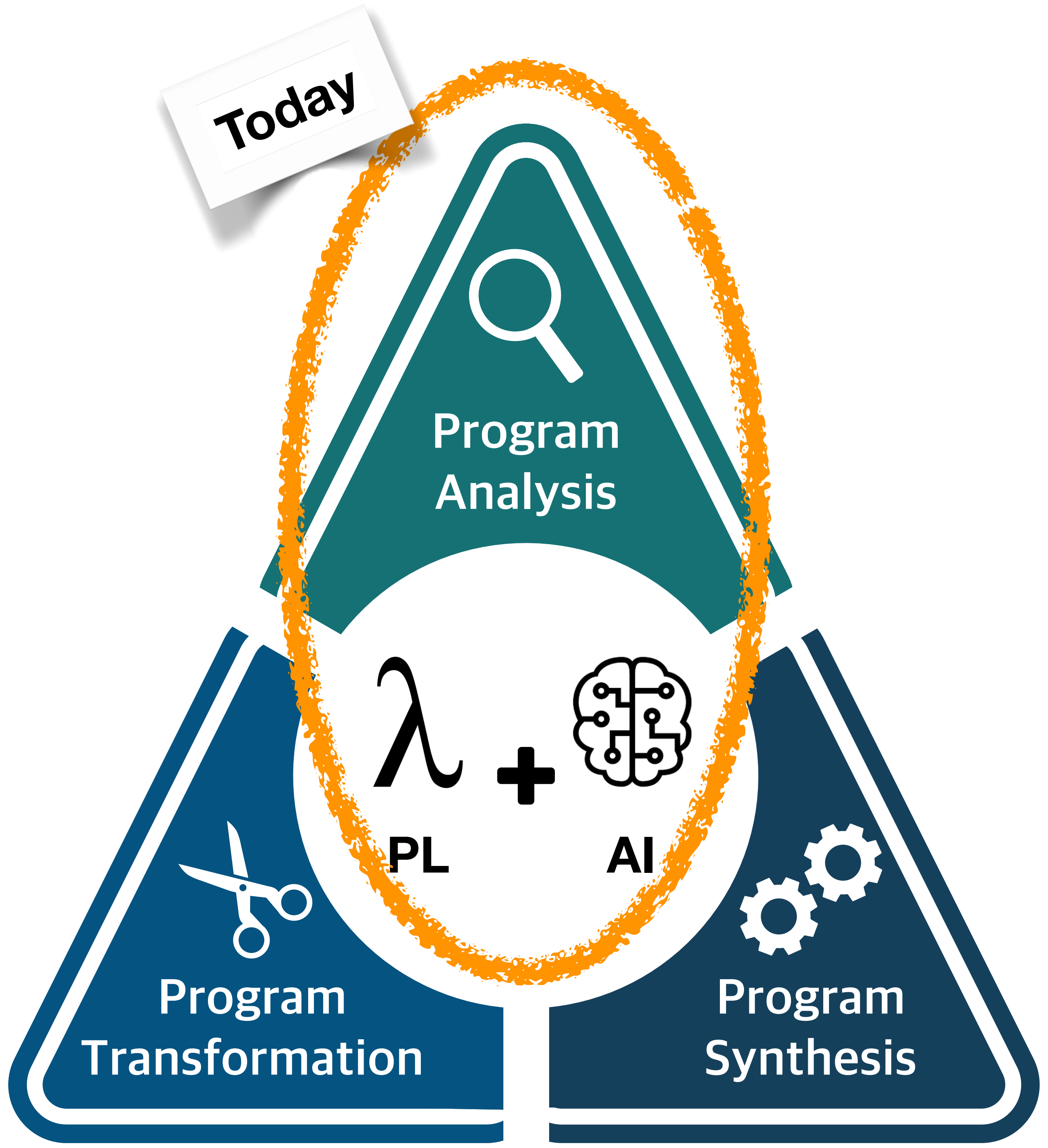
Introduction to Program Analysis

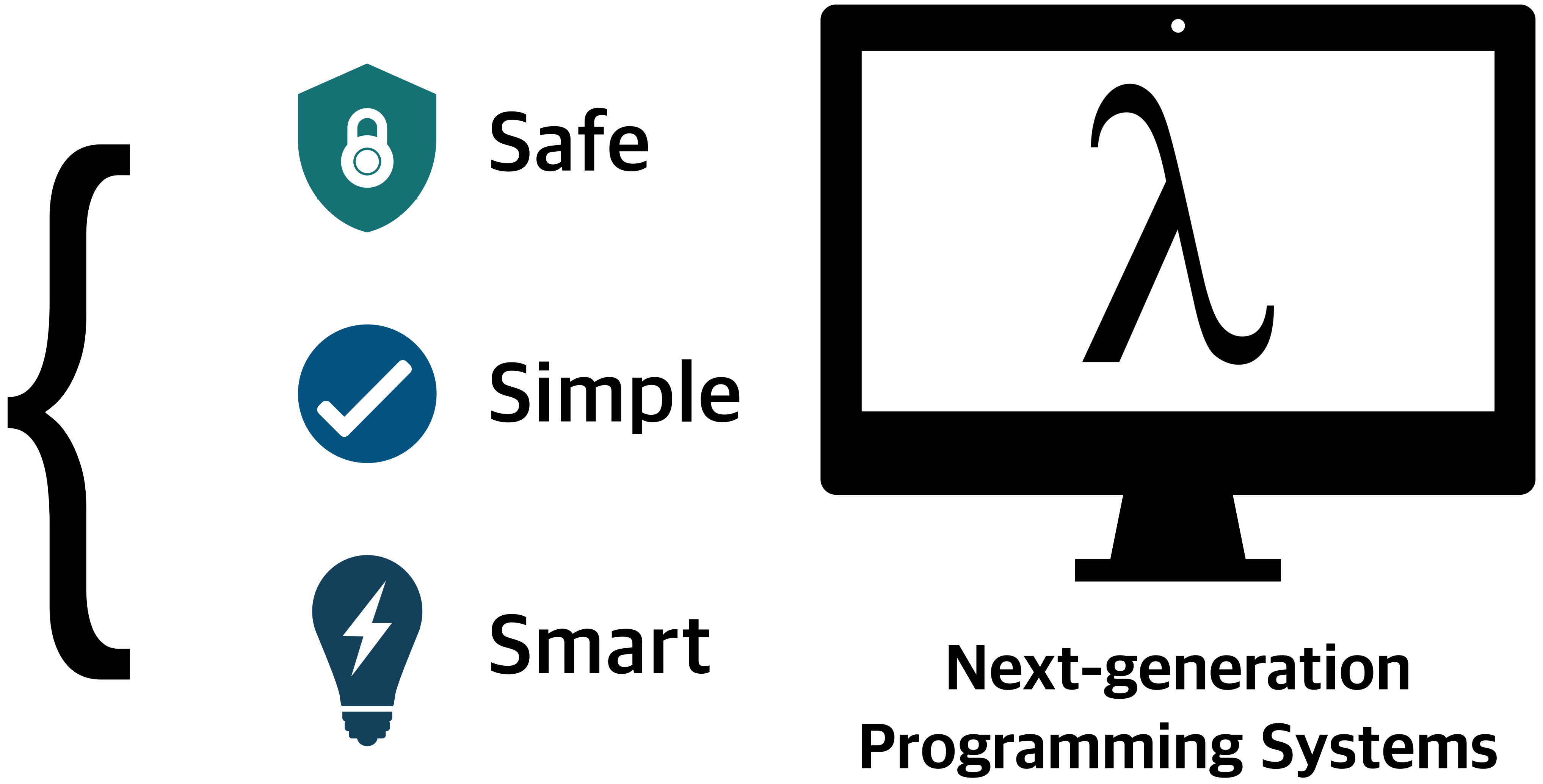
17. Static Analysis with AI

Kihong Heo

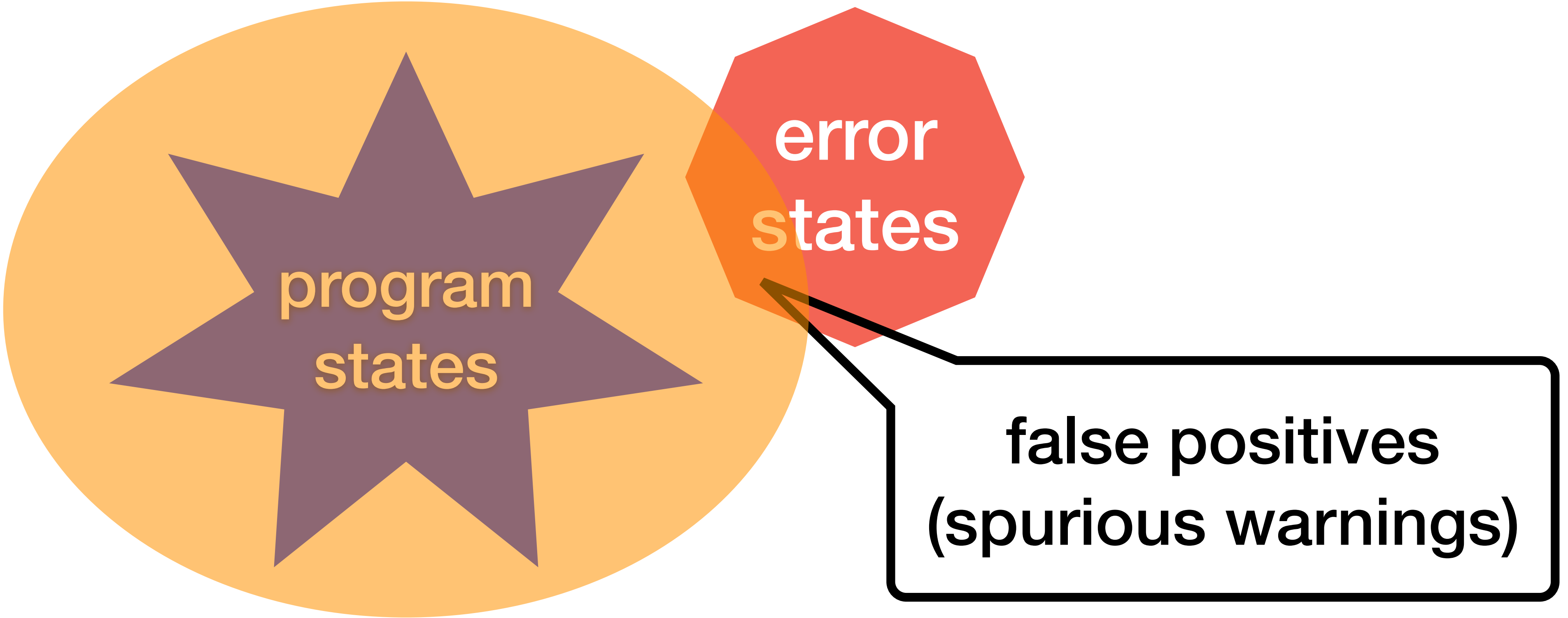
KAIST

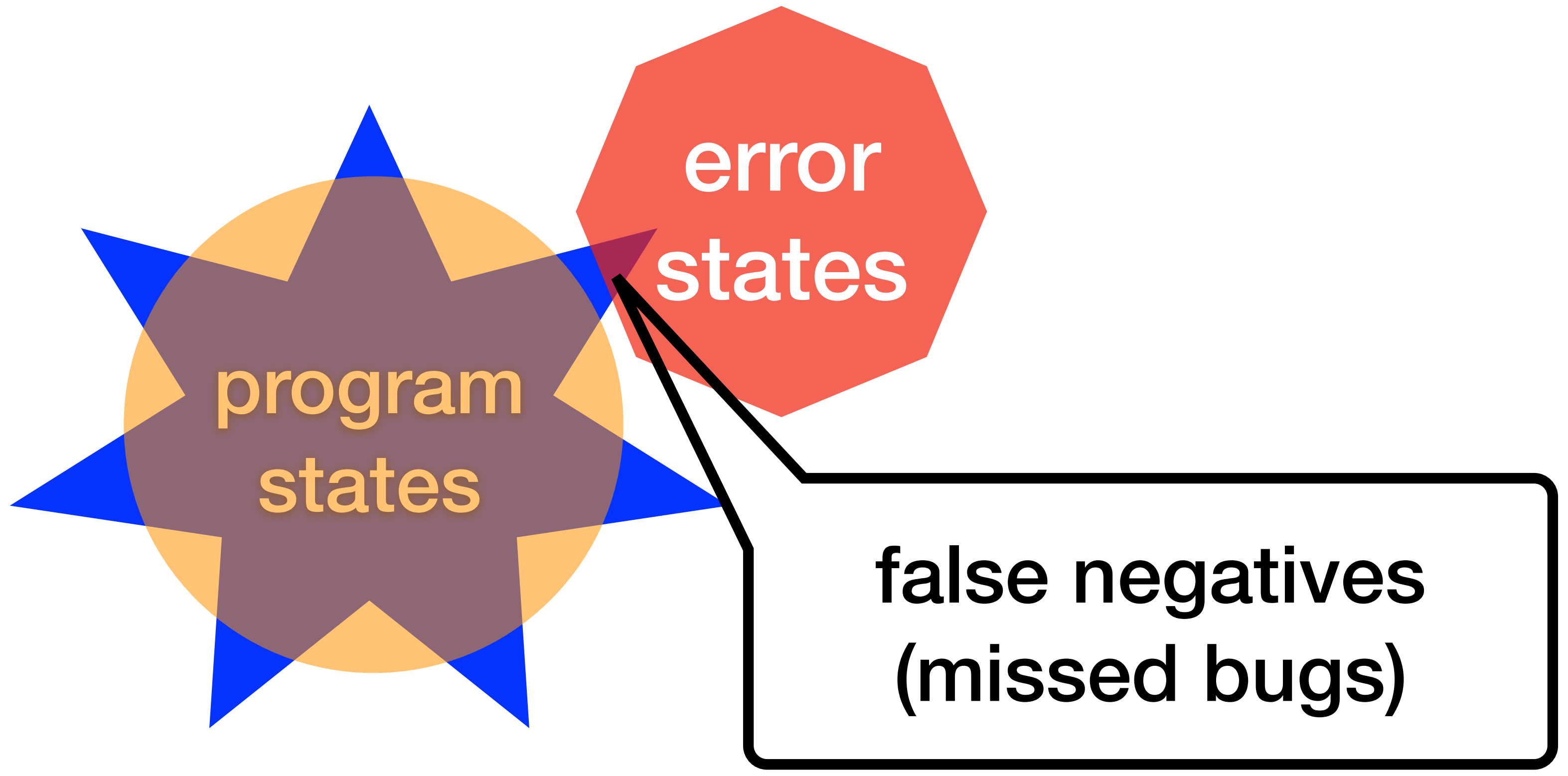
New Waves in Language-based Security





Challenge in Static Analysis



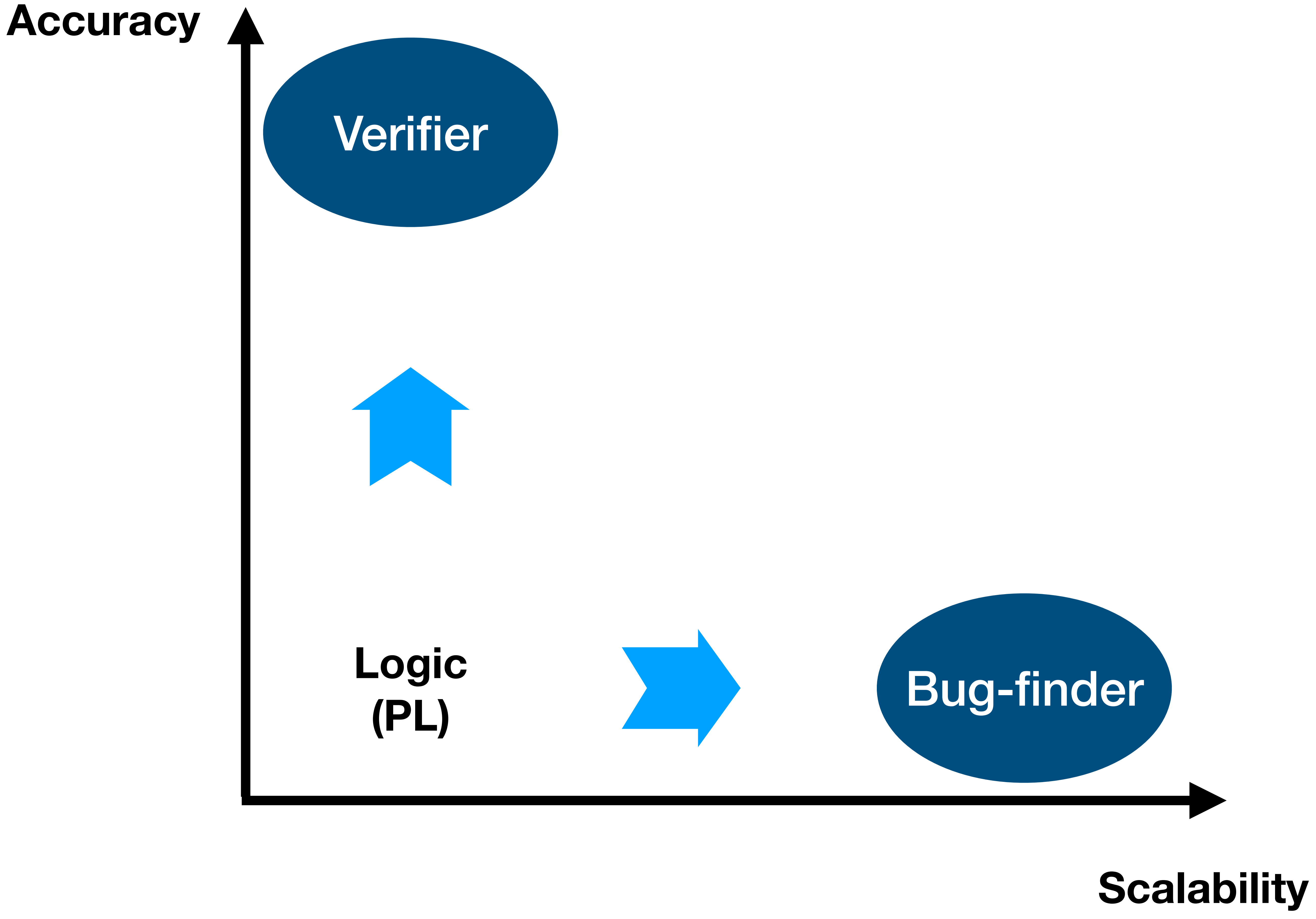


OpenSSL
Cryptography and SSL/TLS Toolkit

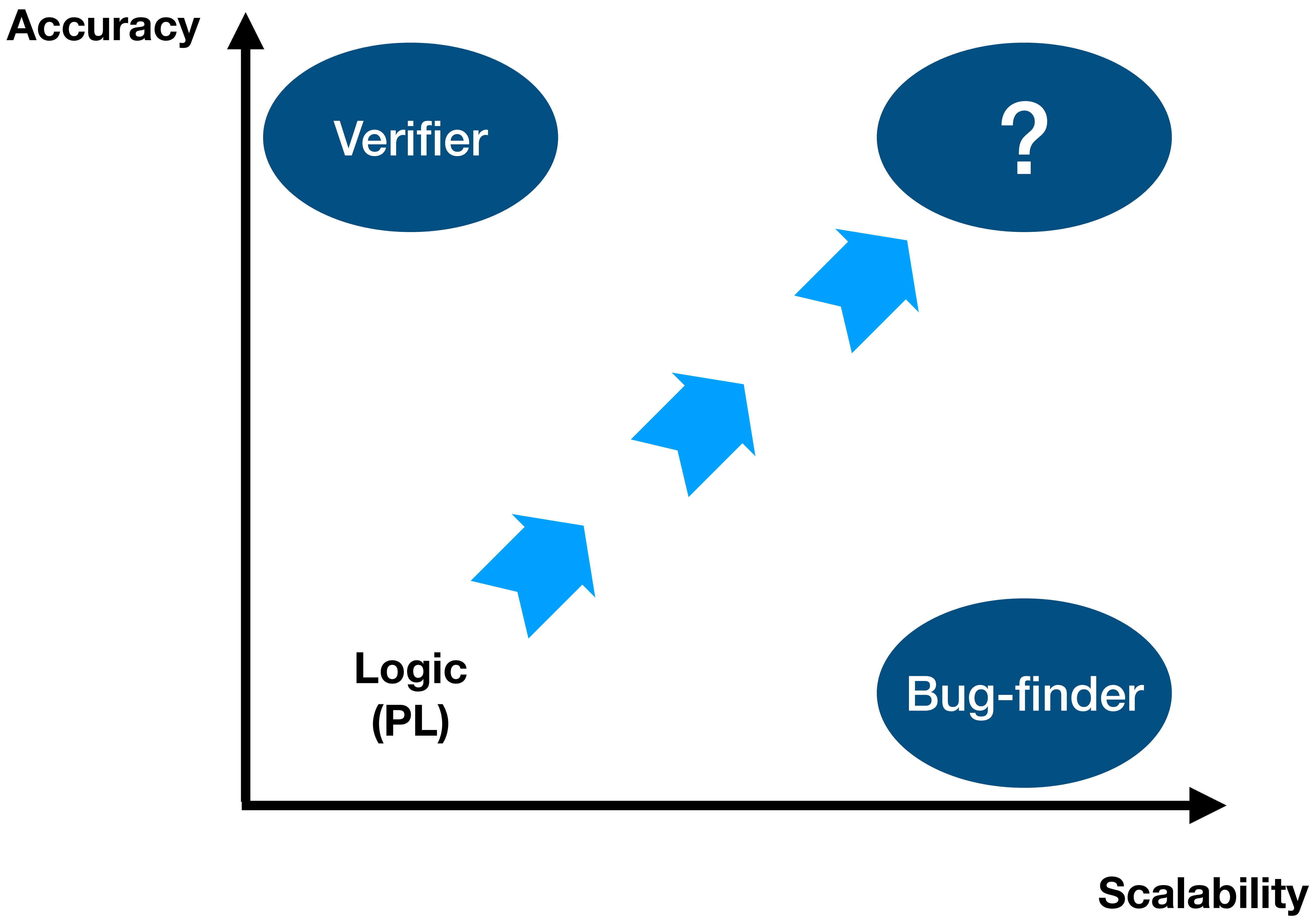
"… can be difficult to do without introducing large numbers of ***false positives*****,** or scaling ***performance*** exponentially poorly. In this case, ***balancing*** these … caused us to ***miss the defect*****."**

— On Detecting Heartbleed with Static Analysis, (Coverity, 2014)

Conventional Static Analysis



How to Go Beyond?

