Striking a New Balance Between Program Instrumentation and Debugging Time

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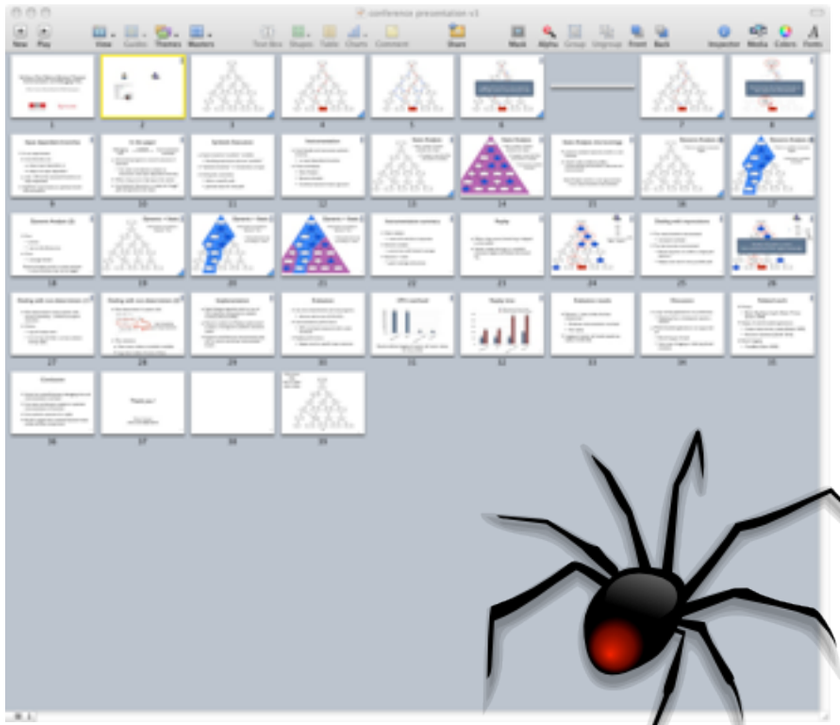
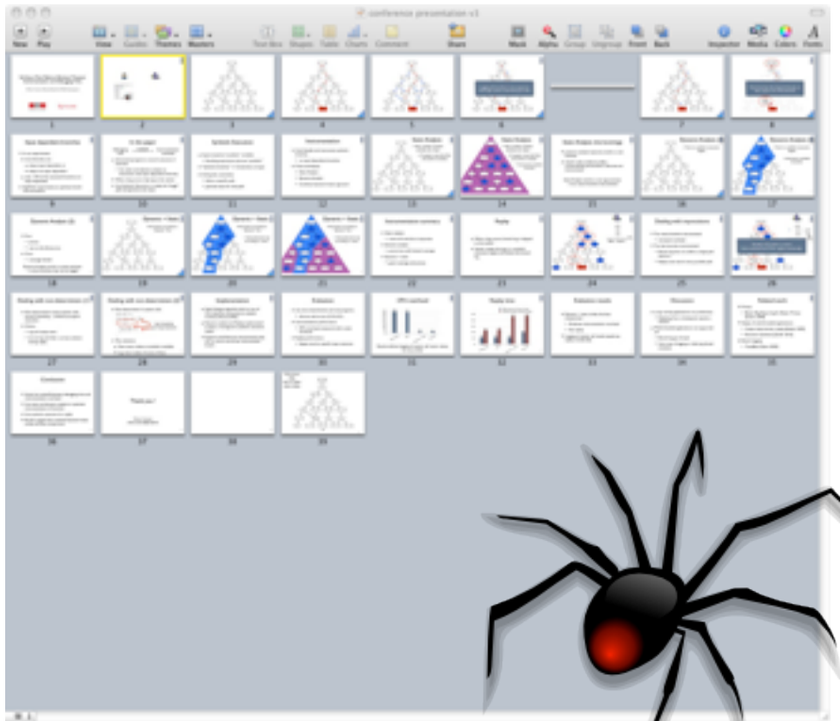
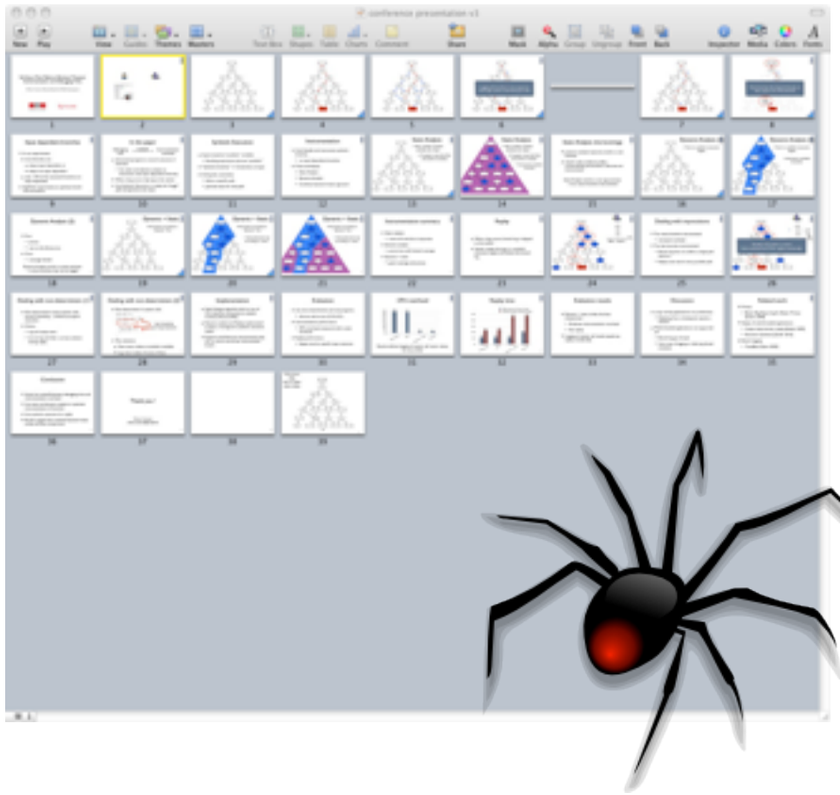
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

RUTGERS



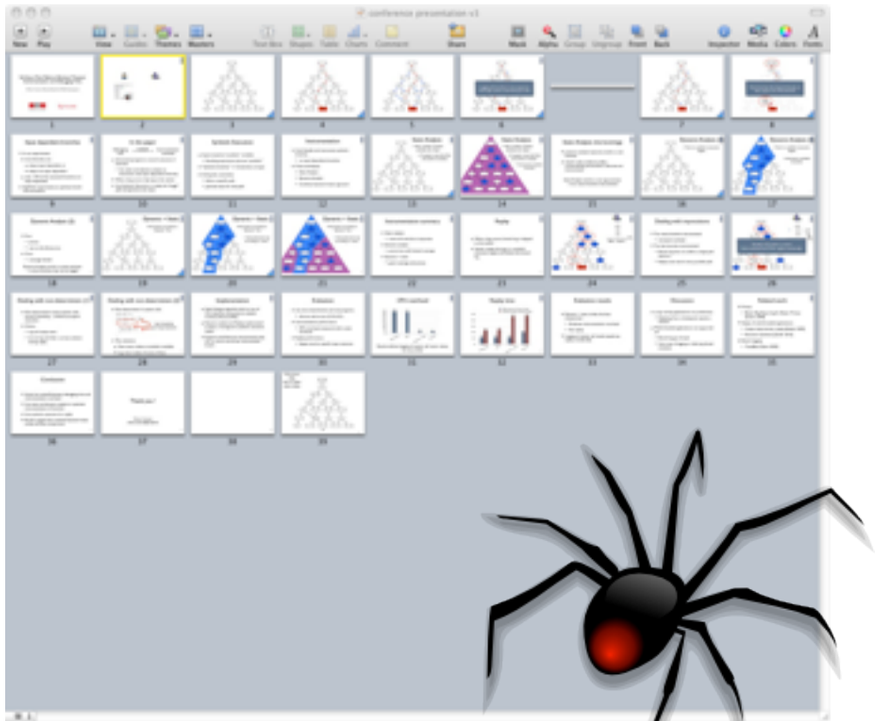


Bug report



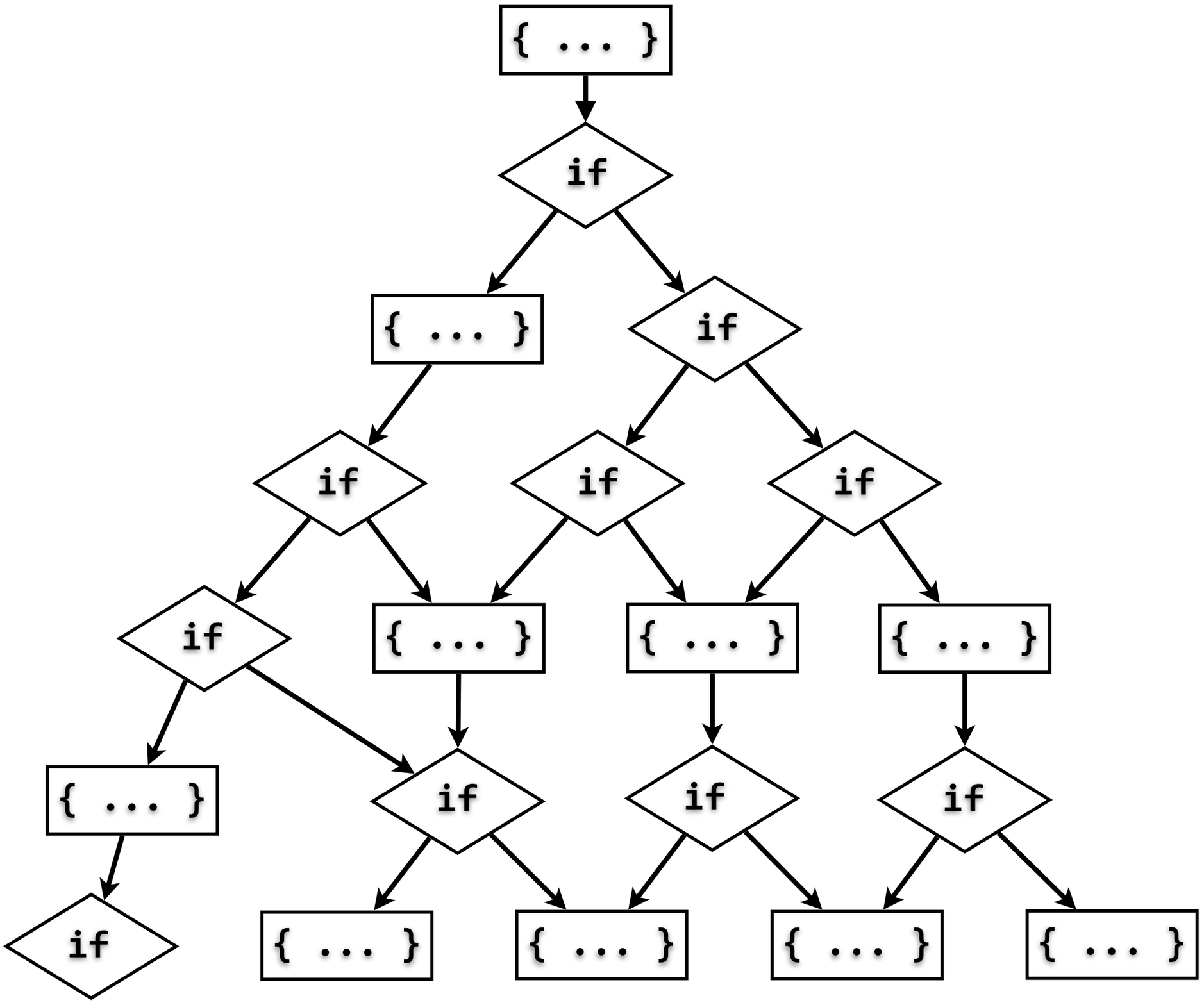
Bug report

- Instrumentation ⇒ Better bug report ⇒ Easy debugging



Bug report

- Instrumentation ⇒ Better bug report ⇒ Easy debugging
- Instrumentation ⇒ Overhead for the user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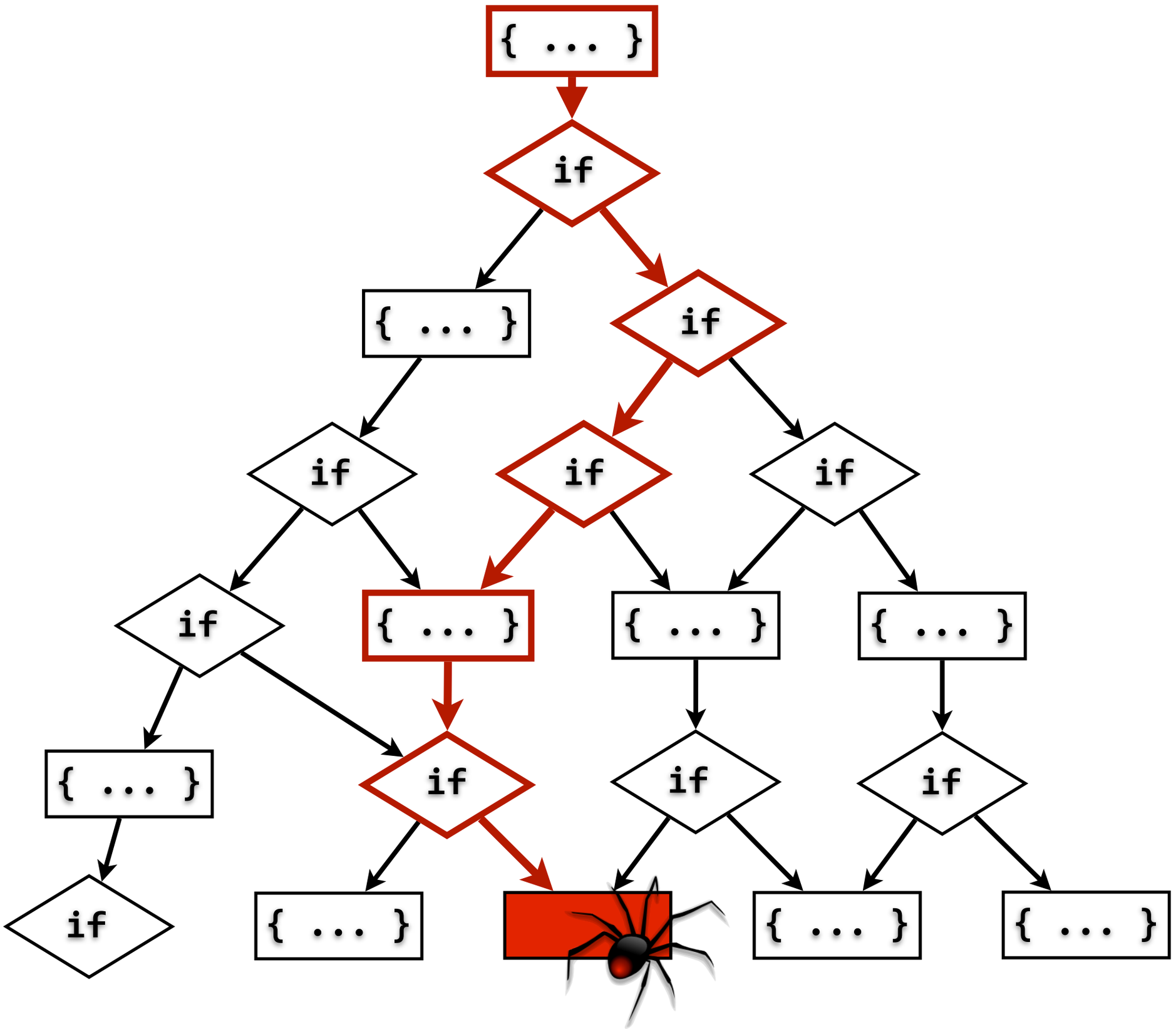
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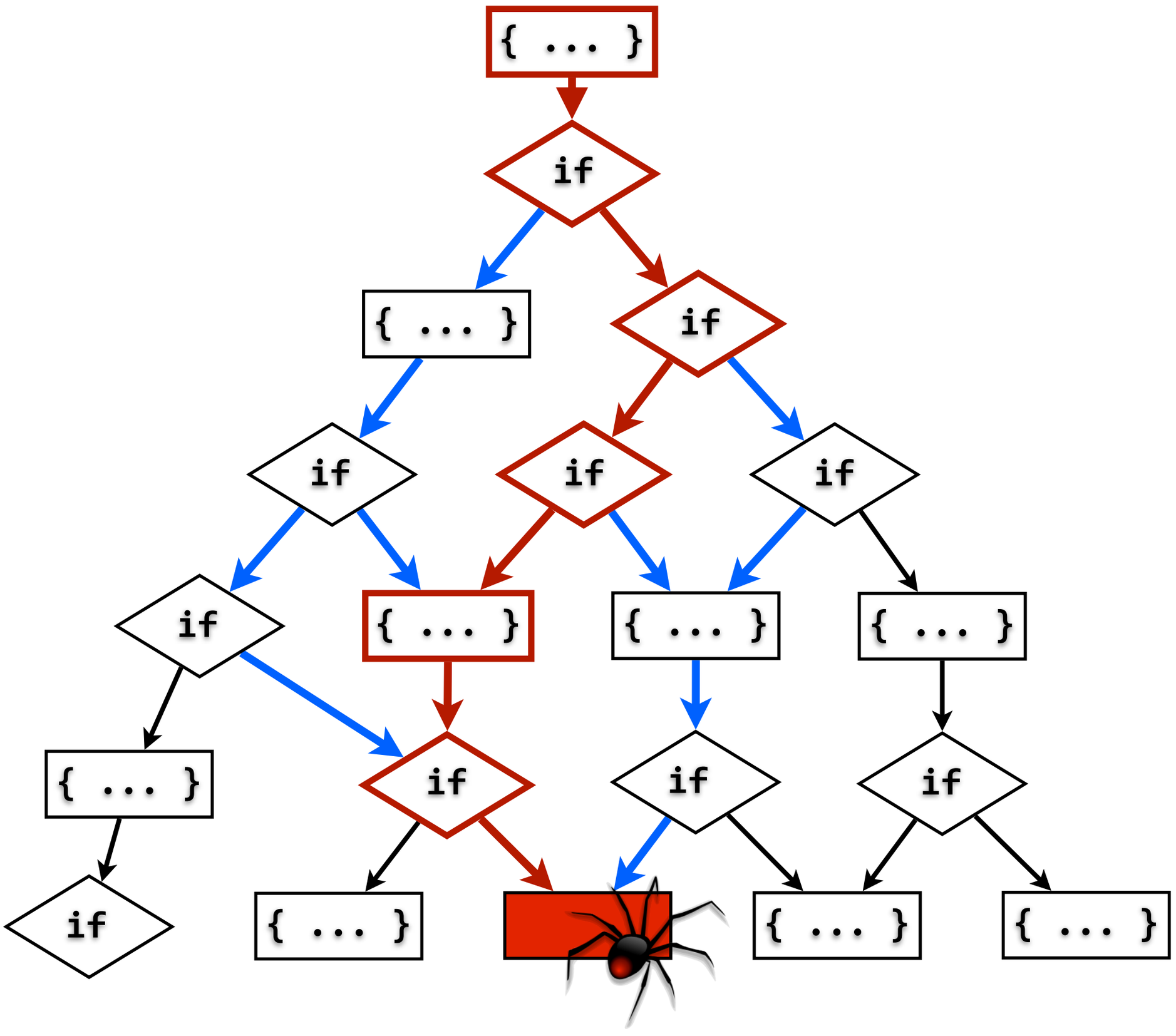
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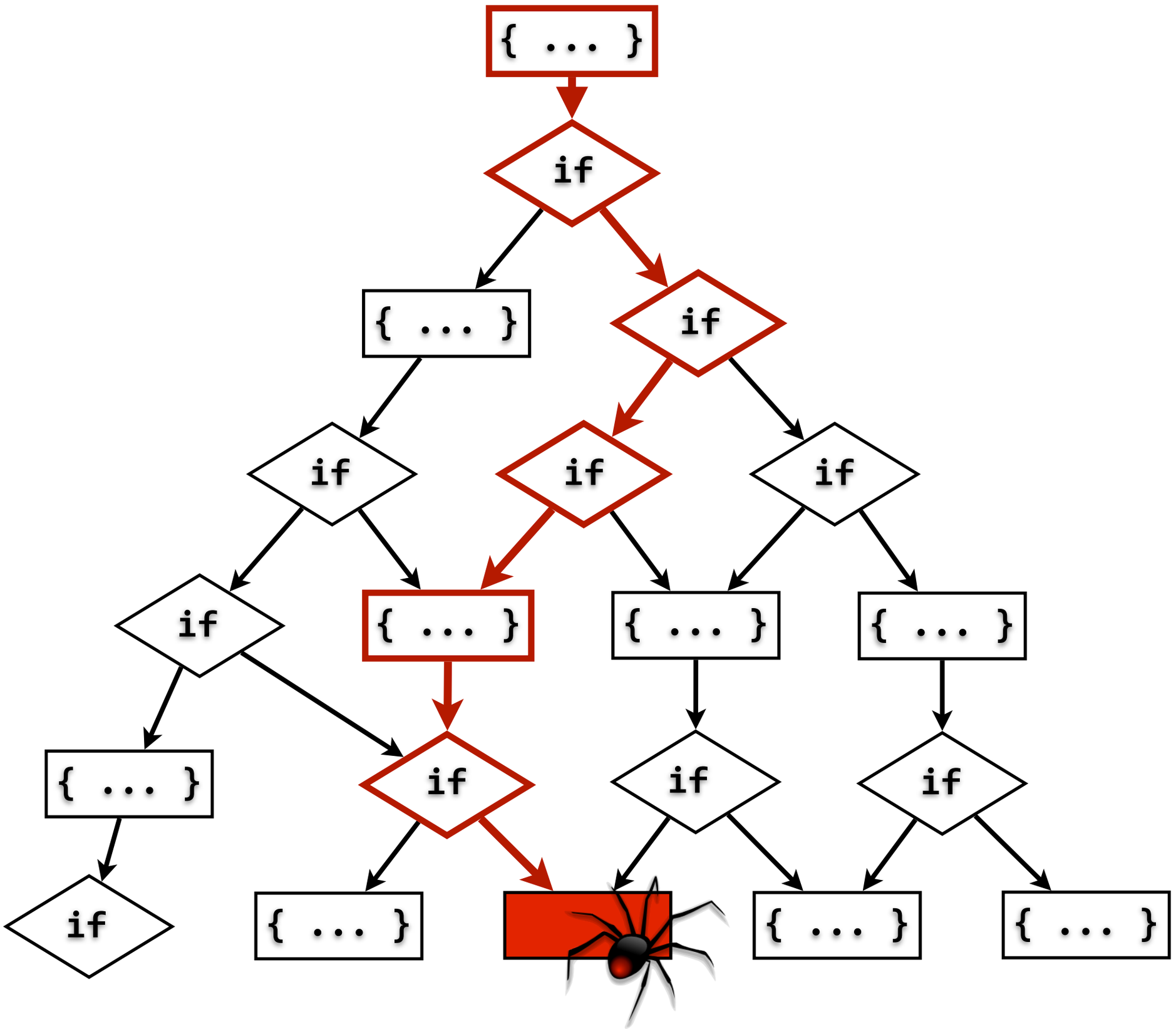
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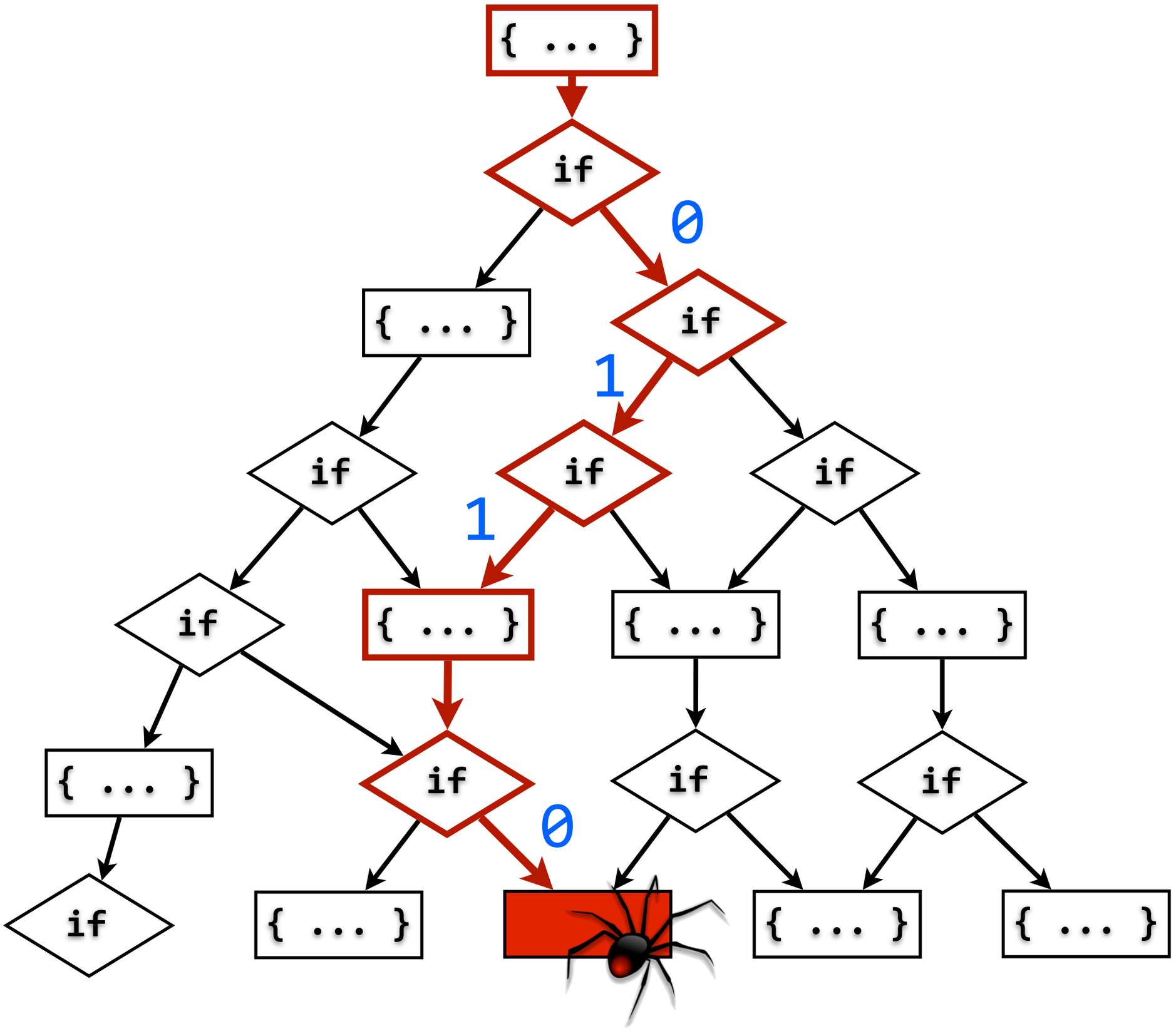
{ ... }
if
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if
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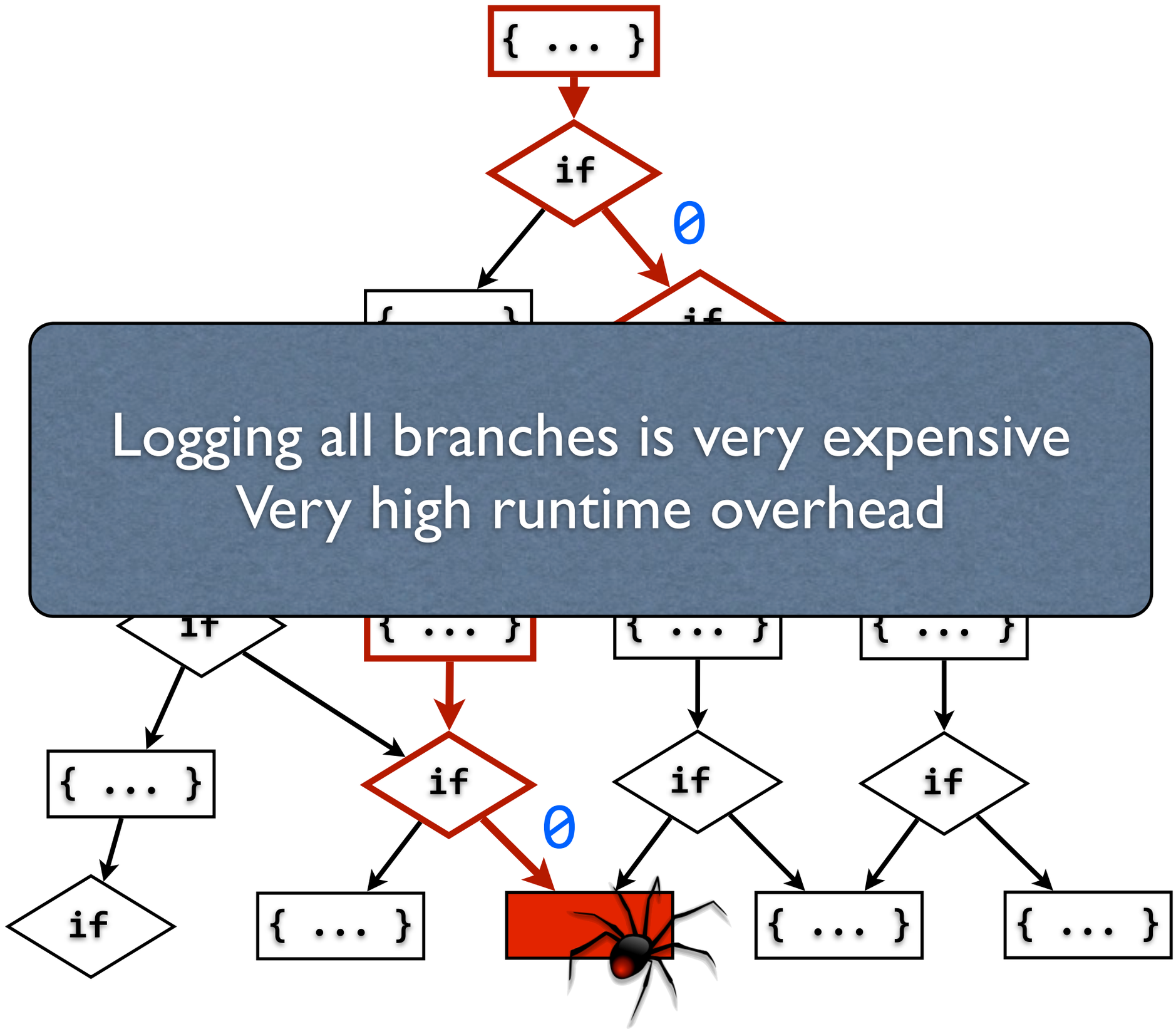

Logging all branches is very expensive
Very high runtime overhead

In this paper

Debugging time

Instrumentation overhead

In this paper

Debugging time ⟷ *tradeoff* ⟷ Instrumentation overhead

- Instrument program to record branches
  - ✦ Static and dynamic analysis to minimize instrumentation

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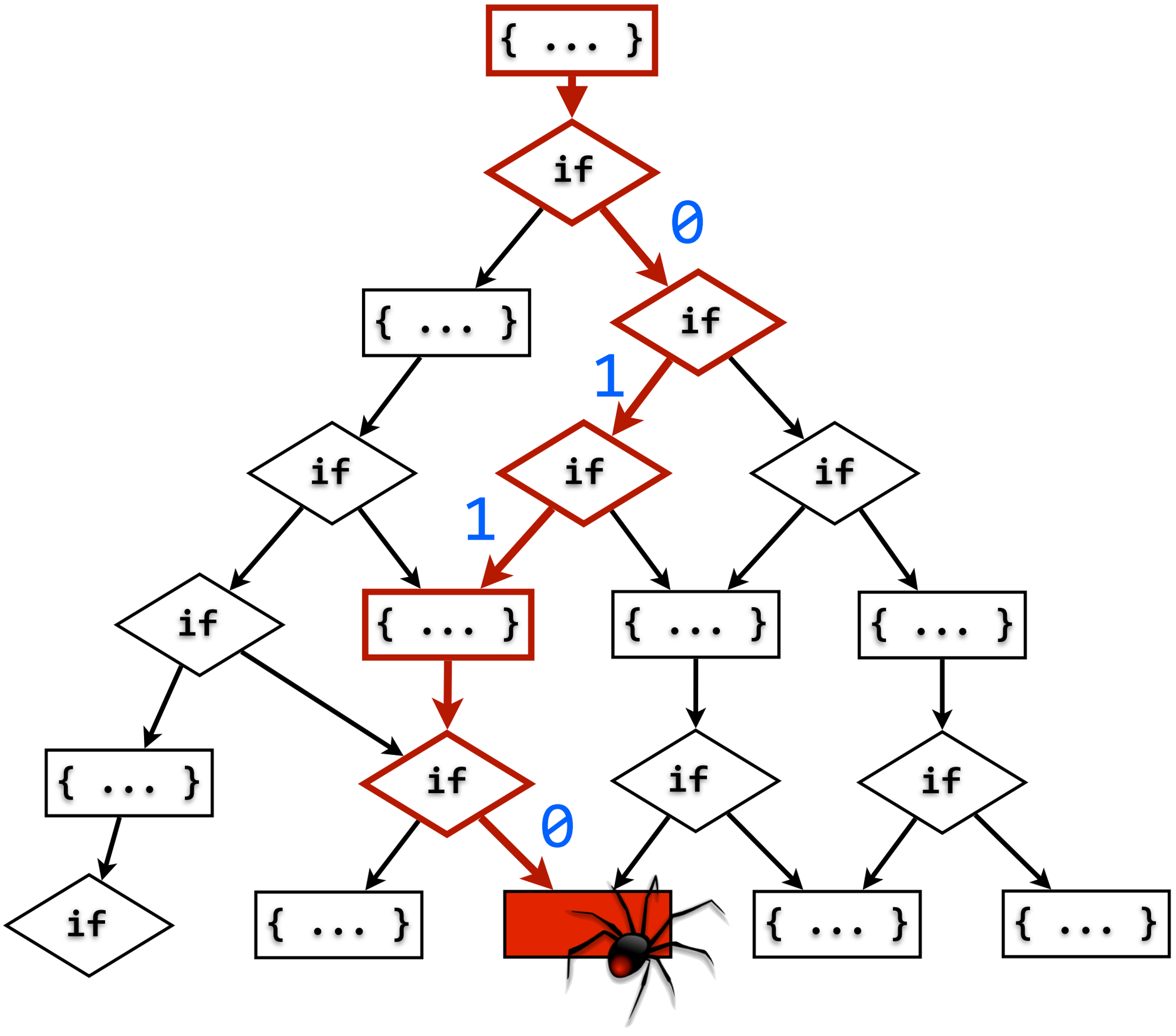
Debugging time ⟷ *tradeoff* ⟷ Instrumentation overhead

