Compiling & Controlling Symbolic Execution

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Midwest PL Summit – Oct 6 2023 – University of Michigan

PURPL

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Symbolic Execution

```
x = user_input()
y = user_input()

if (x > 5) {
    if (y < 10) {
        ...
    } else {
        ...
    }
} else {
    ...
}
```

Symbolic Execution

mark as symbolic

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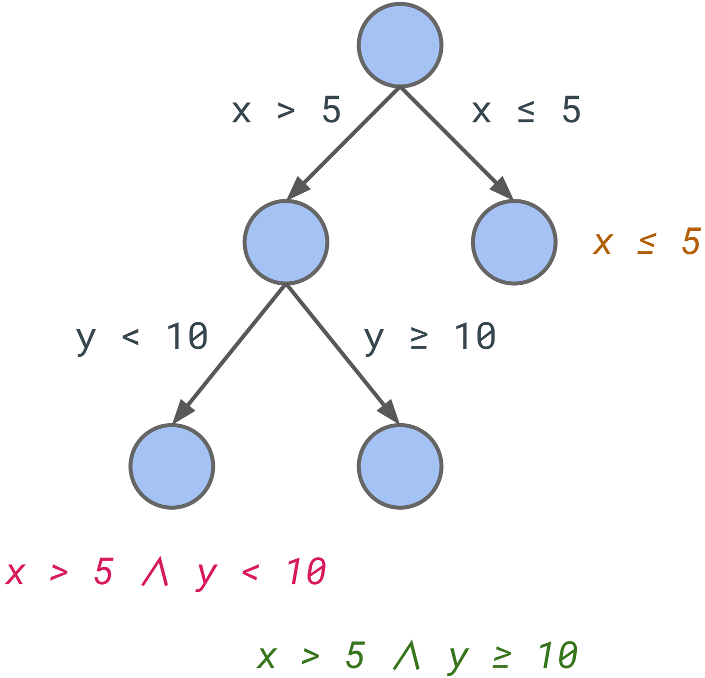
} else {
    ... /* path 3 */
}
```



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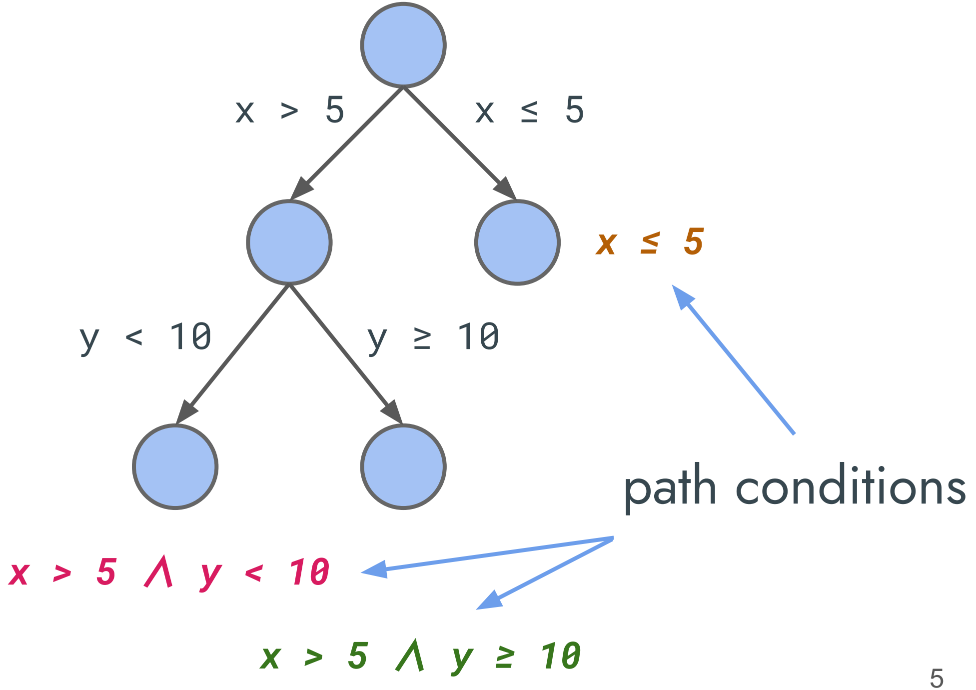

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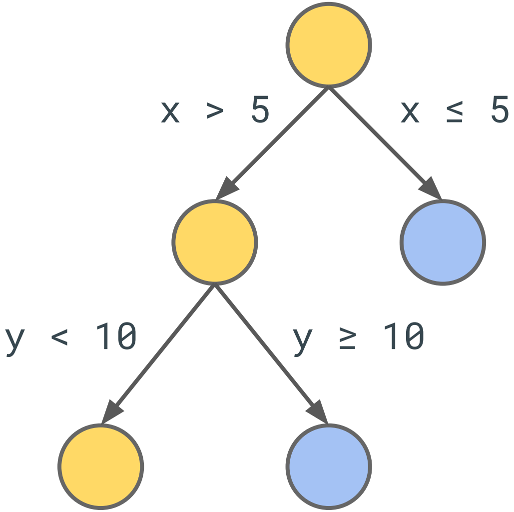


solver(***x > 5 ∧ y < 10*** *) = { x = 6, y = 9 }*

Symbolic Execution – Applications

- automatic test case generation
- bug finding and exploit generation
- program verification
- worst-case execution time analysis
- …

Symbolic Execution Engine

a concrete interpreter `eval: Prog → (Value, State)`

- simulates the execution deterministically

Symbolic Execution Engine

a *symbolic* interpreter $\texttt{eval}_{\texttt{sym}}$`: Prog → Set[(Value, State, PC)]`

- simulates the execution *nondeterministically*
- records the condition of each path

Path Explosion

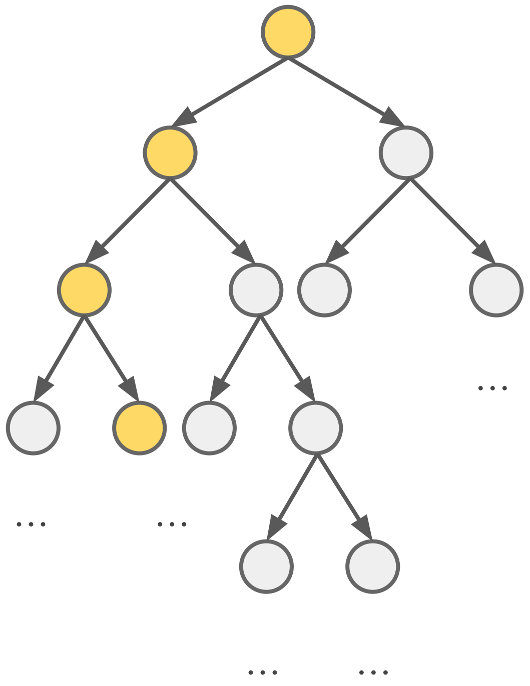
Concrete Execution

1 path

vs

Symbolic Execution

exponential number of independent paths



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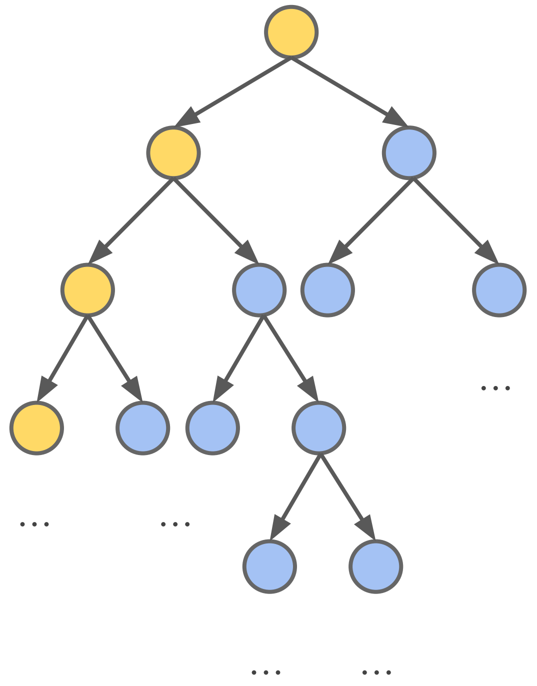

