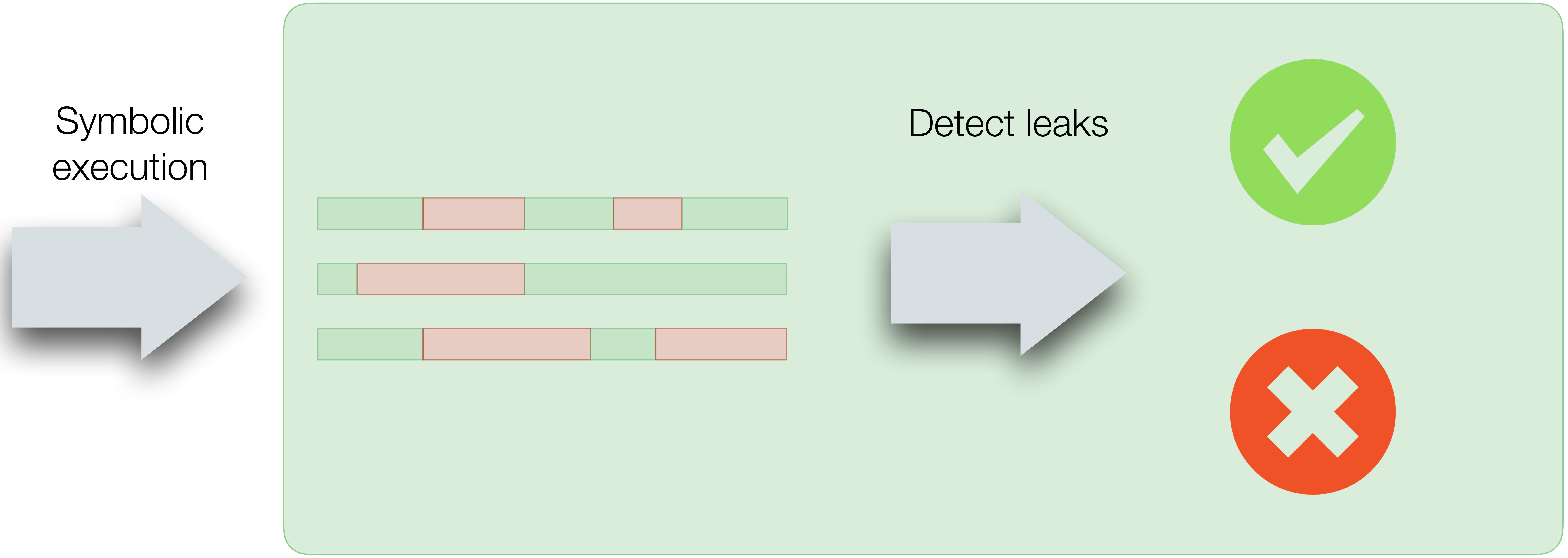

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For each $\tau \in$ **sym-traces**(P)

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

    return $INSECURE$

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

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return $SECURE$

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Memory leaks

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

- Non-sensitive information (determined by policy), *or*
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s_1

s_2

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$$s_1 \models \varphi$$

$$s_2 \models \varphi$$

Memory leaks

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

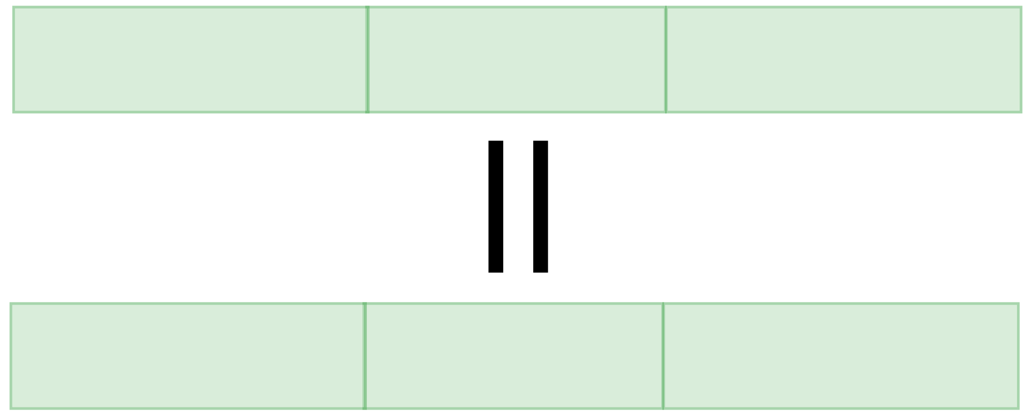
- Non-sensitive information (determined by policy), *or*
- be determined by non-speculative observations