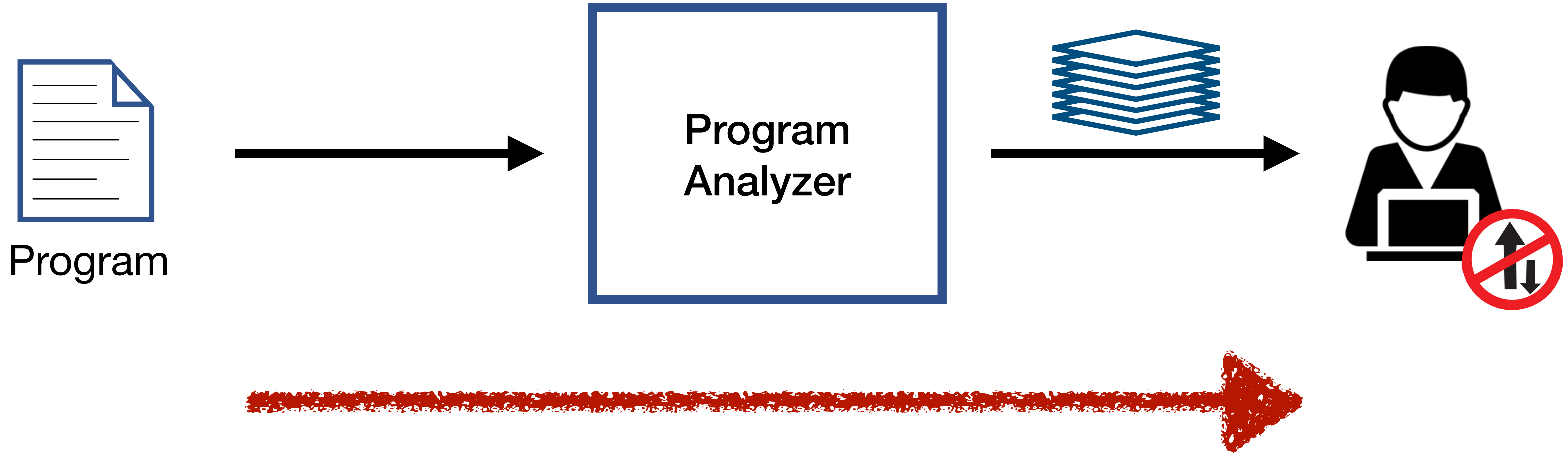


Conventional Static Analysis

Conventional Static Analysis

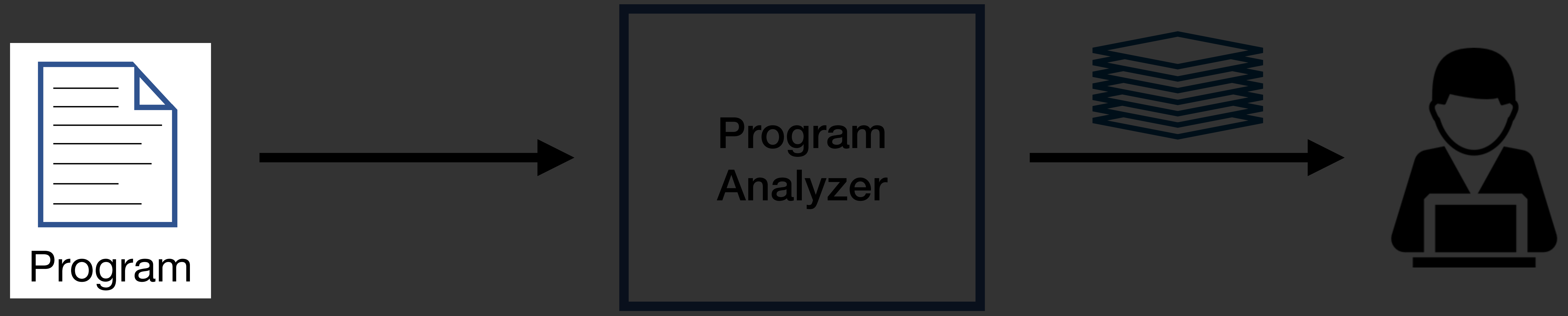
1. Inflexible

Conventional Static Analysis



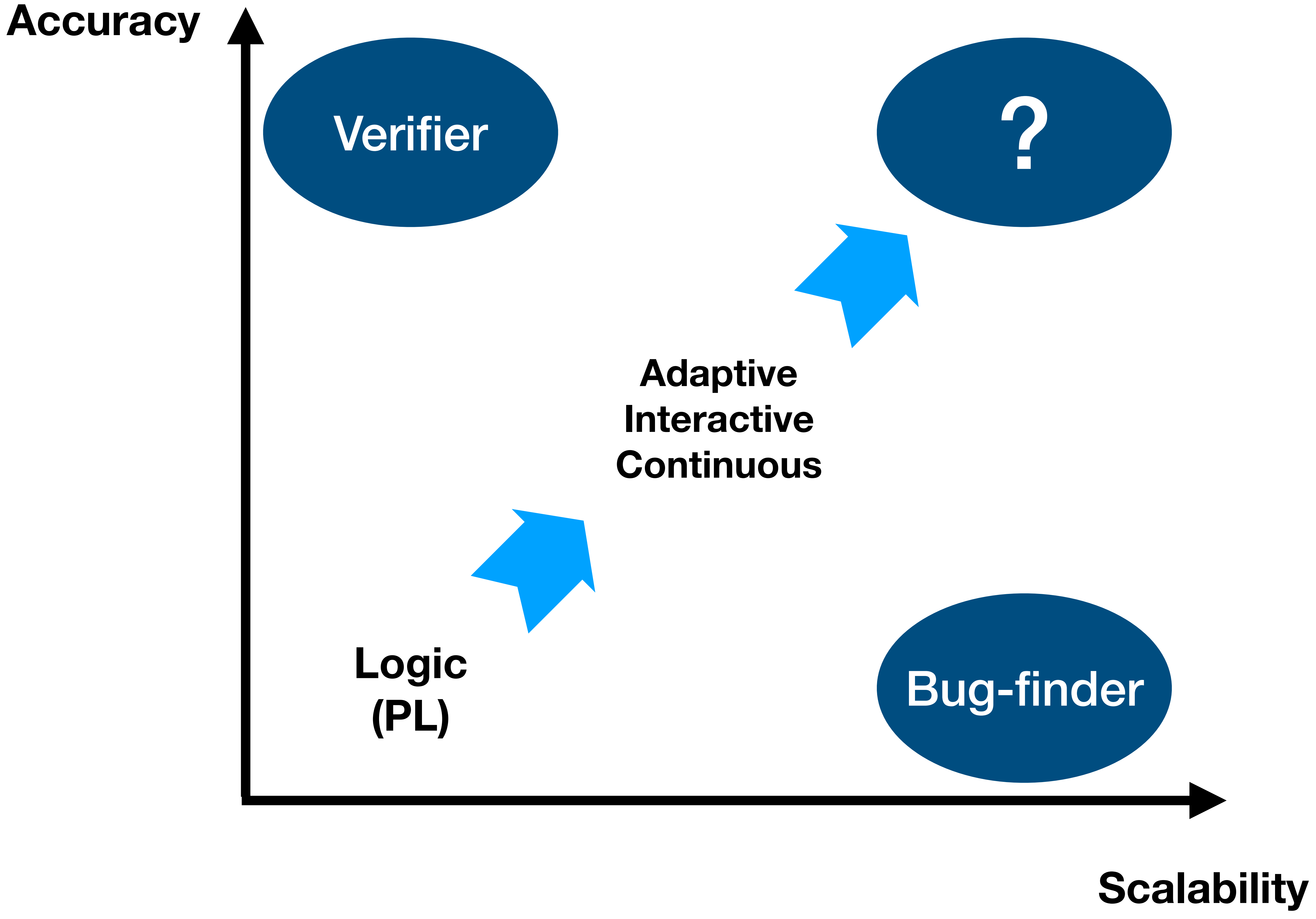
2. Unidirectional

Conventional Program Analysis

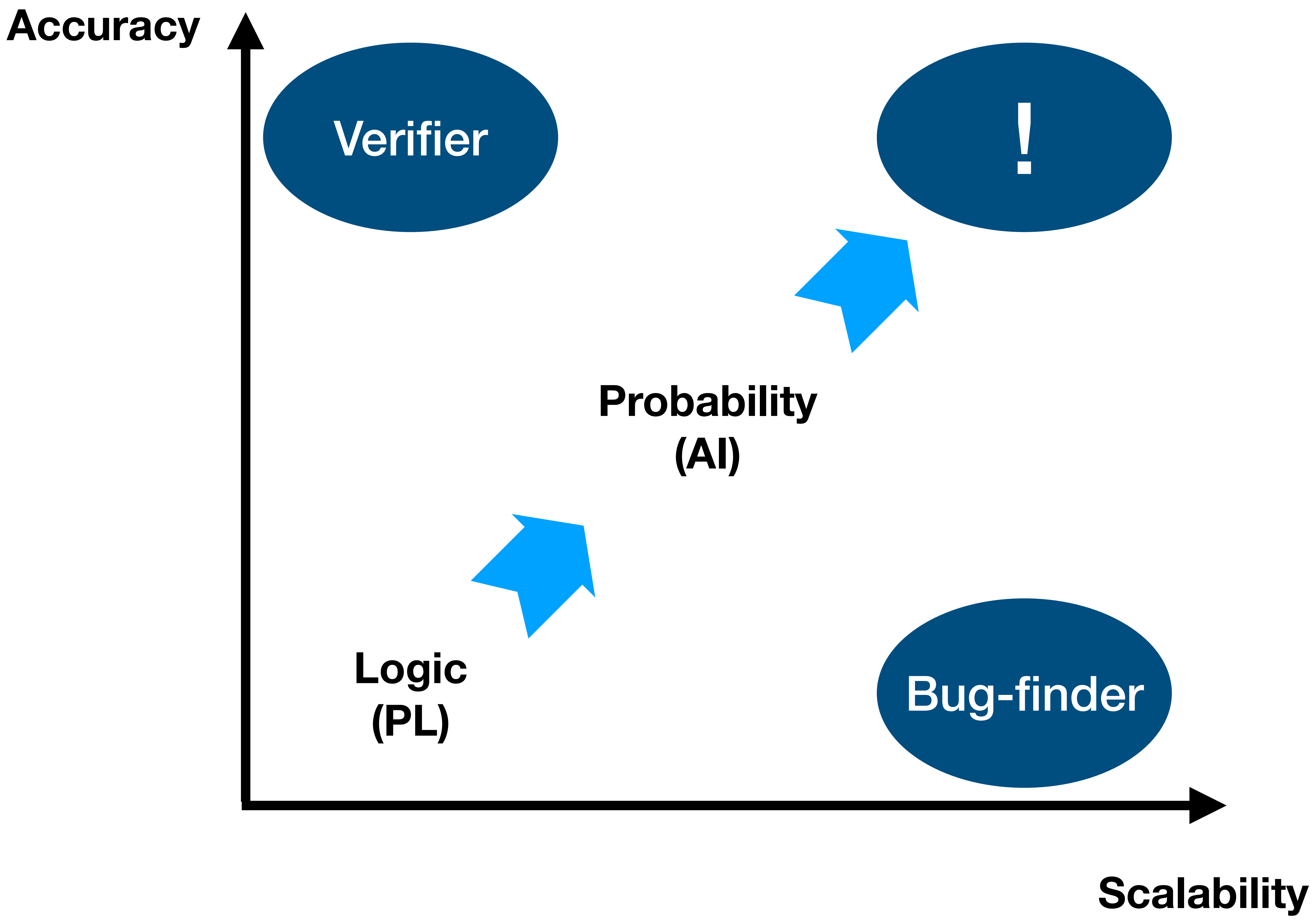


3. Narrow-sighted

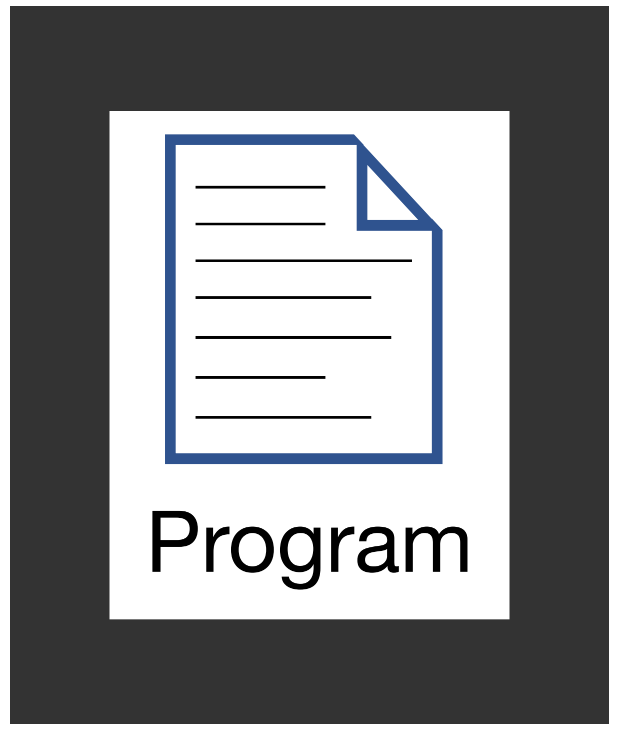
How to Go Beyond?



Static Analysis with AI



Outline

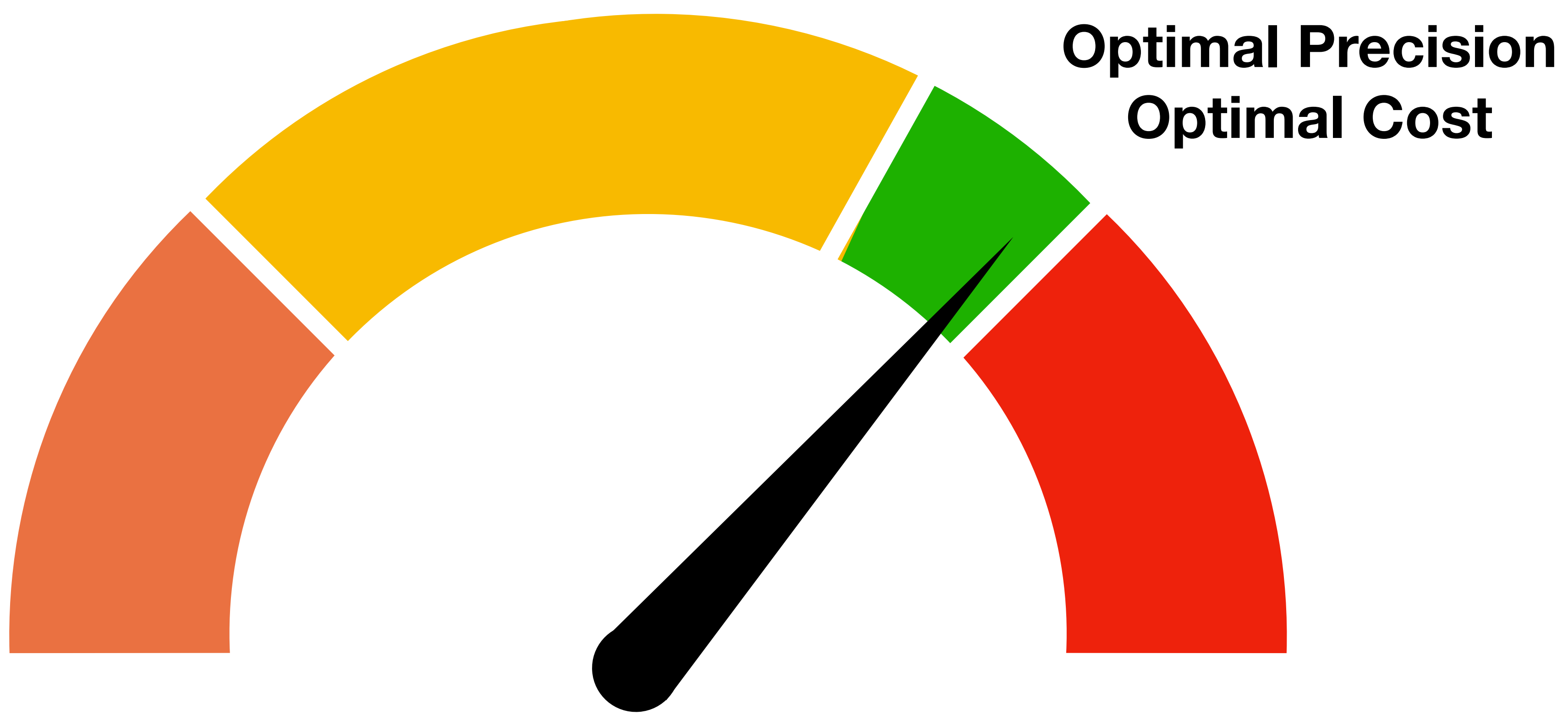


Adaptive Program Analysis

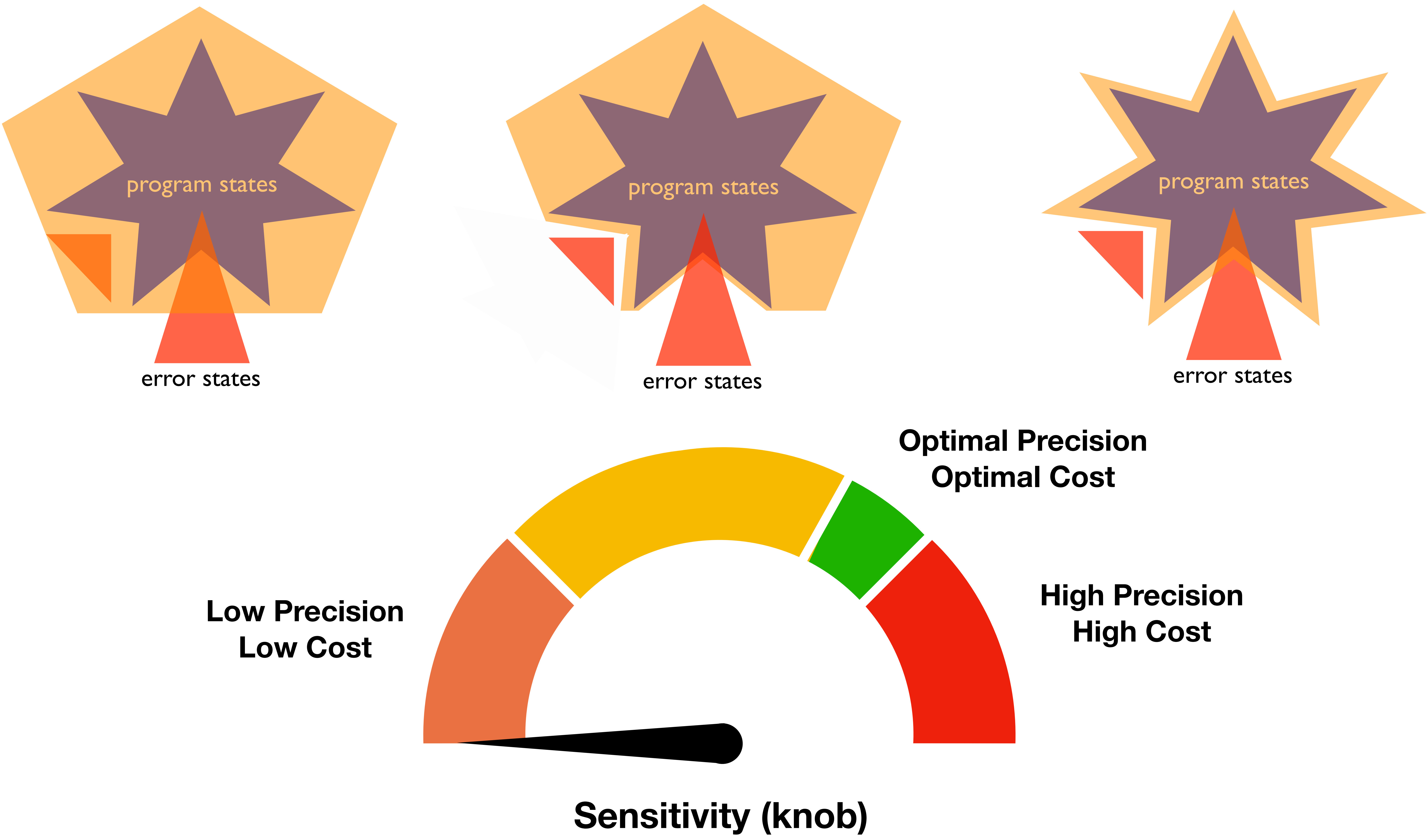
Interactive Program Analysis

Continuous Program Analysis

Adaptive Program Analysis
[SAS'16, OOPSLA'17, ICSE'17, ICSE'19]



Adaptive Program Analysis

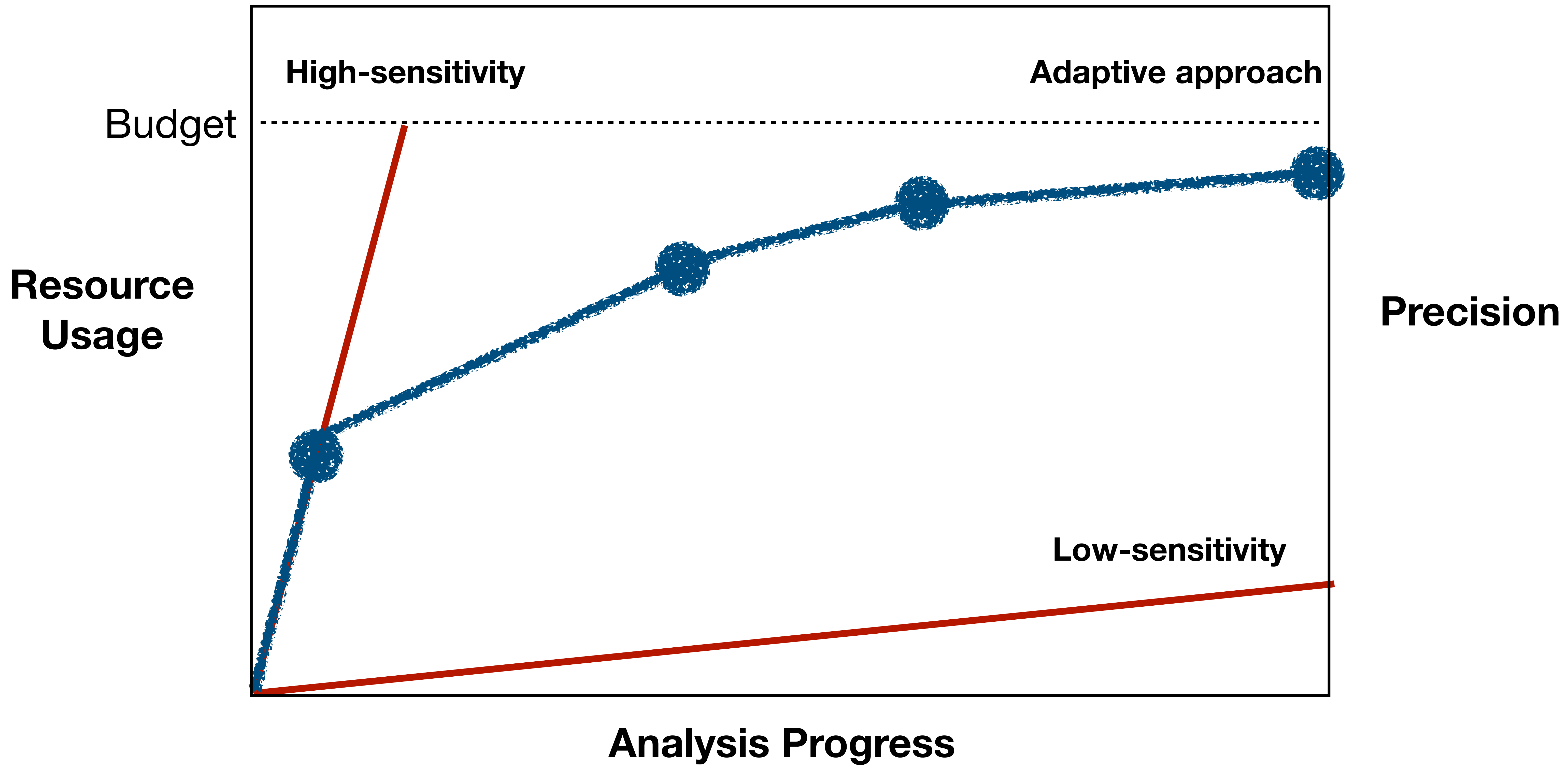


Applications

Abstraction (Knob)	Cost	Online/Offline	Method	Result
Variable Relationship	Running Time	Offline	Supervised Learning	[SAS'16]
Statement Order Variable Relationship	Running Time	Offline	Supervised Learning	[OOPSLA'17]
Loop Unrolling Library Call Handling	Missed Bugs	Offline	Supervised Learning	[ICSE'17]
Statement Order	Memory Consumption	Online	Reinforcement Learning	[ICSE'19]

Resource-aware Analysis

- Achieving **maximum precision** within a given **resource budget**
  - e.g., within 128GB of memory



Knob

- Flow-sensitivity: degree of abstraction of statement order

Flow-sensitive

```
1: x = 0;
2: y = 1;
3: x = 1;
4: y = 0;
```

Line	State
1	{x = [0,0]}
2	{x = [0,0], y = [1,1]}
3	{x = [1,1], y = [1,1]}
4	{x = [1,1], y = [0,0]}

Partially Flow-sensitive

```
1: x = 0;
3: x = 1;
```

```
2: y = 1;
```

```
4: y = 0;
```

Line	FS	FI
1	{x = [0,0]}	{y = [0, 1]}
2	{x = [0,0]}	
3	{x = [1,1]}	
4	{x = [1,1]}	

Flow-insensitive

```
1: x = 0;
```

```
3: x = 1;
```

```
2: y = 1;
```

```
4: y = 0;
```

Line	State
*	{x = [0, 1], y = [0, 1]}

Example

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
x = 0; y = 0; z = 1; v = input(); w = input();
x = z;
z = z + 1;
y = x;
assert(y > 0);      // Query 1 (hold)
assert(z > 0);      // Query 2 (hold)
assert(v == w);     // Query 3 (may fail)
```

Example

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
3: z = z + 1;
4: y = x;
5: assert(y > 0);     // Query 1 (hold)
6: assert(z > 0);     // Query 2 (hold)
7: assert(v == w);    // Query 3 (may fail)
```

Line	Flow-Sensitive Abstract State
1	{x = [0,0], y = [0,0], z = [1,1], v = ⊤, w = ⊤}

3 Intervals

Example

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
3: z = z + 1;
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```

Line	Flow-Sensitive Abstract State
1	{x = [0,0], y = [0,0], z = [1,1], v = ⊤, w = ⊤}
2	{x = [1,1], y = [0,0], z = [1,1], v = ⊤, w = ⊤}

6 Intervals

Example

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
3: z = z + 1;
4: y = x;
5: assert(y > 0);     // Query 1 (hold)
6: assert(z > 0);     // Query 2 (hold)
7: assert(v == w);    // Query 3 (may fail)
```

Line	Flow-Sensitive Abstract State
1	{x = [0,0], y = [0,0], z = [1,1], v = $\top$, w = $\top$}
2	{x = [1,1], y = [0,0], z = [1,1], v = $\top$, w = $\top$}
3	{x = [1,1], y = [0,0], z = [2,2], v = $\top$, w = $\top$}
4	{**x = [1,1], y = [1,1], z = [2,2]**, v = $\top$, w = $\top$}

12 Intervals

Example

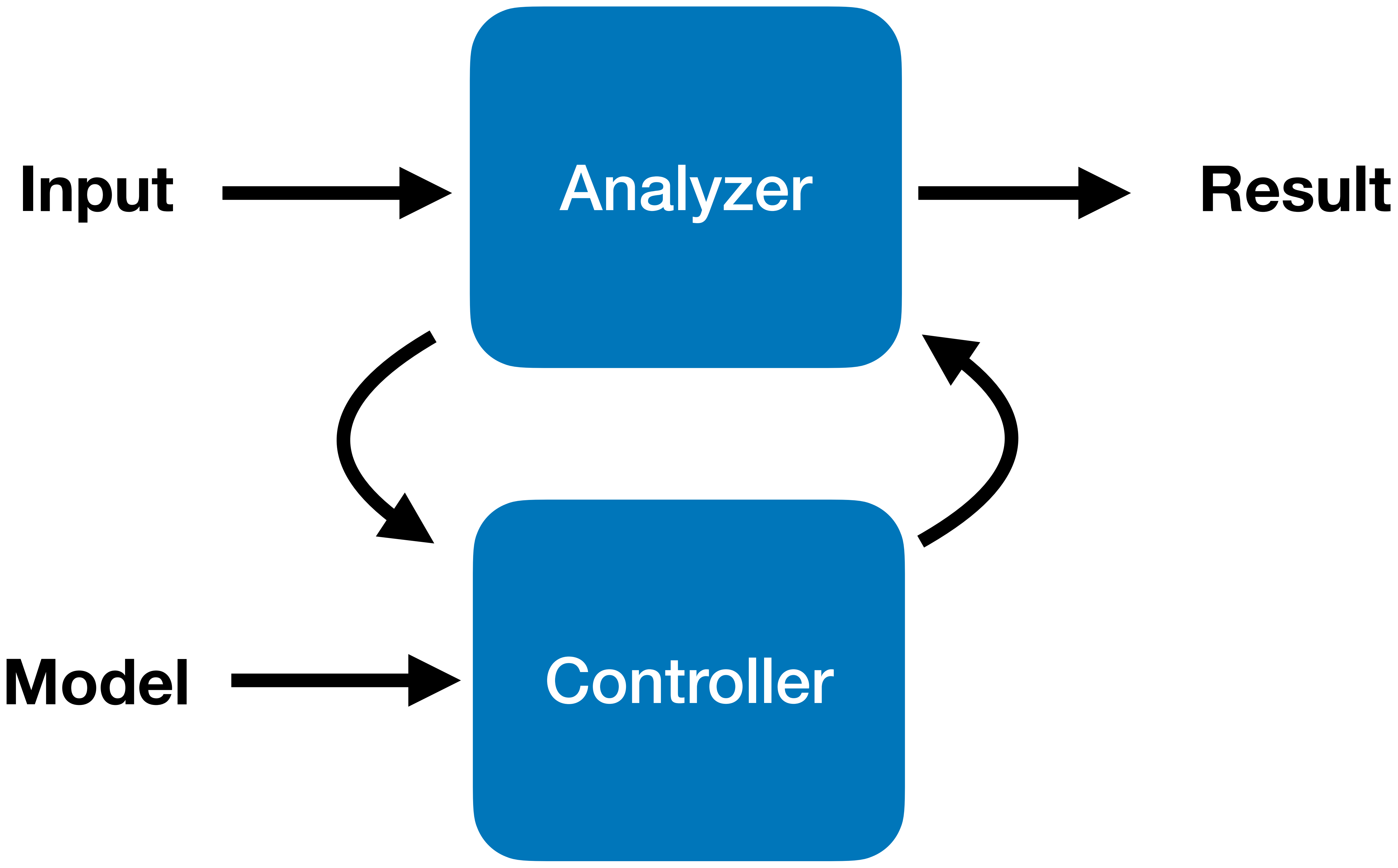
- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
3: z = z + 1;
4: y = x;
5: assert(y > 0);     // Query 1 (hold)
6: assert(z > 0);     // Query 2 (hold)
7: assert(v == w);    // Query 3 (may fail)
```

Line	Flow-Insensitive Abstract State
*	{x = [0,+∞], y = [0,+∞], z = [1,+∞], v = ⊤, w = ⊤}

3 Intervals

Adaptive Analysis



Model

- Model M : Variable $\rightarrow$ [0, 1]
- Importance of each variable in terms of flow-sensitivity
- Learned using Bayesian Optimization
  - represent variables as feature vectors and learn weights of features

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
3: z = z + 1;
4: y = x;
5: assert(y > 0);    // Query 1 (hold)
6: assert(z > 0);    // Query 2 (hold)
7: assert(v == w);   // Query 3 (may fail)
```

$$M(x) > M(y) > M(z) > M(v) > M(w)$$

Controller

- Controller $\boldsymbol{\pi} : \mathbf{F} \rightarrow \mathrm{Pr}(\mathrm{A})$ where $\mathrm{A} = \{0, \cdots, 100\}$
- Input: a feature vector describing current status
  - e.g., memory usage, analysis progress, etc
- Output: prob. distribution on % of vars that should be treated flow-insensitively
- Learned using reinforcement learning

Controller

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
x = 0; y = 0; z = 1; v = input(); w = input();
x = z;
z = z + 1;
y = x;
assert(y > 0);     // Query 1 (hold)
assert(z > 0);     // Query 2 (hold)
assert(v == w);    // Query 3 (may fail)
```

Model: $M(x) > M(y) > M(z) > M(v) > M(w)$

Controller

- Partially flow-sensitive interval analysis (budget: 10 intervals)

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1: x = 0; y = 0; z = 1; v = input(); w = input();
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5: assert(y > 0);     // Query 1 (hold)
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7: assert(v == w);    // Query 3 (may fail)
```

Model: $M(x) > M(y) > M(z) > M(v) > M(w)$

Line	Flow-Sensitive Abstract State
1	{x = [0,0], y = [0,0], z = [1,1], v = ⊤, w = ⊤}
2	{x = [1,1], y = [0,0], z = [1,1], v = ⊤, w = ⊤}

6 Intervals

Controller

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
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5: assert(y > 0);     // Query 1 (hold)
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7: assert(v == w);    // Query 3 (may fail)
```

Model: $M(x) > M(y) > M(z) > M(v) \cancel{> M(w)}$

Line	Flow-Sensitive	Flow-Insensitive
1	{x = [0,0], y = [0,0], z = [1,1], v = ⊤}	{w = ⊤}
2	{x = [1,1], y = [0,0], z = [1,1], v = ⊤}	

6 Intervals

Controller

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
3: z = z + 1;
4: y = x;
5: assert(y > 0);     // Query 1 (hold)
6: assert(z > 0);     // Query 2 (hold)
7: assert(v == w);    // Query 3 (may fail)
```

Model: $M(x) > M(y) > M(z) > M(v) \cancel{> M(w)}$

Line	Flow-Sensitive	Flow-Insensitive
1	{x = [0,0], y = [0,0], z = [1,1], v = $\top$}	
2	{x = [1,1], y = [0,0], z = [1,1], v = $\top$}	{w = $\top$}
3	{x = [1,1], y = [0,0], z = [2,2], v = $\top$}	

9 Intervals

Controller

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
2: x = z;
3: z = z + 1;
4: y = x;
5: assert(y > 0);     // Query 1 (hold)
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```

Model: $M(x) > M(y)$ ~~$> M(z) > M(v) > M(w)$~~

Line	Flow-Sensitive	Flow-Insensitive
1	{x = [0,0], y = [0,0]}	
2	{x = [1,+∞], y = [0,0]}	{z = [1,+∞], v = ⊤, w = ⊤}
3	{x = [1,+∞], y = [0,0]}	

6 Intervals

Controller

- Partially flow-sensitive interval analysis (budget: 10 intervals)