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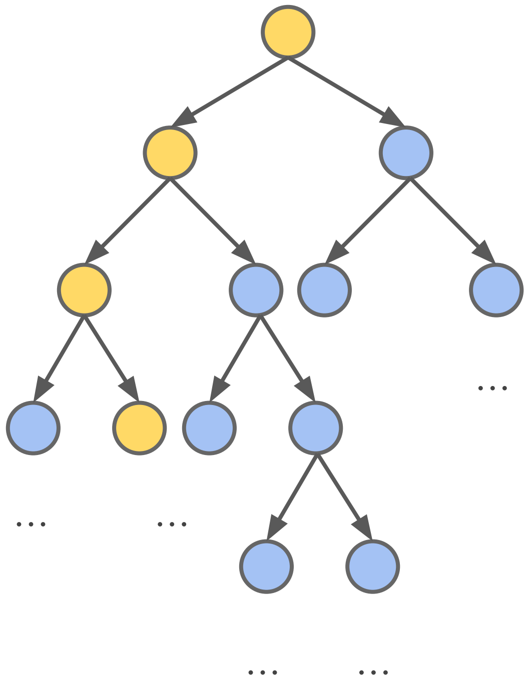

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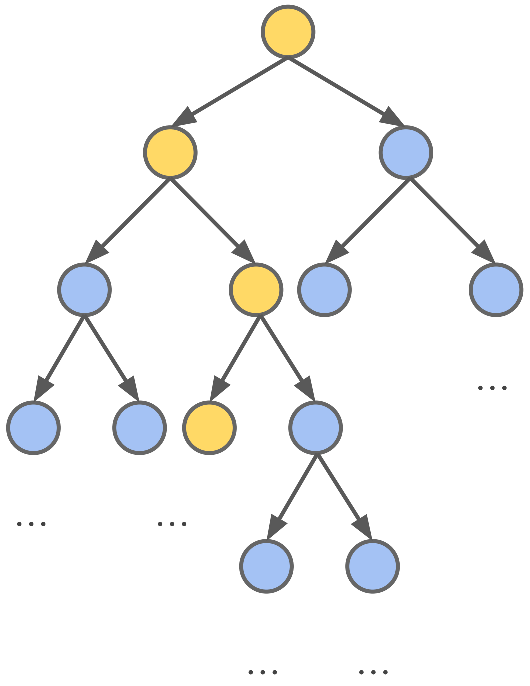

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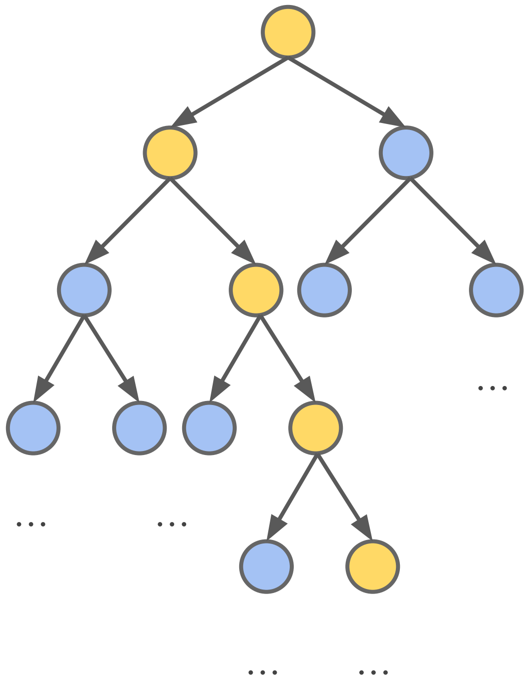

Path Explosion

Concrete Execution

1 path

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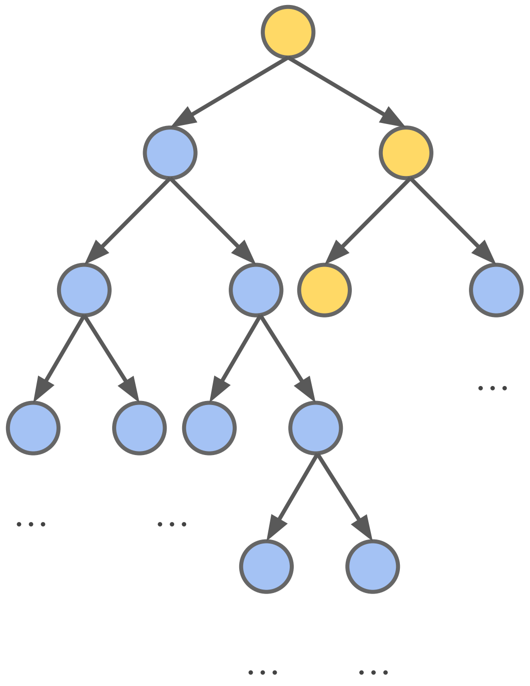
Symbolic Execution

exponential number of independent paths

performance matters



Performance Matters

$\texttt{eval}_{\texttt{sym}}\texttt{: Prog} \rightarrow \texttt{Set[(Value, State, PC)]}$

symbolic interpreter performance
compared to native execution

KLEE (C++)	3,000x slower
angr (Python)	321,000x slower

Data from Qsym: A practical concolic execution engine tailored for hybrid fuzzing. Yun et al., USENIX Security, 2018.

Performance Matters

$\texttt{eval}_{\texttt{sym}} : \texttt{Prog} \rightarrow \texttt{Set[(Value, State, PC)]}$

interpretation overhead

- inspecting program AST/IR
- dispatching the semantics
- recursion at meta-level

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Symbolic-Execution Compilers

To remove these overheads,

compilation is inevitable.

Symbolic-Execution Compilers

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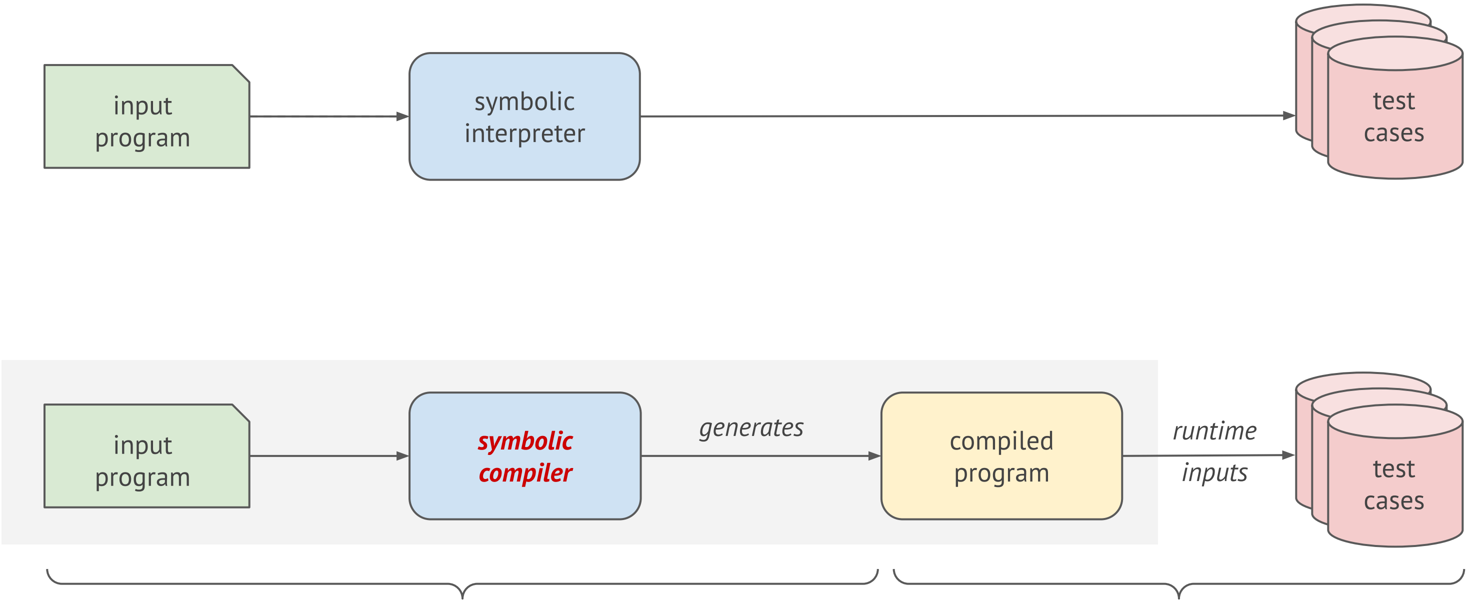
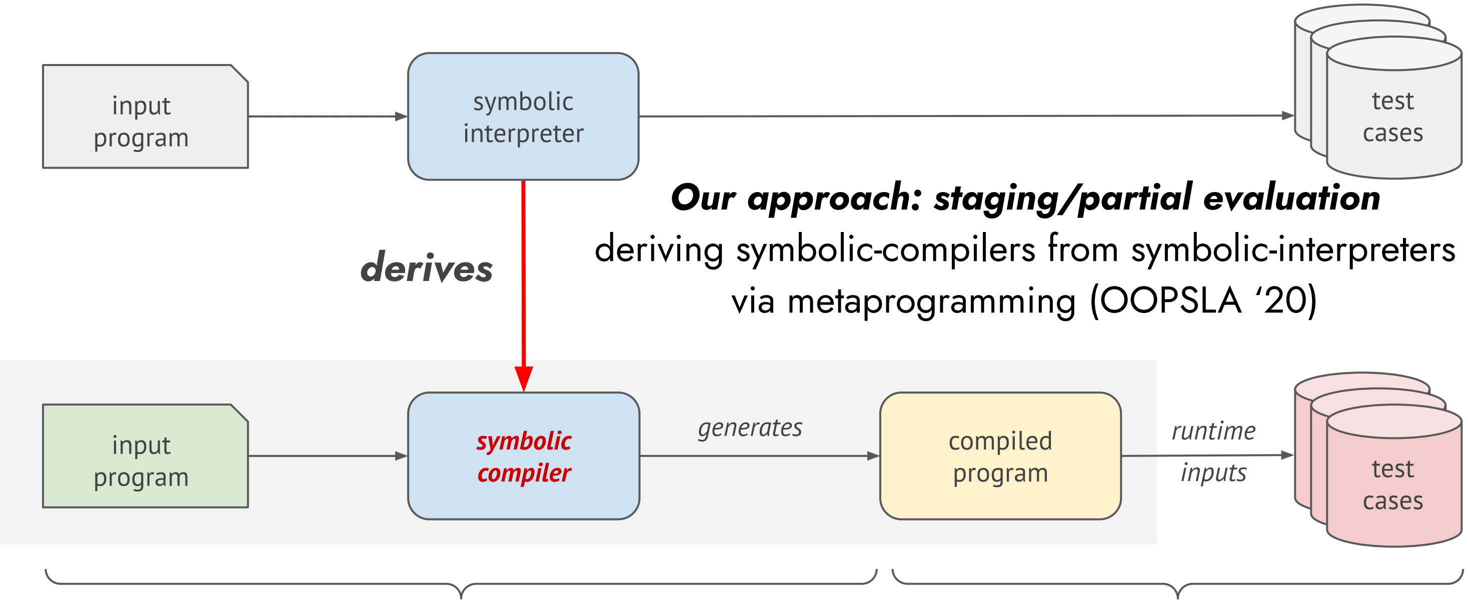


compilation removes interpretation overhead, optimizes programs, etc.