- Instrument program to record branches
  - ✦ Static and dynamic analysis to minimize instrumentation
- Bug ⇒ ship branch log to the vendor
- Symbolic Execution to replay the "buggy" path and generate new input


{ ... }
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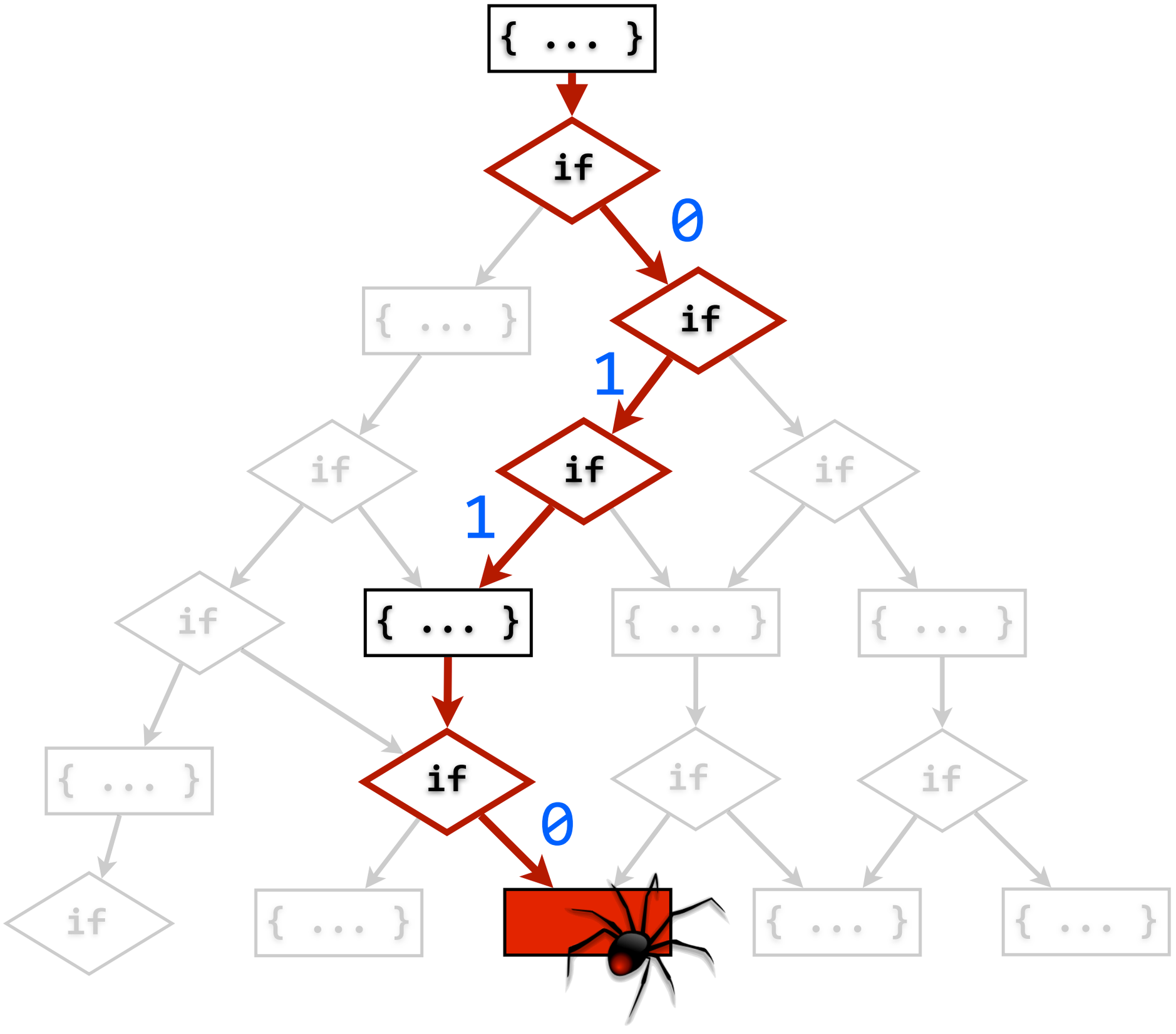
{ ... }
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{ ... }
1
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{ ... }
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if
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if
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{ ... }
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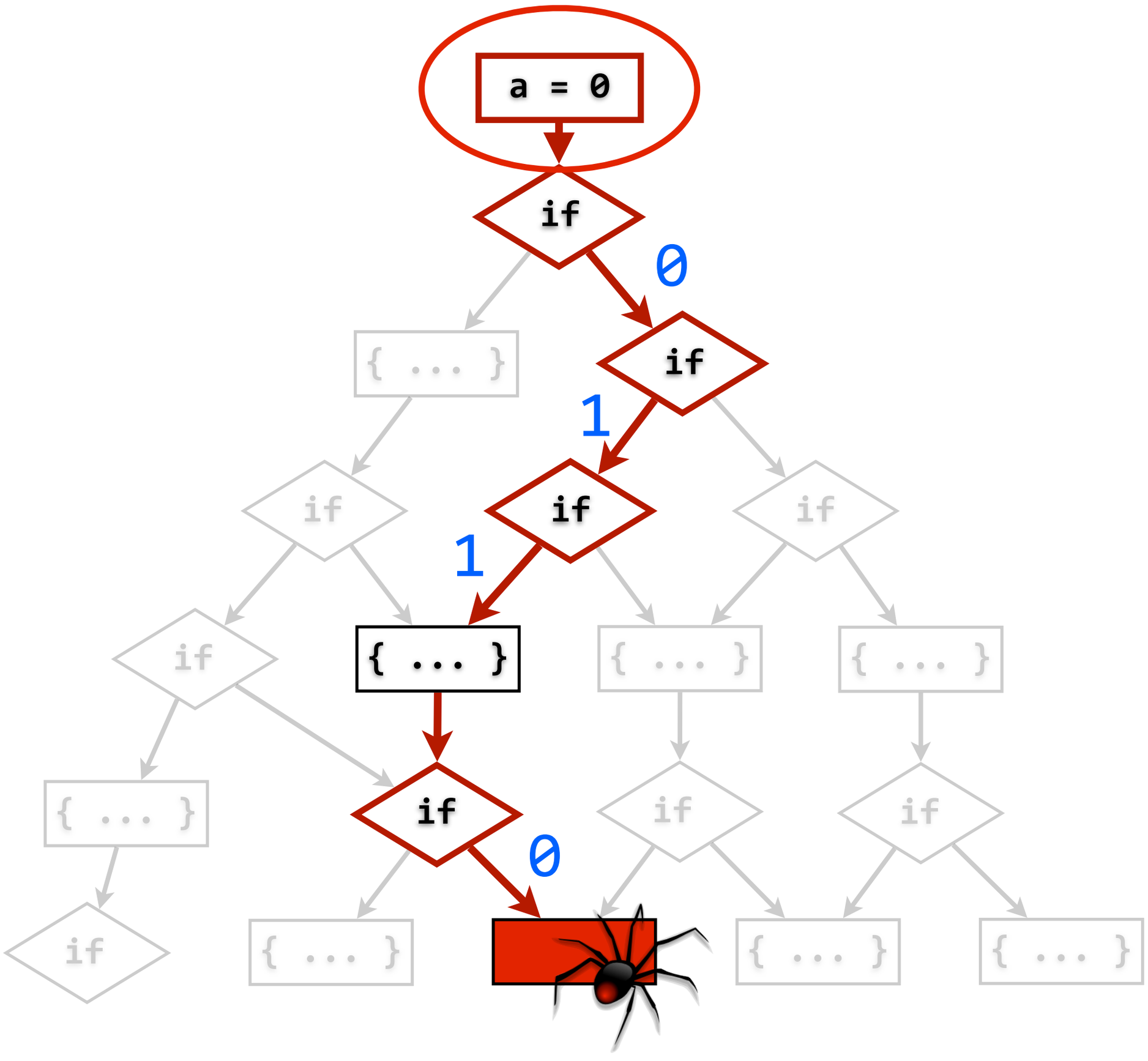
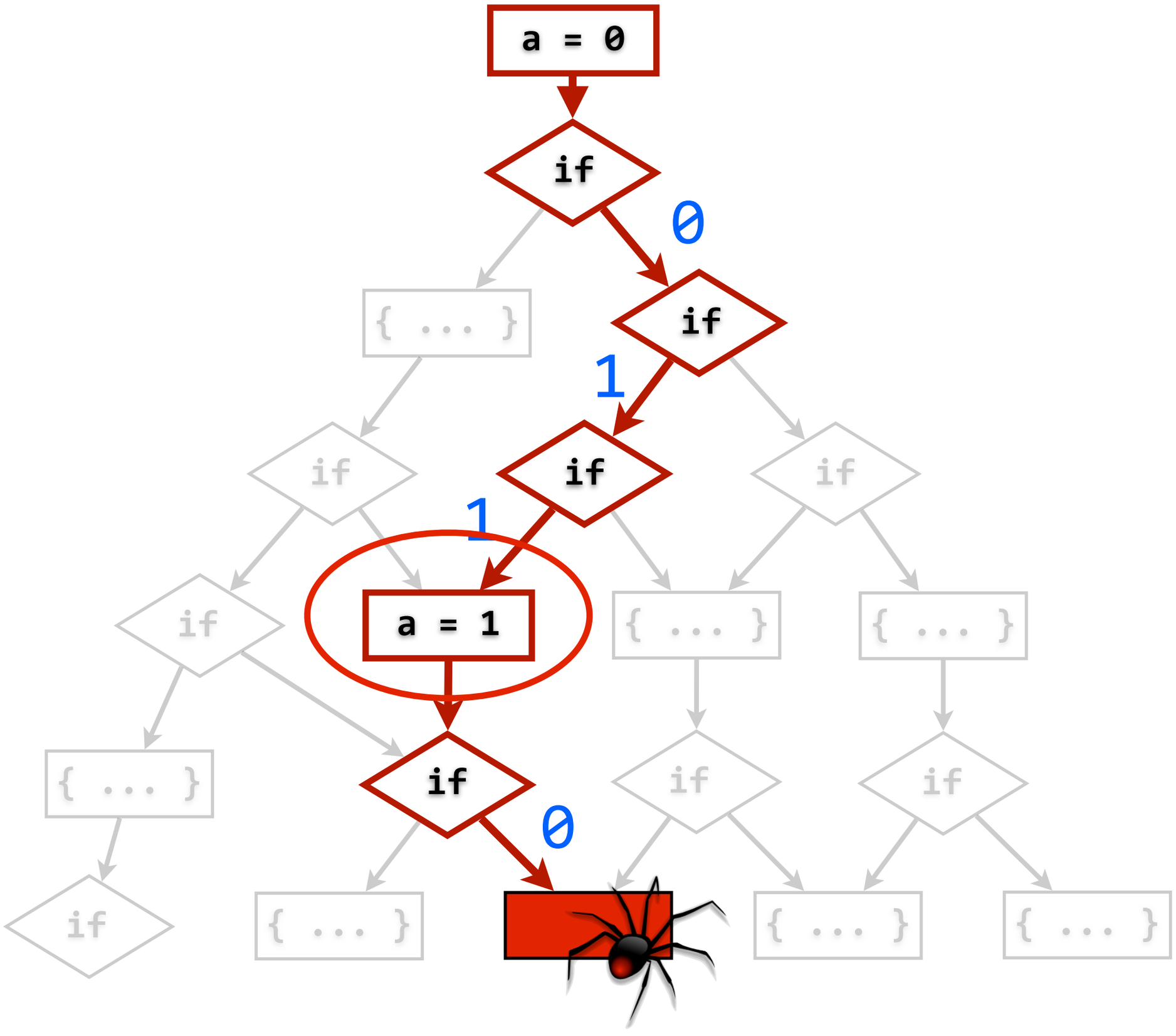
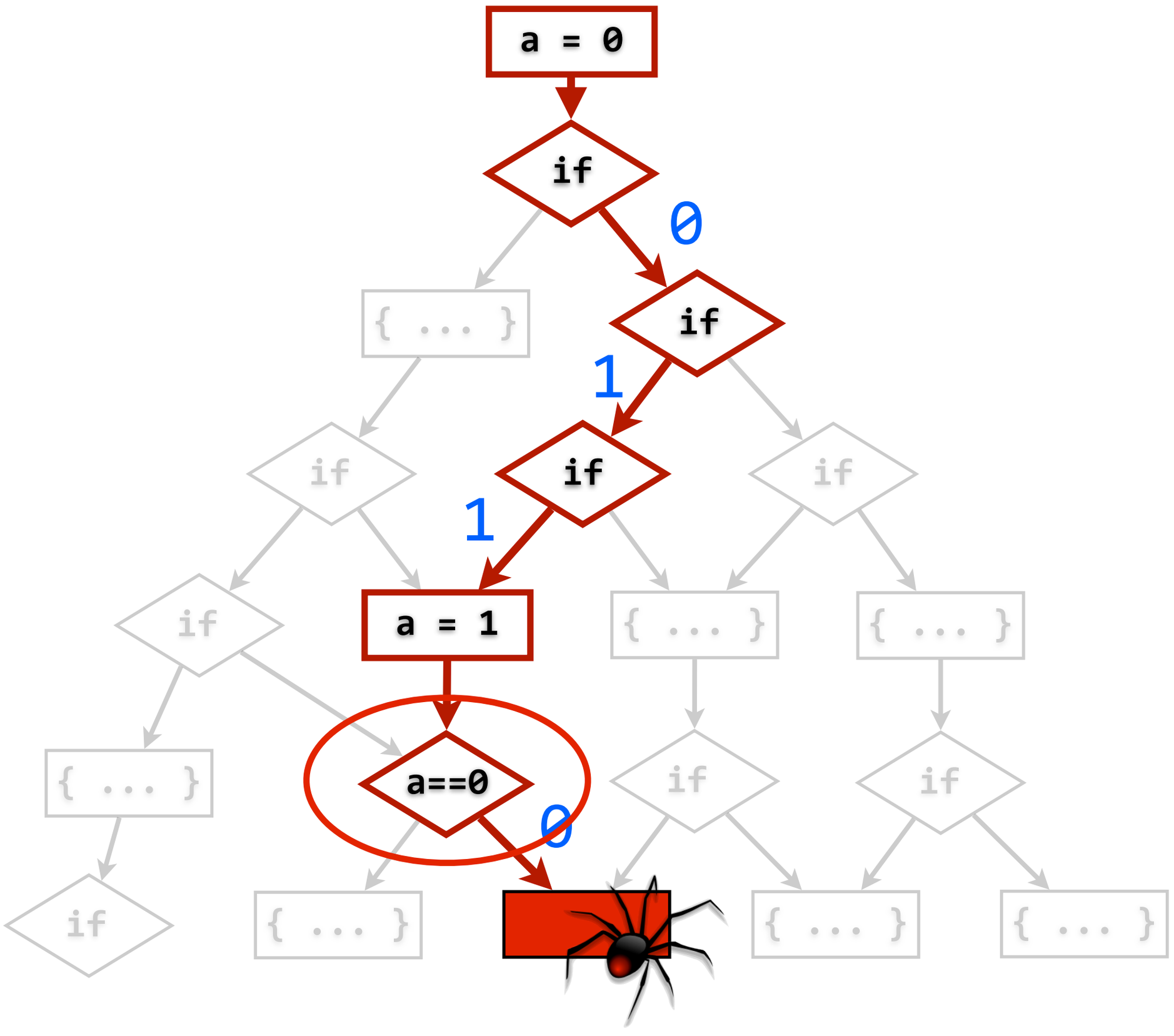
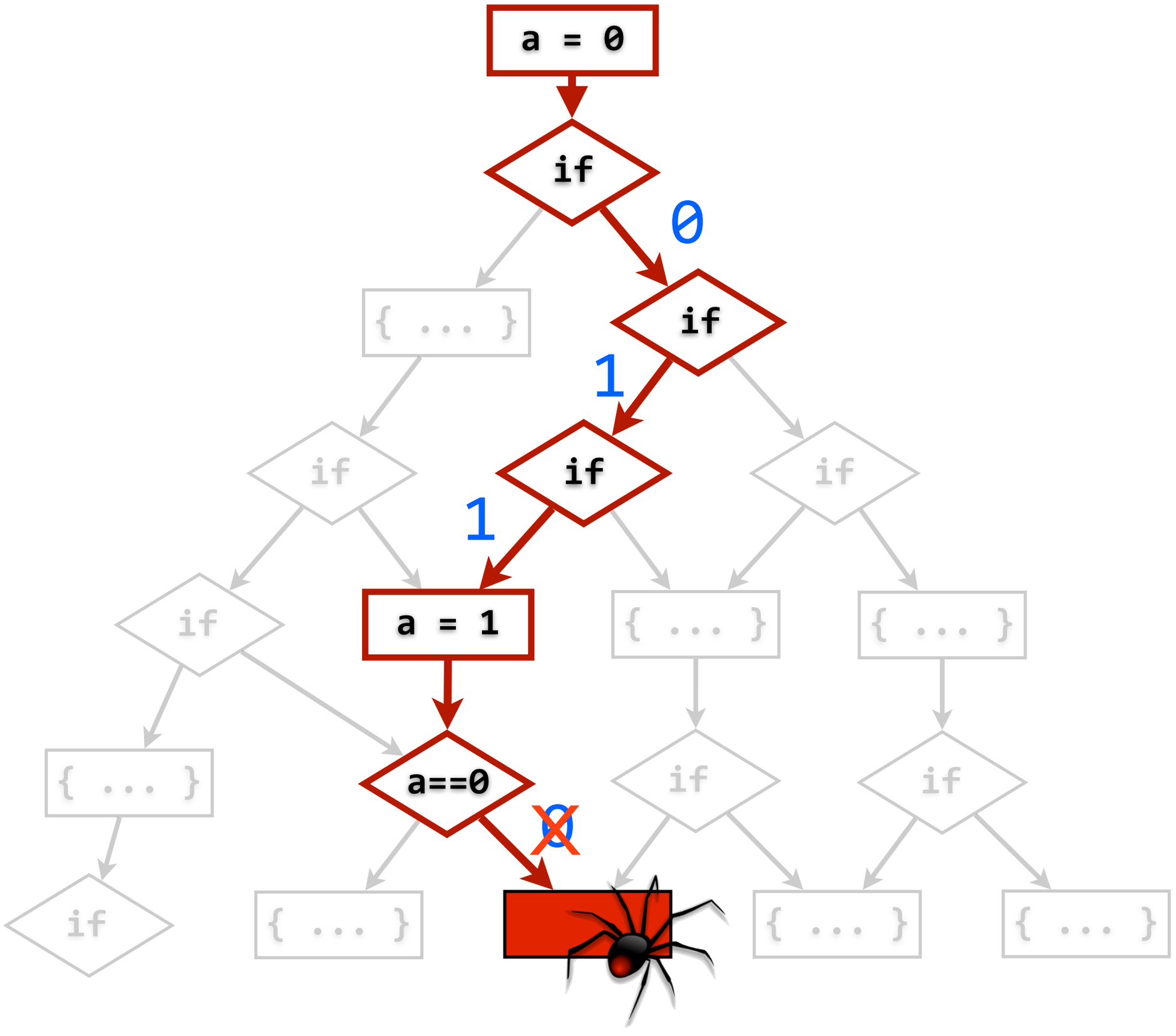
{ ... }
{ ... }


a = 0
if
0
{ ... }
if
1
if
if
if
1
if
{ ... }
{ ... }
{ ... }
if
if
if
{ ... }
if
0
{ ... }
{ ... }
{ ... }


a = 0
if
0
{ ... }
if
1
if
if
if
1
if
a = 1
{ ... }
{ ... }
if
{ ... }
if
if
0
{ ... }
{ ... }
{ ... }


a = 0
if
0
{ ... }
if
1
if
if
if
1
if
{ ... }
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
0
if
{ ... }
{ ... }
{ ... }


a = 0
if
0
{ ... }
if
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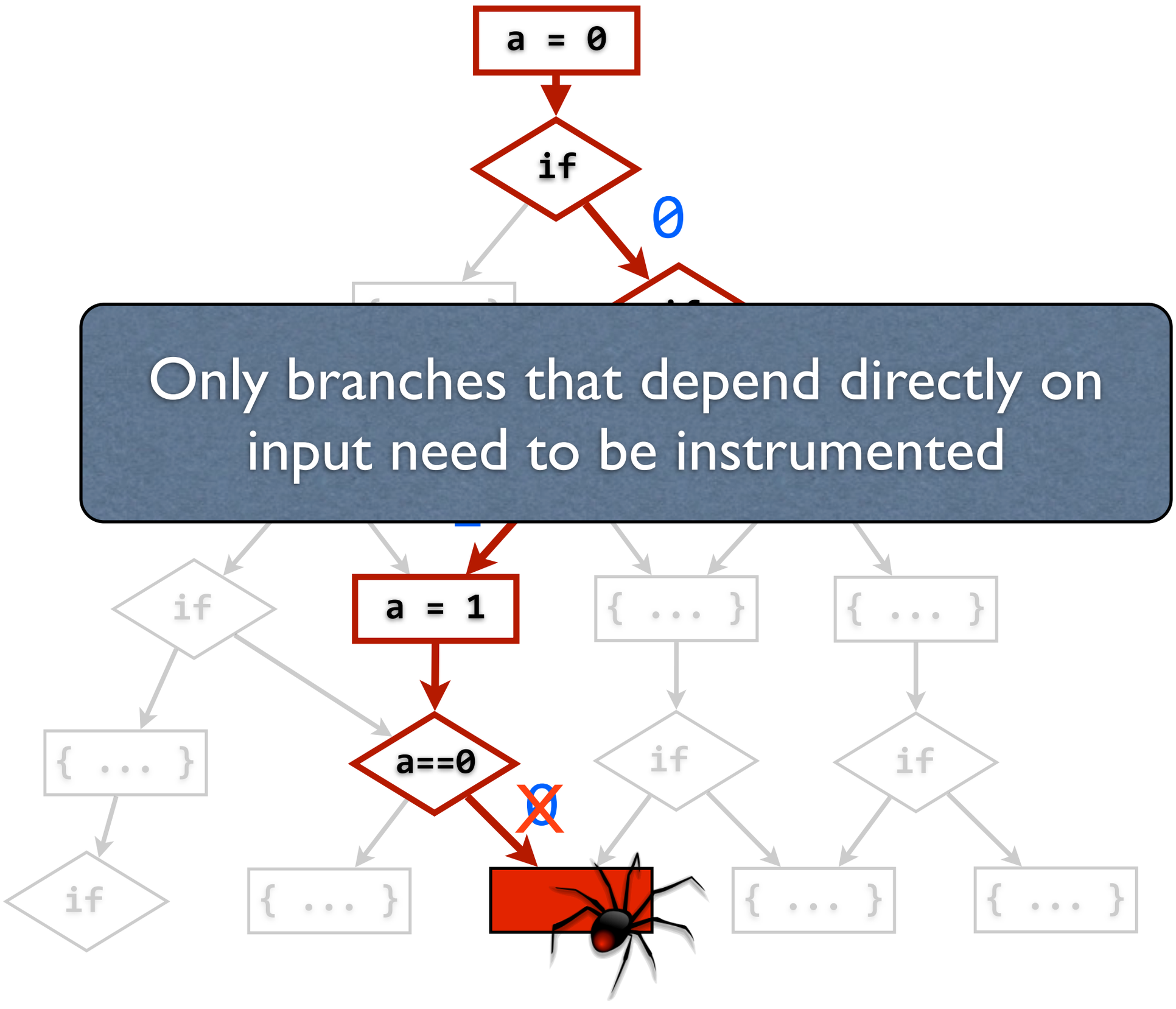
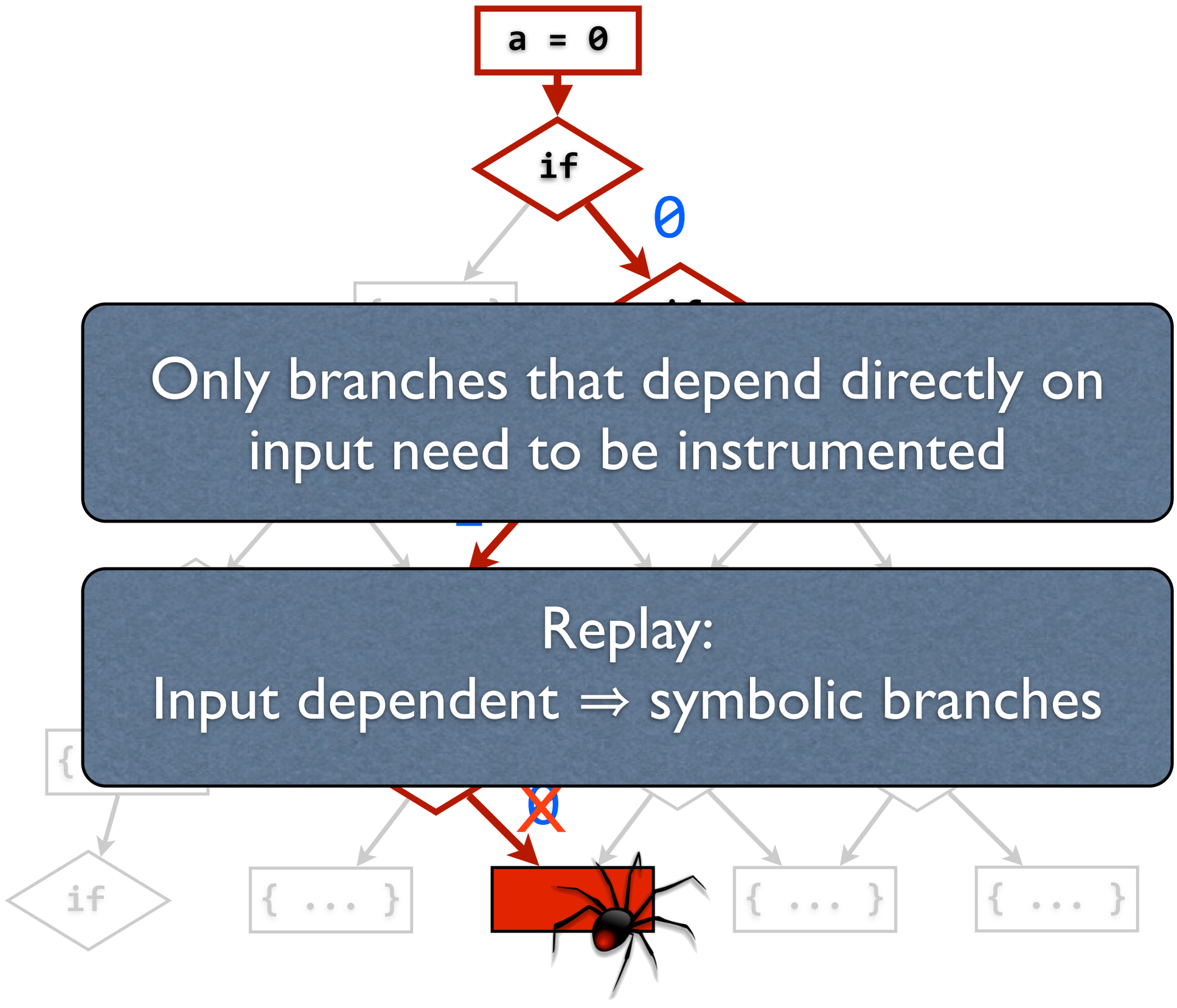
if
{ ... }
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
0
{ ... }
{ ... }
{ ... }
{ ... }


a = 0
if
0
Only branches that depend directly on input need to be instrumented
if
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
0
if
{ ... }
{ ... }
{ ... }
{ ... }


a = 0
if
0
Only branches that depend directly on input need to be instrumented
Replay:
Input dependent ⇒ symbolic branches
if
{ ... }
{ ... }
{ ... }

Symbolic branches

Symbolic branches

- In our experiments:

Symbolic branches

- In our experiments:
  - only ~10% of the branches

Symbolic branches

- In our experiments:
  - only ~10% of the branches
  - most branches are:
    - always symbolic
    - always concrete

Symbolic branches

- In our experiments:
  - Significant opportunity to optimize branch instrumentation
  - always concrete

Instrumentation

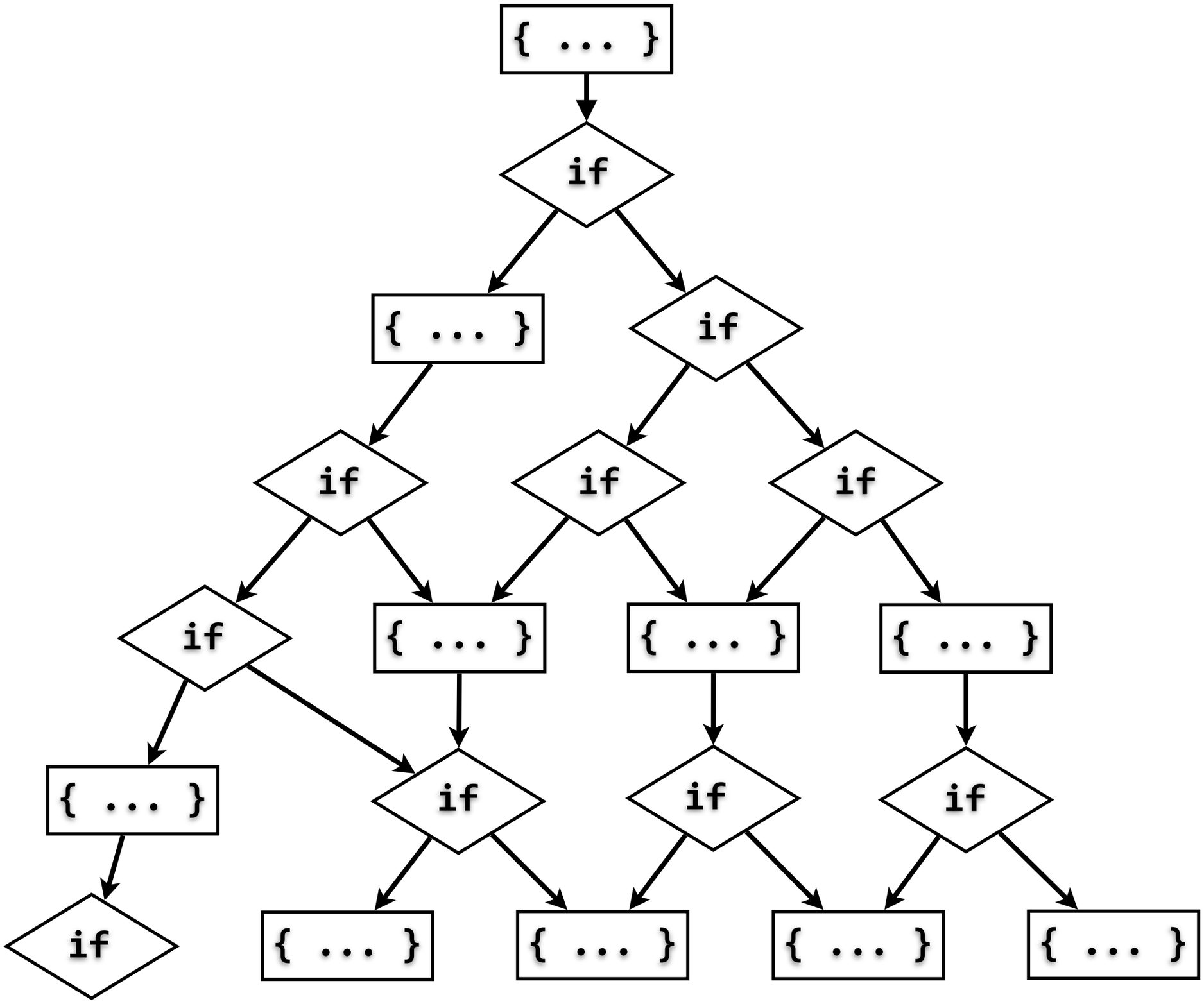
Instrumentation

- Goal:
  - ✦ Instrument symbolic branches

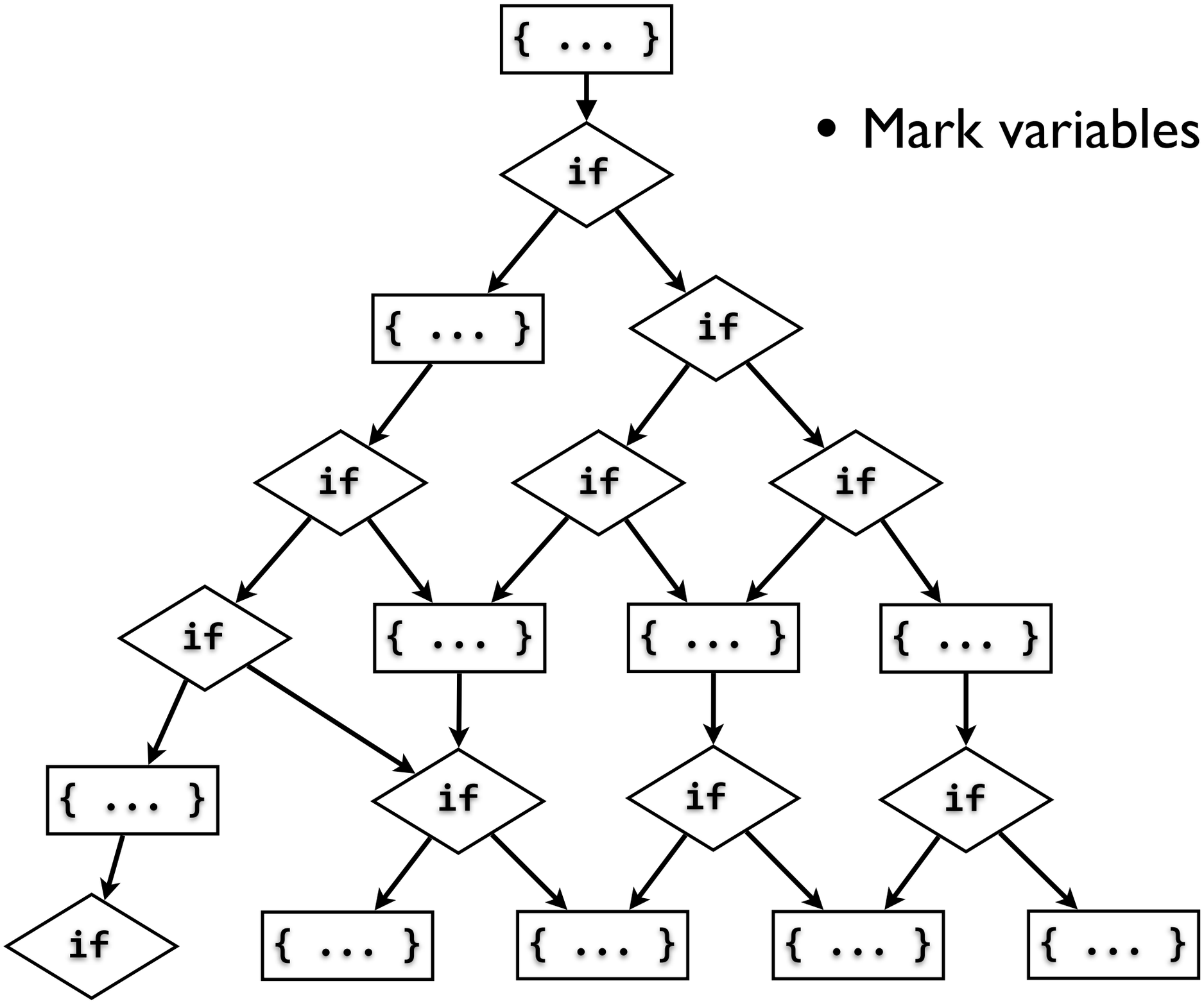
Instrumentation

- Goal:
  - ✦ Instrument symbolic branches
- Three techniques:
  - ✦ Static Analysis
  - ✦ Dynamic Analysis
  - ✦ Combined dynamic+static approach