```
1: x = 0; y = 0; z = 1; v = input(); w = input();
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```

Model: $M(x) > M(y)$ ~~$> M(z) > M(v) > M(w)$~~

Line	Flow-Sensitive	Flow-Insensitive
1	{x = [0,0], y = [0,0]}	**{z = [1,+∞]**, v = ⊤, w = ⊤}
2	{x = [1,+∞], y = [0,0]}	
3	{x = [1,+∞], y = [0,0]}	
4	**{x = [1,+∞], y = [1,+∞]}**	

8 Intervals

Practical Impact

- Achieving **maximum precision** within a given **resource budget**
  - e.g., within 128GB of memory

Conventional Approach*
(10% flow-sensitivity)

- **3/8** run out of memory (128GB)
- **27%** of buffer overrun alarms ↓
- **30%** of null dereference alarms ↓

Adaptive Approach

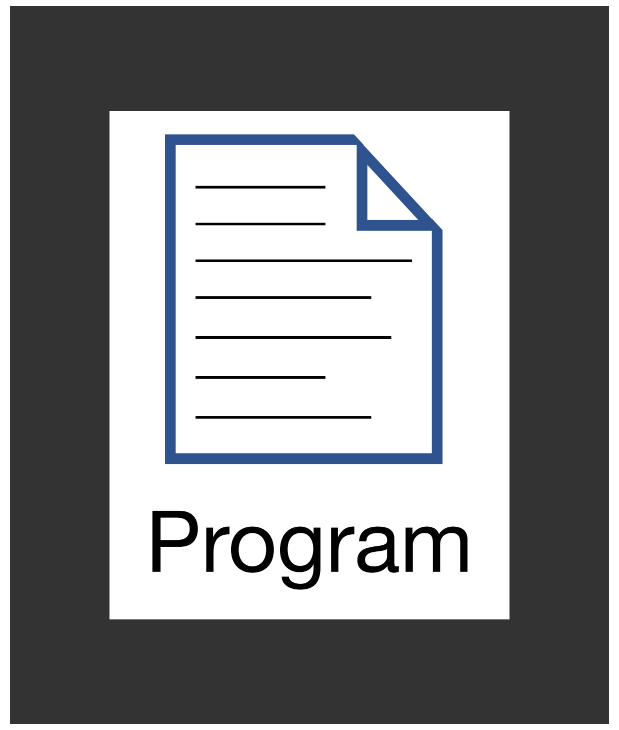
- **0/8** run out of memory (64 / 128GB)
- **28—32%** of buffer overrun alarms ↓
- **33—41%** of null dereference alarms ↓

*Kihong Heo, Hakjoo Oh, Hongseok Yang, Kwangkeun Yi. Adapting Static Analysis via Learning with Bayesian Optimization. ACM TOPLAS, 2018

Outline

**Adaptive
Program Analysis**

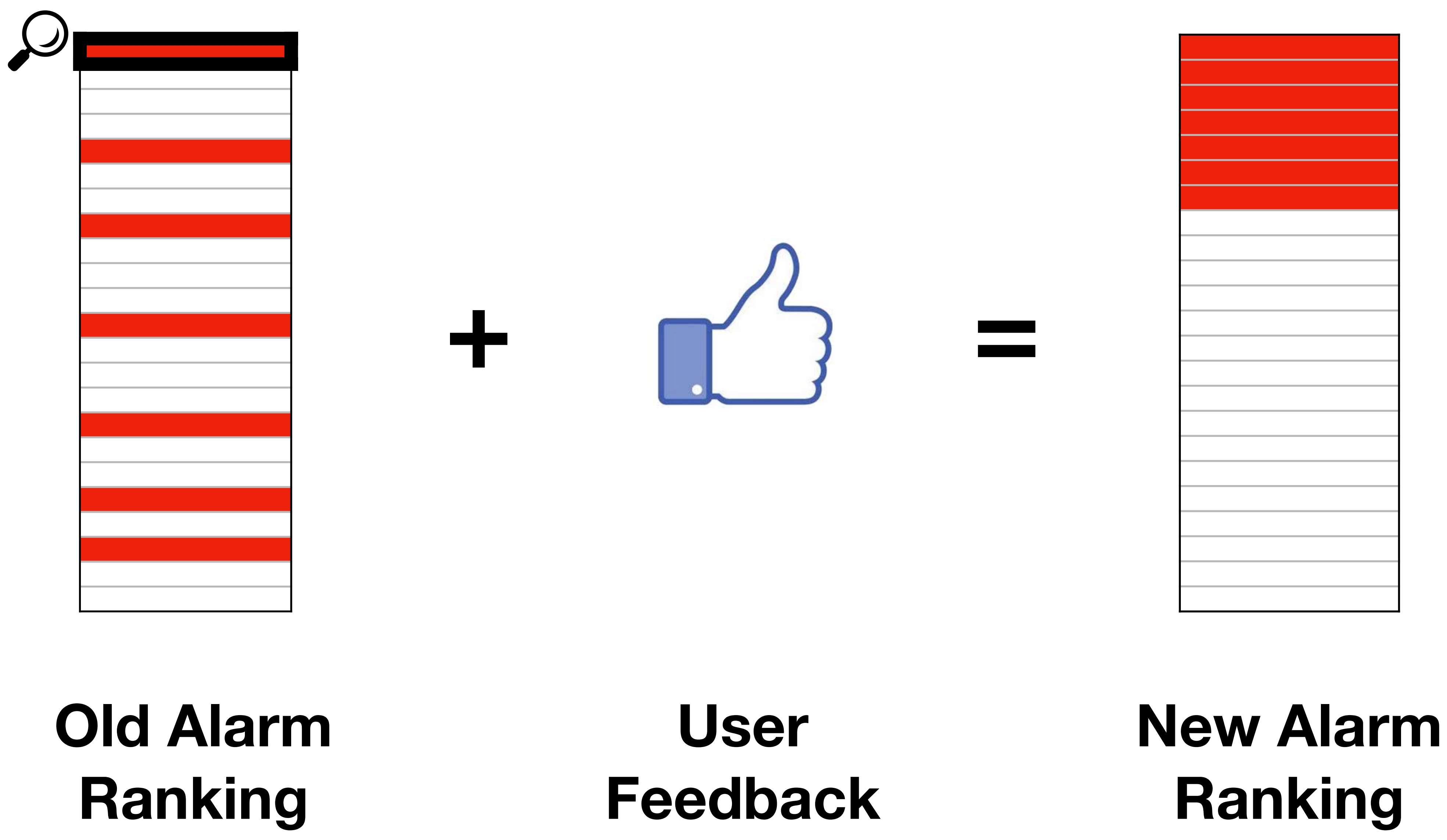
**Interactive
Program Analysis**



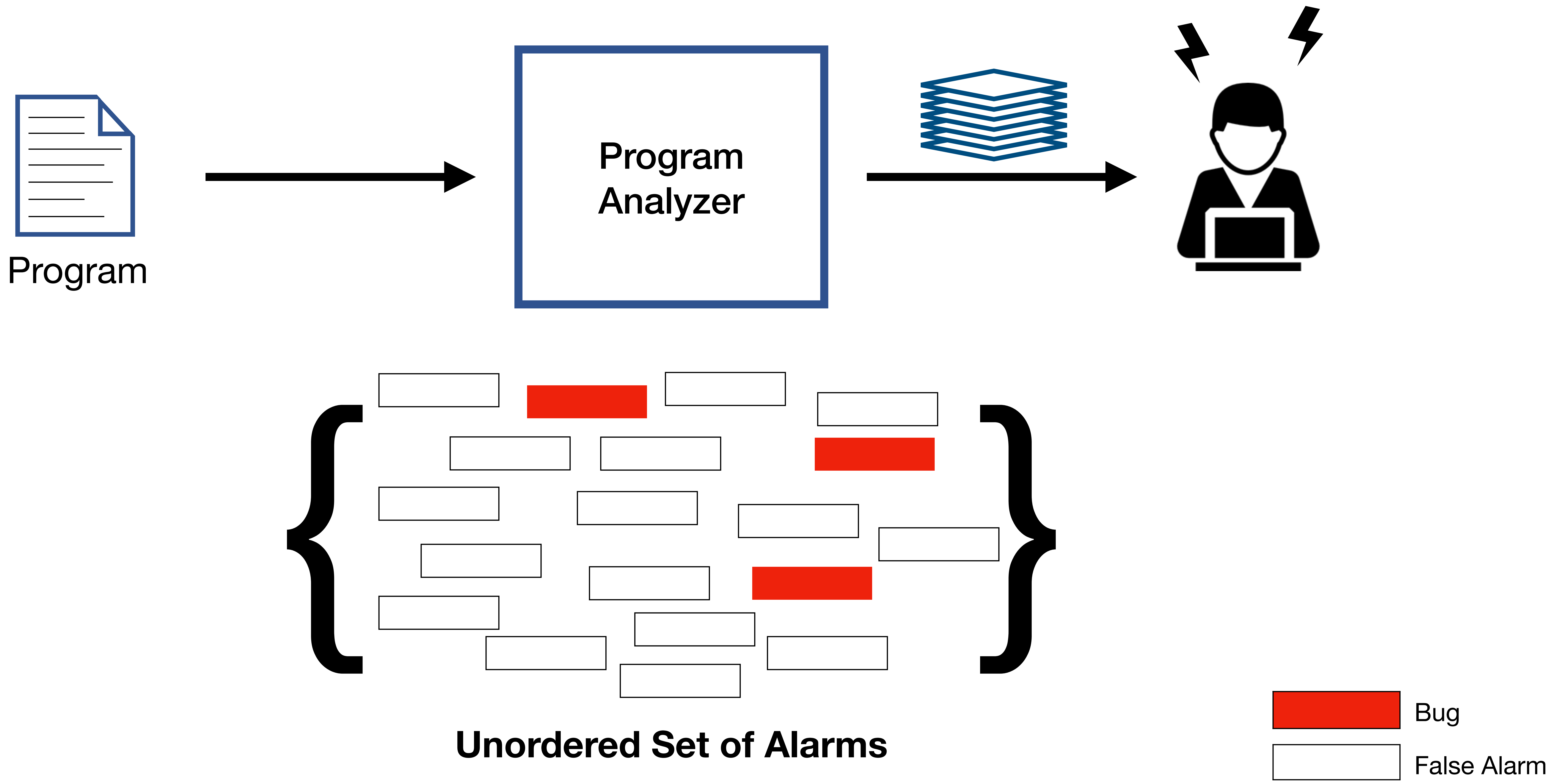
**Continuous
Program Analysis**

Outline

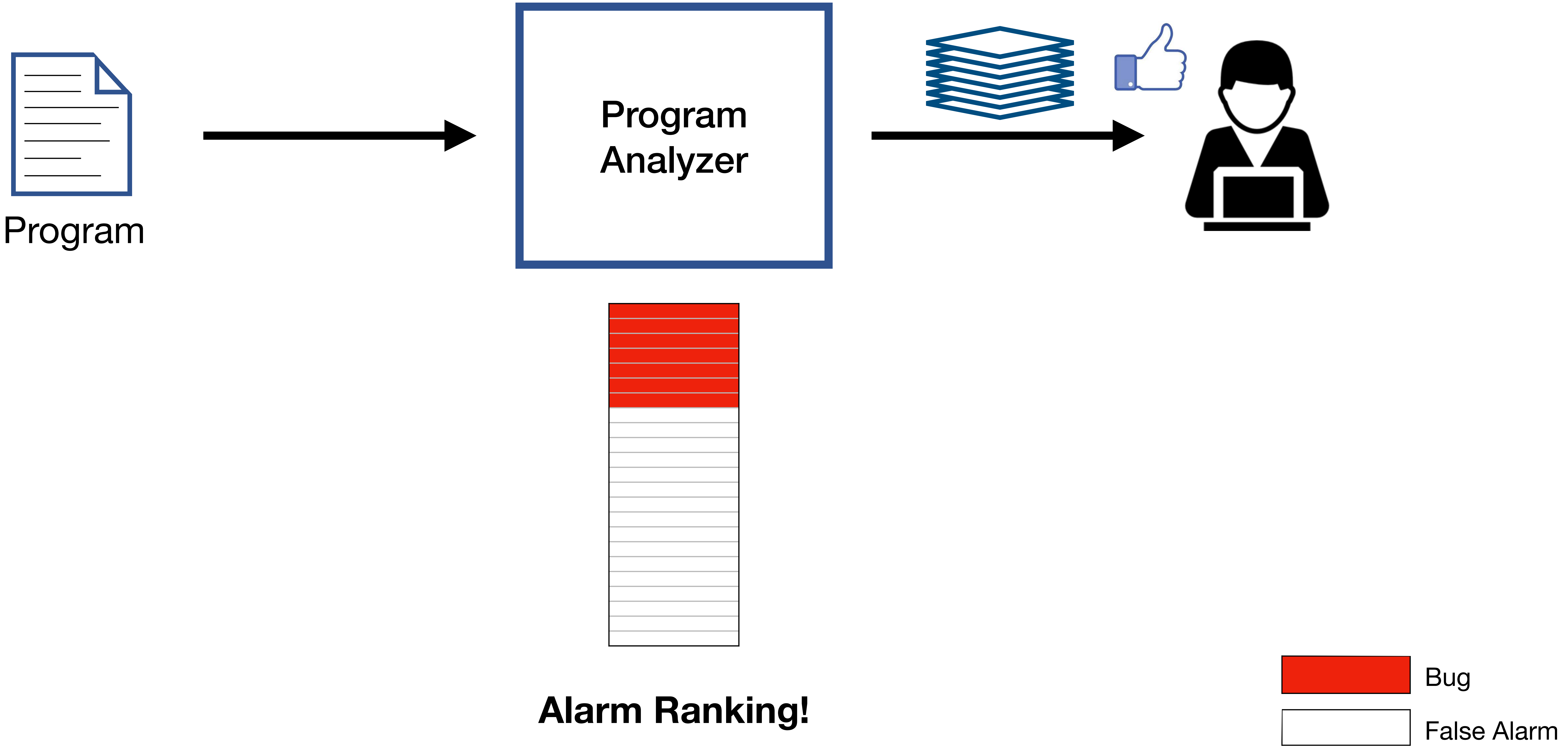
Bingo: Interactive Alarm Ranking System [PLDI'18]



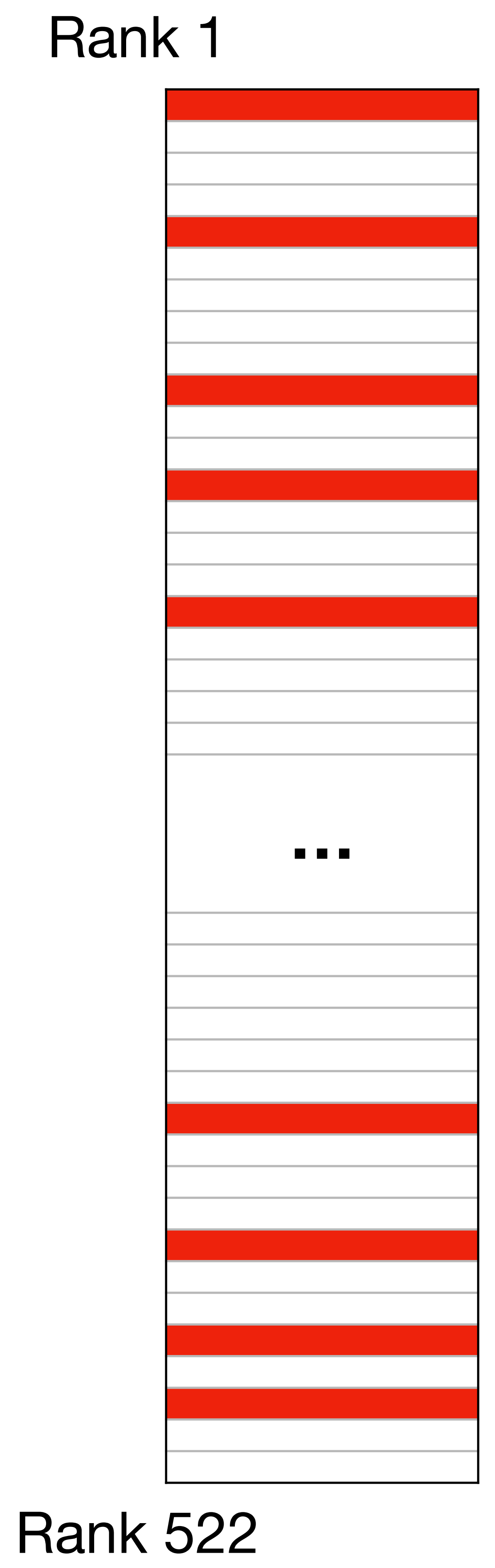
Alarm Report



Goal



Interactive Alarm Ranker

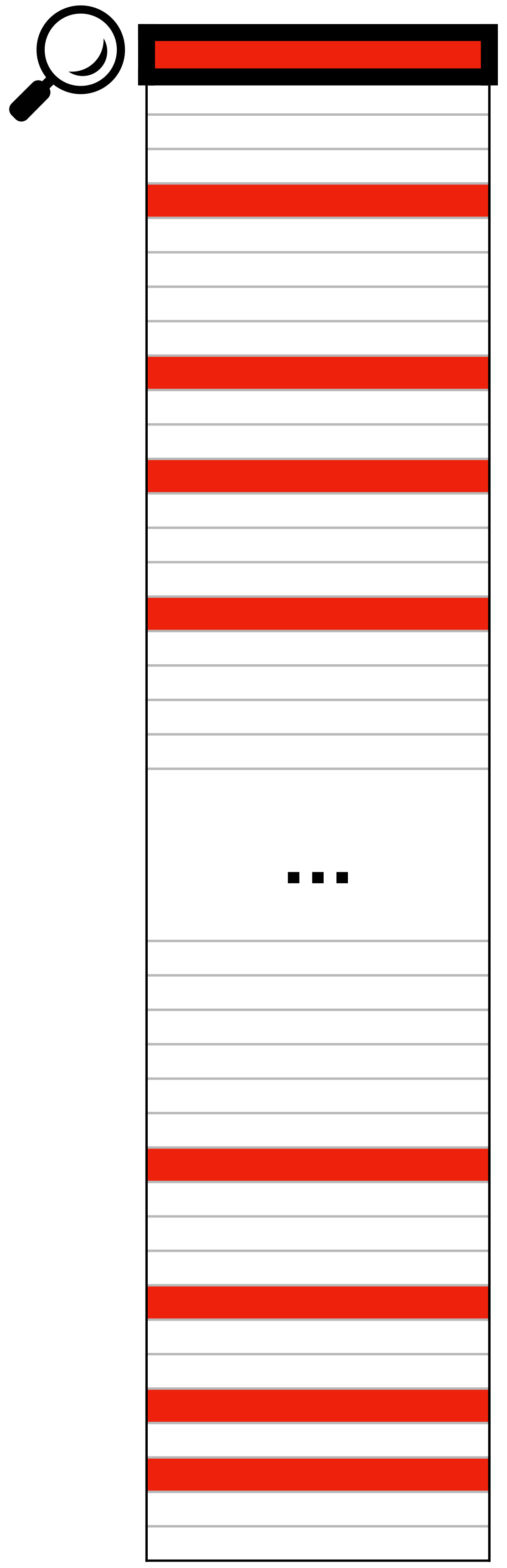


152KLOC
75 Datarace Bugs
522 Total Alarms

Bug
False Alarm

Interactive Alarm Ranker

Rank 1



Rank 522

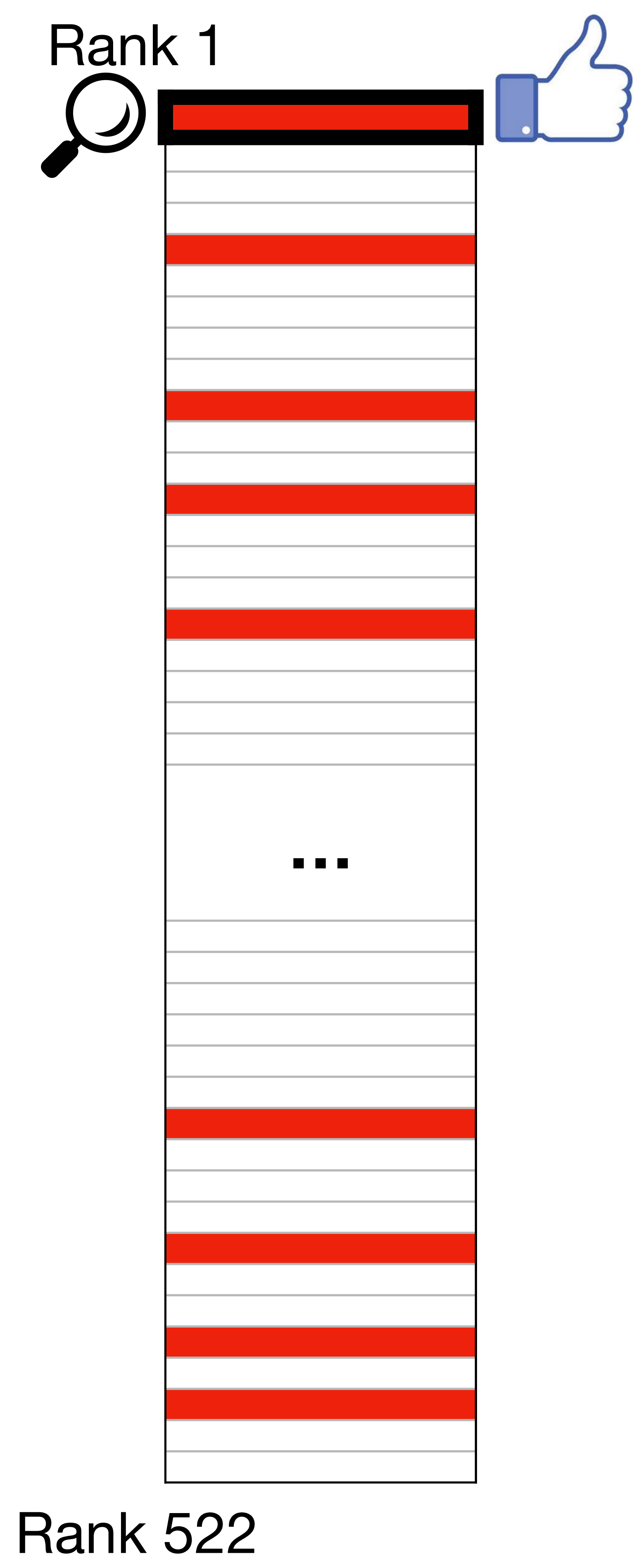
Apache FtpServer

152KLOC
75 Datarace Bugs
522 Total Alarms

Bug

False Alarm

Interactive Alarm Ranker



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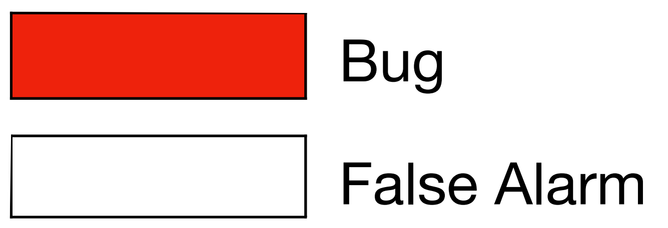
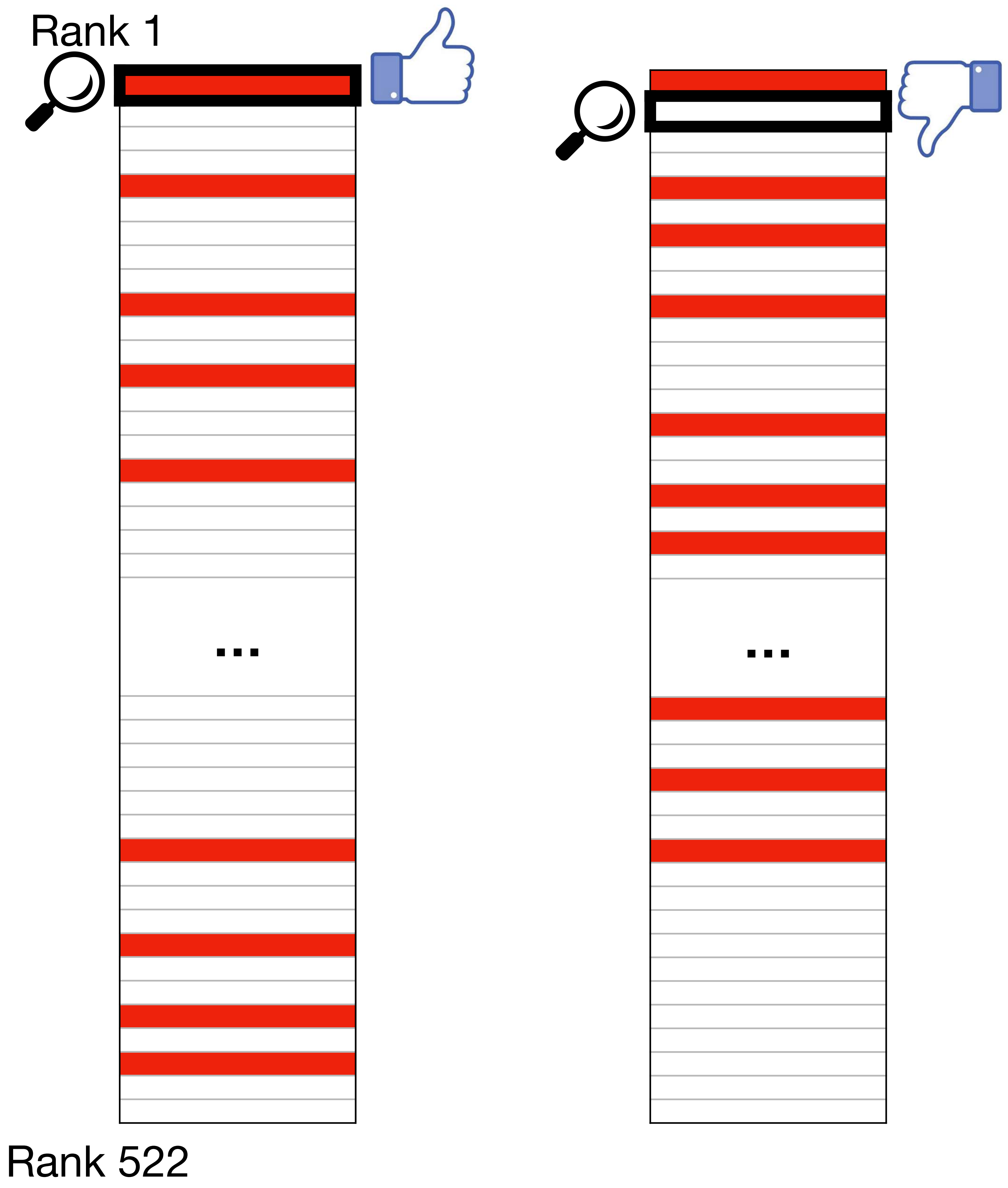


Interactive Alarm Ranker



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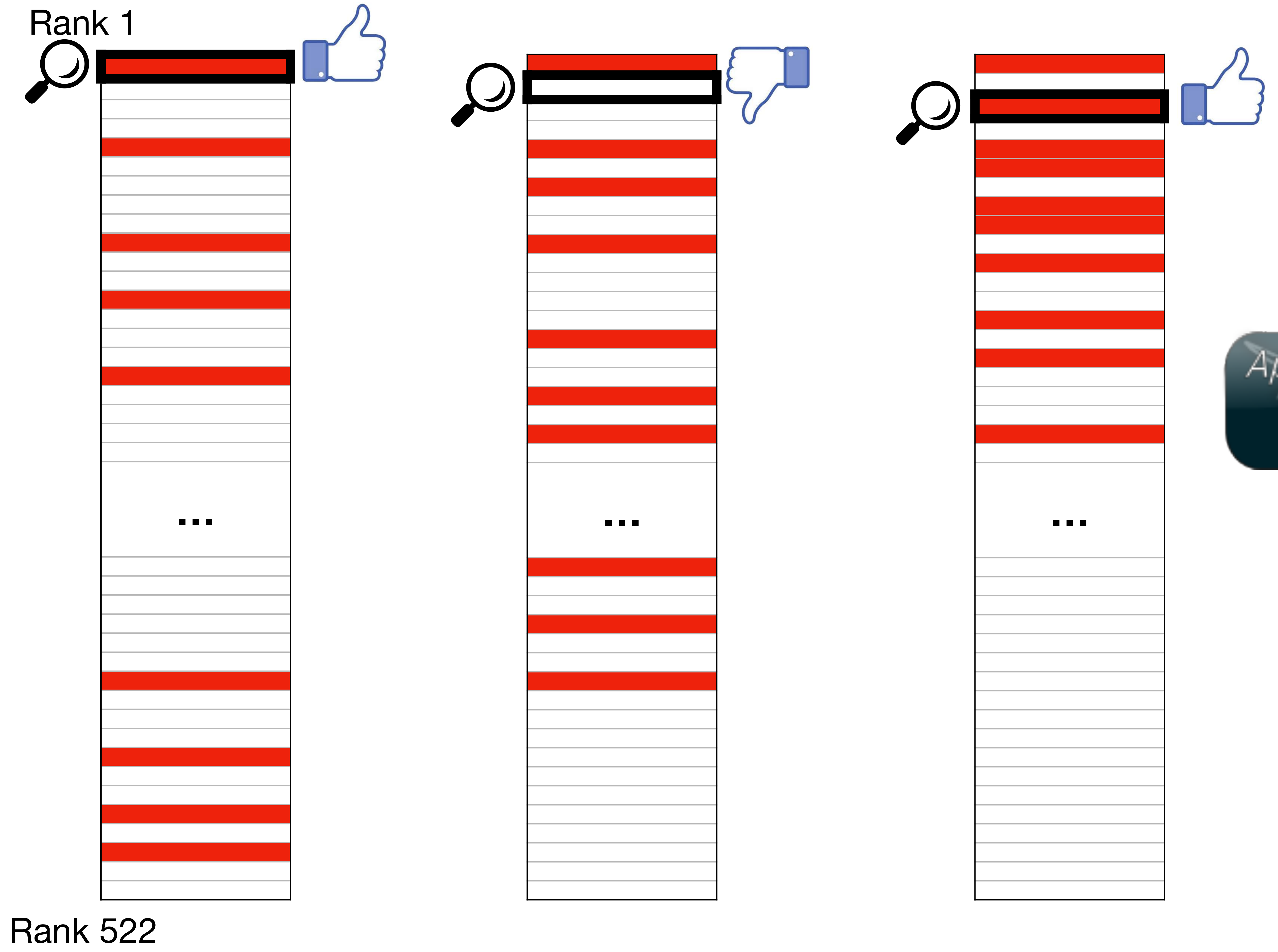

