Finding Code That Explodes Under Symbolic Evaluation

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Automated reasoning tools help us solve hard programming problems

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👷 Does my program still work after the file system crashes? [ASPLOS'16]

Verification

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Synthesis

How do I compile code for this weird new architecture? [PLDI'14]

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How do I teach kids the rules of algebra effectively? [VMCAI'18]

"Programs"

Symbolic evaluators

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Interpreter for file system operations

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Interpreter for new architecture instructions

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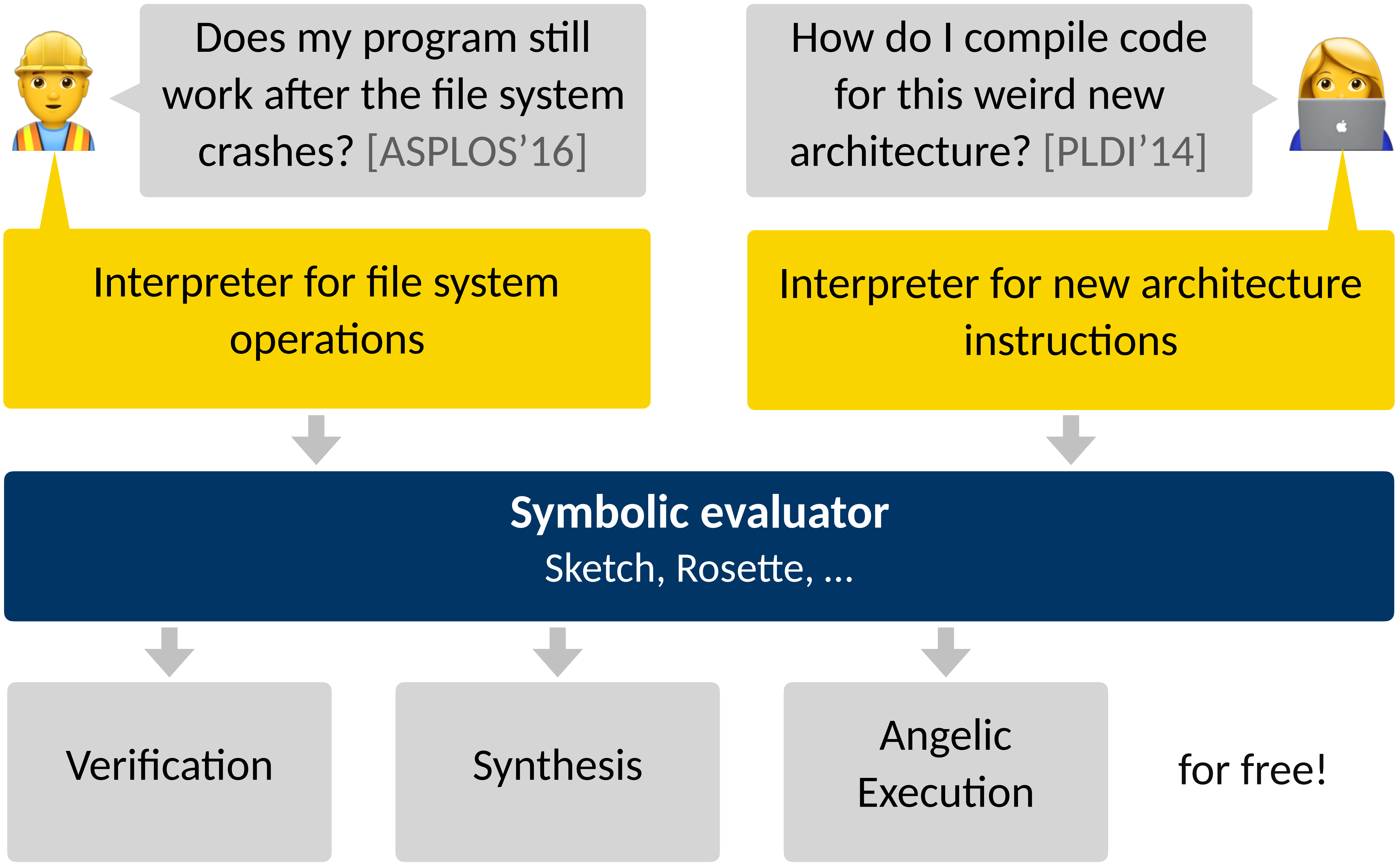
Interpreter for file system operations

Interpreter for new architecture instructions

Symbolic evaluator

Sketch, Rosette, …

Symbolic evaluators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Synthesis
Angelic Execution
for free!

Symbolic evaluators: no free lunch

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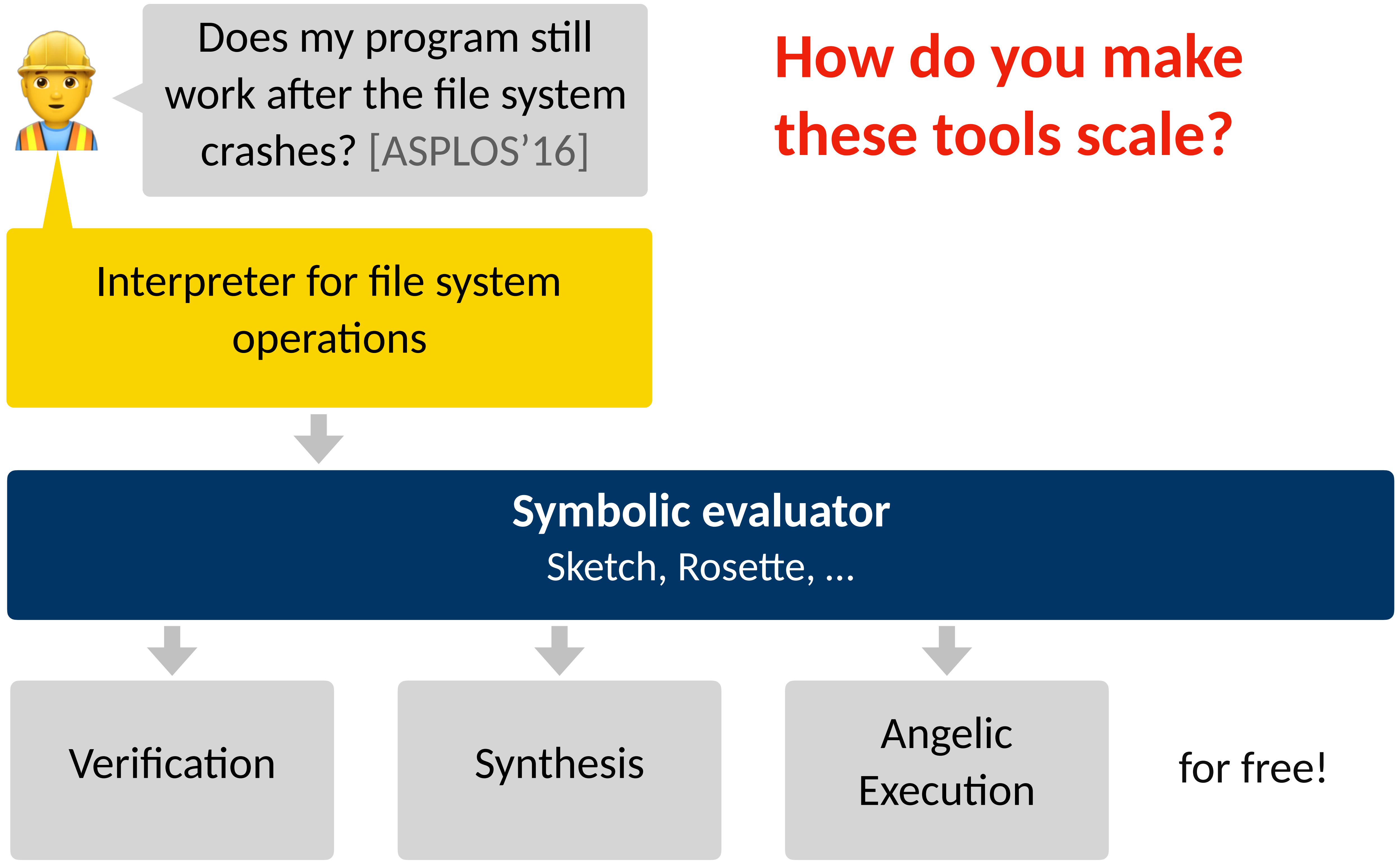
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How do you make these tools scale?

Symbolic evaluators: no free lunch

Does my program still work after the file system crashes? [ASPLOS'16]

How do you make these tools scale?

Interpreter for file system operations

Searching *all paths* through the interpreter

Symbolic evaluator

Sketch, Rosette, …

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Symbolic profiling identifies performance issues in symbolic evaluation

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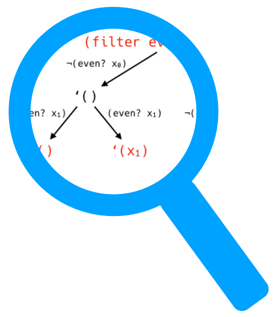
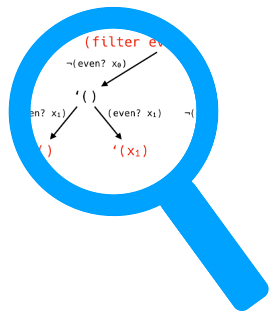


Symbolic profiling

Data structures and analyses

Symbolic profiling identifies performance issues in symbolic evaluation



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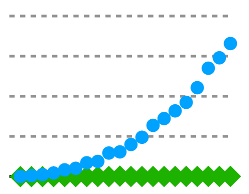
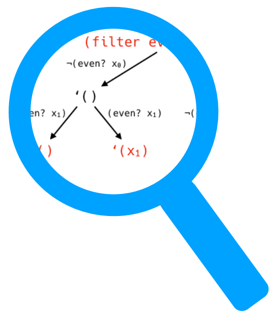


Symbolic evaluation anti-patterns

Common issues and source-level repairs

Symbolic profiling identifies performance issues in symbolic evaluation



Symbolic profiling
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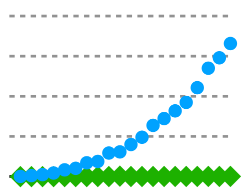
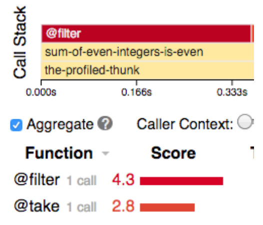
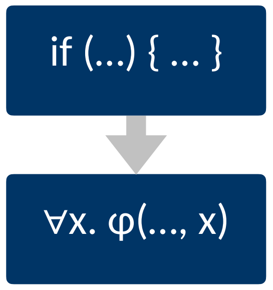


Symbolic evaluation anti-patterns
Common issues and source-level repairs



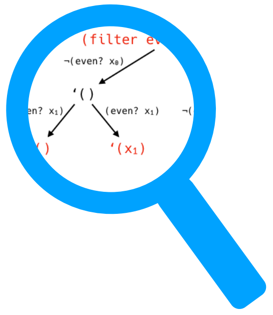
Empirical results
300× speedup on real-world tools

Symbolic profiling identifies performance issues in symbolic evaluation



Symbolic evaluation

All-paths execution of programs



Symbolic profiling

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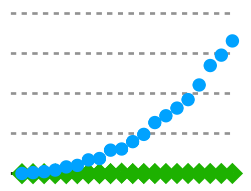

