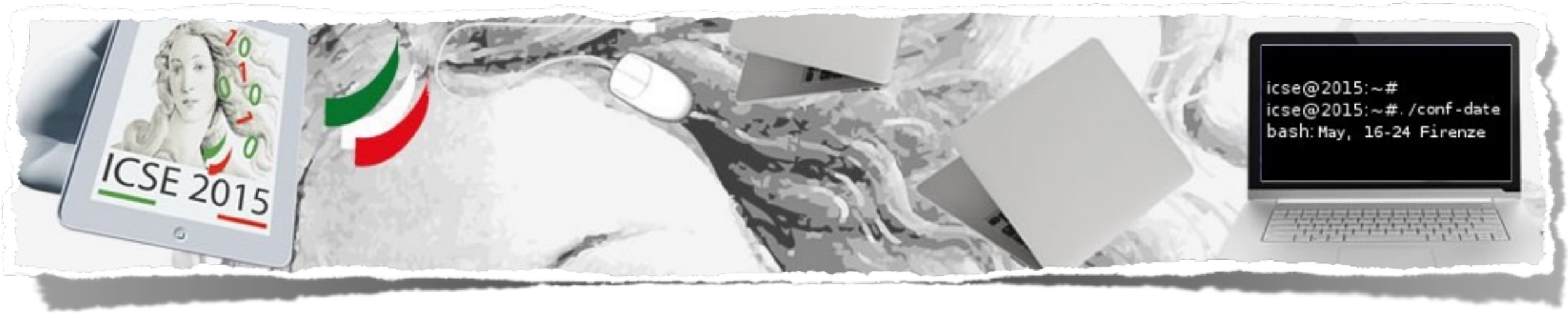

Regular Property Guided Dynamic Symbolic Execution

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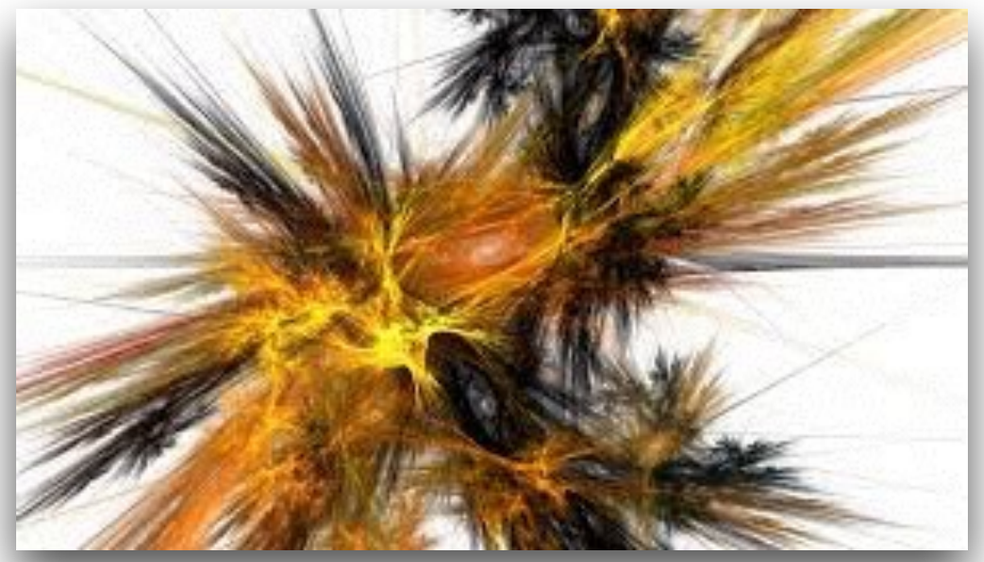
2015.05.22

Dynamic Symbolic Execution (DSE)

- Explore path spaces systematically
  - Test-case generation, bug-finding, bounded verification, …
- Path explosion problem



DSE needs guiding

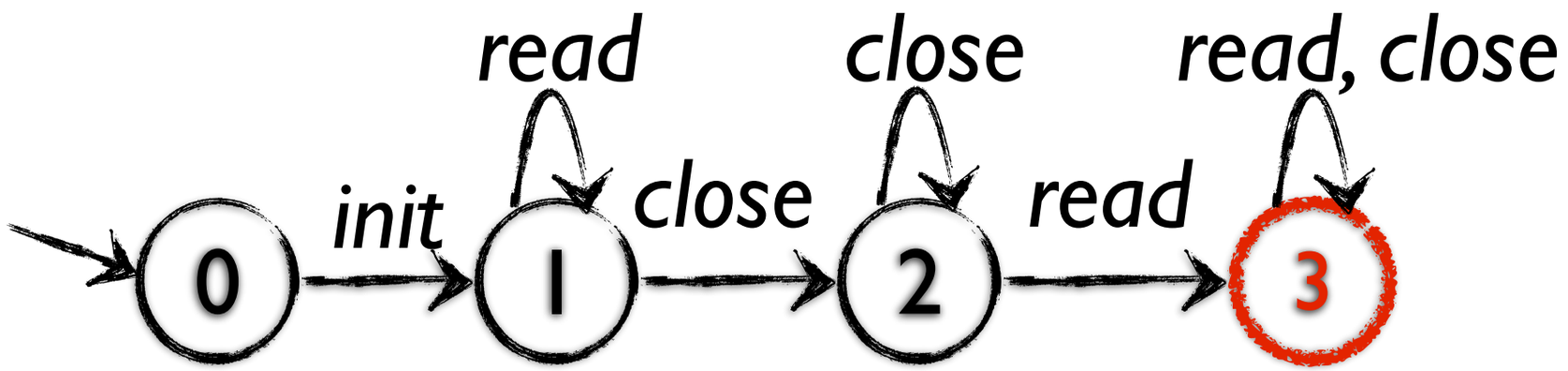
DSE needs guiding

Existing Work of Guiding Symbolic Execution

- Improving coverage
  - KLEE[OSDI'08], CREST[ASE'08], SGS[OOPSLA'13], CGS[FSE'14], …
- Reach program points
  - PEX[DSN'09], ESD[EuroSys'11], SDSE [SAS'11], BitBlaze[ISSTA'11], …
- Exploring the difference between programs
  - DiSE[PLDI'11], ZESTI [ICSE'12], KATCH[FSE'13], …

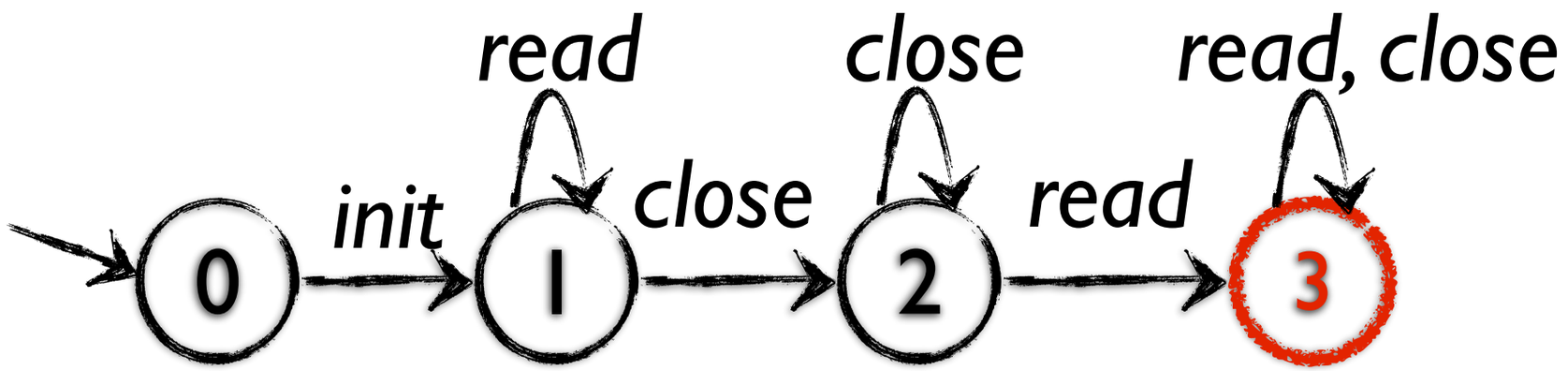
How about a Regular Property?

How about a Regular Property?



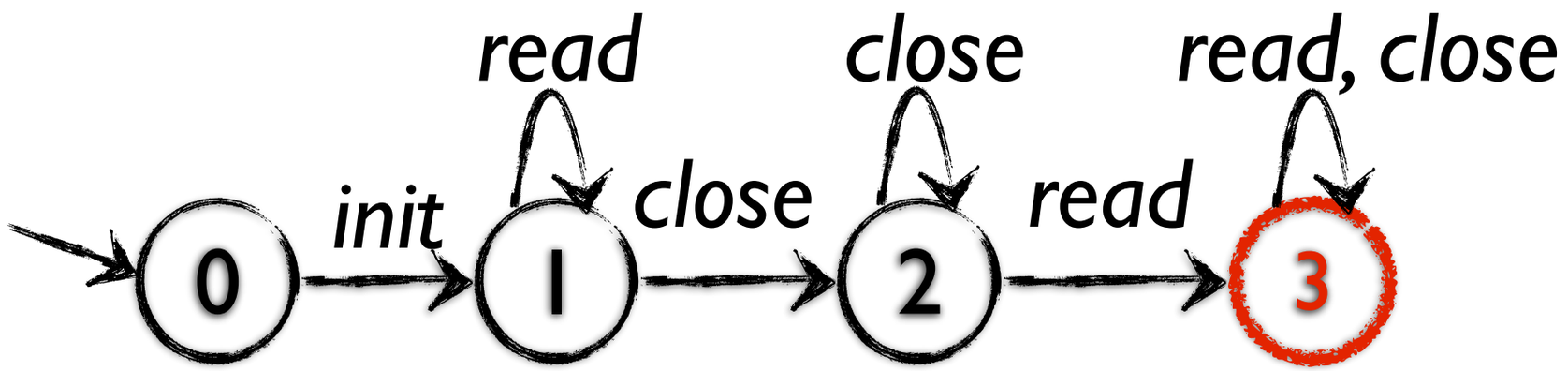
A bug property: a file is read after closed

How about a Regular Property?



A bug property: a file is read after closed

How about a Regular Property?

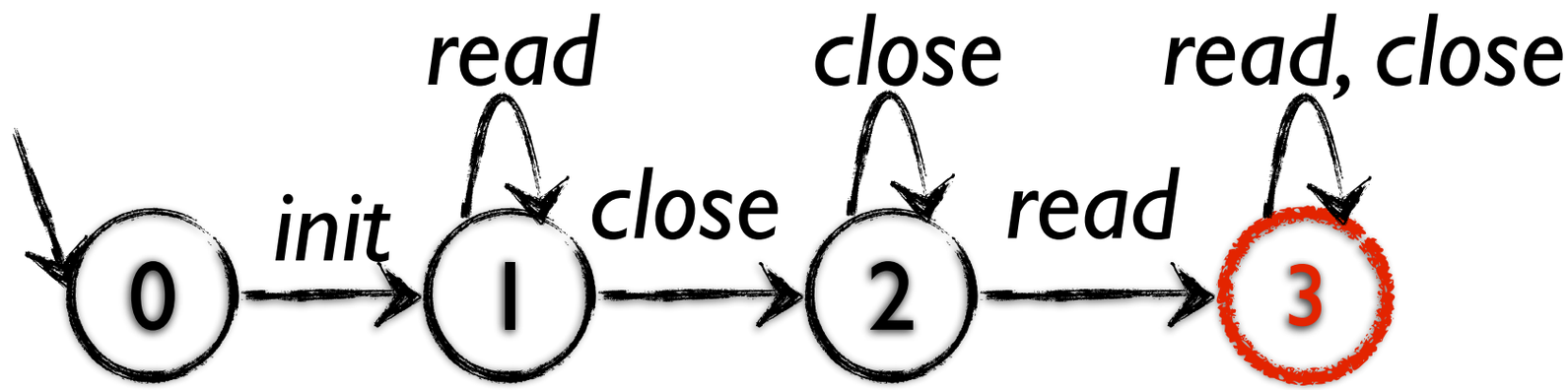


A bug property: a file is read after closed

How to guide DSE to find a program path satisfying P as soon as possible?

Observation and Insight

- Many irrelevant paths exist
- Even for relevant paths, only the ones with specific sequences can satisfy the regular property

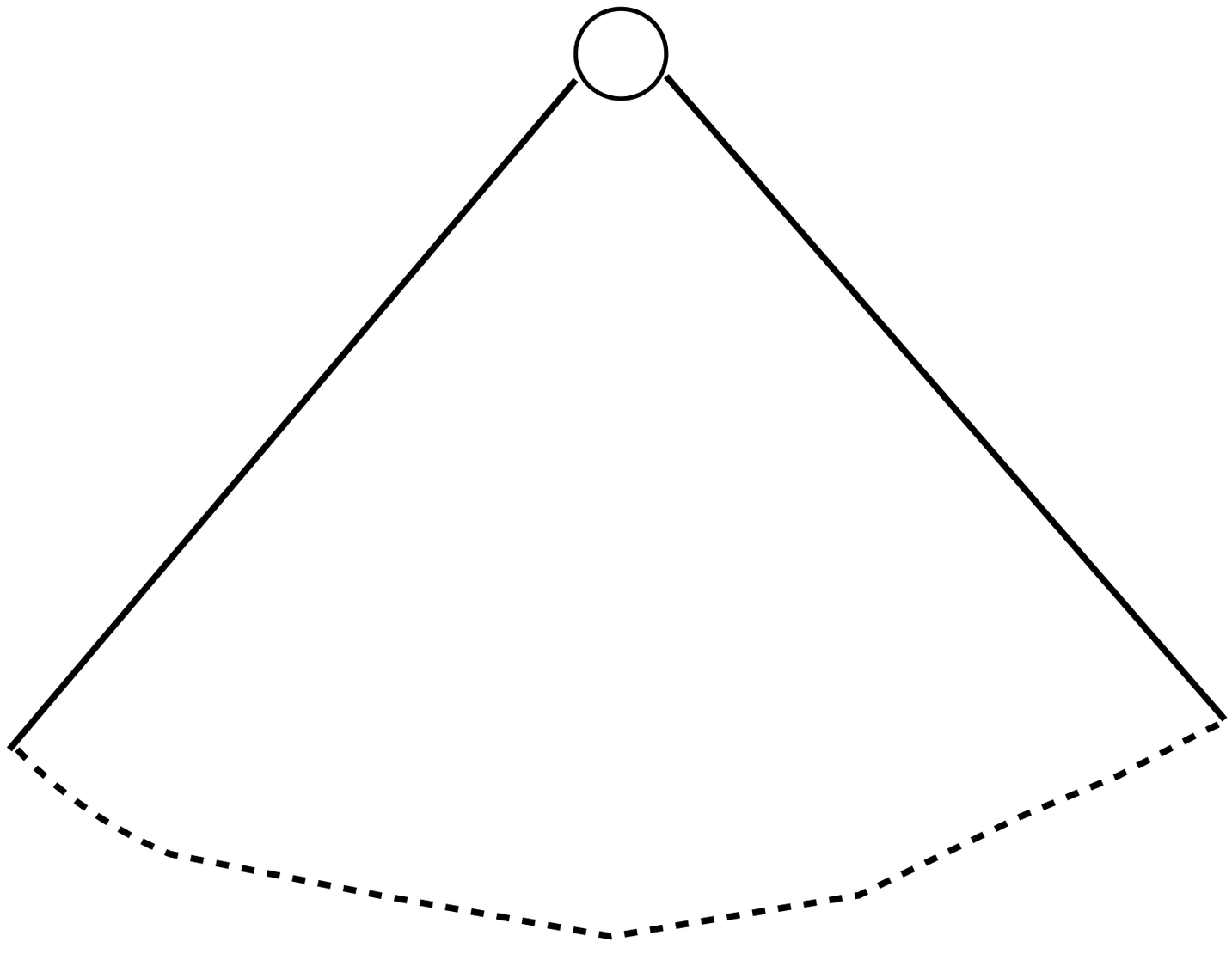


Observation and Insight

- Many irrelevant paths exist
- Even for relevant paths, only the ones with specific sequences can satisfy the regular property

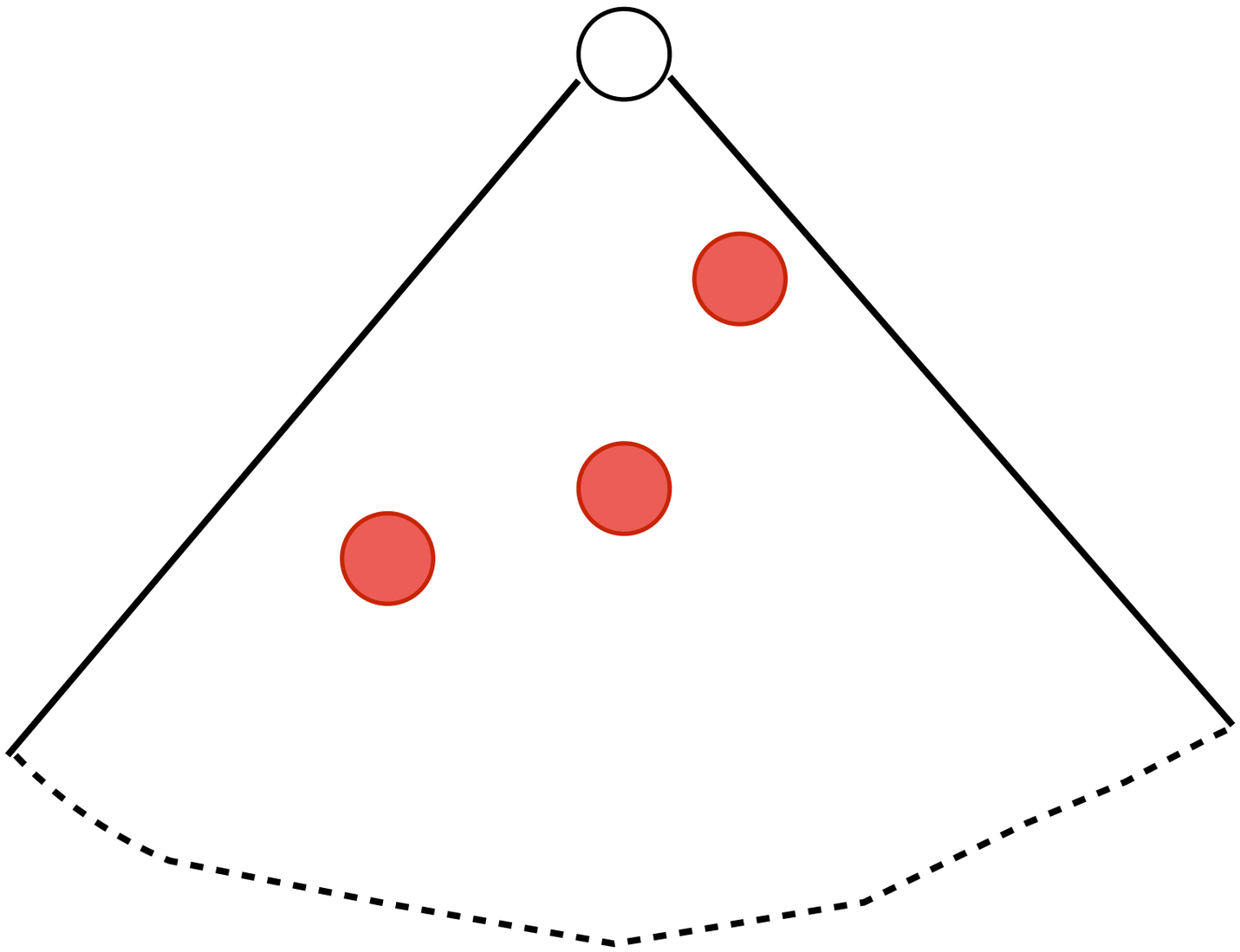
Evaluate the possibility of a branch to generate the paths satisfying the property