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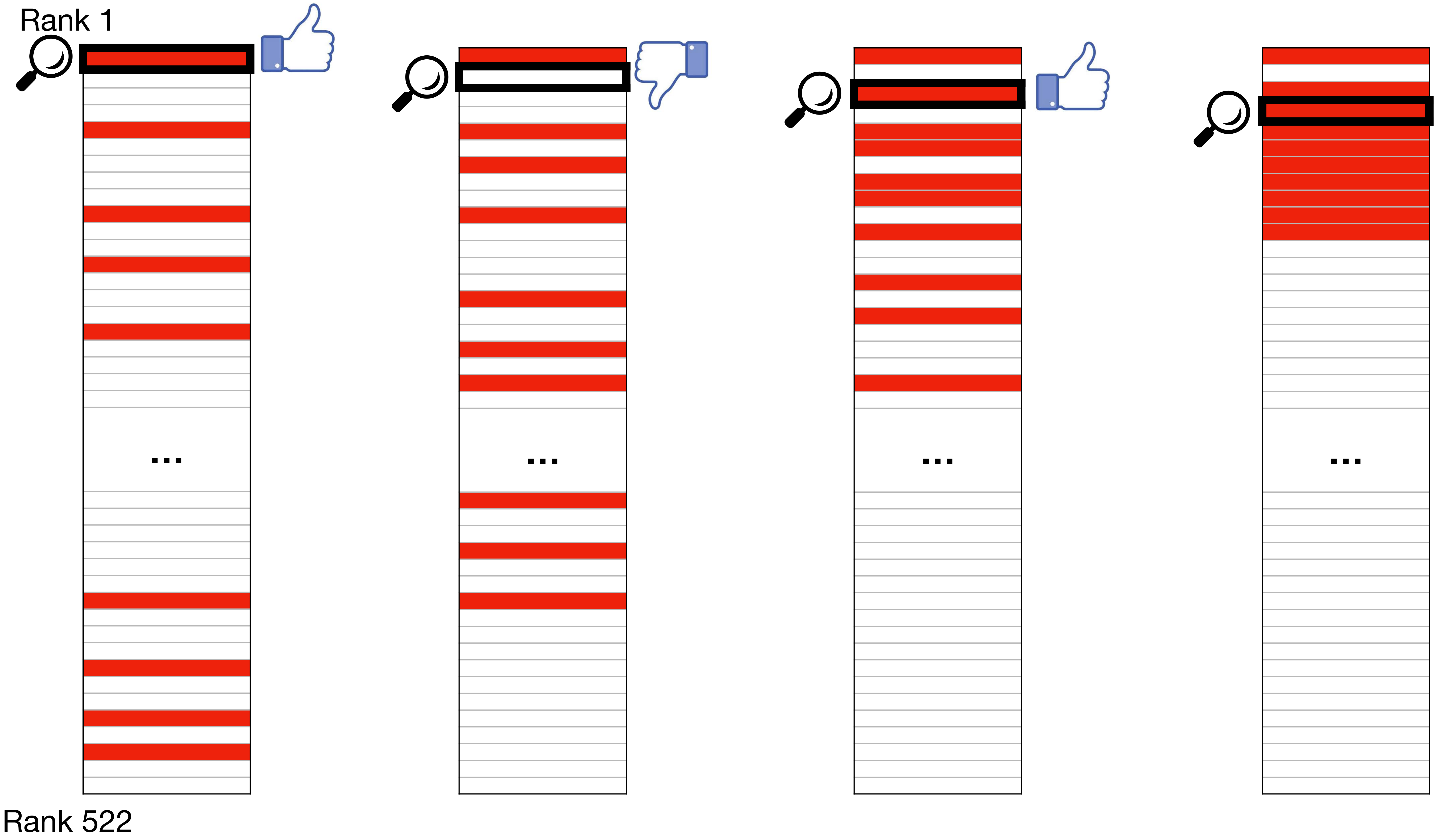
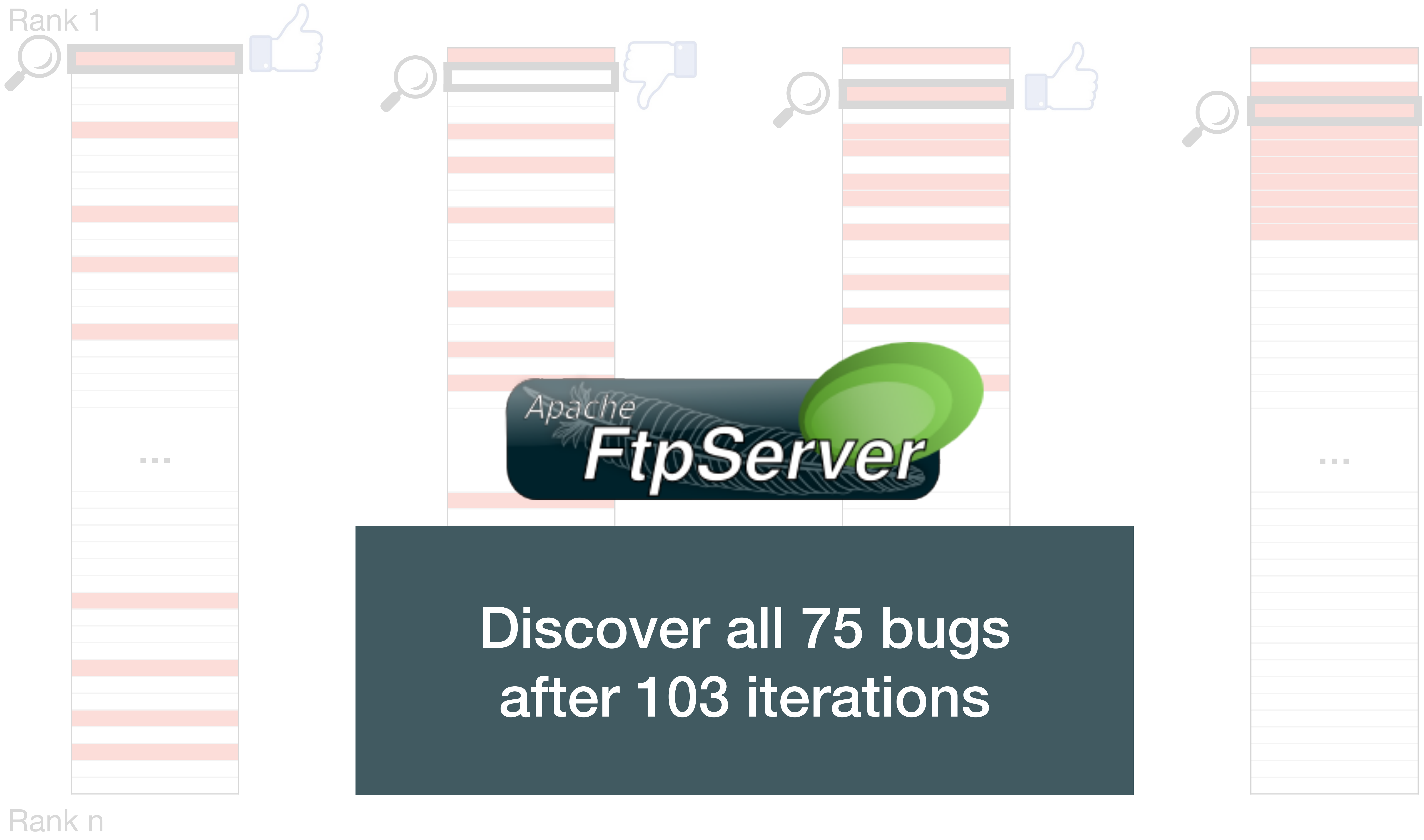


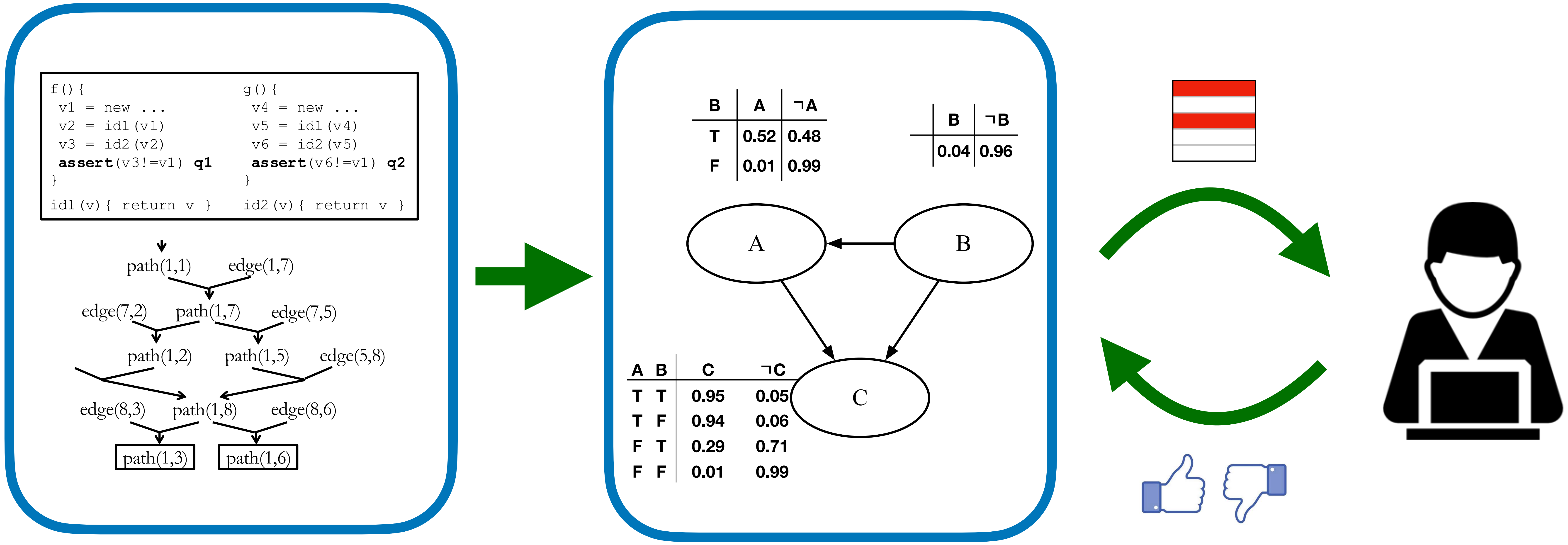
Interactive Alarm Ranker



Discover all 75 bugs
after 103 iterations

Key Idea

Human in the loop + Bayesian inference



Program Analysis Result

Probabilistic Model (e.g., Bayesian Network)

User

Datarace Analysis

Analysis Inputs:

Next(p_1, p_2), Alias(p_1, p_2), Unguarded(p_1, p_2).

Analysis Outputs:

Parallel(p_1, p_2), Race(p_1, p_2)

Analysis Rules:

r$_1$: Parallel(p_1, p_3) :- Parallel(p_1, p_2), Next(p_2, p_3), Unguarded(p_1, p_3).

r$_2$: Parallel(p_1, p_2) :- Parallel(p_2, p_1).

r$_3$: Race(p_1, p_2) :- Parallel(p_1, p_2), Alias(p_1, p_2).

Datarace Analysis

p_i is a program point

Analysis Inputs:

Next(p_1, p_2), Alias(p_1, p_2), Unguarded(p_1, p_2).

Program point p_2 is an immediate successor of p_1

p_1 and p_2 may access the same memory location

p_1 and p_2 are not guarded by the same lock

Analysis Rules:

r$_1$: Parallel(p_1, p_3) :- Parallel(p_1, p_2), Next(p_2, p_3), Unguarded(p_1, p_3).

r$_2$: Parallel(p_1, p_2) :- Parallel(p_2, p_1).

r$_3$: Race(p_1, p_2) :- Parallel(p_1, p_2), Alias(p_1, p_2).

Datarace Analysis

Analysis Inputs:
Next(p_1, p_2), Alias(p_1, p_2), Unguarded(p_1, p_2).

Analysis Outputs:
Parallel(p_1, p_2), Race(p_1, p_2)

Program point p_1 and p_2 can be executed in parallel

Race condition between p_1 and p_2

es

r₁: Parallel(p_1, p_3) :- Parallel(p_1, p_2), Next(p_2, p_3), Unguarded(p_1, p_3).
r$_2$: Parallel(p_1, p_2) :- Parallel(p_2, p_1).
r$_3$: Race(p_1, p_2) :- Parallel(p_1, p_2), Alias(p_1, p_2).

Datarace Analysis

Analysis Inputs:
Next(p_1, p_2), Alias(p_1, p_2), Unguarded(p_1, p_2).

Analysis Outputs:
Parallel(p_1, p_2), Race(p_1, p_2)

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Thread 1

```
…
x = y + 1; // L1
…
```

Thread 2

```
…
z = y + 1; // L2
x = z + 1; // L3
…
```

Datarace Analysis

Analysis Inputs:

Next(p_1, p_2), Alias(p_1, p_2), Unguarded(p_1, p_2).

Analysis Outputs:

Parallel(p_1, p_2), Race(p_1, p_2)

Analysis Rules:

r$_1$: Parallel(p_1, p_3) :- Parallel(p_1, p_2), Next(p_2, p_3), Unguarded(p_1, p_3).

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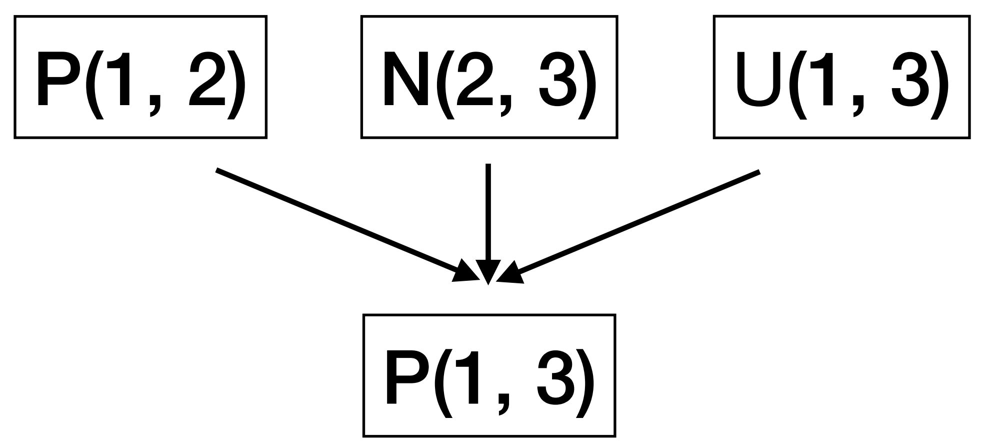
Thread 1

```
…
x = y + 1; // L1
…
```

Thread 2

```
…
z = y + 1; // L2
x = z + 1; // L3
…
```

Derivation



Datarace Analysis

Analysis Inputs:
Next(p_1, p_2), Alias(p_1, p_2), Unguarded(p_1, p_2).

Analysis Outputs:
Parallel(p_1, p_2), Race(p_1, p_2)

Analysis Rules:
r1: Parallel(p_1, p_3) :- Parallel(p_1, p_2), Next(p_2, p_3), Unguarded(p_1, p_3).
r2: Parallel(p_1, p_2) :- Parallel(p_2, p_1).
r3: Race(p_1, p_2) :- Parallel(p_1, p_2), Alias(p_1, p_2).

Thread 1

```
…
x = y + 1; // L1
…
```

Thread 2

```
…
z = y + 1; // L2
x = z + 1; // L3
…
```

Derivation

$$\boxed{P(1, 2)} \rightarrow \boxed{P(2, 1)}$$

Datarace Analysis

Analysis Inputs:

Next(p_1, p_2), Alias(p_1, p_2), Unguarded(p_1, p_2).

Analysis Outputs:

Parallel(p_1, p_2), Race(p_1, p_2)

Analysis Rules:

r$_1$: Parallel(p_1, p_3) :- Parallel(p_1, p_2), Next(p_2, p_3), Unguarded(p_1, p_3).

r$_2$: Parallel(p_1, p_2) :- Parallel(p_2, p_1).

r$_3$: Race(p_1, p_2) :- Parallel(p_1, p_2), Alias(p_1, p_2).

Thread 1

```
…
x = y + 1; // L1
…
```

Thread 2

```
…
z = y + 1; // L2
x = z + 1; // L3
…
```

Derivation

$$\begin{tikzcd} \boxed{\text{P}(1, 3)} \arrow[dr] & & \boxed{\text{A}(1, 3)} \arrow[dl] \\ & \boxed{\text{R}(1, 3)} & \end{tikzcd}$$

Example

```
public class RequestHandler {
 private FtpRequest request;

 public FtpRequest getRequest() {
  return request;                //L0
 }

 public void close() {
  synchronized (this) {          //L1
   if (isClosed) return;         //L2
   isClosed = true;              //L3
  }
  controlSocket.close();         //L4
  controlSocket = null;          //L5
  request.clear();               //L6
  request = null;                //L7
 }
}
```

Analysis Rules:

r$_1$: $\mathrm{P}(p_1, p_3)$:- $\mathrm{P}(p_1, p_2)$, $\mathrm{N}(p_2, p_3)$, $\mathrm{U}(p_1, p_3)$.

r$_2$: $\mathrm{P}(p_1, p_2)$:- $\mathrm{P}(p_2, p_1)$.

r$_3$: $\mathrm{R}(p_1, p_2)$:- $\mathrm{P}(p_1, p_2)$, $\mathrm{A}(p_1, p_2)$.

***Apache FTP Server**

Example

```
public class RequestHandler {
 private FtpRequest request;

 public FtpRequest getRequest() {
  return request;                       //L0
 }

 public void close() {
  synchronized (this) {                 //L1
   if (isClosed) return;                //L2
   isClosed = true;                     //L3
  }
  controlSocket.close();                //L4
  controlSocket = null;                 //L5
  request.clear();                      //L6
  request = null;                       //L7
 }
}
```

Analysis Rules:

r1: $P(p_1, p_3)$:- $P(p_1, p_2)$, $N(p_2, p_3)$, $U(p_1, p_3)$.

r2: $P(p_1, p_2)$:- $P(p_2, p_1)$.

r3: $R(p_1, p_2)$:- $P(p_1, p_2)$, $A(p_1, p_2)$.

Datarace

***Apache FTP Server**

Example

```
public class RequestHandler {
 private FtpRequest request;

 public FtpRequest getRequest() {
  return request;                  //L0
 }

 public void close() {
  synchronized (this) {            //L1
   if (isClosed) return;           //L2
   isClosed = true;                //L3
  }
  controlSocket.close();           //L4
  controlSocket = null;            //L5
  request.clear();                 //L6
  request = null;                  //L7
 }
}
```

Analysis Rules:

r1: $P(p_1, p_3)$:- $P(p_1, p_2)$, $N(p_2, p_3)$, $U(p_1, p_3)$.

r2: $P(p_1, p_2)$:- $P(p_2, p_1)$.

r3: $R(p_1, p_2)$:- $P(p_1, p_2)$, $A(p_1, p_2)$.

False alarm

False alarm

***Apache FTP Server**

Applying the Analysis

Program

```
controlSocket.close(); //L4
controlSocket = null;  //L5
request.clear();       //L6
request = null;        //L7
```

Analysis Rules

r_1: $P(p_1, p_3)$:- $P(p_1, p_2)$, $N(p_2, p_3)$, $U(p_1, p_3)$.
r_2: $P(p_1, p_2)$:- $P(p_2, p_1)$.
r_3: $R(p_1, p_2)$:- $P(p_1, p_2)$, $A(p_1, p_2)$.

Applying the Analysis

Program

```
controlSocket.close(); //L4
controlSocket = null;  //L5
request.clear();       //L6
request = null;        //L7
```

Derivation Graph

P(4, 4)	N(4, 5)	U(4, 5)	
A(4, 5)		N(5, 6)	U(4, 6)

1. Start with inputs

Analysis Rules

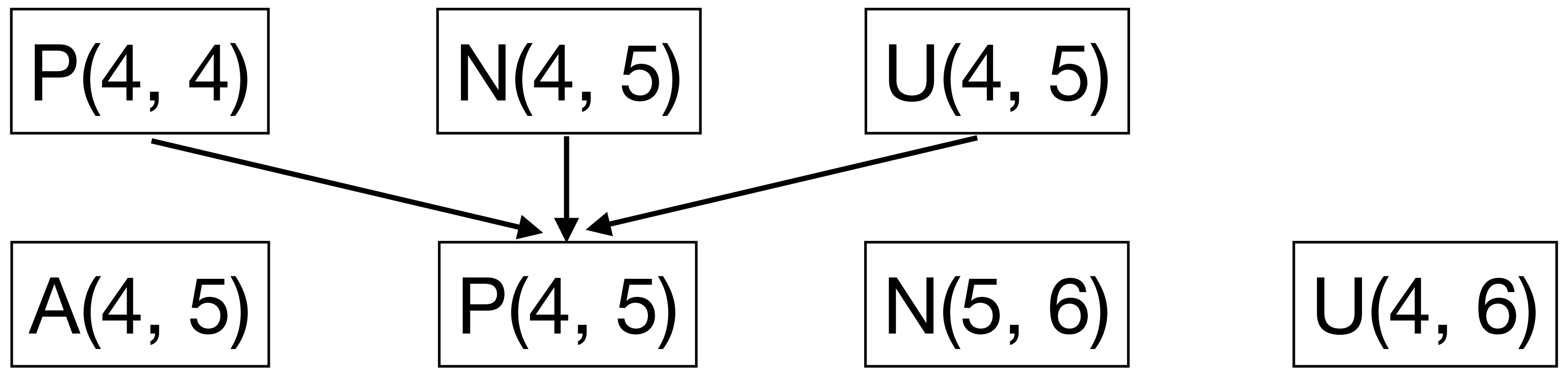
r1: P(p_1, p_3) :- P(p_1, p_2), N(p_2, p_3), U(p_1, p_3).
r2: P(p_1, p_2) :- P(p_2, p_1).
r3: R(p_1, p_2) :- P(p_1, p_2), A(p_1, p_2).

Applying the Analysis

Program

```
controlSocket.close(); //L4
controlSocket = null;  //L5
request.clear();       //L6
request = null;        //L7
```

Derivation Graph



2. Apply rules to inputs

Analysis Rules

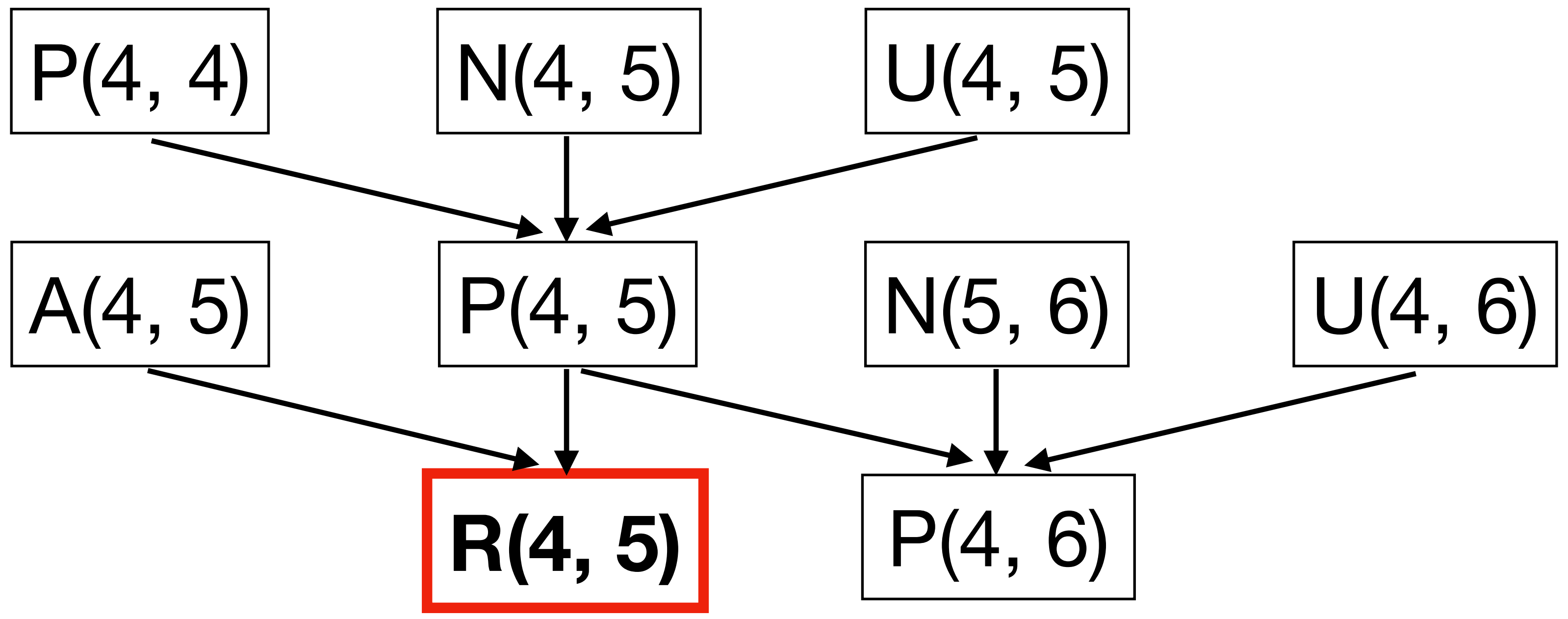
r1: $P(p_1, p_3)$:- $P(p_1, p_2)$, $N(p_2, p_3)$, $U(p_1, p_3)$.
r2: $P(p_1, p_2)$:- $P(p_2, p_1)$.
r3: $R(p_1, p_2)$:- $P(p_1, p_2)$, $A(p_1, p_2)$.

Applying the Analysis

Program

```
controlSocket.close(); //L4
controlSocket = null;  //L5
request.clear();       //L6
request = null;        //L7
```

Derivation Graph



3. Keep applying rules to all intermediate results

Analysis Rules

r1: P(p_1, p_3) :- P(p_1, p_2), N(p_2, p_3), U(p_1, p_3).
r2: P(p_1, p_2) :- P(p_2, p_1).
r3: R(p_1, p_2) :- P(p_1, p_2), A(p_1, p_2).