Symbolic evaluation anti-patterns

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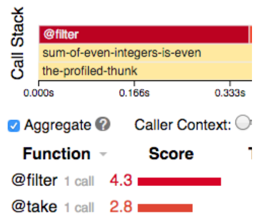

Call Stack

@filter
sum-of-even-integers-is-even
the-profiled-thunk

0.000s 0.166s 0.333s

Aggregate ☑ Caller Context:

Function	Score
@filter 1 call	4.3
@take 1 call	2.8

Empirical results

300× speedup on real-world tools

Symbolic evaluation

All-paths execution of programs

Symbolic evaluation executes *all* paths through a program

```
#lang rosette

(define (first-k-even lst k)
  (define xs (filter even? lst))
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```
(filter even? ‘(x₀ x₁))
```

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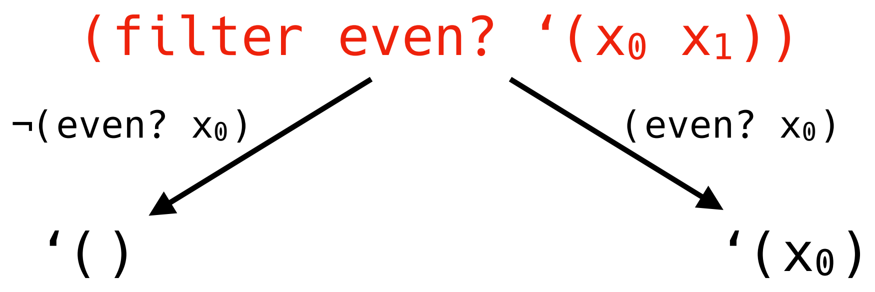

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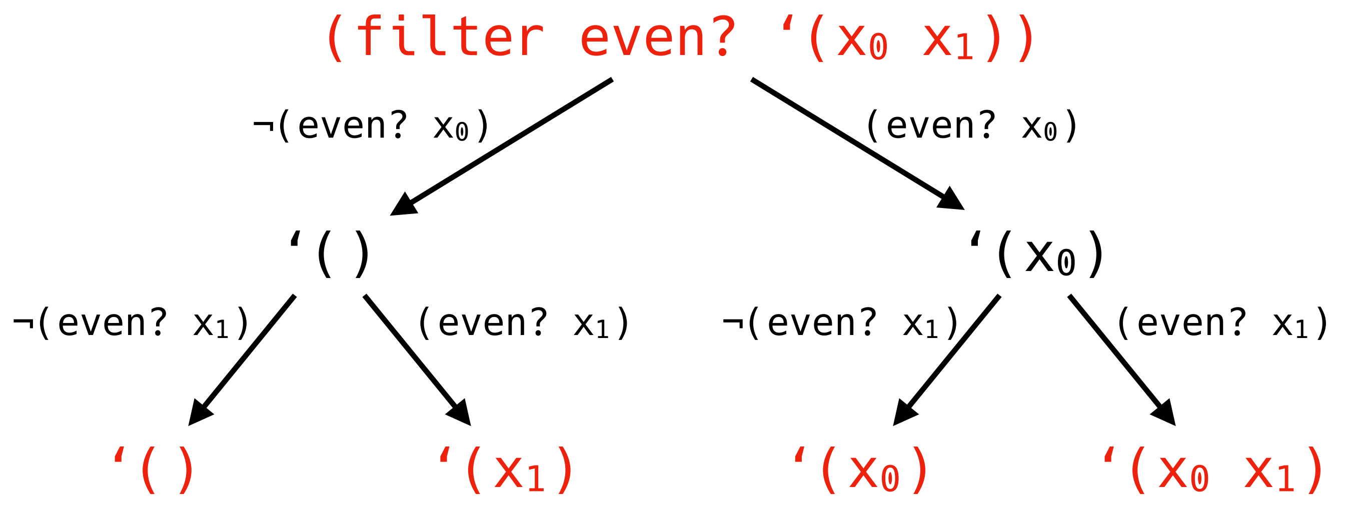

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$$\begin{tikzcd}
 & & & \texttt{(filter even? `(}x_0\ x_1\texttt{))} \arrow[dll, "\neg\texttt{(even? }x_0\texttt{)}"'] \arrow[drr, "\texttt{(even? }x_0\texttt{)}"] & & & \\
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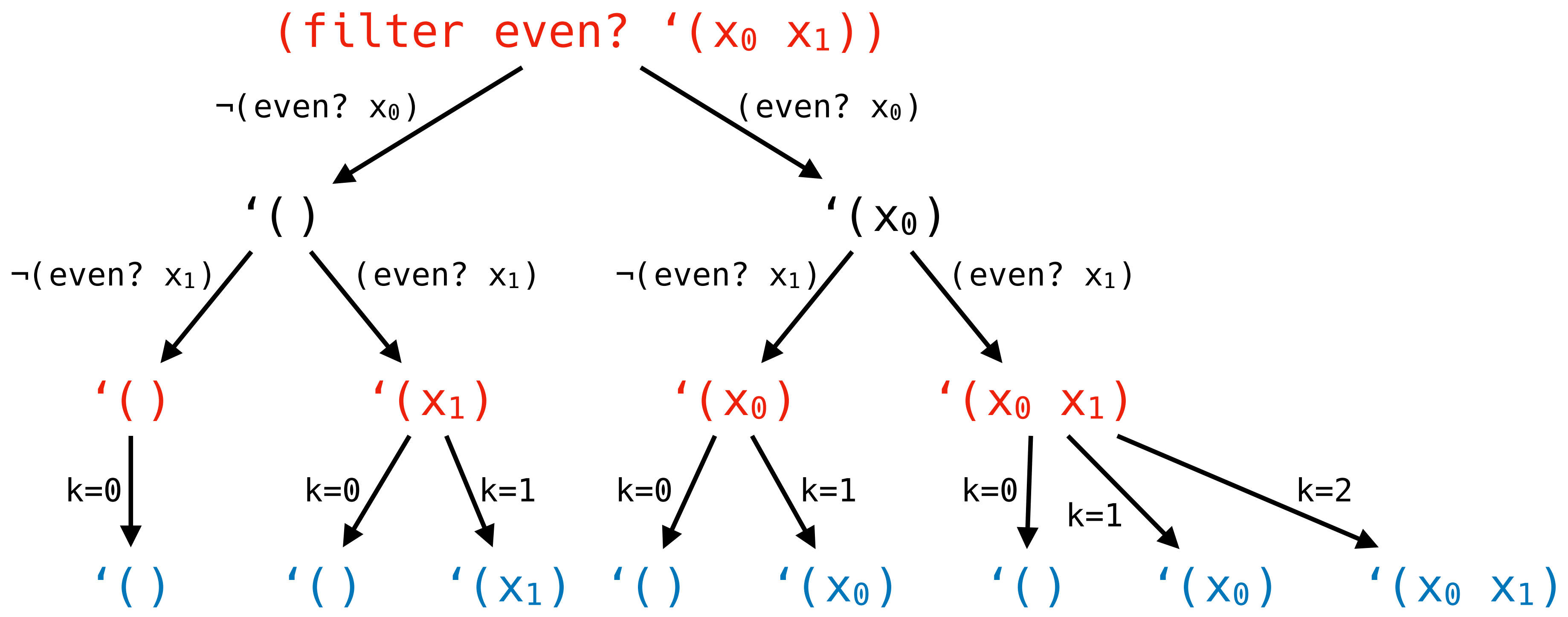
\end{tikzcd}$$

Symbolic evaluation executes *all* paths through a program

```
#lang rosette

(define (first-k-even lst k)
  (define xs (filter even? lst))
  (take xs k))
```

Inputs are *unknown* (trying to find values that violate spec)



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#lang rosette

(define (first-k-even lst k)
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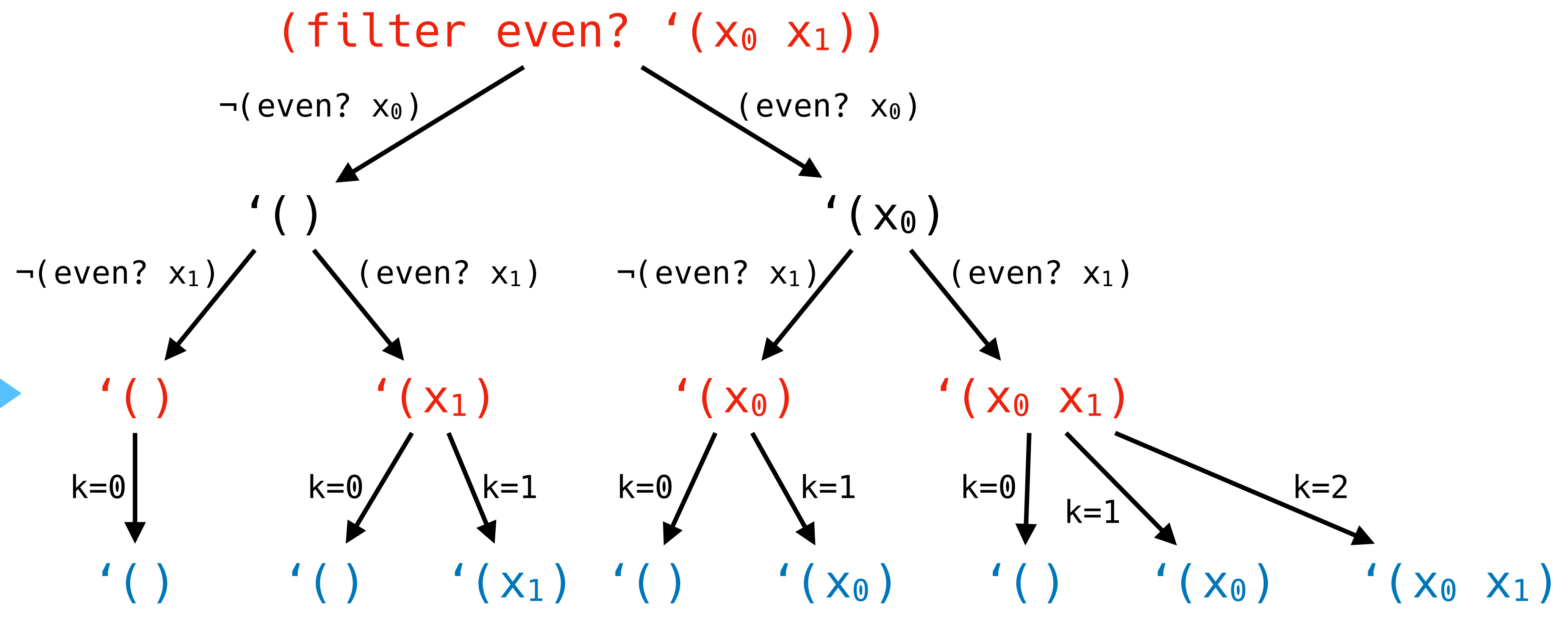
Inputs are *unknown* (trying to find values that violate spec)