Key Idea



Evaluate a branch based on its history and future behaviors

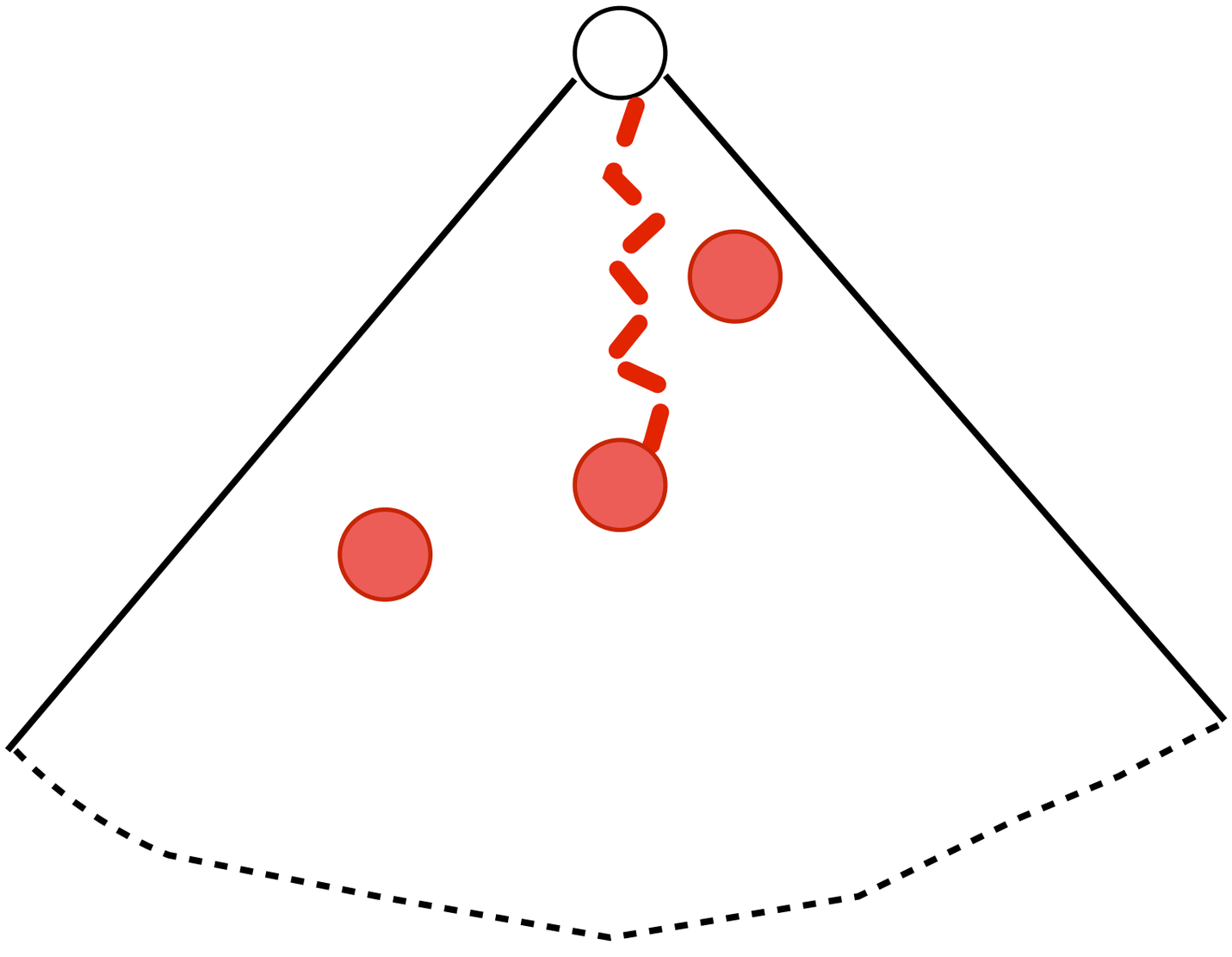
Key Idea



Evaluate a branch based on its history and future behaviors

Key Idea

history

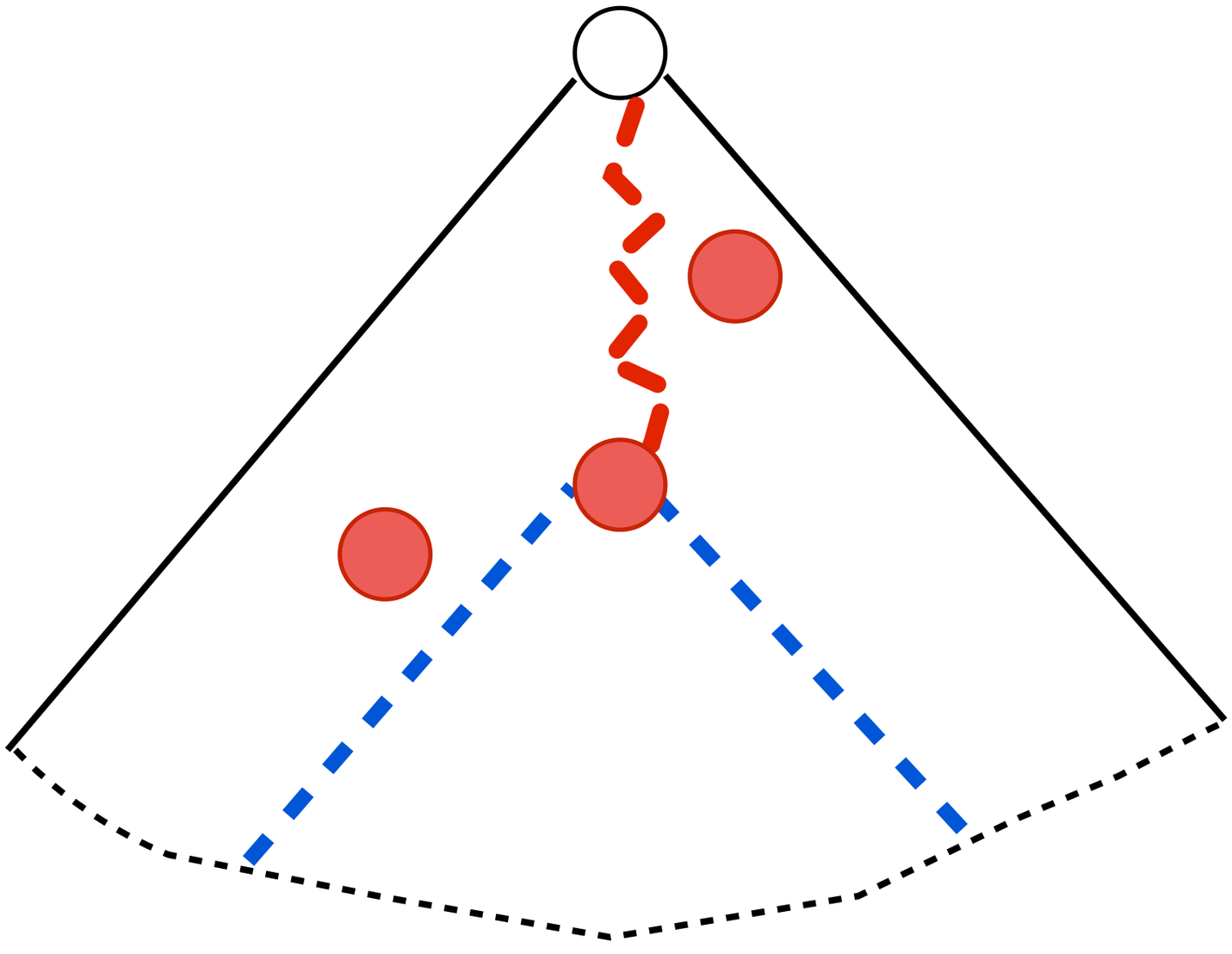


Evaluate a branch based on its history and future behaviors

Key Idea

history

future



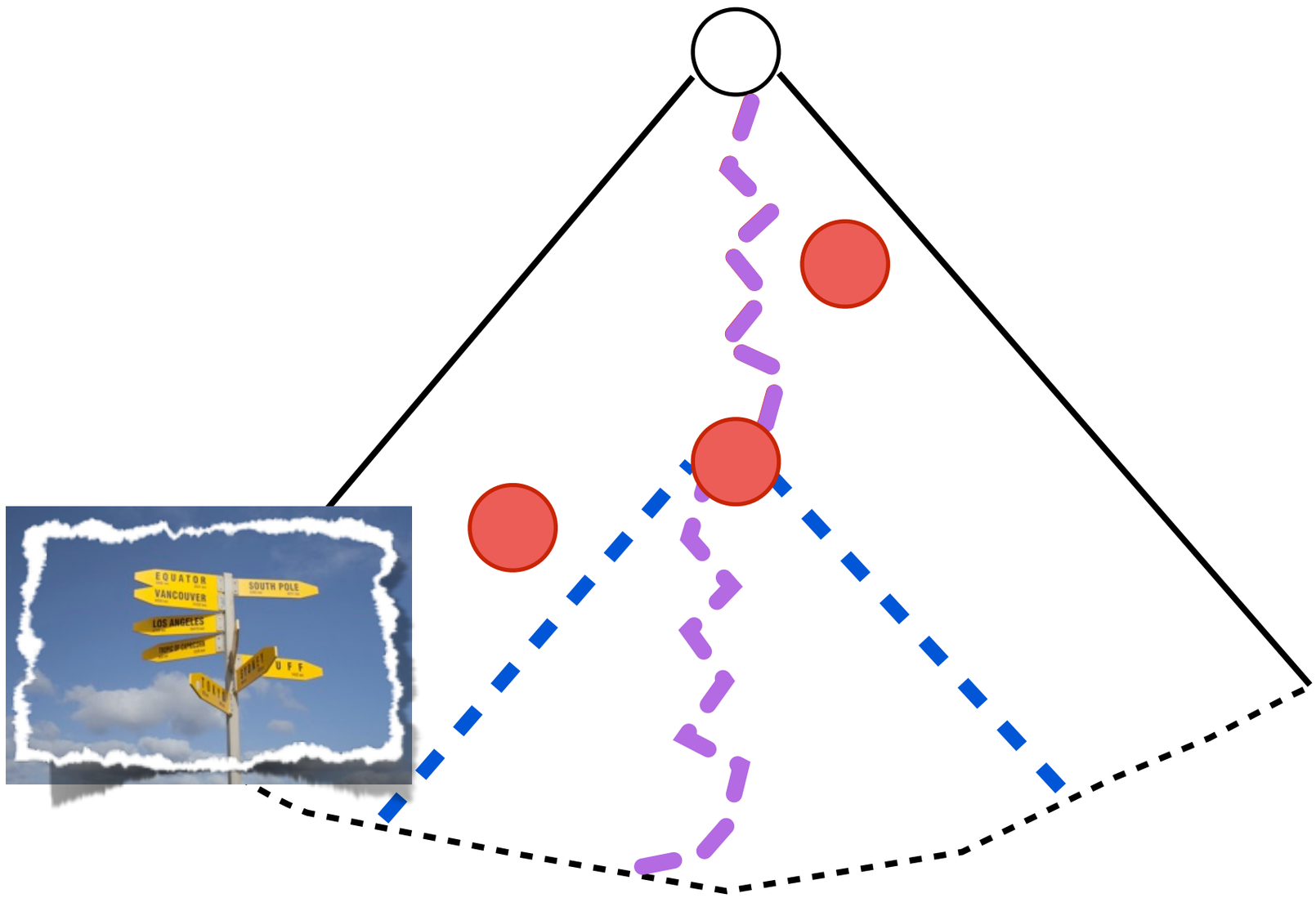
Evaluate a branch based on its history and future behaviors

Key Idea

history $\cap$ *future* $\neq \varnothing$

history

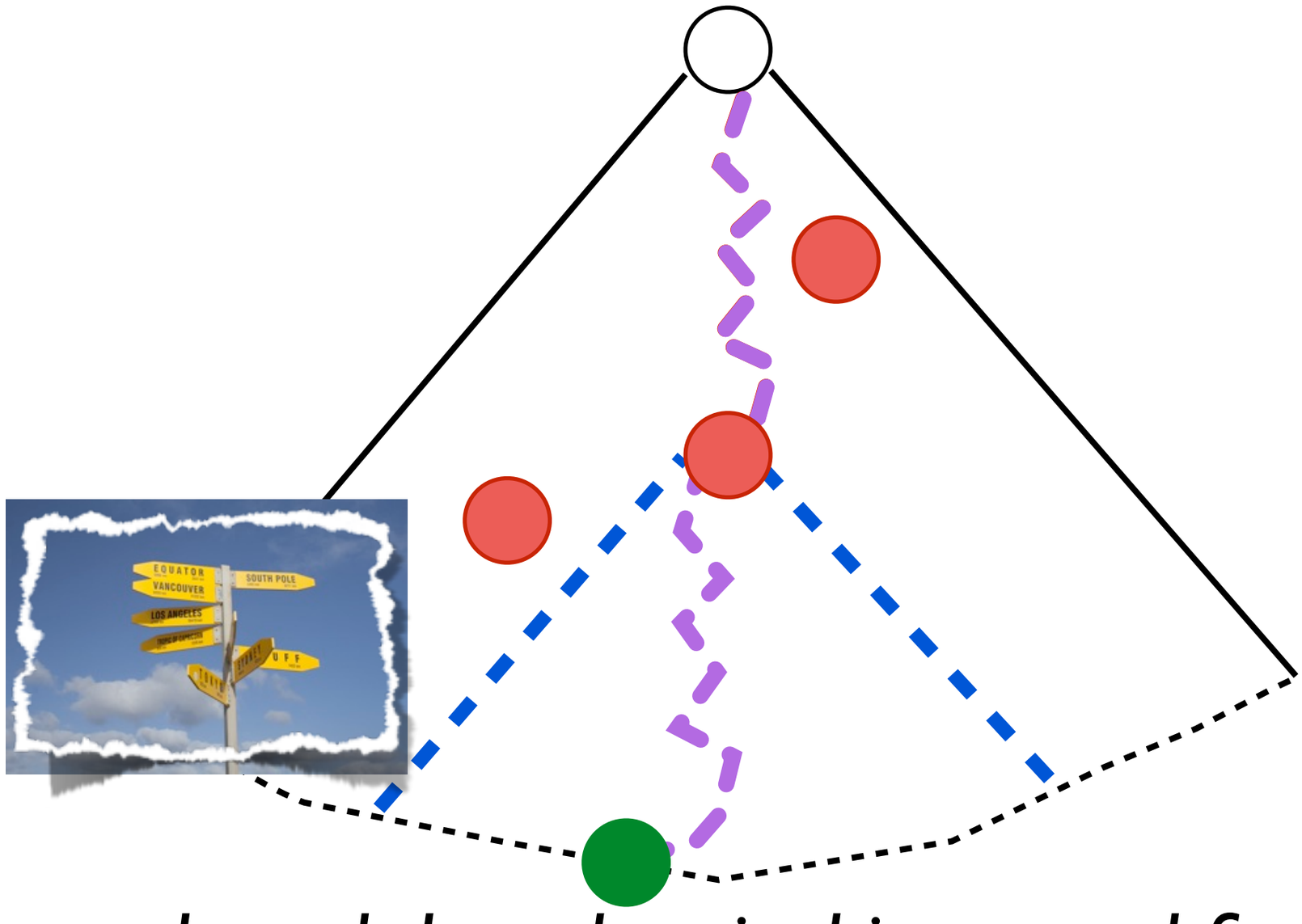
future



Evaluate a branch based on its history and future behaviors

Key Idea

history *history* ∩ *future* ≠ ∅ *future*

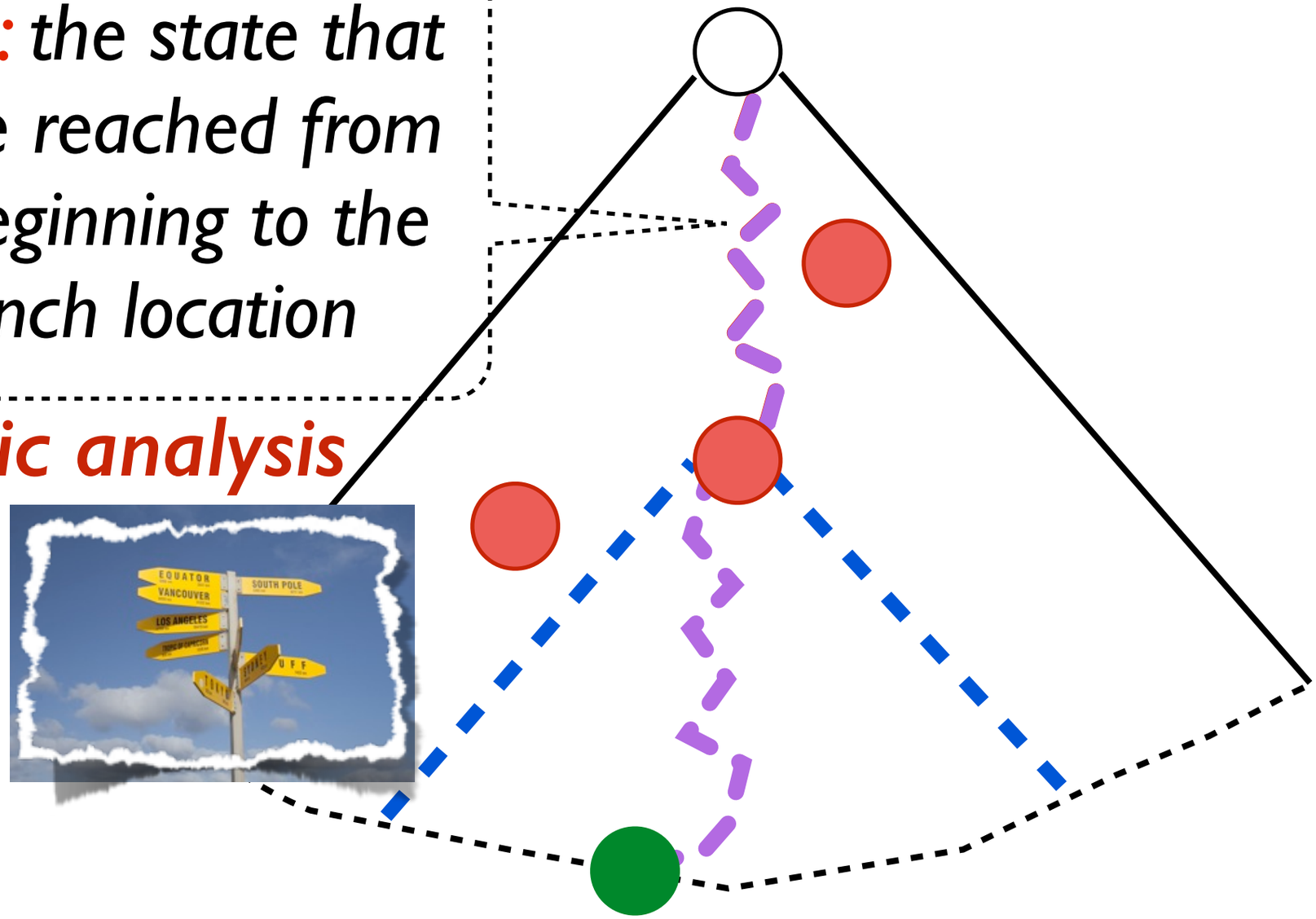


Evaluate a branch based on its history and future behaviors

Key Idea

history *history* ∩ *future* ≠ ∅ *future*

Preset: the state that can be reached from the beginning to the branch location



Dynamic analysis

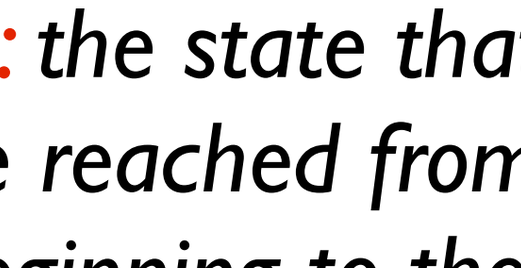
Evaluate a branch based on its history and future behaviors

Key Idea

history *history* ∩ *future* ≠ ∅ *future*

Preset: the state that can be reached from the beginning to the branch location

Postset: the states from which it can reach a final state after executing the rest program after the branch location



Dynamic analysis

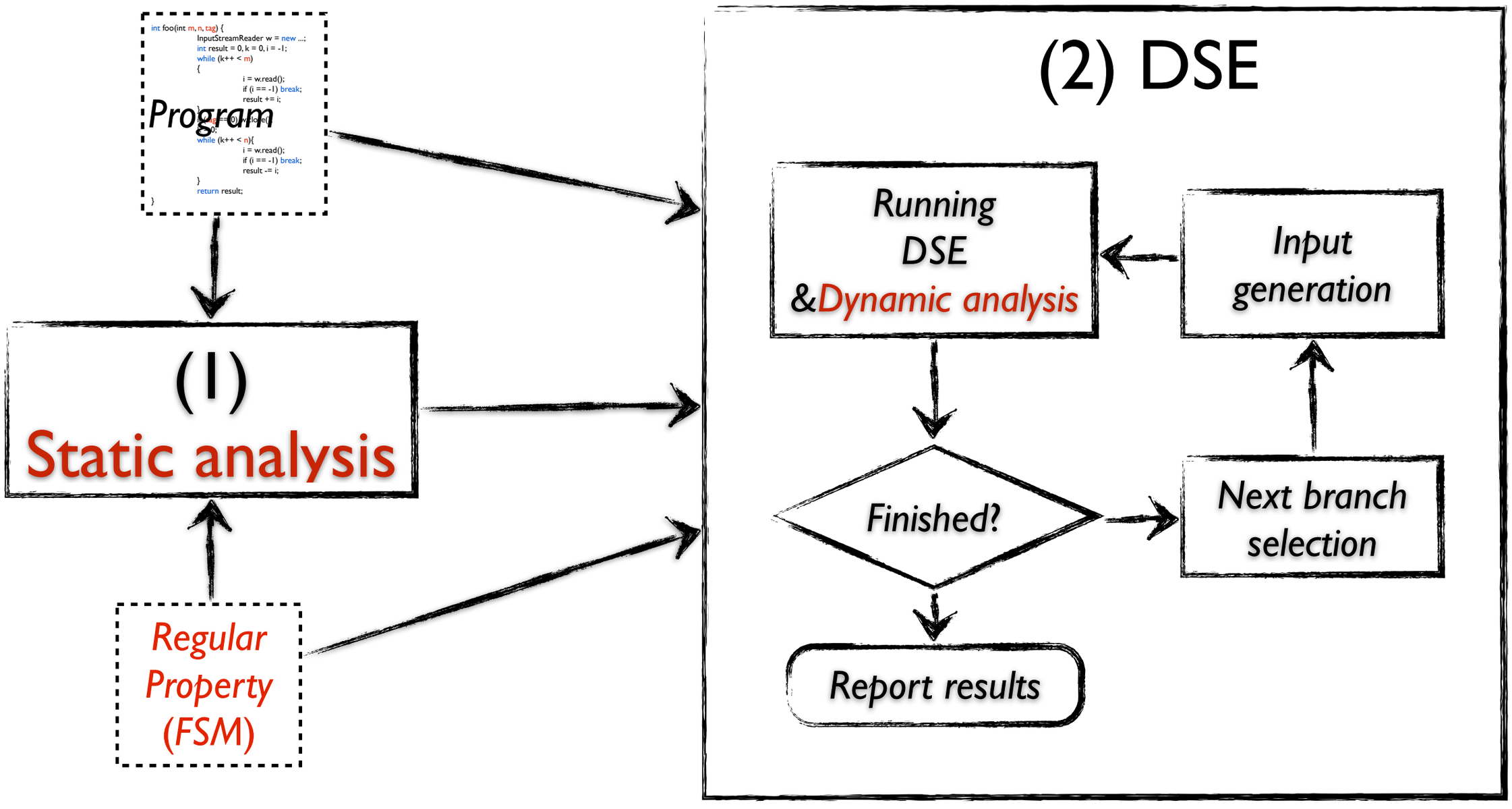
Static analysis

Evaluate a branch based on its history and future behaviors

Sneak Preview of Results

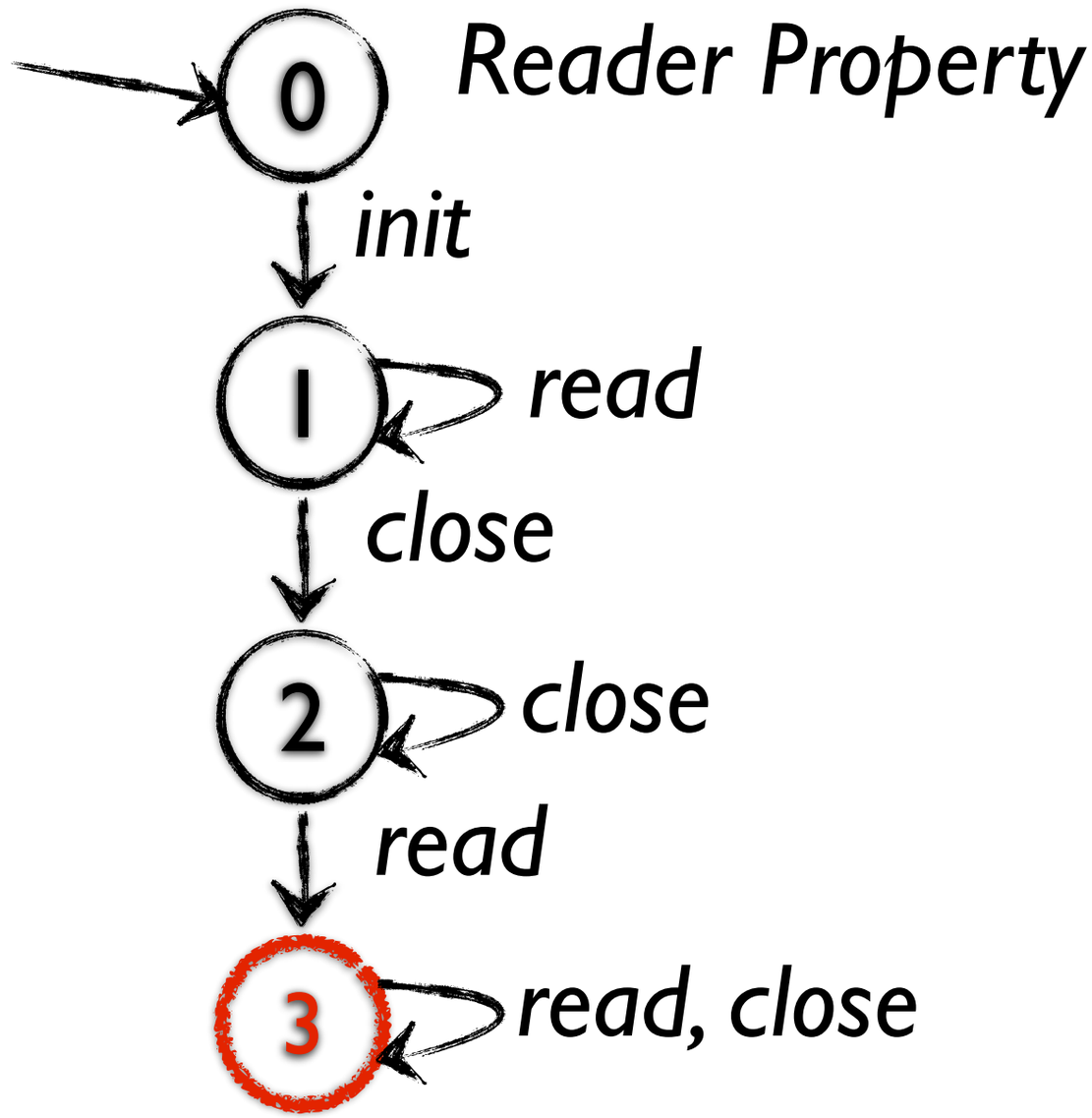
- For finding the first accepted path
  - >1880X speedup on iterations
  - >258X time speedup on the programs whose paths space is bigger than 100
- For 3 out of the 13 real world programs
  - Guided method succeeds in 1 hour
  - Pure method fails in 24 hours

Procedure


int foo(int m, n, tag) {
InputStreamReader w = new ...;
int result = 0, k = 0, i = -1;
while (k++ < m)
{
i = w.read();
if (i == -1) break;
result += i;
}
if (tag == 0) throw();
while (k++ < n){
i = w.read();
if (i == -1) break;
result -= i;
}
return result;
}
Program
(1)
Static analysis
Regular
Property
(FSM)
(2) DSE
Running
DSE
&Dynamic analysis
Input
generation
Finished?
Next branch
selection
Report results

An Example

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```



A reader is read after closed

An Example

```
int foo(int m, n, tag) {
  InputStreamReader w = new ...;
  int result = 0, k = 0, i = -1;
  while (k++ < m)
  {
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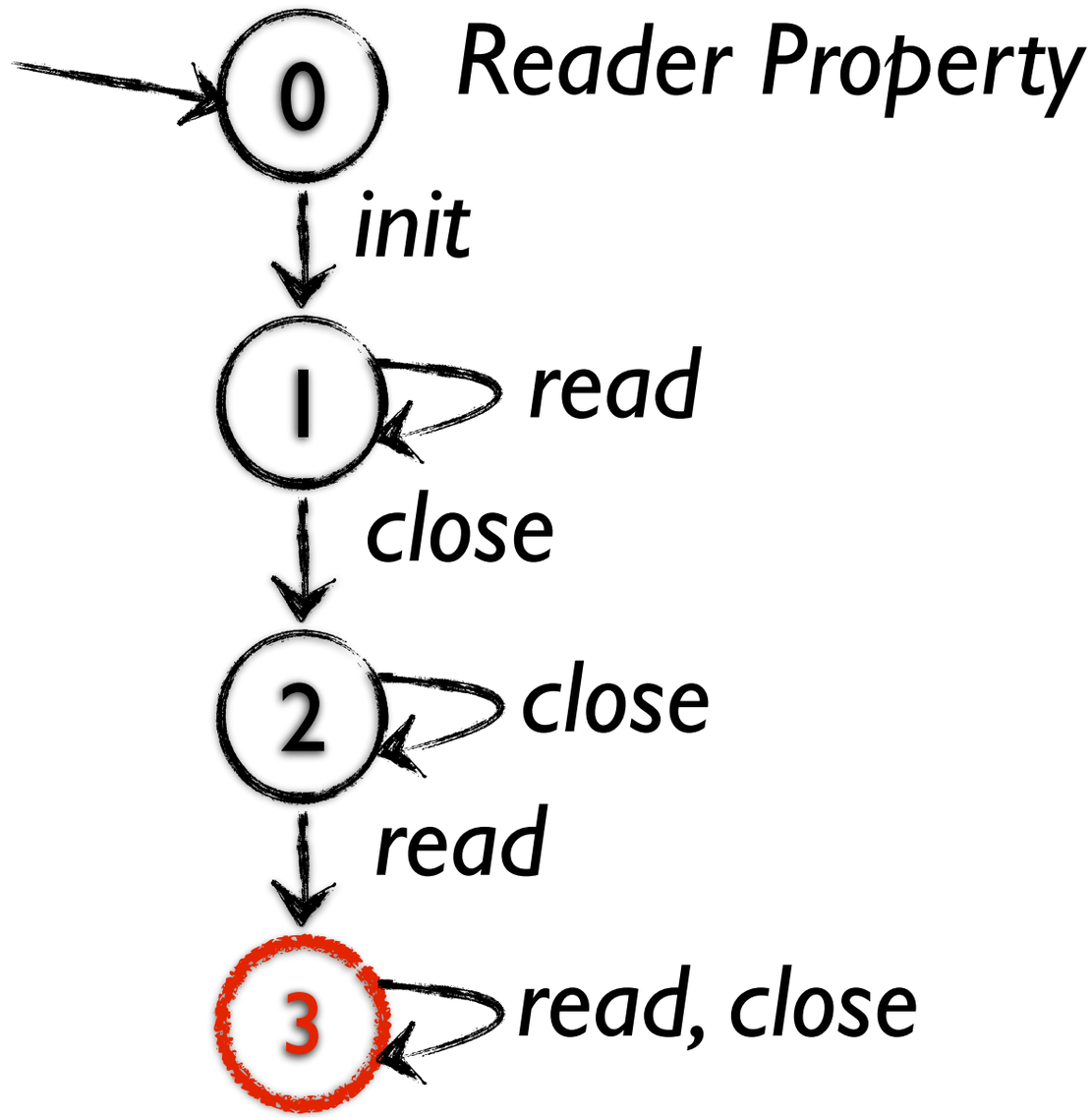
     if (i == -1) break;
     result += i;
  }
  if (tag == 0) w.close();
  k = 0;
  while (k++ < n){
     i = w.read();
     if (i == -1) break;
     result -= i;
  }
  return result;
}
```