Static Analysis

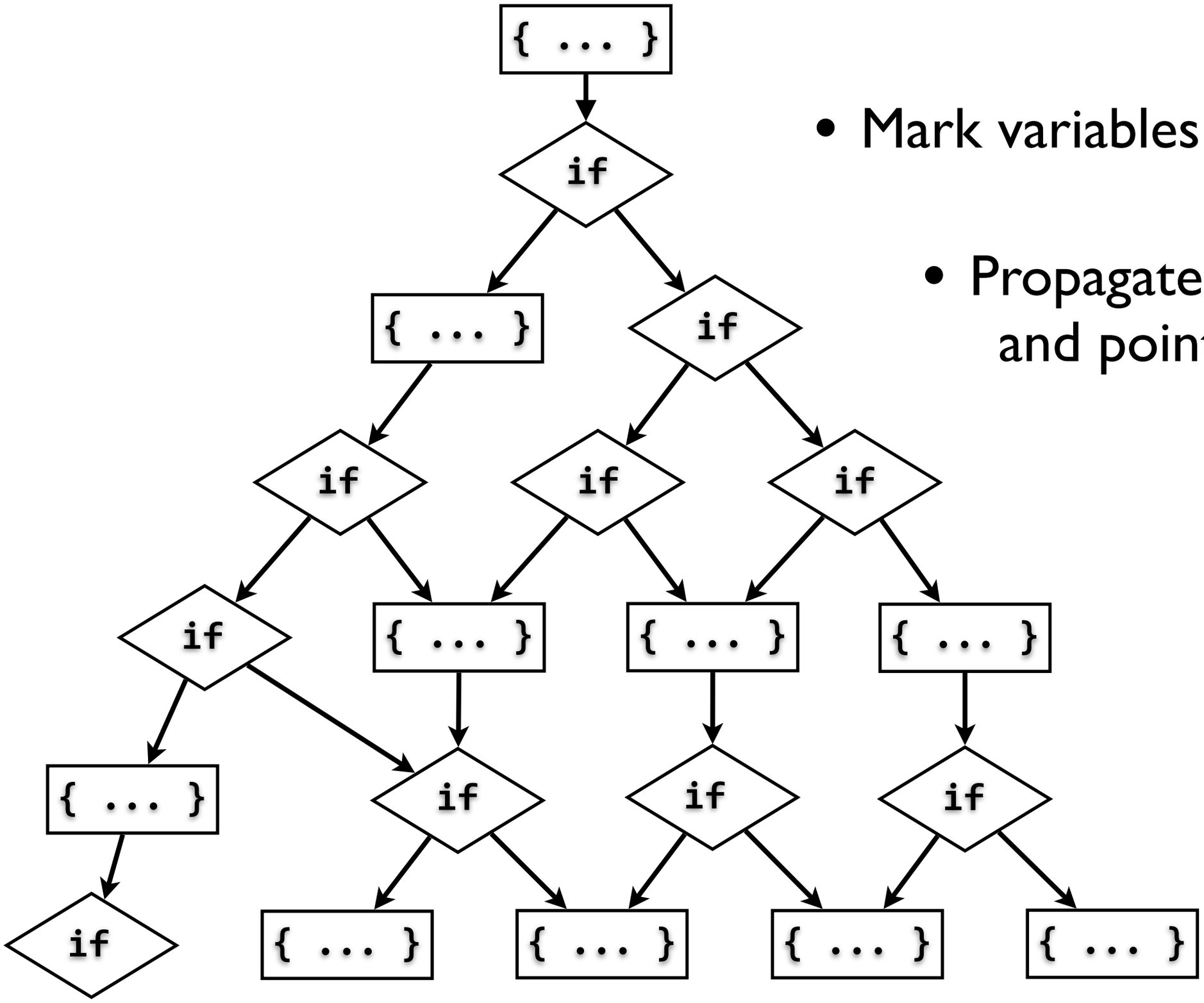


Static Analysis

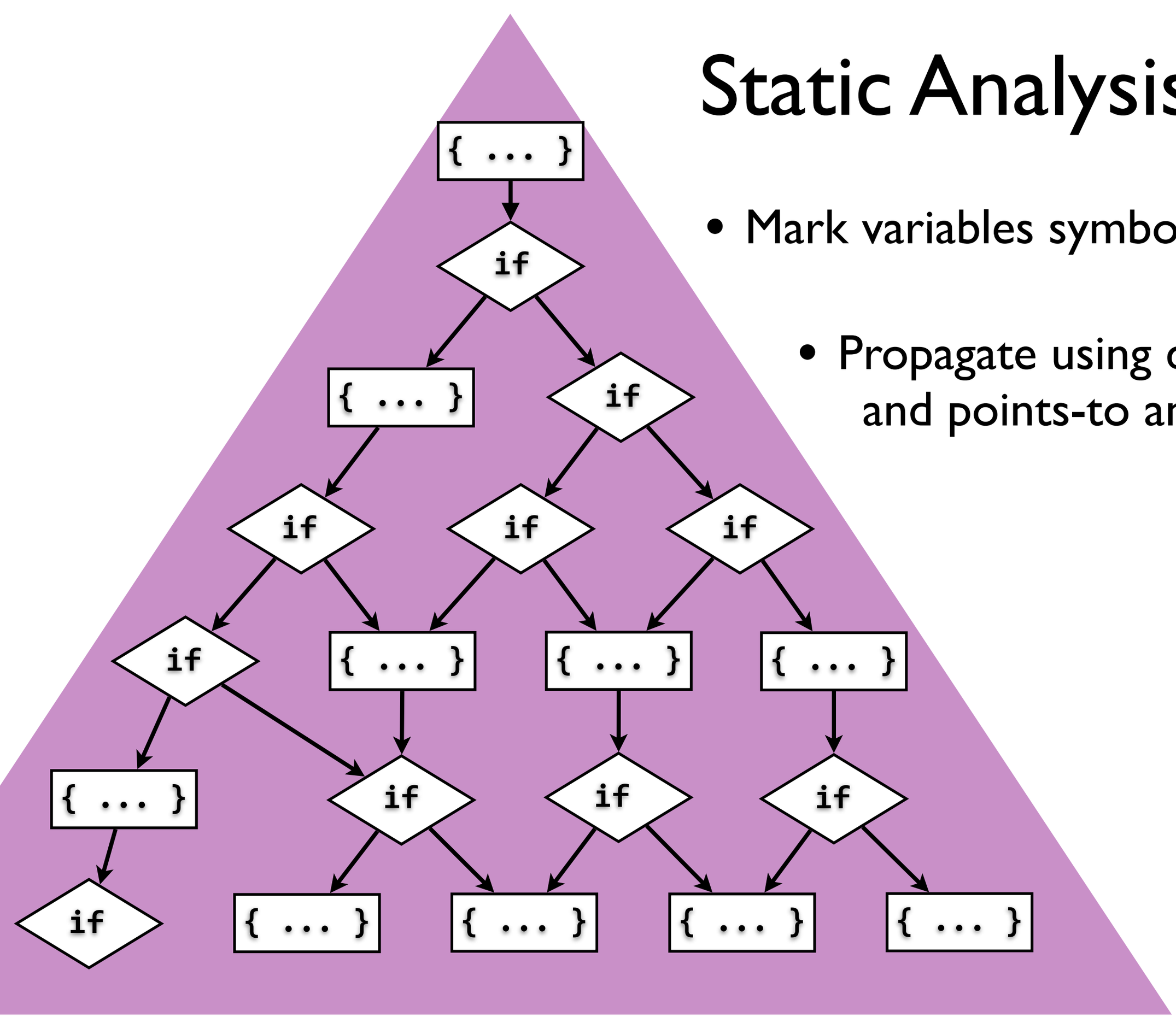


- Mark variables symbolic

Static Analysis



- Mark variables symbolic
  - Propagate using data-flow and points-to analysis



Static Analysis

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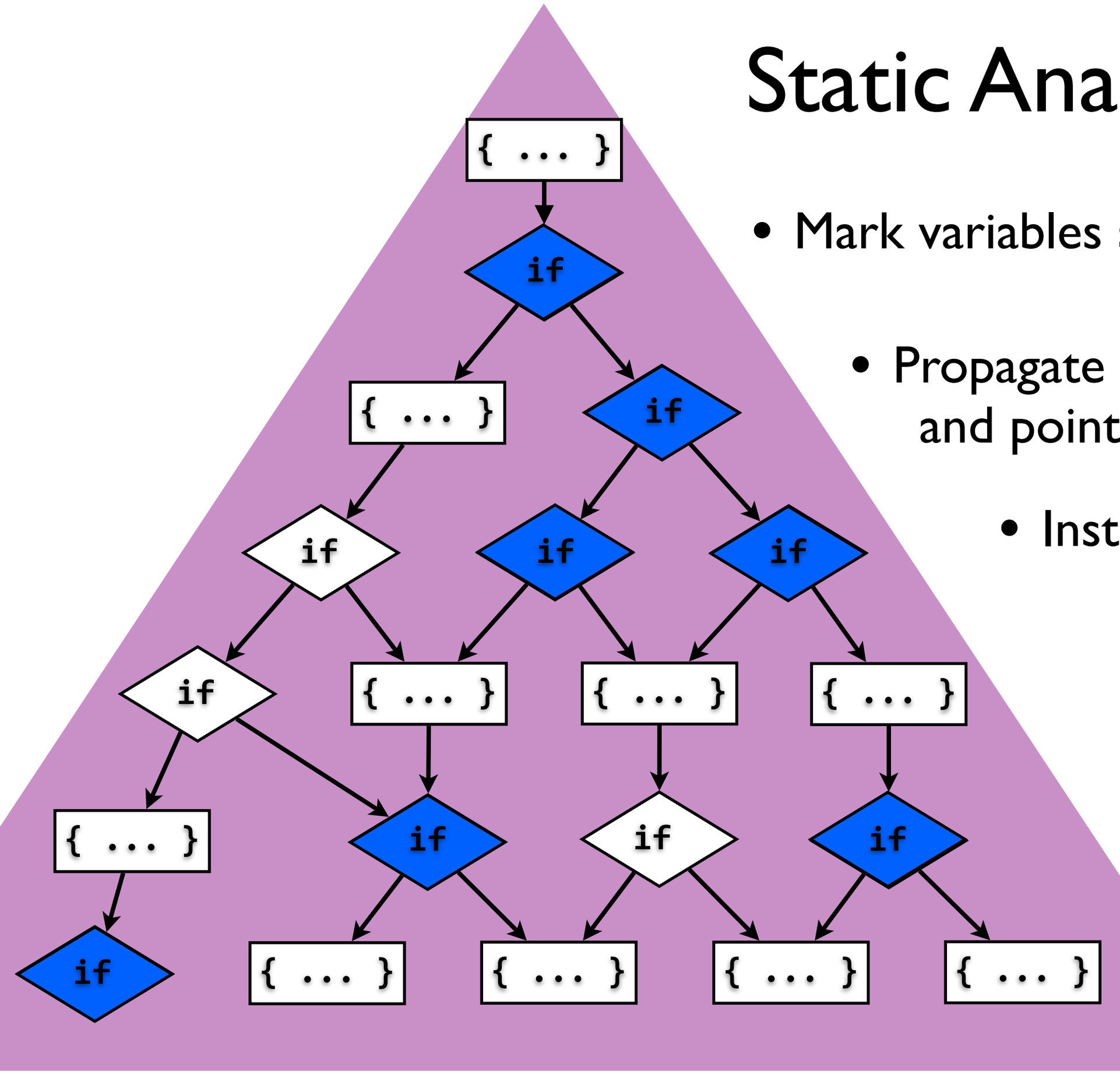

Static Analysis

- Mark variables symbolic
- Propagate using data-flow and points-to analysis
- Instrument symbolic branches

Static Analysis shortcomings

- points-to analysis imprecise, tends to over-estimate
- doesn't scale to libraries (libc):
  - ✦ conservatively, instrument all branches

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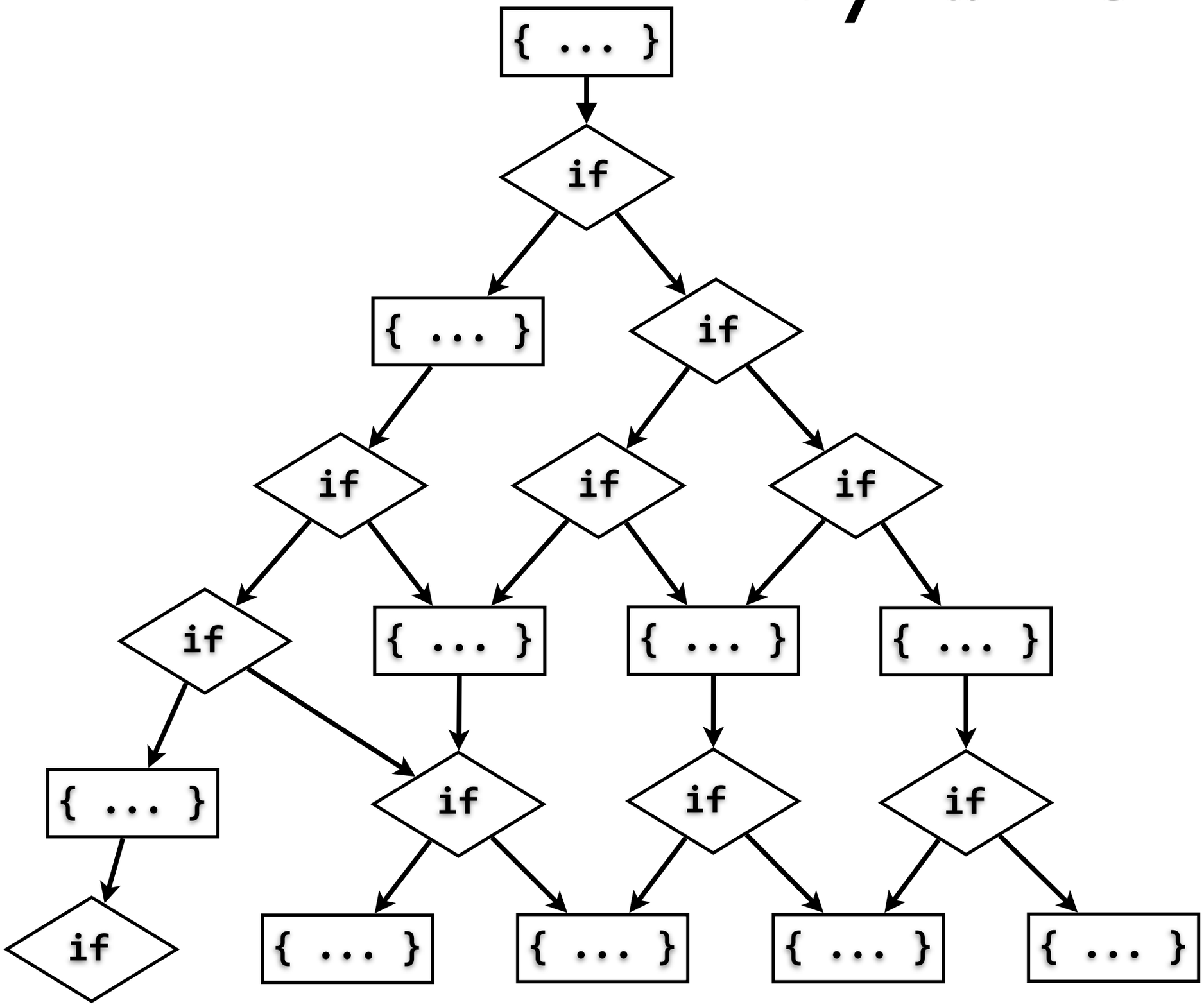
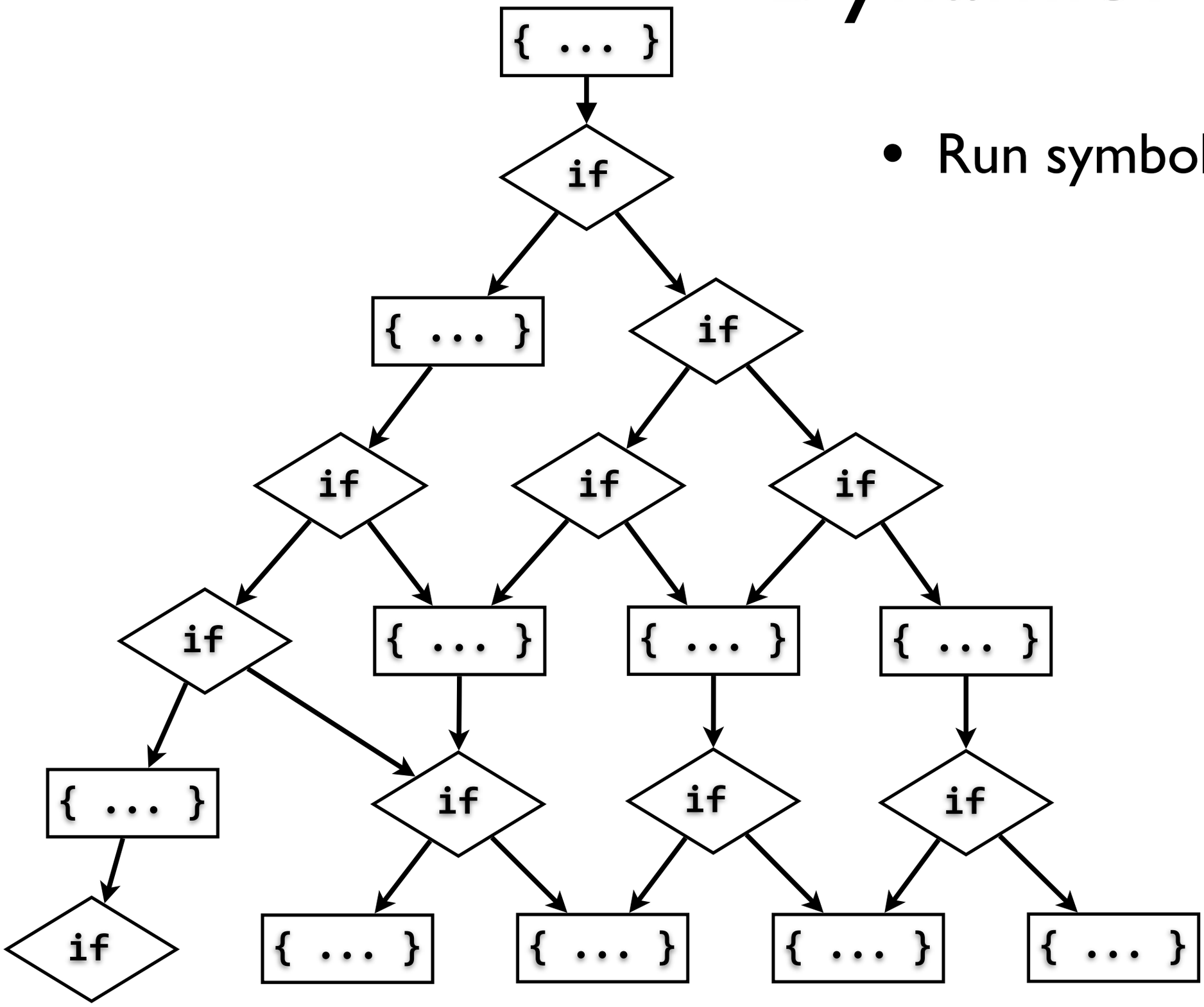
Static Analysis tends to over-approximate:
⇒ too many branches instrumented

Dynamic Analysis (1)

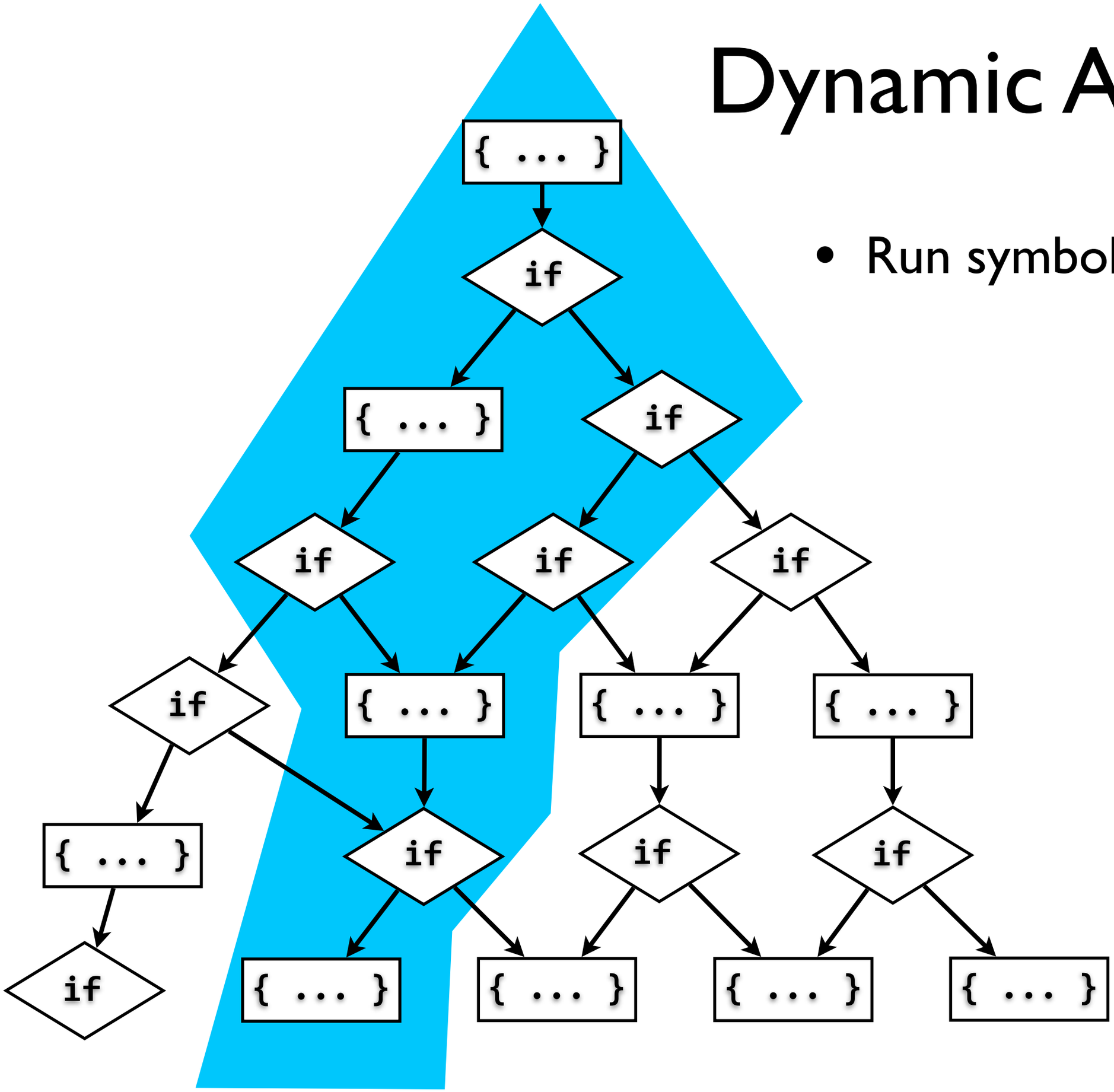


Dynamic Analysis (1)



- Run symbolic execution

Dynamic Analysis (1)



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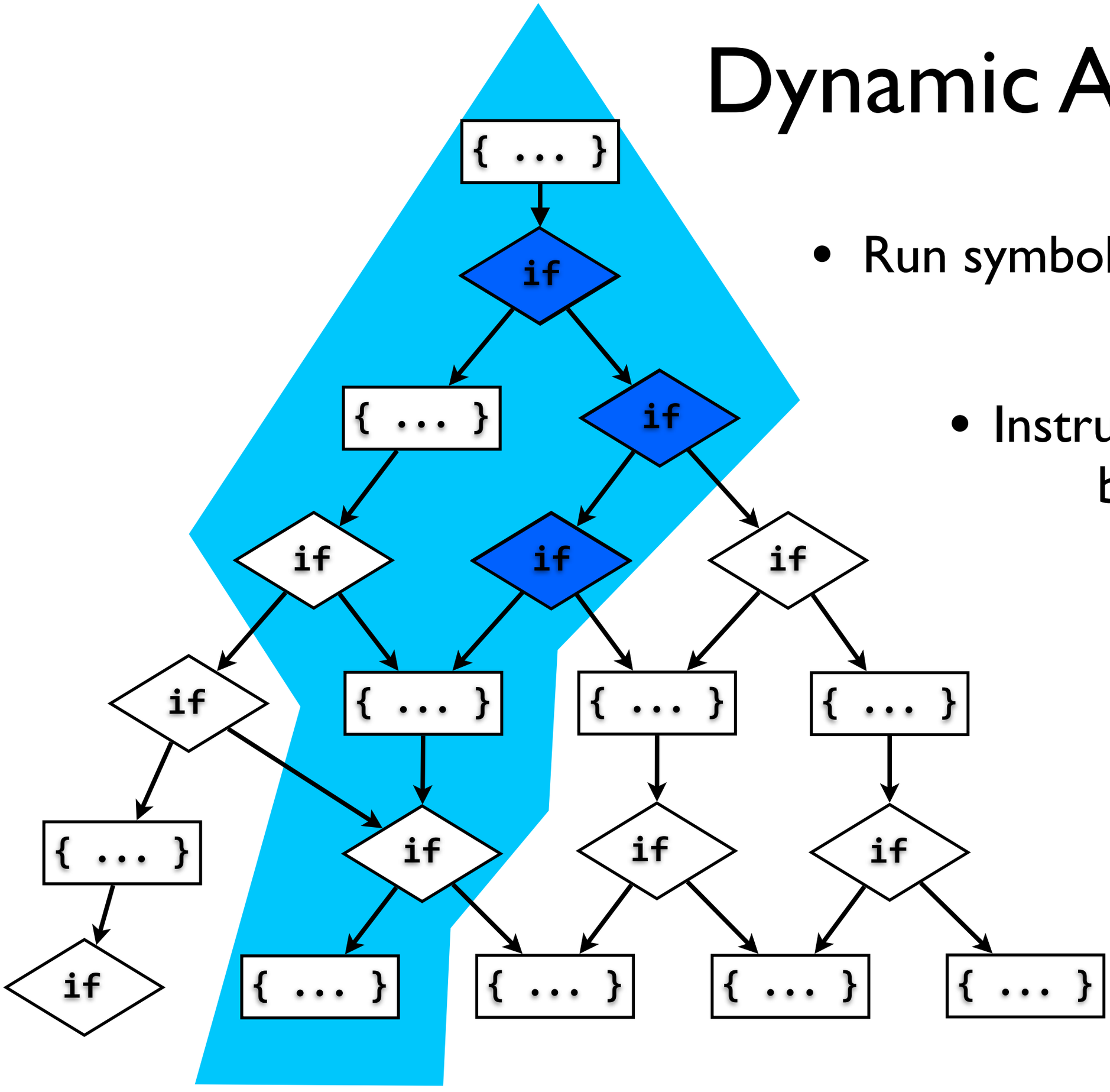

- Run symbolic execution
- Instrument symbolic branches

Dynamic Analysis (2)

- Pros:
  - ✦ precise
  - ✦ runs on the library too
- Cons:
  - ✦ coverage limited

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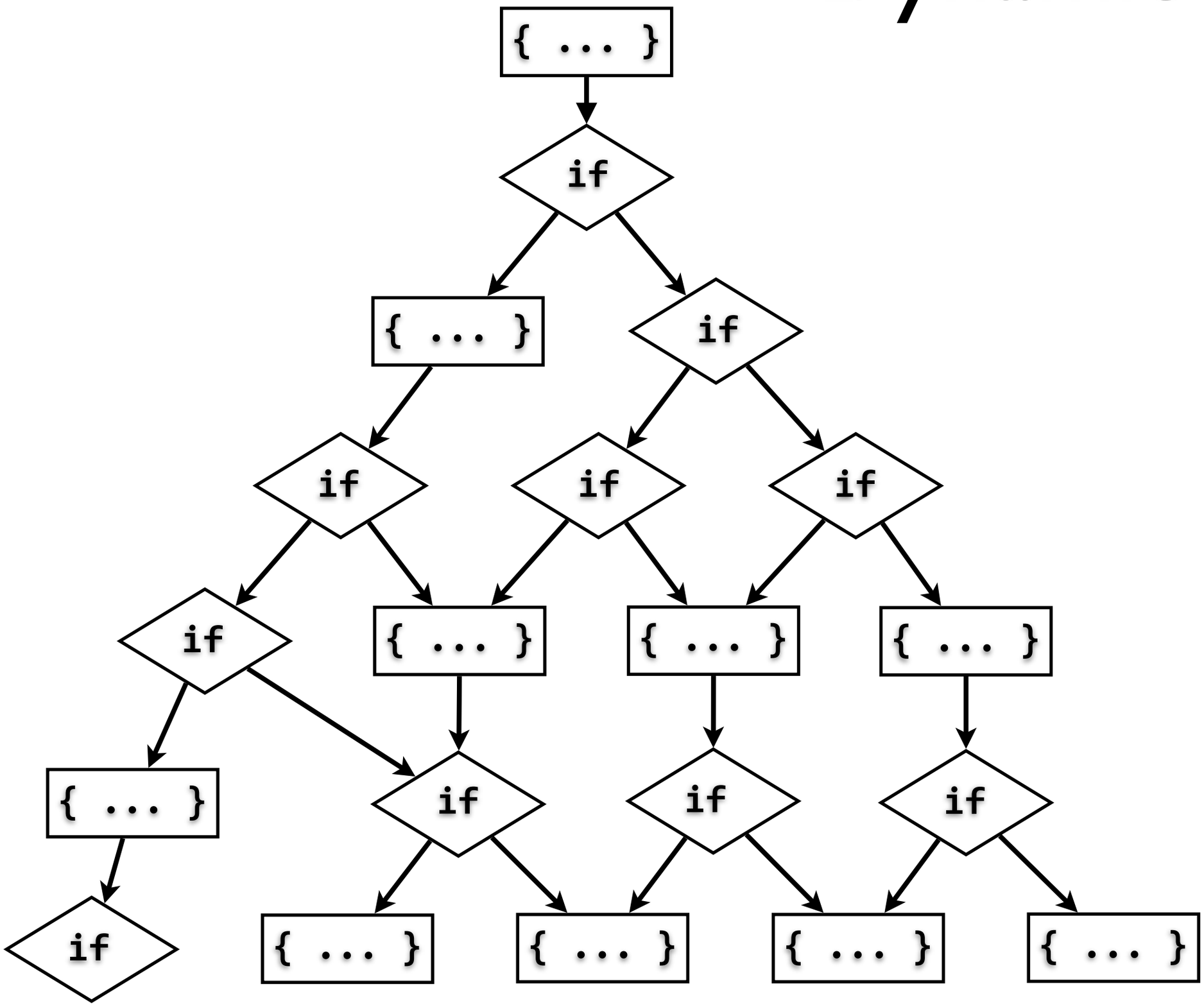
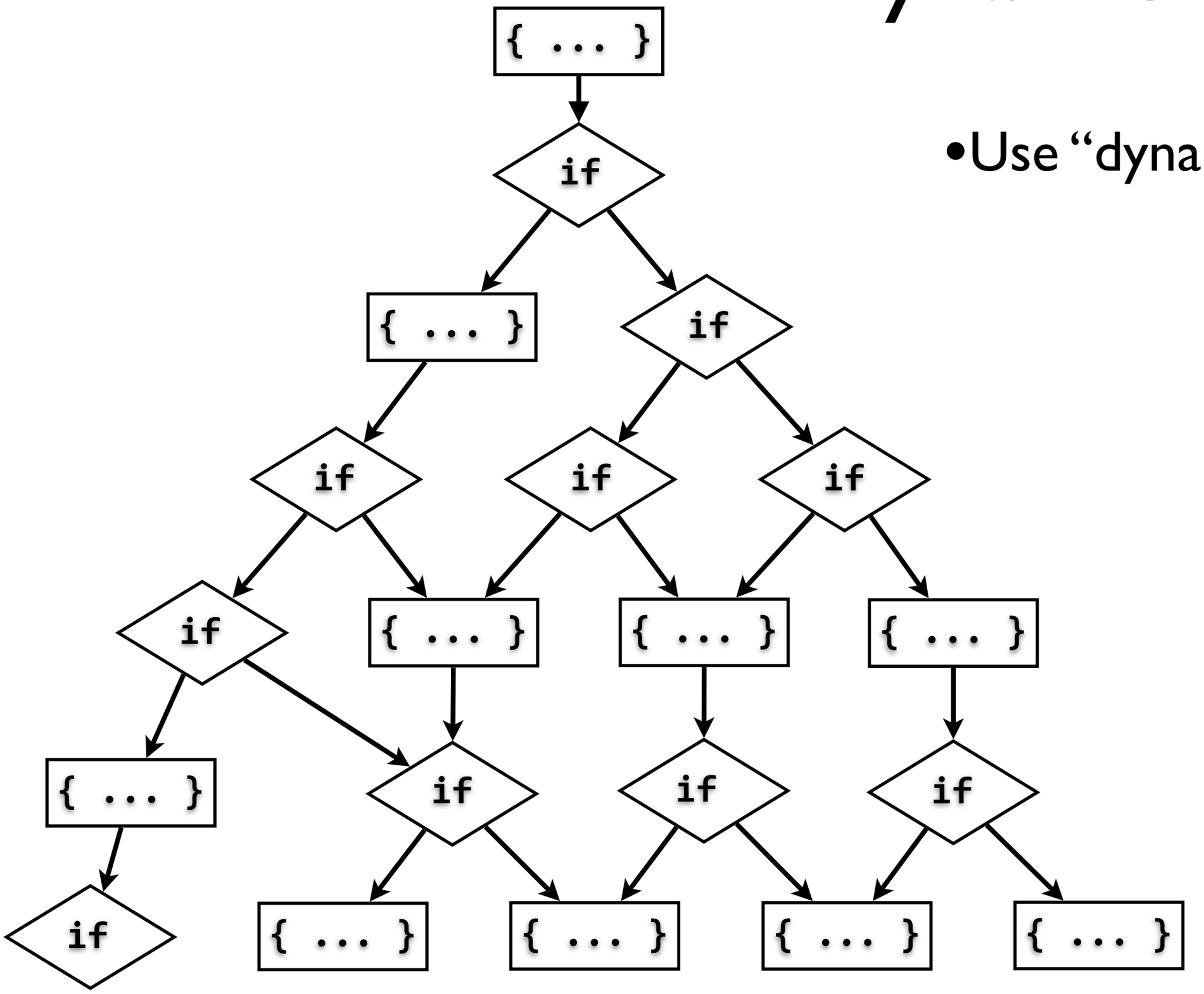
Dynamic Analysis tends to under-estimate:
⇒ some symbolic branches may not be logged