runs faster

Symbolic-Execution Compilers



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Path Explosion, Worse

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while (i < n) {
    <loop-body>
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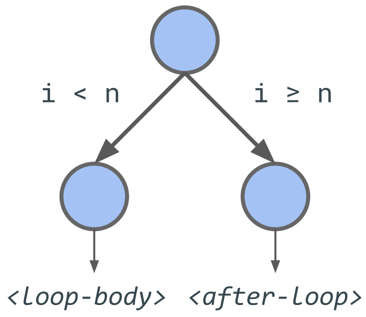

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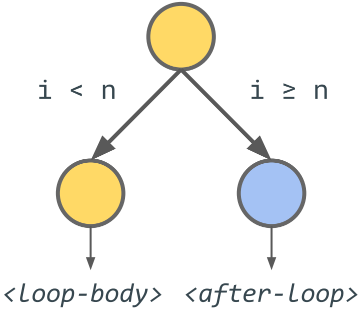

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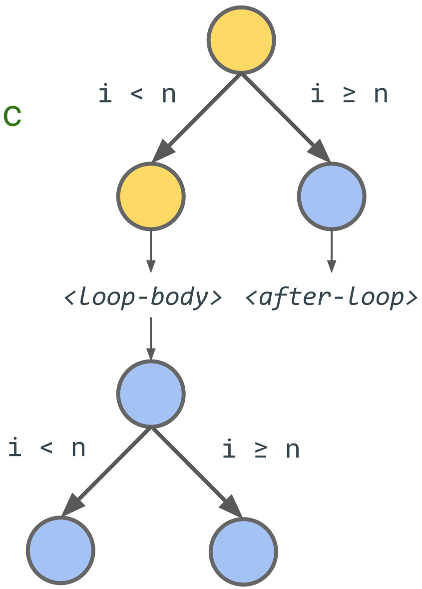

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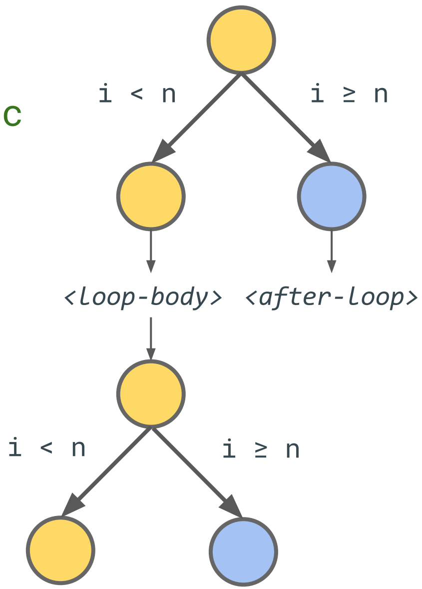

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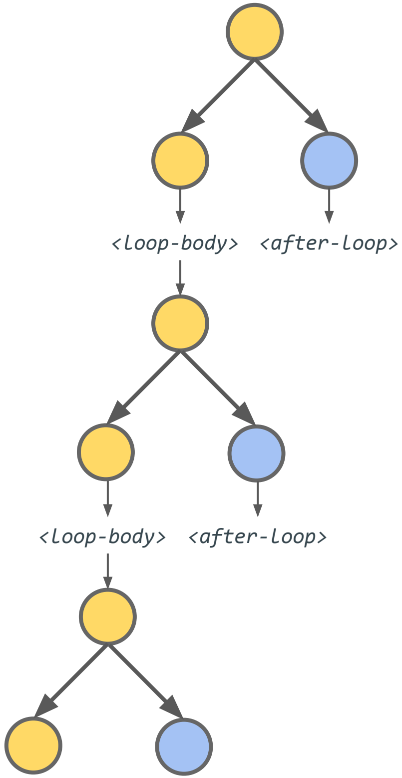

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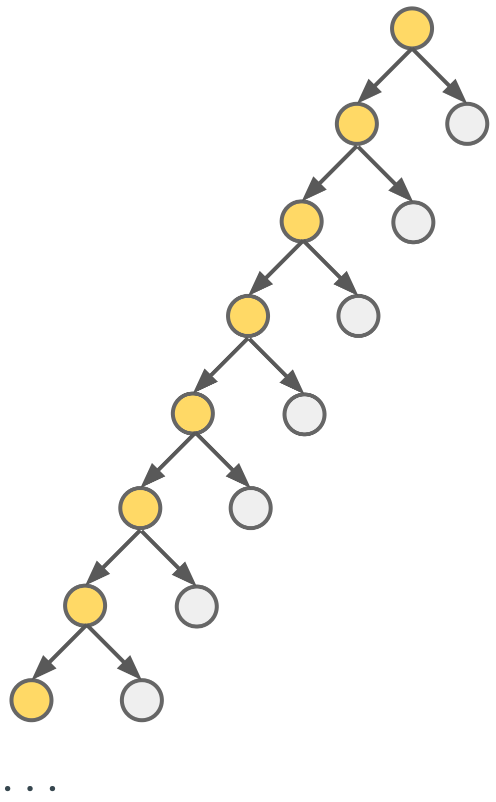

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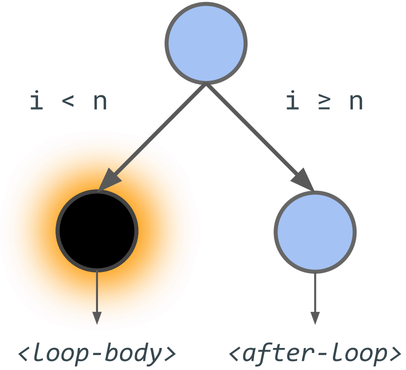

Problem: once running into the black hole,
we cannot effectively explore other parts of the program

Escaping the Black Hole

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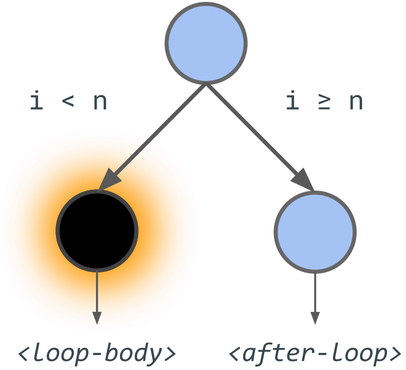
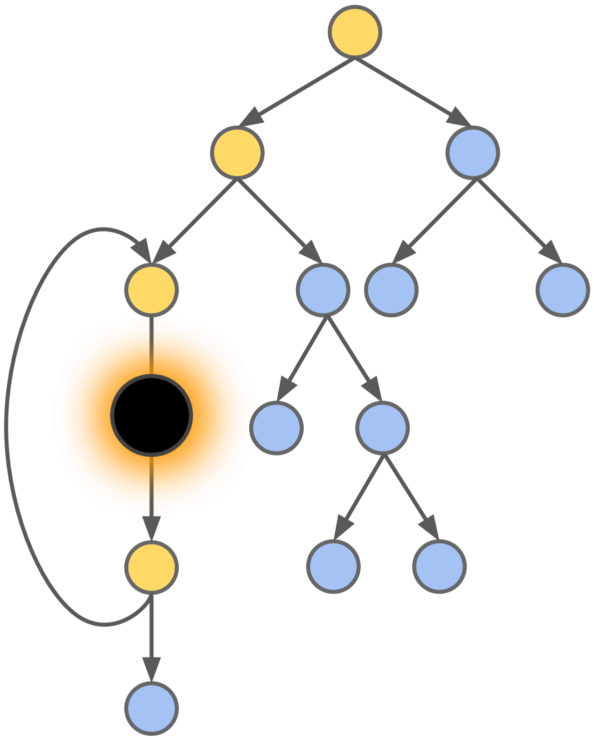


Traditional wisdom: deploys clever path selection heuristics

Escaping the Black Hole

- random state/path selection
- coverage-guided heuristics
- ...