take runs 2^2 times



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(define (first-k-even lst k)
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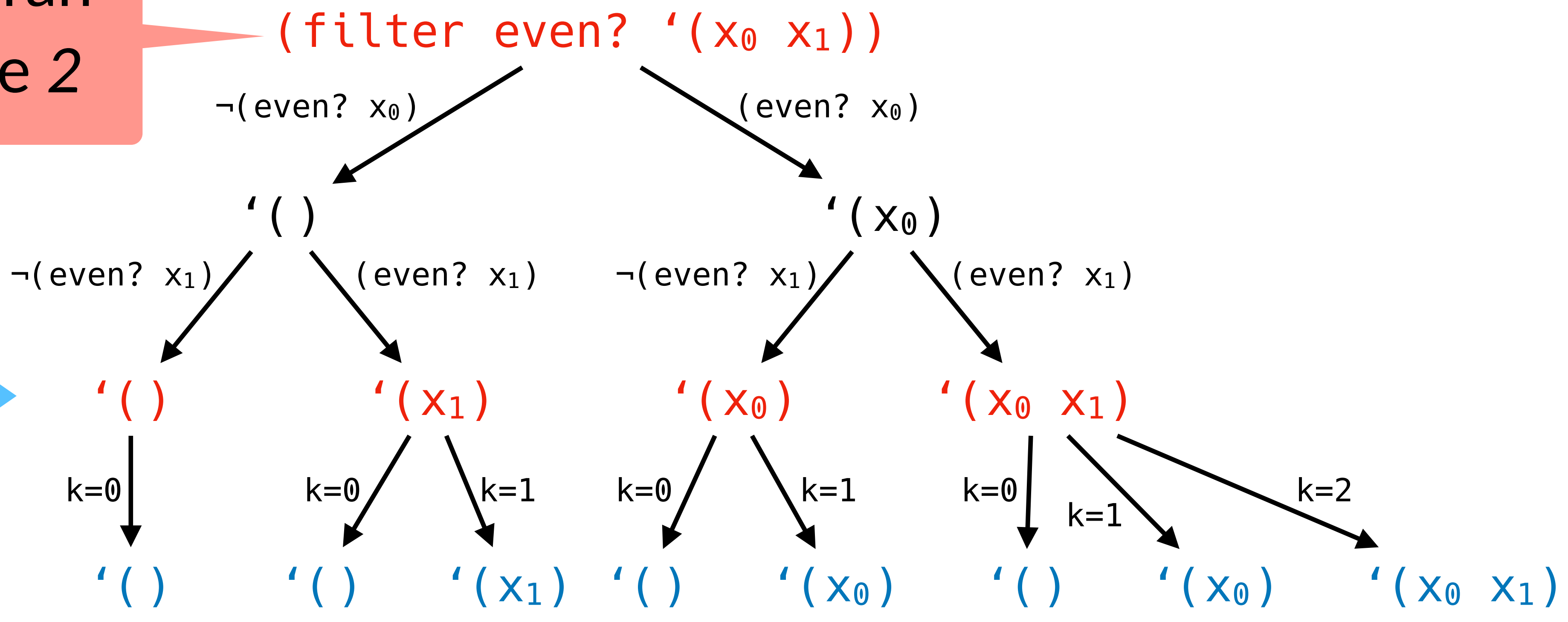
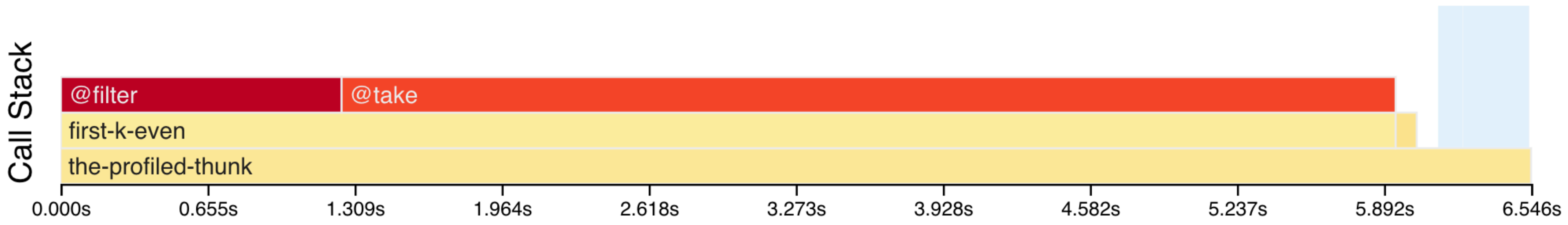
```

Inputs are *unknown* (trying to find values that violate spec)

because filter ran on a list of size *2*

take runs 2^2 times





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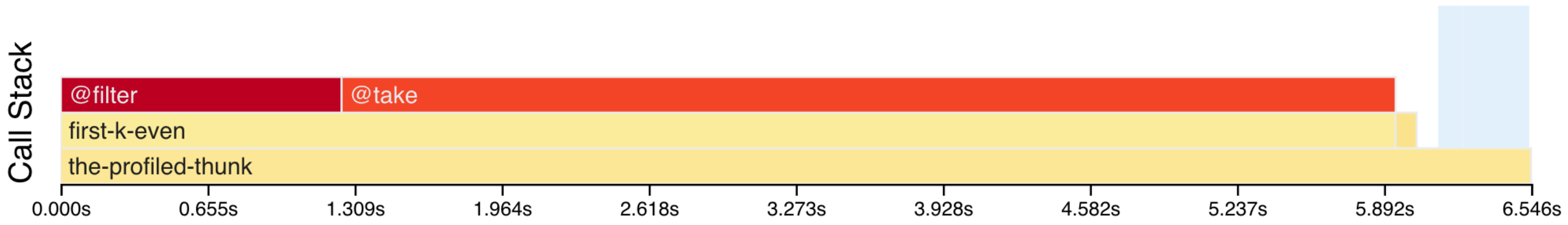
andmap 1 call	0.3	94	14180	14180	0	4097
the-profiled-thunk	0.1	511	66	0	0	0



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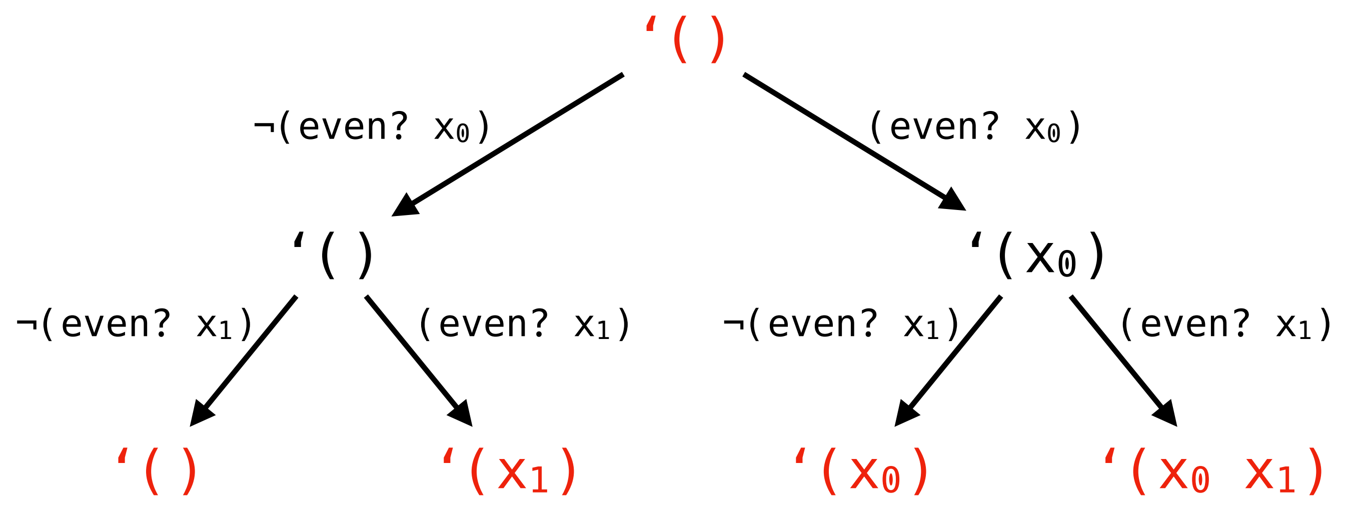
Blaming filter even though it’s not the slowest

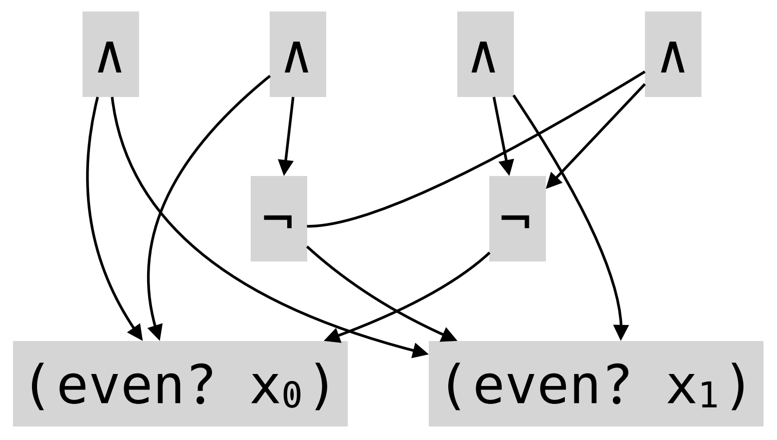
Symbolic profiling

Data structures and metrics

Two data structures to summarize symbolic evaluation



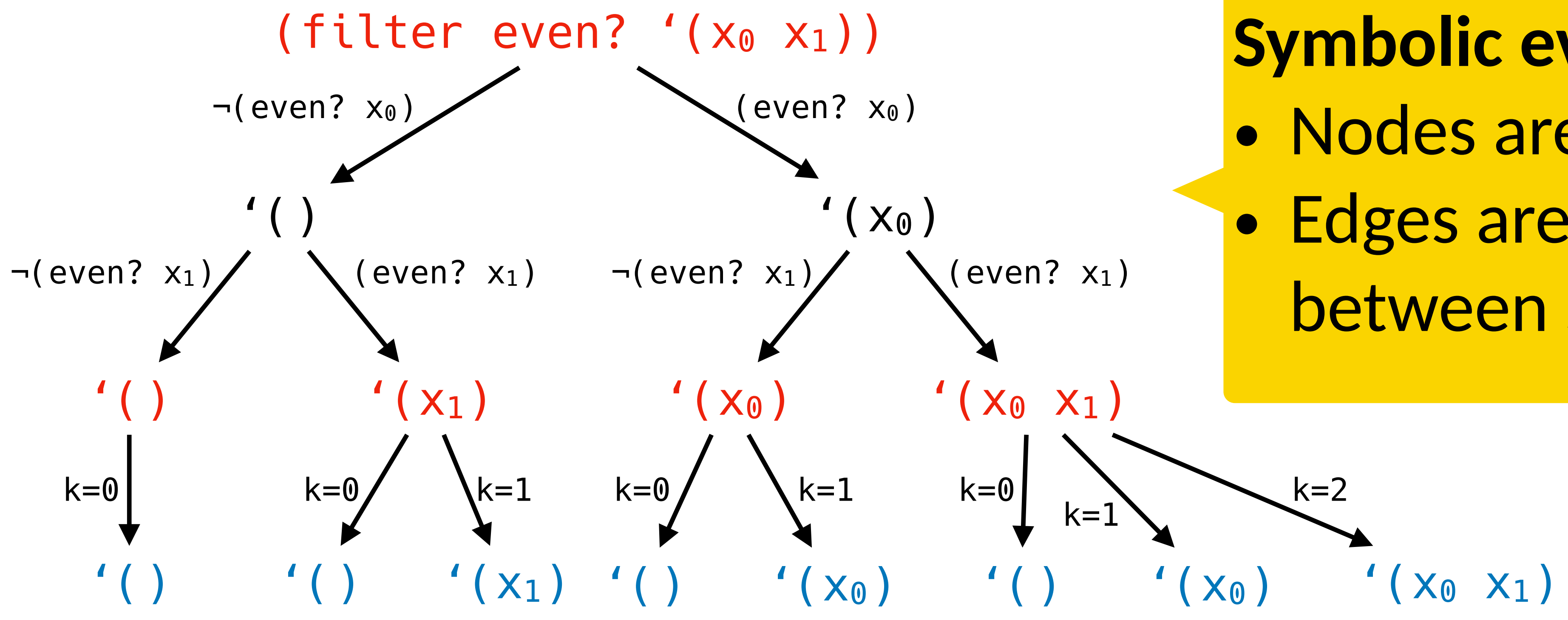
Symbolic evaluation graph
Reflects the evaluator's strategy