Dynamic + Static

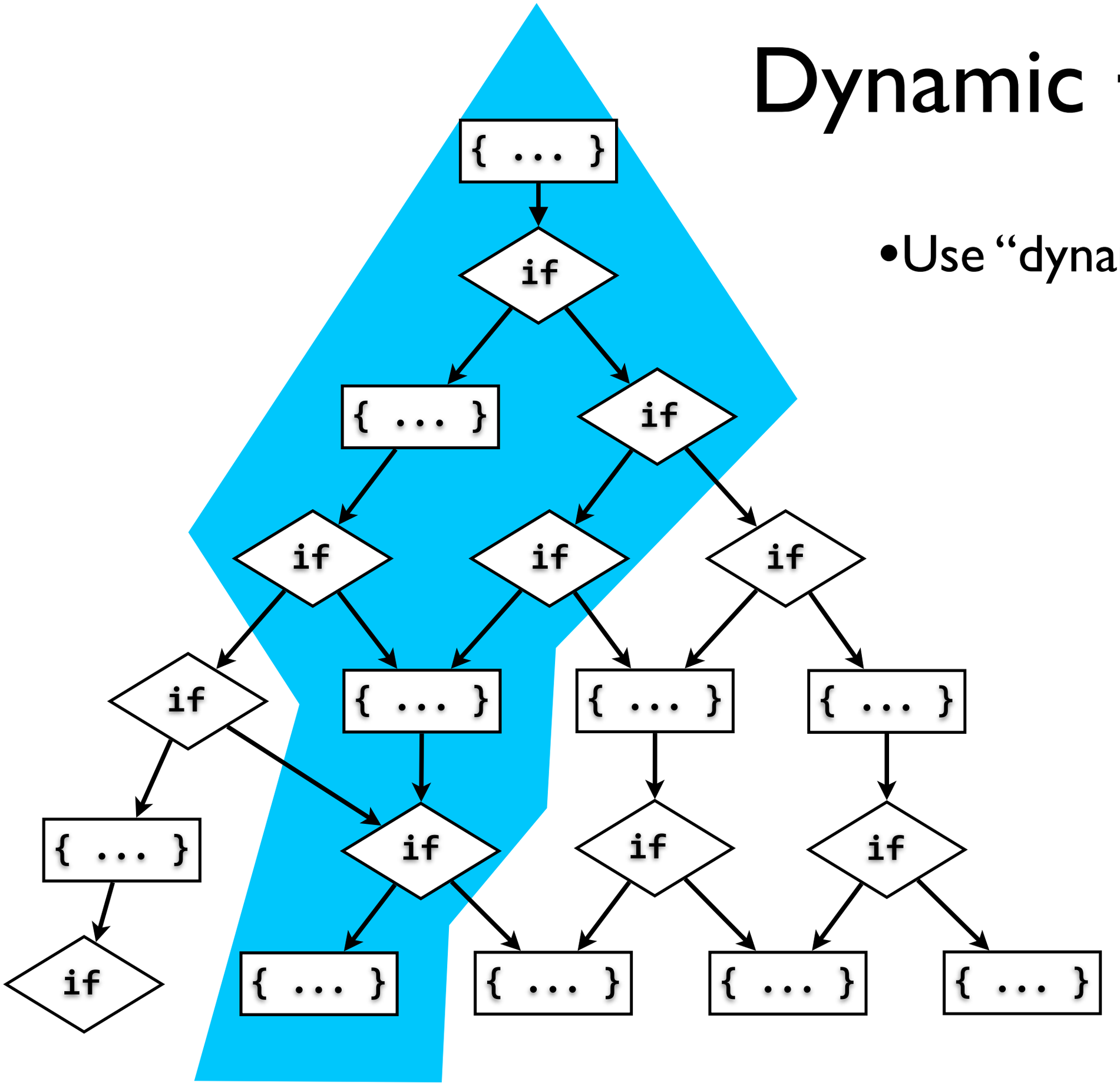


Dynamic + Static



- Use "dynamic" first

Dynamic + Static



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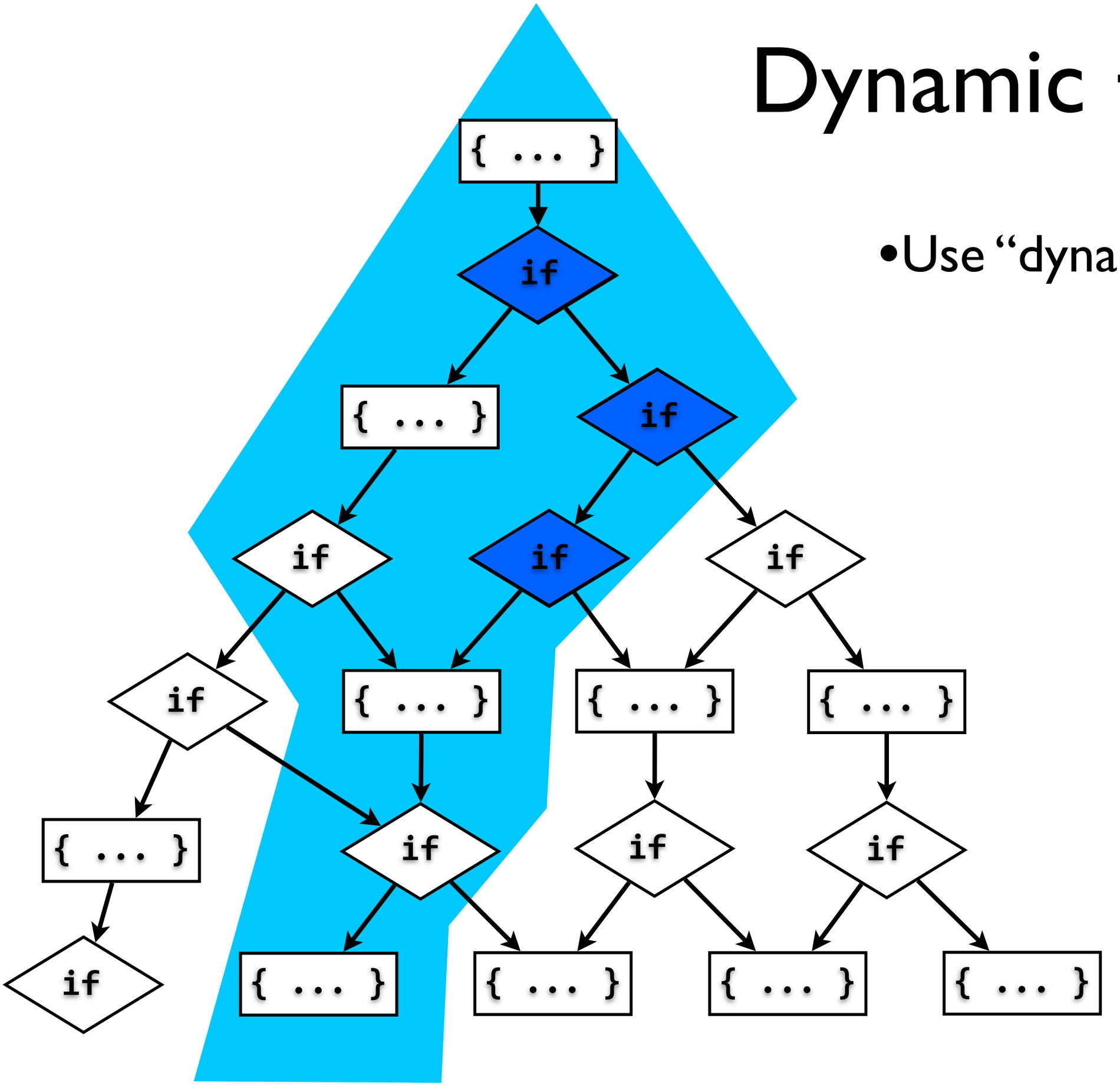
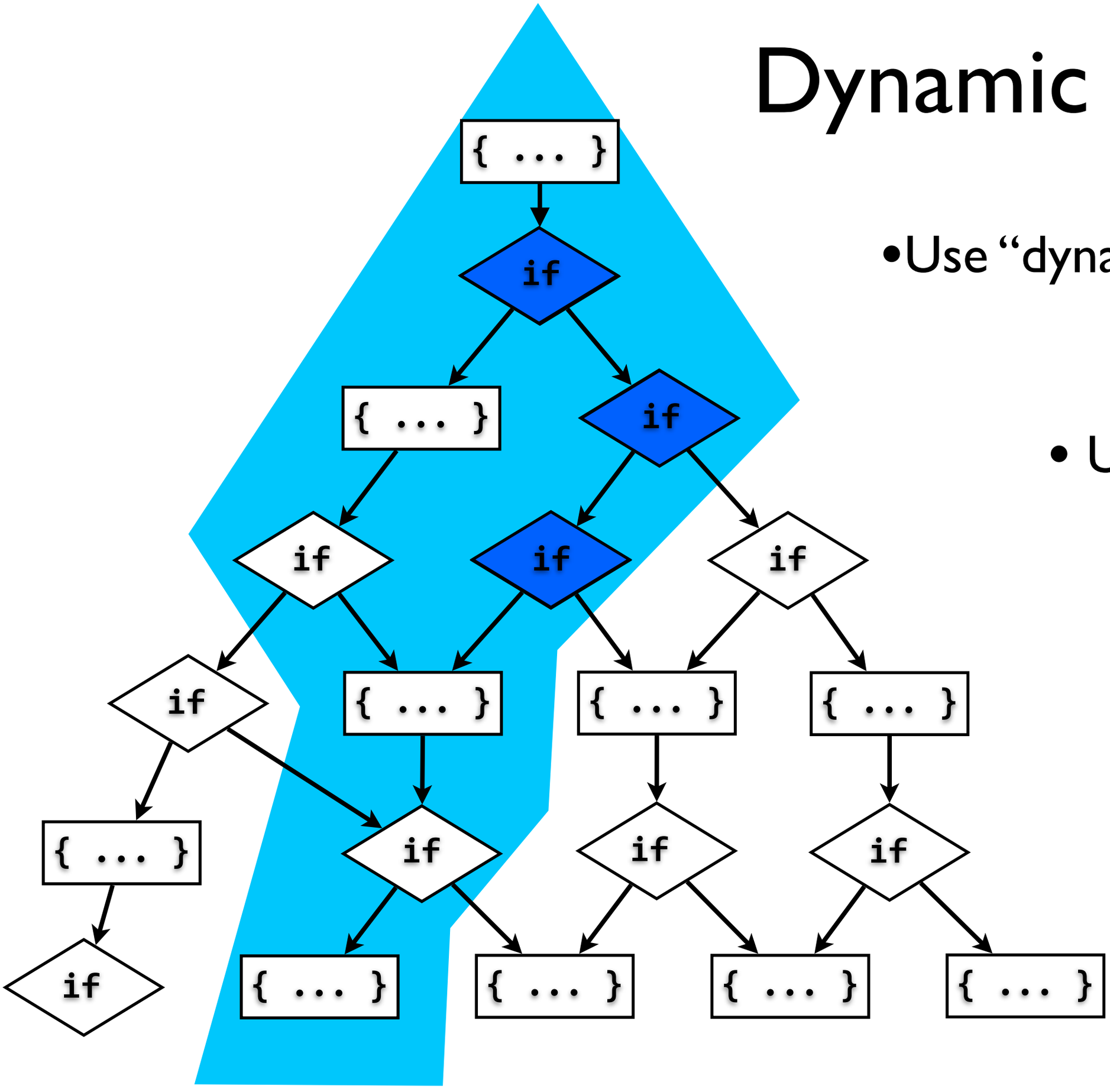


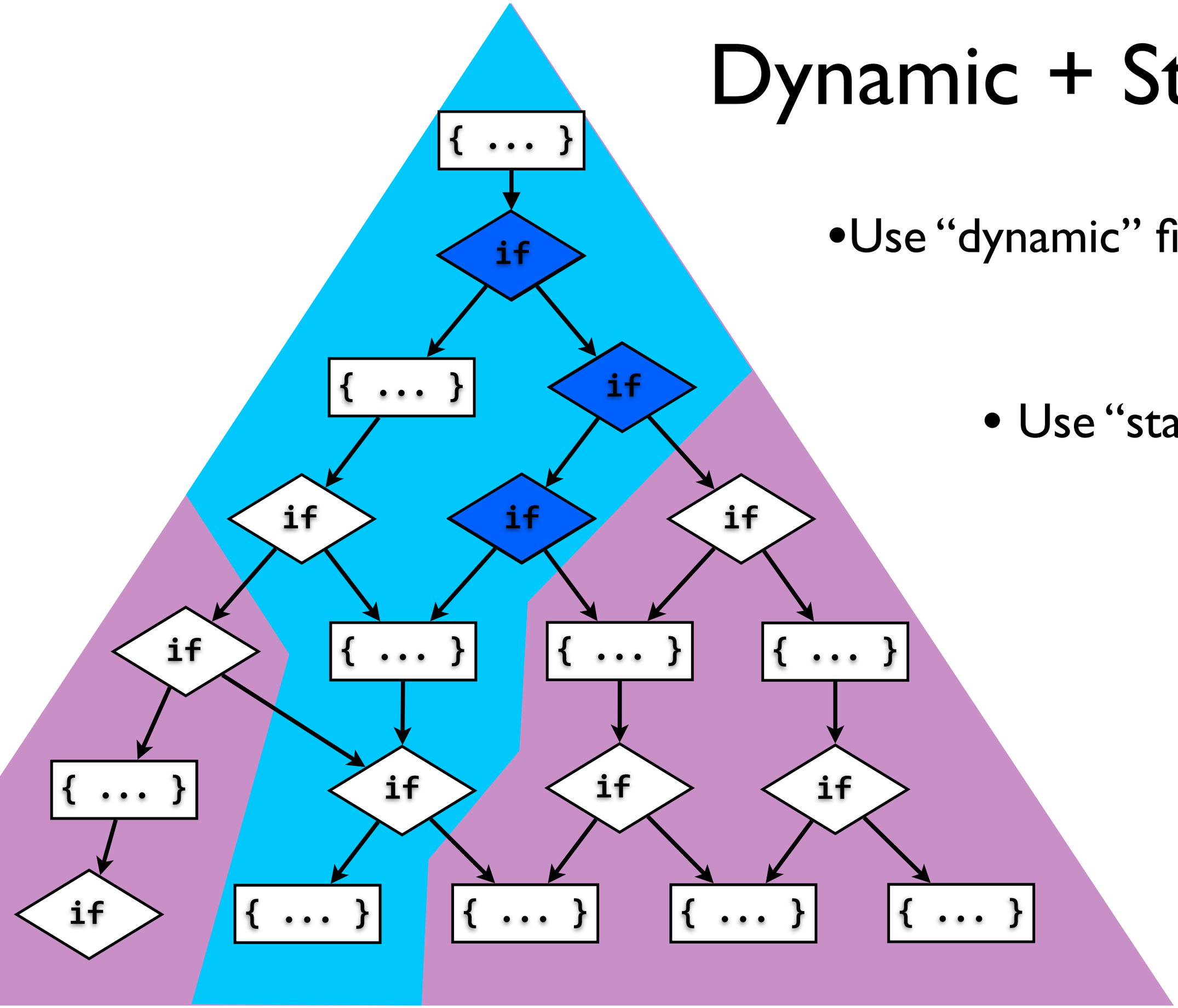
- Use “dynamic” first

Dynamic + Static



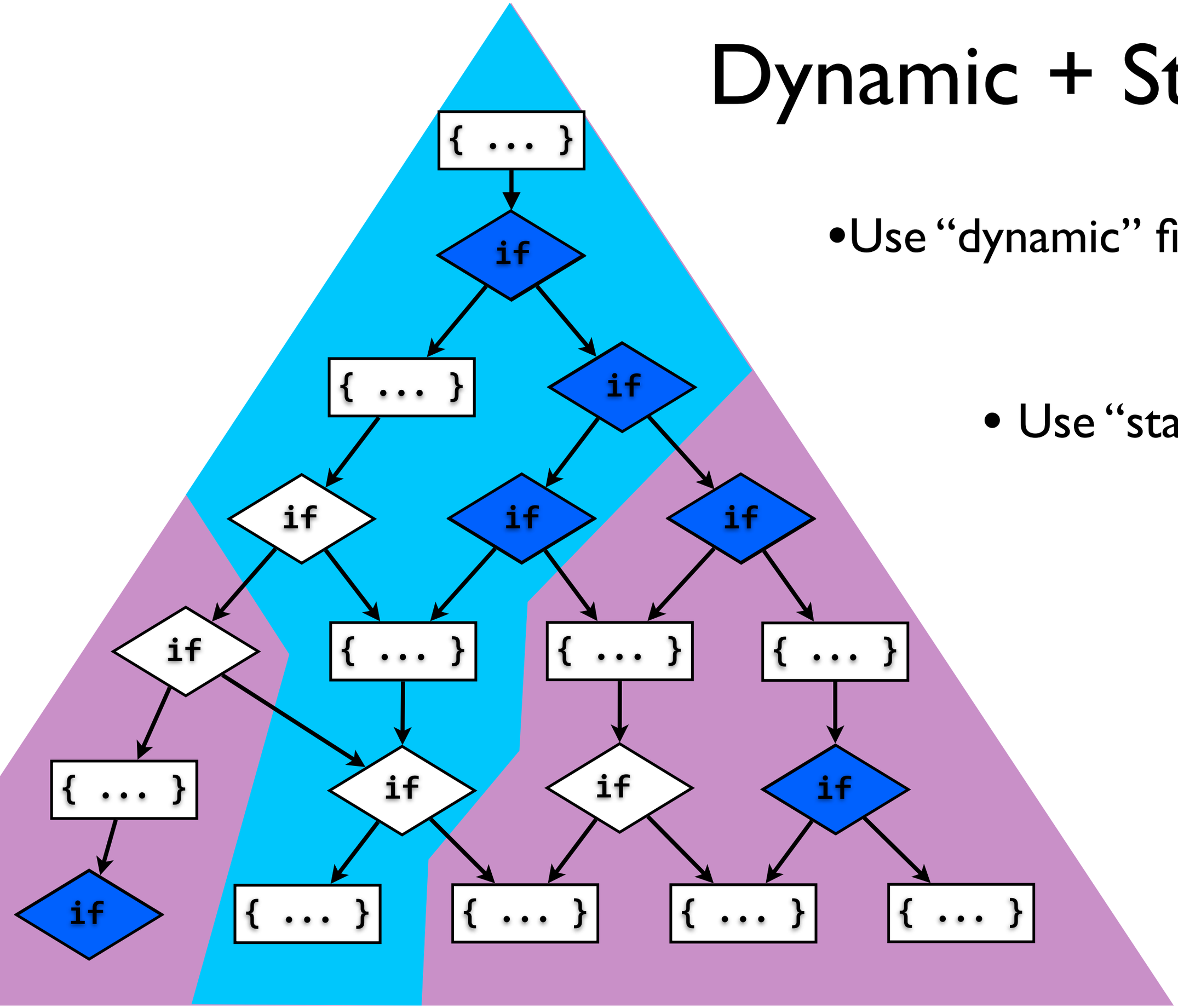
- Use "dynamic" first
- Use "static"

Dynamic + Static



- Use “dynamic” first
- Use “static”

Dynamic + Static



- Use "dynamic" first
- Use "static"

Instrumentation summary

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Instrumentation summary

- Static analysis:
  - ✦ covers all code but is imprecise
- Dynamic analysis
  - ✦ precise but with limited coverage
- Dynamic + static
  - ✦ good coverage and precise

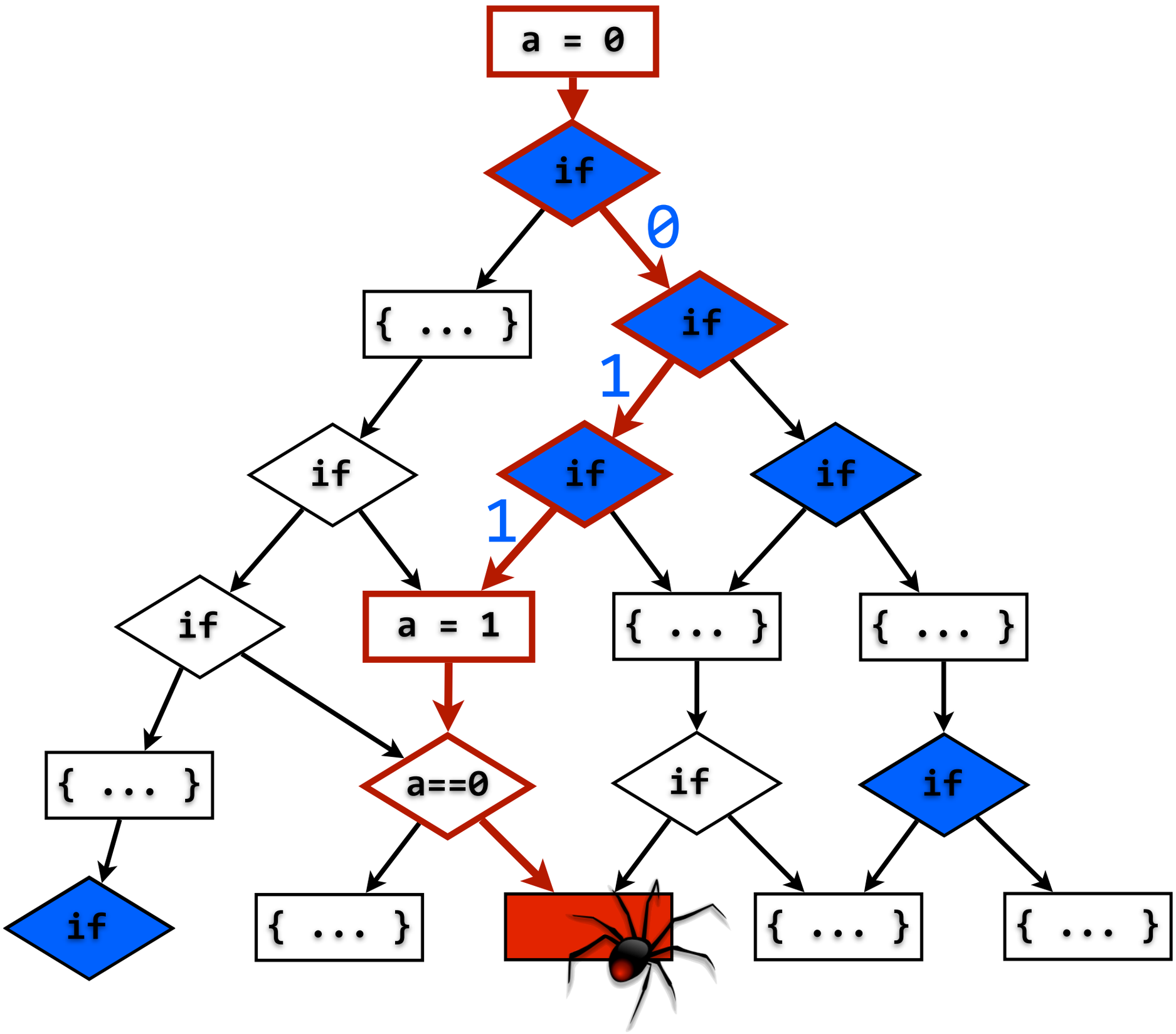
Replay

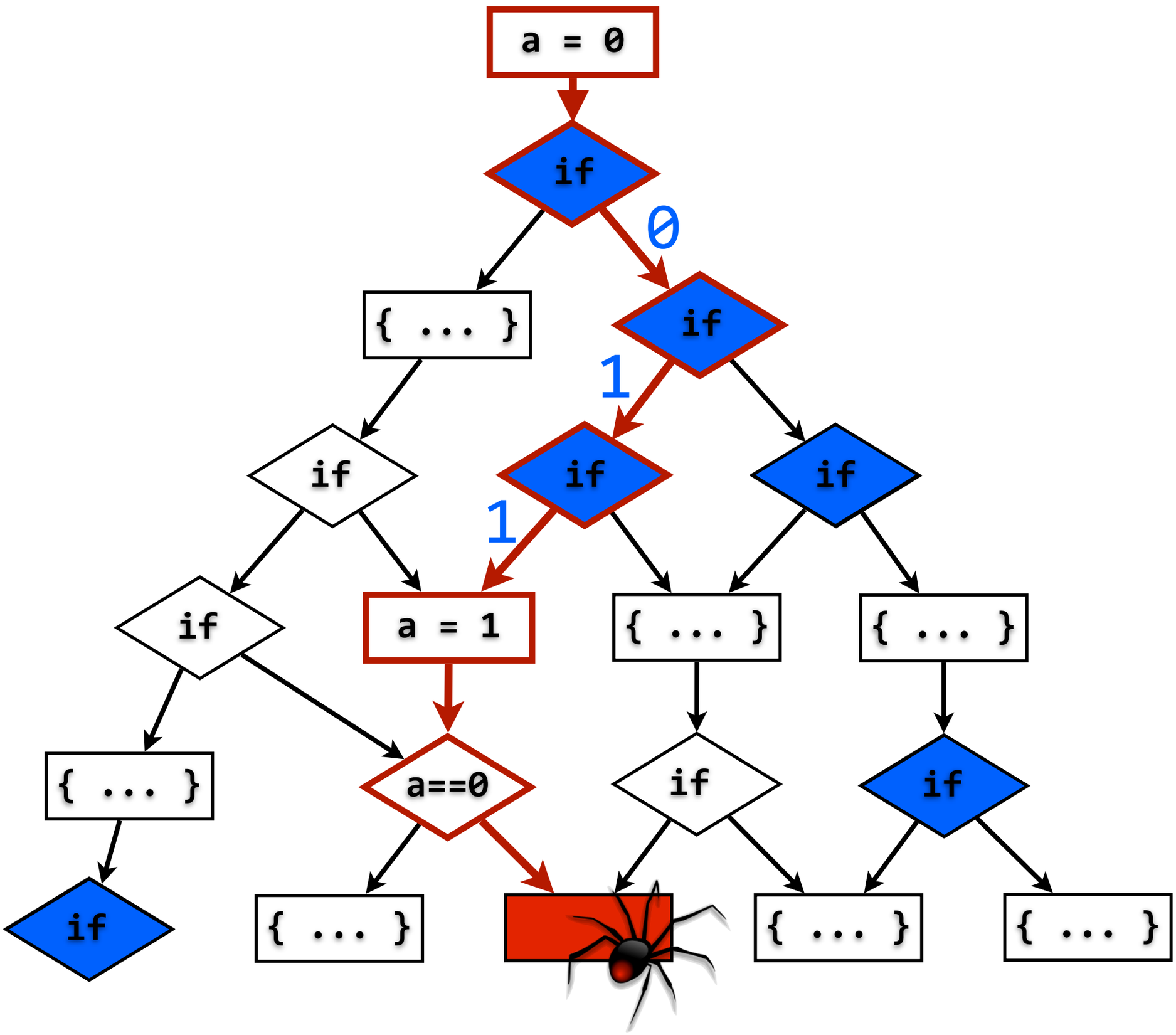
Replay

- Bug ⇒ branch log is shipped to the vendor

Replay

- Bug ⇒ branch log is shipped to the vendor
- Vendor replays the application:
  - ✦ uses symbolic execution
  - ✦ follows the branch log


a = 0
if
0
{ ... }
if
1
if
if
if
1
if
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }


a = 0
if
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if
if
{ ... }
{ ... }
{ ... }
{ ... }

```
0
1
1
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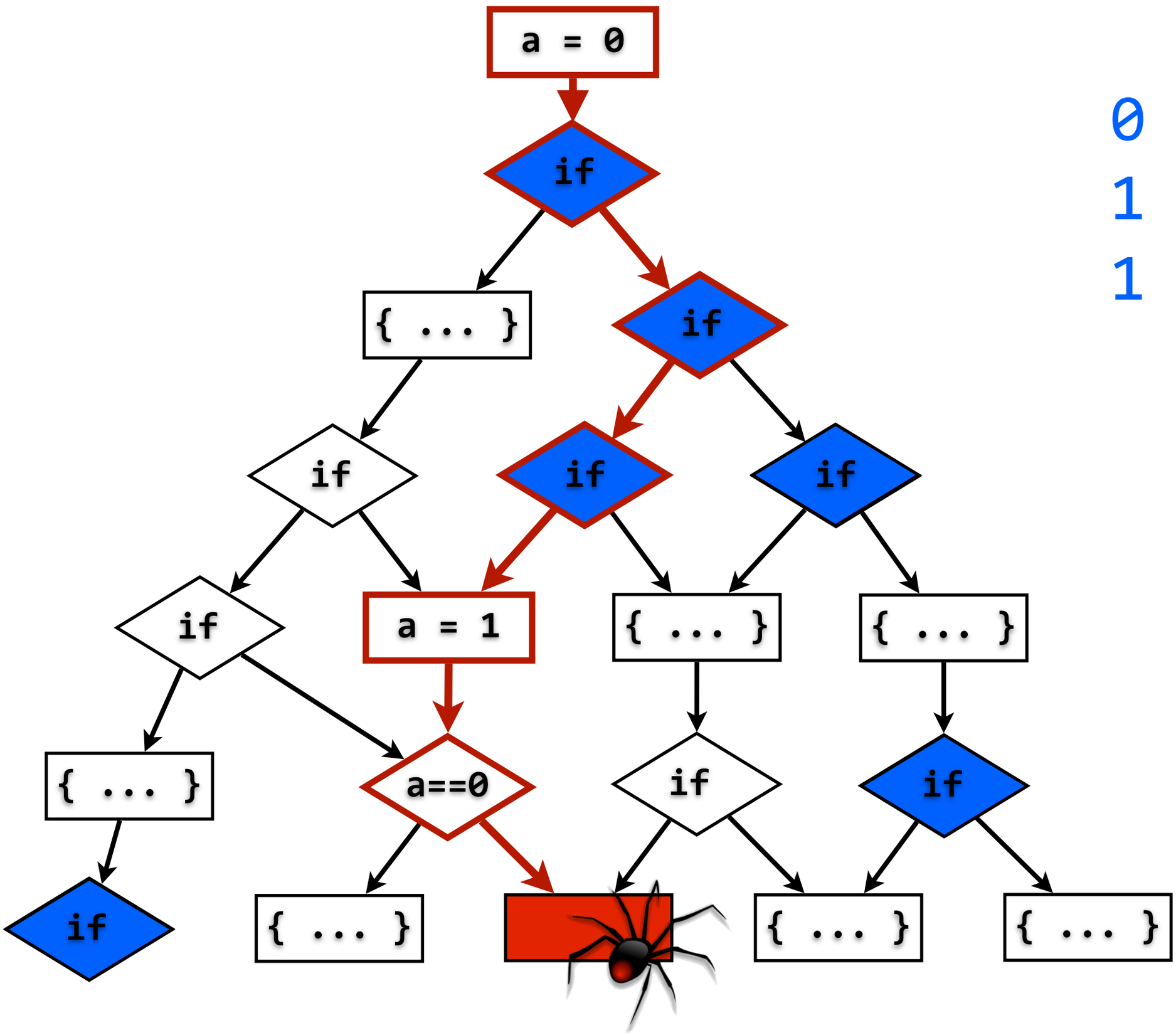

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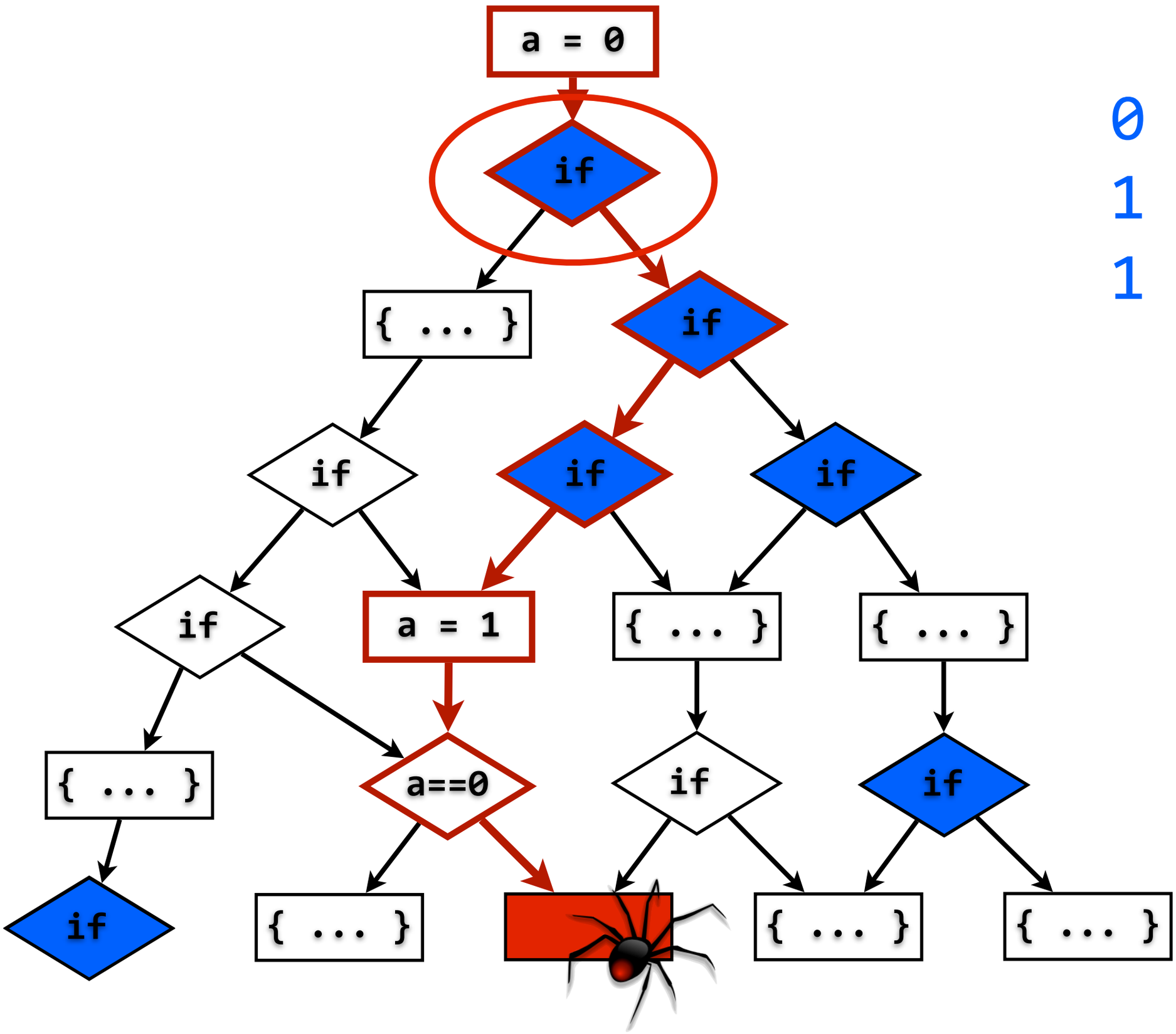

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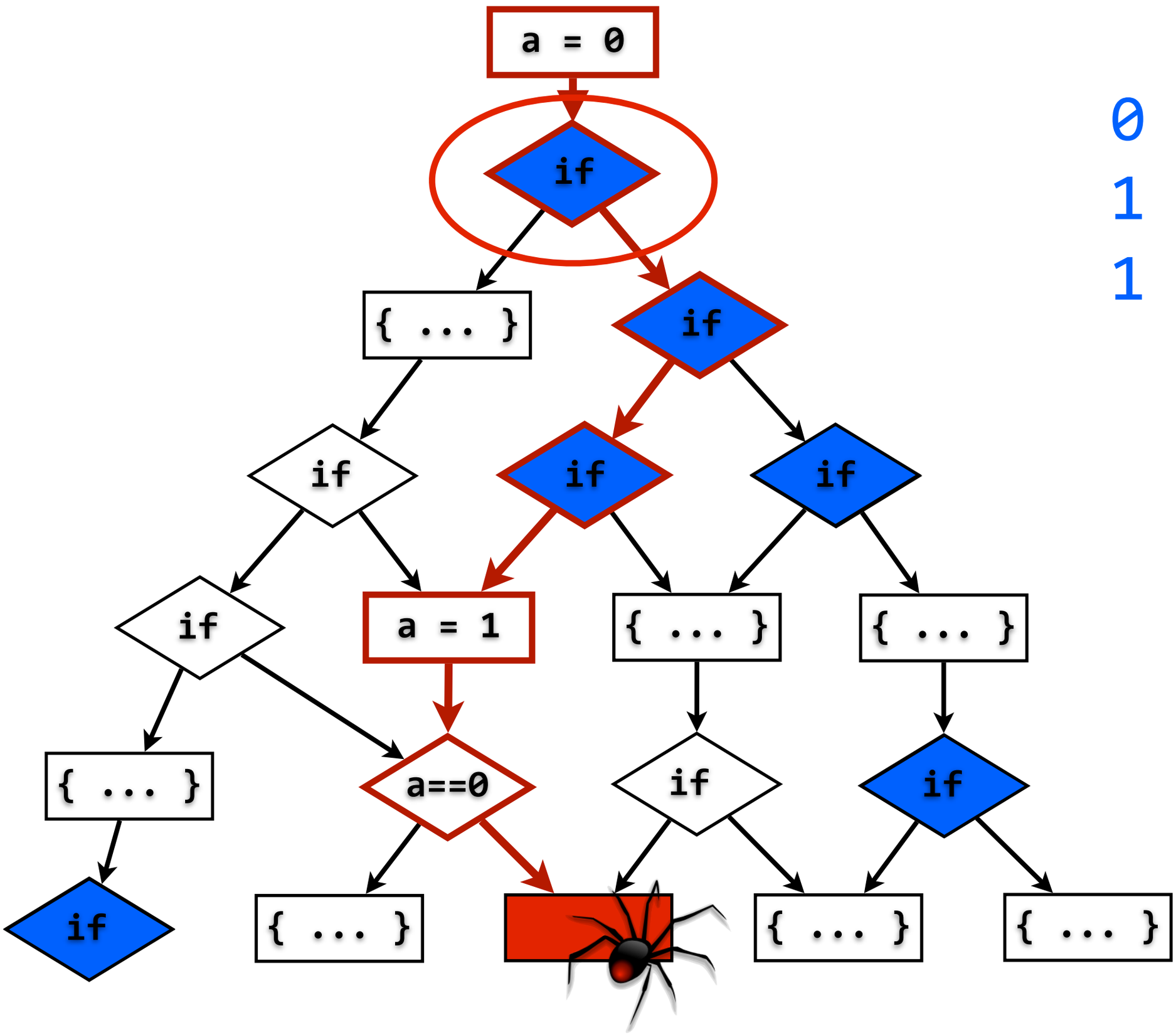

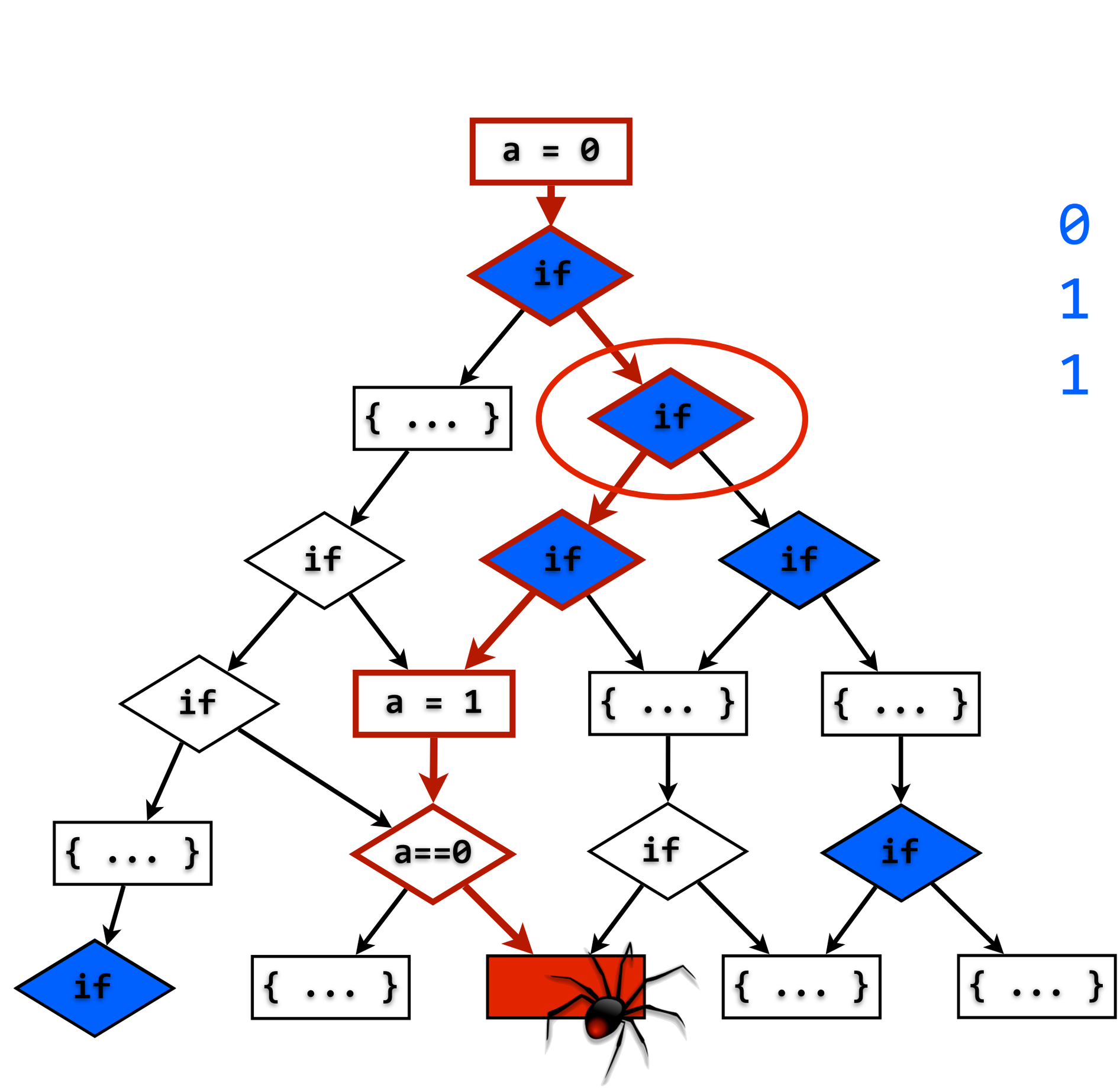

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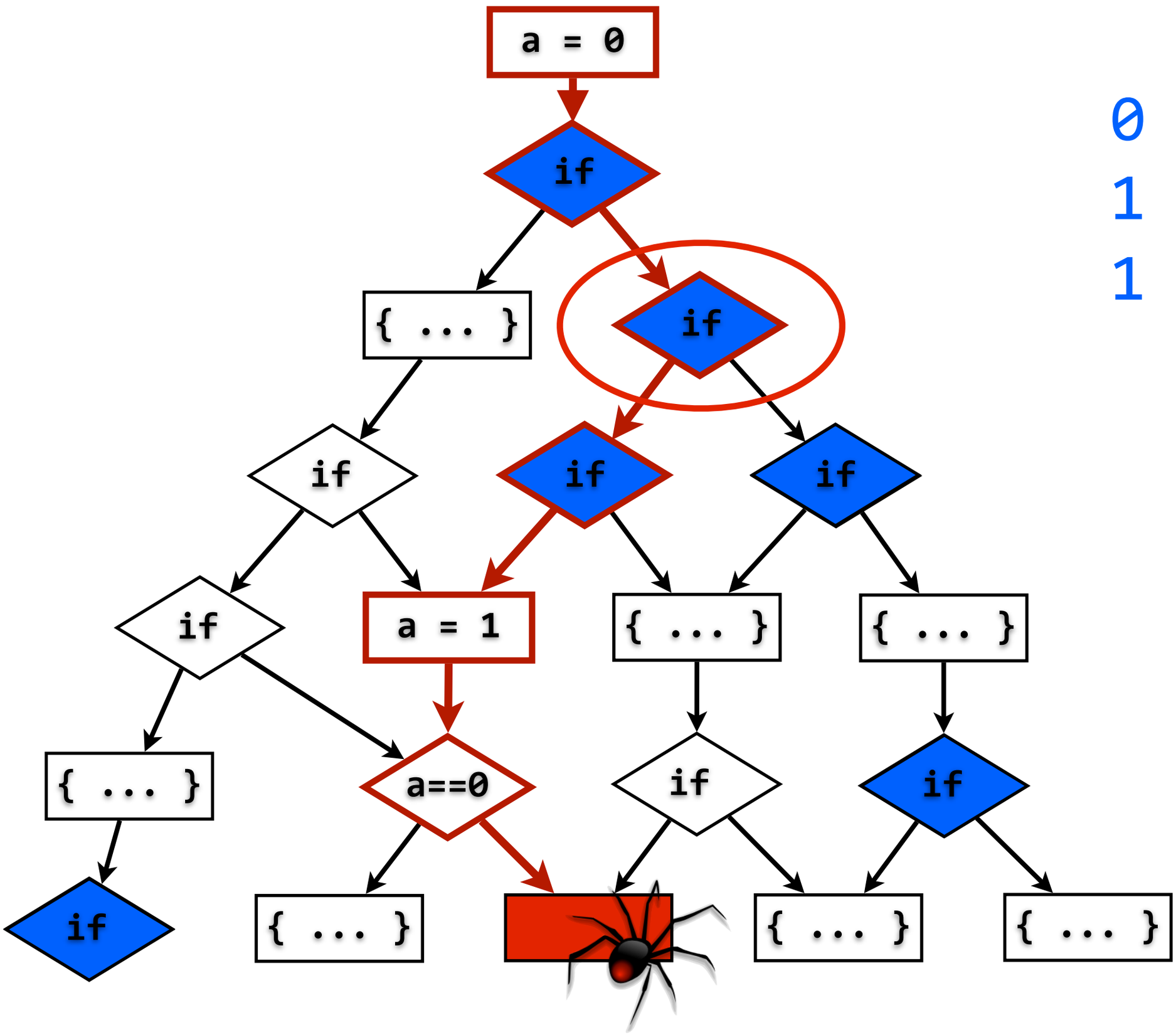

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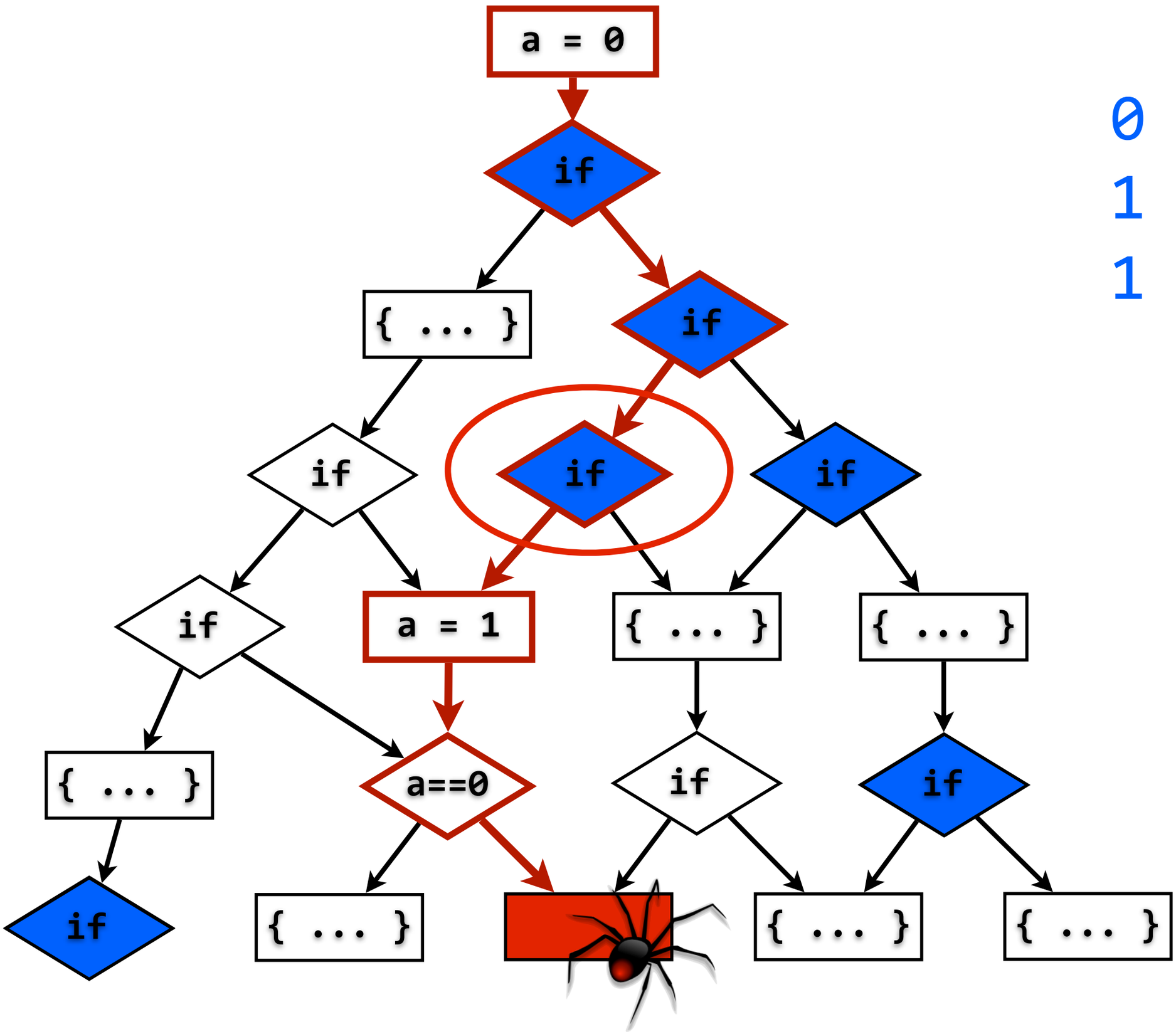

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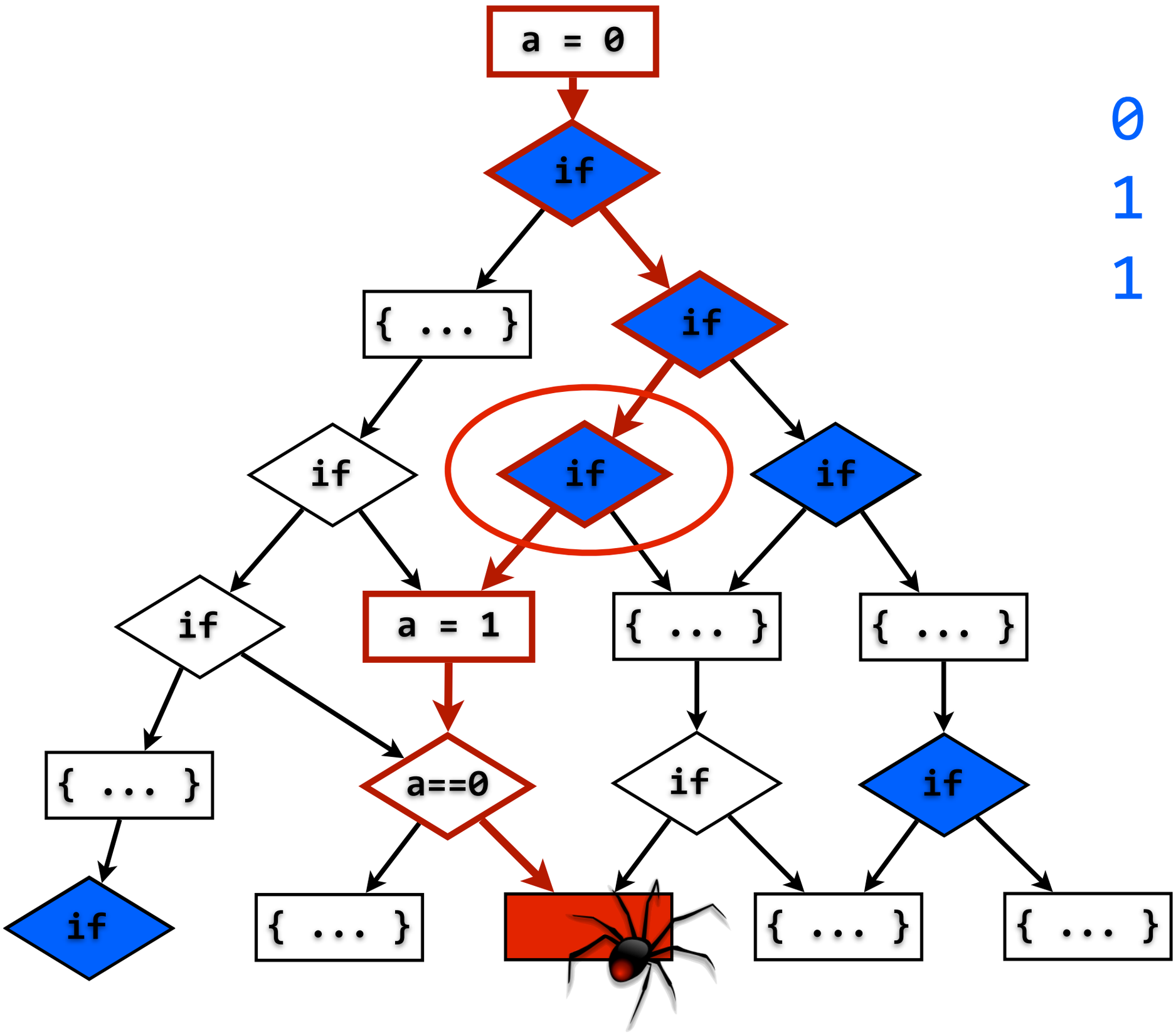

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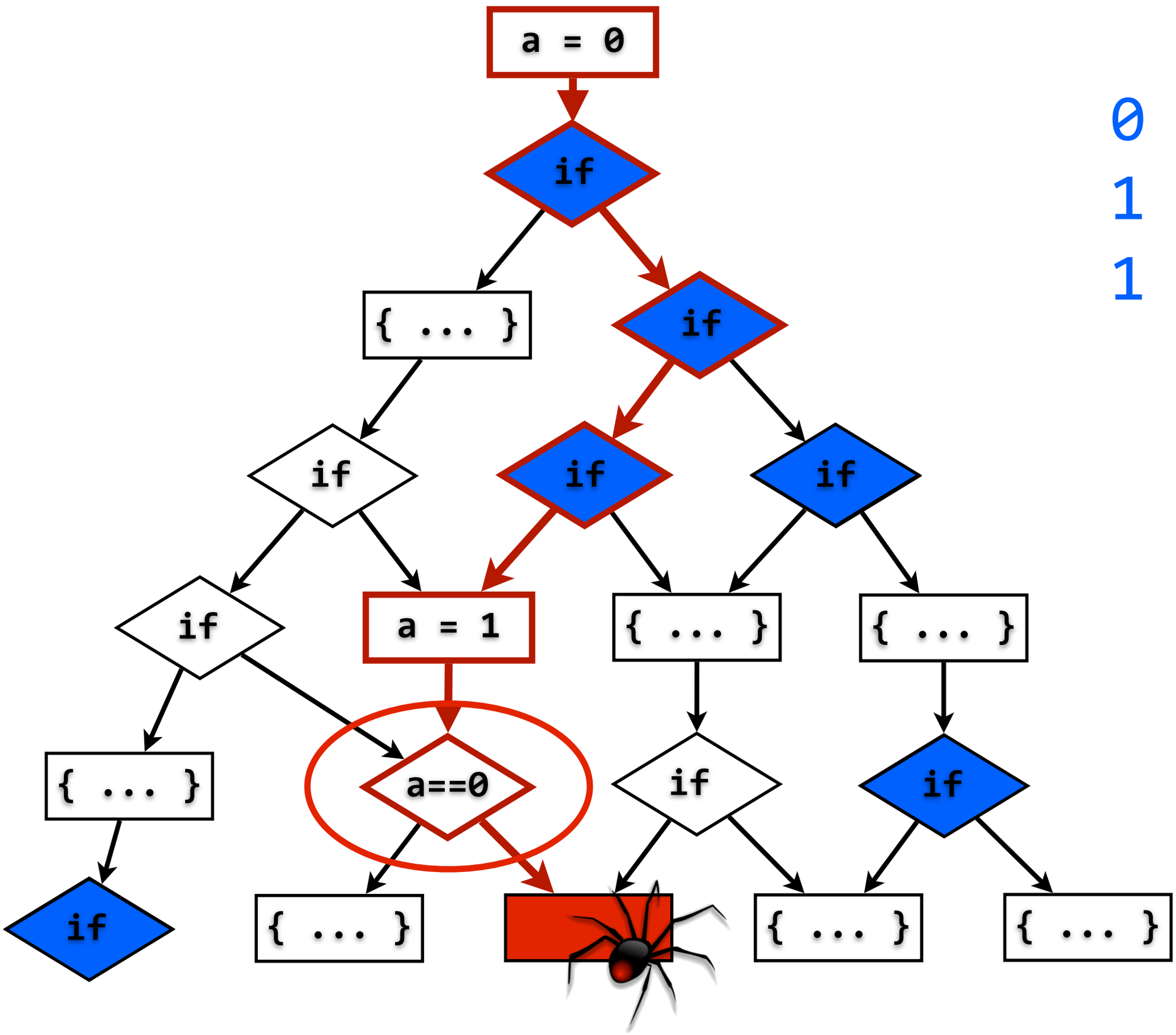

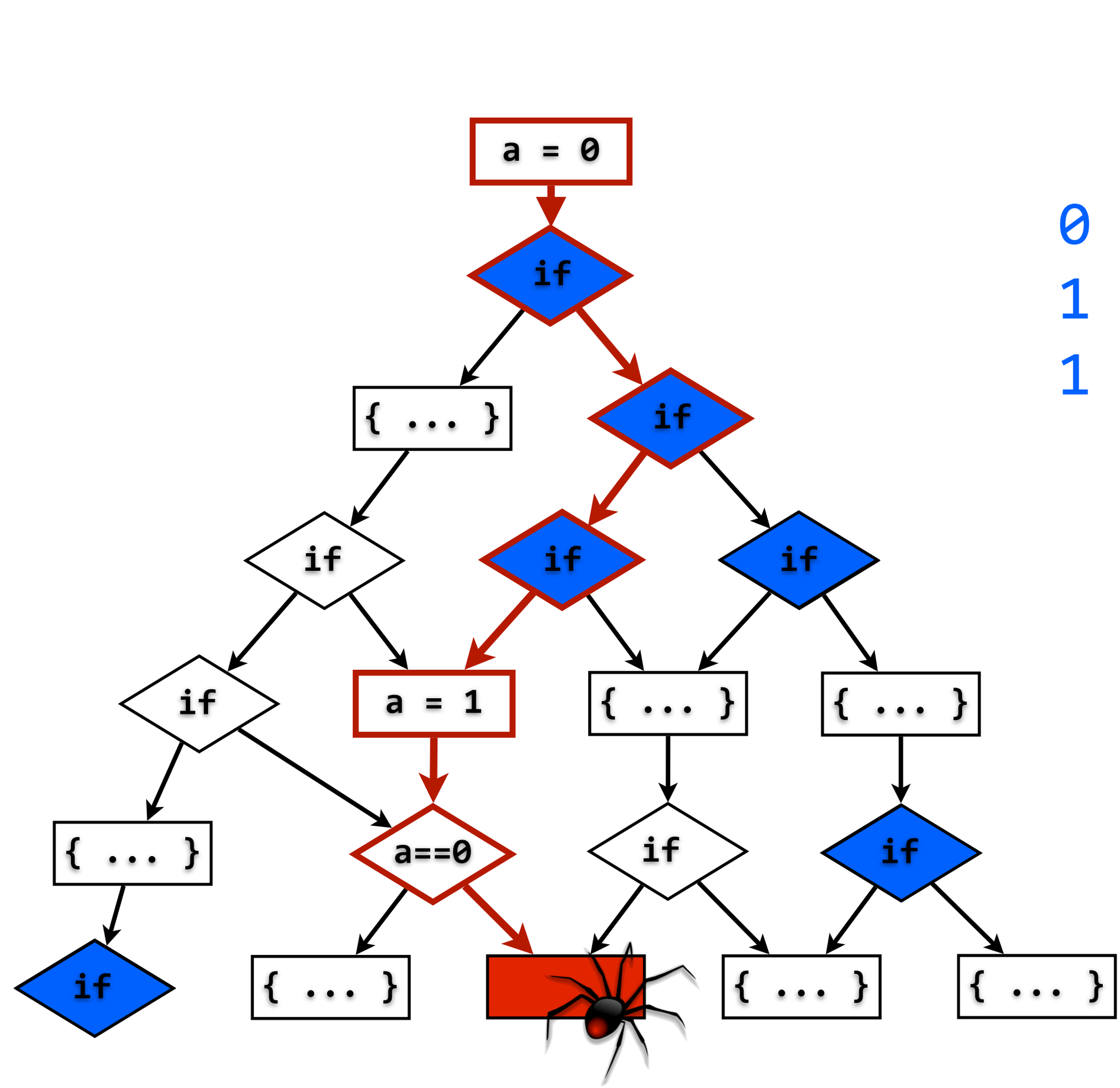

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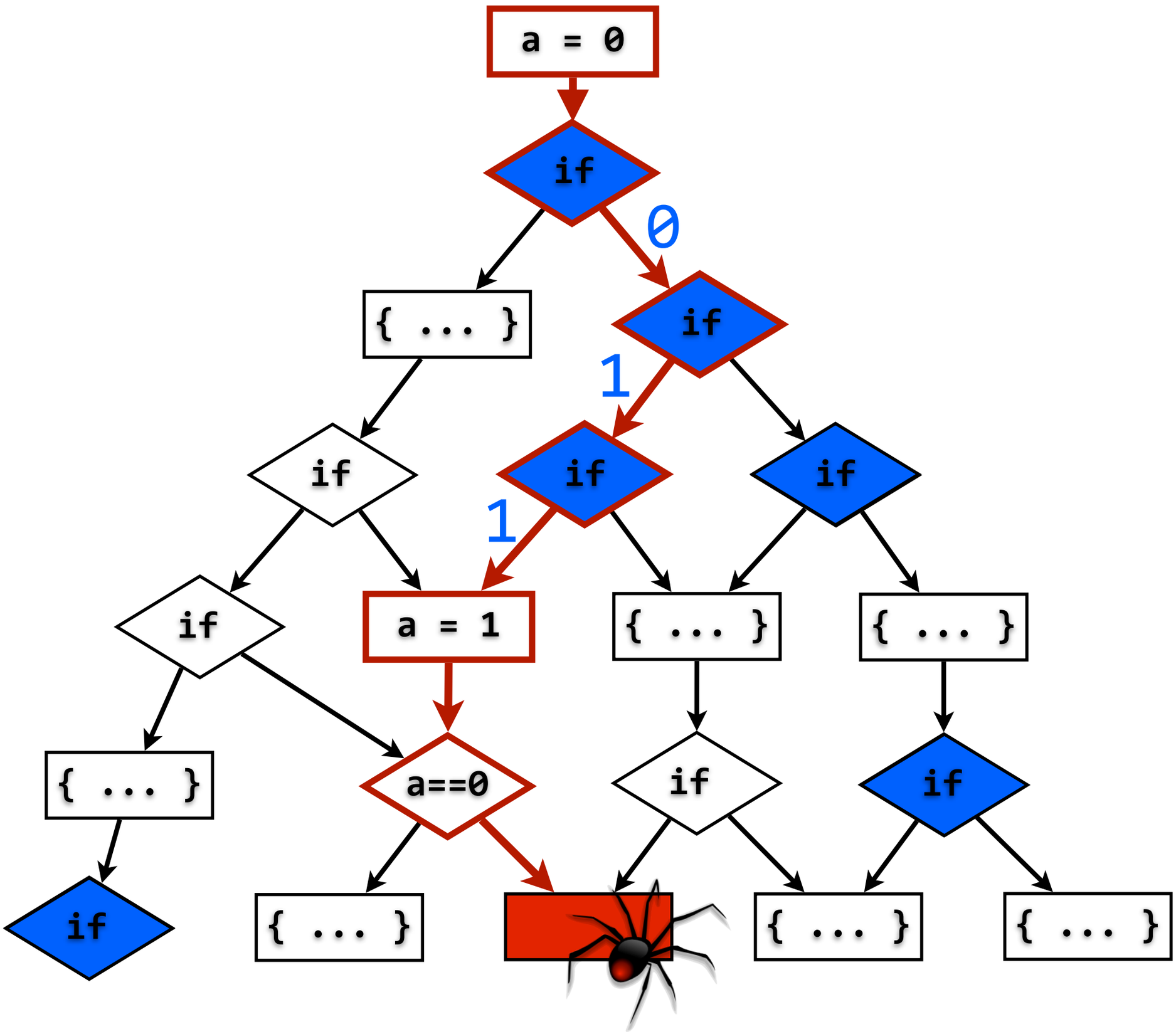
Dealing with approximations

Dealing with approximations

- Too many branches instrumented:
  - ✦ increased overhead

Dealing with approximations

- Too many branches instrumented:
  - ✦ increased overhead
- Too few branches instrumented
  - ✦ Branch log does not define a single path anymore
  - ✦ Replay must search every possible path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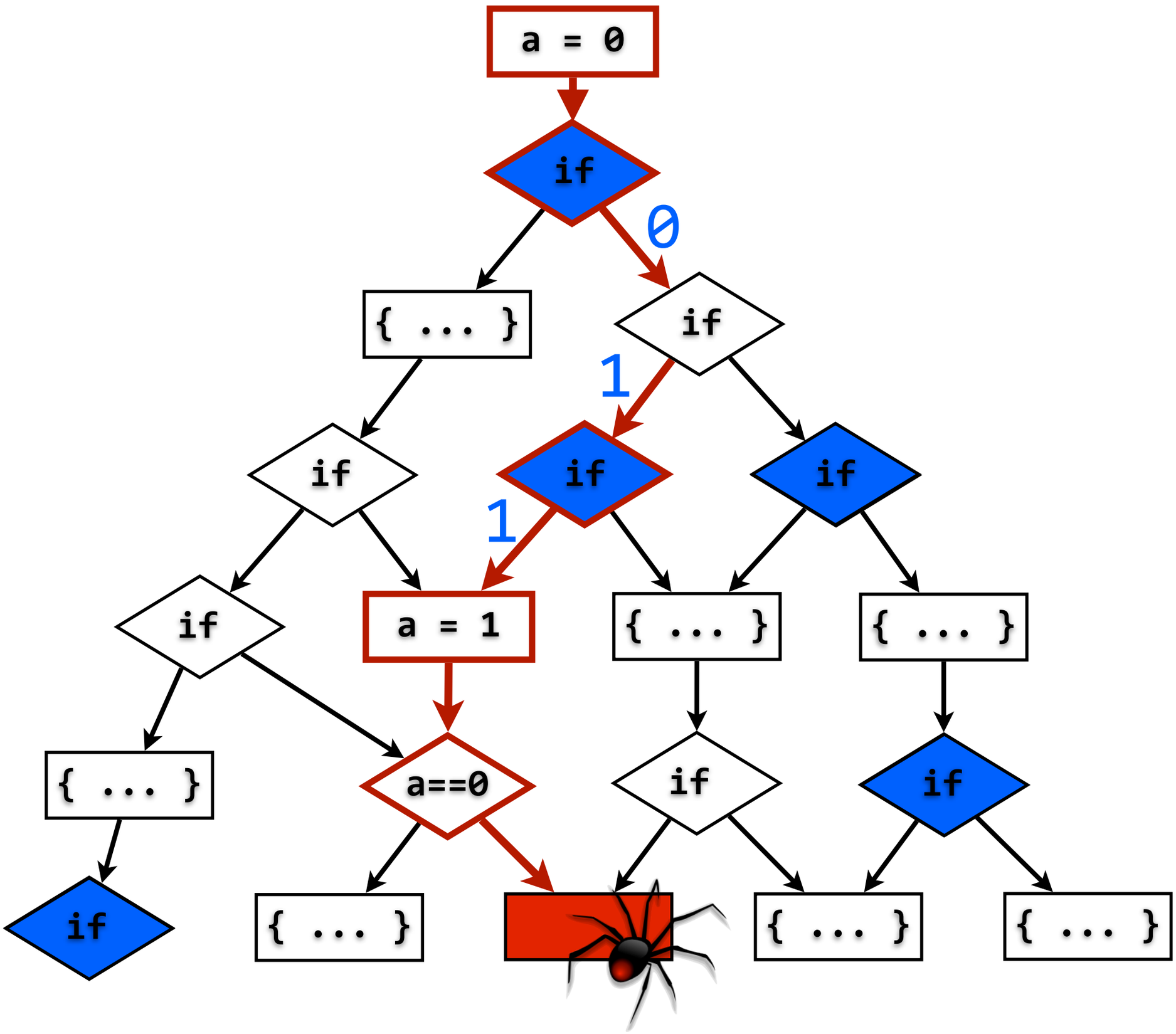
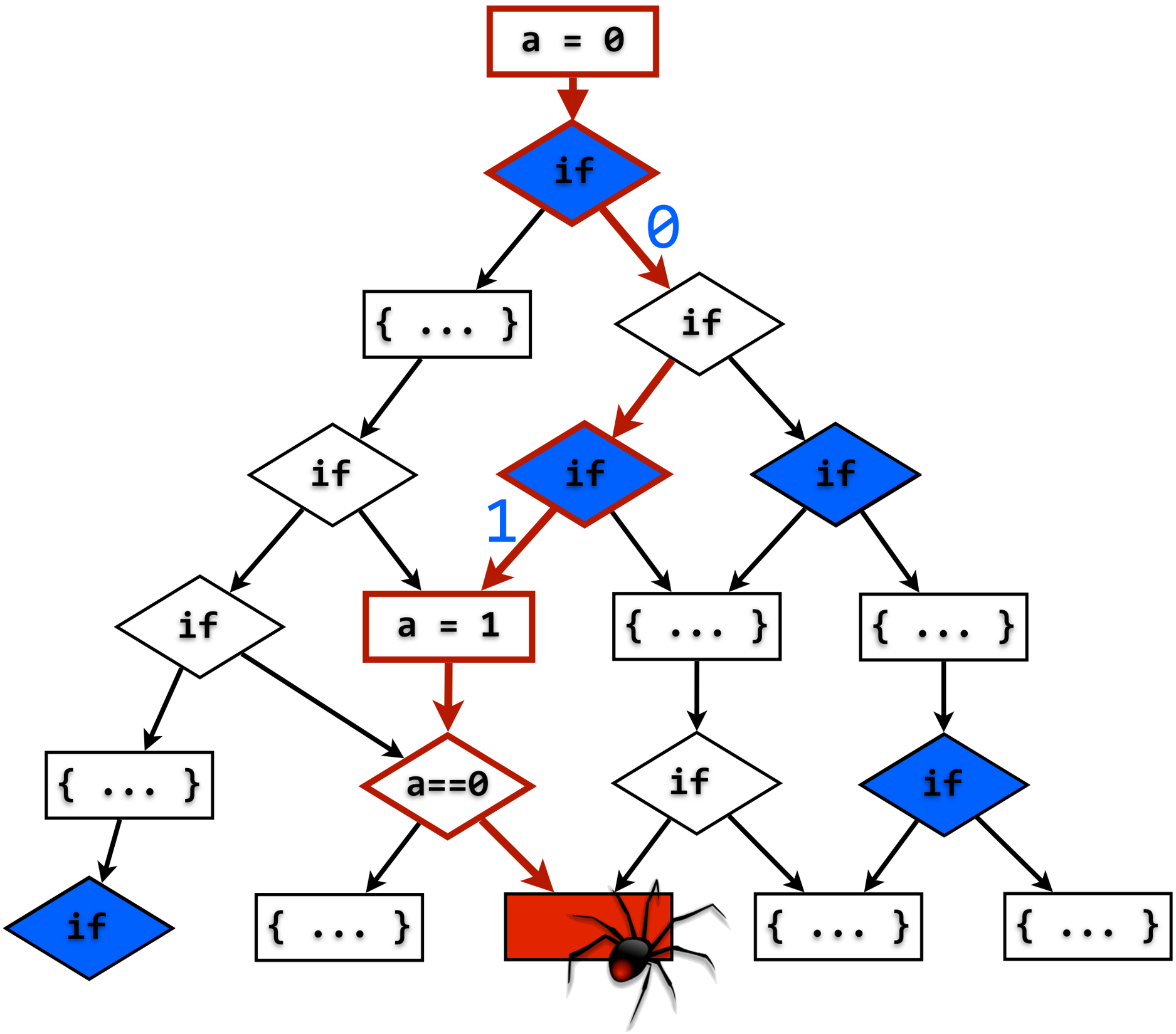
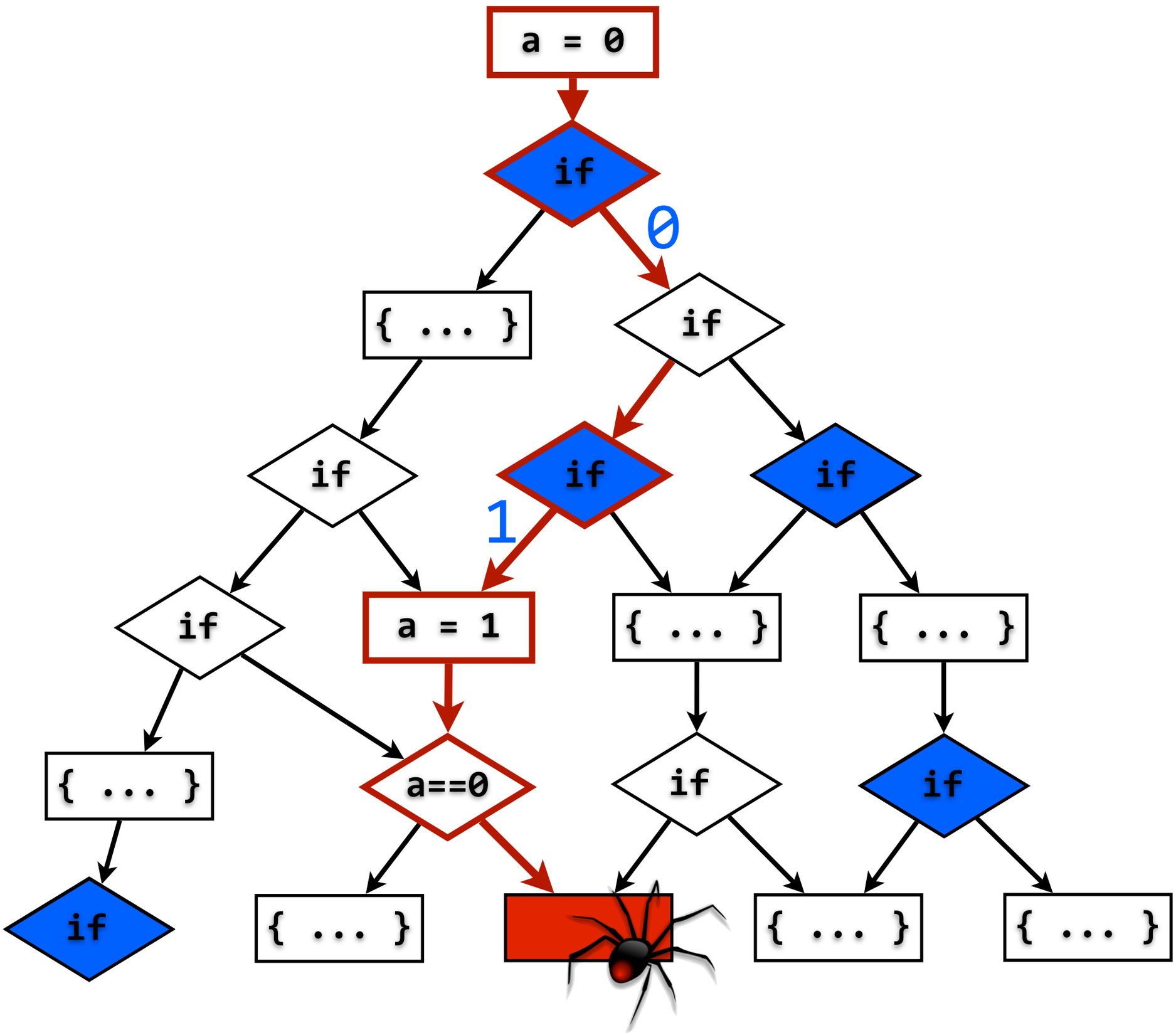
if
0
{ ... }
if
1
if
if
if
1
if
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }

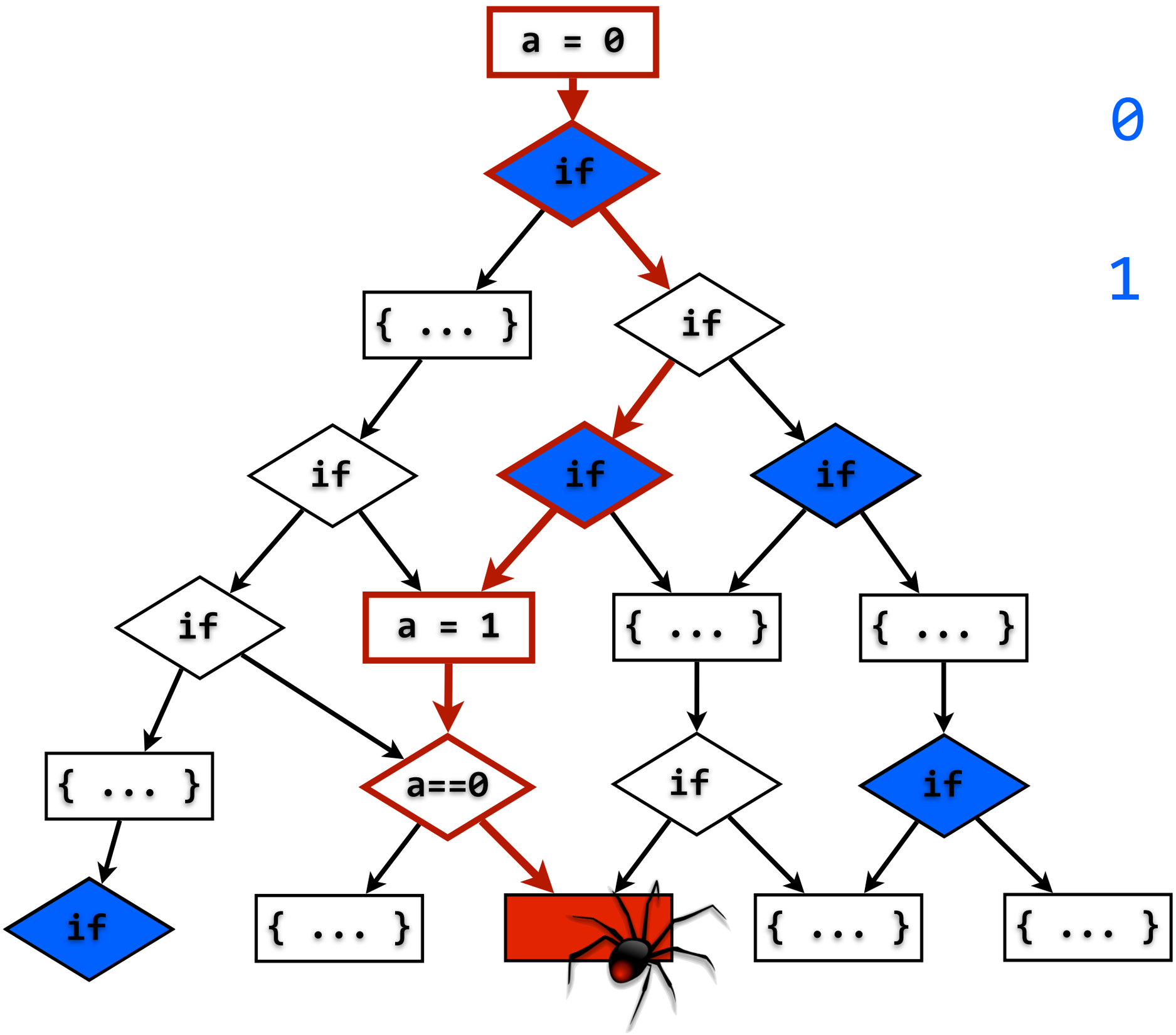

a = 0
if
0
{ ... }
if
1
if
if
if
1
if
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }


a = 0
if
0
{ ... }
if
if
if
if
1
a = 1
{ ... }
{ ... }
if
{ ... }
a==0
if
if
{ ... }
{ ... }
{ ... }
{ ... }


a = 0
if
0
{ ... }
if
if
if
if
1
a = 1
{ ... }
{ ... }
if
a==0
if
if
{ ... }
{ ... }
{ ... }