Applying the Analysis

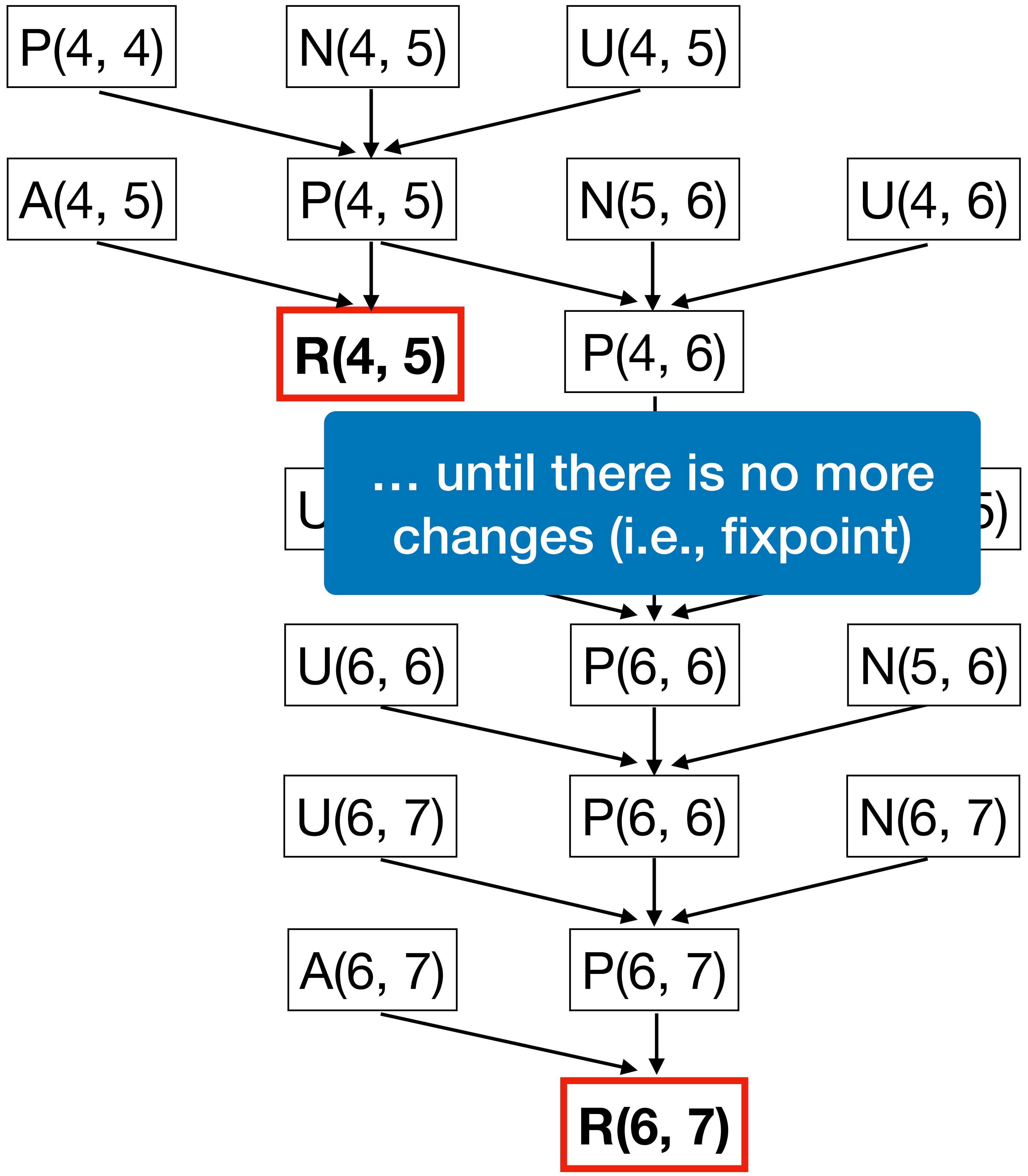
Program

```
controlSocket.close(); //L4
controlSocket = null;  //L5
request.clear();       //L6
request = null;        //L7
```

Analysis Rules

r1: P(p_1, p_3) :- P(p_1, p_2), N(p_2, p_3), U(p_1, p_3).
r2: P(p_1, p_2) :- P(p_2, p_1).
r3: R(p_1, p_2) :- P(p_1, p_2), A(p_1, p_2).

Derivation Graph

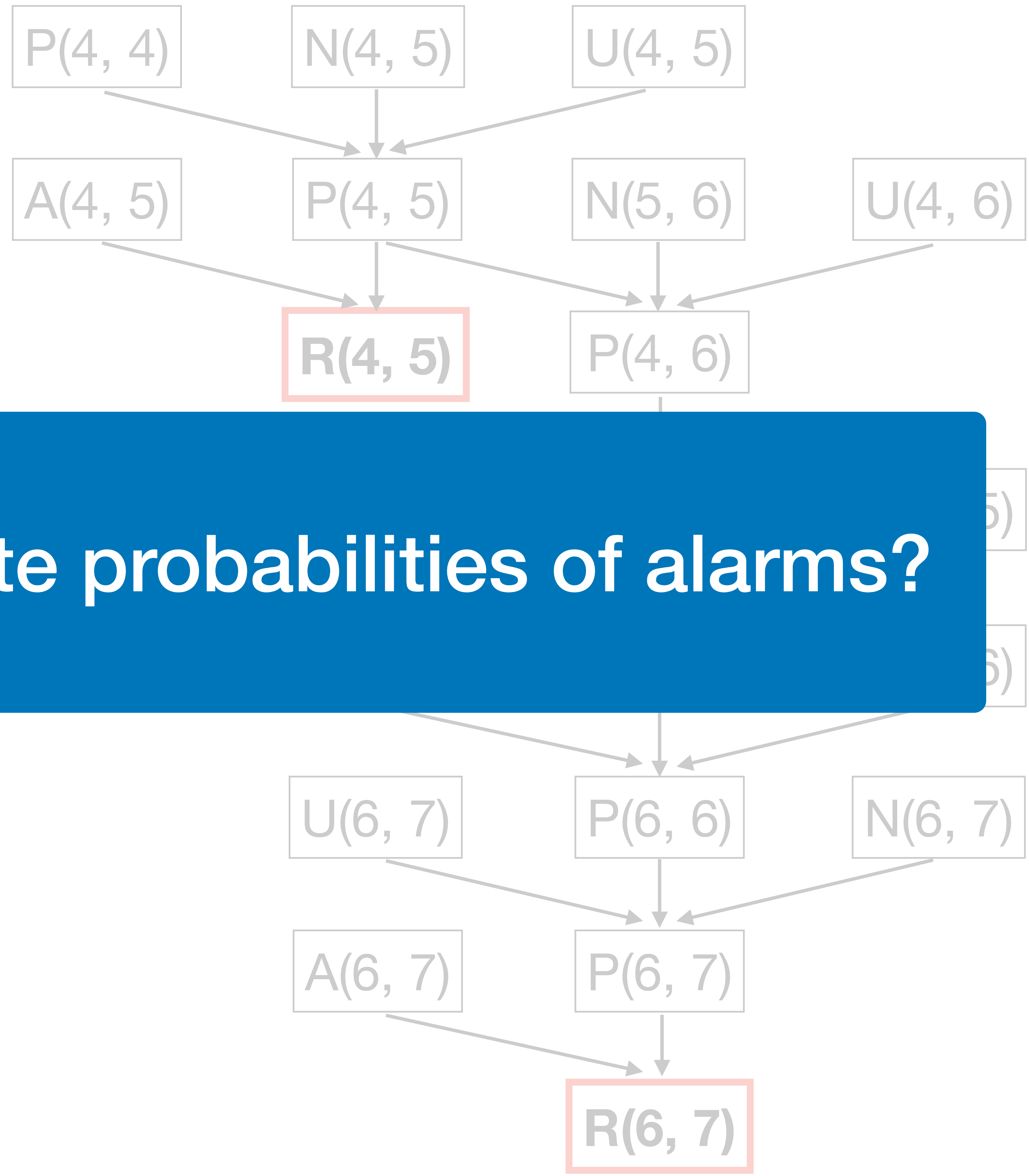


Applying the Analysis

Program

```
controlSocket.close(); //L4
controlSocket = null;  //L5
request.clear();       //L6
request = null;        //L7
```

Derivation Graph



Analysis R

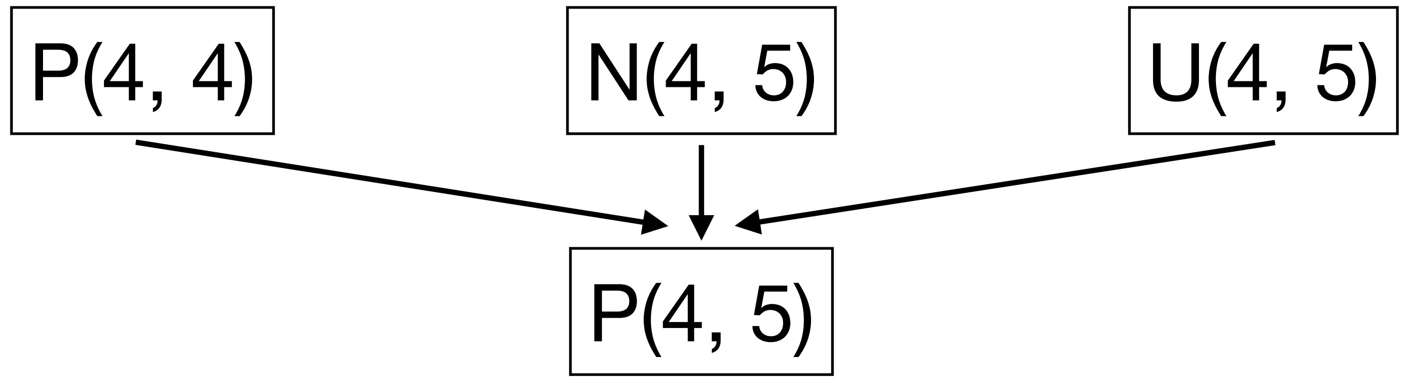
r1: P(p_1, p_3)

r2: P(p_1, p_2) :- P(p_2, p_1).

r3: R(p_1, p_2) :- P(p_1, p_2), A(p_1, p_2).

Q: How do we compute probabilities of alarms?

Bayesian Network



Logical Rule

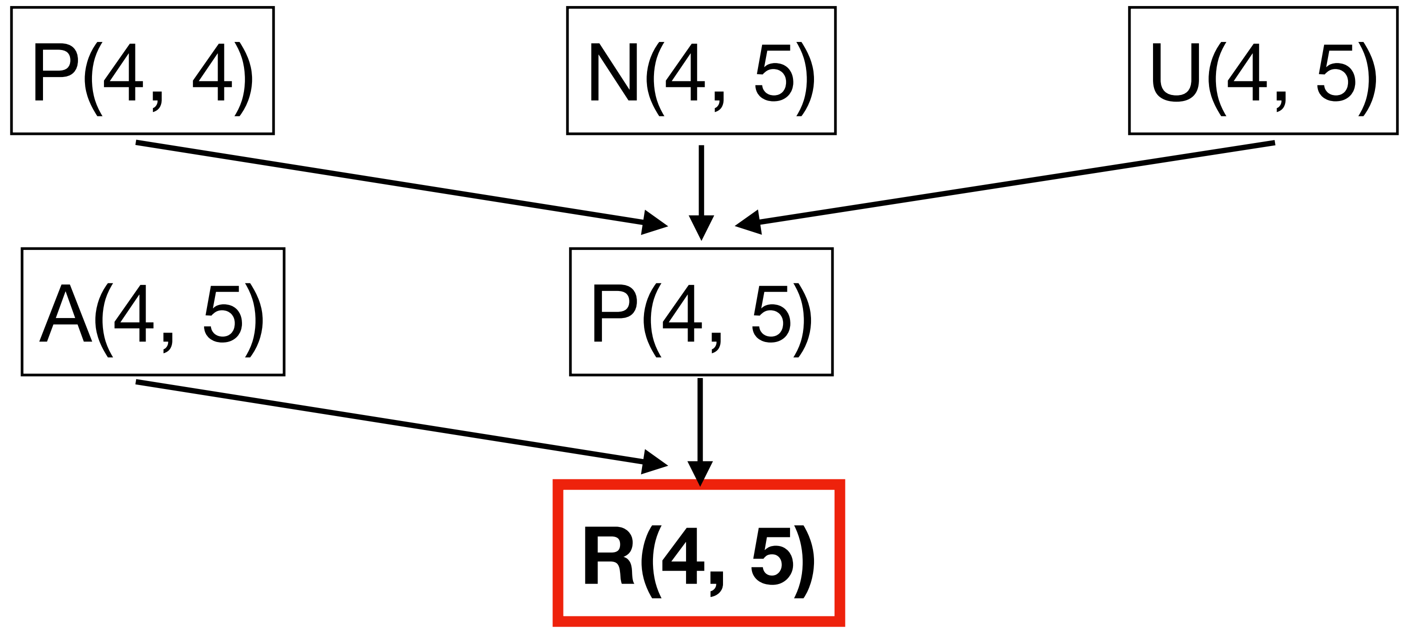
r$_1$: P(p_1, p_3) :- P(p_1, p_2), N(p_2, p_3), U(p_1, p_3).
r$_2$: P(p_1, p_2) :- P(p_2, p_1).
r$_3$: R(p_1, p_2) :- P(p_1, p_2), A(p_1, p_2).

Probabilistic Rule

P(4,4)	N(4,5)	U(4,5)	*Pr*(P(4,5) | …)
TRUE	TRUE	TRUE	0.95*
TRUE	TRUE	FALSE	0
	…		
FALSE	FALSE	FALSE	0

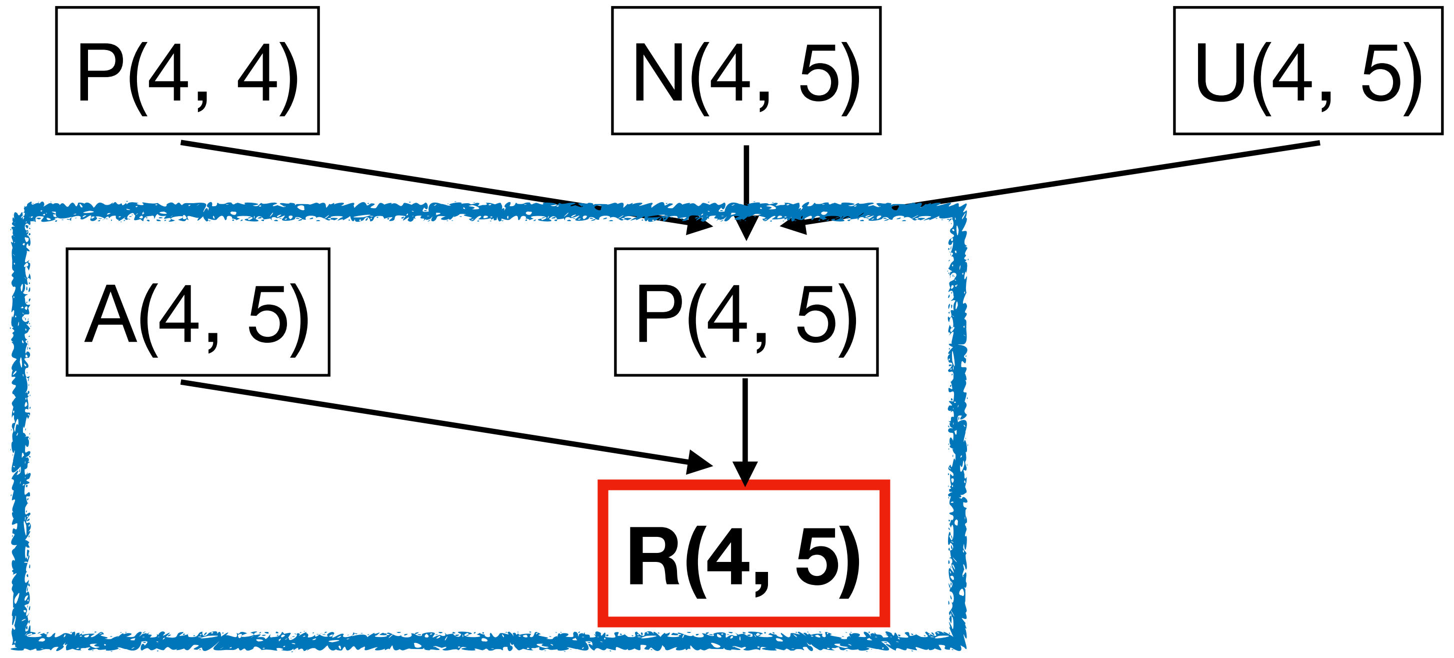
*computed by an offline learning

Marginal Inference



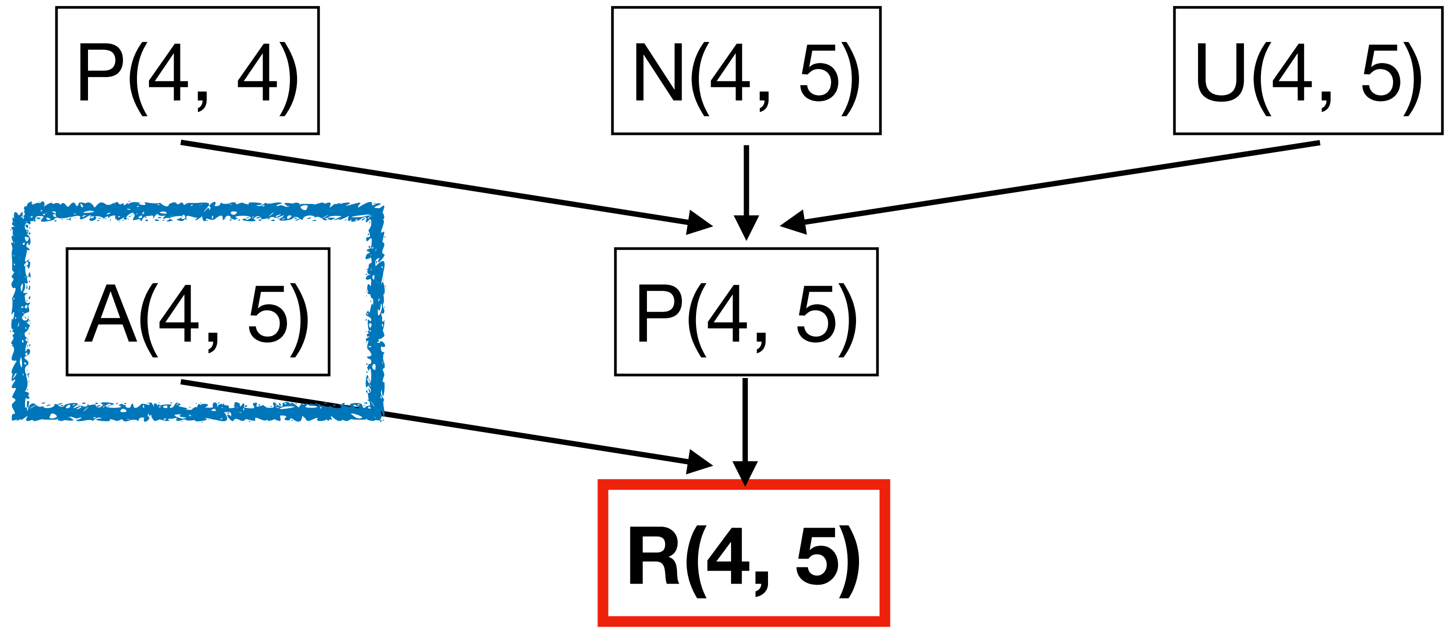
Pr(R(4,5)) =

Marginal Inference



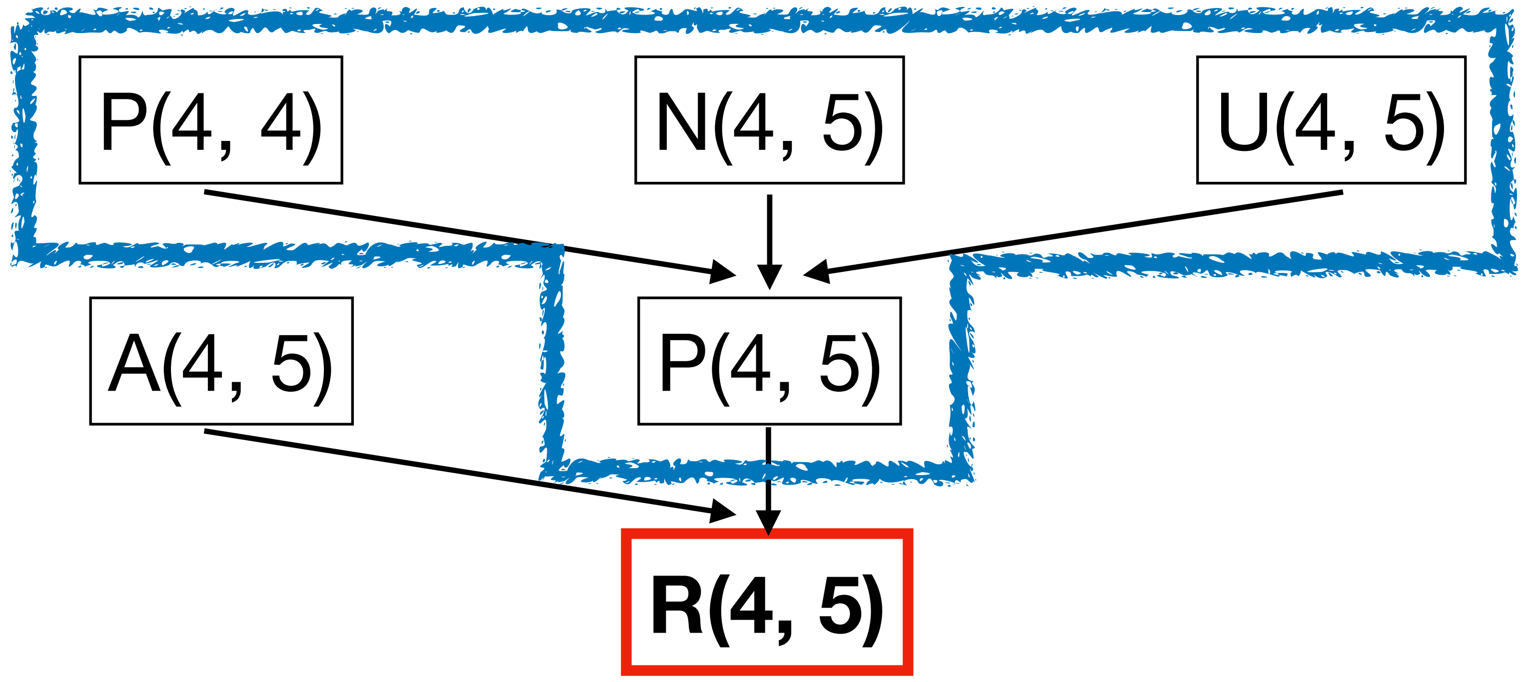
$$Pr(\mathrm{R}(4,5)) = \boxed{Pr(\mathrm{R}(4,5) \mid \mathrm{A}(4,5), \mathrm{P}(4,5))} \times$$

Marginal Inference



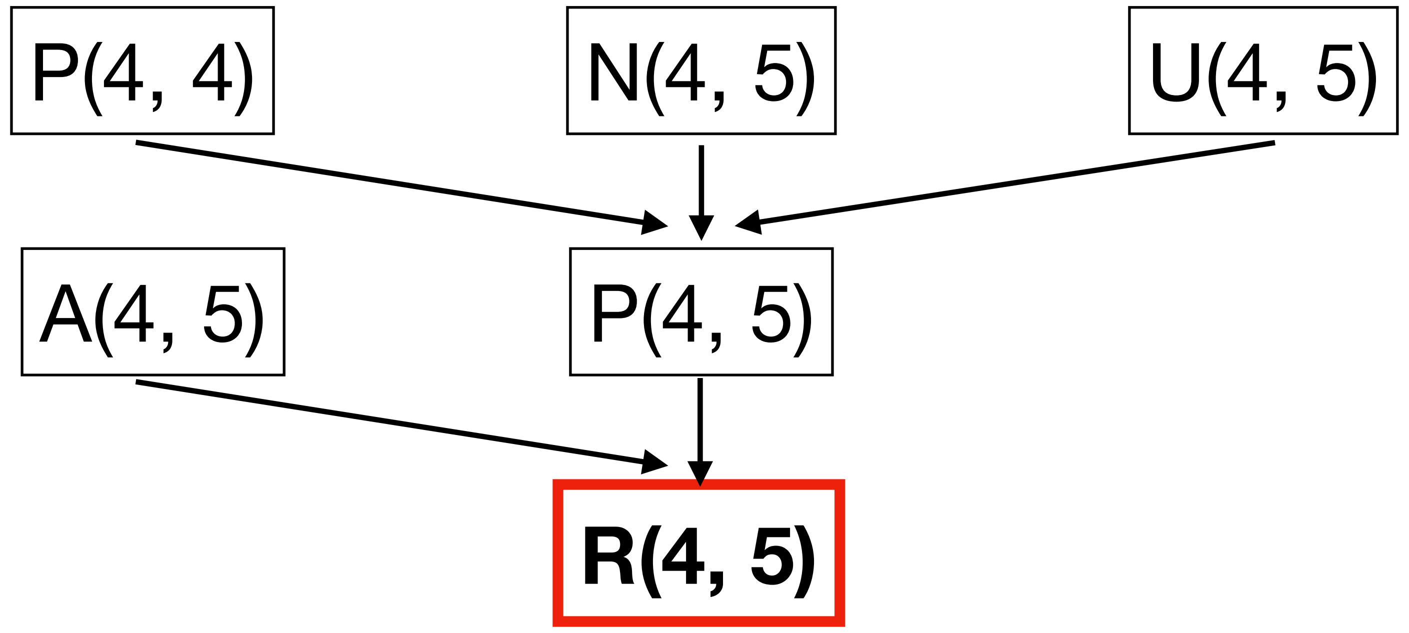
$$
\begin{aligned}
Pr(\mathrm{R}(4,5)) = \; & Pr(\mathrm{R}(4,5) \mid \mathrm{A}(4,5), \mathrm{P}(4,5)) \\
\times \; & \boxed{Pr(\mathrm{A}(4,5))} \\
\times \; &
\end{aligned}
$$

Marginal Inference



$$
\begin{aligned}
Pr(\mathrm{R}(4,5)) = {} & Pr(\mathrm{R}(4,5) \mid \mathrm{A}(4,5), \mathrm{P}(4,5)) \\
& \times Pr(\mathrm{A}(4,5)) \\
& \times \boxed{Pr(\mathrm{P}(4,5) \mid \ldots)} \\
& \times
\end{aligned}
$$

Marginal Inference



$$
\begin{aligned}
Pr(\mathrm{R}(4,5)) &= Pr(\mathrm{R}(4,5) \mid \mathrm{A}(4,5), \mathrm{P}(4,5)) \\
&\times Pr(\mathrm{A}(4,5)) \\
&\times Pr(\mathrm{P}(4,5) \mid \ldots) \\
&\times \ldots \\
&= 0.398
\end{aligned}
$$

by an off-the-shelf marginal inference solver

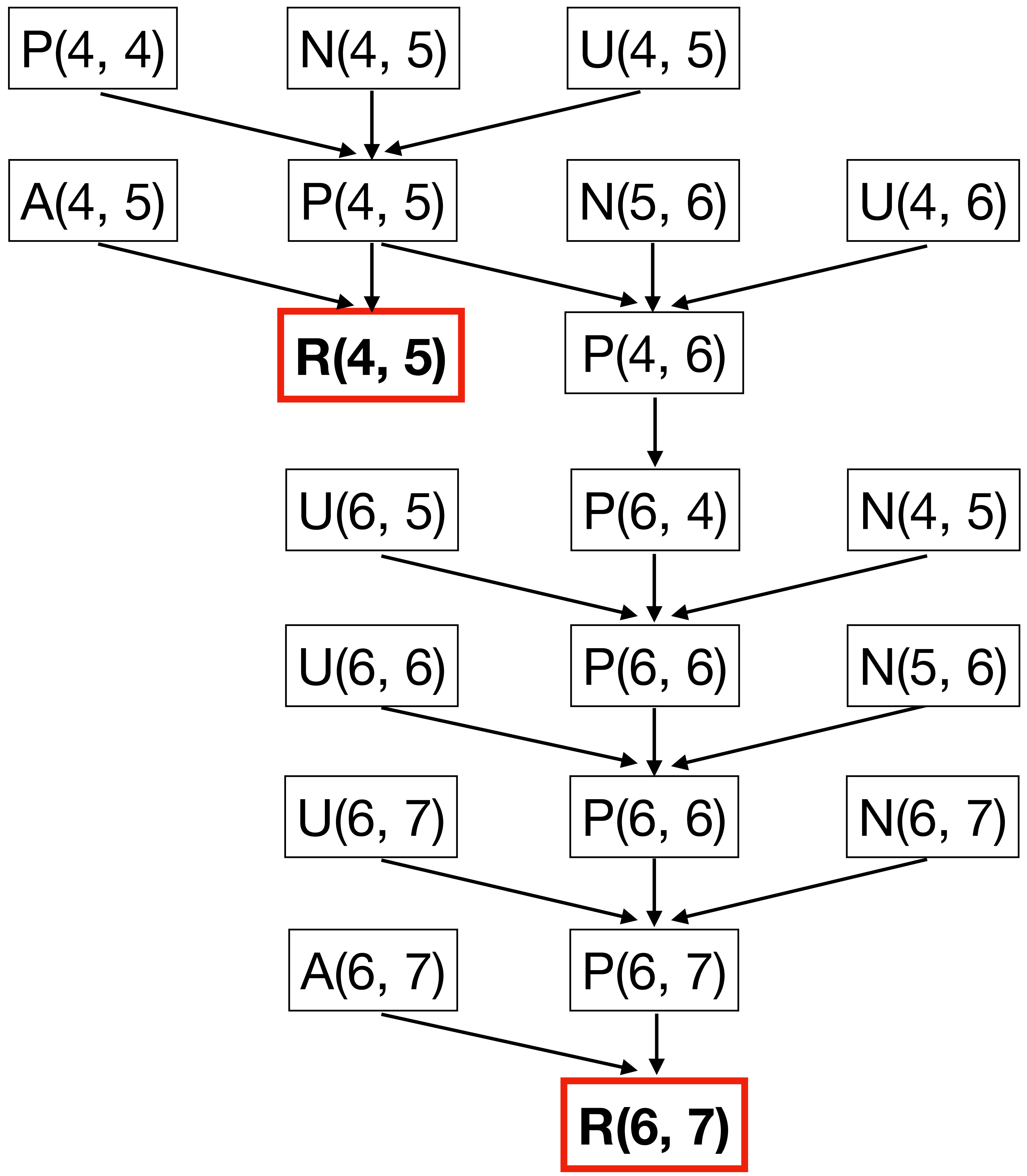
Alarm Ranking

```java
public class RequestHandler {
 private FtpRequest request;

 public FtpRequest getRequest() {
  return request;                //L0
 }

 public void close() {
  synchronized (this) {          //L1
   if (isClosed) return;         //L2
   isClosed = true;              //L3
  }
  controlSocket.close();         //L4
  controlSocket = null;          //L5
  request.clear();               //L6
  request = null;                //L7
 }
}
```