for all-paths execution of the program



Symbolic heap
Shape of all symbolic values
created by the program

Any symbolic evaluation technique can be summarized by these two data structures

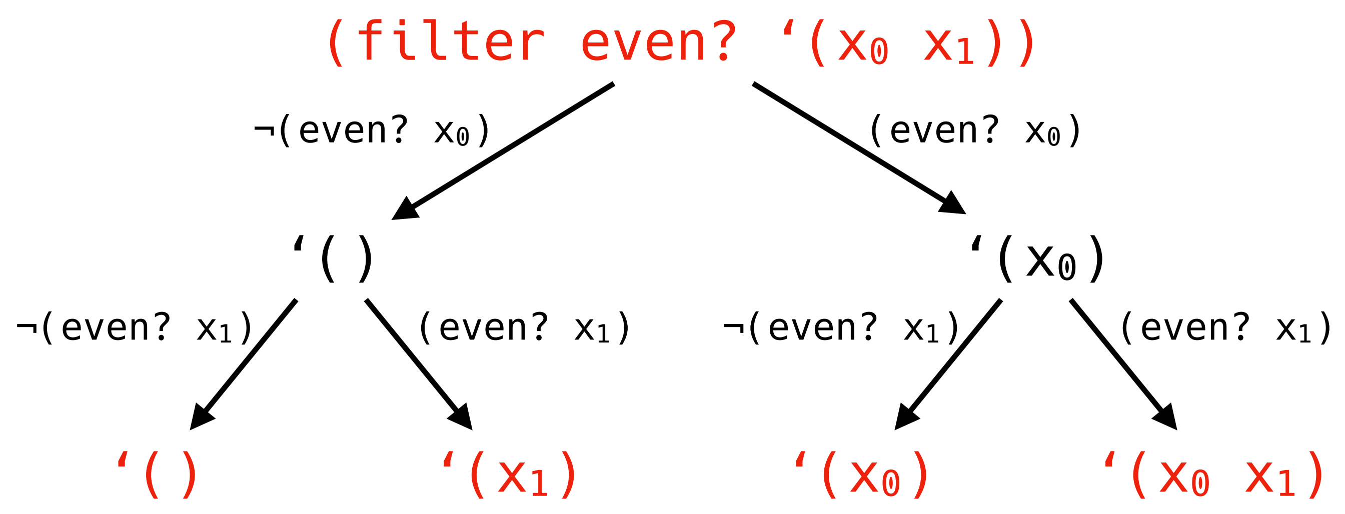
The *symbolic evaluation graph* summarizes branching and merging



Symbolic evaluation graph

- Nodes are program states
- Edges are transitions between states

The *symbolic evaluation graph* summarizes branching and merging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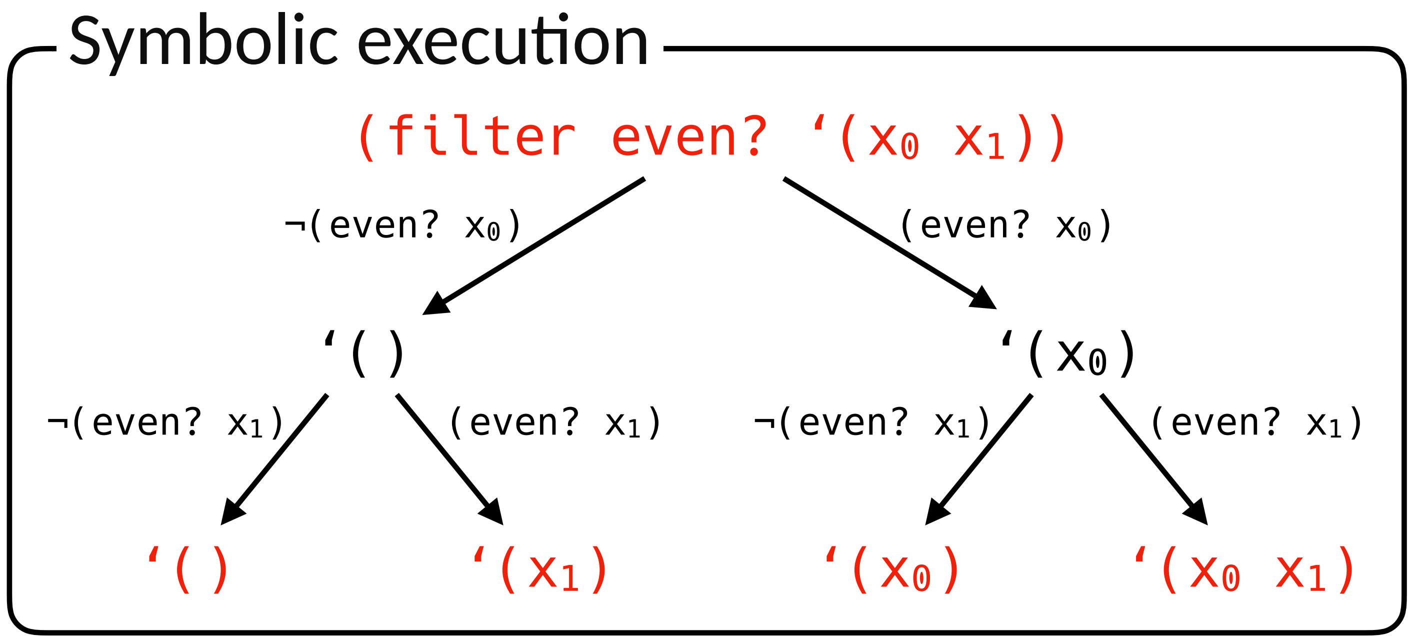

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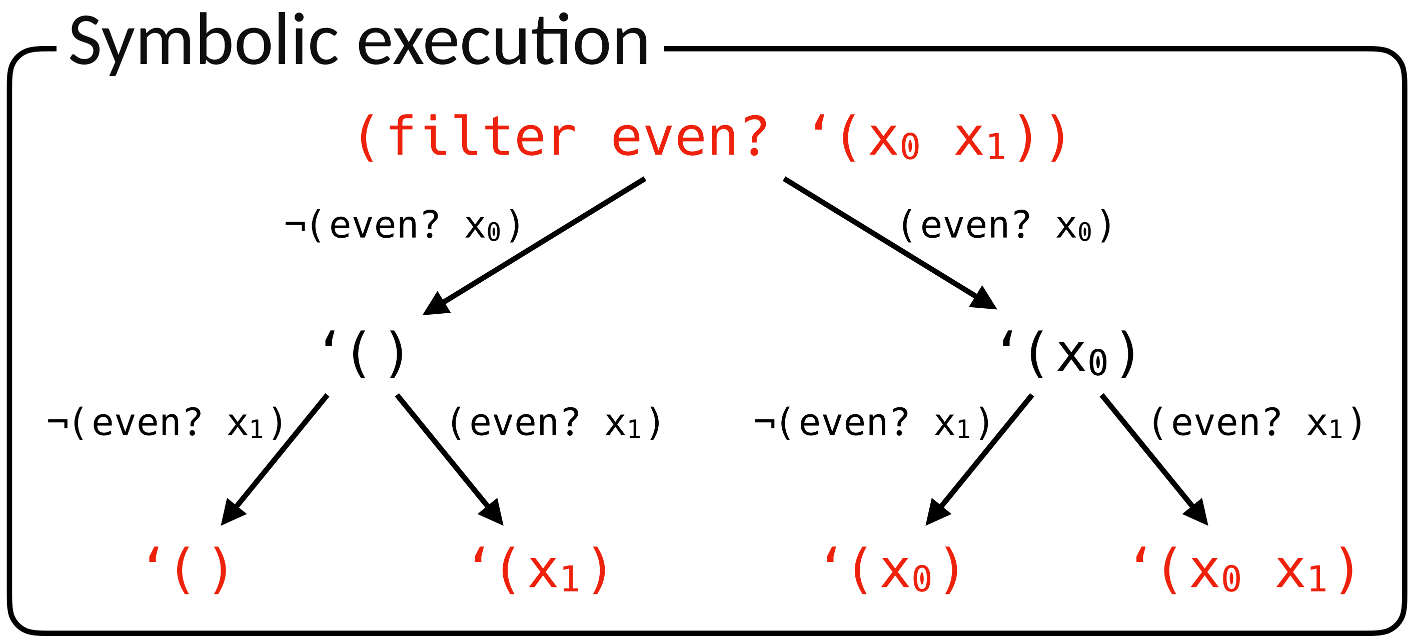

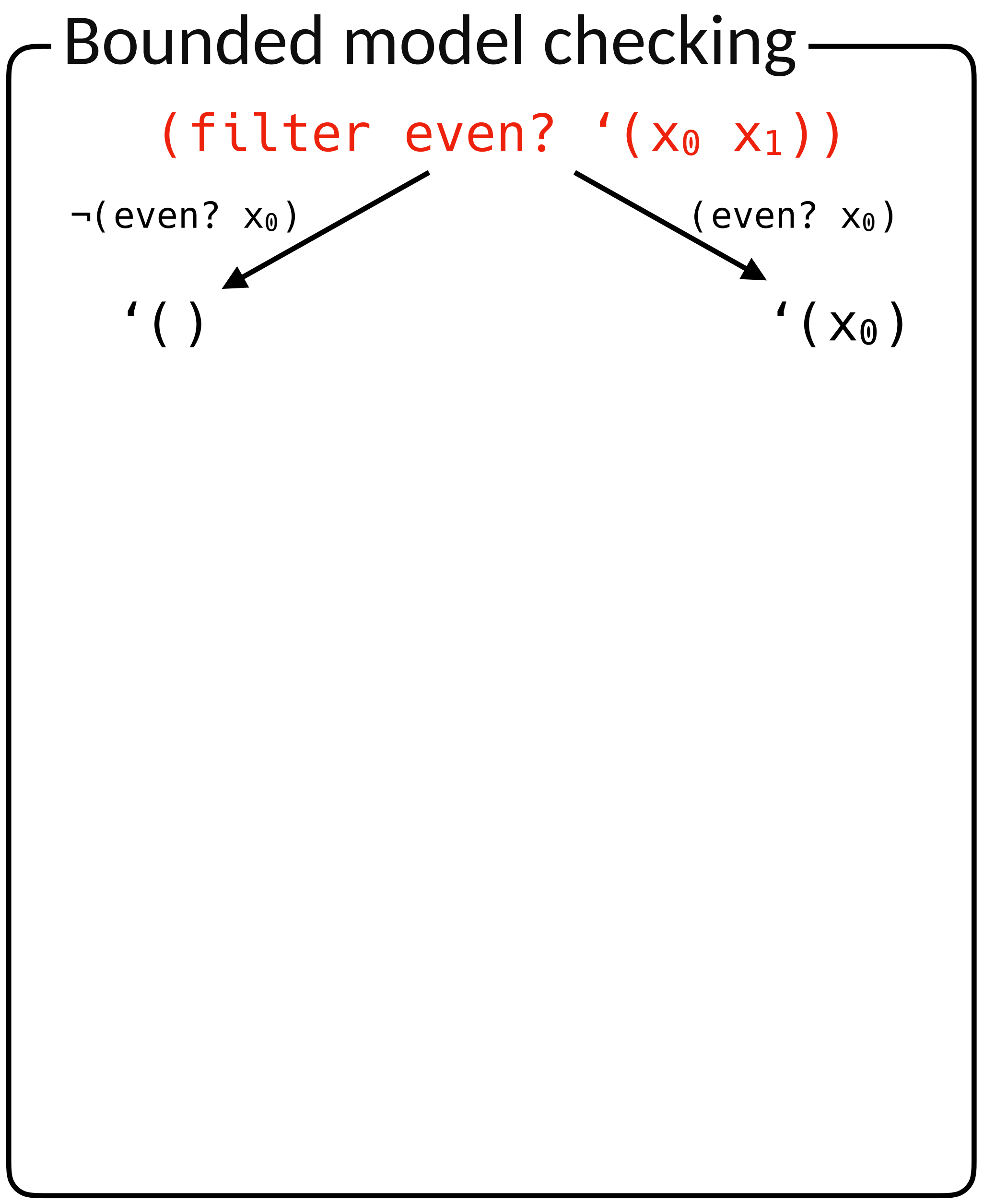

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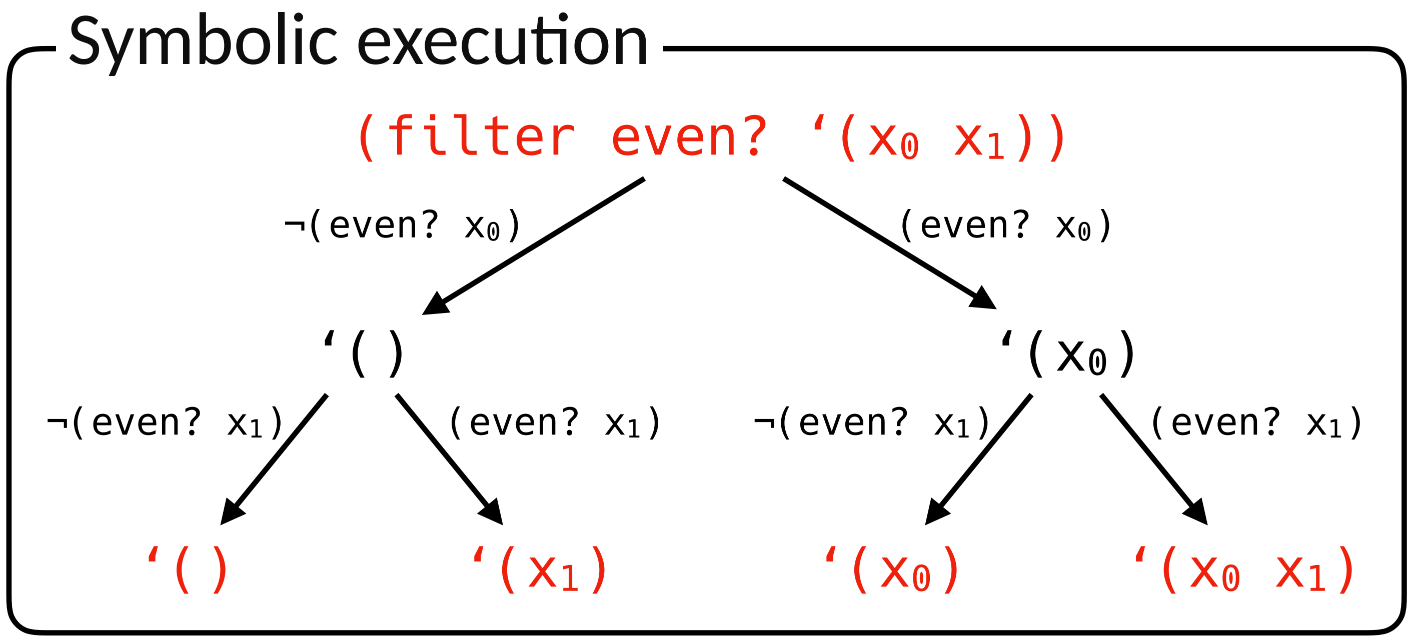
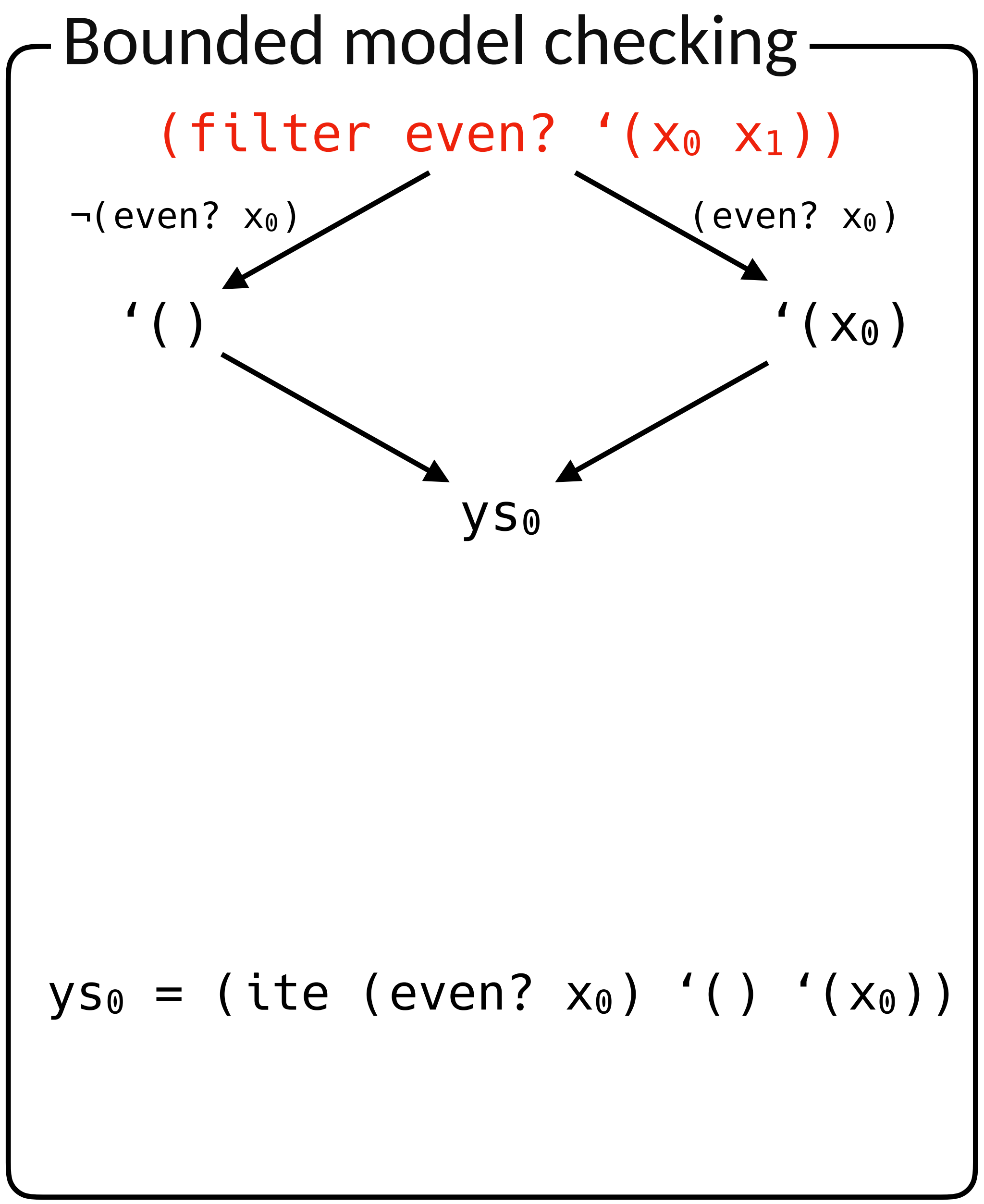
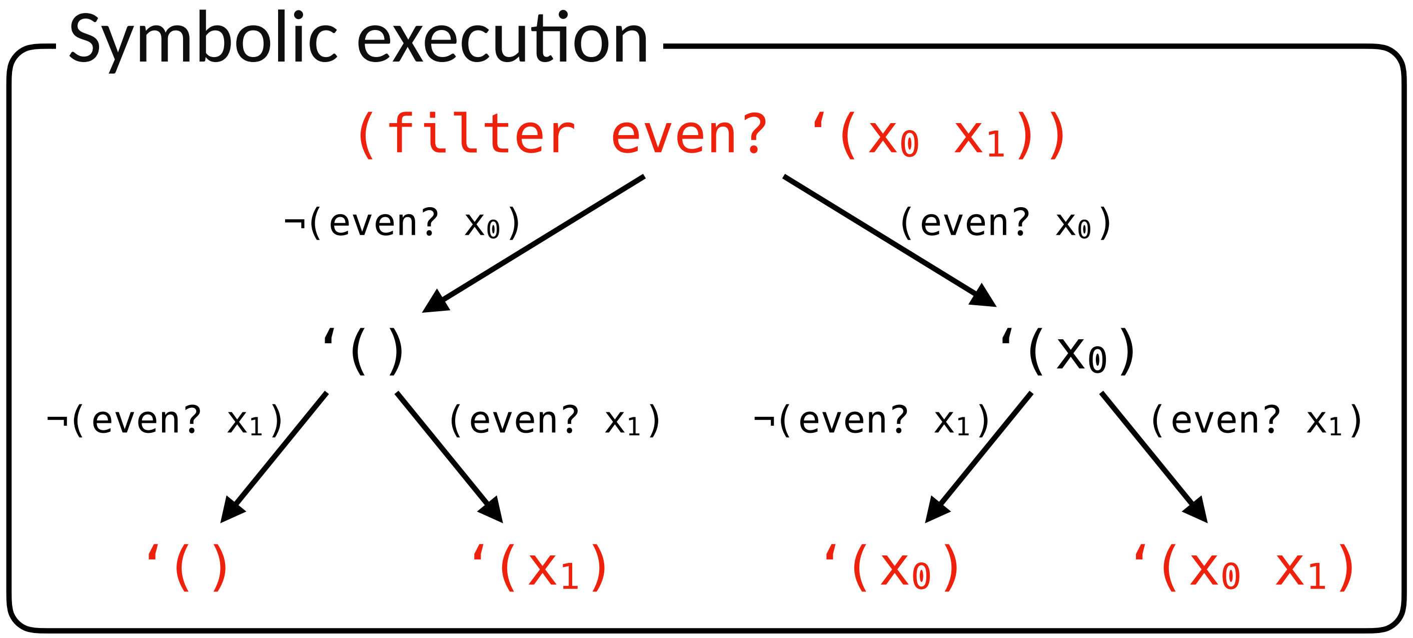
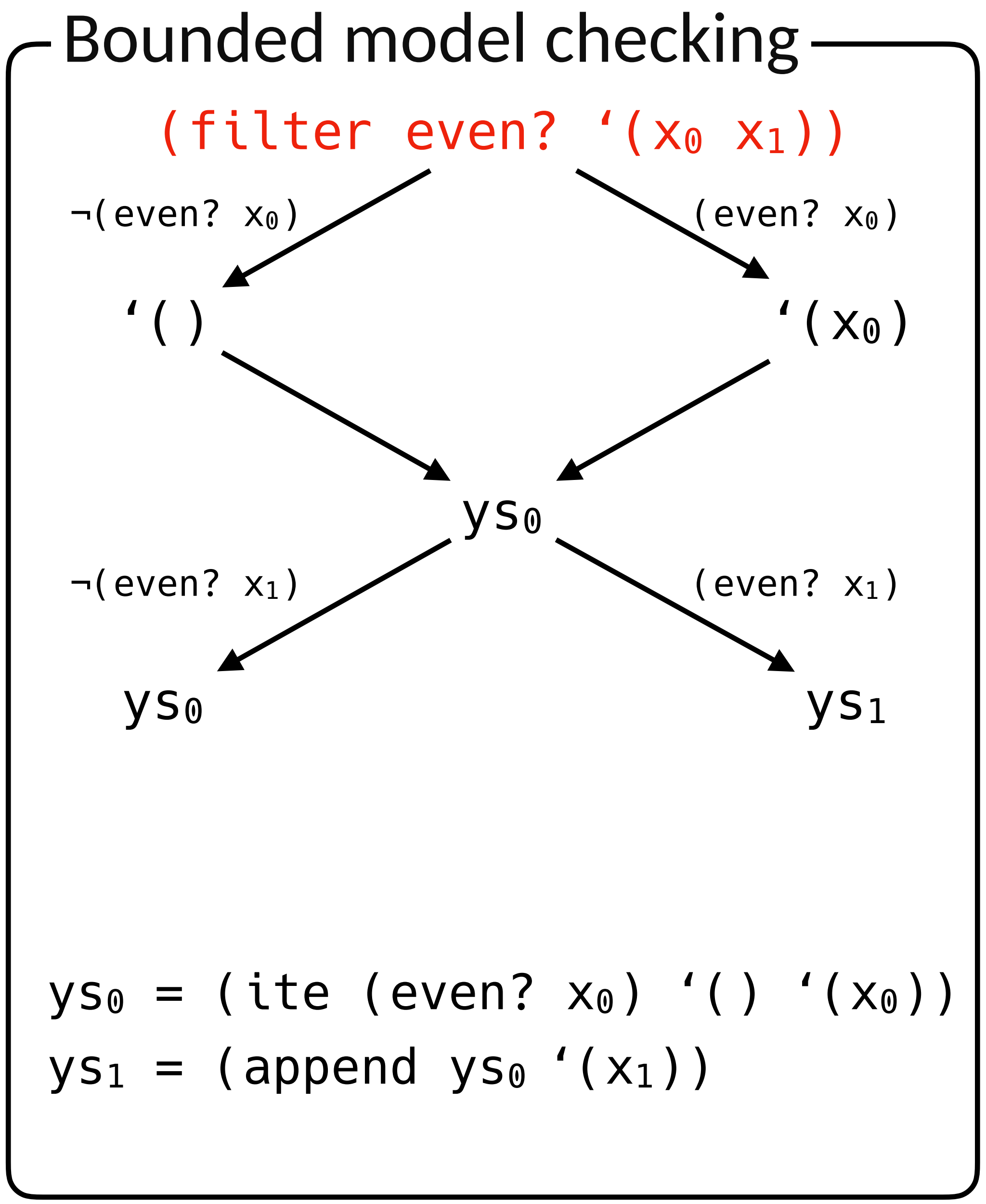