τ

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

$s_1 \models \varphi$

$s_2 \models \varphi$



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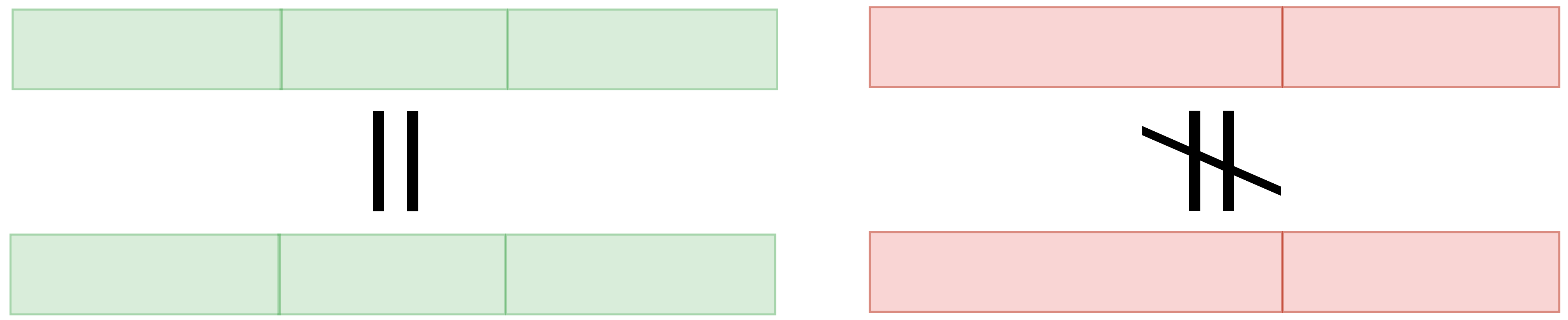
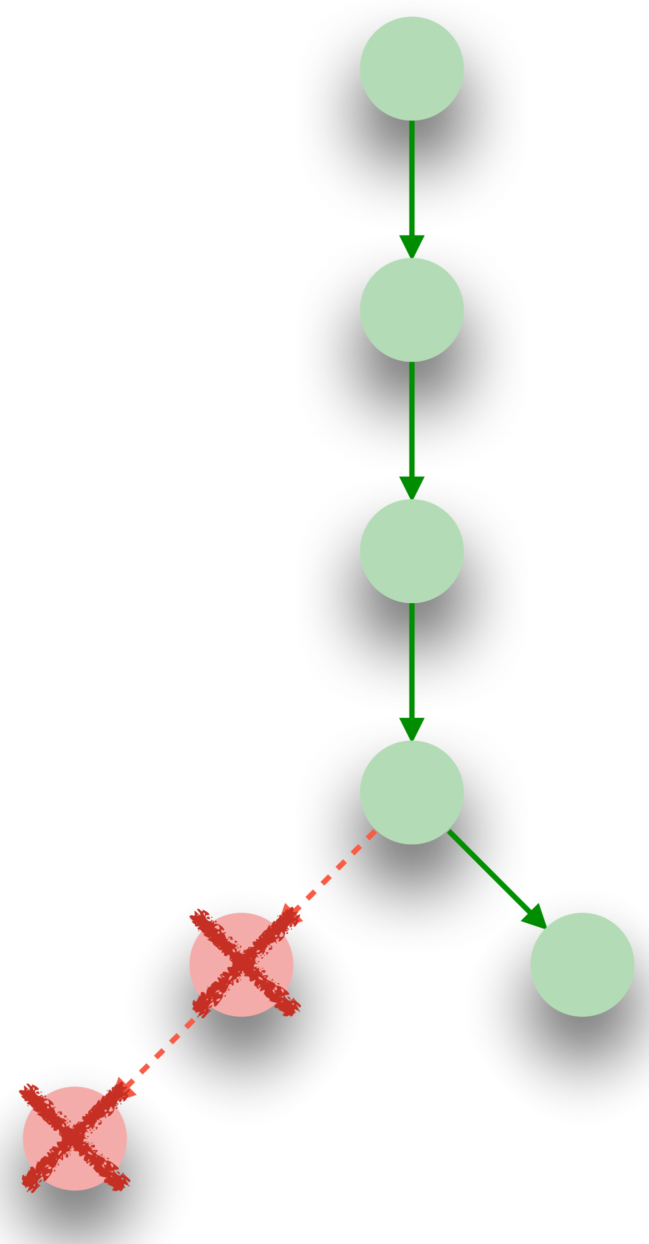
$s_1 \models \varphi$