{ ... }

0

1



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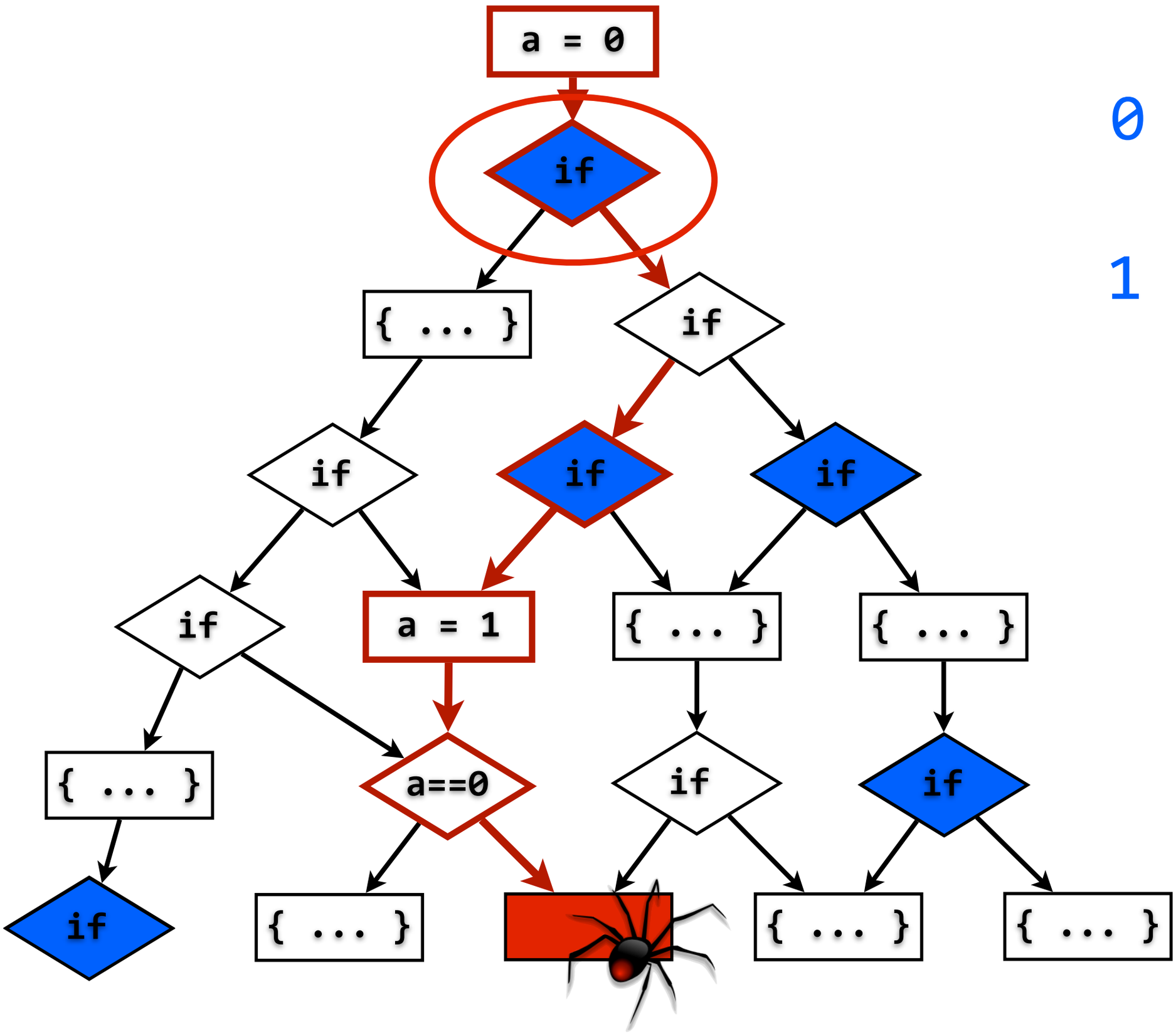
1



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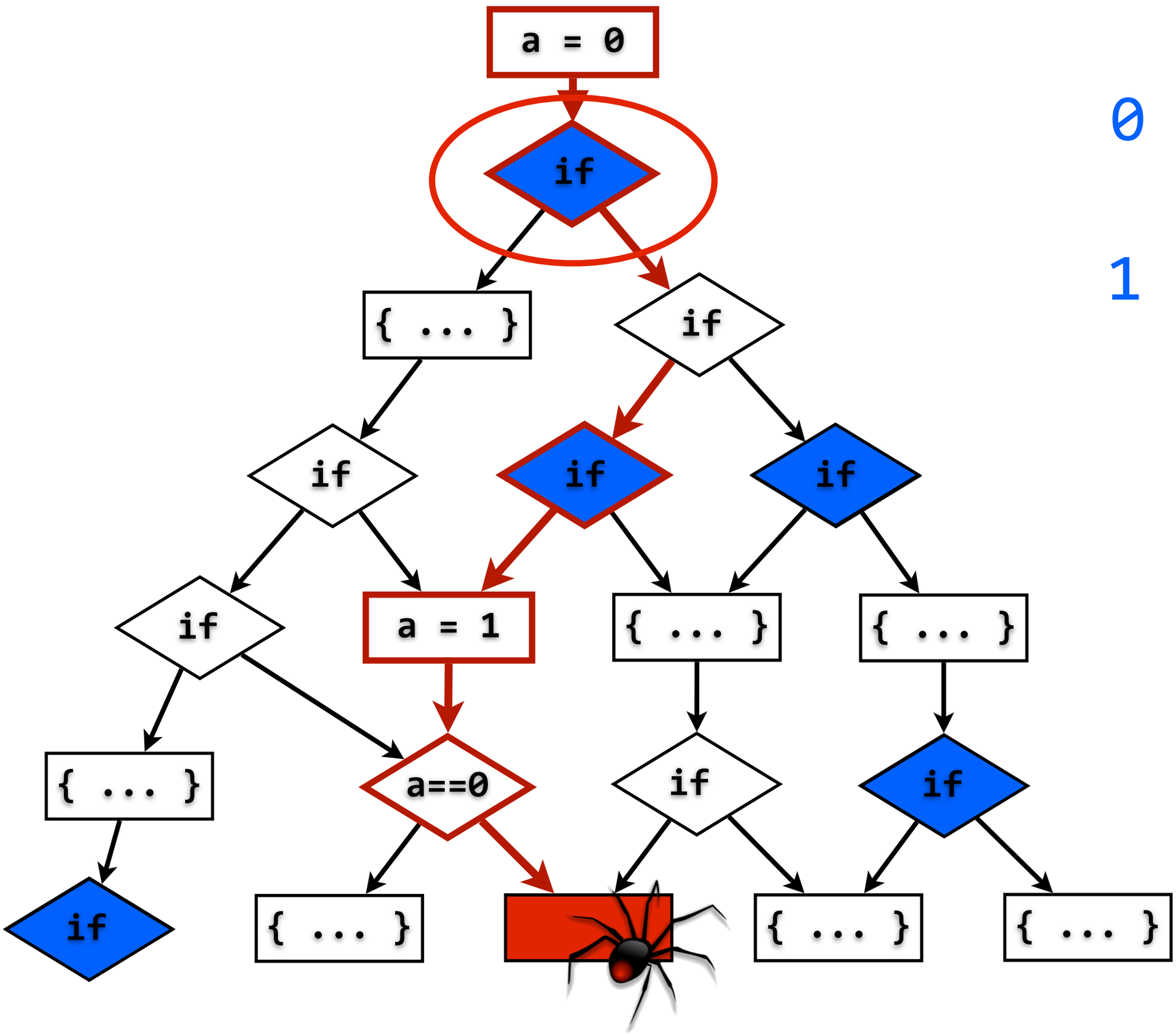
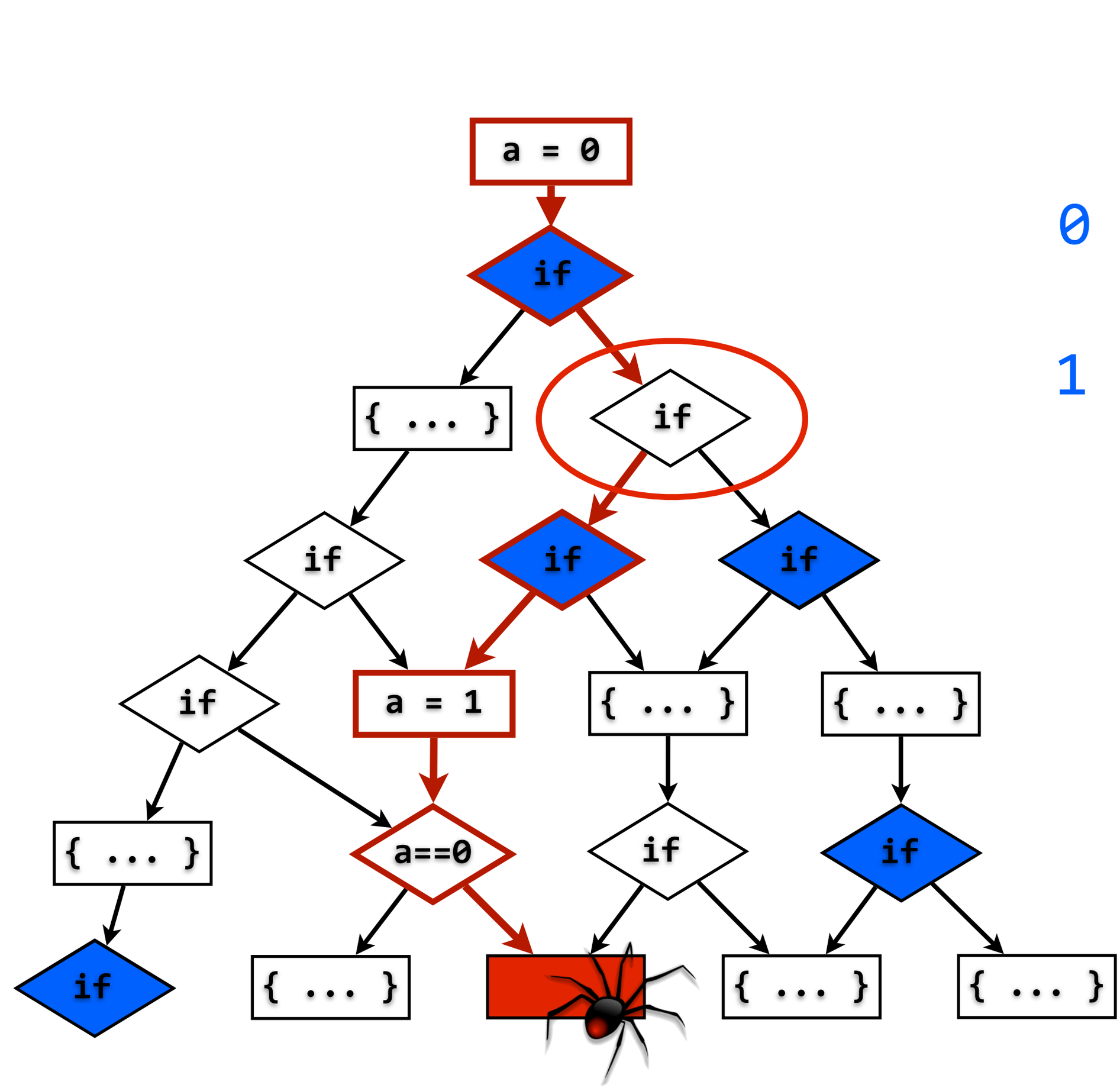
1





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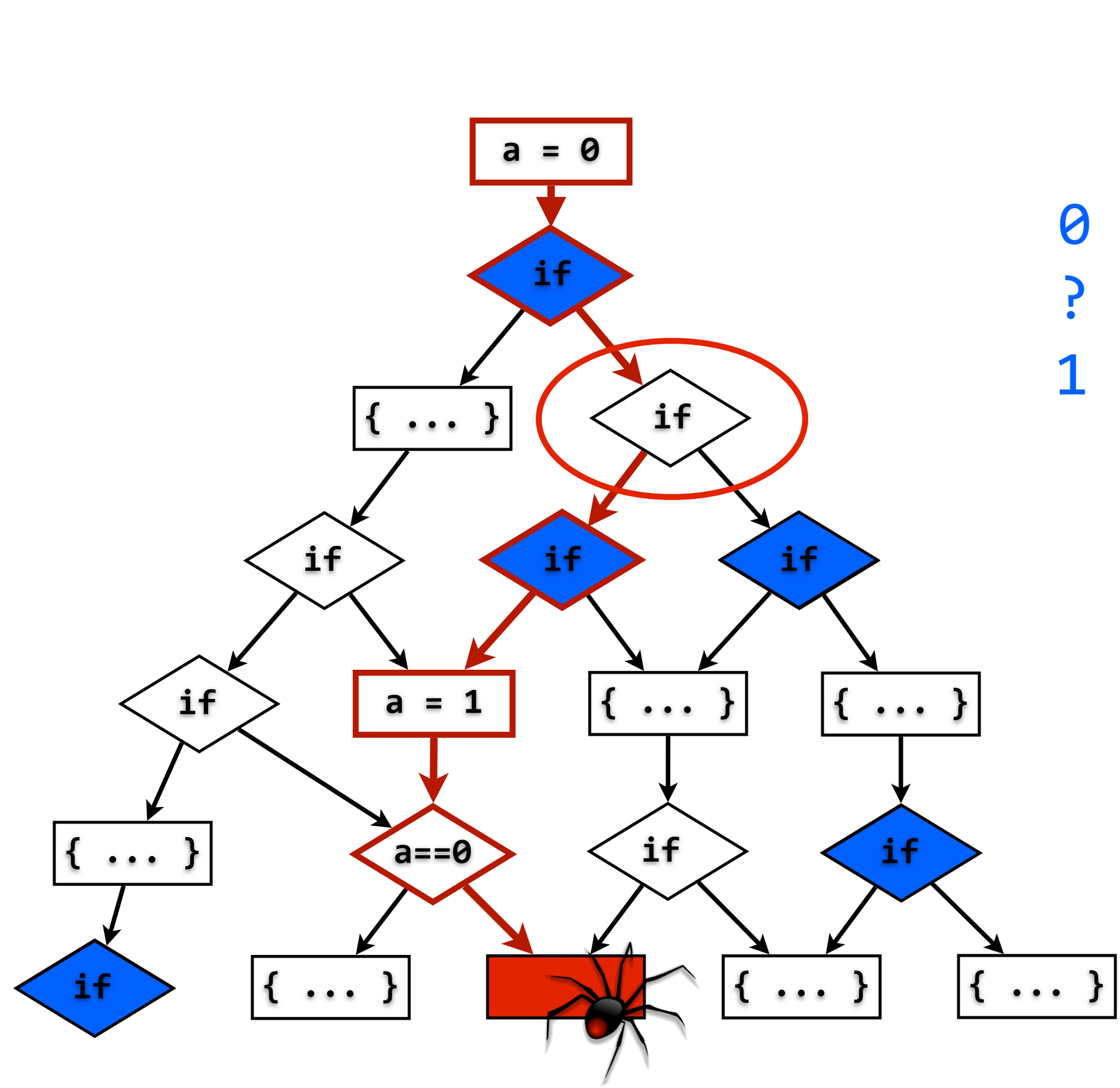

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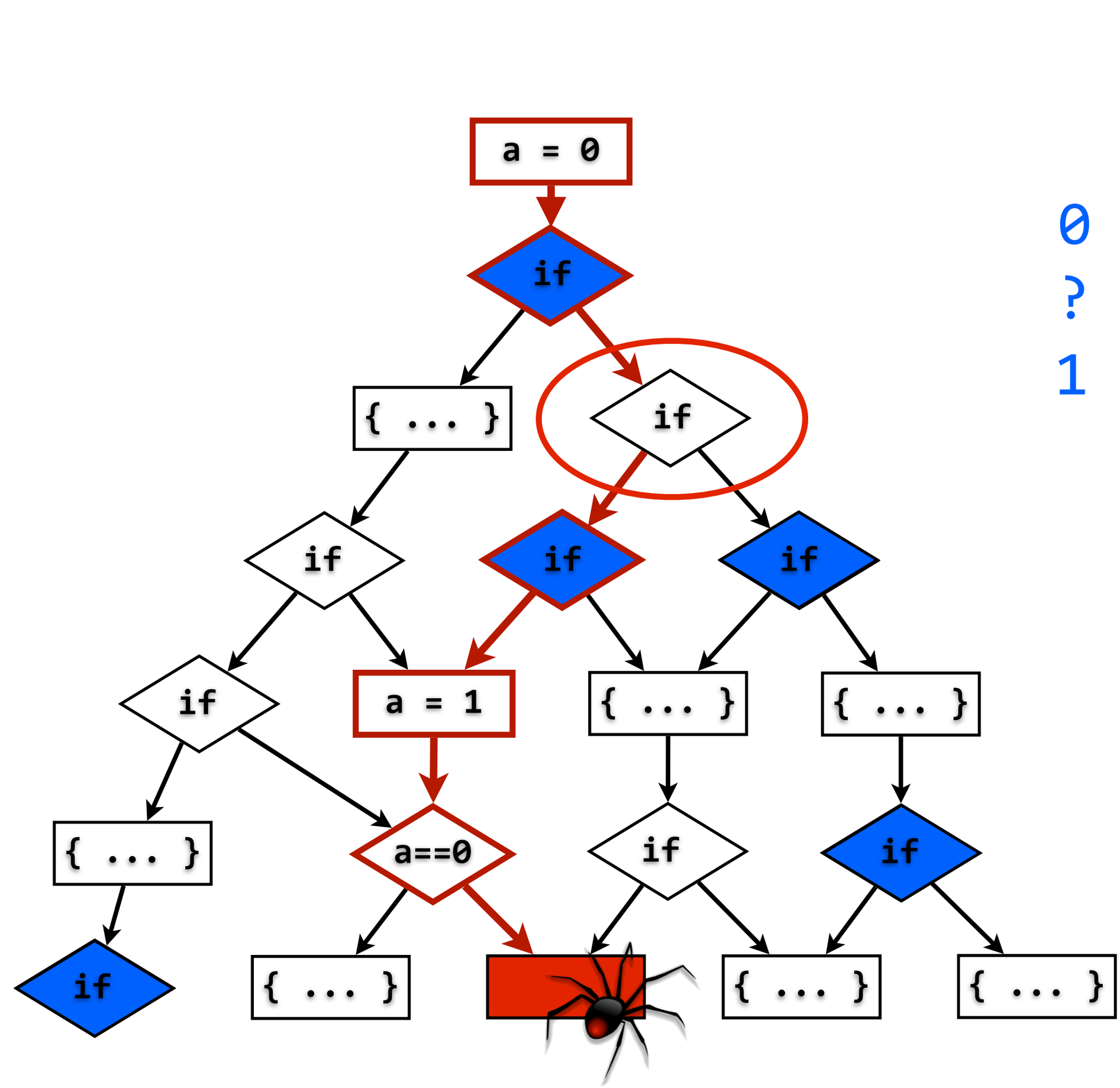
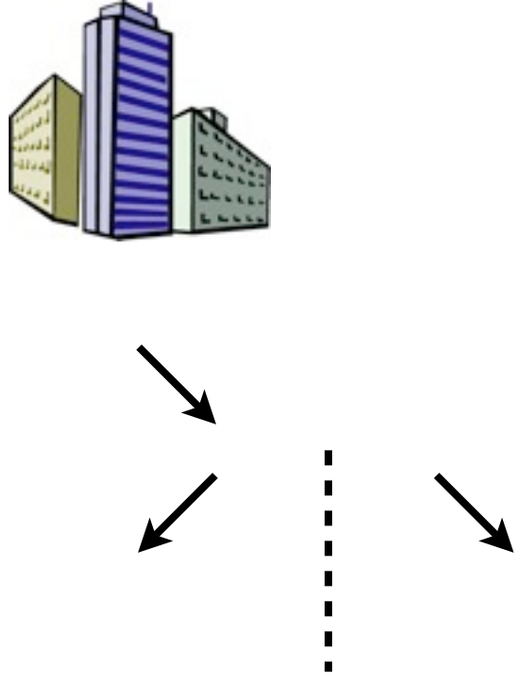

a = 0
if
{ ... }
if
if
if
if
if
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }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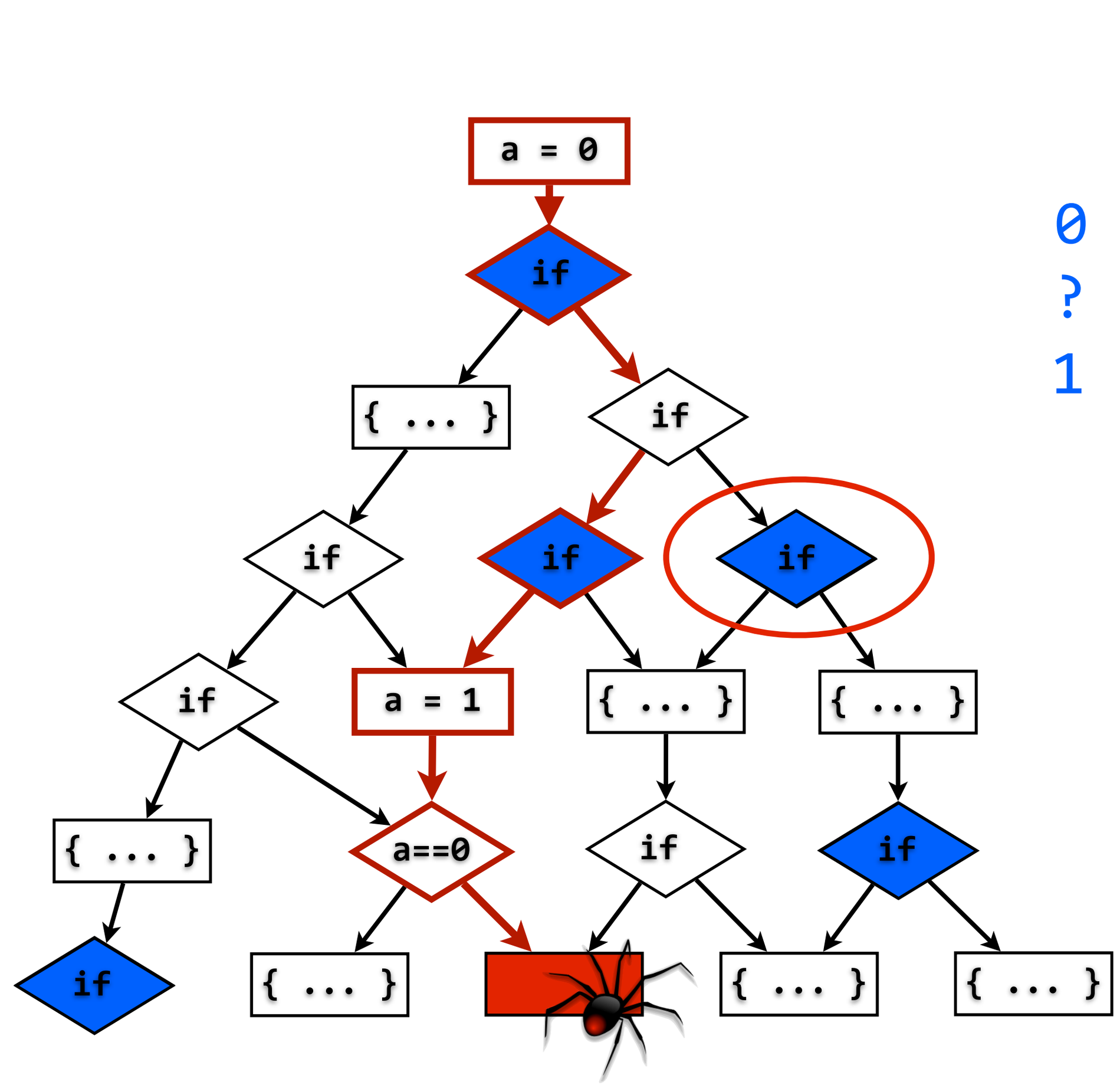
a = 0
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a = 1
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a==0
if
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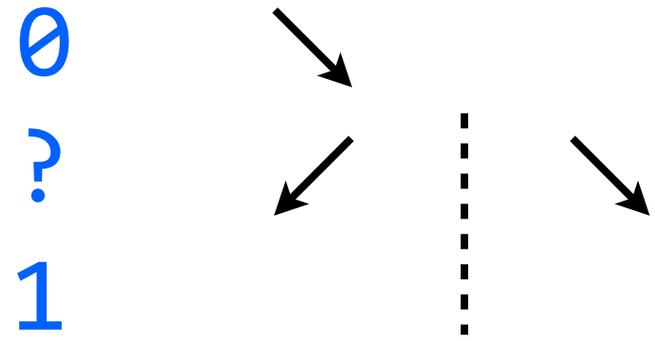
{ ... }
{ ... }
{ ... }
{ ... }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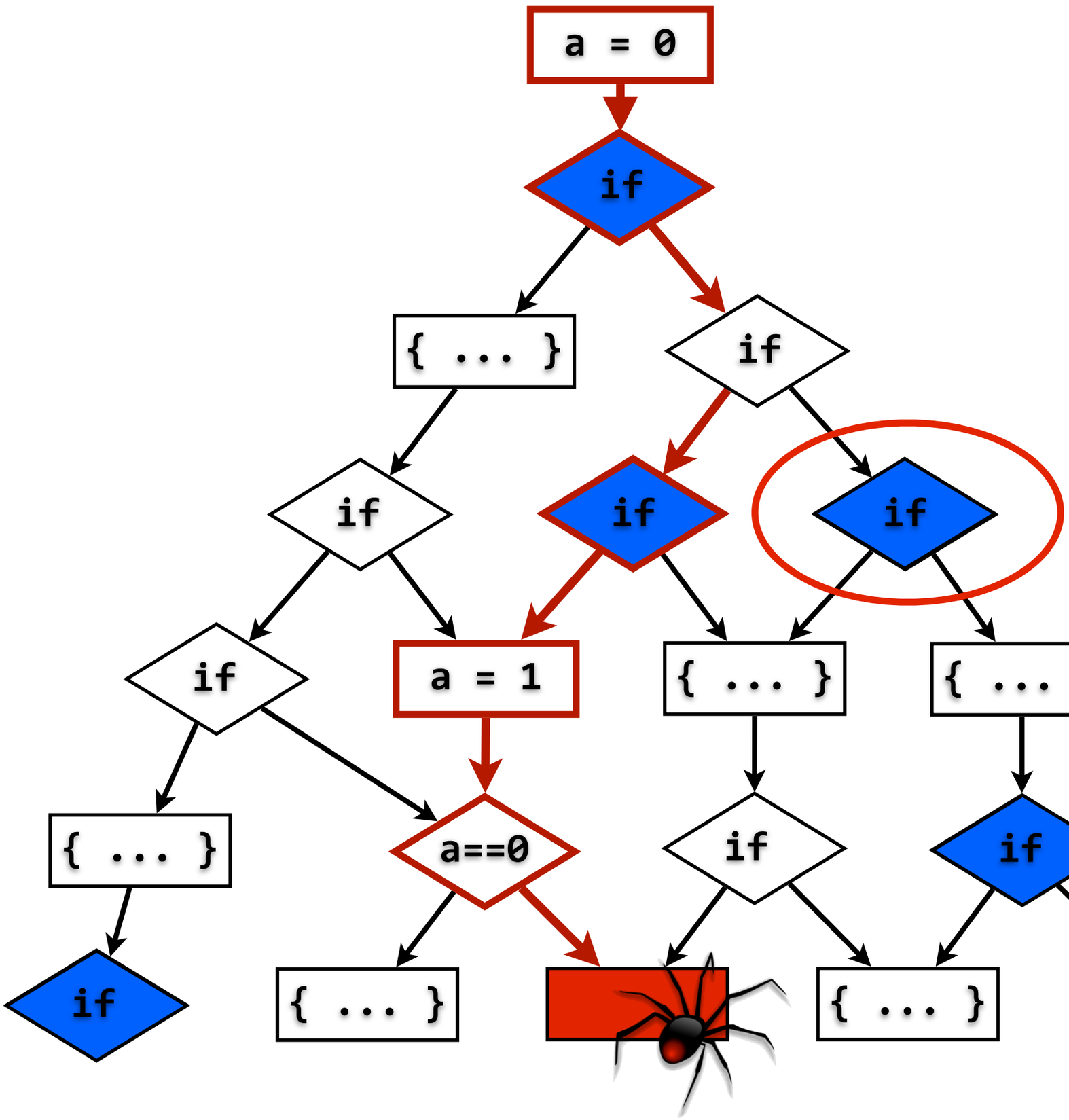
a = 0
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a = 1
{ ... }
{ ... }
{ ... }
a==0
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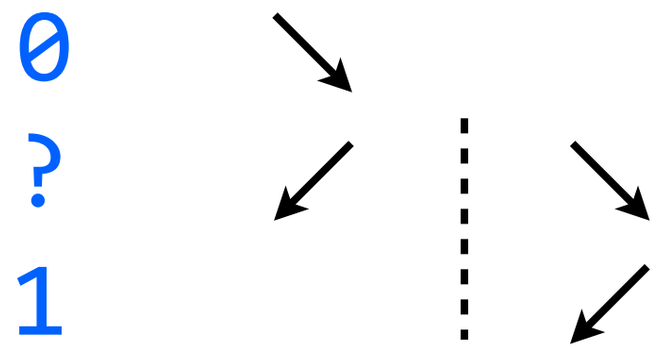
if
{ ... }
{ ... }
{ ... }
{ ... }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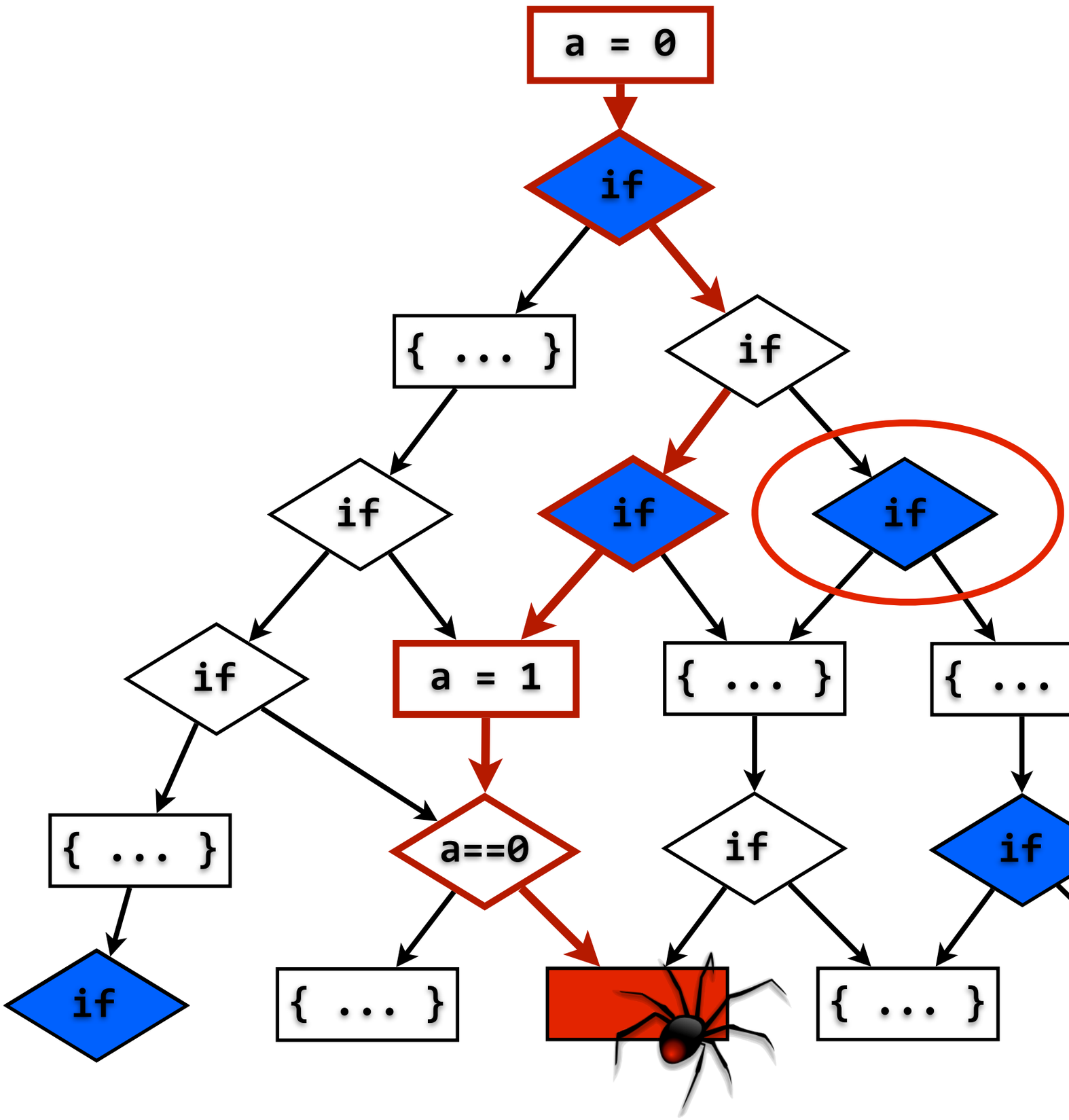
a = 0
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{ ... }
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a = 1
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a==0
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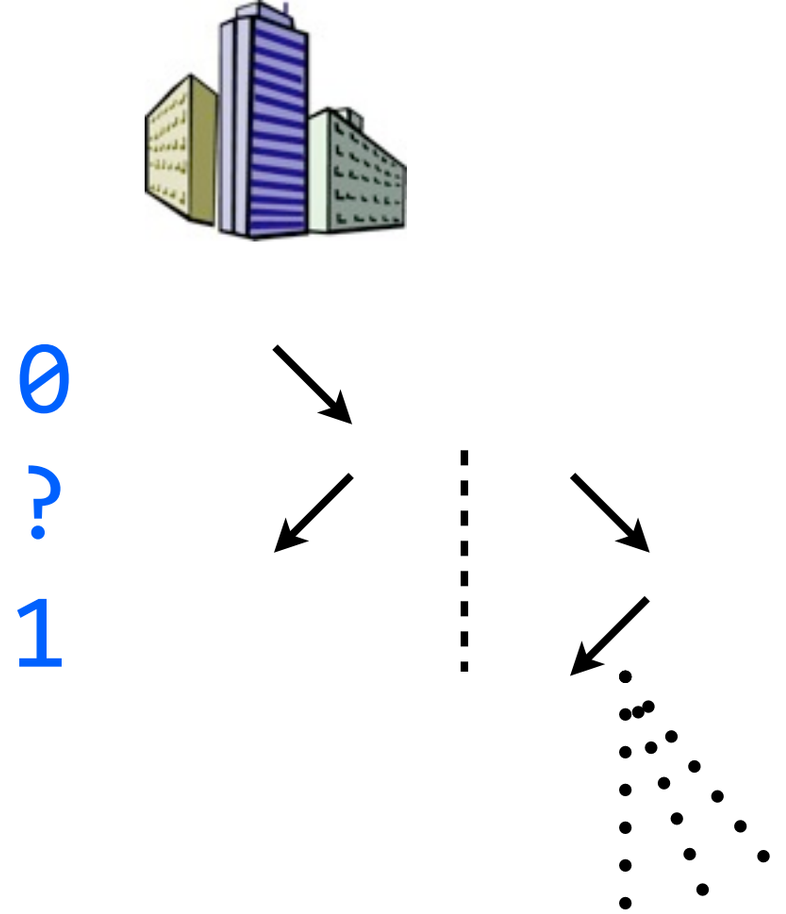
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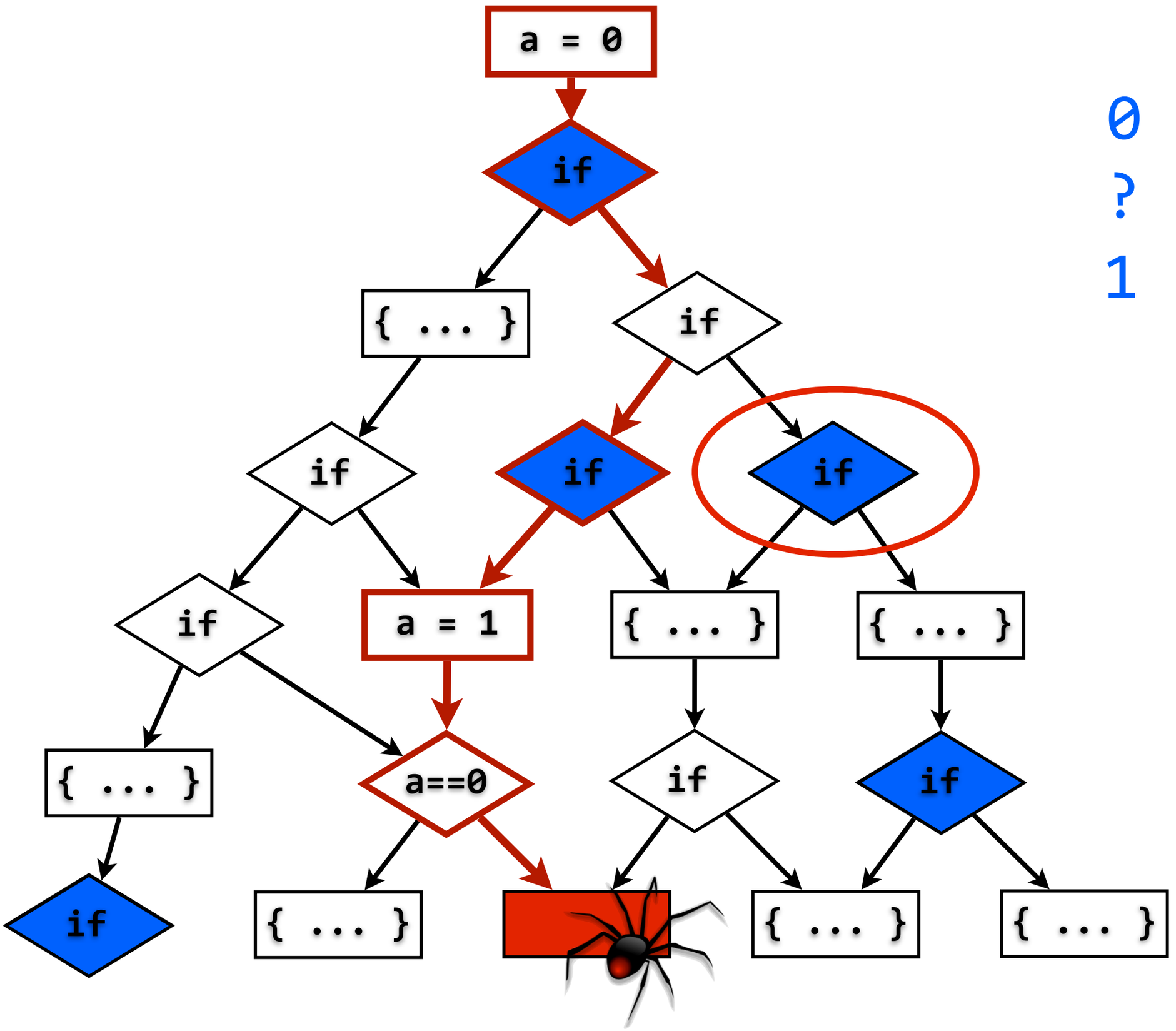
a = 0
if
{ ... }
if
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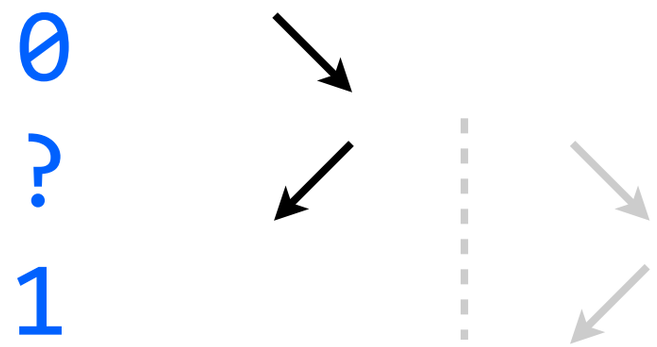
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }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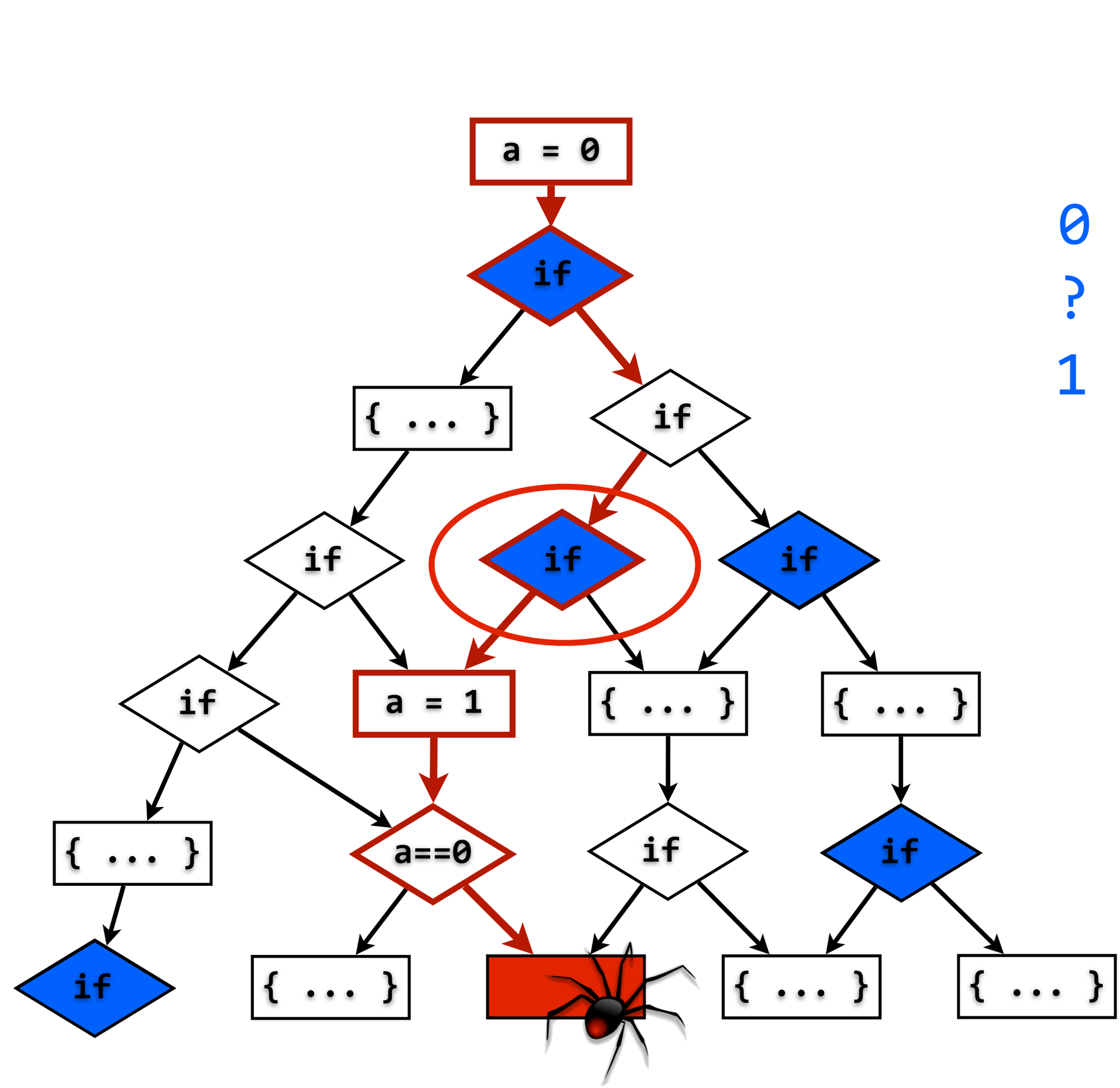