```
ys₀ = (ite (even? x₀) ‘() ‘(x₀))
```

The *symbolic evaluation graph* summarizes branching and merging





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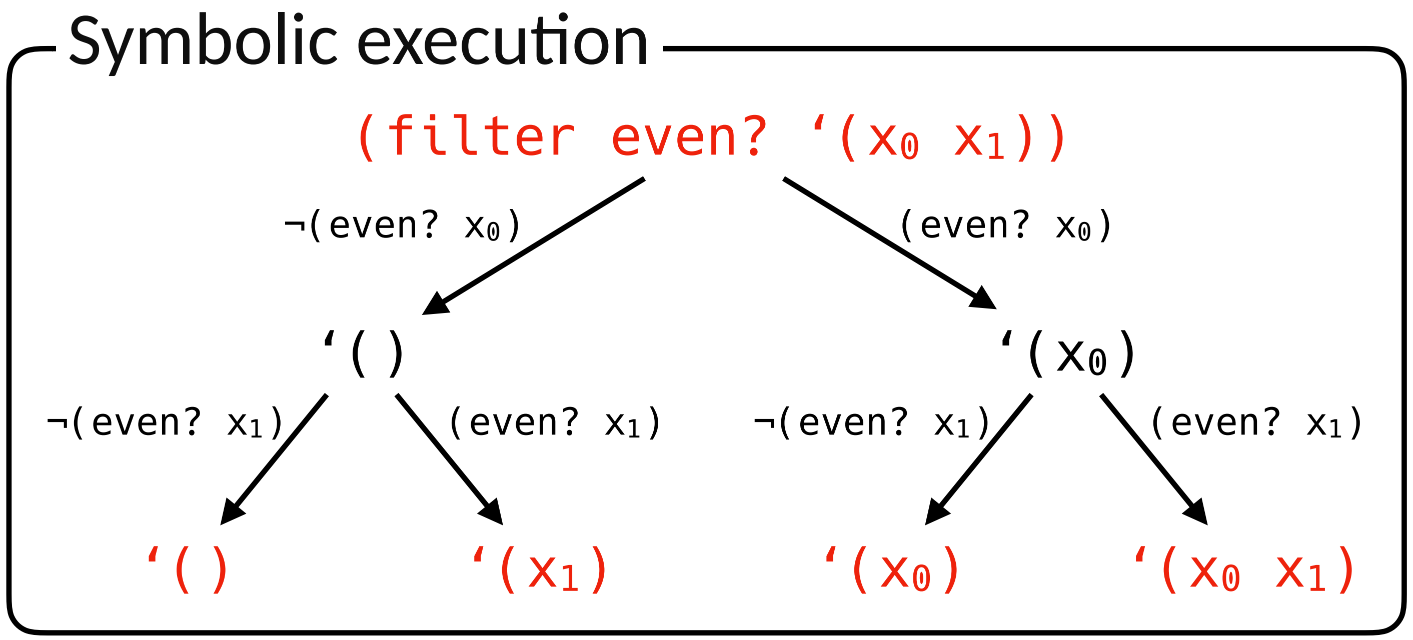
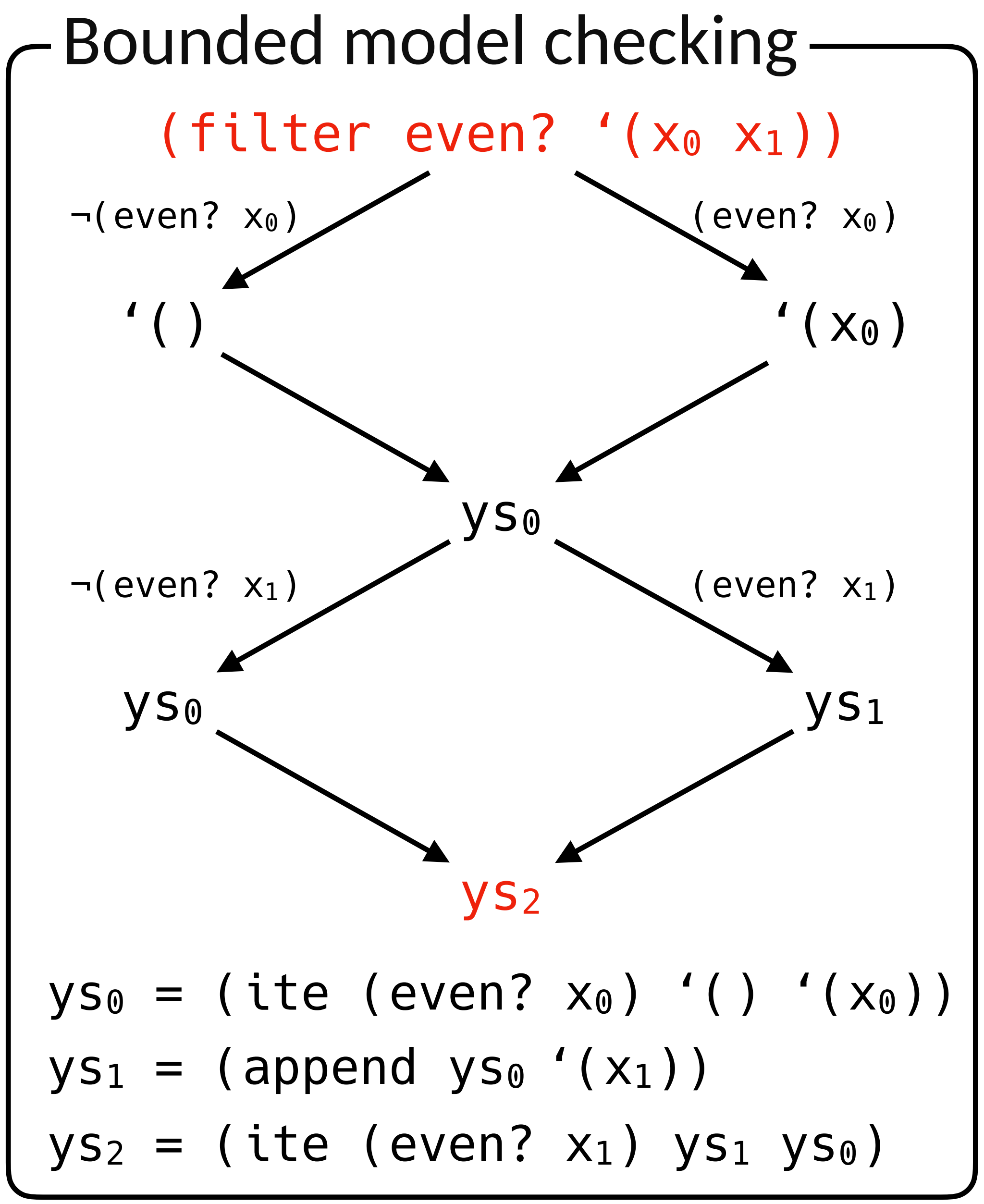
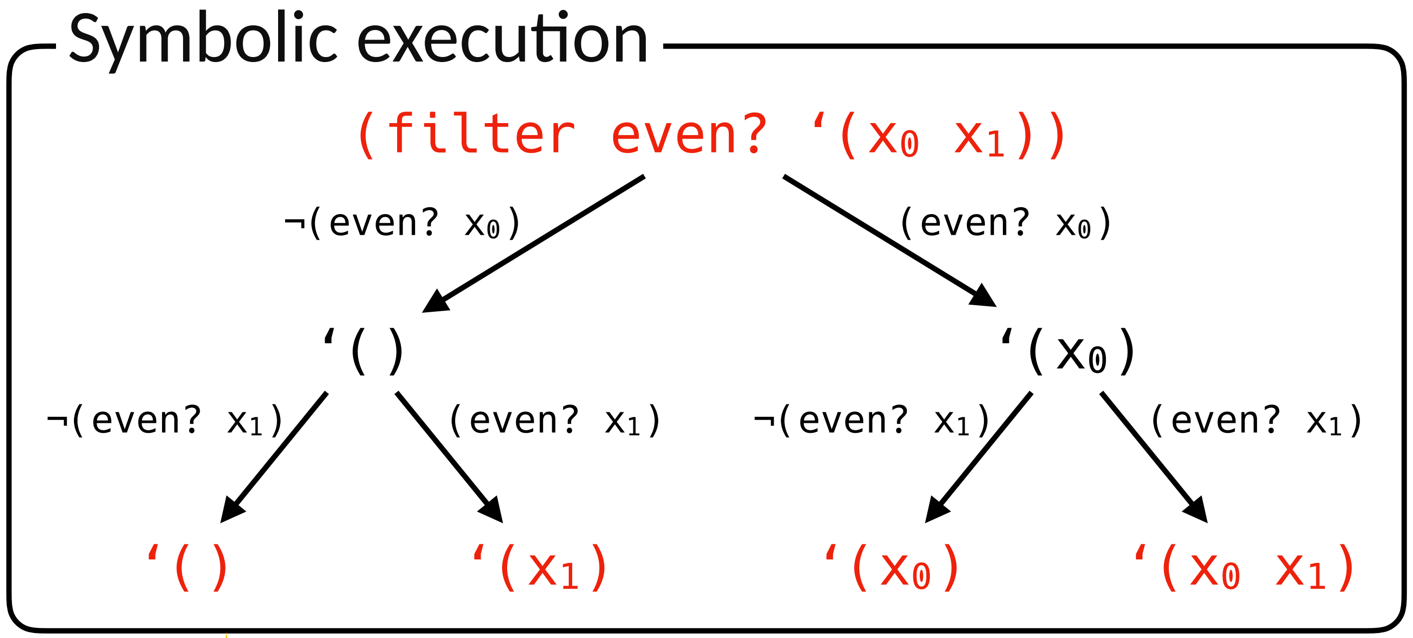