$s_2 \models \varphi$



Memory leaks

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



Policy

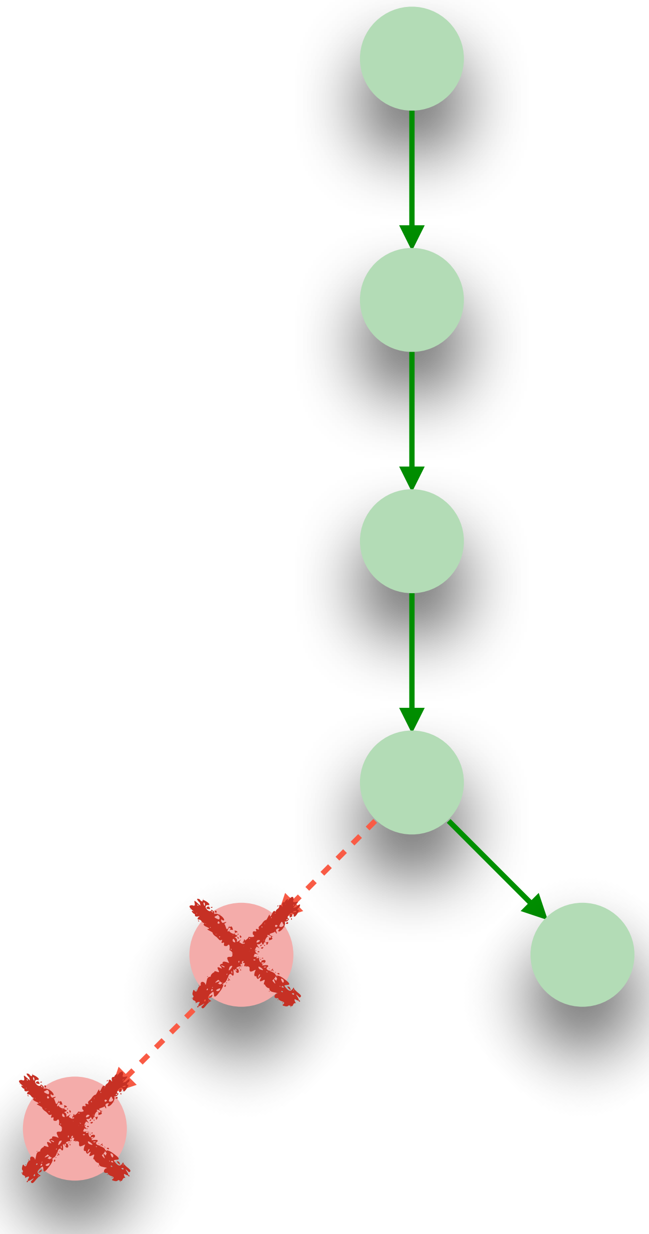
x, ***A_size***, **A**, **B**

are public

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

Memory leaks

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



Policy

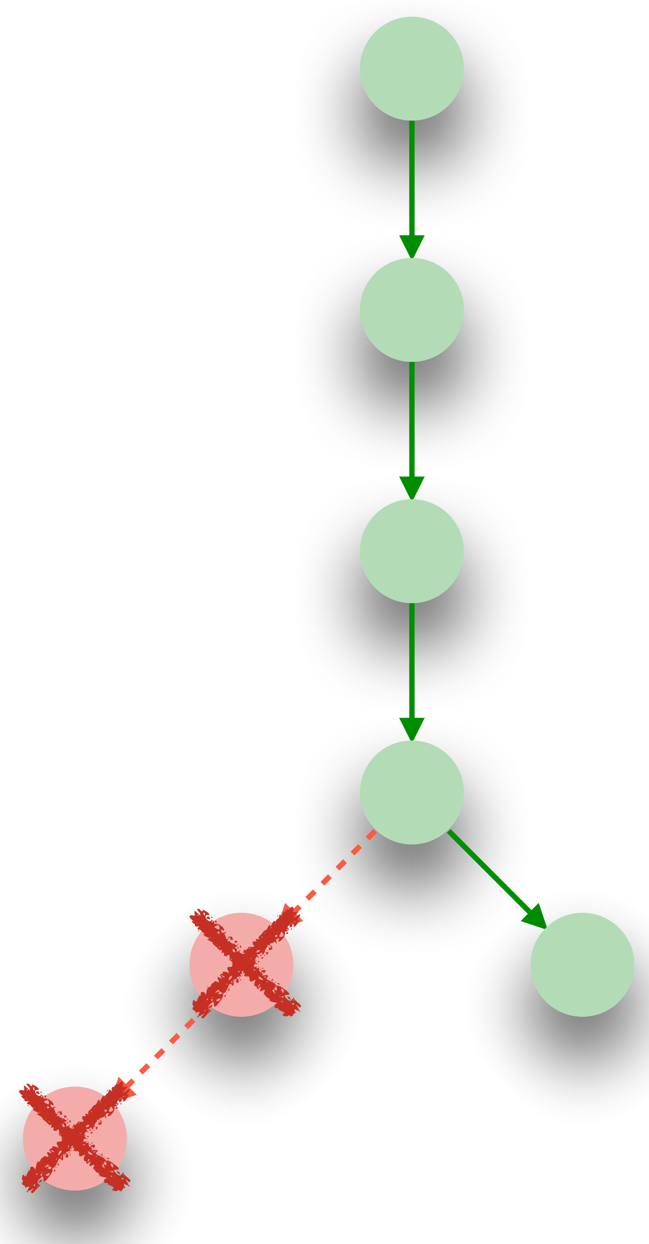