Escaping the Black Hole

- *random state/path selection*
- coverage-guided heuristics
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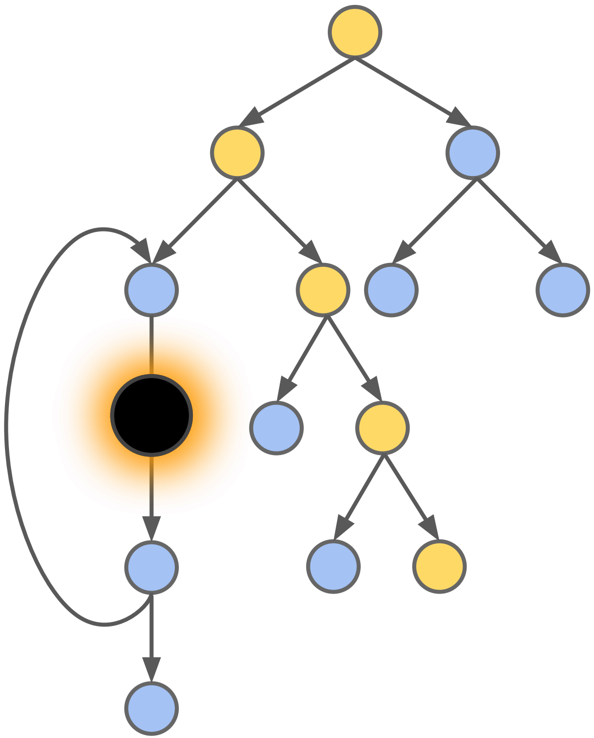

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- random state/path selection
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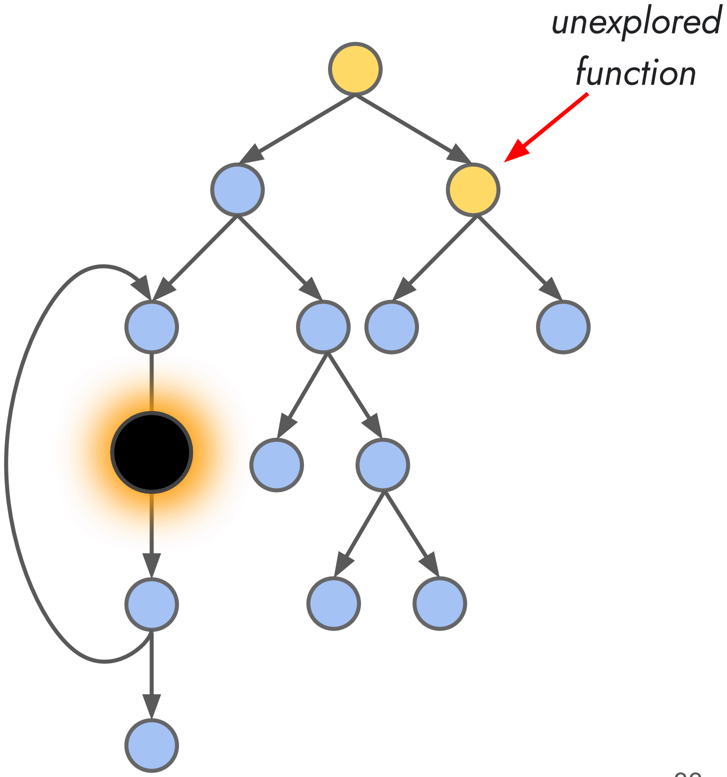

Escaping the Black Hole

- random state/path selection
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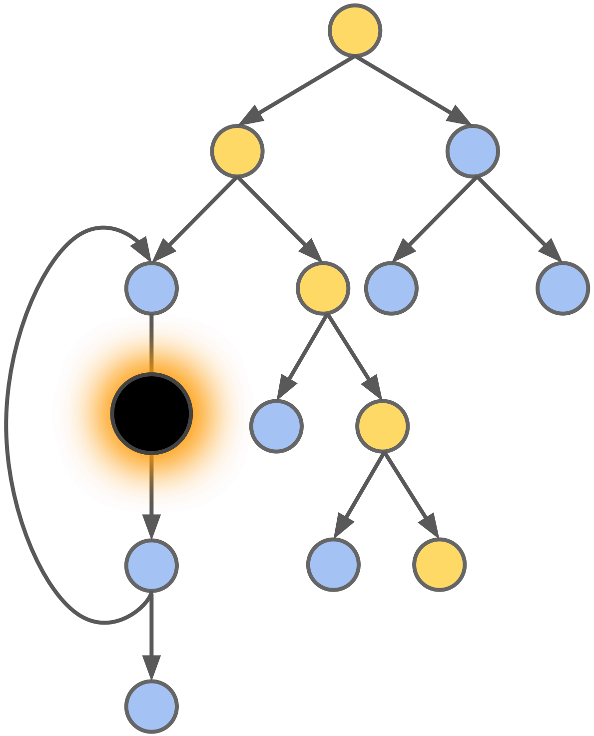
Deploying path selection strategies needs the ability to *pause* and *resume* the execution of paths.



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***Solution**: Compile with continuations, enabling the program to "control" itself.*

Making Control Explicitly

represent the rest of execution as a function k *in the generated code*

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represent the rest of execution as a function *k* *in the generated code*

```
y = g()
z = y + 1
...
```

```
def g() =