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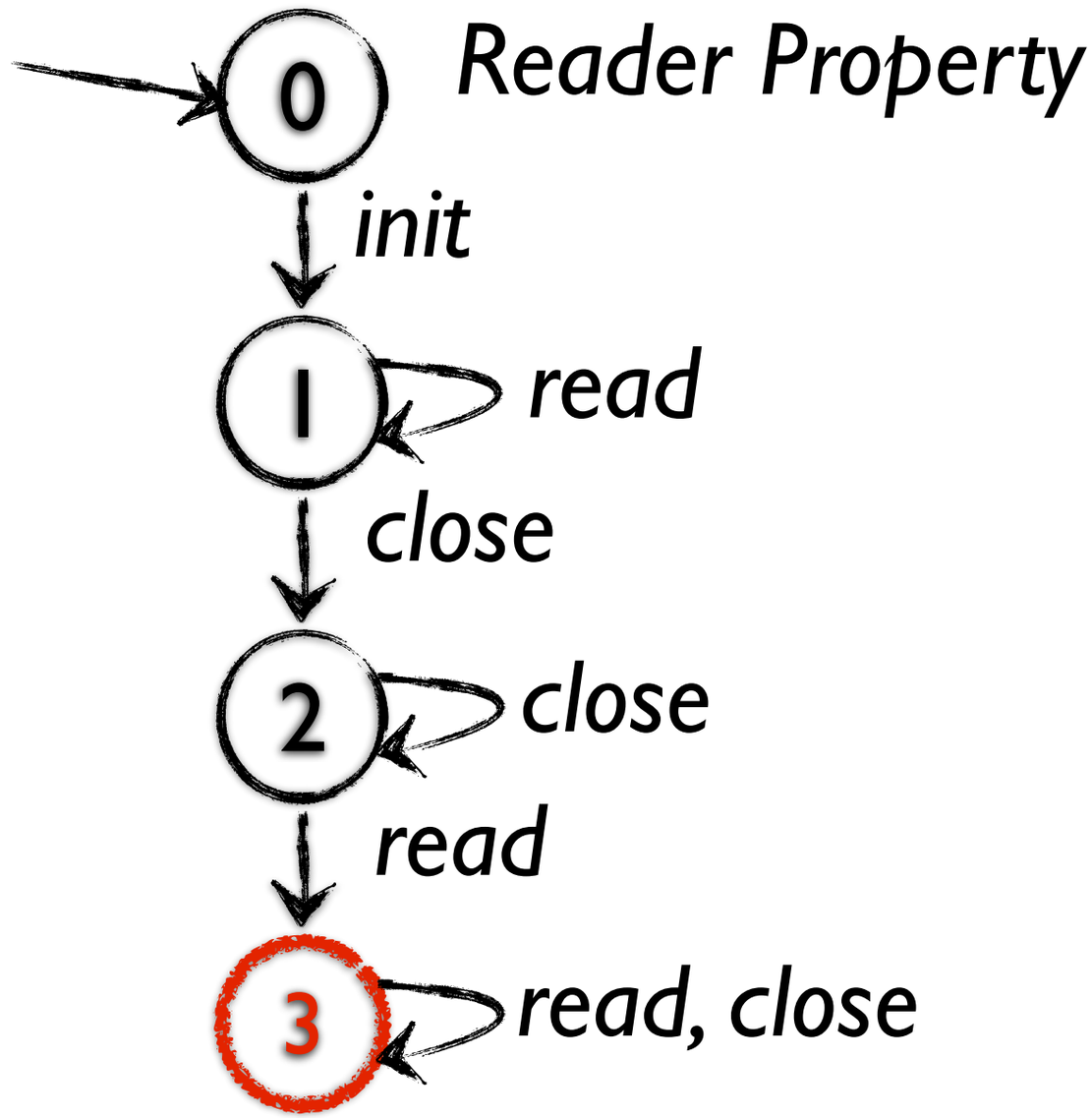
  if (tag == 0) w.close();
  k = 0;
  while (k++ < n){
     i = w.read();
     if (i == -1) break;
     result -= i;
  }
  return result;
}
```



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  }
  if (tag == 0) w.close();
  k = 0;
  while (k++ < n){
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     if (i == -1) break;
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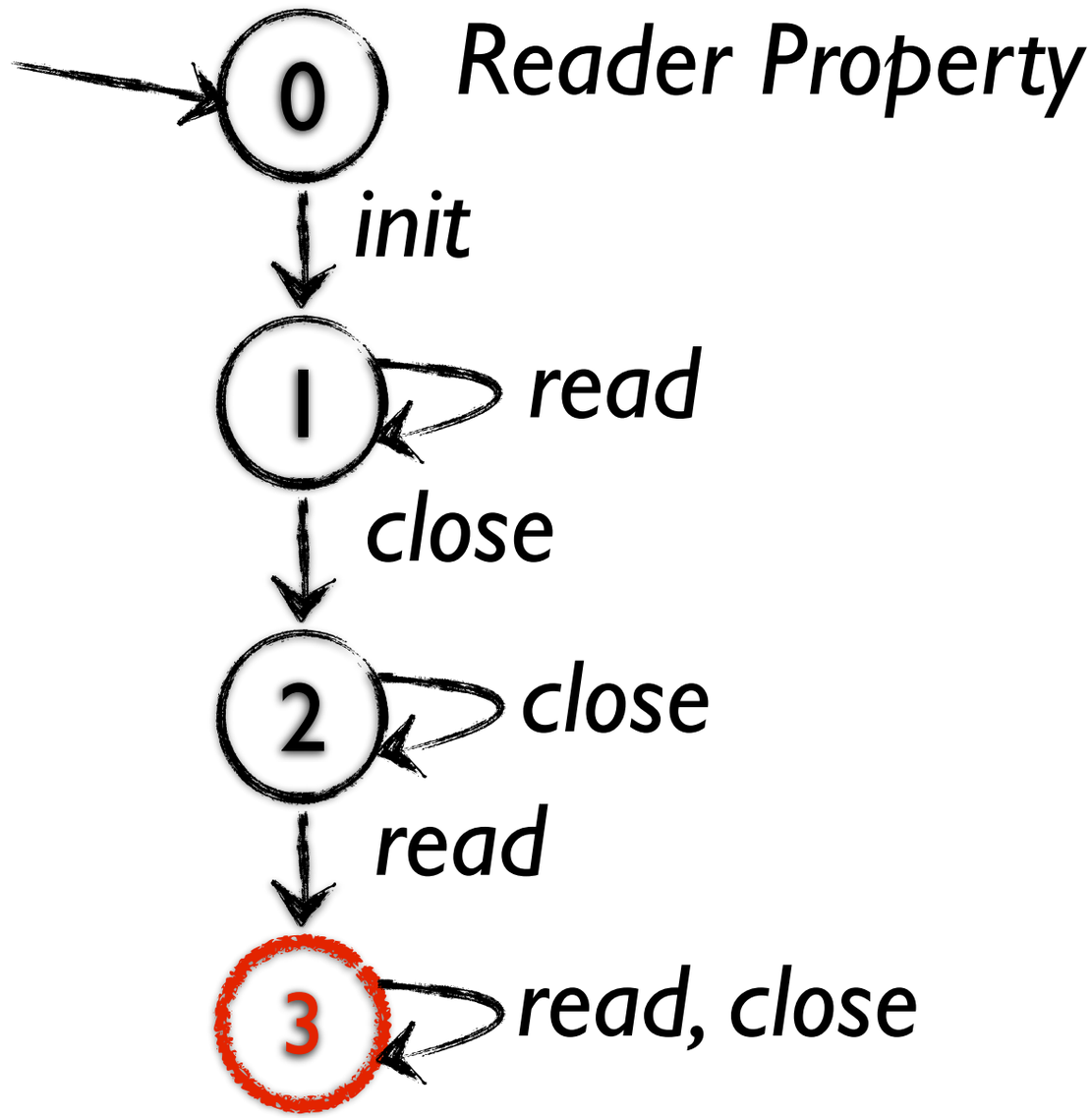
```



A reader is read after closed

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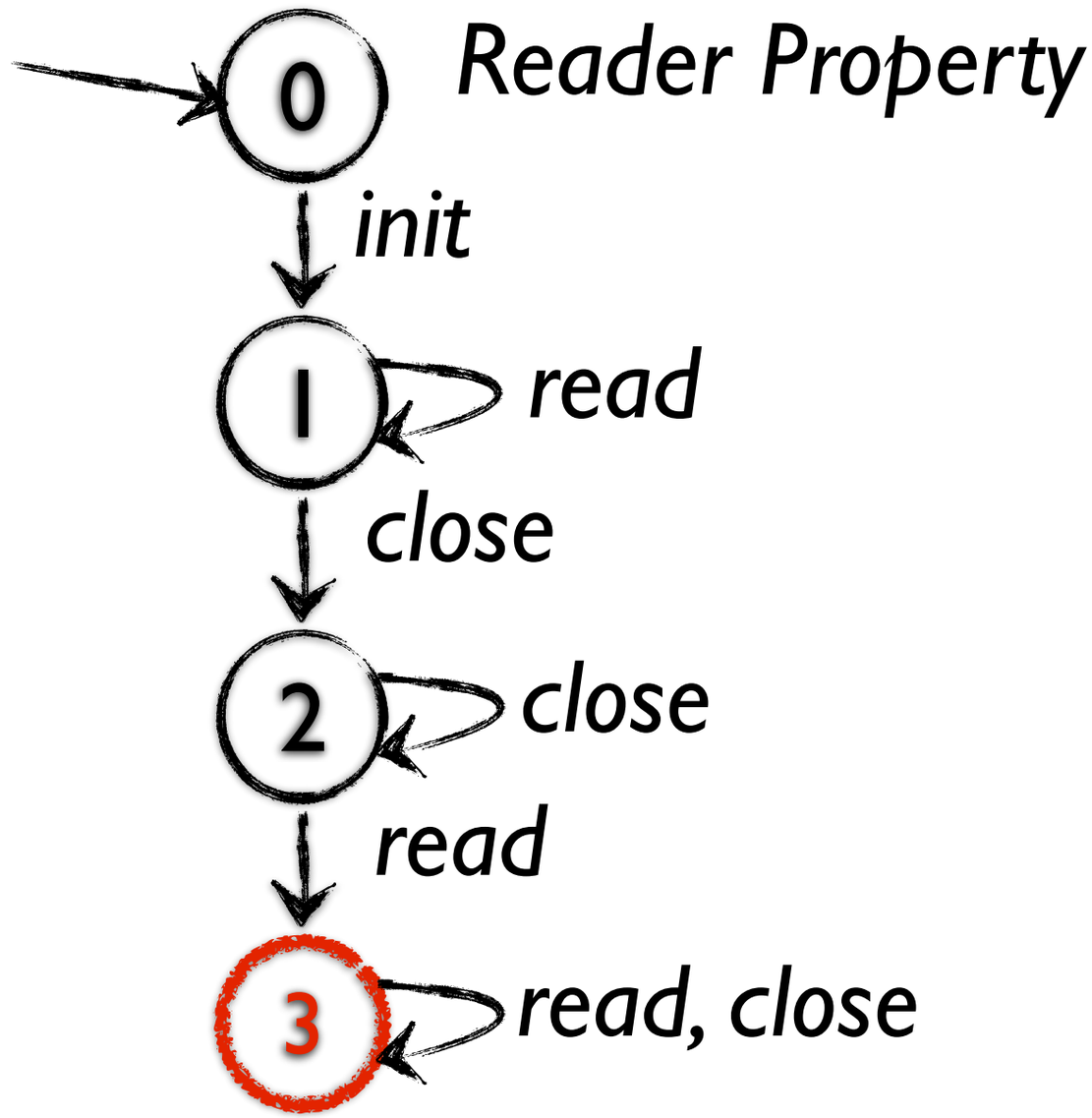
     if (i == -1) break;
     result += i;
  }
  if (tag == 0) w.close();
  k = 0;
  while (k++ < n){
     i = w.read();
     if (i == -1) break;
     result -= i;
  }
  return result;
}
```



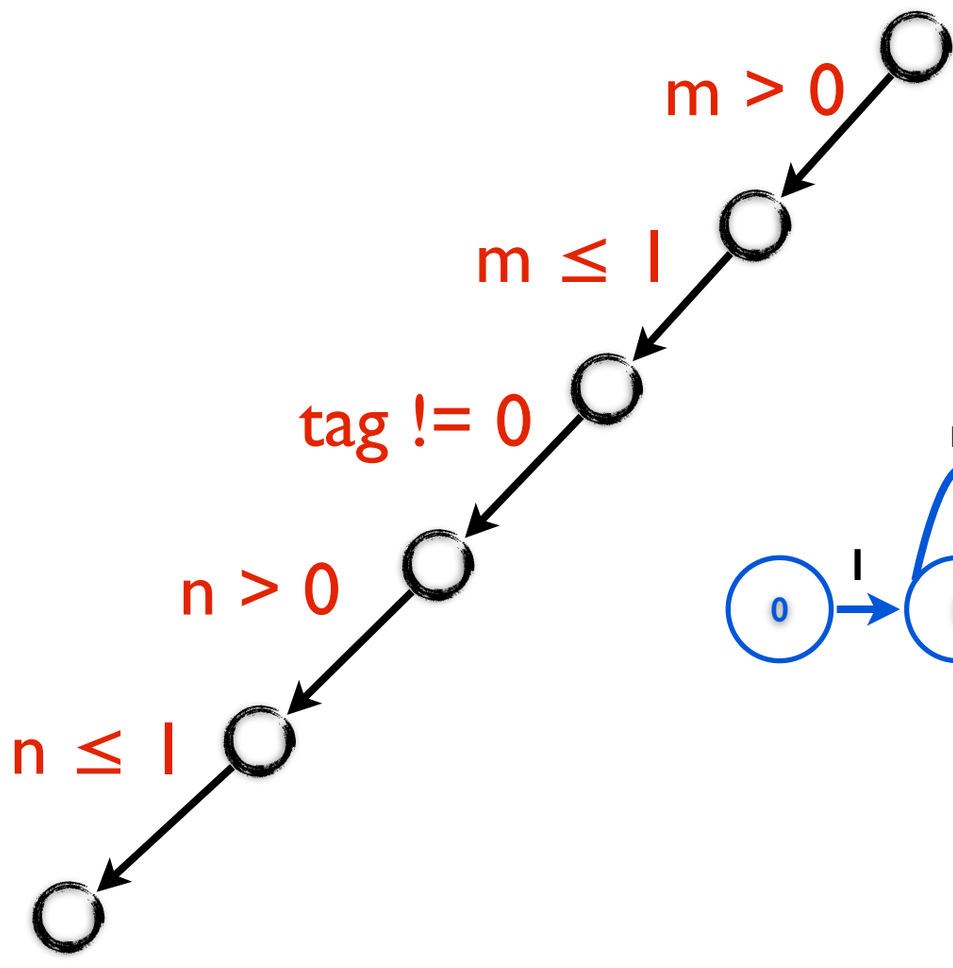
A reader is read after closed

Pure DSE

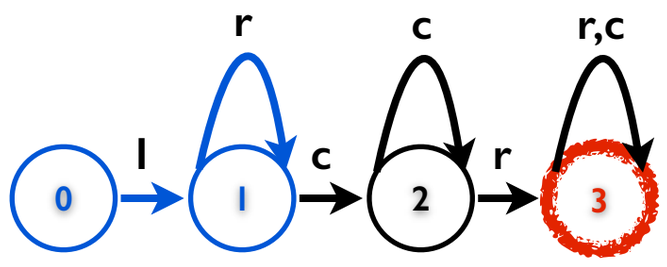
Pure DSE-1st Iteration

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

(m=1, n=1, tag=1)



DFS

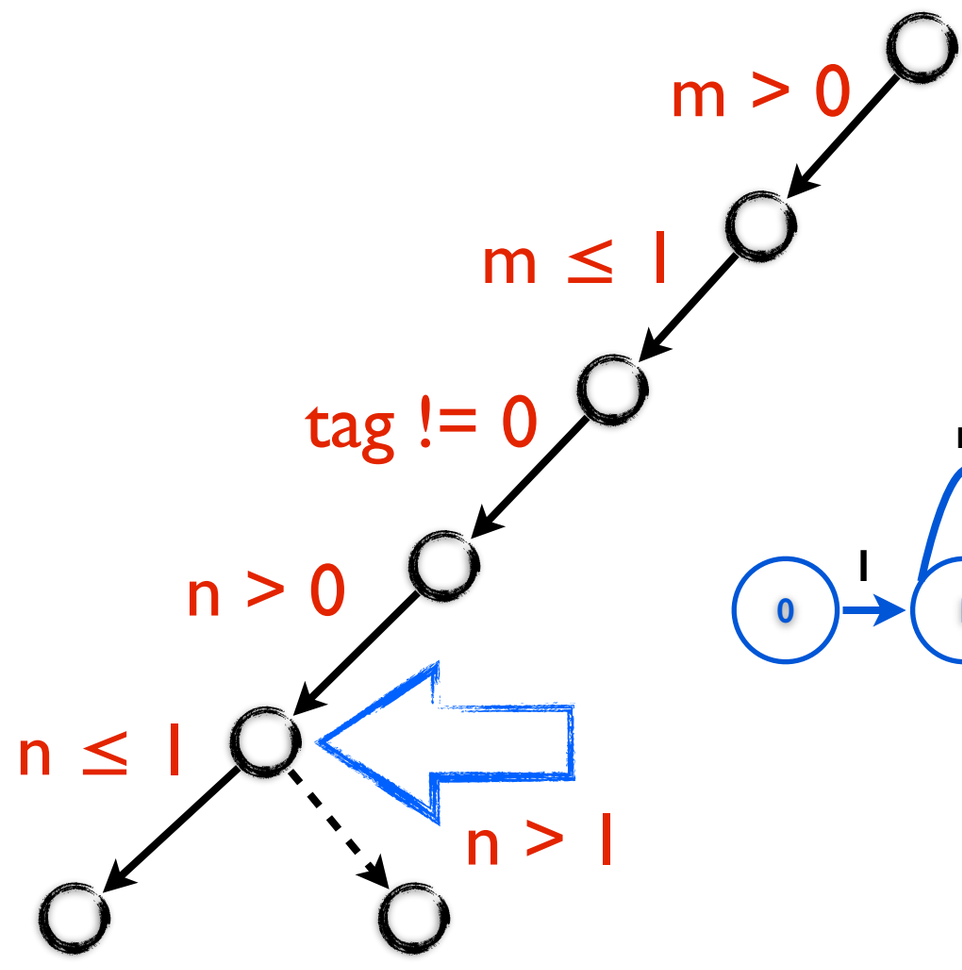


m > 0 ∧ m ≤ 1 ∧ tag != 0 ∧ n > 0 ∧ n ≤ 1

Pure DSE-1st Iteration

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

(m=1, n=1, tag=1)



DFS

m > 0 ∧ m ≤ 1 ∧ tag != 0 ∧ n > 0 ∧ n ≤ 1

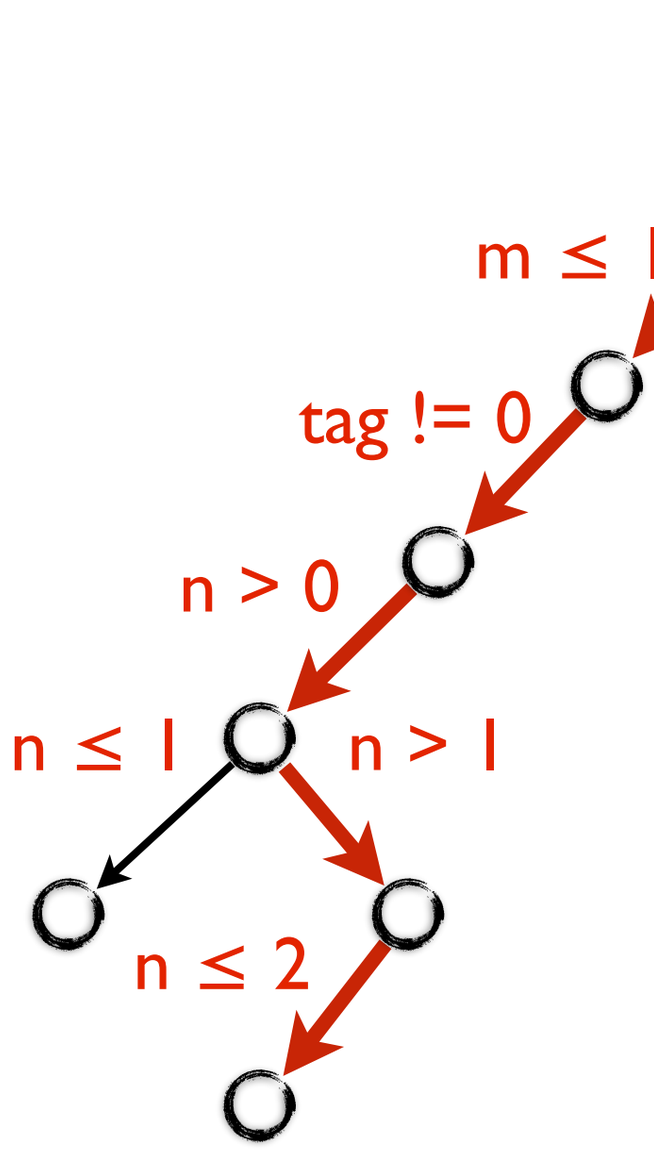
m > 0 ∧ m ≤ 1 ∧ tag != 0 ∧ n > 0 ∧ n > 1

(m=1, n=2, tag=1)

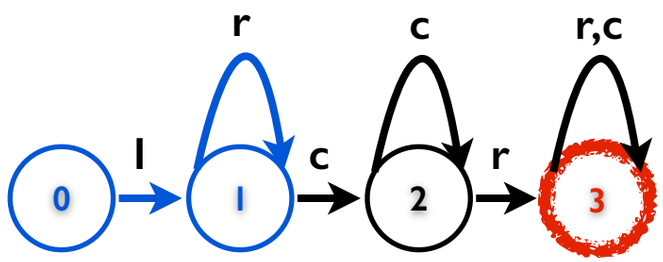
Pure DSE-2nd Iteration

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

(m=1, n=2, tag=1)



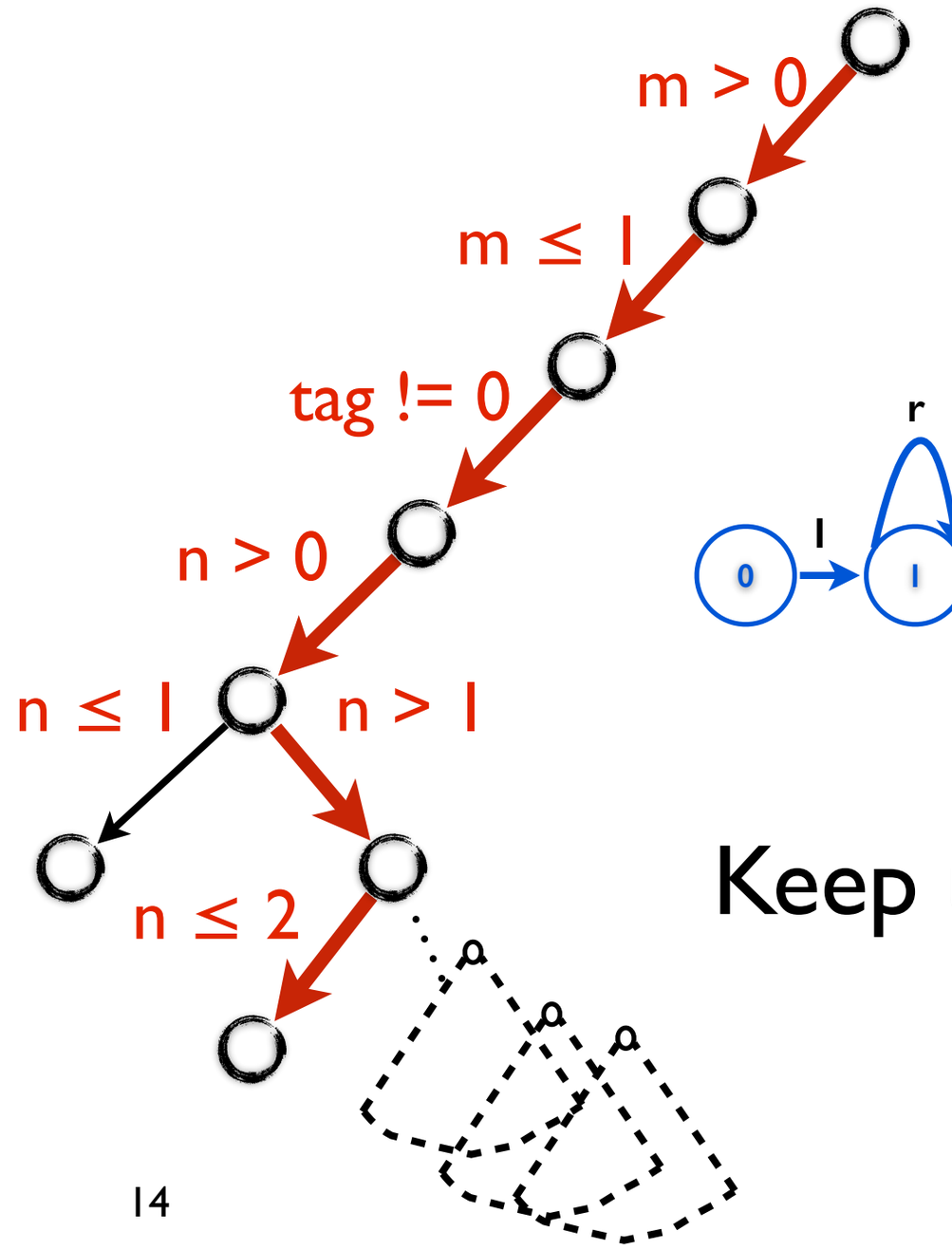
DFS



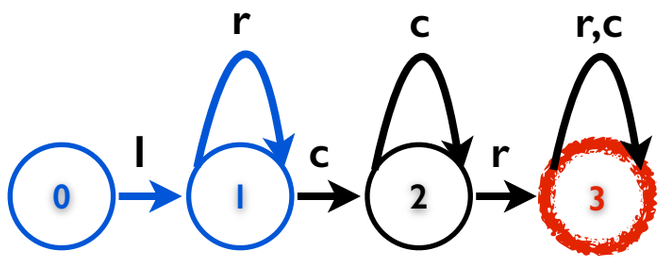
Pure DSE-2nd Iteration

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

(m=1, n=2, tag=1)



DFS

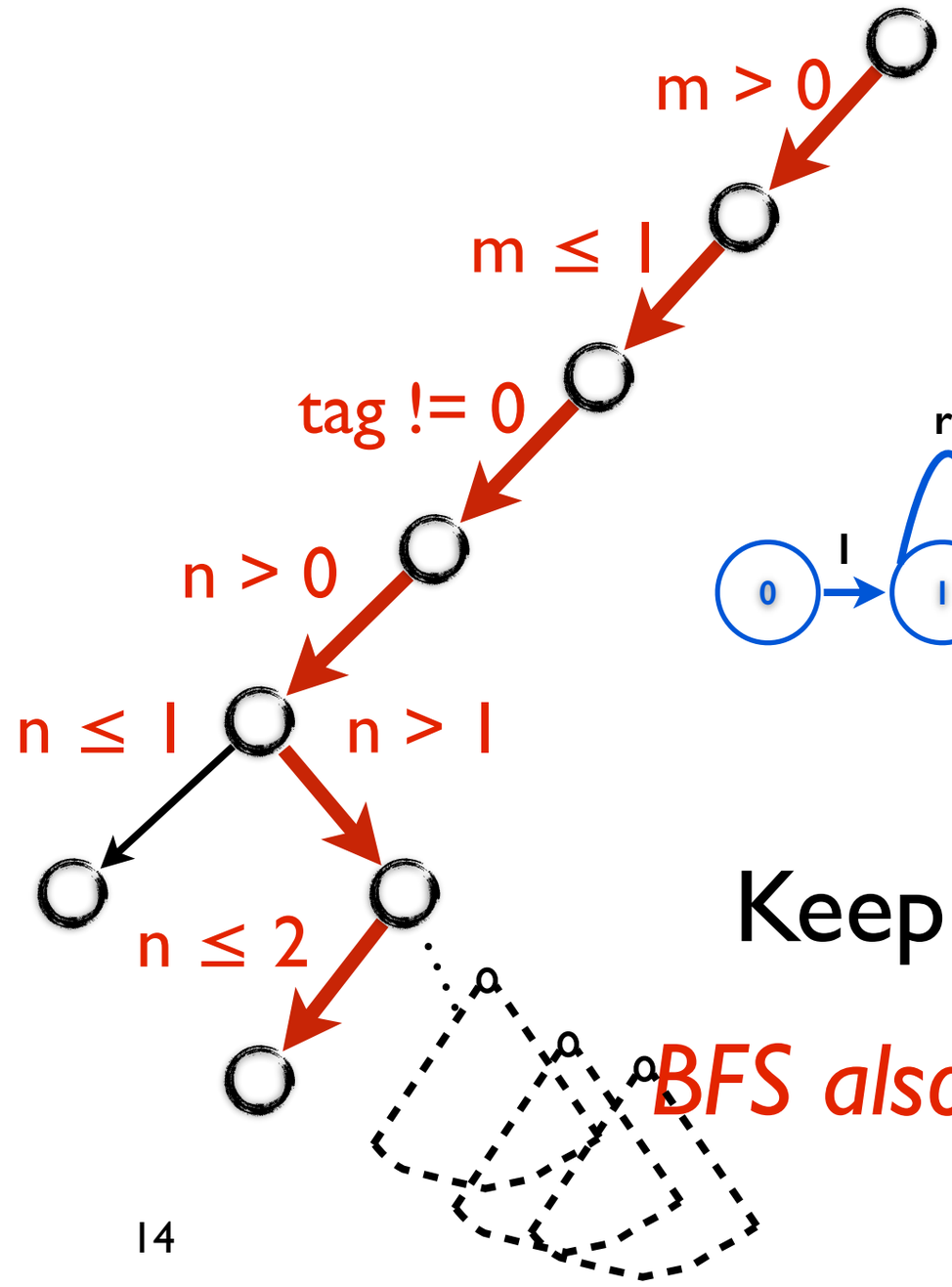


Keep unfolding

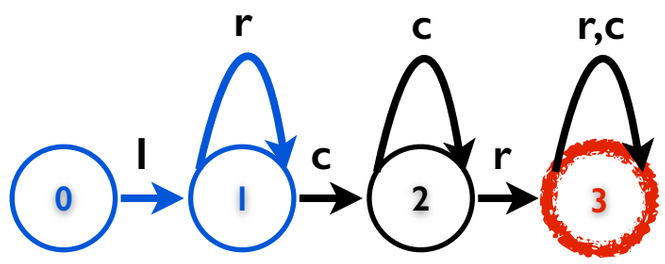
Pure DSE-2nd Iteration

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

(m=1, n=2, tag=1)



DFS

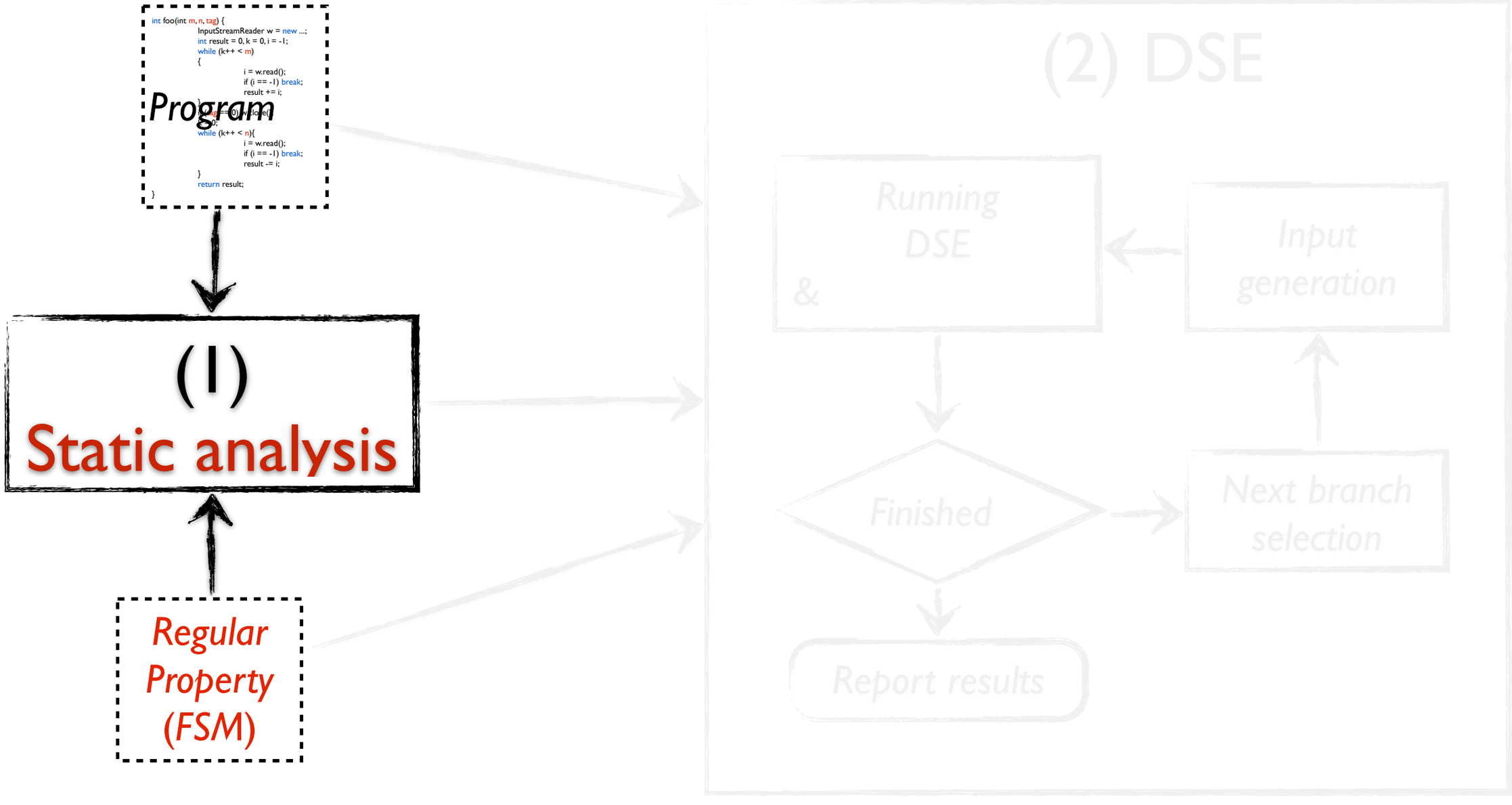


Keep unfolding

BFS also gets stuck

Guided DSE

Guided DSE Procedure



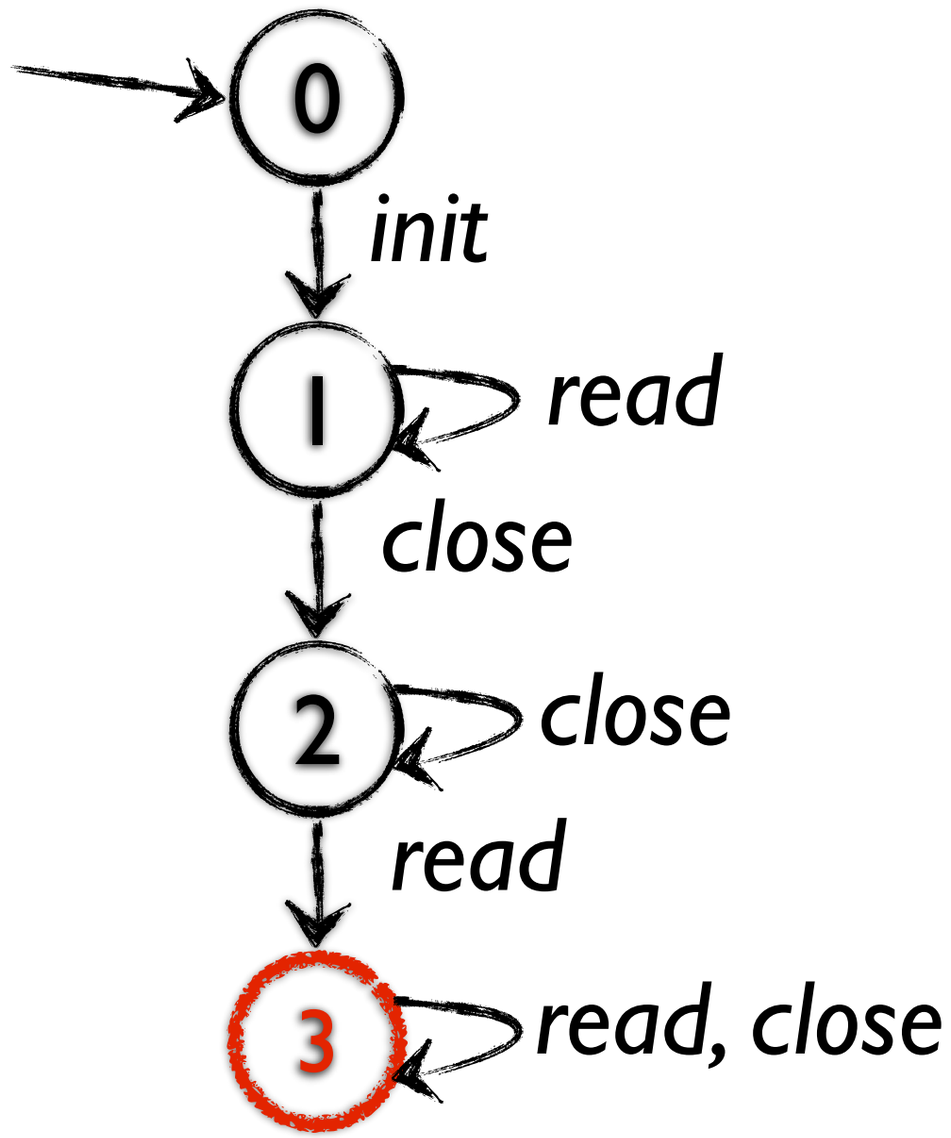
Postset Calculation

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0)
       w.close();
   k = 0;
   while (k++ < n)
   {
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

Postset

Calculation

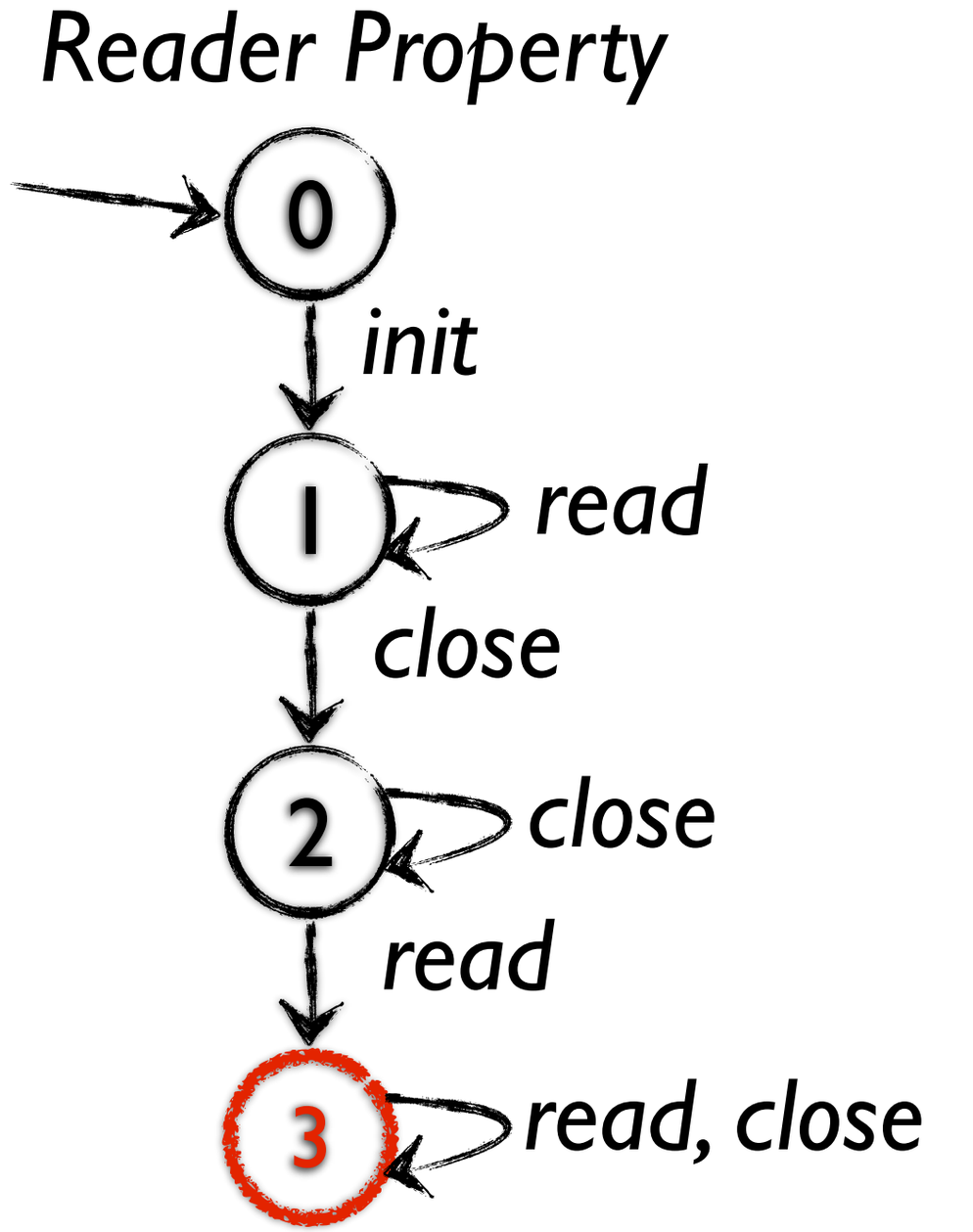
Reader Property



Backward data flow analysis [Clara, ICSE'10]

$O(|E| \times |D|^3)$

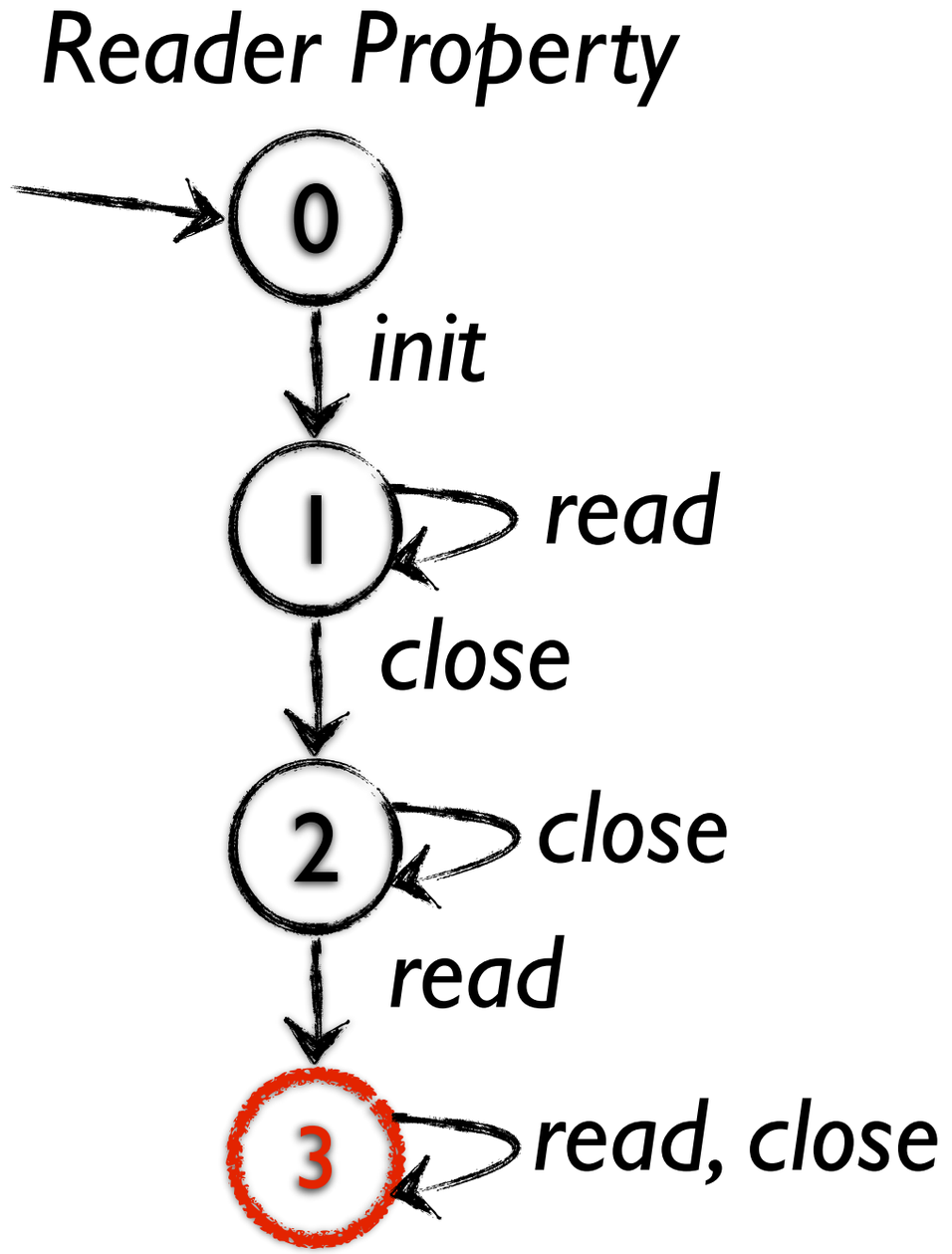
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```



Backward IFDS data flow analysis

$O(|E| \times |D|^3)$

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```



Backward IFDS data flow analysis

$O(|E| \times |D|^3)$