x, *A_size*, **A**, **B**
are public

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

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

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

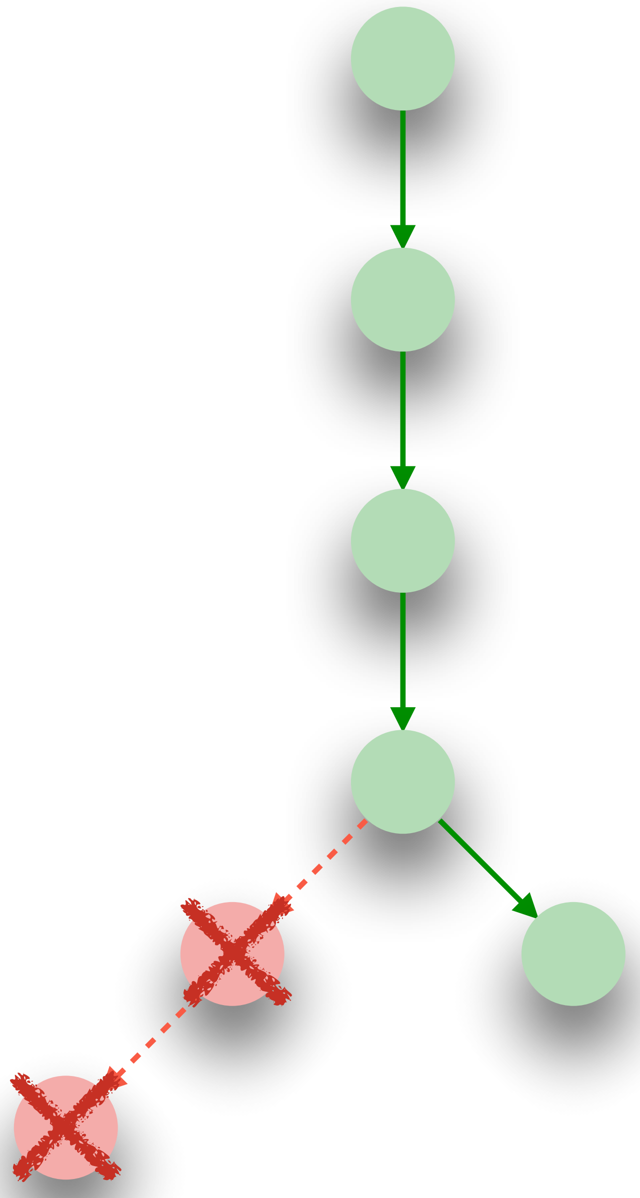
$$pathCnd(\tau) \wedge obsEqv(\tau|_{non-spec}) \wedge \neg obsEqv(\tau|_{spec})$$