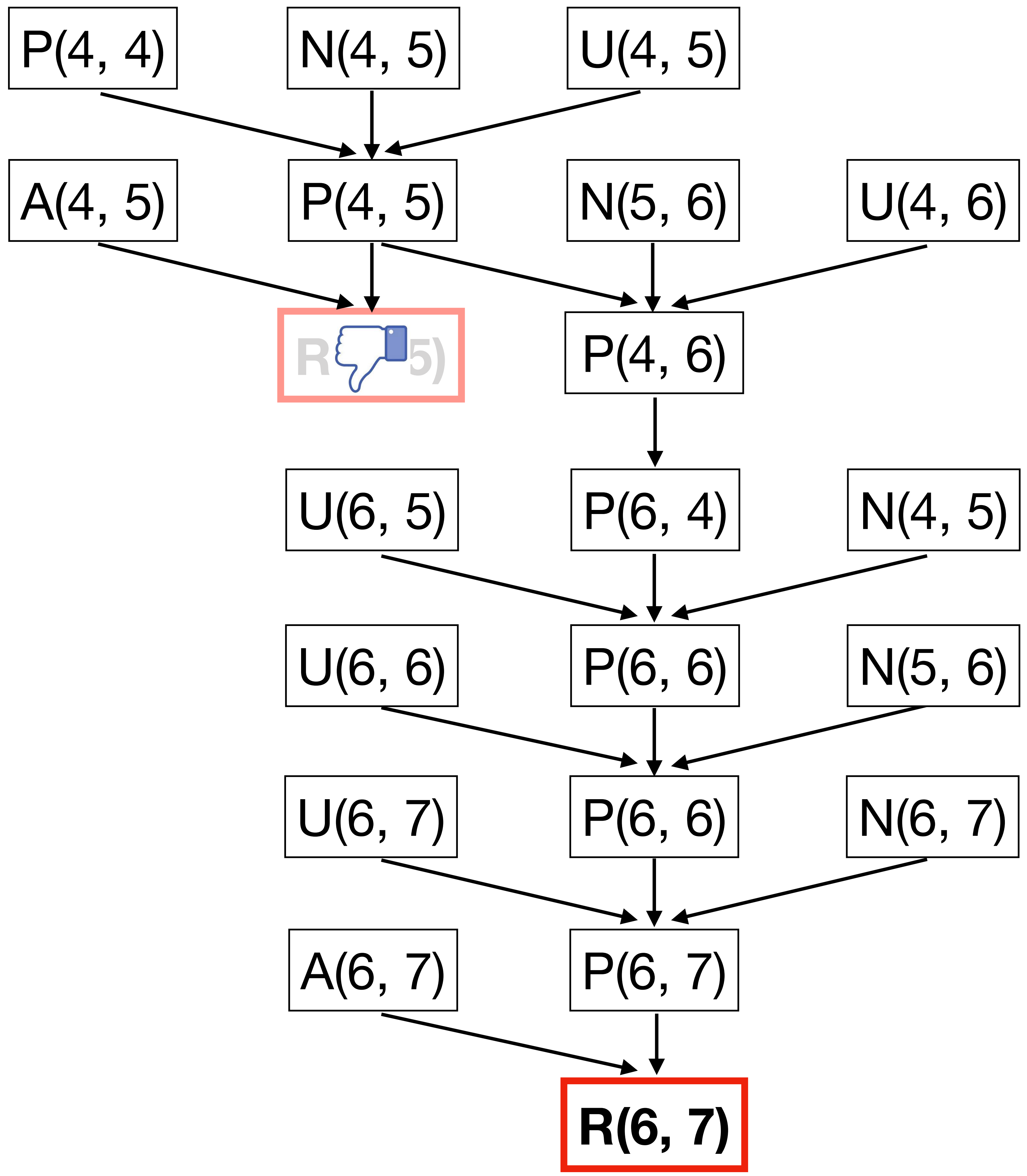
Ranking	Alarm	Confidence
1	R(4, 5)	0.398
2	R(5, 5)	0.378
3	R(6, 7)	0.324
4	R(7, 7)	0.308
5	R(0, 7)	0.279

Q: What are the probabilities of the other alarms when R(4,5) is false?

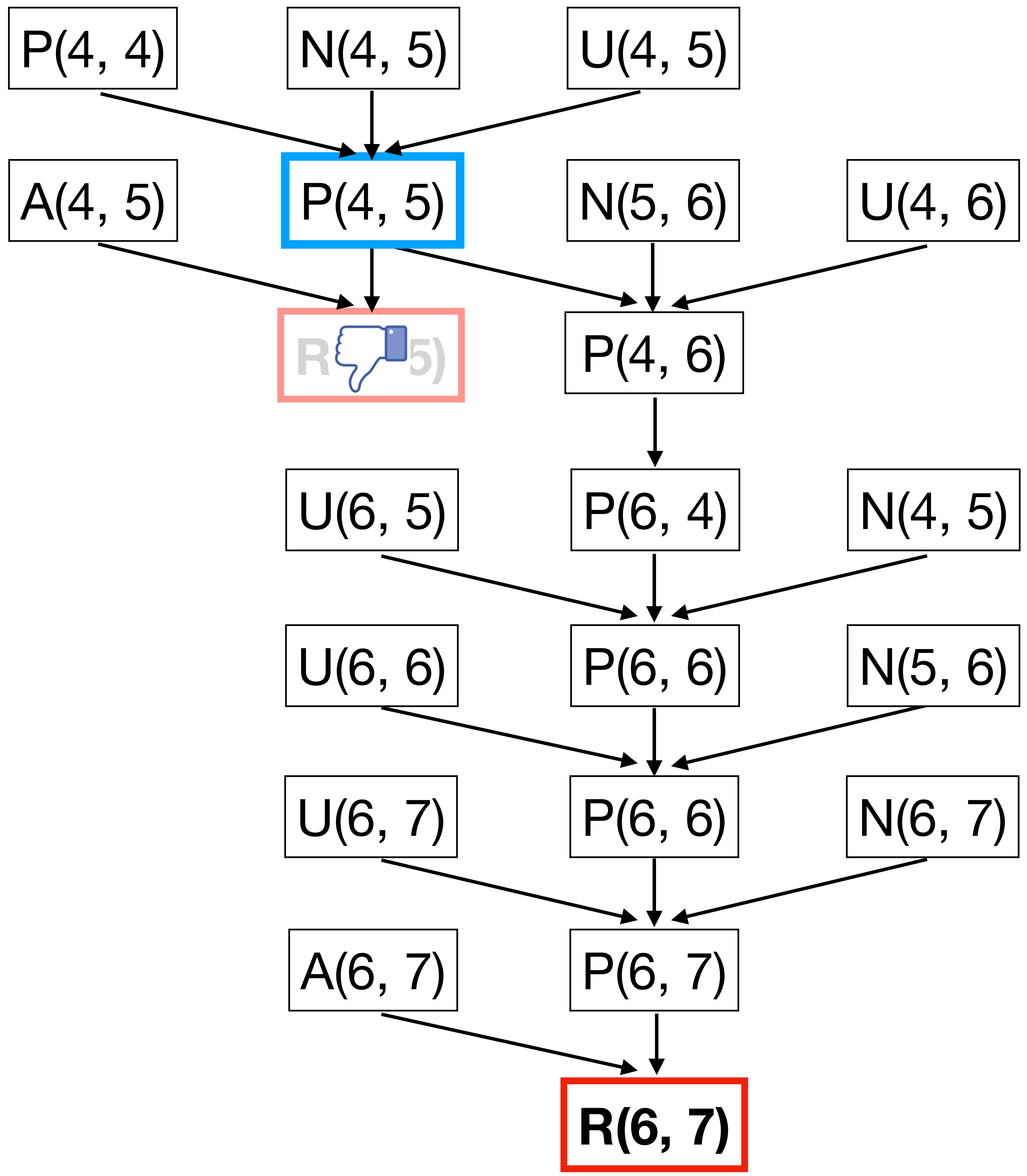
Probability of Alarms



Probability of Alarms

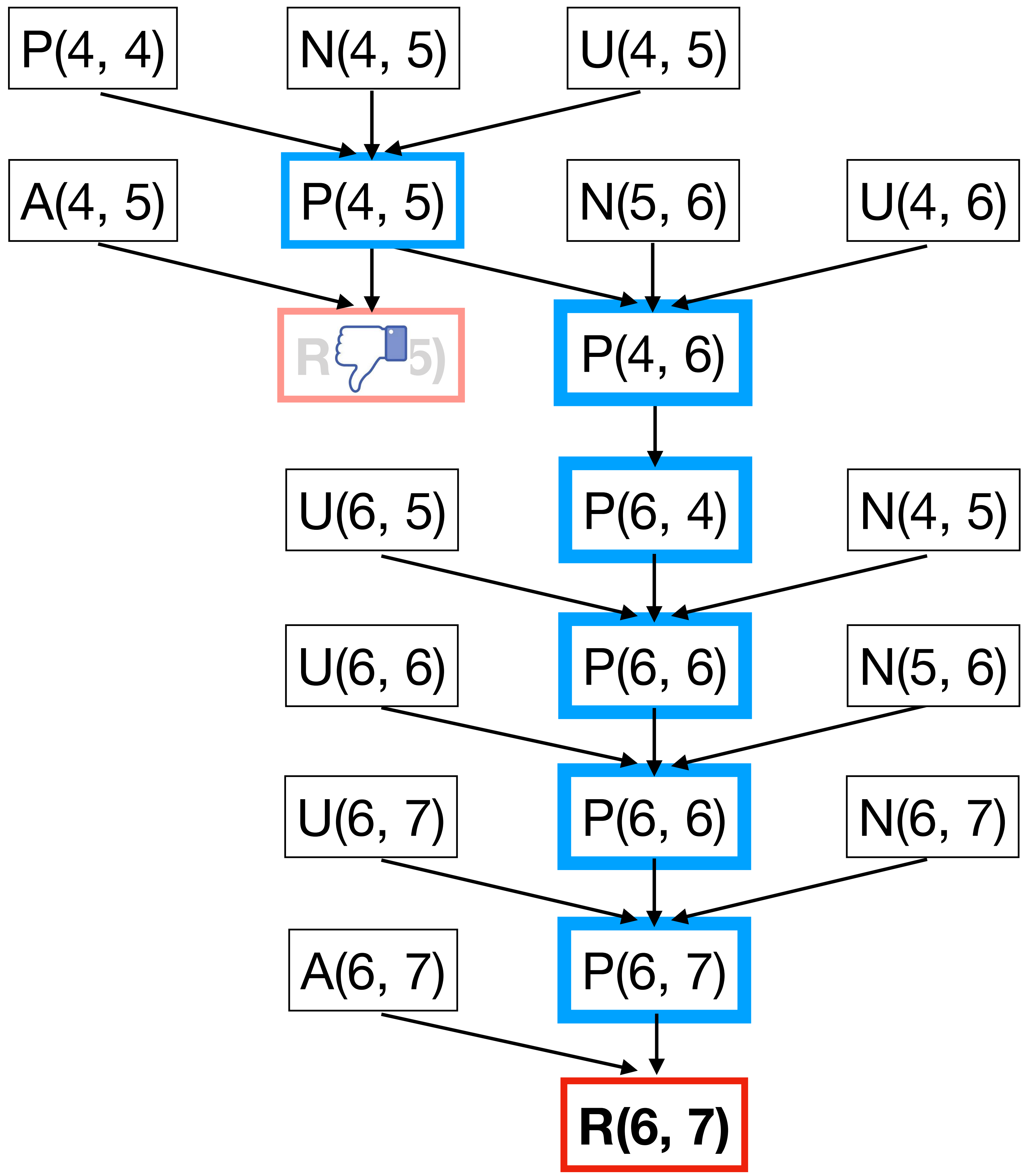


Probability of Alarms



$$
\begin{aligned}
&Pr(\mathrm{P}(4,5) \mid \neg\mathrm{R}(4,5)) \\
&\quad = Pr(\neg\mathrm{R}(4,5) \mid \mathrm{P}(4,5)) * \\
&\qquad Pr(\mathrm{P}(4,5)) \,/\, Pr(\neg\mathrm{R}(4,5)) \\
&\quad = 0.03
\end{aligned}
$$

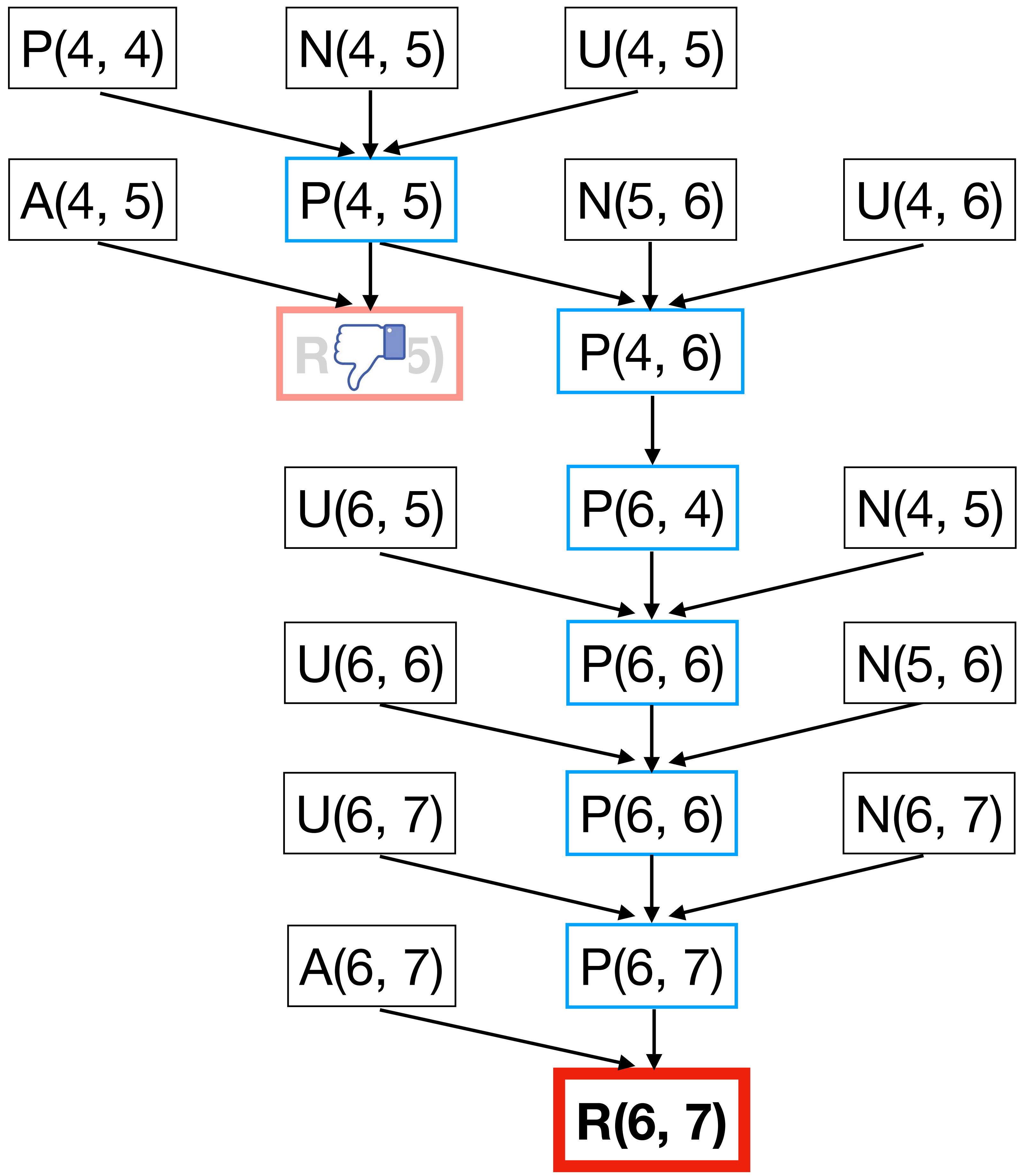
Probability of Alarms



Pr(P(4,5) | ¬R(4,5))
= *Pr*(¬R(4,5) | P(4,5)) * *Pr*(P(4,5)) / *Pr*(¬R(4,5))
= 0.03

By Bayes's Rule:
***Pr*(A|B) = *Pr*(B|A) * *Pr*(A) / *Pr*(B)**

Probability of Alarms



Pr(P(4,5) | ¬R(4,5))
= *Pr*(¬R(4,5) | P(4,5)) * *Pr*(P(4,5)) / *Pr*(¬R(4,5))
= 0.03

By Bayes's Rule:
***Pr*(A|B) = *Pr*(B|A) * *Pr*(A) / *Pr*(B)**

Pr(R(6,7) | ¬R(4,5))
= *Pr*(R(6,7) | P(4,5)) * *Pr*(P(4,5)) | ¬R(4,5))
= 0.03

New Alarm Ranking

Ranking	Alarm	Confidence
1	R(4, 5)	0.398
2	R(5, 5)	0.378
3	R(6, 7)	0.324
4	R(7, 7)	0.308
5	R(0, 7)	0.279

New Alarm Ranking

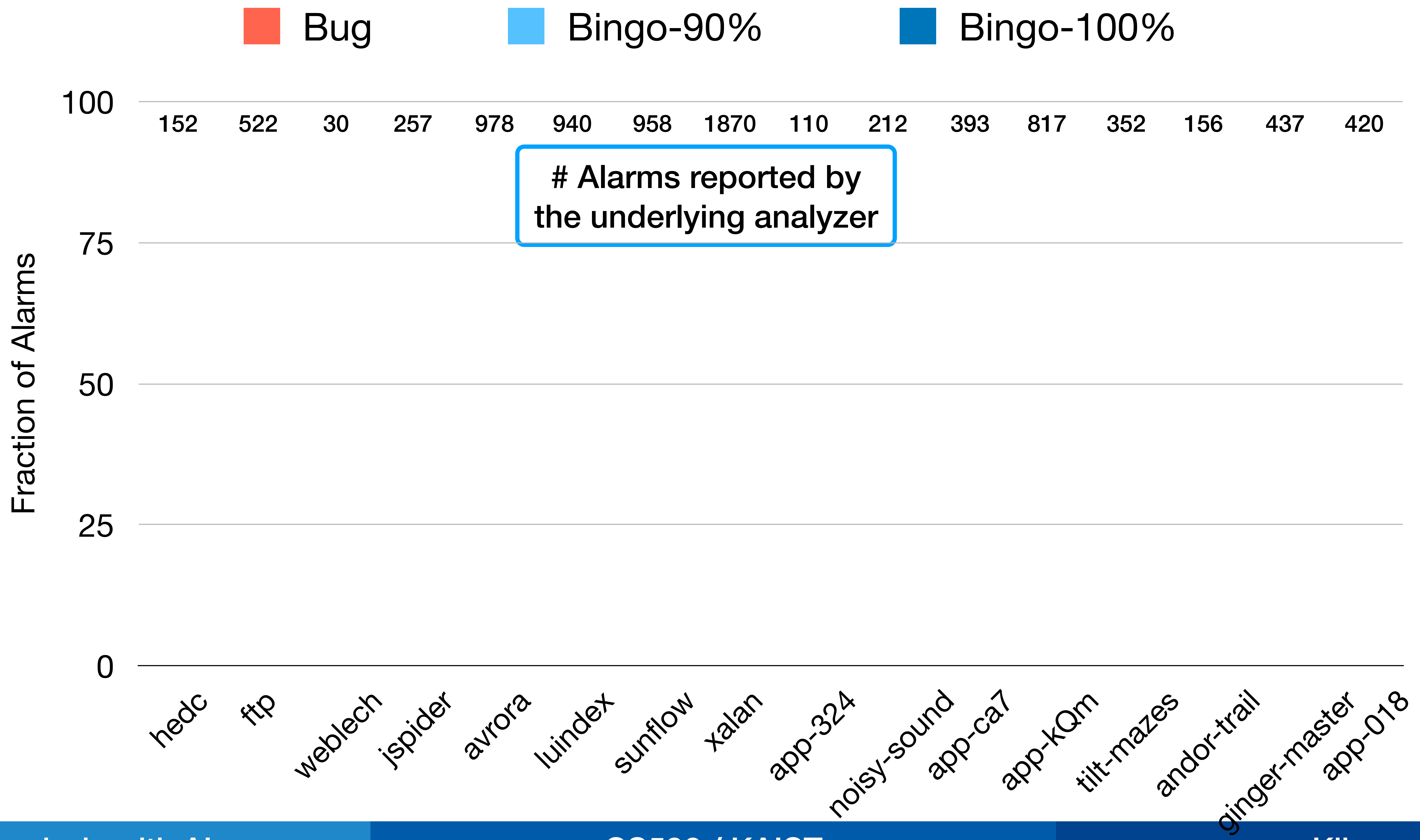
Ranking	Alarm	Confidence
1	R(0, 7)	0.279
2	R(5, 5)	0.035
3	R(6, 7)	0.030
4	R(7, 7)	0.028
5	R(4, 5)	0

Effectiveness

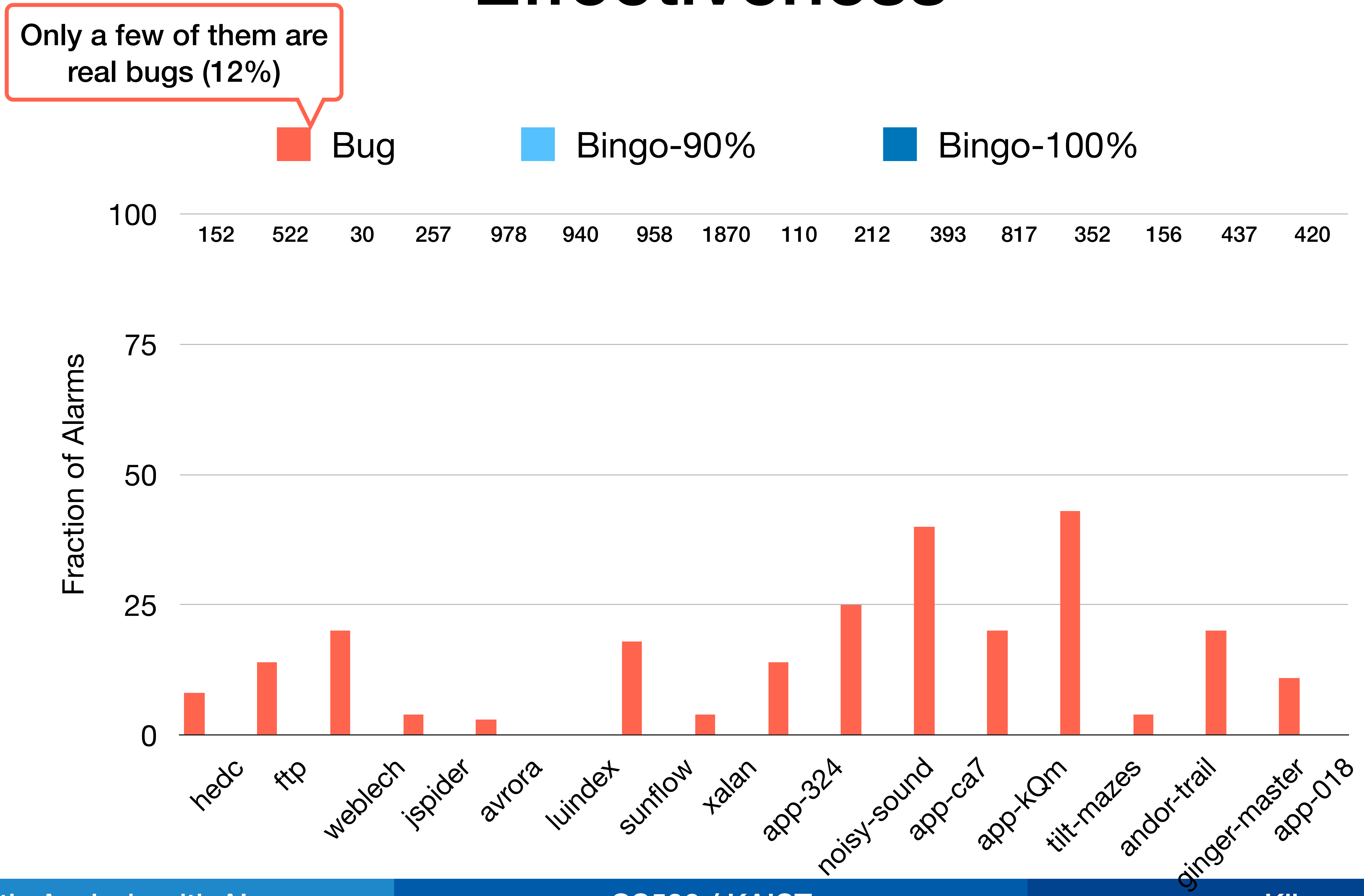
40—616KLOC JAVA Programs
Datarace and Privacy leak analyses

hedc ftp weblech jspider avrora luindex sunflow xalan app-324 noisy-sound app-ca7 app-kQm tilt-mazes andor-trail ginger-master app-018