```
int foo(int m, n, tag) {
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      if (i == -1) break; //{1,2,3}
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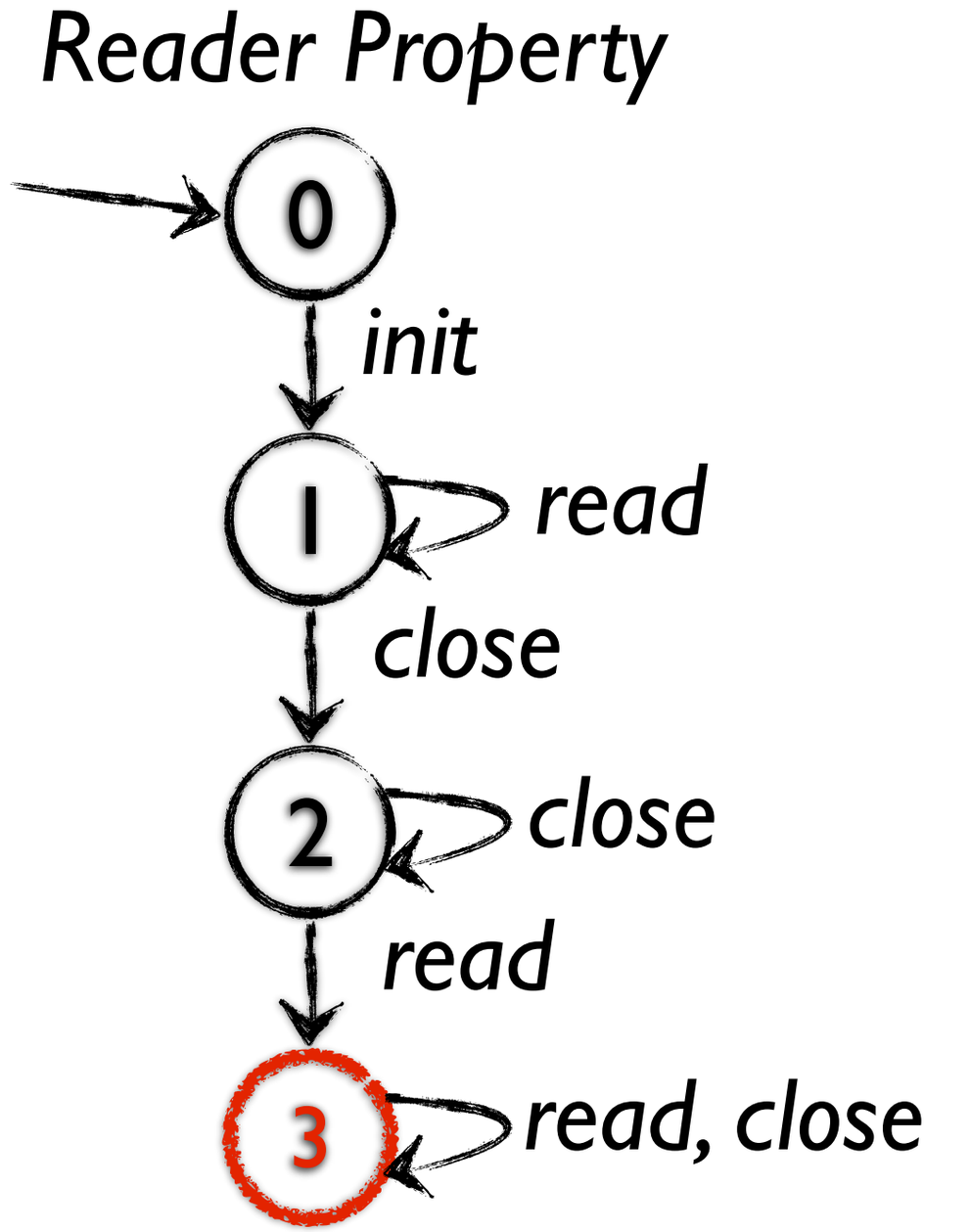
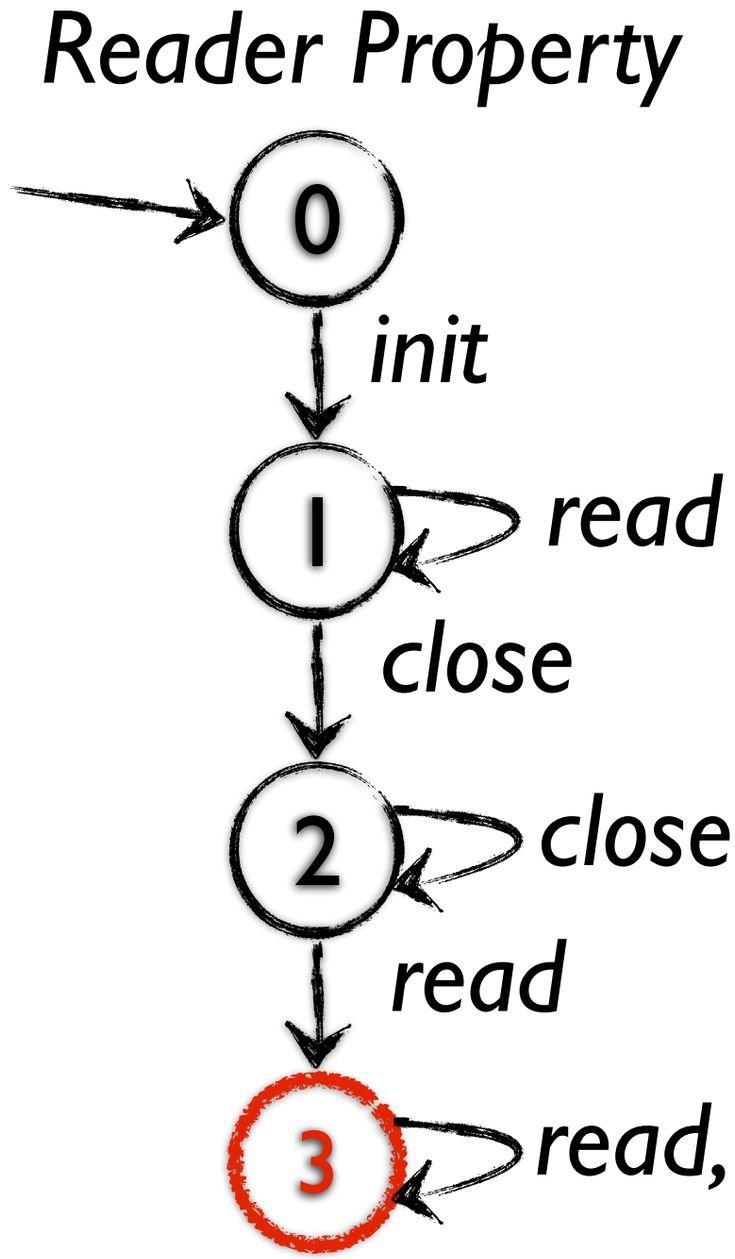
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```