s_1

s_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

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

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

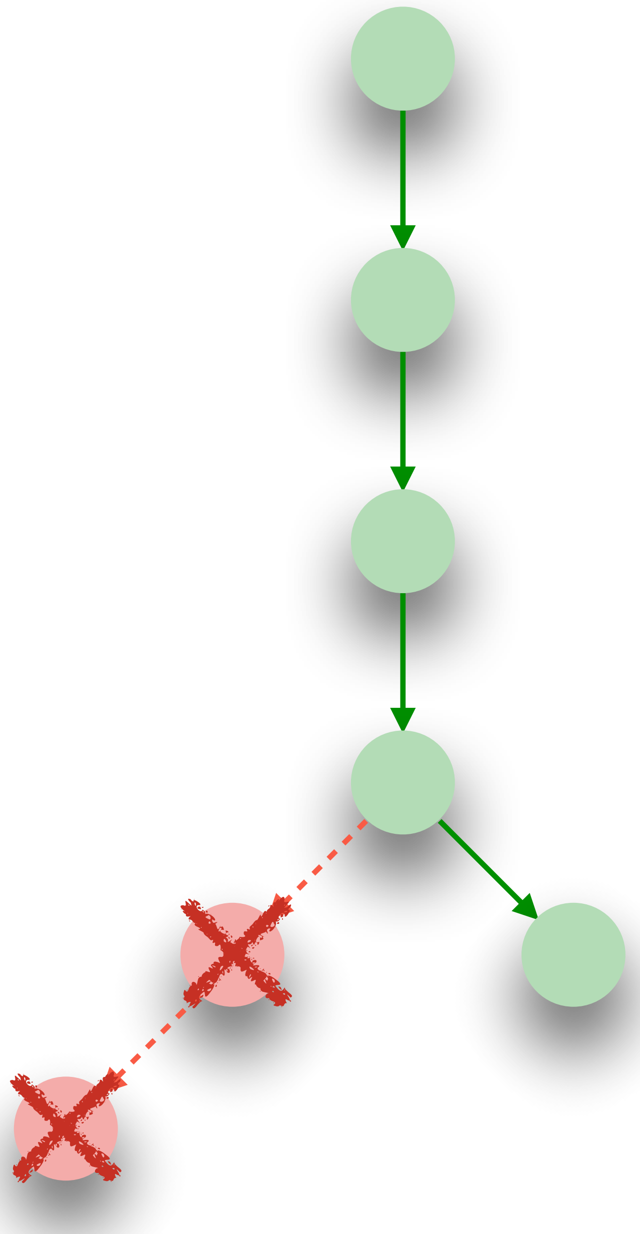
s_1

s_2

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

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

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

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

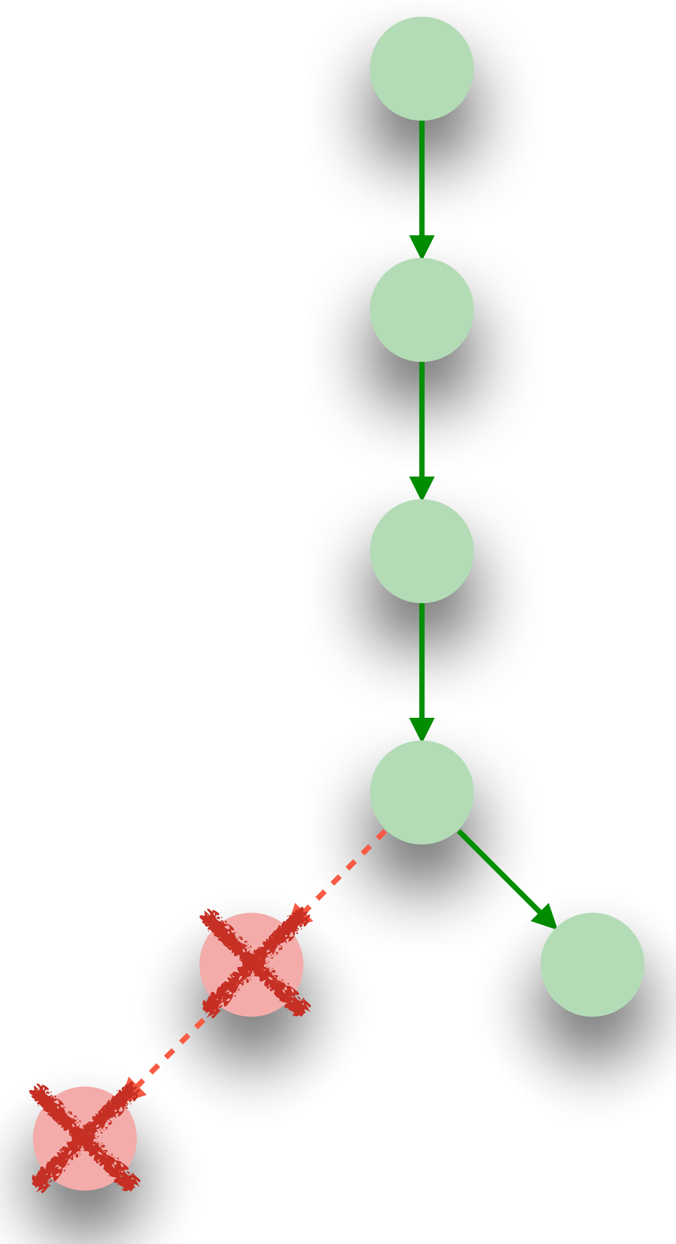
$s_1 \models$ $x_1 \geq A\_size_1$

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

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

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

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

||

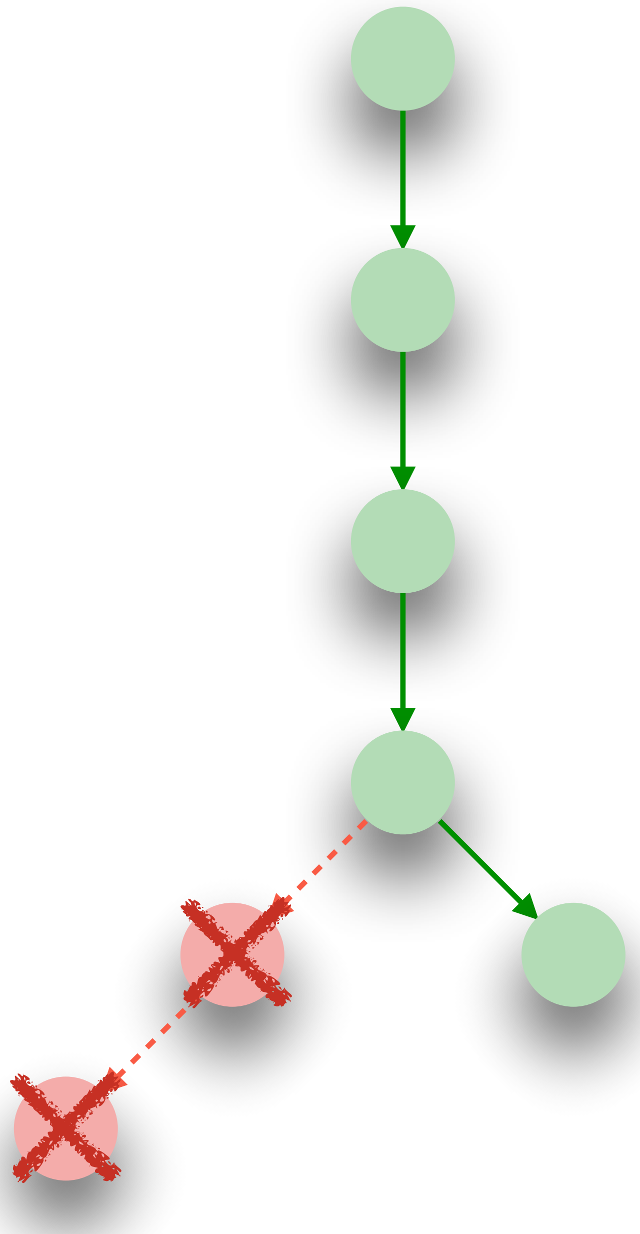
$s_2 \models x_2 \geq A\_size_2$ — pc END