```
ys0 = (ite (even? x0) ‘() ‘(x0))
ys1 = (append ys0 ‘(x1))
ys2 = (ite (even? x1) ys1 ys0)
```

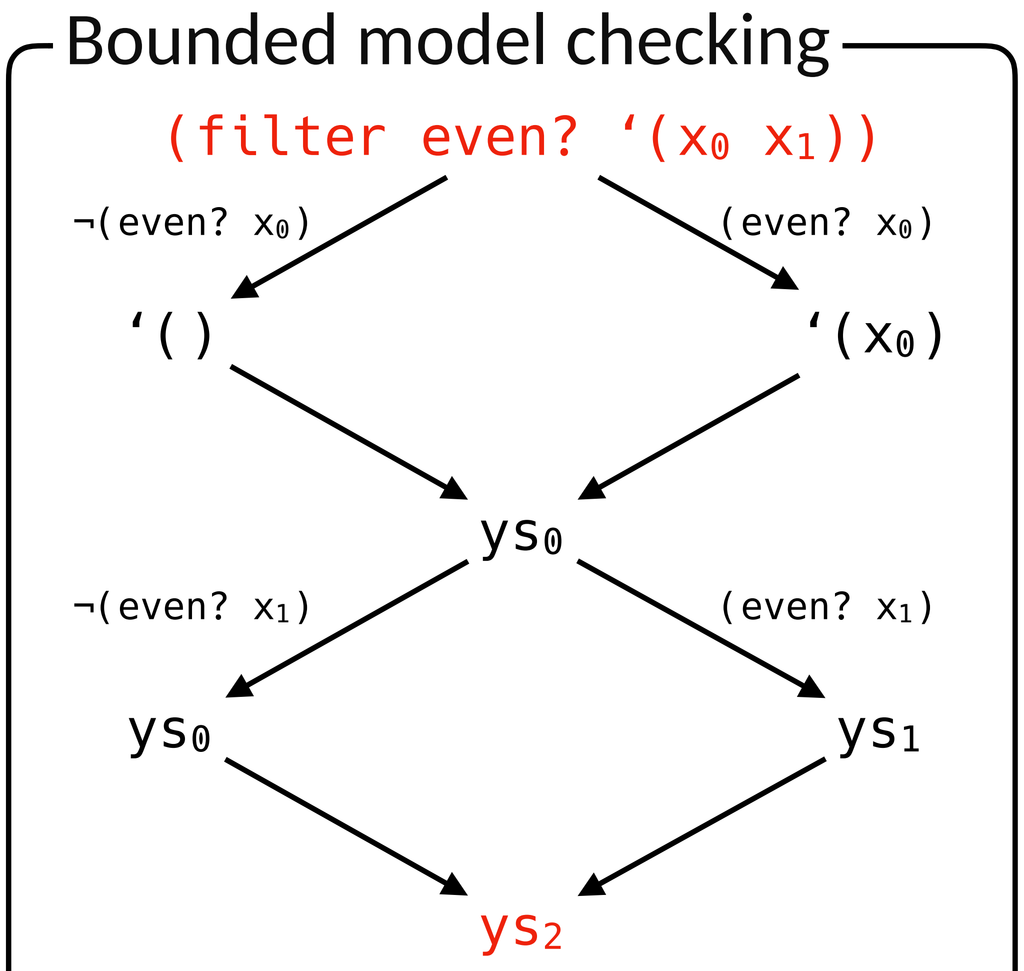
The *symbolic evaluation graph* summarizes branching and merging

Symbolic execution



More states, but more concrete

Bounded model checking

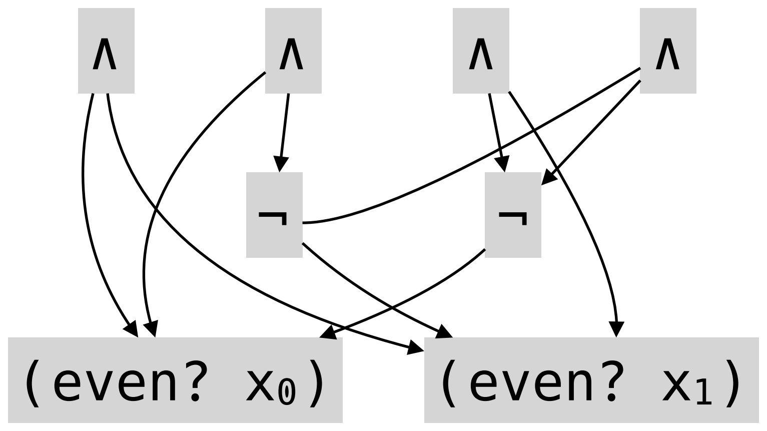