  if (sym_cnd) {
    x = 42
  } else {
    x = 100
  }
  return x
```

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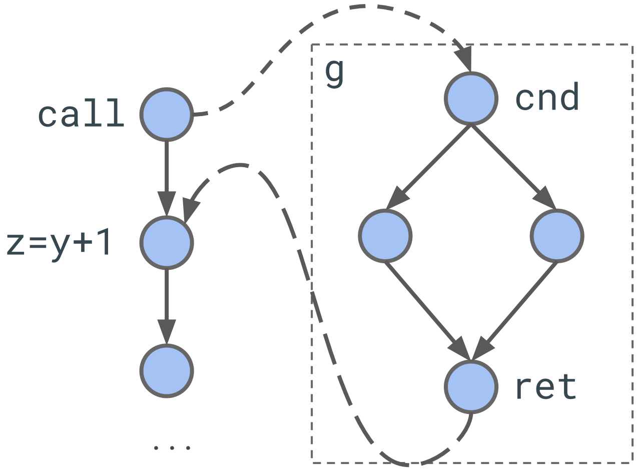

static control-flow graph

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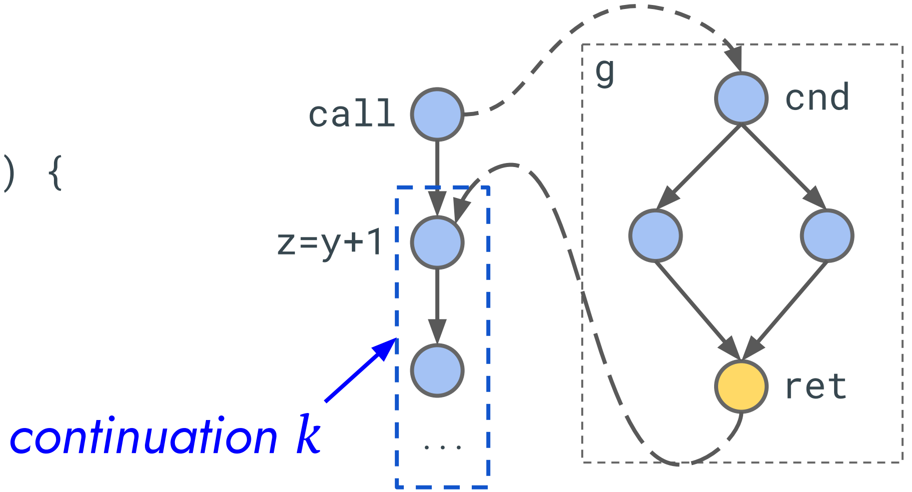

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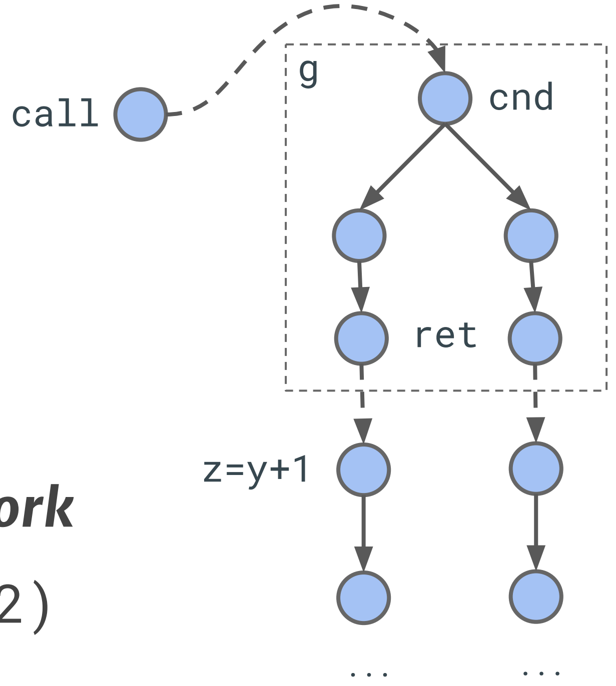

invoke and fork

k(s1); k(s2)

Making Control Explicitly

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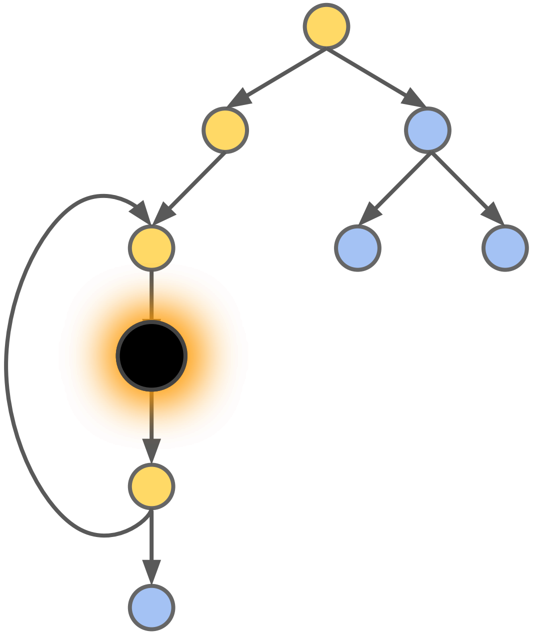

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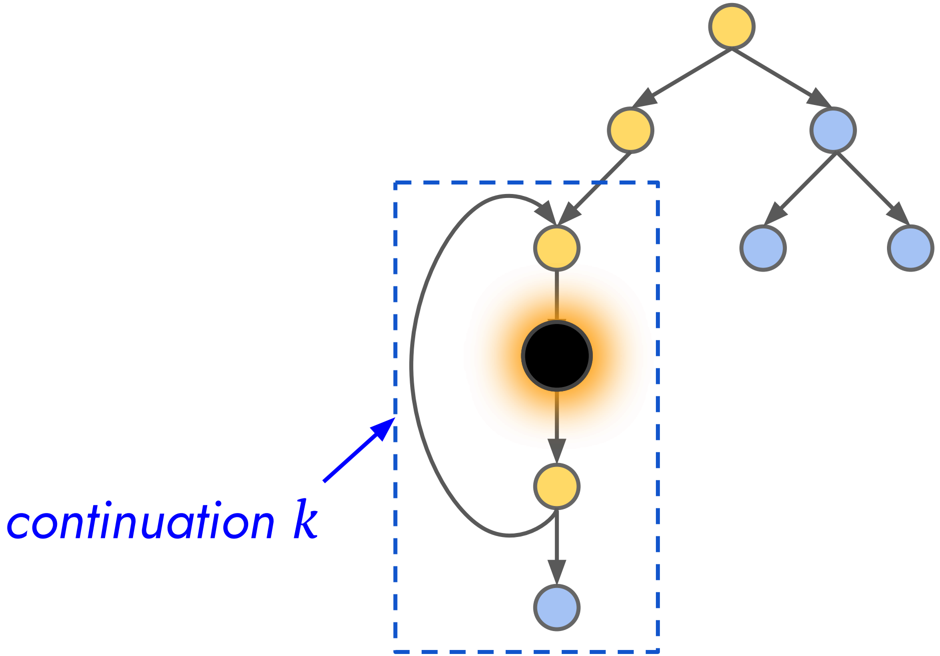
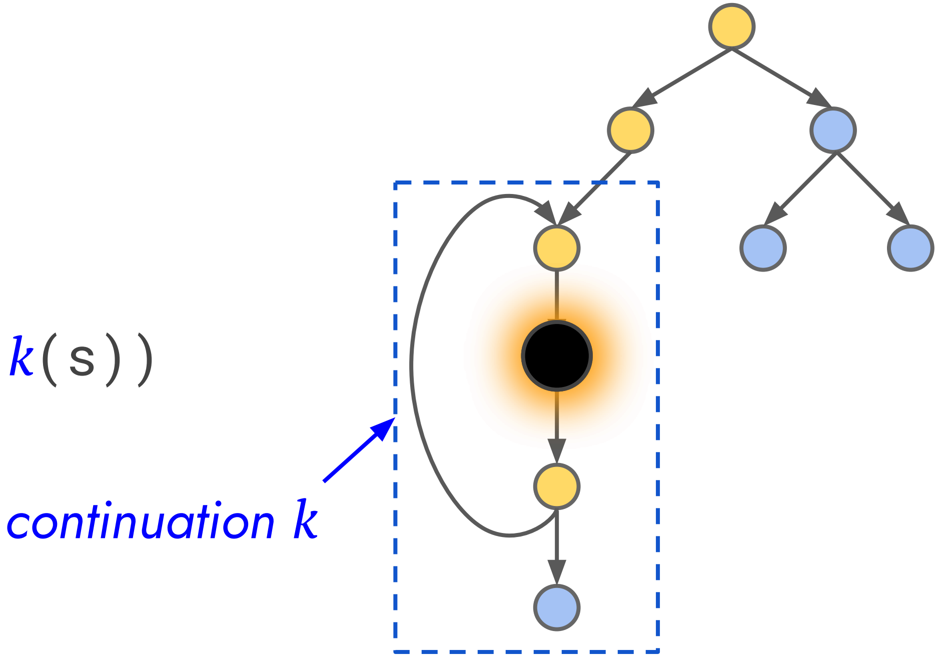


Making Control Explicitly

represent the rest of execution as a function *k in the generated code*

save and pause

```
scheduler.put(() => k(s))
```

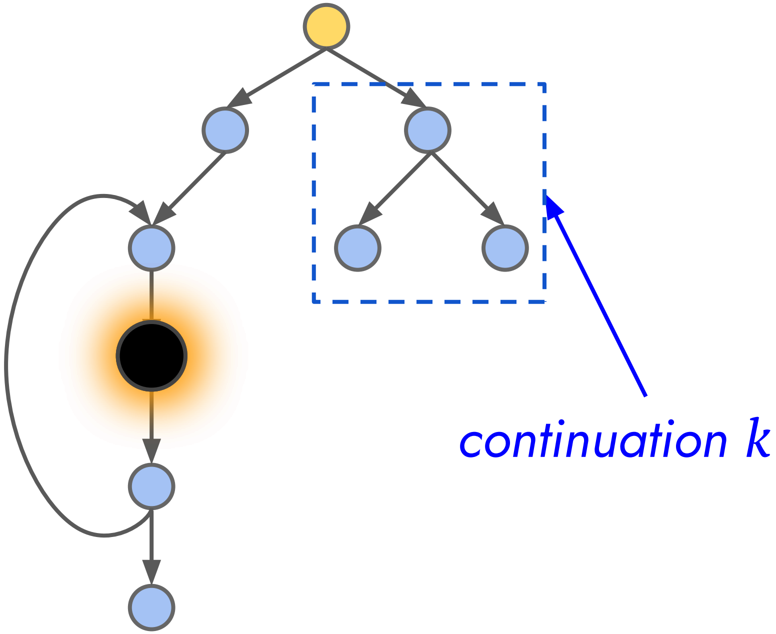


Making Control Explicitly

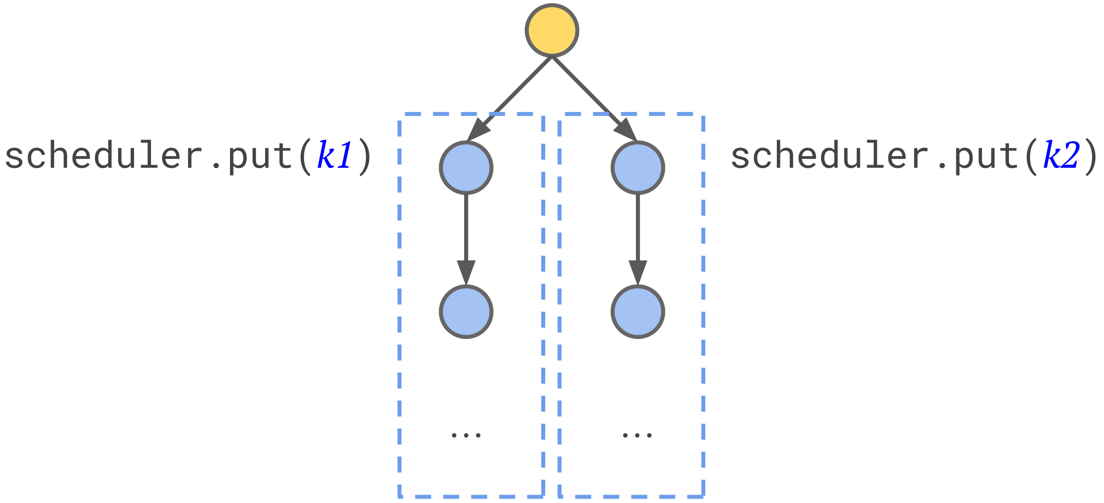
represent the rest of execution as a function k *in the generated code*

dispatch and resume