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

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

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*

||

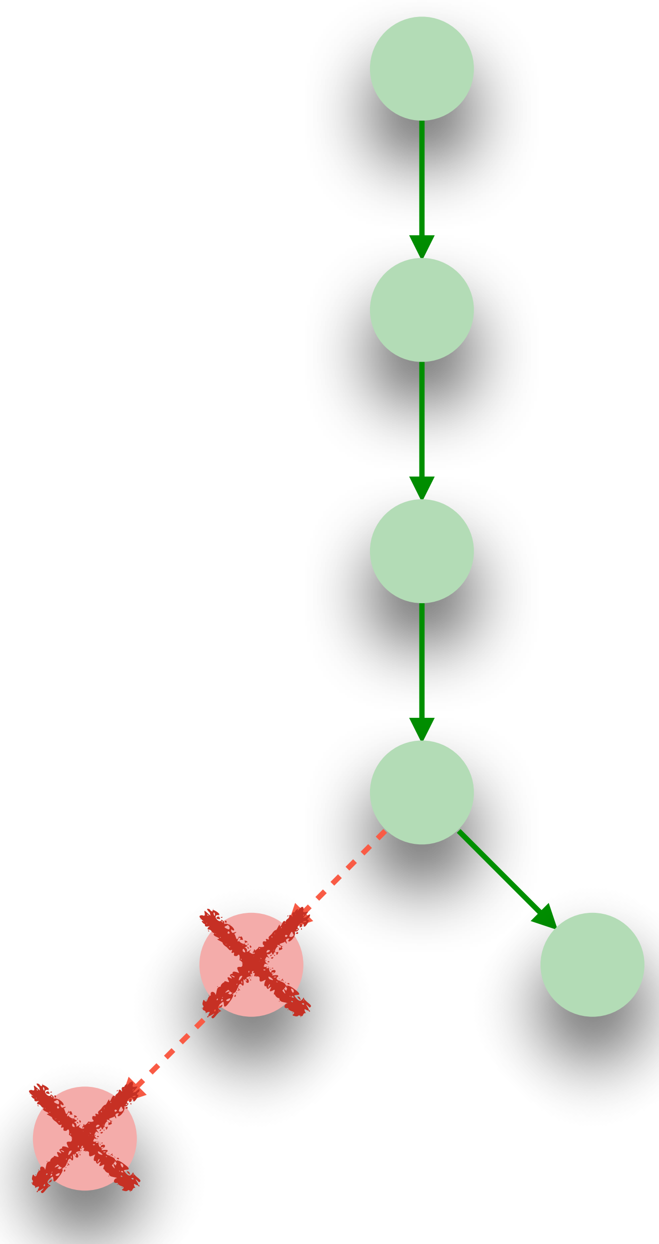
$s_2 \models$ $x_2 \geq A\_size_2$ pc *END*

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

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

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

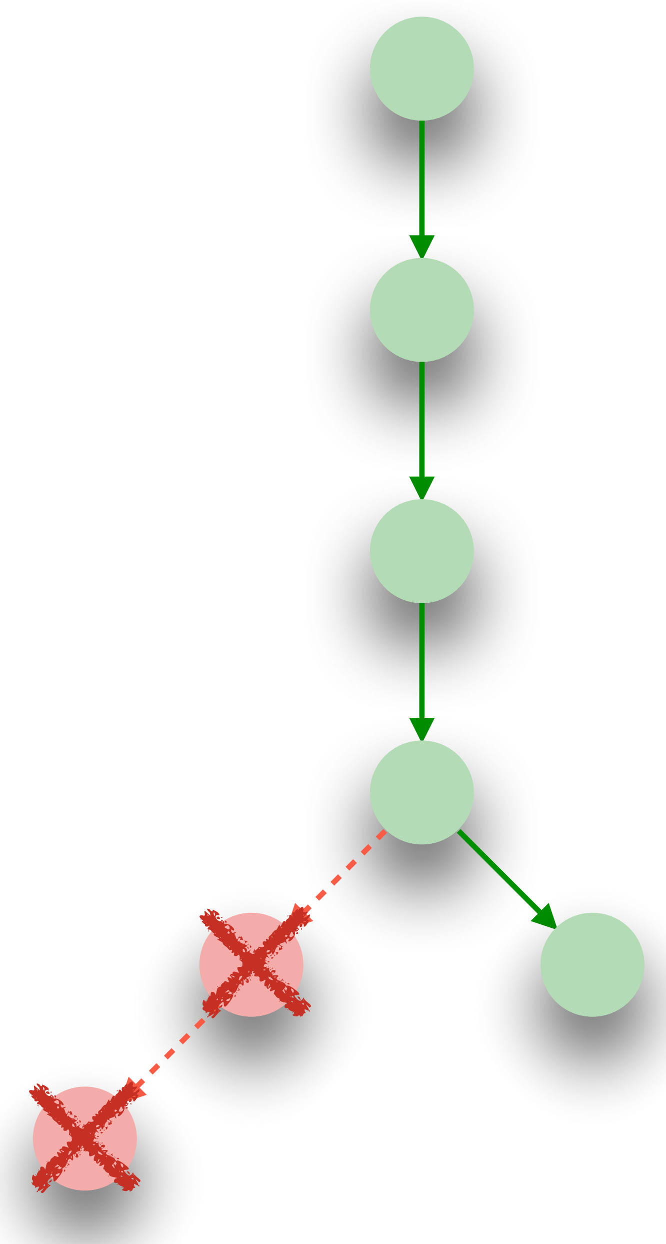
s_1	$\models$	$x_1 \geq A\_size_1$	pc END	$A_1 + x_1$
			$=$	$\neq$
s_2	$\models$	$x_2 \geq A\_size_2$	pc END	$A_2 + x_2$