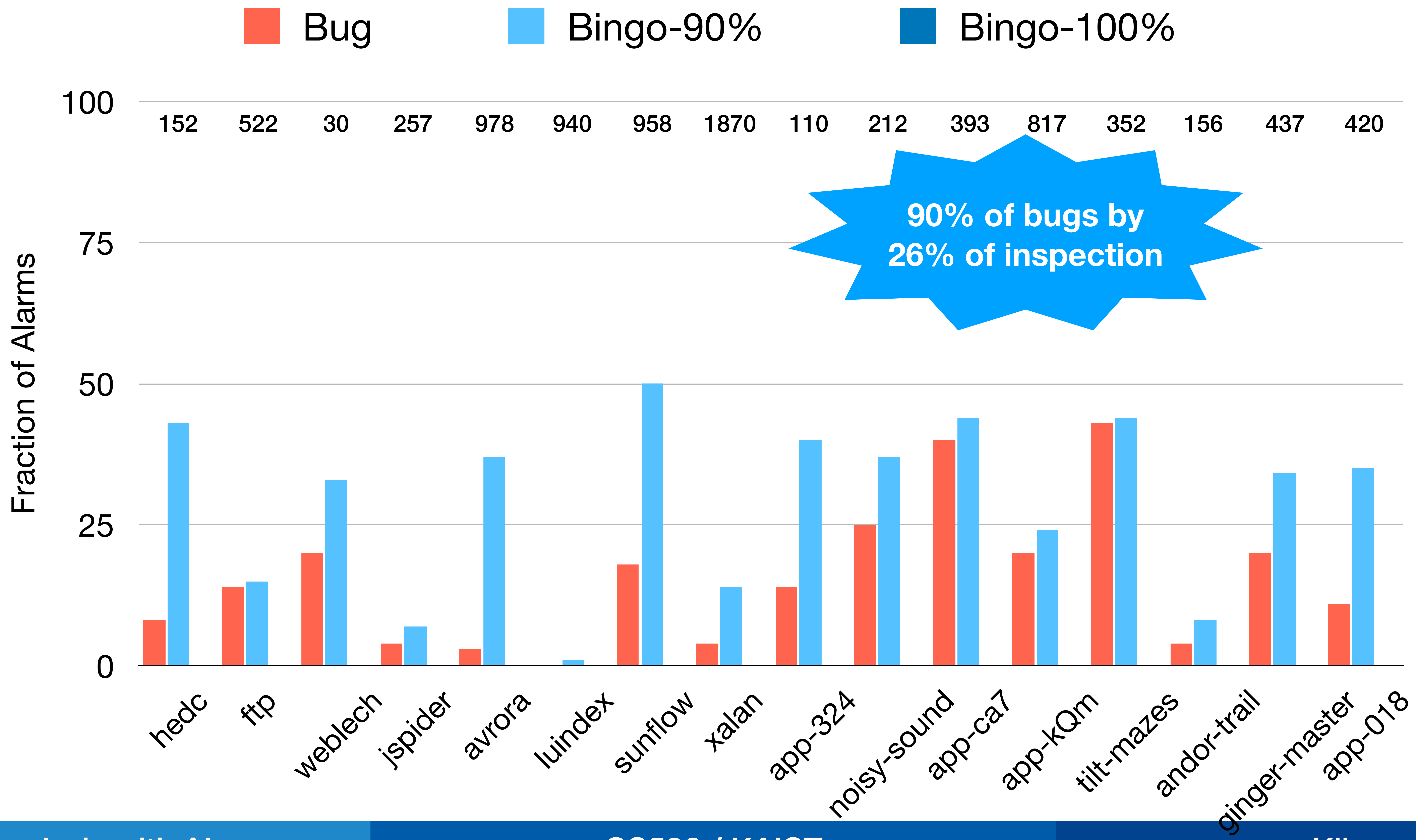
Effectiveness



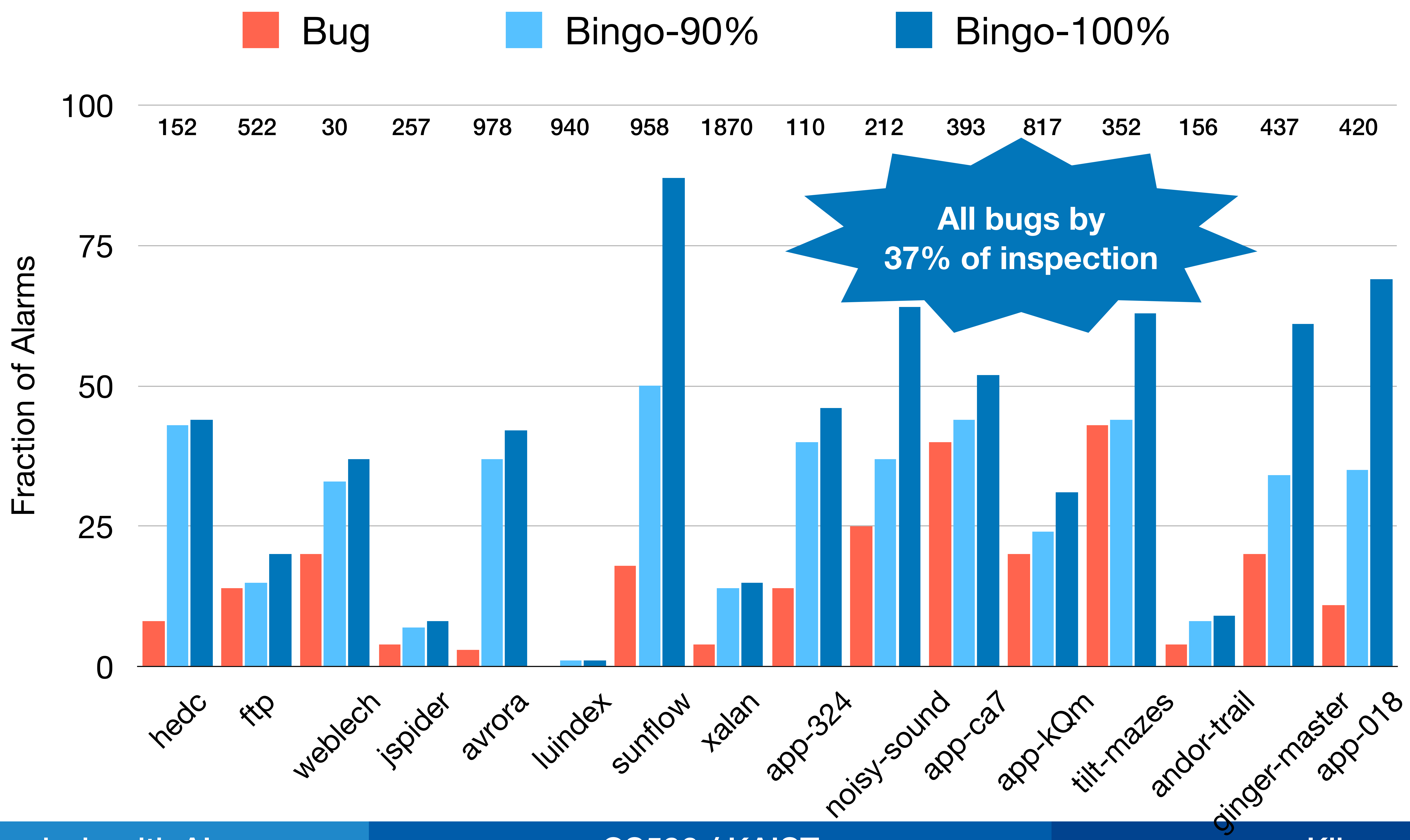
Effectiveness



Effectiveness



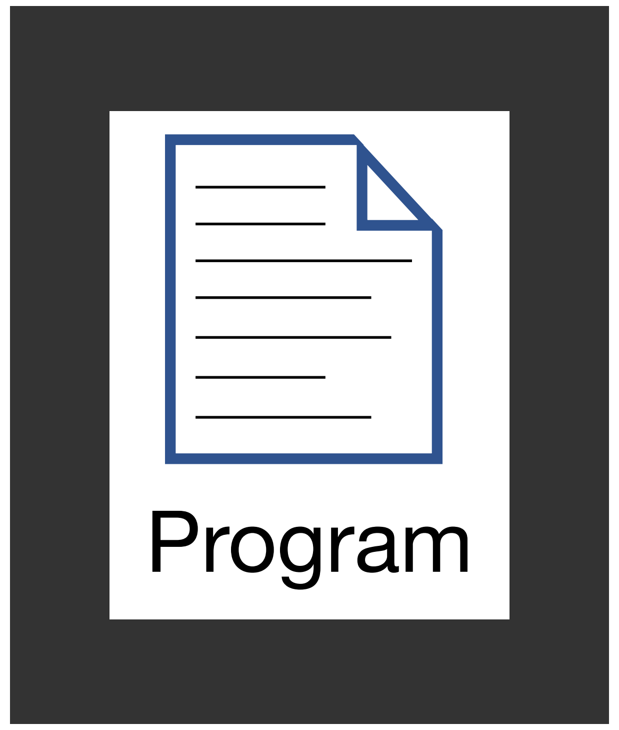
Effectiveness



Outline

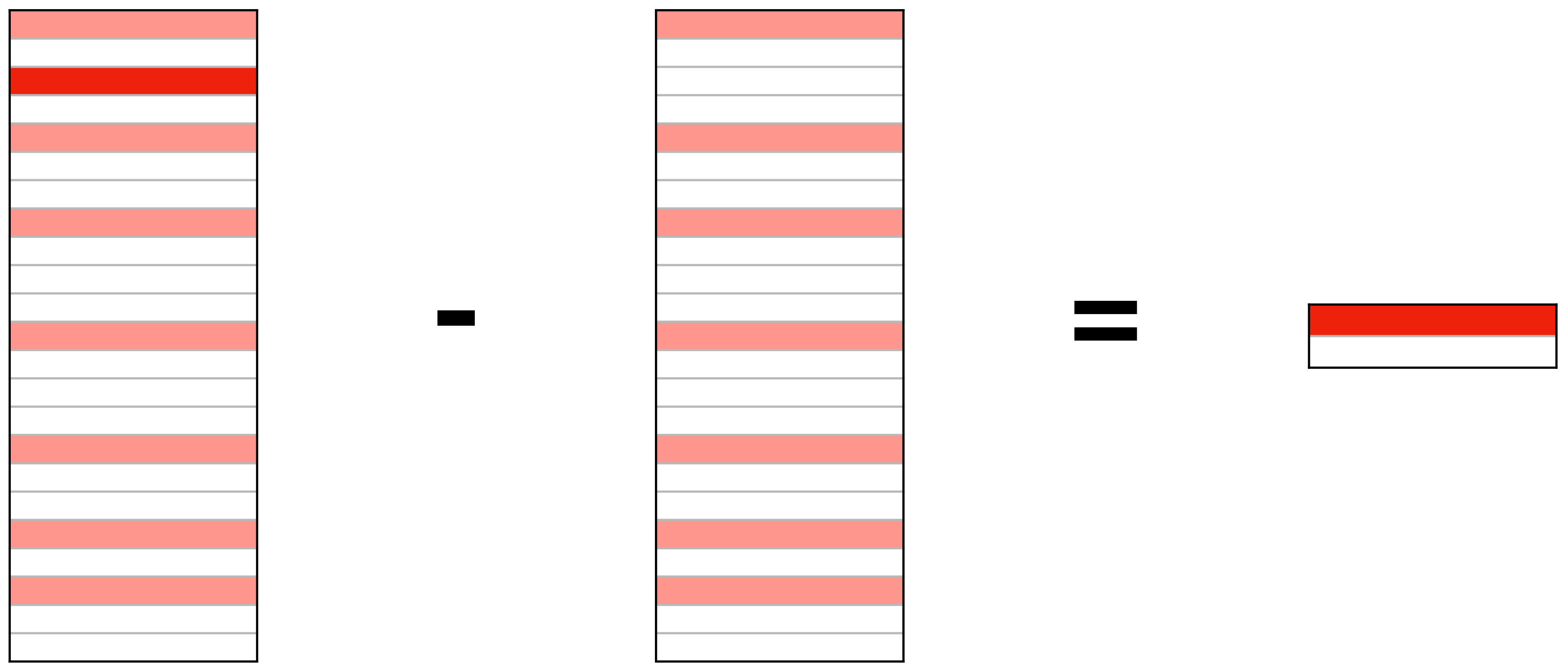
Adaptive Program Analysis

Interactive Program Analysis



Continuous Program Analysis

Drake: Continuous Alarm Masking System [PLDI'19]

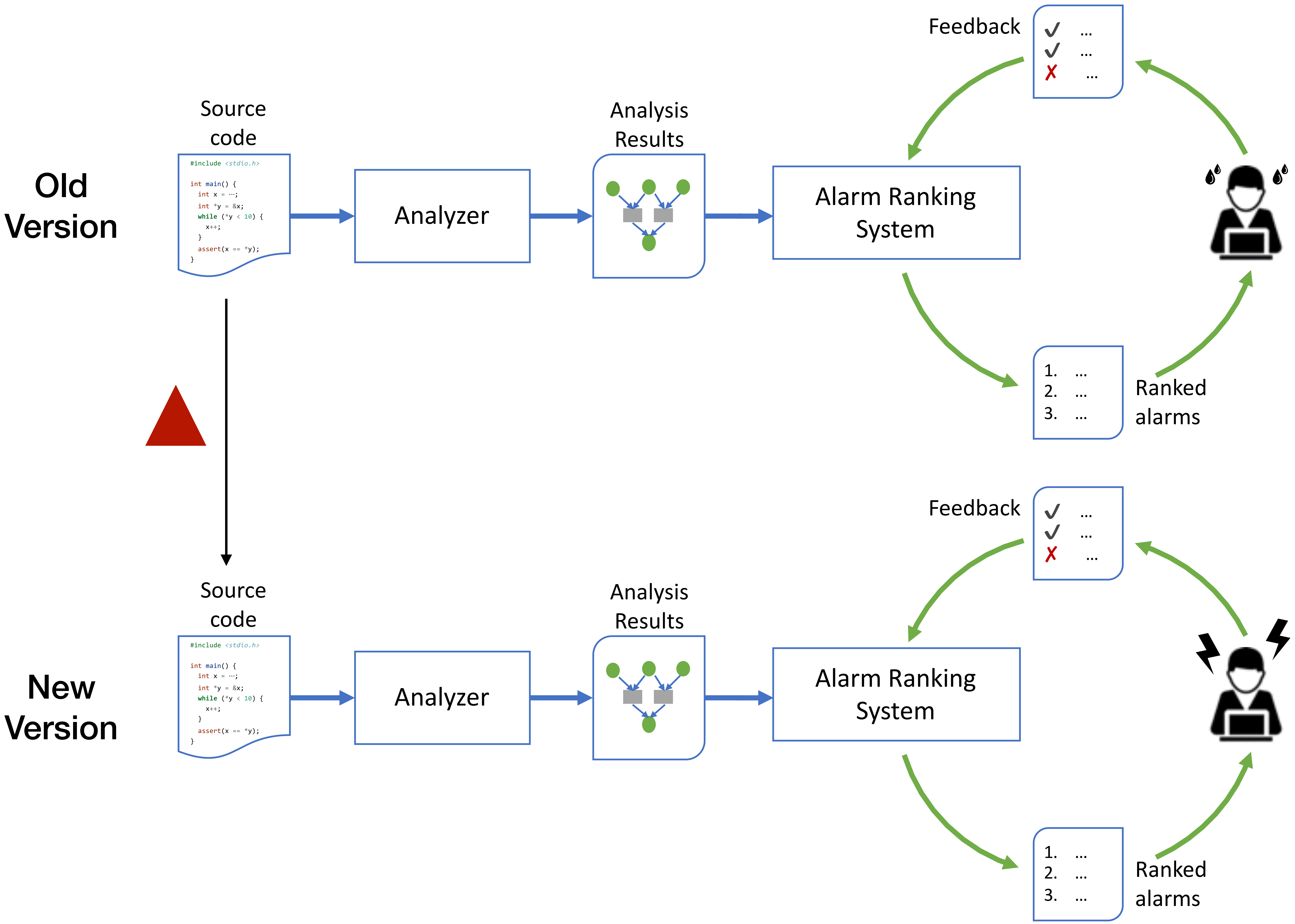


Alarms of New Version

Alarms of Old Version

Alarms Relevant to the Change

Batch-mode Reasoning



Continuous Reasoning

"We only display results for most analyses on **changed lines** by default; this keeps analysis results **relevant** to the code review at hand", - Google, 2015

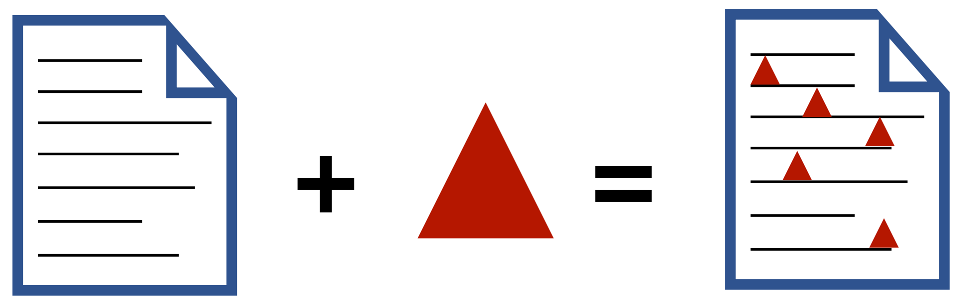
"The vast majority of Infer's impact to this point is attributable to **continuous reasoning at diff time**", - Facebook, 2016

"… is the ability to analyze a **changelist (a.k.a. a commit) rather than the entire codebase.** This functionality can help developers assess the quality and impact of a change …", - Microsoft, 2016

"In order to realize the goal, verification must continue to work with low effort **as developers change the code**. … Neither of these approaches would work for Amazon as s2n is under **continuous development**.", - Amazon, 2018

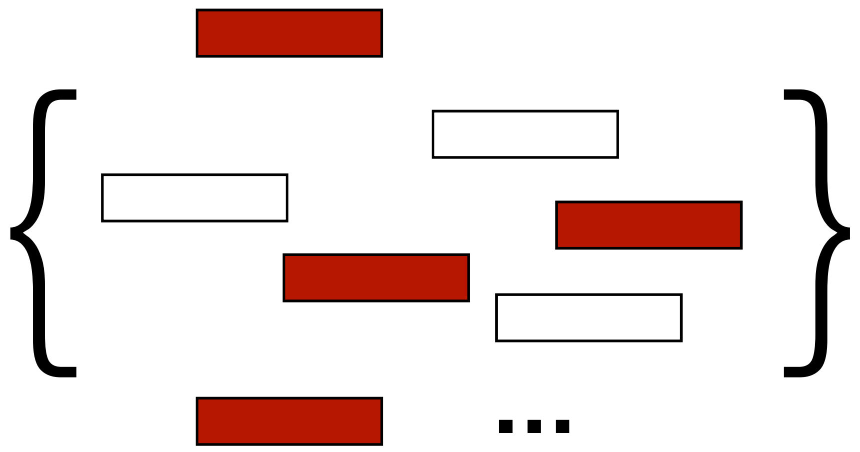
Goal

- Prioritize alarms by their **relevance to the change**



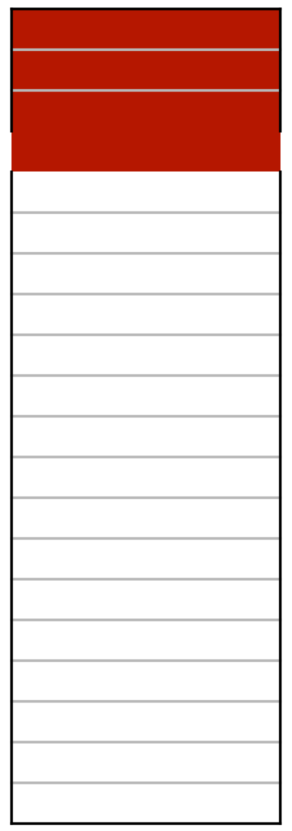
Old Version New Version

Conventional
Batch Mode



Drake

Rank 1



Rank n

: Alarms relevant to the change

: Alarms NOT relevant to the change

Example

Old Version

```
1: x = input();
2: y = input();
3: x = opaque_dec(x);
4: y = opaque_dec(y);
5: x++;  // Alarm
6: y++;  // Alarm
```

x and y can be any integers

Opaque, but “--” actually

Integer overflow alarms at 5 & 6

Example

Old Version

```
1: x = input();
2: y = input();
3: x = opaque_dec(x);
-4: y = opaque_dec(y);
5: x++;   // Alarm ✅
6: y++;   // Alarm ✅
```

New Version

```
1: x = input();
2: y = input();
3: x = opaque_dec(x);
+4: y = identity(y);
5: x++;   // Alarm ✅
6: y++;   // Alarm 🐞
```

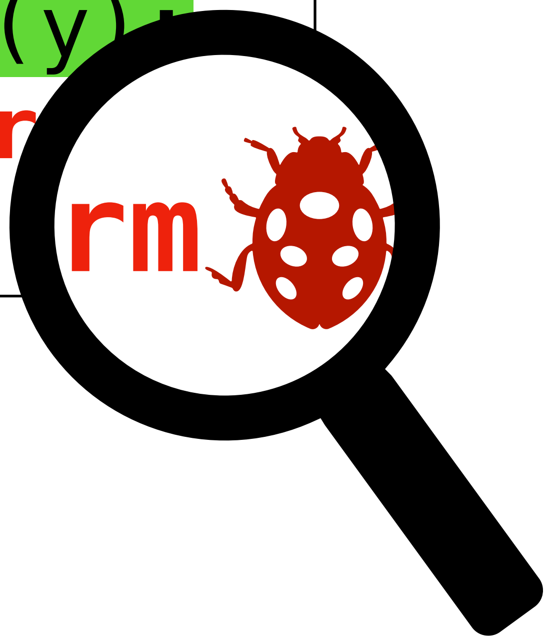
Example

Old Version

```
1: x = input();
2: y = input();
3: x = opaque_dec(x);
-4: y = opaque_dec(y);
5: x++;   // Alarm
6: y++;   // Alarm
```

New Version

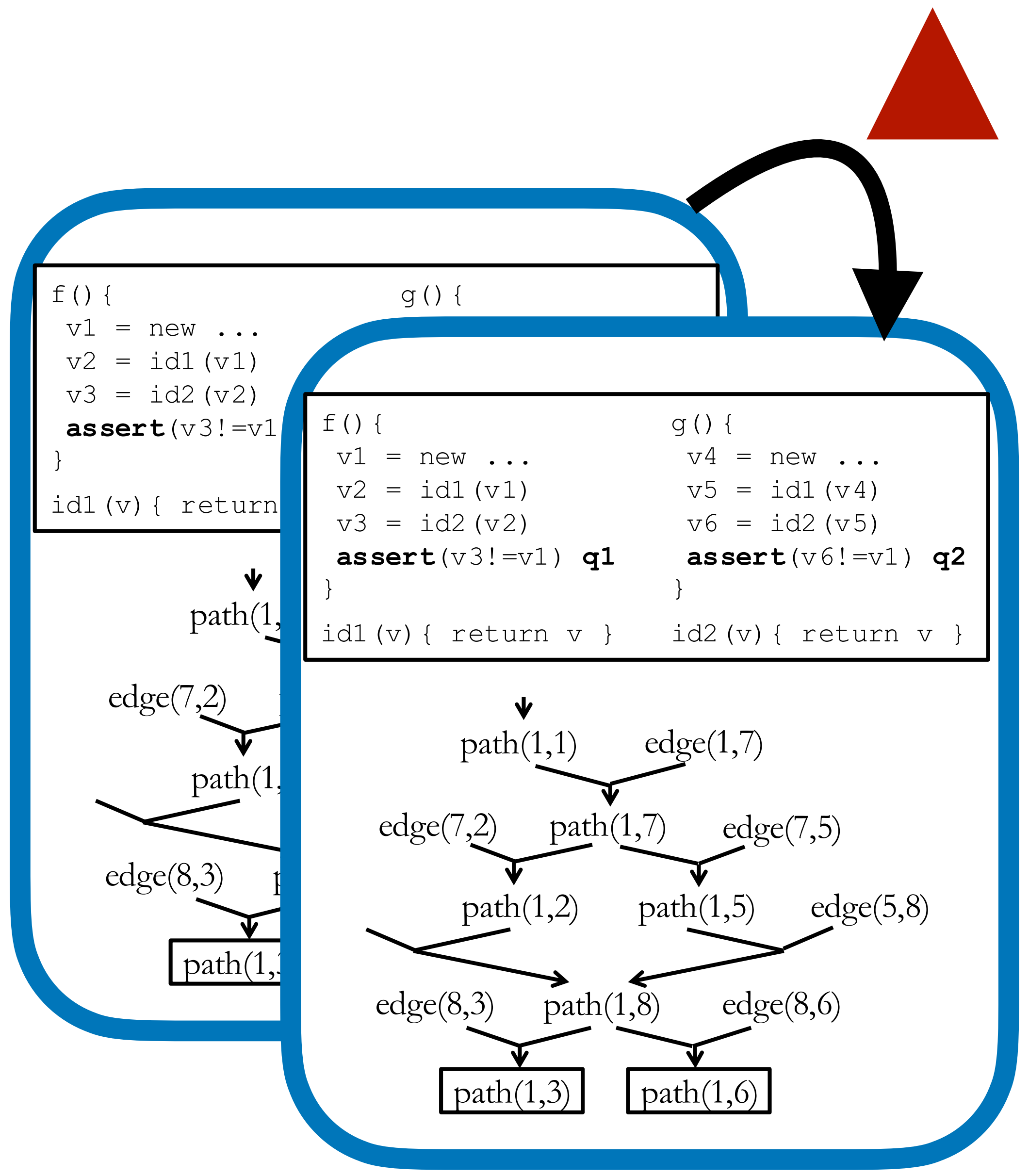
```
1: x = input();
2: y = input();
3: x = opaque_dec(x);
+4: y = identity(y);
5: x++;   // Alarm
6: y++;   // Alarm
```



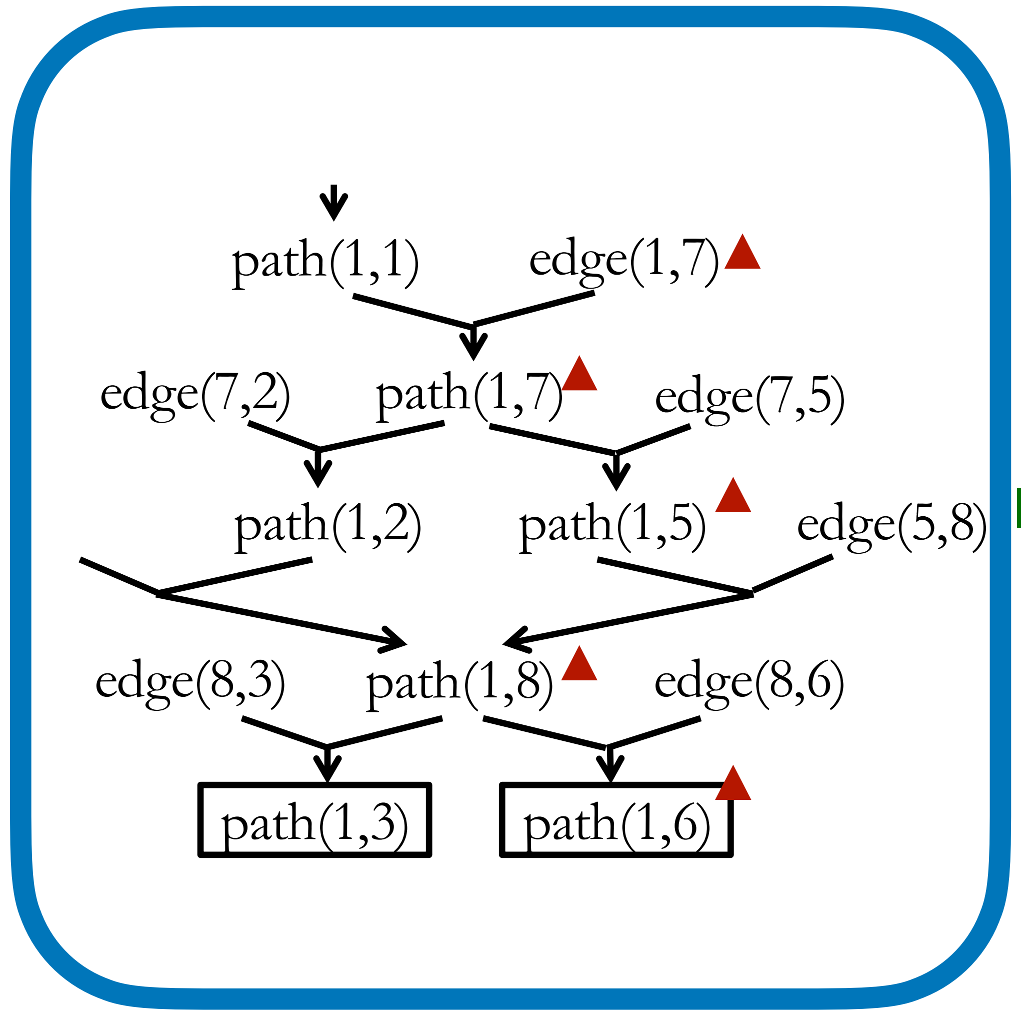
Q: How to emphasize the alarm at 6 that is relevant to this change?

Key Idea

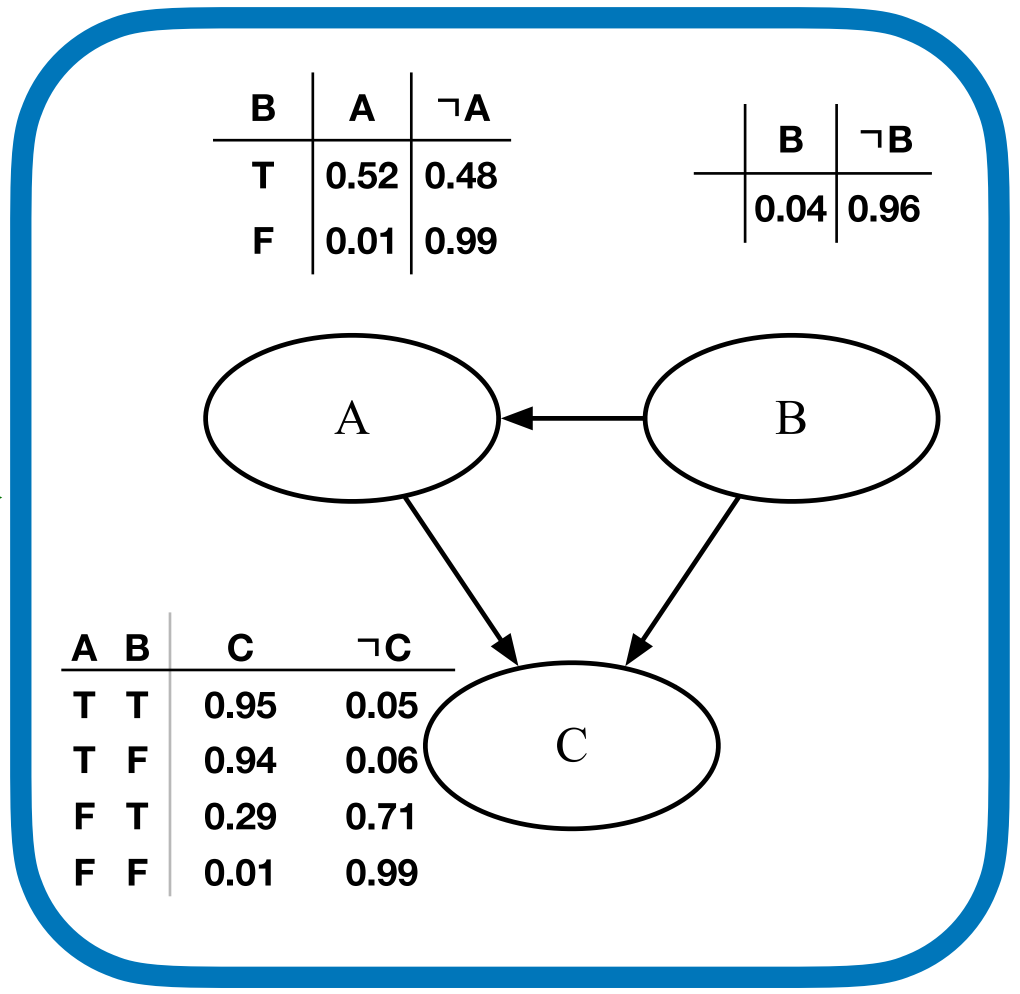
Differential derivation + Bayesian inference



Program Analysis Results
of Two Versions



Differential Derivation



Probabilistic Model
(Bayesian Network)

Program Analysis

Analysis Inputs:

Input(p_1), Edge(p_1, p_2), Inc(p_1)

Read an input at program point p_1

Immediate data flow from p_1 to p_2

Increment expression at p_1

Analysis Rules:

R1: Path(p_1, p_2) :- Edge(p_1, p_2).