Backward IFDS data flow analysis

$O(|E| \times |D|^3)$

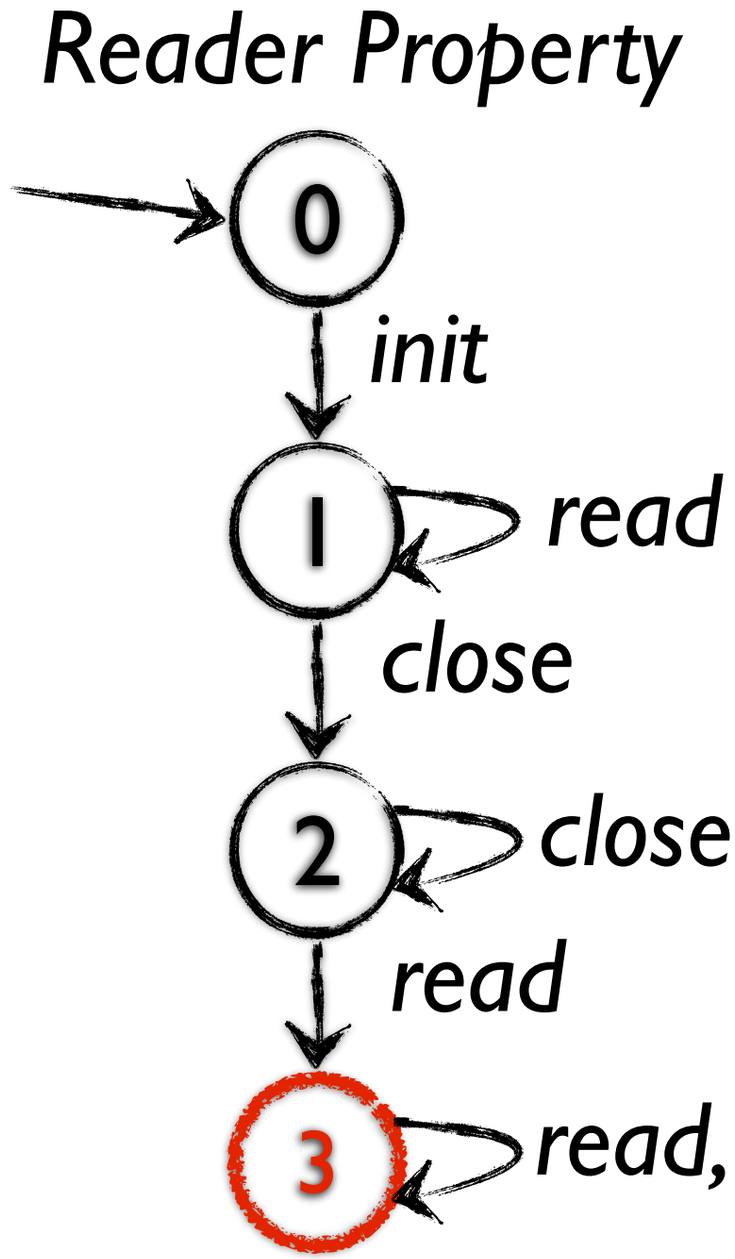
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```



Backward IFDS data flow analysis

$O(|E| \times |D|^3)$

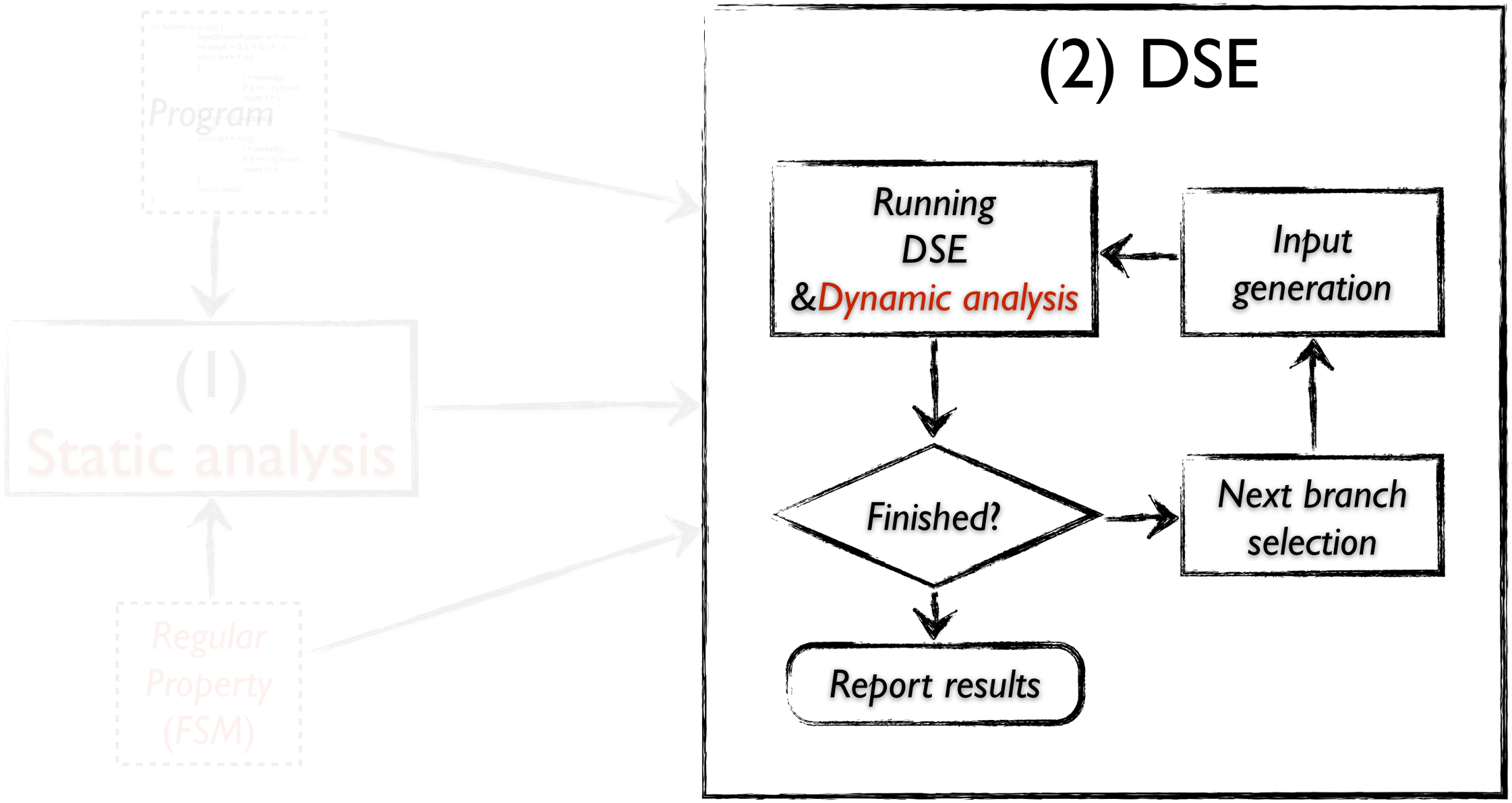
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
      w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```



Backward IFDS
data flow analysis

$O(|E| \times |D|^3)$

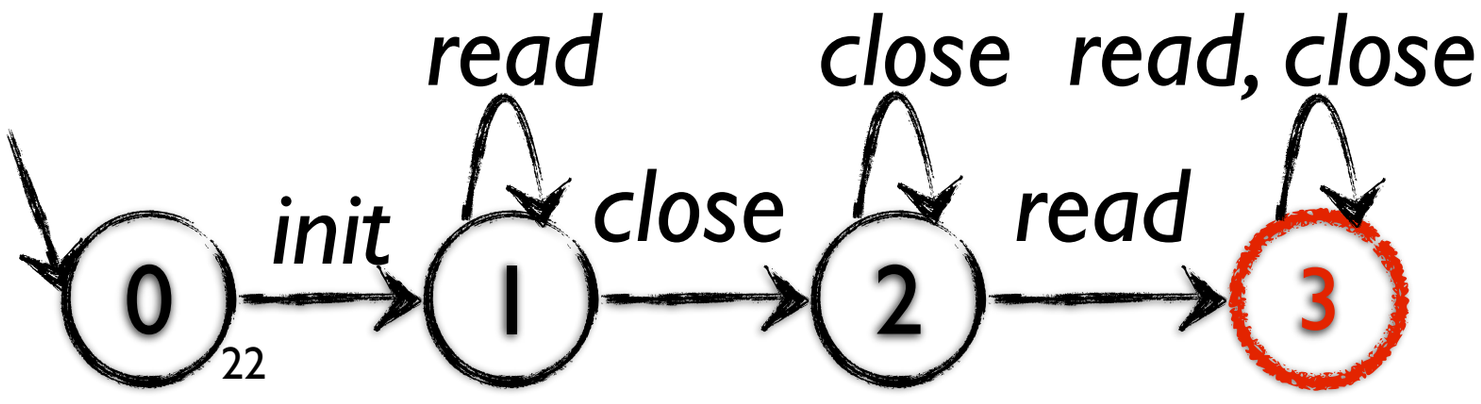
Guided DSE Procedure



Preset-1st Iteration

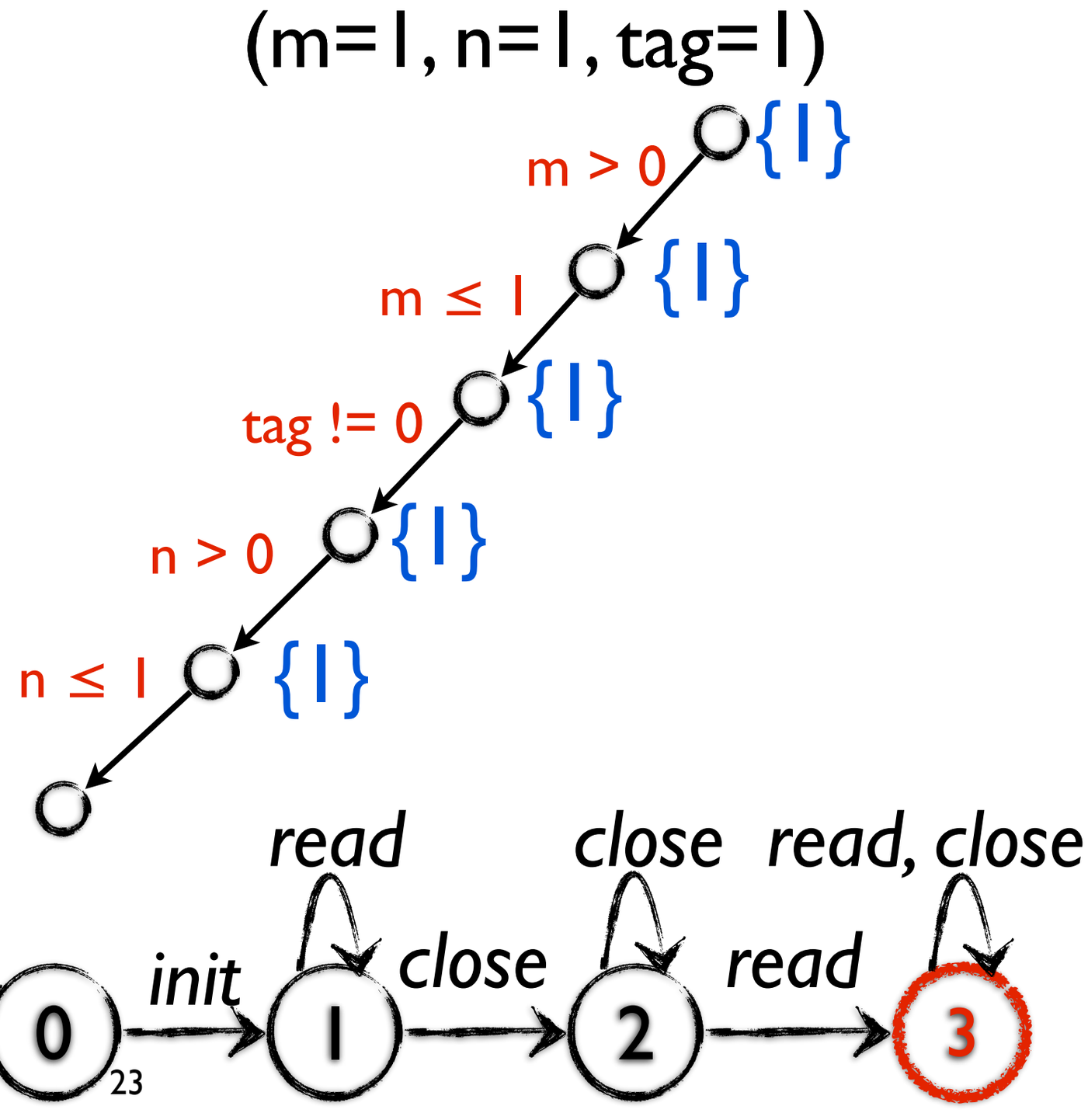
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

(m=1, n=1, tag=1)



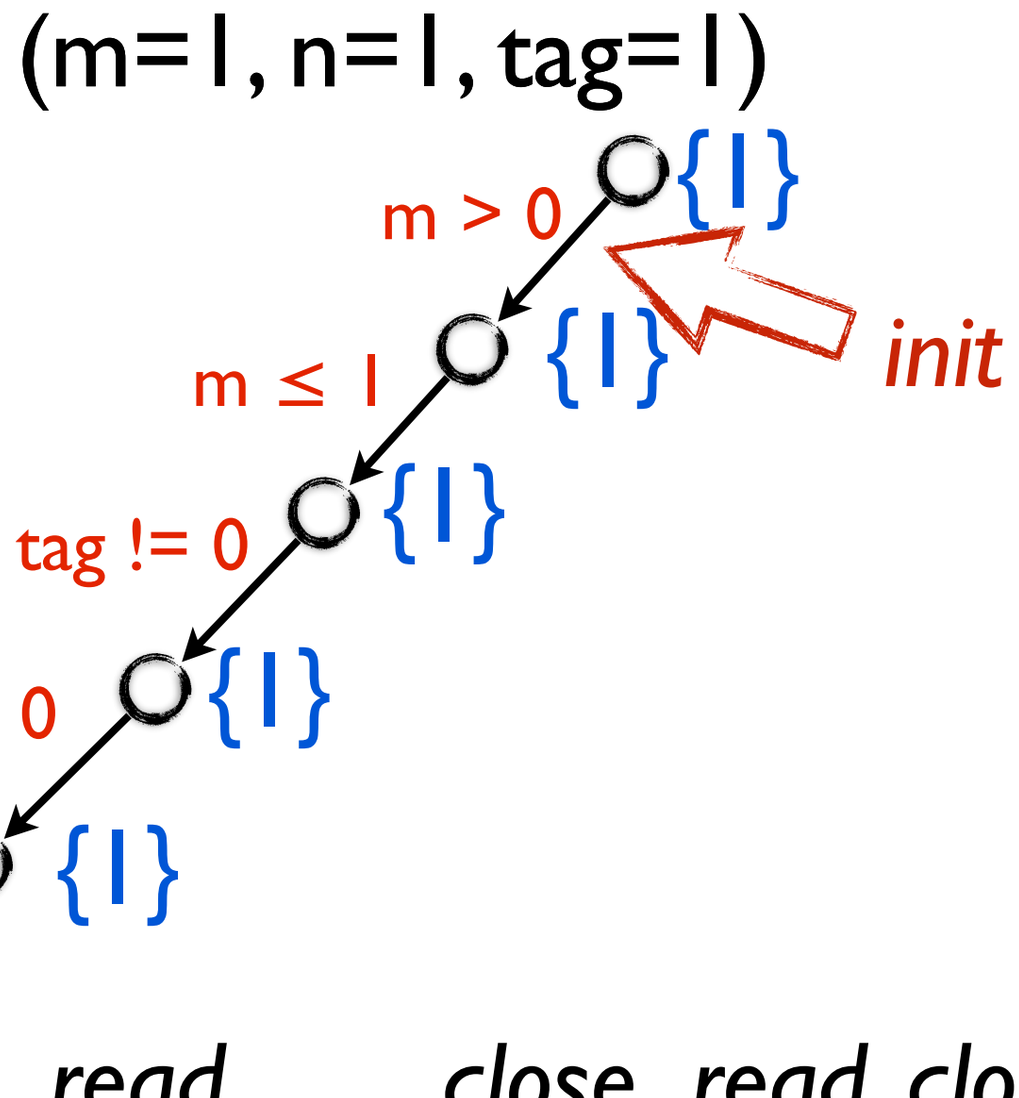
Preset-1st Iteration

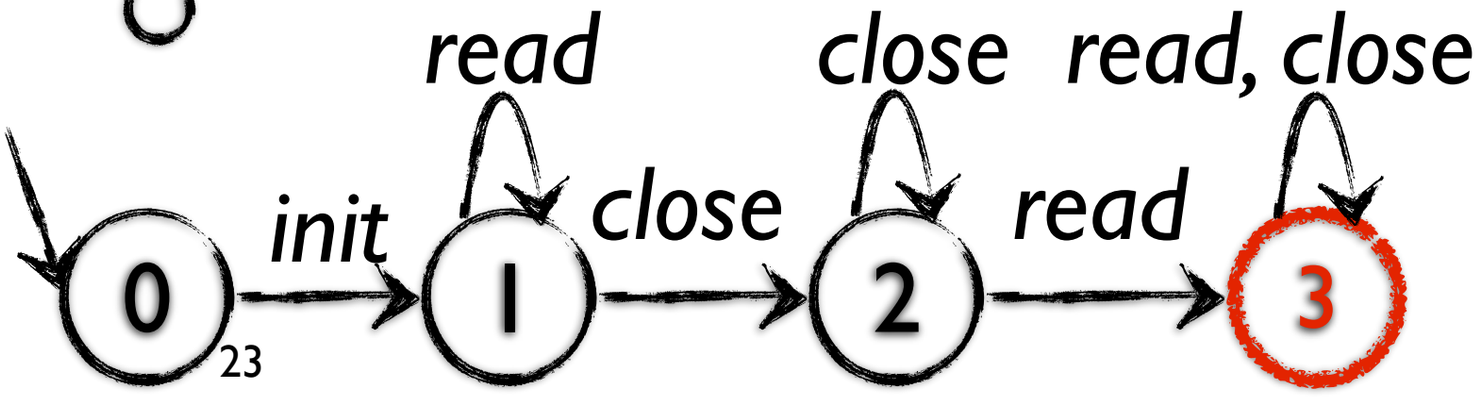
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```



Preset-1st Iteration

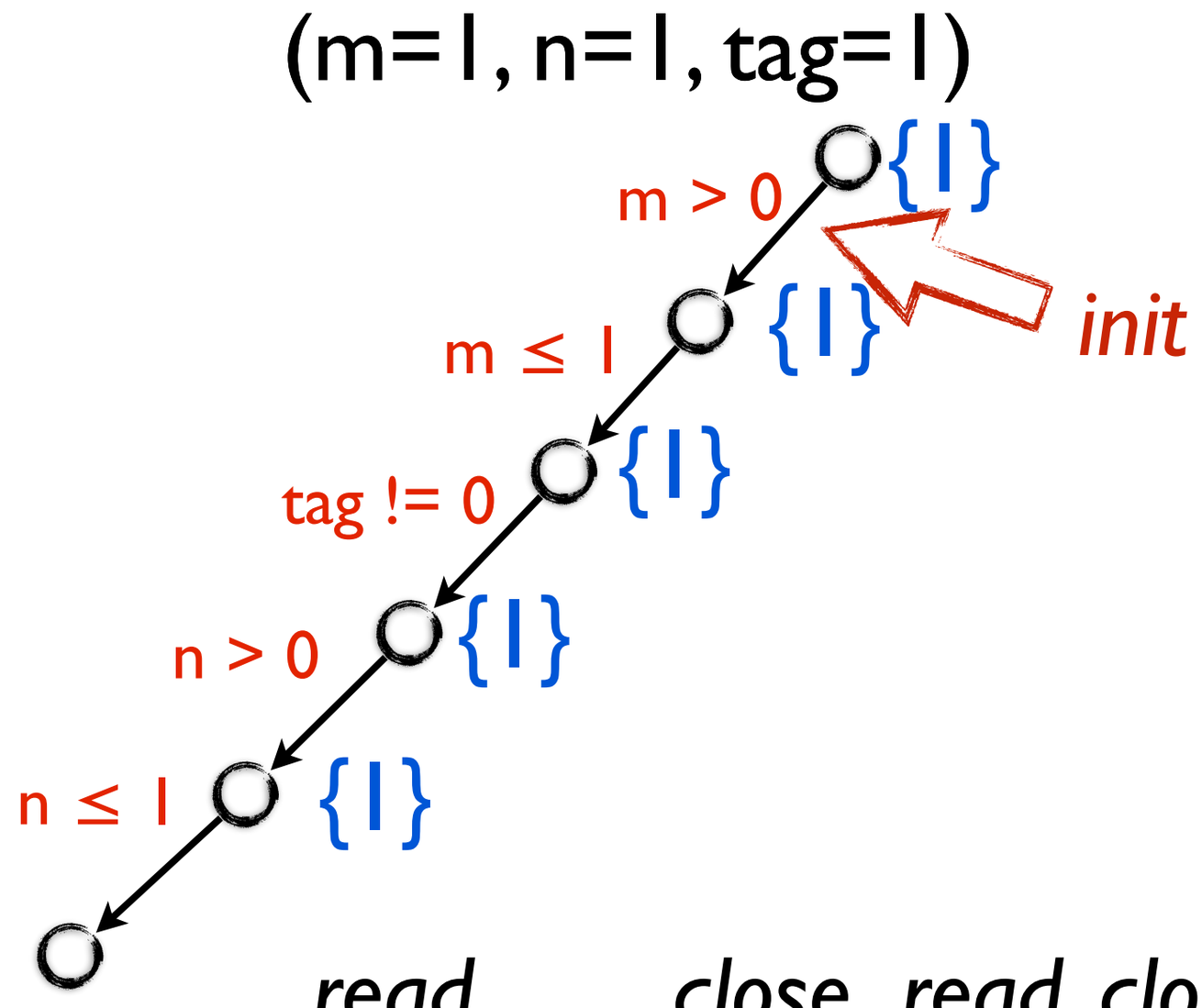
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

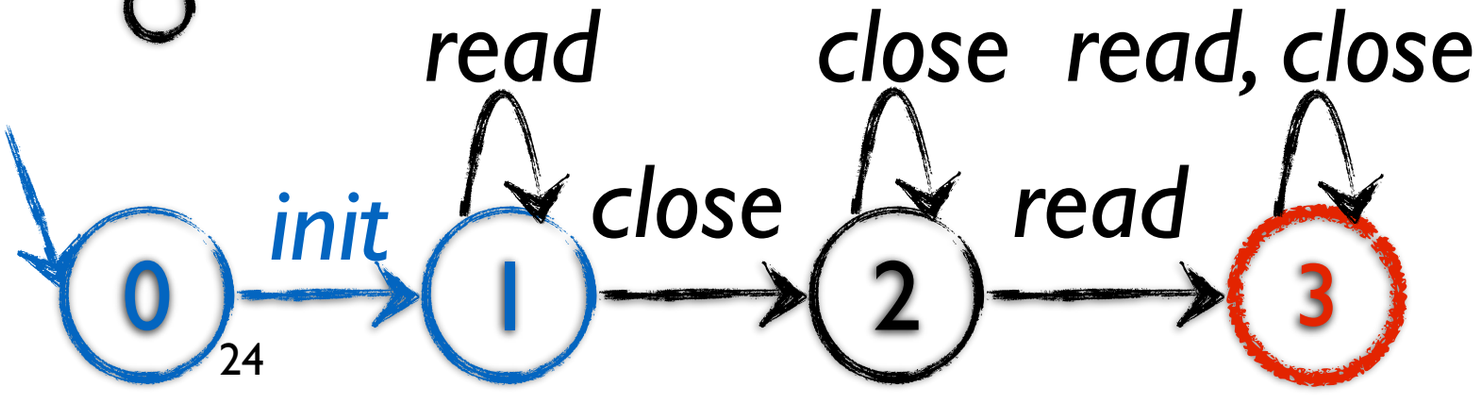




Preset-1st Iteration

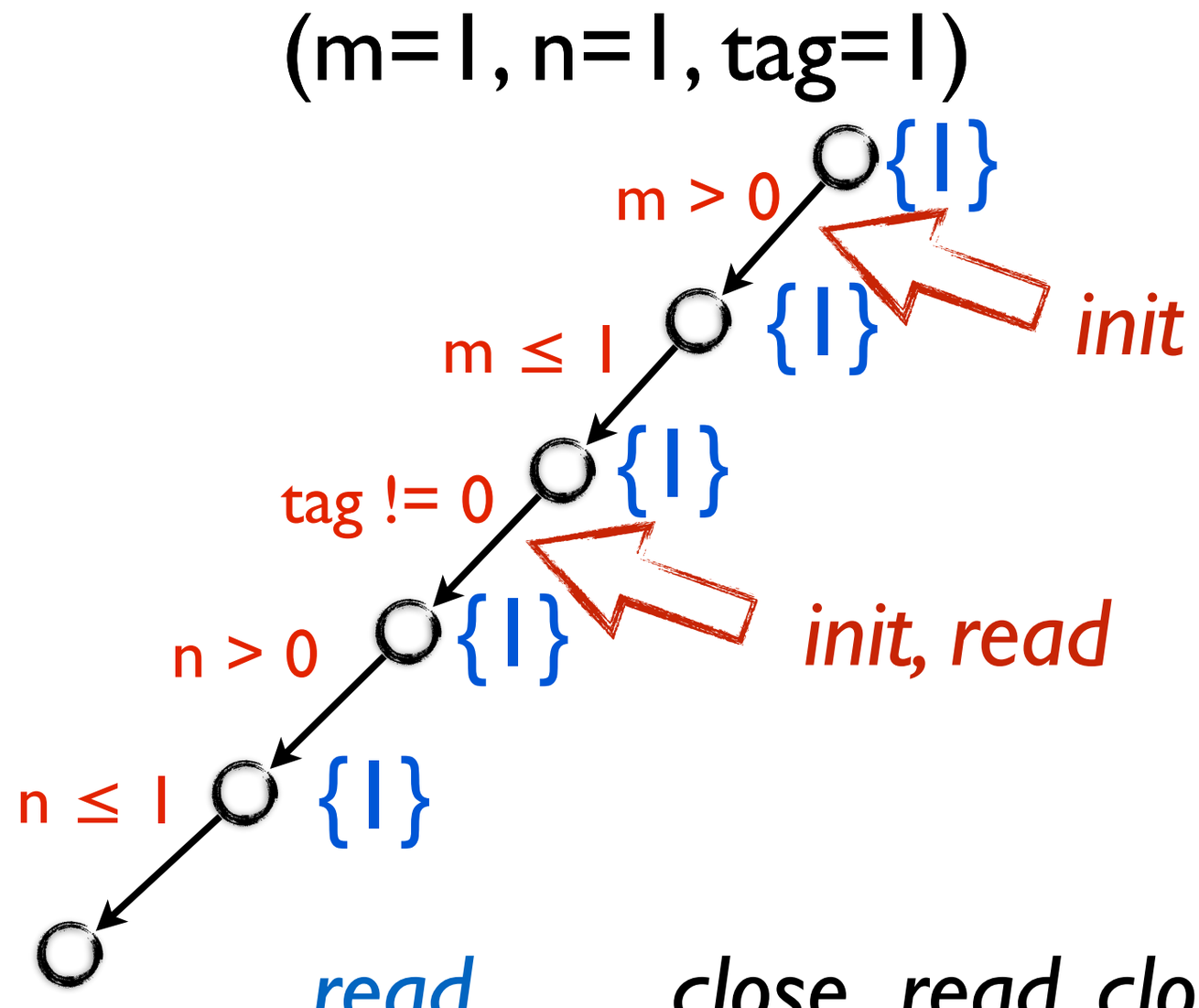
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