k = `scheduler.get();` k`()`



Parallelism for Free



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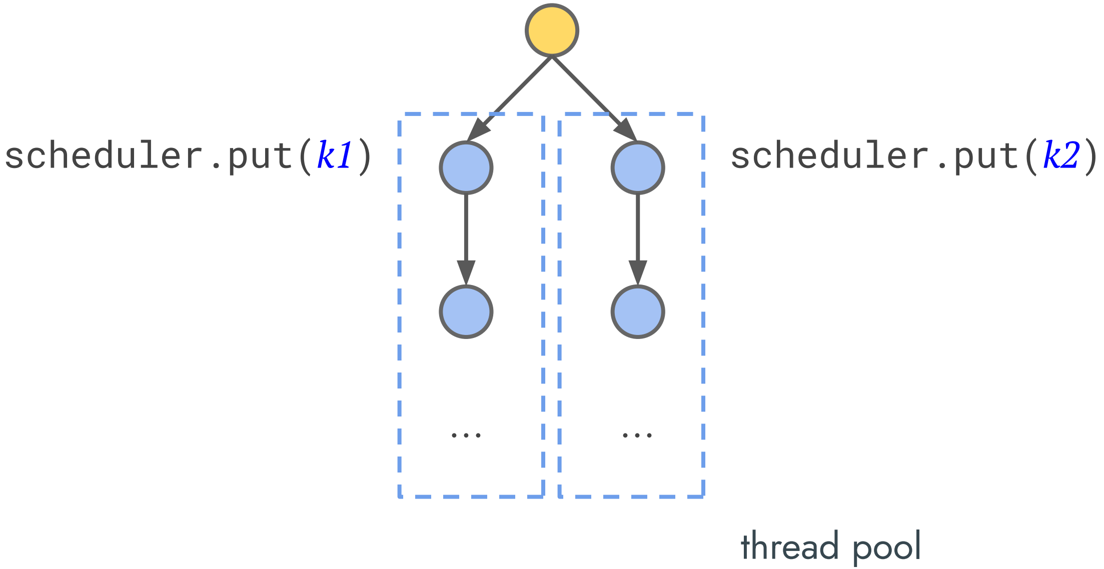



```
worker-thread() {
  k = scheduler.get(); k()
}
```

Making Control Explicitly

represent the rest of execution as a function k *in the generated code*

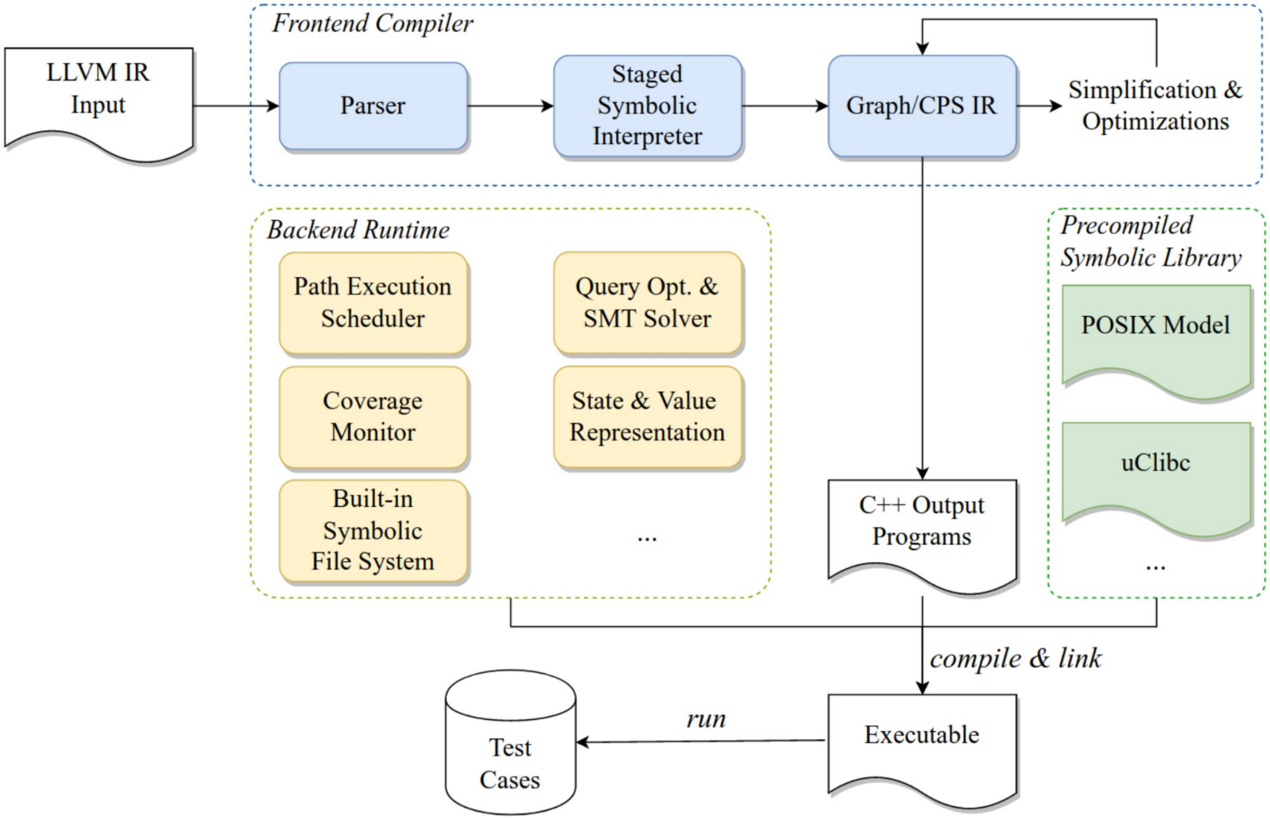
- *invoke and fork*
  `k(s1); k(s2)`
- *save and pause*
  `scheduler.put(() => k(s))`
- *dispatch and resume*
  `k = scheduler.get(); k()`
- *dispatch in parallel*

Compiling Symbolic Execution with Continuations

Specializing a symbolic interpreter
that itself is written in *continuation-passing style*

```
def staged-eval_sym(p: Prog, k: Rep[State] => Rep[Unit]): Rep[Unit]
```

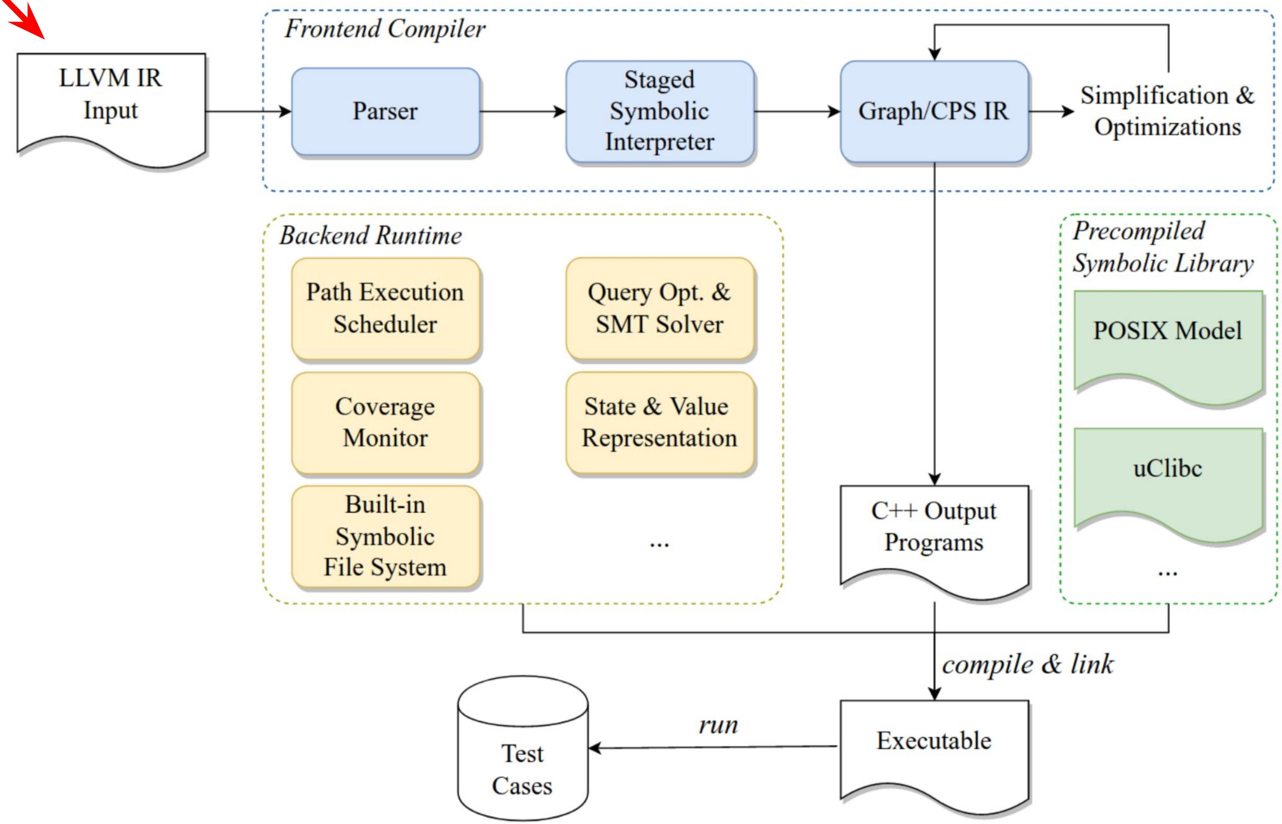
GenSym



Frontend Compiler
LLVM IR Input
Parser
Staged Symbolic Interpreter
Graph/CPS IR
Simplification & Optimizations
Backend Runtime
Path Execution Scheduler
Query Opt. & SMT Solver
Coverage Monitor
State & Value Representation
Built-in Symbolic File System
...