R2: Path(p_1, p_3) :- Path(p_1, p_2), Edge(p_2, p_3).

R3: Overflow(p_3) :- Input(p_1), Path(p_1, p_3), Inc(p_3).

Program Analysis

Analysis Inputs:
Input(p_1), Edge(p_1, p_2), Inc(p_1)

Analysis Outputs:
Path(p_1, p_2), Overflow(p_1)

Transitive data flow from p_1 to p_2

Integer overflow at p_1

R$_2$: Path(p_1, p_3) :- Path(p_1, p_2), Edge(p_2, p_3).
R$_3$: Overflow(p_3) :- Input(p_1), Path(p_1, p_3), Inc(p_3).

Program Analysis

Analysis Inputs:
Input(p_1), Edge(p_1, p_2), Inc(p_1)

Analysis Outputs:
Path(p_1, p_2), Overflow(p_1)

Analysis Rules:
R1: Path(p_1, p_2) :- Edge(p_1, p_2).
R2: Path(p_1, p_3) :- Path(p_1, p_2), Edge(p_2, p_3).
R3: Overflow(p_3) :- Input(p_1), Path(p_1, p_3), Inc(p_3).

```
1: x = input();
2: x = opaque_dec(x);
3: x++;   // Alarm
```

Derivation

$$\text{Edge(1,2)} \rightarrow \text{Path(1,2)}$$

Program Analysis

Analysis Inputs:

Input(p_1), Edge(p_1, p_2), Inc(p_1)

Analysis Outputs:

Path(p_1, p_2), Overflow(p_1)

Analysis Rules:

R$_1$: Path(p_1, p_2) :- Edge(p_1, p_2).

R$_2$: Path(p_1, p_3) :- Path(p_1, p_2), Edge(p_2, p_3).

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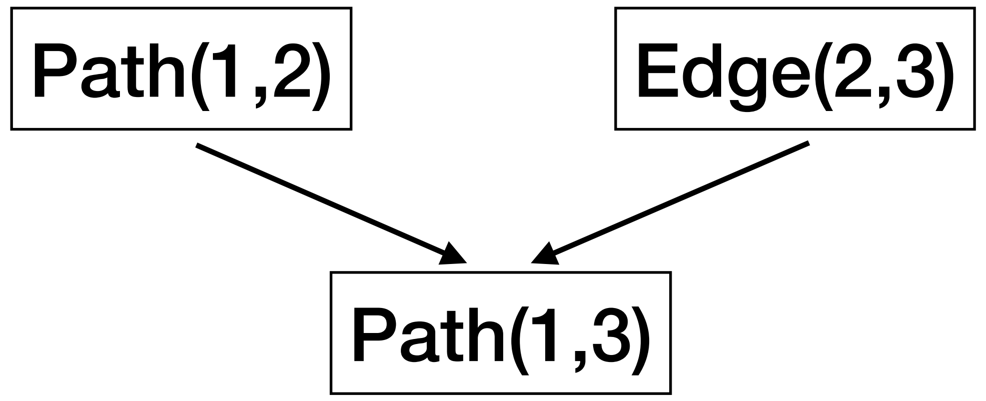
```
1: x = input();
2: x = opaque_dec(x);
3: x++;   // Alarm
```

Derivation



Program Analysis

Analysis Inputs:
Input(p_1), Edge(p_1, p_2), Inc(p_1)

Analysis Outputs:
Path(p_1, p_2), Overflow(p_1)

Analysis Rules:
R1: Path(p_1, p_2) :- Edge(p_1, p_2).
R2: Path(p_1, p_3) :- Path(p_1, p_2), Edge(p_2, p_3).
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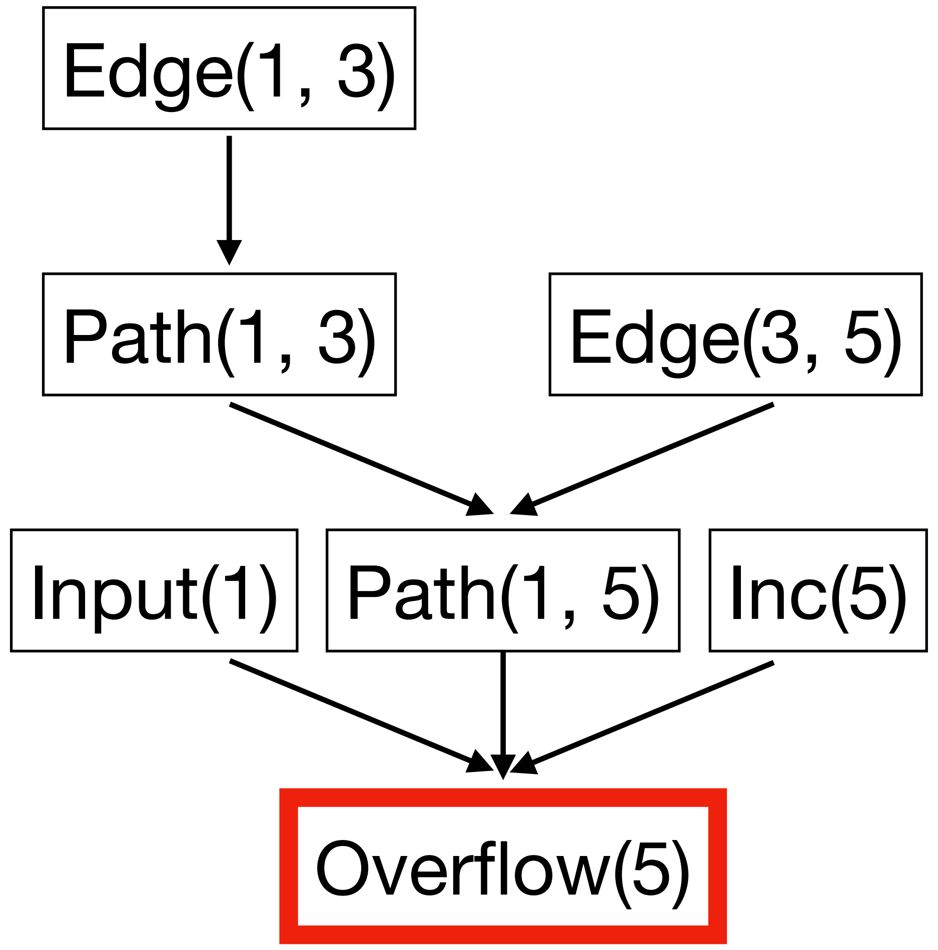
```
1: x = input();
2: x = opaque_dec(x);
3: x++;  // Alarm
```

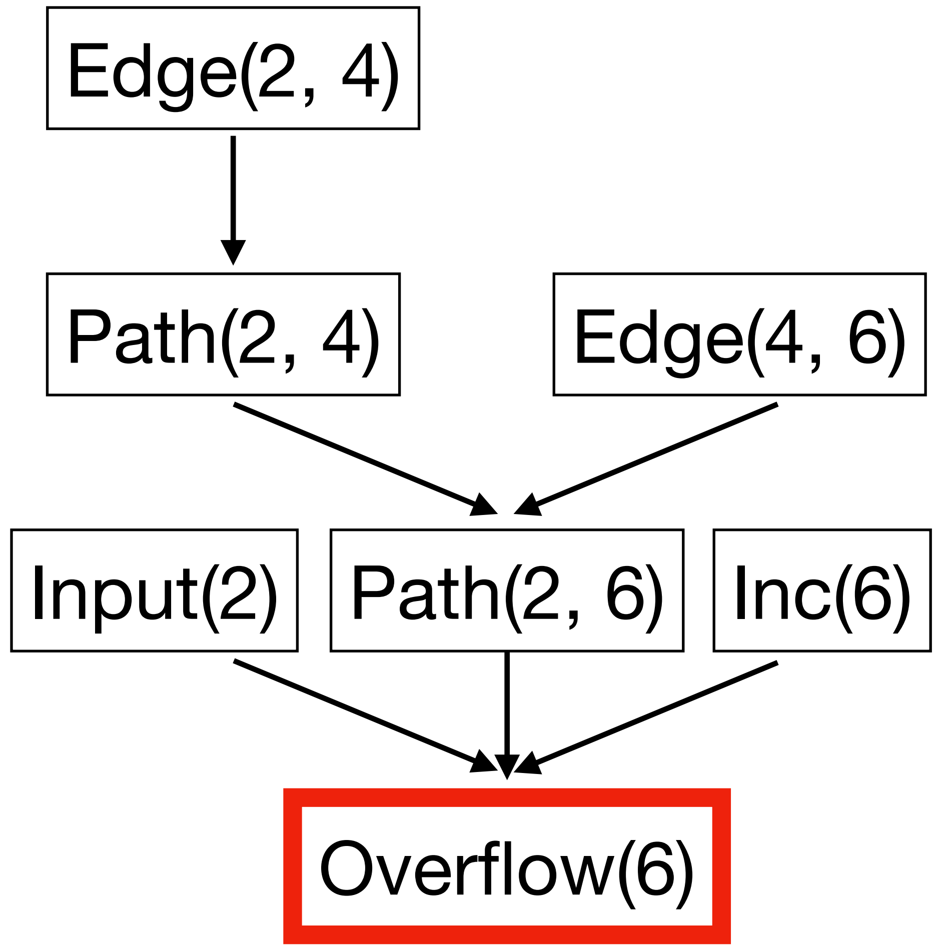
Derivation

Input(1) Path(1,3) Inc(3)
↓
Overflow(1,3)

Differential Derivation

```
 1: x = input();
 2: y = input();
 3: x = opaque_dec(x);
+4: y = identity(y);
 5: x++;  // Alarm
 6: y++;  // Alarm
```



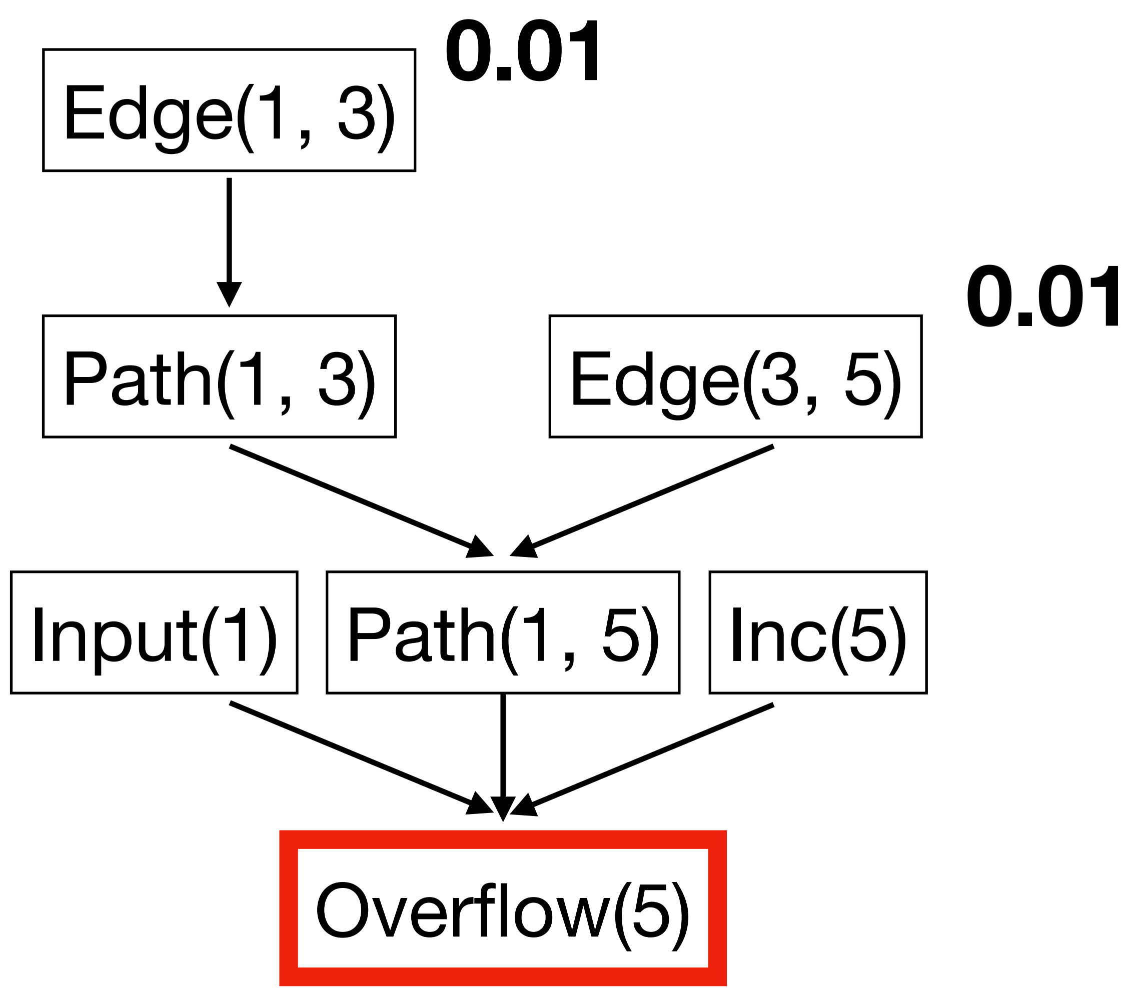


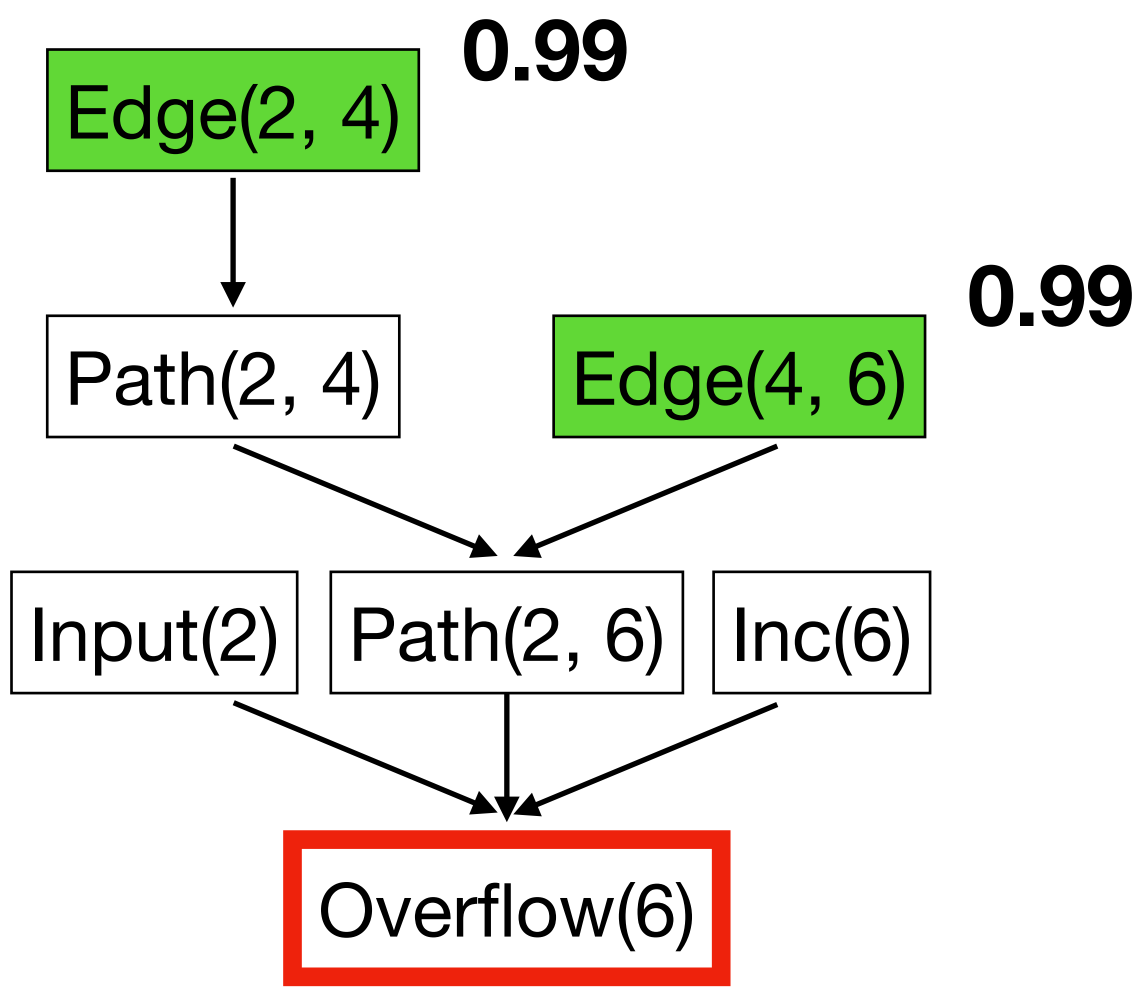
Differential Derivation

```
 1: x = input();
 2: y = input();
 3: x = opaque_dec(x);
+4: y = identity(y);
 5: x++;  // Alarm
 6: y++;  // Alarm
```

Relevance Score

```
 1: x = input();
 2: y = input();
 3: x = opaque_dec(x);
+4: y = identity(y);
 5: x++;  // Alarm
 6: y++;  // Alarm
```





Relevance Score

```
 1: x = input();
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 3: x = opaque_dec(x);
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```
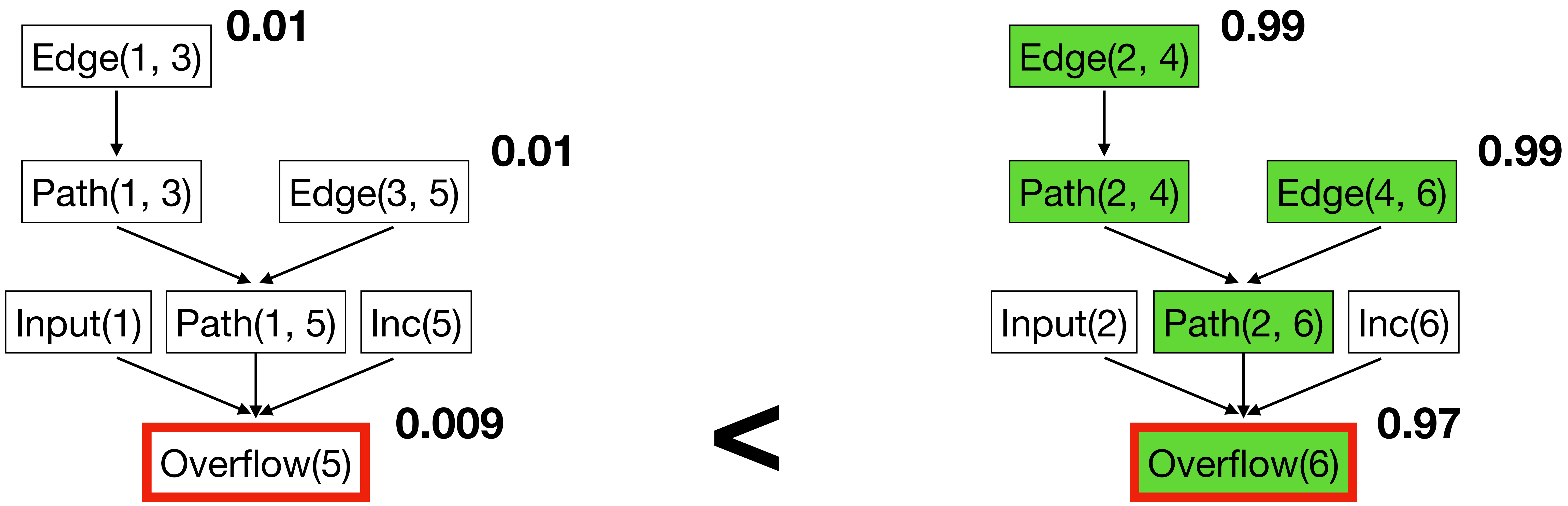
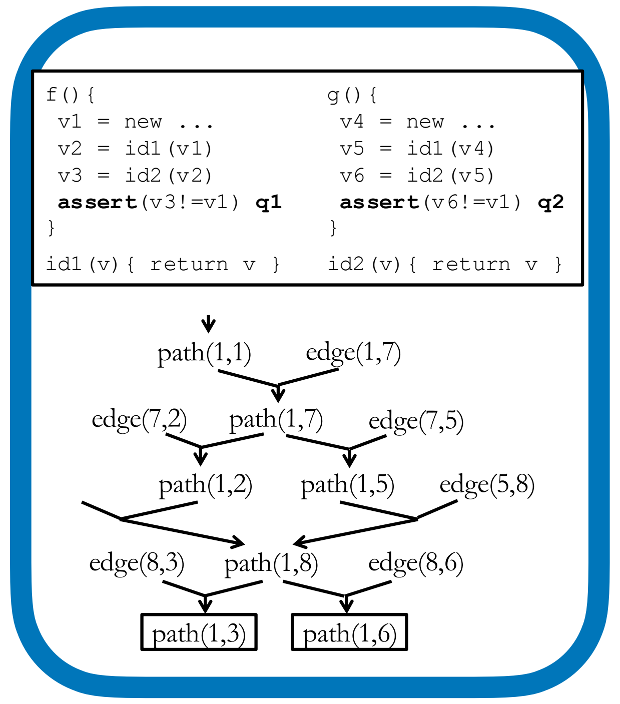



Effectiveness

13—112KLOC C Programs (old and new)
3 bugs on average
Buffer overrun and Integer overflow analyses

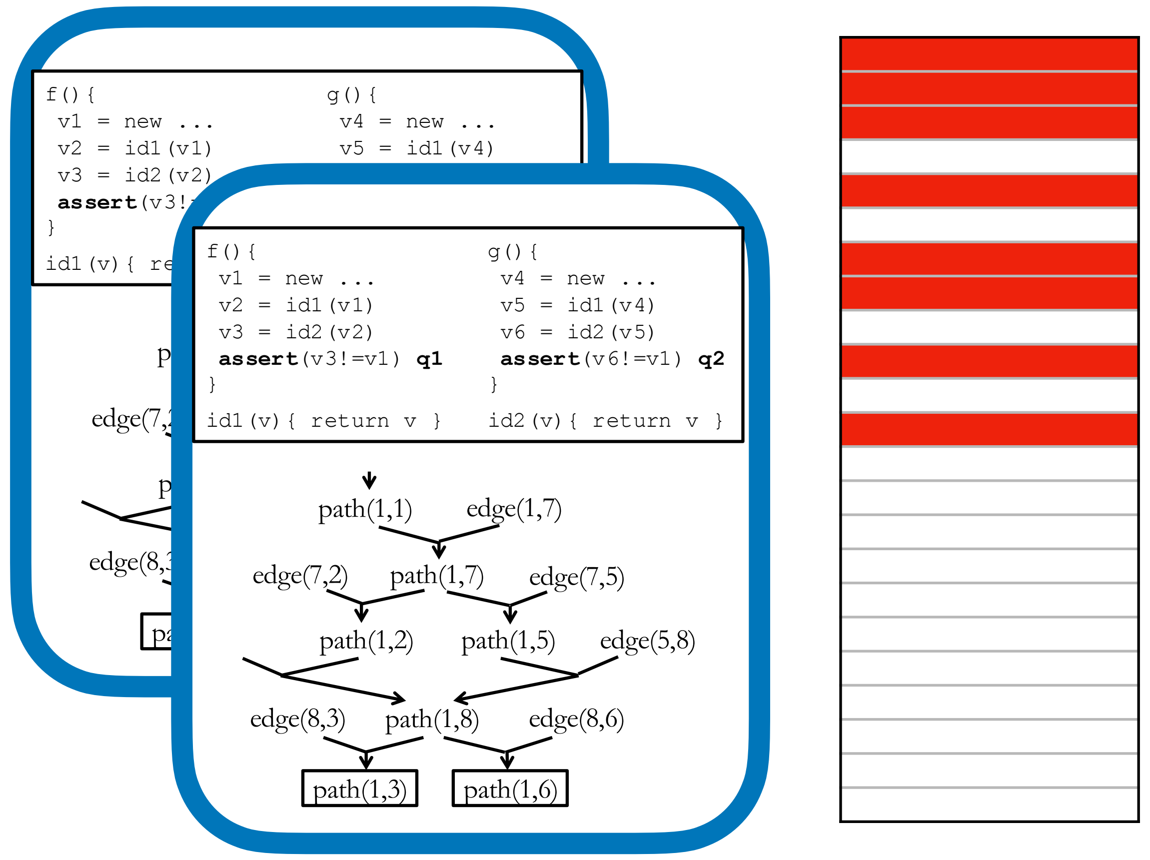
Effectiveness

Avg. inspection burden
to discover 3 bugs on average



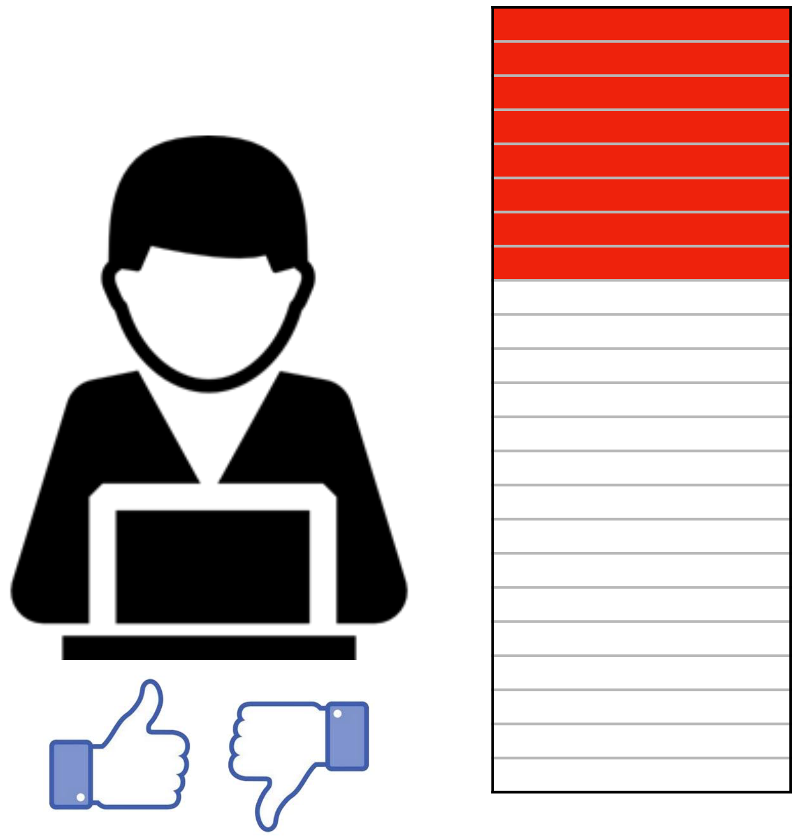
Batch mode

All bugs are interspersed in
563 alarms



Ranking by relevance

All bugs located in
up to rank 94



\+ Ranking by interaction

All bugs are founded
up to 30 iterations

Summary

- Towards next-generation program analysis systems with AI
  - **Adaptive**: automatically find a right abstraction
  - **Interactive**: incorporate user's feedback
  - **Continuous**: keep track of code changes
- Need a lot more research on making AI understand program code
  - E.g., feature engineerings, learning methods, etc