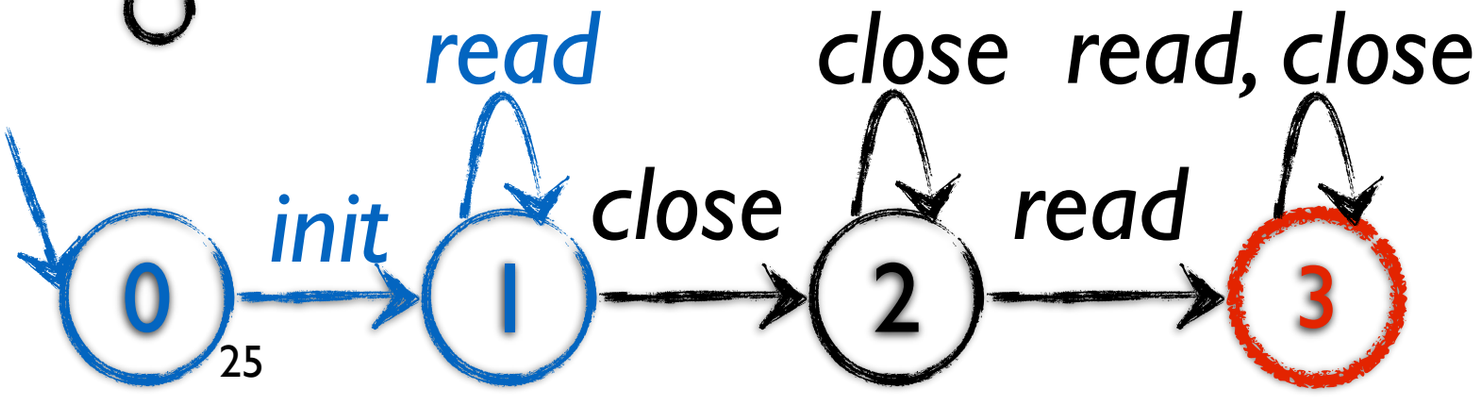




Preset-1st Iteration

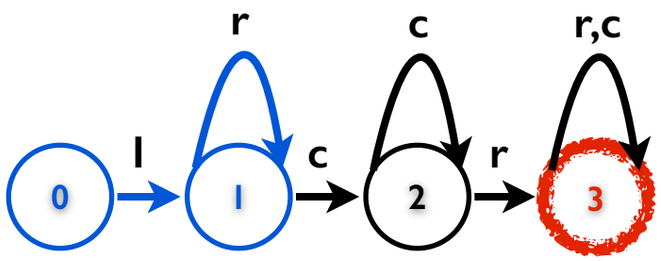
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...;
   int result = 0, k = 0, i = -1;
   while (k++ < m)
   {
      i = w.read();
      if (i == -1) break;
      result += i;
   }
   if (tag == 0) w.close();
   k = 0;
   while (k++ < n){
      i = w.read();
      if (i == -1) break;
      result -= i;
   }
   return result;
}
```

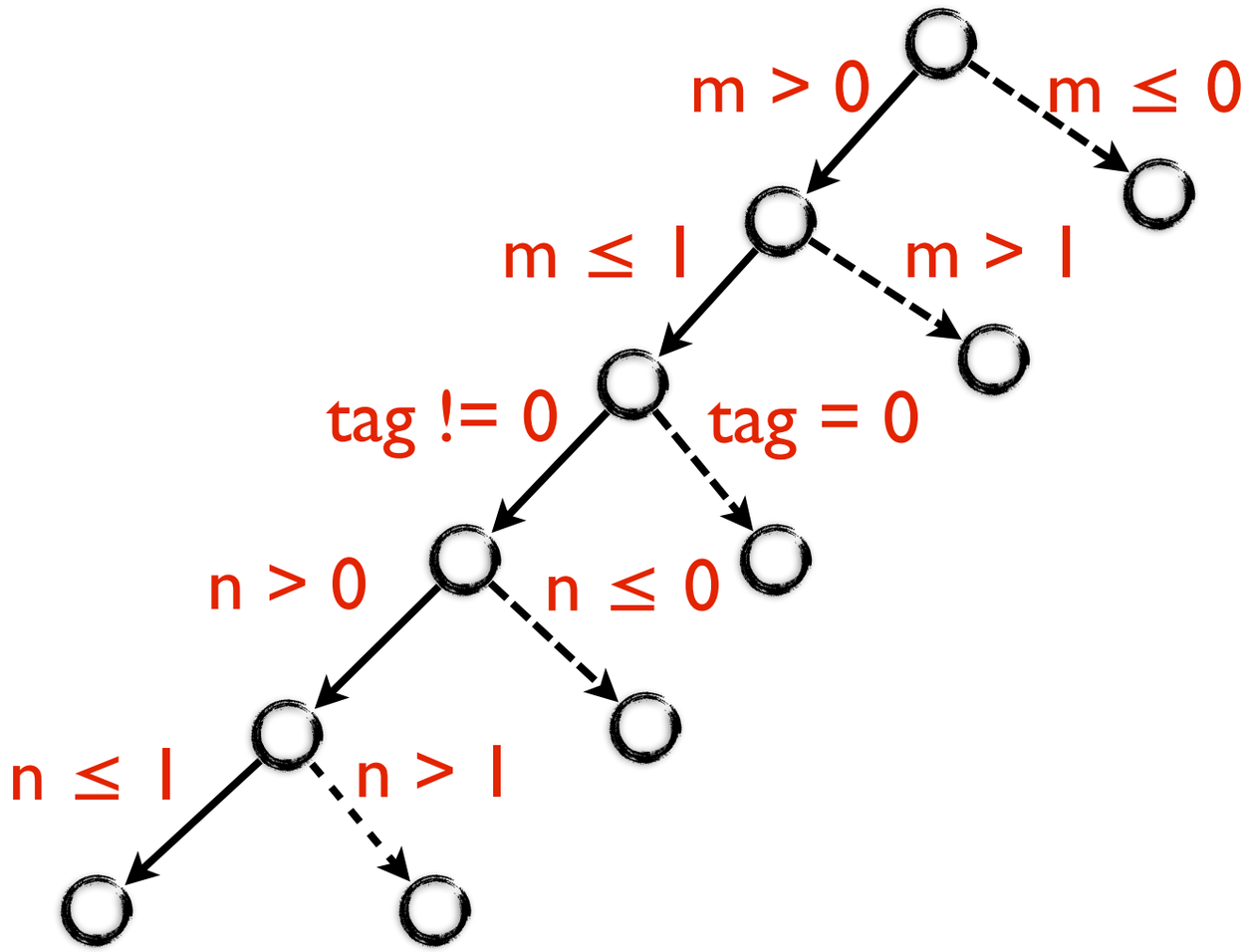




Guided DSE-1st Iteration

(m=1, n=1, tag=1)

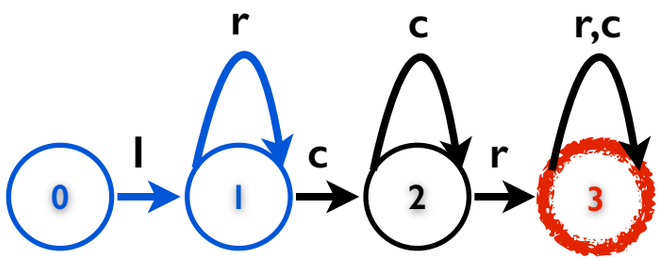


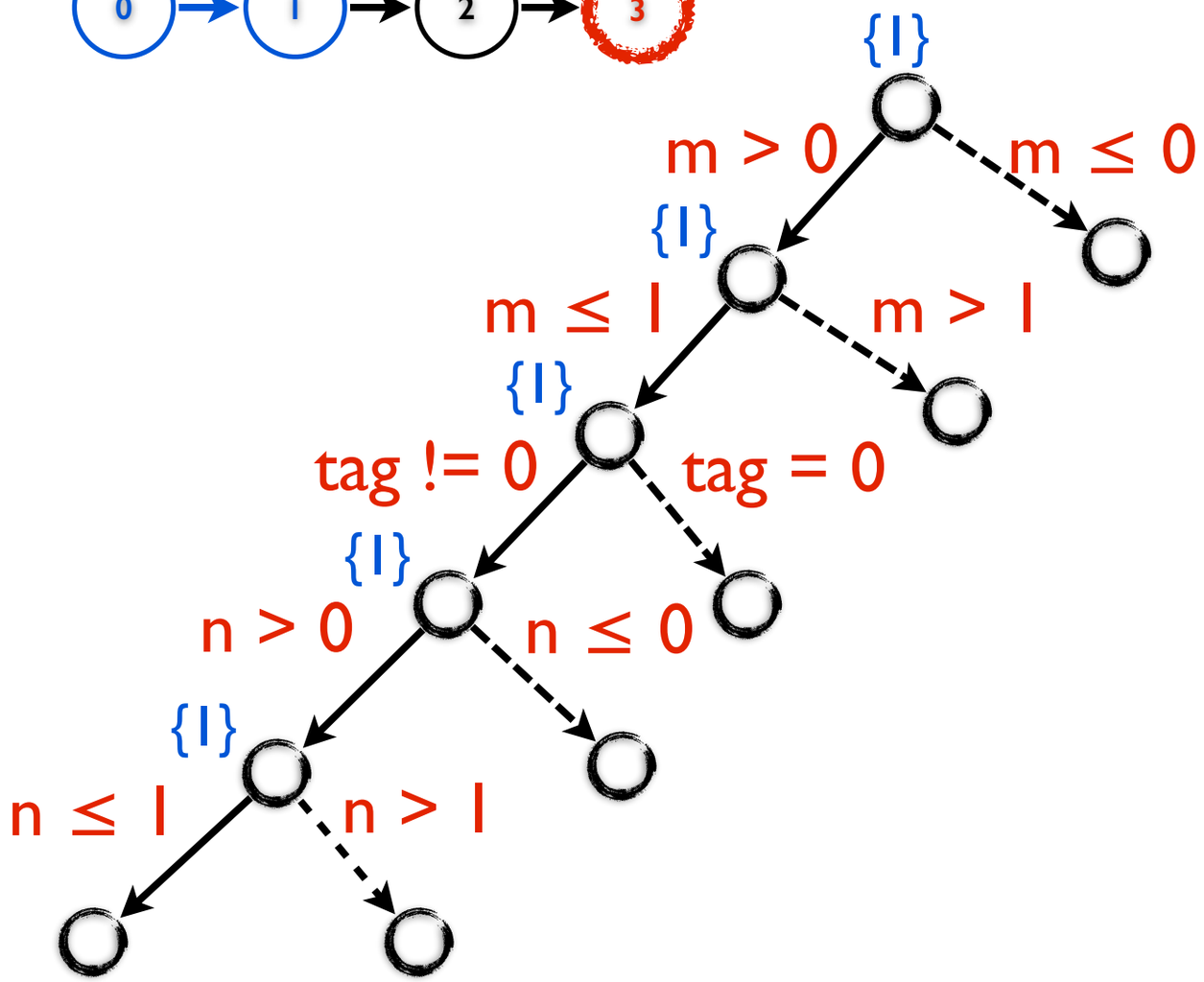



```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE-1st Iteration

(m=1, n=1, tag=1)

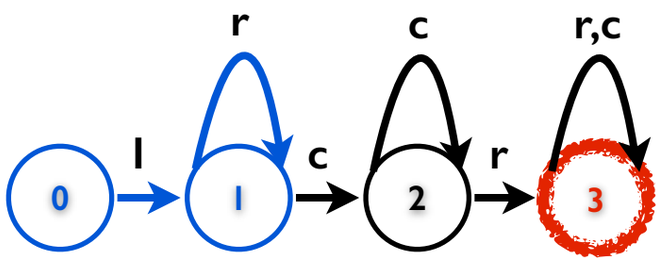


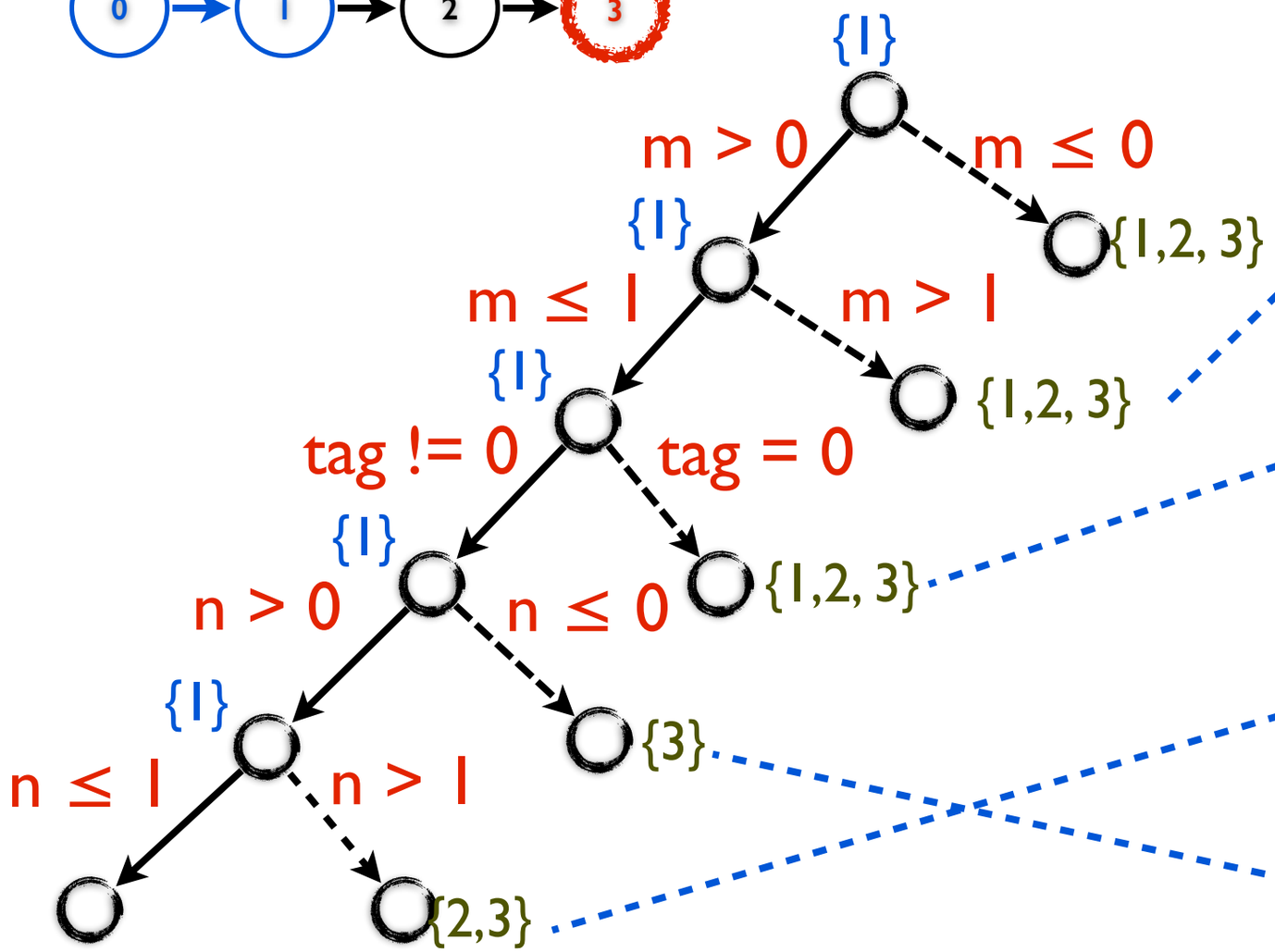



```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE-1st Iteration

(m=1, n=1, tag=1)

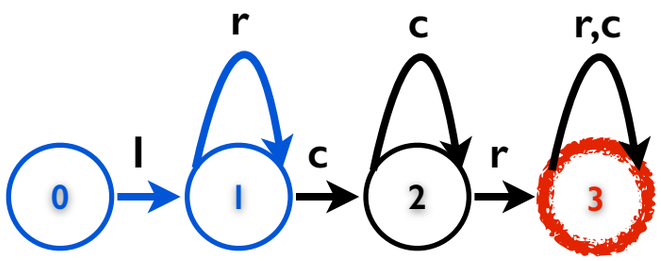


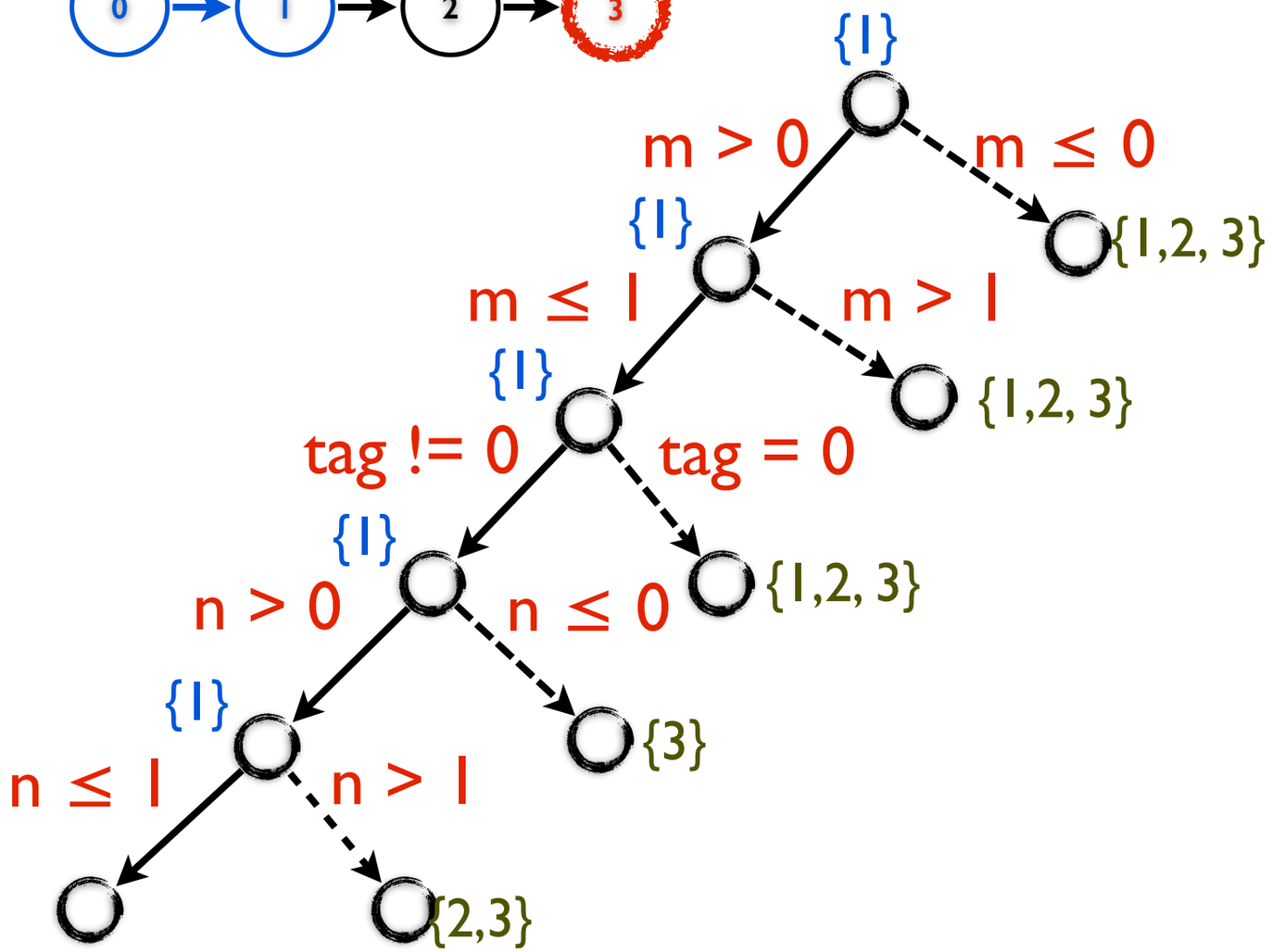



```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
      w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE-1st Iteration

(m=1, n=1, tag=1)