C++ Output Programs
Precompiled Symbolic Library
POSIX Model
uClibc
...
compile & link
run
Test Cases
Executable

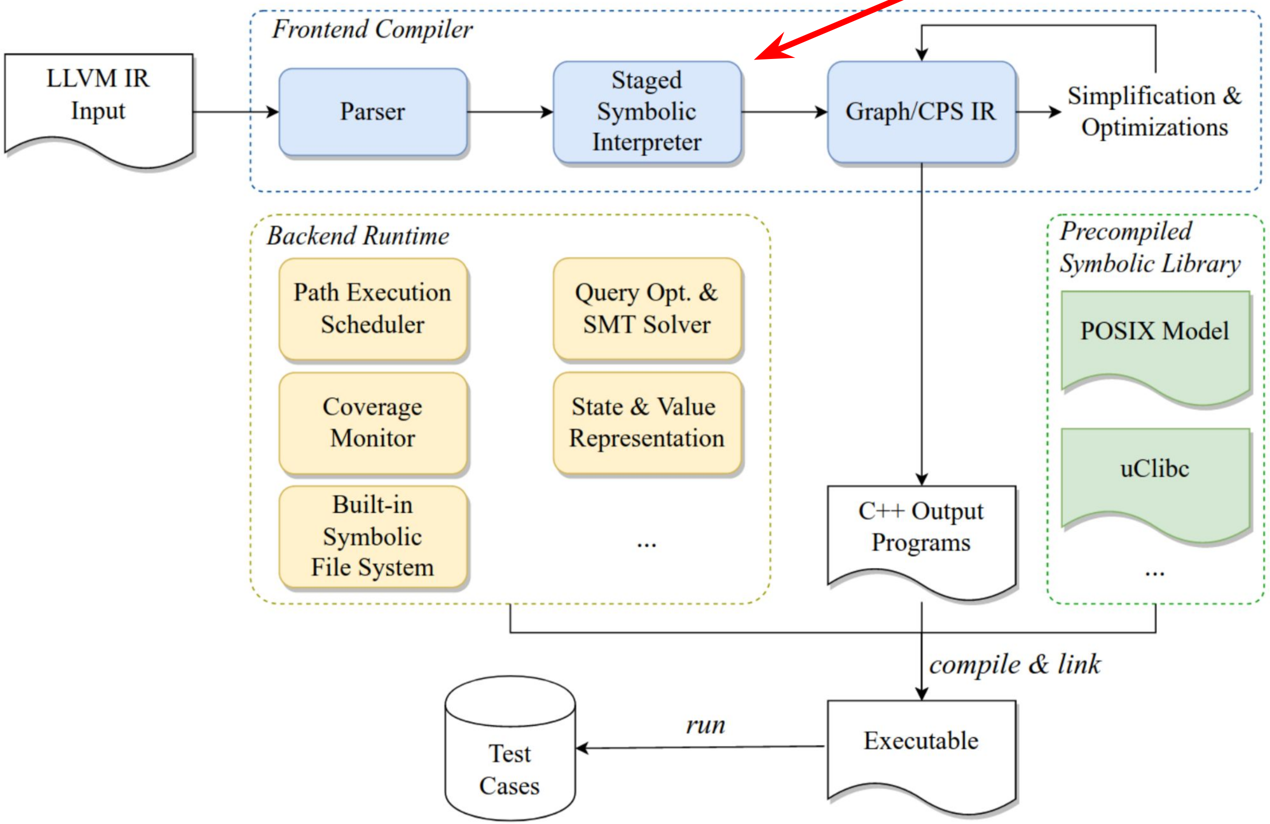
Takes general LLVM IR inputs

GenSym



GenSym

Written in Scala/LMS



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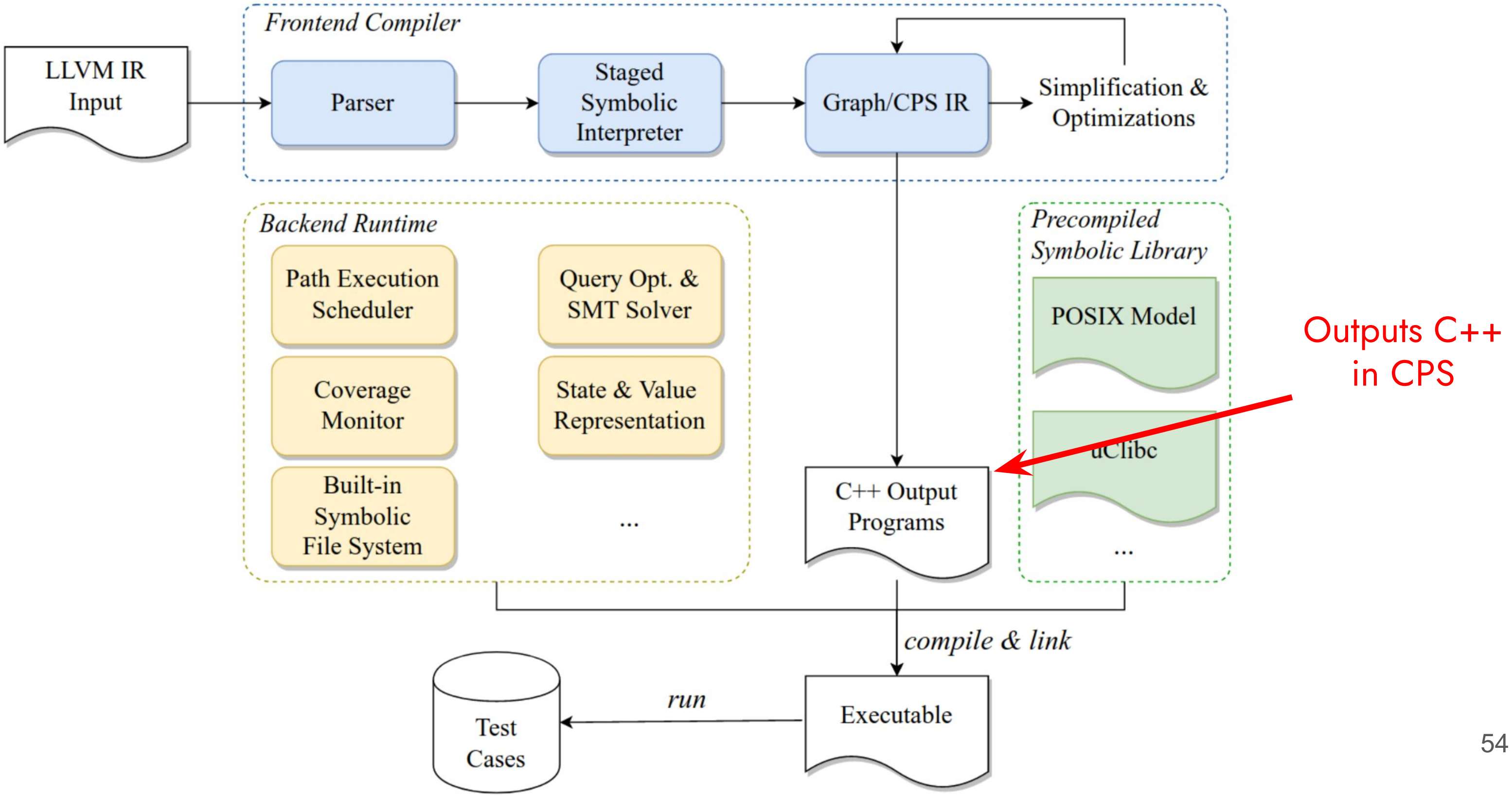

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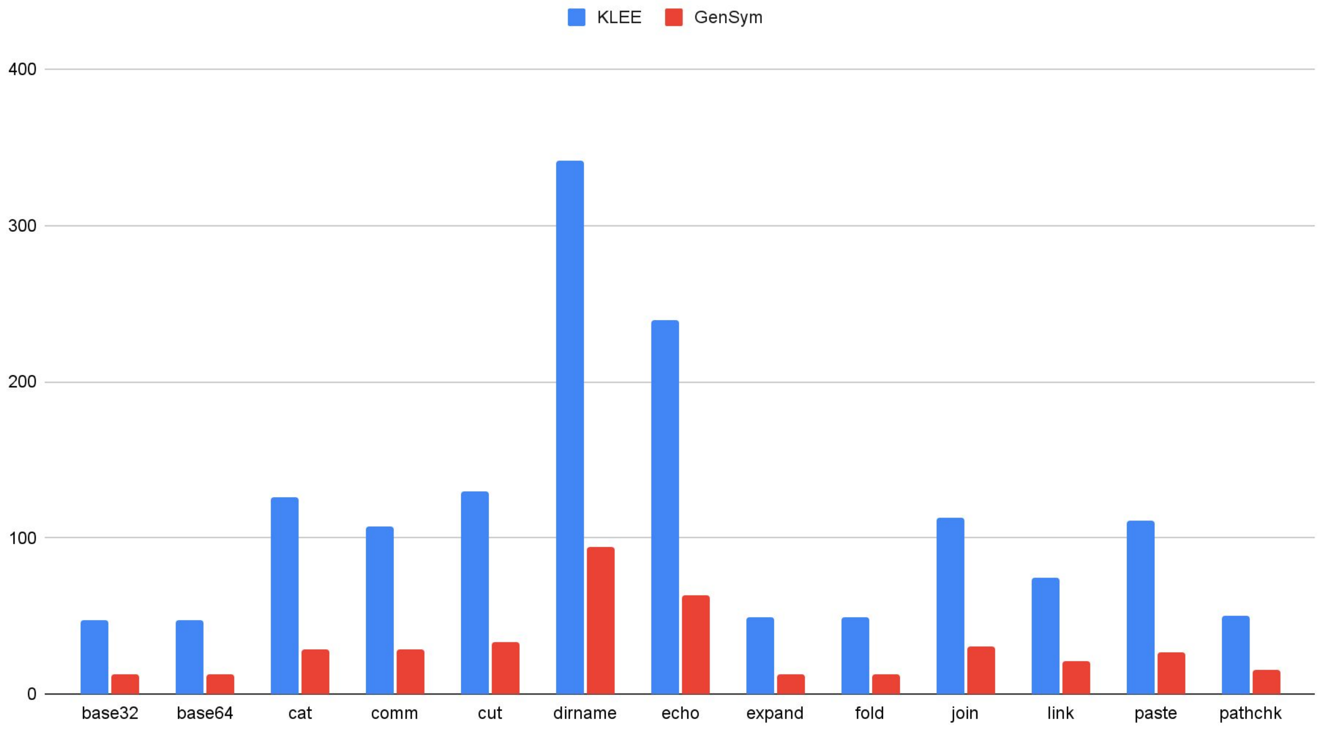
Outputs C++ in CPS

GenSym: Performance Evaluation

- KLEE: state-of-the-art symbolic interpreter for LLVM IR
  - Has been actively developed over 15+ years
  - Written in C++

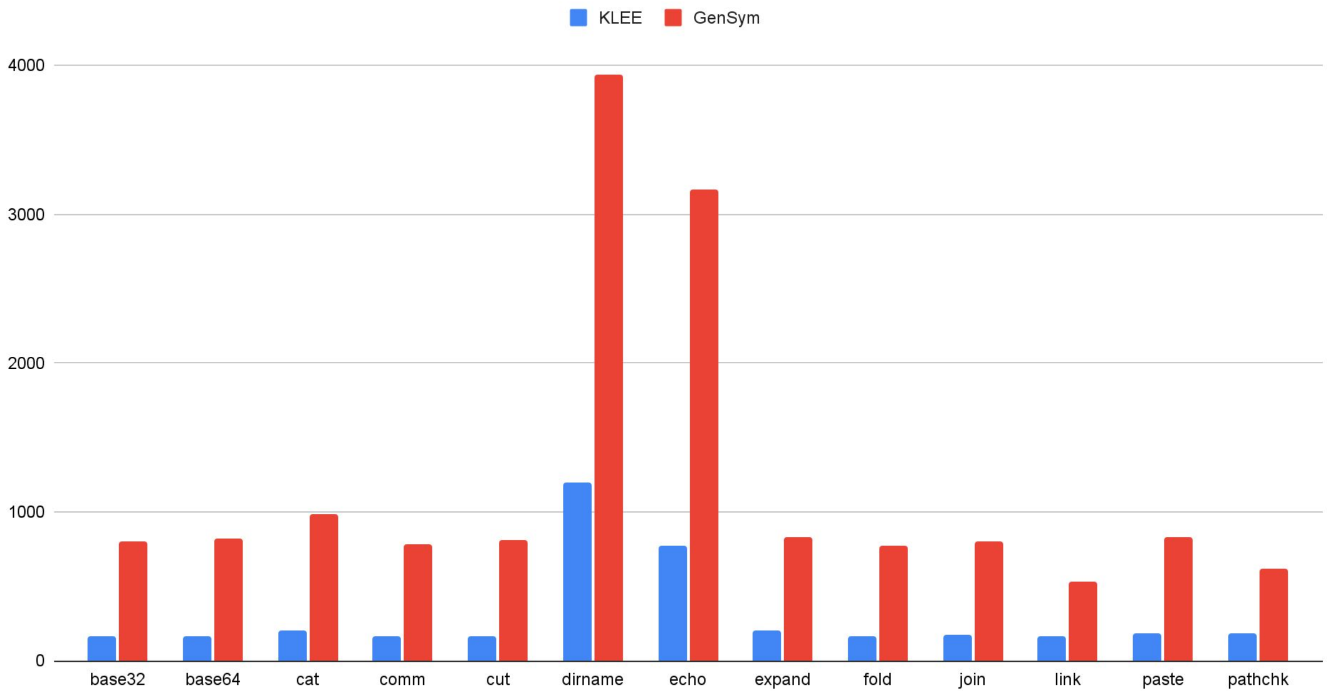
- Evaluated on a set of GNU Coreutils programs
  - Using POSIX file system and uClibc library
  - Average program size 28k LOC of LLVM IR instructions

Single-thread Pure Execution



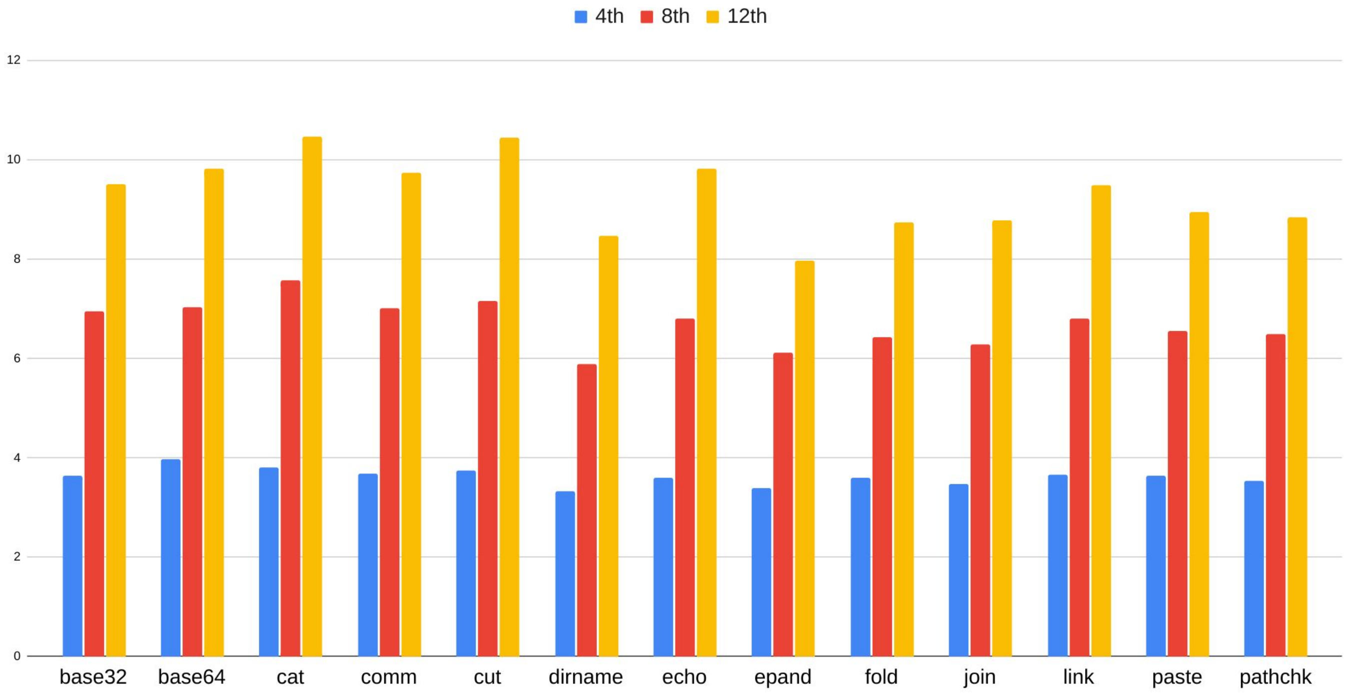
~4x speedups

Single-thread Throughput



Number of explored paths per second in 1 hour: **4.3x more paths on avg**.

Parallel Execution Efficiency



Speedups using more cores/threads

4 threads - 3.6x
8 threads - 6.7x
12 threads - 9.3x

GenSym: *compiling symbolic execution to continuation-passing style to build high-performance and parallel symbolic execution engine*

- ★ Efficient
  - ○ Semantics-based compilation
  - ○ Outperforms state-of-the-art tools
- ★ Effective
  - ○ Forking as concurrency/parallelism
  - ○ Path-selection heuristics

Code: https://continuation.passing.style/GenSym

[ICSE '23] Compiling parallel symbolic execution with continuations.

[OOPSLA '20] Compiling symbolic execution with staging and algebraic effects.

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I'm on the academic job market; happy to chat more about my research!

Questions?

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