```
ys₀ = (ite (even? x₀) '() '(x₀))
ys₁ = (append ys₀ '(x₁))
ys₂ = (ite (even? x₁) ys₁ ys₀)
```

Fewer states but less concrete

The *symbolic heap* shows how symbolic values are used

Symbolic execution

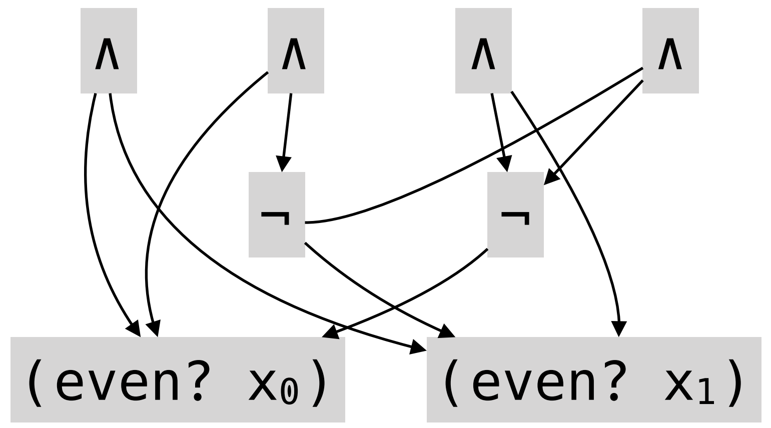


Symbolic heap

- Nodes are symbolic terms
- Edges are sub-terms

The *symbolic heap* shows how symbolic values are used

Symbolic execution



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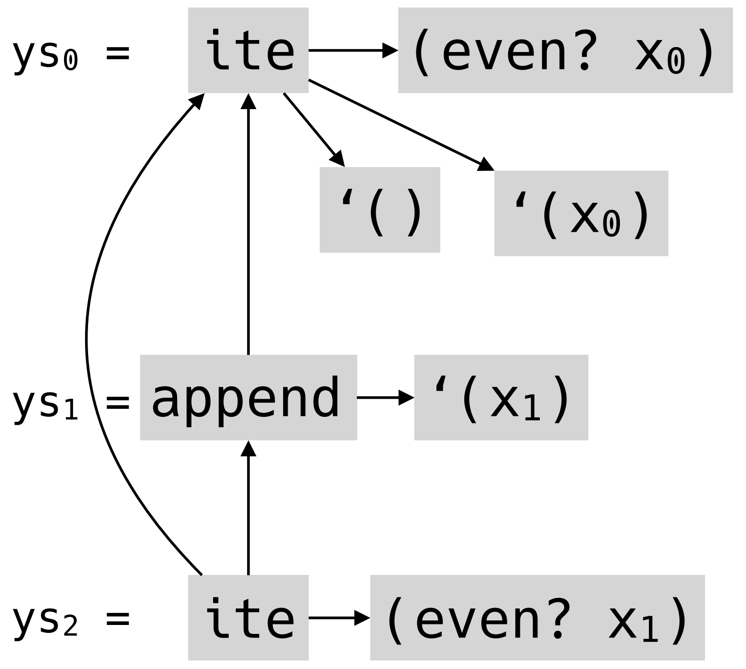

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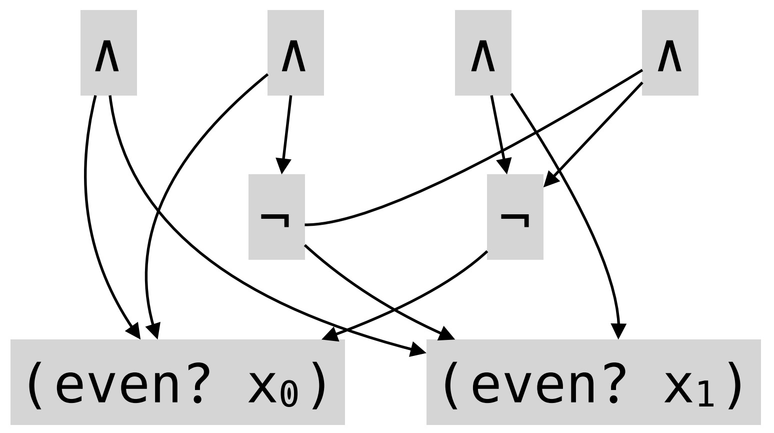

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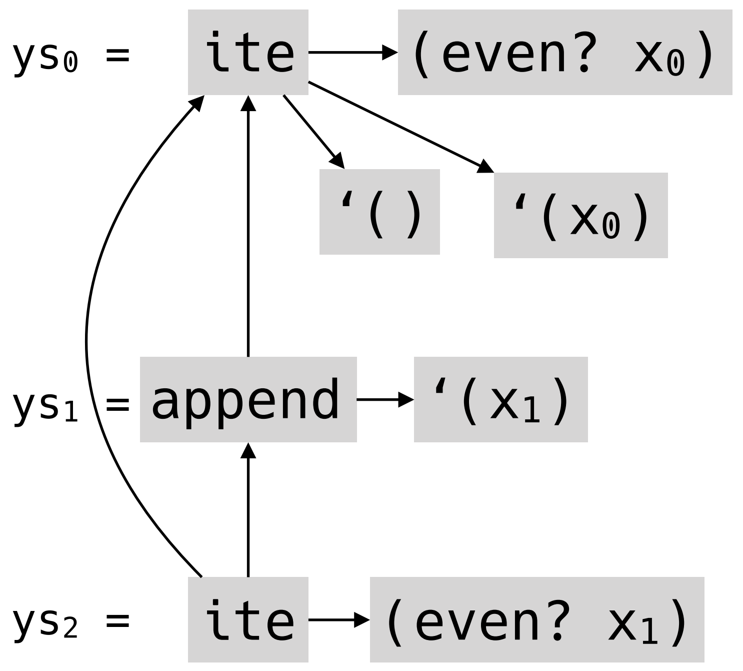

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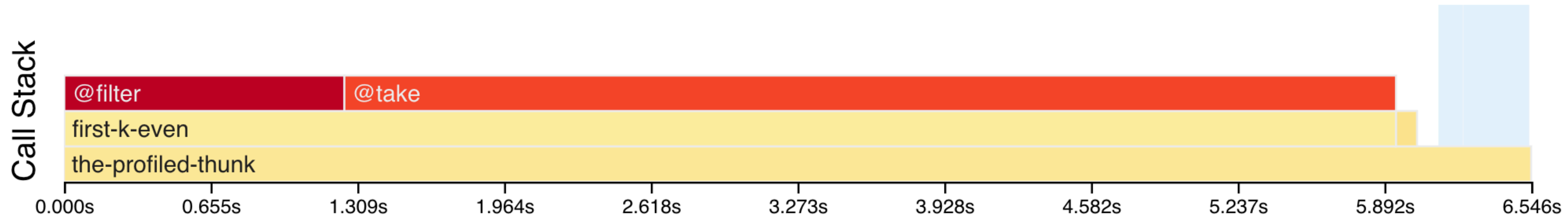
Only conditions in the heap

Conditions and values (lists etc.) in the heap

Analyzing symbolic data structures



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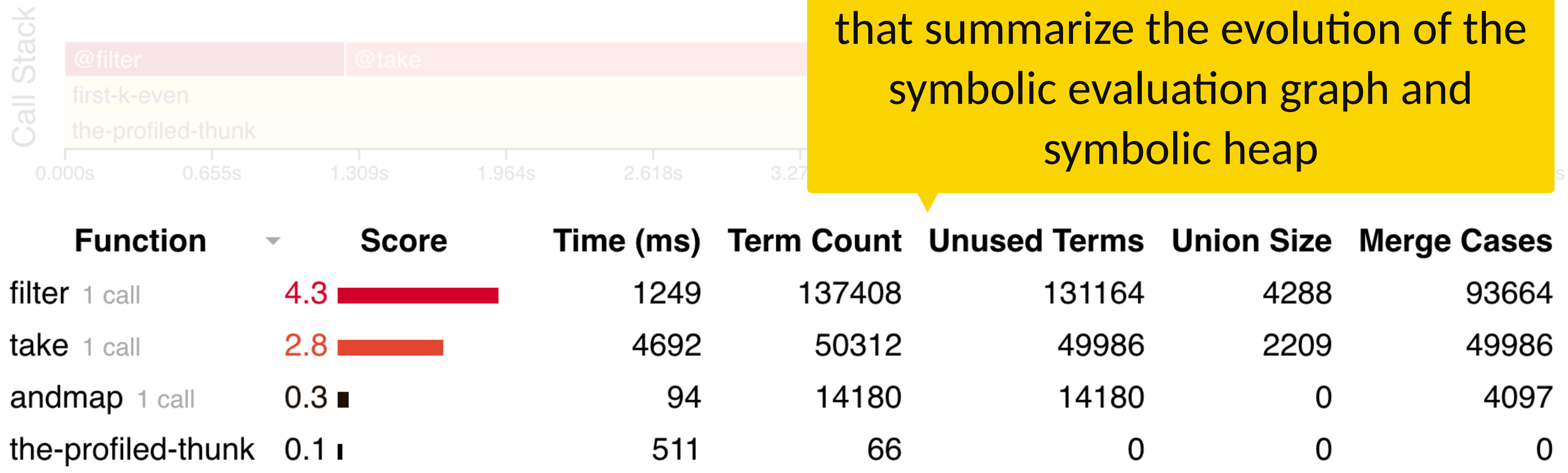
Analyzing symbolic data structures



For each procedure, measure metrics that summarize the evolution of the symbolic evaluation graph and symbolic heap

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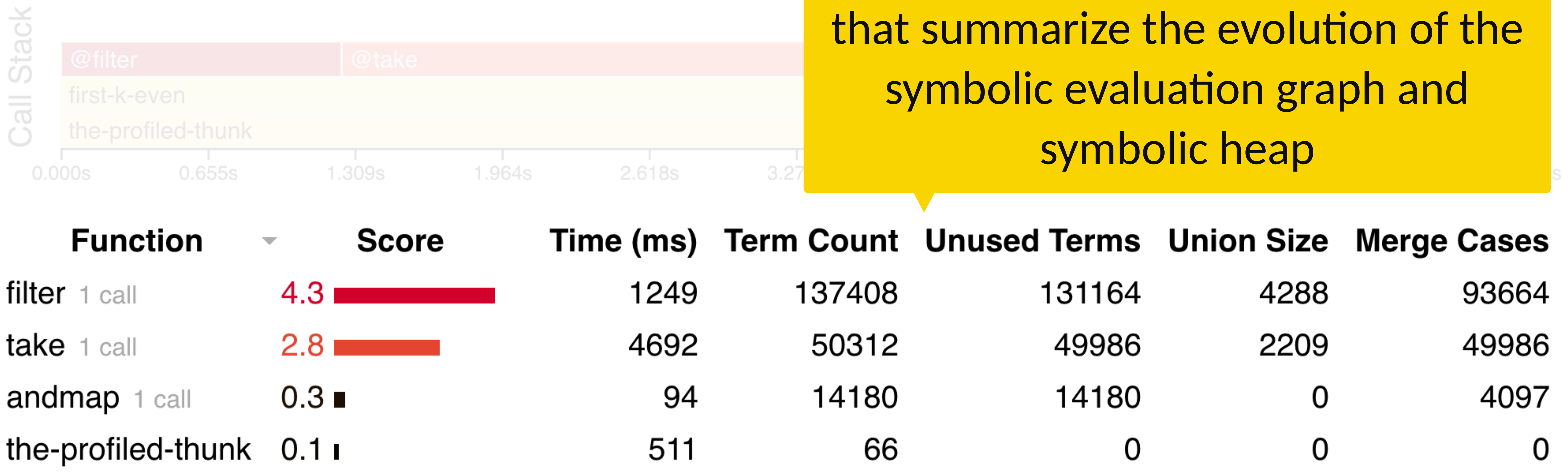

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Summarize metrics as a score to rank procedures in the program

Symbolic evaluation anti-patterns

Common issues and repairs

Common anti-patterns and repairs in symbolic evaluation

- Algorithmic mismatch
  - Algorithms or optimizations poorly suited to symbolic evaluation

Common anti-patterns and repairs in symbolic evaluation

Algorithmic mismatch

- Algorithms or optimizations poorly suited to symbolic evaluation