a = 0
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{ ... }
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a = 1
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{ ... }
{ ... }
a==0
if
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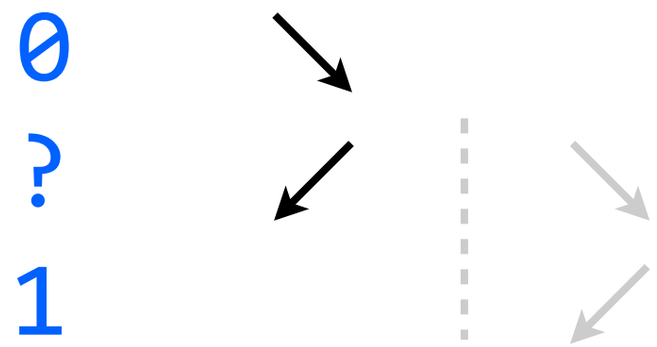
if
{ ... }
{ ... }
{ ... }
{ ... }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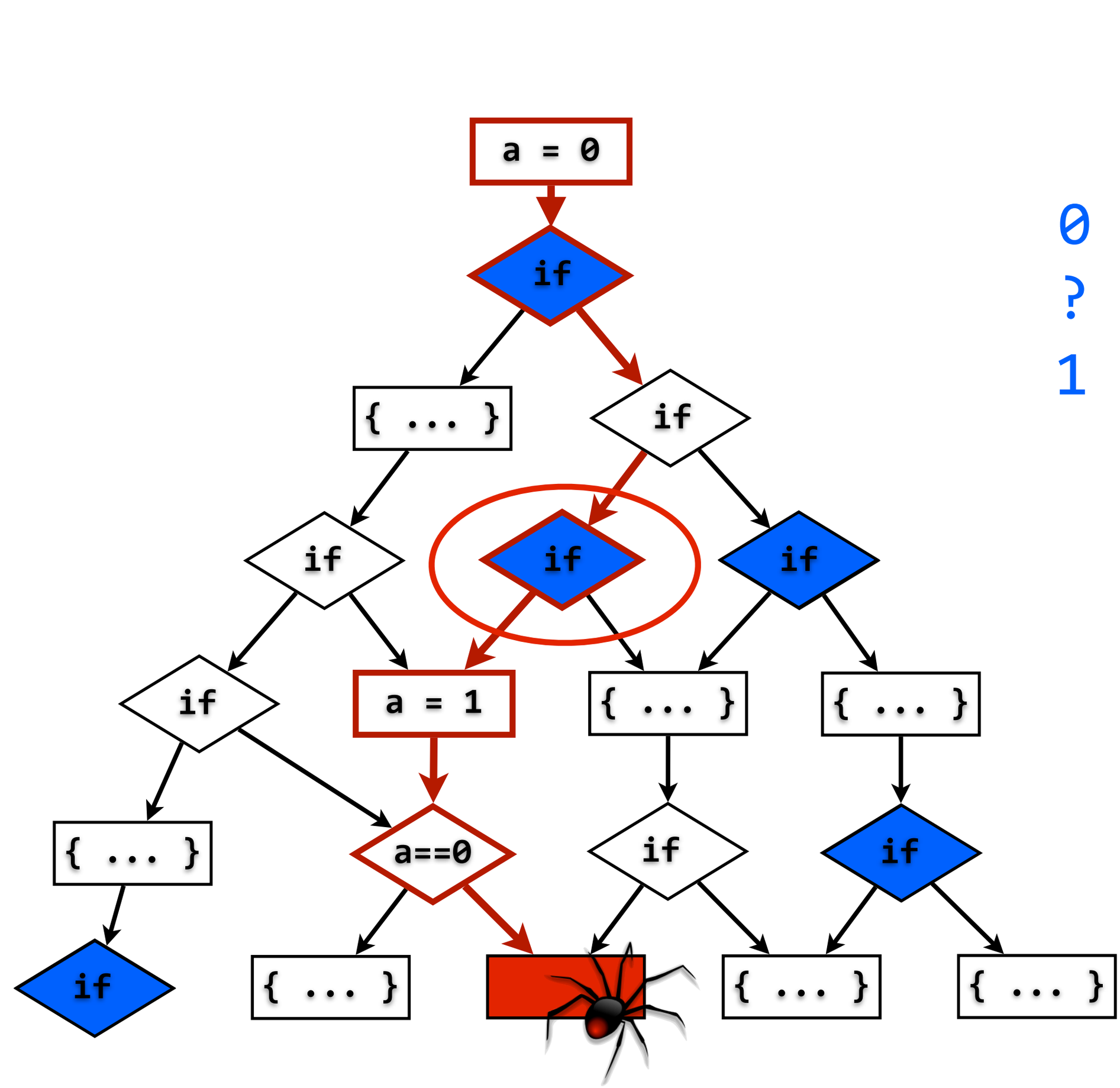
a = 0
if
{ ... }
if
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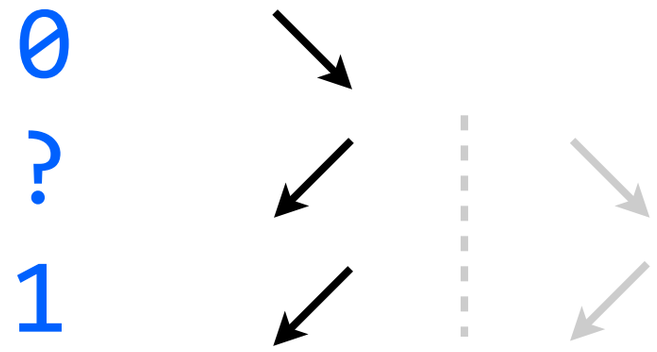
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }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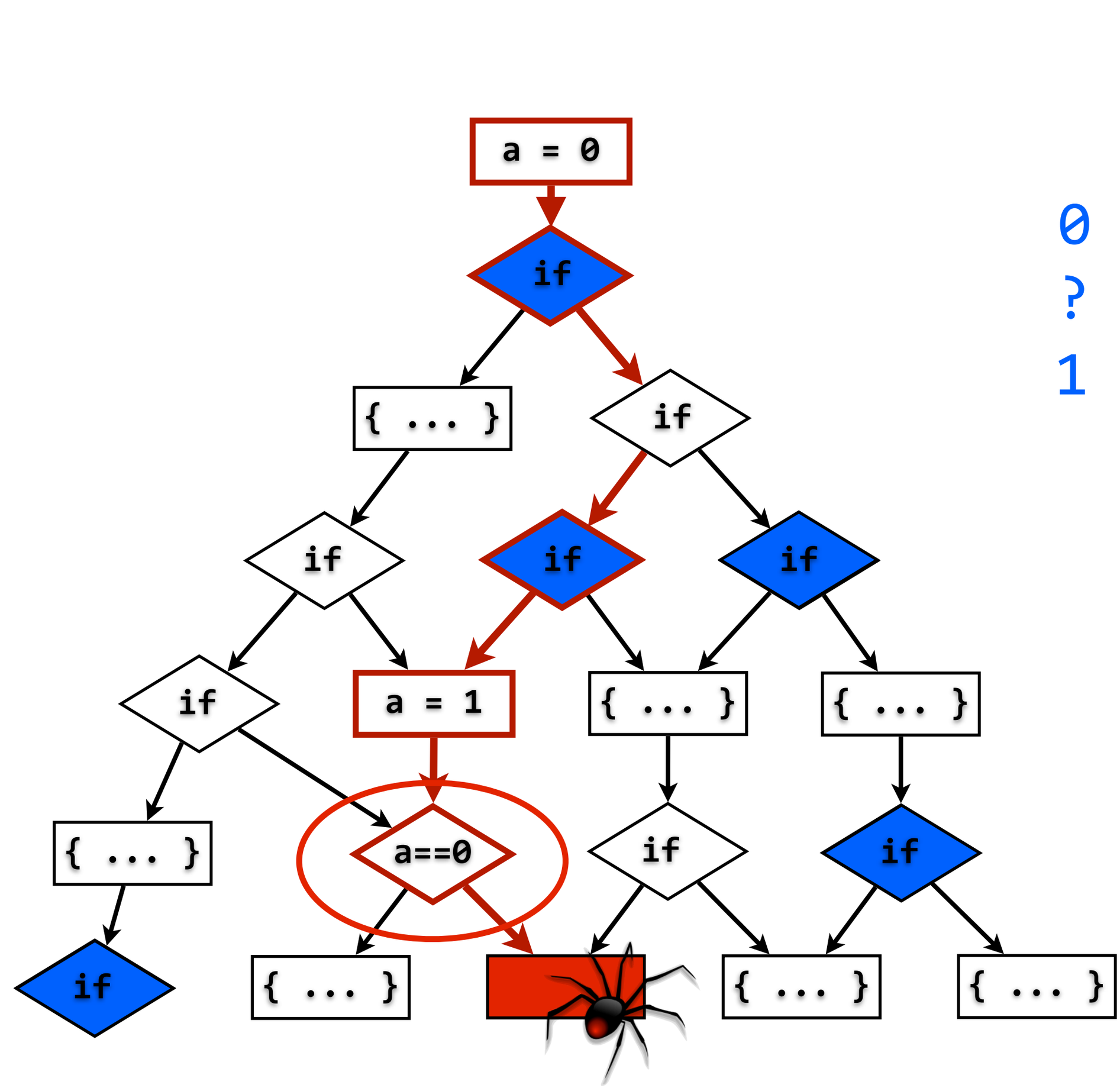
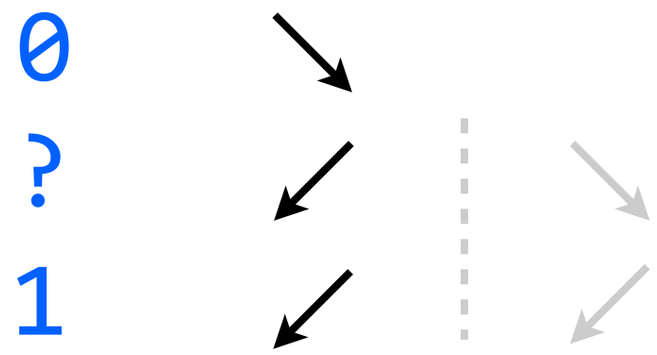

a = 0
if
{ ... }
if
if
if
if
if
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }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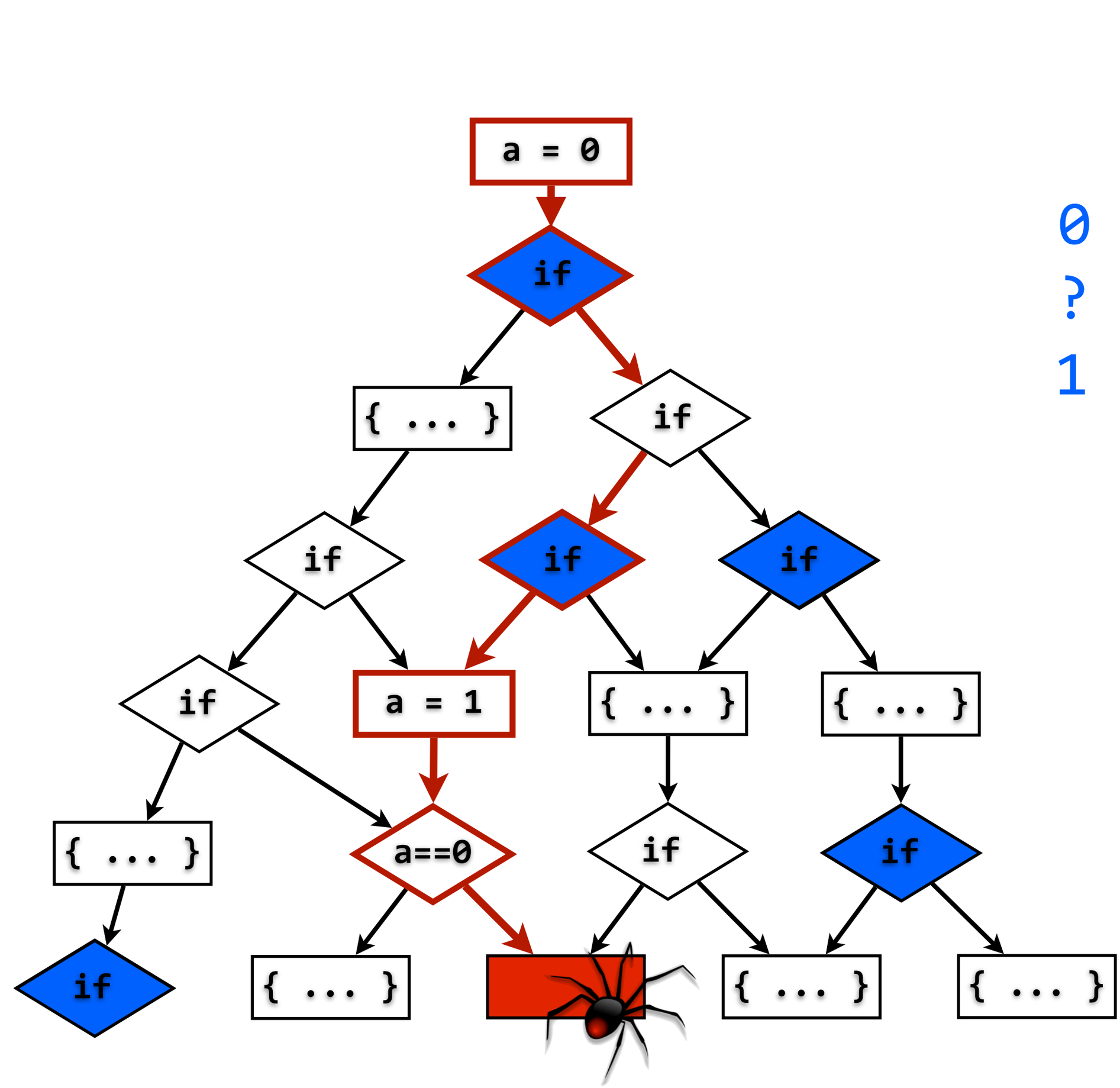
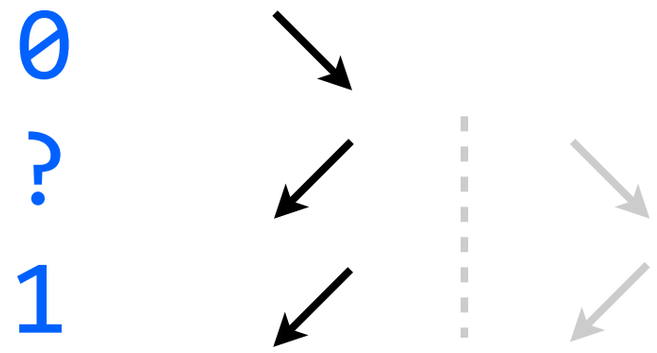

a = 0
if
{ ... }
if
if
if
if
if
a = 1
{ ... }
{ ... }
{ ... }
a==0
if
if
if
{ ... }
{ ... }
{ ... }
{ ... }


0
?
1

0
?
1

a = 0
if
{ ... }
if
{ ... }
if
a==0
{ ... }
if
{ ... }
if
{ ... }

Possibly many paths to search
Back-tracking slows down replay considerably

Dealing with non-determinism (1)

Dealing with non-determinism (1)

- Non-deterministic events:
  - system calls, thread scheduling, ...
  - influence program execution

Dealing with non-determinism (1)

- Non-deterministic events:
  - system calls, thread scheduling, ...
  - influence program execution
- Choice:
  - log and replay event
  - do not log and infer solution during replay

Dealing with non-determinism (2)

Dealing with non-determinism (2)

- Non-determinism in system calls:

Dealing with non-determinism (2)

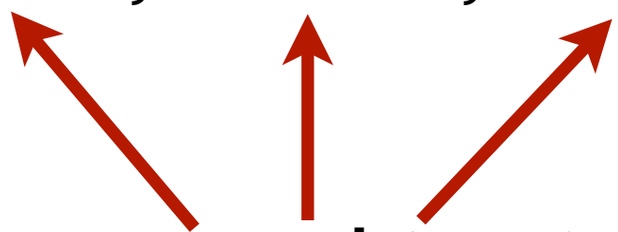
- Non-determinism in system calls:

```
select(n, readfds, writefds, exceptfds, timeout) ;
```

Dealing with non-determinism (2)

- Non-determinism in system calls:

```
select(n, readfds, writefds, exceptfds, timeout) ;
```



Returns any combination of ready file descriptors

Implementation

Implementation

- Static Analysis algorithm:
  - ✦ uses CIL [Necula 2002]

Implementation

- Static Analysis algorithm:
  - ✦ uses CIL [Necula 2002]
- Dynamic analysis and Replay:
  - ✦ Oasis symbolic execution engine

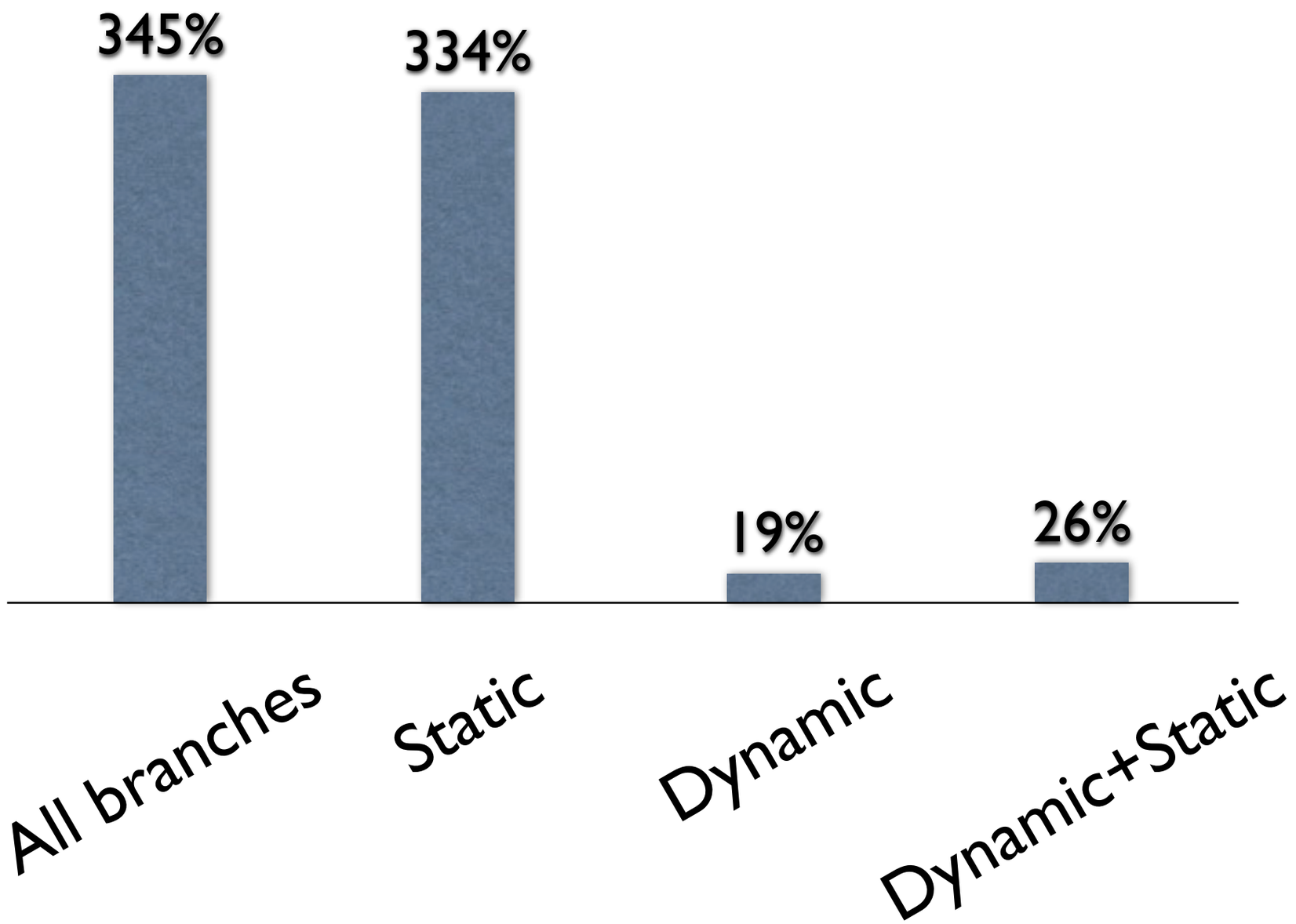
Implementation

- Static Analysis algorithm:
  - ✦ uses CIL [Necula 2002]
- Dynamic analysis and Replay:
  - ✦ Oasis symbolic execution engine
- Program (and libraries) instrumentation:
  - ✦ one bit per branch

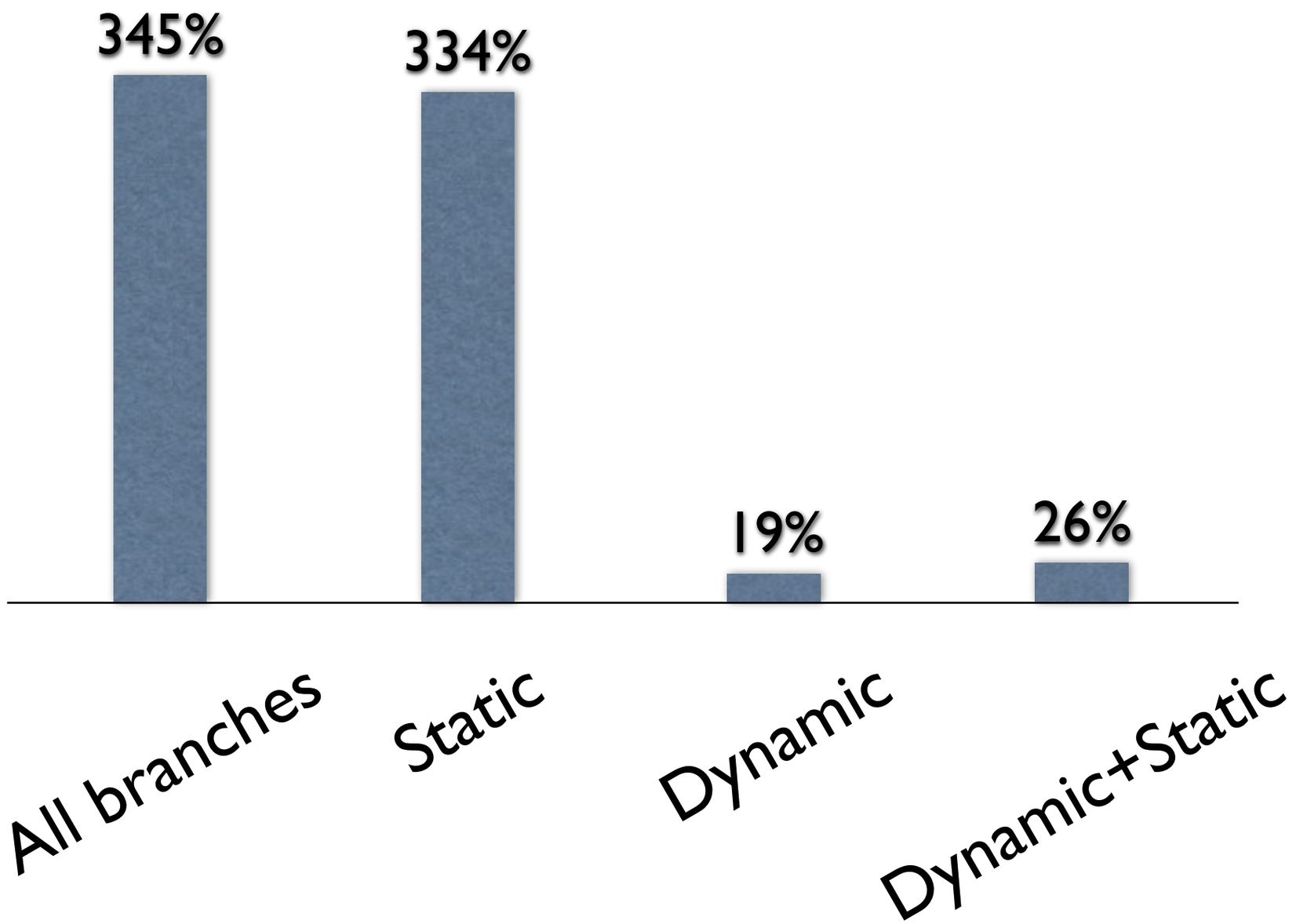
Evaluation

- Use micro-benchmarks and real programs:
  - ✦ uServer, web server (32 KLOC)
- Instrumentation performance:
  - ✦ CPU overhead
- Replay performance:
  - ✦ Replay time for specific input scenarios

CPU overhead



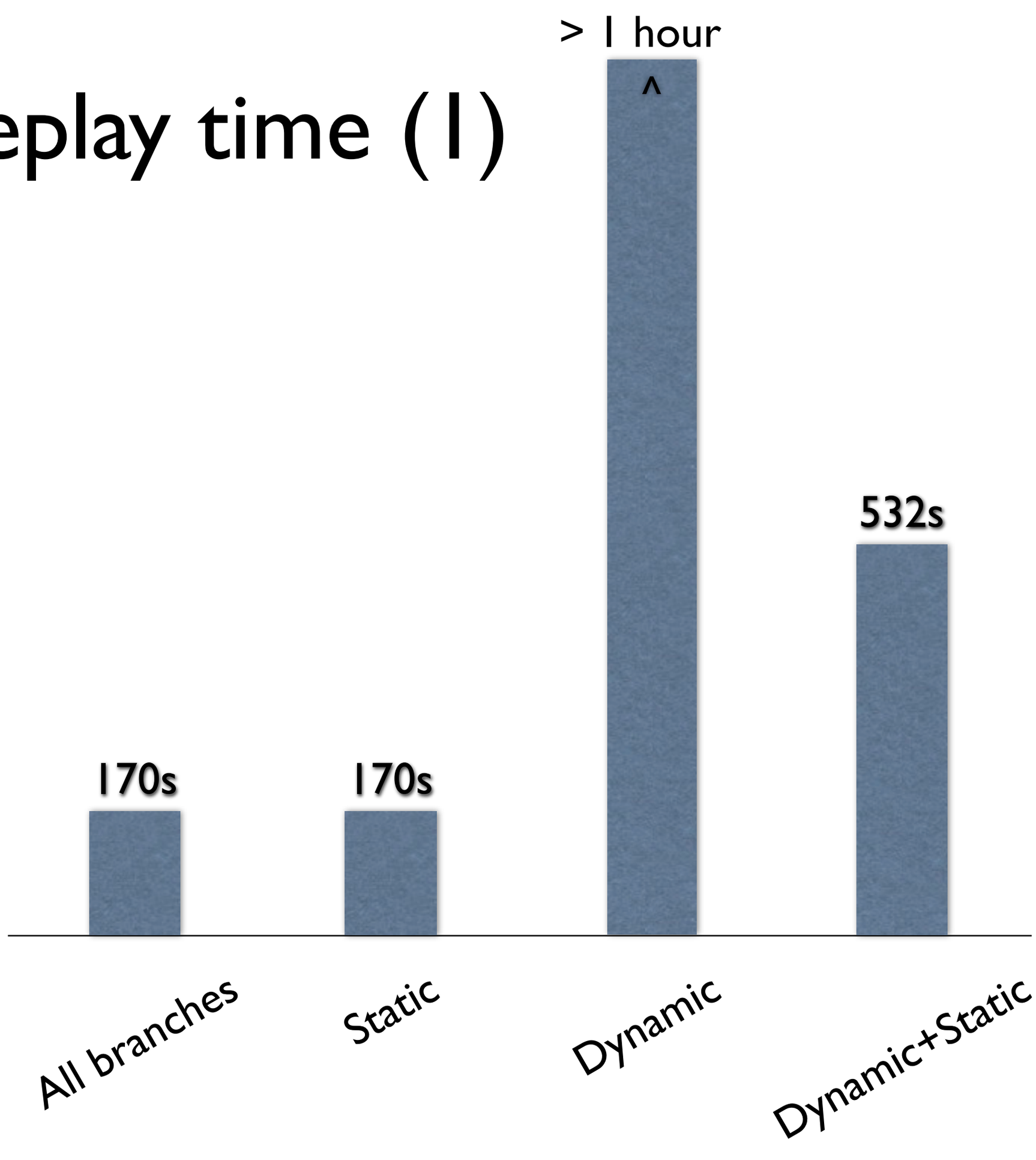
CPU overhead



Results without system call return values are similar

Replay time (1)

Replay time (1)



Replay time (2)

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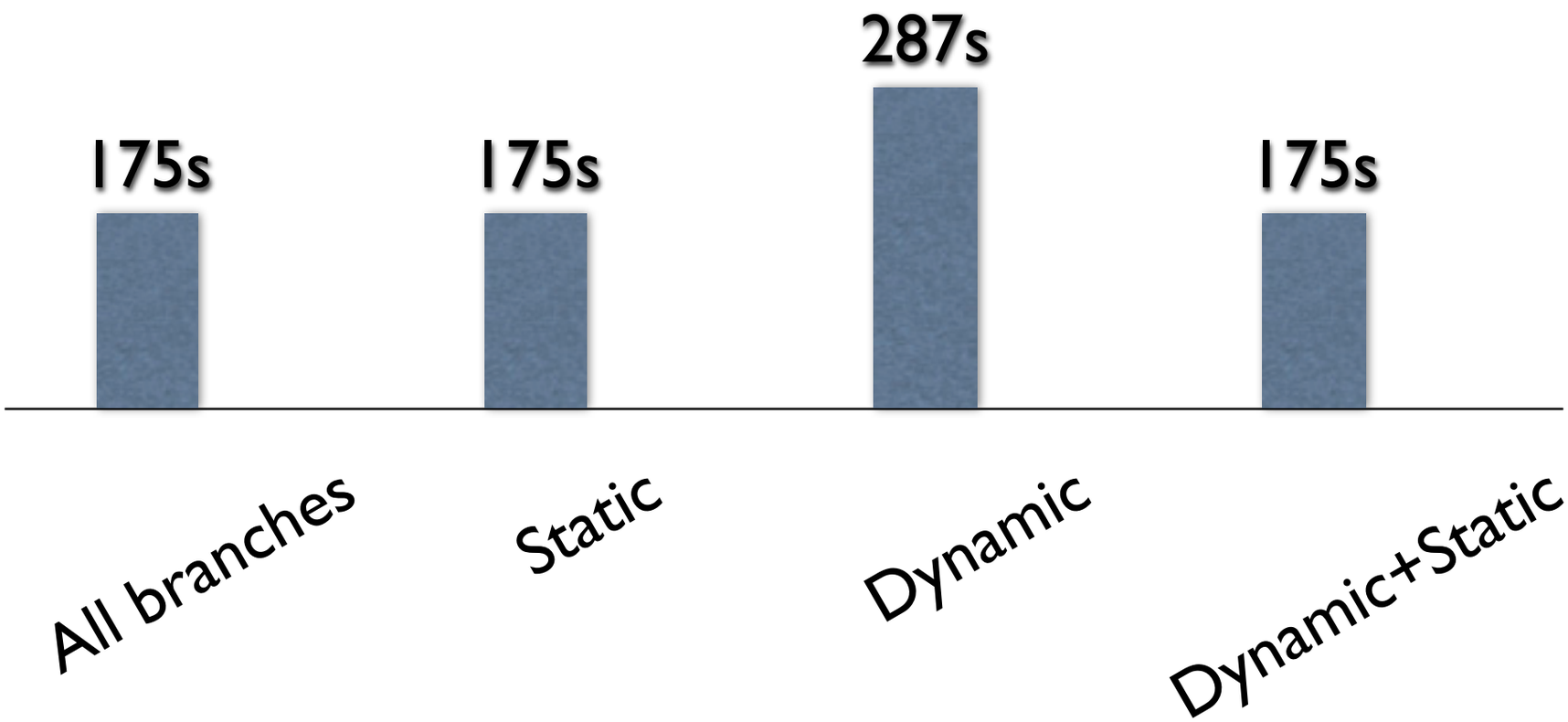
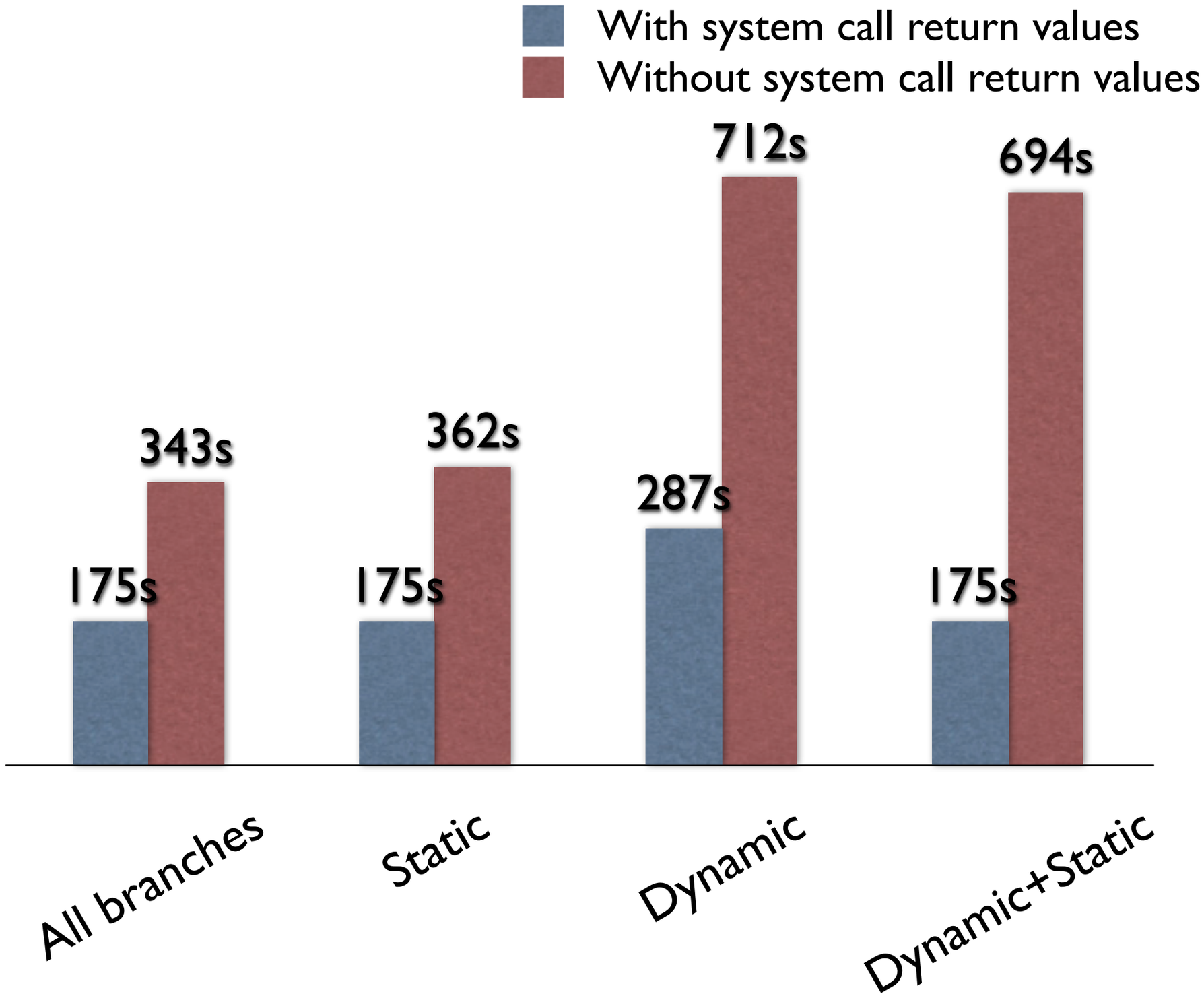
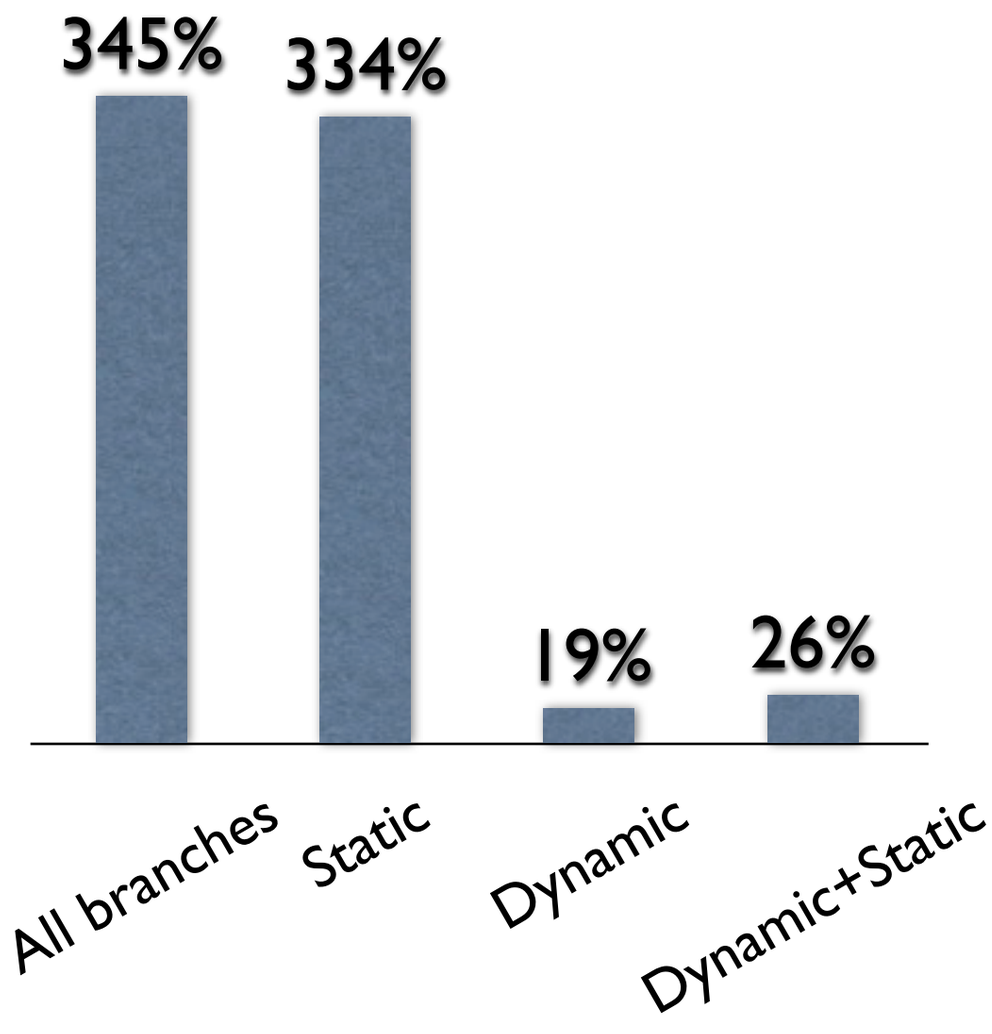


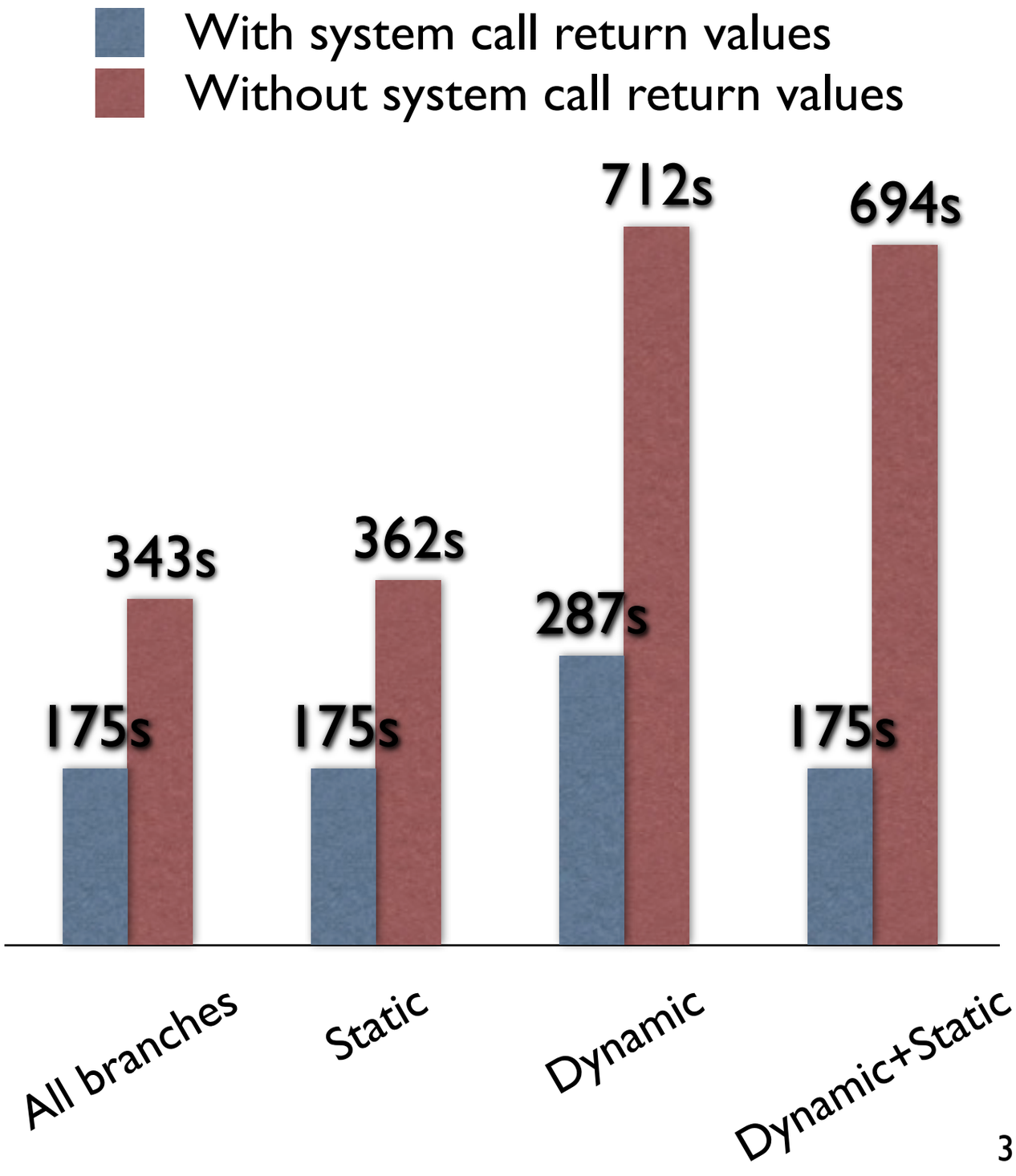
Replay time (2)



CPU overhead



Replay time



Discussion

- Long-running applications:
  - ✦ Replaying from a checkpoint
- Multi-threaded applications:
  - ✦ Branch-log per thread
  - ✦ Logging or inferring thread schedules

Related work

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- Multi-threaded applications:
  - ✦ Output deterministic replay [Altekar 2009]
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- Privacy:
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- Branch logging:
  - ✦ TraceBack [Ayers 2005]

Conclusion

- Study tradeoff debugging time v.s. instrumentation overhead
- Static and dynamic analysis to optimize instrumentation of branches
- Symbolic execution for replay
- Combined dynamic+static strikes the best compromise

Thank you !

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