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

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

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

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

$s_1 \models$ $x_1 \geq A\_size_1$ pc *END* $=$ A_1+x_1 $\neq$ $\lor$

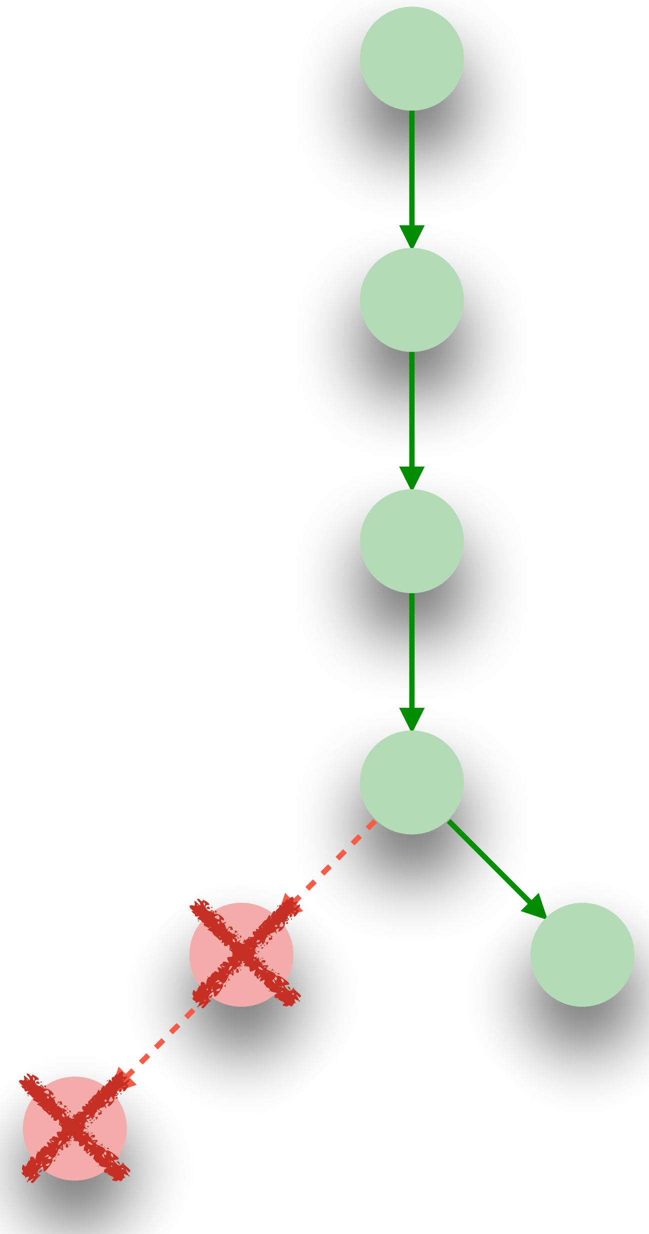
$s_2 \models$ $x_2 \geq A\_size_2$ pc *END* A_2+x_2

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

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

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

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

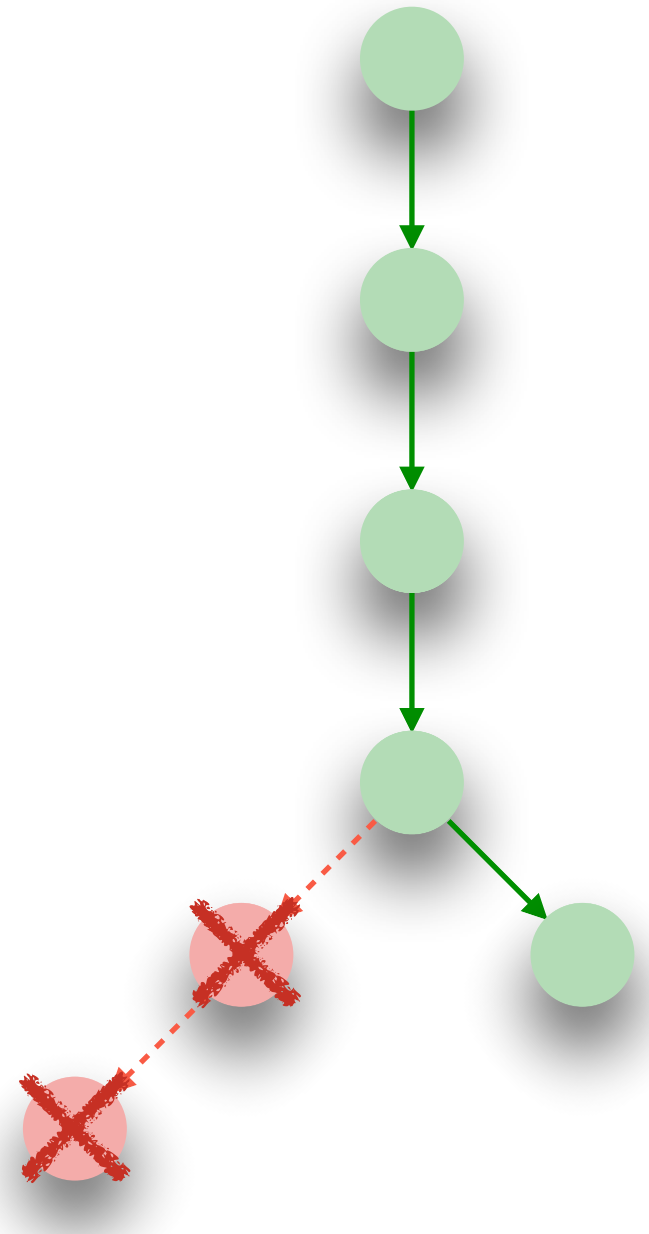
$s_1 \models$	$x_1 \geq A\_size_1$	pc END	A_1+x_1		$B_1+A_1[x_1]$
		$=$	$\neq$	$\vee$	$\neq$
$s_2 \models$	$x_2 \geq A\_size_2$	pc END	A_2+x_2		$B_2+A_2[x_2]$