```
(define (list-set lst idx val)
  (match lst
    [(cons x xs)
     (if (= idx 0)
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Terminates early once *idx* is found

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Algorithmic mismatch

Algorithms or optimizations poorly suited to symbolic evaluation

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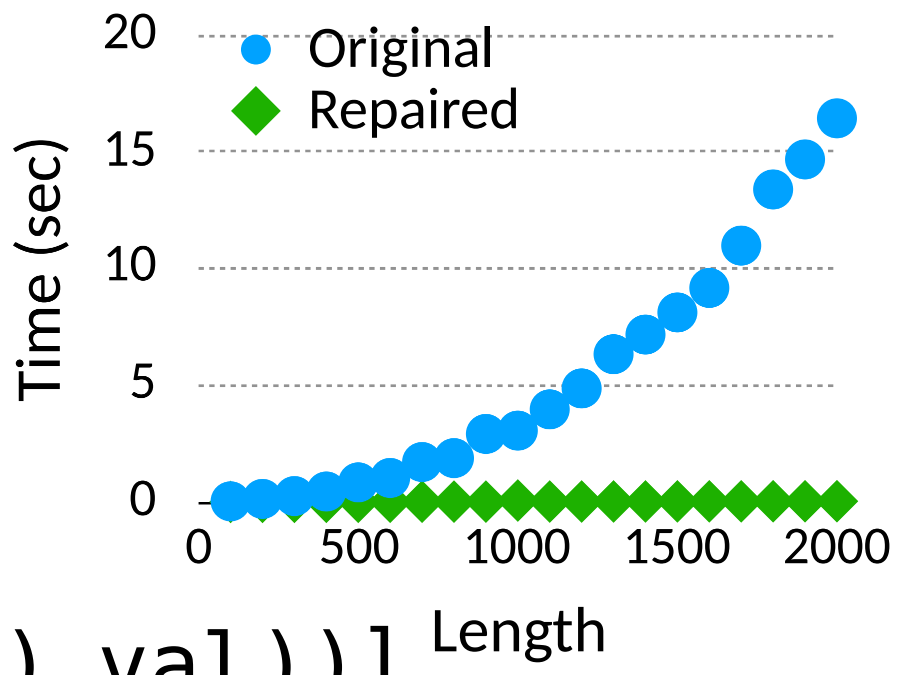

Common anti-patterns and repairs in symbolic evaluation

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Irregular representation

- Data structures of different shapes create different paths

Missed concretization

- Lost opportunities to exploit concrete values

Empirical results

Case studies and evaluation

Three symbolic profilers

We developed two implementations:

- The **Rosette** solver-aided language (Racket)
- The **Jalangi** dynamic analysis framework (JavaScript)

Since publication, based on our work:

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Actionable: real-world bugs

Case studies on published Rosette-based tools

Tool	**Speedup**
Type system soundness checker [POPL'18]	1.35×
Refinement type checker for Ruby [VMCAI'18]	6×
File-system crash consistency verifier [ASPLOS'16]	24×
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Used in production at the UW Medical Center

Multiple patches accepted by developers

Explainable: study real users

Small user study: 8 Rosette users, asked to find known performance bug in 4 programs

Users solved every task more quickly when they had access to symbolic profiling

- 6 failures without symbolic profiling, none with

Qualitative feedback:

- “gave insight into what Rosette is doing”
- “even more useful on my own code”

Symbolic profiling identifies performance issues in symbolic evaluation

Does my program work on all inputs?

Is there a program that does what I want?

Verification

Synthesis

```
raco symprofile file.rkt
```

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