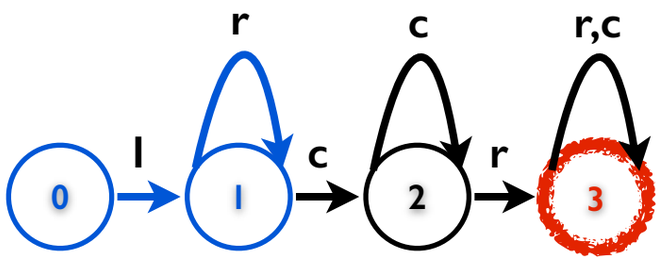


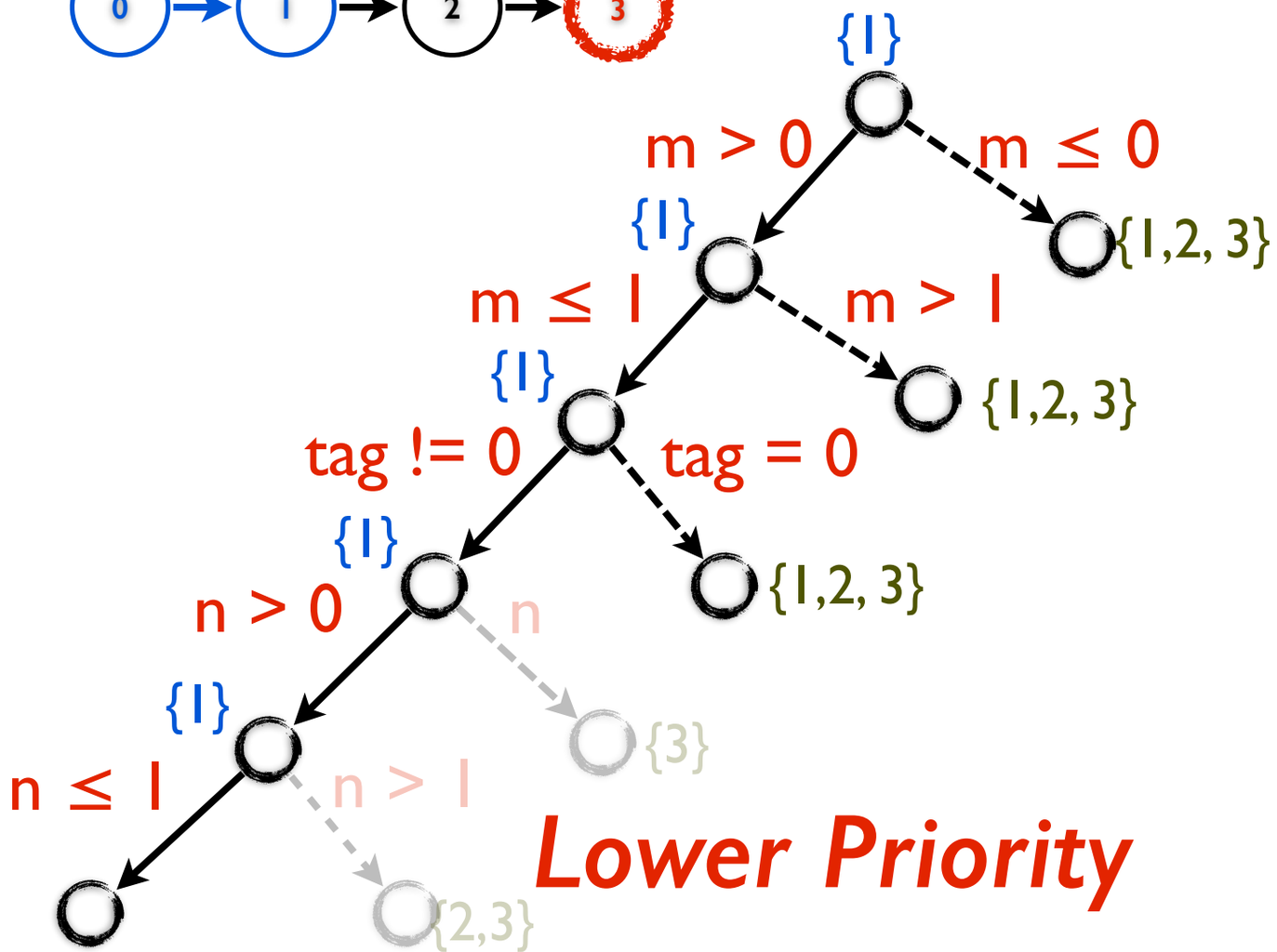



```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE-1st Iteration

(m=1, n=1, tag=1)



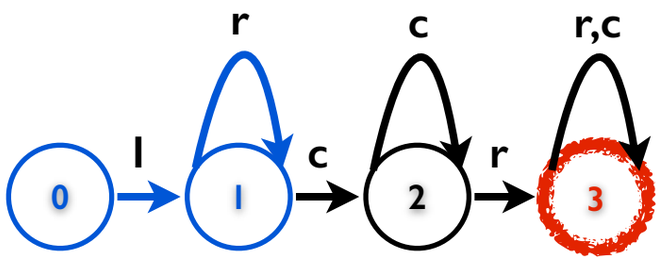


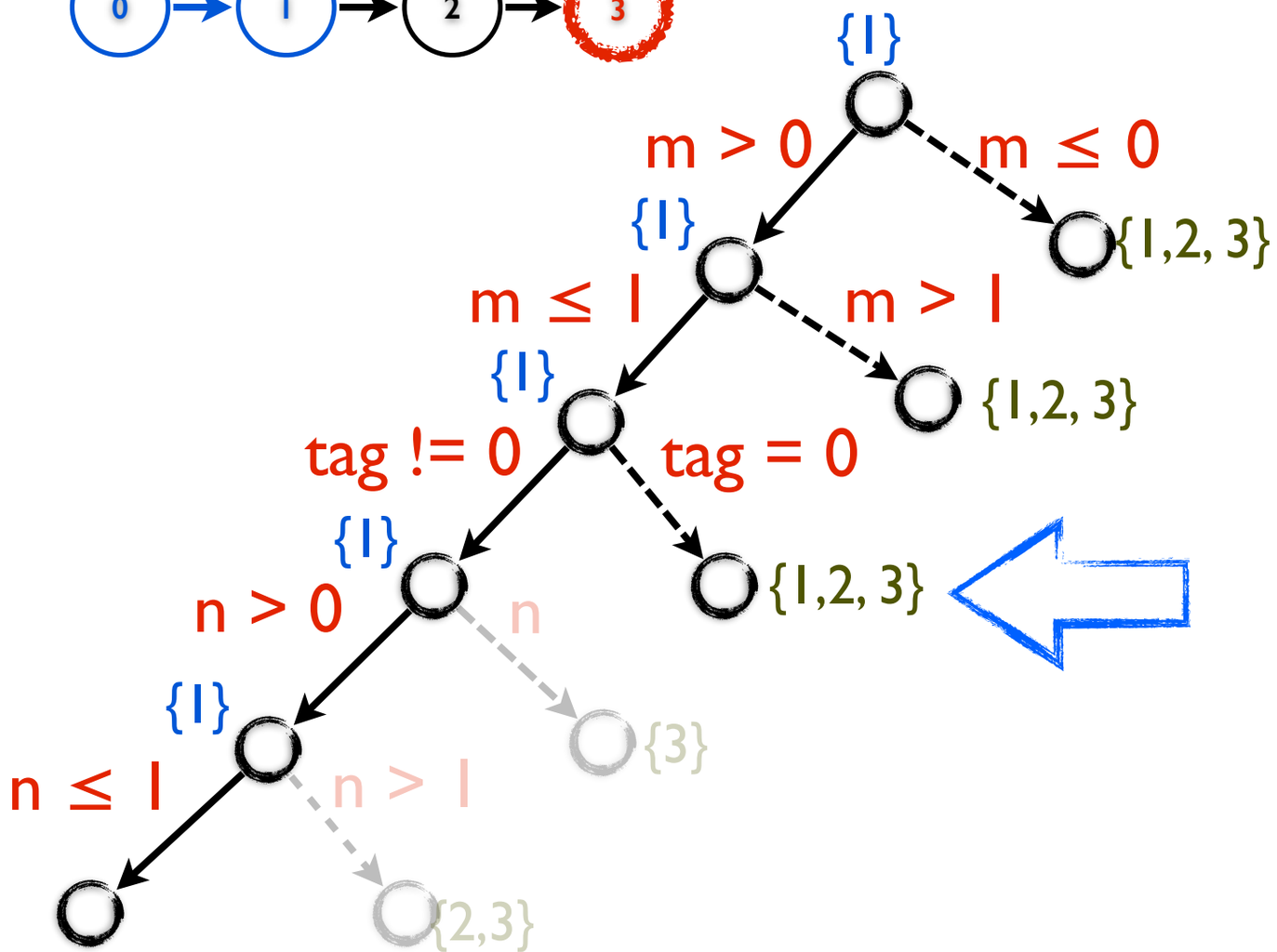
Lower Priority

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE-1st Iteration

(m=1, n=1, tag=1)

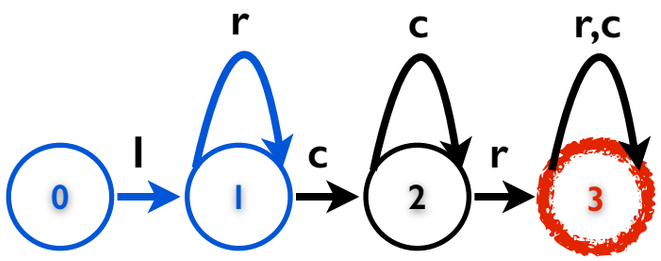


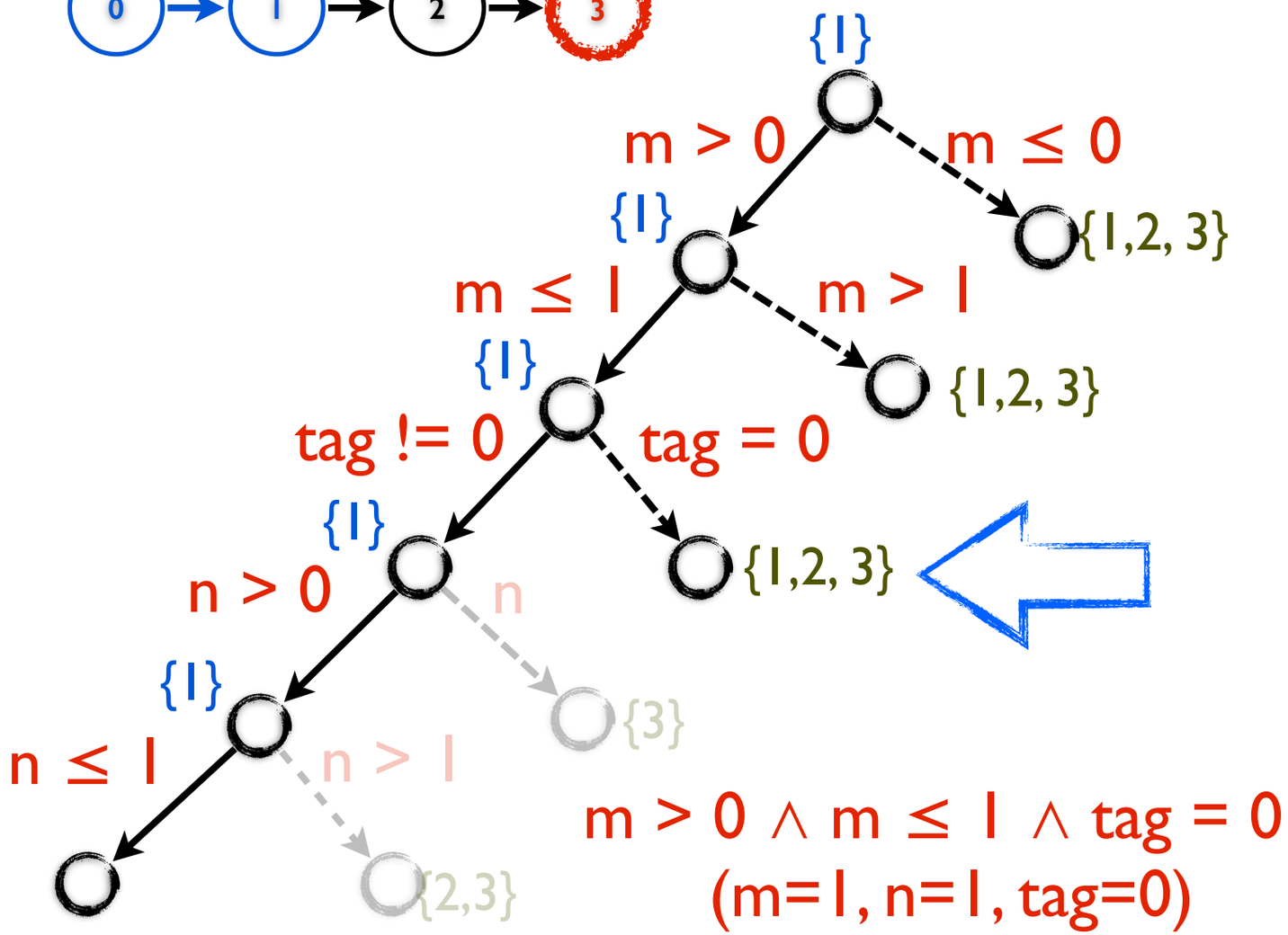



```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE-1st Iteration

(m=1, n=1, tag=1)





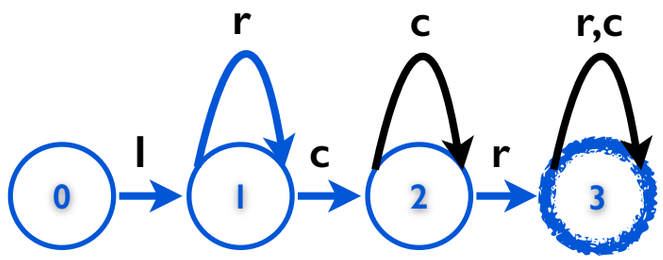
m > 0 ∧ m ≤ 1 ∧ tag = 0

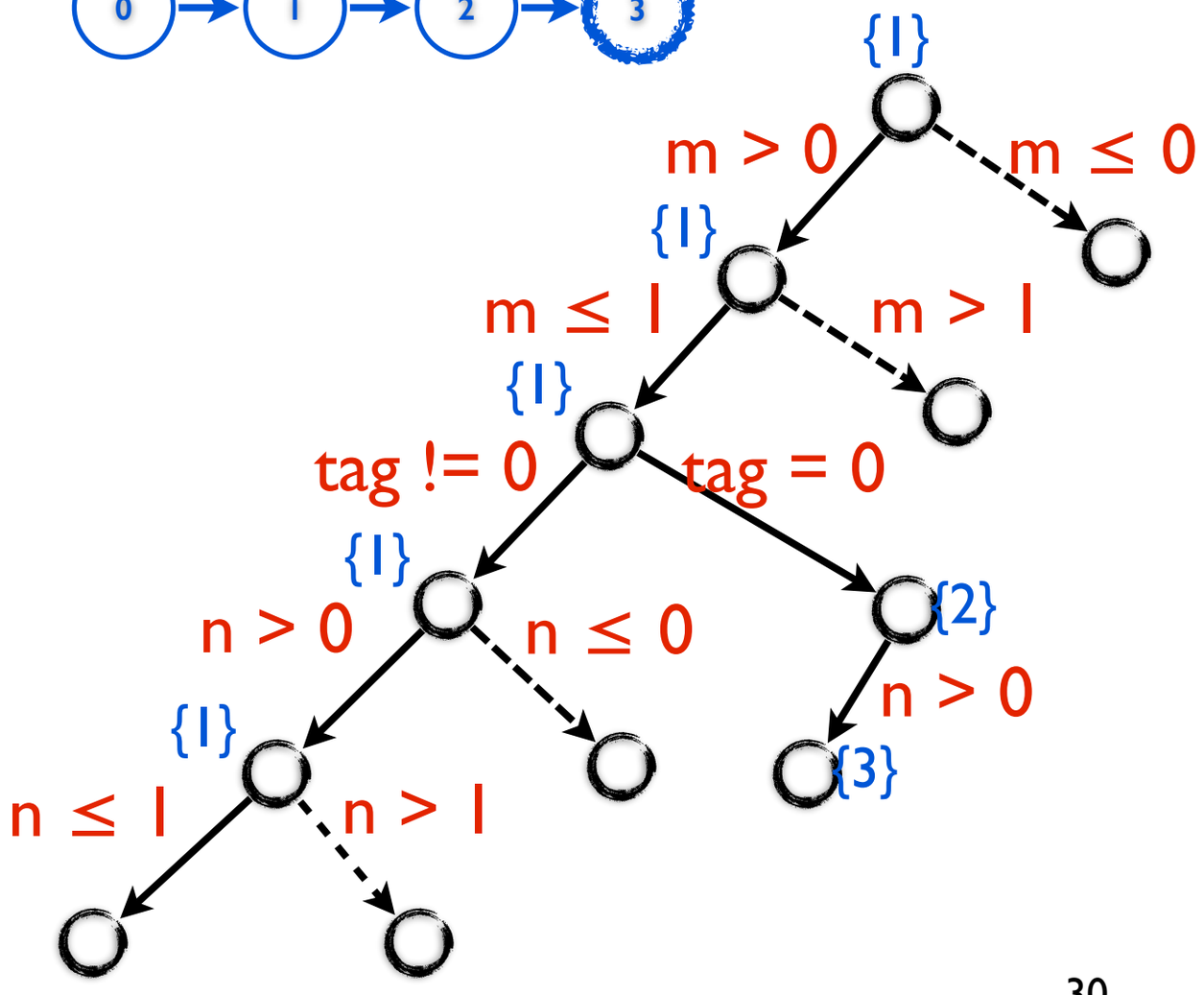
(m=1, n=1, tag=0)

```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE-2nd Iteration

(m=1, n=1, tag=0)

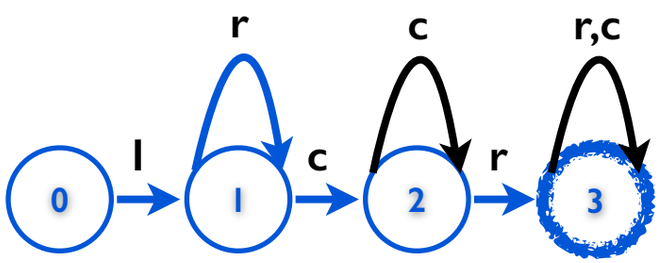


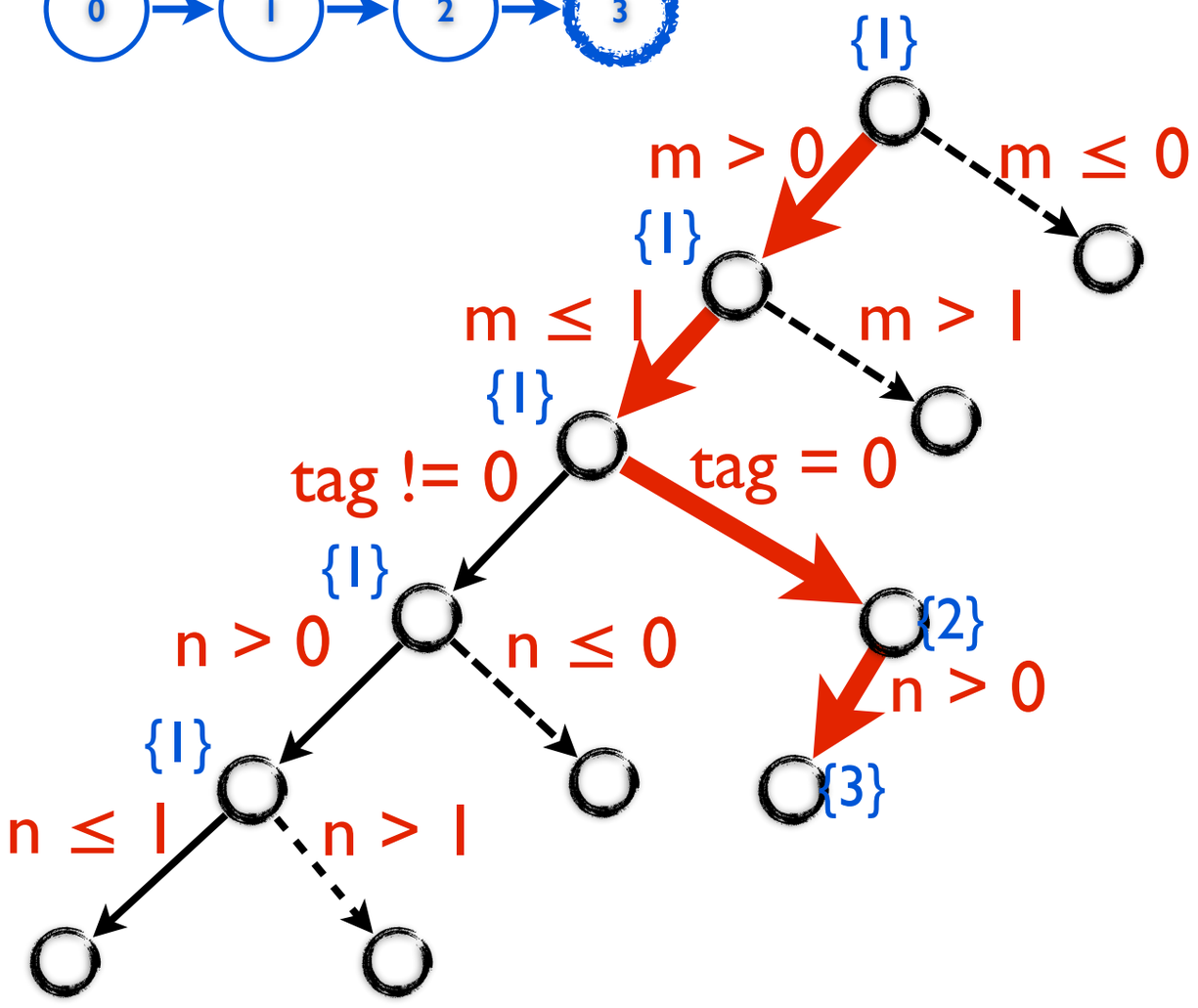



```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE

(m=1, n=1, tag=0)