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

Always true!

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		$B_1+A_1[x_1]$	
		$\|$	$\not\Vdash$	$\vee$	$\not\Vdash$	✖
$s_2 \models$	$x_2 \geq A\_size_2$	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 results

Ex.	VISUAL C++				ICC				CLANG					
	UNP		FEN		UNP		FEN		UNP		FEN		SLH	
	−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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

15 Spectre variants from Paul Kocher

F	UNP		FEN		ICC				CLANG					
					UNP		FEN		UNP		FEN		SLH	
	−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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

15 Spectre variants from Paul Kocher

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

					Icc				Clang					
					Unp		Fen		Unp		Fen		Slh	
	−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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

15 Spectre variants from Paul Kocher

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

[illegible]	[illegible]				ICC				CLANG					
	UNP		FEN		UNP		FEN		UNP		FEN		SLH	
	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2
01	○	○	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	○	○	●	●	○	○	●	●	●	●
04	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	○	●	●	●	●
05	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	○	●	●	●	●
06	○	○	○	○	○	○	●	●	○	○	●	●	●	●
07	○	○	○	○	○	○	●	●	○	○	●	●	●	●
08	○	●	○	●	○	●	●	●	○	●	●	●	●	●
09	○	○	○	○	○	○	●	●	○	○	●	●	●	●
10	○	○	○	○	○	○	●	●	○	○	●	●	●	○
11	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

15 Spectre variants from Paul Kocher

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

[illegible]	[illegible]				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		Slh	
	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2
01	○	○	●	●	○	○	●	●	○	○	●	●	●	●
02	○	○	●	●	○	○	●	●	○	○	●	●	●	●
03	○	○	●	○	○	○	●	●	○	○	●	●	●	●
04	○	○	○	○	○	○	●	●	○	○	●	●	●	●
05	○	○	●	○	○	○	●	●	○	○	●	●	●	●
06	○	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	○	●	●	●	●
07	○	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	○	●	●	●	●
08	○	●	○	●	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●	●
09	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	○	●	●	●	●
10	○	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	○	●	●	●	○
11	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

Ex.	Visual C++				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		Slh	
	-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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

Ex.	Visual C++				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		Slh	
	−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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental r

No countermeasures

Ex.	Visual C++				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		Slh	
	−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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

Automated insertion of fences

Ex.	Visual C++				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		Slh	
	-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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

Speculative load hardening

Ex.	Visual C++				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		Slh	
	−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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

Ex.	Visual C++				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		Slh	
	-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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

Ex.	VISUAL C++				ICC				CLANG					
	UNP		FEN		UNP		FEN		UNP		FEN		SLH	
	-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	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Experimental results

Ex.	Visual C++				Icc				Clang					
	Unp		Fen		Unp		Fen		Unp		Fen		SLH	
	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2	−O0	−O2
01	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
02	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
03	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
04	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
05	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
06	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
07	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
08	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
09	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
10	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	○
11	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
12	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●
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
  - But: Unnecessary fences
- Programs with SLH are secure except #10 and #15

Experimental results

Ex.	VISUAL C++				ICC				CLANG					
	UNP		FEN		UNP		FEN		UNP		FEN		SLH	
	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2	-O0	-O2
01	○	○	●	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
02	○	○	●	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
03	○	○	●	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
04	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
05	○	○	●	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
06	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
07	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
08	○	●	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
09	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	●
10	○	○	○	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	●	●	●	○
11	○	○	○	○	○	○	●	●	○	○	●	●	●	●
12	○	○	○	○	○	○	●	●	○	○	●	●	●	●
13	○	○	○	○	○	○	●	●	○	○	●	●	●	●
14	○	○	○	○	○	○	●	●	○	○	●	●	●	●
15	○	○	○	○	○	○	●	●	○	○	●	●	○	●

Performance

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

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

Microarchitecture: not available publicly, and too detailed for analysis

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*

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!

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!

Thank you for your attention!

Backup

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]
```

```
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 $x \geq$ `A_size`

We can prove security

Example #10 - SLH

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

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]
```

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]
```

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]
```

`lfence` is unnecessary