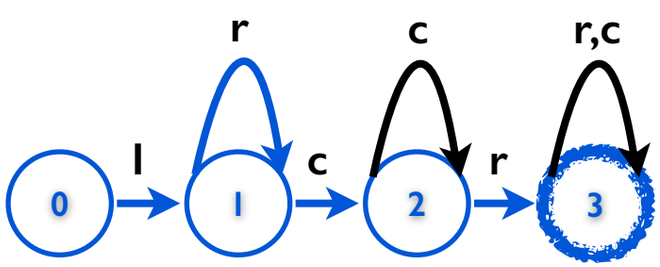


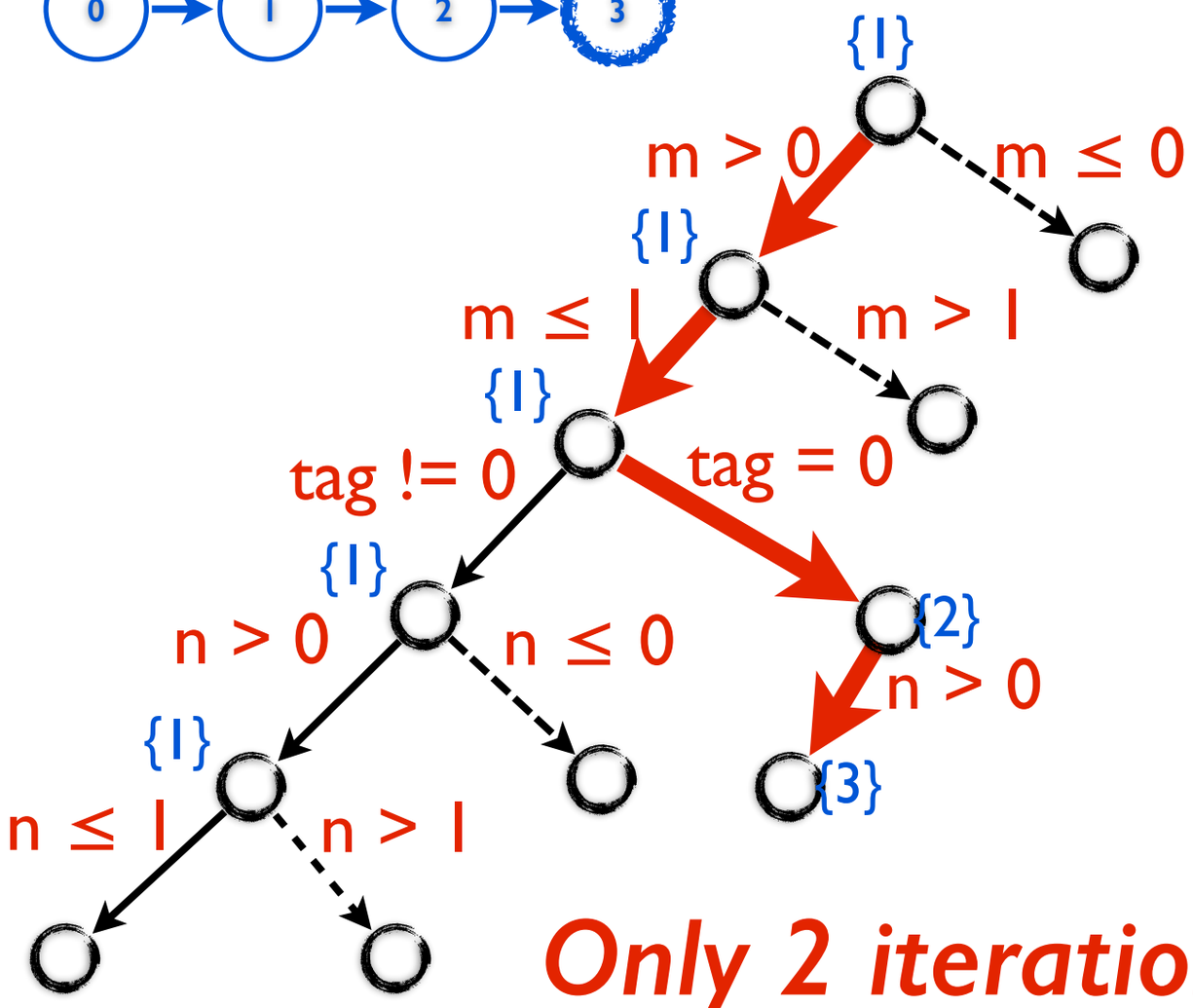



```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

Guided DSE

(m=1, n=1, tag=0)





Only 2 iterations

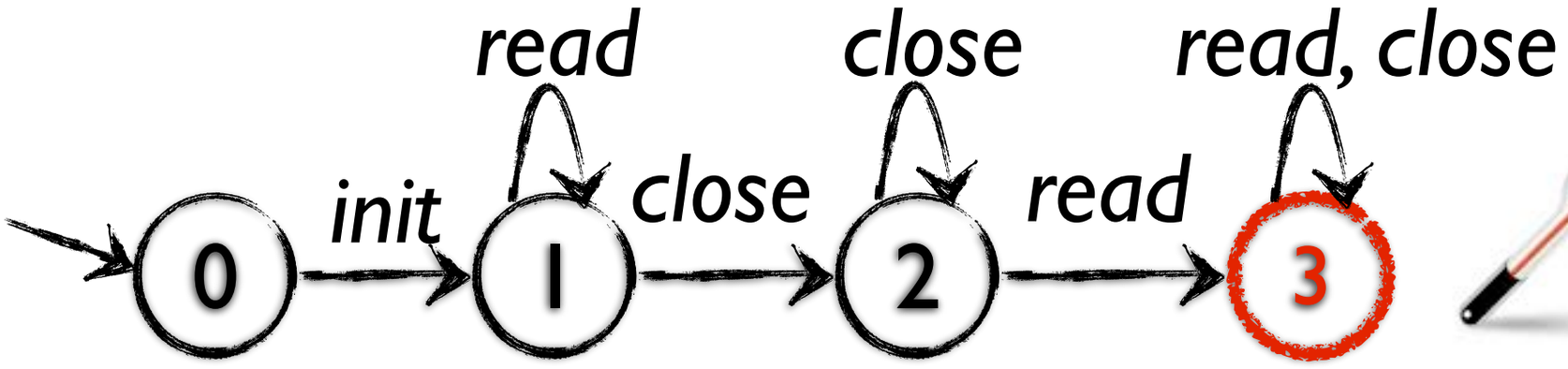
```
int foo(int m, n, tag) {
   InputStreamReader w = new ...; //{0}
   int result = 0, k = 0, i = -1; //{1,2,3}
   while (k++ < m) //{1,2,3}
   {
      i = w.read(); //{1,2,3}
      if (i == -1) break; //{1,2,3}
      result += i; //{1,2,3}
   }
   if (tag == 0) //{1,2,3}
       w.close(); //{1,2,3}
   k = 0; //{2,3}
   while (k++ < n) //{2,3}
   {
      i = w.read(); //{2,3}
      if (i == -1) break; //{2,3}
      result -= i; //{2,3}
   }
   return result; //{3}
}
```

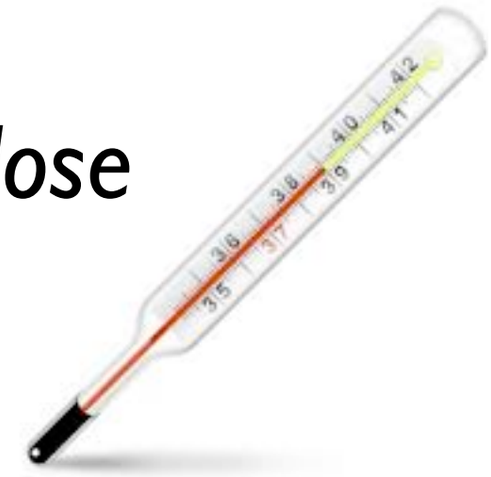
Implementation & Experiment Setup

- Implement based on JPF-JDart and WALA
- 13 real world open source Java programs
  - 225K LOC in total
- Properties
  - Typestate bug && User defined
- Analyze each program/property in 24 hours

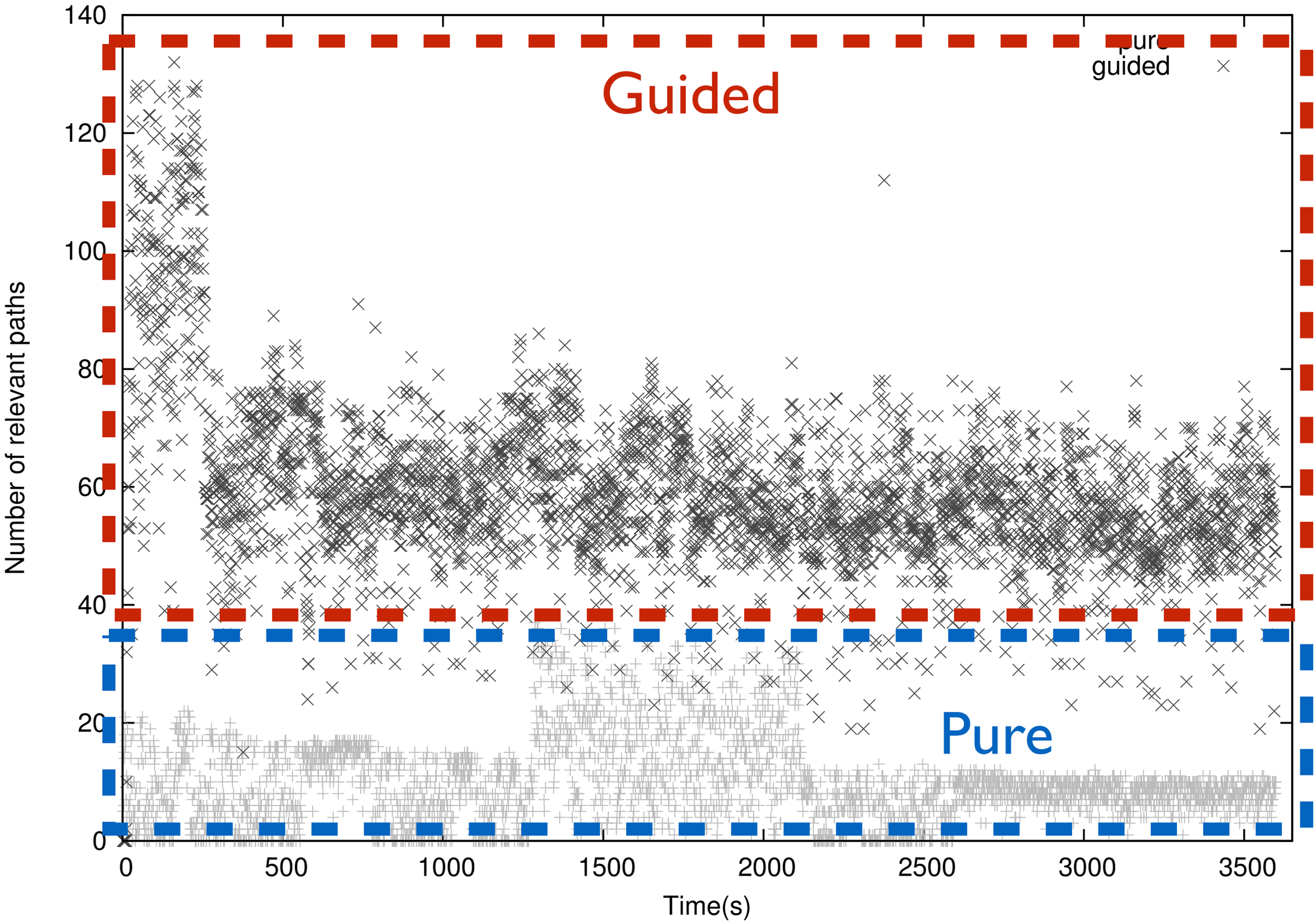
Evaluate Guiding Further

- Relevant path
- Transition times
- Shortest distance to the final state

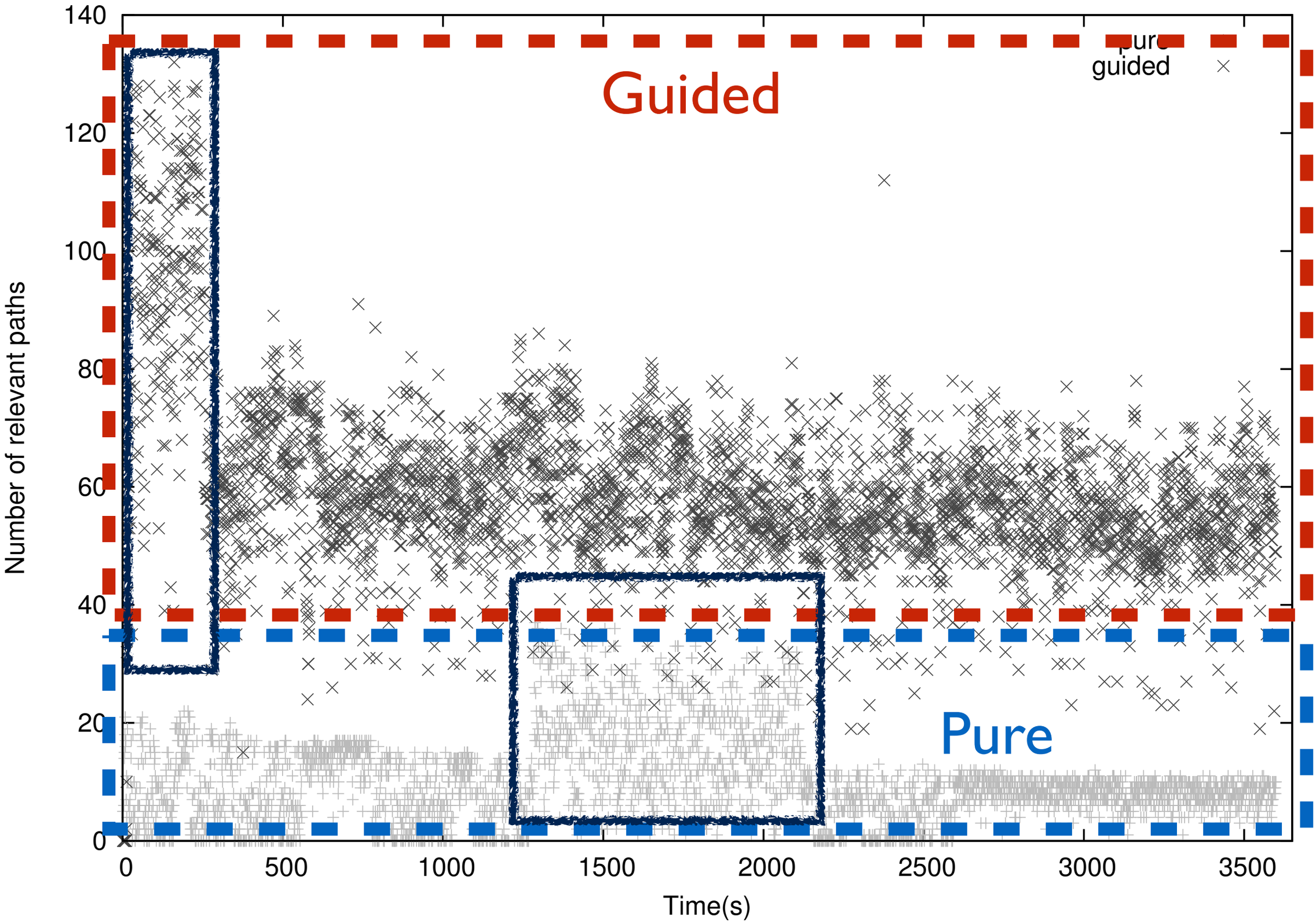




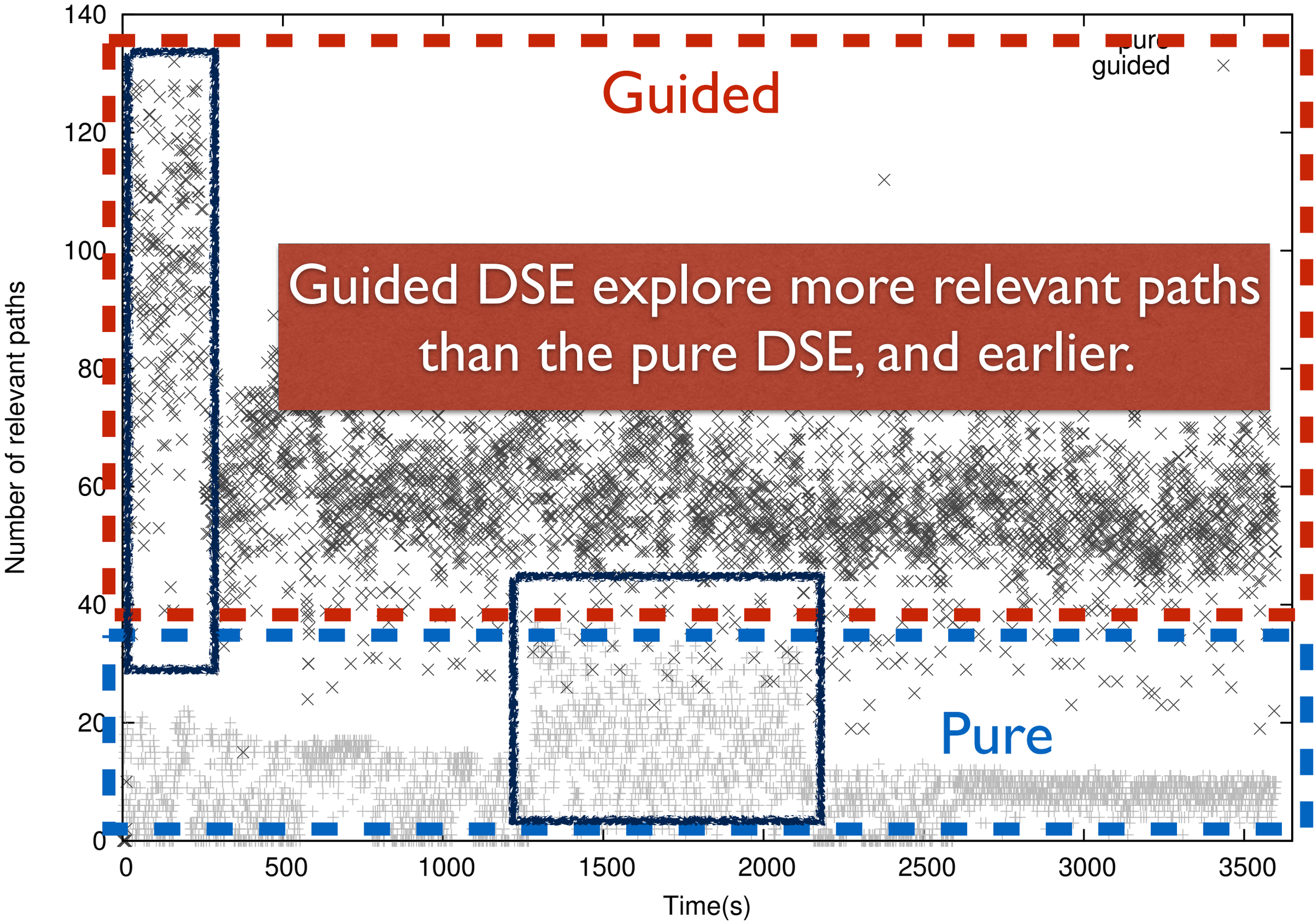
Relevant path distribution



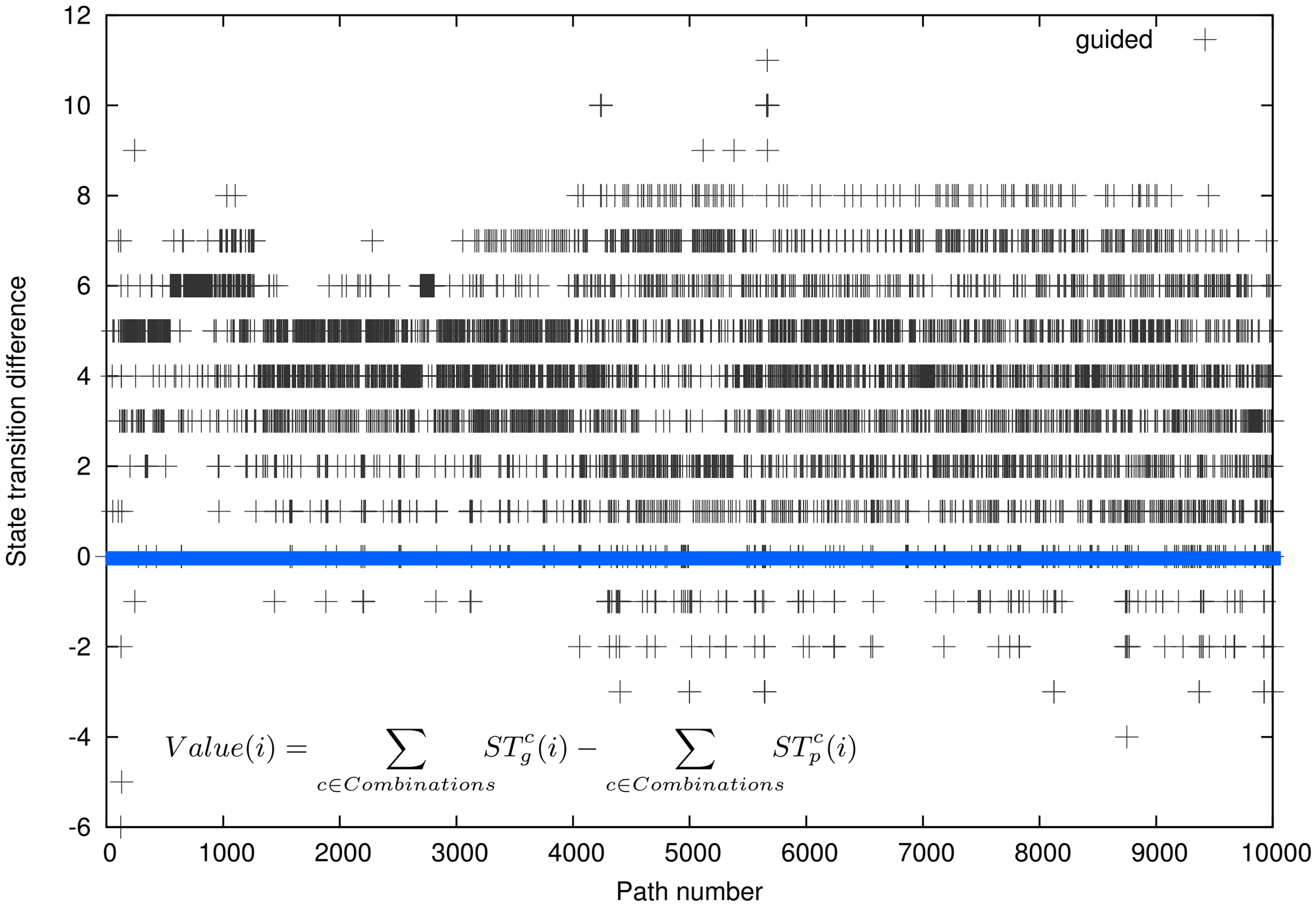
Relevant path distribution



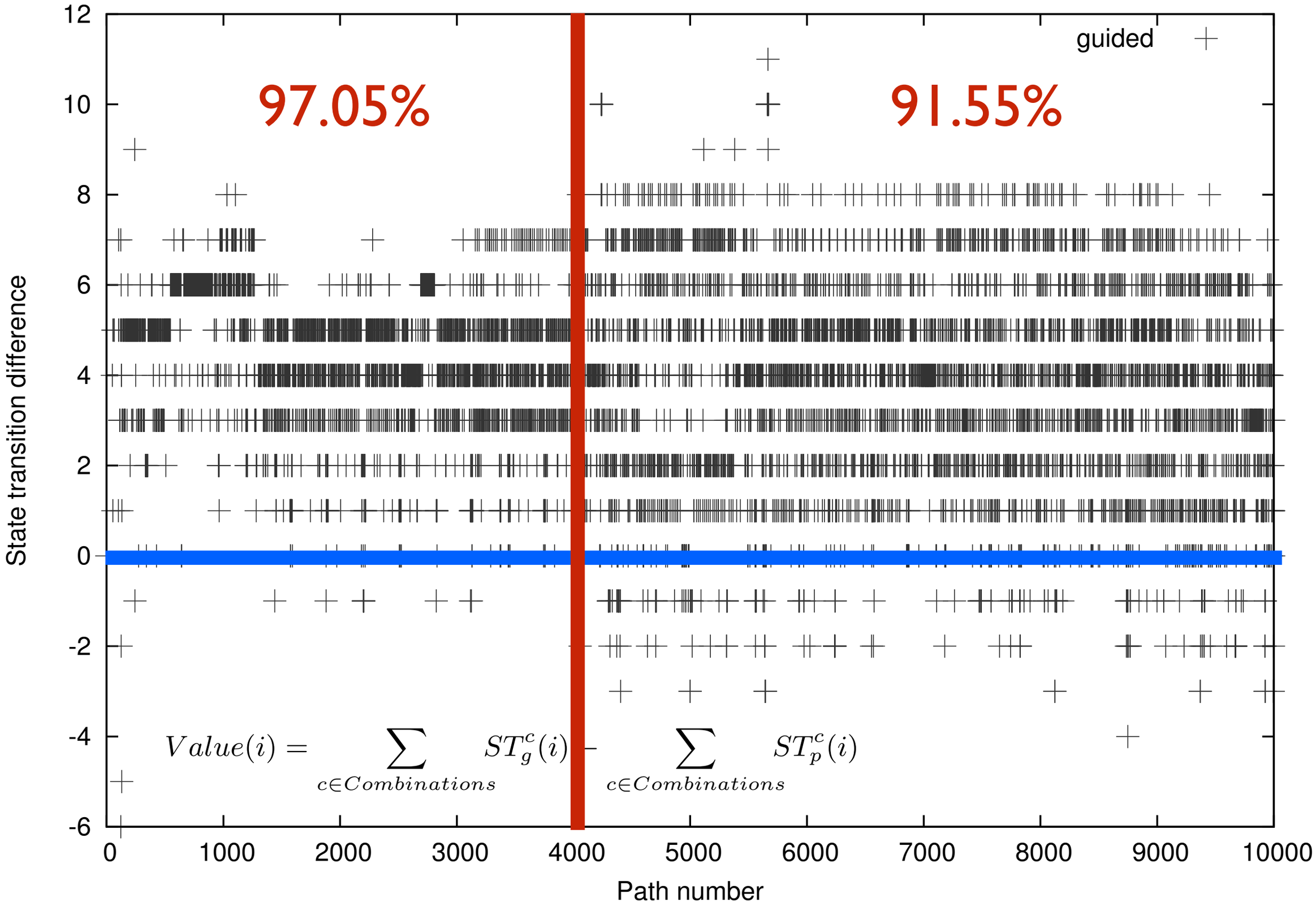
Relevant path distribution



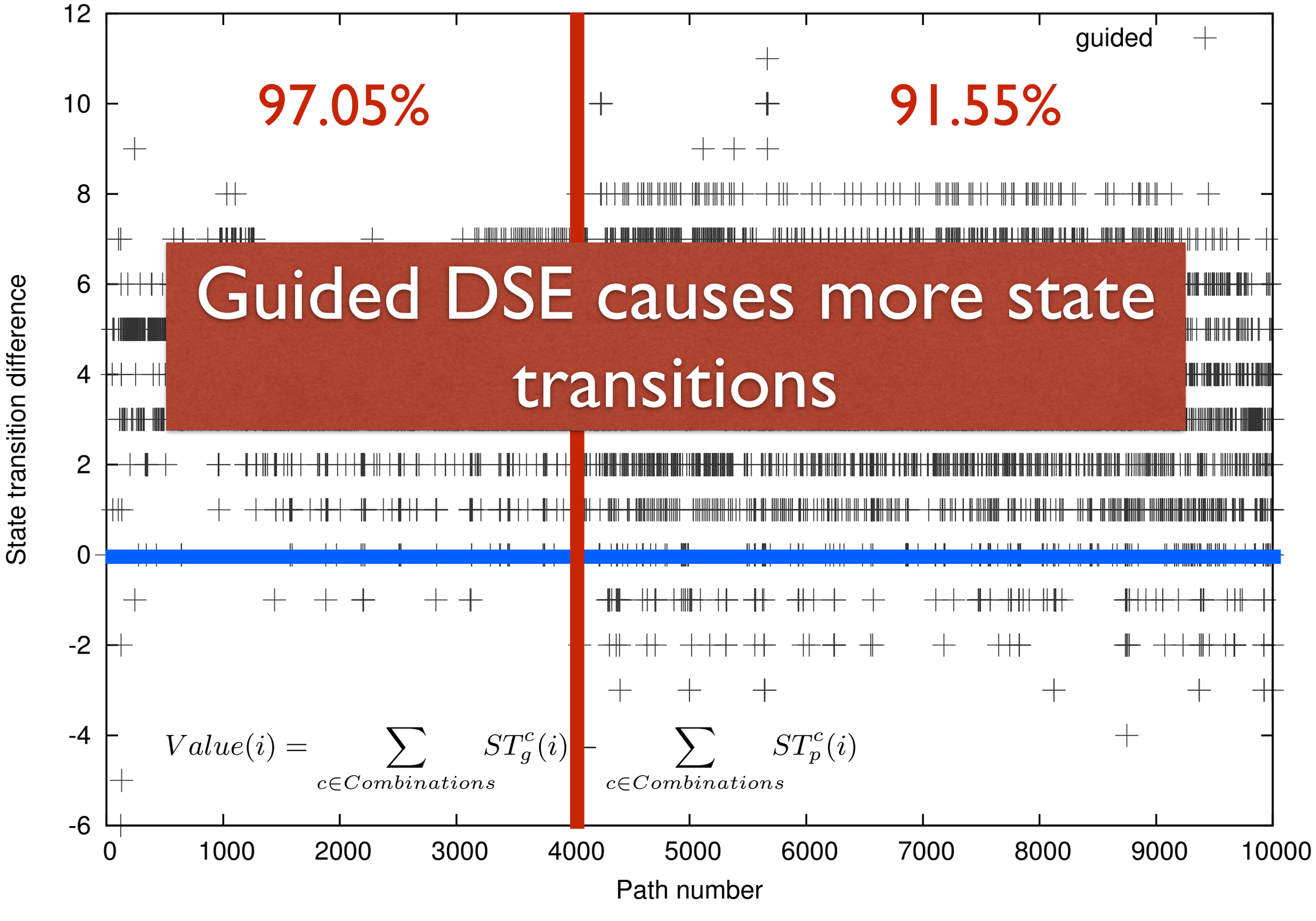
State Transition Difference



State Transition Difference

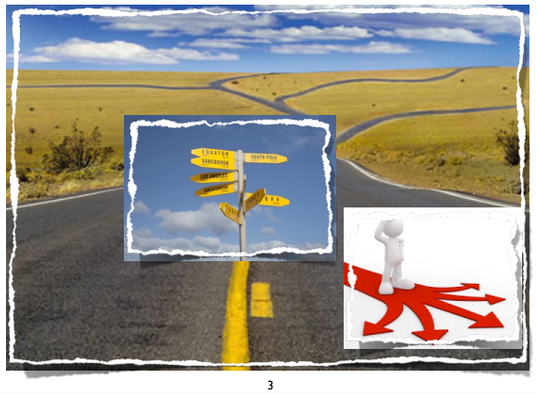


State Transition Difference



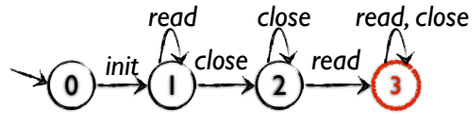
Conclusion

DSE needs guiding



3

How about a Regular Property?



A bug property: a file is read after closed

How to guide DSE to find a program path satisfying P as soon as possible?

5

Key Idea

history *Preset ∩ Postset ≠ ∅* *future*

Preset: the state that can be reached from the beginning to the branch location

Postset: the states from which it can reach a final state after executing the rest program after the branch location

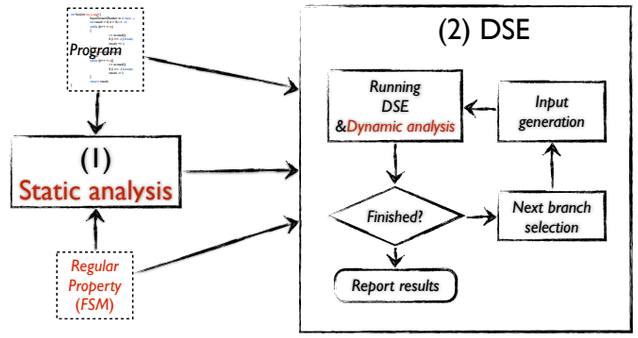
Dynamic analysis

Static analysis

Evaluate a branch based on its history and future behaviors

8

Procedure



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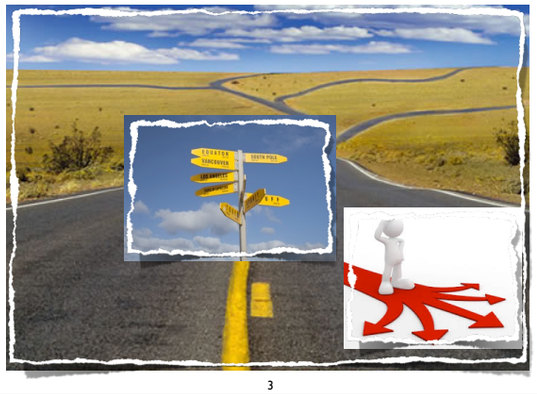

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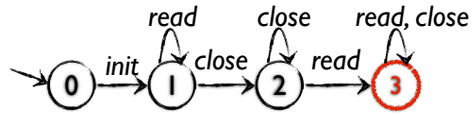

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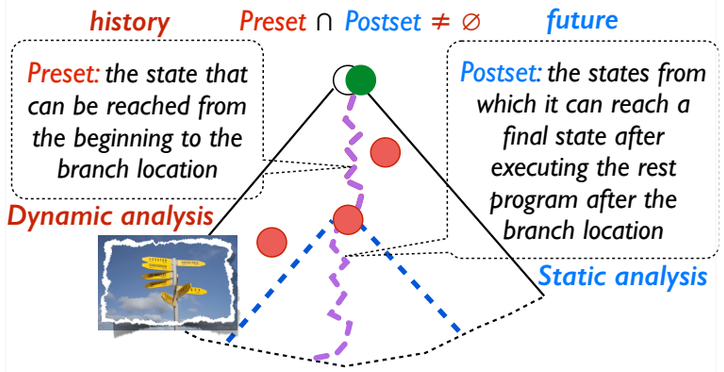

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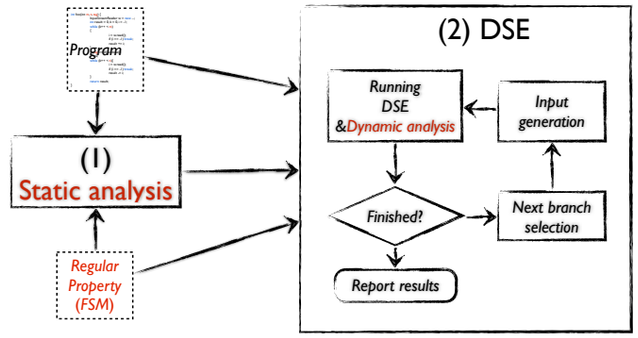
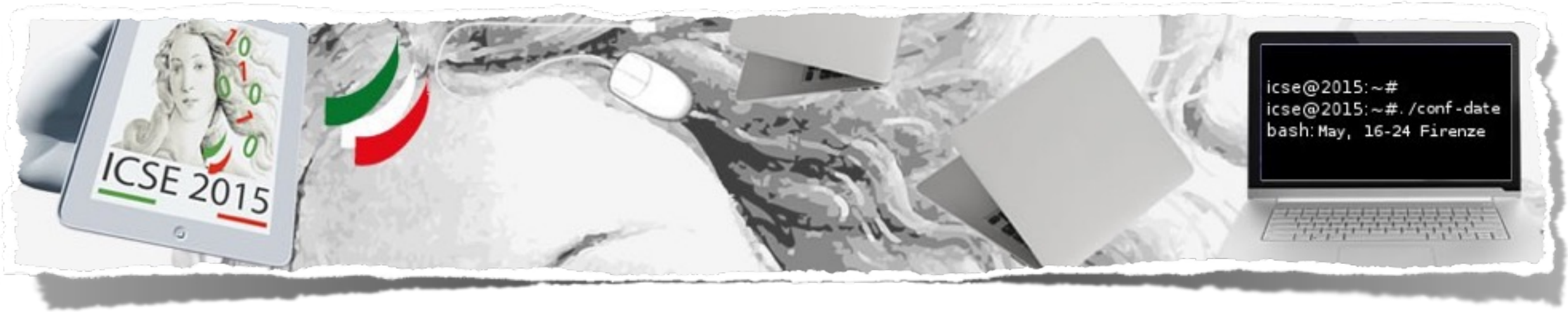
Procedure



- Next step: multi-objects properties, combination with slicing, applications…



Thank you

Any Questions?